physiological objectives in HOT WEATHER HOUSING

an introduction to
HOT WEATHER
HOUSING DESIGN

410-Climate

for use of
UNITED STATES
A.I.D. MISSIONS

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FOREWORD

This study and report was undertaken in 1953 at the suggestion of the International Housing Activities Staff, now known as the Office of International Affairs of the Department of Housing and Urban Development, in order to provide a simple description of the basic physiological principles which should be observed in the design and planning of housing for hot climates. It is intended for use in connection with shelter improvement work in underdeveloped countries which are participating in the technical assistance program.

The report was prepared by Dr. Douglas H. K. Lee, Professor of Physiological Climatology at the Johns Hopkins University under a contract with the United States Government, Department of State, Technical Co-operation Administration, Institute of Inter-American Affairs (now the Agency for International Development).

Dr. Lee, who also made the revisions for this edition, is now Chief, Occupational Health Research and Training Facility, Public Health Service, U.S. Department of Health, Education, and Welfare, Cincinnati, Ohio.

Technical advice and suggestions, and editing of the final report for publication were the responsibilities of the Division of International Affairs.

Osborne T Boyd

Senior Housing and
Urban Development Advisor
Agency for International Development

Thomas R. Callaway

Director
Division of Technology & Documentation
Office of International Affairs
Department of Housing & Urban Development

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INTRODUCTION

ALL WILL AGREE that housing should protect the dweller against the physical stresses of the environment; but the question of how to achieve this gives rise to a wide diversity of opinions. At one extreme is the view that the technology of western nations can provide a practically complete answer and that their practices should be followed. At the other extreme is the belief that "native" people, long resident in an area, must have discovered what protection is necessary, and must have incorporated it in their building practices.

It is not difficult to discover absurdities in either of these extremes. Western technology is geared to western cultural ideals, western material resources, and western living requirements. Indigenous practices, on the other hand, have been selected from a quite limited range of possible methods, are often inextricably mixed with religious requirements and taboos, and are linked to an economic situation, which, in many cases, is rapidly being supplanted. The truth must lie somewhere between these extremes. There are undoubtedly many indigenous building practices admirably suited to the physical conditions of the region and protection of the dwellers therefrom. There are undoubtedly many ideas or even specific techniques which indigenous peoples might well borrow from western culture. But *the selection in each case must be made with understanding and judgment,* and not on the basis of some vague belief in the superiority or adaptive value of one or other culture.

In this confusion, worse confounded by the material and cultural hangovers of a global war, with the too frequent adoption of the trappings rather than the spirit of western civilization, reason must be a primary guide. From a clear statement of the problem, a thorough review of methods of attack, and a critical application of those methods, it should be possible to formulate at least the principles of housing requirements for the guidance of those called upon to assist the less developed areas. If, in the development of the principles, due attention is given to information derivable from indigenous housing practices as well as to more recent western theory, then those principles should be entirely adequate for at least initial use. Indeed, one would hope that the only modification required as time brings greater experience would be in the details of their use.

The principles should be applicable over a wide area, but the exact manner in which the application can be made will necessarily vary greatly from place to place, or group to group. The availability of materials, the economic resources of the people, the religious and other traditions of the group, the detailed living habits of the dwellers, the necessity for security against predators (human as well as animal), requirements for disease control, and a number of other factors may greatly influence or even dictate just how the purpose is to be achieved. But it is this very multitude of detailed demands and possibilities that makes the possession of clearly established principles so necessary. When one knows quite clearly what it is that one is trying to achieve, then one is in a good position to make the best use of what one has, and to get as close to the target as is humanly possible.

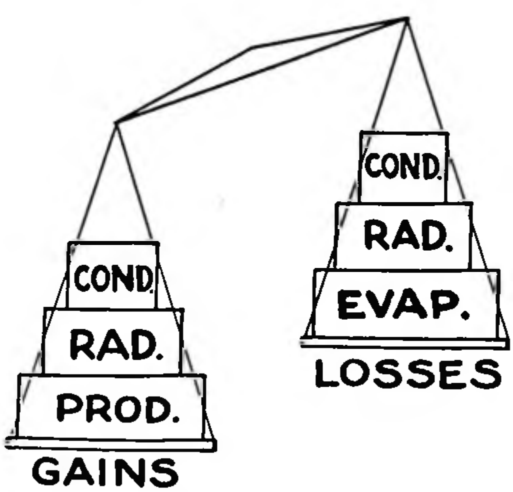
The purpose of this booklet is to present those principles, the observance of which it is believed would minimize the direct effects of hot environments upon man, insofar as housing and shelter can do this. Its addition to the series of documents dealing with the technical assistance program is prompted by the fact that these principles emerged from studies of human climatology, and may thus not be very well-known to those who have had conventional training in architecture and related practices. Their formulation is made the more timely by the fact that imitation of the less worthy features of western construction and the indiscriminate use of materials salvaged from former military operations are rapidly undermining good indigenous practices in many regions, with results which are often more tragic than ludicrous.

Experience has shown that much of the misunderstanding which exists on the utilization of housing as a protection against climatic stress stems from an incomplete realization of what makes up weather and climate, coupled with an incomplete understanding of the way in which climatic elements may act upon man to produce certain undesirable effects. To ensure that the principles themselves shall be understandable and appear for what they are—logical deductions from present knowledge—their enunciation will be preceded in this booklet by a simplified analysis of tropical and subtropical climates, and by an explanation of the way in which they act upon man. Principles of housing will first be developed in some detail for a typical hot dry environment; and then those applicable to a typical warm humid environment will be presented in contrast. Finally, modifications of these basic principles will be discussed to meet more common combinations of climatic types and certain special cases. While some specific methods of application may be mentioned by way of illustration, no attempt will be made to provide detailed instructions for each of the endless variety of cases that must arise in this inconstant world.

SIGNIFICANCE of HOT ENVIRONMENTS for MAN

AS ANY automobile driver knows, machines may have difficulty in hot weather in getting rid of the heat they produce, to the detriment of efficient operation and possible danger to the machine. Man, too, is a machine, producing heat in proportion to his activity and method of operation; but a machine in which the permissible rise of temperature (2°–3°F.) is very much less than in an automobile, and the heat-regulating devices correspondingly more complex and sensitive.

For a due appreciation of the way in which housing can help or hinder his efficient operation in hot environments, it is necessary to examine man's heat regulating mechanism, and the effect upon it of those environmental conditions which may be influenced by housing



HUMAN HEAT BALANCE

Bodily heat regulation is essentially the maintenance of a balance between gains of heat on the one hand and losses on the other. While one thinks of the tropics and even the subtropics as regions in which the problem is essentially that of losing heat rapidly enough, it must not be forgotten that there are occasions when the problem may be one of conserving heat, as in the desert at night or at some elevation above sea level. On each side of the heat balance there are a number of items, as shown in table 1, which merit some description.

Even at complete rest man produces an important quantity of heat—the so-called basal heat production--amounting to 290 B. t. u./hr. for an average adult man. For short periods of time he can increase this rate of production eightfold by violent exercise; but over the normal 24 hours the average heat production would not amount to more than 130 percent of the basal rate for sedentary workers and 300 percent for heavy manual laborers. Bodily processes connected with the eating and digestion of food and assimilation of the digestive products contribute their quota to this total.

Three modes of heat exchange between the body and its surroundings are shown in table 1—radiation, conduction, and water vapor transfer. The simplest of these is *conduction*. It is a well-known fact that, when two objects at different temperatures are placed in contact, heat passes from the warmer to the cooler. Conduction is the name given to this transfer of heat by contact. When the foot is placed on hot ground, for example, heat passes from the ground into the foot, and at a rate determined by some physical properties best summed up as the "thermal diffusivities" of the ground and the foot respectively. In the case of heat transfer between the skin and air, the rate of transfer is further influenced to an important extent by air movement. In perfectly still air the rate of heat transfer is slow; but any movement of the air tends to replace the air next to the skin, which has already come close to skin temperature, with fresh air from outside, and thus speeds up the transfer. It is important to realize that heat can pass by conduction in either direction, toward or away from the body, depending upon which is the hotter, the skin or the contacting air. *Air movement will simply speed up this transfer in whichever direction it is already taking place.*

Table 1.—Heat Balance of the Body

Gains	Losses
1. Heat production by: a. Basal processes b. Activity c. Digestive, etc. processes d. Muscle tensing and shivering in response to cold	
2. Absorption of radiant energy: a. From sun: direct reflected b. From glowing radiators c. From nonglowing hot objects	5. Outward radiation: a. To "sky" b. To colder surroundings
3. Heat conduction towards body: a. From air above skin temperature [1] b. By contact with hotter objects	6. Heat conduction away from body: a. To air below skin temperature [1] b. By contact with colder objects
4. Condensation of atmospheric moisture (occasional)	7. Evaporation: a. From respiratory tract b. From skin: [1] perspiration sweat applied water

[1] Hastened by air movement (convection).

Heat loss by *evaporation* can be examined in very much the same fashion as heat loss by conduction. As water evaporates it absorbs heat from its immediate neighborhood; but this evaporation and the consequent cooling can continue only if the evaporated water vapor is free to move away from the site of evaporation. The ease with which heat is lost from the skin by evaporation depends, therefore, upon the difference between the vapor pressure at the skin surface and the vapor pressure of the surrounding air; just as the ease with which heat is lost by conduction depends upon the difference between the temperature of the skin and the temperature of the surrounding air. (The vapor pressure at the skin surface depends very largely upon the extent of the water film present on the skin, and this may vary from less than 10 percent of the skin area on a cool, dry day to 100 percent when one is bathed in sweat. The vapor pressure of the air, on the other hand, is naturally determined by the amount of water vapor present in it.) Air movement increases the rate of heat loss by evaporation, in the same way as it increases the rate of heat transfer by conduction, since it replaces the saturated air in contact with the skin with fresh air from outside.

While in the case of heat conduction the exchange could readily occur in either direction, to or away from the body, in the case of water vapor transfer the reverse process, i. e. heat gain by condensation, seldom occurs; so that, for all practical purposes, increased *air movement* can be regarded as always *promoting heat loss by evaporation*, although it may work in *either direction for heat exchange by* *conduction.* The net result of increasing air movement will depend upon the relative sizes of these two processes. In this connection it may be said that increasing air movement will always have the effect of increasing the net loss of heat *except under quite hot and dry circumstances* (e. g., air temperature over 105° F., vapor pressure less than 15 mm. Hg, and strong solar radiation).

The physics of heat exchange by *radiation* is rightly regarded as complex, but even here it is possible to reduce the problem to a few fairly simple statements for ease of understanding and approximate calculation. Some such appreciation of its operation is essential, since one of the most important functions of housing in hot regions is to intercept the solar radiation which would otherwise fall on the body and produce an undesirable heat load. A man out of doors is involved in two somewhat different types of radiation—(*i*) visible and short infrared radiation, which will be called solar radiation for brevity, since it originates in the sun; and (*ii*) long infrared, which will be called thermal, since it is due to differences in temperature between the surface of the man and those of surrounding objects such as the ground and buildings. Radiation operates through five channels, as shown in table 2 and figure 1.

The heating effect of *direct solar radiation* is familiar to all. Its intensity on a clear day can reach 320 B. t. u./sq. ft.,hr. on a surface at right angles to the solar beam. The amount of surface presented by man to this radiation varies with the altitude of the sun (angle that the solar beam makes with the horizontal), and with his posture. Because of the high altitude of the mid-day sun in the tropics, the time of greatest receipt by an upright man is not at noon, but between 9 and 10 in the morning and 2 and 3 in the afternoon, when the sun shines more directly upon the vertical parts of his body. Of the solar radiation which falls upon him, only a part is absorbed and converted into heat; the remainder is reflected. About one-half of the solar radiation is in the visible portion of the spectrum, and color is fairly good indication of how much reflection is taking place in this portion; white materials and skin reflecting 90 percent or more, black materials and skin 15 percent or less. Reflection in the remaining half of the solar radiation, the short infrared, is less affected by color, although it is still something of a guide; white reflecting 60 percent and black 40 percent.

Table 2.—*Channels of Radiation Exchange*

Channel	Spectral type
Solar radiation direct	Visible and short infrared.
Solar radiation reflected from cloud, etc.	Visible and short infrared.
Solar radiation reflected from ground, etc.	Visible and short infrared.
Thermal exchange with ground, etc.	Long infrared.
Thermal loss to "sky"	Long infrared.

Wavelengths

Visible	0.3 to 0.7 microns.
Short infrared	1.7 to 2.5 microns.
Long infrared	over 2.5 microns, usually 5–20 microns.

If one holds a disk between one's eye and the sun it is evident that an important quantity of light is being reflected from particles in the air even on a perfectly clear day. With a high altitude sun in a clear sky this amounts to some 15 percent of the intensity of direct radiation (on a horizontal surface) when the whole vault of the sky is exposed; with a low altitude sun the percentage is greater, though the total amount is less. A light haze over the sky may increase the amount of reflection more than it interferes with direct radiation. The maximum effect is obtained when large cumulus clouds float in the sky but none lies between the observer and the sun. The maximum intensity of solar radiation to be received on a horizontal surface from direct and sky reflected solar radiation combined is about 350 B. t. u./sq. ft.,hr.

It is well known that sunlight reflected from dry light soil, white sand, dried lakes, and clouds can reach painful intensities. This reflected visible radiation is accompanied by reflected short infrared, and the two combined can represent an important heat load, amounting, on the vertical surface of an upright man, to one-quarter or more of the intensity of solar radiation on the horizontal ground. Towards reflected solar radiation, whether from sky or terrain, materials and skin show much the same reflectivity as they do towards direct sunshine.

Apart from any reflection of solar radiation, *ground and other surrounding objects will exchange radiant heat with the body* if they are at temperatures different from that of the body surface. In the hot dry regions, as will be seen later, ground and building surfaces may become appreciably warmer than

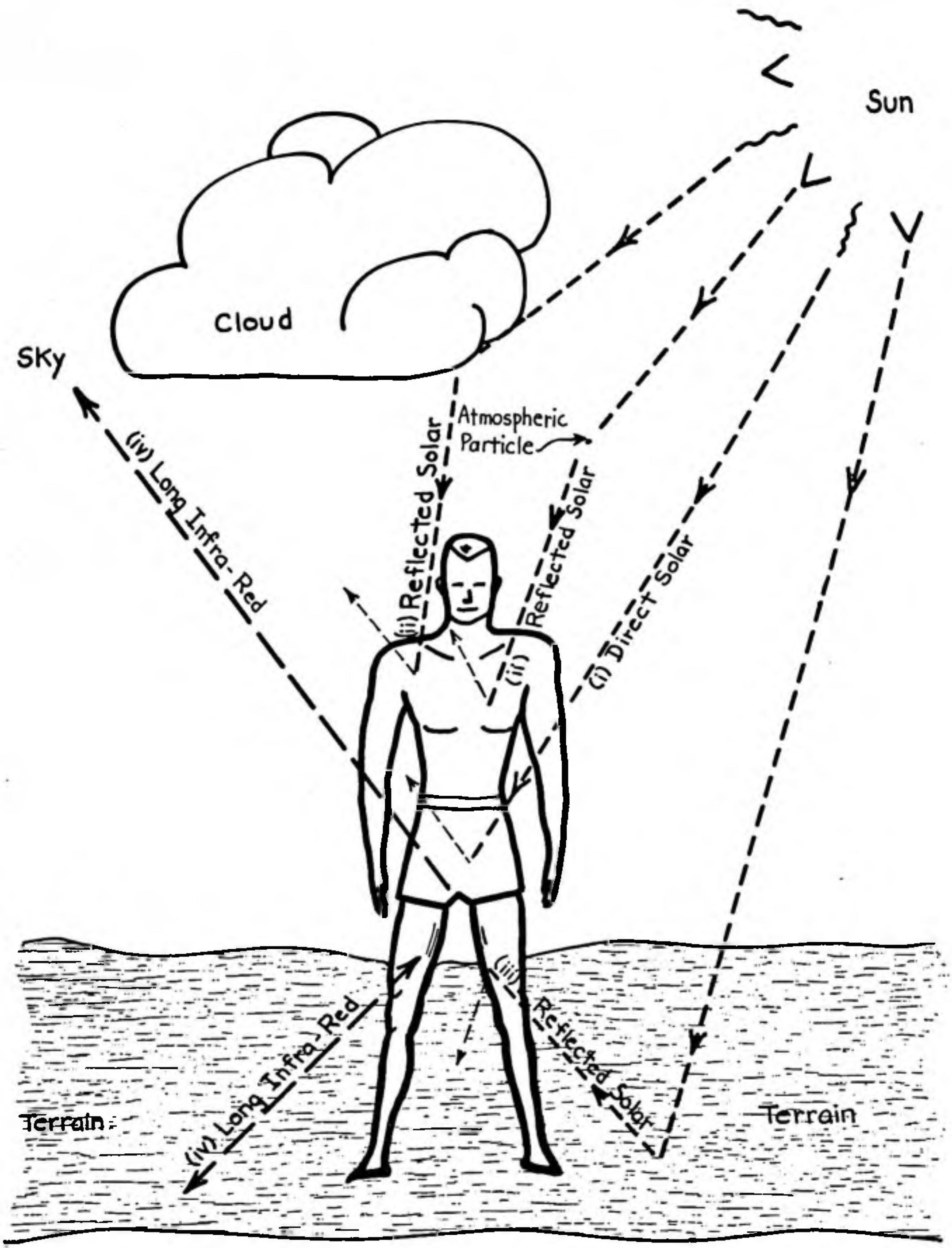


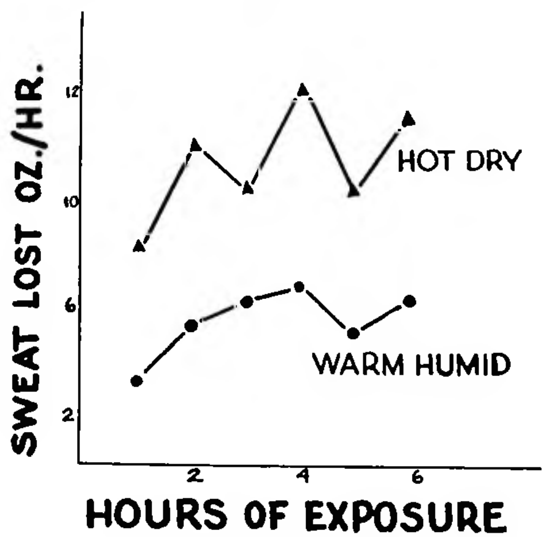
Figure 1.—Radiation Exchange between Man and Surroundings—Visible and short infrared radiation from the sun falls on the body (*i*) directly, (*ii*) after reflection from clouds and particles in the atmosphere, (*iii*) after reflection from the ground. Varying proportions of this incident radiation are reflected from the skin or clothing. Long infrared radiation is exchanged between man and the ground, and lost from man to the "sky."

the body, so that the amount of heat gained by radiation from such sources may be quite important. This radiation is of long wave type, and towards it most surfaces are almost completely absorptive, showing no reflectivity. *Color is of no consequence in considerations of long infrared exchange.* Polished metal surfaces, however, do show marked and sometimes quite high reflectivities towards it, and thus possess some useful protective qualities.

The fifth item in table 2, that of *radiation loss to "sky,"* has been too long neglected, and has some important significance for building practice. If there were nothing between a man and outer space, he would rapidly lose heat to it by radiation, since it virtually has a temperature of —459° F. The atmosphere acts as a barrier, however, so that in reality a man on an open plain radiates to a hemisphere at some intermediate temperature. In the warm humid regions this temperature is not very different from ground temperature; but in dry regions it may be substantially lower (40° F.). Since this is the only channel of radiation loss under such conditions, it has an important significance.

From what has been said, it will be clear that *four climatic elements—temperature, humidity, air movement, radiation—affect man's heat loss.* In this, the elements do not act in isolation, but conjointly. *Their effects are to be ascribed*, not to the elements individually, but *to all four in combination.* The net effect of all four is termed the *heat stress* upon the individual.

CONSEQUENCES of HEAT STRESS



When man fails to lose heat at the same rate as he is gaining heat the results are dramatic and disastrous. *Heat stroke* is a condition in which the body temperature rises to dangerous heights, with unconsciousness and death unless relief is given. Fortunately, this *is rare.* Man's heat-regulating mechanism is excellently designed for coping with those hot environments which occur naturally; in fact, it might be said that a healthy, acclimatized man will not develop heat stroke under naturally occurring climatic conditions unless he is laboring under exceptional emotional stress. Of some 190 cases of heat stroke occurring in the United States Army during World War II, all occurred in the United States and during recruit training. Many of the cases reported as heat stroke or "sun" stroke in times past were probably cases of infection with malarial or other fever-producing organisms, perhaps combined with excessive activity, shortage of water, or other conditions interfering with healthy heat regulation.

Man has an excellent heat-regulating mechanism which seldom lets his body temperature rise to dangerous levels; but this mechanism makes severe demands upon him, and it is *these demands of regulation* which *interfere with his efficiency rather than failure to regulate.* When faced with difficulty in getting rid of heat, the blood vessels of the skin dilate and allow much more blood to pass through it, just as the thermostat in an automobile lets water pass through the radiator when the engine heats up. This increase in capacity of skin blood vessels may outstrip his ability to make a greater volume of blood available. To compensate for this, other blood vessels in the internal organs may be closed down, but the saving may not be sufficient. Under such circumstances of relative blood shortage, the brain, being at the highest part of the body, may be deprived of a sufficient supply. Since it is the tissue which is most sensitive to shortage of oxygen, the brain quickly evidences this fact with inefficient performance and characteristic symptoms of "*heat exhaustion.*" Lassitude, headache, nausea, dizziness, uneasiness, and finally fainting mark the well-developed case; but there is probably a wide range of lesser disturbances which interfere with efficiency without going on to frank exhaustion. In any case, the internal organs cannot be expected to function properly if their blood supply is continually being reduced in order to keep up the supply to the skin.

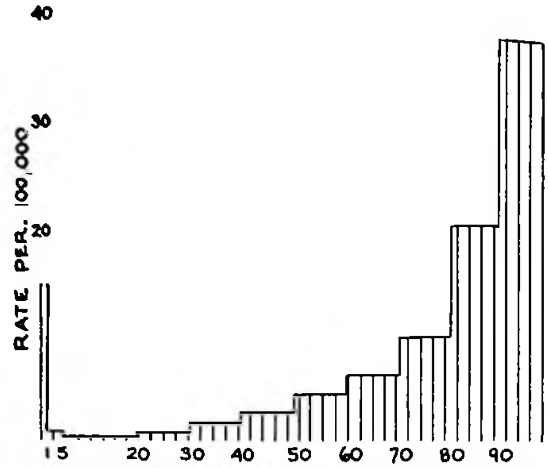
On top of this, man has a remarkable sweating capacity. With moderately hard work under hot dry conditions man can produce 3 pints of sweat an hour. Although he is unlikely to keep this up for more than 2 or 3 hours, he may lose as much as 4 gallons in 1 day, and this must be replaced by drinking. This is a large quantity of water to handle, and even at lower rates there will probably be periods in which the loss of water exceeds the supply. Under such circumstances, the already precarious blood supply must be still further depleted, and the liability to heat exhaustion increased.

Further *indirect consequences of heat stress* which must add their quota to inefficiency are lowered alimentary activity due to the deficient blood supply, discomfort from hot and wet skin, liability to skin disturbances from wet skin which is subjected to rubbing, possible deficiencies of salt due to losses in the sweat, and even urinary stone as a result of reduced urine volume.

From this it will be seen that it is not sufficient merely to provide conditions in which man's body temperature is kept in reasonable limits. One must aim at something better, viz. conditions which will avoid invoking the heat-regulatory processes to the point at which they interfere seriously with the performance of normal functions or the maintenance of health. This does not mean that man should be guaranteed a state of permanent comfort—there are serious arguments against a steady diet of comfort—but it does mean that there is some *intermediate set of conditions in which the saving in human efficiency is worth the effort put in to secure climatic amelioration. This should be the aim of tropical housing.*

INDIVIDUAL VARIATION in RESPONSE

It is well known that individuals, even within a fairly uniform community, vary in their susceptibility to heat, and that even the same individual may vary in his susceptibility from one time to another. This range of variability is certainly not decreased when people from very different communities, with different modes of living, different degrees of health, and different climatic experience are compared. Since this variation may affect final judgment on housing requirements, some note should be made here of the more important circumstances which govern it.



NEW YORK, DEATH RATE FROM EFFECT OF HEAT 1900-1928 BY AGE

Vital statistics show that both *infants under one year of age and elderly people* show an undue susceptibility to heat, at least when they are used to a predominantly temperate climate. This is only to be expected, since at these extremes of the life span resistance to almost any kind of stress is somewhat reduced. It is a common observation, on the other hand, that children from 1 to about 12 years of age, and even adolescents, seem "to feel the heat" much less than adults. Whether this tolerance be physiological or psychological, the social implications seem to be real.

Reputed differences in *sex tolerance* to heat can usually be attributed to other accompanying circumstances, such as differences in clothing, nature of work, or social adjustment.

There is reason to believe that a *high calorie diet* reduces heat tolerance to a certain extent, and that an *excess of weight*, especially if acquired in the second half of life, adds to the heat burden. Heat tolerance does not continue to improve, however, as the diet is reduced below normal. A near-starvation diet reduces resistance to most stresses, including that of heat.

Probably one of the most important of the factors determining the individual heat tolerance of healthy persons is the *mechanical efficiency* with which they carry out their work. The person who spends the least energy, and thus produces the least heat, for a given task, will clearly have the advantage. Training, incentive, psychological adjustment, and experience are all important in this regard, and vary greatly from one individual, one group, or even one nationality to another.

Health understandably affects heat tolerance. Any disease which severely affects the body will tend to reduce its resistance to various stresses, including that of heat. Any condition which interferes with blood flow through the skin, inhibits sweating, or increases heat production must decrease heat tolerance. Diseases which tend to reduce heat production, usually by reducing the person's activity, will tend to increase heat tolerance, but, of course, at the expense of productivity and usefulness.

Clothing may greatly affect a person's ability to lose heat. Many groups living in a state of simple culture have adapted their clothing fairly well to the climatic conditions; but the peoples of more complicated cultures are apt to include certain features which may run counter to physiological requirements, especially if they have recently moved into hot environments from elsewhere. There is a particular danger at the present time that people of simpler culture, with a natural desire to show equality with the incoming "westerners," may imitate those features of western clothing which are least suited to the local climatic conditions. Changing social habits such as these make it difficult for the best intentioned executive of technical assistance programs to achieve his objectives.

That *acclimatization* to heat occurs, and that it is important, is fairly clear and well accepted; although it is hard to explain just exactly how it occurs. In general, there are two types of acclimatization process. One concerns improving the means of losing heat from the body, and this takes place fairly rapidly, being well developed in one to three weeks of exposure. The other concerns reducing heat production, takes longer, and is directed mainly towards improving mechanical efficiency. Since this involves such intangibles as training, incentive, psychological adjustment, and experience, it is hard to measure and varies greatly with individuals and groups. Nevertheless, it is a very real thing, and is the process which usually determines the final degree of success.

While much has been written about *racial differences* in heat tolerance, there is very little factual evidence on which to base a discussion. Most of such evidence as has been collected is not admissible, since it was collected without adequate record of the numerous other circumstances which may have affected the observations. On the face of it, it would seem that such differences in heat tolerance as exist between any two groups of different racial composition could be largely attributed to such factors as differences in nutrition, health, incentive, or experience. What meager evidence is admissible suggests that, between groups similar in all respects except race, the one with the longer racial experience of hot climates may show a slightly better adaptation by doing the same task with less expenditure of effort.

TOLERANCE LEVELS

Various workers have studied the reactions to heat of experimental subjects or of persons engaged in normal occupations. No two workers, however, have made their observations under identical circumstances, so that their results are difficult to compare. Air movement, rate of work, duration of task, and the nature of measured reresponse all vary as well as temperature and humidity. The more illuminating of these results have been drawn as lines on a standard psychrometric chart,[1] and are given here as figures 2 and 3. They will serve as a guide to probable effects of different (shade) environmental conditions, until such time as a more satisfactory scheme is available.

[1] The use of the psychometric chart is described in appendix 2 (p. 73). Wet bulb lines have been omitted for clarity from the body of the base chart used in figures 2 and 3, but their position can be found by joining appropriate points on the two wet bulb scales—that along the 100 percent humidity line, and that along the lower and right margins of the chart.

REPORTED TOLERANCES FOR LIGHTLY AND NORMALLY CLOTHED MEN

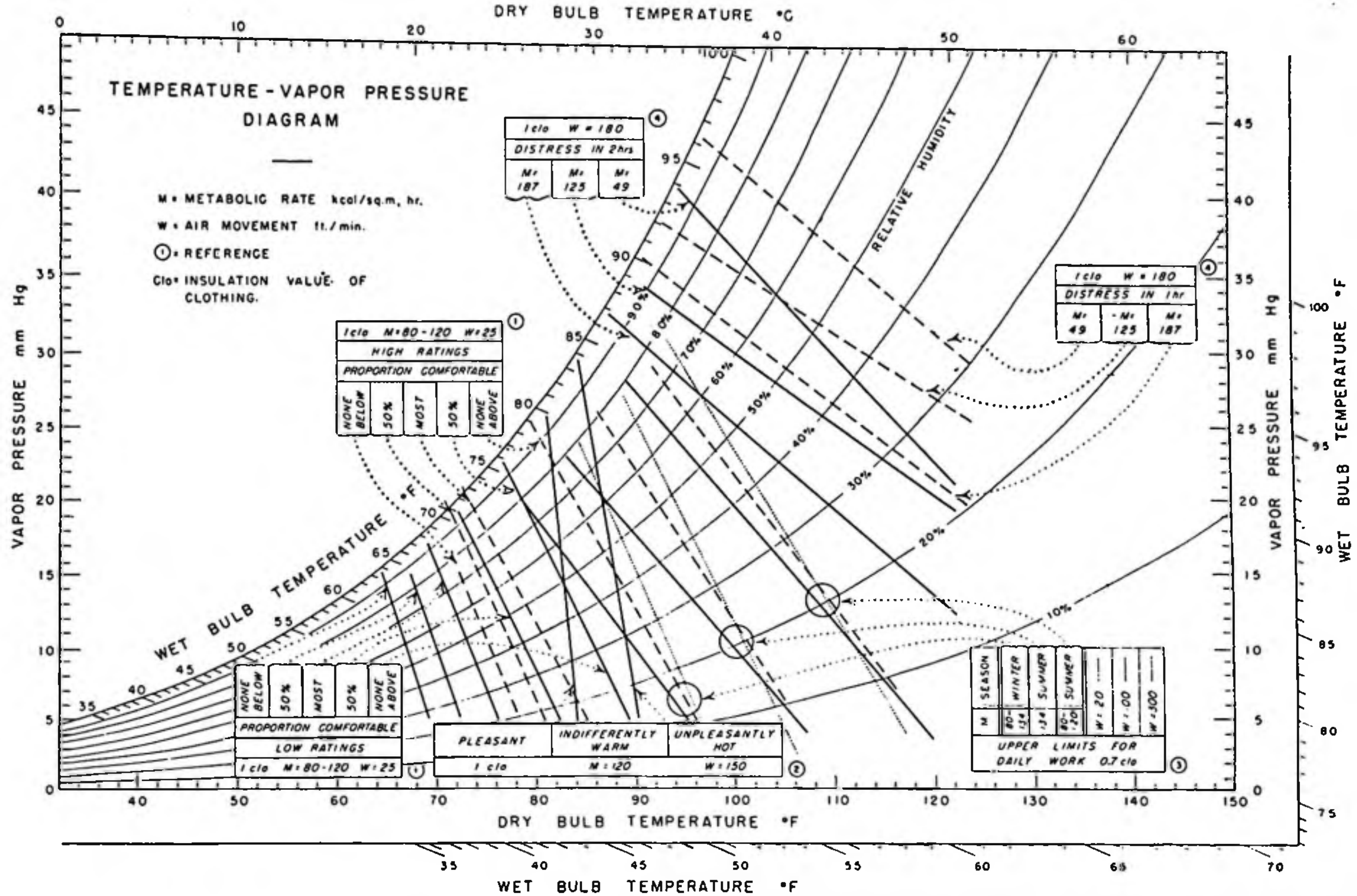


Figure 2.—This and the succeeding chart may be used in two ways: (1) To determine the warmest conditions at which a given activity can be carried out without exceeding given tolerances—select the box which comes closest to describing the activity and tolerance in mind, and then see what combinations of temperature and humidity correspond to this limiting line. (2) To determine what activity can be carried out under given atmospheric conditions—locate the point corresponding to the conditions and then see what activities describe the lines passing near that point.

REPORTED TOLERANCES FOR NUDE AND PARTIALLY CLOTHED MEN

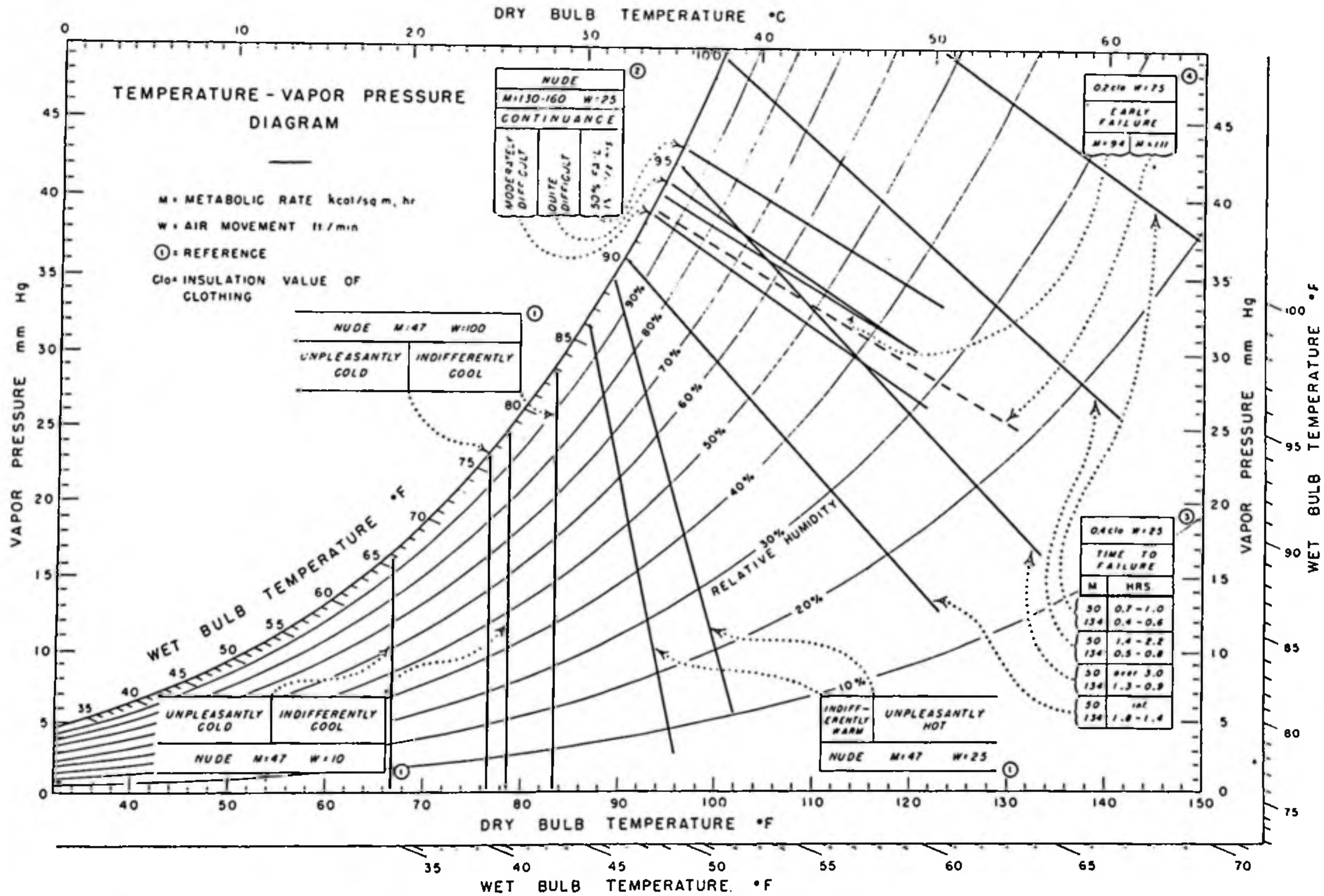
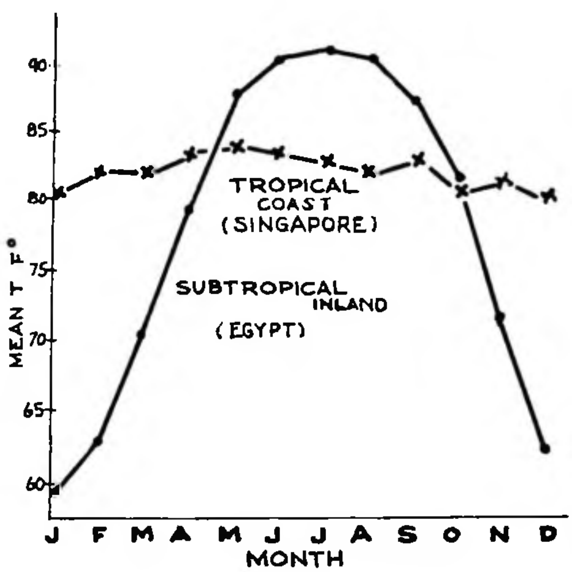


Figure 3.—This and the preceding chart may be used in two ways: (1) To determine the warmest conditions at which a given activity can be carried out without exceeding given tolerances—select the box which comes closest to describing the activity and tolerance in mind, and then see what combinations of temperature and humidity correspond to this limiting line. (2) To determine what activity can be carried out under given atmospheric conditions—locate the point corresponding to the conditions and then see what activities describe the lines passing near that point.

BASIC CLIMATOLOGY of TROPICAL and SUBTROPICAL REGIONS

JUST AS a knowledge of man's bodily functions helps one to appreciate his housing needs in hot environments, so too an understanding of the distribution of hot climates, and of the reasons for their existence, enables one the more systematically to plan measures for counteracting their effects. Indeed, the object of this whole booklet is to explain *why* certain measures are necessary, rather than to catalog detailed but unexplained instructions. In this chapter emphasis will be placed upon those climatic elements—temperature, humidity, air movement, and radiation—which affect man's heat balance, as described in the preceding chapter (p. 1).



AIR TEMPERATURE

Sun the source of heat

For all practical purposes, the gross temperature regime of any large area is determined by the amount of solar heat which falls upon that area from one season to another. Regions which are exposed full-face to the sun for a large part of the year are hot; those which receive sunshine only at a low angle and for smaller portions of the year are cold. From one's everyday knowledge of sun-earth relationships, therefore, one would expect that the equatorial regions would be the hottest and that conditions would get steadily colder as one moves away from the equator towards either pole. A very little reflection, aided perhaps by a glance at world temperature maps, shows that this is true, however, only in a very gross sense. The fall from equator to pole is not uniform, and numerous aberrations appear in temperature maps, since a number of factors enter in to disturb the simple pattern. To understand the temperature pattern of a particular region, one must understand what those disturbing influences are and how they work.

Effect of latitude and season

As one moves away from the equator, the average angle made by the sun with the earth's surface, and thus the intensity of its heating, decreases; but the length of day during that period of the year when the angle is greatest, namely the summer, increases. Moreover, when the angle is large the effect of a small decrease in angle is small. As a result of these conflicting influences, *the maximum receipt of solar radiation on the earth's surface over the whole of a clear summer day is* not at the equator, or even within the tropics, but *somewhere between 30° and 45° latitude* (table 3). At these latitudes, to be sure, this high receipt on a summer's day is offset by low receipt on a winter's day; so that the highest total receipt for the year is at latitudes in the neighborhood of 15°. The summer effect in the middle latitudes is noticeable, however, and enters importantly into housing calculations.

Effect of atmospheric impurities

As solar radiation passes through the earth's atmosphere some of its energy is absorbed, especially by the ozone and water vapor present in the atmosphere. For sunshine passing directly through the atmosphere to fall vertically upon the earth's surface, this absorption amounts to about 15 percent of the energy; but for sunshine falling obliquely on the earth's surface, and thus passing through greater thicknesses of atmosphere, the percentage absorption is much greater. At the extremes of the day, and at high latitudes, this greater absorption in the atmosphere, as well as the low angle of incidence, greatly reduces the intensity of solar radiation. The depletion is greatly increased by impurities in the air, such as dust and smoke, and by high water vapor content. It is greatly increased, of course, when atmospheric water condenses to form clouds. In places where there is much cloud, smoke, or dust, therefore, the actual incidence of solar radiation must be less than might otherwise be expected. This again helps to make temperatures less in the warm humid tropics than in hot dry regions.

Effect of land and water

Dry soil is heated about twice as easily as the same volume of water. Water, moreover, loses some of its heat again by evaporation, which dry soil cannot do. For these reasons a given amount of solar radiation will heat dry earth to a higher temperature than it will heat water or wet earth. It follows that the air, which derives its temperature mainly from contact with the earth's surface, will tend to have higher temperatures when it has been in contact with dry ground exposed to sunshine, than when it has been in contact with water or wet ground similarly exposed—apart from the screening effect of any cloudiness associated with the wetness. It also follows that *high air temperatures will generally be associated with low humidities, and high humidities with only moderately high air temperatures.* For a given latitude in summer it must be expected, therefore, that air temperatures will in general be lowest over large bodies of water, and highest over large tracts of dry land. In winter, however, the reverse might well be the case, since land cools off more rapidly than water when not exposed to sunshine, just as it heats more rapidly when so exposed. *Annual variations in air temperature will be greatest over large tracts of dry land, least over large bodies of water; and diurnal variations from day to night will follow the same general pattern.*

Effect of winds and air mass movement

The explanation so far put forward for geographical and seasonal variations in air temperature would suffice fairly well if air stayed in the same place. But in fact, of course, air is constantly

TABLE 3.—*Total amount of solar radiation received (B. t. u./sq. ft.) by a horizontal surface on a clear day in the middle of the month*[1]

Lat.°	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Avg.
0	1,806	1,917	2,028	2,009	1,869	1,751	1,770	1,880	1,954	1,899	1,844	1,788	1,880
15	1,475	1,678	1,954	2,157	2,213	2,231	2,231	2,194	2,028	1,770	1,549	1,383	1,899
30	1,032	1,327	1,770	2,120	2,378	2,452	2,397	2,194	1,844	1,456	1,143	940	1,751
45	516	866	1,327	1,844	2,249	2,452	2,360	2,083	1,567	1,032	645	442	1,438

[1] From data supplied by F. Loewe, Commonwealth of Australia Meteorological Bureau.

moving across the face of the earth, sometimes to our delight, sometimes to our disgust. The winds bring air whose temperature depends upon what happened to it at various points on its journey. Air coming from the ocean is generally more equable and moist; that from land more extreme in temperature and dry. That coming from polar regions is cold; that from equatorial regions warm. There is a general pattern of wind distribution over the earth, which is diagrammatically expressed in most textbooks of climatology, but persons concerned with the effect of wind on temperature in a particular region will probably do better to refer to a map of actual wind distribution. A world map appears as figure 4; but for more detailed information the publications of the weather bureau of the particular country should be consulted.

Effect of altitude

In the free atmosphere, temperature diminishes with height at the rate of 3.6° F. per 1,000 ft. (0.65° C. per 100 m.). The temperature of air near the ground may be expected to follow the same general trend with altitude, but a host of local factors come in to upset this nice relationship at any particular place on the map. Local contours create wind shadows in some spots and expose others to the full effect of free air. Cold air tends to sink into depressions in the terrain, and warm air tends to rise up the hillsides, creating actual inversions of the expected temperature gradient. Ground exposed to a clear sky at night may lose a considerable quantity of heat by radiation, and markedly reduce the temperature of the air in contact with it if the air is still, again producing an inversion.

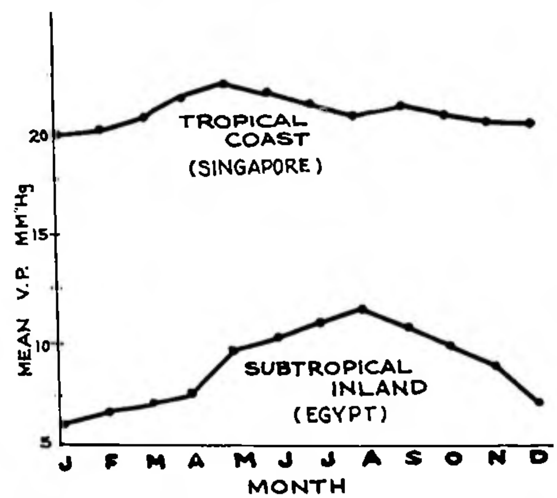
With these local, and often temporary exceptions, air temperature does fall with altitude at more or less the expected rate. It is a remarkable fact that *many of the world's highest elevations occur within or close to the geographical tropics.* The equator traverses the Andes and the highlands of Africa, and passes close to the mountainous core of New Guinea with its surprising snow line. The Himalayas and the southern portion of the Rocky Mountains lie just to the north of the Tropic of Cancer. These elevations add to the considerable variety of climates which can be found between the latitudes of 30° N. and 30° S.

Because altitude reduces temperature, the assumption is sometimes made that the tropical uplands can be regarded as similar to regions of low elevation at higher latitudes; that Kenya, for example, is similar to the Mediterranean littoral. This is not the case, even if the temperature regimes are similar, since the small annual variation in hours of daylight near the equator contrasts markedly with the pronounced variation at higher latitudes. This difference in seasonal variation of hours of daylight has its greatest effect upon crops, but it is also important for many of the considerations which enter into building design.

Understanding the local pattern

From what has been said above, it should be possible for one concerned with the climatic phenomena of a particular area to build up for himself an understanding of the basic temperature pattern, by working out how each factor in turn operates there. Armed with this basic appreciation, he can turn to the local meteorologist for more detailed explanation, especially of temporary disturbances.

VAPOR PRESSURE



In the preceding chapter it was pointed out that the vapor pressure of the air, which is virtually the amount of water vapor present in the air, determines how easily heat can be lost from the skin by evaporation; just as the temperature of the air determines how easily heat can be lost from the skin by conduction. The vapor pressure of the air naturally depends upon the relative amounts of moisture it has gained, usually by evaporation of surface water, and lost, usually by precipitation.

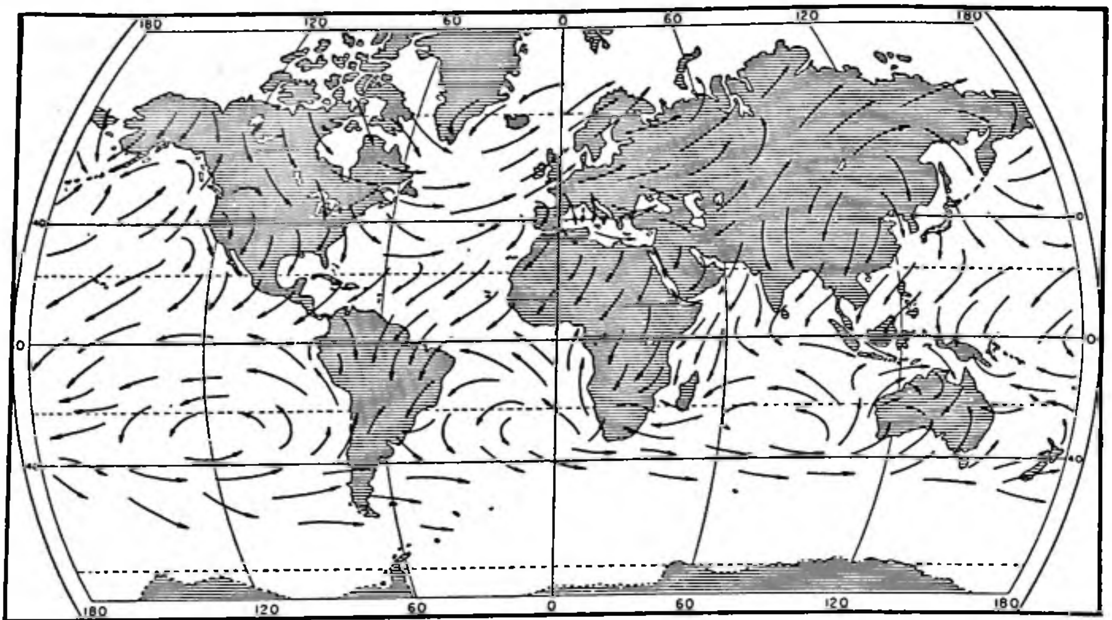


Figure 4(a).—Winds of the World, January. (Ocean data after W. F. McDonald.)

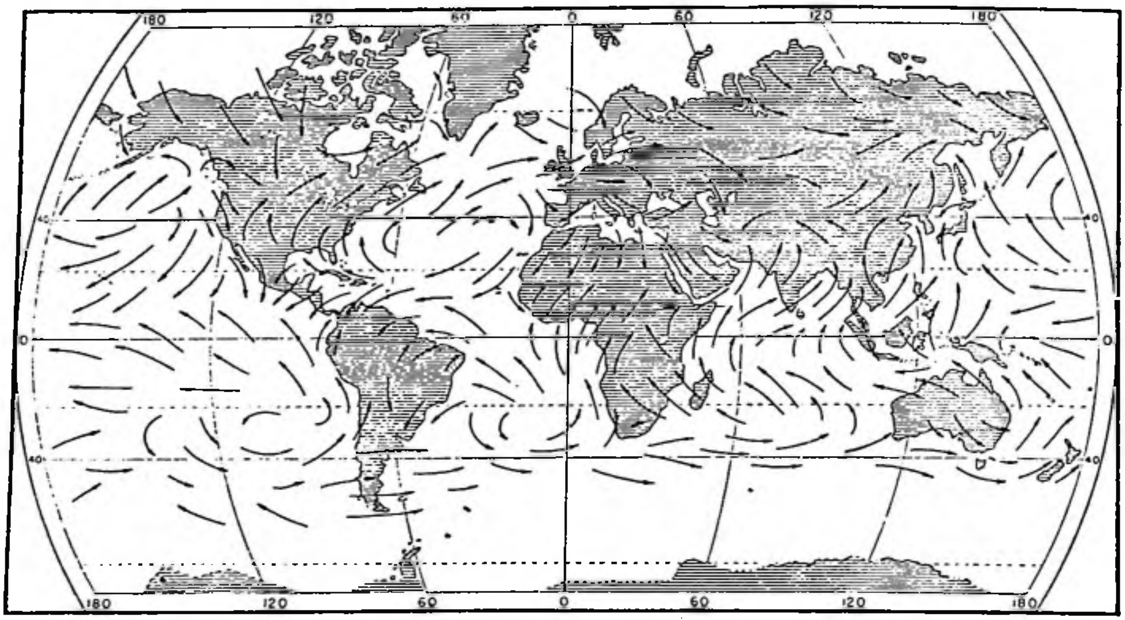


Figure 4(b).—Winds of the World, July. (Ocean data after W. F. McDonald.)

The complicating and often crucial factor in the geographical distribution of vapor pressure is the fact that air can take up only a limited amount of water vapor. The amount it can hold is very small at low temperatures, but rises considerably as the air is warmed. Warm air which has taken up nearly all the moisture it can hold (*i. e.*, is nearly saturated), must lose some of this moisture if it is cooled. The excess water vapor then condenses to liquid particles, which first form clouds and then fall as rain (or snow) if the particles become sufficiently dense to coalesce into drops.

Vapor pressures tend to be *high near the equator*, and to fall off towards the poles, since there is more solar heat to evaporate water near the equator, and the air is warmer and thus able to hold more.

They tend to be ***higher over large bodies of water*** than over large tracts of land, since there is more water to evaporate in the former situation. As was pointed out above (p. 12), ***high air temperatures and high vapor pressures seldom go together.*** The greater the amount of solar heat used for evaporating water into the air, the less there is for heating the ground and air. Over highlands the vapor pressure will drop if the lower temperatures cool air to the point at which vapor condenses. Winds operate to move air from one site to another, with corresponding changes in vapor pressure; so that the vapor pressure of air over land may be raised by a wind from the sea, while areas on the leeward side of mountains may get air which has been dried by precipitation on the way. Figure 5 gives an approximate idea of the world distribution of vapor pressure.

Someone is bound to ask what vapor pressures mean in terms of ***relative humidity***, so that some explanation of the relationships between the two is necessary.

Vapor pressure, it has been pointed out, is a direct measure of the amount of water vapor present in the air. Relative humidity, on the other hand is the ratio between the amount of water vapor actually present in the air and the amount it could hold if it were saturated ***at the same temperature.*** Since the amount of water vapor the air can hold increases rapidly with its temperature, the relative humidity corresponding to a given vapor pressure must vary with the temperature; and to determine one from the other the temperature must be known. For example, ***the same vapor pressure of 20 mm. Hg corresponds to a relative humidity of 100 percent at 72, 50 percent at 93, and only 30 percent at 110° F.***

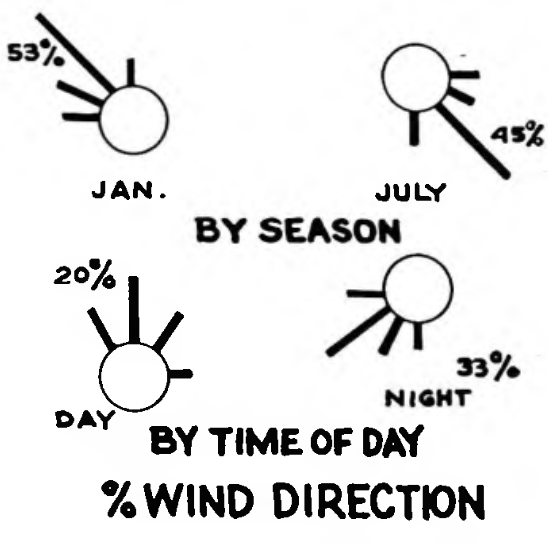
We have become accustomed to describing atmospheric humidity in terms of relative humidity largely because the water content of nonliving absorbent materials, such as paper and cotton, is closely related to the relative humidity. This is due to the fact that they are free to take on the temperature of the air with which they are in contact. The skin and lungs of warm-blooded animals, however, maintain a more nearly constant temperature, and evaporation from them takes place into a contact layer of air at the same temperature. For this reason, relative humidity gives little indication of the atmosphere's ability to accept water vapor from the skin and lungs, and one must first convert the atmospheric humidity into terms of vapor pressure.

From the psychrometric chart given in appendix 2 (figure 15), it will be seen that the relationship between the (dry bulb) temperature, the wet bulb temperature, the relative humidity, and the vapor pressure of an atmosphere is such that, if any two are known the others can be found. Such charts are useful, not only for making such conversions, but also for setting out climatic variations, or for indicating the relationships between certain processes, such as human reactions or water content of wool, and atmospheric conditions.

The "***dew point***," which now appears with increasing frequency in meteorological tables, and the "***absolute humidity***," which is frequently used by engineers, are closely related to the vapor pressure. The unit of millimeters of mercury (mm. Hg) in which vapor pressures are expressed is the conventional metric unit used for barometric pressure. It could, however, be expressed in inches of mercury (1 in. equals 25.4 mm.). Meteorologists now use ***millibars*** as the unit, 1 millibar approximately equalling 0.75 mm. Hg.

Those seeking to use meteorological data in the study of the vapor pressure regime of an area may run into difficulties. What one would like would be the mean of vapor pressures calculated for each day over the month; but what one usually gets are the mean temperature for the month and the mean relative humidity. A mean vapor pressure calculated by applying these two figures to the psychrometric chart may differ by 1 or 2 mm. from the true mean vapor pressure. If one is able to obtain the daily figures from the meteorological service, the increased confidence in the result is worth the trouble of recalculating the data.

AIR MOVEMENT



The major pattern of winds—frequency of both force and direction—is of mechanical importance to the planner, the architect, and the builder, who must erect structures capable of withstanding the stresses. The pattern is important, also, for deter-

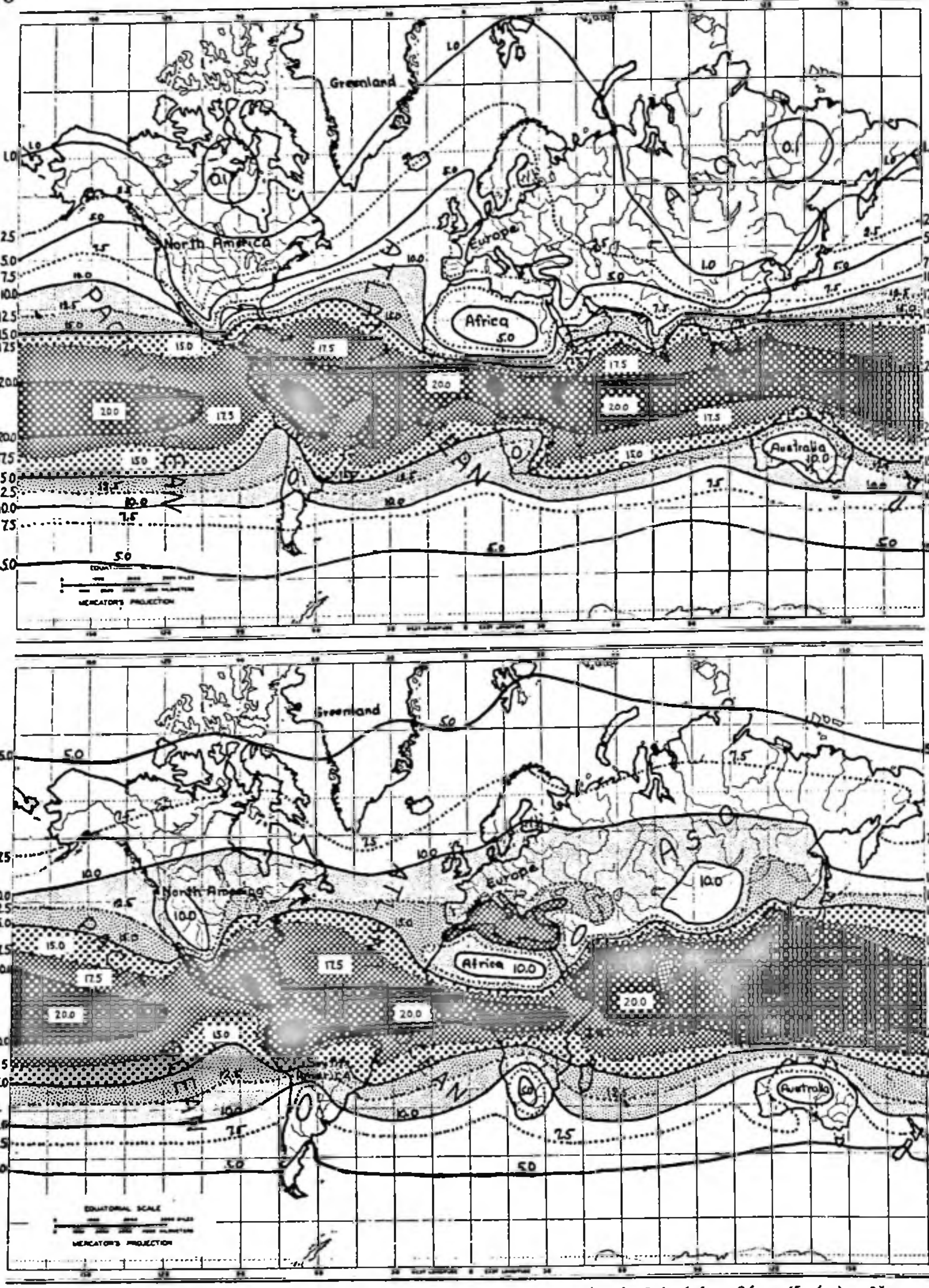


Figure 5.—Distribution of vapor pressure (mm): (a) in January, (b) in July (after Száva-Kovát).—Note southward displacement of the zone of intermediate vapor pressures in January and the northward displacement in July. Note also the relative dryness over continental masses, and the influence of the Mediterranean in July.

mining how best to utilize natural wind in securing both ventilation and internal air movement; and something has been said above (p. 12) on major wind patterns.

In the neighborhood of the equator, but extending further to the north of it, is an area of calms known as the *doldrums*. In this zone, little air movement can be relied upon, unless it is created by local topography, such as mountains rising sharply from the plain; and rain tends to fall straight, without driving. To the north and south of the doldrums lie the two *trade-wind belts*, in which winds blow persistently, especially over the oceans, at mean velocities of 10 to 20 m. p. h. according to season. In the northern hemisphere the "trades" blow from the northeast, and in the southern hemisphere from the southeast. Over the continents in summer these trade winds are usually replaced by winds blowing towards the center of the continent from all sides. Poleward of the trade-wind belts lie the regions of the westerlies, whose latitude is roughly indicated by the phrase "roaring forties."

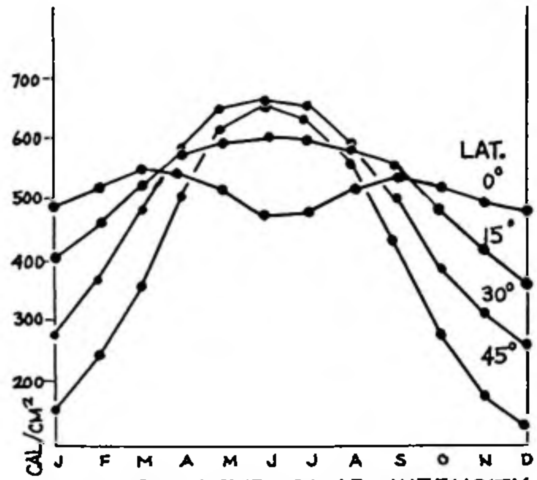
For the individual person, and also very largely for the individual house, *local topography frequently dominates the operating wind pattern*. Valleys tend to channel winds to their own axis; while rising contours opposed to the wind produce upcurrents on the windward side, reverse eddy currents over the crest on the leeward side, and calms at the base of the leeward side if the slope is steep. According to Brooks,[1] wind speed begins to decrease on the windward side of a simple windbreak at a distance equal to about six times the height of the barrier. The lowest speed (15-40 percent of the free wind) is found on the leeward side at an average distance of 3 to 4 times the height of the barrier; and 75-80 percent of the full wind speed is regained at a distance 6 to 12 times the height of the barrier.

RADIANT ENERGY

Direct solar radiation

From what has been said above in connection with air temperature, and from an inspection of the figures given in appendix 3 for the incidence of solar radiation on various surfaces at different seasons of the year and at different latitudes, the following general statements can be derived:

[1] Brooks, C. E. P. Climate in Everyday Life. Philosophical Library, New York. 1951. pp. 270-272.



DAILY RADIATIVE SOLAR INTENSITY (CAL./CM.²) UPON A HORIZONTAL SURFACE AT SEA LEVEL.

(*a*) A maximum incidence of solar radiation upon a horizontal surface of about 145 langleys/min. (870 kcal/sq. m.,hr., or 320 B. t. u./sq. ft., hr.), may be found on a clear day whenever the sun is approximately overhead, i. e. anywhere between 30° N. and 30° S. latitude, in the appropriate season at noon.

(*b*) The maximum total incidence over the year is found in places with clear skies in the neighborhood of 15° latitude N. or S.

(*c*) The maximum total incidence over a day is found at midsummer in places with clear skies in the neighborhood of 40° latitude N. and S.

(*d*) The greater the cloudiness of a region, the less will be the incidence of radiation at the earth's surface. (Rainfall is a guide, but by no means an infallible one, to probable cloudiness.)

(*e*) A high incidence of dust in a region will somewhat reduce the incidence of radiation.

Solar radiation reflected from clouds, etc.

Regions in which the sky is frequently dotted with cumulus clouds in moderate density (e. g. coast of Louisiana, U. S. A.), may have an appreciably higher incidence of radiation on a horizontal surface than one with quite clear skies (e. g. Arizona, U. S. A.), as a result of reflection from the clouds without compensating interference to direct radiation.

Solar radiation reflected from terrain

From the data given in table 4, it will be seen that the percentage of incident solar radiation

Table 4.—*Percentage of Incident Solar Radiation Diffusely Reflected* [1]

Nature of surface	Estimates of percent reflected
Bare ground, dry	10–25
Bare ground, wet	8–9
Sand, dry	18–30
Sand, wet	9–18
Mold, black, dry	14
Mold, black, wet	8
Rock	12–15
Dry grass	32
Green fields	3–15
Green leaves	25–32
Dark forest	5
Desert	24–28
Salt flats	42
Brick, depending on color	23–48
Asphalt	15
City area	10

[1] Data principally from Handbook of Chemistry and Physics, Chemical Rubber Publishing Co., Cleveland, 1949, pp. 2294–2296; and Smithsonian Meteorological Tables, Smithsonian Institution, 1951, pp. 442–3.

reflected from the terrain varies from 5 percent for dark trees to 42 percent for salt flats. It is possibly higher from white coral sand. Since a vertical surface receives half the intensity of the radiation being reflected from the ground that it faces, this reflected solar radiation can constitute a very important load for the man or structure so exposed. Since both high incidence of solar radiation and high reflectivity of the terrain occur in the mid-latitude arid regions of the continents, *these loads typically occur in conjunction with hot dry conditions;* whereas both the incidence of solar radiation and the reflectivity of the terrain are reduced in warm humid environments.

Ground temperatures and thermal radiation

The ground surface temperatures in warm humid environments differ but little from air temperatures. *In hot dry environments,* however, *ground surface temperatures may rise to 160° F. or even more.* Near Yuma, in the southwestern arid region of the United States, for example, average ground surface temperatures were found to vary on clear summer days from 113° F. (with air temperature 98° F.) to 144° F. (with air temperature 116° F.) at different times of the day.[2] Under these conditions, any surface exposed to thermal radiation exchange with such ground will gain an appreciable amount of heat.

"Sky" temperatures and thermal radiation

The atmospheric screen between the earth's surface and cold outer space behaves as though it had a certain temperature, absorbing thermal radiation from warmer objects and occasionally adding thermal radiation to cooler objects beneath. (See p. 5). In warm humid environments this "sky" temperature does not differ much from air temperatures near the earth's surface. But *where the atmosphere is dry, "sky" temperatures may* be appreciably cooler, especially if the air is relatively free from dust, and *permit the loss of important amounts of heat to it by radiation.* Daytime values of average sky temperature measured in the southwestern arid region of the United States,[2] at the same time as the ground surface temperatures quoted above, ranged from 80° F. to 107° F. Sky temperatures would probably be lower where the vapor pressure is lower. Table 5 gives "sky" temperatures recently measured at night near Yuma, Ariz. Lower figures (40° F.) were obtained for the zenith sky at Death Valley, Calif., where the vapor pressures were lower.[2]

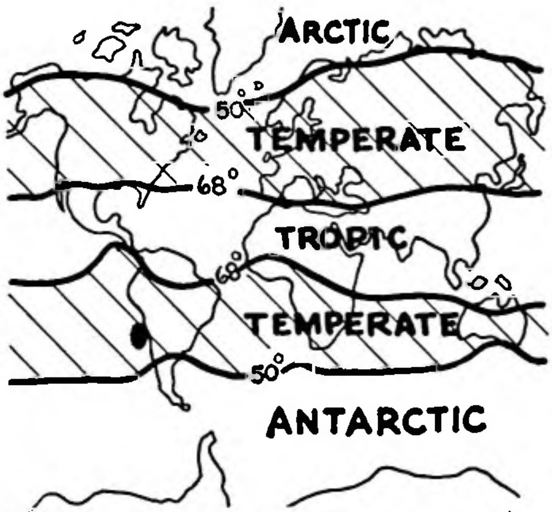
Table 5.—*"Sky" Temperatures (° F.) Measured at Night in Summer near Yuma, Ariz.* [2]

Angle above horizon (°)	9 p. m.	10 p. m.	11 p. m.	12 p. m.	1 a. m.	2 a. m.	3 a. m.	4 a. m.	5 a. m.	6 a. m.
0	88	85	82	82	82	79	78	78	76	79
10	84	82	80	80	78	77	74	74	73	76
20	82	79	76	76	76	73	72	70	71	72
30	78	75	72	72	72	70	69	67	66	68
40	75	71	68	70	68	65	64	63	63	65
50	73	69	64	67	66	63	63	60	61	63
60	72	68	64	65	64	62	61	59	57	60
70	70	66	64	65	63	62	60	59	56	58
80	67	64	63	64	61	61	59	57	55	57
90	64	64	63	64	61	61	57	57	55	57
Air temp	91	86	82	84	82	81	79	79	76	79

Vapor pressure 15 mm. Hg. Dust storm at 6 p. m. left some fine dust in the air, but night was clear.

[2] Data collected by observers of U. S. Quartermaster Corps.

CLASSIFICATION of CLIMATES



Old simple classification inadequate

By the "climate" of a region, one really means the general course or condition of the weather in that region. While weathers may be fairly sharply contrasted with each other, climates, being made up of many weather complexes, are not so easily classified. With few exceptions, the climates of neighboring regions grade rather insensibly into each other. Because of the gradual nature of these transitions, and also because of the irregularities of human reaction to climatic stress, physiologists are cautious about dividing climates into arbitrary classes. Nevertheless, many of man's activities call for some working classification of climates, if only to indicate the general conditions he is likely to experience.

To assist such practical endeavors as housing, it is permissible, therefore, to divide the innumerable climates of the world into a limited number of classes; but both the divider and the user must be fully aware of the *limitations of any such classification*. Wherever a dividing line is put, somebody will want it moved north, and somebody else will want it moved south. If a temperature of 86° F. is used as a dividing point, somebody will ask "why not 85° or 90°?" Furthermore, the data upon which divisions are based are not entirely reliable. At the best they represent conditions at the particular points occupied by the observing stations, and these have an extraordinary variety—tops of buildings, in city streets, on airports several miles from the city of the same name, in irrigated patches of desert, or on bare rocky outcrops. Most published records, again, deal with mean or average values, and say little or nothing about the range of variation. A place with a mean July temperature of 77° F. may have 1 or 2 days in the month up to 95°; or, on the other hand, they may never exceed 85°. Residents naturally remember the exceptional days, and are apt to protest a mean which does not do justice to their sufferings.

The mapmaker, however, must work with the data that are available to him. His product does not represent absolute truth, but the closest he can come to the truth with the evidence at hand. Its only real virtue is its utility.

It was pointed out in the previous chapter (p. 5) that is is the combined effect of the climatic elements—temperature, humidity, air movement, radiation—which is significant for man. It would be perfectly valid to demand, on these grounds, that climatic classifications take cognizance of all four elements. In practice, however, it has so far been found possible to include only two—temperature and humidity. There is not enough information available on the actual radiative conditions in different parts of the world to permit the inclusion of that factor. With air movement, there is so much variation with the exact location, size, and orientation of a particular object or man, that representative figures cannot be given for inclusion in a workable classification of climates. The most that can be done is: (*a*) to indicate the gross frequency of wind distribution (p. 16); and (*b*) to indicate the extent to which the effect of basic climatic conditions, at some hypothetical standard air movement, would be changed by other rates of air movement whenever they occurred.

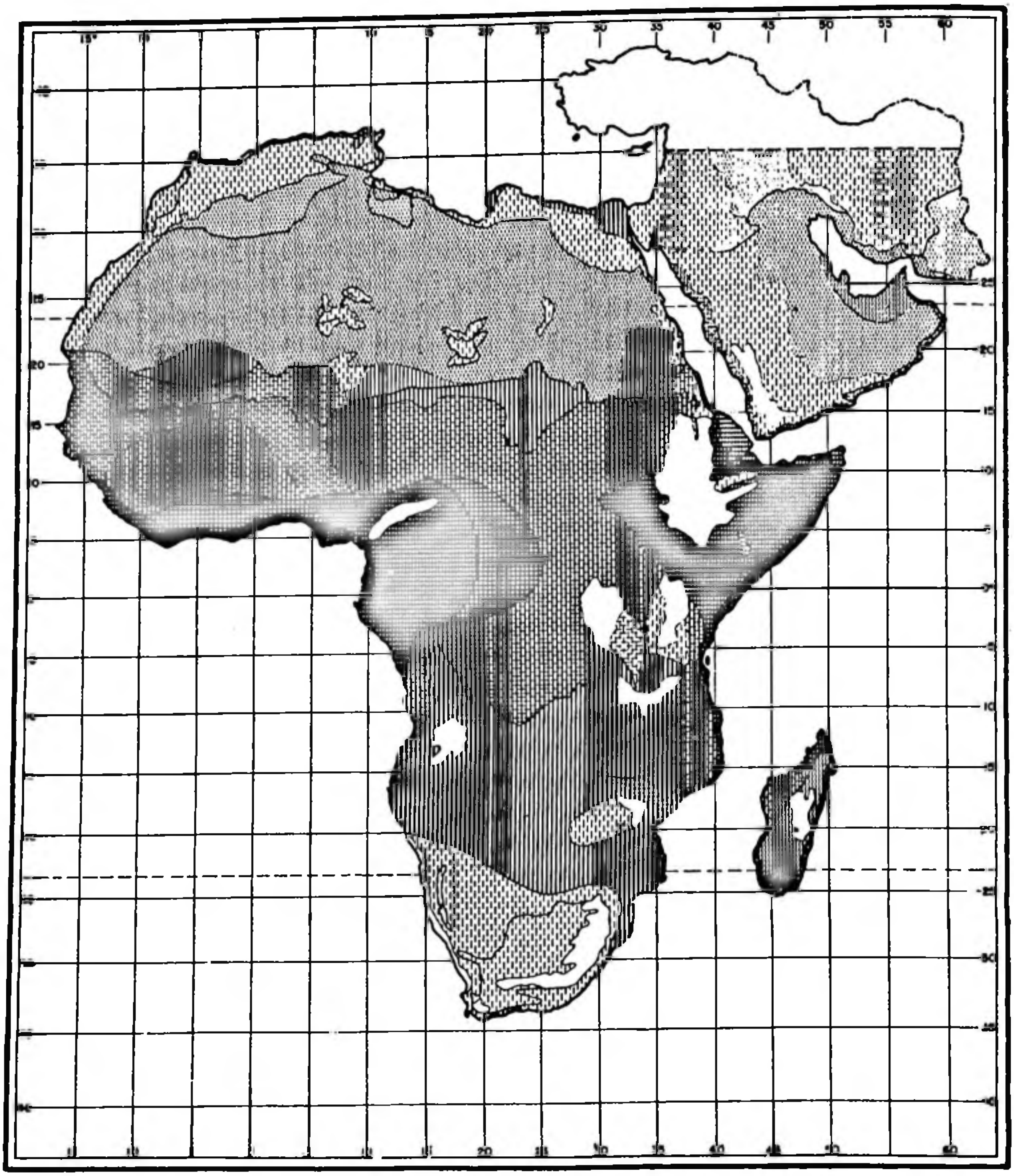
With this booklet are provided three maps (fig. 6), purporting to classify the climates of the world according to their "tropicality." The subdivision is based upon the temperatures and vapor pressures prevailing in the months of January and July. Conditions were divided and named according to the following scheme:

Mean temperature

Over 86° F	Hot.
68°-86° F	Warm.
50°-68° F	Temperate.
Below 50° F	Cool.

Mean vapor pressure

Over 15 mm. Hg	Humid.
Under 15 mm. Hg	Dry.



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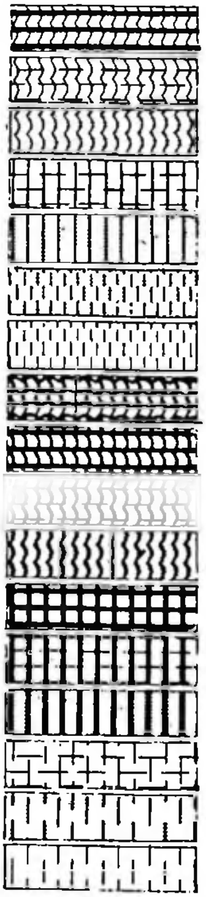
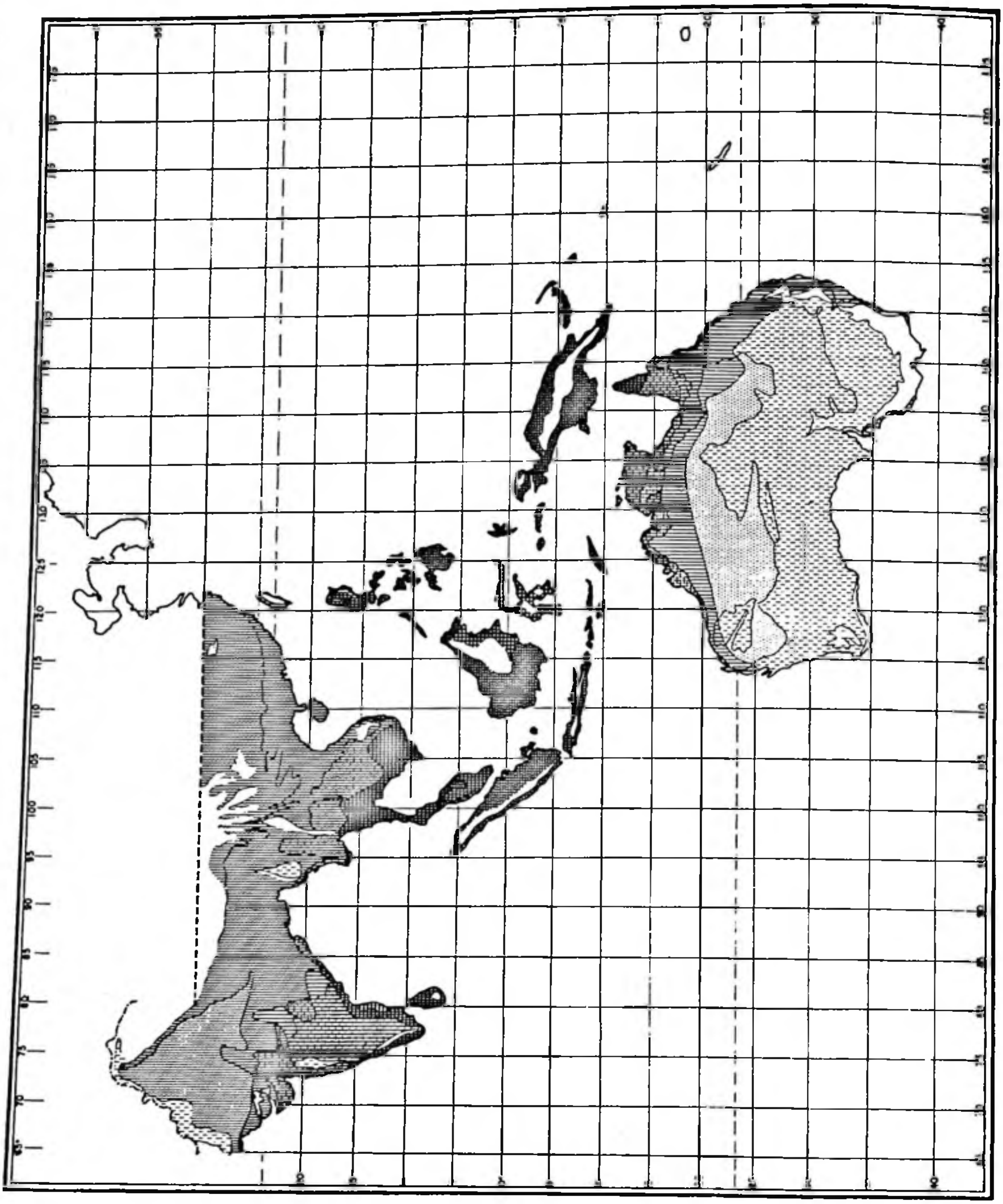


HATCHING	CODE	WARMEST MONTH	COOLEST MONTH
	Hw. Wh.	Hot Wet	Warm Humid
	Hw.Wd	Hot Wet	Warm Dry
	Hw.T	Hot Wet	Temperate
	Hh.Wd	Hot Humid	Warm Dry
	Hh.T	Hot Humid	Temperate
	Hd.T	Hot Dry	Temperate
	Hd.C	Hot Dry	Cool
	Ww.Ww	Warm Wet	Warm Wet
	Ww Wh	Warm Wet	Warm Humid
	Ww.Wd	Warm Wet	Warm Dry
	Ww.T	Warm Wet	Temperate
	Wh.Wh	Warm Humid	Warm Humid
	Wh.Wd	Warm Humid	Warm Dry
	Wh.T	Warm Humid	Temperate
	Wd.Wd	Warm Dry	Warm Dry
	Wd.T	Warm Dry	Temperate
	Wd.C	Warm Dry	Cool

Hot = Mean temp. of month over 86° F.
Warm = Mean temp. of month 68-86°F.
Temperate = Mean temp. of month
Cool = Mean temp. of month below 50° F.

Wet = Mean vapor pressure of month over 20 mmHg.
Humid = Mean vapor pressure of month 15-20 mmHg.
Dry = Mean vapor pressure of month under 15 mmHg.



KEY TO SYMBOLS

HATCHING	CODE	WARMEST MONTH	COOLEST MONTH
	Hw.Wh	Hot Wet	Warm Humid
	Hw. Wd.	Hot Wet	Warm Dry
	Hw.T	Hot Wet	Temperate
	Hw. C.	Hot Wet	Cool
	Hh.Wd	Hot Humid	Warm Dry
	HhT	Hot Humid	Temperate
	Hd. T	Hot Dry	Temperate
	Ha C	Hot Dry	Cool
	Ww. Ww	Warm Wet	Warm Wet
	Ww.Wh	Warm Wet	Warm Humid
	Ww.Wd	Warm Wet	Warm Dry
	Ww.T	Warm Wet	Temperate
	WwC	Warm Wet	Cool
	Wh.Wh	Warm Humid	Warm Humid
	Wh.Wd	Warm Humid	Warm Dry
	Wh.T	Warm Humid	Temperate
	WhC	Warm Humid	Cool
	Wd.T	Warm Dry	Temperate.
	WdC	Warm Dry	Cool

Hot = Mean temp. of month over 86° F.

Warm = Mean temp. of month 68-86°F.

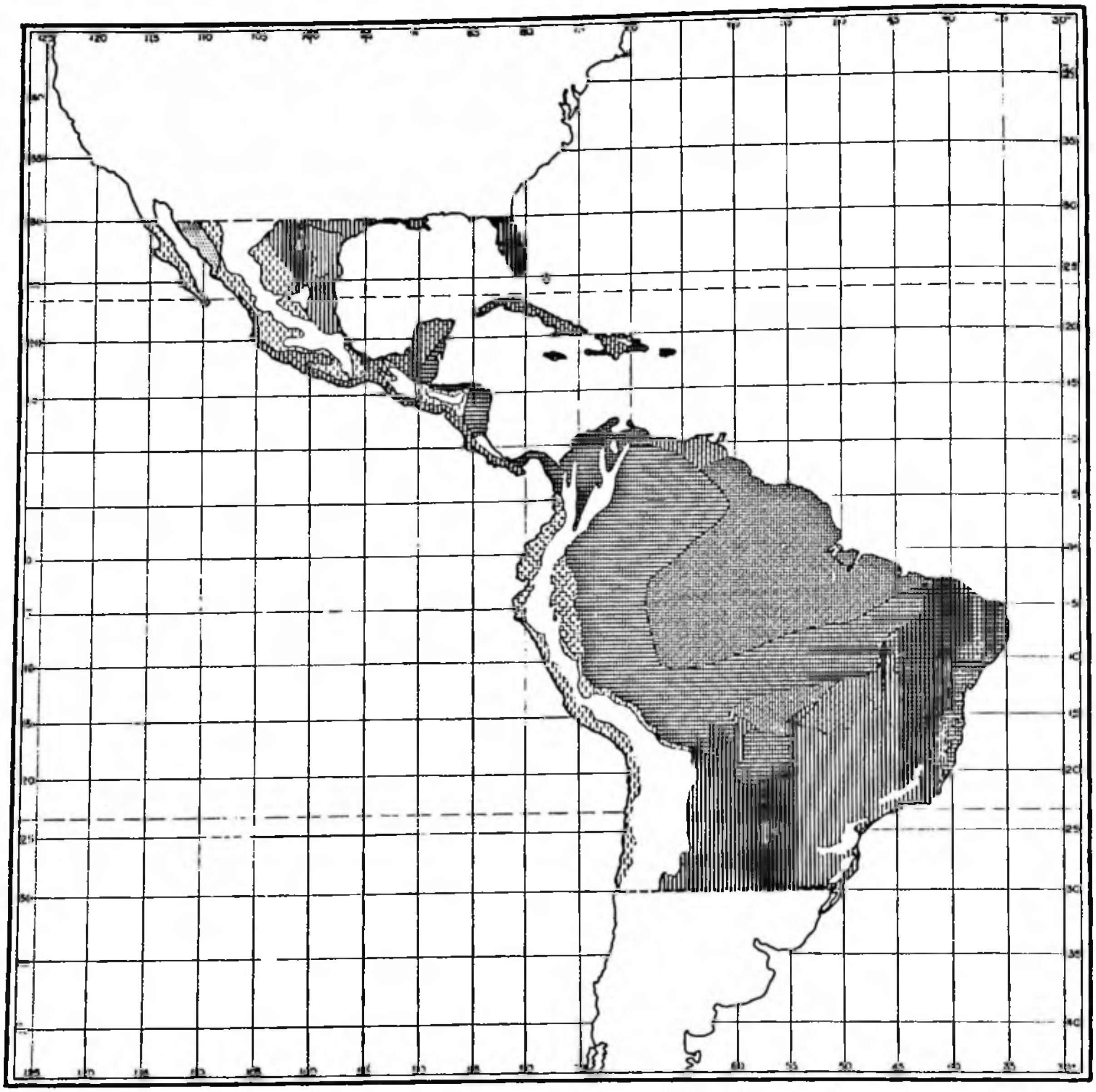
Temperate = Mean temp. of month 50-68°F.

Cool = Mean temp. of month below 50° F.

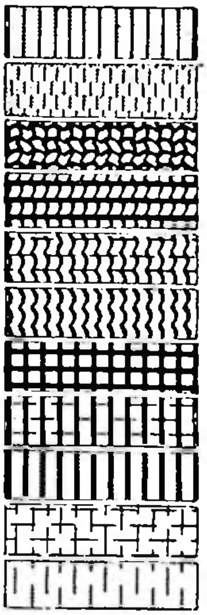
Wet = Mean vapor pressure of month over 20 mmHg.

Humid = Mean vapor pressure of month 15-20 mmHg.

Dry = Mean vapor pressure of month under 15 mmHg.



KEY TO SYMBOLS



Code	Warmest Month	Coolest Month
HhT	Hot Humid	Temperate
HdT	Warm Dry	Temperate
Ww.Ww	Warm Wet	Warm Wet
Ww.Wh	Warm Wet	Warm Humid
Ww.Wd	Warm Wet	Warm Dry
Ww.T	Warm Wet	Temperate
Wh.Wh	Warm Humid	Warm Humid
Wh.Wd	Warm Humid	Warm Dry
Wh.T	Warm Humid	Temperate
Wd.Wd	Warm Dry	Warm Dry
Wd.T	Warm Dry	Temperate

Hot = Mean temp. of month over 86° F.
Warm = Mean temp. of month 68-86° F.
Temperate = Mean temp. of month 50-68° F.
Cool = Mean temp. of month below 50° F.

Wet = Mean vapor pressure of month over 20 mmHg.
Humid = Mean vapor pressure of month 15-20 mmHg.
Dry = Mean vapor pressure of month under 15 mmHg.

When dividing lines for both temperature and vapor pressure zones are put on the map for both January and July, the world becomes cut up into numerous areas, each denoted by four characteristics:

"Summer" temperature.............hot, warm, or temperate.
"Summer" vapor pressure....................humid or dry.
"Winter" temperature.............warm, temperate, or cool.
"Winter" vapor pressure....................humid or dry.

These four characteristics are indicated for each area by filling it in with selected symbols as shown in the key on each map. (Temperate and cool conditions can seldom have vapor pressures over 15 mm. Hg and are thus not subjected to subdivision by vapor pressure.)

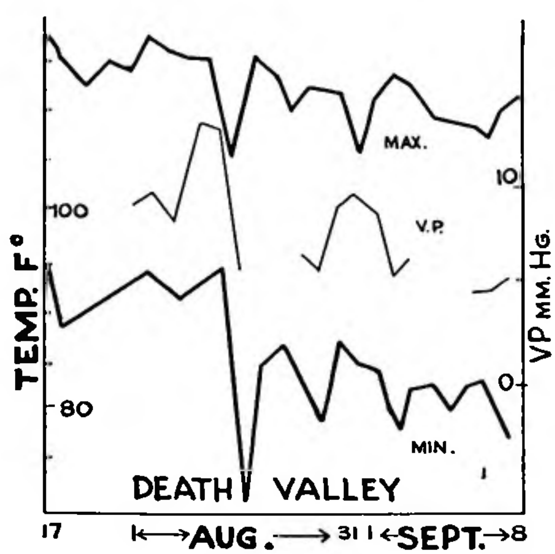
The temperature boundaries used here are those employed by the United States Quartermaster Corps, from whose maps many of the boundary lines are taken. The vapor pressure boundary of 15 mm. Hg is an arbitrary one, which in some places may appear to exaggerate somewhat the occurrence of high humidities. It is felt, however, that if the vapor pressure has a mean value of 15 mm. Hg, then it will attain values of definite physiological significance on an important number of days. This belief is substantiated by recent experience near Yuma in what is conventionally considered a hot dry desert.

It is anticipated that the interested user will carefully scrutinize those areas of the maps in which he is interested, and make his own interpretations. No attempt will be made here to discuss the maps in detail. It should be pointed out, however, that they reveal importantly hot conditions occurring well beyond the limits of what are conventionally considered to be "tropics." Indeed, the *regions of high temperature mostly lie outside of* the zone between the tropics of Capricorn and Cancer. Most of these regions of high temperature are dry, but some (e. g. the Persian Gulf area) acquire high humidities as well from the neighboring water. The *geographical tropics*, by contrast, *have somewhat lower temperatures, but high humidities*. (See also p. 12.)

A further point of great importance will be apparent upon the most casual inspection; and that is how inadequate any attempt would be to divide the map with bold strokes into large areas of uniform climate. The simple division by Supan's lines for instance into five zones, as shown in the small map, is quite inadequate. For example, if one follows the equatorial line across Africa from east to west one goes successively from perpetually warm humid, through warm humid/warm dry, perpetually warm dry, warm dry/temperate, to a perpetually temperate climate; and then back again through intermediate areas to perpetually warm humid. To those without personal experience of "tropical" regions, this may come as a surprise; but the author would like to assure the dubious that this variation accords well with actuality.

HOUSING *as* CLIMATIC PROTECTION *in* HOT DRY ENVIRONMENTS

FROM WHAT has been said concerning the effects of warm and hot environments upon man, and the general nature of hot climates themselves, it should be possible to develop systematic principles for the guidance of house design where such conditions prevail. In the preceding chapter the terms "hot dry" and "warm humid" were used to indicate somewhat contrasting circumstances. While it was seen that naturally occurring conditions do not always fall sharply into one or other of these two classes, the distinction occurs with sufficient regularity to warrant its use for general classification. There is, in addition, another good reason for making this distinction here, since essential differences in the prevailing values of temperature and vapor pressure in these two types of environment call for rather sharply contrasting aims and methods of protection. Of the two, the situation created by hot dry environments will be considered in this chapter, and in some detail. The contrasting situation created by warm humid enivronments can then be discussed in the succeeding chapter without the necessity for repetition of much of the detailed argument.



NATURE of HOT DRY ENVIRONMENTS

As the term suggests, these environments are characterized by high air temperatures (often exceeding skin temperature), dry air, and dry ground. Under these conditions there will be little cloud or mositure vapor in the air to screen off the sun's rays, so that the resulting high intensity of direct solar radiation will heat and dry the ground still further, reinforcing the high temperature of the air and preserving its dryness in a vicious circle of events, until cold or moist air enters from some other place. The dryness of the ground severely restricts plant life, so that the consequently bare as well as dry ground strongly reflects solar radiation, adding to the radiation load on any surface exposed to the reflected rays. In this complex of *high air tempera-*

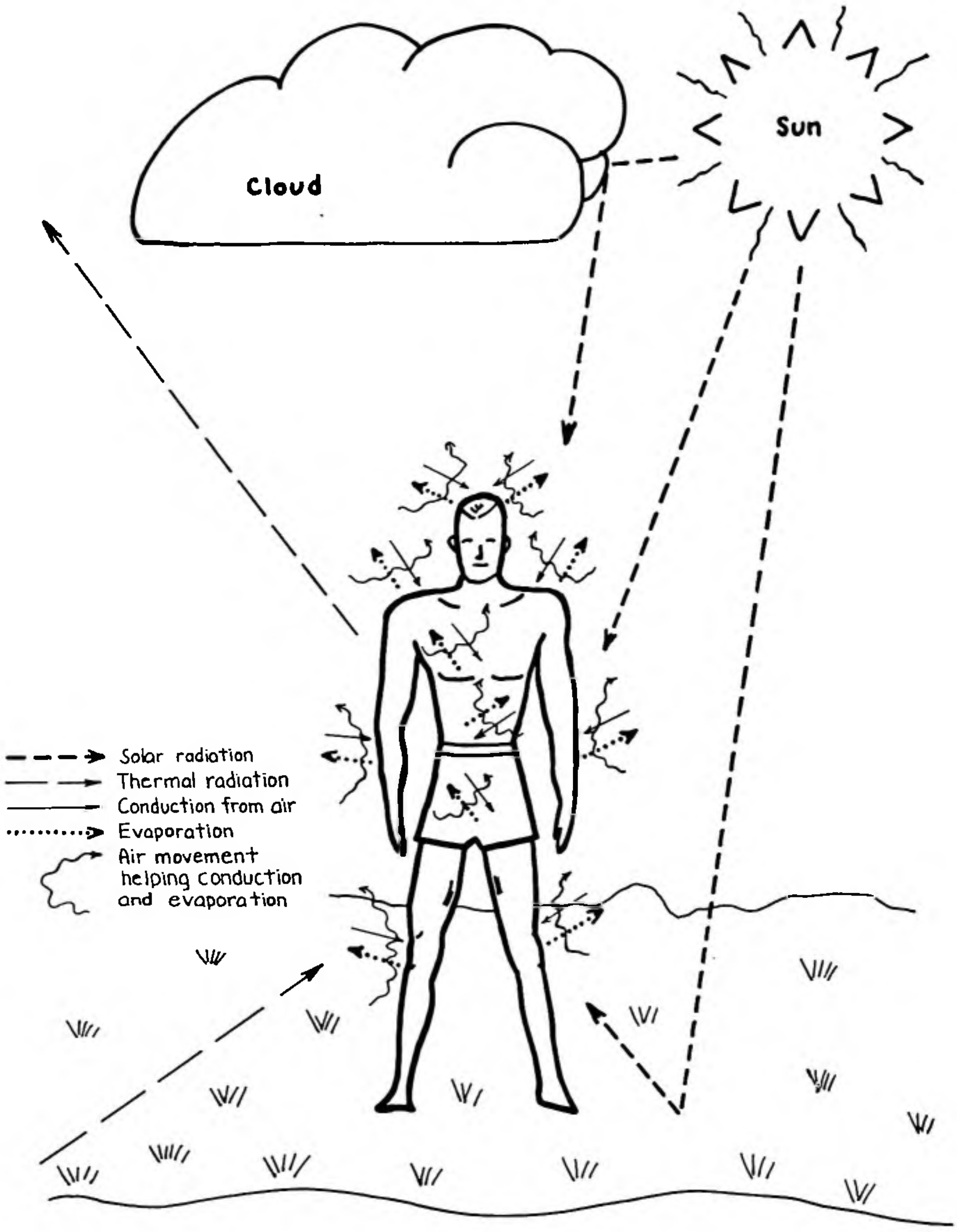


Figure 7.—Heat exchange in hot dry environments.—Note the strong incidence of solar radiation, the gain of long infrared from the hot ground, and the loss of infrared to clear sky. Some heat is gained by conduction, but much is lost by evaporation; both processes being somewhat accelerated by air movement.

TABLE 6.—*Important Characteristics of Hot Dry Environments*

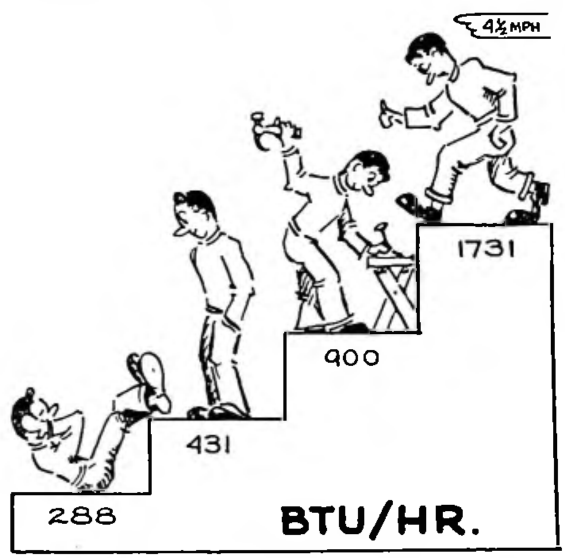
Item	Magnitude	Effect on human heat balance
Direct solar radiation	High, with little natural shade	*Marked* addition to heat *gains.*
Solar radiation reflected from clouds, etc.	Moderate	*Some* addition to heat *gains.*
Solar radiation reflected from ground, etc.	High to moderate	*Marked to moderate* addition to heat *gains.*
Thermal radiation exchange with ground, etc.	Moderate towards body	*Some* addition to heat *gains.*
Thermal radiation loss to "sky"	Moderate	*Moderate* addition to heat *losses.*
Air temperature	Often above skin temperature	May represent *moderate* addition to heat *gains.*
Air vapor pressure	Usually low	*Important* channel for heat *loss* essential to restore balance.
Air movement	Variable, often high	Promotes heat *loss* when vapor pressure high, but *gain* when temperature very high.

tures, intense direct solar radiation, and intense reflection of solar radiation from the ground, there are only two saving graces—the air is dry (absolutely as well as relatively) so that ***evaporation can take place easily;*** and the sky is clear so that ***an important amount of heat can be radiated to outer space.*** (See ch. 1). If at any time these are removed, as by the advent of a moist air mass from outside without cloud formation, or by the restriction of open sky through mountain walls, conditions can literally become unbearable.

The essence of the hot dry situation for an unprotected man is shown in figure 7 and table 6; and the geographical distribution of such environments is indicated in the maps of figure 6.

In the first chapter it was seen that the human heat balance involves four types of processes—(*i*) heat production by the body; (*ii*) heat exchange with the environment by radiation; (*iii*) heat exchange by conduction; and (*iv*) heat loss by evaporation. To derive principles of protection against hot dry environments from a knowledge of the environmental characteristics, it is logical as well as convenient to follow the same general scheme; since what is desired is clearly a series of ways in which the human body, having difficulty in keeping its heat balance, can be helped by housing to reduce its gains and increase its losses. In this, it is not necessary to discuss the effect of each procedure individually on comfort. In most cases, the effectiveness of a procedure is determined by the amelioration it produces in the internal atmospheric conditions, and through them on the human heat balance.

PRINCIPLES DIRECTED to REDUCING HUMAN HEAT PRODUCTION



Much has been made in "western" civilizations of labor-saving devices. While reduction of unnecessary labor is certainly a desirable objective, the methods have too often degenerated into mere "gadgetry," and impressionism has too often been substituted for real worth in their promotion. Saving of unnecessary labor and of the consequent production of heat is certainly desirable in hot climates, but it would be foolish, to say the least, in many such regions to identify laborsaving with a wholesale adoption of western equipment. Much can be done by returning to the basic principles of laborsaving and applying those principles to the situations which actually exist in such regions. A basic principle is convenience of arrangement, and this is a principle that can be put into operation by the architect with the use of little or no special equipment. There is nothing revolutionary about the methods, they are all well known and frequently advocated for temperate dwellings; but they are relatively more important for hot conditions. *Accessibility of water, fuel, and food stores to the point of use; accessibility as well as hygienic construction of waste receptacles; easily cleaned surfaces; avoidance of repeated step-climbing; and conservation of floor space* are familiar examples readily applied even to minimal cost housing. Physiological interests in laborsaving are directed more towards reducing the heat production by the individual than to reducing the number of individuals engaged. The latter consideration has been less frequently important in hot countries than in temperate western regions, but with changing social conditions and increasing industrialization the accent on the individual may be increased.

PRINCIPLES DIRECTED to REDUCING GAINS and PROMOTING LOSSES from the BODY by RADIATION

From table 6 it will be clear that one of the most important protective functions of a house in a hot dry environment is to screen the occupant from incoming radiation; but the setting up of a screen introduces complications which are not always foreseen. One such complication is introduced by the fact that the screen itself heats up and some of this heat passes to the interior. If the space beneath is well ventilated, this may not matter; but if the ventilation is not free, the transmitted heat will accumulate, and much of the advantage of the screen will be lost. From this point of view it must be noted that other circumstances, notably the reflection and emission of radiation from surrounding ground, and the hot ambient air, frequently require that buildings in hot dry climates be closed and ventilation reduced or carefully controlled. Under these circumstances it is very important to see: (*i*) that the screen itself is exposed to as little radiation as possible; and (*ii*) that it passes as little of this heat on to the interior as possible. It will be appreciated, therefore, that there is a series of principles related to radiation screening, each one calling for attention to the extent that the preceding ones have failed adequately to meet the situation.

From the diagrams of figure 8 it will be seen that *the roof is invariably the surface which is exposed to the greatest radiation load* in the broad zone from 30° N. to 30° S. latitude. Of the walls, the one facing the equator is generally subjected to a moderate load throughout the day, while the east and west walls are subjected to somewhat higher loads for part of the day. (By way of offset, however, it must be remembered that the roof has twice the opportunity of the walls (per unit of horizontal area) to lose heat by long wave radiation to the "sky" (see below), and that on a clear night this loss from the roof can be quite important.)

External shade

To the extent that the shade of external objects, such as *trees*, can be used to intercept the incidence of solar radiation on a house, they *certainly should be used*, although certain disadvantages from leaves, falling branches, and access for predators, may have to be considered. Trees, however, are neither numerous nor shady in many hot dry regions, except along watercourses or irrigation channels, and the danger of flash floods often makes watercourses places to be avoided. *Bushes, shrubs, or artificial screens set on the eastern and western aspects* of the house are most effective for screening those walls from radiation, since it is the low altitude sun of morning and evening that contributes their principal load. They are less effective along the equatorial wall, which receives high angle sunshine, but they do help to eliminate radiation reflected and emitted from the ground. Cliffs may give good shade, but carry the hazard of falling debris, and may reflect rather than shade from radiation at certain parts of the day. One house can, of course, shade another house, and *houses set in an east-west alinement* may be mutually advantageous, unless they interfere too much with air movement. The culmination of this process may simply be the consolidation of several houses into one row or block, with the virtual creation of a single larger house. This is a feature, frequently seen in indigenous architecture, which is quite in keeping with requirements in hot dry climates, where insulation is usually more important than air movement. Something of the same effect is obtainable for the more pretentious single house by placing walls or rows of storerooms as western and eastern wings.

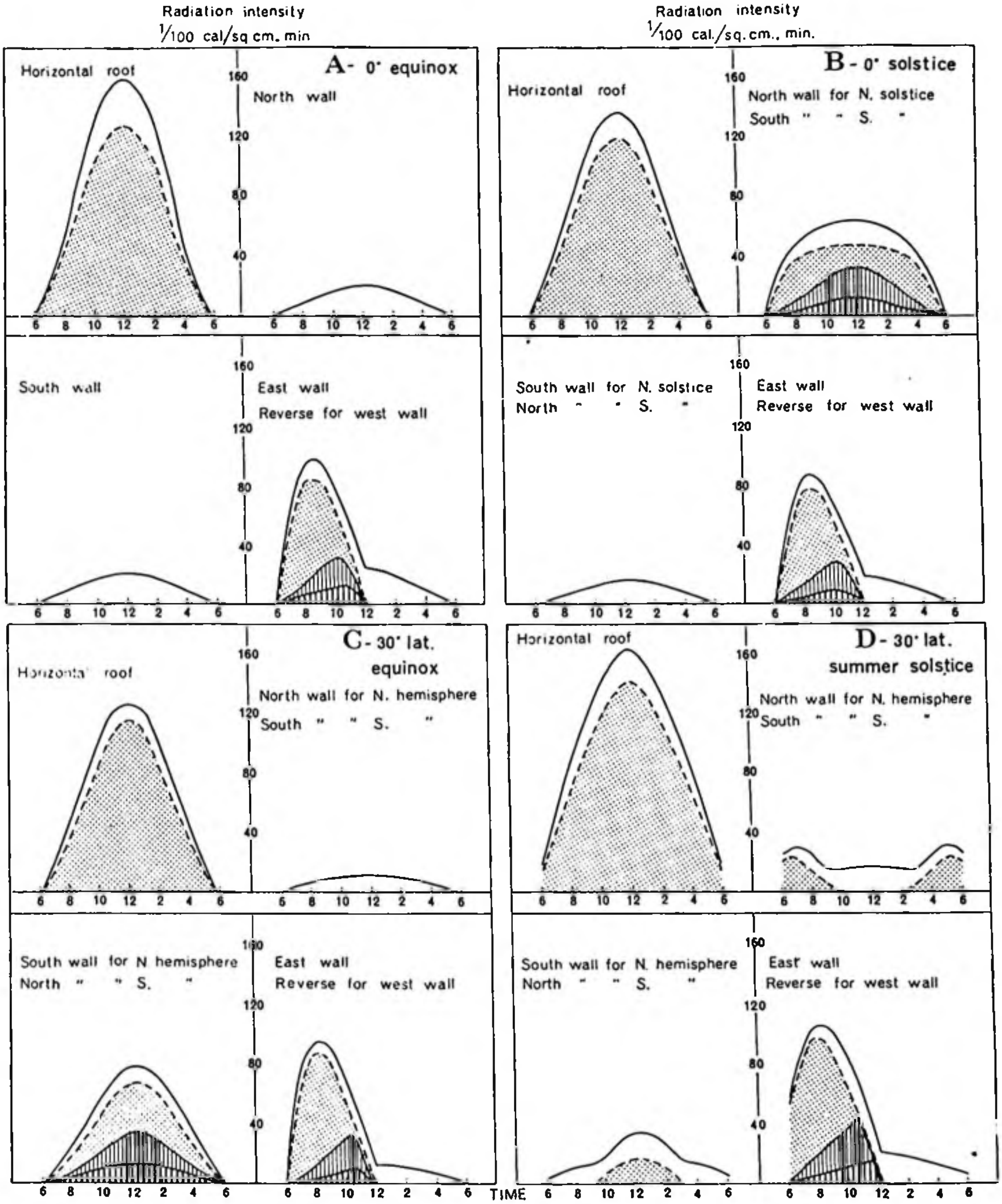
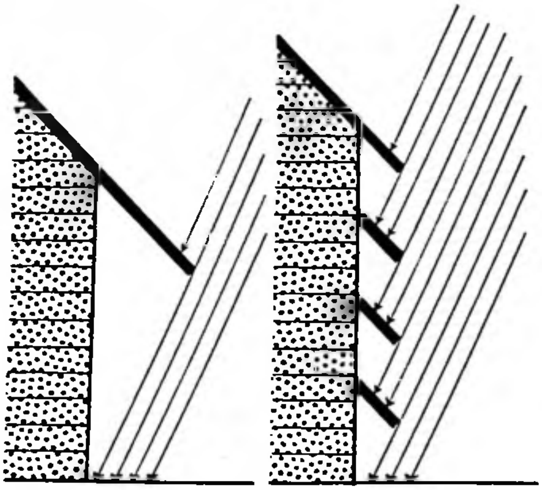


Figure 8—Radiation loads on roof and walls.—Maximum intensity of radiation falling on horizontal roof and walls at different hours of the day. Solid line above white area, total radiation from sun, sky, and terrain; broken line above gray area, direct radiation from sun; solid line above lightly striped area, radiation cut off by horizontal projection at top of wall equal to three-tenths of the wall height; solid line above heavily striped area, radiation cut off by horizontal projection at top of wall equal to one-tenth wall height. (Courtesy: American Geographical Society of New York.)

Reduced ground reflection

Where *grass or some other cover plant* can be grown, both the amount of solar heat reflected from the surface and the thermal emission will be considerably reduced. Where it is not possible to obtain such vegetation, then a *dark color* is to be preferred for exposed ground or concrete near a building. (cf. pl. III d) The temperature of the surface will be raised by its dark color, but in regions with strong sunlight the consequent increase in thermal radiation will usually be more than counterbalanced by the decrease in reflected radiation. The upper surface of ledges and canopies, especially those which may reflect sunlight through windows, should be similarly dark colored.

Attached shade



It is difficult to build a device which will shade the roof without making it an essential part of the roof complex itself; but it is easy to devise one which will shade vertical walls. Any projection from an exposed wall line will cast a shadow on an exposed wall, and the shading will increase with the extent of the projection. Such projections are most effective with a high altitude sun, so that they *are ideally used on the wall facing the equator*, or on both north and south walls for buildings situated near the equator. As such screens become heated they are free to lose heat to the ambient air, especially if some vent is placed near the highest point to allow heated air to pass out. Where the sun is nearly always at a high angle, as on the equator, these wall shades can be provided simply as a continuation of a sloping roof structure; but where it is not desirable to provide complete shading for a wall by a single projection, as for example because of high walls, strong winds, or aesthetic considerations, the same effect can be achieved by repeating smaller projections at various heights. It is *particularly advantageous to place such shading projections over door and window openings*, which otherwise act as radiation traps. (cf. pl. I c, II c, III d) In such positions they can often be combined with devices for excluding rain; but there are many other architectural devices with which shades may be combined. The extent of the saving in radiation load afforded by wall projections is indicated in figure 8. Vertical projections can be used to exclude morning or evening sun from window openings on equatorial walls (pl. II a).

The shading of glazed windows calls for some comment. The "greenhouse effect," whereby glass readily permits the entry of the relatively short wave solar radiation, but allows very little of the long wave thermal radiation from inside to pass back to the sky, is very useful for growing tomatoes in cool climates, but it is not very welcome in a hot dry season. *Blinds, shades, or shutters* absorb varying amounts of the incident radiation. If placed outside the glass, they are free to lose the absorbed heat to the ambient air; but if placed inside the glass this heat will eventually pass into the room. Such structures *should, therefore, be built outside the glass*, where they are twice as efficient. (See pl. II.) North American practice is particularly remiss in this respect. Where it is desired to have these shades adjustable, it is a simple matter to devise controls which can be reached through the open window, and not much more difficult to provide controls which can be operated from inside.

Water cooling of exterior

Spraying roof or wall structures which are exposed to the sun can be quite effective in reducing the heat load on the structure, but it must be remembered that it is only evaporation at the surface that will be effective, and that spray evaporated into the air away from the structure is of little value. Spraying should be intermittent, to permit effective evaporation from the surface. Sloping or vertical surfaces should be water absorbent if, as is usual in hot dry areas, the supply of water is limited.

Needless to say, the deeper layers of the structure should contain some water resistant material to guard against permeation.

An alternative practice on a flat roof is to maintain a water layer of 1 or 2 inches. This is probably less effective, since the solar radiation passes through the water to be absorbed at the underlying roof surface, so that the capacity insulation of the water is partly circumvented, and evaporation takes place at some distance from the point of maximum heating. The presence of a continuous water layer calls for more rigorous waterproofing, and the weight of the layer might be a matter of importance. A flat roof, moreover, is less subject to air movement, especially if it has a parapet, so that evaporation is not so rapid.

Minimal solar projection

The smaller the surface presented by the house to the sun (solar projection), the smaller the total solar load. In table 7 data are given for the solar projection of different basic designs, all with equal floor space, at different latitudes, seasons, times of day and orientation. These data were obtained by the use of models on the instrument known as a "heliodon," and described in appendix 1. Data are given in table 8 for the resultant solar load, taking into account the fact that the intensity of radiation depends also on the thickness of atmosphere that the sun's rays must traverse before reaching the earth's surface.

It will be seen from these tables that *the least proportional solar load is experienced in hot seasons by the tall,*[1] *slab-like building, with the long axis running E.—W.*; and that this type of building has the further advantage of acquiring *a high radiation load in the cool season* of mid-latitudes. It is thus suitable, not only for the equatorial tropics, but also for the subtropical regions with cool winters and hot summers.

[1] Height also aids convective removal of heat from the roof surface exposed to the sun. (See p. 53).

Table 7.—*Solar Projection (sq. ft.) of Buildings per 100 sq. ft. of Floor Space*

Type	Orientation [1]	Latitude 0°					Latitude 30° N.					
		Equinox		Solstice		Average	Summer			Winter		
		12.00 Hours	15.00 Hours	12.00 Hours	15.00 Hours		12.00 Hours	15.00 Hours	Average	12.00 Hours	15.00 Hours	Average
Cube 2 story	N	54	81	71	95	76	58	82	70	76	95	85
	NW	54	95	89	89	82	60	92	77	96	77	86
	W	54	77	72	93	74	58	79	69	82	96	89
Square 1 story	N	109	113	113	110	111	110	117	114	94	99	96
	NW	109	120	123	115	117	110	122	116	115	88	101
	W	109	102	118	114	111	110	108	108	104	99	101
Rectangle 1 story	N	108	121	119	112	115	102	102	102	108	92	100
	NW	108	119	125	103	114	102	120	[2] 113	112	73	[2] 115
	W	108	113	108	116	112	102	115	108	89	95	93
Square 4 story	N	28	77	55	98	65	34	76	55	78	111	95
	NW	28	98	68	87	71	34	92	63	103	84	94
	W	28	74	56	96	64	34	72	53	80	112	96
Slab 4 story	W	28	41	90	103	65	38	53	46	149	139	144
	NW	28	121	76	79	76	38	114	[2] 77	123	48	[2] 110
	W	28	133	39	134	83	38	122	81	47	140	94

[1] Buildings have simple gable roofs, with ridge at right angles to orientation.

[2] Averages for types with rectangular base at intermediate orientation include projections for 0900 (not given separately in this table).

TABLE 8.—*Incidence of Solar Radiation (B. t. u./hr.) on Buildings per sq. ft. of Floor Space*

Type	Orientation [1]	Latitude 0°					Latitude 30° N.					
		Equinox		Solstice		Average	Summer			Winter		
		12.00 Hours	15.00 Hours	12.00 Hours	15.00 Hours		12.00 Hours	15.00 Hours	Average	12.00 Hours	15.00 Hours	Average
Cube 2 story	N.	163	213	200	233	202	193	272	233	205	172	189
	NW.	163	250	250	218	220	199	305	252	259	139	199
	W.	163	203	202	228	199	193	262	228	221	174	198
Square 1 story	N.	328	297	318	270	303	365	388	377	254	179	217
	NW.	328	316	346	282	318	365	405	385	311	159	235
	W.	328	268	332	279	302	365	359	362	281	179	230
Rectangle 1 story	N.	325	318	334	274	313	339	339	339	292	167	230
	NW.	325	313	351	252	310	339	398	[2] 369	302	132	[2] 265
	W.	325	297	303	284	302	339	382	361	240	172	206
Square 4 story	N.	84	203	155	240	171	113	252	183	211	201	206
	NW.	84	258	191	213	187	113	305	209	278	152	215
	W.	84	195	157	235	168	113	239	176	216	203	210
Slab 4 story	N.	84	108	253	252	174	126	176	151	402	252	327
	NW.	84	318	214	194	203	126	378	[2] 252	332	87	[2] 260
	W.	84	350	110	328	218	126	405	266	127	253	190

[1] Buildings have simple gable roofs, with ridge at right angles to orientation.

[2] Averages for types with rectangular base at intermediate orientation include projections for 0900 (not given separately in this table).

The tall [1] building of square floor design also has a low solar load in hot seasons, which is irrespective of orientation; but it does not gain much in the cool season. It is most suitable, therefore, where hot conditions alternate with only mild winters. It is very interesting to find this type of building in the Hadhramaut region of Arabia (pl. IV b), although the reasons for its adoption were probably non-climatic.

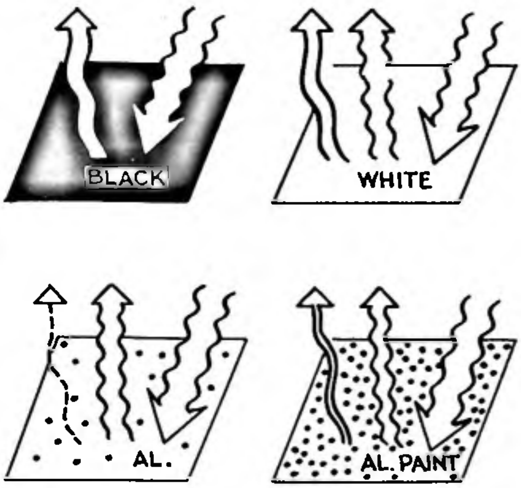
The same is true, though to a lesser degree, of the slab-type building with the long axis running NE.–SW., or N.–S.; and also for the cubical two-story building.

The single-story building, whether square or rectangular, *has the highest solar load under hot conditions* when it is undesirable, *but fails to retain this under cold conditions* when it would be welcome. Yet this is the type introduced by Western custom to many hot regions!

The question is frequently raised as to what effect the pitch of the roof has upon the solar load. This can be answered in fairly simple terms—as long as the altitude of the sun (the angle its beam makes with the horizontal) is greater than the pitch of the roof (the angle the roof makes with the horizontal), the shape of that portion of the roof has no effect upon the solar projection of the house; but when the pitch exceeds the solar altitude (as it must nearly always do at vertical gable ends), then the height of that part above the base does contribute to the solar projection. This can be proved trigonometrically. It can also be demonstrated by means of the heliodon. The net effect in *tropical regions*, where the sun is at a fairly high altitude most of the day, is that *the pitch of the roof has little effect on the solar load.*

[1] Height also aids convective removal of heat from the roof surface exposed to the sun. (See p. 53.)

High reflectivity and high reemission



The greater the proportion of incident radiation that a surface reflects, and the more easily such energy as is absorbed is reemitted as thermal radiation, the less will be the rise in temperature of the structure. To take full advantage of these features, however, one must know something of the physical laws which determine the end result.

As was pointed out in the first chapter (p. 3), *color is a fairly good guide to reflectivity towards solar radiation, but no guide to reflectivity towards thermal radiation.* Towards the latter most surfaces behave as "black bodies", reflecting very little; but *polished metals do reflect high proportions of thermal radiation.* Since emission of radiation from surfaces at ordinary temperatures is entirely of the long-wave "thermal" type, emissivities are simply the converse of these reflectivities towards thermal radiation. The reflectivities of some typical surfaces are given in table 9.

Because of the differences in behavior towards solar and thermal radiation, the net effect of a particular surface varies with circumstances. *When exposed to the sun and a clear sky*, as roof surfaces in hot dry situations usually are, *a white surface will be cooler than one of polished aluminum*, since although the white surface absorbs rather more of the incoming solar radiation, it emits thermal radiation to the cool "sky" very much more readily. *When exposed to the sun and hot ground*, however, as is the case with some walls, *the polished aluminum will be the cooler*, since there is little chance for the white surface to exercise its superior emissivity.

TABLE 9.—*Reflectivities and Emissivities of Some Typical Surfaces* [1]

Surface	Reflectivity percent to solar radiation	Reflectivity percent to thermal radiation	Emissivity percent of thermal radiation
Silver, polished	93	98	2
Aluminum, polished	85	92	8
Copper, polished	75	85	15
White lead paint	75	5	95
Chromium plate	72	80	20
White cardboard or paper	60–70	5	95
Light green paint	50	5	95
Aluminum paint	45	45	55
Wood, pine	40	5	95
Brick, various colors	23–48	5	95
Gray paint	25	5	95
Black matte	3	5	95

[1] Data taken principally from Handbook of Chemistry and Physics, Rubber Chemical Publishing Co., Cleveland, 1949, pp. 2294–2296.

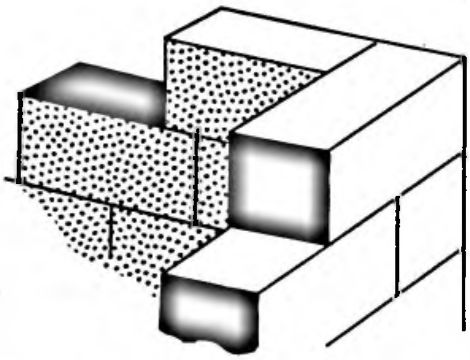
NOTE.—There is often considerable variation from one sample of material to another. The figures given above are to be taken as illustrative, not as means of numerous samples.

It would be well at this point to indicate the difference between a polished aluminum surface and one which is merely covered with aluminum paint. Because the metal is broken up into particles in the paint, it presents a roughened surface to the radiation. With the short-wave solar radiation, this has the effect of reducing the reflectivity from 85 to 45 percent; and with the long-wave thermal radiation, from 92 to 45 percent. Exposed to sun and clear sky, a painted aluminum surface would be definitely warmer than a white painted surface, since it absorbs more and emits less. Its temperature would probably not differ much from that of a polished aluminum surface. Exposed to sun and hot ground, however, the aluminum painted surface would be somewhat warmer than the white surface, and much warmer than the polished aluminum surface.

Convection over surfaces exposed to radiation

Surfaces exposed to strong radiation will be heated by that part of the radiation which is not reflected but absorbed. This heat will tend to be conducted through the material of the roof or wall to the interior, unless it can be removed in some other way. Since the temperature of a surface absorbing much radiation will usually be higher than that of the air, movement of ambient air over the surface will remove some of the heat and thus reduce the amount conducted to the interior. Any opportunity which may arise in construction, therefore, for encouraging air movement over the surfaces exposed to radiation, or at least for giving full scope to natural air currents, should certainly be taken. *Selection of upland or hillside sites, orientation of roof slopes to prevailing breezes, avoidance of obstructing parapets, elimination of "dead" areas between contiguous roof structures, preservation of wind lanes between neighboring buildings (unless they supply shade), and tallness of buildings* are examples of such opportunities for promoting external convection.

Insulation



Physiological Objectives in Hot Weather Housing

In cold climates, where the flow of heat is almost always in the same direction, the simple resistance of the material to the passage of heat, that is, the thermal conductivity, is the important property to be considered, since a low conductivity, or insulation in the usual sense of the word, will retard unidirectional heat flow. But where the flow of heat is alternately inwards and then outwards, important differences arise. As the cycle starts into the inflow phase, as with the first impact of the sun, the newly applied heat is used in warming the outer layers of the exposed material, and passes on into deeper layers only as the outer layer is warmed. This process continues, layer by layer (Fig. 9), until there is a steady gradient through the material. If the material has a high heat capacity and is thick, the chances are that the incidence of heat on the outer surface has begun to diminish by the time that the inner surface has been appreciably warmed, and very soon the properties of the material that delayed the inward passage of heat will be delaying its return passage to the outer surface which is now cooler.

Where the incidence of heat is cyclical, as it is with sunshine on a roof or wall, all that the insulative properties of material can do is: (a) to delay the time at which the temperature on the inner surface (or any other point in the structure) will be at a maximum (or minimum), and (b) damp down the oscillations of temperature at that point about the mean. The mean temperature, however, will not be changed; it will be the same on the inner as on the outer surface, the same, in fact, at all points in the material. The delaying and damping properties of the material depend, not only upon its thermal conductivity, but also upon its specific heat and its density. The combined property is termed the thermal diffusivity ("a" in Fig. 10). The values of the relevant properties for some common materials are given in Table 10b. Where the properties are not known, probable values may be determined from equations given by Mackey and Wright, as set out in Table 10a. The modified type of insulation provided against a cyclical heat load may be termed "*capacity insulation*," since it depends upon the thermal capacity (specific heat x density) as well as the conductivity of the material, as contrasted with "*resistance insulation*" offered to a unidirectional heat load, which depends upon conductivity alone.

Table 10a.—*General Trend of Thermal Properties in Relation to Density*

Density (r) $\frac{\text{lb.}}{\text{Cu. ft.}}$	Nature	Conductivity $\frac{\text{BTU, ft}}{\text{sq.ft.,hr., }^{\circ}\text{F}}$	Specific Heat $\frac{\text{BTU}}{\text{lb., }^{\circ}\text{F.}}$	Diffusivity $\frac{\text{sq. ft.}}{\text{hr.}}$
5-20	vegetable	$0.0137r^{0.3}$	0.328	$0.0418r^{-0.7}$
5-20	mineral	$0.0137r^{0.3}$	0.197	$0.0695r^{-0.7}$
20-60	vegetable	$0.00118r^{1.12}$	0.330	$0.00358r^{0.12}$
20-60	mineral	$0.00118r^{1.12}$	0.203	$0.00580r^{0.12}$
Over 60	vegetable and mineral	$(r/143)^{2.5}$	0.198	$0.0000207r^{1.5}$

Table 10b.—*Insulation Properties of Some Typical Materials*

Material	Conductivity (gcal., cm / sq. cm, sec °C., 10^5)	Specific Heat (gcal. / g., °C.)	Density (g. / cu. cm.)	Specific Heat x Density	Diffusivity (sq. cm. / sec.)
Air	6	0.25	0.00115	0.0003	0.2000
Cork	7-13	0.42	0.24	0.1010	0.0013
Wood	9-30	0.42	0.40	0.168	0.0018
Paper	30	0.37	1.00	0.370	0.0008
Rubber	45	0.45	1.10	0.495	0.0009
Asbestos	19-40	0.20	2.40	0.468	0.0007
Light concrete (30 kg)	59	0.22	1.17	0.256	0.0023
Glass	100-250	0.12-0.20	2.80	0.448	0.0056
Water (20° C.)	143	1.00	1.00	1.000	0.0015
Brick (110 lb.)	195	0.20	2.00	0.398	0.0049
Dry clay	200	0.22	2.60	0.570	0.0035
Ice	220-500	0.53	0.92	0.488	0.0102
Packed earth (70 kg)	347	0.22	3.43	0.755	0.0046
Concrete	347	0.22	2.67	0.588	0.0059
Granite	526	0.19	2.70	0.518	0.0102
Marble	700	0.21	2.80	0.588	0.0119
Steel	10-20 000	0.11	7.80	0.860	0.1282
Aluminum	50 000	0.21	2.70	0.578	0.865
Copper	100 000	0.10	8.90	0.819	1.221

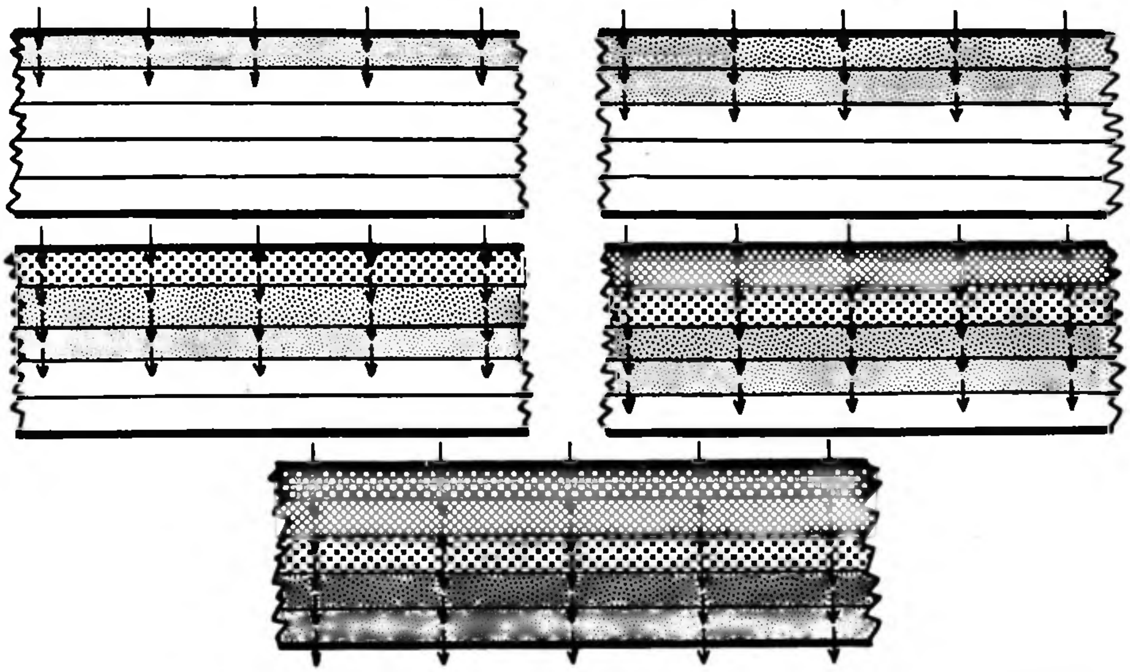


Figure 9.—Successive stages of heat passage through material (density of hatching indicates heat content).—When heat is first applied to a massive insulator it is largely used up in heating the outer layer. Only when this outer layer has been heated to a certain extent is there any appreciable flow of heat to the deeper layer. This process continues until there is a steady gradient throughout the insulator. When the application of heat to the outside is cyclical, an ebb and flow of heat is set up in the insulator, which acts as a temporary store during the application, but gives it off again when the heat is no longer applied.

Once realized, these properties of capacity insulation can be utilized to keep the oscillation of inside wall and ceiling temperatures down to the desired amplitude, and to have them appear at times which are convenient. For example, by suitably arranging materials and thicknesses, the maximum (or minimum) can be made to appear on all walls and ceiling simultaneously, although the external incidence of sunshine will vary considerably. For a bank, it may suffice to postpone the maximum until six in the evening, but for sleeping quarters, ten or eleven at night would be more acceptable, when cool outside air would be available for ventilation. The relation of damping and delay to diffusivity and thickness is shown in Fig. 10.

Precise calculations of cyclical heat flow through thick and complex structures can become quite complicated. For approximate work the author has used the numerical scheme given in Appendix 4.

Convection over inner surfaces

Just as air movement over heated outer surfaces was seen to be advantageous in removing heat which would otherwise have been conducted through the material, so convection over the inner surface will remove such heat as has come through. This is most likely to be important for the ceiling. Provided the air currents can be arranged so that the warmed air is led away without mixing with that in the building proper, this can be a useful adjunct to protection where other measures such as shade, reflection, and insulation are inadequate. The heat itself may supply sufficient motive power to carry the warmed air up through suitably placed vents. For reasons which will appear under discussions of conduction, *air flow* for purposes such as these *must be controlled* so that they do not invade other parts of the interior.

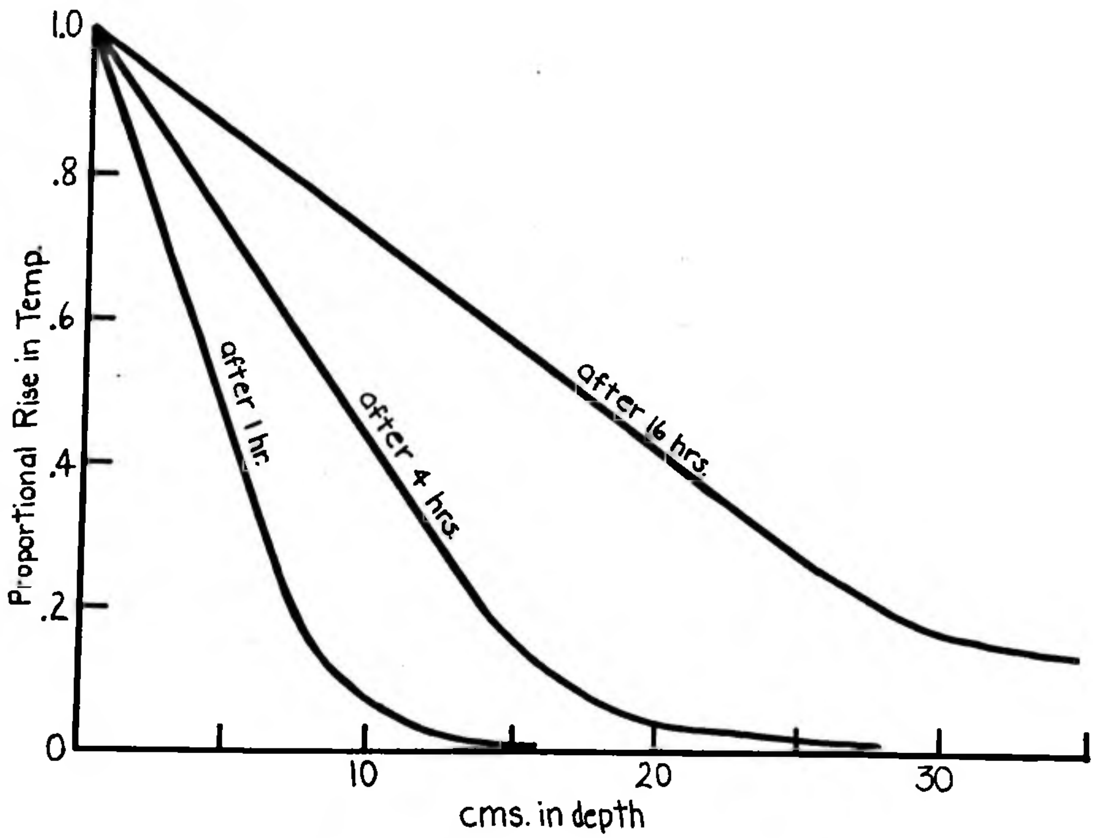


Figure 10.—Delay and damping produced by materials on solar heat load.—The critical feature of the material is the quantity x/a; where x is depth in cm.; a is $\sqrt{k/\rho c}$; and k is thermal conductivity in gcal.cm./sq.cm., sec., °C.; ρ is density in g./cu.cm.; c is specific heat in gcal./g., °C.—The straight line gives the time after maximum insolation (noon for horizontal and equatorial surfaces) that maximum temperature appears on inner face of material.—The curve gives the proportional amplitude of temperature oscillation on the inner as compared with the outer face.

Plate I

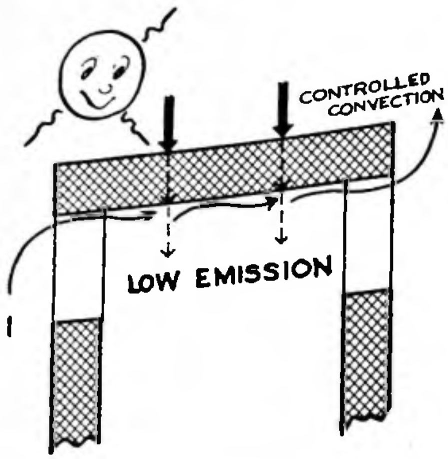
a. "Sweeper's" house, U. P., India. Capacity insulation of mud walls offset by open doorway and dilapidated thatch roof. No through ventilation for warm humid season. Crude drainage for wet season. No opening for escape of smoke. (Photo Lee.)

c. Hotel, Lucknow, India. Massive construction gives capacity insulation, but projections insufficient for shade. Ceilings unnecessarily high, making rooms very hard to heat in winter. (Photo Lee.)

b. Construction of indigenous house, Bahrein, Persian Gulf. Coral rock gives capacity insulation. Flat roof with parapet will give winter day and summer night living space. Large wall openings will have shutters for controlled ventilation and security. (Photo Lee.)

d. Superior residence, Lucknow, India. Wide verandah for wall shade in hot dry, and living space in hot wet season. Heavy construction gives capacity insulation. (Photo Lee.)

Low emissivity of inner surfaces



It would appear logical to advocate a low emissivity for inner surfaces, such as the ceiling, as by a lining of polished aluminum, so that for a given temperature less heat will be radiated inwards into the room. It must be remembered, however, that such heat as does not escape from the surface will build up in its neighborhood, unless it can be removed by convection. Any resulting rise of temperature will increase the radiation, undoing some of the good of low emissivity. Under these circumstances, it is certainly desirable to provide adequate air flow over the surface to convey the heat to the exterior. Reflective surfaces should not be used in rooms containing hot objects such as a stove, since the radiant heat will simply be returned to the room.

Ceiling height

There is a widespread belief, especially in India, that a high ceiling is essential to coolness. A hot ceiling close to the head is decidedly unpleasant, but it is not correct to assume from this that marked improvement will continue as the ceiling is progressively raised. The heat received from a ceiling is of two kinds—that radiated from the ceiling to the person's body, and that conducted from heated air trapped near the ceiling. If, in constructing a high ceiling, a trap for hot air is created, than any improvement from reduced radiation may be largely, if not wholly, offset by the increase in conduction. And this is just what most conventional high ceilings do.

If one calculates the amount of radiant heat that will be received from a ceiling, one finds that it is not very large, unless the ceiling gets abnormally hot. From table 11 it will be seen that, even from an 8 foot ceiling at 125 °F., the amount of radiant heat received does not exceed three-quarters the heat output of a resting man unless the ceiling is relatively extensive. The gains by a person seated and shielded by a table would be only about one-half of those shown in the table. Under most circumstances, the raising of ceiling height from 8 feet to 12 feet results in a quite unsubstantial reduction of radiant heat, and that from a load which was not very great to start with.

TABLE 11.—*Effect of Ceiling Height upon Radiant Heat Gain (B. t. u./hr.)*[1] *by Standing Person* [2]

Room width (ft.)	8 foot ceiling at—				12 foot ceiling at—			
	95° F.	105° F.	115° F.	125° F.	95° F.	105° F.	115° F.	125° F.
8....	20	62	107	118	13	38	65	91
10...	23	71	121	176	15	47	81	116
12...	26	81	139	200	18	53	89	133
20...	33	105	177	218	26	79	135	195
30...	38	117	200	288	31	98	167	240
40...	41	126	215	318	35	109	187	269

[1] Resting heat production (for comparison) 290 B. t. u./hr.
[2] Clothing surface temperature taken as 90° F.

As reported by the Australian Commonwealth Experimental Building Station,[1] high ceilings can detract from indoor comfort by:

(*i*) reducing the shading of external walls by eaves;

(*ii*) the inconvenience of carrying window heads to ceiling level, with consequent trapping of air;

(*iii*) increasing the volume of air and wall surface to be heated in winter. (See pl. I c.)

There seems to be no good reason for increasing the ceiling height of domestic rooms above the eight feet deemed satisfactory for temperate regions. Architectural energy would be better directed to reducing the heat transfer to the ceiling, decreasing its emissivity, and promoting convectional removal of the heated contact air.

[1] Drysdale, J. W., Natural Ventilation, Ceiling Height and Room Size, Dupl. Doc. 22, C'wlth. Exp. Bldg. Sta., 1947.

PRINCIPLES DIRECTED to REDUCING GAINS and PROMOTING LOSSES from the BODY by CONDUCTION

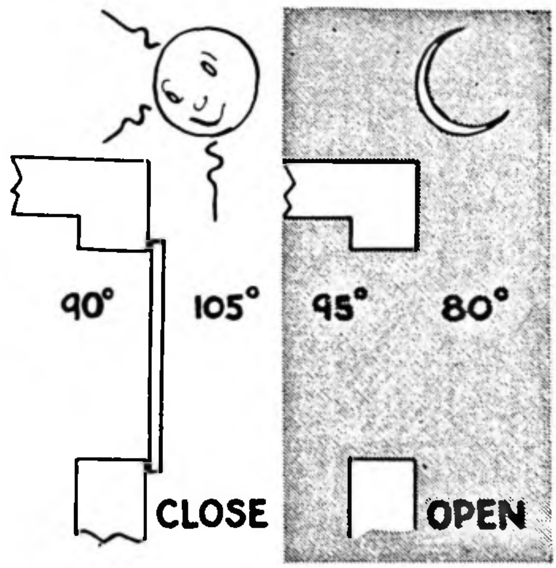
In a hot dry environment, with its typical oscillation between day and night temperatures and still greater oscillation between summer and winter temperatures, there are many occasions during the hot periods when the temperature of air outside a building will tend to be higher than that of walls and objects inside the building. Under such circumstances it would clearly be desirable to promote those features which tend to give lower internal temperatures and to deny entry to the hotter ambient air.

Insulation

It has already been shown that the heat-storage or "capacity" type of insulation, using materials of low thermal diffusivity rather than low thermal conductivity, markedly delays the transmission of radiant heat applied periodically to the exterior. This also applies to the transfer of heat from external air, but the quantities of heat involved are usually smaller. To this extent, therefore, the type of construction which is most suitable for minimizing radiation gains is also suitable for minimizing conduction gains from hot ambient air. If the construction can be so arranged that the maximum temperature of the internal surface comes about 12 hours after the maximum temperature of the external surface, the heat will arrive at the interior when it will be least objectionable or even welcome; and the cool phase will be at its peak when it is most needed.

Controlled ventilation

This promotion of cooler internal surfaces will be of little avail, however, if hot ambient air is free to enter through apertures in the structure. It is very desirable so to construct the roof and walls, therefore, that *the entry of hot external air can be minimized during the hot daytime periods, but the entry of cooler air at night or on cooler days promoted.* This principle of "controlled ventilation" is very important, and well exemplified in much of the indigenous architecture of desert areas (pls. I b and IV b). Fairly small door and window openings, fitted with shutters which can be tightly closed or thrown open according to conditions, meet this need. Glass windows which can be closed or opened are almost as effective, provided they are



shaded from radiation, while they have the advantage of admitting some light. It is sometimes advantageous to place the small windows high up in the wall to reduce the chances of radiation falling directly on the occupant of the room.

It was in the interests of minimizing the entry of hotter outside air that convective cooling of the ceiling was discouraged above (p. 38), but if large quantities of heat accumulate at ceiling level, it might be the lesser of two evils to use it, especially if good control can be maintained over its path.

Ventilation of roof spaces

The efficiency of a solid insulating material increases steadily with the thickness of material, but this is not true for air. As the thickness of an air space increases its insulating value increases less and less rapidly, until any further increase in thickness brings no gain in insulation. This is because differences in temperature set up mixing currents in the air, which are damped down in narrow air spaces but free to transport heat in wider ones. A rough working rule is that the insulating value of an air space is proportional to its thickness up to 0.25 in., but that any further thickness is of no value.

From this it will be seen that the *small air spaces* which occur in or between layers of building materials, not exceeding 0.25 in. in thickness, *are most effective when isolated from ventilation,* so that the stillness of their air content can be maintained.

Plate II

a. New dwelling, Maracaibo, Venezuela. Open tile in wall permits free ventilation while maintaining privacy. Curved tiles permit some ventilation of roof structure. Restoration of natural shade desirable.

b. Barracks, Congo. Essentially block and iron reproduction of tent. Ridge ventilation and rapid cooling of iron favor night occupation, but unsuitable for daytime.

c. Dwelling, near Maracaibo, Venezuela. Open tile parapet permits free ventilation over flat roof while maintaining privacy for personal use.

d. Old and new styles, New Iberia, Louisiana. High "colonial" porch gives little shade, but French windows desirable. Bungalow gives good shade. Attic rooms and dormer windows undesirable in both types. (Photo Lee.)

With large air spaces, such as that between a peaked roof and a ceiling, on the other hand, *ventilation may be very desirable*, especially if the insulation of the roof structure is not very effective, and the air flow can be arranged so that it sweeps the heated air on the under surface of the roof away to the exterior without bringing it into contact with the upper surface of the ceiling (cf. pls. III a, b). The outside air used for this purpose should be drawn through intakes placed close to the roof, so that hotter outside air will not be drawn into the rest of the building. (See fig. 11.) Roof spaces should not be converted into occupied attics in hot climates (cf. pl. II d).

Ground cooling

The earth has such a high heat capacity, that diurnal variations in heating of its surface do not penetrate much deeper than 2 feet, and seasonal variations not much deeper than 15 feet. Earth at greater depths thus maintains a steady temperature not very different from that of the mean annual air temperature. If air can be drawn over a fairly wide expanse of earth at depths greater than, say, 12 feet before entering the house, cooling can be obtained in summer and heating in winter. The ordinary *basement* or cellar uses this principle to a certain extent, but a greater effect can be obtained if the *air* can be *drawn through a fairly long tunnel* (or cave) before being taken into the building. This principle is used quite successfully in a hospital in India (Clara Swain Hospital, Bareilly, U. P.) and by Professor Thoburn at Lahore, Pakistan. Either ambient or recirculated air may be used. The deeper system may be supplemented by a more superficial system at about 2 feet depth, to cool by day and warm by night. When unskilled labor is available at a reasonable wage it may not be too expensive to dig a circuitous trench and line and cover it to form a tunnel; particularly if it is done at the time the building is being constructed.

Evaporative cooling

If air is passed over water and evaporation takes place, the air will be cooled, but its vapor content increased. A man would find it easier to lose heat by conduction to this "conditioned" air, but somewhat more difficult to lose heat by evap-

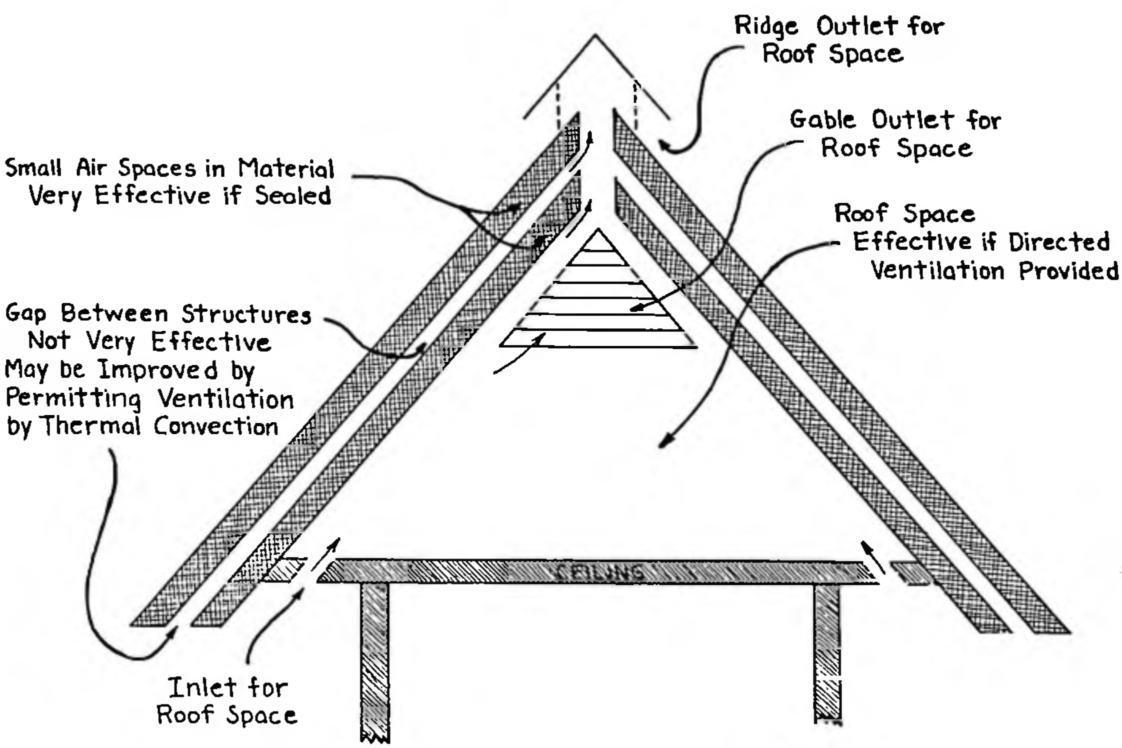
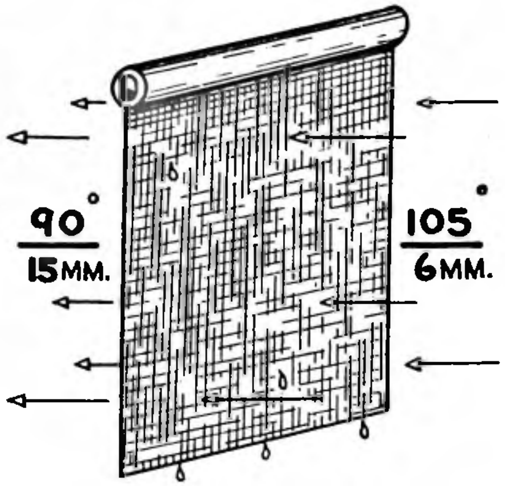


Figure 11.—Ventilation of air spaces in roof structure.



oration. It can be shown, however, that the net effect will always be an improvement, as long as the evaporating device does not interfere with the rate of air movement. ***Under hot dry conditions the improvement will be marked, but under warm humid conditions there will be less improvement and even a chance of reversal if air movement is reduced by the apparatus.***

The virtues of evaporative cooling have been known from ancient times, and a variety of devices have been used to which a greater variety of names have been given in different localities. For building purposes they can be divided into two groups—those directed to cooling the air, and those directed to cooling structures. The latter have been described earlier (p. 32).

The ***water blind*** is simply a piece of water absorbent material, such as burlap, towelling, or a rush screen, which is kept damp and placed in such a position that air will pass through it before impinging upon the man. The water may trickle down from a container which is refilled periodically, or from a perforated pipe where there is a piped supply, or it may be sprayed on. The construction can be kept very simple, permitting easy replacement as the material deteriorates. Mold growth, rust, and mosquito larvae are among the minor drawbacks of this system, but are usually regarded as necessary nuisances. Natural air movement is usually relied upon to pass the air through. It is ***essential to keep the blind thin and readily permeable by air.*** A type currently used in India, made of a thick mass of millet, is practically useless.

The ***box cooler*** is neater and can be built into a closed wall, but requires motive power. It is mply a box containing absorbent material such as cinders or wood wool, over which water drips. Two opposite sides of the box are open except for a retaining mesh, one side facing into the room, the other to the exterior. A fan is required to pull air through the device, but it must be realized that the common domestic fan is not designed to draw air against any resistance, and care must be taken to provide a fan with the necessary characteristics.

Refrigerant cooling

Evaporative cooling is so efficient in hot dry environments that there is no great need to utilize refrigerant cooling; but certain areas with advanced technology or rich resources may wish to adopt it. Under these circumstances there is little condensation of water from the air, so that the problem of defrosting and water disposal is a minor one; but larger coils or evaporative cooling are often necessary to eliminate heat from the compressor.

PRINCIPLES DIRECTED to REDUCING HEAT LIBERATION in the BUILDING

Where man has difficulty in getting rid of heat to the surrounding air, it is obviously undesirable to increase the heat content of that air, whether by raising its temperature through the addition of "sensible" heat or by raising its vapor pressure through the addition of "latent" heat. Yet cooking, lighting, and many industrial processes do this. Improvement could be sought along two lines: (*i*) increasing the proportion of fuel heat which goes into the process, with a decrease of that which escapes as "wild" heat; and (*ii*) removing what does escape in such a way that it does not impinge on man. The first is doubly important where fuel is scarce or costly, as is frequently the case in hot dry regions.

Many widely practiced cooking methods are quite inefficient as regards conservation of fuel. Only a small proportion of the heat liberated in an open fire, or in the wood stove characteristic of many rural areas, goes into the cooking process. The efficiency would be increased and wild heat controlled if the ***site of combustion*** were ***surrounded by capacity type insulation*** (see above p. 36), except for the area actually required for cooking heat. Aluminum foil may be used either to reflect radiant heat back towards the interior of the stove, or to minimize emission from the stove. To act effectively, the polished surface should be in contact only with a layer of still air. Both purposes can be served, therefore, by *including a narrow air space (not more than 0.25 in.) in the insulating structure, and lining it on both sides with foil.* Aluminum foil could also be affixed with advantage to those parts of the external stove surface which do not suffer much wear. (See fig. 12.)

Air draft through the combustion chamber should be controlled so that it is just sufficient to maintain combustion at the desired speed without wasting fuel by sweeping a large proportion of heat up the chimney. Cookers which use liquid or gaseous fuel or electric power are usually made more efficient than the conventional wood stove, but are usually more elaborate and expensive. Where solid fuel is scarce, the additional capital expense may be justified.

The simplest way to minimize the impingent of "wild" heat or evaporated vapor upon man is to have the heat- and vapor-producing apparatus freely open to ambient air; but to the extent that this is not practicable or sufficient, *controlled air movement over the heat source* to the exterior, avoiding man, is desirable. As with the use of convection for cooling air spaces (see above), the intake should be located near the apparatus, so that it will not increase the flow of air through the rest of the building when outside temperatures are high. The heat itself may supply the motive force, but assistance from external air movements or a fan may be considered.

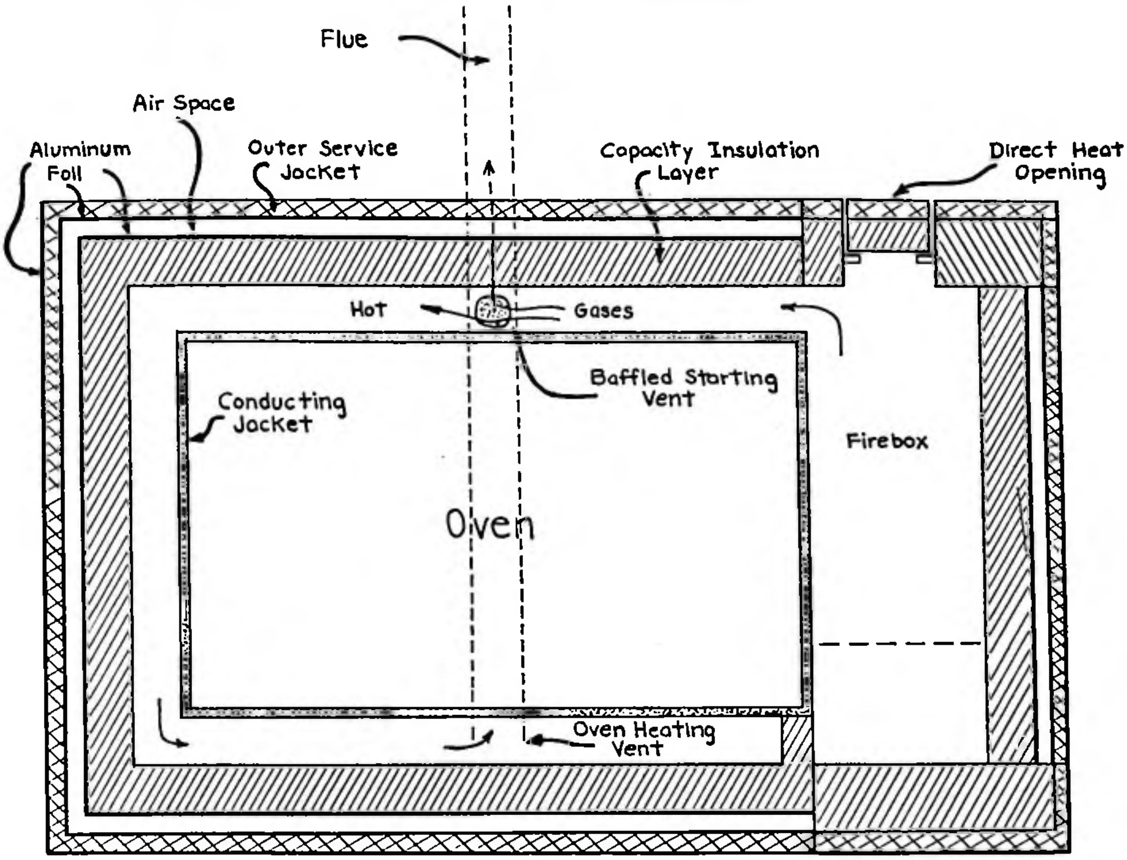


Figure 12—Use of insulation and aluminum foil in wood stove with oven.—Capacity insulation helps to maintain constant heat in spite of fluctuations in the intensity of the fire, as well as preventing the escape of heat into the room. Two opposed layers of reflecting foil, separated by a space, act as insulation against radiant heat losses. The outer layer of foil on nonfunctional surfaces reinforces this. For quick starting of the fire, direct passage of gases from the firebox to the flue is necessary. Once the fire is well started, the baffle can be changed to send the hot gases around the oven before they gain access to the flue.

The "sensible" heat produced by a lamp can be carried away if the lamp is placed under a vent leading to the exterior. A person who has to work close to a lamp can be protected from the radiant heat, without appreciable reduction of light, by the interposition of a filter. A *simple filter can be made from two sheets of glass cemented to a metal strip so as to make a flat-sided vessel, about 1 inch in thickness, which can be filled with water.* The infrared radiation is absorbed by the water, whose heat capacity is such that it will not warm up enough in an ordinary working period to reradiate appreciably. Where plastic of fairly high heat tolerance is available, it can be used in place of both glass and metal, but is liable to lose transparency by scratching.

SUMMARY

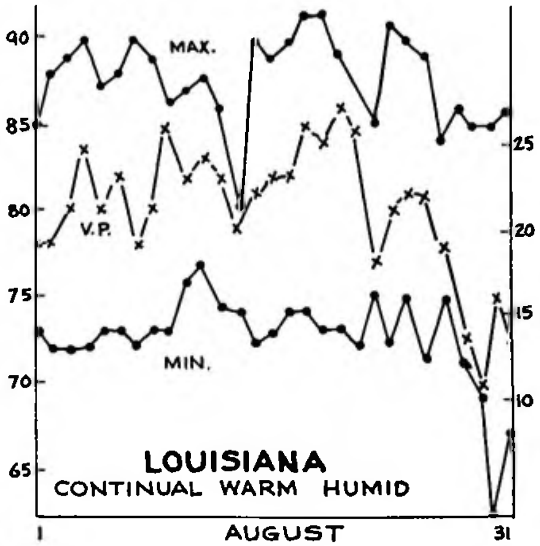
The principles which have been enunciated as a result of a survey of human physiological requirements under hot dry conditions are listed on the left-hand side of table 12, and the more important applications which stem from them are summarized on the right-hand side. A general correspondence will be found between the order in which the principles, on the one hand, and the applications on the other, are given; but some principles naturally affect more than one application, and the exact nature of a particular application may be the result of a compromise between the demands of two or more principles. It is believed that this summarizing table will provide a convenient check list for busy executives; but reference must be made to the text for explanatory and qualifying detail.

TABLE 12.—*Summary of Principles for Hot Dry Environments and Important Applications*

Principles	Important applications	Principles	Important applications
Reducing human heat production Convenience of arrangement. Ease of cleaning.	Convenient storage space. Convenient plan and conservation of floor space. Convenient facilities. Easily cleaned surfaces.	*Reducing gain and promoting losses from body by conduction* Insulation. Controlled ventilation. Ventilation of roof spaces. Ground cooling. Evaporative cooling. Refrigerant cooling.	Avoid parapets and mutual interference of roof structures to wind. Wood, earth, stone, or other material of low diffusivity for roof. Ceiling height generally not over 8 feet. Continuous walls, with capacity insulation where exposed to radiant load. Doors, windows, etc., fashioned for both tight closing and easy opening. Ventilation of roof space and spaces between successive roofing layers. Water blinds, or box coolers with fans. Air intake through earth tunnels. Basement construction. Air conditioning by refrigeration.
Reducing gain and promoting losses from body by radiation External shade. Reduced ground reflection. Attached shade. Water cooling of exterior. Minimal solar projection. High reflectivity and re-emission of exterior. Convection over surfaces exposed to radiation. Insulation (capacity type). Convection over inner surfaces. Low emissivity of inner surfaces. Moderate ceiling height.	Shade trees where possible, especially to roof. Shade bushes where possible, especially to E. and W. exposures. Contiguous building in E.-W. rows or consolidated. Noninhabited wings to E. and W. exposures to provide shade. Vegetation over ground where possible. Dark color for ground exposed to sun. Eaves and other horizontal projections on equatorial exposures. Awnings, external shades, shutters, etc., especially on equatorial exposures. Vertical projections beside window openings on equatorial exposures. Water spraying of roof and walls exposed to radiant load. Water layer on flat roof. N.-Facing slab or tall square shape for inhabited building. Light color for surfaces exposed to solar radiation.	*Reducing heat liberation in building* Minimize heat liberation. Remove liberated heat.	Capacity insulation around oven and firebox. Narrow air space lined with aluminum foil in oven wall. Liquid or gas fuel, or power where economically feasible. Vent to outside over stove. Vents and infrared screens for lamps.

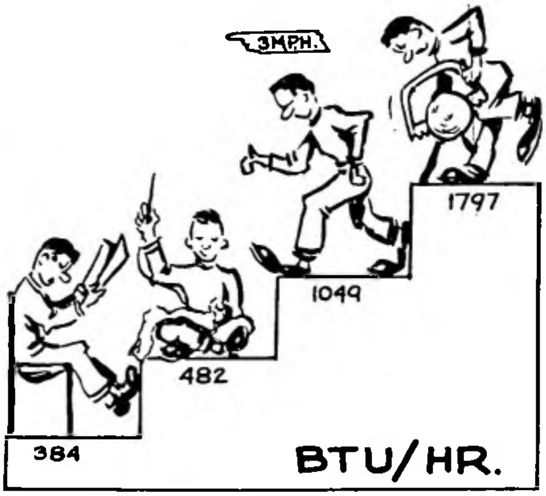
HOUSING as CLIMATIC PROTECTION in WARM HUMID ENVIRONMENTS

IN THE preceding chapter the protective role of housing in hot dry environments was discussed in some detail. Some of the principles established and methods suggested for those environments, such as labor-saving and control of heat liberation, will be equally applicable to warm humid environments; but in other cases there will be marked contrasts, due to the difference between the prevailing temperatures and humidities in the two kinds of environment. In this chapter repetition will be avoided by referring back to those principles which have already been discussed and which are still applicable, and emphasis will be placed upon those cases where the objectives under warm humid conditions differ from those advocated for hot dry conditions.



NATURE of WARM HUMID ENVIRONMENTS

In contrast with hot dry environments, these are characterized by only ***moderately high temperatures (seldom exceeding skin temperature), moist air, and damp ground.*** Cloud and moisture vapor frequently filter out portions of the solar radiation; the damp ground and free water have a high heat capacity and so heat up less readily; and vapor readily condenses and falls as precipitation; so that here, too, a cycle of events tends to perpetuate itself. In fact, ***near the equator, variation is minimal*** unless local topography, such as the relation of mountains to winds, introduces seasonal variation. ***Further away from the equator,*** of course, the annual march of the sun and seasonal winds introduce variation, so that the ***typically warm humid conditions are limited to one period of the year.*** The moisture, combined with moderate heat, is favorable to the growth of vegetation, which still further reduces radiation by its low reflectivity. It will be seen, therefore, that the radiation load is usually not great, and that there is usually some opportunity for heat loss by conduction, so that the amount of heat that the human body has to eliminate by evaporation does not greatly exceed that produced by metabolic processes. *Evaporation*, however, *is usually difficult*. To establish a vapor pressure sufficiently higher than that of the ambient air, the skin has to develop an extensive water film. Sometimes, indeed, even complete wetness is barely sufficient to maintain the necessary difference, and a wet skin is distinctly uncomfortable as well as susceptible to certain disorders. Air movement facilitates the evaporation, but jungle growth is often an effective screen against air movement.



The essence of the warm humid situation for an unprotected man is shown in figure 13 and table 13, and the geographical distribution of such environments is indicated in the maps of figure 6.

The same general order will be followed in the discussion as before.

PRINCIPLES DIRECTED to REDUCING HUMAN HEAT PRODUCTION

It is at least as important to eliminate unnecessary heat production in warm humid as in hot dry environments (p. 29). Some would maintain that it is even more necessary, since many persons have a greater dislike for the discomfort induced by "sticky" conditions, and particular difficulties are introduced into housekeeping by the prevalence of molds, insects, and general dampness. *Accessibility of stores to the point of use, accessibility of waste receptacles, easily cleaned surfaces and utensils, avoidance of step climbing, and conservation of floor space* are all important and applicable to low cost housing.

Since floor cleanliness is an important item and one in which an important amount of daily labor may be expended in humid climates, the general matter of floor construction might be mentioned here. To be satisfactory, floors should meet certain minimum standards: (i) they should be comfortable to walk on and strong enough to support the occupants of the house and any necessary equipment and furniture; (ii) they should be easily cleaned; (iii) they should not be wet or noticeably damp; (iv) they should be reasonably durable; and (v) they should be designed to exclude insects, rodents, and other pests. In humid tropical regions it is not as easy to meet these requirements as in

TABLE 13.—*Important Characteristics of Warm Humid Environments*

Item	Magnitude	Effect on human heat balance
Direct solar radiation	Moderate to high, but shade abundant	*Moderate to fairly marked* addition to heat *gains*.
Solar radiation reflected from clouds, etc.	Moderate	*Some* addition to heat *gains*.
Solar radiation reflected from ground, etc.	Little	Little effect.
Thermal radiation exchange with ground, etc.	Little	Unimportant.
Thermal radiation loss to "sky"	Little	May be *some* heat *loss*.
Air temperature	Slightly below skin temperature	*Slight* addition to heat *loss*.
Air vapor pressure	High	*Restricts* opportunity for the heat *loss* essential to restore balance.
Air movement	Variable	*Promotes* heat *loss*.

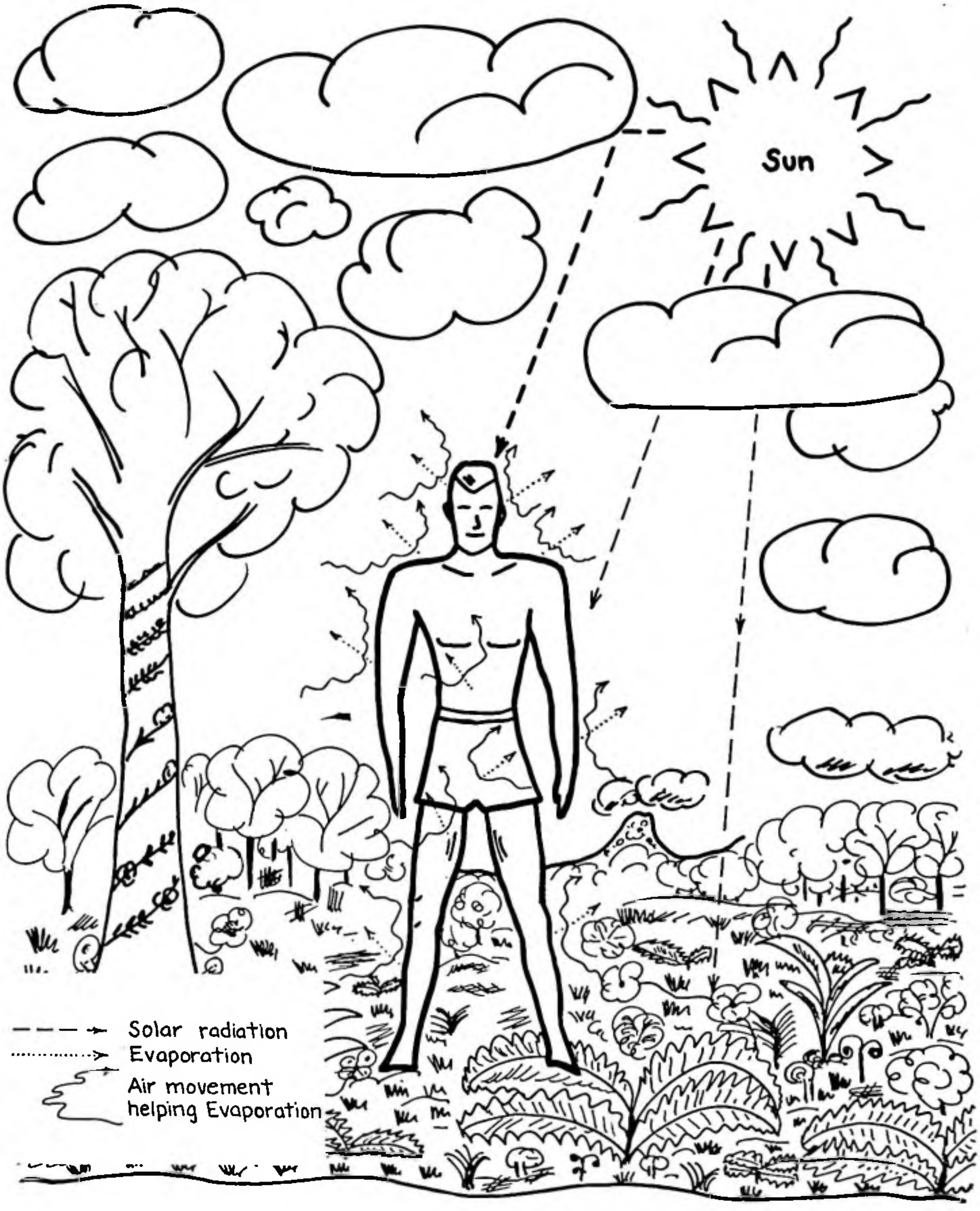


Figure 13.—Heat exchange in warm humid environments.—Note the intermittent incidence of direct solar radiation, and the absence of reflection from the ground. Reflection from clouds, however, may be considerable. Note also absence of long infrared exchange with ground or "sky." There is virtually no heat exchange by conduction. Heat loss by evaporation is difficult, but very much accelerated by air movement.

temperate areas, particularly where high cost is a factor.

An *earthen floor* maintains a fairly constant temperature, somewhat below the mean air temperature, but is likely to be damp or even wet most of the time and thus produce a layer of humid air near it. It is difficult to keep clean, harbors many pests, and easily becomes infected if sanitation is faulty. The chief asset is negligible cost. (See pls. I a, III c.) Some of the objections to earthen floors can be reduced by stabilizing the earth with cement, bituminous materials, or other suitable chemicals to render them less absorbent and make them easier to clean.

Semiabsorbent material resting on earth (e. g. wood) tends to follow air temperature a bit more closely, and to be somewhat less wet than the earth itself; but of course it will share in any surface flooding. It is generally easier to clean, though dirt will readily accumulate in cracks between structural units, which are difficult to clean out. Deterioration from fungus and termite action is likely to be great and must be matched against the cost of construction.

Impervious material resting on earth (e. g. concrete or tile) will preserve a fairly constant temperature about the mean of air temperature, and it will be relatively dry unless its temperature happens to fall below the dew point of the air in the house. It can be easily cleaned and even washed thoroughly without harm; continuity of structure will help in this. It will eliminate the penetration of pests from the earth and contamination of the earth from the house. It should be durable.

If the floor is *constructed off the earth*, many considerations are altered. In general, the floor will be drier and a little cooler. Cheaper semiabsorbent materials can be used, and continuity of structure is not so important. Crevices can provide some increased perflation for the floor region, which usually has a layer of stagnant air, and also a drain for wash water. If access is provided to the under surface, crevices and the earth beneath can be cleaned. Pests and vermin can usually be excluded by continuing the outer walls from floor to ground as a sheathing. Deterioration of floor materials is not likely to be rapid. Where termites are a threat, metal shields should be placed between the floor and wall structure and the supporting posts, piers, or foundation walls. (See pl. IIc). The supports themselves should be resistant to termites and should preferably be of masonry or concrete. In some areas hardwood posts treated with creosote, pentachlorophenol, or other preservatives may prove satisfactory. In any case, walls or supports should be accessible for periodic inspection. If the supports are high, the space beneath can be utilized for many purposes, such as the drying of laundry or recreation. (See p. 67)

PRINCIPLES DIRECTED to REDUCING GAINS and PROMOTING LOSSES from the BODY by RADIATION

Although the average intensity of direct solar radiation is less under warm humid conditions, it is still fairly considerable on the roof, and at times rises to intensities close to those characteristic of hot, dry regions. Walls, on the other hand, are subjected to much less reflected and thermal radiation from the ground. The various principles discussed in the previous chapter for protection against radiation still largely apply to the roof, though in reduced intensity, but may be modified in relation to walls.

External shade

Since trees are usually abundant, they can be utilized to shade the roof and walls and the surrounding ground, but account has to be taken of falling branches, the harborage given to pests such as sandflies and bats, and the access they provide for unwelcome visitors, whether animal or human.

The bungalow type structure can take advantage of spreading shade trees and thus offset its greater roof projection (pl. II d). *Mutual shading of houses is much less desirable here*, since proximity would restrict the highly desirable air movement between and through houses. The same objection applies to bushes or other screening growth too densely planted. The lack of privacy brought about by open walls (see below) also makes separation of households desirable. Apartment-type buildings are open to this objection.

Reduced ground reflection

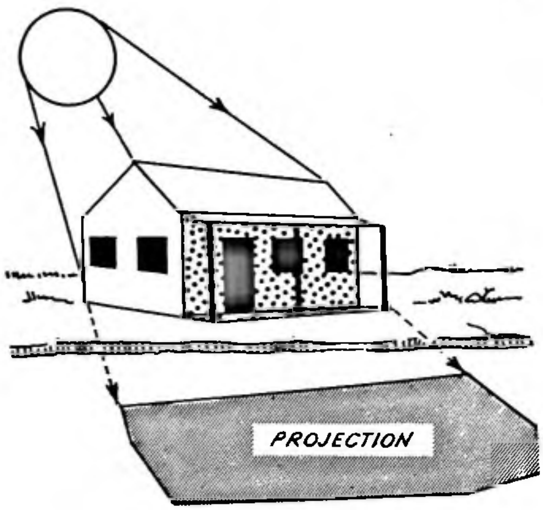
Vegetation normally covers the ground under warm humid conditions, and full advantage should be taken of the reduction in reflection and thermal emission given by it. The moisture content of the ambient air is little affected by substituting cement or other quick-drying surfaces for grass-covered earth, but both the reflection and the thermal emission may be increased, so that such surfaces are not desirable close to the building.

Attached shade

The proper use of attached shades (see p. 32), combined with the screening effect of trees and bushes, can eliminate dependence upon continuous wall structure for radiation protection, and this is often an advantage where, as will be pointed out below, maximum perflation by the ambient air currents is desired. In spite of the reduced average intensity of radiation, therefore, *wall shades* retain a marked importance in warm humid environments since they *may substitute for the walls proper.* They may be provided simply as continuations of a sloping roof, as attachments to vertical supporting members, combined with rain protection over wall openings, or incorporated in other architectural devices. The verandah (see p. 66 and pls. I d, II d, III) is simply the logical development of attached shade. All shades should be provided with vents for the escape of trapped hot air.

Minimal solar projection

If the vertical faces of the building are adequately protected by vegetation or attached shades against direct solar radiation, they do not enter into questions of solar heat load on the house. Such heat as is absorbed by those shades is returned



to the ambient air and not added to the house itself. Under these circumstances, it is the *solar projection of the roof alone* which *should be minimized.* With a high altitude sun, this is proportional to the horizontal area covered by the roof, the shape of the roof entering into the determination only where its pitch exceeds the solar altitude. Under these conditions the roof of a *multi-stored house* would have a smaller solar projection than that of a single storied house with the same floor space, but effective wall shading becomes more difficult as the wall height increases, so that a compromise may be necessary. Height increases convection by natural air movement (see below), but also puts greater mechanical strain on the relatively flimsy construction frequently employed in these regions.

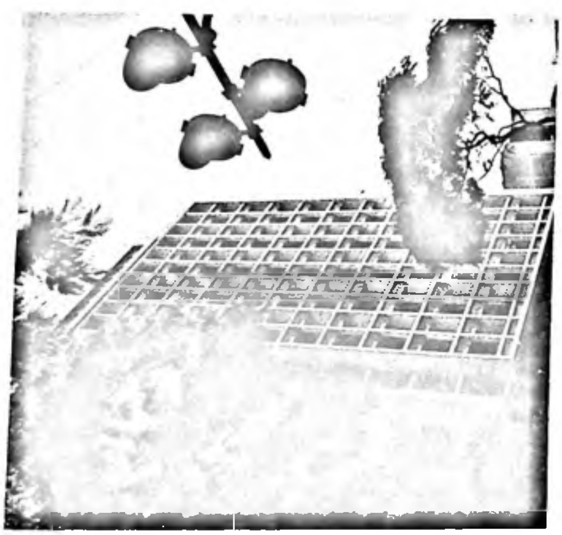
High reflectivity and high reemission

High reflectivity towards incoming solar radiation is still important, but high reemission is less so than under dry conditions, since the water vapor content of the air largely filters out thermal radiation loss to the "sky," sky temperatures approaching more closely to those of the ambient air. (That this is so is indicated by the fact that one is much less impressed by a sense of coolness on stepping out at night from beneath a canopy in a warm humid than in a hot dry environment.) The superiority of a white painted roof surface as compared with a polished metal surface might be expected, therefore, to be less (see p. 35) under warm humid conditions.

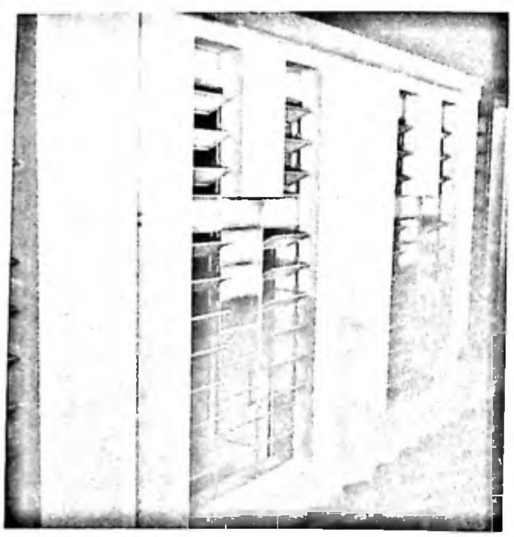
Plate III

a. Apartment dwellings Puerto Rico. Cross ventilation permitted, but roof ventilation desirable to minimize heating of top story. Advantage not taken of rich natural shade.

c. Office windows, Belem, Brazil. Adjustable louvers over most of wall height surrounded by ample veranda permit maximum use and control of natural breezes. Applicable to dwellings or halls.

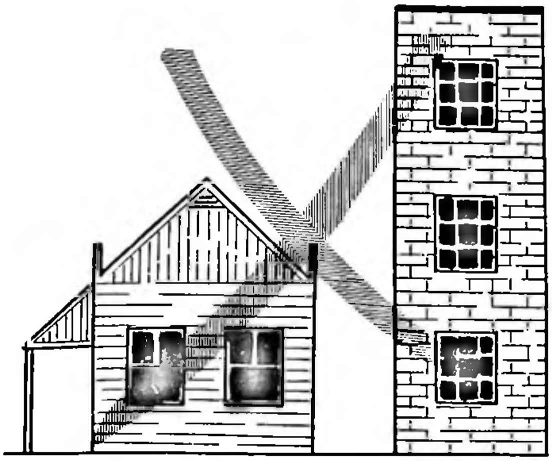


b. Office building, San Paulo, Brazil. Horizontal and vertical projections give good shade while preserving illumination. Design applicable to less pretentious structures.



d. Lath and mud dwellings, Belem, Brazil. Ventilation incompatible with privacy. Encourage vermin unless kept in perfect repair. No protection from high water table.

Convection over surfaces exposed to radiation



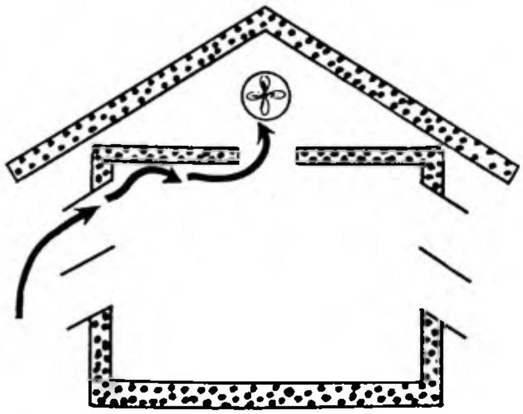
This is still desirable, especially as surfaces will often be damp, and air movement will tend to promote cooling by evaporation. In dry periods spraying may be used on the roof (see p. 32) to supplement this effect. The higher the roof above the ground level, the greater will the air movement tend to be over it. This is one effect of the practice common in Latin America, Siam, and Australia of placing dwellings on piles (pl. II c, III a). *Buildings* placed *upon an elevation* will similarly tend to enjoy greater air movement. The mechanical hazards of wind must be borne in mind, however. *Obstructing parapets should be* avoided in roof design.

Insulation

Inasmuch as the roof is exposed to periodic heating by solar radiation, capacity type insulation (see p. 36) is that which is the more effective for that structure; but since the average load is somewhat less than in the hot dry environment, the insulation requirement may be somewhat less. For walls which are adequately shaded there will be no requirement for insulation against radiation loads (pl. III b, c). (This does not mean that concrete, or other capacity insulation, should not be used for walls if it is readily available, but simply that it is not necessary.)

So unimportant are walls, as long as the weather is kind, that provision should be made wherever possible in warm humid environments for outdoor living. With shade provided by trees, and sufficient privacy given by shrubs and hedges, eminently liveable conditions can be obtained for a large proportion of at least the daylight hours. The space beneath houses raised on piles can be very well utilized in this connection (cf. pl. III a).

Convection over inner surfaces and ventilation of roof space

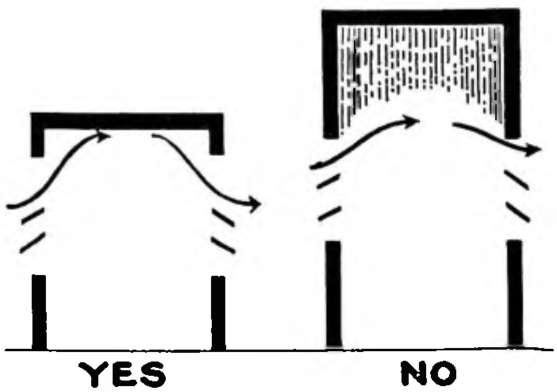


This may be used to offset inadequacies in insulation, but in warm humid environments there is no reason for localizing the intake to the ceiling region, and the flow may well be made a part of the general perflation, which will be discussed later.

Low emissivity of inner surfaces

This may be used as was suggested for hot dry conditions (p. 40), with the same proviso that air flow be used to take the heat away from the surface which cannot now emit it so readily.

Ceiling height



There is even less advantage to be gained from high ceilings here than under hot dry conditions (see p. 40), since the ceiling temperatures are apt to be less. In fact, it is highly desirable that ceilings be kept sufficiently low for *window openings to reach to the ceiling line*, permitting hot humid air to be swept out by ventilation. (See below.)

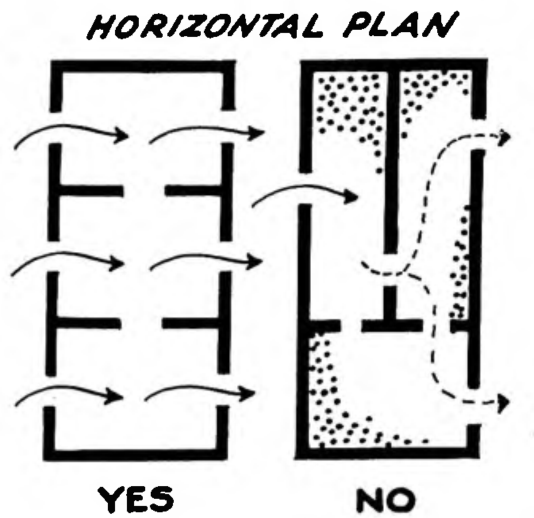
PRINCIPLES DIRECTED to PROMOTING LOSSES from the BODY by EVAPORATION

In hot dry environments evaporation takes place so readily that skin evaporation seldom requires special encouragement as long as the skin can supply sufficient water; but under warm humid conditions difficulty of evaporation into the moisture laden air is the critical process. Heat exchange by conduction, on the other hand, fades into comparative unimportance. *Basements* and other *devices for heat exchange with the ground* are *generally not effective* in these environments, and may involve trouble from the usually high water table. For these reasons, the section on principles directed to conduction which appeared in the chapter on hot dry environments is replaced here by a section on principles directed to evaporation. It should be mentioned, however, that water cooling (p. 32) may still work sufficiently well on a roof heated by the sun to warrant consideration.

Ventilation (Volume flow)

Unless some method of dehumidification is used, vapor pressures inside a house will tend to be raised above those outside by sweating, washing, and cooking. Under these conditions it is *desirable to have external air replace the internal;* and the more frequently this is done, the more easily will internal vapor pressures be kept from rising. This replacement of internal by external air is properly termed *ventilation*, and is best expressed as the number of air changes per hour, or, for a given structure, as cubic feet per minute. It is essentially a rate of volume change. Natural air currents will help to secure this through openings suitably placed in relation to the wind direction, one set facing the wind for entry and one away from the wind for exit (cf. pls. I a and III). *Contours, the orientation of the house, and position of surrounding structures* may all markedly affect the efficiency of this natural ventilation. It may be supplemented by fans where power is available.

Air movement (Velocity of flow)



The more rapidly air moves over the skin, the more readily will evaporation occur. It is important, therefore, in warm humid environments where evaporation is difficult, not only to keep the average vapor pressure of the air in the room down by ventilation, but also to speed up the rate at which that air moves over the skin. The natural air currents can be used to promote this as well as to promote the ventilation, but *some type of fan is generally desirable as* well.

Where major dependence is placed upon natural air currents, the external conditions which were mentioned as promoting ventilation—contours, orientation, position of neighboring structures, location of openings—must be supplemented by structural provisions. The velocity of the incoming air can be kept up if it is *channeled by partitions* through occupied areas instead of being dissipated by eddies in unoccupied backwaters. Partitions should not run athwart the direction of air flow, but if some thwartwise structure cannot be avoided, it should have several openings and be separated by a space from both floor and ceiling.

Wall openings should not only be of maximum extent, but also be *free of obstruction*, and this point should be borne in mind when the provision of insect screening is considered. In those tropical areas free from the organisms of insect-borne disease and not possessing power for fans, inhabitants often prefer to put up with the nuisance of insects rather than to restrict the breezes. There is some evidence that the airflow is promoted if the extent of openings on the lee side is greater than that on the windward.

Exclusion of rain from wall openings is fairly easily obtained by *overhangs* in the equatorial zone, where winds are seldom of driving force; but in other regions this may present quite a problem. Open *verandahs* represent areas that can be abandoned to the rain when necessary; *louvres* and *jalousies* provide controllable openings as long as they fit well and someone is there to operate them. *Blinds* which can be rolled, made of rattan or other material, constitute a compromise, but are only partially efficient and are best used on verandahs.

Manpower (e. g. the "punkah wallah") is no longer generally available for operating fanning devices, so that electric power is usually necessary before mechanical reinforcement of natural air currents can be contemplated. High-speed fans blowing in a fixed direction are not very suitable for domestic use, since the high velocities disturb objects and are unpleasant to the skin. Eddying air currents are in some ways even more effective than linear air currents in cooling the body, so that fans which set up a general turbulence, though of lower average velocity, are desirable. *Large, low-speed, overhead fans* do this quite well. (These overhead fans are sometimes regarded as "old-fashioned"; but they do the desired job better than many "modern" substitutes.) Smaller, medium-speed, oscillating, wall fans give a useful compromise. A design which has become popular in the United States recently consists of a medium-speed fan blowing upwards on to a cone, which deflects the air stream outwards and upwards. The unit is portable, and can be placed on or near the floor in the position the individual finds most acceptable. It has the great virtue that it does not blow papers and other light objects off the table or desk.

Dehumidification

Whereas for hot dry conditions the stress in air conditioning is on reducing air temperature, with little consideration for its humidity, the emphasis under warm humid conditions is on reducing the vapor pressure, with only minor consideration for temperature. The more commonly used method of dehumidification is probably that of *cooling the air below the dew point* so that an appreciable proportion of the contained vapor is condensed. An alternative method is to remove the vapor by *absorption* on silica gel, which is subsequently regenerated by heat. It is unlikely for a long time to come that either of these methods can be extensively used in what are commonly regarded as under-developed countries. To the extent that partial use may be possible, *sleeping quarters, critical work rooms, indoor recreational facilities, and hospitals call for prior attention.*

PRINCIPLES DIRECTED to REDUCING HEAT LIBERATION in the BUILDING

Since wood is usually fairly abundant, the low capital cost of a wood-burning stove has much to recommend it in a warm humid region, but the problem of avoiding the effects of "wild" heat upon the operator is still very important. The various comments made on this matter in the previous chapter are just as cogent under warm humid as under hot dry conditions. *Capacity type insulation, an air space in the oven wall lined with reflective foil, low emissivity of the outer surface, and removal of heated and humidified air by directed air flow* are very desirable.

SUMMARY

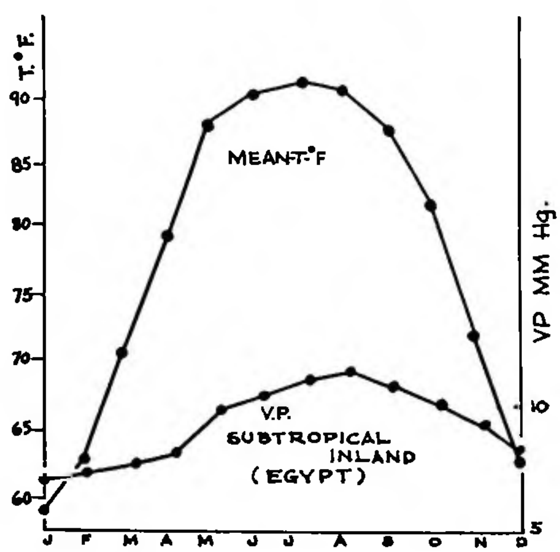
Table 14 sets out the principles and more important applications which have been advocated in the design of buildings for warm humid environments, in so far as man's physiological requirements are concerned. As in the case of table 12, there is a general correspondence between the two columns of the table, but any particular item on one side may be associated with more than one on the other. This table should provide a useful check list, but reference must be made to the text for details and for explanation.

TABLE 14.—*Summary of Principles for Warm Humid Environments and Important Applications*

Principles	Important applications	Principles	Important applications
Reducing human heat production Convenience of arrangement. Ease of cleaning.	Convenient storage space. Convenient plan and conservation of floor space. Convenient facilities. Easily cleaned surfaces, especially floor.	*Promoting losses from body by evaporation* Ventilation (volume flow). Air movement (velocity of flow). Dehumidification.	Wood, stone, or other material of low diffusivity for roof. Ceiling height generally not over eight feet. Maximum wall openings for breeze, with blinds, louvres, etc. against rain. Cross ventilation directed and without obstruction. Ventilation of roof space and spaces between successive roofing layers. Turbulence-producing fans. Dehumidification by refrigeration or absorption.
Reducing gain and promoting losses from body by radiation External shade. Reduced ground reflection. Attached shade. Water cooling of exterior. Minimal solar projection. High reflectivity of exterior. Convection over surfaces exposed to radiation. Insulation (capacity type) to roof. Convection over inner surfaces. Low emissivity of inner surfaces. Moderate ceiling height.	Shade trees, especially to roof. Shade bushes etc., especially to E. and W. exposures, but without obstructing wind. Separation of buildings. Vegetation over ground. Eaves and other horizontal projections on equatorial exposures. Awnings, verandahs, etc., especially on equatorial exposures. Vertical projections beside window openings on equatorial exposure. Water spraying or water layer on roof in dry weather. Minimum solar projection of roof. Light color or polished metal for surfaces exposed to solar radiation. Avoid parapets and mutual interference of roof structures to wind.	*Reducing heat liberation in building* Minimize heat and vapor liberation. Remove liberated heat and vapor.	Capacity insulation around oven and firebox. Narrow air space lined with aluminum foil in oven wall. Liquid or gas fuel, or power, where economically feasible. Vent to outside over stove. Vents and infrared screens for lamps.

MODIFYING EFFECTS of CLIMATIC FLUCTUATIONS

IN THE preceding chapters housing design has been considered in relation to each of two rather sharply contrasted sets of conditions, which have been called "hot dry" and "warm humid" respectively. For the sake of clarity in presenting the basic principles, the discussion was conducted as though the building were called upon to function more or less continuously in one or other of these two contrasted "climates." While it is true that the climate is more or less continuously warm humid in a large part of the lowland equatorial regions, there are many parts of the world in which the climate is hot dry or warm humid at one season of the year, but something else at other seasons. This is clearly indicated by the maps of figure 6. The purpose of this chapter is to discuss what modifications may be necessary in designs drawn for typically hot dry or warm humid conditions at different seasons of the year. It is not feasible, of course, to consider every possible case, but enough should emerge from this discussion to indicate the way in which compromises can be effected.



ALTERNATION of HOT DRY and COOL TEMPERATE CONDITIONS

The geographical factors of latitude, continentality, and wind regime, which make many regions hot and dry in summer, also make them cool in winter. This wide annual range of temperature is reflected to a certain extent also in wide diurnal flunctuations in temperature, so that even in summer cool nights are by no means exceptional. The arid regions of northern Africa, Arabia, Australia, and certain parts of the Americas, have climatic fluctuations of this nature, and call for housing practices which will give protection, not only from the hot dry conditions, but also from fairly cold conditions.

The applicability to cool temperate conditions of design objectives recommended for hot dry conditions is briefly set out in table 15. At first sight, it might appear from this table that the numerous conflicts between the requirements for the two seasons would make suitable compromise design a difficult matter; but on closer examination it will be seen that *fairly simple solutions are possible.* Deciduous trees, for example, provide shade in summer but interfere little with sunshine in winter. Attached shade can be of such dimensions and so slanted that it excludes most of the high angle summer sun but lets a large proportion of the low angle winter sun fall on the wall or window; or else it can be made retractable (pl. II b). From table 8 it will be seen that tall square buildings, or more particularly slab type buildings with the long axis E.–W., present a small solar projection in summer but a large solar projection in winter. One useful modification to the basic design for hot dry conditions is the provision of a sun area, external to the main insulation, but sheltered from the wind, in which advantage can be taken in winter of the solar warmth. Ideally this will be glass-enclosed, but less costly provisions can be designed for more modest resources.

The characteristics of the external surface affecting radiation exchange—reflectivity, emissivity, and convective flow—are not readily adjustable, and should be determined by the relative importance of summer gains and winter losses in the particular place under consideration. The frequency of cloud cover in the two seasons may be a deciding factor in that.

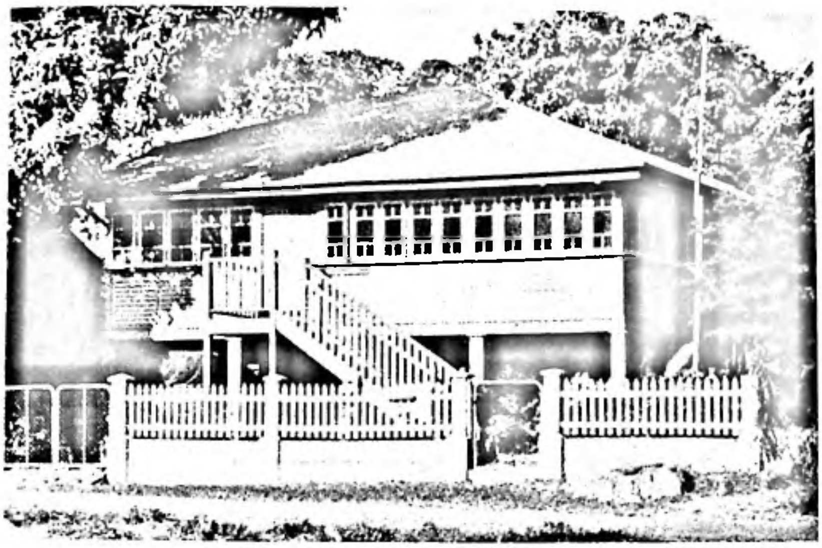
The important fact revealed in table 15 is that the *capacity insulation*, which is so important as a protection against heat gain in summer, *is equally important as a protection against heat loss in winter.* The importance lies, not only in the major protective role of insulation, but also in the fact that the necessity for insulation markedly affects the basic design of the house. It is indeed fortunate that it serves a good purpose in both extreme seasons. It is similarly fortunate that the same ground system can be used for warming the air in winter, as for cooling it in summer.

The general undesirability of internal convection in winter is easily arranged, since control of ventilation has already been postulated as a most important character of hot dry design, and all that is necessary is that the convection be closed off in winter, just as it is closed off during the hot hours of a summer day. Facilities for evaporative or refrigerant cooling, if provided, are simply not used during the cool periods; with no inconvenience, except perhaps through non-utilization of invested capital. It should not be difficult to modify protective devices on kitchen stoves, etc.,

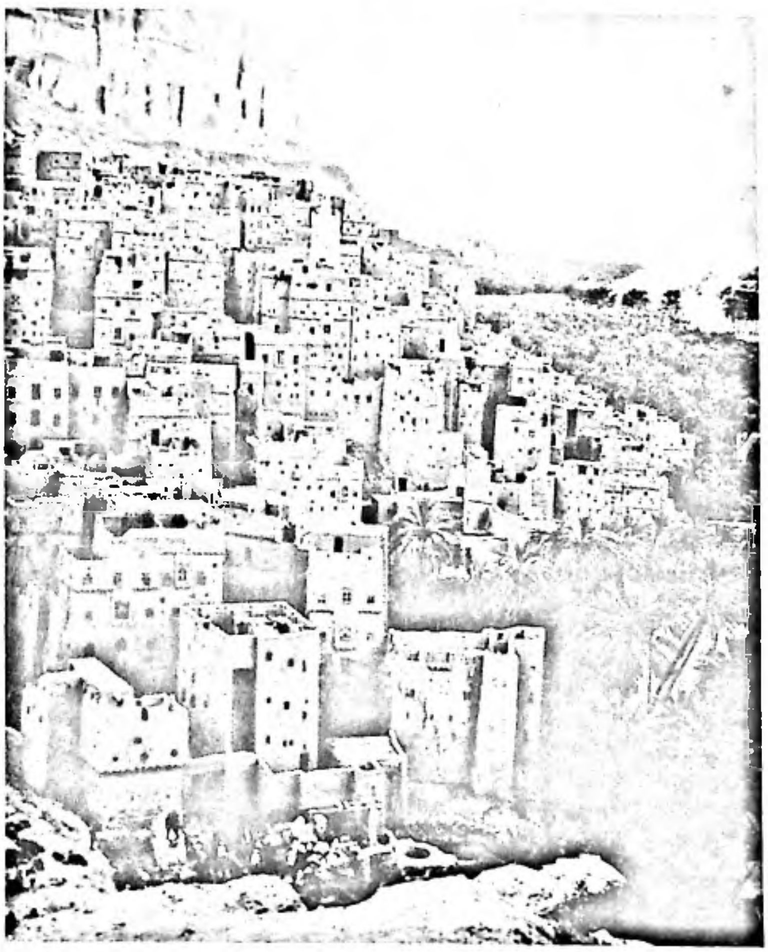
TABLE 15.—*Applicability of Design Objectives for "Hot Dry" to Other Seasonal Conditions.*

Item	Applicability to cool temperate	Applicability to warm humid
Reduced heat production by man	Not important	Still important.
External shade	Not desirable	Still important.
Reduced ground radiation	Not desirable	Still important.
Attached shade	Minimal effect desired	Still important.
Water cooling	Not desirable	Operative on roof.
Minimal solar projection	Greater projection required	Still important.
High reflectivity	Not desirable	Still important.
High reemissivity	Not desirable	Immaterial.
External convection	Not desirable	Still important.
Insulation	Desirable against reverse heat flow	Still important in roof. Immaterial in walls.
Internal convection	Not desirable	Still desirable.
Low internal emissivity	Desirable	Immaterial.
Controlled ventilation	Closed	Wide open.
Roof space ventilation	Closed	Open.
Ground cooling	Now operates for heating	Nonoperative.
Evaporative cooling	Not required	Relatively ineffective.
Refrigerant cooling	Not required	For dehumidification.
Reduction of heat liberation	Heat may be required	Still important.

Plate IV



a.—Residence, Townsville, Australia. Verandah almost entirely vitiated by glazing, and internal rooms created. Louvered lower part insufficient compensation. Steps unprotected. (Courtesy, Commonwealth Experimental Building Station.)

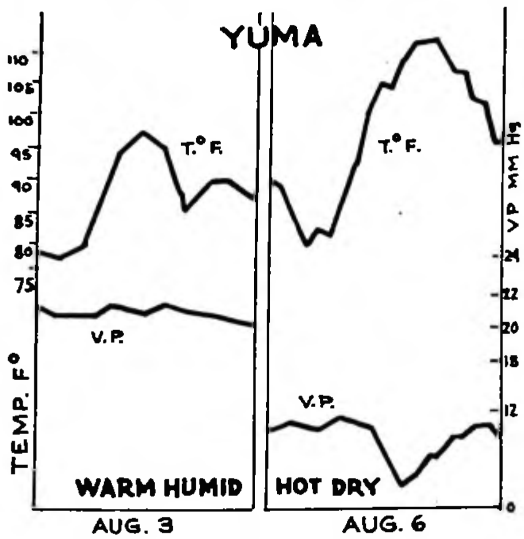


b. Hadhramaut, Arabia. Characteristic construction results in minimum solar projection in summer but large in winter. Crowding of buildings gives mutual shading. Note living space on roofs. Small windows give control of ventilation. (Courtesy H. von Wissmann.)

so that the heat can be used to warm the house if desired.

All in all, therefore, *the design for hot dry climates requires very little special attention or modification* to make it entirely acceptable *for alternating cool temperate seasons.*

ALTERNATION of HOT DRY and WARM HUMID CONDITIONS



The monsoon climates of India are characterized by two hot seasons, the first being hot dry, the second warm humid; and this succession occurs in other subtropical areas as well. Some regions which are normally regarded as hot dry get short periods of summer rain, and for those periods take on more the character of warm humid areas. Houses which are designed for hot dry conditions may become decidedly uncomfortable under these warm humid conditions, unless provisions have been made by modifications to the basic hot dry design.

The applicability to warm humid conditions of design objectives advocated for hot dry conditions is briefly set out in table 15. The discrepancies are few, but they are quite important. A little forethought in planning can result in quite satisfactory adjustments; but failure to include them will cause unnecessary discomfort for the inhabitants.

For low cost housing the most important feature is the provision of *large window and door openings*, with attention to the requirements for *cross ventilation*, as described for warm humid climates (p. 54). But whereas the closure of such openings, except against rain, is of little importance in continually warm humid climates, *careful attention* is necessary in these alternating climates *to see that they can be closed, and closed adequately against hot dry conditions.* The *wall area between openings*, moreover, should be *of capacity insulation type* instead of the relatively flimsy construction that suffices for continuously warm humid climates. Roof space ventilation designed for hot dry climates, on the other hand, will serve adequately for the warm humid periods without modification.

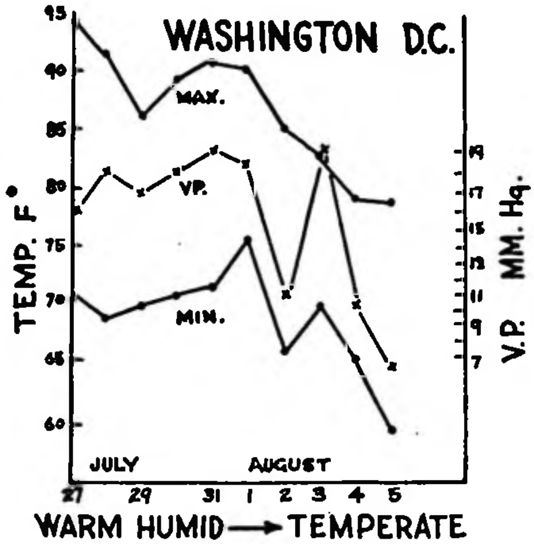
Where *fans* can be provided, these should certainly be included in the fittings of buildings for these alternating climates. Where *refrigerant cooling* is available, it can be utilized for dehumidification in the warm humid periods as well as cooling in the hot dry periods; but the unit must be designed for this purpose. One frequently hears the complaint in India, for example, that unit air conditioners "break down" in the monsoon season; whereas what is really happening is that a refrigerator suitable for cooling dry air satisfactorily is proving inadequate for dehumidifying moist air. Continuous operation in humid atmospheres, moreover, causes refrigerators to "frost up," so that allowance must be made for periodic nonoperation to allow the accumulated moisture to drain away.

With these modifications, there is no reason why *a design* cannot be provided which is *equally satisfactory for each of alternating hot dry and warm humid seasons.*

ALTERNATION of WARM HUMID and COOLER CONDITIONS

While coastal and insular areas near the equator usually enjoy a fairly continuous warm humid climate, similar areas closer to the Tropics of Capricorn and Cancer experience greater seasonal variation, so that those which are warm humid in summer have temperate winters. (See maps of fig. 6.) At still higher latitudes there are some areas which have a significant share of warm humid weather in summer, but actually experience cold winters. The applicability to temperate and cold temperate conditions of design objectives advocated for warm humid conditions is briefly set out in table 16.

Warm humid and temperate



It will be seen from this table that the alternation of temperate and warm humid seasons can be fairly easily met. The major modifications required in the basic design for warm humid conditions are the inclusion of reasonable *insulation in the wall area between window and door openings*, and the construction of *windows and doors* so that they *can be closed* in the cooler periods. There is no need for very tightly fitting closures, however, unless the building has to provide protection against hot dry periods as well.

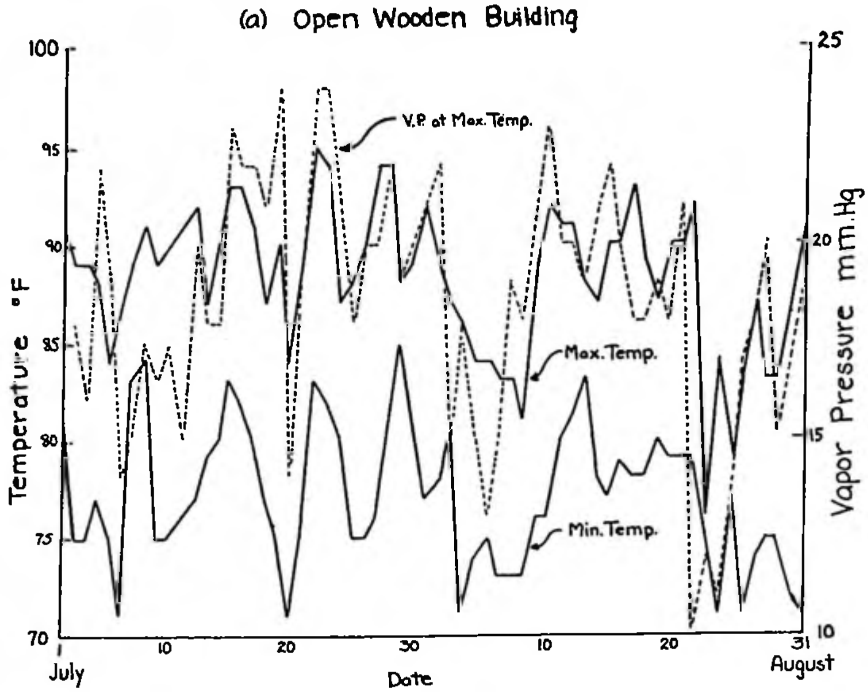
Warm humid and cold temperate

Greater thought has to be given to reconciliation of requirements for alternating warm humid and cold seasons (table 16). Questions of shade can be treated in the same way as was recommended (p. 58) for alternating hot dry and cool temperate conditions—the use of deciduous trees for external shade, adjustment of attached shade so that it excludes high angle but does not seriously obstruct low angle sunshine; or use of retractable shades or awnings. In the same way, use can be made of tall and slab forms to obtain small solar projection in summer and larger projection in winter. (See above, p. 58). *Polished aluminum seems to have a particular application* for external construction under these circumstances. Its high reflectivity of solar radiation is an advantage in summer, but causes little disadvantage in winter since there is then little sunshine. Its poor emissivity in the infrared is an advantage in winter, but causes little disadvantage in summer since the high water vapor content of the atmosphere then interferes in any case with this outward radiation. Other polished metals may show similar behavior, but generally to a lesser degree.

Very little can be suggested for seasonal control of external convection, unless there is a markedly seasonal distribution of wind direction, and contours or location of natural timber can be used as windbreaks in winter.

Table 16.—*Applicability of Design Objectives for "Warm Humid" to Other Seasonal Conditions*

Item	Applicability to temperate	Applicability to cold temperate
Reduced heat production by man	Immaterial	Encouragement to heat production occasionally desirable.
External shade	Immaterial	Not desirable.
Reduced ground reflection	Immaterial	Immaterial.
Attached shade	Immaterial	Minimum effect desired.
Minimum solar projection	Immaterial	Greater projection required.
High reflectivity	Immaterial	Resultant poor emission may counterbalance.
External convection	Immaterial	Not desirable.
Roof insulation	Immaterial	Desirable against reverse heat flow.
Unimportance of wall insulation	Some insulation desirable	High insulation desirable against reverse heat flow.
Internal convection	Not desirable	Not desirable.
Low internal emissivity	Immaterial	Resultant poor absorption desirable.
High ventilation	Immaterial	Not desirable.
High air movement	Not desirable	Not desirable.
Roof space ventilation	Immaterial	Not desirable.
Dehumidification	Not wanted	Not wanted.
Control of heat liberation	Not necessary	Heat may be required.



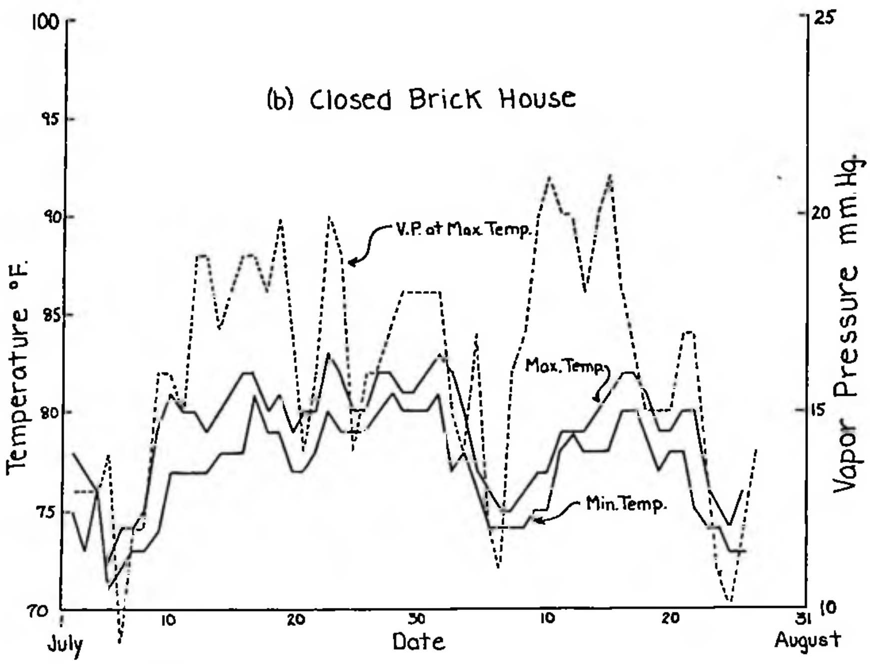


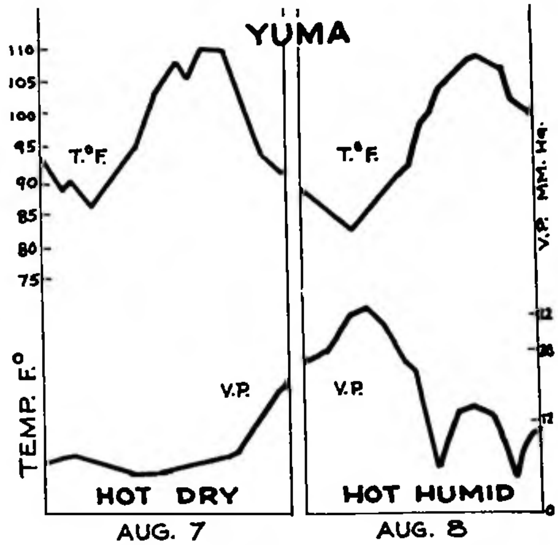
Figure 14.—Effect of insulation and closure on room conditions in variable climate.—The ambient conditions were virtually the same in both locations. In the open wooden building the marked diurnal cycles of temperature, and marked fluctuations from day to day reflected variable outside conditions. In the closed brick house the diurnal cycle was small, the maximum temperature being especially reduced. The fluctuations from day to day were also decreased. Temperature conditions are markedly stabilized, and the mean lowered, by closed brick construction in an alternating warm and temperate climate. Vapor pressure is little affected by these differences in construction.

Capacity type insulation is essential if protection is to be afforded against cold winter conditions. Where, as is often the case, the warm humid periods in summer are broken up by more temperate intervals, this capacity insulation will be found to stabilize internal temperatures in a desirable fashion—provided that ventilation is reduced to a minimum by *closing windows and doors during the hotter periods* and *air movement is provided entirely by internal fans*. (See fig. 14.) In short, under these conditions, if high capacity insulation is provided by the walls and roof, better results are obtained by building for cold conditions and relying upon fans to tide over the warm humid periods than by the reverse process. Just where the line lies between these choices— building for winter and getting through the summer, or building for summer and getting through the winter—is determined by a number of factors such as capital cost, custom, and relative duration of warm periods and intervals.

To eliminate undesirable air movement in winter, the *window and door openings* which may be desirable in summer should be *capable of being tightly closed*. If the winter conditions are sufficiently severe, a second outer covering in the form of a shutter or "storm window" may be desirable, but this can be of very simple design. In many countries thin plastic sheets are now available for this purpose, with clips or wingnuts for retention.

MOIST AIR MOVEMENT into HOT DRY AREAS

Along the immediate southwest coast of the Persian Gulf, and to a lesser degree over the low-lying portions of the southwest coast of the Red Sea and over the basin to the north of the Gulf of California, moist air can move in from the adjacent body of water at low altitudes over what would otherwise be typical hot dry desert. (See maps of fig. 6.) This moist air may not form clouds to interfere with the incidence of solar radiation, so that the unfortunate person out of doors has the full benefit, not only of the high radiation and temperature, but also of the high humidity. On



many occasions in the Persian Gulf, and at times in the other areas, these conditions can become, not merely uncomfortable, but well-nigh unendurable.

While neither the incidence [1] nor the physiological effects of these conditions have been studied in full detail, it is fairly clear that either dehumidification or the maintenance of a fairly brisk air movement over the human skin is necessary, if adverse effects are to be avoided.

Evaporative cooling is less effective here than under typical hot dry conditions, and if the apparatus interferes with air movement the "conditioned" air may be even less acceptable than the ambient air.

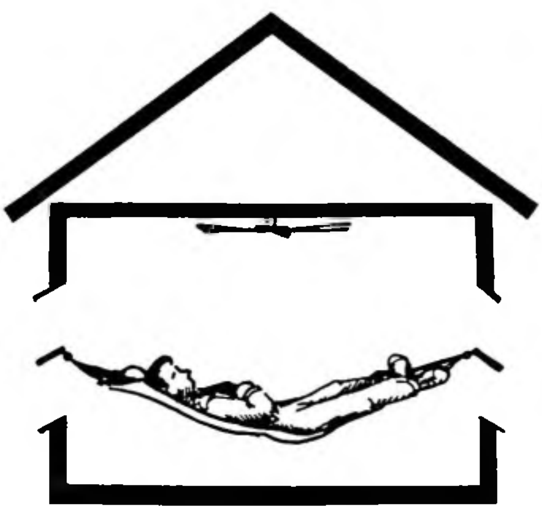
Design features advocated for typical hot dry conditions need modification in these areas by *more definite provision for securing free or forced air movement* when desired; by *minimizing any interference to air movement* caused by evaporative cooling devices; by giving even *greater attention to insulation* and other heat protective devices; and by *selecting the design of any refrigerant devices* so that they can give some dehumidification as well as cooling.

[1] The maps of fig. 6 suggest that there may be other areas, notably in India and Australia, in which similar conditions may occur on an important number of days.

FUNCTIONAL CONSIDERATIONS

TO MANY occupiers, aspects of the dwelling which affect daily activities are of greater consequence than general principles of design or construction, however greatly these may benefit their daily well-being. In hot regions certain of these functional aspects have been firmly fixed in the popular mind by specific customs or by disputation for very many years. They consequently merit separate discussion, even though they will be found in many cases to be but special cases of principles already mentioned.

Sleeping quarters



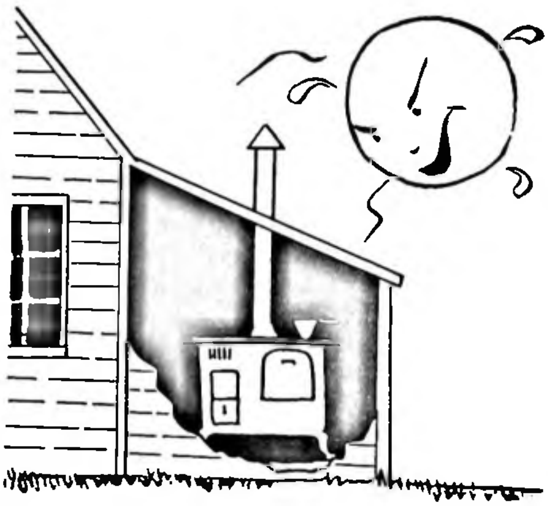
On warm humid nights, and sometimes on exceptionally hot dry nights, many people find difficulty in sleeping. As medical attendants well know, statements of "not being able to sleep all night" must be heavily discounted; but the fact that the person feels that way about it indicates that all is not well, and that a full measure of efficiency, especially in unsupervised mental pursuits, cannot be expected on the following day. It would appear only reasonable, therefore, that special attention should be given to the sleeping quarters in selection of site, design, and equipment. *In hot dry areas*, full advantage should be taken at night of radiation to the relatively cool sky, as well as the cooler air, by *sleeping in the open*. Rain, insects and other undesirable bedfellows, privacy, and early morning sun, are items to be taken into consideration; but these are regarded by a large number of accustomed inhabitants as minor difficulties to be fairly easily overcome. In *warm humid weather*, or when sleeping in the open is not possible for other reasons, quarters on the *northeastern aspects* (southeastern in the southern hemisphere), with ample opportunity for *entry of cooler night air*, boosted if possible by a fan, is to be recommended. *Openings should come to floor level*. Where insect screening or mosquito netting is used, a *fan inside* *the screen or net* is very desirable; but it is generally considered important that the actual rate of air movement over the sleeper should not exceed 150 ft./min., and that it should be of an intermittent, fluctuating or turbulent nature. Where air conditioning is available, its use is most justified in the sleeping quarters—but the objective should be simply to *remove the disturbing degree of heat*, not to produce a really temperate atmosphere.

One of the biggest impediments to restful sleep on a hot night is the standard western bed. Derived from countries with cold winters, it manages to present a minimum area of skin to the air, even if the sleeper lies naked. The thermally most suitable sleeping device under hot and humid conditions is the *string hammock*, especially if it is kept spread by crossbars at head and foot. Those accustomed to soft sleeping will demand something between them and the string, but this should be thin, porous, and absorbent. Sponge rubber and all but the most open-work plastics are definitely not admissible. Individual ingenuity will furnish suitable modifications of the hammock design for those who desire stability or space not provided by the standard article.

Verandah

The verandah is simply attached shade carried sufficiently far to give space for outdoor activities in a climate in which natural air movement is something to be desired. (See pls. I d, II d, III a, III d.) It is *much more functional in warm humid* than in hot dry weather. Kept free from all but weatherproof chairs and blinds, it can be abandoned to the elements whenever these are inclement. To the extent that insect screening is considered a necessity, that electric fans are available for forced convection, and that insulating walls can be substituted for attached shade in a seasonal climate, the verandah loses some of its usefulness. But the main objection to the verandah stems from *man's ability to misuse it*. Bit by bit, with one "justifiable" excuse after the other, the typical verandah-user turns it into a totally enclosed room (pl. IV a). In addition to affording less protection than a properly designed room, this also converts the main rooms of the house into dismal dark dungeons, redeemable only by full air conditioning and fluorescent lighting.

Kitchen



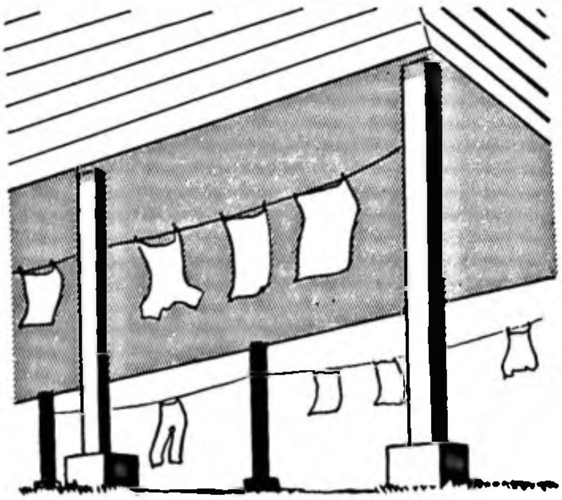
One obvious solution to the kitchen problem in hot climates is to separate the kitchen from the house proper, so that the heat and odors will not permeate the living space. This is a solution, however, which can work satisfactorily only when cooking is done by outside help. The housewife who has to take care of all the domestic work wants the kitchen as close to the dining space as she can get it—in fact, for the less formal occasions, she may prefer to have the dining space right in the kitchen. Furthermore, merely removing the problem to a distance does not necessarily solve it—at least for those who work in the kitchen.

For low cost housing, and for servantless families, the kitchen must be considered as an integral part of the dwelling. In such housing, the location of the kitchen is too often dictated by a standardized house plan, location of street, or access to services; but where any selection is possible, ***the shady side of the dwelling*** is obviously the position of choice, with a second thought to the ***direction of the prevailing breeze. At least as much consideration should be given to protecting the kitchen from the hot environment as is given to the rest of the house.*** The state of affairs too often seen in Australia, of a low, unceiled, galvanized iron, skillion roof over the kitchen of an otherwise well constructed and ceiled house, is inexcusable. In hot dry climates, special ventilation may be restricted to the outward carriage of heat from the cooking area but without first taking it over the cook. In warm humid climates, free ***ventilation,*** but again ***directed outwards from the stove,*** is highly desirable. Evaporative cooling in hot dry climates, or refrigeration in warm humid climates, may be used to give added comfort, but should be considered only as supplementary to proper ventilation of the stove area and construction of the heating units in such a way that "wild" heat is minimized (see p. 45). ***Convenience of layout,*** with easy access to storage space, disposal facilities, and serving area have been mentioned previously (p. 30) as important to conservation of effort.

Where separate kitchen facilities are acceptable, advantage can usually be taken of their isolation to secure better ventilation; but, of course, a greater solar projection is provided by the same isolation. The best approach is to treat such isolated facilities as a building in itself and to apply the principles already set out for the appropriate climatic conditions. It will also be necessary in these circumstances to provide some protection against sun and rain for the communicating passageway to the house (see pl. III a).

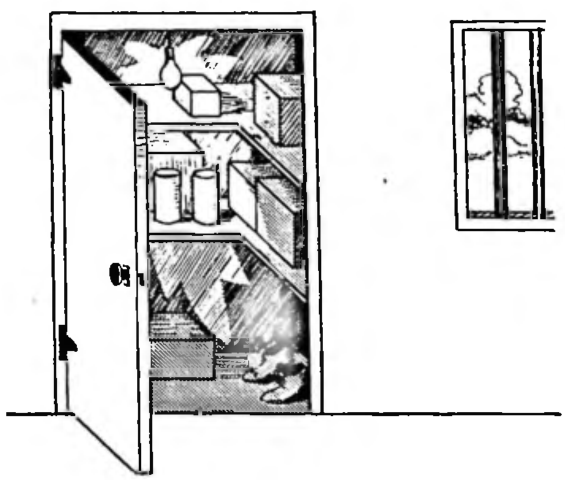
Laundry space

To people accultured to washing their clothes by the river bank, laundry space must seem a veritable abstraction. But as they congregate in towns the need for this must become more apparent. The actual process of washing takes little space, but that of drying may be more demanding. The demand is small under hot dry conditions where thin clothes dry almost as fast as they are hung; but on warm humid days the process is much slower, and more space, preferably protected from



rain, is required. This requirement may pose an important problem with small dwellings closely placed or combined into an apartment-type structure, and constitutes one more reason for not recommending the apartment-type house for warm humid climates (see also p. 51). It can be solved, however, by the provision of a ***communal covered drying space,*** portion of which may be convertible to recreational purposes at other times.

Security and storage



There are few communities in which the social conscience is so developed that security measures by the individual household are unnecessary. The steps that are felt to be required vary all the way from simple closing of gates to the creation of walled fortresses; but as one ascends the scale of felt requirements one finds building practices more and more dominated by this theme. (See pls. I b and IV b.) In some instances the provisions for security blend happily with those for environmental protection. Thus the thick walls and small shuttered openings of the Arab type house eminently meet both desires. In warm humid environments, on the other hand, enclosure of the living space must inevitably interfere with air movement unless the community is one in which power is readily available for fans or air conditioning. The tree house is an admirable way of effecting reconciliation of requirements, but is hardly compatible with progressive development. The raising of the house on piles, so commonly seen in Siam (pl. III a), Australia (pl. IV a), and tropical America (pl. II c), provides a happy compromise, to which bars and other deterrants to intruders can be added as necessary. Since this design provides other desirable features at the same time, such as improved ventilation, and shaded laundry and recreation space, its widespread adoption is not surprising.

To store things, it is not sufficient merely to have a secure storage place. Biblical authority places moths and rust on an equal footing with thieves. Deterioration is particularly frequent in warm humid climates, since such atmospheres are eminently suitable for the growth of fungi which destroy, discolor, or etch a wide variety of materials with abandon. A relatively small fall in temperature may bring goods below the dew point, and the resultant condensation of atmospheric moisture will add to the ruin of prized possessions. This may easily occur even inside a closed container, if it were last opened in a particularly warm moist atmosphere. It is essential, therefore, that storage spaces in such climates be dry and clean. One simple device which is extensively employed where power is available, is to keep an *electric light bulb burning inside any closet.* By raising the temperature it minimizes the chance of the dew point being reached at night or during a cool spell, and thus prevents condensation. The individual articles should be kept separated, so that any moisture which does condense can reevaporate easily. More elaborate apparatus, such as a silica gel dehumidifier can be used, of course, where resources permit.

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The climatic maps were prepared under the author's direction by C. von Koschembahr, the larger drawings by R. Detwiler, the smaller drawings by F. K. Hilton, and the tolerance charts by Elizabeth Mason. The heliodon was built by the Johns Hopkins Institute of Cooperative Research, and the projections determined by F. K. Hilton.

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APPENDIX 1——The Heliodon

Instruments for tracing the apparent motion of the sun have been in vogue ever since man developed a firm theory of the cosmogony; but the application of such an instrument to housing problems seems to have been quite recent. Dufton, working for the Experimental Building Station near London, England, developed an instrument, which he called a heliodon, in the early 1930's.[1] This was somewhat modified by the workers of the Australian counterpart and described in a duplicated document dated 1948.[2] The present author added a modification of his own, and the instrument was brought to its present compact design mainly through the activities of a group of his graduate students [3] in the Johns Hopkins School of Hygiene.

The heliodon consists essentially of a lamp emitting approximately parallel rays of light, to represent the sun, and a platform carrying a model house, which can be moved in relation to the "sun" in such a way as to imitate the relative movements imposed upon an actual house by season, time of day, latitude, and orientation. The distribution of light and shadow about and inside the model is then a duplicate in small scale of the distribution of sunlight and shadow about an actual house under these conditions.

Photographs of the present model appear as plates V a and b. The rigid base (A) is first leveled, and then the lamp representing the sun is set in the line of the optical axis as far away as will still give sufficient contrast. (Pinholes in the mounts of the platform allow the lamp to be sighted on the target mark (B) of the backboard when the instrument is set at 0° declination and 6.0 a. m.) The closer the lamp, the less sharp will the shadow edge be, and the greater the magnification imparted to the shadow.

The handwheel (C) moves the sectors (DD), and the crossbar carried by them, for 23½° on either side of the vertical, around the horizontal line running through the apices of the sectors, which also traverses the center of the platform. This movement, which is at right angles to the incoming "sun's" rays, imitates the change in the inclination of the earth's axis to the sun during its annual passage, and thus the effect of season. One of the sectors carries a scale (E), visible through a window in the mount, from which the sector can be set for any desired date or declination.

The crossbar carries a pin about which a U-frame (F) can rotate to imitate the daily rotation of the earth, and thus the effect of time of day. The position of the U-frame is indicated by the movement of a pointer on a graduated plate (G) fixed to the crossbar.

The U-frame in turn carries the platform (H), which is free to turn about an axis between the apices of the frame. This movement gives the effect of latitude, or the angular displacement of the horizontal plane at a particular point of the earth's surface from that at the equator. The latitude setting is indicated on a disk (I) fixed to the platform and read through a window in one of the U-frame uprights.

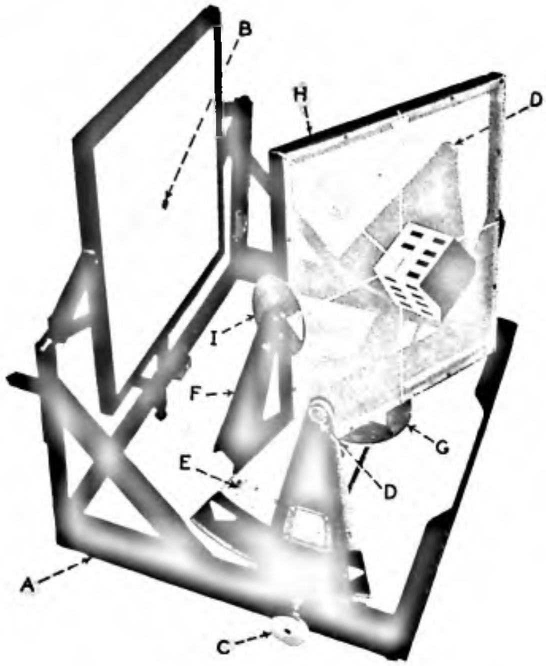
The platform represents the horizontal plane at the location desired, and, by rotation of the model itself on the mount, the orientation of the

[1] Dufton, A. F., J. Sci. Inst., 9, 251-256, 1932.

[2] Phillips, R. O., Sunshine and Shade in Australia. Dupl. Doc. 23, C'wlth. Exp. Bldg. Sta., 1948.

[3] Brown, R. Z., Jackson, W. B., and Schein, M. W.

Plate V



a. Heliodon, showing construction. (Photo C. H. Weber.)

b. Heliodon, showing shadows in operation. (Photo C. H. Weber.)

house in relation to the points of the compass can be simulated.

As stated above, the distribution of light and shadow (J) about and in the model indicates the distribution of sunlight and shadow about an actual house of this design at the season, time of day, latitude and orientation for which the model is set.

The distribution on the ground can be better seen and sketched if a sheet of white paper is placed over the platform before the model is attached. The mount is left transparent, however, so that the interruption to the solar beam caused by the model can fall on the backboard (K), which is at right angles to the solar beam. The area of shadow (L) so formed on the backboard is a direct measure of the total solar radiation falling upon the house, if the intensity of the solar radiation is known, or can (as is usually the case) be assumed. If a piece of squared paper is fixed to the backboard, and the shadow traced out, the area of the shadow can be estimated by counting the squares. The area can also be determined by using a planimeter on the traced shadow, or by cutting out the traced area and weighing it on a sensitive balance.

The instrument pictured here is constructed so that it can be used either with a horizontally placed "sun" (convenient for working at sufficient distance to minimize distortion) or with a vertically placed "sun" (convenient for demonstration to people walking around the instrument).

This instrument can be used for the following purposes:

(*i*) To demonstrate the distribution of sunlight and shadow about a house at different seasons of the year;

(*ii*) To measure the solar load upon a structure under varying conditions;

(*iii*) To investigate the suitability of designs in relation to solar protection or solar heating;

(*iv*) To construct tables and curves of solar loading without recourse to complicated mathematics.

APPENDIX 2—The Psychrometric Chart

The psychrometric chart (fig. 15) expresses the relationships between the four thermolytic variables—(dry bulb) temperature, wet bulb temperature, relative humidity, and vapor pressure—which are such that when the value of any two are known, the corresponding values of the other two can be found.

The *dry bulb temperature* is that given by an ordinary thermometer exposed to air, but protected from any important source of radiant energy. The values of dry bulb temperature in ° F. are marked off along the base of the chart, from which vertical lines carry the values into the chart.

The *wet bulb temperature* is that given by a thermometer encased in a damp sleeve, over which air is moving fairly rapidly. The values of wet bulb temperature in ° F. are marked off along the curved left-hand margin of the chart, from which oblique lines continue the values into the chart.

The *relative humidity* may be measured directly by the change in length of a fiber, such as a hair, as it takes up or gives off moisture. Different values of relative humidity appear on the chart as a series of curved lines.

The *vapor pressure* is not usually measured directly, but determined from the chart by entering it with the dry bulb temperature and *either* the wet bulb temperature *or* the relative humidity. Values of vapor pressure expressed as mm. Hg are marked off along the right-hand vertical margin of the chart, from which horizontal lines continue the values into the chart.

The *dew point* is the temperature at which air containing a certain amount of water vapor will be saturated and thus tend to deposit condensed moisture. Dew points appear on the chart as the points at which dry bulb temperature lines meet the 100 percent relative humidity curve, or, what is the same thing, the points at which dry bulb and wet bulb temperatures coincide.

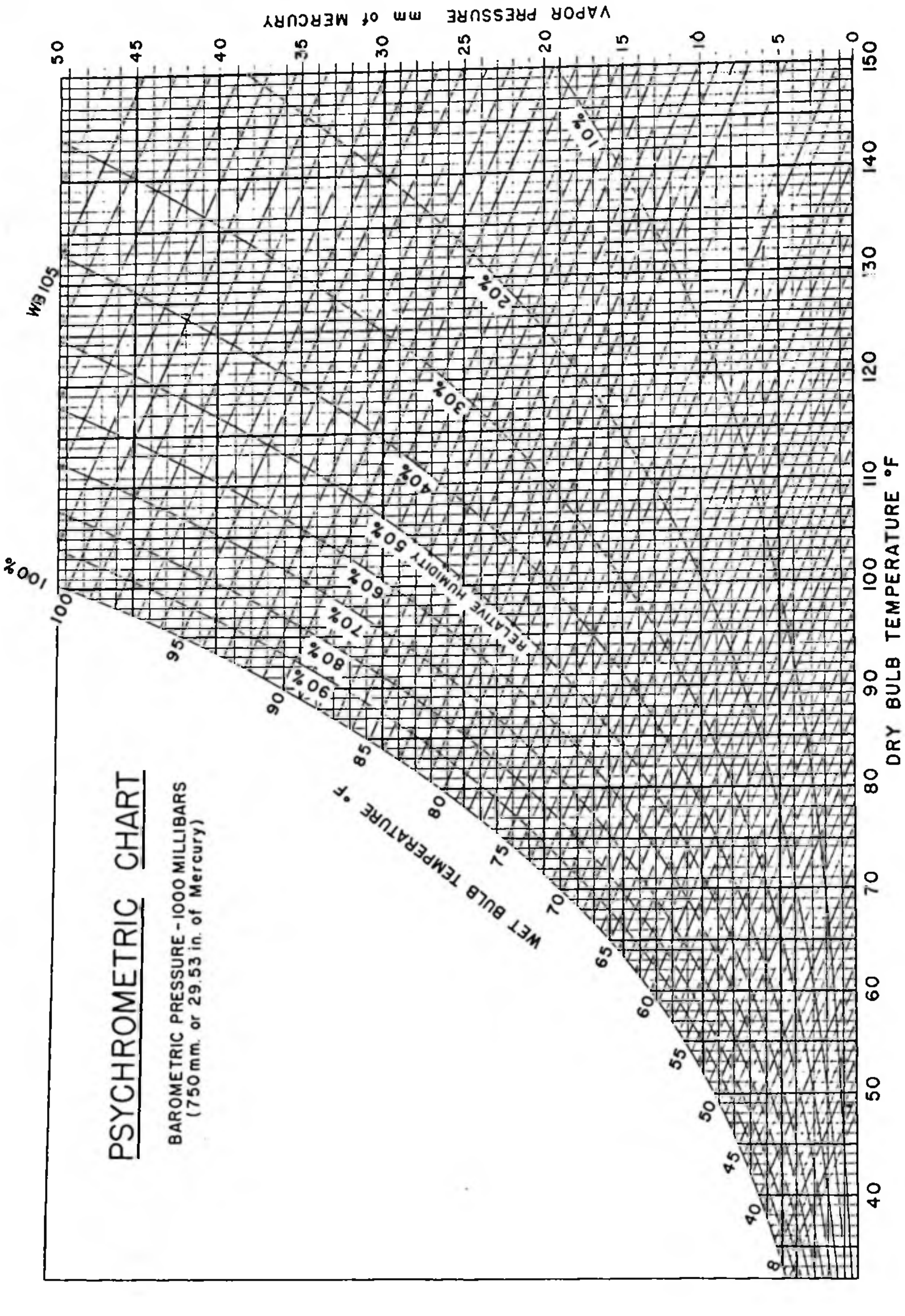
EXAMPLES IN THE USE OF THE CHART

1. *The dry bulb temperature is 93° F., and the wet bulb temperature 72° F. What are the corresponding values of relative humidity, vapor pressure, and dew point?*

Follow the vertical line for 93° F. dry bulb temperature until it meets the oblique line for 72° F. wet bulb temperature. This point lies about 6/10 of the way between the 30 percent and 40 percent relative humidity lines; so that the relative humidity corresponding to these two temperatures is approximately 36 percent. By following the horizontal lines to the right from this point, it will be seen that the corresponding vapor pressure is about 14.5 mm. Hg. By following the horizontal lines to the left from the point it will be seen that this air would become saturated if its temperature fell to about 62.5° F., so that the dew point for this atmosphere is 62.5° F.

2. *The dry bulb temperature is 93° F. and the relative humidity is 36 percent. What are the corresponding values of wet bulb temperature, vapor pressure, and dew point?*

Follow the vertical line for 93° F. dry bulb temperature until it reaches a position 6/10 of the distance between the 30 percent and 40 percent relative humidity curves. This point lies on the oblique line corresponding to a wet bulb temperature of 72° F. By proceeding horizontally from this point to the right the vapor pressure of 14.5 mm. Hg is obtained, and to the left the dew point of 62.5° F.


PSYCHROMETRIC CHART
BAROMETRIC PRESSURE - 1000 MILLIBARS
(750 mm. or 29.53 in. of Mercury)
VAPOR PRESSURE mm of MERCURY
DRY BULB TEMPERATURE °F
WET BULB TEMPERATURE °F
RELATIVE HUMIDITY 50%
100%
90%
80%
70%
60%
40%
30%
20%
10%
WB105
40
50
60
70
80
90
100
110
120
130
140
150
0
5
10
15
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25
30
35
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45
55
65
75
85
95

Figure 15.

3. ***Air at 100° F., with a vapor pressure of 25 mm. Hg, is cooled to 65° F. What will happen to its moisture content?***

The horizontal line for 25 mm. Hg vapor pressure meets the 100 percent relative humidity curve at 78° F. The air will therefore maintain its vapor pressure of 25 mm. Hg, but the relative humidity will progressively increase, as it is cooled from 100° F. to 78° F. At this point, however, moisture will start condensing, and the air will now progressively lose moisture and drop in vapor pressure, but maintain 100 percent relative humidity. At 65° F. it will have a vapor pressure of 16 mm. Hg. If it were now reheated to 100° F., it would have a relative humidity of only 31 percent, instead of the original 51 percent. (This is the principle of dehumidification by refrigeration.)

APPENDIX 3——Tables of Incidence of Solar Radiation

The incidence of solar radiation through a clear sky, at different times of the day upon various surfaces, is given in the following tables (17, 18, 19) for 4 latitudes at 4 seasons of the year.

TABLE 17.—*Daily Variation of Solar Radiation (B. t. u./sq. ft., hr.) upon a Horizontal Surface* [1]

Date	°N. lat.	5 a.m. / 7 p.m.	6 / 6	7 / 5	8 / 4	9 / 3	10 / 2	11 / 1	12
Mar. 20 and Sept. 23	0	....	....	39	114	184	239	278	292
	15	....	....	38	112	180	238	278	293
	30	....	....	34	97	163	214	248	258
	45	....	....	29	81	132	169	197	205
June 21	0	....	....	31	95	161	206	241	252
	15	....	9	64	135	203	259	292	307
	30	....	27	88	157	219	270	303	318
	45	....	53	108	164	214	256	283	292
Dec. 21	0	....	....	35	97	161	212	248	263
	15	....	....	11	64	124	175	206	214
	30	....	....	....	29	80	122	150	159
	45	....	....	....	....	29	60	82	88

[1] Data in tables 17-19 taken from material supplied by F. Loewe, Commonwealth of Australia Meteorological Bureau.

TABLE 18.—*Daily Variation of Solar Radiation (B. t. u./sq. ft., hr.) upon a Vertical Surface Facing East (a. m.) or West (p. m.)*

Date	°N. lat.	5 a.m. / 7 p.m.	6 / 6	7 / 5	8 / 4	9 / 3	10 / 2	11 / 1	12
Mar. 20 and Sept. 23	0	....	....	145	196	184	138	74	.....
	15	....	....	148	200	187	141	80	.....
	30	....	....	151	199	188	143	76	.....
	45	....	....	152	197	185	139	74	.....
June 21	0	....	....	117	170	161	122	55	.....
	15	....	75	168	194	179	137	73	.....
	30	....	124	194	212	188	141	75	.....
	45	84	172	210	214	188	139	73	.....
Dec. 21	0	....	....	128	170	161	124	75	.....
	15	....	....	73	150	166	119	66	.....
	30	....	....	....	119	139	115	62	.....
	45	....	....	....	....	108	101	57	.....

TABLE 19.—*Daily Variation of Solar Radiation (B. t. u./sq. ft., hr.) upon a Vertical Surface Facing South (North)*

Date	°N. lat.	5 / 7	6 / 6	7 / 5	8 / 4	9 / 3	10 / 2	11 / 1	a. m. 12 p. m.
Mar. 20 and Sept. 23....	0	....	....	....	....	....	....	....	....
	15	....	....	11	29	49	65	74	81
	30	....	....	20	58	96	125	145	153
	45	....	....	30	83	134	172	199	207
June 21.....	0	....	....	(62)	(93)	(106)	(113)	(119)	(122)
	15	....	(33)	(62)	(66)	(62)	(57)	(46)	(46)
	30	....	(46)	(49)	(31)	(9)	15	31	35
	45	(42)	(53)	(27)	11	53	84	108	115
Dec. 21.....	0	....	....	51	82	93	99	102	102
	15	....	....	35	93	133	155	166	172
	30	....	....	....	86	146	188	210	219
	45	....	....	....	....	119	179	217	228

APPENDIX 4—Proforma for Approximately Determining Temperature Regime on Inner Surface of Homogeneous Walls

1. Hour of day (H)
2. Air temperature °F. (t_a)
3. Solar radiation on surface (BTU/sq.ft./hr.) (S_a)
4. Reflection from ground (for walls only) $\frac{f}{2} S_h$
5. Radiation absorbed $\frac{b}{c} (S_a + \frac{f}{2} S_h)$
6. Solair temperature (t_o)
   $t_a + \frac{b}{c} (S_o + \frac{f}{2} S_h) - L$
7. Resultant inner temperature (t_i)
   $t + \frac{\theta}{\theta_m} (t_o - \bar{t}_o)$
8. Corresponding time H + D

Notation: f reflectivity of terrain; S_h solar radiation on horizontal surface; b absorptivity of surface for solar radiation; c outdoor air film coefficient (ASHVE Guide, 1955, Chapter 9); L Long infra-red loss to sky; θ/θ_m reduction factor from Fig. 10; $\bar{t}_o$ mean solar-air temperature for 24 hours; D time delay from Fig. 10.

APPENDIX 5—Important References

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