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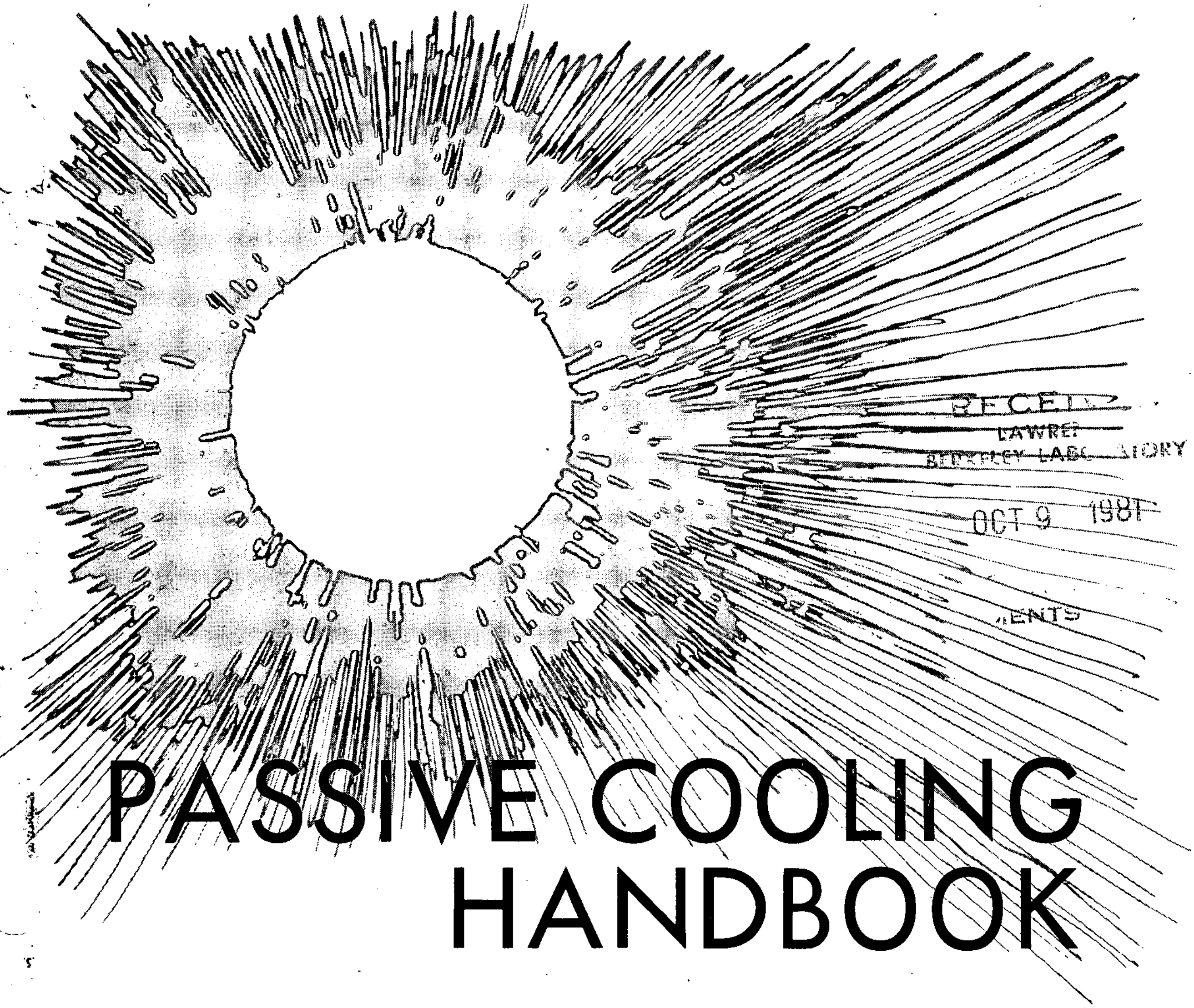


PASSIVE COOLING HANDBOOK

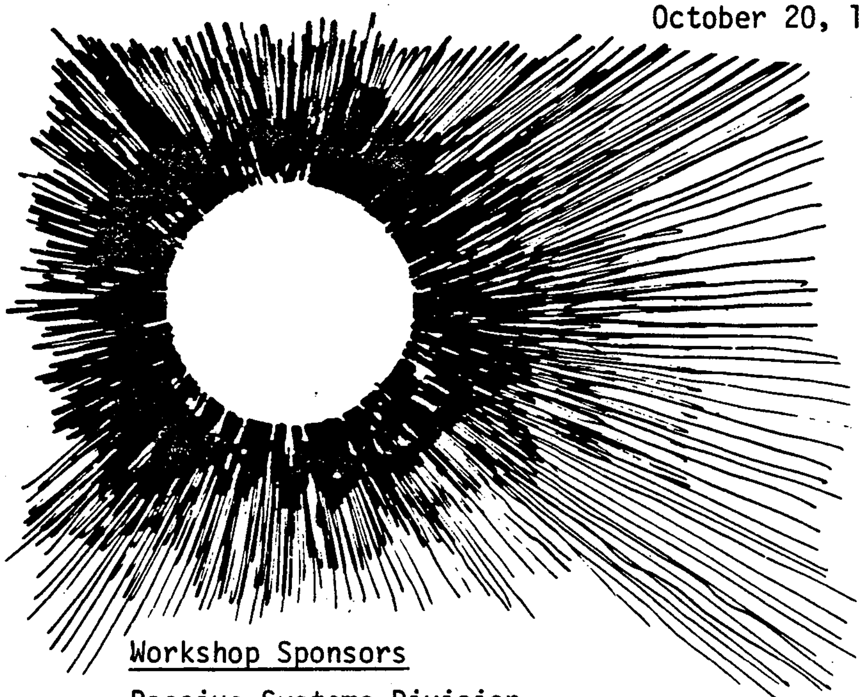
Sponsored and Developed by
U.S. Department of Energy,
Lawrence Berkeley Laboratory,
the Passive Cooling Working Group,
and the Florida Solar Energy Center

Prepared for the PASSIVE COOLING WORKSHOP held in conjunction with the FIFTH NATIONAL PASSIVE CONFERENCE, Amherst, Massachusetts

Prepared for the U.S. Department of Energy under Contract W-7405-ENG-48

PASSIVE COOLING APPLICATIONS HANDBOOK

Prepared for the Passive Cooling Workshop
Amherst, Massachusetts
October 20, 1980



PASSIVE SOLAR 1980

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Crowther and Hull, Davis, California

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PREFACE

Message from the Organizers

Perspective

PREFACE

A) Message from the Organizers

Passive cooling is one of the most difficult solar technologies to deal with, and at this time, still one of the least developed, particularly in comparison to passive heating. The purpose of the Amherst Passive Cooling Workshop is to further the knowledge of passive and hybrid cooling technologies by bringing together experts from all over the country to make presentations and be available for a dialog with others who wish to know more about passive cooling. Through this forum, we hope to establish passive cooling as a legitimate concern, on a par with passive heating, and emphasize that the two are inextricably linked, that the best solar home will be one where heating and cooling are integrated in order to produce a synergetic whole. We also want to encourage industry to become more involved in the field and expect that the workshop will be a step toward commercialization of passive cooling technologies.

The speakers have been chosen for their expertise in the respective fields. Some are well-known; others are not. Passive cooling is a new field and many of the technologies have not been fully tested. Thus, wherever possible, we have encouraged speakers to present their papers such that their experience may be used directly by designers. However, in some of the fields, that type of information was not yet available. Several of the speakers have recently received grants from the Department of Energy to further pursue this work. We look forward to the results.

The interactive sessions with the speakers ("An Evening with the Experts") should be one of the most exciting and valuable parts of the workshop. This is where those experimenting in the field, designing their own projects, or planning to work on passive cooling projects can have a direct and informal opportunity to speak one-on-one with the speakers to discuss only one particular subject during those sessions, since many of them have considerable expertise in several areas.

This workshop is part of a continuing series of cooling workshops developed by the Passive Cooling Working Group (PCWG). The first two took place at the 4th National Passive Conference in Kansas City and at the AS/ISES Solar Jubilee in Phoenix. The workshop series is designed to develop and convey information about passive and hybrid cooling techniques. These workshops at the AS/ISES national conferences will be expanded into a program of support for a continuing series of grassroots local cooling workshops. The Florida Solar Energy Center and the Florida Governor's Energy Office will conduct the first of these local workshops, which will be sponsored by the Lawrence Berkeley Laboratory and the DOE, with the participation of the PCWG. The Passive Cooling Working Group is a group of people who originally assembled during the

ISES Silver Jubilee in Atlanta to exchange information on passive cooling. The PCWG was spontaneously formed and is composed of volunteers from around the country. In addition to sponsoring the workshop series, the PCWG has proposed an International Passive and Hybrid Cooling Conference, which is currently being planned under the auspices of the Passive Systems Division of the AS/ISES. Other activities of the PCWG include a networking committee, which compiles a file of passive cooling projects around the world, the newsletter committee, which publishes an irregular periodical entitled, "The Passive Cooling Newsletter," and the conference committee which has been putting on these workshops. Anyone who wishes to join the Passive Cooling Working Group and help further the development of passive cooling techniques is most welcome to do so by contacting Don Elmer (see the "Information Resources" section for the address).

We would like to take this opportunity to express our appreciation to those who helped put this workshop and handbook together and without whose help it would not have happened. In particular, thanks go to Don Elmer whose undying enthusiasm has been an inspiration. Credit goes to him especially for securing funding for this workshop. We also wish to thank Art Bowen, who along with other members of the PCWG helped develop the workshop program, as well as the speakers and others, especially Karen Crowther, who spent much time writing papers for the handbook. We would also like to thank Harry Miller, who edited and coordinated the printing of the handbook. Special thanks also go to the institutions and groups who sponsored the workshop.

This handbook is not intended to be an end; it is only a beginning. Over the following months and years, it will be added to and improved upon and made available to all of you who wish to share your knowledge and to use these passive cooling techniques.

Helen J. Kessler   Karen Crowther   Chris A. Beck

B) Perspective

There is one other message which the Passive Cooling Workshops convey, namely the value of cooperative effort in addressing regional and local problems. The PCWG has developed these workshops, and the related activities of the Cooling Newsletter and the upcoming Cooling Conference, in an attempt to deal with serious unaddressed problems of human comfort cooling in building design. The insight into the importance of the problem was combined with the expertise of many individuals and institutions around the country to develop a body of useful information. The upcoming local workshops will continue this pattern of cooperative action arising out of local needs.

The fundamental perspective of the Passive and Hybrid Cooling Workshops is the importance of human comfort and climate in building design. This perspective is equally applicable to heating as well as cooling of buildings, and to energy conservation approaches as well as "solar" design. The basic assumption of these workshops is that passive and hybrid techniques and devices can provide comfortable conditions under almost all climate and building use circumstances.

Passive and hybrid cooling is a maturing part of solar and energy conservation strategies. It combines very ancient climate sensitive design with unresolved issues of basic physical science. For example, the Persians made use of radiative heat loss mechanisms in the manufacture of ice for more than 10 centuries. Yet it is only in the last few years that definitive work has been undertaken at the Lawrence Berkeley Laboratory and elsewhere, which validates and refines earlier work by Bliss, Yellott, and others on the radiative properties of the sky. Marketplace application of these principles in both residential and commercial/industrial applications depends on the development of materials which provide significant heat loss to the daytime sky, while restricting convective and radiative heat gain from the atmosphere and the sun.

This combination of ancient techniques and modern scientific exploration of fundamental issues has lead many to assume that passive and hybrid cooling is not yet mature enough to discuss. This viewpoint is incorrect. Building design which is sensitive to climate and exploits the site and building specific heat control mechanisms, and the site heat sinks is being practiced today. One of the functions of this workshop, and of the conference and larger workshop series, is to communicate the most perceptive and effective designs to the largest possible audience.

These new designs are based, to a varying degree, on an explicable pattern of analysis. This pattern of analysis is as important as any of the design approaches or devices which are part of passive and hybrid cooling. It begins with a subtle understanding of human comfort for occupants under unprotected conditions for the particular climate.

This brings into consideration all of the average and peak or special conditions of the climate. This process allows the designer to identify the particular comfort problems imposed by local conditions. These comfort problems imply possible solutions which applicability is a matter of building design and materials, orientation and site planning, and devices. It is the interaction of modern building materials, construction practices, and designs with the possible comfort solutions which guides the design and analysis process.

This workshop hopes to demonstrate, at both the abstract level and in practice, the analytic pattern which seems most suited to working with cooling and dehumidification problems. This pattern is expressed in the way in which the information has been organized for both the workshop and the handbook.

Both begin with a discussion of human comfort factors in cooling, and proceed to a discussion of bioclimatic regions. This is fo-lowed by a discussion of each major climate zone in terms of basic climate description, climate and building factors affecting comfort, cooling strategies, examples of solutions -- both single and multiple strategies, and design considerations. This natural progression is as important a product of the workshop as any of the specific design or device information which attendees may carry away with them.

This workshop should be replicated on the local level across the country. Local experts and local climate data should be utilized. Local solutions which recognize economic and thermophysical realities should be publicized at these sessions. National workshops, like this one at Amherst, find their purpose in stimulation of cooperative local efforts to develop and discuss cooling approaches for their own conditions.

This handbook will be part of the source material made available for sponsors of future workshops. The Lawrence Berkeley Laboratory is joining with the PCWG and others to develop a package of applications-oriented materials for these workshops. This handbook represents a shift in emphasis away from purely theoretical discussions of passive and hybrid cooling, towards a discussion of practical applications and design procedures. It also presents a snapshot of the state of the art in cooling. This aspect of the handbook will be continued in the Passive Cooling Sourcebook which will be developed by the Lawrence Berkeley Laboratory.

Don Elmer

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INTRODUCTION

The Cooling Problem --
Don Elmer

Human Comfort --
Philip Fairey

Some Historical Indicators for Building Design Under Natural Conditions in Overheated Regions --
Arthur Bowen

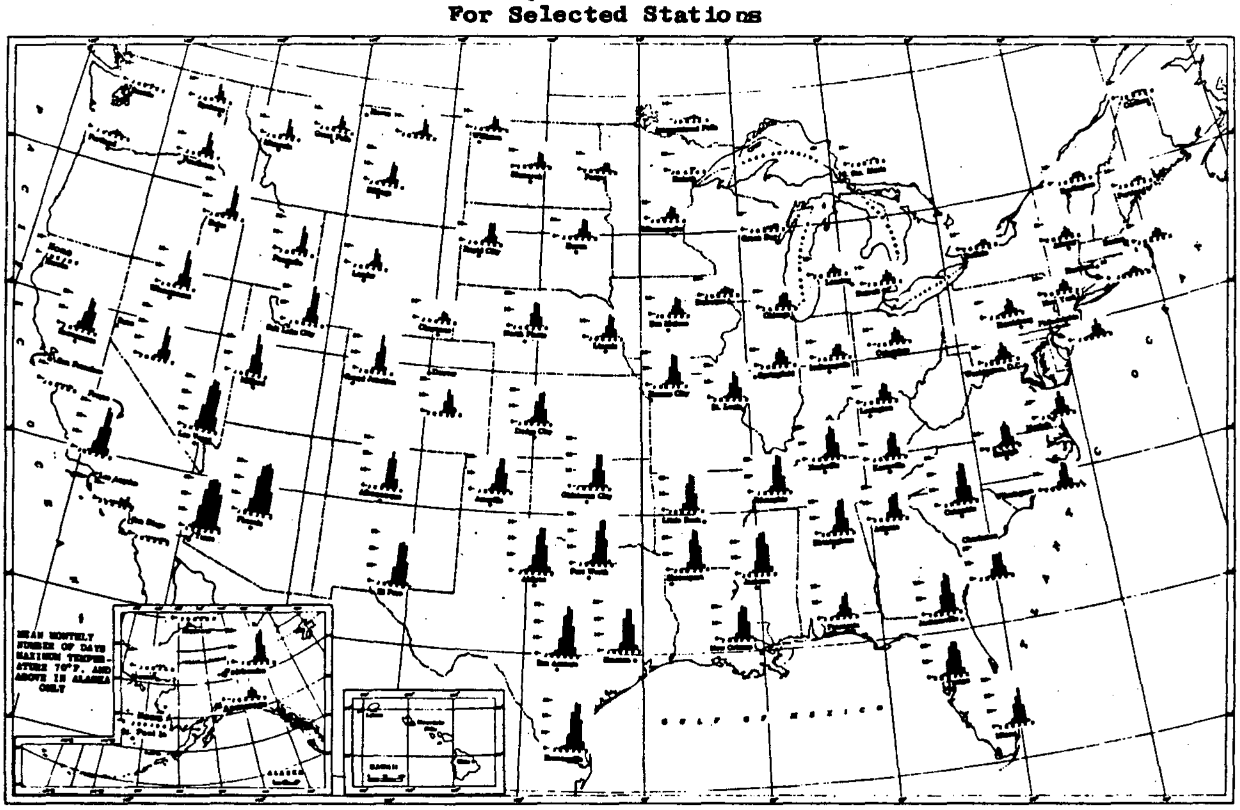
THE COOLING PROBLEM

Don Elmer

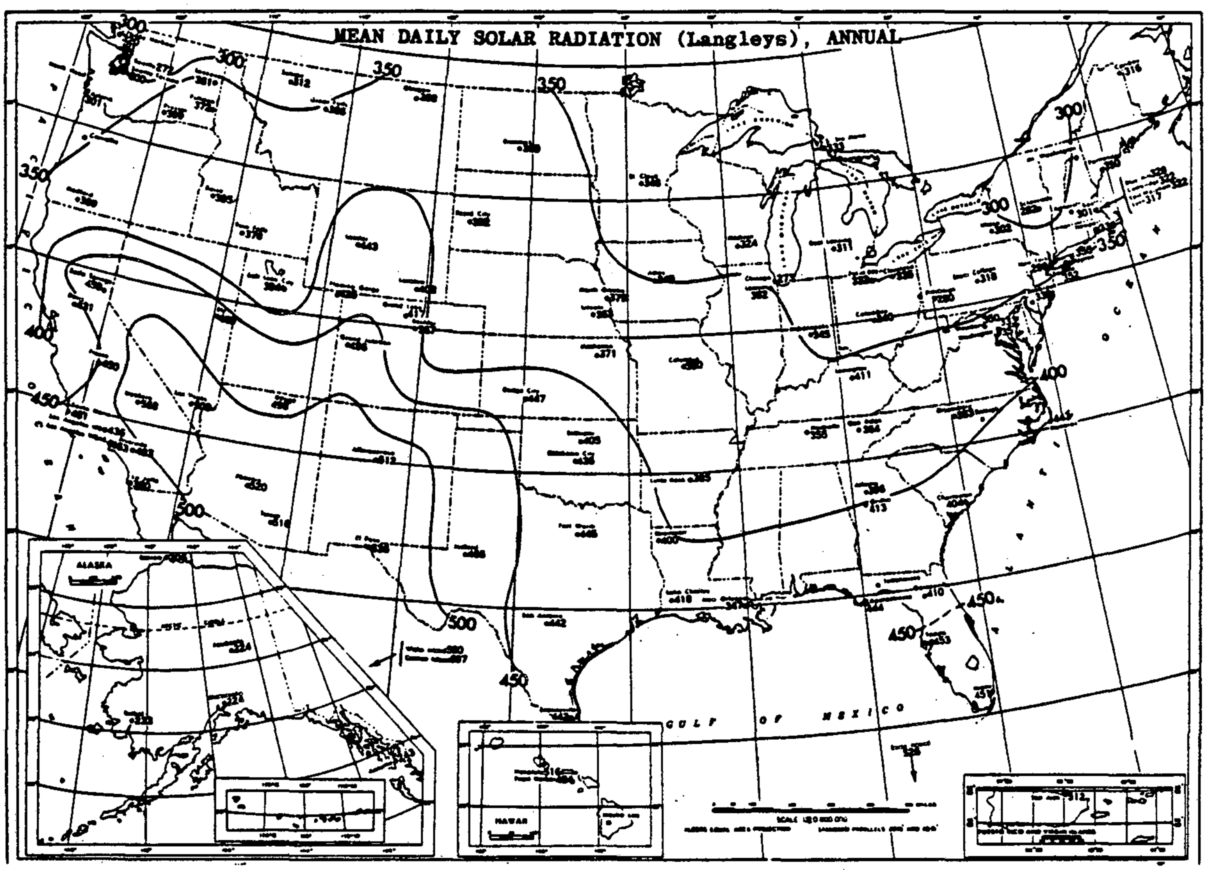
The nature of the cooling problem in the United States must be understood on many levels simultaneously. Human comfort is the measure by which we assess the need for cooling. Climate is the major constraint in designing to meet this need. Buildings are the mechanism by which we attempt to create enviornments that achieve comfort within uncomfortable climatic conditions.

The climatic contribution to the cooling problem itself has many parameters, including humidity, direct and diffuse solar radiation, wind, and air temperature. The following map, taken from the Climatic Atlas of the United States, illustrates the large area of the U.S. which has air temperatures of more than 90°F. for significant periods of the year. Notice that there is extreme variability even within otherwise overheated areas, with coastal plains and mountain slopes being much cooler than their surroundings. The overheated zone may be taken to include all of the isopleths of 60 or more days.

MEAN MONTHLY NUMBER OF DAYS MAXIMUM TEMPERATURE 90°F. AND ABOVE EXCEPT 70°F. AND ABOVE IN ALASKA For Selected Stations



The next map, from the same source, illustrates the intensity of solar radiation on an annual average basis across the overheated areas. This variable is more constance since local conditions do not affect it. The overheated zone may be taken to lie within the 400 Langley per day isolines. Notice the rough correspondence between the preceding map of high temperatures and total solar irradiance.



There is a third important feature to note, namely that the regions of high humidity which do not fall into the overheated zone on an average annual basis often suffer from overheating for part of the summer. Compare the following map of maximum temperatures in August with the map of average annual humidity levels from the preceding page. The Eastern Seaboard and the Great Lakes regions both have periods where high humidity and high temperatures coincide. These regions can be characterized as Temperate Regions with some overheating.

This climatic information implies that the <u>outside</u> conditions in the overheated regions are hot, with an abundance of sunshine; and for a large part of the region -- simultaneous high levels of humidity. This information must be related to thermal comfort for human beings. While there are other economically important occupants of buildings (cows, pigs, chickens all occupy structures and display a sensitivity to heat and humidity as evidenced by variations in milk and egg production and weight gain), human beings are the typical subjects of building design.

Human comfort is a function of many variables; including the rate of air flow over the skin, the mean radiant temperatures of the interior surfaces, the humidity levels of the air, the ambient air temperature, the amount and style of clothing, and the level of human activity. Definitive studies of the coincident conditions necessary for human comfort have been developed by the Olgyay brothers, Givoni, Threlkeld, Fanger, ASHRAE, and others.

In general, during the summer months, the conditions necessary for Human comfort are not met by the outside environment of the overheated states. These exterior conditions must be referenced to the characteristics of a wide variety of structures which are located within these states in order to understand the implications for interior comfort conditions. This is no simple task. The environment contributes to the interior comfort conditions through air temperature, solar and thermal radiation, humidity, and air flow. The operation of equipment and appliances and the activity of people within the structure also contribute to the interior comfort conditions.

The relative contribution of environmental and internal heat gain to the building interior varies with climate, with building style, with use patterns, and across the range of building scales. Small scale buildings, residences for instance, tend to be dominated by the external conditions to a large degree. Large scale commercial structures are much more controlled by the internal load generation and often must run their cooling systems during winter months to remove internal heat.

The following generalizations can be made about comfort, overheating and buildings:

1. Hot environment summertime temperatures are usually less than 20^{o}F. above the upper limits for comfort, while wintertime temperatures can be as much as 60^{o} F. below comfort conditions in severe climates;

2. Infiltration due to temperature differences alone is less important than wind driven infiltration which can contribute to both heat and humidity problems within the structure;

3. Solar irradiance is a major source of interior overheating and interacts with building geometry and climate conditions in specific ways which lead to characteristic patterns of heat gain for buildings of various styles, location, and orientation;

4. Solar irradiance also contributes to the internal load through windows, which not only pass the visible radiation but also form an interior surface with a high mean radiant temperature due to high outside air temperatures and low thermal resistence;

5. Day and night temperature swings which allow buildings to cool off overnight are useful in dry enviornments and non-existent in humid ones;

6. Infrared reflection and re-radiation from the site contributes an unknown amount to the interior heat load, and may be a large problem in the urban setting;

7. 7. Internally generated heat and humidity is important in structures at all scales;

8. Human discomfort problems are highly complex, involving high mean radiant temperatures, high dry bulb air temperatures, humidity extremes, high levels of direct solar and infrared irradiance, and clothing and activity levels; and

9. Cultural expectations and attitudes influence perceptions of discomfort.

The Cooling Approaches: Active, Passive, and Hybrid

The various classes of solar cooling approaches -- active, hybrid, and passive -- aim, in part, at removing heat from the interior environment and transferring it to the exterior environment. Active systems are capable of imitating conventional vapor compression air conditioners and pushing heat from the interior to the exterior even when the outside air temperatures are relatively high. Passive and hybrid techniques and devices rely on the use of natural heat sinks -- that is, places which are cooler than interior conditions.

The chief natural heat sinks are the clear sky, the atmosphere, the ground, and bodies of water. In general passive and hybrid systems rely on relatively small temperature differences, on the order of 10° - 40° F. The heat sink for active cooling systems is generally the atmosphere, though such systems can be configured to utilize the earth or water as sinks.

Effective use of enviornmental heat sinks is only part of preventing buildings from overheating. Equally important is the attenuation of heat flow from both enviornmental and interior heat sources. These heat gain prevention techniques are critical to all building design in the overheated zones, regardless of the primary heat loss device, system, or design. These techniques include shading and orientation, control of air flow through and around the structure, management of internal load generating devices and activities, as well as control of the site to reduce incident solar radiation or infrared re-radiation or reflection.

These techniques are the backbone of indigenous, vernacular, and regional architecture worldwide. The high mass walls of the adobe building of the Wouthwest dampen out the daytime heat flow and perform a bunction somewhat analogous to that performed by the verandas and awnings of the Southeast.

Another major function performed by cooling is the removal of humidity. The active cooling system, like the mechanical vapor compression system not only cools, but also dehumidifies. There are no exact analogies in passive or hybrid design, although some innovative work is being done on hybrid open cycle desiccant systems and other approaches.

In general, the passive designer must cope with humidity by increasing air flow, reducing air temperature, or lowering the mean radiant temperature of the interior walls. This is not always sufficient to shift interior conditions into the comfort zone. Consequently, various researchers are engaged in developing hybrid dehumidification devices and systems, and some builders are beginning to use very small air conditioning units to dehumidify the air in buildings where the other comfort conditions are within the comfort zone because of the effects of proper passive design.

The achievement of human comfort in real buildings must account for all of the factors which have been listed, as a minimum. Regional architectural and construction practices vary; regional climate and site microclimate conditions vary, use patterns vary and no specific device or system will be able to meet every need. This was the unfulfillable promise of mechanical vapor compression air conditioning. Solar cooling must, of necessity, be more subtle and varied.

HUMAN COMFORT

Philip Fairey*

ABSTRACT

The basic principles of human comfort and the thermal environment are reviewed as they are applicable to passive solar cooling problems. Specific areas of interest covered are human body mechanisms, psychrometrics, the effects of air motion and mean radiant temperature, and various passive design techniques which can be employed to overcome uncomfortable ambient conditions in overheated climates.

Introduction

The obvious goal of effective passive building design is to provide comfort for its inhabitants. This introduces an intriguing problem for engineers and building designers since the sensation of comfort is often a very individual matter which is sometimes as much subjective as objective.

In the past fifty years energy costs have been so low that human comfort as it is related to building design was of little concern to the majority of us because mechanical systems could easily control the environment of almost any structure conceived by the designer. Today, however, the parameters of comfort are being closely examined by engineers and designers as we attempt to move toward building designs which have the ability to provide a measure of comfort without extensive mechanical assistance.

The enigma which is posed by the concept of human comfort is exemplified by the ASHRAE definition of thermal comfort - "that state of mind which expresses satisfaction with the thermal environment." It is obvious that quantification of a "state of mind" is by no means a simple problem. Additionally, the problem is greatly compounded by the fact that our thermal environment is affected by a great number of variables. The wall thermostat reads only the dry bulb air temperature, but our degree of comfort is also governed by relative humidity, air movement, and mean radiant temperature.

As if this were not enough, there are other factors impinging on our comfort. The amount of clothing we wear and our activity level directly affect comfort conditions and psychologists have suggested that certain psychological factors such as decor, color, and personal expectation also have minor affects on our degree of comfort. Thus the problem of quantifying and predicting the comfort of a proposed building design becomes one of significant magnitude.

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The views expressed are those of the author and not necessarily of the Florida Solar Energy Center

Human Body Responses

A number of statistical studies have been performed on large numbers of subjects of all ages, sexes, and nationalities in order to arrive at numbers which quantify these variables and provide goals and design parameters for human comfort in buildings. The results of the studies indicate that the human body is a remarkable piece of machinery which has a relatively wide tolerance and can make it's own adjustments to environmental conditions. It is important in a discussion of comfort to at least touch on these body mechanisms.

The human body generates heat. This is accomplished through the metabolic process whereby the intake of food is converted to useful body energy through digestion. This energy is in turn used to perform useful work, and as a by-product, heat. The amount of heat produced by the body is proportional to our level of activity, with higher activity levels producing higher levels of thermal energy. Since humans are warm blooded mammals the body temperature needs to remain relatively constant in order to prevent serious medical implications. The body accomplishes this in rather remarkable ways. For instance, if the environment is very cold the body will involuntarily shiver, thereby producing more body heat, keeping the body temperature at its required level. Likewise, the body has a number of mechanisms to dissipate heat when the environment is overheated. The human body exhibits all normal heat transfer mechanisms (conduction, convection and radiation) in addition to the rather remarkable ability to perspire and cool itself by evaporative heat loss.

Under optimum temperature and humidity conditions (75^{o}F, 50% RH) the vast majority of body heat loss occurs through convection and radiation with only about 20% occuring through evaporation. Very little loss occurs through conduction. However, as environmental conditions change, bodily temperature regulation systems react accordingly. For instance, if activity is held constant and dry bulb temperature rises, losses through convection and radiation virtually switch places with evaporation and as the dry bulb temperature rises above 90^{o}F, about 80% of the body's heat loss is through evaporation, resulting in profuse perspiration (Reference 4).

As environmental conditions change and as temperatures approach 98.6^{o}F, virtually all body heat loss must occur through evaporation. If the environmental air quality exhibits a high relative humidity (vapor pressure) the potential for evaporation to take place is greatly reduced. Theoretically, when relative humidity reaches 100% the body can no longer evaporate moisture and if temperatures exceed 98.6^{o}F the potential for very serious and even terminal body overheating exists.

Basic Psychrometrics

The interdependence of several air quality variables has led to psychrometrics. Psychrometrics primarily concerns itself with the characteristics and thermal energy potential of our air environment, and is a graphic definition (Psychrometric Chart) of the interrelatedness of temperature, humidity, energy content, and volume of environmental air under all possible conditions. Psychrometrics is important to us because it is capable of directly defining a number of simultaneous factors which affect human comfort.

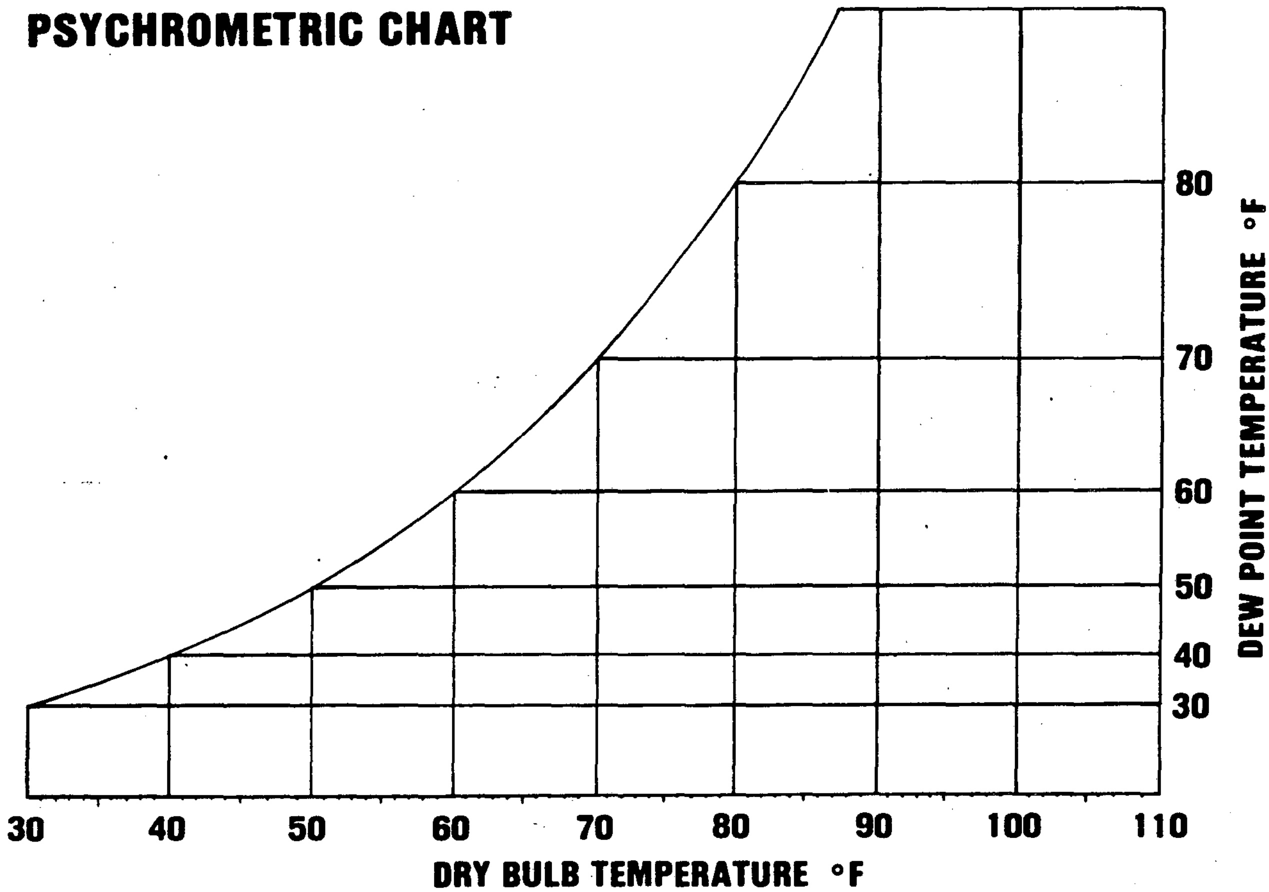


Figure 1

Dry bulb and Dew point temperature - the basic comparison made by the psychrometric chart is the relationship between air temperature and air moisture content. The air temperature scale forms the abscissa of the psychrometric chart and is labeled as dry bulb temperature. The ordinate of the chart represents the air moisture content scale. The dew point temperature of air is a measure of moisture content. It is the lowest temperature to which a given unit of air can be driven without condensation occurring. The various dew points (the point at which dry bulb and dew point temperatures are equal) constitute the line of 100% relative humidity and form the other boundary of the psychrometric chart.

In terms of process definition, sensible heating and cooling follow the lines of dew point temperature, and condensation follows the outer curved saturation boundary of the chart. Whenever dry bulb temperature is lower than dew point temperature, air will follow the dew point line to the outer boundary (saturation line) of the chart and moisture will condense from the air. Condensation will continue, following the saturation line and lowering dew point temperature, until the dew point temperature reaches the dry bulb temperature. The common air conditioner removes moisture from the air in this manner. Moist room air (roughly 78°F dry bulb and 65°F dew point) is passed over cooling coils containing a working fluid which is approximately 55°F. The room air follows the 65°F dew point line to the saturation line and at that point condensation begins to occur on the coils and latent heat (moisture) is removed from the air until the wet bulb temperature of the air reaches the coil temperature (55°F). The air is then reintroduced to the room as cooled, dehumidified air (55°F dry bulb and 55°F wet bulb). Normal heat loads on building interiors then reheat the air sensibly (along the 55° wet bulb line) and room air conditions ultimately come to 75°F dry bulb temperature and 55° dew point temperature (50% RH).

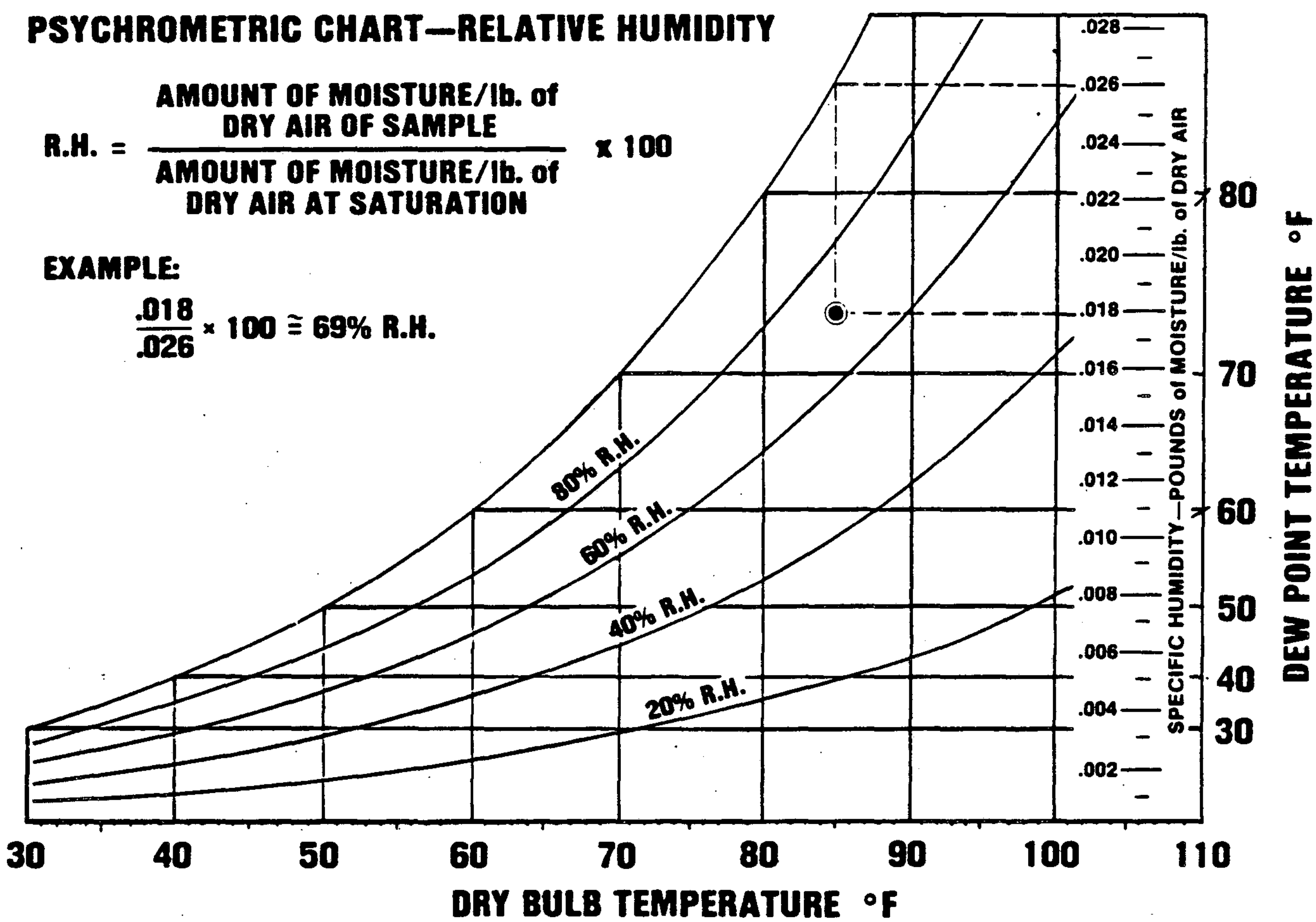


Figure 2

<u>Specific and relative humidity</u> - the specific humidity of air is the measure of the absolute weight of water vapor which is contained in a unit of air at a given dry bulb temperature. The relative humidity is the percentage ratio of the weight of water vapor in that air (specific humidity) as compared to the weight of the water vapor which that air is capable of holding at saturation, (100% RH), at that same dry bulb temperature.

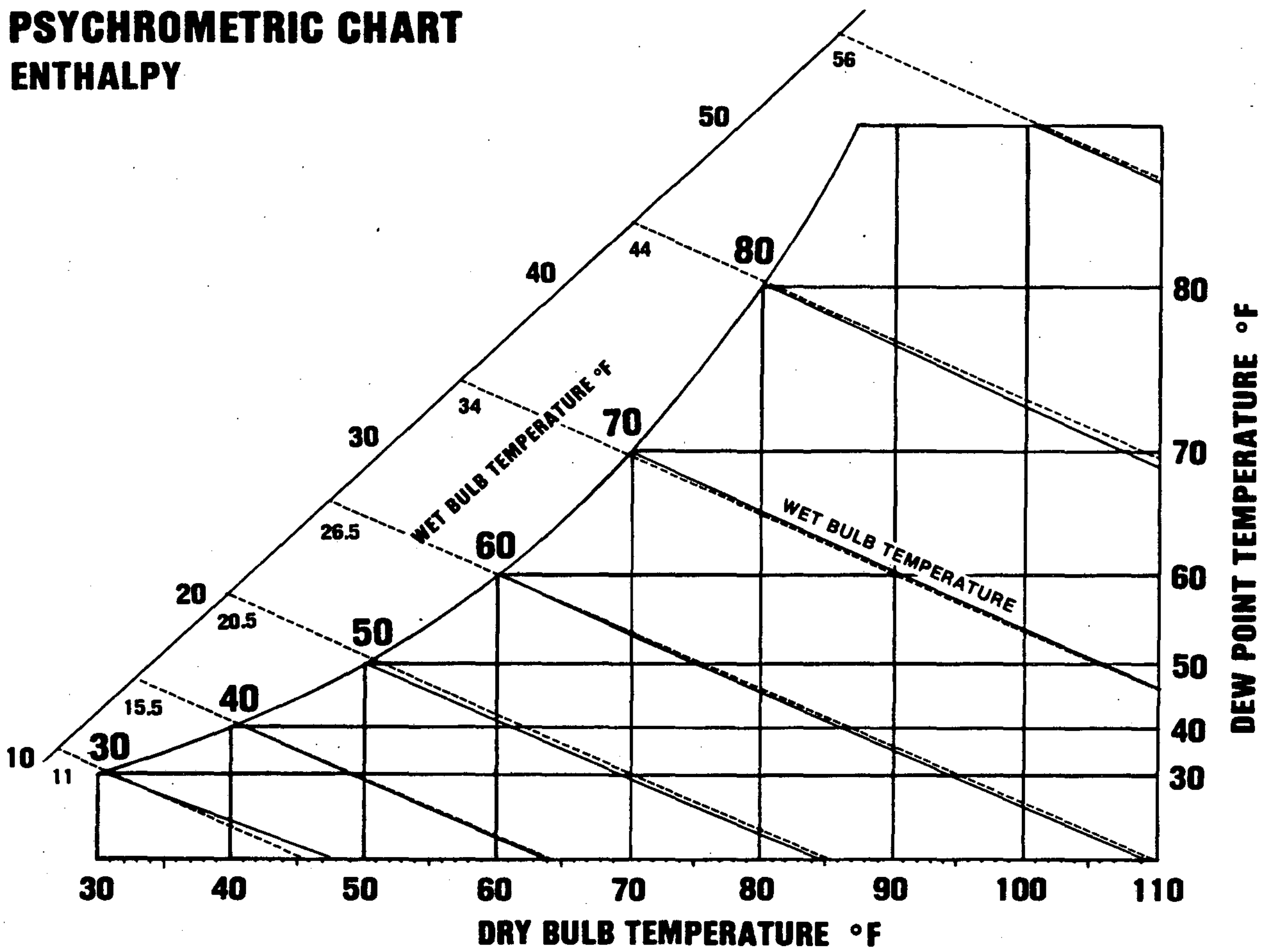


Figure 3

Energy Content - a given unit of air contains two types of energy, sensible energy and latent energy. The sensible energy content of air is a measure of the thermal energy of the air and the latent energy content of the air is a measure of the heat of vaporization associated with the moisture vapor contained in the air. Enthalpy is the total heat/energy content of the air and its associated moisture (sensible heat plus latent heat). Wet bulb temperature is closely related to enthalpy and represents the lowest temperature to which a given unit of air can be driven through adiabatic (evaporative) cooling. In other words, as air is evaporatively cooled and the heat of vaporization necessary for evaporation is extracted from the air, the humidity of the air will increase along the line of wet bulb temperature until saturation (100% RH) is reached. The dry bulb temperature will fall, and the enthalpy content will remain almost unchanged. At saturation, dry bulb, wet bulb, and dew point temperatures will be equal.

The wet bulb temperature lines are important process lines in passive design. Adiabatic cooling potential is limited by wet bulb temperature and the lines are used in the process definition of evaporative passive cooling techniques. Additionally, the action of desiccant adsorption of moisture closely follows the wet bulb temperature lines with only a 5%-10% entropy associated with the process. Therefore during desiccant dehumidification a given quantity of air will increase in dry bulb temperature while decreasing in relative humidity and the total enthalpy content of the air will rise slightly, following almost the opposite pattern of adiabatic cooling.

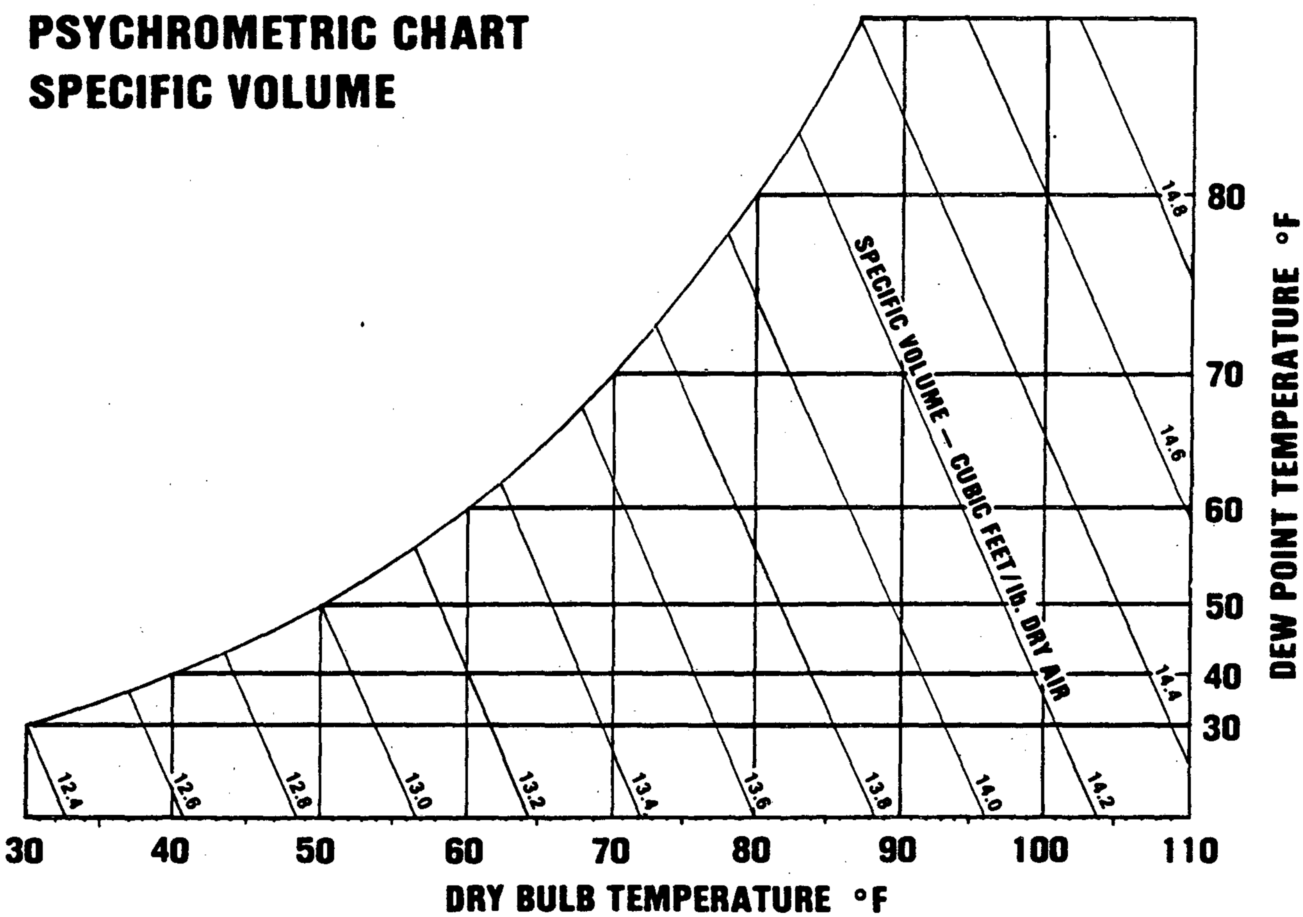


Figure 4

<u>Specific Volume</u> - as air is heated and as it absorbs moisture vapor, it becomes more buoyant (it weighs less per unit of volume). The psychrometric chart provides a method of determining the volume of air which will weigh one pound under various conditions through the lines of specific volume.

The complete psychrometric chart is useful to the engineer and building designer for two primary reasons. It enables a thorough understanding of all of the variables of air quality given any two of those variables, and it can be used to directly and indirectly define the conditions under which comfort will occur. Additionally, it is a useful tool in the understanding of the mechanisms of comfort conditioning. It is used extensively by mechanical and thermal engineers in the design of comfort conditioning systems. In passive cooling the psychrometric chart is very useful for process definition.

Comfort Zones and Standards

The psychrometric chart is used by ASHRAE and many researchers as the graphic base line for the definition of comfort. In ASHRAE's comfort chart an additional set of parameters is added to the psychrometric chart. The effective temperature (ET*) is represented on the psychrometric chart by dashed lines. The effective temperature is an attempt to integrate temperature and humidity into one scale which represents lines of constant body stress. Toward extreme cold, the effective temperature lines approach the dry bulb temperature scale and toward extreme heat they approach the wet bulb scale. The index line for the effective (ET*) scale is 50% relative humidity curve.

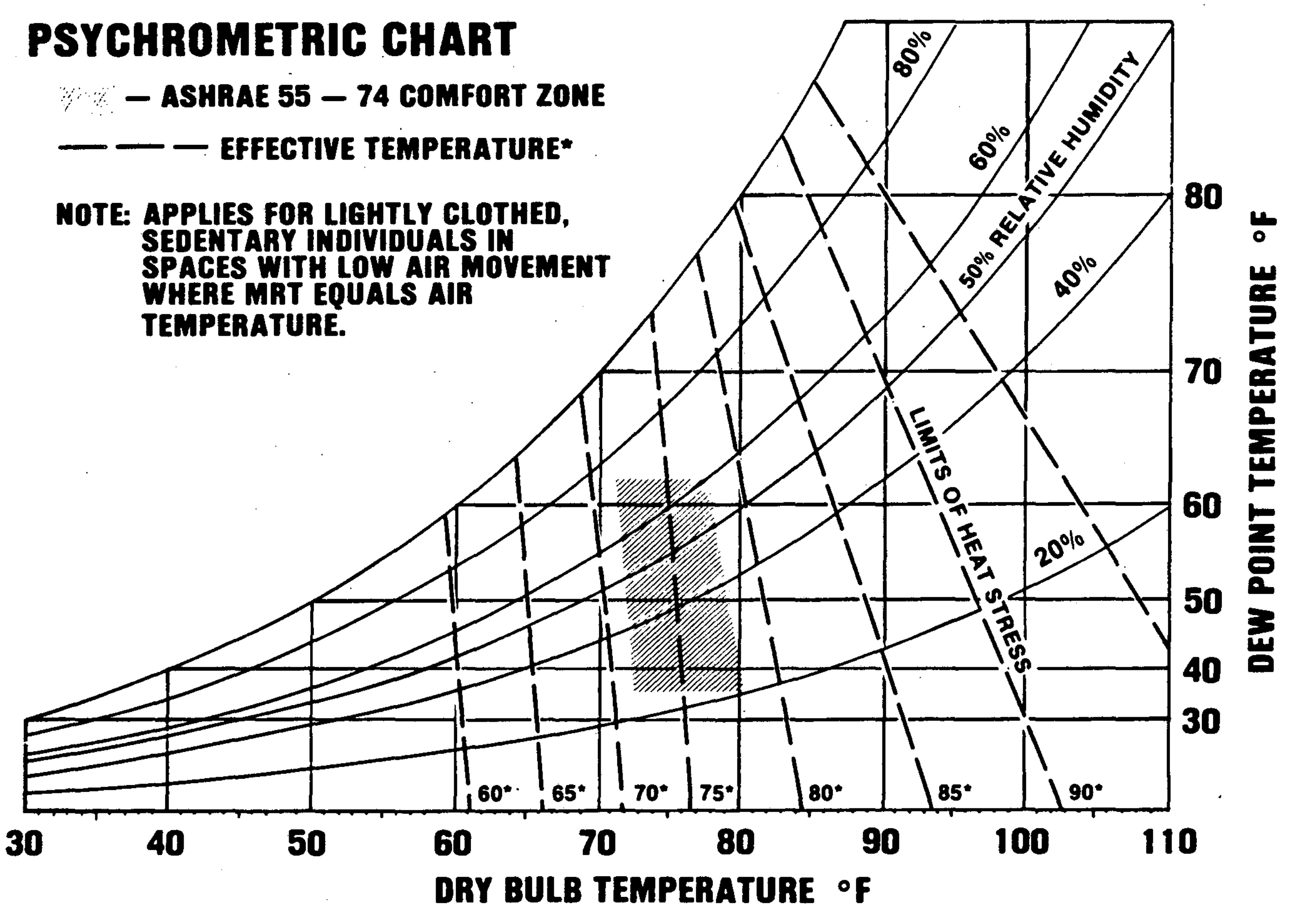


Figure 5

ASHRAE Standard 55-74 Comfort Zone

The ASHRAE comfort zone is defined by the air conditions under which 80% of tested subjects would express thermal comfort. The chart is applicable only to lightly clothed, sedentary individuals in spaces with low air movement, where mean radiant temperature equals air temperature.

Additional Factors

While both air temperature (dry bulb) and humidity (wet bulb) are correlated by psychrometrics, there are factors of human comfort which are not directly understood through the psychrometric chart. Four more factors directly affect body heat exchange and comfort. Air motion, mean radiant temperature (MRT), activity levels (Metabolic rate - met units), and the thermal resistance of clothing (clo-value) are not directly modeled in psychrometrics. They have, however, been extensively studied as to their affect on comfort and can be indirectly expressed through the psychrometric chart.

A set of comfort equations developed by P.O. Fanger (Reference 5) allows for the empirical calculation of comfort conditions under environmental conditions which incorporate all the physiological variables affecting comfort. The effect of increasing air movement or reducing mean radiant temperature is to move the comfort zone. Likewise, changes in clothing and activity levels also move the comfort zone.

Air Motion and Humidity

In most overheated climates, air motion is one of the most valuable methods of attaining comfort when dry bulb temperature and humidity levels preclude comfort in the natural environment. Fanger's work indicates that comfort can be attained, for example, at 82°F and 100% RH if air motion of 1.5 m/s (300 fpm) is maintained. Generally, 300 fpm is considered the normally acceptable upper limit of air motion for human comfort (References 3 and 4). The new ASHRAE draft standard 55-74R, however, places a maximum allowable limit of 160 fpm (0.8 m/s) on air motion.

It should also be noted that, although the ASHRAE handbook recommends the use of Fanger's generalized comfort charts, both the existing ASHRAE standard 55-74 and the draft revision 55-74R place an upper limit of 62°F dew point temperature (0.012 lb/lb) on moisture level. Fanger and others, however, have shown that comfort can be attained at higher dew point temperatures.

In warm and humid climates as occur in the southeastern United States this can be an important consideration. If the standard for comfort is limited to a maximum dew point temperature of 62°F, warm and humid climate zones, (often having dew point temperatures in excess of 70°F), cannot maintain the standard of comfort without mechanically removing moisture from the air.

Mean Radiant Temperature

It is now relatively well known among passive solar enthusiasts that the mean radiant temperature (MRT) of a building environment is of great importance to comfort levels. At optimum comfort levels (75^{O}F, 50% RH) the radiant exchange of the human body with its surroundings accounts for approximately 40% of its ability to lose heat. Therefore, if the MRT is increased the net radiant exchange from the body to its surroundings will decrease, and if MRT is decreased the net radiant exchange from the body to its surroundings will increase. In the ASHRAE draft standard 55-74R the "operative temperature" of a space is the simple average of the air temperature and the MRT, provided there is little air movement (less than 80 fpm) and temperature is less than 120^{O}F.

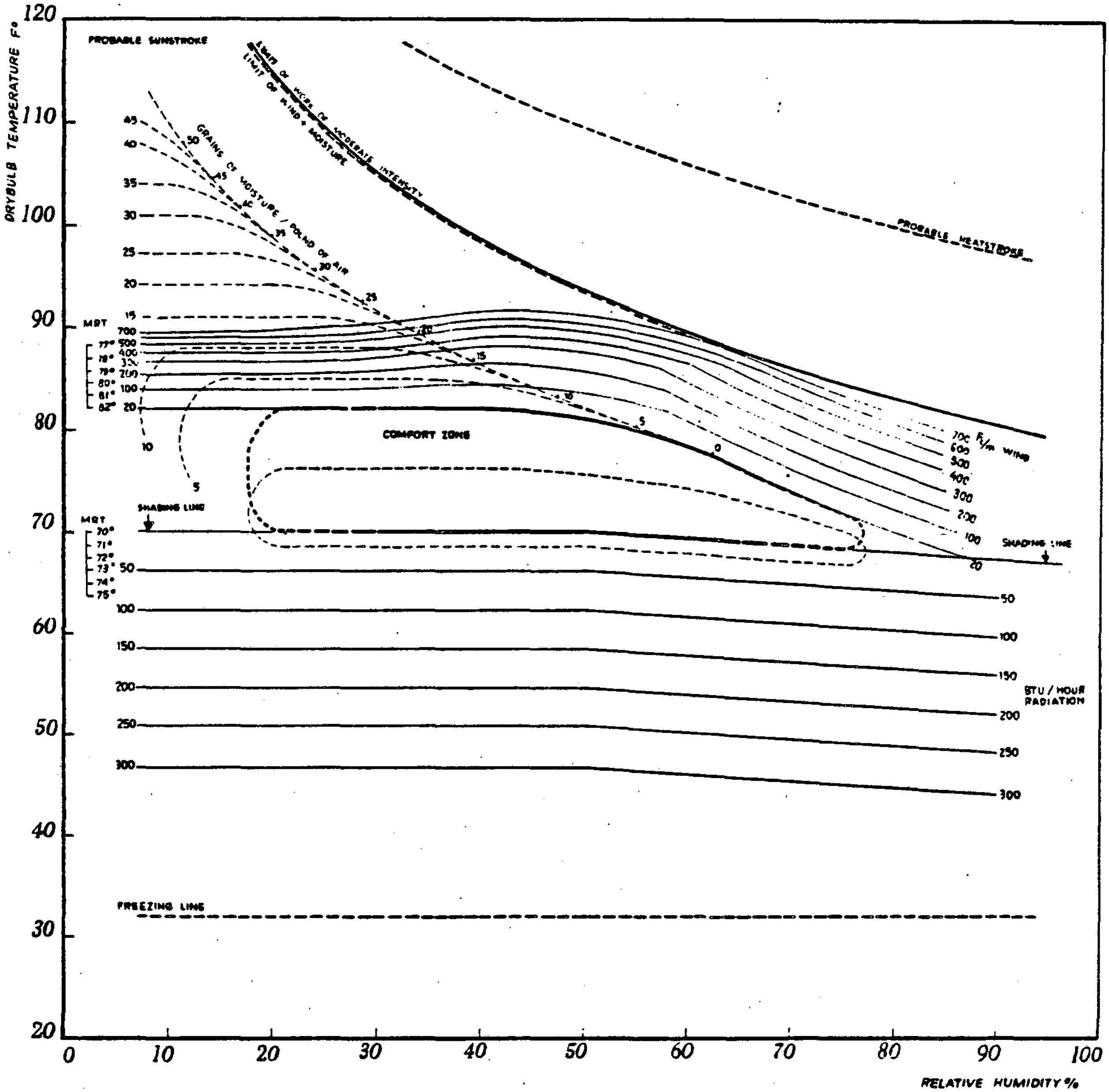
This has proven to be a very powerful passive technique, both for heating and cooling. Through the use of thermally massive materials and heat collection and rejection techniques passive designers have effectively used this principle in a number of design configurations. The most notable historic examples are the American Indian dewllings of the warm, dry desert southwest where large volumes of mass, strategic placement of windows, and large diurnal temperatures combine to produce dwellings which maintain almost constant internal comfort.

Warm, humid climates, however have some difficulty in employing this technique to its fullest extent. Since high humidities (and therefore high dew point temperatures (prevail in these zones, it is impractical to maintain very low MRT's. For example, it is possible to lower the temperature of a radiating surface as much as 20^{O}F below ambient air temperature through night sky radiation. However, if this is done in warm humid climates the dew point temperature is passed and moisture will condense on the radiating surface (the ceiling on a roof pond residence). Therefore, alternative strategies and dehumidification techniques are badly needed in warm humid climates.

Winter Comfort Vs. Summer Comfort

One additional area is the concept of dual comfort zones. The existing ASHRAE standard shows only one zone for human comfort. This appears to be supported in the majority of the literature. However, researchers have pointed out that clothing levels change with the seasons and the assumption of year round light clothing (0.6 clo) within the building environment does not reflect reality. The new draft ASHRAE standard 55-74R reflects this change and shows a winter (0.8-1.2 clo) and a summer (0.35-0.6 clo) zone. The concept is still under debate with some researchers claiming the dual zone should be based on acclimatization rather than clothing. But, by-in-large the two zone concept based on clothing levels appears to prevail, with no proven difference in the physiological response of the human body between winter and summer.

Graphic depictions of the comfort zone are not entirely new. Perhaps the first attempt was by Victor Olgyay in his classic work <u>Design with Climate</u>.



Bioclimatic Chart, for U.S. moderate zone inhabitants.

Figure 6

Bioclimatic Chart by Olgyay (Reference 7)

Olgyay's bioclimatic chart was an attempt to define all parameters affecting building environment comfort on one chart. Even this chart, however, falls short of a complete explanation of potential building environments which are attainable through various design strategies. For instance, Olgyay's chart does not make provisions for strategies such as thermally massive structures to mediate ambient climate conditions. Similarly, other passive design strategies are not evident through Olgyay's chart. In addition to this, his chart can not be used as effectively as the psychrometric chart to define engineering processes associated with environmental air quality changes.

More recently, Baruch Givoni, (References 6 & 8) author of Man, Climate and Architecture has provided a mechanism, using the psychrometric chart, for expressing the potential effects of passive cooling building design on human comfort. The system expresses the design strategies which can effectively bring given ambient climate conditions into the comfort zone through proper building design. In all, three major cooling design strategies are covered:

- o Evaporative cooling
- o High thermal mass, and
- o Natural and mechanical ventilation

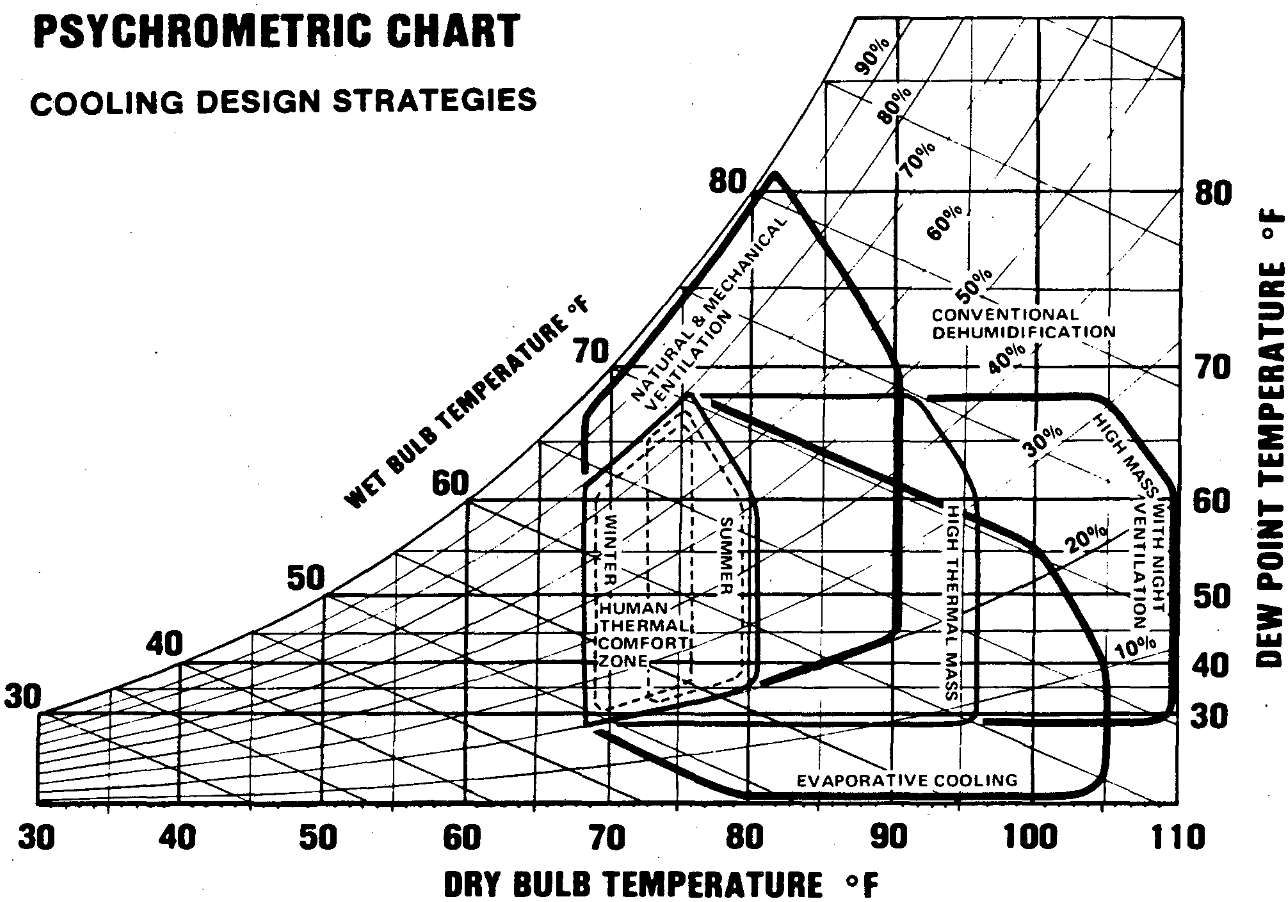


Figure 7

In terms of building design, each of the cooling techniques have maximum ambient climate conditions. For evaporative cooling that limit is set at a wet bulb temperature of 70°F. For high thermal mass structures a dew point temperature of 68 F is the boundary condition. And for natural and mechanical ventilation the limit seems to be a line roughly corresponding to (but with a more negative slope) and crossing the 90°ET* line at 50% RH.

Two major strategies, however, which are the major subject of much cooling research presently being done, are not included in Olgyay's chart.

- o Radiative night sky cooling, and
- o Passive dehumidification

Radiative night sky cooling exhibits characteristics which are based on climatic conditions and its boundary conditions could be plotted on the psychrometric chart. They may be quite similar to those for evaporative cooling but with a higher wet bulb boundary (perhaps 75-76°). This gives the passive designer a greater variation in design strategy but does not increase the area of climatic conditions already covered in the chart. Again, moisture level becomes the boundary condition.

Dehumidification has become the major limiting factor in passive cooling. The potentials of passive solar desiccant systems, are the subject of both research and controversy. Desiccant regeneration and adsorption efficiencies, and mass transfer and air flow rates in passive dehumidification schemes have not been experimentally shown. The implications of bed geometry and regeneration cycles has not been fully explored and a considerable body of research remains to be done in sizing, solar orientations, and practical applications of passive desiccant systems. If results of present research efforts prove to be positive, however, desiccant dehumidification can provide a major source of comfort for the human environment.

There already exists a major body of knowledge which allows sensitively designed buildings to provide substantial amounts of comfort without the aid of mechanical air conditioning systems. In all but our most humid climates substantial reductions in building energy requirements may be achieved using only our present knowledge. With the eventual solution of moisture removal, building comfort potentials will greatly increase, there is ample reason and knowledge available to justify an optimistic attitude toward the potential effectiveness of passive cooling in overheated climates.

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SOME HISTORICAL INDICATORS FOR BUILDING DESIGN UNDER NATURAL CONDITIONS IN OVERHEATED REGIONS *

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INTRODUCTION

The overheated areas of the world enbrace a variety of climates which, seasonally, may be very hot and arid, warm and humid, temperate dry or humid, or cool to cold dry or humid. Almost all geographical locations experience seasonal and daily climate changes, resulting in composite climate considerations when designing buildings for a specific site. Globally, a vast land mass is affected. This discussion is limited to climates whose annual averages lead to the following classifications:

1.) Hot/warm and arid/semi-arid regions
2.) Warm and humid regions
3.) Temperate - both arid and humid regions.

A schematic representation identifying each of the above, for daily and seasonal variations is provided as predominantly overheated (Fig. 1) and seasonally overheated (Fig. 2).

HOT DRY CLIMATES (ARID AND SEMI-ARID)

Distribution and Characteristics

The dry desert climates of the world are found roughly between latitudes 15° and 30°, North and South, even extending as far as 45°. They are located in the central and western parts of Asia, tropical and sub-tropical parts of Africa, North and South America and in central and western Australia. The driest deserts in the world include the Atacama deserts of Southern Peru and Northern Chile, the Central Sahara and Southern Arabia. (Figs. 3,4,5)

The aridity in these regions is related not only to the amount of humidity and precipitation, but also to the intense solar radiation, up to 800 Kcal/m2h on horizontal surfaces. The hot dry air pulls the moisture from the ground like a suction pump, so moisture for plant growth is not available in the ground. Due to the lack of vegetation, the barren light coloured terrain reflects much of the radiation, thus augmenting the direct solar radiation. The total direct and reflected radiation becomes an important factor in human comfort and building design. (Fig. 6)

* Extracted from a paper presented at the Annual Conference of the Afro-Asian Housing Organization at N.B.O., Nirman Bhavan, New Delhi, India. Nobember 1975.

The intense heating of the ground gives rise to convection currents mainly in the afternoon. Dust storms and dust haze are frequent due to these convective currents. The sky is clear for the greater part of the year. The absence of cloud or water vapour in the air, to diffuse the sun's rays, results in higher intensity of direct solar radiation, to heat and dry the ground, further reinforcing the high temperature of the air.

The high luminosity, lack of cloud cover and low humidity results in a wide diurnal temperature range. The desert surfaces heat up rapidly in summer to over 160°F during the day, while at night rapid loss of this heat through long wave radiation by the earth, cools the surface to 60°F or below. The daily range of air temperature is normally 40°F. The summer temperatures during the day are 100°- 125°F and at night within the range of 50°-75°F. The annual range in temperatures is largely a function of latitude. The maximum ever recorded is 136°F in the shade in the Algerian Sahara. The difference between the temperature in the sun and the temperature in the shade is very high, and there is a sudden drop in surface temperature with the setting sun.

Vapour pressure is fairly steady, varying with location and season, from about 5 to 15 mm Hg. Relative humidity ranges from below 20% in the afternoon to over 40% at night, fluctuating with the air temperature. Lows experienced can drop below 10%.

Wind speed is generally low in the morning, rising towards noon with the heating of the ground. It reaches a maximum in the afternoon coming in gusts equipped with sand and dust. Nights are still and clear and without the heat haze that blurs distant views during the day.

Islands in predominantly hot and arid regions, possess climate modifications resulting in increased humidity and lowering of temperatures. Breezes are usually pleasant as they have generally crossed a large water body. Highlands in hot-arid regions are much cooler than the surrounding plain. Under these conditions, vapor pressure may not vary much.

Comfort Requirements

The wide seasonal and daily temperature range creates problems of human adjustment and physiological comfort. Maintenance of body comfort is expensive in terms of high energy consumption for mechanical means of cooling, shortened work periods, and increased effort required to keep cool.

Buildings designed for summer conditions may include adaptable components to satisfy winter comfort requirements. Careful orientation, choice of materials and design detailing would be necessary to achieve a satisfactory interior environment and to minimize stress due to extreme heat, although the use of mechanical means of cooling is indicated.

In the hot arid regions natural ventilation, as obtained through open windows and doors, is to be discouraged during the day, since the internal temperatures would then closely follow changes in the outdoor air temperatures.

Also, the human body would gain heat through convective currents or breezes inside a building as a result of cross ventilation. On the other hand, since sweat evaporation is adequate due to the dryness of the air even when the air is still, there is no need for air to be kept moving over the skin, so as to prevent discomfort caused by moist skin (as in warm humid climates).

Thus during the day, natural ventilation is unnecessary for evaporative cooling and undesirable for convective heat exchange. Efforts should be made to keep the interior air cool or to retain its coolness while maintaining the required ventilation (air changes) in keeping with health standards. In the evening, however, with a fall in outdoor air temperatures below the level of indoor temperatures, ventilation would enable rapid cooling of the interior. Also heat would be lost at night by the building through outward radiative and convective cooling. The addition of moisture, to lower temperature, is very desirable.

A frequent problem in hot dry regions is that of discomfrot through dust entering the building. This problem may be reduced at different points through town planning, layout of housing, skillful use of design elements and detailing. Maintenance of comfort conditions can be assisted in such a climate by the proper adaptation of living habits by the individual.

Strenuous activities could be restricted to early morning, late afternoon or night. Outdoor activity hours could be changed, or times, to coincide with pleasant or bearable outdoor conditions. Saving of unnecessary labor (and the consequent production of heat) in such a hot climate is desirable. Proper clothing is another important means of assisting in the achievement of comfort conditions. Loose fitting and rather heavy, loose woven clothing is recommended since it would permit a free circulation of air around the body aiding in evaporation. The head and back of the neck should be shaded by means of a loose insulated hat. Although physical adaptation of the human body is achieved within a short time, maybe a month, social adaptation - food, clothing, work, rest, play, etc. - is found to take much longer and in some cases never completely accomplished.

Building Design in the Hot Dry Regions

Traditionally, houses in hot dry climates have been built close together, depending on each other for mutual shading and insulation. The buildings themselves have flat, vaulted and domed roofs, with walls of heave, thermal-lag materials and very small openings.

In rural areas stone or mud bricks is the favourite material for walls, and flat roofs are composed of a thick layer of dried mud covered with a second impervious layer. Reinforced concrete and brick is used in urban areas. Domes and vaults are constructed from mud bricks and plastered over with mud.

The heat storage capacity of thick exterior walls and roofs tends to narrow the internal temeprature range, bringing it to a level fairly close to the average external temperature. Small openings in walls are used to minimize ventilation and restrict the entry of hot, dust-laden outdoor air. This also has the result of reducing glare arising from the hot, shimmering, reflective surfaces outside. Buildings are compact and close together, so as to expose a minimum surface to radiation and hot, exterior air, while providing maximum volume for interior use.

Buildings tend to face inwards on sheltered courtyards, which offer not only privacy but shelter from the dust-laden wind. Courtyards and roofs are used for sleeping. This is partly due to the fact that the thick heat absorbing walls have, by evening, started to radiate heat into the interior, thereby making the interior warmer than the exterior at night. The most important consideration to achieve comfort conditions in buildings in hot arid conditions is to reduce the internal day temperature.

Consequently, screening occupants from incoming solar radiation is essential. In this, it is very important to see that the building envelope itself is exposed to as little radiation as possible and that it transmits as little of this heat to the interior as possible.

As highest levels of radiation are experienced on a horizontal plane (Fig. 7), in low structures roofs play an important role in cooling interior spaces. Their importance diminishes as structures grow taller. With walls, a north-south orientation of longer walls is preferable, since east-west oriented walls are subjected to higher radiation loads during the day than are north-south oriented walls.

Equator oriented walls are subjected to low levels of radiation during the summer and high levels of radiation during winter days. However, considerable relief would be obtained if solar radiation could be prevented from reaching the building envelope in the first place. Trees, bushes, shrubs could be used wherever possible to shade building walls. Artificial screens and shading devices are useful.

The low thermal resistance of windows and other such openings, makes them a very important route of heat flow to the interior and they should, invariably, be shaded. Their location, size and shape must be correctly coordinated, so that they can be small enough to minimize heat flow, but still provide efficient ventilation when open. Insulation in hot-dry areas is usually more important than air movement.

Reflected radiation from nearby structures and the ground surrounding the house, are two important factors to be taken care of in hot climates. Where possible, grass or some cover plant could be grown. Where this is not possible, it is preferable to use subdued colors on these surfaces. The use of subdued colors would raise the temperature on these surfaces, with the consequent increase in thermal radiation, but this would be more than off-set by reduced reflection of the very strong sunlight from the ground, experienced in hot regions.

There are various architectural devices which can be used for shading elements like walls, doors, windows, etc., and these should be employed wherever appropriate. (Fig. 8)

Another way or reducing the radiation impact on the building is by increased reflectivity at the surface. This is especially important in the hot arid regions where direct and reflected solar radiation is intense. The effect of light external colors in minimizing internal day temperatures, is far greater than that of increasing either thermal resistance or thermal capacity. But this light color or whitewash needs to be renewed quite frequently, if the building envelope is not to absorb enormous quantities of solar energy. Painting in light color is especially important for the roof component which receives a great amount of radiation. (Fig. 7) The heat from a roof tends to find its way to the ceiling, raising its temperature level above the other internal surfaces and making this an almost continuous heating element in a building.

In areas where water is available, spraying the roof or walls which are exposed to the sun is very effective in reducing the heat load through evaporative cooling. The surfaces should be water absorbent, as in hot dry areas water is limited. An alternative practice on a flat roof is to maintain a water layer of one or two inches. This is less effective since solar radiation passes through the water to be absorbed at the underlying roof surface. Evaporation tends to take place at the surface of the water, that is, away from the point of maximum heating. The presence of a continuous water layer requires vigorous waterproofing. The weight of the water layer might also be important. Water may be a breeding place for mosquitoes in some places.

A double roof or composite roof might provide a more satisfactory solution to the problem of radiation on the roof. If a heavyweight layer is provided with an external layer of efficient insulating material, itself protected by a waterproof light coloured covering, heat flow during the day from external to internal layers would be restricted by the insulation and only a small proportion of the potential heat would be abosrbed by the roof element. Even this absorbed heat could be removed in the evening by ventilating the interior. With large air spaces, like those between a sloping roof and a flat ceiling, ventilation may be very important, especially if the insualtion of the roof structure is not very effective. The airflow could be so arranged as to sweep 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. Care must be taken to see that hot outside air will not be drawn into the rest of the building.

Investigations at various Building Research Stations indicate the effectiveness of heavyweight insulation when used with certain specific design features in reducing the overall internal temperatures.

Concrete walls (as also earth walls) due to their high heat capacity are well suited for hot and dry climates when insulated on the exterior by rockwool expanded plastics.

Calculations would have to be made for the different solar radiation loads on walls with varying orientations. These calculations would determine the thickness of the concrete and the insulation, taking into account the outdoor maximum temperatures. The openings in walls would be adequately protected from the solar radiation and diffuse or reflected radiation. Movable insulated shutters would give the desired amount of flexibility.

Like walls, roofs would be of composite construction, perhaps with well protected openings (closed during the day) so that interiors would be quickly cooled by ventilation in the evening. The upper layer of the composite roof would be a waterproofing layer followed by an insulation layer similar to that used in walls.

In choosing an insulating material, it should be noted that the heat loads with which we have to deal are not constant, but fluctuating; air temperatures and radiation loads go up by day and down by night. Insulators like those used for protecting hot boilers, steam pipes, etc., known as resistance insulators would not be effective. The better insulator would be a capacity insulator to absorb and store a large quantity of heat, while retarding its passage to the interior, during the day and emitting it rapidly when the load is off. The low conductivity of such an insulator should combine with its relative high density to give a low emissivity.

The capacity type of insulating property (heat storage) is particularly desirable for roof structures since in hot dry regions they receive regular periodic high radiation loads from clear skies.

The traditional use of internal and semi-internal courtyards is valid for these areas. The whitewashed roof would slope toward this courtyard. This whitewashed roof will lose its heat comparatively quicker than the surroundings in the still air of evening through radiation, and the air in contact with this roof will be cooled at night and be channeled by the slope into the courtyard and then into the interior.

SUMMARY

The heat exchange system involved in design for hot aird regions may be analysed as follows:

- The building is heated during the day, only through the insulated external envelope.
- Between sunset and sunrise, the building interior is cooled convectively through openings, by exterior air at temperatures below indoor levels.
- Between sunset and sunrise, the fabric and the building generally is cooled by heat loss through long-wave infrared re-radiation to the atmosphere.
- Conducted heat loss from the building's fabric is accelerated by airflow across its surface, at all times.

WARM HUMID CLIMATES

Distribution and Characteristics

The humid tropical climates in general are located in a zone that is on either side of the equator in Africa, South America, Asia and Northern parts of Australia. These climates extend, roughly, from about latitude 5° to 10° South and to latitude 15° North on the western side of the continents and to about the Tropics of Cancer and Capricorn on the eastern sides. (Figs. 1,2,3)

The temperatures and humidity are high and there is a constant daily temperature pattern throughout the year especially near the equator. Average monthly temperatures do not fall belwo 65°F, whereas, the annual mean temperature is about 80°F. Maximum temperatures are usually about 85°F with extreme temperatures seldom reaching 95°F. Hot and humid conditions, with temperatures exceeding 100°F and relative humidity over 75%, rarely ever occur and are seasonal in a few earthly locations.

Especially in the equatorial zone, the humdity and rainfall are high during most of the year. The air is moist and the ground damp. Clouds and water vapor in the air tend to filter a much larger portion of solar radiation than in the hot dry regions. (Fig. 7)

The incidence of rain is very regular, usually occuring in the afternoon. Near the equator the variation of climatic factors is minimal, unless local topography such as relation of mountains to winds introduces seasonal variation. Precipitation is of a convective nature, caused when the air brought in by the trade winds converges from the north and south hemispheres onto the euqatorial zone. Rising at the intertropical fronts it expands and cools at the same time. These rains are accompanied by violent electrical storms.

Around the equator there is no real winter season as far as temperatures are concerned. Along the coast, the constant heating and cooling patterns of land and sea create regular land and sea breezes. Further away from the equator, the annual movement of the sun and seasonal winds introduce variation, so that unlike the equator, typically warm humid conditons are limited to a particular period of the year. Rainfall is produced by the trade winds, becoming moist when passing over the ocean and giving their moistures as they pass over land. Hurricanes are frequent in these areas.

The conversion of radiant energy to latent heat containing water vapour is great in the warm humid climates and the surplus energy from the surface is removed by the ascendance of water vapour. Moisture combined with solar radiation and the warmth, encourages the growth of vegetation. The ground being damp and covered by vegetation tends to have a low reflectivity. The relative humidity is frequently 90% and above with vapour pressures of 22 mm or more.

The high tempeature and humidity levels encourage the breeding of insects and the growth of fungi. Termites flourish below the ground or in mud castles above the ground.

Islands located in warm-humid regions are blessed with cooling, moisture-laden, prevailing breezes. These breezes are more consistent and of higher velocity than coastal plains, resulting in increased comfort conditions. Highlands within these regions experience increased rainfall; more rain and cooler temperatures. Temperate humid conditions will prevail at high elevations.

Comfort Requirements

Since climate conditions in warm humid regions are fairly uniform throughout the year, the requirements to achieve comfort are seasonally similar. The human body is remarkably capable of adapting itself to increases in temperature through various cooling devices and adjustments. It is the combination of high humidity and high temperature that leads to the feeling of discomfort.

The predominance of high humidity requires a correspondingly high air velocity to increase the efficinecy of sweat evaporation (evaporative cooling) and to avoid, as far as possible, the discomfort due to moisture on the skin and clothes. Thus, continuous ventilation is required over the skin and this becomes the primary comfort requirement. It effects all aspects of building design like building orientation, size and location of openings etc. Ventilation should ensure a sweat evaporation rate, sufficient not only to maintain thermal equilibrium, but also to enable the evaporation on the skin, so that there is no discomfort due to the feeling of wetness or claminess.

Psychological effects of high heat and humidity are important considerations in design.

The building envelope should offer protection from the intense solar radiation, as well as from the diffuse radiation reflected from overcast skies. It must also offer protection from torrential rains, as well as from the considerable spray that arises out of the lashing of rain on vertical and horizontal surfaces.

With free ventilation, the indoor temperatures would closely follow the outdoor temperatures. However, with a drop in wind speed, the internal surface may rise considerably above the outdoors in a badly designed building, in which case air movement would have to be created through fans, etc.

Clothing should be absorbent and loose, with a minimum of skin coverage. Constricting items, such as neckties and garters, should be avoided as they restrict capilliary blood and air circulation. They also provide sites for fungus infection.

The growth of fungus, moulds on food, paper, clothing, wood, etc., also contribute towards general discomfort and adequate precautions must be taken to protect various articles.

Building Design in Warm Humid Regions

Building design in warm humid regions should provide continuous and efficient ventilation, offer proteciton from sun, rain and insects, prevent internal temperature rise during the day and keep evening and night tempeatures to a minimum. All occupied areas of the building should have adequate openings on both the windward and leeward sides, in order to facilitate adequate cross ventilation.

Buildings should be oriented to preferably face the desirable wind direction. In this the site contours, location of surrounding structures, position of vegetation masses, etc., should be carefully studied. It is the communication between opposite pressure (windward +ve, leeward -ve) that ensures air movement, and not merely the size or nature of openings although these are contributory factors.

In general, open planning and wide free spaces between buildings, help to achieve good ventilation. Provision of outlets larger than inlets helps in achieving an increased air velocity through a room. Raising the building on stilts would also protect the living area from possible floods and to some extent from termite attack. Openings like doors, windows, etc., should be as large as possible not only to provide adequate ventilation but also to enable cooling of the interior at night. These openings must of course be protected from sun, rain, insects and provide security. Louvres and jalousies provide controllable openings, as long as they fit well and there is someone to oeprate them. Blinds, which can be rolled, made of split bamboo, reeds, etc., can be used to advantage especially in verandahs and balconies.

It is particularly important to have openings as close as possible to the occupied zone. In bedrooms, window sills should be close to the height of beds, to ensure an adequate airflow around the occupant's sleeping area. At these times when the outdoor windspeed is very slow, louvres, horizontally pivoted windows, etc., should be adjustable so as to direct the airflow downwards on the occupants when open. Hollow block walls, or breathing walls, could be used in order to protect semi-outdoor areas from rain, sun, glare, etc. These walls not only afford visual privacy but cast patterns of sunlight on the floor or walls and create visual interest. Large sliding walls or doors could be used. These could have adjustable louvres, incorporated in them. These sliding walls could be kept open most of the time but closed during sotrms. The use of adjustable screens, mesh, louvres, grills, glass, etc., may provide good control of conflicting requirements for ventilation, alternating with wind and rain protection during storms. The achievement of flexibility and versatility in terms of the quality and size of openings should be aimed at.

It is necessary to shade the large area of openings that are required in a warm humid climate. Shade is required not only against direct solar radiation, but also against diffused radiation from the sky, which in tropical regions reach very high intensities. Elements such as roof and walls should also, as far as possible, be protected from the radiation effect, direct as well as diffused.

Trees, which are usually abundant in the warm humid regions can be utilized to shade the roof, walls and the surrounding ground. Vines and creepers could be used on pergolas and vertical trellis works. Due consideration should be given in selecting trees and vines to such factors as appearance, transpiration rate, fruit, flowers, leaves, the falling of leaves and branches, harbourage given to pests such as sandflies, bats and insects, the access offered to unwelcome animal or human visitors, the species of birds attracted by the tree, etc. Vegetation should also be used as ground cover to take advantage of the reduction in ground reflection and thermal emission.

The proper use of the screening and shading effect of trees and shrubs, combined with attached wall shades can eliminate dependence on walls for radiation protection. Wall shades are especially important since they may substitute for walls proper. They may be provided as continuations of a roof, or of a floor slab as in balconies and verandahs; or as attachments to vertical supporting members, combined as rain protection over wall openings or incorporated in other architectural devices.

All shades should be provided with vents for the escape of trapped hot air. In multi-storied buildings, window overhangs tend to reflect an appreciable amount of solar radiation onto the walls and into the windows of upper floors. This can be prevented by inclining shading devices in such a way that they reflect the solar radiation outwards and away from the building. Shading devices should be free from the building, as far as possible, so that the heat that they gain from exposure to solar radiation is not conducted into the building. Also, care must be taken to see that these shading devices do not become, in their own turn, secondary sources of radiation. This is especially true of some concrete shading devices, which during the day absorb solar radiation and continue to re-radiate heat into the building long after the sun has set.

As in the hot arid regions, the strongest thermal impact occurs on the roof in warm humid climates. While the design emphasis is on providing good cross ventilation through the enclosing walls, it is vital to additionally provide a cool roof. (Fig. 7) Excessive heat is generated during the day (although lesser than in hot arid regions). The problem is one of reducing the penetration of heat into the interior and dispersing the accumulation of day heat, to prevent re-radiation at night.

A ventilated double roof is desirable. The top layer of the roof should be in a light reflective colour as it would intercept the sun and its heat from reaching the ceiling layer. The spaces between the two layers should be ventilated so as to cool the roof layers by conduction and also to convect away the build up of hot air. Double roofs must be adequately strengthened to ensure resitance to the upsurge of stormy winds. Roofs in general should be lightweight and reflective with low heat capacity. Thermal insulation either at ceiling level or beneath the upper roof layers is preferable.

An aluminum foil, placed beneath the roof to reduce radiant heat flow from roof to deiling, may be supplemented by an insulating layer above the ceiling and by ventilation of the attic space. With concrete roofs of higher heat capacity, an insulating layer placed below the ceiling is preferable in order to reduce heat flow during the day and permit a rapid lowering of ceiling temperature through ventilation at night. Roof projections are especially important in protecting the upper surfaces and tops of walls as in copings, parapets, etc.

Tropical rains can be sudden, heavy and wind borne and the almost horizontal wind driven rain tends to penetrate through joints and cracks. Unprotected walls tend to become saturated and the rapid succession of wetting and drying tends to disintegrate outer and badly weathered surfaces. The heaviness of the rains requires the provision for the disposal of the resultant large runoff. In storms, rain falls with such force and quantity, that it tends to splash the earth far up the walls leaving bands of earth coloration on the walls. This splashing also tends to loosen and carry away the earth around foundations. Soil erosion due to the unusually heavy rains is another factor which can be reduced by the judicious use of ground cover and by taking into account the site contours.

In places where there is no piped water and where water is scarce during the dry part of the year, rainwater from the roof may be used for washing, gardening, etc. Rainwater could be stored in surface or underground tanks, the air and water inlet and the overflow pipe need protection by gauze to prevent the entry of mosquitoes and other insects.

Every climate has its specific destructive atmospheric agencies. The main factors to be taken into account in the choice of materials for walls, doors, windows, etc., are the damp humid conditions, especially the alternating of wet and dry conditions, the likelihood of biological attack by insects, termites and fungoid growth and the photo-chemical action of strong solar radiation. For warm humid climates thermal resistor materials are preferred, since thermal-lag may cause undesirable night re-radiation of heat and morning condensation.

SUMMARY

The heat exchange system involved in design for warm humid regions may be analysed as follows:

- The building is heated during the day, only through the insulated envelope.
- The building interior is cooled convectively through openings, both day and night, by exterior air at temperatures below indoor levels.
- Between sunset and sunrise, the fabric and the building generally, is cooled by heat loss through long-wave infrared re-radiation to the atmosphere.
- Conducted heat loss from the building's fabric is accelerated by airflow across its surface, at all times.
- Extremely large amounts of latent heat loss is experienced after rainfall, from the building and its surroundings, resulting in cooler convective airflow.

TEMPERATE CLIMATES

Distribution and Characteristics

In general terms there are four temperate regimes to consider - (1) marine, (2) continental, (3) mountain (4) island. Their characteristics vary, however, some generalizations can be established, such as - (a) warm to hot summers and cool to cold winters, (b) high levels of solar radiation, especially in the summer, (c) seasonal precipitation which may be experienced as rain in the summer and rain, hail or snow in the winter, and (d) varying levels of humidity.

A characteristic of these climates is that they seldom achieve the extremes of heat, cold, humidity and aridity. Consequently, the techniques and appliances that may be employed to achieve comfort conditions may be simple and inexpensive. Adaptability in design is clearly indicated.

In temperate areas annual temperatures vary exceedingly, causing overheating in summer (with a consequential need for shading and cooling), to underheating in winter (resulting in a need for solar exposure and heating). Spring and fall, generally representing half the year, exhibit average temperatures with no need for heating or cooling in well designed buildings. Greenhouses, particularly in dry regions, will minimize the need for heating, thereby shortening the months of winter thermal discomfort. Thermal flow, in or out of buildings, can be manipulated with judicious use of thermal capacitor and resistor materials in varying combinations of permanence and movability, to heat or cool the buildings' fabric and interior as desired. In this way mechanical equipment and auxiliary energy needs are reduced. Human comfort in buildings is effected in three ways:

1.) Heating or cooling of the enclosing fabric,
2.) Heating or cooling of the interior space,
3.) Heating or cooling of human skin.

The factors that effect the above are:

a.) level of exposure to solar and thermal radiation,
b.) ambient and interior air temperature,
c.) ambient and interior vapor pressure,
d.) air movement to accelerate heat flow in the direction it is already taking place through convection.

How these factors combine conjointly to dictate human and building comfort in the four principal climate regimes in temperate areas is discussed below.

TEMPERATE MARINE CLIMATES

These are to be found near large bodies of water, such as the sea or large lakes. Characteristic temperatures range from summer 85°F (day) to 70°F (night) and winter 65°F (day) to 35°F (night). The diurnal range varies between 7°F to 15°F and the vapor pressure is high in summer - 20 to 22 mm Hg.

Wind directions will vary according to location, but are relatively low 6-10 ft/sec during the day, dropping even lower at night. The amount of precipitation increases northward as a function of latitude. Rains are periodic and of high intensity.

Comfort Requirements

As these climates are on the whole unacceptably humid, ventilation control is a prime consideration. The provision of air movement in buildings is for (a) hygienic purposes and (b) thermal comfort needs. While air exchange for hygienic purposes is germane to all buildings in all regions, the question of air movement for thermal comfort needs to be treated with caution. In summer, moist skin will be the principal cause for discomfort, demanding cross ventilation or mechanical cooling, whereas in winter or even spring and fall this cross ventilation will be undesirable. All efforts to avoid overheating in summer and underheating in winter msut be made, with flexibility during transition periods to achieve desired results. As wind velocity drops at night, the rapid cooling of the interior is necessary during the summer, since vapor pressure will increase. It is important to prevent the temperature of building interior surfaces rising above ambient outdoor temperatures in summer, while in winter these temperatures should be kept at 70°F, more or less.

Simple "natural" heating supplemented with inexpensive auxiliary systems will suffice for comfort.

Building Design

Main considerations can be enumerated as follows:

- Summer - cross ventilation at appropriate levels to assure the main airflow over human skin for evaporative cooling. Air cooling of the building's interior space and structure. Protection of the building's interior space and external surfaces from undesirable solar and thermal radiation exposure. Provision, in appropriate locations around building, of combinations of shade trees, ground cover and shrubs to protect the building from the sun and allow desirable air movement. The higher a building's elevation, the faster the airflow. Exposed surfaces receiving sunlight should be light colored, preferable white for reflection. Care should be taken in areas receiving summer rain to provide protection while permitting desirable prevailing winds and local breezes. Orientation and shape of the building must respond to wind direction (desirable) and sun angles (undesirable). The building fabric should be well ventilated, particularly roofs, while openings should be large and protected from the sun. Balconies, porches and verandahs are useful to protect the building's interior and provide protected exterior living. Strategically locate thermal resistor materials.

- Winter - cross ventilation is undesirable at this time. As the wind direction normally changes with season, care should be taken to plant combinations of trees and shrubs as wind screens, provided this does not interfere with desirable solar gains. Solar and thermal radiation must be encouraged to warm the building fabric and interior space, so seasonally exposed areas should be colored dark to encourage absorption. The greeenhouse effect through glazed openings is to be encouraged and the integration of glass houses into buildings is recommended for the provision of additional warmth. Thermal capacitor materials, in selected areas of the building fabric, can effectively assist in the storage and transfer of desirable heat. The capture and conservation of exogenous and endogenous energies is the key to the winter energy budget. Orientation and building shape are crucial to building energy optimization for solar gain and protection from undesirable prevailing and local winds. Air sealing of the building fabric is essential.

- Transitional spring and fall periods - seasons for building component flexibility to control solar and thermal gains and losses and varying degrees of ventilation and cross ventilation. The greenhouse is an important contributor to 'shorten' the winter period and provide desirable living areas. Human comfort in buildings is easily regulated by alternate opening and closing of doors and windows. It is important to control and exhaust interior-made heat as needed.

TEMPERATE CONTINENTAL CLIMATES

Although by definition these are inland climates, they may be found at relatively short distances from major bodies of water, including the sea. Characteristic temperatures range from summer 110°F (day) to 70°F (night) and winter 60°F to 30°F, the diurnal range varies between 15°F to 30°F and the vapor pressure is moderately low averaging 15 mm Hg, with variable relative humidity 20% to 50%. While winter temperatures are usually above freezing, temperatures below freezing frequently occur. Winds, accompanied by occasional dust storms, may be strong in the afternoons. Average rainfall is small, but variable.

Comfort Requirements

Provided indoor temperatures do not exceed 76°F, thermal comfort can be achieved without cross ventilation. Due to the dry atmosphere, cross ventilation is not needed to dry the skin to provide evaporative cooling as a result of a sufficient vapor pressure difference between the skin's surface and the air in contact with it. On the contrary, cross ventilation poses a danger when ambient air temperatures fall below 65°F (too cool) or rise above skin temperature - 92°/93°F (too warm). While over half the year presents pleasant comfort conditions, the two extremes of hot and cold will need building design techniques to ammeliorate the feeling of discomfort. In most cases the overheated summer conditions are brought into the comfort range through evaporative cooling procedures, little else is needed. Underheated winter conditions can have sufficient warmth added through direct and indirect solar gain, because of clear atmospheres and a high incident of solar radiation. Dust near ground level is likely to be a nuisance and the need to seal openings is symbiotic with the desire to prevent cross ventilation. Additionally, vegetation in the building's vicinity will reduce the quantity of dust, which diminishes as a function of height. Over 30 feet the dust problem generally becomes insignificant.

Building Design

Main considerations can be enumerated as follows:

- Summer - In these areas compact forms reduce heat gain through walls in summer and combat undesirable cross ventilation. Night radiation plays an important role in the cooling of the building fabric and particularly the interior surfaces during the summer, when the diurnal difference may average 30°F. To facilitate interior cooling at night, ventilation of enclosed space is essential during the overheated period. Correct orientation and shape make notable contributions to heat gains and losses of the building. It is important to keep the building surface and hence the fabric from overheating, at this time, in an uncontrolled manner. A light surface color, preferably white, will reflect considerable quantities of solar radiation, while in these circumstances water spray of roofs, walls and site are found to produce very effective evaporative cooling. Patio houses provide excellent outdoor living during dry periods and the use of pergolas and trellises are effective shading devices. All surfaces which may encounter sunlight should be properly protected. Air cooling of the building fabric is essential.

- Winter - Through openings and parts of the building that intersect winter sun, direct and indirect solar gain is desirable. Thermal capacitor materials, with acceptable time-lag, should be judiciously employed. Thermal resistor materials can appropriately be used to conserve daily collected ambient and interior energies in a diurnal cycle. Greenhouses in these regions provide a much welcome winter warmth and reduce the quantity of auxiliary energy needed. Generally, this auxiliary energy may be supplied through the simplest means for effective comfort attainment. Air sealing of the building fabric is essential.

- Transitional spring and fall periods - Greenhouses are gainfully employed to diminish the winter period by providing additional warmth in confined glazed areas. Pools of water in these glass houses assist in raising the relative humidity to desirable levels. These greenhouses may additionally generate a low grade of summer cooling. Flexibility in the manipulation of thermal resistor materials will further assist in the provision of heating and/or cooling as desired.

In this climate detailed building design and careful selection of materials with appropriate construction methods will determine if, and to what extent mechanical heating and/or cooling is required. Generally large openings are not needed, as cross ventilation is undesirable and these openings will be used for the provision of solar gain, daylight, night radiation, night ventilation and visual purposes only.

TEMPERATE MOUNTAIN CLIMATES

These are distinguished from the two former by having temperate summers and colder winters, so that the winter aspects dominate. Monthly winter temperatures may average 35°F with nightly temperatures continually below freezing. Summer averages may be 70°F to 80°F (day) with night temperatures dropping to 55°F to 70°F. Vapor pressures are higher than the continental climates and lower than the marine climates varying from 5 mm Hg to 15 mm Hg, depending on location and season. Precipitation may be heavy and experienced as either rain or snow, accompanied by strong winds - especially in valleys.

Comfort Requirements

In the summer months unnecessary overheating of buildings should be avoided as ambient conditions are mainly in the human comfort range. In the winter, the main concern is the provision of sufficient heat for comfort and warmth. Due to possible heavy precipitation, problems of condensation deserve attention in design detial and materials choice. In the humid mountain areas dehumidification of interior spaces is desirable. The four seasons are more discernable than in the other temperate climates.

Building Design

Main considerations can be enumerated as follows:

- Summer - Site location in valleys, north or south facing leeward or windward slope, will determine design strategies. Building materials, design details, orientation and shape will assist in providing the desired level of ambient energy utilization in a climate period that needs little assistance through sensitive handling. South-facing hillside terraces need careful treatment to avoid overheating. Judicious planting of deciduous trees and shrubs will contribute to success. Controlled release of interior-made heat is essential.

- Winter - As above, site location largely determines strategies. A major problem is caused by condensation, but this may be solved by correct construction methods and selection of contributing materials. Employment of a greenhouse will greatly assist much needed warmth. Building materials should be dark in color and of rough texture to maximize solar gain. Thermal capacitor materials should be used internally to assist in flattening the temperature curve and on the exterior where solar gain is achievable Elsewhere resistor materials should be used on the exterior face of walls to resist outward thermal flow. Operable resistor panels can be employed in heat gain areas to assist in conserving energy. Internally-made heat is an important source of energy for storage and use in these climates. Landscape planting of evergreen trees and shrubs must be located as wind barriers of undesirable winds. Double glazing of windows and doors is necessary. Air sealing of building fabric is essential.

- Transitional spring and fall periods - As seasons are most pronounced in these climates and summers are temperate, assistance for the capture and retention of natural warmth is imperative. At this time auxiliary energies need not be employed in well-designed buildings that use materials appropriately. Greenhouses will most often be used at this time as a living area. While they must be located to gain solar energy they msut also be protected form chilling breezes. Combinations of deciduous and evergreen trees and shrubs planted for other periods must carefully provide for the needs of this period.

TEMPERATE ISLAND CLIMATES

Islands within temperate zones experience climate modification of seasonal extremes, with accelerated and reliable, moisture-laden prevailing winds, which will improve comfort conditions, in both arid and humid situations. Clearer atmospheres experienced, will increased radiation gains and losses. Consequently, cooling needs in summer are not as great as the coastal and continental locations. Problem solutions, discussed above, should be modified to accommodate these variations. Natural solutions will suffice in well designed buildings.

SUMMARY

The heat exchange system involved in design for temperate regions may be analysed as follows:

- The building is heated, during the summer, from sunrise to sunset. In winter the heat loss, may exceed heat gain, over the same period.
- In summer, interior-made heat must be exhausted. In winter, interior-made heat must be conserved.
- In summer, at all times, the building's interior is cooled convectively through openings, by exterior air at temperatures below indoor levels.
- Between sunset and sunrise, the fabric and the building generally is cooled by heat loss through long-wave infrared re-radiation to the atmosphere.
- Conducted heat loss from the building's fabric is accelerated by airflow across its surface, at all times.
- Precipitation (rain or moderate snow) radically effects the latent heat exchange from the building and its surroundings, thereby adjusting the micro-climate.

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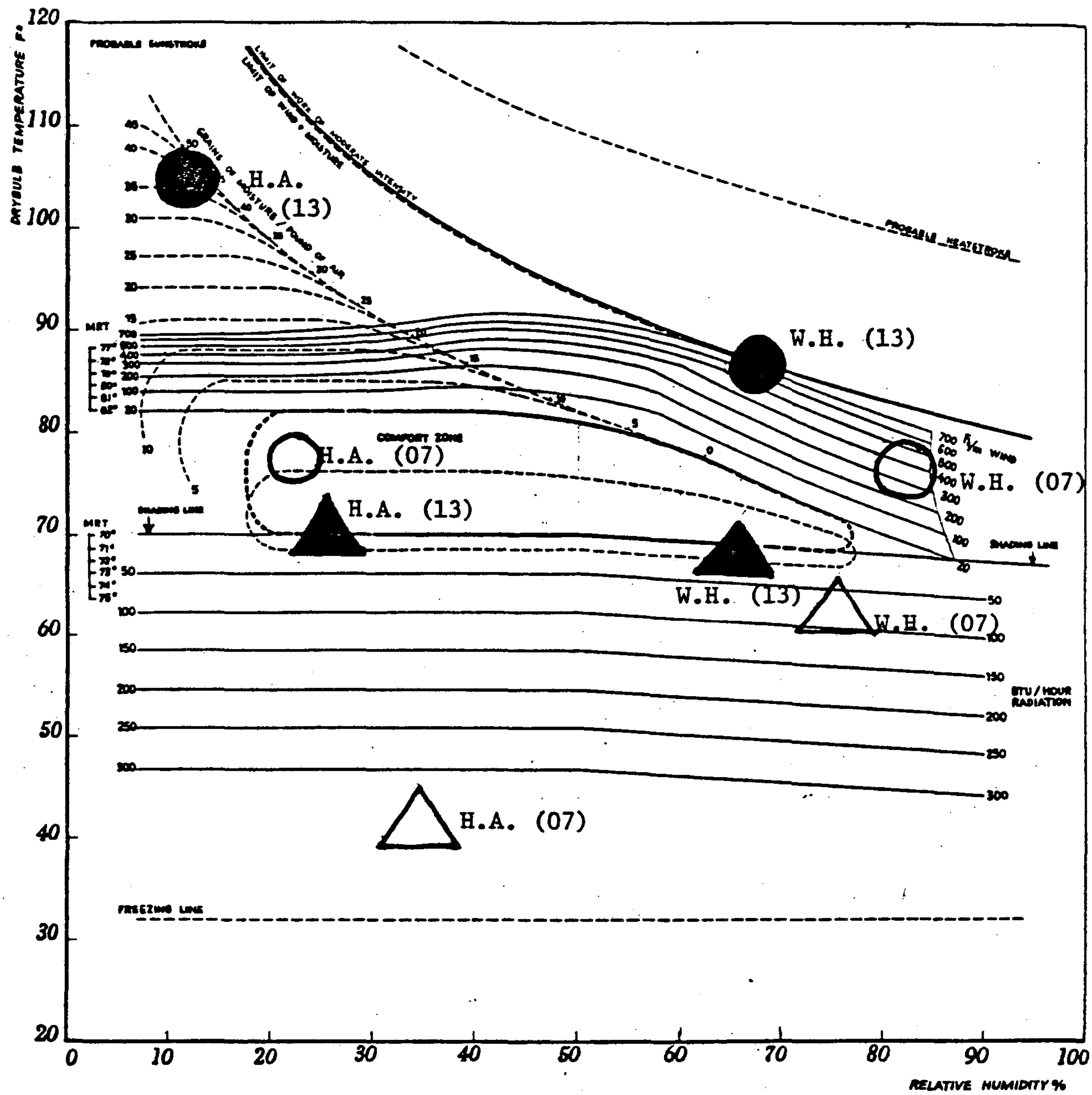


Fig. 1 - Overheated Arid and Humid Schematic

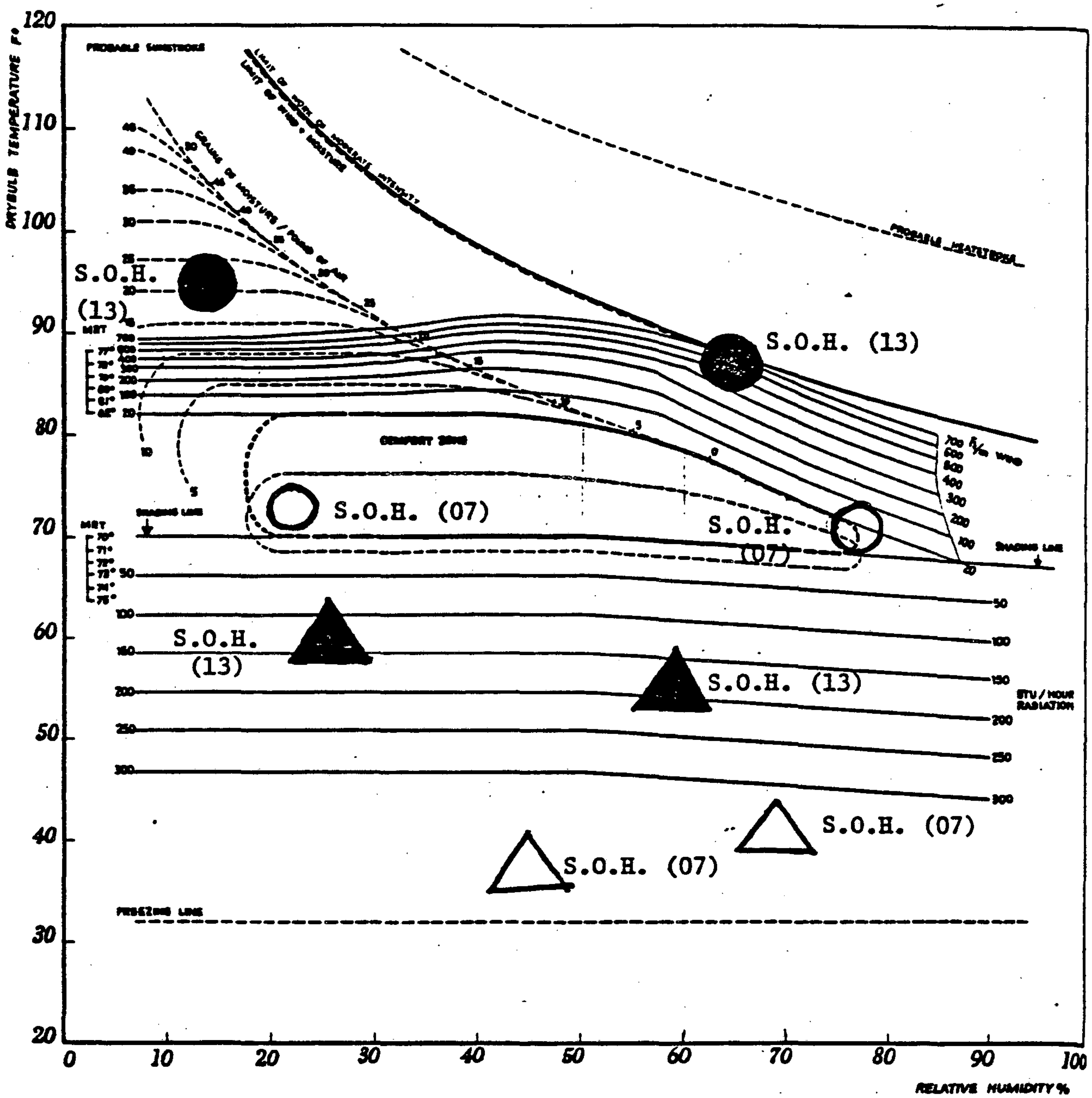
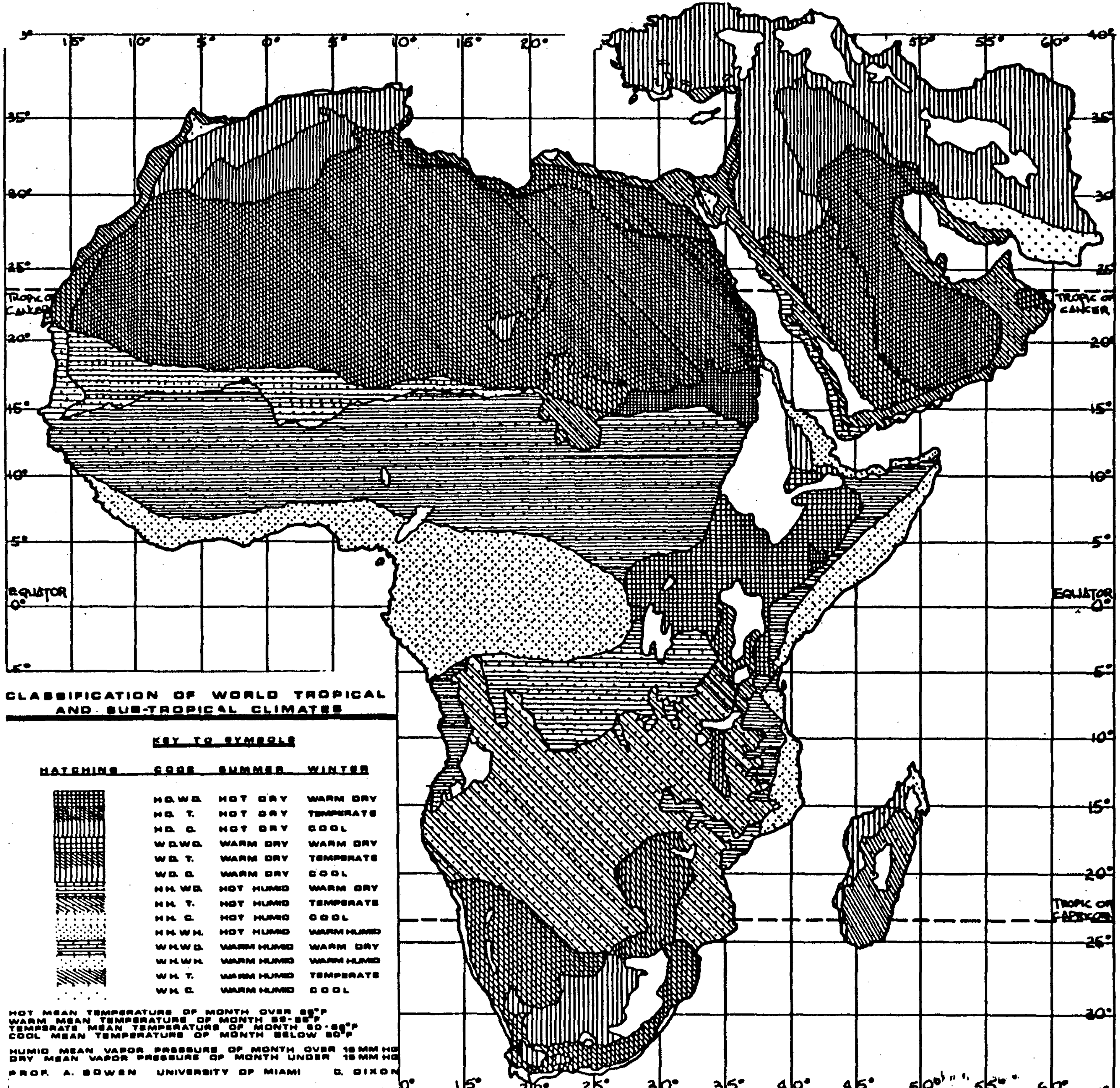
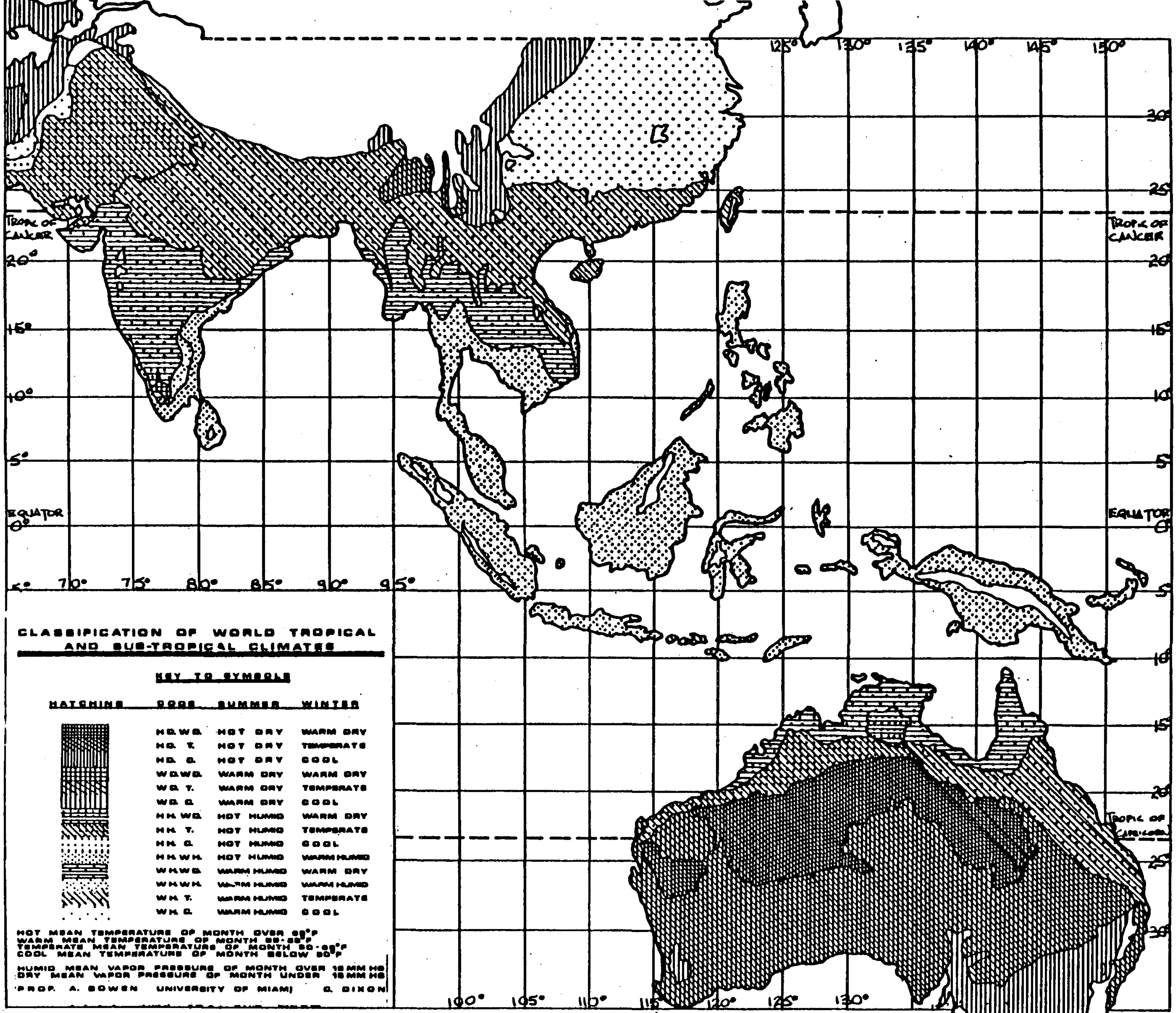


Fig. 2 - Seasonally Overheated Arid and Humid Schematic


CLASSIFICATION OF WORLD TROPICAL AND SUB-TROPICAL CLIMATES
KEY TO SYMBOLS
HATCHING CODE SUMMER WINTER
H.D.W.D. HOT DRY WARM DRY
H.D. T. HOT DRY TEMPERATE
H.D. C. HOT DRY COOL
W.D.W.D. WARM DRY WARM DRY
W.D. T. WARM DRY TEMPERATE
W.D. C. WARM DRY COOL
H.H.W.D. HOT HUMID WARM DRY
H.H. T. HOT HUMID TEMPERATE
H.H. C. HOT HUMID COOL
H.H.W.H. HOT HUMID WARM HUMID
W.H.W.D. WARM HUMID WARM DRY
W.H.W.H. WARM HUMID WARM HUMID
W.H. T. WARM HUMID TEMPERATE
W.H. C. WARM HUMID COOL
HUMID MEAN VAPOR PRESSURE OF MONTH OVER
DRY MEAN VAPOR PRESSURE OF MONTH UNDER 15 MM HG
PROF. A. BOWEN UNIVERSITY OF MIAMI D. DIXON
TROPIC OF CANCER
EQUATOR
TROPIC OF CAPRICORN
Fig. 3


CLASSIFICATION OF WORLD TROPICAL AND SUB-TROPICAL CLIMATES
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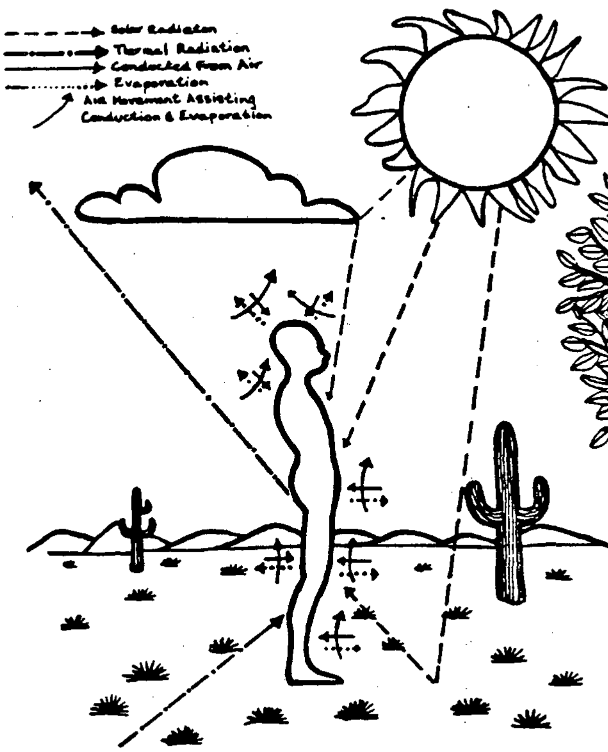

Fig. 6a - Heat exchange in hot dry environments. - Note the strong incidence of solar radiation, the gain of long infrared from the hot ground, & the loss of infrared to clear sky. Some heat is gained by conduction, but much is lost by evaporation; both process being somewhat accelerated by air movement.

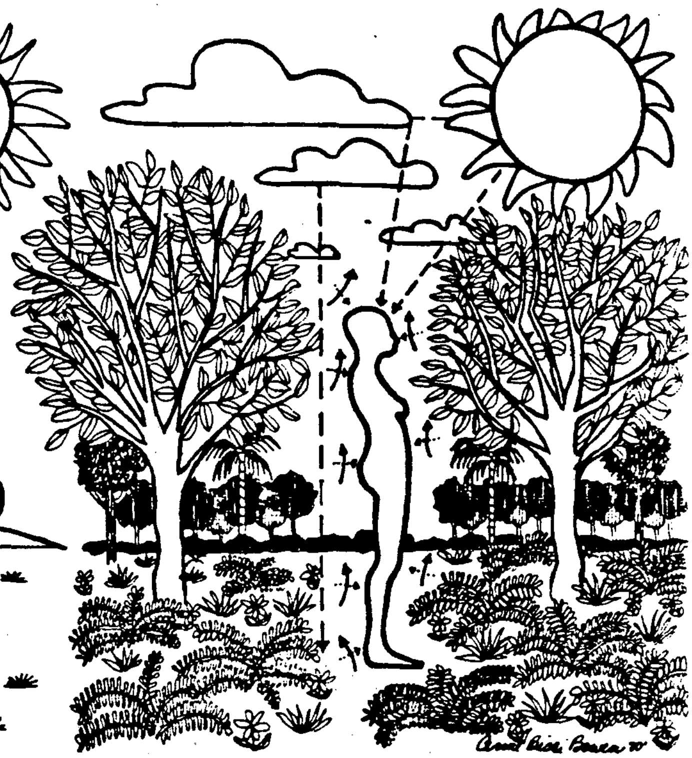

Fig. 6b - Heat exchange in warm humid environments. - Note the intermittent incidence of direct solar radiation, & the absence of reflection from the ground or 'sky'. There is virtually no heat exchange by conduction. Heat loss by evaporation is difficult, but very much accelerated by air movement.

LEGEND

① Horizontal
② North
③ South
④ East & West
⑤ Northeast & Northwest
⑥ Southeast & Southwest

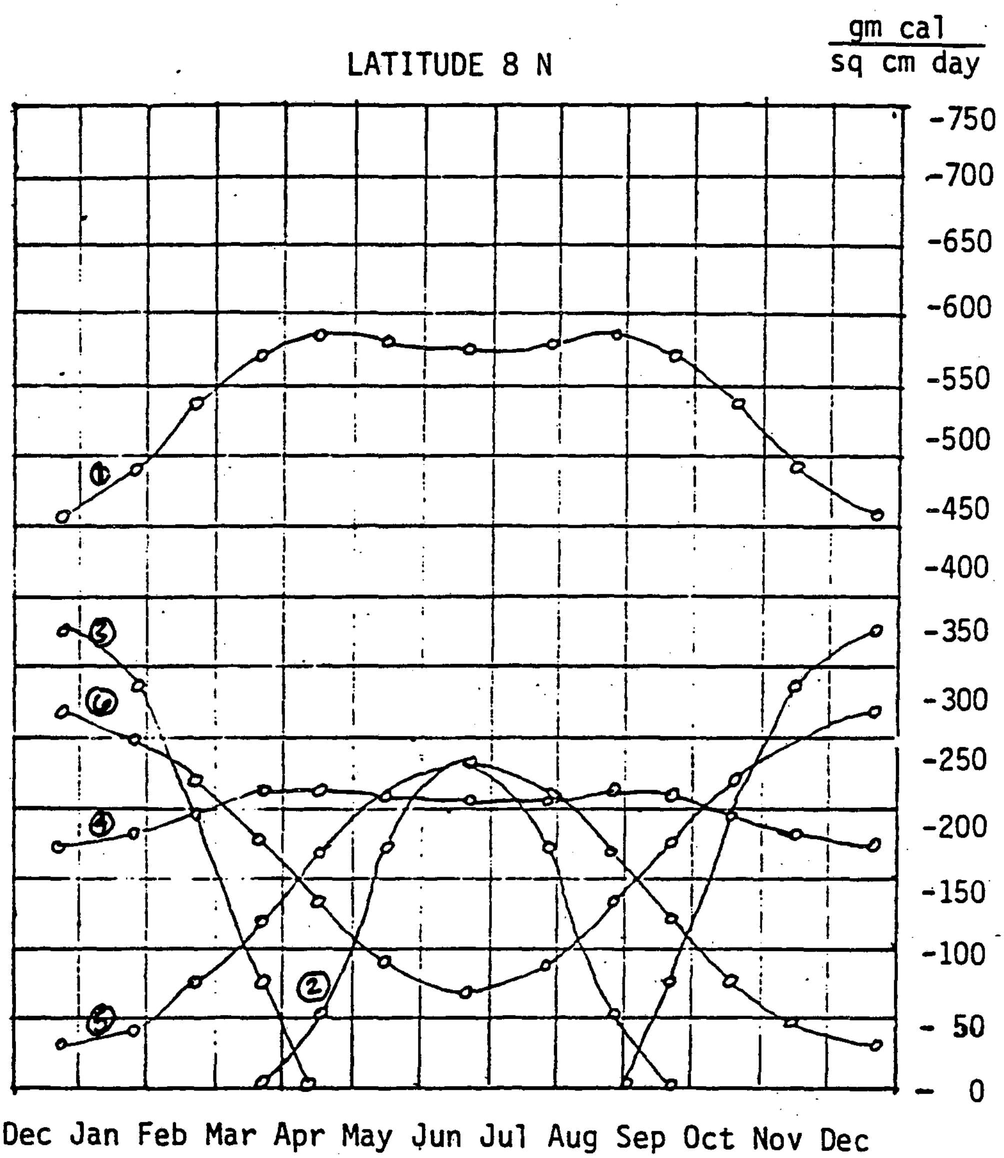

Fig. 7a - Direct solar radiation incident upon variously oriented vertical surfaces and a horizontal surface on clear days. A compilation of daily totals throughout the duration of one year.

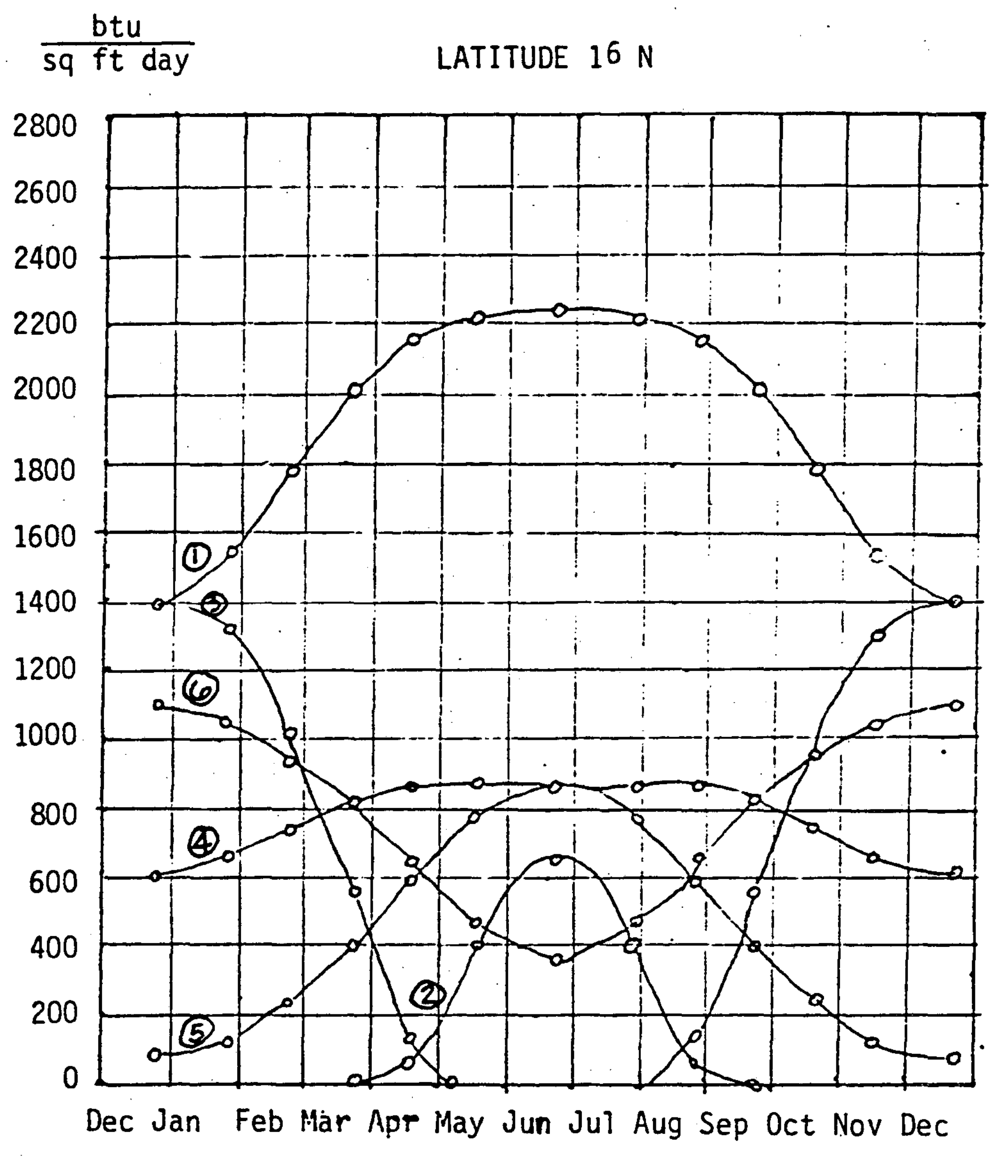

Fig. 7b - Direct solar radiation incident upon variously oriented vertical surfaces and a horizontal surface on clear days. A compilation of daily totals throughout the duration of one year. See legend with Fig. 7a.

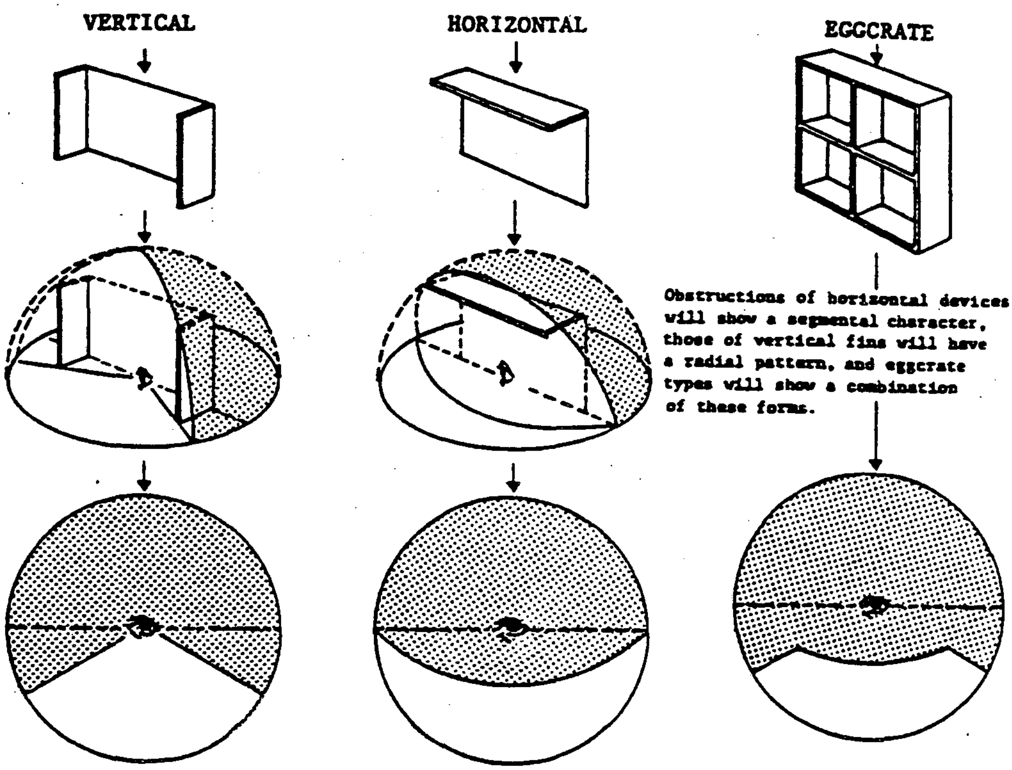

Fig. 8 - Three general types of shading devices (Olgyay)

TABLE 1. IMPORTANT CHARACTERISTICS OF HOT DRY CLIMATES

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.

TABLE 2. SUMMARY OF PRINCIPLES FOR HOT DRY ENVIRONMENTS AND IMPORTANT APPLICATIONS

Principles	Important Applications
REDUCING HUMAN HEAT PRODUCTION	
o Convenience of arrangement	o Convenient storage space Convenient plan and conservation of floor space Convenient facilities
o Ease of cleaning	o Easily cleaned surfaces
REDUCING GAIN & PROMOTING LOSSES FROM BODY BY RADIATION	
o External shade o Reduced ground reflection o Attached shade o Water cooling of exterior o Minimal solar projection o High reflectivity & remission of exterior o Convection over surfaces exposed to radiation o Insulation (capacity type) o Convection over inner surfaces o Low emissivity of inner surfaces o Moderate ceiling height	o Shade trees where possible, especially to roof o Shade bushes where possible, especial to east and west exposures o Contiguous building in east-west rows or consolidated o Non-inhabited wings to east and west exposures to provide shade o Vegetation over ground where possible o Dark color for ground exposed to sun o Eaves & other horizontal projections on equatorial exposures o Awnings, external shades, shutters, etc., especially on equatorial exposures o Vertical projections beside window openings on equatorial exposures o Water spraying of roof and walls exposed to radiant load o Water layer on flat roof o North-facing slab or tall square shape for inhabited building o Light color for surfaces exposed to solar radiation o Avoid parapets & mutual interference of roof structures to wind o Wood, earth, stone, or other materials of low diffusivity for roof o Ceiling height generally over 8 feet

TABLE 2. SUMMARY OF PRINCIPLES FOR HOT DRY ENVIRONMENTS AND IMPORTANT APPLICATIONS CONTINUED

Principles	Important Applications
REDUCING GAIN AND PROMOTING LOSSES FROM BODY BY CONDUCTION	
o Insulation o Controlled ventilation o Ventilation of roof spaces o Ground cooling o Evaporative cooling o Refrigerant cooling	o Continuous walls, with capacity insulation where exposed to radiant load o Doors, windows, etc., fashioned for both tight closing and easy opening o Ventilation of roof space and spaces between successive roof layers o Water blinds, or box coolers with fans. o Air intake through earth tunnels o Basement construction o Air conditioning by refrigeration
REDUCING HEAT LIBERATION IN BUILDING	
o Minimize heat liberation o Remove liberated heat	o Capacity insulation around oven and firebox o Narrow air space lined with aluminum foil in oven wall o Liquid or gas fuel, or power where economically feasible o Vent to outside over stove o Vents and infrared screens for lamp

TABLE 3. 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 ex - change 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.

TABLE 4. SUMMARY OF PRINCIPLES FOR WARM HUMID ENVIRONMENTS AND IMPORTANT APPLICATIONS

Principles	Important Applications
REDUCING HUMAN HEAT PRODUCTION	
o Convenience of arrangement o Ease of cleaning	o Convenient storage space o Convenient plan and conservation of floor space o Convenient facilities o Easily cleaned surfaces, especially floor
REDUCING GAIN AND PROMOTING LOSSES FROM BODY BY RADIATION	
o External shade o Reduced ground reflection o Attached shade o Water cooling of exterior o Minimal solar projection o High reflectivity of exterior o Convection over surfaces exposed to radiation o Insulation (capacity type) to roof o Convection over inner surfaces o Low emissivity of inner surfaces o Moderate ceiling height	o Shade trees, especially to roof o Shade buses etc.,especially to east and west exposures, but without obstructing wind o Separation of buildings o Vegetation over ground o Eaves and other horizontal projections on equatorial exposures o Awnings, verandahs, etc., especially on equatorial exposures o Vertical projections beside window openings on equatorial exposure o Water spraying or water layer on roof in dry weather o Minimum solar projection of roof o Light color or polished metal for surfaces exposed to solar radiation o Avoid parapets and mutual interference of roof structures to wind
PROMOTING LOSSES FROM BODY BY EVAPORATION	
o Ventilation (volume flow) o Air movement (velocity of flow) o Dehumidification	o Wood, stone, or other material of low diffusivity for roof o Ceiling height generally not over 8 feet o Maximum wall openings for breeze, with blinds, louvres, etc., against rain o Cross ventilation directed and without obstruction o Ventilation of roof space & spaces between successive roofing layers

TABLE 4. SUMMARY OF PRINCIPLES FOR WARM HUMID ENVIORNMENTS AND IMPORTANT APPLICATIONS CONTINUED

Principles	Important Applications
	o Turbulence-producing fans o Dehumidification by refrigeration or absorption
REDUCING HEAT LIBERATION IN BUILDING	
o Minimize heat and vapor liberation o Remove liberated heat and vapor	o Capacity insulation around oven and firebox o Narrow air space lined with aluminum foil in oven wall o Liquid or gas fuel, or power, where economically feasible o Vent to outside over stove o Vents and infrared screens for lamps

TABLE 5. IMPORTANT CHARACTERISTICS OF TEMPERATE ARID CLIMATES

Item	Magnitude	Effect on Human Heat Balance
o Direct solar radiation	o Moderate to high	o Acceptable addition to heat gains
o Solar radiation reflected from clouds, etc.	o Little	o Some addition to heat gains
o Solar radiation reflected from ground, etc.	o Moderate	o Moderate addition to heat gains
o Thermal radiation exchange with ground, etc.	o Moderate	o Moderate addition to heat gains
o Air temperature	o Often below skin temperature	o May represent moderate heat loss
o Air vapor pressure	o Below average	o Channel for moderate heat loss
o Air movement	o Moderate	o Pleasant. Little effect
o Thermal radiation loss to 'sky'	o High	o Significant for cooling

TABLE 6. SUMMARY OF DESIGN PRINCIPLES FOR TEMPERATE ARID ENVIRONMENTS AND IMPORTANT APPLICATIONS

Principles	Important Applications
REDUCING HUMAN HEAT GAIN	
o Convenient arrangements	o Convenient storage space, facilities and plan o Conservation of floor space. Convenient operation of manual controls
o Cleaning ease	o Easily cleaned surfaces. Dust abatement techniques in surrounding site. No dust shelves. Sprinkle building site with water.
REDUCING GAIN AND PROMOTING LOSSES FROM BODY BY RADIATION	
o External shade	o Deciduous trees and shrubs. Strategically located pergolas and trellises with deciduous vines. Earth berms.
o Attached shade	o Porches, verandahs, balconies, shading devices.
o Reduced ground reflection	o Subdued colors. Vegetation over ground. Rough surfaces.
o Water cooling of exterior	o Wetting of planted and hard areas. Use of pools, fountains, streams, etc.
o Solar gain	o Provide full shade in summer. Part shade in fall and spring. Exposure in winter. Resistor insulation strategically located.
REDUCING GAIN AND PROMOTING LOSSES FROM BODY BY RADIATION	
o High reflectivity and remission of exterior	o Building envelope should use materials, on outer skin, possessing high emmission and reflection characteristics
o Convection over surfaces exposed to radiation	o Double skin vented walls and roofs with effective operable inlets and outlets
o Resistor insulation	o Use materials possessing poor conduction characteristics on exposed outer skin

TABLE 6. SUMMRY OF DESIGN PRINCIPLES FOR TEMPERATE ARID ENVIRONMENTS AND IMPORTANT APPLICATIONS CONTINUED

Principles	Important Applications
o Thermal mass material	o May be used internally as 'cold sink', or in sufficient thickness on exterior walls and roofs to counter daily thermal transmission
o Convection over inner surfaces	o Airflow promotes heat loss, seasonally.
o Emission of inner surfaces	o High absorption and low emission materials and surface promote cooling and very effective when arid.
o Ceiling height	o May be 8 feet when internal heat exhaustion has been contrived in a separate system. Otherwise, ceilings should exceed 9 feet in domestic buildings
SITE CONTROL	
o Orientation	o Shade during overheated period. Sun exposure during underheated period. Protect from cold and hot winds. Promote seasonal cooling breezes.
o Landscape strategy	o Earth berming and sod roofs are effective. Water pools and fountains, greenhouses and atriums should be encouraged. Subdued materials to reduce summer glare and overheating.
REDUCING GAIN AND PROMOTING LOSSES FROM BODY BY CONDUCTION	
o Controlled ventilation	o Convective cooling of interior space in summer. Air sealing of interior space in winter. Availability of adjustable ventilation.
o Structure cooling and heating	o Summer shading, winter exposure. Adjustable ventilation of fabric for summer cooling and winter warmth.

TABLE 6. SUMMARY OF DESIGN PRINCIPLES FOR TEMPERATE ARID ENVIRONMENTS AND IMPORTANT APPLICATIONS CONTINUED

Principles	Important Applications
o Interior space cooling and heating	o All interior skins and surfaces, must be maintained at low temperatures in summer and high in winter
o Skin comfort by air flow	o Increase air velocity to drain away heat from hot surfaces in summer. The reverse for winter.
o Ground coupling	o Impressive year-round results to ammeliorate comfort extremes
o Evaporative cooling	o Very effective during overheated period. Simple measures - pools, fountains, etc. may suffice.
o Refrigerant cooling	o Only needed in extreme summer heat.
INTERIOR HEAT CONTROL	
o Minimize heat liberation	o During underheated period by closing all vents at low or high levels
o Remove liberated heat	o During <u>both</u> overheated and temperate conditions as needed, by adjustable vents. A matter of degree.
o Partial heat liberation	o By adjustable vents for daily and seasonal operations

TABLE 7. IMPORTANT CHARACTERISTICS OF TEMPERATE HUMID CLIMATES

Item	Magnitude	Effect on Human Heat Balance
o Direct solar radiation	o High to moderate, seasonal shade	o Acceptable addition to heat gains
o Solar radiation reflected from clouds, etc.	o Moderate	o Moderate addition to heat gains
o Solar radiation reflected from ground, etc.	o Little	o Little
o Thermal radiation exchange with ground, etc.	o Little	o Unimportant
o Thermal radiation loss to 'sky'	o Little	o Unimportant
o Air temperature	o Often below skin temperature	o May represent moderate heat loss
o Air vapor pressure	o Above average	o Moderate restriction of heat loss
o Air movement	o Moderate	o Little effect. Pleasant at low velocity

TABLE 8. SUMMARY OF PRINCIPLES FOR TEMPERATE HUMID ENVIRONMENTS AND IMPORTANT APPLICATIONS

Principles	Important Applications
REDUCING HUMAN HEAT GAIN	
o Convenient arrangement o Cleaning ease	o Convenient plan, facilities, storage space and operation of manual controls o Easily cleaned surfaces. No dust shelves. Dust abatement techniques surrounding site.
REDUCING GAIN AND PROMOTING LOSSES FROM BODY BY RADIATION	
o External shade	o As before, but no earth berms
o Attached shade	o As before, care should be taken to maintain airflow during overheated periods.
o Reduced ground reflection	o As for temperate arid. No water on east and west orientations.
o Water cooling of exterior	o Not crucial
o Solar gain	o As for temperate arid
o High reflectivity and remission of exterior	o As for temperate arid
o Convection over surfaces exposed to radiation	o Desirable in summer, but in winter.
REDUCING GAIN AND PROMOTING LOSSES FROM BODY BY RADIATION	
o Resistor insulation	o May be used on both skins of building envelope, but necessary on outer skin.
o Thermal mass material	o May be used internally as 'cold sink', or in inner skin of building envelope.
o Convection over inner surfaces	o Airflow will promote heat loss all year.
o Emission of inner surfaces	o High absorption and low emission materials and surfaces promote cooling
o Ceiling height	o As for temperate arid

TABLE 8. SUMMARY OF PRINCIPLES FOR TEMPERATE HUMID ENVIRONMENTS AND IMPORTANT APPLICATIONS CONTINUED

Principles	Important Applications
SITE CONTROL	
o Orientation	o Shade during overheated period. Sun exposure during underheated period. Seasonal cooling by prevailing wind of first importance
o Landscape strategy	o Deciduous trees and shrubs on solar gain orientations. Evergreen trees and shrubs to form winter wind barriers or directional cooling precision planting.
REDUCING GAIN AND PROMOTING LOSSES FROM BODY BY CONDUCTION	
o Controlled ventilation	o As for temperate arid, but vital to assure skin cooling during overheated conditions.
o Structure cooling and heating	o As for temperate arid. Also essential for fungus control.
o Interior space cooling and heating	o As for temperate arid.
o Skin comfort by airflow	o Essential year-round, except when ambient air temperatures fall below 72°F
o Ground coupling	o Poor results in summer. Otherwise good.
o Evaporative cooling	o Effective in reducing structure and ground temperatures, but limited attainment in air temperatures
o Refrigerant cooling	o Only needed in extreme summer heat and humidity.
INTERIOR HEAT CONTROL	
o Minimize heat liberation	o As for temperate arid
o Remove liberated heat	o As for temperate arid
o Partial heat liberation	o As for temperate arid

Passive and Hybrid Cooling Strategies in Hot/Arid Climates -- John Peck, Helen Kessler, Lewis Thompson

Seasonally Overheated Climates -- Karen Crowther

PASSIVE AND HYBRID COOLING STRATEGIES IN HOT/ARID CLIMATES

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ABSTRACT

Strategies for passive and hybrid cooling of buildings in hot, arid climates, including shading and heat rejection techniques as well as ventilative, evaporative, radiative and earth contact techniques, are discussed. Methods for combining these techniques and for enhancing comfort are described. A short discussion of the climate and comfort as related to various building types in the hot, arid region is also presented.

I. The Climate of the Region and Comfort

Climate

The hot, arid region is generally characterized by hot, dry and sunny days, with a significant drop in temperature at night. Thus the primary concern is to moderate the effect of the high daytime temperatures and high insolation, and take advantage of the cooler nighttime temperatures. In many areas of the region, seasonal rainfalls occur, which raise the humidity and add to the cooling problem. During the early part of the summer, hot, dry conditions prevail with maximum design dry bulb temperatures of 37 C to 44 C (99 F to 111 F), and coincident wet bulb temperatures between 18 C annd 22 C (65 F and 72 F). In mid-summer, dry bulb temperatures are not as high because of frequent thunderstorms which increase humidity. Clouds from these afternoon thundershowers may last well into the night, decreasing the nocturnal radiation. During much of the summer, average outside temperatures are above the comfort range. High diurnal temperature ranges, between 14 C and 17 C (25 F and 30 F), are characteristic of the region.

Conditions in Tucson are periodically representative of the climates in other areas of the region since the lower and higher temperatures experienced are often typical of other areas. Temperature peaks during June are often characteristic of normal Mojave Desert and lower Arizona and Nevada desert conditions, while cool periods are characteristic of higher elevations in the zone. During July and August, maximum humidity and temperature levels can be characteristic of Phoenix and other more humid locations. Peak dry bulb temperatures in the Mojave Desert in California and peak wet bulb temperatures in Yuma are higher than those in Tucson, but the low population in those areas makes them less significant at this time.

Winters in this region are generally mild. Average daily temperatures in January are about 10 C (50 F) (for Tucson), with winter lows between -4 C and

-1.5 C (25 F and 29 F). High solar intensity and low seasonal rainfall are characteristic of the entire region.

In Tucson, and other more populated areas of the region, the average wind speed is generally low, about 11 to 14.5 km/hr (7 to 9 mph). Since it ranges from a dead calm to 129 km/hr (80 mph), the wind is an unreliable source of ventilation.

Comfort

Victor Olgyay, in his book, Design with Climate, has devloped a "Bioclimatic Chart" which explains comfort as a function of wet and dry bulb temperatures, air motion, evaporation (adding moisture to the air), mean radiant temperature and solar radiation (for outdoor conditions) (1). Thus, if the combined temperature and humidity are out of the comfort range, the latter four variables can be used to create desirable conditions. There seems to be some doubt about the validity of the Olgyay Bioclimatic Chart. According to Givoni, this Bioclimatic chart does not take into account the internal conditions of a particular structure, but is based on external conditions (2). However, the variables which influence comfort remain the same.

Discomfort is generally felt more in low mass structures in this region since low mass surfaces may be heated and cooled rapidly. High daytime mean radiant temperatures due to warm walls and ceilings contribute to the uncomfortable conditions in an already warm environment. Cooling low mass structures by ventilation and evaporation is effective during dry weather. However, the rapid passage of heat through the low mass walls increases the heat input to the building during the day when cooling devices and techniques are least effective. Unless low mass structures are extremely well insulated, only marginal comfort can generally be attained during the humid part of the summer.

High mass structures provide a thermal flywheel effect, and may be cooled at night by nocturnal radiation or by nocturnal ventilation and evaporation, when the latter conditions are most effective. During the following day in the dry season, the cool mass in the structure renders daytime cooling unnecessary. The cool walls keep the mean radiant temperature below the air temperature (3). When nocturnal ventilation and evaporative cooling are no longer adequate, the cool walls decrease interior daytime peaks when evaporative cooling is used all day (4). Comfort may be improved by increasing air motion with small, low wattage fans. This is especially important when the partial pressure of water in the air approaches the partial pressure of water in the skies, since air motion increases the evaporation rate. However, when the temperatures are too high, increased air motion no longer has a significant effect or requires unpleasant air velocities. In high mass structures, the high mean radiant temperatures of large, hot window surfaces are a major problem to be eliminated. ERL has developed several techniques to solve this dilemma.

A combination of high mass and low mass structures (a traditional building technique), provide the maximum comfort attainable with such techniques: a protected high mass refuge, cooled at night, for daytime use, and a rapidly cooled (by ventilation and/or evaporation) low mass area for nighttime use.

Many of the passive cooling techniques can be integrated into single family residences and townhouses. To take advantage of nocturnal cooling techniques based on the thermal flywheel effects, mobile homes will need some extra storage, such as a rockbed or water heat sink, possibly located under an attached patio. The high mass, common walls required in multi-family residences and apartments provide mass at low cost, since they are required for other reasons. However, more mechanical passive cooling options, such as evaporative cooling will be required for most present structures, since they are relatively low in mass. The quality of effective mass, in some present buildings, can be increased by outside insulation techniques. Earth contact and sky radiation effects are used in new structures for obvious reasons. Additions to buildings could incorporate such systems. Commercial buildings may also use many of the passive cooling approaches to achieve comfort. However, additional approaches which can reduce internal heat gains from people, lights and equipment may be necessary. Large thermal storage for super cooling at night may prove to be another option.

II. Passive Cooling Approaches in Hot/Arid Regions

Although the various passive cooling approaches may be defined separately, they work best when combined into a synergetic whole. As with passive solar heating, the optimum passive solar cooling system is one which minimizes the need for cooling in the first place. Responsive house design with proper orientation, optimized window area, good shading and insulation, minimal air infiltration, and optimum color for solar reflection should be considered before specific passive cooling systems are proposed. The following discussion of passive cooling approaches is based on a classification system developed by Lawrence Berkeley Laboratory and the Solar Energy Research Institute.

Shading and Heat Rejection Techniques

Windows generally are the major source of heat gain and need to be well shaded, preferably outside the window. Various exterior shading devices or vegetation can be used. However, the need to constantly exhaust relatively cool air from directly evaporatively cooled structures allows the use of techniques which interpose this cool air between the building interior and the hot, ambient air. They allow solar heat to be rejected into the ambient air, and keep interior window or drape surfaces cool, thus lowering the mean radiant temperature, as well as reducing heat gain.

Most of these heat rejection techniques (including exhausting cool air through hot attic spaces and wall mounted solar collectors), are easily used on both retrofit and new construction. They will be included in the passive cooling option classification category entitled COMFORT ENHANCEMENT. A double roof system where outside air is vented through the attic, which shades the insulated ceiling below and keeps it at ambient air temperature, will also be discussed.

Ventilation

Ventilation techniques are useful when the ambient air is at or below comfortable temperatures for significant periods of time. There are two drawbacks. One is that during many summer nights in this region, the ambient air only reaches comfortable temperatures during one or two hours in the early morning. The other is the inconsistency of the wind. However, if ceiling vents are provided, a thermal diode effect allows hot air to rise into the attic and out, drawing cooler outside air in without wind. Ventilation may be affected by changes in microclimate caused by growing vegetation and changes in the surface contour of the surrounding area. Excessively high air velocities are uncomfortable and should be avoided (5).

Evaporation

Evaporation techniques are very usful in hot, arid regions where they can provide cooling at times when the air is too warm for ventilation to be effective. The Psychrometric chart is used to determine output temperatures of evaporative cooling devices. In Tucson, evaporation will produce comfortable temperatures during much of the summer, but the output dry bulb temperatures can increase from 21 - 24 C (70-75 F) (minima) to 24 - 28 C (75-82 F) (maxima) during short, very humid periods. Evaporative cooling is either used directly by blowing evaporatively cooled air into a space, or in various advanced forms integrating cooling towers, heat exchangers, rock beds, etc., which lower the output temperatures. Some techniques use the cool air exhausted from the structure to decrease the output air temperature of the evaporative cooling device.

DIRECT ATMOSPHERE - fan driven evaporation/ventilation

Direct evaporative cooling is the simplest form and is very suitable for retrofitting. Ambient air is cooled by evaporation as it drawn through wet, porous sheets of material. The air is usually cooled approximately 60% to 80% of the difference between the wet and dry bulb temperatures, although some media can approach 95% cooling efficiency. Relatively cool air is exhausted from the structure, since re-humidification is self-defeating. As mentioned previously, this relatively cool air can be exhausted through sources of heat to reduce heat gain into the structure. Massive construction can allow direct evaporative cooling to be used primarily at night, when it works most efficiently. The structure can then coast through much of the day on the stored coolness in the walls. Thus mass can help to improve comfort and reduce the power requirements of direct evaporative cooling.

Although direct evaporative cooling does use parasitic energy, it uses about one-fifth to one-third as much as refrigerated air conditioning (a common form of cooling in the warmest areas of this region). During the most humid periods, direct evaporative cooling is often not considered satisfactory; however, when many of the optimizing techniques developed at ERL are used, comfortable conditions may be achieved.

DIRECT ATMOSPHERE - two-stage evaporative cooling

Two-stage evaporative cooling is accomplished by pre-cooling ambient air without humidification, before further cooling by evaporation. The cool air entering the structure is then exhausted, preferably through sources of heat gain. The pre-cooling step can be accomplished by a combined cooling tower/heat exchanger unit, by a nocturnally cooled rock bed or possibly by other methods. The second stage is accomplished by a standard commercial evaporative cooling device. Output temperatures below the wet bulb temperature are possible with this method. At the Environmental Research Laboratory, two-stage evaporative cooling has been combined with active and hybrid solar heating systems using the same storage (rock bed) system for both seasons (7). It is primarily suitable for new construction. It works well during hot, humid periods in Tucson or Phoenix, using only slightly more power than direct evaporative cooling. The comfort attained is similar to that with refrigerated air conditioning.

DIRECT ATMOSPHERE - recuperative and regenerative evaporative cooling

Recuperative and regenerative evaporative cooling options do not humidify the air in the structure, and use the relatively cool air exhausted from the structure to improve the performance of the evaporative cooling device. Evaporatively cooled water cools ambient air in a heat exchanger, without humidification, as it enters the structure. The cool, dry air warms a few degrees as it passes through the structure, and exits through the evaporative cooling device (a cooling tower, in some cases). Since the exiting air is cool and dry, its wet bulb temperature is lower, and the water produced by the evaporative cooling device is cooler than if ambient air were used. Sometimes the heat exchanger and the evaporative cooling device are combined in one unit. Output temperatures approximately equal to the ambient wet bulb temperature in such devices have been reported (8). Regenerative systems may also be used with an underfloor rock bed. If the rock bed is used to store heat in the winter, the cost effectiveness of the system may be improved.

DIRECT ATMOSPHERE - indirect evaporative cooling

Indirect evaporative cooling is accomplished by pumping evaporatively cooled water through an air/water heat exchanger in the structure. Air in the structure is circulated through the heat exchanger, and is cooled without humidification. The output temperatures are 3 to 6 C above the wet bulb temperature due to the approach temperatures of the cooling tower and the heat exchanger. Thus this method is often not effective in times of high humidity, when wet bulb temperatures are above approximately 21 C (70 F). However, this technique can often be easily integrated with two-stage evaporative cooling systems, using the same equipment.

Most of the aforementioned advanced evaporative cooling devices are designed to provide comfort during humid periods. They are generally more retrofitable to existing structures than passive devices. If integrated into a high mass structure that can take advantage of nocturnal cooling, their size, and thus their power usage, may be reduced.

Evaporative methods that use natural convection and wind forces are described below.

DIRECT ATMOSPHERE - wind/convection driven evaporation/ventilation

A tower may be constructed that uses two complementary principles of natural convection: Cool, moist air flows down, while heated air flows up. Thus air cooled by a water mist in a tower above the structure flows down, while air heated in a solar heated attic will flow up through chimneys, thus using convective forces in both directions. Since this system uses towers for air intake and exhaust, wind forces can easily be used to assist convection. The only parasitic power used is that needed to run the high pressure mist pump, which must be carefully chosen so its power usage is minimal. Such a cooling device was tested at ERL, and is called the Thompson-Moody tower, after the team that designed and tested it. This system has similar comfort constraints to standard direct evaporative cooling (high indoor humidity). It will probably work best during the day and on windy nights. Due to its unusual features, acceptance in the local community may not be rapid, although it can be constructed using standard materials. However, with proper presentation, and in the proper economic climate, it may find wide utility.

INDIRECT ATMOSPHERE - flat shaded storage roof with wind augmented evaporation

Another evaporative cooling method, which uses no parasitic power, is the shaded roof pond. The structure is cooled by radiation and convection to and from the cool ceiling. Interior "water walls" can be used to increase the interior cool surface area available for convection and radiant heat exchange (9). Cool water is allowed to thermosiphon into the water walls when the walls are warmer than the roof pond. As will be explained later, evaporative roof ponds are sometimes used in conjunction with nocturnal radiation. This system will provide dry cooling of the interior space and has the potential to be quite comfortable during humid periods while using no parasitic energy. It is primarily suitable for new one story (and possibly two story) construction, if water walls are used. However, it may take quite a while to be assimilated into the housing market.

Radiative heat loss

Nocturnal radiation can be a powerful cooling method and in some cases uses no parasitic energy. Nocturnal radiative cooling is achieved by a body at the earth's surface radiating to the cold upper atmosphere and infinite heat sink of outer space. The effective radiative sky temperature is usually below the surface air temperature, due to "windows" of low absorptivity in the atmosphere's infrared absorption spectrum. Absorption of infrared radiation in the atmosphere is primarily due to the carbon dioxide and water vapor content of the air, and when either of these is increased, the potential for cooling by nocturnal radiation is decreased. Cloud cover also decreases the effectiveness of nocturnal radiative cooling. Thus the effectiveness of nocturnal radiative cooling is least during humid weather, when the need for cooling is greatest. Indeed, this effect is partially responsible for large cooling requirements during humid weather, since the low rate of nocturnal radiation prevents the earth from cooling adequately during such humid or cloudy periods. The relatively small effect of the method, especially during humid weather, necessitates the use of large radiative surface areas. The temperatures of a metal plate above the surface of the earth have been measured at a maximum of 5-6 C (9-11 F) below the ambient minimum temperatures during dry, clear nights (10).

INDIRECT SKY - storage roof with movable insulation, night sky radiation

In this system the entire roof is used, both for the nocturnal radiation of heat upwards, and as a radiative/convective heat sink over the entire ceiling area. The roof is covered with water contained in flexible plastic containers, which are cooled by nocturnal radiation. Insulation and shading are required during the day. These techniques, which are primarily suitable for very well constructed, single story residences, may be quite costly due to the complexity of construction; however, some claim that their costs can be almost the same as those of a standard home. Since no parasitic energy is used and ventilation is generally not desired, oppressive conditions may occur by the end of the summer. These conditions might be alleviated by the use of small fans.

INDIRECT SKY - storage roof with movable insulation, evaporation plus night sky radiation

In such systems, the roof is flooded, is open to the night sky, and is insulated and shaded during the day. Thus nocturnal radiation and evaporative cooling combine to maximize cooling in this type of system. Interior thermosiphoning water walls can also be used with this technique. Since clouds reduce the effectiveness of nocturnal radiation, comfort conditions will probably not be achieved for significant periods of time in the hotter, more humid areas of the hot, arid zone. Contrary to the stereotyped picture of regular afternoon thundershowers, followed by clear nights, areas such as Tucson and Phoenix frequently have cloud cover at night. Thus, augmenting nocturnal radiation with evaporative cooling will be useful.

INDIRECT SKY - night sky radiation cooling via heat exchanger

Instead of using a high mass roof structure for nocturnal radiation, a low mass roof through which house air is circulated and cooled at night may be used. The mass will then be in the walls of the structure or possibly in a rock bed. Although this method uses more parasitic energy (a small fan may be necessary), it may fit into standard construction practices more readily. Moveable insulation is not required since the roof is isolated from the structure and may be vented during the day.

One of the best examples of this generic system was the precursor of ERL, the office of the Solar Energy Laboratory at the University of Arizona. Nocturnal radiation from a copper roof with integral water tubes ("Tube-in-Strip," Revere Copper Co.), cooled water pumped through the tubes. When this cool water was pumped through a copper ceiling similar to the roof, the office was cooled by convection and radiation to the cool ceiling. A small heat pump (whose C.O.P. was raised by the cool water), augmented the cooling when nocturnal radiation was insufficient. This system, and the outside insulation on exterior masonry walls was quite novel in 1958, when this office was built.

An interesting variation of this technique would be to use nocturnal radiation from the roof to cool ambient air drawn under it at night. The air would then be evaporatively cooled (two-stage evaporative cooling). While the potential for two-stage evaporative cooling at night is limited by the relatively smaller difference between the wet and the dry bulb temperatures, a decrease in the evaporative cooler output temperature of only a few degrees can be important when the evaporative cooler output temperature is above 24 C (75 F).

Nocturnal radiation may also be improved by the use of selective radiators. This subject is currently being studied by Lawrence Berkeley Laboratory, the Desert Research Institute in Las Vegas and others (11, 12). Most of the published data on the performance of such selective radiators also involves the use of a cover sheet transparent to long wave length infrared radiation which appears to be the major improvement in such combined radiator/cover sheet tests.

Convective barriers prevent ambient air from warming the radiative surface. However, they are generally very thin (i.e., 2 mil polyethylene), and their utility is generally drastically reduced when dust collects on their surface (a frequent problem in deserts). These systems were evaluated by T. Lewis Thompson of ERL in the mid 1960's. He concluded that the dust problem on the cover sheet, and the moderate potential efficiency increase beyond that of white paint due to the radiative surface alone were barriers to further research at that time. We also have had considerable experience in the attachment and annual replacement of polyethylene film (6-12 mil thick) greenhouse roof covers (10-15 acres) and are familiar with the difficulty of designing attachments for such films when they are exposed to the sun, wind and rain (and especially when they are only approximately 2 mil thick). However, white paint is basically quite effective and low cost.

Roof systems using nocturnal radiation may be used for heating in the winter, thus improving their life cycle costs. However, repainting them annually may be costly, unless a dark roof is used during all seasons, as was done in the University of Arizona's Solar Energy Laboratory office.

Mass and insulation techniques

The use of mass has been alluded to in the previous discussion. Mass, or the almost total lack of mass, is the traditional defense against unwanted heat gain in the hot arid regions. Mass simply stabilizes the interior temperatures of a structure, and is not a passive cooling device by itself. Thus, it is used in combination with actual cooling techniques such as nocturnal or diurnal evaporation, and nocturnal ventilation or evaporation. When the mass is cooled at night, interior temperatures may be comfortable for much of the day. High mass and low mass structures can be combined so that nighttime living may take place in the rapidly cooled low mass portions.

The lowest cost high mass structure in terms of displacement of competing fuels is one constructed of sun fired adobe, a traditional building material in this region. Not only is adobe inexpensive to make, it is relatively inexpensive to transport since the materials necessary for making it are often indigenous to most building locations. If adobe walls cannot be made thick enough to provide adequate resistance to heat flow, they can be improved by insulating their exterior surface, which "captures" the mass inside. High mass construction is also useful because of its compatibility with wintertime passive heating. Since high mass structures must be cooled at night, which takes time on warm nights, a rapidly cooling, low mass structure is often a useful adjunct to a high mass structure.

DIRECT GROUND COOLING

The ultimate high mass structure is one that is partially or totally buried underground, using the earth as an enormous heat sink. One family living in an earth integrated (buried to the roof on the north, east and west sides) passive solar house, located in this region, was comfortable without auxiliary cooling on all but a few days (13).

Semi- or entirely-buried structures act as a thermal diode for cool air. When the air in the structure is hotter than the ambient air, it rises and is replaced by the cooler ambient air. When the interior air is cooler than the ambient air, it stays put. However, when night temperature minima are above 27 C (80 F), such effects are not useful, and comfort is dependent on heat flowing into the surrounding soil, and the low interior mean radiant temperatures induced by the cool walls of the structure.

COMFORT ENHANCEMENT - cool zones

If necessary, one almost completely buried zone of the structure could be used as the final refuge in times of severe heat, as was done in traditional homes in the Middle East and North Africa (14). It may be necessary on some occasions to lower the ambient temperature artificially at night, by evaporative cooling.

ISOLATED GROUND - ground cooling via heat exchanger

Earth tubes may also be used to supplement direct cooling by radiation and convection, in a similar manner to the ground cooling via heat exchanger concept. Since soil temperatures are approximately 21 C (70 F) at depths greater than 2 meters, these effects can be significant if the interior heat gain of the structure is not great. The use of heat pipes with heat exchanger fins on one end may improve the performance of this system.

ISOLATED GROUND - ground cooling via evaporatively cooled heat exchanger

Ground contact cooling techniques can also be combined with evaporative cooling techniques (15). Long tubes buried in the earth can be lined with unglazed ceramic tiles, which permit soil moisture to penetrate to the interior surface. The soil is kept moist by drip irrigating "gray" water on to the soil over the tubes. Three mechanisms of cooling exist: heat transfer into the earth, using the earth as a large heat sink; dampening of the ambient minima and maxima by thermal inertia of the surrounding soil; and evaporation of the surface of the tubes. Analysis is required to determine the relative effects of these mechanisms.

The use of simple forms of ground contact cooling has the potential for the greatest comfort with the least amount of parasitic energy. Construction materials are fairly standard. It would primarily be used in new construction for both single family homes and townhouses. Multi-family units already simulate earth contact living.

COMFORT ENHANCEMENT - air stratification

Mass can also be used in combination with air stratification. The high (approximately 3.3 to 4 meters (11 to 13 feet) ceilings in many older structures were used as a reservoir for warm air, which was vented when cooler conditions made venting practical. This technique was used to assist nocturnal cooling. The massive structure (including earth contact) is cooled at night by ventilation, evaporative cooling, or even "off peak" air conditioning, and coasts through the day on stored cool air. As the structure warms during the day, the warmed air rises to the ceiling or to an upper story (also massive) where some of the warm air is cooled by the walls, and flows back down to the lower portions of the structure. The warmest air always remains at the highest level. It cannot be vented out during the day, since to do so would admit hot ambient air, and place added strain on the limited cooling capacity of the mass in the structure. This technique can be used on both above ground level and earth contact structures and would be inexpensive to use on a two story structure where the bottom level is used as the final refuge from higher temperatures.

COMFORT ENHANCEMENT - mass

The use of mass in reducing peak parasitic power usage should not be ignored. However, it has immediate benefits, both to minimize the peak power usage in problem cities such as Phoenix, lowering power bills when time-of-day billing is completely instituted (it has already begun in Phoenix), and to make it possible to retrofit such massive structures with more completely passive techniques at some later date. Peak power usage for evaporatively cooled structures can also be reduced in masonry buildings.

COMFORT ENHANCEMENT - nocturnal evaporation, dessication and mass

The use of solar regenerated, passive dessicant "cooling" techniques in arid climates may seem strange to some. However, direct evaporative cooling is, and will remain, the system of choice for an increasing number of desert dwellers. It is emminently retrofitable, and easily available commercially. However, evaporative cooling converts relatively dry, hot desert air into cool, humid air. If it is used to cool massive structures at night, which then coast through the day, the structure remains humid as the temperatures inside gradually rise. By removing 20 to 50% of the moisture in a solar regenerated, dessicant cart or fixed system in at least one area of the structure, the structure will be more comfortable at a given temperature, and remain comfortable at higher temperatures. However, dessication of air heats the air (the opposite of evaporative cooling), thus requiring the removal of that energy. The nocturnally cooled mass of the structure can act as a sink for this heat which in a modest 140 square meter home could be as little as 4,200 - 8,400 KJ (4-8,000 BTU). Thus the combination of mass, dessication, and nocturnal evaporative cooling can, potentially, increase the comfort of such structures. Solar regenerated dessicant cooling techniques, if shown to work well, can be used in any high mass, nocturnally evaporatively cooled structure, new or old.

DIRECT ATMOSPHERE - wind driven ventilation

The utility of mass in structures has been discussed. The almost complete lack of mass is also useful; it is a traditional defense against heat when used as an adjunct to mass. Low mass frame porches cool rapidly at night by natural ventilation, while the massive portions of the structure are being cooled down. They can be screened or open. The "solar/screen porch" that uses a removable glazing technique developed at ERL makes this concept useful in all seasons since, when glazed, the porch can be used as a source of heat, a greenhouse, and a sunroom.

DIRECT SKY - night sky radiation

Low mass roof decks open to the sky also cool rapidly. A person on the deck is cooled by the combined effect of nocturnal ventilation and nocturnal radiation directly from the body. The latter is an especially powerful technique, since indirect effects are never as powerful as direct effects.

CONCLUSION

From the previous discussion, it is apparent that many techniques for passive and hybrid cooling in hot, arid climates are available. Those with the greatest chance for success at this time (with least power usage) appear to be standard direct evaporative cooling techniques combined with traditional cooling strategies such as high mass construction, earth integration and associated life style changes, such as sleeping outdoors at night. Mechanical evaporative cooling systems, such as two stage evaporative and recuperative systems, work well but have fairly high initial costs as well as higher operating costs than the passive systems. However, when combined with passive techinques, their size and, consequently, their cost and power usage may be reduced while providing very comfortable conditions.

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SEASONALLY OVERHEATED CLIMATES

Karen Crowther*

In seasonally overheated climates buildings should trap heat in the winter and dissipate heat in the summer. Summer cooling strategies much be designed so that they don't detract from winter heating. Winter heating systems should not contribute to summer <u>over</u>heating. Almost any approach to this problem will involve compromise. Ideally the components of the heating system (mass, windows, etc.) can double as part of the cooling system.

Since seasonally overheated regions can be either arid or humid, the cooling strategies discussed in the preceding sections on those climates will apply. It is, however, important to choose only those strategies which do not seriously impair winter heating performance.

This section will review some of the compromises that must be made between heating and cooling and mention some dual purpose systems that can be used for both.

COMPROMISES

WINDOW SHADING

In summer all windows should be shaded since direct sun entering through the windows contributes a huge amount of heat. Solar radiation through the windows is usually the biggest heat gain mechanism in a building that doesn't have a significant internal load from lots of

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people, lights, or machinery (i.e., a building with a skin-dominated load). But in winter we want sunlight to enter the windows (particularly the south windows) so that solar energy can be put to work heating the house. Summer window shading without winter sun blockage can be accomplished in four ways:

1. Movable Overhangs: Anything which blocks the sun but can be removed or pushed out of the way in winter can be used. Some suggestions are:

- canvas shades
- off-the-shelf vinyl or aluminum awnings
- masonite or plywood panels which bolt to a permanent framework
- bamboo or vinyl shades which hang vertically in front of the window and can be rolled up out of the way (Leave an air gap between the top of the shade and the building so that heated air is not trapped next to the window.)

Size movable overhangs generously. Deep overhangs will cut down on the amount of sun that is reflected off the ground and into the windows.

2. Deciduous Plants: The summer leaves shade the windows (and roof and walls). In winter the bare branches allow the sun to enter the windows. Bushy trees are especially effective with east and west windows which are hard to shade because of the low sun angle. Be sure you know how tall the tree will be and what kind of branch structure it will have (i.e., don't expect a short, compact tree to shade a second-story window). Check that the trunk and bare branches won't shade too much in winter.

A popular technique is to construct a wire trellis over a south patio and allow a deciduous vine such as grapes to grow over the trellis to shade the south windows.

3. Exterior or Interior Shutters: Exterior shutters are better since the sun will be blocked before it enters the living space and both shutter and window will act as insulation. Interior shutters (unless they are covered with some reflective surface) will absorb the sun *after* it passes through the glass window so that the insulating effect of the window is useless. Even if a reflective surface is used (unwrinkled household aluminum foil is best), 10 percent of the solar energy is absorbed every time the light passes through a pane of glass. This means that a double-paned window with an interior reflective shutter will absorb about 34 percent of the incident sun.

Whether an interior or exterior shutter is used, it is advantageous to use *insulating* shutters. This will not only cut down on summer heat gain but will make a significant contribution to winter performance.

4. Calculated fixed overhangs: South window overhangs can be designed to admit winter sun (which is low in the south) and exclude the summer sun (which is high and not as southerly). (Note: This discussion applies to the northern latitudes only.) Figure A shows the summer and winter sun paths. Figure B shows how a calculated fixed overhang works.

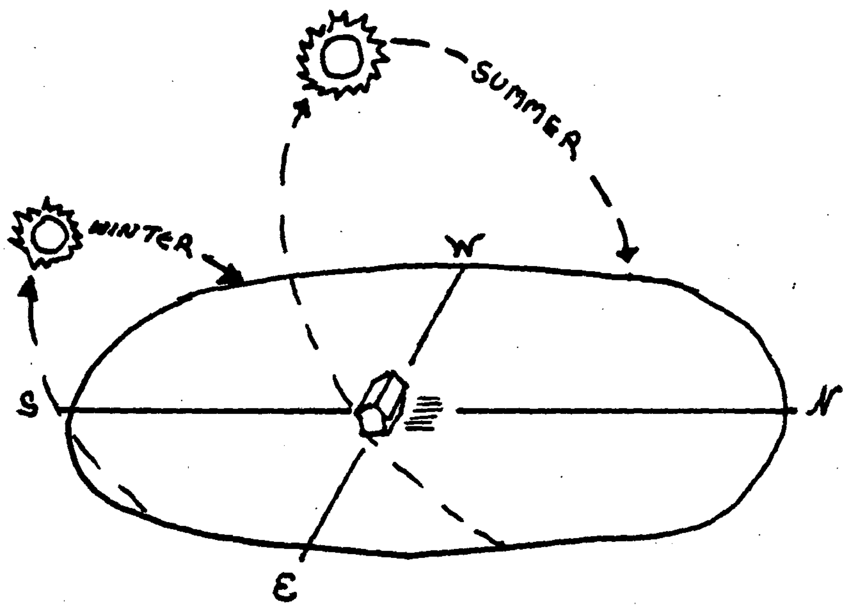

Figure A. Summer and Winter Sun Paths

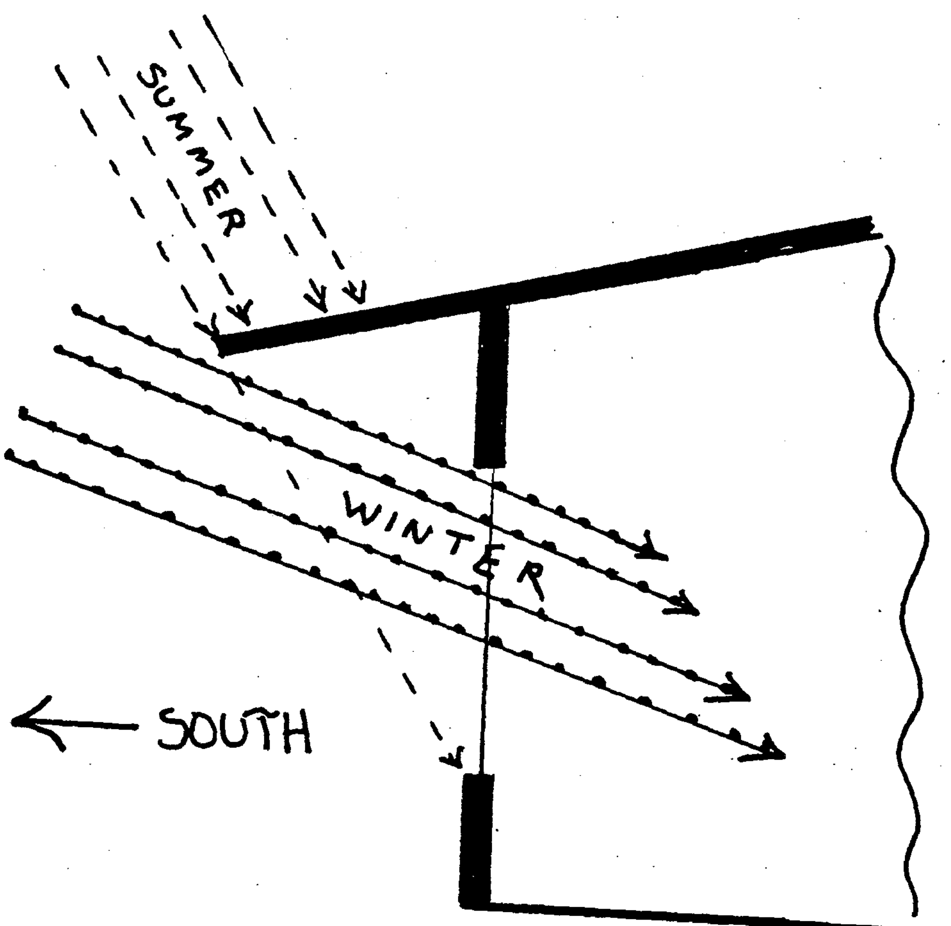

Figure B. Calculated Overhang

The advantage of this method of shading is that it is permanent, inexpensive, and requires no seasonal adjustments. There are two disadvantages:

a. Because the sun position changes constantly and gradually (highest in the sky in June, lowest in December), the windows will be partially shaded during some winter months and the sun will strike part of the windows during some summer months.

b. The hottest months do not correspond exactly to the months during which the sun is highest in the sky. For instance, September is often hot. Excluding the sun in September results in excluding the sun in March (sun angles are the same in March and September). March is often a cold month during which solar heating is desirable.

A later section contains a method of calculating overhang geometry if one knows the latitude, the window size, the month during which all sun must be excluded, and the month during which the window must be completely unshaded.

WALL AND ROOF SHADING

The sun can triple the amount of heat passing through the walls of a building. Shading can have a big effect on this major heat gain source. Shading can be provided by:

- Other buildings, hills
- Wing walls and overhangs
- Double walls which allow air flow between the layers

- Well-ventilated attic (at least one square foot of screened opening per 100 square feet ceiling area)
- Trees, shrubs, and vines

Keep in mind that heated air wants to rise and use this effect to exhaust air by providing a high opening (exhaust) and a low opening (inlet). Figures C and D show two schemes for taking advantage of this effect.

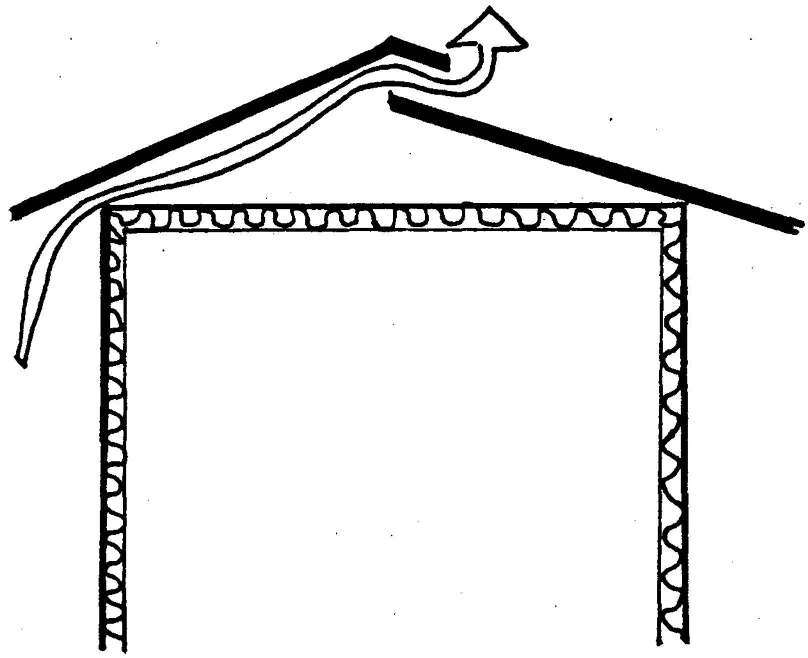

Figure C. Vented Attic Using Natural Convection Flow

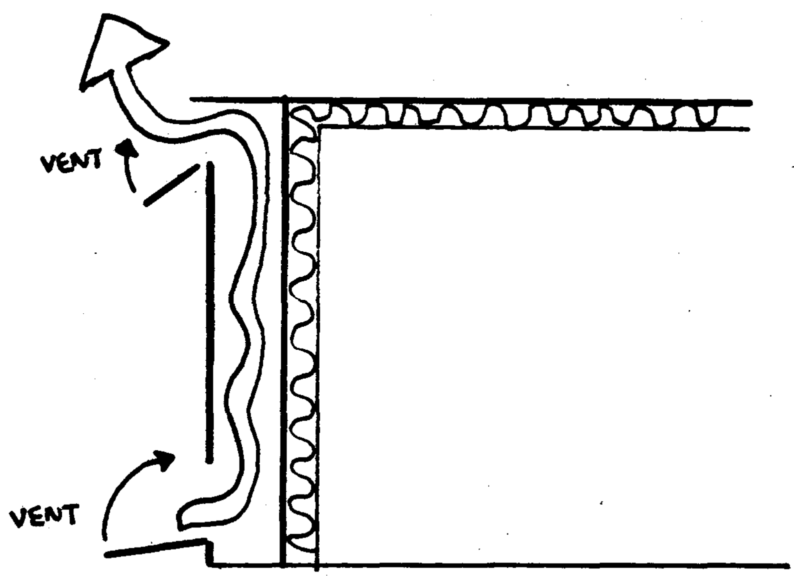

Figure D. Vented Wall Using Natural Convection Flow

It is helpful to use reflective metal roofs or light-colored walls and roofs so that any sun that does strike the building will tend to be reflected rather than absorbed. A very dark surface absorbs more sun than a light-colored one.

INTERNAL LOADS

Internal loads (people, appliances, lights, etc.) contribute slightly to heating in winter but often put a huge load on the summer cooling system. In nonresidential buildings the heat generated by people and lights is often an order of magnitude greater than even the heat gain due to solar radiation. Because of this, it is worthwhile, even in seasonally overheated climates, to reduce internal loads as much as possible. Some suggestions follow.

1. Use the lighting which has the highest light-to-power ratio so that you get the most light for the least heat gain. Day-lighting can be very beneficial as discussed in a later section. Fluorescent lighting is more efficient than incandescent. Reduce general lighting levels and use task lighting. Consider lighting angles, since the proper mix of light angles can reduce the necessary light intensity.

2. Isolate and/or insulate and vent appliances such as refrigerators and stoves. Make sure the hot water heater is on the outside of the building.

3. Use good conservation. Eliminate pilot lights on gas appliances and use the most efficient appliances available.

WINDOW PLACEMENT

Table I shows the solar radiation that will pass through a square foot of window on July 21 (clear sky, 32^{o} North Lat.).

Table I - July

South	496	Btus/day-ft^2
West	1,147	"
North	462	"
East	1,147	"
Horizontal	546	"

It is not difficult to shade south windows since the sun is high in the sky when it is to the south. East and west windows receive more than double the energy which north and south windows receive. East and west windows are very difficult to shade since the sun is nearly perpendicular to the windows in the morning and afternoon. For this reason designers in seasonally overheated regions try to eliminate all east and west windows. This works well since in winter these windows can only contribute about 1/3 as much solar energy as south windows. (See Table II.)

Table II - December (32^{o} N. Lat.)

South	1,704	Btu/ft^2-day
West	571	"
North	142	"
East	571	"
Horizontal	880	"

North windows can be shaded by wing walls since the sun will be low in the east or west sky when it is to the north of the building.

An equally important consideration in window placement is ventilation paths. It is advantageous to provide cross-ventilation in the direction of the prevailing summer breezes. NOAA climate data can provide monthly prevailing wind directions if the information is not commonly known. If the prevailing summer wind is from the southwest it would be good to put openable windows on the southwest and the northeast. However, such windows would be difficult to shade. Placing the windows on the south and north would be even better. North and south windows would be easy to shade and still take advantage of the natural breeze. Windows can usually be placed up to 45^{o} from the wind direction and still be effective.

Areas with prevailing east or west winds present a problem which can be solved by using insulating shutters over east and west windows or non-transparent ventilation openings.

To sum up:

1. Windows should be placed on the south so that they are easily shaded in summer and provide solar energy in winter.
2. If the prevailing breeze is from any direction except east or west, windows should also be placed on the north to provide a ventilation path. These north windows can be shaded by side walls.
3. Try not to use east and west windows. They are extremely difficult to shade and receive the most solar radiation in summer.
4. Skylights should only be used when their contribution to day-lighting is important or if they have insulating shutters.

COOLING/HEATING SYSTEMS

DIRECT GAIN SYSTEMS:

Most passive solar heated buildings contain thermal mass (concrete, water, phase change material, etc.) which is used to store heat. This same mass can be used to store "coolth" in summer.

Mass which is located within the living space can be cooled at night by either ventilation or mechanical means. Night ventilation can be natural or fan-assisted.

When night temperatures drop below about 65-70^{o}F the interior mass can be cooled by night ventilation. If the building is shut up tight during the day, the cooled mass can absorb the heat and keep the occupants cool. The mass will not only keep the air temperature down but can provide significant radiative cooling to the occupants. The Ventilation Cooling section discussed night ventilation cooling in detail.

In areas where night temperatures are too high, the interior mass can be cooled nightly by either a swamp (evaporative) cooler or compression cooler. Both these devices will operate more efficiently at night and use off-peak electricity. There may not be any significant savings in the amount of electricity used, but off-peak use can be less expansive and help prevent the need for new electrical generating plants.

ROCK BED SYSTEMS:

Some solar heating systems use rockbeds for storing heat. During the summer these rockbeds can be cooled nightly by fans or swamp coolers. During the day air is drawn through the rockbed where it is cooled before entering the living space. This technique has the same advantages as night cooling of interior mass. However, it has one disadvantage: Fans must be used during the day to transfer the cooled air from the rockbed to the living space. Since rockbeds present a lot of frictional resistance to air flow, these fans usually consume a significant amount of power. When operated both day and night the electrical power used can be about 200 - 300 KWH per month for an average residence. The Evaporative Cooling section will discuss evaporative cooling of rockbeds.

WATER SYSTEMS:

Some solar heating systems use water as their heat transfer and storage medium. These systems are not as efficiently converted to cooling for two reasons: 1) Additional power is needed to cool the water (chillers or swamp coolers), while in solar heating the sun's heat is free. 2) The water can usually only be chilled 10-30°F lower than room temperature, whereas in solar heating the water can be heated 60-90°F above room temperature. Because the cooling temperature difference is small the pumping and fan power is a much bigger proportion of the energy transferred. For these reasons, the cooling use of water systems is usually much less efficient than the heating use. However, some preliminary testing of hybrid water systems indicates that they can be more efficient than air conditioners.

SOLAR COLLECTORS:

Radiative cooling of water in glazed solar collectors at night does not provide significant space cooling. However, solar collectors can be used in dessicant systems. In damp climates, summer humidity can be a major factor affecting comfort. Dessicants such as zeolite or silica gel can absorb moisture from the air. When the dessicants become saturated with water, heated air from the solar collectors is used to drive the moisture out of the dessicant so that it can be reused. A discussion of dessicants appears in the section on Dehumidification.

ROOF PONDS:

Roof pond systems such as Harold Hay's Skytherm can be used for cooling. The insulated lid is opened at night so that the water (which is encased in vinyl bags) can cool by radiating to the sky. Flooding the water bags increases cooling by adding evaporation. The insulated lid is closed during the day to keep out solar energy. The water-cooled uninsulated ceiling cools the living space. Winter heating is acceomplished by opening the lids during the day (to absorb the solar energy) and closing the lid at night (to keep the water warm).

OTHER SYSTEMS:

Other heating systems such as unshaded Trombé walls do not function too well in summer. If they are used, it is important to prevent summer overheating by providing outside venting of the hot air and using movable shading where possible.

Some cooling systems such as evaporating roof ponds in direct contact with the ceiling (no lids or insulation) are not suitable for seasonally overheated regions since they will detract from winter heating.

NONRESIDENTIAL BUILDINGS:

In nonresidential buildings, internal heat sources like people and lights plus outside air ventilation requirements quite often make it impossible to cool the building with thermal mass. Even if every interior surface of the building is composed of massive material at approximately 65^{o}F, the heat simply cannot be absorbed fast enough. The building will become uncomfortably warm. In situations where there are large ventilation requirements and where the internal heat load is high (theaters, meeting rooms, industrial buildings, etc.), the ventilation air must be cooled. This problem has not been studied completely, but some possible solutions may be:

- Air to air heat exchangers which use the outgoing air to precool the incoming outside ventilation air
- Indirect evaporative coolers
- Swamp coolers
- Rockbeds with fans
- Heat pumps which use ground water or swimming pools as their heat sink

SUMMARY

Seasonally overheated regions present a challenge to the designer. This challenge can be met with dual purpose cooling and heating systems and with design compromises. If both heating and cooling needs are kept in mind and the building is designed with an understanding of the environmental factors such as sun angles and climate, an energy-efficient structure will result.

Evaporative Cooling

Evaporative Cooling for Hot Arid and Semi-Arid Regions --
John Peck and Helen Kessler

Evaporative Cooling: Roofs as Dissipators --
Fred Loxsom and Brian Kelly

EVAPORATIVE COOLING FOR HOT ARID AND SEMI-ARID REGIONS

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ABSTRACT

Various methods of using evaporative cooling to enhance comfort are discussed. Simple direct evaporative cooling methods, as well as the more complex two-stage, indirect and recuperative (regenerative) cooling systems have been used. By combining evaporative cooling with other passive cooling strategies such as earth integration or mass, rejecting heat before it enters a space and flexible zoning, greater comfort, potentially at less cost, may be obtained. Use of the psychrometric chart, as well as some sizing guidelines are also discussed.

INTRODUCTION

Various forms of evaporative cooling have eased the travail of life in hot arid regions for much of mankind's existence. The medieval Arab's view of paradise was a garden, evaporatively cooled by fountains and water transpired from the leaves of green plants. Natural drafts through openings in walls filled with wet twigs, or through damp chimneys and tunnels in the earth have also been used. The latter also incorporates the beneficial effects of the lower temperatures present in the earth itself and points out the advantages of integrating evaporative cooling and other methods of passive cooling in order to maximize their cooling effects.

Modern direct evaporative cooling is simple and convenient and is available in a compact manufactured box. A fan draws ambient air through wet fiber pads, cooling the air by evaporation before blowing it into the house. The air is exhausted out through windows and other openings, preferably through sources of heat gain, so that solar heat is rejected before it enters the occupied spaces. However, during particularly hot and relatively humid conditions, direct evaporative cooling may not provide desired comfort levels.

Since the 1930's, innovative technologists have been devising methods of using two evaporative cooling processes in series to produce still colder or drier air. These are called "two stage, indirect, or recuperative evaporative cooling systems". Two basic evaporative cooling devices were available to designers, a cooling tower, which produces cold water or an evaporative air cooler, which produces cool air.

Unfortunately, simply blowing air from one evaporative cooler into another does not produce significantly colder air. Two stage evaporative cooling is only achieved by pre-cooling air <u>without humidification</u> before further cooling by evaporation. The first stage can be a cooling tower, an ordinary evaporative cooler, or any other cooling effect, such as nocturnal radiation. A heat exchanger then uses the cool fluid or cooled air from the first stage to precool (without humidification) outside air entering the second stage evaporative cooler, thus producing lower output air temperatures. The cool air flows through the house, and out, preferably through sources of heat, as in direct evaporative cooling. We have developed a system where a large rockbed is cooled at night. The following day, the rockbed is used to precool air without humidification before further cooling by evaporation. The thermal storage inherent in this system has several advantages, including two stage evaporative cooling output temperatures lower than those produced in systems which do not have thermal storage.

Indirect evaporative cooling, another evaporative cooling method, does not humidify the air in the structure. An evaporative cooling device, commonly a cooling tower, is used to cool the air in the house indirectly through an air-water heat exchanger over which interior air is recirculated. This prevents the house air from being humidified. However, heat exchangers cannot cool the house air to the temperature of the cooling tower water or air in them, and very dry conditions are required for this system to work well.

To circumvent the above limitation, indirect recuperative (regenerative) evaporative cooling systems were developed. Instead of recirculating house air through a heat exchanger, as in the above indirect system, outside air is continuously cooled by the heat exchanger as it enters the house. Since air leaving the house is considerably cooler than the outside air, and has not been humidified, it can be used as the input air to the evaporative cooling device. This lowers the output temperature of the evaporative cooling device, thus lowering the temperature of the heat exchanger, and lowering the temperature of the house below that which would be attained by a non-regenerative system. (This is not perpetual motion!). Many systems of this type use a cooling tower as the evaporative cooling device. One uses a dual rockbed, and another uses a rotating wheel which alternately cools outside air and is cooled by an evaporative cooler.

The following discussions about these forms of evaporative cooling do not cover all of the possible systems. The particular variation which you think of may not be strictly original, but it is your idea if you independently thought of it. Conditions in our changing world, new materials, or even methods of algae control may make it an idea whose time has come.

For a thorough description of evaporative cooling and evaporative cooling devices developed before 1963, see John Watt's book, Evaporative Air Conditioning (1).

I. Direct Evaporative Cooling

A. Evaporative Cooling Devices

Many kinds of direct evaporative cooling devices are commercially available. Some are used on residences, while others are used on commercial buildings where low maintenance is a factor. Others are site-built and used primarily on greenhouses.

1. Drip-Type Direct Evaporative Air Coolers

This is the ubiquitous residential and light commercial evaporative cooler used throughout dry areas of the southwest. It consists of a metal box containing a fan with fiber pads on 3 or 4 sides of the box. While city water pressure can be used to drip water through the pads, in most installations a pump recirculates water through the pads in order to improve the efficiency.

The fan in such drip-type coolers blows air out the bottom or the side of the box. Units that blow the air upwards have advantages in ground mounted installations and are commercially available on special order.

These economical units are easily maintained by the homeowner. The large areas of fiber pad on each unit (and consequent low air speeds) make them efficient coolers.

Most manufacturers publish certified curves of airflow vs the duct pressure drop. These, rather than the so-called "nameplate" airflow rates, are used for design purposes since the cooler never produces the nameplate airflows, even without any external resistance to airflow.

2. Spray Type Evaporative Air Coolers

In some cases, fine misting nozzles are installed in a large corrosion resistant duct. Air is blown through the duct, and is evaporatively cooled by contact with the fine water mist. CSIRO, in Australia used such a cooler, but report that due to the lack of mist eliminators, the mist carries over into the ductwork.

3. "Slinger" and Horizontal Pad Evaporative Air Coolers

The "slinger" is a commercial type of evaporative cooler which combines the drip and spray types. A rapidly rotating wheel throws a sheet of water in the air, which is broken up into droplets by the incoming air, cooling the air somewhat before wetting a fiber pad like those in the drip-type cooler. This wetted pad further cools the air. These devices have fewer clogging and scaling problems than drip-type coolers.

The horizontal aspen pad evaporative cooling devices installed on some greenhouses are similar. Water is sprayed over horizontal aspen pads. Cooling occurs both by evaporation from the misted water as well as from the wet pads, which serve as a mist eliminator. As in the slinger, clogging and scaling are greatly reduced as compared to vertical pads, and the pads do not tend to sag and form air leaks. The efficiency of the system improves as the droplet size of the sprayed water decreases.

4. The Rotary Pad Evaporative Air Cooler

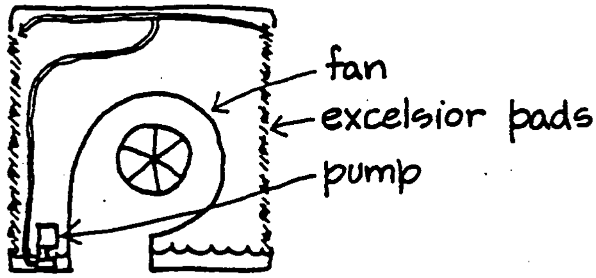


Figure 1. Direct Evaporative Cooler

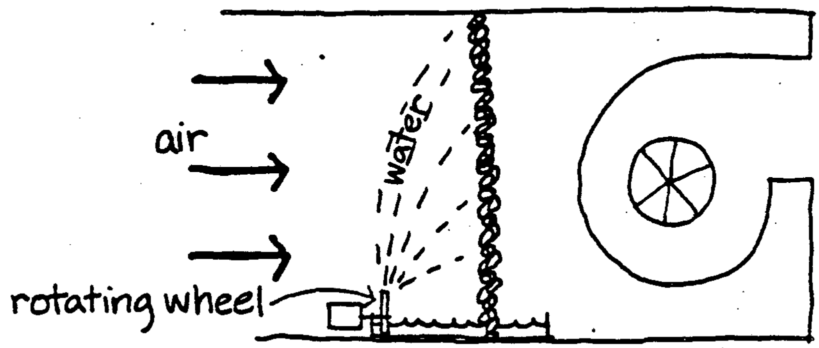


Figure 2. "Slinger" Evaporative Air Cooler

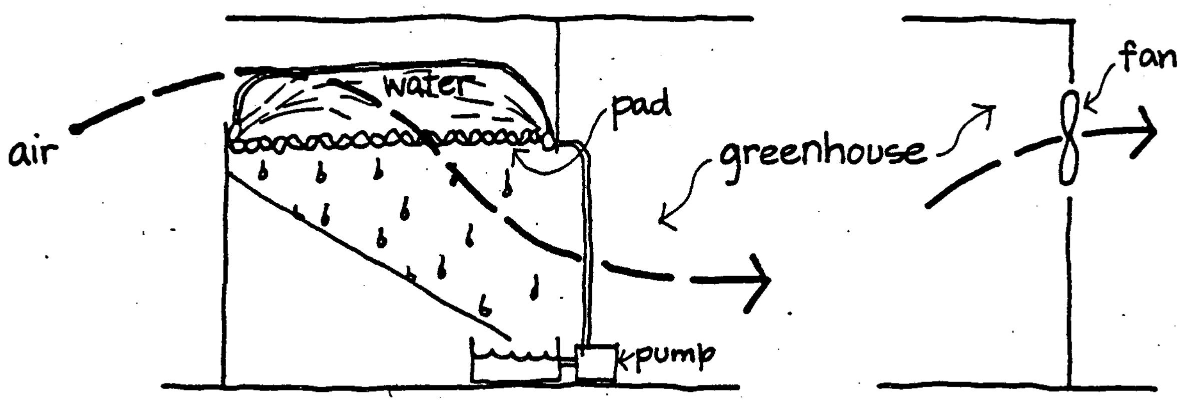


Figure 3. Greenhouse Evaporative Cooler

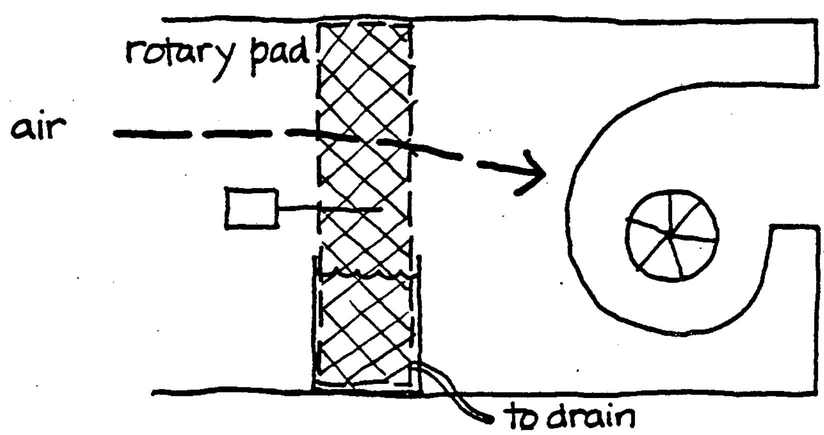


Figure 4. Rotary Pad Evaporative Cooler

This device is considered to have the lowest maintenance requirement of all the evaporative coolers and is very quiet during operation. It is also the most expensive. A rotating piece of wire mesh (generally copper) passes through a water tank, and then rotates slowly into the airstream entering the building, cooling the air as the water on the wires evaporates. Both its shape and the lack of mist from the rotating drum make this cooler useful.

The water tank is drained periodically by a timer. Clogging and scaling are almost non-existent. Rotary pad coolers can also be easily used in multiple groupings. We have operated one at ERL for three years. No maintenance has been required.

B. Use of the Psychrometric Chart

The Psychrometric Chart, available in the ASHRAE Handbook (2) and many mechanical systems texts, is used to depict the changes in the state of the air as it is cooled evaporatively. In a direct evaporative cooling system, the psychrometric chart is used as follows:

When ambient air enters the evaporative cooler at A (see figure 5), the evaporative cooler cools the air along the constant wet bulb temperature line to B. This is because most evaporative coolers will cool the air approximately 70% ± 10% of the distance from point A to the curved line at the extreme left of the psychrometric chart. In the process of evaporation, latent heat has been substituted for sensible heat. If the temperatures in the structure can be maintained in the low 70's, the amount of latent heat in the air does not effect comfort until it almost reaches saturation levels.

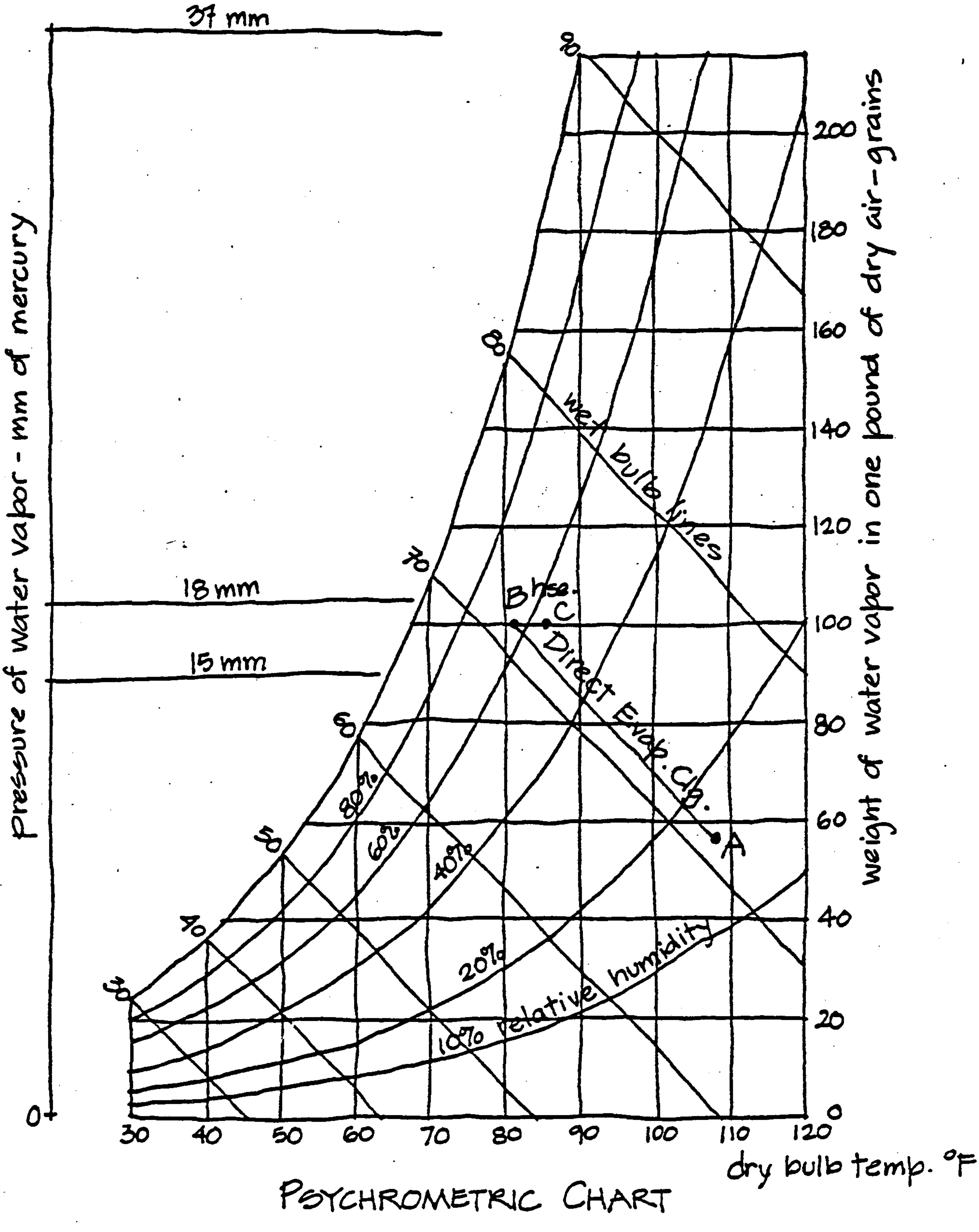
C. Ambient Weather Requirements for Evaporative Cooling.

ASHRAE tables of design wet bulb temperatures are helpful in determining areas where evaporative cooling will be useful (3). In general, if the location has wet bulb temperatures of less than 70°F most of the time, direct evaporative cooling will work very well all the time. If the maximum wet bulb temperatures are greater than 75°F, relief is all that can be expected for significant periods of time.

A direct evaporative cooler will cool the air approximately 70% ± 10% of the difference between the dry bulb and the wet bulb temperature along the wet bulb line on the psychrometric chart. This can be applied to the ASHRAE coincident dry bulb temperature/wet bulb temperature data to arrive at an approximation of the output temperature of a direct evaporative cooler in a particular area.

D. Sizing Direct Evaporative Coolers

Always use a two-speed cooler where possible since the low speed position uses 2/3 as much air at 1/3 to 1/2 the power cost. Size the cooler so that the house air is changed (on high speed) every 2 1/2 minutes in a poorly insulated house with lots of glass, and up to every four minutes or slightly more if the house is well insulated, and the windows



Direct Evaporative Cooling A→B→C

Figure 5

are shaded. This rule is for climates similar to Tucson. Modify these values accordingly for a climate different from Tucson, using the ASHRAE weather table. Local practice can often be a very good guide to the sizing of coolers. If you want to calculate hourly heat gains for the average or maximum days, you can calculate the approximate temperature rise of the air as it passes through the house from the formula $\Delta T(^{\circ}F)=\frac{\text{BTU/hr(heat gain into house)}}{\text{ft}^3\text{/min(airflow thru house)}}$ When combined with estimated cooler output temperatures, this approximate equation allows the temperature of the air as it leaves the house to be estimated. If the temperatures are too high, the airflow can be increased and the ΔT decreased.

Always use the biggest cooler and the smallest motor, unless you are forced to use a duct system with a high pressure drop. For example, a "5500" cooler comes with a 1/2 hp motor. A "6500" cooler is exactly the same size, but has a 3/4 hp motor installed. Since the pad size is the same, the faster airflow rate through the "6500" cooler results in less evaporation efficiency.

E. Ducts

The maximum airflow rate in ducts can be up to 1500 ft per min., but 1000-1200 ft per min is preferable to avoid high pressure drops and excessive noise. Keep ducts as straight as possible, and use turning vanes in elbows and extractors in outlets. Extractors are a set of turning vanes, and are relatively low in cost. They guide the air from the duct through the register. They can be moveable if desired, so they can selectively direct the air into occupied areas of the house. This is illustrated in Fig. 6.

These extractors are not expensive. A 10"x24" unit recently cost $13. Installations detail are in Fig. 7.

Evaporative cooling uses large volumes of air, and forcing this air through small ducts, around sharp corners, and out small outlets costs money.

In some cases, the best duct system is none. Just blow the air into a large daytime occupancy room, and through the house and out bedrooms, bathrooms, and kitchens.

F. Rejecting Heat Before it Enters the House

Since evaporatively cooled air may not be recirculated, but must be exhausted from the house, it can be used to reject incoming solar heat. Areas where heat may be rejected include the attic, hot air solar collectors and Klos windows.

Louvers with fire dampers may be installed in the ceiling of a home with an attic to exhaust air out vents on the gable ends or under the soffit. Each one square foot louver should be used to exhaust about 500 cfm of airflow. The gable ends should also have about the same area of opening. Such louvers should be put in all rooms except the kitchen. In addition to keeping the attic cool, they also allow one to keep the cooler on without opening windows.

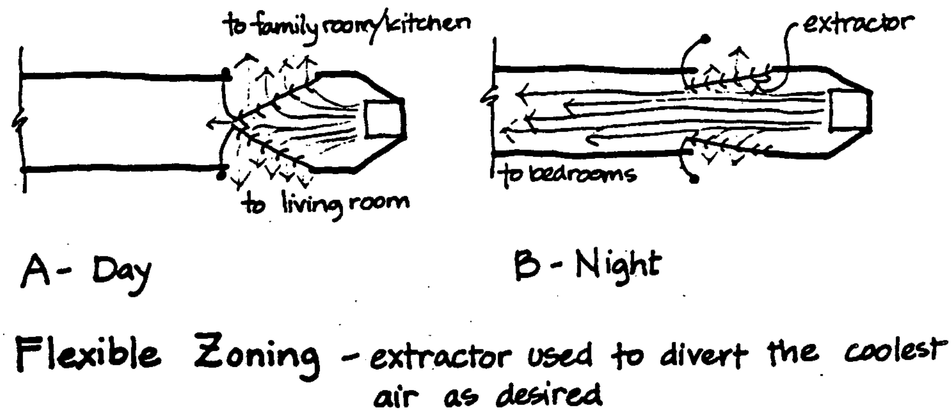


Figure 6

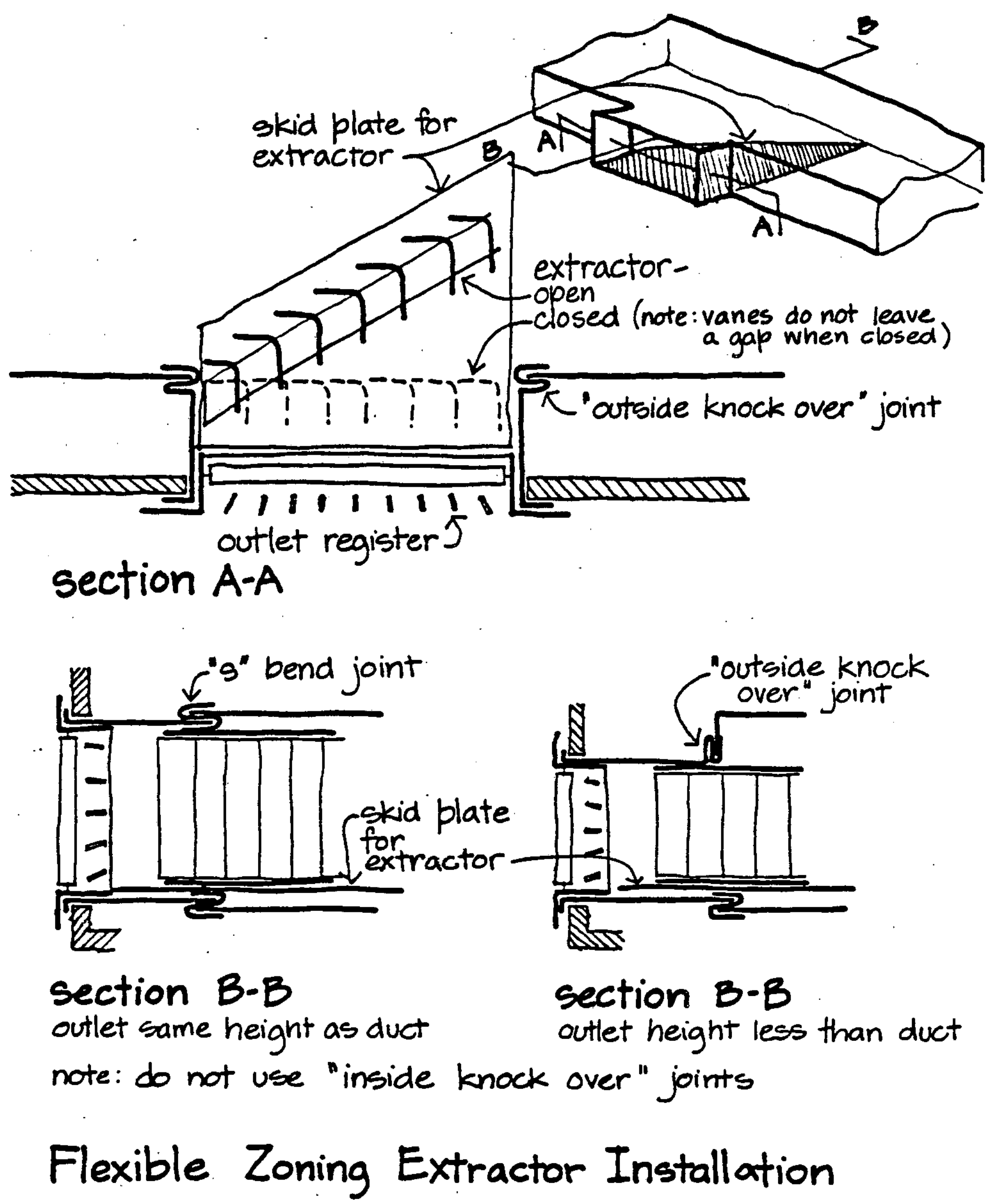


Figure 7

A second source of heat, are hot air solar collectors such as the ClearView Solar Collector (5). When such collectors are vertical, very little heat enters them in the summer. The heat that does penetrate the glass is absorbed by the absorber plate (venetian blinds, tinted glass, or metal plates which shade the wall) and is efficiently removed by the cool air flowing through the collector. Due to this self-shading feature, no overhang is needed. Barometric dampers, shown in Figure 8, allow the air to pass through the collector in one direction but prevent hot outside air from entering the house.

Klos windows are also useful for rejecting heat (as well as for collecting solar heat in the winter). They are made up of two windows with a duotone venetian blind hung in an air space in-between. The windows open on opposite ends and evaporatively cooled air is exhausted through the airspace to the outside. See Figure 9. During the summer, the window can effectively reject 95% of the incoming heat, including both radiation and conduction gains. (6).

G. The Use of Fans to Improve Comfort

The key to improved comfort in most evaporatively cooled homes is the use of small fans which keep the air moving in localized areas. Several such fans may be purchased and placed in various rooms of the house where the occupants spend the most time. The fans should be located where they can easily be turned on when one enters a room and turned off when one leaves the room. They are especially useful in homes where the cooler has been used to cool the mass of the home at night and where it is turned off during the following day.

H. Cooler Location

Direct evaporative coolers can be located on the roof or on the ground. Maintenance, a frequent requirement of most direct evaporative coolers, is easier in the ground location. However, a ground mounted cooler should be under a large shaded area, and must have free air access. If the cooler is surrounded by high fences and vegetation, put the cooler on the roof. If a duct is used, it will cost more with a ground mounted cooler, since larger ducts are required. When a roof mounted cooler is used, the airflow can be split immediately after it leaves the cooler, thus reducing the duct size required.

I. Alternate Non-Duct Systems

As mentioned previously, it is possible to blow the air from an evaporative cooler directly into a large daytime occupancy room. This is especially useful in retrofit situations, since ducts in existing homes are generally under sized for evaporative cooling. This method introduces the coolest air into the areas occupied during the day, and allows the cool air to flow through the house (the largest duct system available) and out unoccupied bedrooms, bathrooms, or sources of heat such as the kitchen. If additional cooling is desired in the bedroom areas at night, a second cooler can be installed for these areas.

J. Mass In Direct Evaporatively Cooled Homes

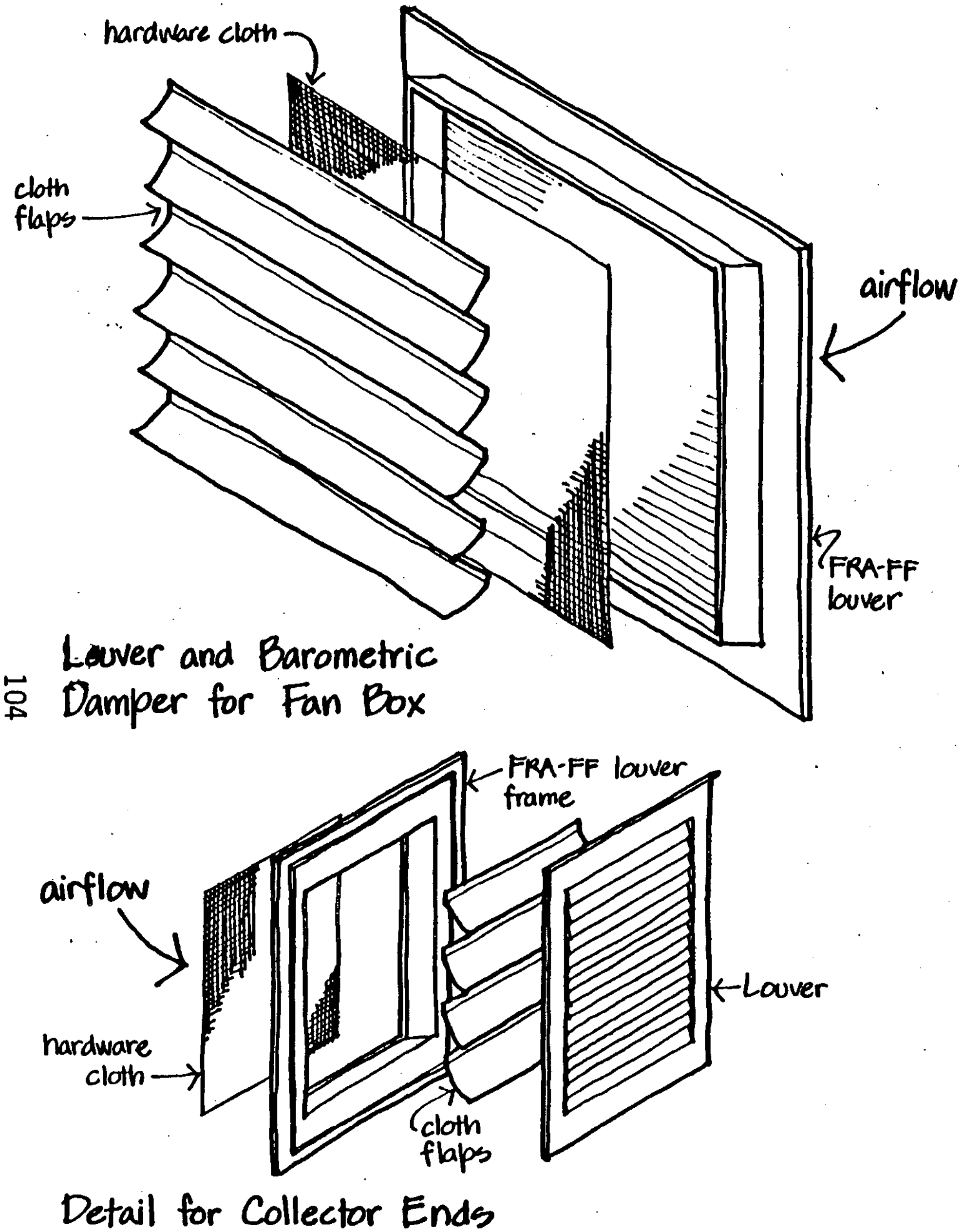


Figure 8. Barometric Damper

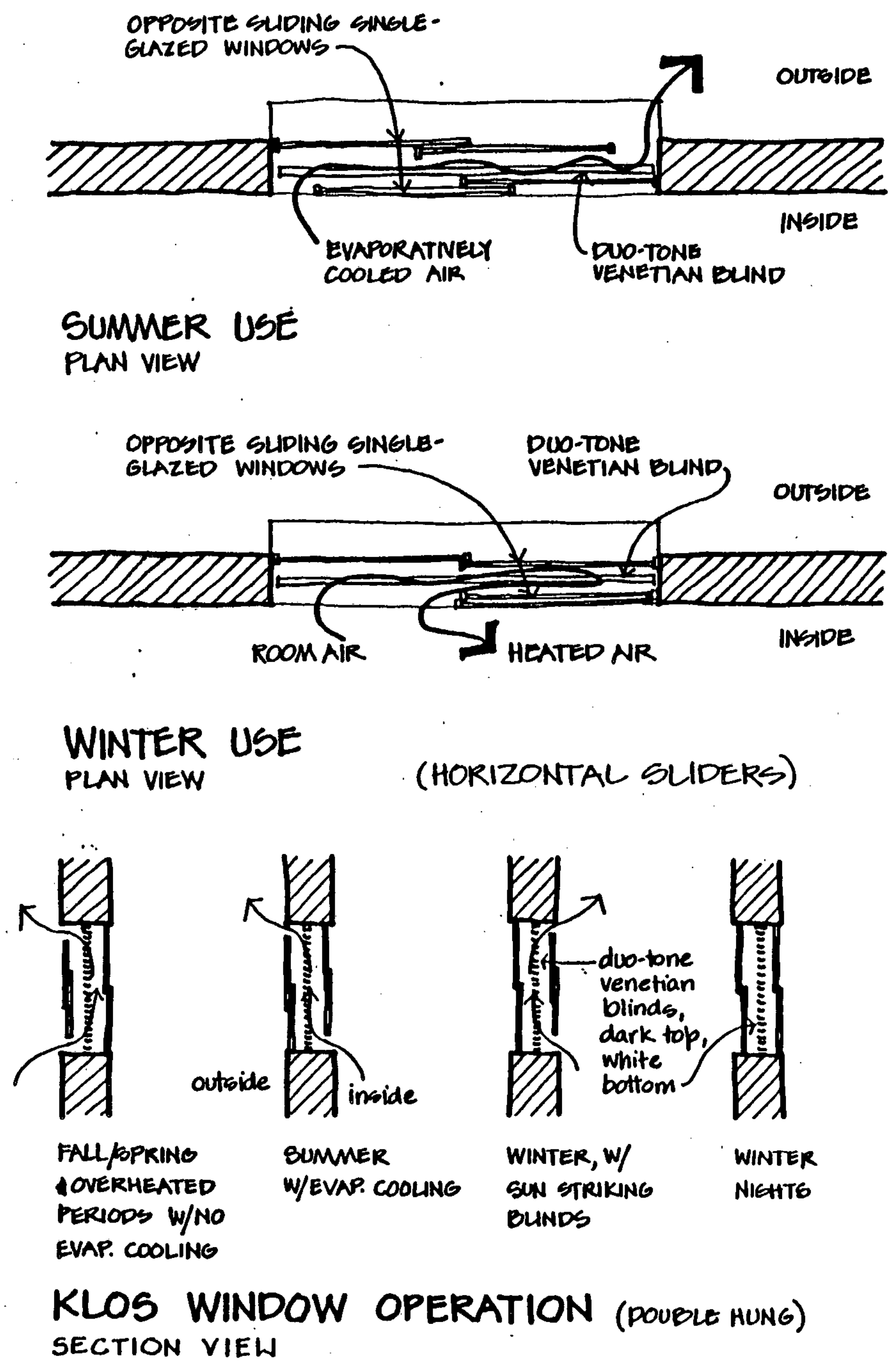


Figure 9

The above airflow patterns are especially useful in high mass homes (7). The cooler cools the mass in the daytime occupancy areas at night. The mass in those areas warms the air flowing out the bedrooms slightly, preventing excessive cooling (and reducing one's tendency to turn the cooler off at night). The next day, the cooled mass reduces the peak temperatures in the house, compared to those in a low mass house with the same evaporative cooling facilities. Figure 10 compares the interior conditions in a high mass (left side) and a low mass home with identical floor plans. Figure 11 illustrates the effect of mass in stabilizing interior temperatures, in the same two homes.

Such high mass homes also provide an opportunity to utilize dessicant systems to improve comfort. Although not experimented with yet, theoretically, one could use a dessicant to help dry out the air in an evaporatively cooled home. Since the air is heated only slightly as it dries, this minimal amount of heat could be absorbed by the cool walls of a high mass house. The dessicant would then be regenerated in a solar heater.

K. Cooler Maintenance

An evaporative cooler will perform well and last much longer if a schedule of weekly and yearly maintenance is carefully adhered to. Some tips for cooler maintenance are enumerated below.

1. The inside of the cooler should be completely tarred with black asphalt before it is ever used. This will extend its life significantly.

2. The cooler should be cleaned and retarred once a year, preferably at the end of the cooling season.

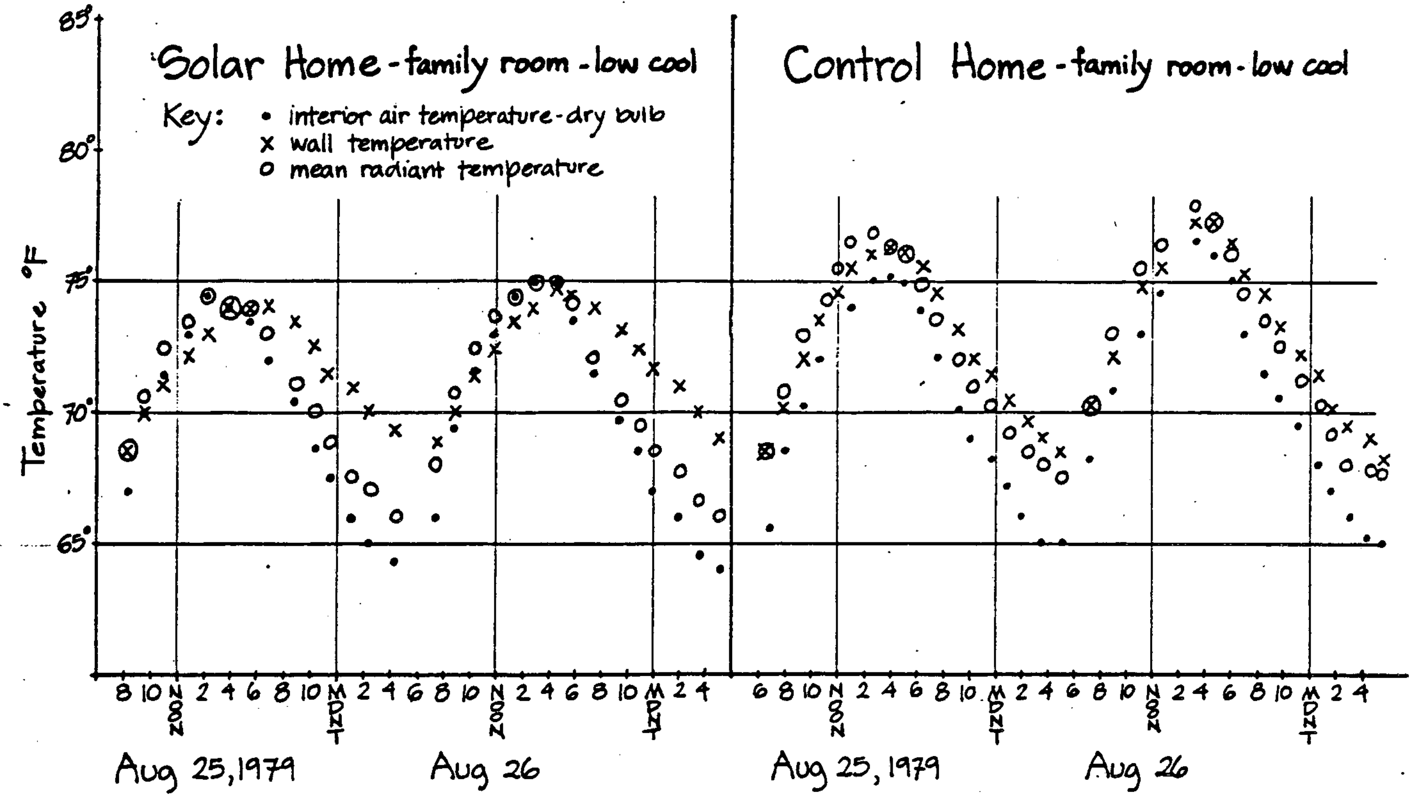
3. The excelsior pads should be changed at least once a year. Although it's more convenient to replace them when the cooler is being cleaned in the spring or fall, it may be more effective to change them in late June, just before the high heat of the summer. Pads with a cheesecloth covering should be avoided since they promote clogging by scale on the outer surface.

4. If a regular thumping sound is heard, the belt is cracked and should be replaced immediately — before it breaks at some inconvenient moment.

5. In order to reduce scale build-up on the pads (from minerals dissolved in the water), a "bleed off" kit may be installed. The kit allows a small amount of water to be removed constantly while the pump is on. Scale may also be controlled by draining the sump at least once a month.

6. The blower bearings should be oiled at least monthly.

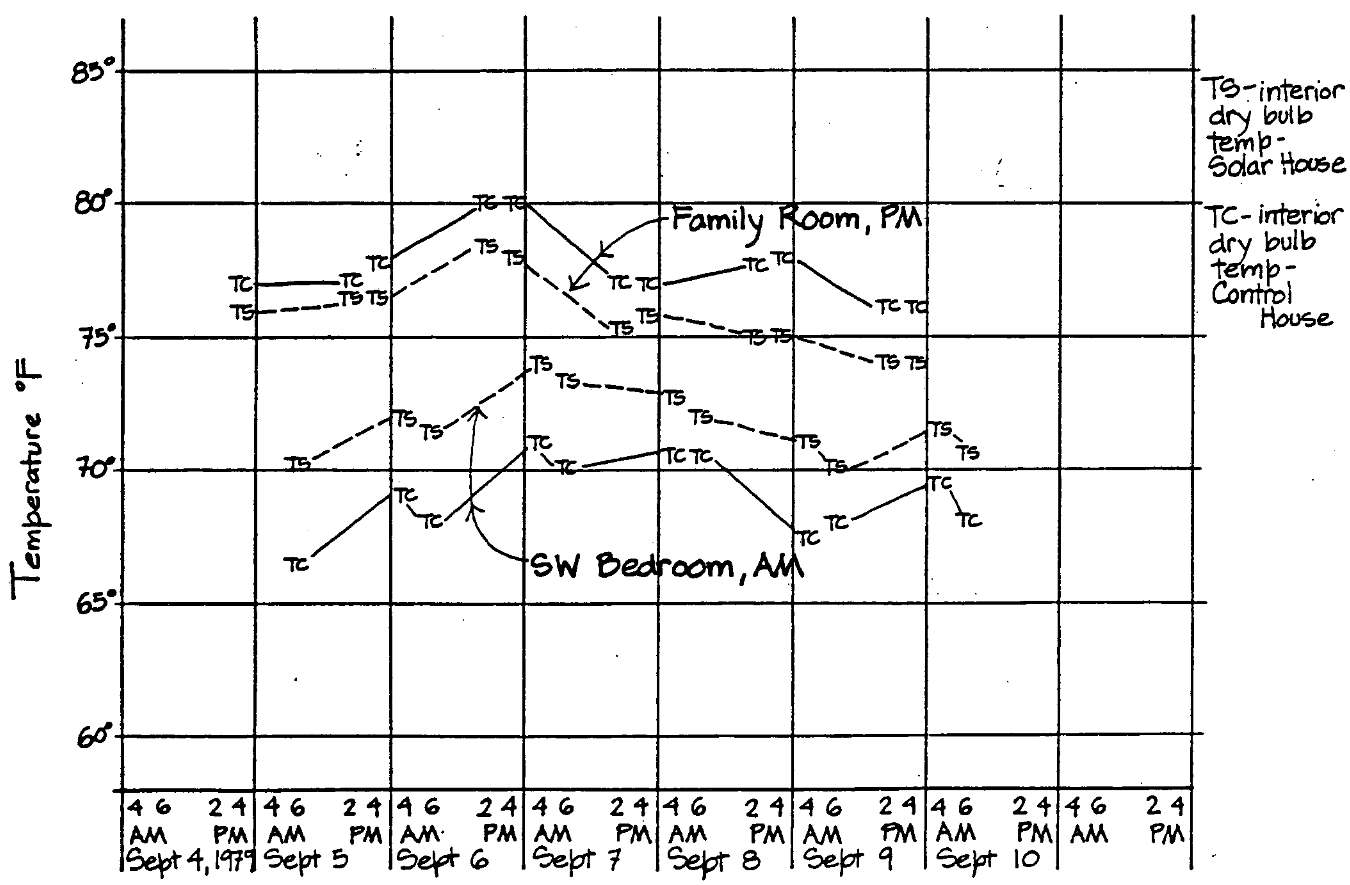
7. When the pads are only partially wet, they may produce a fishy smell. This can generally be avoided by either being sure the



Effect of High Mass Walls on Interior Air, Wall and Mean Radiant Temperatures

Figure 10

Modes SOLAR - Low Cool CONTROL - High Cool



Interior Dry Bulb Temperatures - Massive Solar & Standard Control House

Figure 11

pads are fully wetted before the blower is turned on or by using chemical tablets which destroy the biological growths causing the smell.

II. Two Stage Evaporative Cooling

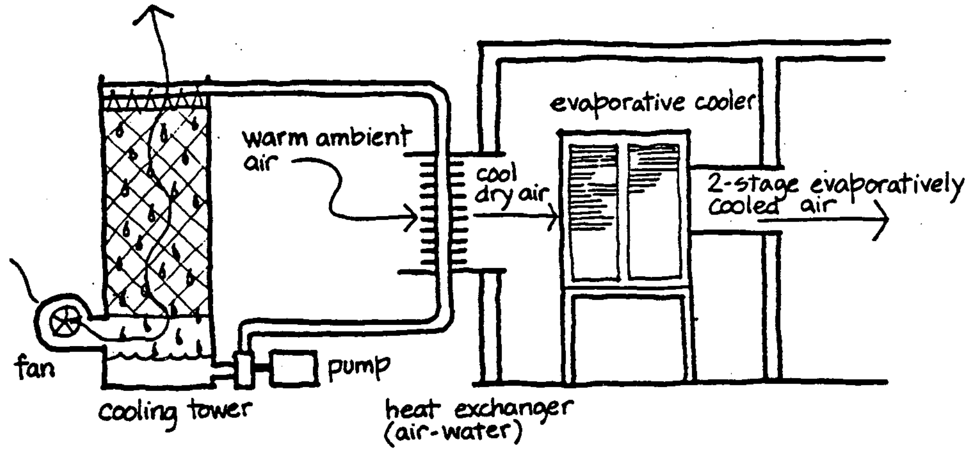
A system which precools air without humidification before evaporatively cooling it further is called a two-stage evaporative cooling system. A common type of two-stage evaporative cooling system uses a cooling tower as the first stage (8). The cool water from the cooling tower flows through an air-water heat exchanger (like a car radiator), and cools fresh air flowing over it without humidification. This precooled air is then cooled in an evaporative air cooler. See figure 12. The air washer (rotating drum type) of evaporative cooler or a spray type evaporative cooler (section I) have advantages over the standard box type evaporative cooler using aspen

Such systems produce cool air although some complaints about the humidity level have been noted during abnormally hot, humid weather. One was operated successfully at the Environmental Research Laboratory (ERL) for three years. It used a large water tank from a solar heating system to allow the coolth produced at night by the cooling tower to be stored for daytime use. Since we did not want to mix the cooling tower water with the water in the large storage tank, a water-to-water heat exchanger was placed between the cooling tower and the water tank. This system performed as designed, producing output temperatures approximately 6^{o} below that of a standard evaporative cooler. The limitations of this type of design are the approach temperatures of the various heat exchangers and the cooling tower.

When designing such systems, the power requirements of the entire system must be considered carefully, especially when fractional horsepower pumps and fans are used. A seemingly low sum of motor horsepower can draw surprisingly large amounts of current.

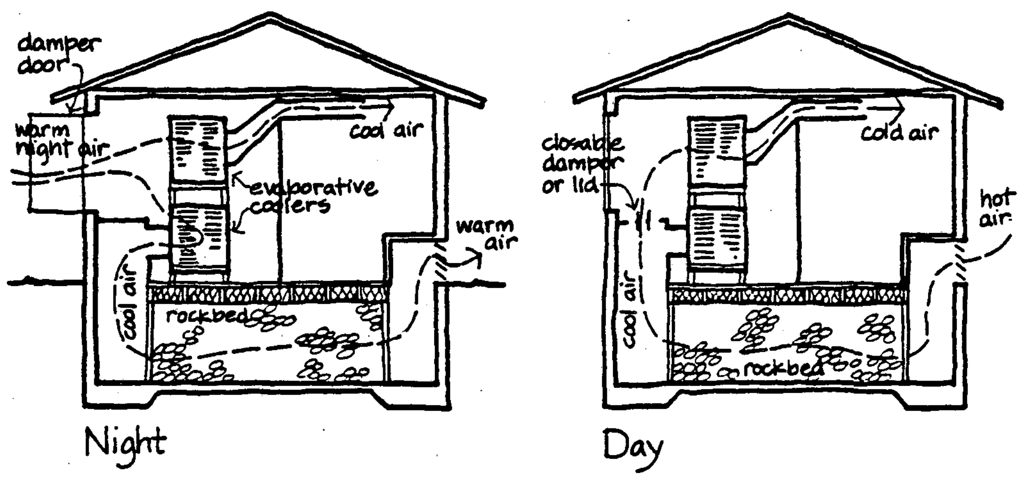
It is also possible to use an air-to-air heat exchanger to couple two evaporative coolers using the cool air from the first one to indirectly cool the air entering the second cooler. Unfortunately, air-to-air heat exchangers are relatively inefficient, and are rather difficult to obtain. Thus, a cooling tower has been preferred in systems described in the literature. An air-to-air heat exchanger is similar to the heat exchanger in a furnace, where the hot combustion gasses are separated from the warmed house air by a series of metal tubes.

Two-stage evaporative cooling systems using large rockbeds have been independently developed at CSIRO in Australia (9) and at the Environmental Research Laboratory (10). See figure 13. In this system, a large rockbed is evaporatively cooled at night and is used to precool air without humidification during the following day. Total power requirements can be quite small if the duct system and the rockbed are properly sized. Since the rockbed is an extremely efficient heat exchanger due to its large surface area, the out-put air temperatures of the rockbed are virtually identical to the rock temperatures themselves. Thus, the rockbed cools the



Two Stage Evaporative Cooling System using Cooling Tower

Figure 12



Schematic Diagram of Two Stage Evaporative Cooling w/ Rockbed

Figure 13

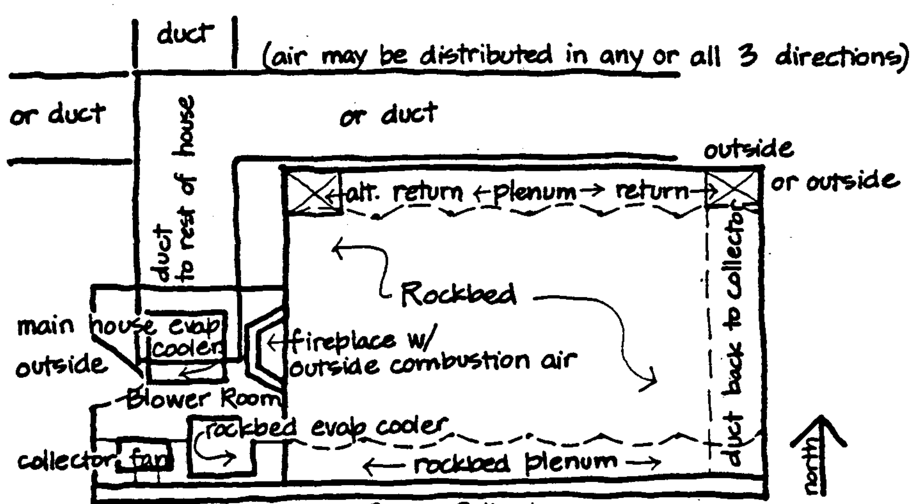


Figure 14

air passing through it during much of the day to temperatures available only at night. Systems without such thermal storage can only precool air to temperatures limited by daytime conditions. Thus, this system is actually more than a two-stage system.

On the debit side, this method does require a very large rockbed (which may be minimized through proper house design). Also, ordinary one stage evaporative cooling is used at night. However, this need not be a serious problem, since ordinary cooler output temperatures are lower at night because nocturnal radiation reduces both ambient dry and wetbulb temperatures. Because of the necessity of locating large openings near the rockbed for access to outside air, as well as locating evaporative coolers with outside air access near the rockbed, constraints are placed on the design of the house. A schematic layout of how one might incorporate a two-stage system in a house is shown in figure 14.

Data from the system at the Environmental Research Laboratory, which uses standard evaporative cooling, is shown in figure 15.

The psychrometric chart should be used at all times to analyze the effect of changing air conditions in these systems. While, as a rule of thumb, precooling the air 10°F will cause an approximately 3°F decrease in the output temperature of an evaporative air cooler, the improper use of this rule can lead to errors in judgement when analyzing the results of changing conditions.

The psychrometric chart in figure 16, schematically shows the changes in air as it passes through the various stages of a rockbed type two-stage cooling device. As the air is cooled without humidification, it moves from A to B along a constant moisture content line. Then it is evaporatively cooled from B to C along a constant wet bulb temperature line. If the ambient air had only been cooled by direct evaporative cooling, it would have been cooled from A to D along a constant wet bulb temperature line. Note that while the humid two-stage evaporatively cooled air is below the critical 15 mm Hg partial vapor pressure line mentioned by Olgyay (11), the direct (1-stage) evaporatively cooled air is above this level, and a fan is required for comfort. While one-stage or direct evaporative coolers have been deemed unsatisfactory during much of the hot and somewhat humid summers in Phoenix, two-stage cooling has been found to be comfortable, albeit a bit humid, some of the time. (In Tucson, the majority of people are satisfied with direct evaporative cooling except for about two weeks during the summer).

The two stage evaporative cooling systems described above do not directly use the relatively cool air exhausted from the home to improve the performance of the system. However, as has been described in Section I-G, this cool air can be exhausted through the hot air solar collector, windows and the attic so as to intercept heat before it heats the air inside the home. This reduces the size of the system required.

III. Indirect Evaporative Cooling

Indirect evaporative cooling is a very attractive form of evaporative

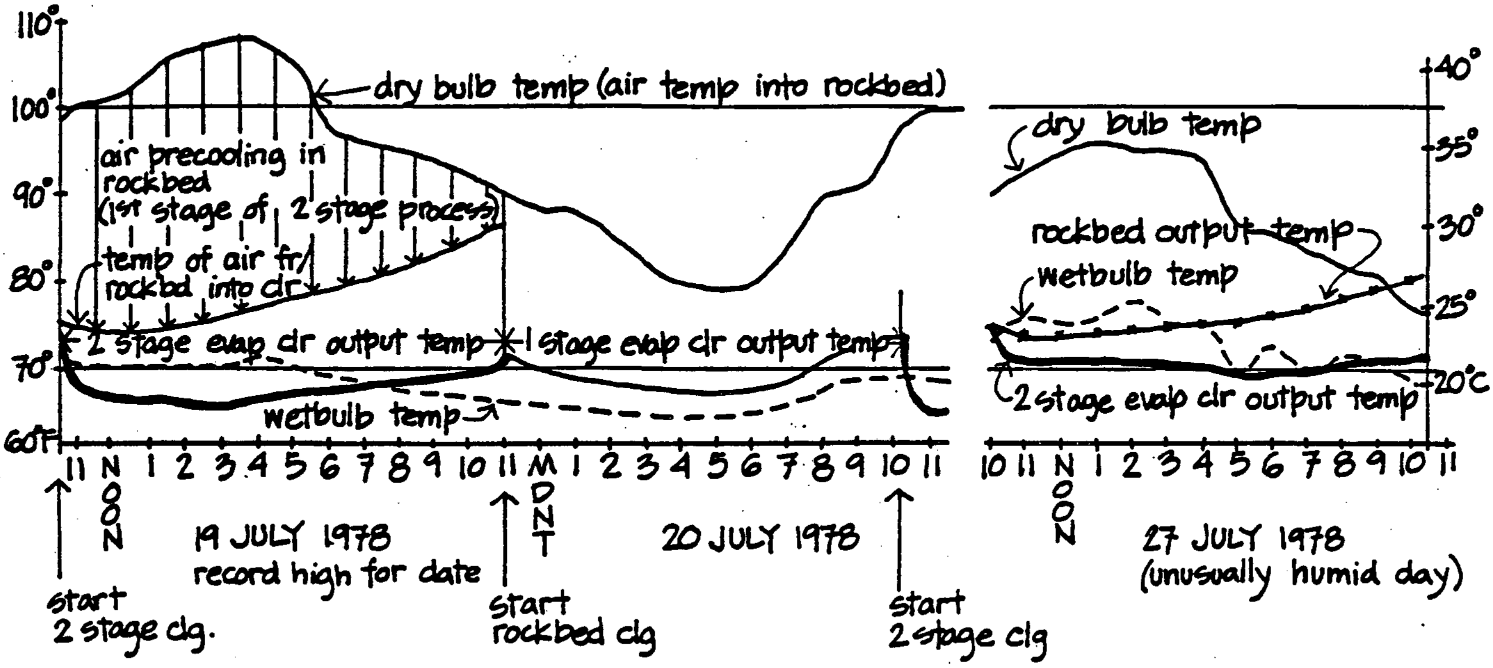


Figure 15

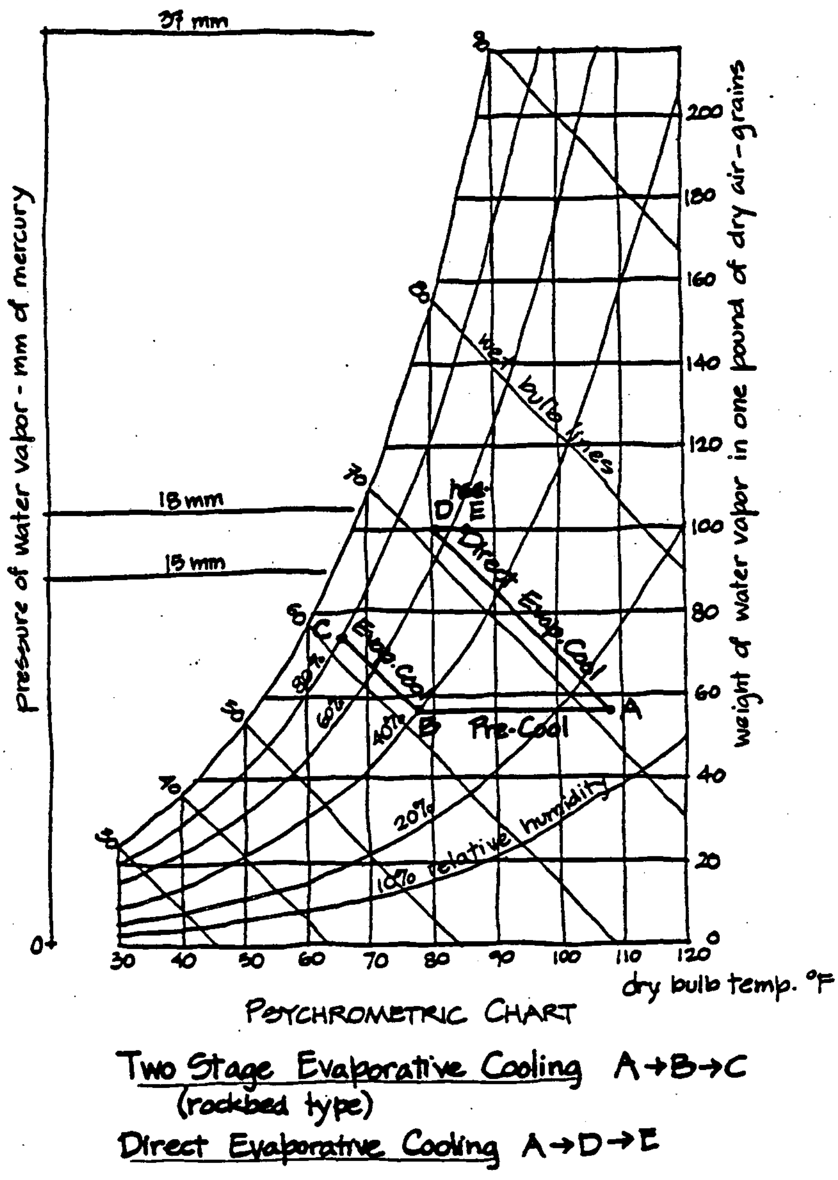


Figure 16

cooling, since the air is not humidified. However, since fluid cooled by an evaporative cooling device only approaches the wet bulb temperature, and since the house air only approaches the temperature of this cool fluid, the wetbulb temperature must be quite low (approximately 65°F or less) to keep the house interior at less than 80°F. This means that the method generally does not work well during humid summer weather. However, it was appreciated in the 1930's, since it was one of the few available methods of cooling.

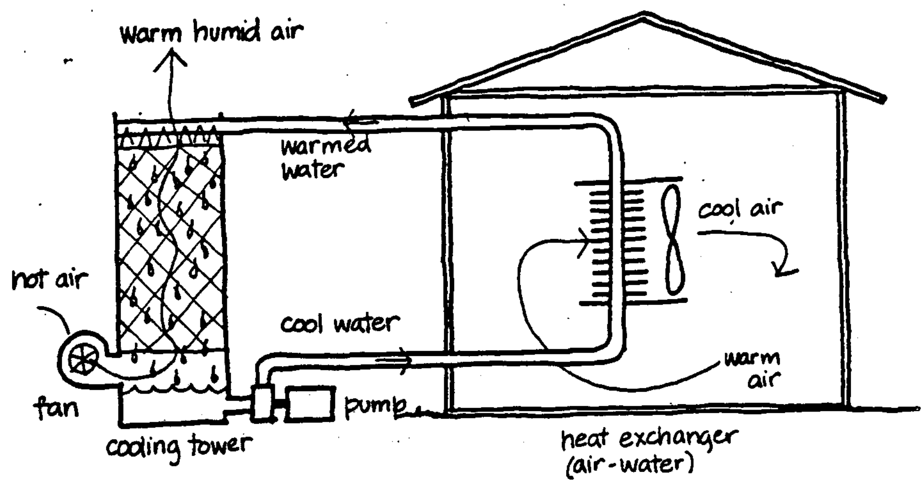
In the classic form of this system, water from a cooling tower is circulated through an air-water heat exchanger over which house air is recirculated (Fig. 17) (12). It is possible to design this system so that it is used for indirect evaporative cooling during drier weather, and two-stage cooling during humid weather, as was done at the Environmental Research Laboratory installation in 1974. In at least one case, the outside air was cooled by the heat exchanger and blown out through windows (13), instead of recirculating home air through the heat exchanger.

We have also used indirect evaporative cooling in our rockbed installations. As with two-stage evaporative cooling, the rockbed is cooled at night. Then, outside air is drawn through the rockbed during the day and enters the house without further cooling. During the dry periods in June and September, the output air is quite cool (Fig. 18 - "Dry Cool" on June 20 and 21). A further option would be to recirculate house air through the rockbed, which requires more power dampers.

IV. Recuperative (Regenerative) Evaporative Cooling Systems.

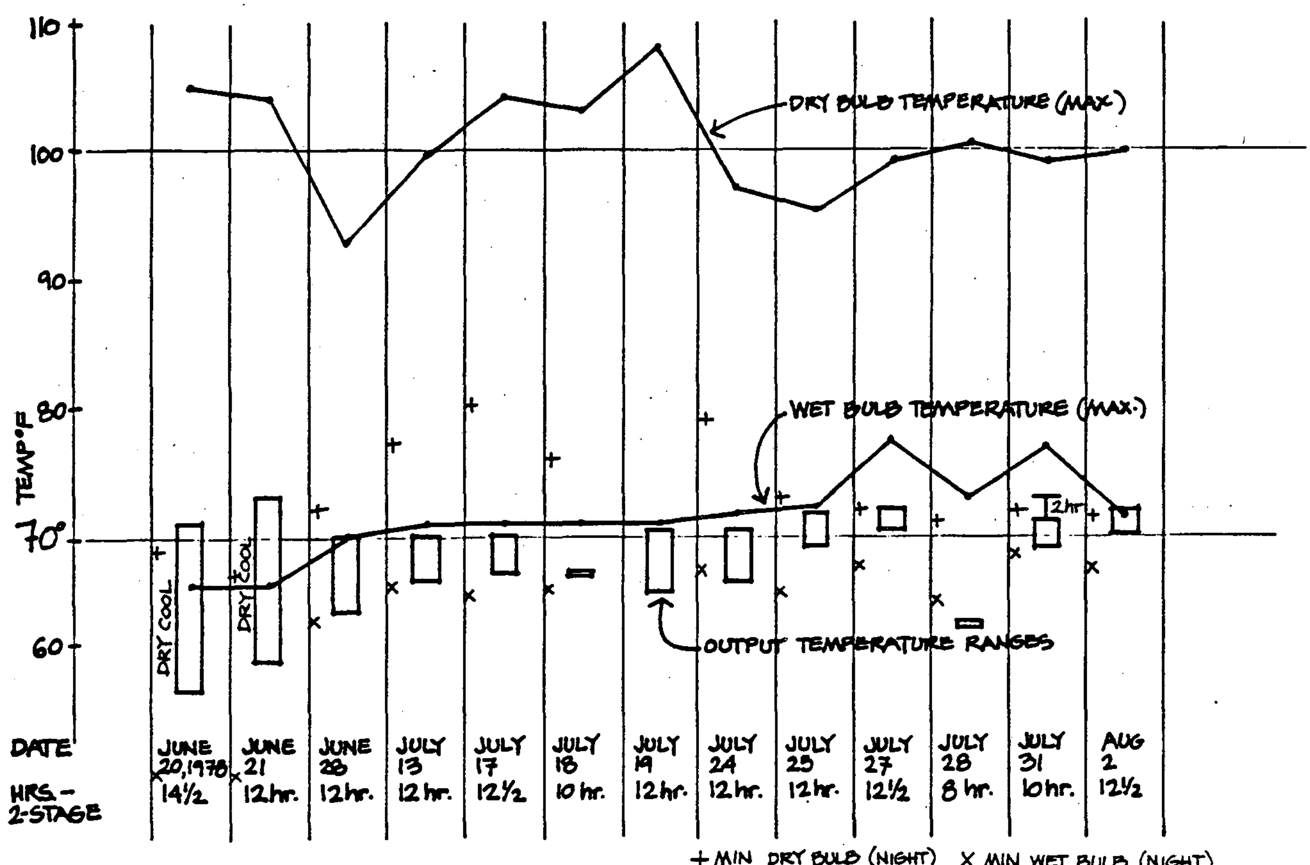
In a recuperative evaporative cooling system, outside air entering the house is cooled in a heat exchanger, flows through the house, and is exhausted through the evaporative cooling device that provides the cool fluid pumped through the heat exchanger. Since the house air exhausted through the evaporative cooling device is precooled and not humidified, the evaporative cooling device produces colder fluids for use in the heat exchanger and thus lowers the input temperature to the house. See Figure 19. Unfortunately, since air entering the house must be exhausted through the evaporative cooling device, the possibility of exhausting air so as to eject heat before it reaches the inner parts of the house is reduced. However, some installations exhaust the relatively cool air from the cooling tower through the attic (14).

One form of this device uses a cooling tower to produce the cool water flowing through the air-water heat exchanger, which cools the outside air entering the home. This air is precooled but not humidified, and exits through the cooling tower water, lowering the output temperature of the cooling tower water as compared to a cooling tower using outside air. For example, if the air rises 5 F as it passes through the house, if the heat exchanger has a 7 F approach temperature, and if the cooling tower has a 4 F approach temperature, the following would occur: Ambient air at 100°F drybulb/71°F wetbulb (A) entering the home is cooled to 76°F drybulb/63-1/2 wetbulb (B) (69°F water in the heat exchanger), and warms up to 81°F dry bulb/ 65°F wetbulb (C) as it passes through the house (5°F above the temperature of the air entering the house). The house air is then exhausted through the cooling tower which cools the water to 65°F (D). The



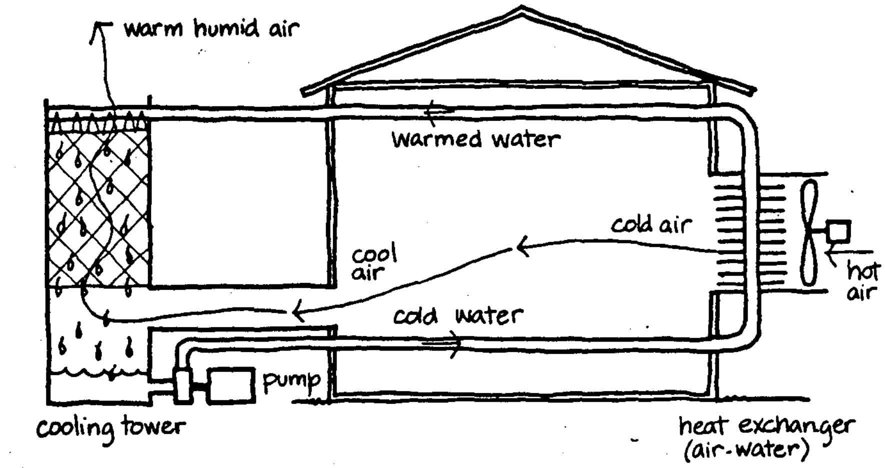
Indirect Evaporative Cooling

Figure 17



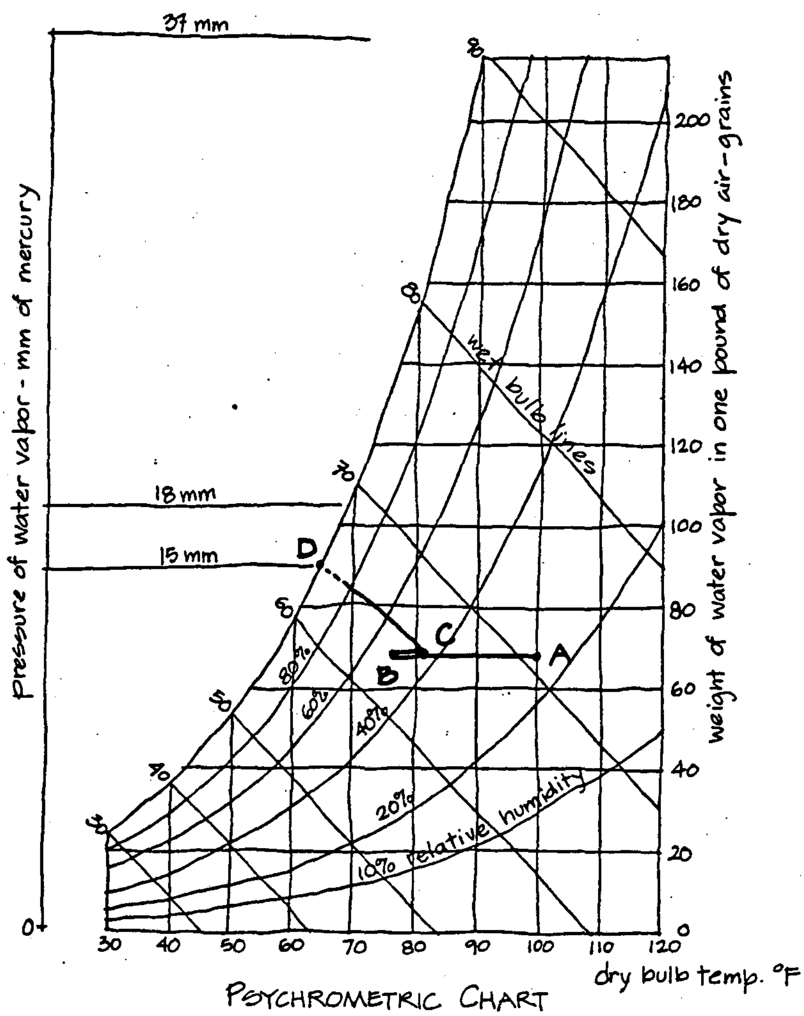
TWO STAGE EVAPORATIVE COOLING – (ERL INSTALLATION)
OUTPUT TEMPERATURE RANGES AND AMBIENT CONDITIONS

Figure 18



Regenerative Evaporative Cooling using Cooling Tower

Figure 19



Recuperative Evaporative Cooling (w/cooling tower & air/water heat exchanger)

Figure 20

cool water is circulated through the heat exchanger and the cycle begins again with the hot ambient air being cooled to 76°F drybulb/63 1/2°F wetbulb. See Figure 20. Thus, reasonable conditions (since the air is not humidified) can be maintained. However, in hotter and more humid climates, such as Phoenix, AZ, this system may occasionally produce less than the ideal conditions. However, they may still be quite acceptable when compared to ordinary air conditioners operated at high temperatures to minimize costs, or when compared to ordinary evaporative cooling systems. Closer approach temperatures can be used, but at greater capital and operating costs. (It should be noted that it is not possible to depict the temperature changes exactly on a psychrometric chart when a cooling tower and an air system are combined since the chart deals only with the properties of air).

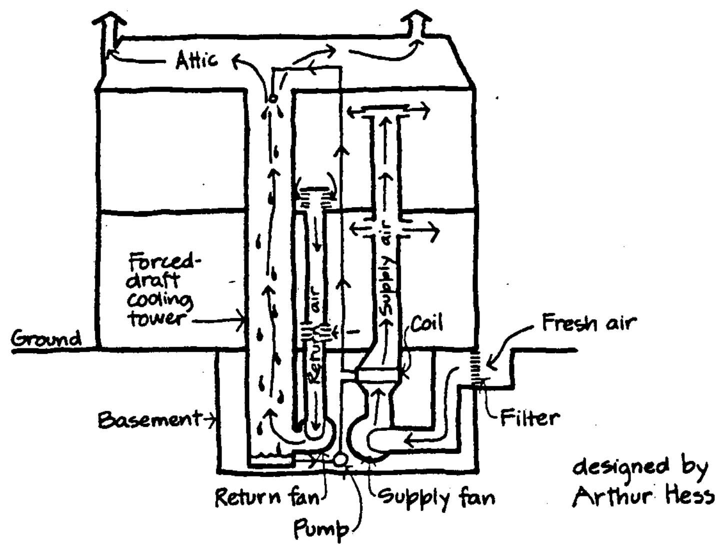
While it may be possible to use only one fan to blow air into and out of the house in this system, this can result in an objectionable pressure difference between the inside and the outside of the home. If properly balanced, two fans can reduce this effect.

The cooling tower water needs regular chemical treatment and "blowdown" (either constantly bleeding off small amounts of water or periodic changes of the water). This necessity to "blowdown" the cooling tower makes chemical treatment a continuous process.

Watt describes a regenerative cooling system built into the old Administration Building at the University of Arizona (15). The cooling tower was a central shaft in the building itself (Fig. 21) to facilitate exhausting all the cooled air in the building through it. The cooling tower air was exhausted through the attic to reduce heat flow from the roof to the rooms below. Otherwise, the system operated as previously described. Such a system with a built-in cooling tower might be useful in a home if the architect is willing to let the system influence the design of the house. Each room might have a heat exchanger in it with individual airflow controls.

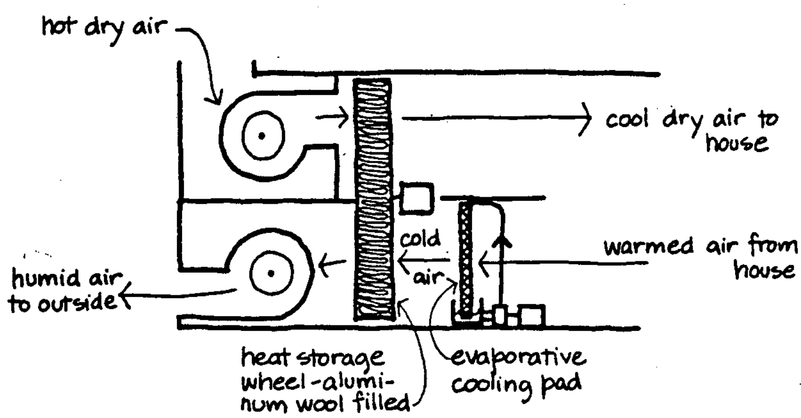
Regeneration wheel techniques have also been tested. Neal Pennington of Tucson used a rotating heat storage wheel one foot thick and filled with fine "aluminum wool" (Fig. 22) (16). The aluminum wool is cooled by air from an ordinary excelsior pad, drip type evaporative cooler, in the lower section. As it rotates into the upper section, it cools outside air drawn through the aluminum wool without humidification. The air cools the house, and exits through the evaporative cooling pads in the lower section, thus utilizing regeneration. Watt was impressed by the system, whose scaling and spray nozzle clogging problems are only those of a standard evaporative cooler. It has counter flow heat exchange, and in winter the heat storage wheel can be used to recover heat from ventilation air. Watt mentions that a calcium chloride desiccant wheel was added later, which partially dried the cool air entering the home (this does heat the air, however). This desiccant wheel was dried later in the process with fossil fuel derived heat. However, it could possibly be dried by a solar heated hot air device.

The famous Australian regenerative rockbed (RBR) uses the same principles, but has the advantage of the low approach temperatures inherent



Schematic diagram - University of Arizona Administration Building regenerative dry-surface system, 1936-52

Figure 21



Pennington heat storage wheel regenerative evaporative cooling device

Figure 22

in rockbeds due to their large surface area. Design equations and graphs are presented by Dunkle (17).

An older RBR (1965-1968), schematically illustrated in Fig. 23, (18), is used to explain the system initially, since it is simpler to understand than the newer version. Ambient air is drawn by the first fan through a 5" deep layer of closely sized 1/4" gravel (left side), which has been previously cooled. Then the air flows through a thinner 2" deep layer of the same size rock, also precooled. This cool unhumidified air enters the house and rises slightly in temperature as it cools the house. It is then exhausted by the second fan on the opposite side through a 2" layer of rock which was sprayed for a few seconds with water, at the start of the cycle. This layer of rock functions as an evaporative cooling pad.

The cooled air then cools the 5" layer of rock above the evaporative cooling layer. Since the air entering this side from the house is not humidified and is much cooler than the ambient air, these rocks are cooled more than would otherwise be possible. After five minutes, when the 2" rock layer on the right has dried out, the airflow is reversed. The outside air is then cooled without humidification by the right side, and the left side is cooled, or regenerated.

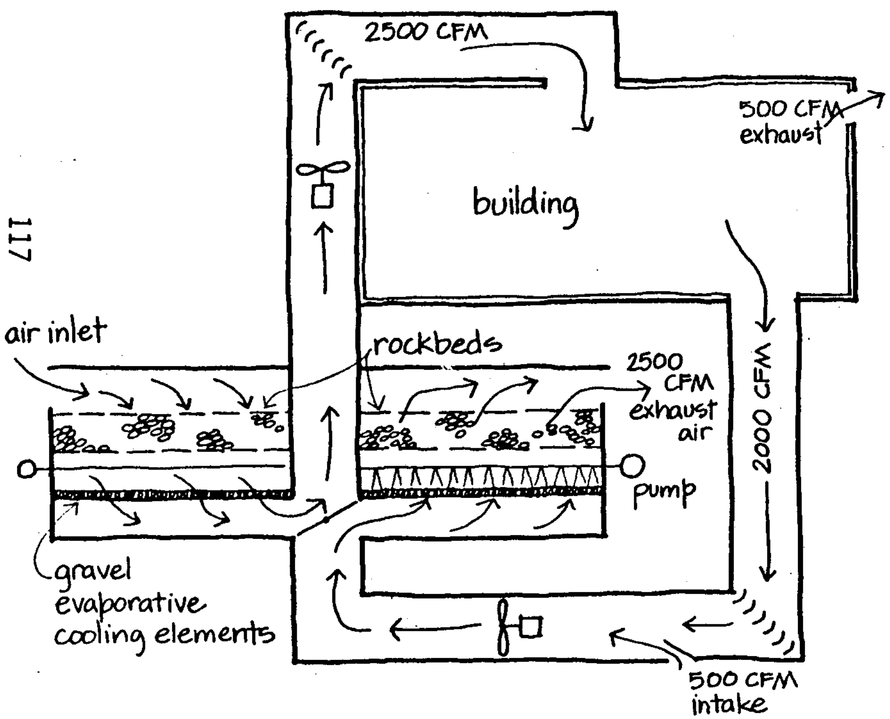
The newer Mark IV system is schematically illustrated in Fig. 24 (19). It is an 8'x12' x 2 1/2' deep metal box, divided into two compartments. A continuously wetted evaporative cooling rock layer is on one side only, and cools the 5" rockbed on either side, controlled by the dampers in the center. All rocks (gravel) are coated with a bituminous compound to reduce moisture absorption.

The path of the air on a psychrometric chart as it passes through a rockbed regenerative or recuperative evaporative cooling system is shown in Figure 25. Air at point A is cooled in the heat exchanger to point B where it enters the house. As it passes through the house, it warms slightly from B to perhaps C. As it is exhausted through the evaporative cooling pad and out through the rockbed being regenerated, it passes from C to D. Thus the house is essentially maintained at a temperature between B and C. If ordinary direct evaporative cooling were used, air at state point A would be cooled along a constant wet bulb line to state point E where it would enter the house and warm slightly to perhaps F.

This system appears to be quite good. Performance reports include mention of successful use in hard water areas, and that they have had no odor problems. Hogg (20) reports that the RBR produces output drybulb air temperatures approximating the ambient wetbulb temperature, without humidification.

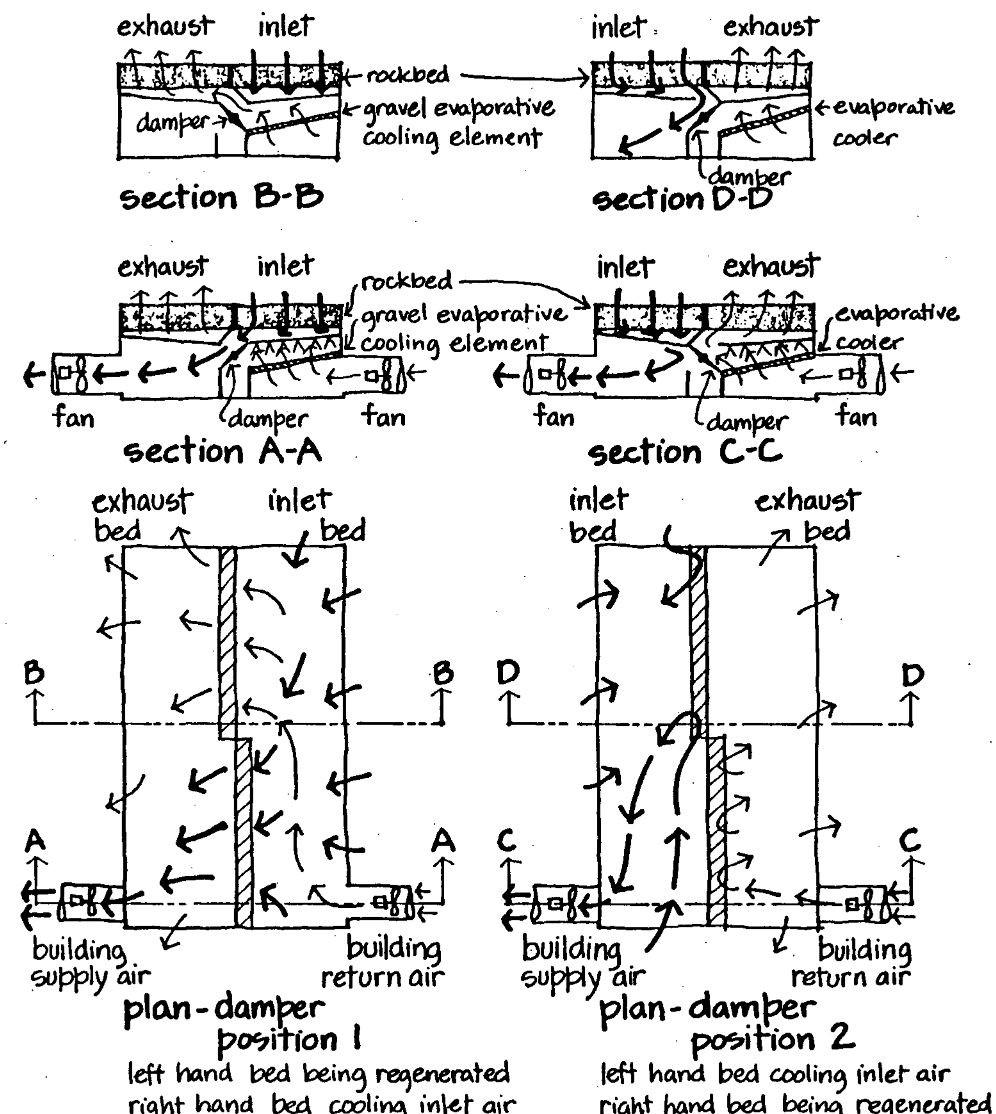
The RBR, as designed by CSIRO, does not appear to be immediately useful as a rockbed for a solar heating system. Design changes might allow this. However, since the CSIRO group is noted for its solar work, and did integrate their larger two-stage rockbed with solar heating, it is likely that no simple designs were evident for linking the RBR to a solar heating system.

The CSIRO group also used two fans in the system, so that the house is



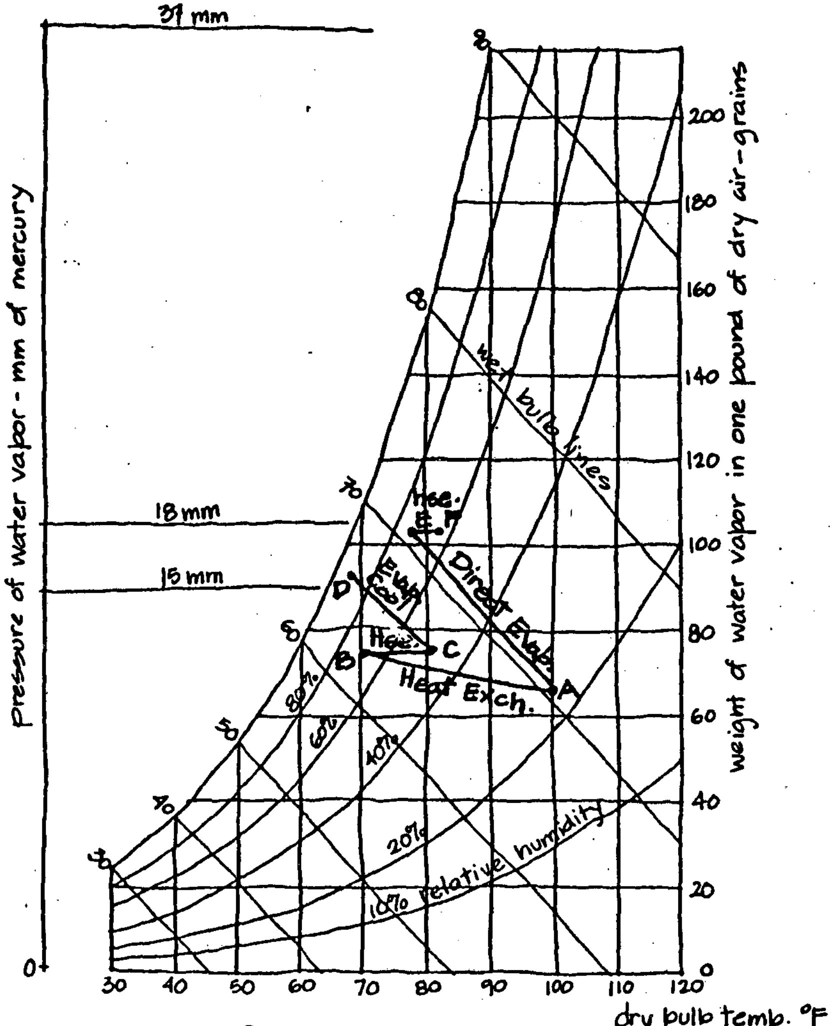
Schematic Diagram of Rock Bed Regenerative Cooling System (designed by CSIRO, Australia)

Figure 23



Rock Bed Regenerative Airflow Diagram (Mk IV) (designed by CSIRO, Australia)

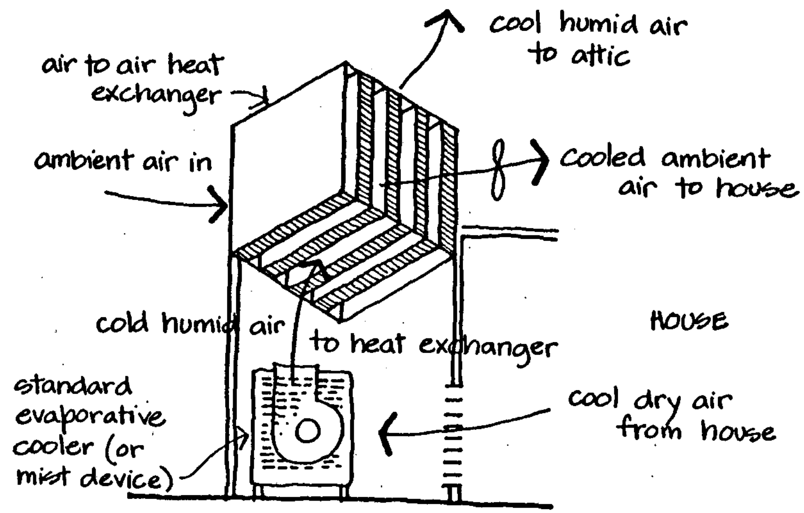
Figure 24



PSYCHROMETRIC CHART

Recuperative Evaporative Cooling A→B→C→D
(rockbed type)
Direct Evaporative Cooling A→E→F

Figure 25



Schematic Diagram of Recuperative Evaporative Cooling System w/air to air heat exchanger

Figure 26

neither under positive or negative pressure during operation of the system. If one fan were used, then the house would be under positive or negative pressure, depending on whether the fan is at the exit or the intake to the house.

Dr. Stanley Mumma of Arizona State University has done work on a system similar to the RBR in principle, but using standard evaporative coolers instead of the evaporative cooling rockbed. (21).

Pescod, of Australia (22), has developed a regenerative evaporative cooler that uses a plastic heat exchanger, which is a combination of a cooling tower and the air-water heat exchanger previously mentioned. Similar devices are made in the U.S. at this time. In the latter, ambient air flows across the dry surface of plastic tubes, which cool the air. This cooled ambient air passes into the house as before, warms slightly, and is exhausted over the wet outside surface of the aforementioned plastic tubes (covered by a fabric cylinder) onto which water is sprayed. Since, as in all regenerative systems, the air entering the tubes is cooled and has not been humidified, it can then lower the water spray to temperatures below those normally reached with ambient air. Thus, the ambient air entering the house is cooled to lower tempertures. Unfortunately, we could not obtain any reports with detailed drawings of the Pescod device. All these devices require a very large number of small tubes to attain sufficient surface area.

Pescod reports that he regularly achieved output dry bulb temperatures in his device equal to the ambient wetbulb temperature. The U.S. made devices achieved drybulb temperatures within 4°F of the wet bulb temperatures in a Phoenix, AZ installation. With lower airflow rates, the performance may have equaled that of the Pescod device.

Watt reports similar devices made of very large areas of parallel plates of metal which separate the air being cooled from the surface cooled by a water spray (23). Such units were built by Pernot and Rich. They did not use regeneration. Apparently, 100% outside air was cooled without humidification, or building air was partially recircuated through these units.

Watt reviews several devices similar to the above which he tested. He calls them "plate type" indirect or regenerative evaporative coolers. He showed that regeneration is effective, where air that has cooled the house is used as the air input into the water spray cooled chambers. However, if cool dry air from the device itself is immediately used as input air to the spray chambers, performance is reduced. This is due in part to the large total volume of airfow required to maintain a given flow rate through the house, and to the small incremental temperature reduction achieved by such practices. He also notes that the water sprays should be directed downward in "plate type" coolers, since water mist is not reliably carried far by air flowing horizontally.

It should also be possible to use parallel plate air to air heat exchangers coupled with the standard evaporative cooling devices described in section I.A. Ambient air would be cooled by one set of heat exchange surfaces, blown through the house, evaporatively cooled and blown through the other set of heat exchange surfaces (see Figure 26.). If this air enters the attic, it can be exhausted out in an area remote from the ambient air intake of the system, avoiding inadvertent recirculation of air, but without using an expensive duct system.

V. Other Evaporative Cooling Systems

Evaporative cooling may be used to cool air directly or to cool surfaces which cool air inside a space. For instance, as B. Givoni has suggested, an earth integrated house (which already takes advantage of the stabilizing effect of the earth), could be cooled further if the earth surrounding the structure is evaporatively cooled. One way this could be achieved is by irrigating the soil surface around the building. The surface could be covered with plants or pebbles (or both) for shade. (24). Kusuda has measured the effect of various surfaces on the seasonal temperature changes in the earth, noting that grasses lower the seasonal maximum temperature, and raises the seasonal minimum temperature. (25).

Porous earth tubes have also been used. Outside air is cooled by a combination of earth contact and evaporative cooling (by water in the soil diffusing to the surface of the tubes). Due to the length of the tubes that are used, the output temperatures are quite uniform. (26).

These systems would take advantage of both the stabilizing effects of the earth and evaporation.

Another evaporative cooling system which needs further study is the downdraft wind tower. A water mist is sprayed in the wind tower. As hot air is evaporatively cooled by the water, it flows downward into the structure. The airflow is aided by any wind present. The actual performance of a small unit tested at ERL by Charles Moody conformed quite well to his predicted performance. However, large well-insulated multi-directional wind towers will be needed for this cooling system. A solar chimney which passively vents air out of the opposite side of a structure may potentially improve the performance of the wind tower.

In relatively milder (cooler) arid climates, such as Las Cruces, night ventilation over a fountain such as the system in Dr. Ed Lumsdaine's home are effective in addition to being aesthetically pleasing and quite soothing. We have now returned to the paradise of the medieval arab mentioned in the introduction.

CONCLUSION

The large and extremely varied types of systems for evaporative production of "coolth", are a monument to the explosive inventiveness of mankind when a basic principle bearing upon a universal problem becomes widely known. However, we believe that due to cost, direct evaporative cooling (modified in some cases by the improvements described in section I) will be the predominant system in most hot arid regions.

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EVAPORATIVE COOLING: ROOFS AS DISSIPATORS

Fred M. Loxsom *   Brian Kelly *

ABSTRACT

Passive cooling using a building roof as a dissipator surface can use evaporative cooling to increase the cooling rate. Equations, graphs, and maps which enable a designer to estimate the cooling rate of a wetted horizontal roof are presented.

INTRODUCTION: DISSIPATOR ROOFS

There are many ways to use evaporative cooling in passive and hybrid cooling systems. In this paper, the application of evaporation will be limited to wetted horizontal roofs. These roofs might be storage roofs with moving exterior insulation (Fig. 1a) or permanent shading (Fig. 1b). Alternatively, these roofs might be light weight cooling roofs with slab storage (Fig. 1c). Coupling between the dissipator roof and the living space might be by convection alone (Fig. 1d).

The details of the coupling between the roof and the living space on the roof and storage will not be discussed here; instead we will look carefully at the ability of the wetted horizontal roof to dissipate heat to its exterior environment. The designer of a passive building which will use a wetted roof as a heat dissipating surface needs to know the cooling potential of this roof under local ambient conditions. This paper is designed to give the designer the means for making an estimate of this cooling potential.

The roof will be treated as a horizontal surface which is flooded with a continuous layer of water.

COOLING PROCESSES

A wetted horizontal roof will exchange energy with its exterior environment by four processes:

a. thermal radiative transfer (radiation)
b. evaporation,
c. convection, and
d. solar gain.

In most cooling situations, convection and solar gain represent a cooling load which the surface must dissipate.

The net cooling rate for a surface, $\dot{Q}_T$, represents the sum of these four terms:

$$\dot{Q}_T = \dot{Q}_R + \dot{Q}_E + \dot{Q}_C + \dot{Q}_{SG} , \tag{1}$$

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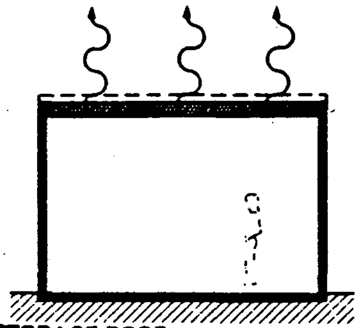
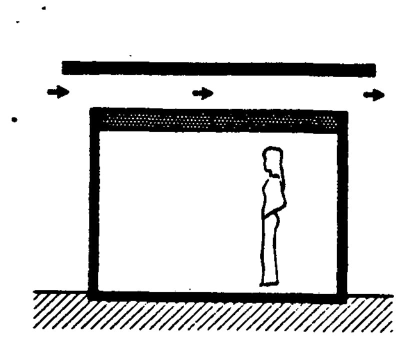


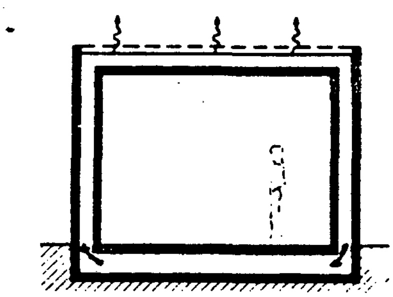
STORAGE ROOF
(NIGHT-SKY RADIATION)
(REQUIRES MOVING INSULATION)

FIGURE 1A



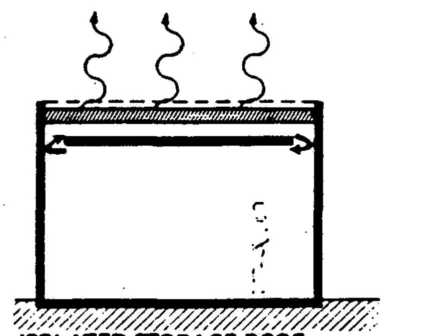
FLAT SHADED STORAGE ROOF
(WIND-AUGMENTED EVAPORATION)

FIGURE 1B



COOLING ROOF WITH
STORAGE FLOOR
(NIGHT-SKY RADIATION)

FIGURE 1C



ISOLATED STORAGE ROOF
(NIGHT-SKY RADIATION)
(REQUIRES MOVING INSULATION)

FIGURE 1D

where

$\dot{Q}_R$ = net radiative loss from surface,

$\dot{Q}_E$ = evaporative loss from surface,

$\dot{Q}_C$ = convective loss from surface, and

$\dot{Q}_{SG}$ = solar gain by surface.

The convention used here is that a loss from the surface is a positive number; therefore, $\dot{Q}_{SG}$ is always a negative number.

The radiative cooling resource is represented by effective sky temperature; clouds will drastically reduce this resource. In another chapter of this handbook, Paul Berdahl and Gene Clark discuss in detail this important cooling resource.

The evaporative cooling resource is represented by the wet-bulb temperature; a combination of high temperature and high humidity will reduce this resource.

COOLING RATE EQUATIONS

Exact Equations

Each of the terms in Equation 1 may be represented by a cooling rate equation:

$$\dot{Q}_R = \varepsilon\sigma \, (T^4 - T_S{}^4), \tag{2}$$

where

ε = surface emissivity,

σ = Stefan-Boltzman constant,

T = absolute surface temperature, and

T_S = absolute effective sky temperature.

$$\dot{Q}_C = h_C \, (T - T_A), \tag{3}$$

where

h_C = convective heat transfer coefficient, and

T_A = ambient drybulb temperature

$$\dot{Q}_E = (H_{FG}/(Le \; C_p)) \; h_C \; (W_S - W_A), \tag{4}$$

where

H_{FG} = Enthalpy of evaporation for water

Le = Lewis Number

C_p = heat capacity of moist air

W_S = saturation humidity ratio at T, and

W_A = humidity ratio at T_A

$$\dot{Q}_{SG} = - \alpha \, I_{TH} \tag{5}$$

where

α = effective absorption coefficient of surface, and

I_{TH} = total insolation on the horizontal.

Convective heat transfer coefficient

Heat transfer between a surface and the environment may be characterized as free, forced laminar, or forced turbulent. Since forced turbulent conditions will usually dominate heat transfer for passively cooled buildings, only heat transfer for forced turbulent flow[1] will be discussed here:

$$h_C = C\left(\frac{k}{L}\right) Re^{0.8} \quad Pr^{0.33} \tag{6}$$

where

k = thermal conductivity,

L = characteristic length,

Re = Reynolds number,

Pr = Prandtl number, and

C = is a constant.

Approximate Equations

Equations (3) and (4) may be combined and approximated by a well known equation[2].

$$\dot{Q}_{EC} \equiv \dot{Q}_E + \dot{Q}_C = 3h_C \left(\frac{T+T_{WB}}{64.7} - 1\right) (T - T_{WB}), \tag{7}$$

and h_C may be approximated by[3]

$$h_C = 1 + 0.3V, \tag{8}$$

where

T_{WB} = ambient wet bulb temperature,

V = windspeed in mph,

T and T_{WB} are expressed in ^{o}F, and

$\dot{Q}_{EC}$ is in BTU/hr - sq. ft.

Figure 2 and Table 1 illustrate the relationship between the exact cooling rate and the approximate cooling rate for typical conditions.

For these comparisons, L was set equal to 20' and C was taken to be 0.054. This value of C includes the effect of surface roughness.

In general, the approximate equations over-estimate the cooling resource.

FIGURE 2

COMBINED EVAPORATIVE AND CONVECTIVE HEAT LOSS

vs.

WIND SPEED

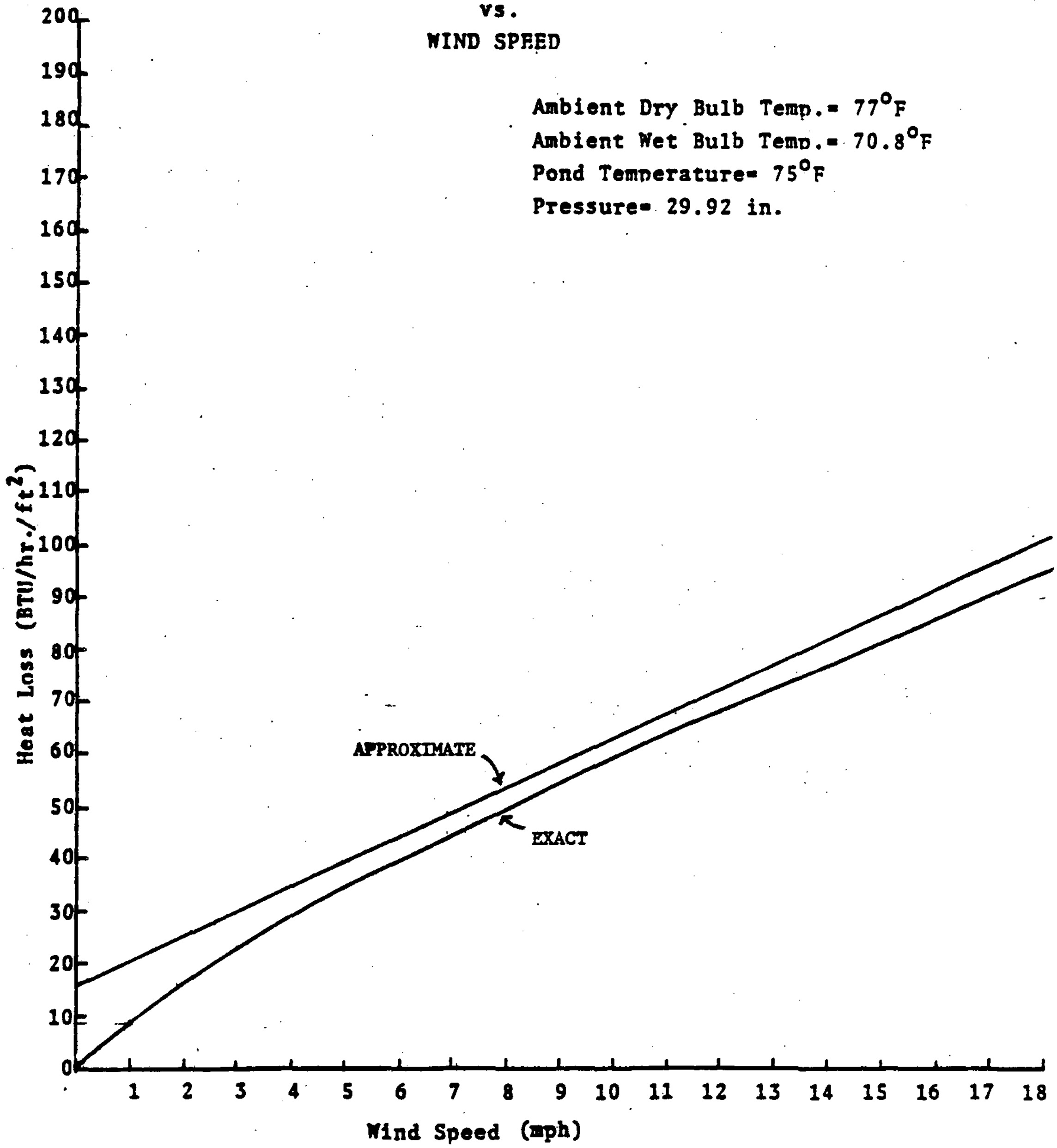


TABLE 1

Average July Nocturnal Passive Cooling Rates for Combined Evaporative, Convective, and Radiative Heat Transfer Average Hourly Data (1955-1964); Pond Temperature = 75°F.

CITY	Cooling Rate (BTU/Day/Sq. Ft.) EXACT	APPROXIMATE	DIFFERENCE
El Paso	1535	1470	+65
Los Angeles	1528	1422	106
Detroit	1504	1414	+90
Miami	30	14	+16
Little Rock	222	160	+62
Phoenix	830	760	+70
San Antonio	267	204	+63

Two basic insights may be gained by examining Eqs. (7) and (8). Evaporative cooling rates go to zero at $T = T_{WB}$; without the use of radiation cooling, a wetted roof can not cool below the wetbulb temperature. Cooling rates are very windspeed dependent; evaporation may be greatly increased through the use of natural or mechanically enhanced air flow over the wetted surface.

ESTIMATING NOCTURNAL COOLING RATES

Moving Insulation

Harold Hay's Skytherm System[4] is an example of the storage roof and represents a thermally superior application of passive cooling. Moving insulation covers the dissipator roof whenever a net heat gain would occur. Although this moving insulation presents a serious architectural challenge for the designer, the advantage of cutting out heat gains during the day, and including full sky radiation at night are considerable. For these reasons, Trinity University with the support of U.S.D.O.E. has carried out a national assessment[5] of the cooling resource available to a storage roof or a cooling roof with moving insulation. A large open wetted surface is assumed to be exposed to the night sky and covered by a highly insulating cover during the day. The nocturnal cooling rates (BTU/NIGHT-sq. ft.) for 77 U.S. cities were calculated for a typical July using the exact equations discussed in the previous section. These results form the basis of the estimation method discussed here.

Although the equations used for these simulations are theoretically sound, considerable uncertainty exists about the role of roughness for a real surface. In these simulations, roughness is taken into account by setting C equal to 0.054. The characteristic length L is assumed to be 20'. This uncertainty must be resolved by further experimental work.

July Cooling Rate Contours

Estimating the nocturnal cooling rate for your location begins by locating the site of the proposed passive building on Figures 3 through 8. These contour maps may be used directly to estimate the July cooling rate of any contiguous U.S. location for surface temperature from 60^0 to 78^0F.

July Cooling Rate Graphs

In order to allow more accurate estimation of cooling rates for a given site Figures 9 through 17 display July cooling rates for 29 U.S. cities for temperatures 66^0F to 78^0F.

These graphs together with the contour maps can be used to estimate the cooling ratio with a higher accuracy than with the contour maps alone.

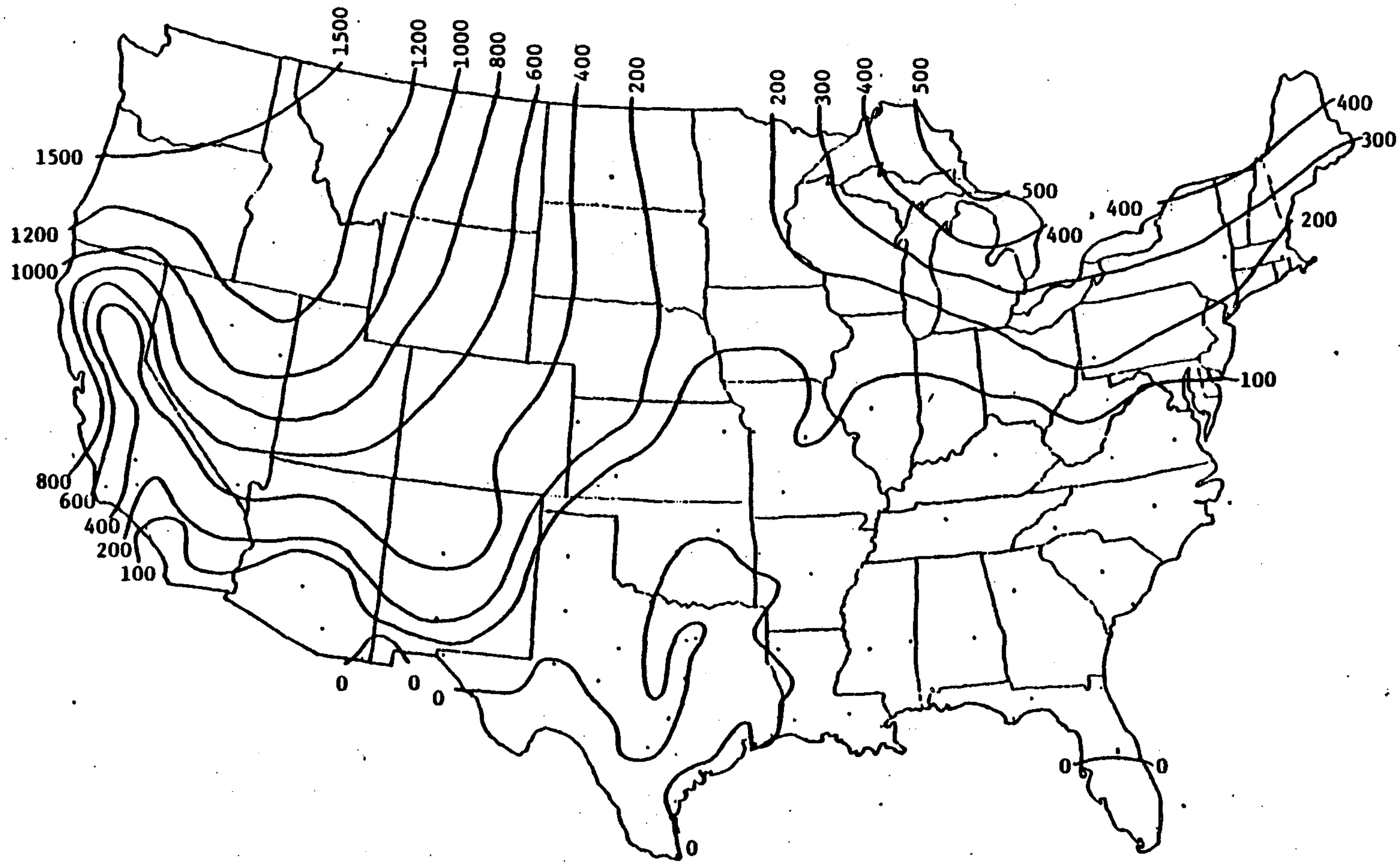
Variation in Cooling Rates for Four Different Months

The previous figures have displayed average values of cooling rate for July only. For many applications, it is important to know the distribution of cooling rates within a given month and to know cooling rates for months other than July. Tables 2 through 7 contain average, maximum, and minimum cooling rates for June, July, August, and September for six representative U.S. cities. The region which each of these cities represents may be estimated from Figures 3 through 8.

FIXED EXTERIOR INSULATION

Since moving insulation above a mass storage roof poses serious architectual and maintenance problems, heat dissipating roofs with fixed shading offers a distinct architectual advantage. If natural convection between the shades and the roof is supplemented by mechanical means, higher cooling rates can be achieved. In order to simulate this system, a horizontal roof covered by a horizontal insulating shade is assumed; the shade is modelled to be at roof temperature and blocks all radiative exchange. All heat transfer (day and night) is by convection and evaporation.

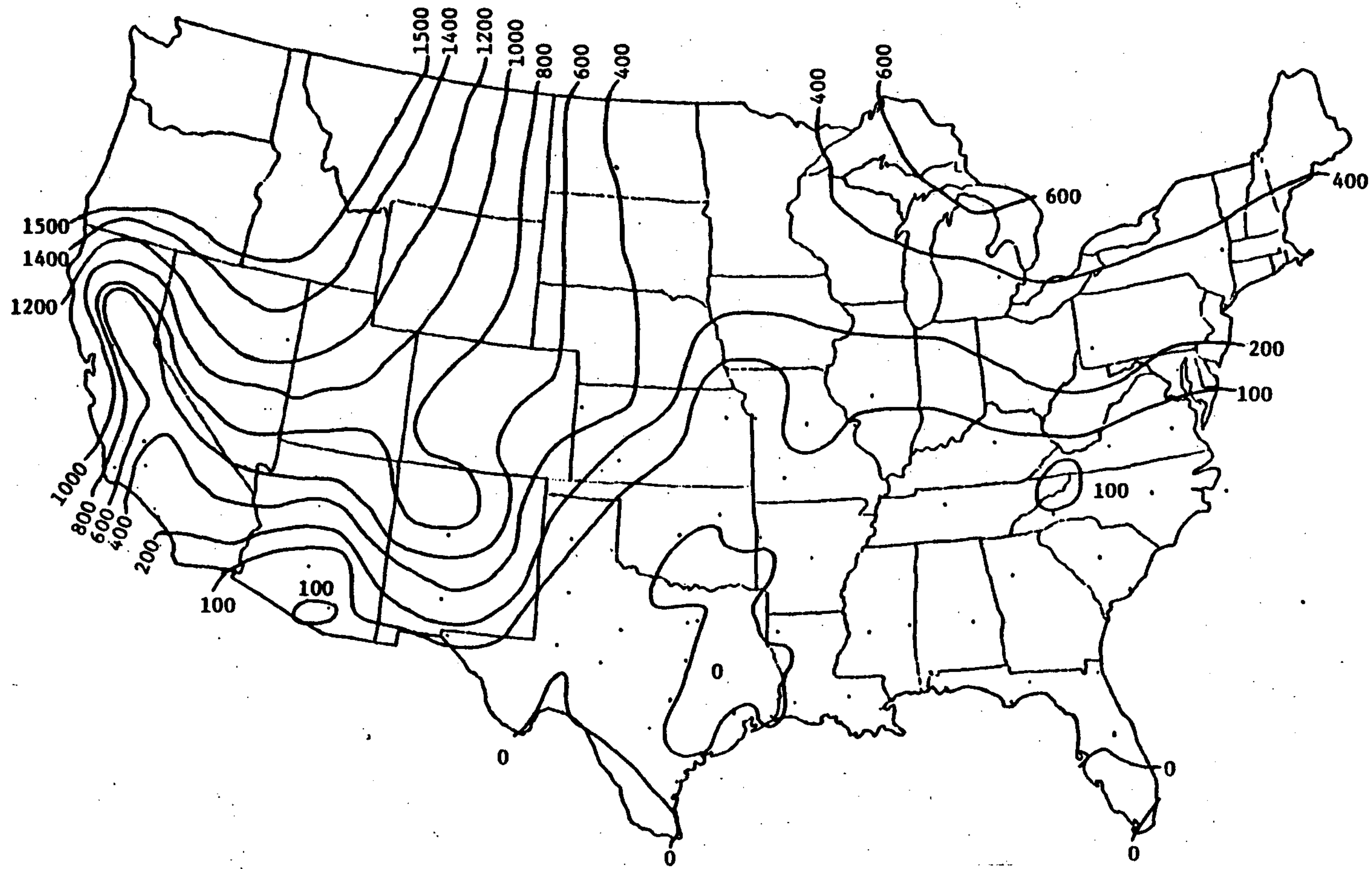
Comparision of cooling rates for roofs with fixed insulation (an insulating shade) and roofs with moveable insulation are shown in Table 8. For this comparison, the windspeed between the roof and the shade is assumed to equal the ambient. This comparison shows that at low dissipator surface temperatures (below 76^0F), moveable insulation offers a distinct advantage over fixed in most locations. Estimates of cooling rates with fixed insulation can be made assuming that the cities listed in Table 8 are representative of regional climate types.



TYPICAL JULY NOCTURNAL NET COOLING RATE FOR WET SURFACE AT 60°F (BTU $FT.^{-2}$ DAY^{-1})

(77 CITY HOURLY DATA BASE. SURFACE IS PERFECTLY INSULATED WHENEVER IT CANNOT DISSIPATE HEAT.)

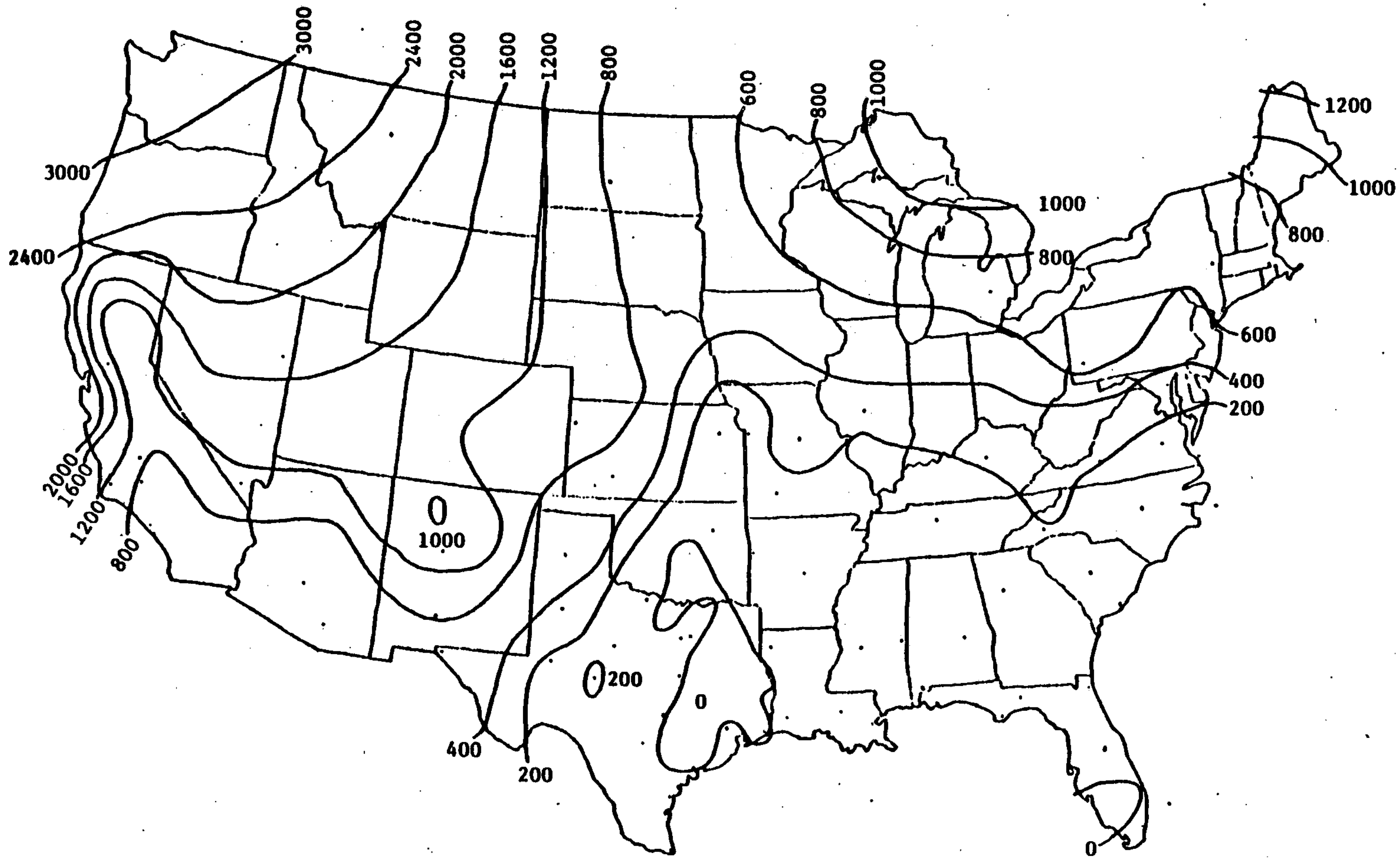
FIGURE 3



TYPICAL JULY NOCTURNAL NET COOLING RATE FOR WET SURFACE AT 62°F (BTU FT.$^{-2}$ DAY^{-1})

(77 CITY HOURLY DATA BASE. SURFACE IS PERFECTLY INSULATED WHENEVER IT CANNOT DISSIPATE HEAT.)

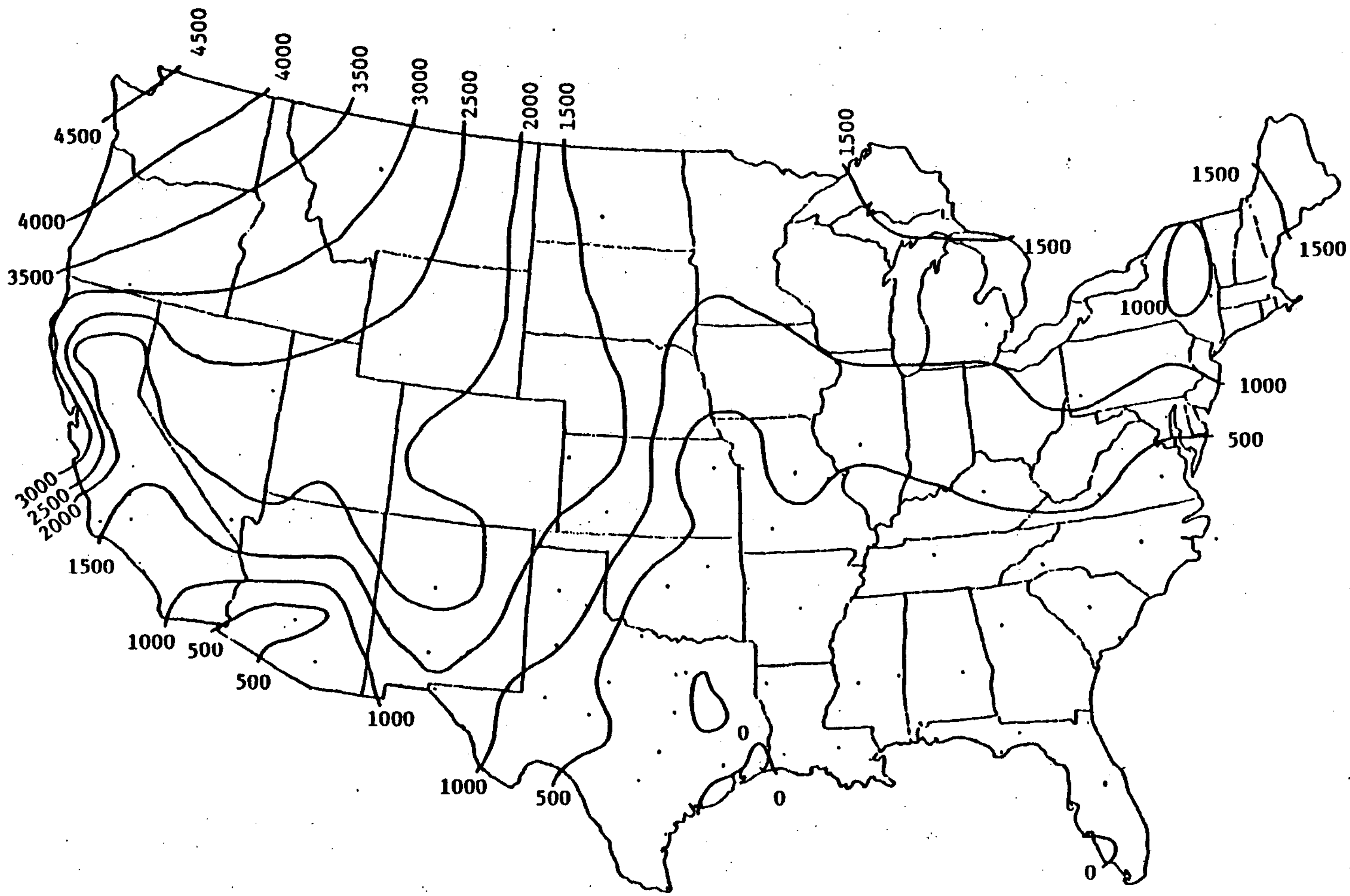
FIGURE 4



TYPICAL JULY NOCTURNAL NET COOLING RATE FOR WET SURFACE AT 66°F (BTU FT.$^{-2}$ DAY^{-1})

(77 CITY HOURLY DATA BASE. SURFACE IS PERFECTLY INSULATED WHENEVER IT CANNOT DISSIPATE HEAT.)

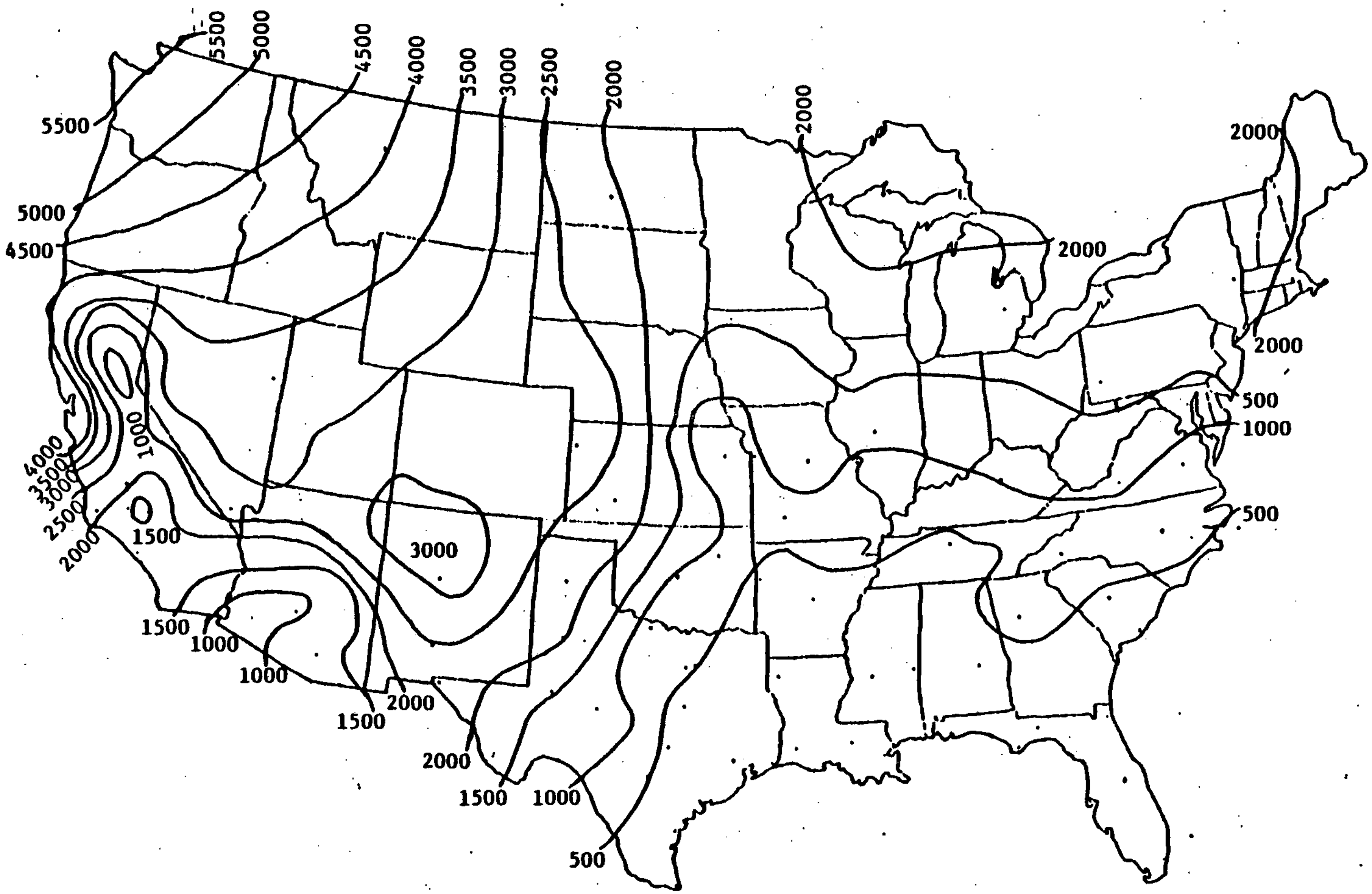
FIGURE 5



TYPICAL JULY NOCTURNAL NET COOLING RATE FOR WET SURFACE AT 70°F (BTU FT^{-2} DAY^{-1})

(77 CITY HOURLY DATA BASE. SURFACE IS PERFECTLY INSULATED WHENEVER IT CANNOT DISSIPATE HEAT.)

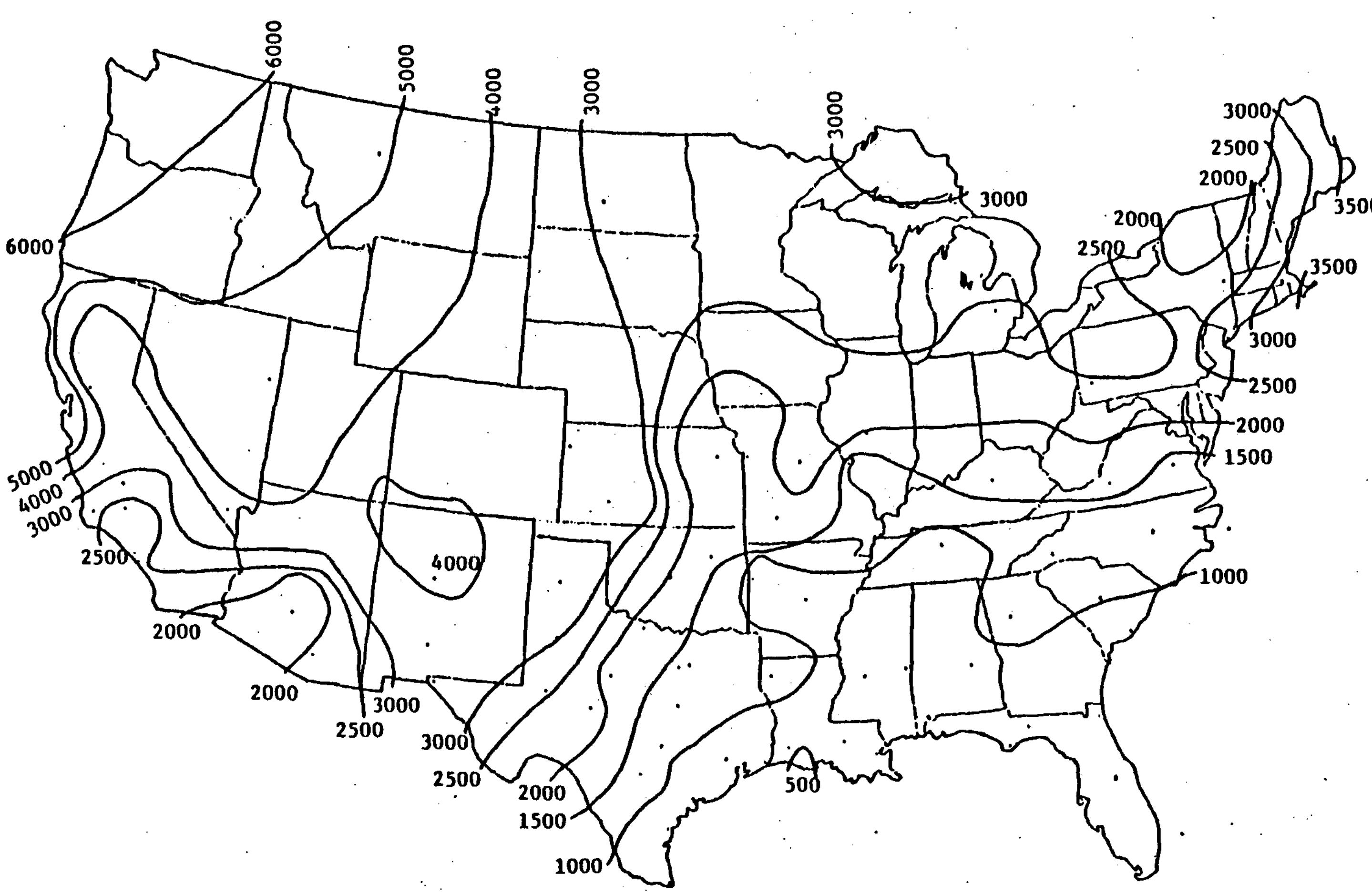
FIGURE 6



TYPICAL JULY NOCTURNAL NET COOLING RATE FOR WET SURFACE AT 74^{0}F (BTU FT.$^{-2}$ DAY^{-1})

(77 CITY HOURLY DATA BASE. SURFACE IS PERFECTLY INSULATED WHENEVER IT CANNOT DISSIPATE HEAT.)

FIGURE 7

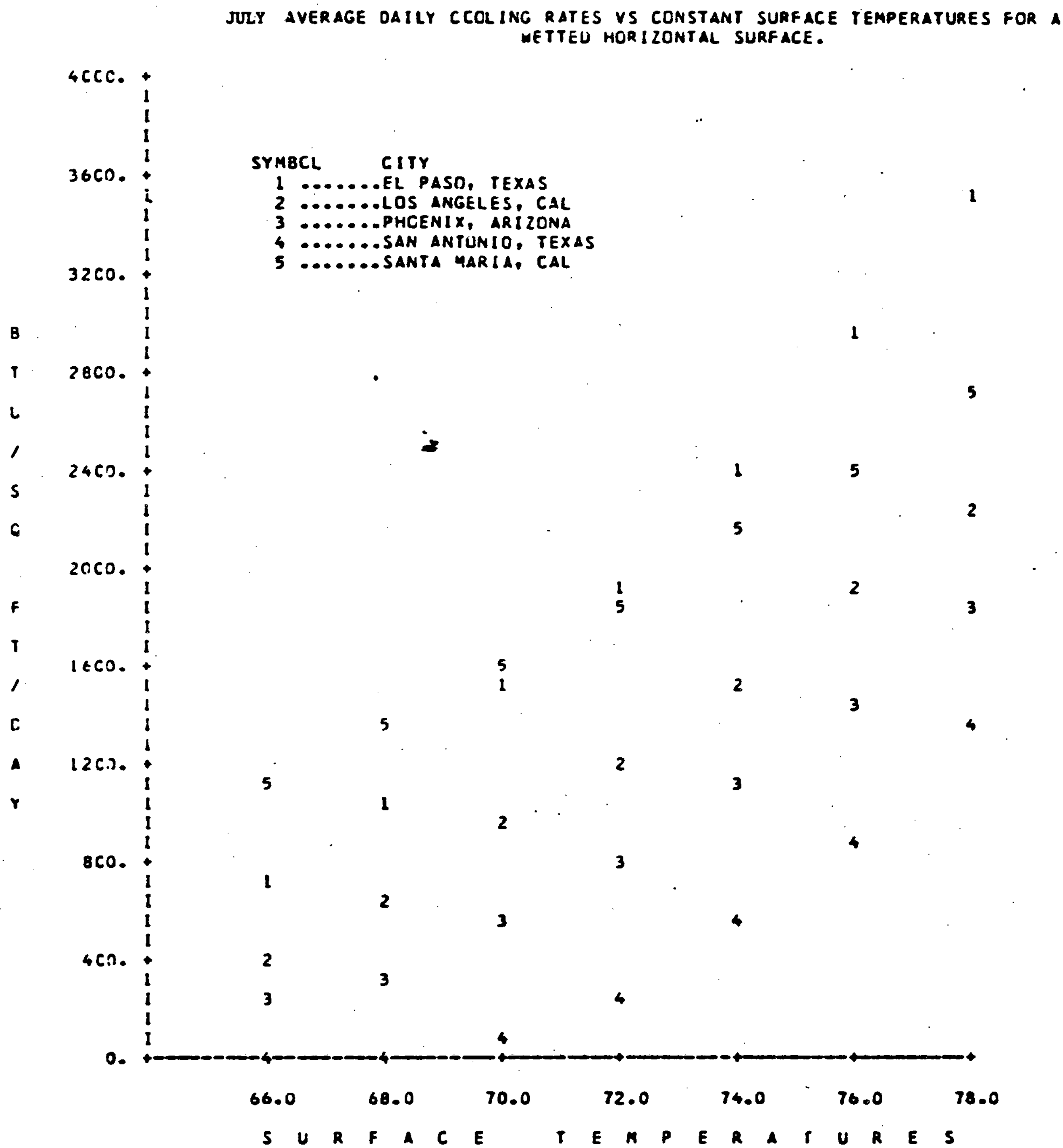


TYPICAL JULY NOCTURNAL NET COOLING RATE FOR WET SURFACE AT 78°F (BTU FT.$^{-2}$ DAY^{-1})

(77 CITY HOURLY DATA BASE. SURFACE IS PERFECTLY INSULATED WHENEVER IT CANNOT DISSIPATE HEAT.)

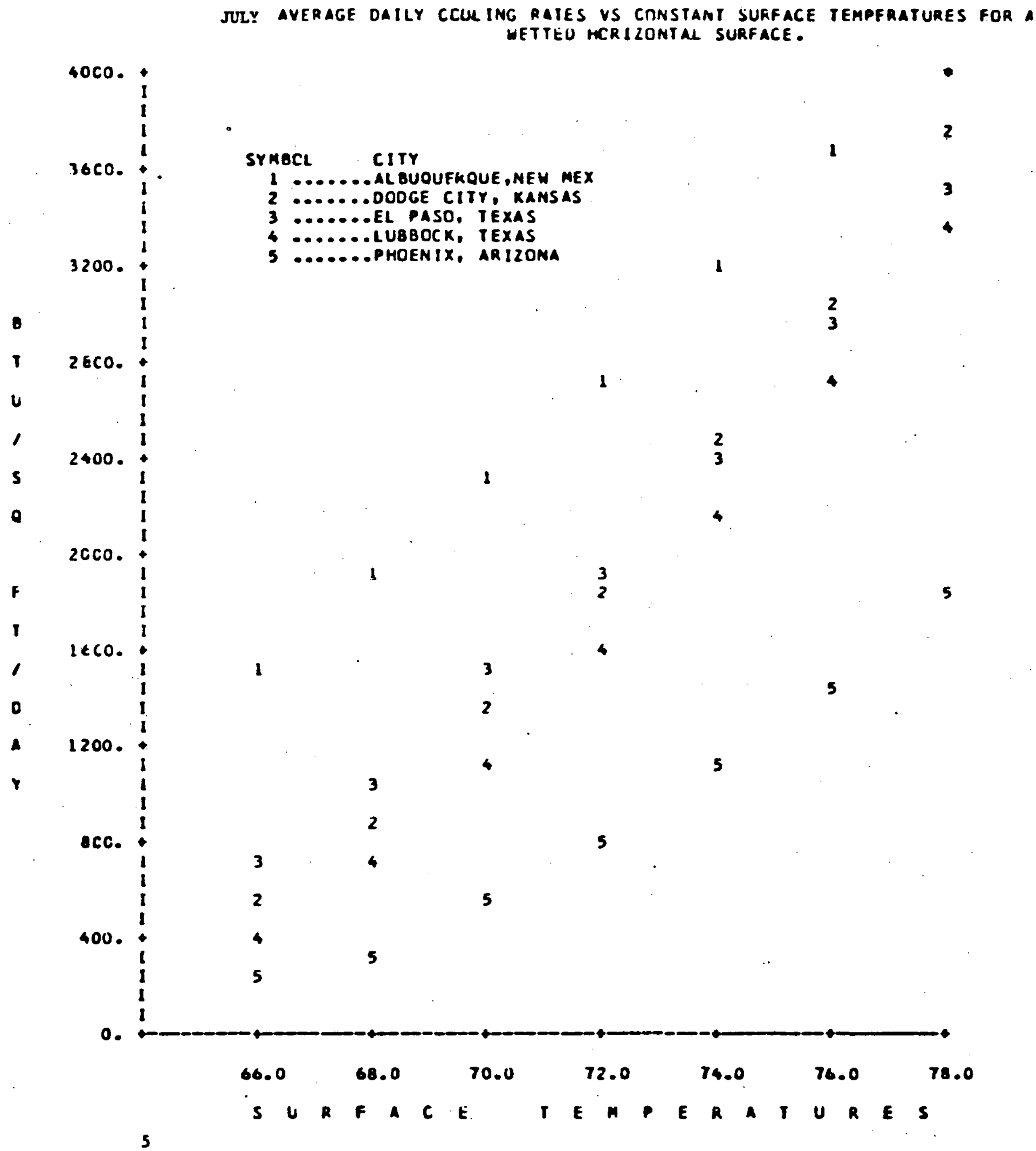
FIGURE 8

FIGURE 9


JULY AVERAGE DAILY COOLING RATES VS CONSTANT SURFACE TEMPERATURES FOR A WETTED HORIZONTAL SURFACE.
SYMBOL CITY
1 ....EL PASO, TEXAS
2 ....LOS ANGELES, CAL
3 ....PHOENIX, ARIZONA
4 ....SAN ANTONIO, TEXAS
5 ....SANTA MARIA, CAL
BTU/SQ FT/DAY
4000.
3600.
3200.
2800.
2400.
2000.
1600.
1200.
800.
400.
0.
66.0
68.0
70.0
72.0
74.0
76.0
78.0
SURFACE TEMPERATURES

3

FIGURE 10



JULY AVERAGE DAILY COOLING RATES VS CONSTANT SURFACE TEMPFRATURES FOR A WETTED HORIZONTAL SURFACE.
SYMBOL CITY
1 ....ALBUQUERQUE,NEW MEX
2 ....DODGE CITY, KANSAS
3 ....EL PASO, TEXAS
4 ....LUBBOCK, TEXAS
5 ....PHOENIX, ARIZONA
4000.
3600.
3200.
2800.
2400.
2000.
1600.
1200.
800.
400.
0.
B T U / S Q F T / D A Y
66.0
68.0
70.0
72.0
74.0
76.0
78.0
S U R F A C E T E M P E R A T U R E S

FIGURE 11

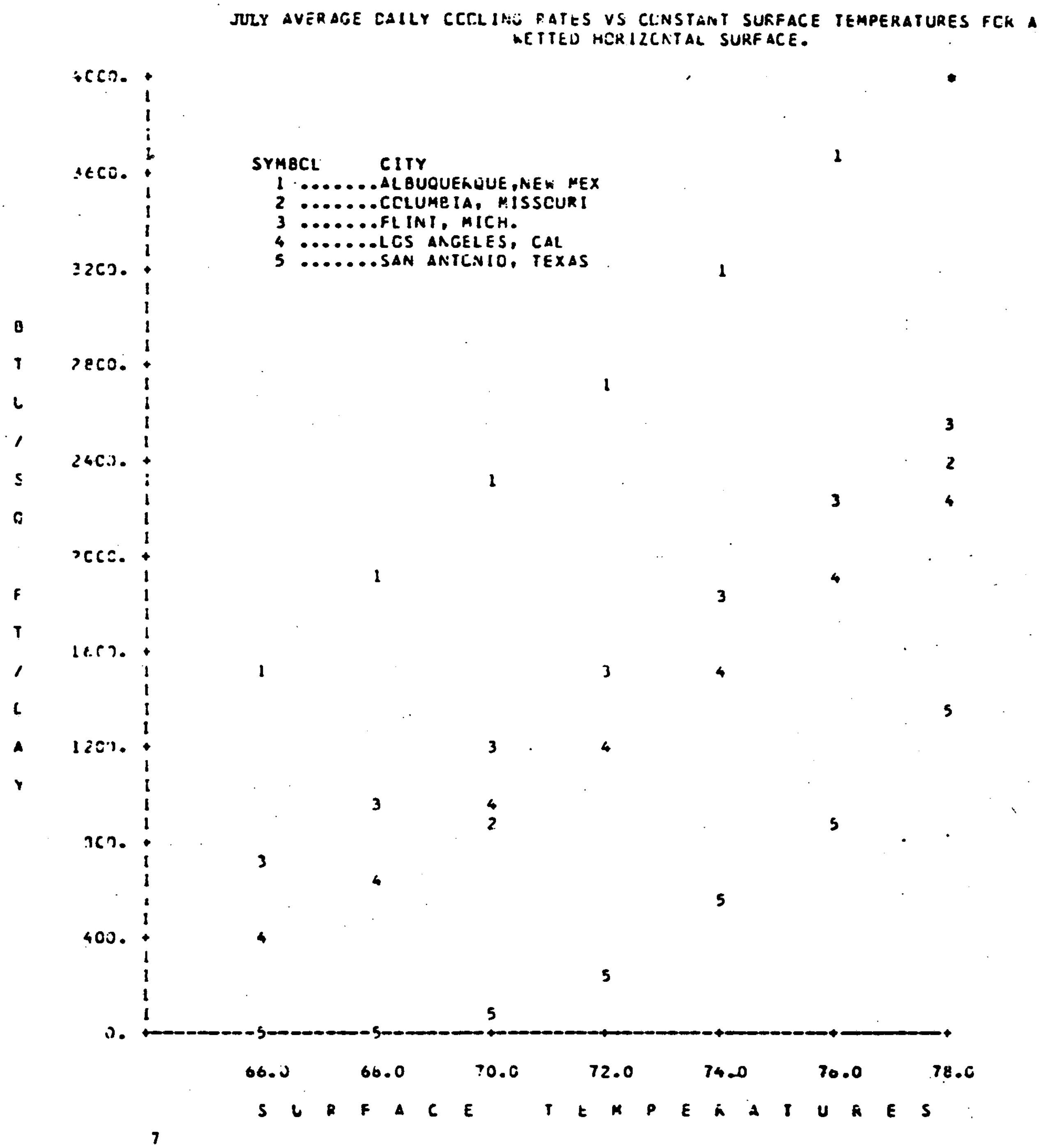

JULY AVERAGE DAILY COOLING RATES VS CONSTANT SURFACE TEMPERATURES FOR A WETTED HORIZONTAL SURFACE.
SYMBOL CITY
1 ....ALBUQUERQUE,NEW MEX
2 ....COLUMBIA, MISSOURI
3 ....FLINT, MICH.
4 ....LOS ANGELES, CAL
5 ....SAN ANTONIO, TEXAS
BTU/SQ FT/DAY
SURFACE TEMPERATURES

FIGURE 12

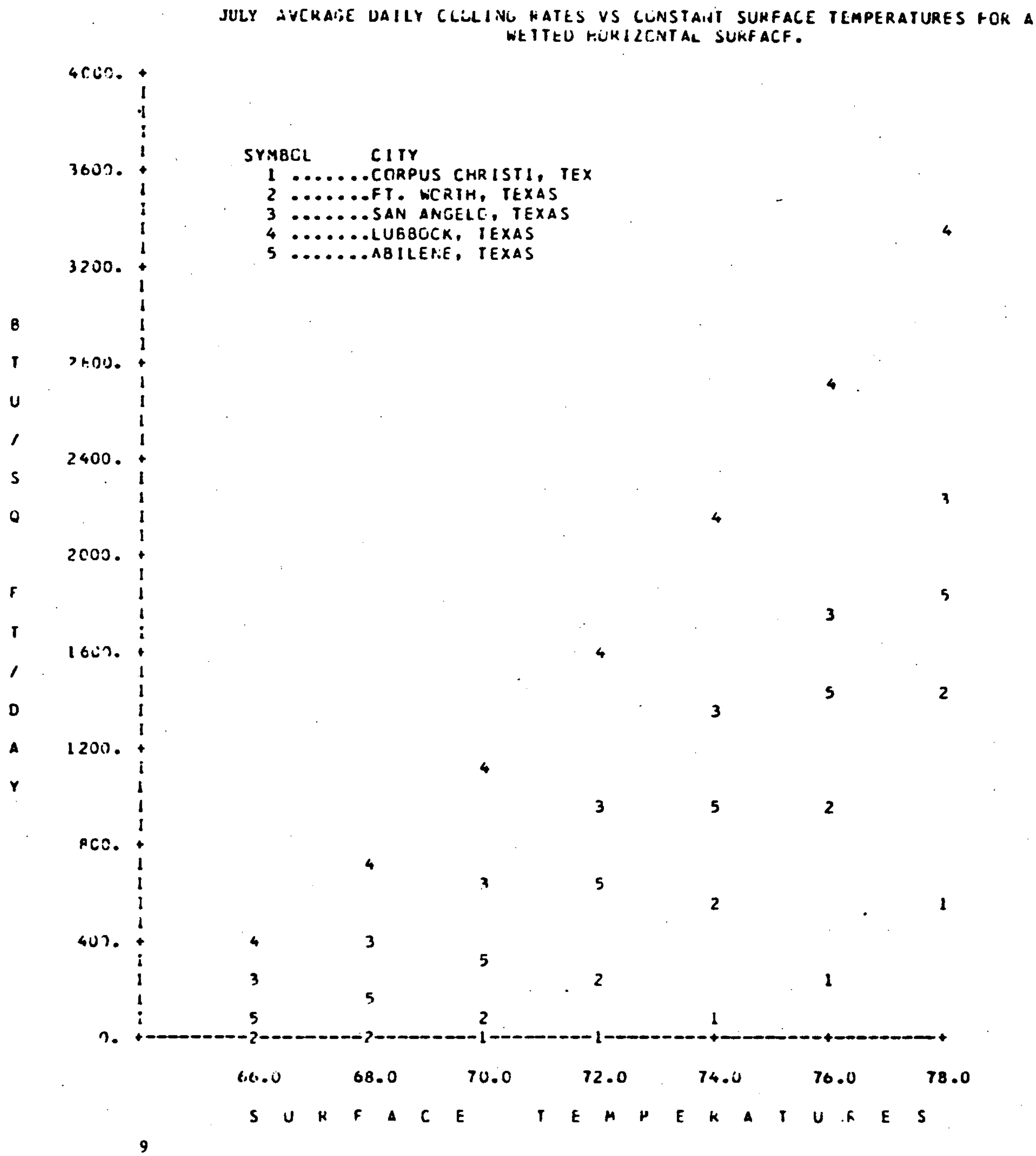
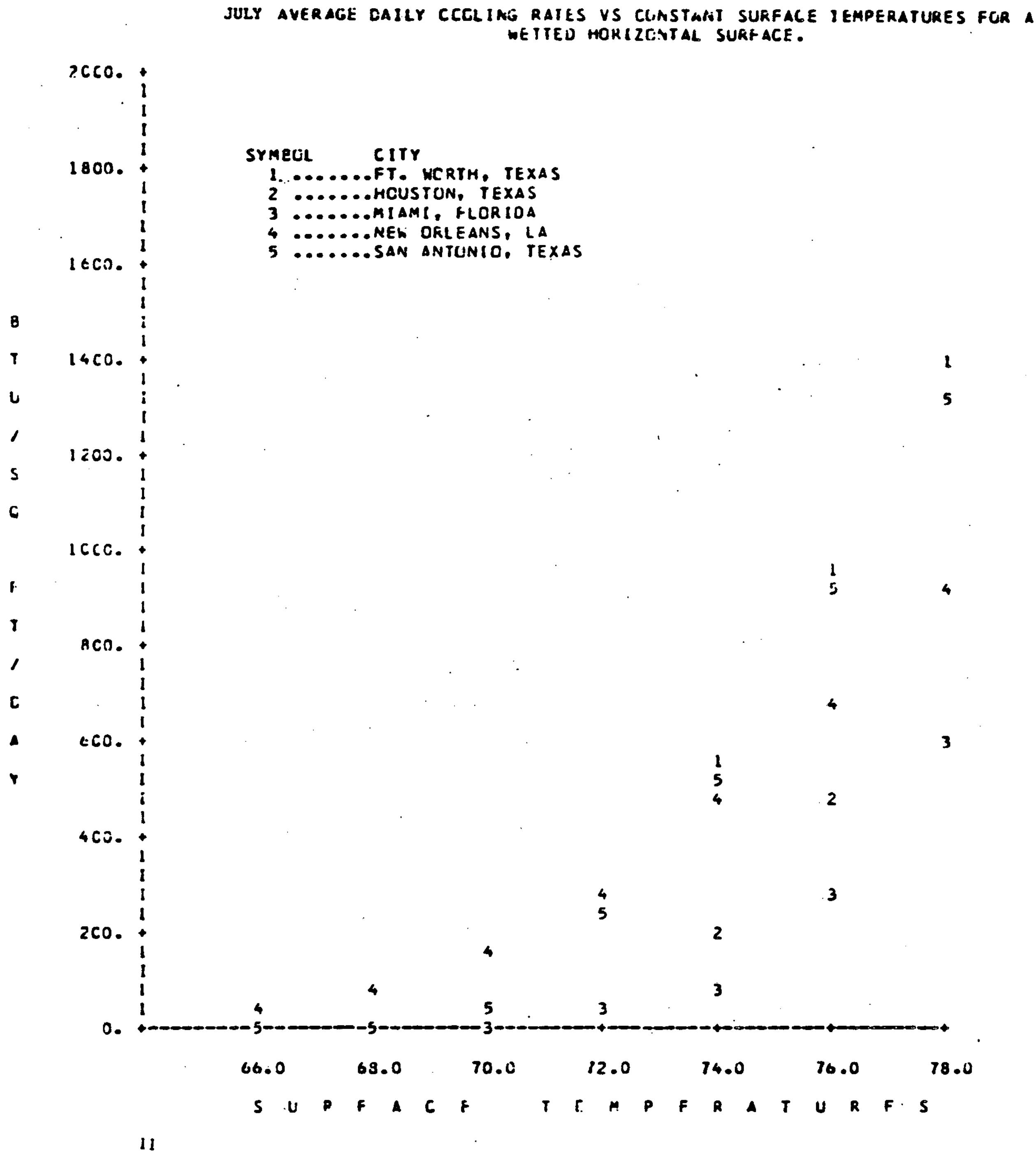
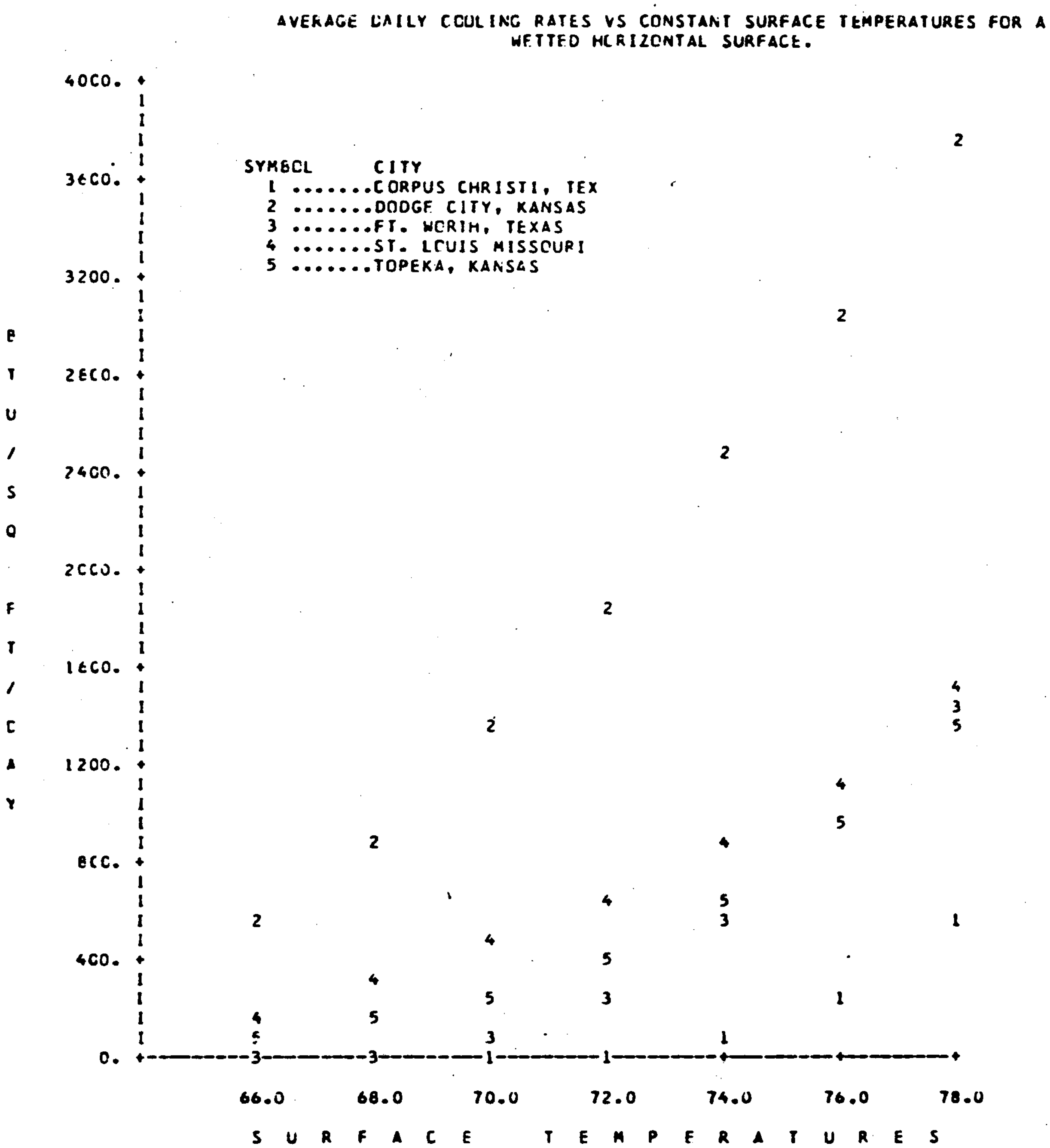

JULY AVERAGE DAILY COOLING RATES VS CONSTANT SURFACE TEMPERATURES FOR A WETTED HORIZONTAL SURFACE.
SYMBOL CITY
1 ....CORPUS CHRISTI, TEX
2 ....FT. WORTH, TEXAS
3 ....SAN ANGELO, TEXAS
4 ....LUBBOCK, TEXAS
5 ....ABILENE, TEXAS
BTU/SQ FT/DAY
4000.
3600.
3200.
2800.
2400.
2000.
1600.
1200.
800.
400.
0.
66.0
68.0
70.0
72.0
74.0
76.0
78.0
SURFACE TEMPERATURES
9

FIGURE 13



JULY AVERAGE DAILY COOLING RATES VS CONSTANT SURFACE TEMPERATURES FOR A WETTED HORIZONTAL SURFACE.
SYMBOL CITY
1 ....FT. WORTH, TEXAS
2 ....HOUSTON, TEXAS
3 ....MIAMI, FLORIDA
4 ....NEW ORLEANS, LA
5 ....SAN ANTONIO, TEXAS
BTU/SQ FT/DAY
2000.
1800.
1600.
1400.
1200.
1000.
800.
600.
400.
200.
0.
66.0
68.0
70.0
72.0
74.0
76.0
78.0
SURFACE TEMPERATURES

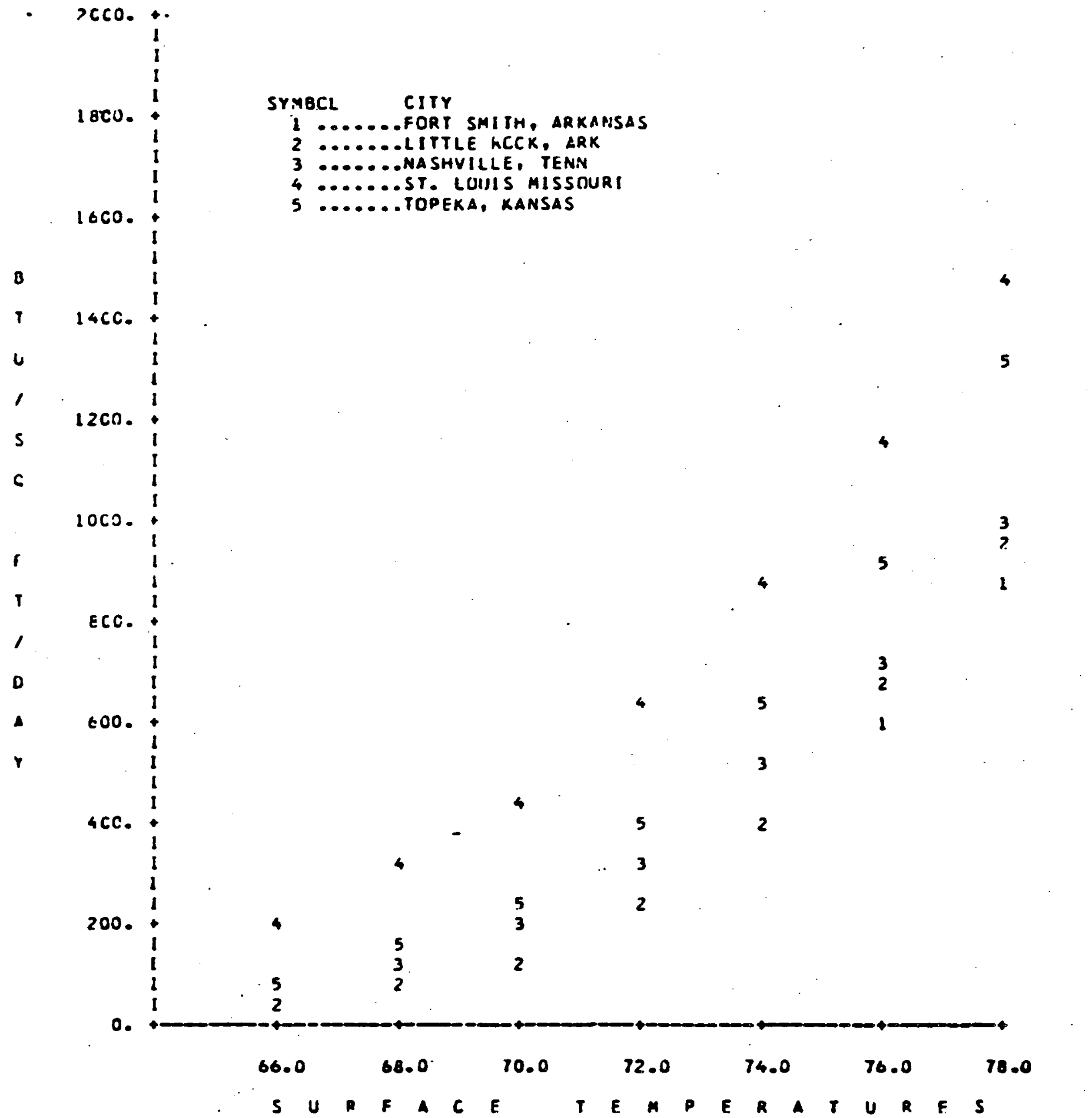
FIGURE 14


AVERAGE DAILY COOLING RATES VS CONSTANT SURFACE TEMPERATURES FOR A WETTED HORIZONTAL SURFACE.
SYMBOL CITY
1 ....CORPUS CHRISTI, TEX
2 ....DODGE CITY, KANSAS
3 ....FT. WORTH, TEXAS
4 ....ST. LOUIS MISSOURI
5 ....TOPEKA, KANSAS
B T U / S Q F T / D A Y
S U R F A C E T E M P E R A T U R E S

13

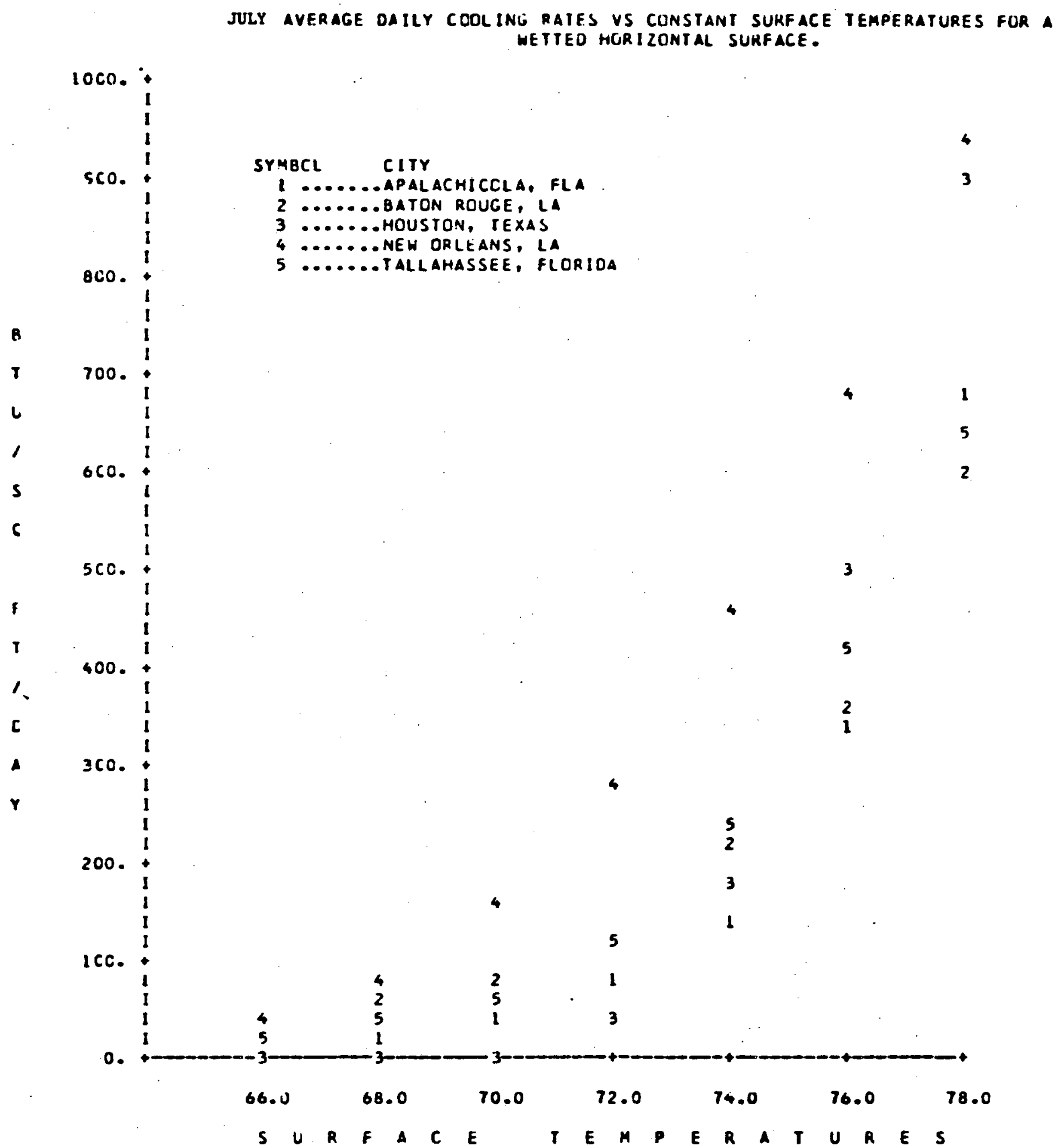
FIGURE 15

JULY AVERAGE DAILY COOLING RATES VS CONSTANT SURFACE TEMPERATURES FOR A WETTED HORIZONTAL SURFACE.



15

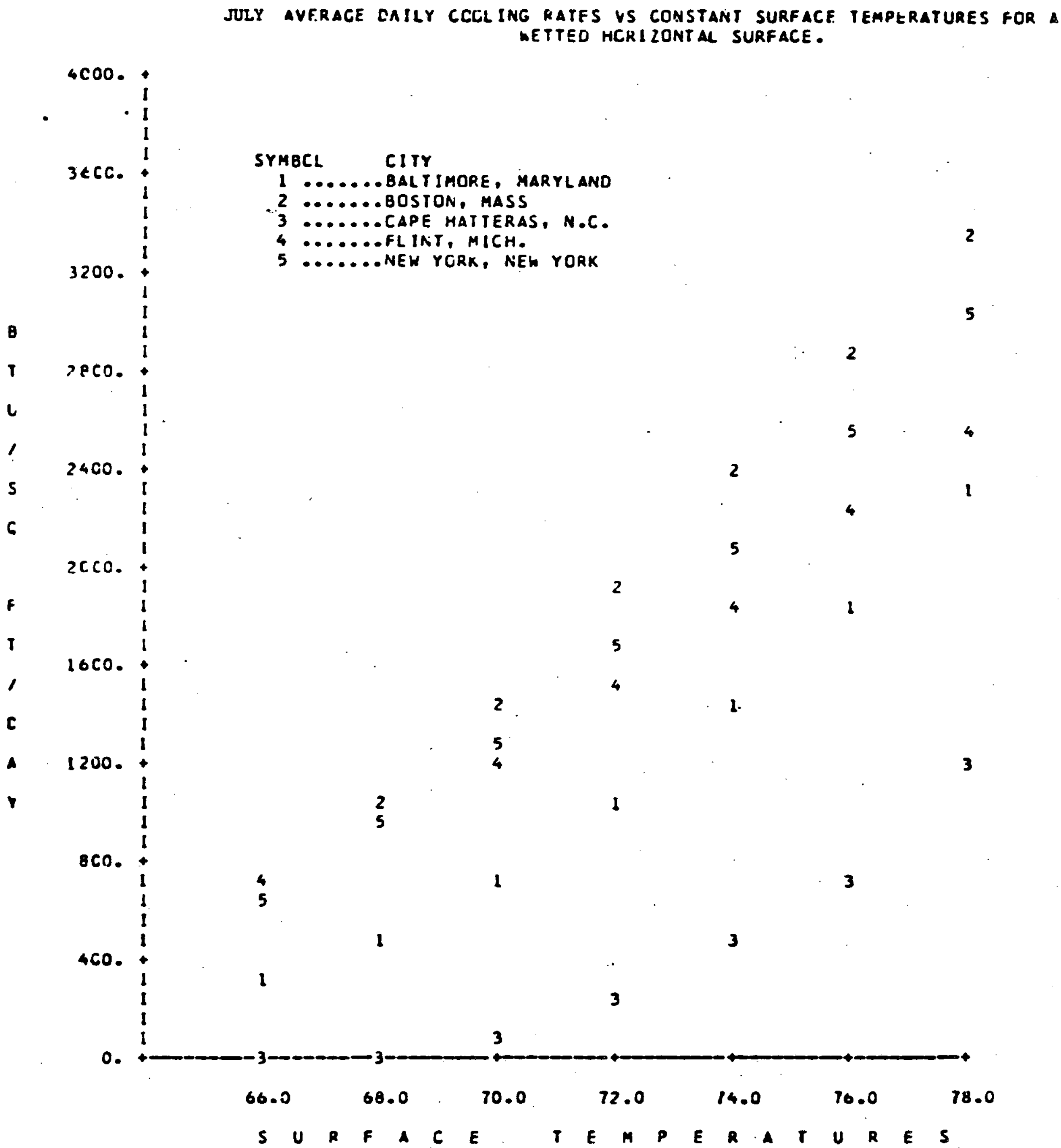
FIGURE 16



JULY AVERAGE DAILY COOLING RATES VS CONSTANT SURFACE TEMPERATURES FOR A WETTED HORIZONTAL SURFACE.
SYMBCL CITY
1 .......APALACHICCLA, FLA
2 ....BATON ROUGE, LA
3 ....HOUSTON, TEXAS
4 ....NEW ORLEANS, LA
5 ....TALLAHASSEE, FLORIDA
BTU/SC FT/DAY
1000.
900.
800.
700.
600.
500.
400.
300.
200.
100.
0.
66.0
68.0
70.0
72.0
74.0
76.0
78.0
SURFACE TEMPERATURES

17

FIGURE 17


JULY AVERAGE DAILY COOLING RATES VS CONSTANT SURFACE TEMPERATURES FOR A WETTED HORIZONTAL SURFACE.
SYMBOL CITY
1 ....BALTIMORE, MARYLAND
2 ....BOSTON, MASS
3 ....CAPE HATTERAS, N.C.
4 ....FLINT, MICH.
5 ....NEW YORK, NEW YORK
B T U / S C F T / D A Y
SURFACE TEMPERATURES
66.0
68.0
70.0
72.0
74.0
76.0
78.0
0.
400.
800.
1200.
1600.
2000.
2400.
2800.
3200.
3600.
4000.

19

TABLE 2

PHOENIX, ARIZONA — WETTED HORIZONTAL SURFACE

MONTHLY DAILY TOTAL COOLING RATES (BTU/SQ FT./DAY)

CONSTANT SURFACE TEMPERATURE (DEG. F)

	60	62	64	66	68	70	72	74	76	78	80
*** JUNE ***											
AVERAGE	495.1	665.1	861.6	1088.9	1355.9	1654.1	1980.5	2335.6	2714.8	3118.2	3546.7
MAXIMUM	1399.3	1793.9	2204.9	2656.2	3169.3	3704.7	4263.8	4847.9	5458.4	6096.8	6764.8
MINIMUM	0.0	0.0	5.5	37.6	116.5	250.1	414.8	602.0	796.2	1032.2	1309.0
*** JULY ***											
AVERAGE	28.8	51.1	103.6	200.6	343.9	540.0	798.2	1116.4	1472.8	1869.8	2296.9
MAXIMUM	156.2	274.4	454.8	672.0	900.6	1190.7	1518.3	1863.6	2375.7	2924.5	3498.6
MINIMUM	0.0	0.0	0.0	0.0	0.0	0.0	40.5	205.7	521.5	947.1	1359.8
*** AUGUST ***											
AVERAGE	3.3	13.6	34.3	71.3	133.7	248.5	435.8	698.2	1005.2	1344.2	1711.2
MAXIMUM	57.2	184.4	363.7	585.7	832.4	1111.5	1402.3	1708.2	2045.1	2413.3	2792.2
MINIMUM	0.0	0.0	0.0	0.0	0.0	2.6	24.8	110.1	313.1	565.2	850.3
*** SEPTEMBER ***											
AVERAGE	51.8	105.1	185.9	296.8	444.8	649.1	918.4	1233.3	1586.3	1965.4	2366.5
MAXIMUM	473.9	679.8	893.9	1116.7	1365.7	1626.1	1897.6	2180.6	2476.3	2784.9	3131.4
MINIMUM	0.0	0.0	0.0	0.0	0.0	0.0	39.8	199.7	504.3	775.0	1090.9

TABLE 3

HOUSTON, TEXAS

WETTED HORIZONTAL SURFACE

MONTHLY DAILY TOTAL COOLING RATES (BTU/SQ.FT./DAY)

CONSTANT SURFACE TEMPERATURE (DEG. F)

*** JUNE ***

	60	62	64	66	68	70	72	74	76	78	80
AVERAGE	4.4	8.2	14.3	24.0	45.2	91.9	187.9	354.2	604.1	918.0	1278.2
MAXIMUM	14.4	24.4	35.6	84.4	171.8	456.3	798.9	1174.6	1603.5	2051.2	2529.7
MINIMUM	0.0	0.0	0.0	0.0	0.0	0.0	0.0	34.5	151.1	453.5	773.7

*** JULY ***

	60	62	64	66	68	70	72	74	76	78	80
AVERAGE	0.2	0.4	0.8	1.3	2.2	5.5	41.2	188.4	494.3	903.3	1380.0
MAXIMUM	0.8	3.3	5.9	8.5	11.1	19.0	190.8	476.2	811.5	1210.5	1677.7
MINIMUM	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	63.6	539.7	895.3

*** AUGUST ***

	60	62	64	66	68	70	72	74	76	78	80
AVERAGE	0.0	0.1	0.2	0.3	0.3	1.6	31.1	165.4	403.9	723.3	1096.6
MAXIMUM	1.0	3.4	5.7	8.1	10.5	23.3	124.0	464.6	864.5	1319.2	1850.8
MINIMUM	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	135.6	384.7	644.1

*** SEPTEMBER ***

	60	62	64	66	68	70	72	74	76	78	80
AVERAGE	36.0	69.0	124.8	214.8	356.1	553.0	824.5	1168.7	1577.7	2053.9	2576.2
MAXIMUM	462.5	778.5	1132.2	1639.7	2213.2	2812.6	3437.8	4090.5	4772.0	5484.2	6228.6
MINIMUM	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	29.6	274.9	576.4

TABLE 4

MIAMI, FLORIDA — WETTED HORIZONTAL SURFACE

MONTHLY DAILY TOTAL COOLING RATES (BTU/SQ.FT./DAY)

CONSTANT SURFACE TEMPERATURE (DEG. F)

	60	62	64	66	68	70	72	74	76	78	80
*** JUNE ***											
AVERAGE	0.5	1.3	3.3	15.0	41.8	94.9	184.4	328.1	584.8	924.3	1307.9
MAXIMUM	3.1	5.1	13.6	202.8	549.2	999.1	1551.8	2205.3	2920.4	3667.8	4449.1
MINIMUM	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.7	101.2	341.4	579.1
*** JULY ***											
AVERAGE	0.1	0.8	2.2	4.3	7.0	11.9	27.1	92.6	284.3	595.6	963.1
MAXIMUM	4.1	14.2	24.5	34.8	45.3	65.4	120.7	354.4	648.2	1059.2	1694.1
MINIMUM	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	61.2	252.5	507.0
*** AUGUST ***											
AVERAGE	0.2	0.8	2.6	5.4	8.6	12.3	26.1	88.5	279.1	571.9	908.0
MAXIMUM	4.5	11.6	18.7	25.9	33.3	57.1	201.5	390.4	615.9	872.8	1375.2
MINIMUM	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	101.2	278.0	501.6
*** SEPTEMBER ***											
AVERAGE	0.6	3.1	8.5	16.2	24.6	33.8	57.8	124.7	281.1	522.3	805.8
MAXIMUM	6.5	15.0	33.7	55.6	78.8	102.2	138.3	417.9	945.8	1550.7	2184.3
MINIMUM	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	13.3	228.1	356.8

TABLE 5

ST. LOUIS, MISSOURI WETTED HORIZONTAL SURFACE

MONTHLY DAILY TOTAL COOLING RATES (BTU/SQ.FT./DAY)

CONSTANT SURFACE TEMPERATURE (DEG. F)

	60	62	64	66	68	70	72	74	76	78	80
*** JUNE ***											
AVERAGE	102.1	153.3	228.7	334.7	485.4	688.1	957.0	1284.1	1651.8	2056.6	2497.6
MAXIMUM	867.3	1147.7	1452.0	1777.7	2127.6	2492.4	2872.8	3269.8	3684.3	4117.3	4569.8
MINIMUM	0.0	0.0	0.0	0.0	0.0	0.0	50.6	188.2	425.7	742.7	1135.0
*** JULY ***											
AVERAGE	40.3	72.0	123.8	196.2	303.2	445.4	631.5	868.1	1158.9	1486.5	1846.8
MAXIMUM	270.8	383.7	515.2	675.9	907.7	1224.1	1597.6	1987.5	2394.4	2835.2	3360.4
MINIMUM	0.0	0.0	0.0	0.0	0.0	0.0	0.0	115.5	315.2	483.4	679.3
*** AUGUST ***											
AVERAGE	84.3	146.5	236.6	353.5	503.1	690.3	914.9	1178.3	1472.4	1792.6	2133.7
MAXIMUM	416.9	588.8	776.1	978.3	1199.1	1446.4	1734.2	2058.5	2442.0	2842.6	3261.3
MINIMUM	0.0	0.0	0.0	0.0	0.0	41.2	109.5	241.1	510.6	886.3	1306.6
*** SEPTEMBER ***											
AVERAGE	540.5	711.2	911.5	1141.5	1405.2	1707.2	2045.6	2410.9	2797.2	3203.1	3628.1
MAXIMUM	2665.6	3067.7	3486.1	3921.5	4375.1	4848.0	5341.1	5855.8	6393.2	6954.6	7541.4
MINIMUM	0.0	0.0	0.0	0.0	0.0	0.0	108.0	386.7	612.7	850.9	1098.8

TABLE 6

LITTLE ROCK, ARKANSAS — WETTED HORIZONTAL SURFACE

MONTHLY DAILY TOTAL COOLING RATES (BTU/SQ.FT./DAY)

CONSTANT SURFACE TEMPERATURE (DEG. F)

*** JUNE ***

	60	62	64	66	68	70	72	74	76	78	80
AVERAGE	40.6	75.2	125.4	201.1	305.5	452.2	654.6	916.4	1233.1	1590.2	1981.8
MAXIMUM	228.0	359.1	518.3	797.5	1116.8	1449.5	1818.3	2244.1	2710.9	3198.5	3708.0
MINIMUM	0.0	0.0	0.0	0.0	0.0	0.0	1.7	111.1	338.2	592.9	876.4

*** JULY ***

	60	62	64	66	68	70	72	74	76	78	80
AVERAGE	14.8	22.3	32.9	49.3	77.6	133.7	243.7	419.9	660.0	947.3	1273.9
MAXIMUM	183.9	255.4	350.7	476.0	644.9	826.9	1045.1	1297.4	1580.9	1893.8	2221.6
MINIMUM	0.0	0.0	0.0	0.0	0.0	0.0	0.0	13.6	82.5	241.2	535.3

*** AUGUST ***

	60	62	64	66	68	70	72	74	76	78	80
AVERAGE	7.3	18.2	44.8	90.2	165.0	273.2	431.9	645.9	920.7	1250.5	1626.8
MAXIMUM	57.4	174.2	400.3	706.9	1085.9	1499.0	1946.2	2434.1	2943.2	3474.8	4030.2
MINIMUM	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.9	67.8	197.9	413.7

*** SEPTEMBER ***

	60	62	64	66	68	70	72	74	76	78	80
AVERAGE	259.5	339.8	435.8	550.1	695.3	887.6	1125.5	1427.6	1785.0	2174.2	2589.5
MAXIMUM	1390.7	1760.6	2169.8	2595.6	3039.2	3501.4	3983.5	4486.5	5011.6	5650.3	6378.0
MINIMUM	0.0	0.0	0.0	0.0	0.0	0.0	0.0	168.6	520.2	931.0	1170.3

TABLE 7

BALTIMORE, MARYLAND — WETTED HORIZONTAL SURFACE

MONTHLY DAILY TOTAL COOLING RATES (BTU/SQ.FT./DAY)

CONSTANT SURFACE TEMPERATURE (DEG. F)

*** JUNE ***

	60	62	64	66	68	70	72	74	76	78	80
AVERAGE	312.6	442.6	613.0	819.5	1076.7	1387.9	1745.9	2137.5	2560.3	3011.9	3490.0
MAXIMUM	1451.2	1772.1	2127.5	2499.4	2886.9	3290.7	3711.8	4151.3	4610.1	5089.4	5590.3
MINIMUM	0.0	0.0	0.0	0.0	5.2	146.1	330.3	567.3	834.3	1131.3	1477.1

*** JULY ***

	60	62	64	66	68	70	72	74	76	78	80
AVERAGE	86.2	136.0	208.5	322.5	483.5	715.7	1028.9	1402.9	1827.0	2291.8	2795.6
MAXIMUM	723.7	1036.2	1381.2	1757.5	2161.4	2641.2	3174.5	3733.1	4316.4	4925.9	5562.9
MINIMUM	0.0	0.0	0.0	0.0	0.0	11.4	143.1	415.7	694.8	1036.0	1418.8

*** AUGUST ***

	60	62	64	66	68	70	72	74	76	78	80
AVERAGE	69.6	125.2	214.6	336.7	507.5	729.7	999.5	1317.8	1678.0	2072.2	2493.8
MAXIMUM	645.1	916.4	1203.0	1516.1	1845.8	2212.1	2605.1	3075.0	3645.0	4241.0	4864.3
MINIMUM	0.0	0.0	0.0	0.0	0.0	0.0	45.8	170.3	497.6	804.9	1136.7

*** SEPTEMBER ***

	60	62	64	66	68	70	72	74	76	78	80
AVERAGE	605.9	761.8	948.6	1172.1	1444.3	1771.2	2154.1	2586.9	3059.7	3568.8	4109.8
MAXIMUM	2820.1	3257.9	3713.3	4187.4	4681.2	5195.9	5732.7	6292.9	6877.9	7488.9	8127.5
MINIMUM	0.0	0.0	0.0	0.0	0.0	0.0	7.6	91.8	304.8	607.4	1016.4

TABLE 8

COMPARISON OF ROOF WITH FIXED AND ROOF WITH MOVABLE INSULATION: TYPICAL JULY AVERAGE DAILY TOTAL COOLING RATE (BTU/DAY-SQ.FT.)

	T = 72^{0}F		T = 76^{0}F		T = 80^{0}F	
CITY	FIXED	MOVABLE	FIXED	MOVABLE	FIXED	MOVABLE
HOUSTON	-972	26	454	422	2016	1277
OKLAHOMA CITY	93	519	1713	1385	3492	2493
ST. LOUIS	691	606	1671	1100	2751	1763
MIAMI	-1203	18	9.7	245	1342	896
FT. WORTH	-194	197	1212	884	2753	1822
PHOENIX	927	662	2005	1302	3192	2098

BUILDING CONSIDERATIONS

Some rough rules of thumb for roof pond buildings.

Thermal Mass of A Roof Pond

The cooling load which is generated inside a building or enters through the building envelop enters the storage roof during the day; this same energy is dissipated by the roof at night. The diurnal temperature fluctuation of the storage roof is then:

$$\Delta T = \pm \frac{\dot{Q}_T}{24\ M} \tag{9}$$

where

M = mass of roof pond (in LB/Sq.Ft.)

If the designer would like ΔT to be ±0.5 ^{0}F/Day, and $\dot{Q}_T$ = 200 BTU/DAY/SQ.FT then

M = 17 LB/Sq.Ft.

Since one cubic foot of water weighs 64.7 lb, this corresponds to ≈ 3.1" of water. A six inch pond would contain more than enough mass.

Temperature of Building Interior

The rate at which heat flows from the building into the roof pond is:

$$\dot{Q}_{B\to P} = U_C \quad (T_B - T), \tag{10}$$

where

U_C = U value for building's ceiling, and

T_B = building interior temperature.

On average $\dot{Q}_{B\to P} = \dot{Q}_T$; therefore

$$T_B = T + \frac{\dot{Q}_T}{U_C} \tag{11}$$

For example, if $\dot{Q}_T$ = 200 BTU/DAY Sq. Ft. and U_C = 40 BTU/Day/Sq.Ft./°F,

then $T_B = T + 5^oF$.

Volume of Evaporated Water

$$\dot{Q}_E \approx \dot{Q}_T$$

Since the enthalpy of evaporation for water is approximately 1100 BTU/lb, and there are 64.7 lb of water/ft^3, the volume of evaporated water per day is

$$\dot{V} = \dot{Q}_T \;/\; (7 \times 10^4 \text{ BTU/ft}^3) \tag{12}$$

If $\dot{Q}_T$ = 200 BTU/ft^2-day, then $\dot{V} = 3 \times 10^{-3}$ (ft^3/ft^2)/day.

For a 1000 ft^2 roof, $\dot{V}$ = 3 ft^3 or 21 gallons/day.

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Ventilation Cooling

Passive Cooling by Natural Ventilation: Principles and Design Implications -- Subrato Chandra

Wind Generated Ventilative Cooling -- Harris Sobin

Night Ventilation Cooling of Mass -- Karen Crowther

PASSIVE COOLING BY NATURAL VENTILATION PRINCIPLES AND DESIGN IMPLICATIONS

Subrato Chandra*

ABSTRACT

The basic physical principles of wind driven natural ventilation are explained. The existing world literature on the subject is discussed and design strategies to enhance ventilation of buildings in the hot and humid climate are outlined.

Introduction

This discussion is limited to the subject of natural ventilation of residential and small commercial buildings in hot or warm and humid climates where natural ventilation can aid both day and nighttime summer cooling.

In hot and arid regions, buildings are designed with high thermal mass and protection from sun and daytime winds. Cool night winds are allowed to circulate inside by means of small openings, strategically placed to take advantage of stack ventilation. If this is not sufficient, evaporative and radiative cooling may be used. These techniques are relatively ineffective in humid climates.

In the hot and humid climates of the world, buildings traditionally have been designed for natural ventilation primarily because of the high cost of owning and operating mechanical air conditioners. This is particularly true in parts of the world where the populace cannot afford the luxury of such devices. In such places, natural ventilation aided by portable or ceiling fans is the only technique for cooling a building already protected from the sun through shading devices, orientation and design.

In the U.S., with its relatively low cost of electricity and energy as compared to Europe and most other parts of the world, buildings usually are designed with little consideration for nature and are mechanically conditioned. This is true even in the hot and humid climate of Florida. Although modern

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The views expressed are those of the author and not necessarily of the Florida Solar Energy Center

Florida's residential dwellings tend to use more glass areas to create an "open and airy feeling" than similar dwellings in the north, little thought is given to the placement or design of windows to aid natural ventilation. Seldom seen in modern-day housing are the design features of Florida "cracker" houses--lived in by early settlers when the state had no electricity--with floors raised above the ground level, walls protected by large overhangs and verandahs, and windows placed to capture the prevailing summer breezes.

The physics and aerodynamics of naturally ventilated buildings are complex. The theory must consider three-dimensional bluff bodies (buildings) with apertures placed in a turbulent shear flow (the winds in the vicinity of the ground) with poorly defined mean flow and turbulent characteristics (due to variations in terrain and diurnal and seasonal variations of the winds). Since an analytical or numerical solution to the problem has not been possible, all research performed to date has been conducted experimentally.

A review of the literature indicates that the qualitative features of natural ventilation in terms of basic physics and architectural design implications are fairly well understood. Not surprisingly, most of the post-1960 work has been performed outside the United States (Givoni in Israel; Aynsley in Australia; Van Straaten in South Africa), and most of the early work in the U.S. (Caudill, Holleman, Evans at Texas A&M, Olgyay at Princeton) was performed when mechanical air conditioning was uncommon. This raises an interesting question regarding the applicability of existing work to current U.S. needs.

The objective of the early U.S. work and the later work abroad--to understand the basic physics of natural ventilation and the architectural implications in hot, humid climates--was subject to the constraint that mechanical air conditioning was not a practical alternative. Natural ventilation was considered the <u>only</u> solution, and the problem was to understand which design was better, <u>relative</u> to other designs (e.g., having windows directly opposite each other in a room or staggered so that air has to change direction before exiting). As long as <u>mechanical air conditioning was not an alternative</u>, wind tunnel flow visualization studies and air speed measurements in the room were deemed sufficient to determine the best design strategies.

However, the context is now different. Mechanical air conditioning <u>is</u> an alternative and building design in the U.S. must take into consideration the comfort levels Americans are accustomed to. It is not enough to design a naturally ventilated building with strategically placed windows. If that building cannot maintain comfort, the occupants will close the windows and turn on the air conditioning. Or they may do that anyway for nighttime safety or because of a neighbor's noisy air conditioner. A better approach to U.S. conditions may be innovative roof designs with suitable roof apertures so that the winds create a low static pressure region there independent of prevailing wind direction, and innovative underfloor plenum air inlet designs with perhaps a whole-house venting fan to aid air movement.

Whatever designs we employ, it is imperative that we be able to predict the annual energy consumption of buildings with or without natural ventilation. This will then enable the design of buildings that minimize life-cycle mechanical energy costs and reduce U.S. and global consumption of non-renewable fuels.

It should be noted, however, that if photovoltaic/wind-generated electricity costs come down as projected there may be another feasible approach: To design a very well-insulated house (adequately ventilated to health standards) and to mechanically condition it with photovoltaic or wind generated electricity and high EER and COP heat pumps. The ultimate solution may be to design a house that is in harmony with nature and does not create unreasonably large mechanical loads if nature fails to maintain comfort, and then to supply to the house electricity from photovoltaic or wind power.

External Aerodynamics of Buildings

Extensive knowledge exists concerning mean wind loads on buildings. See Cermak (Ref. 14, pp. 85-103), Newberry (Ref. 3, pp. 26-35) and MacDonald (Ref. 10, pp. 80-107) for comprehensive reviews of the subject. The dynamic loading of buildings under high gusts or tornados are poorly understood and not relevant here.

Prismatic buildings in wind are aerodynamically equivalent to three-dimensional bluff bodies with sharply defined separation edges placed in a turbulent shear flow. The flow structure is complex and highly dependent on wind direction and building geometry. Architectural features such as eaves, canopies, parapets, wing walls and neighboring buildings change the flow pattern around a simple building significantly. Also significant is the effect of landscaping (Refs. 5 and 6).

The flow past a simple building shape is shown in figure 1 and the pressure distribution in figure 2. The wind is slowed against the windward face and generates a positive pressure (i.e., greater than the free stream pressure) which diminishes towards the edges. This cushion of pressure on the windward side diverts the air around the sides and over the roof of the building. Note the eddy near the lower part of the windward wall which creates an air flow opposite to the direction of the wind. The flow in this eddy spirals along the sides creating the high suctions shown on the side of the building. (Figure 2a.) The separated flow at the back and the sides create a uniform suction as shown. Flow separates on the leeward roof surface. Flow may also separate at the leading edge of the windward surface, the probability increasing with decreasing roof pitch (flat roofs usually create vortices when exposed to oblique winds) and increasing building height.

With increasing obliqueness in the wind direction, positive pressures can develop on both or one windward side depending on wind direction and building length-to-width ratio. Flow reattachment is possible if the length of the side along the wind direction is significantly greater than the length of the sides normal to the wind. Projecting canopies and overhangs modify the air flow, particularly if they are on the windward side. Usually, a pressure is created on the underside of the overhang and suction above it. For flow details see previously cited references, and also Akins et al (Ref. 12) who have collected extensive wind tunnel data on rectangular buildings.

Physics of Natural Ventilation

The air flow rate (V) through a building aperture may be modelled as an orifice flow and expressed as

$$V = K\ A\ (\Delta P)^{m} \qquad (1)$$

where A is the aperture area, K is the discharge coefficient, ΔP is the total differential pressure head driving the flow and is the sum of thermal and velocity pressure heads. The exponent m is 0.5 corresponding to turbulent flow (the usual case), although m may vary between 0.5 and 1 depending on the flow structure.

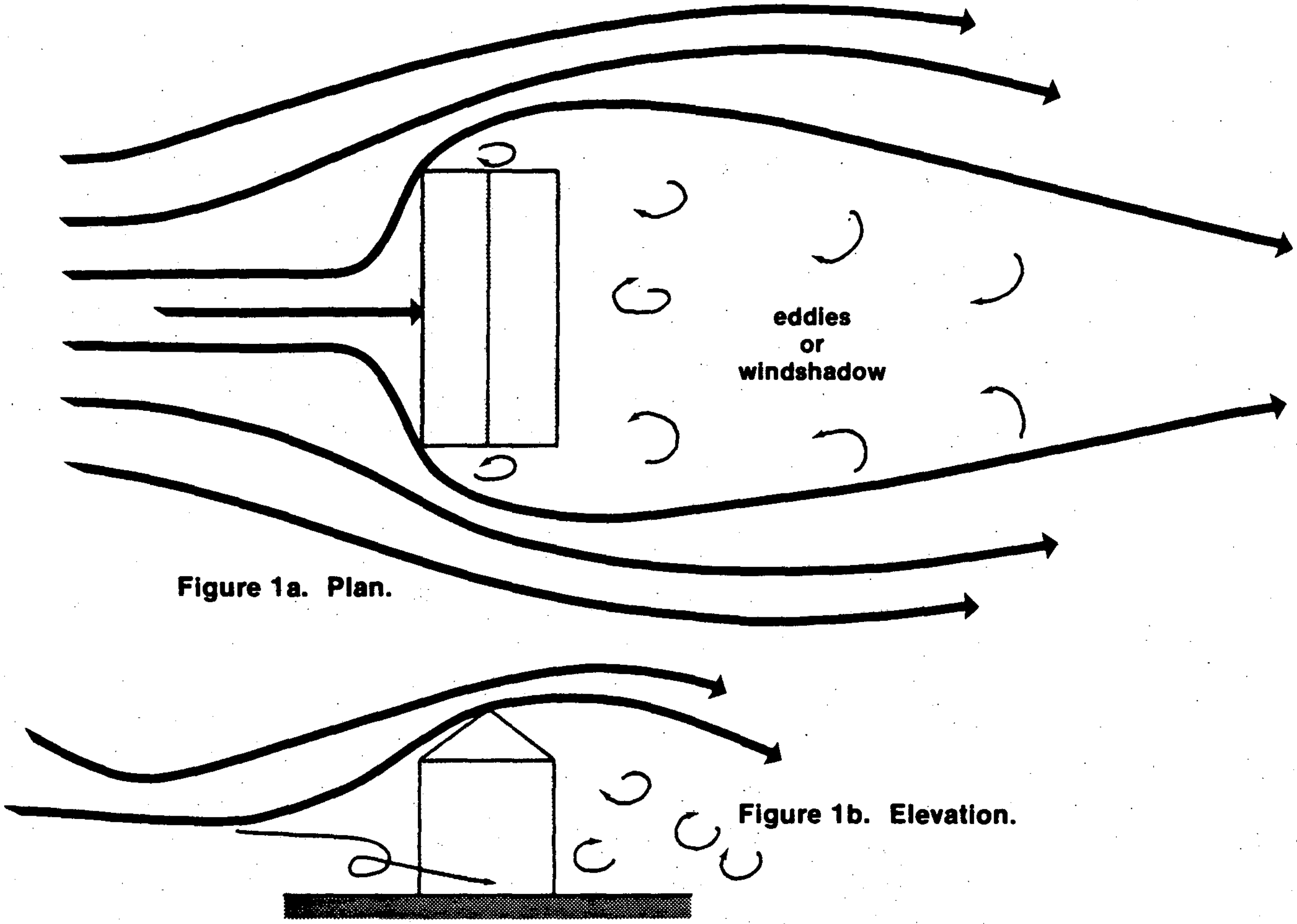

Figure 1a. Plan.

Figure 1b. Elevation.

Figure 1. Airflow around a building.

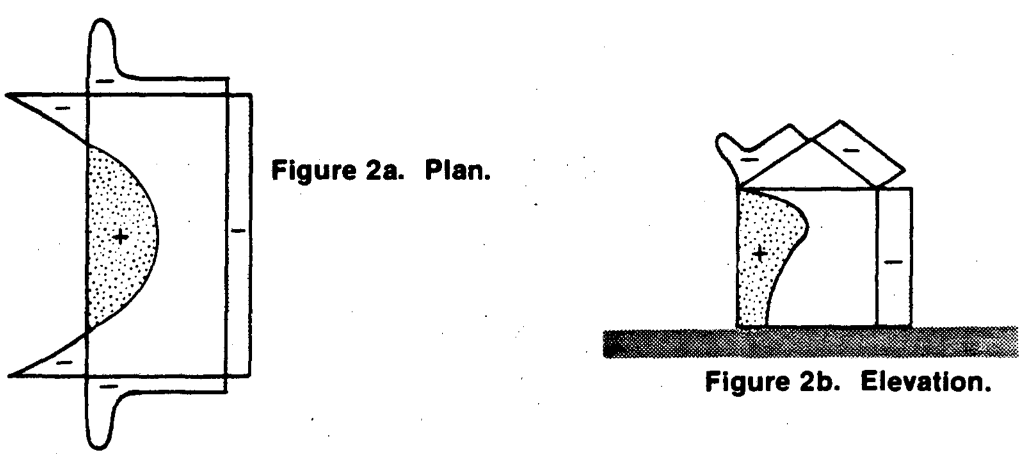

Figure 2a. Plan.

Figure 2b. Elevation.

Figure 2. Pressure distributions.
+ higher than free stream pressure.
— lower than free stream pressure.

Depending on building and aperture geometry, the flow is dominated either by the thermal stack head or the velocity head due to the square-root dependence of the total flow to the total head. Since in most naturally ventilated buildings in hot and humid climates the difference in average inside and outdoor temperature is small, the velocity head will prevail. For example, to maintain comfort, the indoor average air temperature cannot be greater than, say, 85°F. The outdoor air in hot and humid summers seldom drops below 70°F. This 15°F or 8°C ΔT, in a poorly ventilated building where the height difference between inlet and exit apertures is, say, 3 meters at most, will create a stack head of (Ref. 9, p. 282)

$$\Delta P_t = \frac{h\Delta T}{8.5T} \quad \text{cm of } H_2O \tag{2}$$

$$= 0.0095 \text{ cm of } H_2O = 0.0194 \text{ psf}$$

The dynamic head of air at U fps at standard conditions is given by

$$q = \Delta P_U = \tfrac{1}{2}\rho U^2 = U^2/841 \text{ psf} \tag{3}$$

Therefore, the above 0.0194 psf thermal stack head is equivalent to dynamic pressure from a 4 fps wind or 2.75 mph wind.

Thus, it is seen that even with moderate breezes and unless the building is especially designed for stack effect, the wind effect will clearly dominate the ventilation of buildings in hot humid climates. Further discussion will consider only wind-driven ventilation.

For a simple, naturally ventilated building or zone with one windward and one leeward opening, the motive force for the air flow through the building will be the difference between the average <u>stagnation pressure</u> (stagnation pressure = static pressure + dynamic pressure) across the windward opening and the average <u>static pressure</u> at the leeward opening. This is perhaps intuitive and is rigorously proven by Aynsley (reference 2 of Ref. 15). In principle these required pressures can be measured in wind tunnel tests of buildings with <u>open apertures</u>. An indication of this motive ΔP can be obtained by measuring it for <u>solid</u> buildings, but since the external air flow pattern changes with the internal flow in open apertures, the ΔP's from solid models may be inaccurate.

Almost all of the existing literature is on pressure distributions on solid buildings--measured mostly on wind tunnel models but also on full-scale buildings and large outdoor models (Refs. 3, 9, 10, 12, 14). To our knowledge the only published data relating to the above question is from Aynsley in Australia (Ref. 15). Based on two model geometries and normal incidence winds tested in a boundary-layer wind tunnel, Aynsley concludes that solid model ΔP's underestimate wind speeds through openings of up to 20 percent porosity and overestimate if porosity exceeds 35 percent. Clearly, much more experimental work is necessary on buildings with open apertures if air flow rates through naturally ventilated buildings are to be correlated to ΔP's that depend on building/aperture geometry and external wind speed/direction.

Estimation of room air change rates, average room surface temperatures and room air temperatures will enable one to predict the cooling or heat removal rate for natural ventilation. However, it is very important to note that the room air change rate may not be related to air flow rates through aperture openings. Consider normal wind incidence and windward and leeward openings directly in line with one another. Depending on the ratio of the areas of opening, the air can rush through without significantly mixing and entraining room air. As a result, little heat will be removed and circulation in many parts of the room will be poor. Staggered windward and leeward openings that force the air to turn are better for ventilation. For similar reasons, winds at an oblique rather than normal incidence provide better cooling if the apertures are not staggered.

Estimation of the air speed in the room is vitally important to determination of comfort. So room air speeds and directions, in addition to air change rates, must be measured to compare different natural ventilation techniques. At present, empirical correlations for average room air speeds as a function of external wind speed and direction exist only for a few isolated cases. See Givoni (Ref. 9, p. 293) for square rooms at normal incidence with inlet/outlet windows at opposite walls. See Aynsley (Ref. 15) for rectangular buildings on ground or above-ground at normal incidence with multiple inlet and outlet apertures, all in the direction of the normal incidence wind. Correlations for oblique winds and the effect of partitions, fly screens and such architectural features as wing walls or canopies are scant. See references 1 and 2 for some data. Also, existing correlations assume that air flow rate through windows is equal to the room air change rates, which need not be the case.

Architectural Implications

The architectural implications of natural ventilation are discussed in detail by Evans (Ref. 1), Caudill (Ref. 2), Givoni (Ch. 15 of Ref. 9), Olgyay (Ref. 8), Aynsley (Ref. 15). The implications of landscaping (trees and hedges) are described by White (Ref. 6). See Bowen (Ref. 11) for a review. References 1 and 2 are recommended as required reading for anyone planning to design a naturally ventilated building. Some of the findings are summarized below.

a. Airflow is governed by three guiding principles
   - --Air has inertia, i.e., air does not necessarily travel in the shortest path between an inlet and an outlet in an adjacent wall.
   - --Moving air produces friction in contact with bodies and as a result slows down or forms into eddies.
   - --Air moves due to pressure differences.

b. The designer must determine the prevailing breezes at the site. Note that local topograhical conditions, landscaping and adjacent buildings can dramatically influence the winds at the site. Thus, recorded wind speeds and direction data at a nearby meteorological station may be of little value.

c. A study of the external airflow patterns is necessary to determine the best locations for windows or other apertures. Inlets should be placed in the high pressure regions and outlets in the low pressure regions.

d. Window inlets must be so designed and placed so as to provide maximum airspeeds at the desired locations (sitting level in living rooms, just above the bed level in bedrooms).

e. Window types greatly influence the airflow direction in a room. One of the best type of window for natural ventilation purposes seem to be awning or louvered windows which can be manually rotated to direct the wind to desired locations inside the room. Such windows will also generally provide the maximum aperture area, afford proctection from the rain and allow installation of bug screens. Although window types affect the airflow direction, they do not significantly affect the overall ventilation rate.

f. The best location for an inlet is near the vertical and longitudinal center of a wall which is perpendicular to the wind. This is where the pressure is the highest. If the inlets are too high or are near to the side edge of a wall, overhangs or wingwalls should be provided to induce a high pressure zone.

g. The outlet should be exposed to the eddy or wind shadow (eddies in Figure 1a) which is the low pressure zone. The outlet may be placed high, near the ceiling, to take advantage of the stack effect, if any. However, it may be ill advised in locations without a prevailing wind direction, or in some coastal areas where the prevailing wind fluctuates between two opposite directions.

h. In many cases, oblique winds at 45° provide better or equally well ventilation as normal winds. Consider a cross-ventilated room with inlet and outlet windows directly in line with each other. Winds normal to the windows will have a tendency to move through the building without mixing well with the room air. Therefore, regions near the wall will not be well ventilated. Whereas, oblique winds will create a circulating airflow pattern in the entire room providing greater ventilation rates and lower local airspeeds. This has profound design implications in those humid areas where the prevailing summer breezes are easterly or westerly, the direction most difficult to shade and ventilate at the same time. If the prevailing breeze is easterly, one can orient the inlet wall to face southeast or northwest, directions which are easier to shade with long overhangs. Thus simultaneous shading and ventilation are possible.

i. Although windows on only one side of a room do not induce appreciable ventilation, it is possible to design vertical projections (wing walls) to induce appreciable ventilation under oblique winds.

j. For cross-ventilated rooms, both inlet and exit window sizes need to be increased to increase ventilation rates. However, making the inlet smaller than the outlet creates higher windspeeds near the inlet wall, which may be desirable.

k. The effect of indoor partitions is greatest when they are close to the inlet window. But on the average, the ventilation rate is not greatly reduced.

l. Fly screens--a necessity in bug-infested hot and humid regions--result in a percentage decrease in total air flow that is greater (50-60 percent) at low wind speeds (1.5-2 mph) than at higher wind speeds (25 percent at 10 mph), for normal incidences. Wind direction effects are significant. Screening a whole balcony produces more ventilation than screening the window.

m. Extended eaves and end walls are very effective for ventilation with oblique winds for buildings on the ground. Their effectiveness is further increased when the building is elevated above the ground.

n. Hedges and trees can significantly aid or deter ventilation, depending on plant height and spacing from building.

In summary, a considerable body of qualitative knowledge exists based on international and early U.S. work which can be put to use today.

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WINDOW DESIGN FOR PASSIVE VENTILATIVE COOLING: AN EXPERIMENTAL STUDY

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ABSTRACT

Preliminary results are reported of an experimental wind tunnel study of the wind-powered ventilative cooling performance of various window configurations. The effect of various architectural factors on indoor air movement is discussed, including wind orientation, cross-ventilation, inlet/outlet area ratio, inlet shape, window location, and window accessories.

In designing window systems for passive ventilation cooling, four essential steps can be identified. First, it is important to have a clear picture of the directional range of the wind on the site involved throughout both diurnal and annual cycles. Second, it is necessary to make an assessment of the need for ventilative cooling (both diurnally and seasonally) for thermal comfort. Third, it is necessary to evaluate the shielding or "wind shadow" effect of neighboring structures or topography. And fourth, it is vital to choose a window system which corresponds in its functional characteristics to both the wind and to our thermal comfort requirements.

TEST PROGRAM

The author has carried out a test program concerned with the last of these four design factors. The study was undertaken at the Department of Tropical Studies of the Architectural Association (London) during the period 1963-1966. The primary objective of the program was to systematically investigate the degree and manner in which various window configurations convert the kinetic energy of the natural wind into useful indoor air movement.

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Particular emphasis was placed on examining the airflow effect of (1) orientation to wind; (2) cross-ventilation; (3) the relative size of inlet and outlet openings; (4) the shape of inlets; (5) window location; and (6) the type of "window accessories" utilized. The test schedule included some window configurations previously tested either qualitatively or quantitatively, together with a substantial number of window shapes and accessories not previously studied.

A total of 255 configurations were evaluated. These various configurations were tested with the aid of a one-room building model in an open circuit blower type wind tunnel, with a 3 foot square working section. A slatted screen was used to generate a natural wind velocity (power law) profile with an exponent of 0.25, corresponding approximately to the wind over moderately rough wooded country, small towns, or at the outskirts of large cities. The scale of the model used was 1:12 (1 inch = 1 foot). Maximum model blockage was 11% of the cross-sectional area of the tunnel.

The performance of each configuration was examined for at least two wind orientations: 90° (perpendicular wind) and 45° ("oblique" wind). During each test, airflow velocity measurements were made (using a glass bead thermistor probe and a linearized anemometer circuit) at 25 points in a horizontal plane 3'-9" above the floor and 25 points in a vertical plane down the model centerline, giving a total of 50 points on plan and section across the room interior for each configuration. The airflow velocity at each point was expressed as a "speed ratio", i.e., as the ratio between the airflow velocity at the given point and the unobstructed wind speed outdoors 4 feet above ground level ($100\ \frac{\bar{u}}{V}$). The performance of each configuration was summarized as an average speed ratio on plan and in section, with the average plan speed ratios utilized as a convenient overall "figure of merit" in comparing the performance of various window configurations. While the processing of project data is not yet complete, those data which have been reduced permit some preliminary conclusions to be drawn. Those conclusions are summarized below.

ORIENTATION

The effect of orientation to wind or wind angle on ventilative cooling was found to vary with the physical characteristics of the window configuration used, and in particular the characteristics of window location, shape, size and accessories. Generally speaking, for the majority of window configurations tested, orientation of inlets at 90° to the wind provided the highest average indoor speed ratios, with airflow velocities dropping off rapidly with external wind shifts to either side of 90°. Significantly enough, however, it was found that certain combinations of inlet characteristics (especially shape), while providing substantially similar results with 90° wind are also capable of providing equal or better ventilative cooling in oblique (up to 45°) winds than they do in normal (90°) winds. This is a finding of particular importance since wind direction is of course rarely if ever constant. If window systems are to take maximum advantage of wind-powered ventilation, they should be selected where possible to provide a reasonably "broad band", not a strongly "peaked" directional response,providing greater effectiveness under customary conditions in which the wind changes direction over a certain range of directions on an hourly, daily, or seasonal basis. This is the case even in areas of great directional constancy, such as tradewind locations, where, as on the coastal regions of Caribbean islands, directional shifts take place of up to 90° during each 24-hour period. These directional effects are described with respect to each of the window design characteristics discussed below.

CROSS-VENTILATION

Test results confirm that for optimum ventilative cooling, a sufficient effective area of inlet and outlet openings is required, with the inlet/s located in a zone of positive pressure and the outlet/s in a zone of negative pressure. Rooms equipped with inlets only tend to provide very much reduced indoor speed ratios (though demonstrating somewhat improved performance in oblique winds), especially in the case of horizontally-shaped openings (Fig. 1) The configuration with inlets only corresponds to the frequently encountered arrangement in which rooms are provided with windows on one side of a building only. Where the single opening is located on a windward facade, the relative improvement produced by oblique wind can amount to as much as 250%, but the overall result even under this condition at best amounts to only one third of the average speed ratios provided by a cross-ventilating configuration. Smoke-tracing investigations of "one-sided" configurations show that in oblique and normal winds, a single opening functions as both inlet and outlet. Motive power for indoor airflow thus originates in pressure differences across the opening (almost always small in 90° wind, but somewhat more substantial in oblique wind).

INLET/OUTLET AREA RATIO

Test results confirmed that where inlet and outlet opening are equal, as their areas increase, increases occur in the amount of indoor ventilative cooling they produce. Since, however, window sizes are not determined by ventilation alone but must also take into account other architectural factors such as daylighting, privacy, security, and solar control, a significant question for ventilation purposes is how best to distribute a given and usually limited amount of opening area. An important parameter here is the relative distribution of area as between the inlet/s and outlet/s. Preliminary test results suggest that for a given total opening area, the highest average indoor speed ratios throughout rooms are achieved when the ratio $\frac{A_o}{A_i}$ is approximately 1.25, that is, when the inlet is slightly smaller than the outlet. Inlets substantially smaller than outlets produce high local velocities in the vicinity of the inlet itself, but lower speed ratios when results are averaged across the entire room. It thus appears advisable to provide approximately equal inlets and outlets, or a very slightly smaller inlet,where maximum ventilative cooling is required.

INLET SHAPE

A review of preliminary test results suggest that inlet shape is the single most important window design parameter in determining the efficacy of wind-driven ventilative cooling. Fig. 2 shows the ventilation performance of equal areas of horizontal, vertical and square inlets, for various wind angles, in cross-ventilated rooms. As can be readily seen from this comparison, square and vertical inlet openings produce a sharply peaked or "narrow-range" response under conditions of changing wind direction, with both types attaining maximum performance in a perpendicular (90°) wind, but falling off rapidly in efficiency with even small departures of wind direction from the perpendicular. At 45°, for example, vertical inlet performance has decreased by more than 17%, that of square inlets by more than 26%.

On the other hand, horizontal inlets not only have a substantially higher average performance for all wind angles, but in contrast to square and vertical inlets, horizontal inlets actually improve their effectiveness in angled winds, producing two maxima at wind angles in the vicinity of 45° to either side of the perpendicular, while showing a relatively flat, or "wide-range" response throughout this 90° quadrant of wind angles (or orientations). The improvement of horizontal inlets in oblique compared to perpendicular wind angles can amount to 30% or better and depends on the relative opening sizes used. For example, given equal areas of inlet and outlet, where each opening is equal to 22% of the inlet and outlet wall areas respectively, the increase in average indoor speed ratio for horizontal inlets in a 45° wind compared to a 90° wind is typically on the order of 16%. Horizontal inlets were found to increase their performance in oblique winds in fully cross-ventilated rooms (openings in opposite walls), in diagonally-ventilated rooms (openings in adjacent walls), and in rooms with inlet openings only.

From the results of his (1962) ventilation study, Givoni reached the general conclusion that better ventilation is often achieved when the wind is oblique to inlets. With respect to this conclusion, however, it should be noted that all inlet and outlet openings actually tested by Givoni were in fact horizontally shaped; no "square" or "vertical" opening shapes were included in his test program. Another of Givoni's conclusions not supported by the results of the present study concerns his explanation for the superiority of oblique wind angles. Givoni suggests that when airflow has to change direction inside a room, as it must with wind oblique to the ventilation-axis*, a larger proportion of room volume becomes involved in the flow, resulting in higher average velocities. Test results from the author's study indicate, however, that a change in direction of airflow inside a room does not necessarily lead to increased air movement, but on the contrary often substantially reduces it. Smoke-tracing shows, for example, that in oblique winds, strong directional changes take place inside rooms equipped with square or vertical inlets, yet these two inlet types consistently provide substantially lower average indoor speed ratios in oblique than in perpendicular

* the ventilation axis can be defined as a line drawn between the center points of the inlet and outlet openings.

wind, typically showing relative losses of 25% or more in a 45° wind. A more comprehensive hypothesis, capable of explaining the full range of observed changes in performance with different opening shapes appears to require inclusion of at least two factors in addition to flow patterns: (1) the influence of wind angle on the <u>effective</u> inlet area, and (2) external wind-pressure distributions. It should also be observed that horizontally-shaped inlets tend to produce a broader, flatter, more "room-wide" jet or sheet indoor airflow than do vertical or square ("hole-in-a-wall") shaped inlets. This fact may help to explain, at least in part, their clearly superior ability to provide higher average amounts of ventilative cooling throughout the interior of rooms.

WINDOW LOCATION

Preliminary results suggest that in general, ventilative cooling performance is improved when the inlet and outlet are arranged so that the ventilation axis is parallel to the wind. This condition occurs either (a) when the inlet and outlet are located directly in line with one another on opposite walls of a room, with the wind perpendicular to the inlet; or (b) when the inlet and outlet are located in adjacent walls of a room, and an oblique wind passes successively through the inlet, through at least one corner of the room, then passes through the outlet. It should be noted that in both of these cases, the main tube or jet of airflow passes directly from inlet to outlet without changing direction inside the room. The only previous study to have examined the diagonally-ventilated room configuration (Givoni, 1962) and which reported a test result contrary to that attained in the present study, proceeded to use this result as a basis for concluding that ventilation is improved whereever airflow changes direction inside a room. Additional testing of this type of configuration appears to be indicated. While a large number of other tests were carried out to examine the effect of inlet and outlet location, the results of these tests are not yet available for analysis and evaluation.

WINDOW ACCESSORIES

Window accessories have been traditionally designed to work as sunshading, privacy or security devices, not as airflow controls. However, window "equipment" designed to produce solar or rain protection, visual privacy, shielding and other non-aerodynamically-related purposes can frequently have unintentioned, yet at times seriously deleterious effects on wind-powered ventilative cooling. Earlier studies have recognized this problem; the present results confirm its importance.

One instance of the unfavorable effect of window equipment revealed by present test results is the aerodynamic effect of fixed or movable horizontal and vertical louvers. The effect of primarily horizontal louvers or canopies on indoor airflow speeds and patterns is chiefly manifested in section. As described by previous workers, for example, and confirmed by the present study, horizontal louvers ("jalousies") have the tendency, when adjusted to typical angles, to direct airflow toward the ceiling, thus greatly reducing ventilative cooling effectiveness within the room's occupied zone. However, the effect of primarily vertical louvers chiefly shows up on plan. For example, horizontal louvers used on vertical inlets do nothing to alter the basically peaked, "narrow-band" and symmetrical plan-response of this type of opening to changing wind angles, regardless of the blade setting angle. The same phenomenon is created by inlet accessories which incorporate vertical elements, which also tend to produce a strongly peaked, "narrow-band" directional response, providing maximum average indoor airflow when the vertical elements present the minimum degree of airflow resistance, i.e., when they are parallel to the wind. For example, when vertical louvers are set perpendicular to the plane of an inlet opening, they tend to cut off diagonal wind; yet when oriented at an oblique angle they sharply favor diagonal winds ariving at angles close to that same direction. By the addition to vertical control elements, it is also possible to "convert" the typical "broad-band" directional response of horizontal inlets, into the "narrow-band" response of square or vertical inlets (Fig. 3).

In general, as the wind angle shifts, vertical "window furniture" produces an effective change in inlet area. The degree of change depends on the angular relationship between the accessory elements and wind direction. Increasing the angle increases "narrowing", and decreasing the angle increases effective inlet area. Where it is not possible or desirable to orient opening accessories to face the wind, flow-directing accessories such as louvers can be placed within or across the inlet opening to "turn" wind to enter a building. But results show that considerable resistance losses of up to 50% or more are incurred by the use of such techniques, suggesting that wherever possible flow-directing accessories should be located adjacent to inlets, not within them.

CONCLUSIONS

It is apparent from a partial review of processed data from the experimental study that a substantial number of different window systems are capable of providing indoor airflow velocities of 25% or better of the wind speed at "standard" measuring height of 33 feet (assuming a "rough open country" or "suburban" natural wind velocity profile). Of the various window systems analyzed which were found to have the capacity to provide this higher level of performance, those which make use of horizontally-shaped inlets appear to enjoy a clear margin of superiority over the other systems tested. This superiority is reflected in their unequalled ability to provide more complete ventilative "coverage" of the full area of a room. It is also reflected in their exceptionally broad-band or "wide range" response to varying wind angles, giving them a high degree of ventilative efficiency over a much wider range of wind directions than more conventionally shaped square or vertical inlets. The study data also confirms the conclusions of previous investigators concerning the desirability of providing cross-ventilation in some form, the need to keep inlet and outlet areas approximately equal, and the existence of a ventilation penalty which is frequently imposed by the use of window "accessories".

Current plans for the project include completing the remaining scope of data reduction and processing at the University of Arizona together with full publication in the near future of project results in the form of a design-oriented guide to the selection of window systems on the basis of their potential for passive ventilative cooling.

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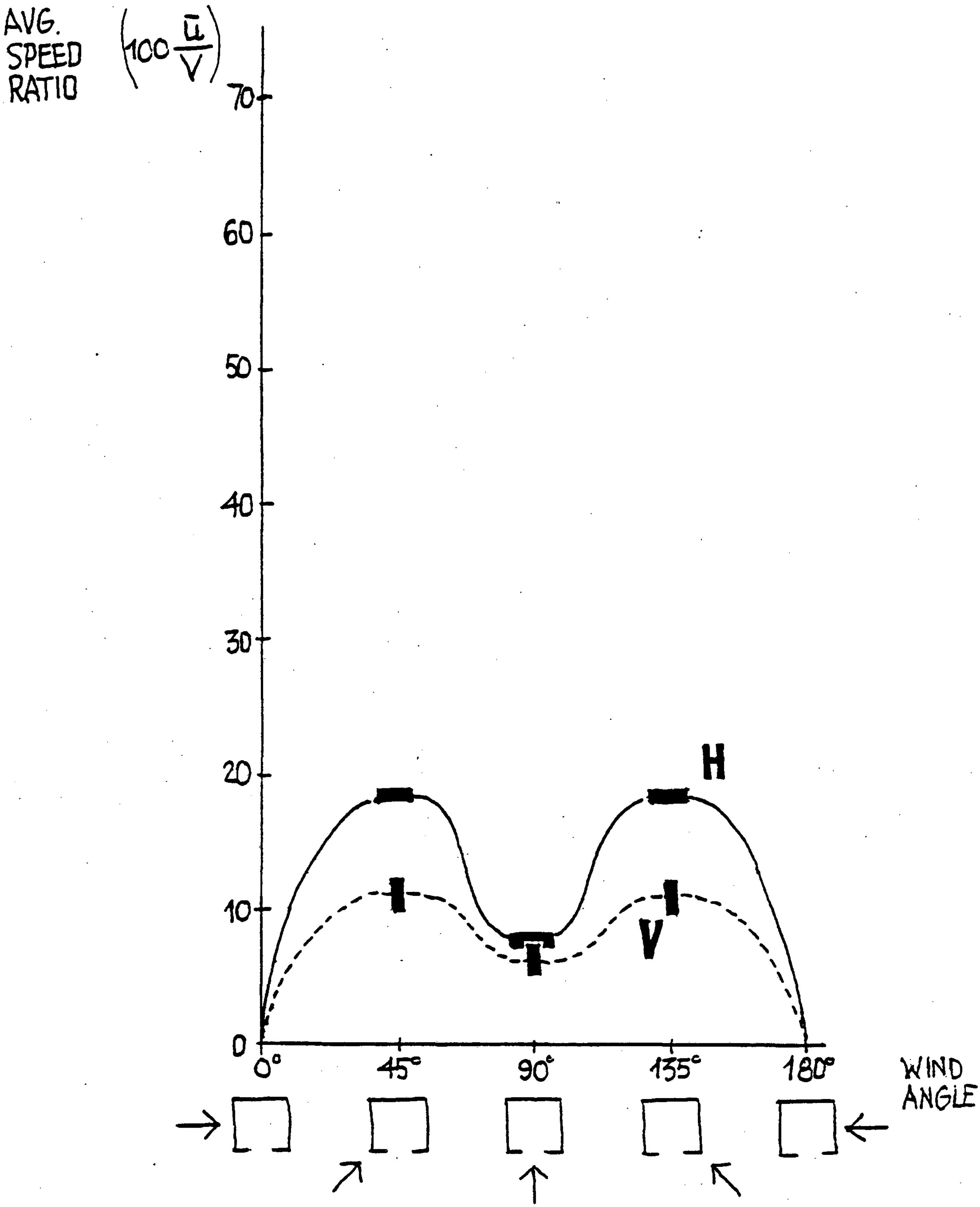

Fig. 1 Effect of wind direction on average indoor airflow velocity in rooms with inlet openings only [total inlet area = 22% of inlet wall area].

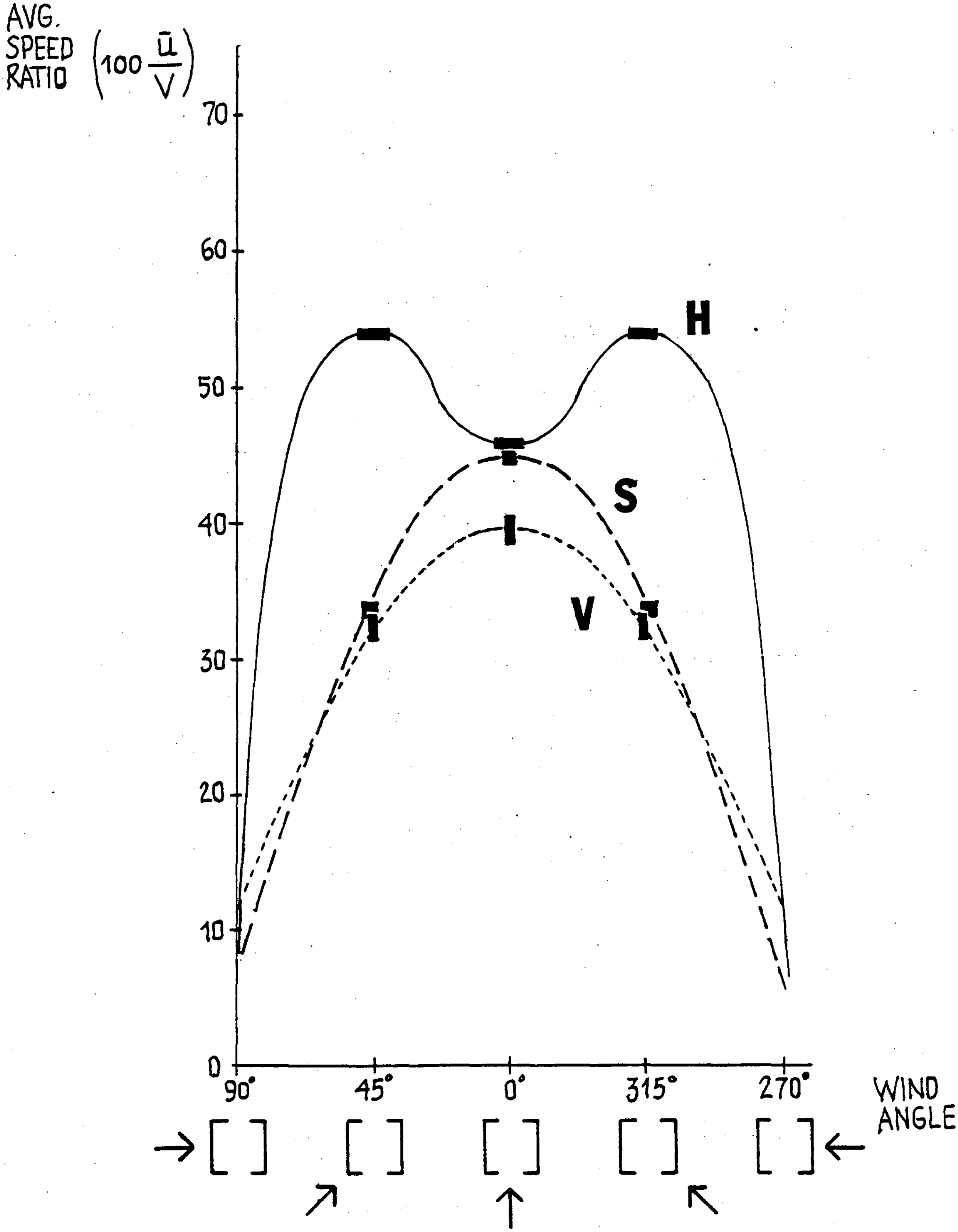

Fig. 2 Effect of wind direction on average indoor airflow velocity in relation to opening shape. [for cross-ventilated rooms equipped with square, vertical and horizontal openings; inlet area = outlet area = 22% of inlet or outlet wall area].

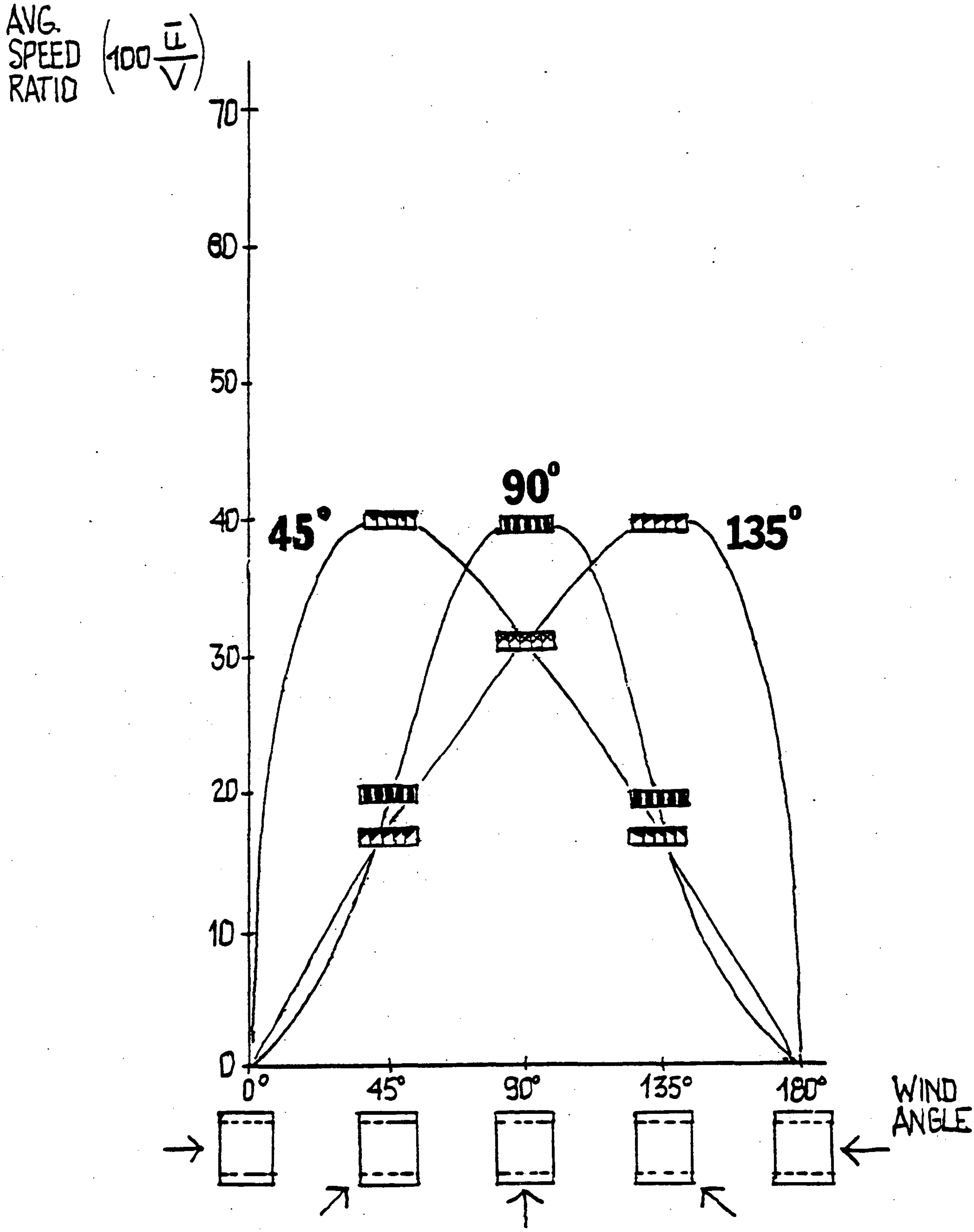

Fig. 3 Effect of wind direction on average indoor airflow velocity in rooms with window openings equipped with "window accessories" placed obliquely (45° and 135°) and normally (90°) to the window plane [vertical louvers in horizontal openings; inlet area = outlet area = 22% of inlet or outlet wall area].

NIGHT VENTILATION COOLING OF MASS

Karen Crowther

GENERAL DESIGN TIPS

1. Use lots of mass surface.

Surface area of the mass must be large. (That is why phase change material does not work as well as slab floors, masonry walls, etc.) It is useless to have a lot of heat capacity unless there is enough surface area to absorb the heat. Large surface areas are much more important in natural cooling than they are in solar heating.

2. Expose the mass surface to the occupants.

Make sure that the surface of the mass is exposed to the people. This doubles the cooling ability of the mass since it will not only cool the air but cool the people directly by radiation. (At low air velocities radiation can cool as effectively as convection.)

3. Protect the mass from direct sunlight.

Direct sun can heat up the mass as much as twenty times as fast as the air can cool it.

HAND CALCULATION OF NIGHT VENTILATION COOLING OF MASS

Included is a worksheet to help organize simplified hour-by-hour calculations. The calculations will show how much cooling the mass can reasonably provide, determine whether there is adequate surface area for the peak demand, and predict the lowest mass temperature. This routine has been used in the dry California Central Valley and appears to be conservative. It is offered here as a first approximation until more sophisticated routines become available. The assumptions used in this routine are listed after the worksheet. The listing of a program for a Hewlett Packard hand-held calculator (i.e., one using Reverse Polish Notation) is also included.

WORKSHEET

HAND CALCULATION OF MASS COOLING

A. Mass surface area . . . . ________ ft^2

B. Mass heat capacity . . . . ________ BTU/°F

C. Floor area. . . . . ________ ft^2

(1) Hour	(2) Outside Air Temp. (°F)	(3) Cooling BTU	(4) Mass Temp. (°F)
8 p.m.	________	________	________
9	________	________	________
10	________	________	________
11	________	________	________
12	________	________	________
13	________	________	________
14	________	________	________
15	________	________	________
16	________	________	________
17	________	________	________
18	________	________	________
19	________	________	________
20	________	________	________
21	________	________	________

D. Total mass cooling . . . . ________ BTU

E. Final Mass temperature . . . . ________ °F

F. Other cooling . . . . ________ BTU

G. Mass plus other cooling. . . . . ________ BTU

H. 24-hour cooling load . . . . ________ BTU

I. Peak hourly cooling by mass . . . . ________ BTU/hr

J. Peak hourly cooling load . . . . ________ BTU/hr

WORKSHEET DIRECTIONS

A. Mass surface area. Include only exposed surface. Do not count rug-covered floors or insulated walls. Include both sides of a wall if both sides are exposed.

B. Mass heat capacity. (mass volume) x (density) x (specific heat)

Add:
(volume of water [ft^3]) x 62.4
(volume of concrete [ft^3] x 22.5
(volume 8" grout-filled masonry) x 18.7
(volume of bricks [ft^3] x 15.6
other mass heat capacity

C. Floor area of a building which has a significant amount of walls, roof, or floors whose mass was not counted in part A. (For example, if you have a house built completely of adobe with no interior sheetrocked walls you would enter 0. If your mass were in the form of water containers with standard construction you would enter the entire floor area here. For buildings with very large rooms do not enter the full floor area since this calculation is based on residences.)

Column 2. List hourly outside temperatures either from published data or from a reasonable interpolation between maximum and minimum daily temperatures. Only list those temperatures which are less than 75°F. If it is above 75° until midnight, then just ignore the hours before midnight. If average figures are used then average performance will be calculated. If worst case figures are used, then worst case performance will be calculated.

Column 3.

$$\text{Cooling} = \left(\begin{array}{l}\text{last mass temp.}\\ \text{from Col. 4}\end{array} - \begin{array}{l}\text{outside temp.}\\ \text{from Col. 2}\end{array}\right) \times \begin{array}{l}\text{Surface Area}\\ \text{from line A}\end{array}$$

(for the first hour use 75°F as the "last mass temp.")

Column 4.

$$\text{Mass Temp.} = \begin{array}{l}\text{Last mass temp.}\\ \text{from Col. 4}\end{array} - \left(\begin{array}{l}\text{Cooling}\\ \text{from Col. 3}\end{array} \div \begin{array}{l}\text{Mass heat capacity}\\ \text{from line B}\end{array}\right)$$

STOP if the mass temperature is lower than the outside

D. Total mass cooling. Add all the figures in Column 3.

E. Final mass temperature. This is the last temperature in Column 4.

F. Other cooling: $\left(75 - \begin{matrix}\text{last mass temp.}\\ \text{from line E}\end{matrix}\right)$ X 2.25 X Floor area from line C

G. Add lines D plus F.

H. 24-hour cooling load. Use ASHRAE <u>Fundamentals</u> or the simplified heat gain calculation given in the appendix. This figure is the gross amount of heat gain that the building will experience during the day.

I. Peak hourly cooling by mass. This is a very, very rough calculation and is only included here so that the designer can get some idea of whether the mass can meet the peak cooling demand. It assumes that the mass has given up 2/3 of its "coolth" by the peak hour and that the combined radiation and convection heat transfer coefficient is 2.3 BTU/hr-ft^2-^{o}F.

$$\text{Peak Cooling} = \left\{64 - \left(.77 \times \begin{matrix}\text{last mass temp.}\\ \text{from line E}\end{matrix}\right)\right\} \times \left(\begin{matrix}\text{surface area}\\ \text{from line A}\end{matrix}\right)$$

J. Peak hourly cooling load. Calculate this from ASHRAE or from the simplified calculations in the Heat Gain Calculation section.

If line G is greater than line H, then the cooling load can be met by the mass. If line I is greater than line J, then there is probably enough surface area and mass "coolth" to take care of the peak load.

Program for Calculating Night Ventilation Cooling of Mass - HP Programmable

Step 1	--	Press "FA"	
Step 2	--	Store Mass Surface Area (ft^2) in R_0	STO 0
Step 3	--	Store Mass Heat Capacity (BTU/^oF) in R_1	STO 1
Step 4	--	Store Building Floor Area (ft^2) in R_4	STO 4
Step 5	--	Press "A"	
Step 6	--	Enter Outside Temperature (^oF) and Press "B"	
Step 7	--	Repeat Step 6 Every Time Display Pauses. Calculator will Automatically Print when Outside Temperature is Too High to Cool Mass	

OUTPUT

69.3 *** Final Mass Temperature (^oF)
42765. *** Cooling Provided by Mass (BTUs)
12850. *** Additional Cooling by Building Materials (BTUs)

55615. *** Total Possible Cooling (BTUs)

001	*LBLB	21 16 11
002	0	00
003	ST03	35 03
004	7	07
005	5	05
006	ST02	35 02
007	R/S	51
008	*LBLA	21 11
009	RCL2	36 02
010	R/S	51
011	*LBLB	21 12
012	-	-45
013	X<07	16-45
014	GTOb	22 16 12
015	ROL0	36 00
016	x	-35
017	ST+3	35-55 03
018	RCL1	36 01
019	÷	-24
020	ST-2	35-45 02
021	GTOA	22 11
022	*LBLb	21 16 12
023	RCL2	36 02
024	DSP1	-63 01
025	PRTX	-14
026	ROL3	36 03
027	DSP0	-63 00
028	PRTX	-14
029	7	07
030	5	05
031	ROL2	36 02
032	-	-45
033	RCL4	36 04
034	x	-35
035	2	02
036	.	-62
037	2	02
038	5	05
039	x	-35
040	PRTX	-14
041	RCL3	36 03
042	÷	-55
043	SPC	16-11
044	PRTX	-14
045	SPC	16-11
046	R/9	51
047	RTN	24

ASSUMPTIONS USED IN COOLING ROUTINE

1. Convective heat transfer into the mass is the controlling factor. Conductive resistance within the mass can be neglected. (A good assumption for water in metal containers: as optimistic assumption for concrete, masonry, adobe, etc.)

2. The mass is at a uniform temperature.

3. The building interior cools down at a uniform rate so that there is no net radiation het transfer. (A pessimistic assumption since the lower massed walls will cool faster and there will be a net radiative loss from the mass to these walls.)

4. The outer mass furfaces (not counted in the mass surface area) are perfectly insulated. (A pessimistic assumption.)

5. Slabs on grade do not transfer heat except through their interior surfaces. (This may be a pessimistic assumption since it appears that even in summer there is a net loss of heat to the surroundings.)

6. The heat transfer coefficient is 1 BTU/hr-^{o}F-ft^{2} in the calculator program. This is the figure that has been used although the heat transfer coefficient could be anywhere between .6 (no radiation, no air speed) to, say, 4 BTU/hr-^{o}F-ft^{2} where there is a significant wind blowing through the building.

Earth Contact Cooling

A Comparison of Ground and Above-Ground Climates for Identifying Appropriate Cooling Strategies --
Kenneth Labs and Keith Harrington

A COMPARISON OF GROUND AND ABOVE-GROUND CLIMATES FOR IDENTIFYING APPROPRIATE COOLING STRATEGIES*

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Abstract

A mathematical model of undisturbed ground temperature is applied to the problem of assessing the value of earth tempering techniques in six regions of the contiguous United States. Synthesized ground temperature tables and comparative normal and design air temperatures are presented and briefly discussed with regard to the suitability of subgrade construction and earth-air heat exchangers. Emphasis is placed on evaluating earth tempering within the context of other passive cooling strategies, which are identified as to the percentage of annual hours that each is effective within the six study regions. It is concluded that ground cooling techniques are of greatest value in temperate and arid areas, and of limited benefit in warm, humid zones, in which they may even be counterproductive by compromising natural ventilating capability.

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* This paper is based in part upon material from a forthcoming report, "A Regional Analysis of Ground and Above Ground Climate for Evaluating the Suitability of Earth Tempering Practices in Architectural Design," which is being prepared through sponsorship of the Oak Ridge National Laboratory for the U.S. Department of Energy. This paper will appear in the inaugural issue of the Passive/Hybrid Journal which will be co-published by SERI, U.S. DOE, and the Passive Systems Division of the AS/ISES.

Introduction

Interest in the cooling potential of the ground has expanded rapidly in the past two years. Unfortunately, there exists at this time little in the way of a ground temperature data base or methodology for making design decisions about earth tempering practices. Although theory of ground climate is well documented in the literature of geophysics, agronomy, and other fields, little of this information has found its way into the hands of building designers and researchers. As a result, old myths continue to be promulgated in the professional as well as popular press. A recent government-sponsored report on climate design guidelines for energy conserving homes, for instance, makes reference to "taking advantage of the stable temperature conditions of approximately 56F, below the frost line"—conditions which certainly don't exist anywhere near central Florida, to which this recommendation was directed.

This paper presents ground temperatures synthesized by an often validated theoretical model for six regions in the United States. Although these represent undisturbed temperatures which would be elevated by the presence of some ground "coolth"-exploiting device, they do offer a first attempt at identifying where an at-least initial useful cooling potential exists in the ground.

With the belief that no climate control strategy should be considered in isolation of alternative or complementary practices, ground temperature data are presented here in juxtaposition with corresponding simultaneous air temperature normals, ASHRAE design temperatures and a bioclimatic analysis of appropriate above-surface design strategies.

Temperature model

In 1965, T. Kusuda and P.R. Achenbach [1] posited that periodic heat conduction theory can be used to model annual temperature variation in the ground with sufficient accuracy to suit most building engineering purposes. An extensive review of earth temperature literature in the fields of geophysics, agronomy, and other branches of the sciences generally confirms this position, and has provided insights into the limitations of the model as well [2]. Although data synthesized by Kusuda's method has been widely published, it appears in the form of seasonal average temperatures of a soil profile extending from the surface to a depth of 10 feet. This has been used for estimating the temperature of the earth surrounding fallout shelters [3], heat losses from buried steam lines [4], and as input for building load simulation models [5].

The theoretical model is employed here for estimating instantaneous temperatures for a range of selected depths and for computing the average temperature of various subgrade profiles. The theory itself is developed in numerous textbooks on heat conduction and environmental physics [6, 7]. In a form in which time is represented in days, the model may be written,

$$T_{(x,t)} = T_m - A_s e^{-x\sqrt{\frac{\pi}{365\alpha}}} \cos\left[\frac{360}{365}\left(t - t_o - \frac{x}{2}\sqrt{\frac{365}{\pi\alpha}}\right)\right] \qquad (1)$$

where

$T_{(x,t)}$ = temperature of soil at depth x and time t
T_m = mean annual earth temperature (steady state temperature)
A_s = amplitude of surface temperature wave
x = depth below surface
α = thermal diffusivity of soil (ft^2/day)
t = time of year (days)
t_o = phase constant (days)

An expression for the average temperature of any selected profile ranging from depth a to depth b is obtained by integrating equation (1) with respect to depth x, and dividing the result by the height of the profile (b-a),

$$T_{(a-b,t)} = T_m + \frac{A_s}{(b-a)r\sqrt{2}} \; e^{-xr} \cos\left[\frac{360}{365}\left(t - t_o - 46 - \frac{x}{2}\sqrt{\frac{365}{\pi\alpha}}\right)\right]\Bigg|_b^a \qquad (2)$$

where

a = upper bounds of soil profile
b = lower bounds of soil profile

$$r = \sqrt{\frac{\pi}{365\alpha}}$$

Selection of variables

The theoretical model applies to a semi-infinite homogenous solid, the properties of which are constant over time, with a perfectly sinusoidal temperature variation at the surface. None of these conditions are strictly met in soils, yet analysis of most observed ground temperature measurements reveals remarkably good agreement with theory. The major problem, therefore, is accurate estimation of the variables of the model, most of which will be unknown to the investigator at any given location.

Criteria for selecting values for the variables and their ranges are discussed in detail in reference [2], and will not be dealt with at length here. The values chosen for use in generating the tables presented in this paper are given with brief explanations below.

Ground temperature mean, T_m

A recently prepared isothermal map of well water temperatures has been obtained from the National Water Well Association. It was constructed from records of observed ground water temperatures in wells ranging from 50 to 150 feet in depth. This is believed to be the best available regional index of steady state ground temperatures and is considered adequately accurate for selecting T_m for use in the mathematical model (see Figure 1). For locations in which actual ground temperature records have been kept, these records have been considered in verifying or adjusting values obtained from the map.

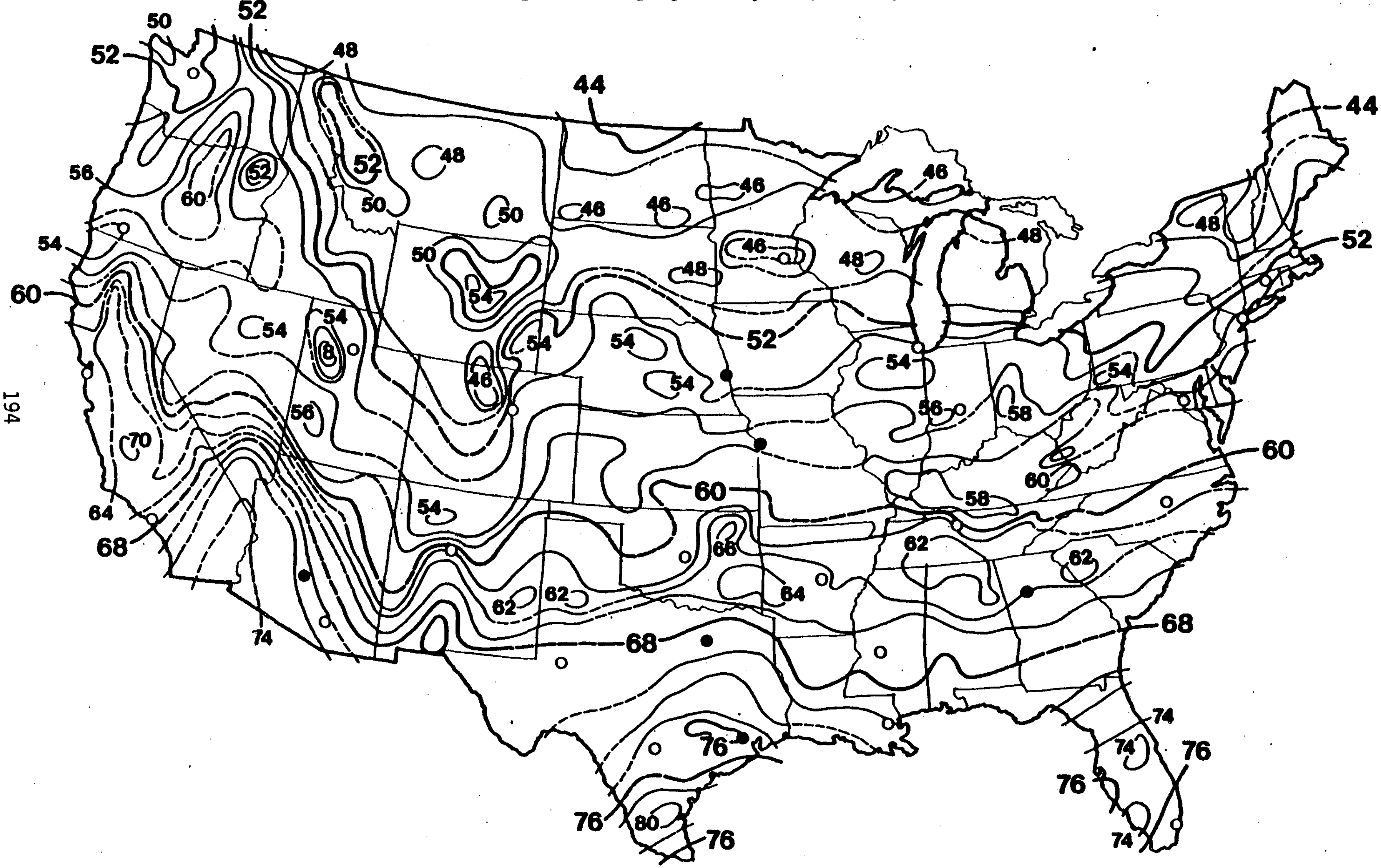
It is clear from the form of Equations (1) and (2) that every degree by which T_m is misjudged will result in a one degree error in ground temperature estimate, regardless of depth. Assumed T_m for each of the six cities discussed here is indicated on the respective tables.

Figure 1

Surface temperature amplitude A_s

All other things being equal, surface temperature amplitude increases with latitude; many other factors complicate the relationship, however, so no simple regional generalizations can be made. The values selected here have been estimated from records of nearby stations, as reported by Kusuda [8] and others. For soils of average thermal diffusivity, a difference of every two degrees in amplitude at the surface creates a difference of one degree amplitude at a depth of 6 feet, so a reasonable approximation of A_s is considered adequate.

Figure 1. Assumed T_m values, redrawn from a map of observed well water temperatures prepared by Doug Bacon, National Water Well Association.



Thermal diffusivity, α

Thermal diffusivity is the least knowable of parameters in the ground temperature model, as it varies with soil type, depth, moisture content, and consequently, with time. Comparison of predicted temperatures with field observations show that a constant α does produce good agreement, provided that it is well chosen.

Analysis of observed ground temperature records through a least squares technique with Equation (1) yielded thermal diffusivity values ranging from approximately 0.25 to 0.85 ft^2/day [8]. The arithmetic average of 71 of these computed values is 0.508 ft^2/day. A cluster analysis was performed by the authors to select average values from three groupings intended to represent soils of low, medium, and high thermal diffusivity. The results obtained were 0.332, 0.527, and 0.752 ft^2/day. According to ASHRAE's characterizations [3], 0.26 corresponds to a light, dry soil, 0.48 to a light, damp or heavy, dry soil, 0.6 to a heavy, damp soil, and 0.79 ft^2/day to dense concrete.

Givoni [9] has analyzed the attenuation of measured temperature amplitudes with depth by a graphic technique. He reports that an envelope bounding the observed data is described by the expression

$$\frac{A_s}{A_x} = e^{-0.32x} \qquad (3)$$

for "humid" locations (Minnesota, Washington, D.C., Kentucky), and by

$$\frac{A_s}{A_x} = e^{-0.48x} \qquad (4)$$

for "dry" locations (Texas, Israel, Egypt), where x here is given in meters. In the English system, equations (3) and (4) correspond to thermal diffusivity values of 0.4 and 0.9 ft^2/day, respectively. One would expect lower α in arid regions and higher α in soils of higher moisture content; however, since α can also be expected to vary locally with soil type, topography, and other factors, no rational basis was felt to exist for predicting regional distribution of thermal diffusivity. A constant α of 0.52 ft^2/day has, therefore, been applied to all regions except Phoenix. Since Dallas and Phoenix share the same T_m and A_s values, a lower α of 0.33 ft^2/day was assigned to the latter for the purpose of comparison between these.

Phase constant, t_o

The delay in phase of the ground temperature wave with respect to air temperature is largely responsible for the usefulness of the ground for cooling. Theory indicates that the minimum surface temperature should occur 1/8 cycle after minimum surface heat flux, on December 21 (in the absence of snow cover and latent heat exchanges), that is, December 21 + 45 days = the 35th day of the calendar year. Although a sampling of stations analyzed by Kusuda exhibit an average phase constant of almost 35 days, individual stations may vary up to 10 days or more to either side of the average. Moreover, plotting the predicted temperatures against observations sometimes shows a discrepancy of several weeks, with the observed ground temperature wave usually preceding the predicted wave (i.e., $t_o < 35$).

Large departures in t_o from the norm of 35 days assumed in the tables are likely to be responsible for the greatest errors that may occur in the use of the model. This is especially important when temperature events in the ground are being compared to long term air temperature normals as an indication of relative benefit of above and below grade climatic conditions at any fixed point in time. It is recommended that users of the tables graphically plot the predicted temperatures and shift the $t_0 = 35$ curve forward and backward in time so as to examine the possible range of ground temperatures resulting from conditions other than $t_0 = 35$ (see Figure 2).

Figure 2

Earth tempering as a cooling strategy

Earth cooling is one of sixteen hypothetical climate control strategies, of which eight are identified for overheated conditions (Figure 3). Not all of these are, in fact, practicable, so the list of total fundamental control strategies reduces to eight, seven of which are applicable to overheated conditions. Of the latter, three are strategies to minimize heat gain, while only four can be regarded as "cooling" in the sense of disposing of heat already present.

Figure 3

Givoni [10, 11] has proposed a procedure whereby weather data can be analyzed to assess the relative appropriateness of ventilation, thermal mass, evaporative cooling, and the number of comfort hours when only shading is necessary (Figure 4). Although soil temperatures cannot be analyzed directly by the Givoni method, the percentage of annual hours that synthesized ground temperatures or profile temperatures fall below, within, or above comfort limits can easily be counted and evaluated in parallel to the

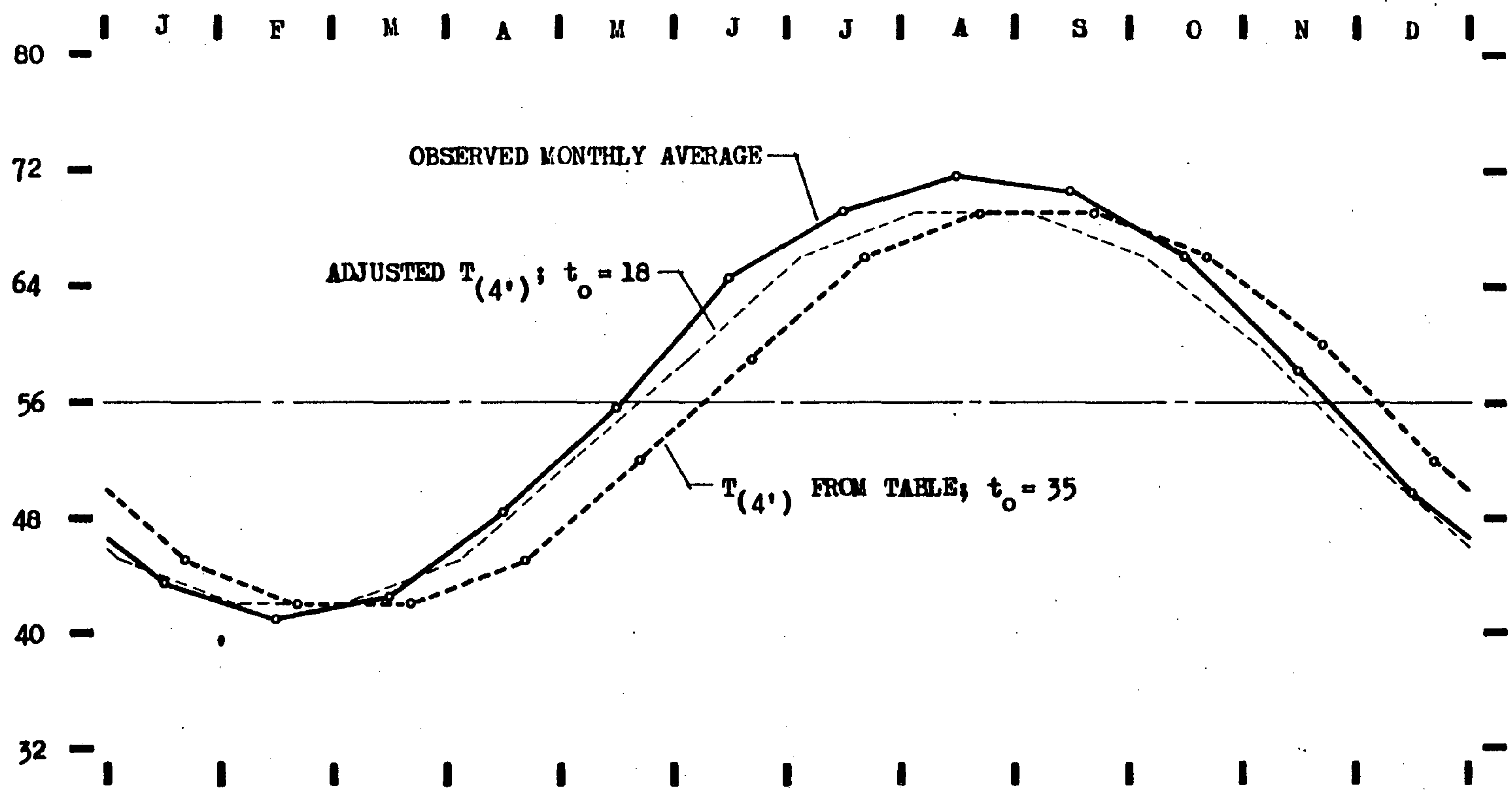


Figure 2. Monthly averages of observed ground temperatures at the 4 foot depth in Manhattan, Kansas are compared to predicted temperatures (Table 4) in the Kansas City vicinity, using $t_o = 35$. The relatively large difference between the curves is corrected by shifting the phase of the predicted temperatures by 2 1/2 weeks, so that $t_o = 18$ days. Agreement is then within 3F for the entire year.

	CONDUCTION	CONVECTION	RADIATION	EVAPORATION
PROMOTE GAIN			promote solar gain	
RESIST LOSS	minimize conduction	minimize infiltration		
RESIST GAIN	minimize conduction	minimize infiltration	minimize solar gain	
PROMOTE LOSS	earth cooling	promote ventilation	nocturnal radiation	evaporative cooling

Figure 3. Earth cooling is one of sixteen hypothetical climate control strategies, or one of seven usable strategies for overheated periods. Some combinations of strategies are mutually beneficial, while other combinations may act against one another.

hours of effectiveness of other strategies. The simultaneous conditions presented in the tables then offers a means of assessing if ground cooling potential occurs at a useful time.

Figure 4

In using undisturbed ground temperatures for evaluation, it must be recognized that the soil surrounding a building or a device which exchanges heat with the ground will increase in temperature above predicted undisturbed levels. The temperatures given here, therefore, represent initial conditions and, as such, the lower <u>limits</u> of temperatures in the ground. This means that if ground temperatures appear to be of marginal value for heat absorption at their undisturbed state, with their elevated operating levels and with carryover of winter building heat losses (where applicable), they are certain to be of no value.

Earth tempering may be understood to include recessed placement and berming ("earth sheltering"), the use of earth-air heat exchangers ("earth pipes"), and sod roofs. The desirability of sod roofs is indicated in part through the appropriateness of thermal mass as a control strategy in the Givoni scheme. Not accounted for here is the evaporative cooling effect of a well-watered ground cover, which alone typically dissipates 75 percent or more of net solar radiation during summer months.

In application, earth sheltering practices usually either complement or conflict with other climate control strategies. Past and present uses of cooling tunnels and shafts in the ground with evaporative sprays are well documented, as are fountains and water walls in courtyards, which may be recessed to serve as a catch basin to collect cool, downward draining night-

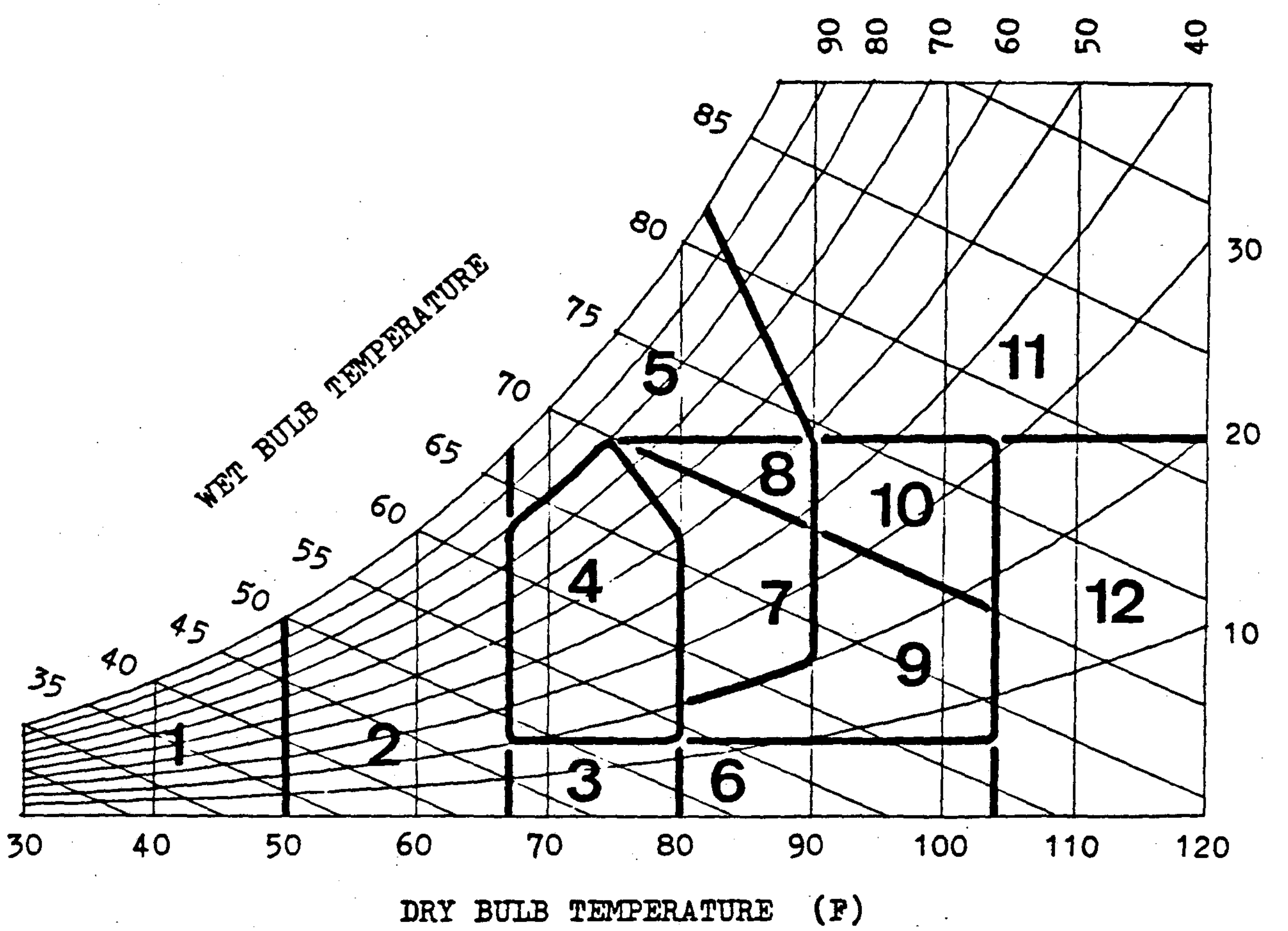


Figure 4.

APPROPRIATE CLIMATE CONTROL STRATEGIES

- RESTRICT CONDUCTIVE HEAT FLOW: **1, 2; 11, 12**
- RESTRICT INFILTRATION: **1, 2; 11, 12**
- PROMOTE SOLAR HEAT GAIN: **1, 2**
- PROMOTE NATURAL VENTILATION: **5, 7, 8**
- RESTRICT SOLAR HEAT GAIN: **4, 5 - 12**
- PROMOTE EVAPORATIVE COOLING: **6, 7, 9**
- PROMOTE RADIANT COOLING: **7 - 10**

time air [12]. Unfortunately, the spate of earth sheltered houses constructed in the past two years appear largely to have been designed with no regard for ventilation whatsoever. Eager builders seem willingly seduced by a belief that we have but to snuggle into Mother Earth to avert the often bewildering complexities of climate responsive design. Like all design, earth tempering requires an integrated approach, one which is able to exploit the best of both surface and subsurface climates. This can only be achieved through study of simultaneous above and below ground conditions.

Presentation and discussion of data

Synthesized ground temperatures for six regions are presented in Tables 1 - 6, in juxtaposition with simultaneous surface temperature normals and ASHRAE design temperatures [13]. Also presented by region are the results of the building bioclimatic analysis of appropriate cooling strategies, in terms of the percentage of hours of the year that each is effective. The percentage of hours of the year that undisturbed soil profile temperatures fall in the ranges of less than 68F, between 68 and 78F, and in excess of 78F are included here as a means of relating earth sheltering to the other cooling strategies.

Each reader will interpret the data presented here in different ways, depending upon individual areas of interest and working needs. A detailed discussion of the results is not, therefore, considered necessary,* although

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* Discussion of the comparative data given here will be contained in a larger report,"A Regional Analysis of Ground and Above Ground Climate for Evaluating the Suitability of Earth Tempering Practices in Architectural Design," to be released at the end of this year.

some remarks are warranted.

Southern coastal zones

The Gulf Coastal Region is characterized by such high ground temperatures that even a fully subgrade wall is expected to see profile temperatures in the 80's from the end of July through November. During October and November, profile temperatures exceed not only comfort limits, but normal daily air temperature maxima as well. In Houston, ventilation is the only important passive cooling strategy; it is required for more than 95 percent of the entire overheated period, or 54.4 percent of annual hours. Considering that the temperature of a 2 - 12 foot profile exceeds 78F for 36 percent of the year and never falls below 68F, there seems to be little to recommend earth sheltering here. Design emphasis should be placed on optimizing ventilation effectiveness.

Humid and arid southern inland zones

Although isolated from the coast by 260 miles, Dallas nonetheless experiences high enough humidity levels to render ventilation its single most important cooling strategy. Ventilation is normally effective for 77.5 percent of the total overheated period, and it is the exclusive means of comfort control for 46 percent of total overheated hours. While evaporation is effective for 12 percent of the cooling period, most of these hours overlap with ventilation hours, so given adequate ventilation, evaporative cooling is not a significant control strategy. Only thermal mass offers significant additional value, being effective for 54 percent of the overheated period, and being uniquely effective for 20 percent of the cooling period.

A shallow bermed or basement space (0-6' profile) will see ground temperatures exceeding comfort limits for 27 percent of the year, including the most overheated months of the year, July and August. The average undisturbed temperature of a deep profile (2-12') escapes temperatures in excess of 78F, although this limit itself is reached in September. For this same profile, 58 percent of annual hours are spent between 68 to 78F. While undisturbed temperatures do not constitute a source of heat gain, neither do they offer a useful sink for an overheated interior space. Given the little cooling ability of the earth in such warm, mildly humid climates, therefore, it can be concluded that ventilating ability should be optimized and, if earth sheltered design compromises free ventilation, its overall effect can be counterproductive. Fan-forced and passive-induced forms of ventilation and ground temperature modification techniques could override this conclusion, so earth sheltering here seems to be of marginal value.

As in Dallas, ventilation is the most important cooling strategy in Atlanta. Proper ventilation can provide adequate cooling for 94 percent of overheated hours, and it is uniquely capable (among surface strategies) of attaining comfort conditions for 62 percent of overheate hours. Although neither deep nor shallow ground profiles exceed 78F, their temperatures are not low enough either to absorb significant amounts of heat from the interior. Given relatively high humidity levels, condensation could be expected to be a problem with subgrade walls and earth pipes.

The overwhelming effectiveness of ventilation clearly makes it the strategy to guide design in Atlanta. Earth tempering may be viewed as marginal in its applicability, and if achieved at the expense of reducing ventilating capability, it may be counterproductive.

Ground temperatures in the Phoenix area are very similar to those of Dallas, Even though, for the sake of argument, a thermal diffusivity value of 0.33 ft^2/day has been used in generating the Phoenix temperature table, it can be seen that the results are not remarkably different from when $\alpha = 0.52$ ft^2/day. Accordingly, the comments made concerning the Dallas ground climate apply in Phoenix as well. The priority of above surface cooling strategies are quite different, however, so the usefulness of the ground can be viewed in a different light. Thermal mass and evaporative cooling, for instance, are favored for 88 percent and 62 percent of the overheated period. Ventilation is relatively unimportant, being able to attain comfort conditions for a total of 38 percent of overheated hours, but of which only 5 percent are uniquely met by ventilation. Since earth tempering techniques are not incompatible with thermal mass and evaporative cooling strategies, the milder climate of the ground can be exploited without compromising other desirable design devices. Given this fact and the extreme temperature conditions prevalent throughout the Southwest, earth tempering should be a useful climate control agent here, especially if used to enhance its companion control strategies.

Midwestern region

Kansas City has an overheated period of 20.5 percent of annual hours. The most important traditional cooling strategies here are ventilation and thermal mass, which are normally able to meet comfort requirements for 17.4

and 11.6 hours of the year, respectively. Ventilation is an exclusive climate control strategy for 43 percent of the overheated period, so its role is significant.

The earth remains relatively cool throughout the summer; deep profile temperatures range 15 to 20F below the daily air temperature average during July and August, and not until October does the 2-12' profile average rise above the air temperature average. During these months, also, undisturbed temperatures at the relatively shallow depth of 4 feet fall about 20F below daily maxima. The deep profile average temperature never exceeds 65F and the shallow 0-6' profile average rises above 68F for only 24 percent of the year.

It is apparent that earth tempering offers valuable cooling potential in the Kansas City region, even though ventilation, mass, and evaporative cooling are theoretically able to meet normal comfort needs. Detailed analysis of individual buildings would be of interest to determine how self-sufficient earth cooling practices may be in this area.

The ground climate of Omaha is much like that of Kansas City, especially since the larger amplitudes in part cancel out the effect of the 2F lower annual mean. The above surface climate of Omaha is oddly different from that of Kansas City, however. A long heating period passes into an overheated season of 28.8 percent annual hours, with insignificantly few naturally occurring comfort hours. Also unusual is the fact that Omaha is the only city of six analyzed here in which above-surface passive control measures are inadequate for a significant period of time—5.4 percent of annual hours.

These extremes, coupled with the fact that ventilation is uniquely effective for only 9.8 percent of the overheated season, makes earth cooling a major climate control strategy for this part of the Midwest.

Despite the period of hot, humid conditions, the preponderance of relatively dry hours favors mass and evaporative cooling techniques, both of which are usually compatible with earth tempering. Ground temperature lowering techniques are also feasible, and the low ground temperature can be even better exploited by delaying the phase of the ground temperature wave. Efforts to suppress the amplitude of surface variation could also be of some value: note, for example, that while Omaha has a T_m that is 2F lower than that of Kansas City, 1 percent more hours are spent above 68F in the shallow 0-6' profile.

Conclusion

It is believed that the data presented here offer a means of assessing the usefulness of earth tempering practices for cooling purposes in a variety of regions. Although subgrade construction and the use of earth pipes and other devices shows some merit in almost all regions, the value of these is frequently eclipsed in warm, humid areas by the need for maximum ventilation and by the likelihood of condensation, which can be problematic in itself. The value of earth cooling seems to be greatest in the more temperate parts of the country, where the carryover of winter cold is proportionately better able to satisfy the less demanding summer cooling requirements.

The discussion presented here is not intended to be conclusive, in that numerous methods of lowering and altering the phase of ground temperatures are possible. The desirability of temperature modification techniques can be deduced from the ambient conditions predicted by the tables. An excellent review of several ground temperature depression practices is contained in reference [9]. Insulation practices to enhance summer cooling in northern zones are discussed in reference [14], and fundamentals of ground climate and some control opportunities are described in reference [2].

The final realization of cooling benefits from the ground will always be a matter of effective design. It is hoped that the data presented here contribute toward that end.

Acknowledgment

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TABLE 1 CITY: Atlanta

T_m 62		TEMPERATURE ON 21st DAY OF											
A_s 18		J	F	M	A	M	J	J	A	S	O	N	D
AIR	DAILY MAX	52	55	62	73	80	85	87	86	80	71	60	51
AIR	DAILY AVG	43	46	52	63	70	77	78	77	71	61	49	43
AIR	DAILY MIN	34	36	42	53	61	68	70	68	62	50	39	34
GROUND	2	49	48	50	55	61	68	73	75	74	69	62	55
GROUND	4	54	51	51	54	59	64	69	72	72	69	65	59
GROUND	6	57	54	53	54	57	61	66	69	70	69	66	62
GROUND	8	60	57	55	55	57	60	63	66	68	68	66	63
GROUND	10	61	59	57	57	57	59	62	64	66	66	66	64
GROUND	12	62	60	59	58	58	59	61	62	64	65	65	64
GROUND	15	63	62	60	59	59	59	60	61	62	64	64	64
PROFILE AVG 0-6		51	49	50	55	60	67	71	74	73	69	63	57
PROFILE AVG 2-12		58	55	54	55	58	62	65	68	69	68	65	62

BIOCLIMATIC ANALYSIS OF COOLING EFFECTIVENESS, % ANNUAL HOURS

HEATING TOTAL		59.3
COMFORT (SHADING)		13.8
COOLING TOTAL		26.9
VENTILATION	25.4	
THERMAL MASS	10.3	
EVAPORATIVE COOLING	3.4	
BEYOND PASSIVE CAPABILITY	0	

GROUND TEMPERATURE PROFILE RANGES, % ANNUAL HOURS

	0-6 PROFILE	2-12 PROFILE
$T < 68$	66	81
$68 < T < 78$	34	19
$T > 78$	0	0

SUMMER DESIGN TEMPERATURE (DBT), AIR (WITH COINCIDENT WBT)		
	5%	90 / 73
	2½%	92 / 74
	1%	94 / 74

SUMMER DESIGN TEMPERATURES (WBT), AIR		
	5%	75
	2½%	76
	1%	77

TABLE 2 CITY: Dallas

T_m 70 / A_s 20		TEMPERATURE ON 21st DAY OF											
		J	F	M	A	M	J	J	A	S	O	N	D
AIR	DAILY MAX	55	61	68	78	84	92	96	95	86	77	64	57
	DAILY AVG	45	51	57	68	75	83	86	85	76	66	54	47
	DAILY MIN	36	41	46	58	66	74	77	76	67	56	43	38
GROUND	2	56	54	56	62	69	77	83	85	83	78	70	62
	4	61	58	58	61	66	73	78	81	81	78	73	67
	6	65	61	60	62	65	69	74	77	79	78	74	70
	8	67	64	63	63	64	68	71	74	76	76	75	72
	10	69	67	65	64	65	67	70	72	74	75	74	72
	12	70	68	66	65	65	67	68	71	72	74	74	73
	15	71	70	68	67	67	67	68	69	71	72	72	72
PROFILE AVG 0-6		58	56	57	62	68	75	81	83	82	78	71	64
PROFILE AVG 2-12		65	62	61	63	65	70	74	77	78	77	74	70

BIOCLIMATIC ANALYSIS OF COOLING EFFECTIVENESS, % ANNUAL HOURS

HEATING TOTAL		48.8
COMFORT (SHADING)		14.2
COOLING TOTAL		37.0
VENTILATION	28.7	
THERMAL MASS	19.9	
EVAPORATIVE COOLING	4.5	
BEYOND PASSIVE CAPABILITY	.07	

GROUND TEMPERATURE PROFILE RANGES, % ANNUAL HOURS

	0-6 PROFILE	2-12 PROFILE
T < 68	45	42
68 < T < 78	28	58
T > 78	27	0

SUMMER DESIGN TEMPERATURE (DBT), AIR (WITH COINCIDENT WBT)

5%	97 / 75
2½%	100 / 75
1%	102 / 75

SUMMER DESIGN TEMPERATURES (WBT), AIR

5%	77
2½%	78
1%	78

TABLE 3 CITY: Houston

T_m 76 / A_s 18		J	F	M	A	M	J	J	A	S	O	N	D
		TEMPERATURE ON 21st DAY OF											
AIR	DAILY MAX	62	67	73	81	87	92	94	94	89	82	71	65
AIR	DAILY AVG	52	56	62	71	77	82	83	83	78	69	59	54
AIR	DAILY MIN	42	46	51	61	67	72	73	72	67	56	48	43
GROUND	2	63	62	64	69	75	82	87	89	88	83	76	69
GROUND	4	68	65	65	68	73	78	83	86	86	83	79	73
GROUND	6	71	68	67	68	71	75	80	83	84	83	80	76
GROUND	8	74	71	69	69	71	74	77	80	82	82	80	77
GROUND	10	75	73	71	71	71	73	76	78	80	80	80	78
GROUND	12	76	74	73	72	72	73	75	76	78	79	79	78
GROUND	15	77	76	74	73	73	73	74	75	76	78	78	78
PROFILE AVG 0-6		65	63	64	69	74	81	85	88	87	83	77	71
PROFILE AVG 2-12		72	69	68	69	72	76	79	82	83	82	79	76

BIOCLIMATIC ANALYSIS OF COOLING EFFECTIVENESS, % ANNUAL HOURS

HEATING TOTAL		39.0
COMFORT (SHADING)		6.3
COOLING TOTAL		54.7
VENTILATION	54.4	
THERMAL MASS	2.7	
EVAPORATIVE COOLING	0.1	
BEYOND PASSIVE CAPABILITY	0	

GROUND TEMPERATURE PROFILE RANGES, % ANNUAL HOURS

	0-6 PROFILE	2-12 PROFILE
T < 68	27	0
68 < T < 78	31	64
T > 78	42	36

SUMMER DESIGN TEMPERATURE (DBT), AIR (WITH COINCIDENT WBT)	5%	92 / 77
	2½%	94 / 77
	1%	96 / 77
SUMMER DESIGN TEMPERATURES (WBT), AIR	5%	79
	2½%	79
	1%	80

TABLE 4 CITY: Kansas City

T_m 56 / A_s 24		TEMPERATURE ON 21st DAY OF											
		J	F	M	A	M	J	J	A	S	O	N	D
AIR	DAILY MAX	36	44	52	67	76	84	89	86	77	67	50	39
AIR	DAILY AVG	28	35	43	58	66	75	79	77	67	57	41	31
AIR	DAILY MIN	19	26	33	48	57	67	70	67	57	46	32	23
GROUND	2	39	37	40	46	55	65	71	74	72	65	56	47
GROUND	4	45	42	42	45	52	59	66	69	69	66	60	52
GROUND	6	50	46	44	46	50	55	61	65	67	65	61	56
GROUND	8	53	49	47	47	49	53	58	61	64	64	62	58
GROUND	10	55	52	50	49	50	52	56	59	61	62	61	59
GROUND	12	57	54	52	51	51	52	54	57	59	60	60	59
GROUND	15	57	56	54	53	52	52	53	55	57	58	59	59
PROFILE AVG 0-6		42	39	41	46	54	62	69	72	70	65	58	49
PROFILE AVG 2-12		50	47	46	47	51	56	60	64	65	64	61	56

BIOCLIMATIC ANALYSIS OF COOLING EFFECTIVENESS, % ANNUAL HOURS

HEATING TOTAL		64.2
COMFORT (SHADING)		15.3
COOLING TOTAL		20.5
VENTILATION	17.4	
THERMAL MASS	11.6	
EVAPORATIVE COOLING	4.5	
BEYOND PASSIVE CAPABILITY	0	

GROUND TEMPERATURE PROFILE RANGES, % ANNUAL HOURS

	0-6 PROFILE	2-12 PROFILE
T < 68	76	100
68 < T < 78	24	0
T > 78	0	0

SUMMER DESIGN TEMPERATURE (DBT), AIR (WITH COINCIDENT WBT)		
	5%	93 / 74
	2½%	96 / 74
	1%	99 / 75

SUMMER DESIGN TEMPERATURES (WBT), AIR		
	5%	76
	2½%	77
	1%	78

TABLE 5 CITY: Omaha

		J	F	M	A	M	J	J	A	S	O	N	D
T_m 54		TEMPERATURE ON 21st DAY OF											
A_s 25		J	F	M	A	M	J	J	A	S	O	N	D
AIR	DAILY MAX	32	40	50	67	76	85	89	87	77	67	47	36
AIR	DAILY AVG	22	39	39	55	65	74	78	75	64	54	37	26
AIR	DAILY MIN	12	19	28	43	53	63	66	63	52	41	27	16
GROUND	2	37	34	37	44	53	63	70	73	71	64	54	45
GROUND	4	43	39	39	43	50	57	64	68	68	64	58	50
GROUND	6	47	43	42	44	48	53	59	63	65	64	60	54
GROUND	8	51	47	45	45	47	51	56	60	62	62	60	56
GROUND	10	53	50	47	47	48	50	54	57	59	60	60	57
GROUND	12	55	52	50	48	48	50	52	55	57	59	59	57
GROUND	15	56	54	52	51	50	50	51	53	55	56	57	57
PROFILE AVG 0-6		39	37	38	44	52	61	67	70	69	64	56	47
PROFILE AVG 2-12		48	45	43	45	48	54	59	62	64	62	59	54

BIOCLIMATIC ANALYSIS OF COOLING EFFECTIVENESS, % ANNUAL HOURS

HEATING TOTAL		71.1
COMFORT (SHADING)		0.2
COOLING TOTAL		28.8
VENTILATION	22.1	
THERMAL MASS	20.6	
EVAPORATIVE COOLING	15.9	
BEYOND PASSIVE CAPABILITY	5.4	

GROUND TEMPERATURE PROFILE RANGES, % ANNUAL HOURS

	0-6 PROFILE	2-12 PROFILE
T < 68	81	100
68 < T < 78	19	0
T > 78	0	0

SUMMER DESIGN TEMPERATURE (DBT), AIR (WITH COINCIDENT WBT)	5%	88 / 74
	2½%	91 / 75
	1%	94 / 76
SUMMER DESIGN TEMPERATURES (WBT), AIR	5%	75
	2½%	77
	1%	78

TABLE 6 CITY: Phoenix

T_m 70 A_s 20		TEMPERATURE ON 21st DAY OF											
		J	F	M	A	M	J	J	A	S	O	N	D
AIR	DAILY MAX	65	70	75	85	94	103	105	102	97	86	72	65
AIR	DAILY AVG	51	56	61	69	78	86	92	88	83	70	58	52
AIR	DAILY MIN	38	42	46	53	61	69	79	75	68	55	43	38
GROUND	2	57	55	57	61	69	76	81	84	83	78	71	64
GROUND	4	63	60	59	61	65	71	76	79	80	78	74	69
GROUND	6	67	64	62	62	65	68	72	75	77	77	75	71
GROUND	8	69	67	65	64	65	67	69	72	74	75	74	72
GROUND	10	71	69	67	66	66	67	68	70	72	73	73	73
GROUND	12	71	70	68	67	67	67	68	69	71	72	72	72
GROUND	15	71	70	70	69	68	68	68	68	69	70	71	71
PROFILE AVG 0-6		60	57	58	62	68	74	79	82	81	78	72	66
PROFILE AVG 2-12		67	64	63	63	65	69	72	75	76	76	74	71

BIOCLIMATIC ANALYSIS OF COOLING EFFECTIVENESS, % ANNUAL HOURS

HEATING TOTAL		44.7
COMFORT (SHADING)		19.7
COOLING TOTAL		35.6
VENTILATION	13.6	
THERMAL MASS	31.5	
EVAPORATIVE COOLING	22.2	
BEYOND PASSIVE CAPABILITY	1.8	

GROUND TEMPERATURE PROFILE RANGES, % ANNUAL HOURS

	0-6 PROFILE	2-12 PROFILE
T < 68	45	42
68 < T < 78	28	58
T > 78	27	0

SUMMER DESIGN TEMPERATURE (DBT), AIR (WITH COINCIDENT WBT)

5%	105 / 71
2½%	107 / 71
1%	109 / 71

SUMMER DESIGN TEMPERATURES (WBT), AIR

5%	75
2½%	75
1%	76

Radiative Cooling

Radiative Cooling: Resource and Applications --
Eugene Clark and Paul Berdahl

RADIATIVE COOLING: RESOURCE AND APPLICATIONS

Eugene Clark *　　　　Paul Berdahl +

ABSTRACT

The radiative cooling resource is assessed for clear skies as a function of ambient dry bulb and dew point temperatures. An empirical opaque cloud cover correction is presented. The effects of convective heat intrusion are evaluated. National contour maps of net July nightly cooling are presented for exposed, horizontal radiators. The regional benefits of preventing convective heat intrusion with polyethylene windscreens are assessed using a validated computer simulation. The results of applying radiative cooling in a 'Skytherm' type roof pond residence are simulated for various U.S. cities. Air conditioning displaced and comfort conditions in unassisted roof pond residences are simulated.

INTRODUCTION

Radiative cooling, the net transfer of heat by thermal infrared radiation from a warm radiator to a cooler heat sink, has two different applications in comfort cooling of buildings. One application is direct radiative cooling of people by control of the mean radiant temperature of their environment. The second application is the discharge of heat from a radiative heat dissipator (typically a roof) to the cool nocturnal sky. This paper deals with cooling to the sky.

Radiative cooling often operates simultaneously with convection and evaporation. In humid climates, radiative cooling even plays an important role in total heat losses from wet surfaces exposed to the sky because the high wet bulb temperatures limit evaporative cooling. In such a climate, the nocturnal sky is usually the coldest available environmental heat sink. Typically the effective nocturnal sky temperature is 20°F below the ambient air temperature near the ground.

Results to follow show that under typical summer conditions, a horizontal ambient temperature radiator can discharge about 20 Btu h^{-1} ft^{-2} to the night sky. This rate of heat dissipation could meet residential cooling loads with a radiator roof anywhere in the country. In fact, in most U.S. locations a well designed residence has a sensible cooling load near 100 Btu/day per square foot of floor space. However, heat dissipation does not assure comfort. We must achieve the required heat dissipation rates at a radiator temperature which can assure interior comfort. In most U.S. climates, this comfort requirement will force the radiator to operate below the ambient air temperature much of the night. As a result, much of the radiative heat loss is cancelled by convective heat gain. The following discussion examines these two heat transfer processes for surfaces exposed to the environment. Information is provided which will allow the building designer to determine the temperature at which the radiator will reach the heat dissipation rate required to meet the cooling load.

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BASIC FACTS ABOUT RADIATIVE COOLING

If the radiator surface is non-selective (a grey body) and has no glazing or cover, the basic equation for computing the cooling rate R due to thermal radiative exchange is

$$R = \varepsilon_r \sigma T_r^4 - \varepsilon_r S. \quad (1)$$

Each of the symbols is defined as follows. T_r is the absolute temperature in degrees Rankine (English units will be used). T_r is equal to 459.7 plus the ordinary Fahrenheit temperature. The Stefan-Boltzmann constant, σ, has the value 0.1712×10^{-8} Btu h^{-1} ft^{-2} $^oR^{-4}$. ε_r represents the radiator emissivity, a number between 0 and 1. The fact that ε_r is assumed independent of wavelength within the 5-40 micron wavelength range of interest is what is meant by a grey body radiator. If $\varepsilon_r = 1$, the radiator is called a black body. The last symbol to be defined is S, which is the thermal radiance of the atmosphere.

Several properties of equation (1) for the cooling power merit further discussion. The first term on the right hand side represents the radiation (in Btu h^{-1} ft^{-2}) emitted from the radiator. The second term is the radiation emitted by the sky which is absorbed by the radiator. If the cooling power is greater than zero, then it is advantageous to have the largest emissivity possible. Table 1 shows the emissivity of a number of ordinary materials[1,2]. These values are technically called hemispherical total emissivities and were estimated (when necessary) from the normal total emissivities according to a method described in Chapter 5 of reference 1. Most materials other than bare metals are good radiators, including water and glass. If a surface is rough, its emissivity is increased compared to a smooth surface. Given the large emissivities of ordinary materials, there can be no economic justification to use exotic materials as non-selective radiators.

Table 1. Total Hemispherical Emissivities (ε_r) of Common Materials

Material	ε_r	Remarks
Clean metal surfaces including aluminum, iron, copper, lead, and tin.	0.02 - 0.07	Oxide coatings increase emissivity.
Anodized aluminum for various oxide thicknesses:		Anodized aluminum is a type of selective radiator. See Ref. 3.
0.03 mil	0.1	
0.1 mil	0.6	
0.2 mil	0.7	
0.4 mil	0.8	
Brick, mortar, plaster	0.88	
Glass	0.88	
Most paints	0.80 - 0.93	The visible color of the paint has no relation to the value of ε_r.
Tarpaper	0.88	
Water	0.92	
Wood (Oak)	0.90	

Another observation about the equation for R is that the atmospheric radiation S works against the production of cooling. One would like to know a great deal about S in order to be able to compute how much cooling a given system can produce. The sky emits radiation like a black body with a temperature like that of the air near the ground except in the 8 to 13 micron "window", where the radiation is much weaker, especially when the atmosphere is clear. The atmospheric radiation coming from the position of the sky near the horizon is also much like black body radiation; the radiation from the zenith region of the sky is much weaker. Thus the actual cooling process proceeds primarily at wavelengths from 8 to 13 microns and at zenith angles less than 70°. Because the zenith part of the sky is "coldest", radiators situated horizontally can produce more cooling than those in other orientations. Therefore, we will only consider horizontal radiator surfaces unless stated otherwise. Model calculations performed by Berdahl and Martin[4] with the computer code LOWTRAN give some additional basic information about the sky radiation. The most important meteorological parameters for determining the sky radiation and hence cooling rates are, in order of decreasing importance: temperature, cloud cover, water vapor, ozone, carbon dioxide, and aerosols. Of these parameters only temperature, cloud cover and water vapor cause substantial changes in the sky radiation from day to day and month to month.

Sky Emissivity

One useful way of specifying the amount of sky radiation S is to use the sky emissivity ε_s defined by

$$S = \varepsilon_s \sigma T_a^4 . \qquad (2)$$

where T_a is the air temperature near the ground. In terms of this sky emissivity, the cooling rate equation (1) becomes

$$R = \varepsilon_r \left[\sigma T_r^4 - \varepsilon_s \sigma T_a^4 \right] . \qquad (3)$$

Often it is easier to estimate the sky emissivity than it is to estimate the atmospheric radiation directly. Representative values for ε_s are 0.7 for clear and very dry atmospheric conditions, 0.8 for clear humid or dry partly cloudy conditions, 0.9 for complete overcast, and 1.0 for fog conditions. When $\varepsilon_s = 1$, the sky "looks like" a black body at air temperature and the resource for radiative cooling has vanished.

Sky Temperature

Another method, perhaps more popular than sky emissivity, for specifying the amount of sky radiation is the concept of sky temperature T_s. The defining equation is

$$S = \sigma T_s^4 . \qquad (4)$$

The sky temperature is the lowest temperature which a horizontally exposed grey-body radiator can reach in the absence of conductive or convective loss mechanisms. It does not correspond to any actual atmospheric temperature at any elevation, except by chance. The relation between sky temperature T_s and sky emissivity ε_s can be found by eliminating S from equations (2) and (4):

$$T_s = \varepsilon_s^{1/4} T_a. \tag{5}$$

In terms of T_s the cooling equation is

$$R = \varepsilon_r \left[\sigma T_r^4 - \sigma T_s^4\right]. \tag{6}$$

Consider now the linearization of T^4 in this equation. Both T_r and T_s will be in the approximate range of 50°F to 80°F for cooling applications. In Rankine degrees this range is 510°R to 540°R. In terms of the absolute temperature the percentage variation in temperature is small. Choosing a reference temperature T_o (which will be set equal to 67°F = 527°R), one can write for any temperature T,

$$T = T_o + \Delta T,$$

where $\Delta T \ll T_o$. Now the fourth power of T is given by

$$T^4 = T_o^4 + 4T_o^3\Delta T + 6T_o^2\Delta T^2 + 4T_o\Delta T^3 + \Delta T^4.$$

Each term in this expansion is smaller than the prior term by a factor of about 50. For most purposes we can keep just the first two terms in the expansion. Using this approximation for T_r and T_s in equation (6) gives

$$R \cong \varepsilon_r 4\sigma T_o^3 \left[T_r - T_s\right].$$

If the radiator is infrared-black ($\varepsilon_r = 1$) we have

$$R = h(T_r - T_s) \tag{7}$$

with

$$h = 4\sigma T_o^3. \tag{8}$$

Equation (7) shows a primary reason for the popularity of the sky temperature concept. Mathematically the heat transfer between a radiator and the sky is just like the conduction of heat from a warm radiator at temperature T_r to the colder sky at temperature T_s. Furthermore, it turns out (for black radiators) the conduction coefficient h is equal to 1.00 Btu h^{-1} ft^{-2} $°F^{-1}$ (If we had chosen a reference temperature T_o different from 67°F the value of h would be different only by a few percent.) Therefore, one can estimate the cooling rate of a radiator panel in Btu h^{-1} ft^{-2} as being equal to the sky temperature depression $T_r - T_s$ in degrees Fahrenheit. For example, if the sky temperature is 20°F less than the radiator temperature, the cooling rate is 20 Btu h^{-1} ft^{-2}.

SKY RADIATION FROM CLEAR SKIES

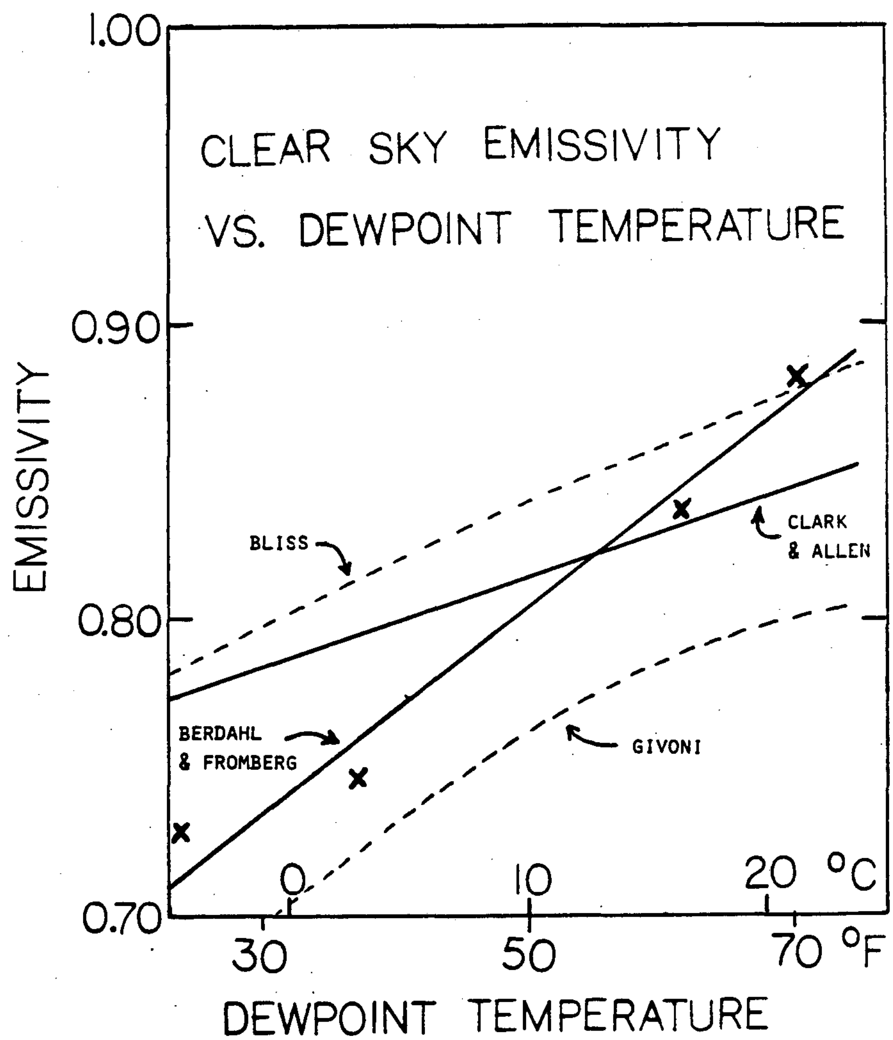
For clear sky conditions it is possible to estimate the magnitude of the atmospheric or "sky" radiation with reasonable accuracy. Sky conditions with cirrus clouds are virtually equivalent to clear sky conditions because these clouds are thin and very cold, typically -40°F. Other types of cloud cover have a strong effect on the radiation, as will be discussed later.

In principle it is necessary to know both the temperature and humidity as a function of height in the atmosphere in order to compute the amount of sky radiation. In practice, it is necessary to make estimates based on the surface temperature and humidity only. It is a fairly good assumption that the radiation is proportional to the absolute air temperature to the fourth power, so that it is only necessary to estimate the sky emissivity ε_s as a function of dewpoint temperature and then use equation (2) to compute the sky radiation or use equation (5) to compute the sky temperature.

Recent Measurements

Figure 1 shows the relationship between the emissivity of clear skies and the

Fig. 1. Correlations of clear sky emissivity versus dewpoint as given by the references.[5,6,8,9,10] The X's are results from the computer code LOWTRAN discussed in reference 4: From left to right the model atmospheres were midlatitude winter, U.S. Standard, midlatitude summer, and tropical



dewpoint temperature, as given by several researchers. For orientation average July dewpoint temperatures in several cities are given in Table 2.

Table 2. Average July Dewpoint Temperatures for a Few Cities

Miami, Florida	73°F
San Antonio, Texas	68°F
Atlanta, Georgia	68°F
St. Louis, Missouri	66°F
Washington, D.C.	65°F
Gaithersburg, Maryland (estimate)	65°F
New York, New York	62°F
Tucson, Arizona	56°F
Albuquerque, New Mexico	49°F
Las Vegas, Nevada	39°F

The two solid curves in Fig. 1 are based on measured correlations obtained by Clark and Allen[5] and by Berdahl and Fromberg[6].

The measurements by Clark and Allen were made over a small rooftop waterpond in San Antonio, Texas for the period October, 1976 through September, 1977. Altogether, 800 nighttime measurements were made at times during which the weather service reported zero tenths of opaque cloud cover. A Fritshen type net radiometer (Weathermeasure model 422) was employed and, of course, the presence of the water surface was accounted for in the data analysis. The standard error of estimate --- which is the typical deviation of a single measurement from the predicted value --- was 3.2 Btu h^{-1} ft^{-2} error in the sky radiance. This is roughly 0.028 error (2.8%) on the emissivity scale of Fig. 1. This error is, of course, in part due to measurement errors but it can largely be explained as being due to variations in temperature and humidity above the site, which can occur for identical values of temperature and humidity at the site.

The measurements of Berdahl and Fromberg are similar in intent to those of Clark and Allen: a primary goal of the measurements is to develop relationships useful for passive cooling applications. The measurement techniques are, however, rather different. Berdahl and Fromberg acquired sky radiance data using Eppley pyrgeometers located at Gaithersburg, Maryland; St. Louis, Missouri; and Tucson, Arizona. This data was acquired primarily during the summer of 1979 but two wintertime months were also used from the Gaithersburg data set. These pyrgeometer data sets were used together with data from the spectral infrared sky radiometers developed by Berdahl and Martin[7]. For the current application, the spectral radiometer was used to detect the presence of clouds; it was also used to calibrate the Eppley pyrgeometers. Most of the adjustment to the Eppley calibration constants were less than 2%. Surprisingly, no systematic site-to-site variation of the correlation of sky emissivity versus dewpoint was found despite the fact that Tucson is much less humid than the other two sites. Summertime correlations for each site individually fall within 1% (0.01 on Fig. 1) of the mean for the three sites. For the summary correlation shown on Figure 1, the standard error of estimate for individual measurements was 0.0031 emissivity units (3.1%). The correlation is based on 2900 individual nighttime measurements.

The correlation developed by Berdahl and Fromberg has some additional support from LOWTRAN model calculations[4]. This model contains several "typical" model atmospheres. The X's on Fig. 1 show the values of sky emissivity produced by the LOWTRAN model for four of the model atmospheres: midlatitude winter, U.S. standard atmosphere, midlatitude summer, and tropical. The agreement is quite good. It should be emphasized, however, that the state of the art of measurement of sky emissivity is an accuracy of about 0.03 units. Therefore, for summertime conditions (dewpoint temperatures primarily above 32°F) there is good agreement of the measurements of Berdahl and Fromberg with those of Clark and Allen.

Two Other Relationships

The dashed curves on Figure 1 are included because they are likely to be used by the solar community. We recommend that these relationships not be used. The curve ascribed to Givoni[8] originates with a correlation derived by Geiger[9], with the cooling rates of a surface at air temperature reduced by 17%, as suggested by Geiger and adopted by Givoni. Our measurements suggest that the resulting relationship still overestimates cooling rates. In addition, the measurements upón which Geiger based his estimates of sky radiance were all made prior to 1937 for general climatological purposes. The more recent measurements, made specifically with radiative cooling applications in mind, should be more accurate.

The curve given by Bliss[10] shown in Figure 1 is based on a theoretical analysis of radiative transfer in the atmosphere. His analysis is clear and complete, and his article is therefore recommended reading for the student of radiative cooling who wishes to pursue the subject in more depth. However --- as pointed out by Bliss --- there were substantial uncertainties in the values he used for the emissivity of water vapor. Measurements of the atmospheric emissivity show that his values for the emissivity of water vapor may be too high.

Estimating Cooling Rates Under Clear Skies

The correlations shown in Figure 1 can, of course, be used to estimate radiator cooling rates. Figures 2 and 3 may, however, be more straightforward to use. These figures show cooling rates of black ($\varepsilon_r = 1$) surfaces situated horizontally under clear skies, based on the correlation of Berdahl and Fromberg. For non-black surfaces, these cooling rates should be multiplied by ε_r. The user must estimate the air temperature and dewpoint temperature. Figure 2 assumes that the radiator temperature is equal to air temperature. Figure 3 assumes that the radiator has cooled to 10°F below air temperature. How far the radiator has actually cooled below air temperature depends upon the system design and upon the wind speed. Under some conditions, of course, the radiator may be above air temperature.

Since the sky temperature is a convenient parameter for use in estimating cooling rates, it is plotted on Figure 4. This figure shows the sky temperature depression, that is, the air temperature minus the sky temperature. An air

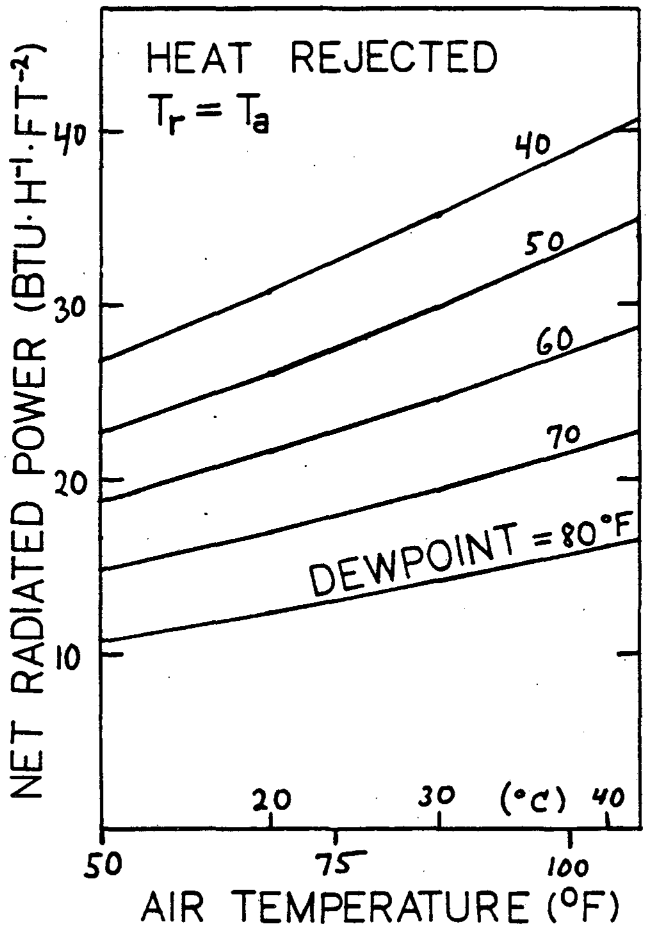


Fig. 2. Net radiated cooling power, in Btu h^{-1} ft^{-2}, of an infrared-black surface at air temperature for clear skies. The plot is based on the Berdahl-Fromberg correlation shown in Fig.1, using equation (3) in the text.

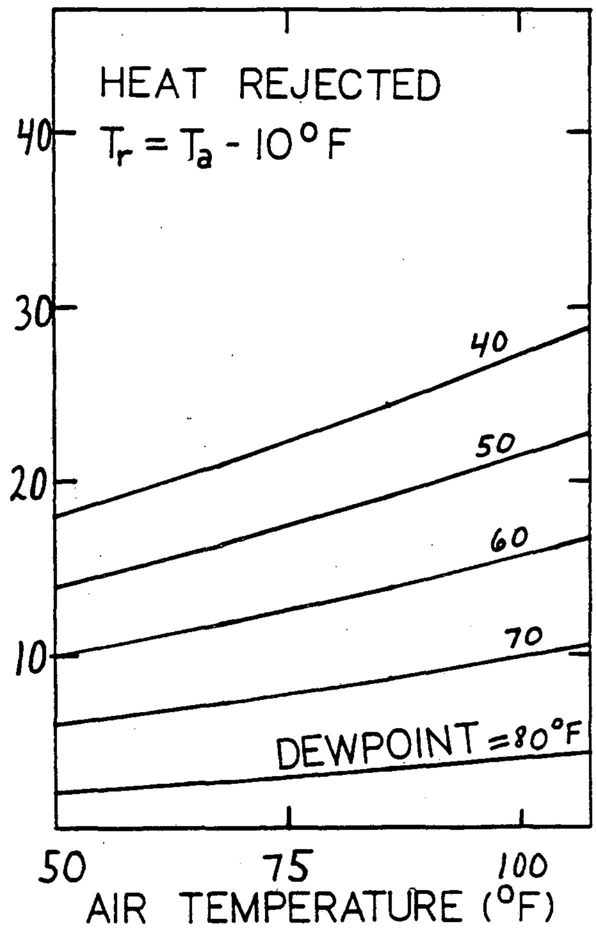


Fig. 3. Net radiated cooling power of an infrared-black surface $10^{\circ}F$ below air temperature for clear skies. The plot was derived in the same manner as Fig.2.

temperature of $75^{\circ}F$ was assumed in making the plot, but the plot is not very sensitive to this assumption. If the air temperature is increased to $100^{\circ}F$, the sky temperature depression increases by about $1^{\circ}F$.

Errors in Estimates of Cooling Rates

Suppose a passive cooling system is under test and the experimenter wants to know the sky temperature. He knows the night in question was clear, and that the dewpoint temperature was $60^{\circ}F$. With Figure 4 he estimates the sky temperature depression to be $24^{\circ}F$ and hence that (based on equation (7)) the rad-

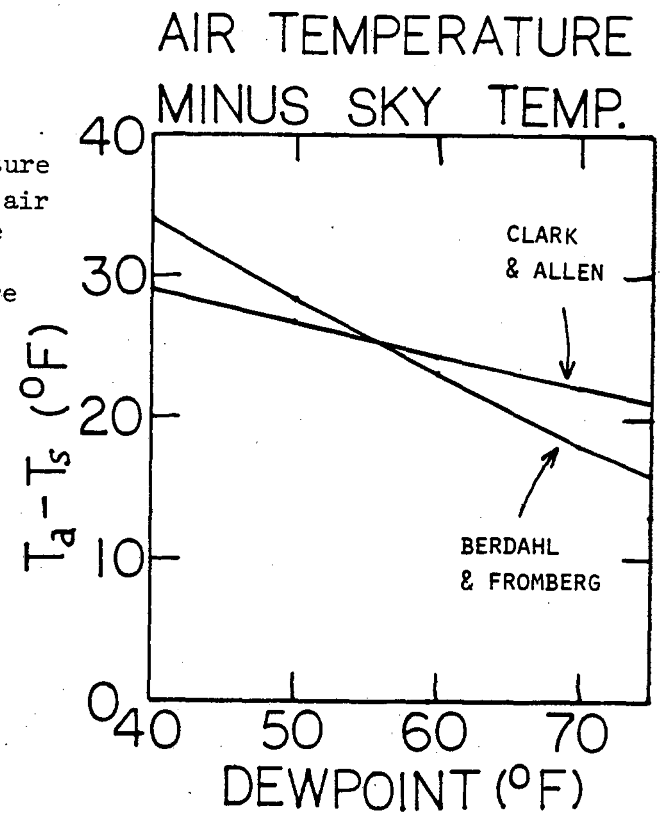


Fig. 4. Sky temperature depression, equal to air temperature minus the sky temperature. Conditions assumed are clear skies and an air temperature of 75°F. This plot is not very sensitive to the value of air temperature assumed.

iative cooling rate of his black, exposed, radiator at air temperature to be about 24 Btu h^{-1} ft^{-2}. How uncertain is this estimate?

Each 0.01 (1%) error in the sky emissivity causes about 1.6°F error in the sky temperature. Thus the 3% systematic error cited earlier corresponds to a 4.8°F error in the sky temperature depression. This error is caused by the measurement uncertainty and the possible systematic difference when correlations based on measurements at one site are used at another site. These sources of error are responsible for the difference between the two curves shown in Figure 4. The other type of error present in the current problem is random in nature. It is due to the fact that the profiles of moisture and temperature above the site in question are not precisely determined by the surface temperature and dewpoint. Based on the measurements by Clark and Allen, and by Berdahl and Fromberg, this probable error is also 3% on the emissivity scale, or 4.8°F in the sky temperature. The standard rule for the addition of errors now gives

$$\Delta T_s = \left[(4.8)^2 + (4.8)^2\right]^{\frac{1}{2}} = 6.8^{\circ}F \ .$$

Thus the probable error in the sky temperature is 7°F, the sky temperature depression for our problem is 24 ± 7°F, and the cooling rate in question is 24 ± 7 Btu h^{-1} ft^{-2}. These errors are rather large and emphasize the need for caution in computing cooling rates. Even when an experimenter measures the sky radiance directly during an experiment the residual errors are still 3% in sky emissivity or 5°F in sky temperature!

INFRARED RADIATION AND CLOUDS

In part of the infrared spectrum, particularly at wavelengths between 8 and 13 micrometers, the cloud free atmosphere is relatively transparent. In this part of the spectrum, radiation received at the ground originates in the high altitude cold part of the atmosphere. Because an opaque cloud radiates like a blackbody at the cloud base temperature, low level opaque clouds significantly increase the ground level atmospheric radiation.

A cloud correction factor has been developed as an empirical correlation with "opaque sky cover". Opaque sky cover is estimated once hourly by National Weather Service observers at all major weather stations and results are reported as n, the tenths of sky obscured measured from one to ten. The cloud correction factor for atmospheric radiation is defined as:

$$C_S = \frac{\text{atmospheric radiation with n tenths opaque sky cover}}{\text{clear sky atmospheric radiation}}$$

An empirical fit to 1,433 hours of cloudy sky data in San Antonio, Texas is[5]

$$C_S = 1 + .0224n - .0035n^2 + .00028n^3. \qquad (9)$$

Equation 9 is plotted in Figure 5 together with standard deviations of the data from this fit. Equation 9 was developed from data dominated by low level clouds; higher level opaque clouds will be colder and so will have less effect on atmospheric radiation. High altitude cirrus clouds have little effect.

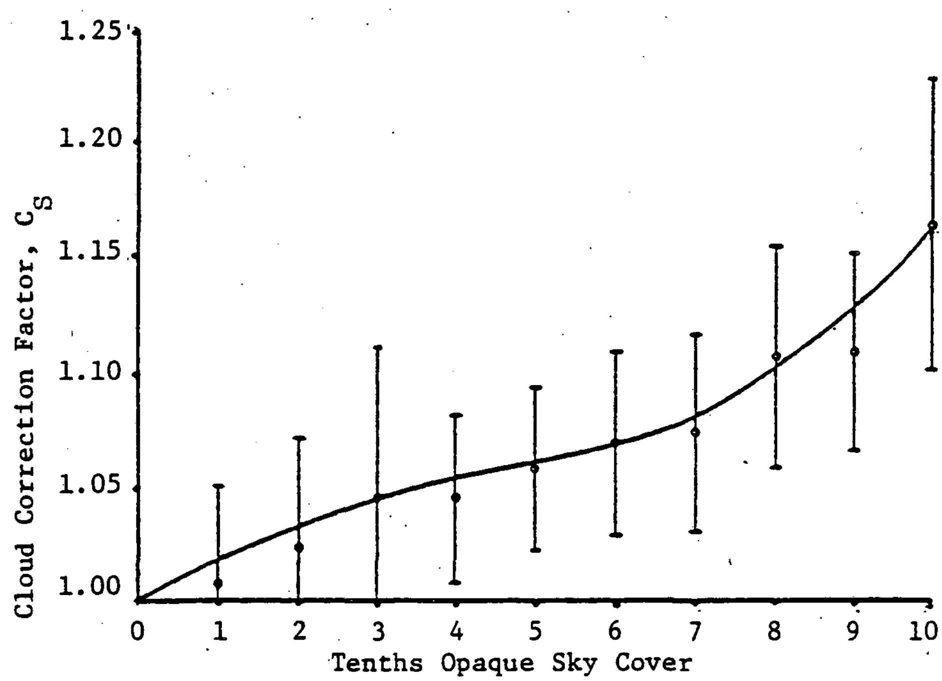


Figure 5 A Cloud Factor for Atmospheric Radiation

Figures 6-8 illustrate the relationships between dry bulb, dew point, wet bulb, and sky temperatures for an average July day in three cities representing various U.S. climates. The plotted profile of T_S was based on Equations 5 and 9 where ε_S was calculated from the Clark-Allen relationship shown in Figure 4. The effect of clouds is particularly apparent in the San Antonio profile from 2 a.m. to 9 a.m.

The sky temperature depressions shown in Figures 6-8 are typical of many others and a useful rule of thumb is that the sky temperature on an average summer night is 15 to 20^{o}F below the dry bulb air temperature near the ground.

CONVECTIVE HEAT INTRUSION

If radiative cooling to the nocturnal sky were the only heat transfer process operating, then, on an average summer night, it would be possible to cool a horizontal surface to a temperature 15 to 20^{o}F below the ambient temperature. However, as the exposed surface cools below the ambient air temperature, heat is convected into the surface from the air. In windy places, this convective heat intrusion can counter a significant fraction of the radiative cooling resource.

In the simulation results to follow, the convective heat exchange with the ambient air, Q_c, was described by the convection coefficient h_c, in the usual form:

$$Q_c = h_c\ (T_r - T_a). \qquad (10)$$

There are three cases and the value used for h_c was:

A. Heat flow down ($T_r < T_a$) and free convection (wind speed, $V < 0.17$ mph)

$$h_c \equiv 0.139\ \text{Btu/hr/ft}^{2\,o}\text{F} \qquad (11)$$

B. Heat flow upward ($T_r > T_a$) and free convection ($V < 1.0$ mph)

$$h_c \equiv 0.612\ \text{Btu/hr/ft}^{2\,o}\text{F} \qquad (12)$$

C. Turbulent flow (any T_r; V greater than the critical speeds listed above)

$$h_c = (.054\ Re^{0.8}\ Pr^{0.33})\ k/L \qquad (13)$$

where

k is the thermal conductivity of the air (Btu/hr/ft^{o}F)

L is a characteristic length of the radiator (here taken as 20 ft)

Re - Reynolds number

Pr - Prandtl number.

(The particular coefficient used in equation 13 (0.054) has been increased above the smooth surface value (0.036) in order to account for surface roughness[11].)

Over a windspeed range of 3-10 mph, Equation 13 is well approximated by the more intuitive equation

$$h_c = (0.5 + 0.3\ V)\ \text{Btu/hr/ft}^{2\,o}\text{F} \qquad (14)$$

Figure 6

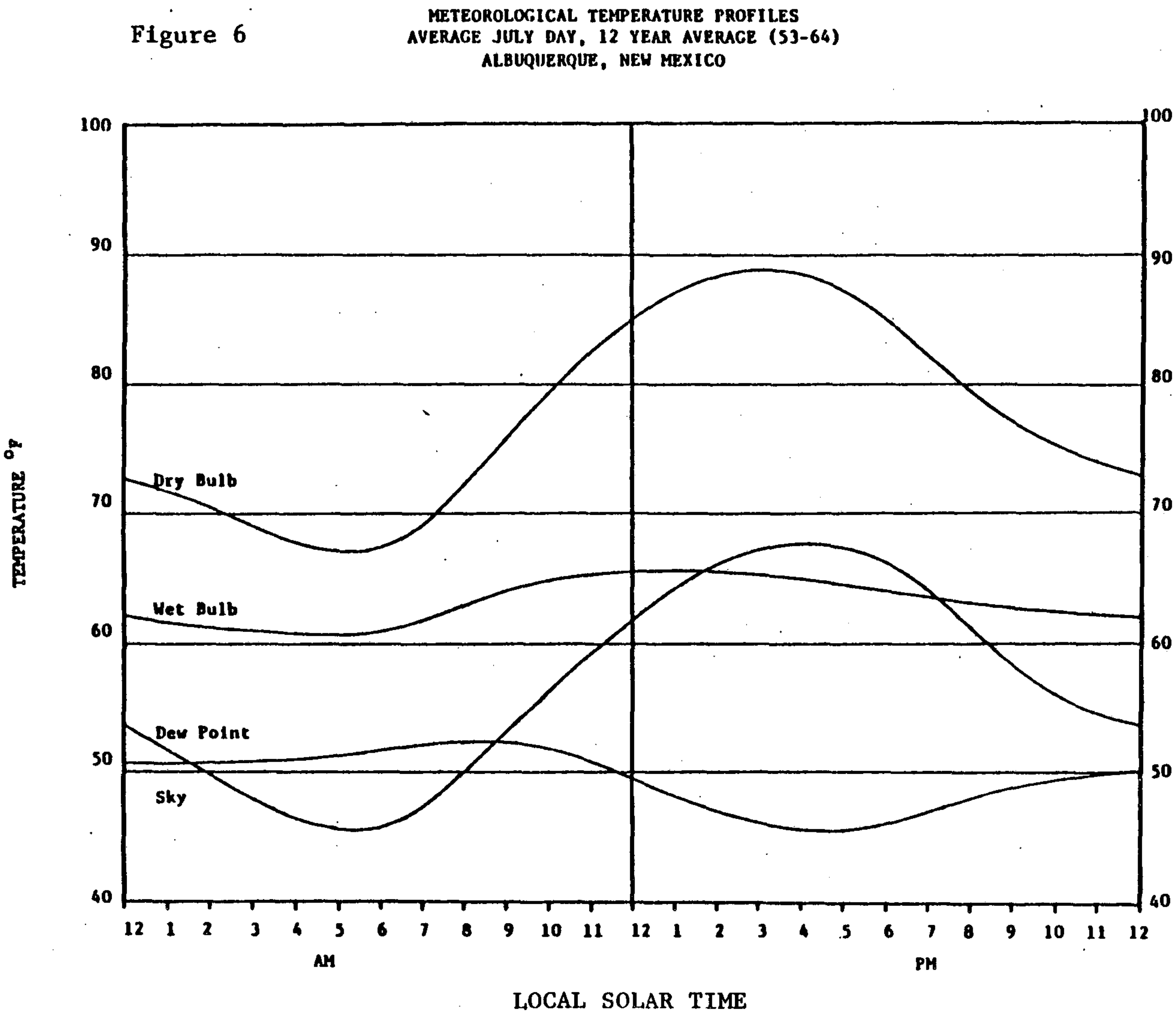

METEOROLOGICAL TEMPERATURE PROFILES
AVERAGE JULY DAY, 12 YEAR AVERAGE (53-64)
ALBUQUERQUE, NEW MEXICO
100
90
80
70
60
50
40
TEMPERATURE °F
Dry Bulb
Wet Bulb
Dew Point
Sky
12 1 2 3 4 5 6 7 8 9 10 11 12 1 2 3 4 5 6 7 8 9 10 11 12
AM
PM
LOCAL SOLAR TIME

Figure 7

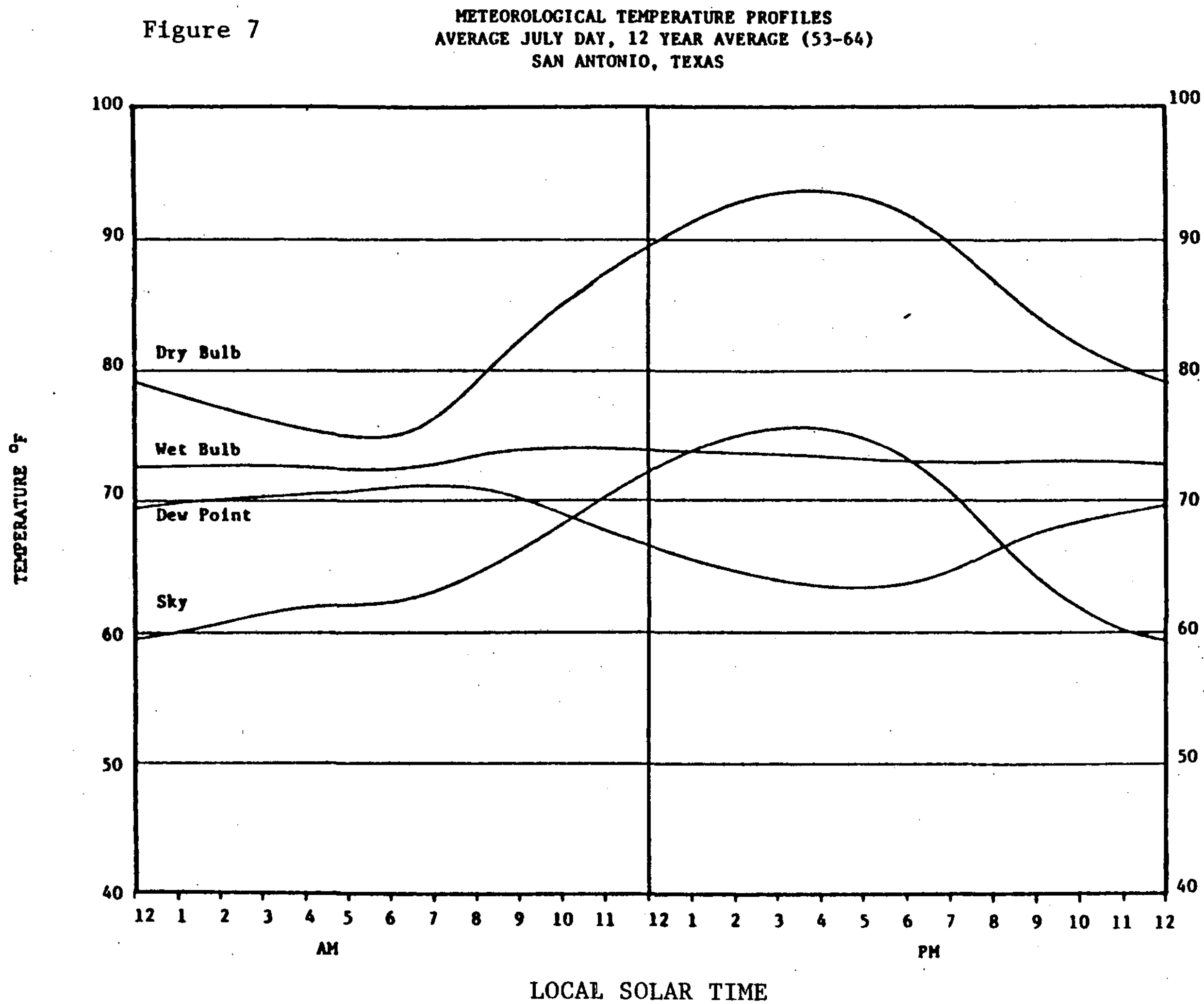
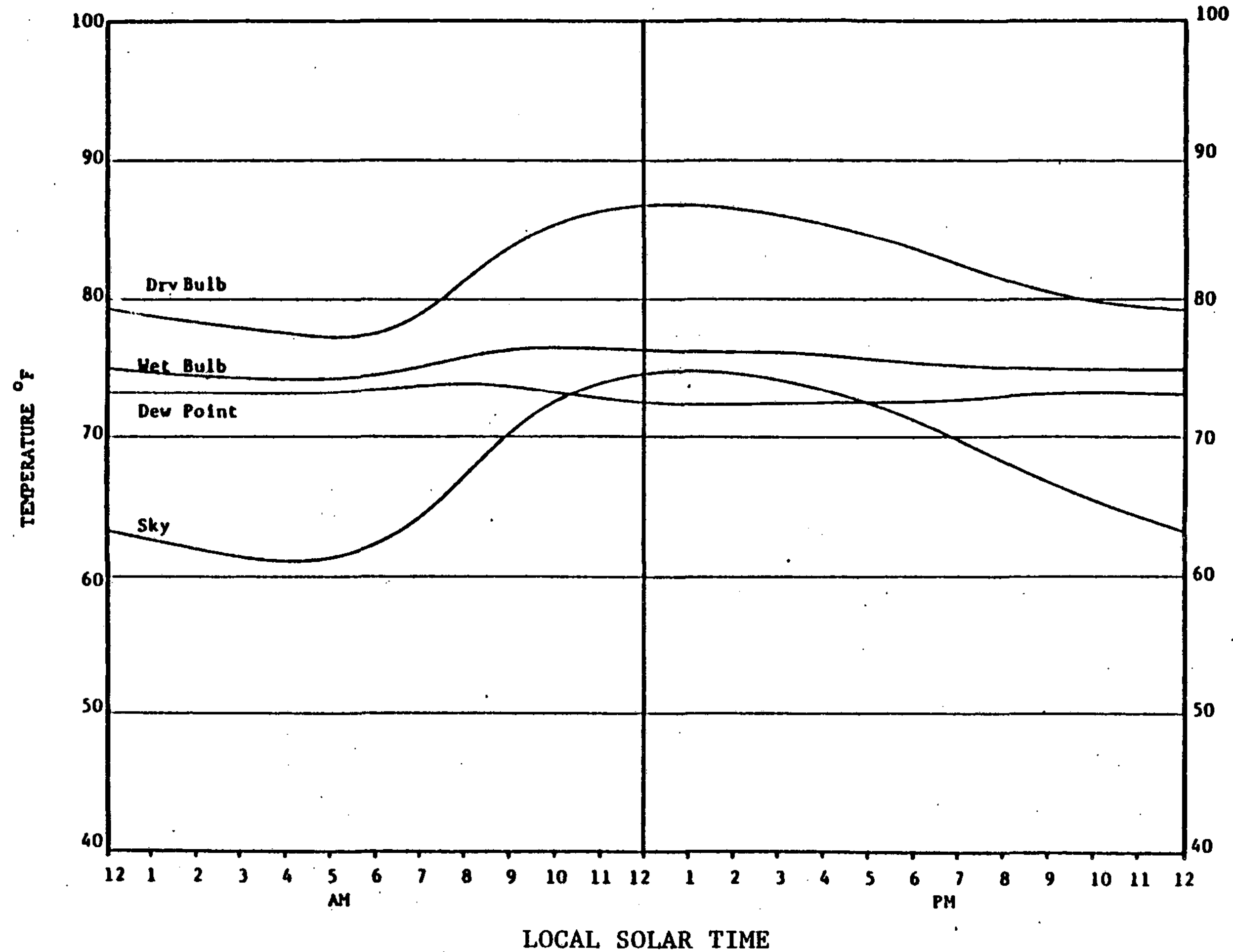

METEOROLOGICAL TEMPERATURE PROFILES
AVERAGE JULY DAY, 12 YEAR AVERAGE (53-64)
SAN ANTONIO, TEXAS
100
90
80
70
60
50
40
Dry Bulb
Wet Bulb
Dew Point
Sky
TEMPERATURE °F
12 1 2 3 4 5 6 7 8 9 10 11 12 1 2 3 4 5 6 7 8 9 10 11 12
AM
PM
LOCAL SOLAR TIME

Figure 8

METEOROLOGICAL TEMPERATURE PROFILES
AVERAGE JULY DAY, 12 YEAR AVERAGE (53-64)
MIAMI, FLORIDA



where V is the windspeed in mph. For windspeeds less than 3 mph, Equation 14 overestimates convection effects.

The net available cooling resource, Q_{net}, is the difference between radiative loss and convective gain. Using the approximate Equations 7 and 14 for an exposed blackbody radiator,

$$Q_{net} = R - Q_c = (T_r - T_S) - (0.5 + 0.3\ V)(T_a - T_r) \qquad (15)$$

for 3 mph $\leq$ V $\leq$ 10 mph. Equation 15 can be solved for the stagnation temperature of the radiator, $T_{r,stag.}$, the temperature at which $Q_{net} = 0$. If we assume that $T_a - T_{sky} = 20^oF$, the approximate result for $T_{r,stag}$, is

$$T_a - T_{r,stag.} = 20^oF/(1.5 + 0.3\ V). \qquad (16)$$

Equation 16 is plotted in Figure 9. For V = 0 and $T_a - T_S = 20^oF$, Equations 11 and 15 predict $T_{r,stag.} = 17.5^oF$.

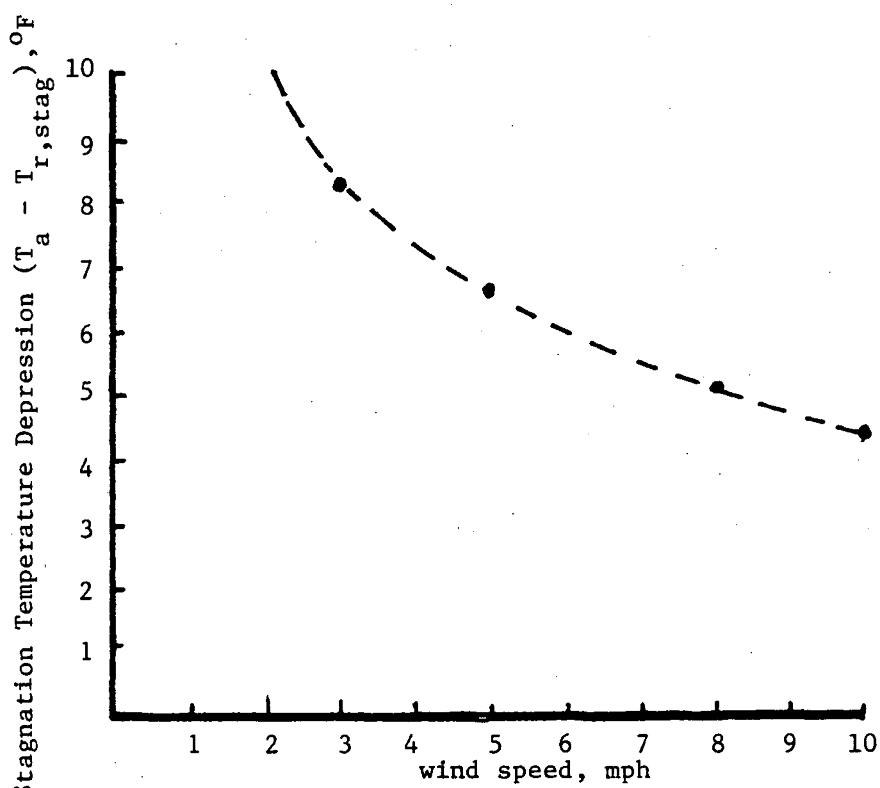


Figure 9 Stagnation Temperature Depression As a Function of Windspeed, $T_a - T_S = 20^oF$.

NET COOLING RATES: EXPOSED DRY SURFACES

The effective temperature of the clear sky as well as the warming effects of clouds and warm winds show regional variations. Hourly meteorological data for carefully selected typical July periods in 77 U.S. cities have been used to prepare contour maps of net cooling rates for the U.S. These cooling rates assume that the radiator has an emissivity of 0.95 and is horizontal and exposed to the windspeed measured at the nearest National Weather Service site. Sky emissivity was calculated using the Clark-Allen formula and T_S was cloud corrected using

Equation 9. Convective intrusion was calculated using Equations 10-13. The radiator is assumed to be held at a constant temperature and is perfectly insulated whenever cooling stops. Contours are drawn through the 77 city grid using a computerized least squares technique. The resulting contour maps for $T_r = 66^oF$, 70^oF, 74^oF and 76^oF are included as Figures 10, 11, 12 and 13. These maps should be considered preliminary. More exact maps which include more detail in the critical South-Central and South-Eastern U.S. are being prepared[12].

Figures 14 and 15 show the net cooling rates as a function of radiator temperature for selected cities.

EFFECTS OF IR TRANSPARENT WINDSCREENS

Convective heat intrusion into the radiating heat dissipator can be decreased by the use of an infrared transparent windscreen suspended above the radiator[13]. If the windscreen is supported by overpressure or tension so that it does not flutter in the wind, then a stagnant cold air layer can form over the radiator and this air layer effectively insulates the radiator from the warm ambient. Extensive theoretical analysis and measurements of the heat transfer and optical properties of windscreen equipped radiators have been completed at Trinity University[14,15,16,17]. These measurements imply that the net heat loss rate for a non-fluttering windscreen is nearly independent of windspeed. At present, polyethylene film without UV inhibitors seems to be the most practical available windscreen material. This polyethylene would have to be protected from sun (or changed annually). Other more durable materials currently available have significantly less infrared transmittance.

Detailed computer models have been developed for the infrared optical properties for polymers exposed to nocturnal infrared radiation and these models have been validated by direct measurements for polyethylene[15,16,17]. The results for the effective values of the effective transmittance, τ, and effective reflectance, ρ, and emittance, ε, for polyethylene (no UV inhibitors) are given in Table 3. The listed ε refers to the windscreens own hemispherical emittance. The listed τ and ρ refer to total effective values when the clear or cloudy (n=10) sky is the source of radiation. The cloudy τ is slightly greater than the clear sky τ because more of the radiation is incident at small incidence angles (near the zenith) when the sky becomes cloudy. The tilted windscreen τ, ρ listed in Table 3 refer only to the sky as the source; the radiation received from the ground is <u>not</u> included when calculating these properties. The windscreen τ, ρ for radiation received from the ground are listed independently in Table 4.

Figure 16 presents the results of 230 hours of measurements of net heat dissipation rates for a 4 mil polyethylene windscreen suspended rigidly 1.25 inches above a horizontal radiator (ε=0.92)[15,16]. The three curves shown are best fits through clear, partly cloudy, and cloudy data. Standard deviations of the three curves from the data are 3 Btu/ft^2/hr. Additional experimental details, analytic fits to the curves shown in Figure 16, and data for other windscreen materials have been described by Manning[15,16].

The τ and ρ of the polyethylene windscreen when the radiator surface is the source are equal to the τ and ρ listed when the horizontal windscreen views the isotropic cloudy sky.

Figure 10 JULY NOCTURNAL NET COOLING RATE FOR DRY SURFACE AT 66°F (BTU/SQ.FT.-DAY)

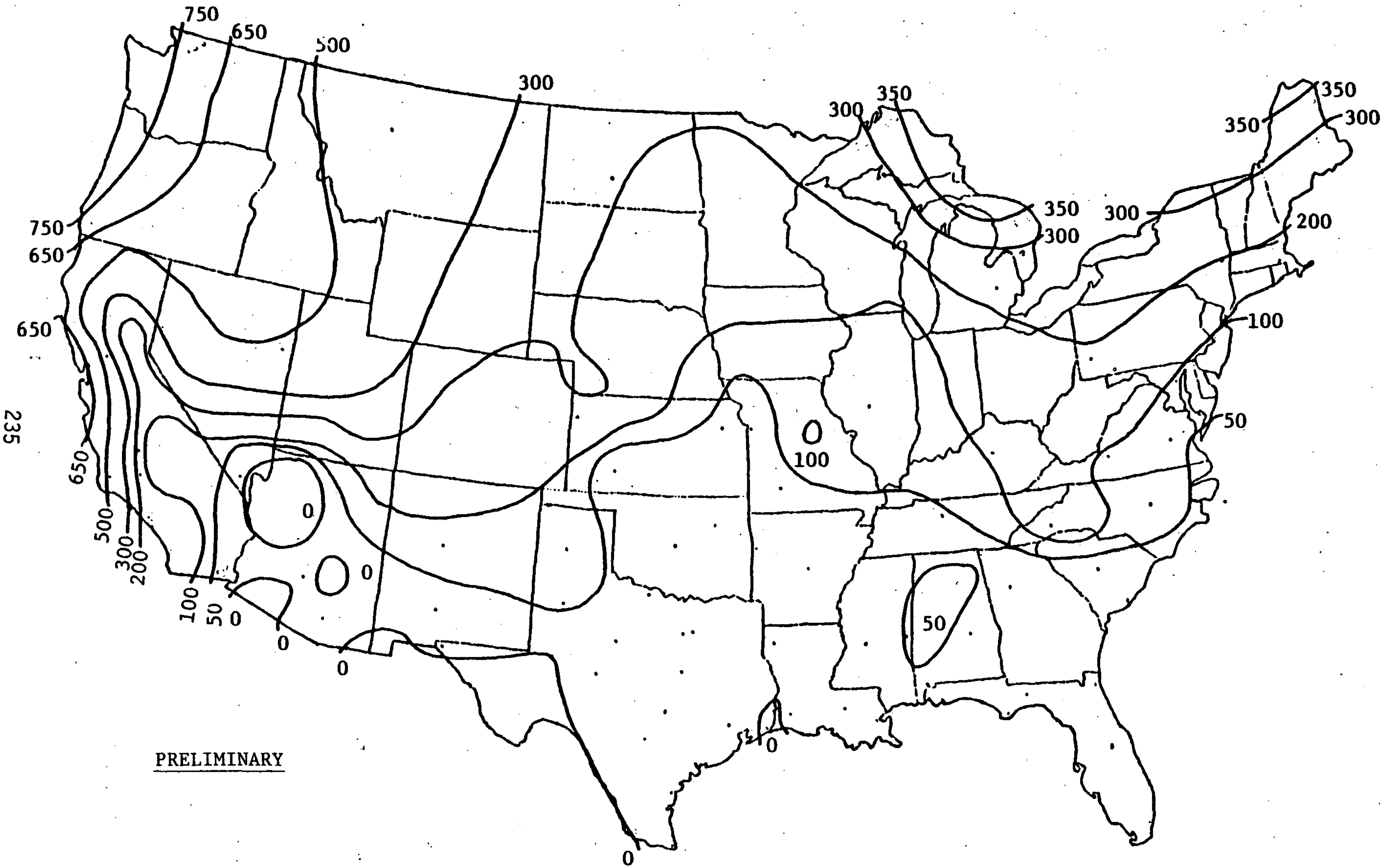


Figure 11 JULY NOCTURNAL NET COOLING RATE FOR DRY SURFACE AT 70°F (BTU/SQ.FT.-DAY)

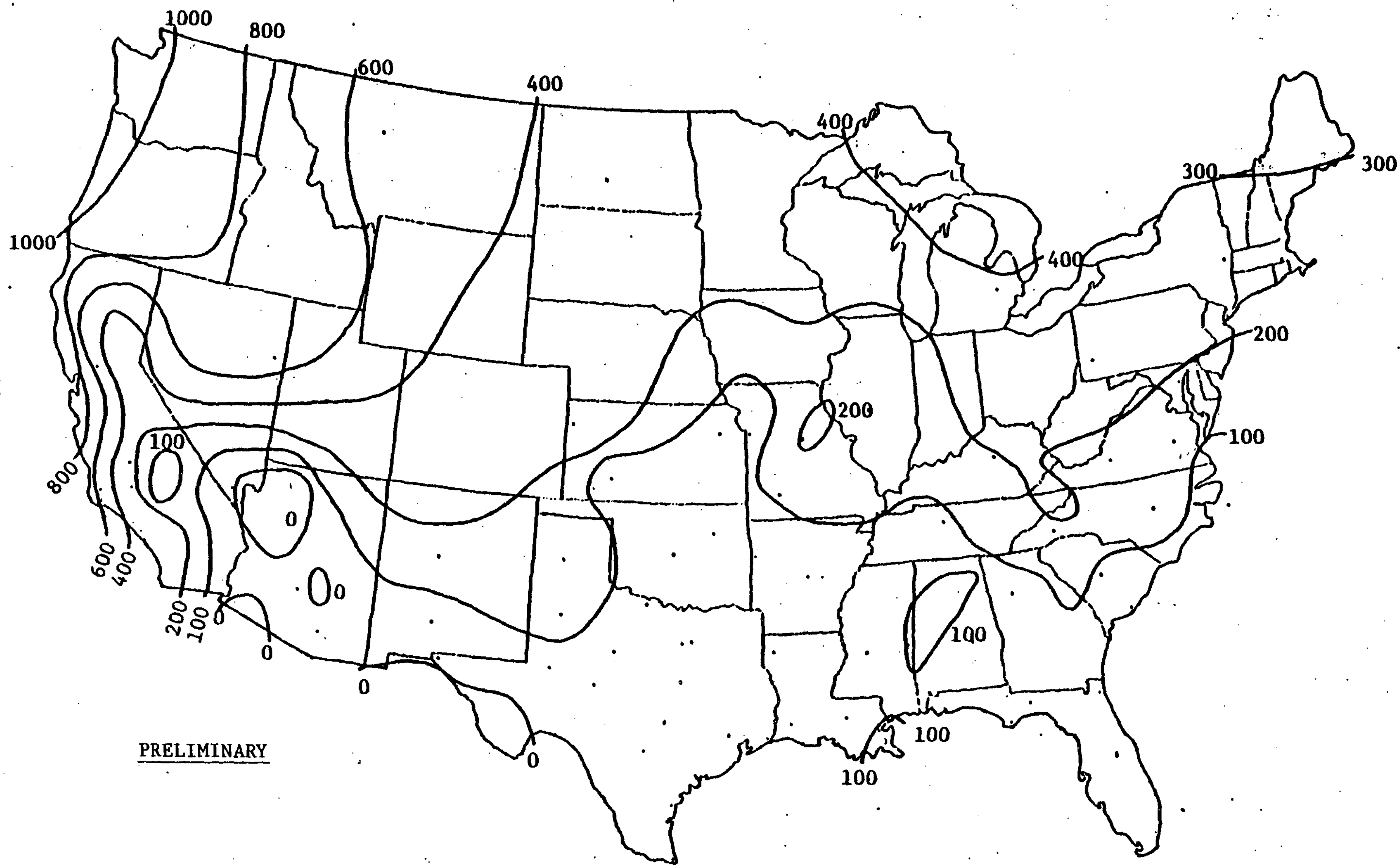
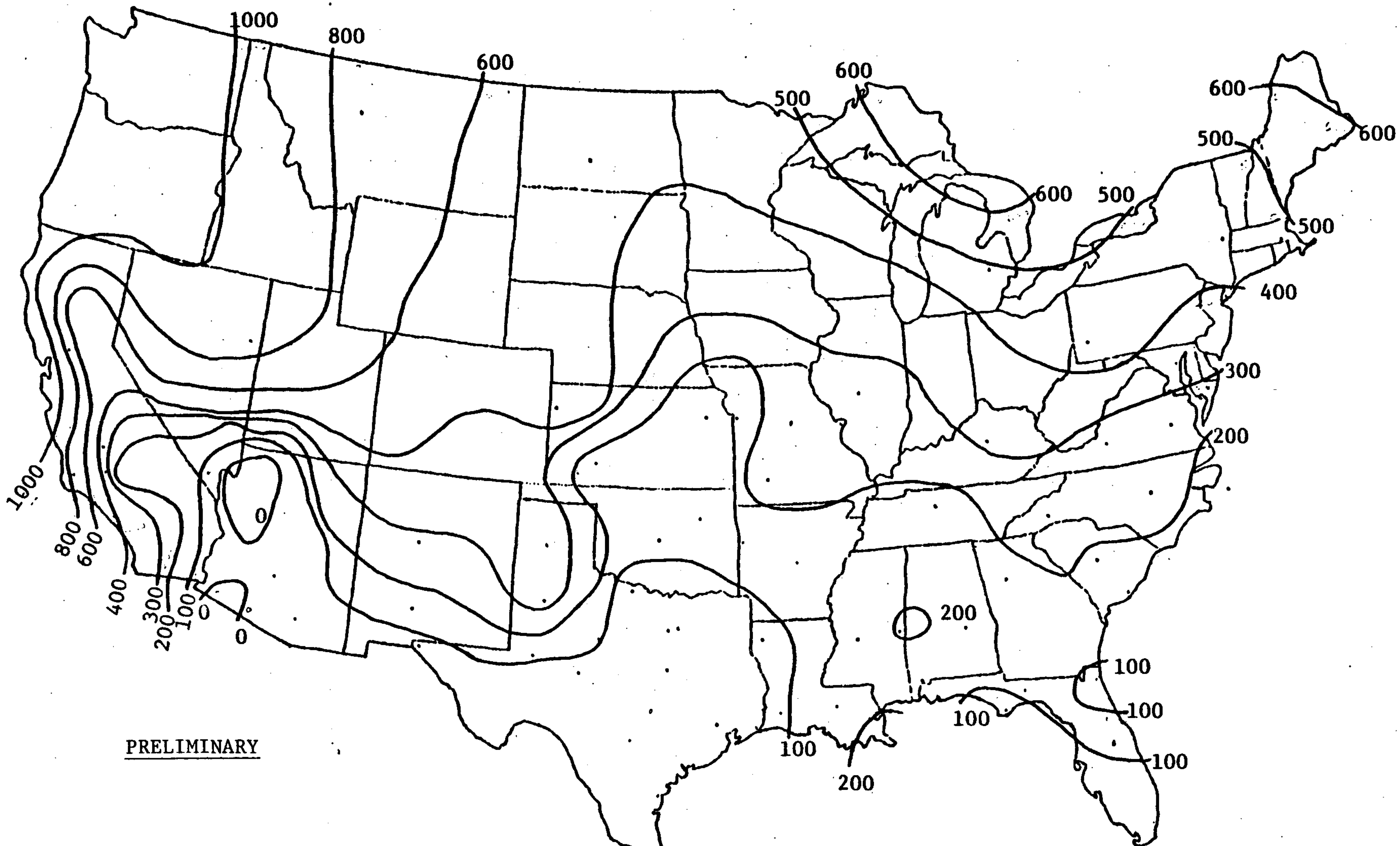
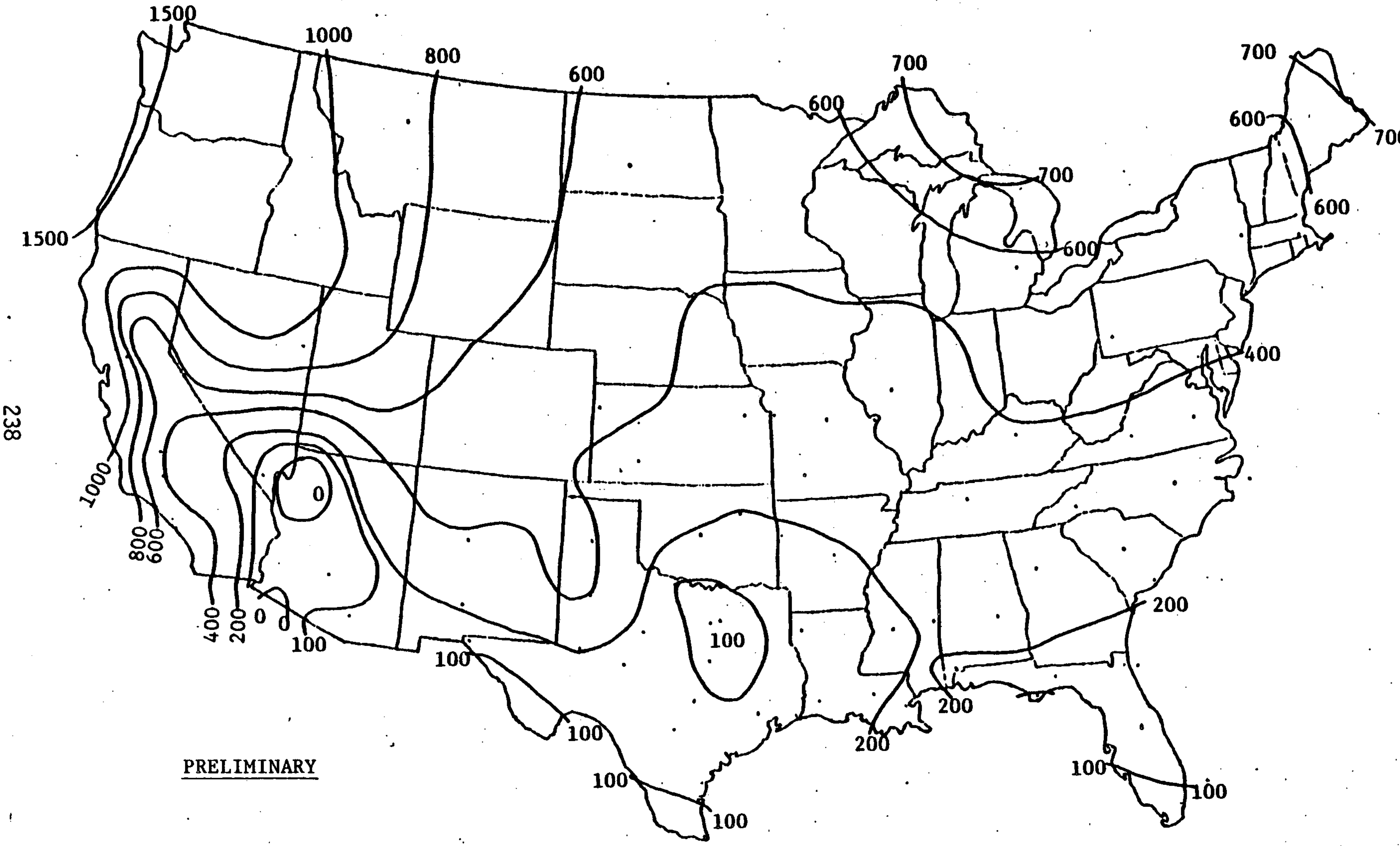


Figure 12 JULY NOCTURNAL NET COOLING RATE FOR DRY SURFACE AT 74°F (BTU/SQ.FT.-DAY)



PRELIMINARY

Figure 13 JULY NOCTURNAL NET COOLING RATE FOR DRY SURFACE AT 76°F (BTU/SQ.FT.-DAY)



PRELIMINARY

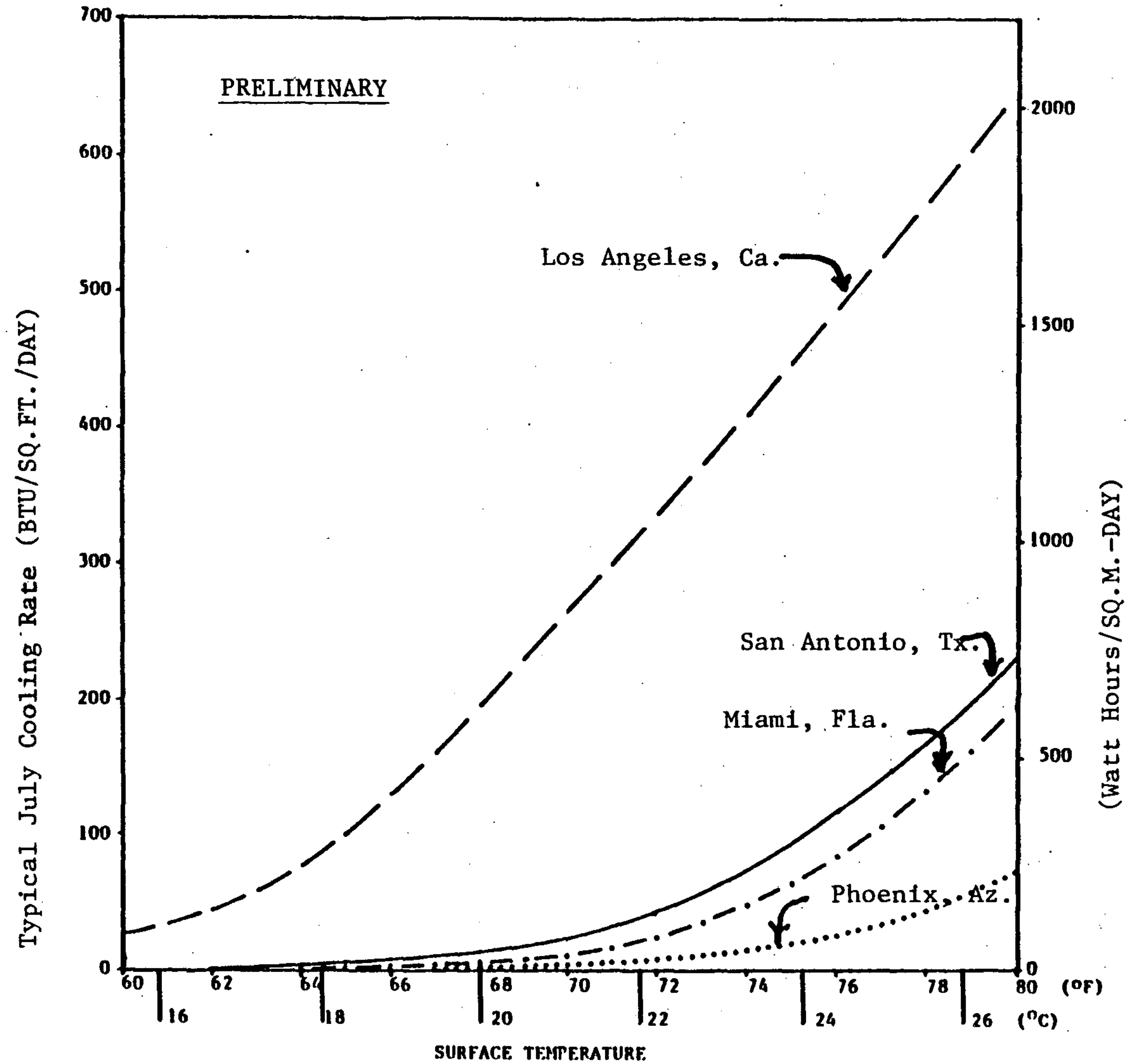


Figure 14 Net Cooling Rate Versus Radiator Temperature in Various Cities

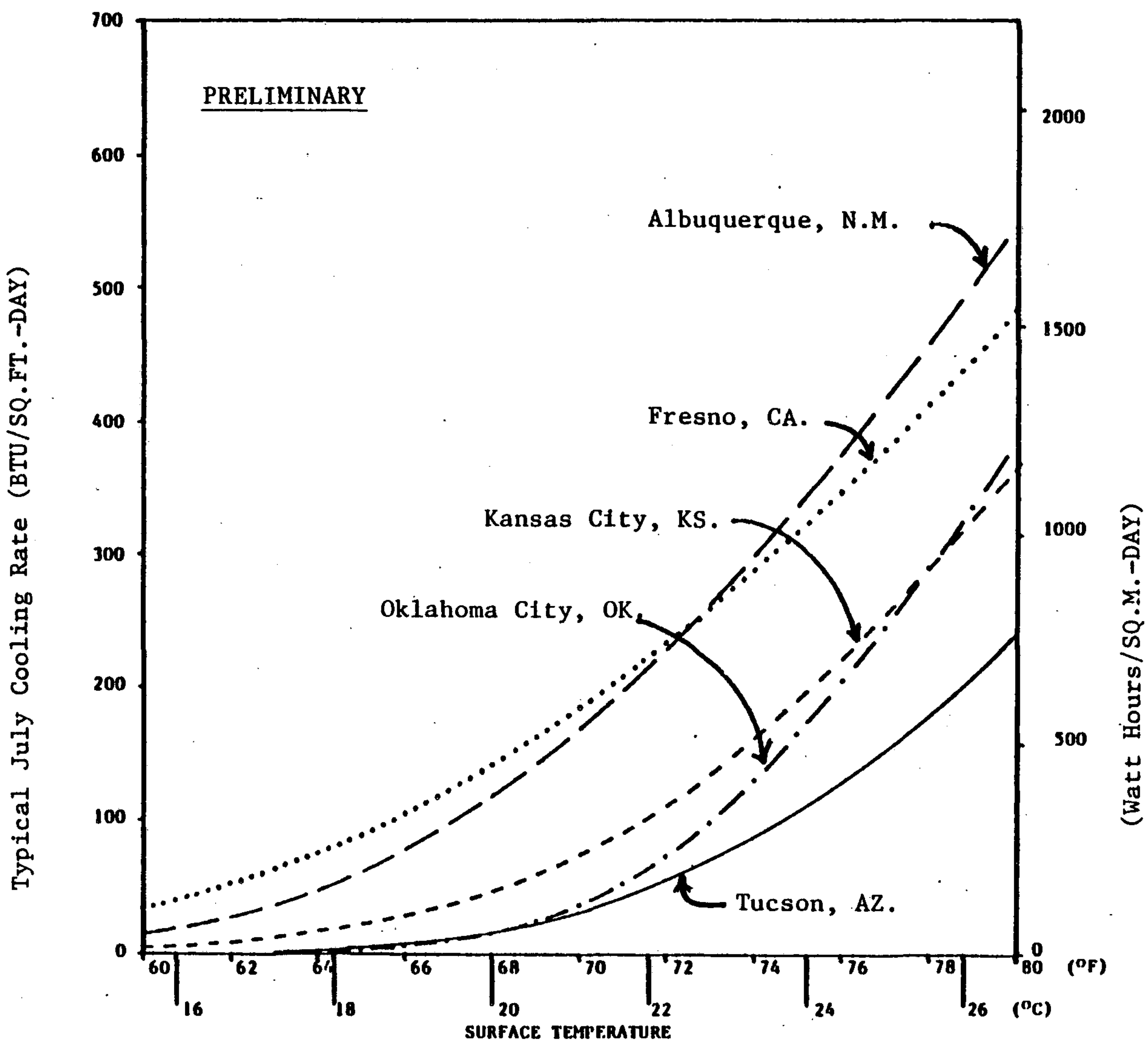


Figure 15 Net Cooling Rate Versus Radiator Temperature in Various Cities

Table 3

Calculated Polyethylene Radiative Properties with Respect to Clear and Cloudy Skies

Surface Tilt (degrees)	Film Thickness (mils)	τ		ρ		ε
		Clear	Cloudy	Clear	Cloudy	
.0	2	.754	.766	.154	.142	.092
0	6	.652	.656	.142	.130	.214
0	8	.613	.613	.139	.126	.262
30	2	.777	.783	.132	.126	.092
30	6	.672	.670	.121	.115	.214
30	8	.632	.627	.118	.111	.262
60	2	.783	.784	.127	.125	.091
60	6	.677	.672	.116	.114	.213
60	8	.637	.629	.113	.111	.260
90	2	.769	.767	.140	.141	.092
90	6	.663	.656	.128	.130	.215
90	8	.622	.613	.125	.126	.262

Table 4

Calculated Polyethylene Radiative Properties with Respect to the Ground Surface

Surface Tilt (degrees)	Film Thickness (mils)	τ	ρ	ε
30	2	.548	.357	.095
30	6	.455	.332	.212
30	8	.421	.324	.254
60	2	.716	.189	.095
60	6	.607	.174	.218
60	8	.565	.169	.265
90	2	.767	.141	.092
90	6	.656	.130	.214
90	8	.613	.126	.262

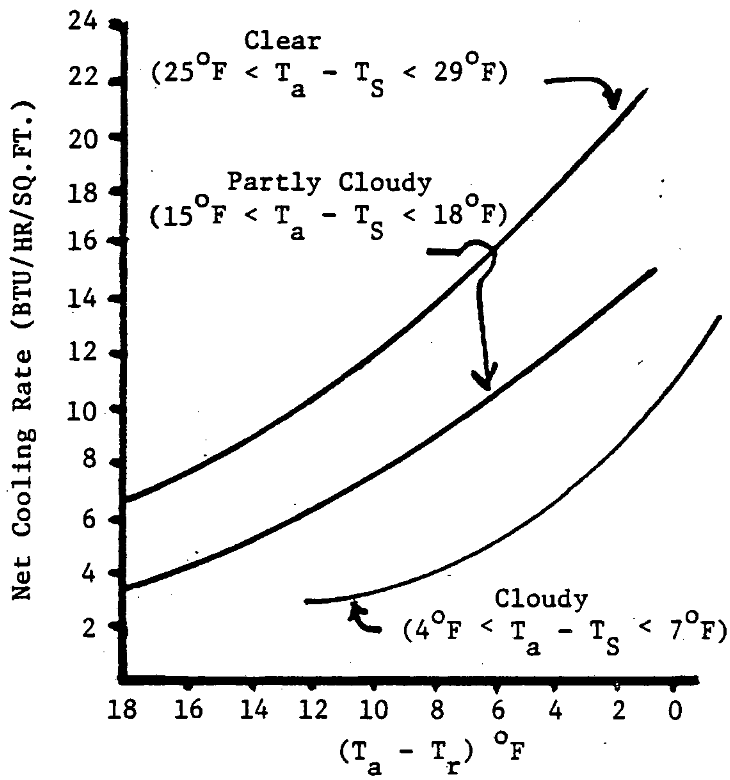


Figure 16 Net Cooling Rate, 4 mil Polyethylene Windscreen

Regional Benefits of Windscreens

A windscreen provides more increase in the net cooling rate as the radiator temperature is depressed further below the ambient air temperature. Warm, windy places are candidates for windscreens. Figure 17 provides physical insight into the heat transfer processes separately operating with windscreens. The example chosen, Ft. Worth, is a marginal climate for radiative comfort cooling with or without a windscreen. However, at $T_r = 72^oF$, the net cooling rate is more than doubled by the use of a 2 mil polyethylene windscreen.

Table 5 lists the radiator temperatures in 10 U.S. cities at which the net cooling rate through the listed windscreen equals the exposed surface cooling rate. Only at lower T_r would a windscreen begin to justify its added cost. Relevant meteorological information is also listed.

EFFECTS OF TILTING THE RADIATOR ABOVE HORIZONTAL

Because the lowest radiative temperature in the environment is the part of the sky within 70° of the zenith, a horizontal radiator will achieve the greatest cooling rates. However, practical considerations (e.g., roof drainage) may require the radiator to be tilted. As the radiator is tilted above horizontal it sees the warmer near horizon sky and the ground. Net cooling rates are significantly decreased by tilts of only 30°.

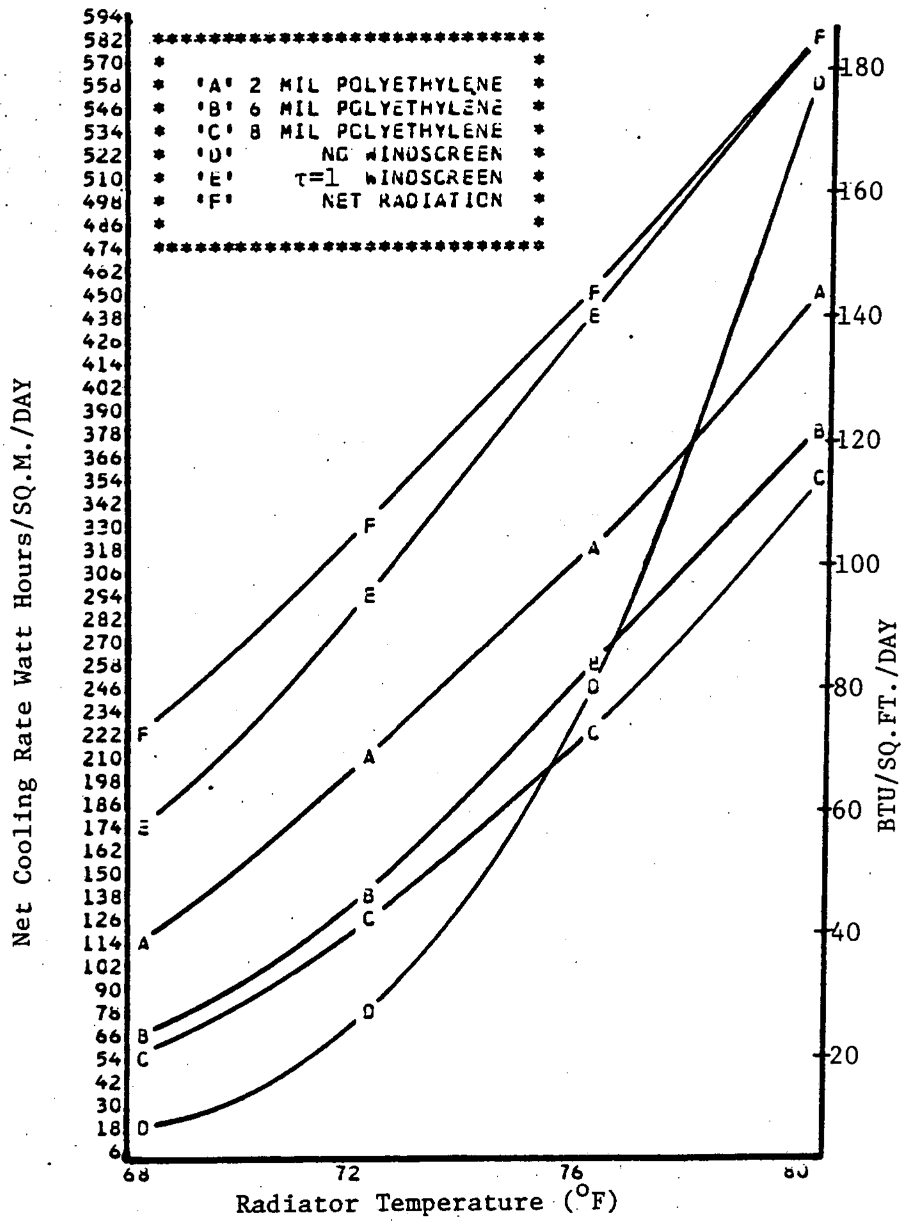


Figure 17 **Typical July Cooling Rates**
Fort Worth, Texas
Horizontal Surface (ε = 0.93)
Average Ambient, 8 p.m.-6 a.m. = 80°F

Table 5

Surface temperature at which average nightly cooling equals that from an unglazed radiator, surface perfectly insulated when cooling stops.

(degrees Fahrenheit)

City	2 mil poly	6 mil poly	Average T (ambient) During Operation (76 F radiator)	Nocturnal Avg. Windspeed (mph)
El Paso	76	73	78.9	10.4
San Antonio	77	75	78.8	-
Houston	75	74	77.4	8.0
Phoenix	>80	80	86.4	7.2
Miami	77	76	79.8	6.0
Fort Worth	78	76	80.2	9.0
Little Rock	73	70	75.0	4.9
Atlanta	71	69	73.4	5.9
Las Vegas	>80	79	85.1	-
Santa Maria	<68	<68	55.8	-

Figure 18 is the result of simulation and shows the decrease in cooling as the surface is tilted from horizontal to vertical[17]. This example, for a 76°F radiator in San Antonio, is typical of roof type radiator applications in the South-Central U.S. A tilt of 30° decreases the net cooling from an exposed radiator by 21% and decreases the net cooling through a 6 mil windscreen by 30%. Windscreened radiators are more sensitive to tilt because of the increase in τ shown in Tables 2 and 3 and because the stagnant insulation air layer is disturbed by tilting.

These results assume that the ground is at ambient temperature and has $\varepsilon = 0.95$. Tilted radiator performance would be further degraded if the ground is warmer (e.g., an asphalted area).

APPLICATION: RADIATIVE COMFORT COOLING OF RESIDENCES

The performance of a variety of residential passive cooling systems has been simulated at Trinity[12]. All of these systems, even those which employ water trickling over the roof at night, dissipate a significant part of their total cooling by radiation. The radiative component of the cooling is especially important in humid climates where the high wet bulb suppresses evaporative cooling. In this section only one type of radiative cooling application is examined, the "Skytherm" roof pond residence. The excellent thermal couplings between the sky and the heat dissipator, between the dissipator and storage, and between storage and the conditioned space imply that the thermal performance of this system cannot be exceeded by other passive cooling systems[18].

Simulation Results for Air Conditioner Assisted Residences

Detailed hourly simulations of comfort conditions and supplemental air conditioning have been developed. A standard 1,224 square foot residence has been defined with the roof pond area equal to the floor area. A similar energy conserving residence of conventional design was also simulated for comparison. A scheduled internal sensible heat load of about 50,000 Btu per day is included in each residence. Additional sensible loads due to infiltration and about 40,000 Btu per day of diffuse solar gain through windows are also included, thus the total sensible load is of the order of 100,000 Btu per day. Envelope conductive loads become significant in the arid South-West. Latent loads due to infiltration and internal moisture total as much as 70,000 Btu per day in very humid coastal climates[12]. Details of the thermal design of the residences and the simulation methodology (based on NBSLD) are provided by Haves, et.al.[18].

Figure 19 illustrates the total simulated air conditioning required to maintain a wet roof pond residence, a dry roof (water in bags) pond residence, and a conventional energy conserving residence within ASHRAE Comfort Standard 55-74. The June through August total is presented for 12 U.S. cities. In warm arid climates, negligible supplemental air conditioning is required. In humid climates the supplemental air conditioning requirement is dominated by dehumidification, not by sensible cooling. Much more optimistic conclusions can be drawn for humid climate passive cooling applicaiton if efficient mechanical dehumidifiers or passively regenerated solar dehumidifiers are available. The conventional air conditioner assumed in Figure 19 unavoidably provides sensible cooling while dehumidifying and so displaces much of the passive cooling effect.

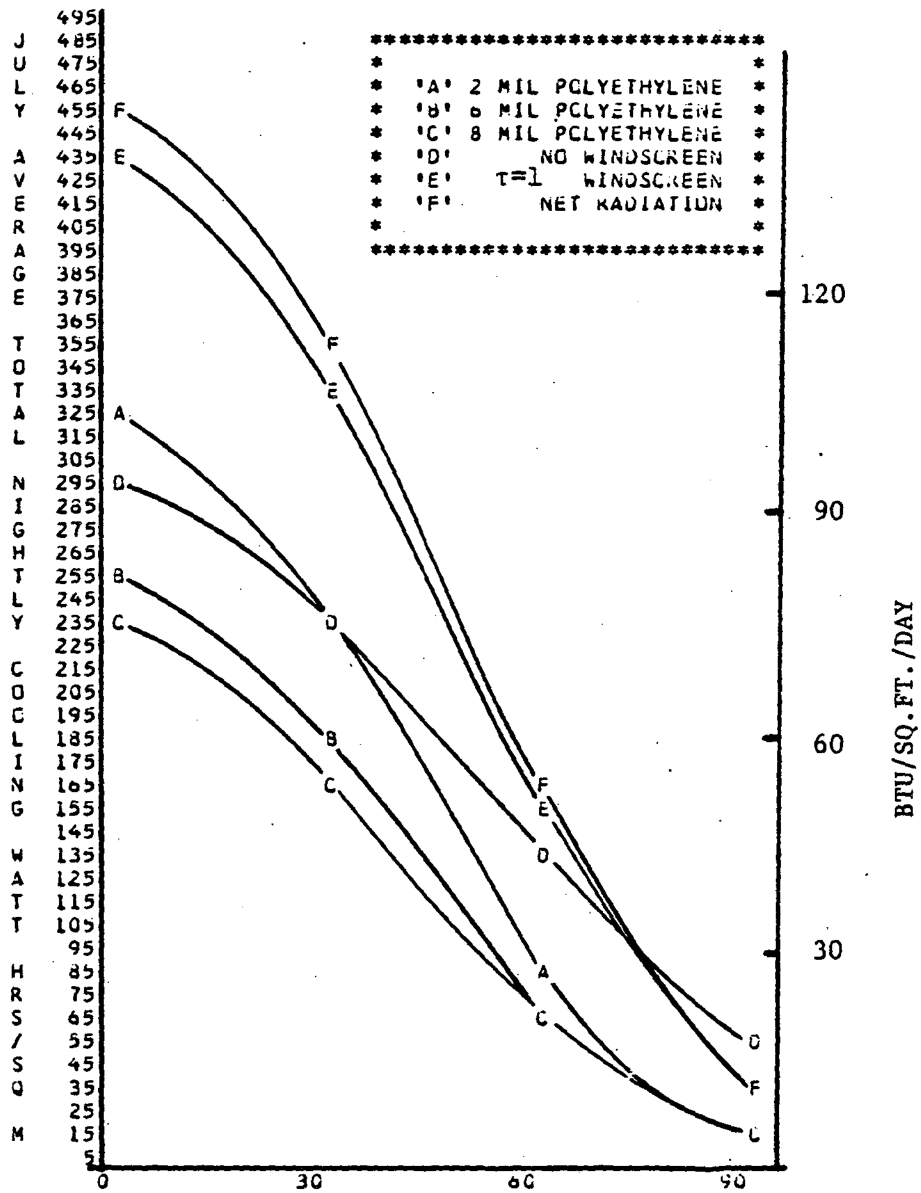


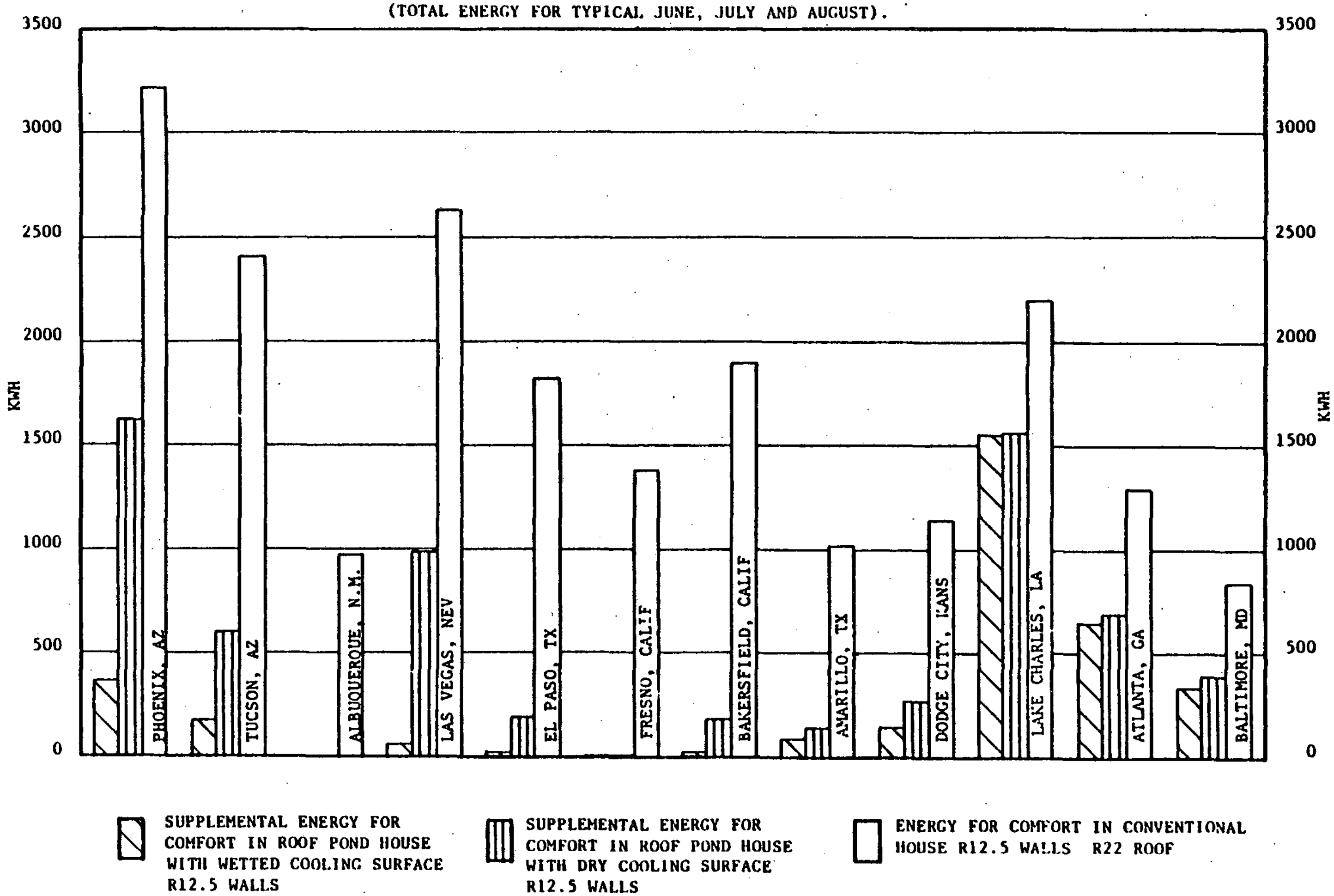
Figure 18 TILT OF RADIATOR SURFACE, DEGREES

JULY AVERAGE NIGHTLY COOLING VS. TILT

SAN ANTONIO, TEXAS
RADIATOR TEMPERATURE = 76 F

Figure 19

ELECTRICAL ENERGY REQUIRED FOR COMFORT COOLING IN
A ROOF POND RESIDENCE AND IN A SIMILAR CONVENTIONAL RESIDENCE.
(TOTAL ENERGY FOR TYPICAL JUNE, JULY AND AUGUST).



Comfort as defined by ASHRAE 55-74
Houses are 1224 ft^2, Slab on grade. ½ Air change per hour.
6" Pond depth, 150 Square feet window area. No East or West windows.

Comfort Conditions in Unassisted Roof Pond Residences

A second comfort strategy has also been simulated; instead of air conditioning for humidity control, the house is vented whenever the ambient temperature is less than the interior air temperature. In this simulation, hourly comfort conditions were evaluated using Fanger's PMV or "Predicted Mean Vote" parameter[19]. Comfort reactions associated with particular values of PMV are:

-3 = cold	+1 = slightly warm
-2 = cool	+2 = warm
-1 = slightly cool	+3 = hot
0 = comfortable	

(The comfort reaction at PMV = 0.2 is negligibly different from PMV = 0.)
All of the attached simulations of PMV assume light office clothing (CLO = 0.5) and sedentary activity.

Figures 20 - 25 present the hourly distribution of PMV in unassisted dry roof pond residences. Interior air speed is treated as an adjustable parameter which can be achieved by interior circulation fans during periods when ambient temperatures are too high for venting.

The comfort conditions simulated here are conservative in two ways. A significant fraction of the diffuse insolation gain through windows could be prevented. Even more important, convective coupling between the cool ceiling and the conditioned space was always simulated assuming that the room air was not circulated across the ceiling. Interior space temperatures can be decreased 1°F to 3°F during peak load periods if ceiling fans are used to increase convective coupling[20].

Additional simulation details and comfort assessments during extremely hot periods and for wet roof ponds have been completed by Clark and Allen[20].

The building performance simulations have only limited validation. A facility which will provide accurate validations is nearing completion on the Trinity University campus.

Use of Constant Temperature Cooling Rate Charts For Feasibility Assessment

The cooling contours presented in Figures 10 - 15 assume that the cooling surface is held constantly at the listed temperature during the night. In a roof pond application the pond temperature, T_w, will rise 3°F - 5°F during the day and will decrease the same amount during the night. Comparisons of dynamically simulated heat loss rates for roof ponds and the loss rates suggested by Figures 10 - 15 show reasonable agreement. If the pond temperature is taken as the 24 hour average T_w and this temperature is used with Figures 10 - 15 the resultant cooling rate is 20 to 30% above the dynamically simulated cooling rate. Constant temperature cooling rates overestimate the effective cooling rate for a dry roof pond because the majority of the heat is dissipated during the post midnight hours when the environment has cooled and the roof pond is below its average temperature by 1-2°F.

Figures 10 - 15 can be used to assess feasibility for radiative comfort cooling with a roof pond in the following way.

1. Find the total sensible cooling load and convert this to a pond temperature rise during the day. For example, a load of 100 Btu/ft^2/day will increase the temperature of a 6" deep pond about 3°F.

TOTAL HOURS AT LISTED PMV

PMV

INTERIOR AIR SPEED (M/SEC)

	LESS THAN .2	.2 - .5	.5 - 1.0
.1	744	-	-
.3	744	-	-
.5	744	-	-
1.0	744	-	-
1.5	744	-	-

Figure 20 Albuquerque

Typical July, Dry Roof, 6"

$T_w = 69^oF$

TOTAL HOURS AT LISTED PMV

PMV

INTERIOR AIR SPEED (M/SEC)

	LESS THAN .2	.2 - .5	.5 - 1.0
.1	377	241	126
.3	634	99	11
.5	700	43	1
1.0	738	6	0
1.5	743	1	0

Figure 21 Houston

Typical July, Dry Roof, 6"

TOTAL HOURS AT LISTED PMV

INTERIOR AIR SPEED (M/SEC)	PMV LESS THAN .2	PMV .2 - .5	PMV .5 - 1.0
.1	619	79	46
.3	701	37	6
.5	718	25	1
1.0	737	5	0
1.5	737	2	0

Figure 22 Little Rock

Typical July, Dry Roof, 6"

TOTAL HOURS AT LISTED PMV

INTERIOR AIR SPEED (M/SEC)	PMV LESS THAN .2	PMV .2 - .5	PMV .5 - 1.0	PMV 1.0 - 1.5
.1	415	258	71	0
.3	658	82	4	0
.5	711	33	0	0
1.0	740	4	0	0
1.5	743	1	0	0

Figure 23 San Antonio

Typical July, Dry Roof, 6"

$T_w = 75.1^oF$

TOTAL HOURS AT LISTED PMV

PMV

INTERIOR AIR SPEED (M/SEC)

	LESS THAN .2	.2 - .5	.5 - 1.0	1.0 - 1.5
.1	269	228	239	8
.3	511	144	89	0
.5	595	100	49	0
1.0	662	61	21	0
1.5	694	39	11	0

Figure 24 Fort Worth

Typical July, Dry Roof, 6"

$T_w = 76.6^oF$

TOTAL HOURS AT LISTED PMV

PMV

INTERIOR AIR SPEED (M/SEC)

	LESS THAN .2	.2 - .5	.5 - 1.0	1.0 - 1.5	1.5 - 2.0	2.0 - 2.5
.1	40	46	234	313	111	0
.3	96	100	226	240	82	0
.5	152	87	235	202	68	0
1.0	213	98	208	161	59	5
1.5	244	103	195	145	52	5

Figure 25 Phoenix

Typical July, Dry Roof, 6"

$T_w = 81.7^oF$

2. Add this pond rise to the peak temperature difference between the space and the pond. This peak temperature difference can be roughly calculated using a ceiling coefficient of $u_c = 1.7$ Btu/hr/ft^2°F and then

$$T_{interior} - T_w = (\text{peak load})/u_c. \qquad (17)$$

For example, if the peak load is 12 Btu/hr/ft^2 (a typical value), then the peak temperature difference between the pond and interior is 7°F.

This temperature difference and the daytime increase in pond temperature can be used to establish a minimum pond temperature requirement. For example, if the peak space temperature is to be 82°F, the daytime rise in pond temperature is to be 3°F and the peak value of ($T_{interior} - T_w$) is 7°F, then the pond must drop to 72°F in the early morning. The average temperature of the pond during the night would be about 73.5°F. Use of Figures 10 - 15 to assess the nocturnal pond heat loss assuming this fixed temperature will overestimate dynamic heat loss rate by 20 to 30%.

If required, ceiling fans can be used to increase u_c to 2.7 Btu/hr/ft^2°F or more and so decrease peak values of ($T_{interior} - T_w$).

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Dehumidification

Dehumidification in Passively Cooled Buildings --
Frances Arnold

DEHUMIDIFICATION IN PASSIVELY COOLED BUILDINGS

Frances H. Arnold*

ABSTRACT

Passive cooling techniques can meet the sensible portion of cooling loads, but not the latent portion. In hot, humid climates and in seasonally overheated climates where high humidities are common, comfort cannot be achieved without humidity control or air circulation. Suppression of mold, mildew and degradation of building materials may require dehumidification even where air movement will provide comfort. Significant reductions in energy consumption for air-conditioning can be achieved using passive cooling techniques combined with high-efficiency dehumidification. In this paper, methods of latent load reduction and dehumidification techniques are presented. Materials and design parameters for solar-regenerated liquid and solid desiccant dehumidifiers are discussed in detail, and a sizing method for solar dehumidification systems is given. Detailed studies underway at SERI to model heat and mass transfer in desiccant channels and packed beds are described. Preliminary results indicate that desiccant machines show promise for high-efficiency solar dehumidification.

INTRODUCTION TO COOLING IN HOT, HUMID CLIMATES

The cooling problem in hot, humid climates and in many seasonally overheated climates can be summed up in one word: humidity. Evaporative cooling is ineffective because the wet bulb temperatures in these climates are often outside the comfort zone. Furthermore, the need to limit the moisture added to the interior space calls for more complicated, indirect systems. Humidity in the atmosphere inhibits the radiative cooling at night that provides relief from high daytime temperatures. Whereas the diurnal temperature swing can be 50°F in hot and arid regions, it is reduced to 12-19°F in hot, humid states like Florida.

Passive cooling techniques that take advantage of natural low temperature sinks such as underground or surface water, the night sky, the atmosphere and the earth itself can provide sensible cooling, but no appreciable latent cooling. Detailed simulations at Trinity University[1] have shown roof ponds to yield sufficient sensible cooling for cities in the very humid Southeastern and Southwestern States, but the resultant indoor conditions are not within the comfort zone unless there is considerable air movement or dehumidification.

Alternatives to dehumidification for achieving comfort are air movement, and, to a small extent, reducing the radiant temperature of surrounding surfaces. While a high moisture content of the surrounding air will limit the body's ability to cool itself by perspiration, additional heat can be dissipated by convection and radiation from the skin. A simple, but useful quanitification of the effect of air movement across the skin is shown in Fig. 1, the hot, humid portion of Olgyay's bioclimatic shart.[2] Air movement of up to 300 fpm can extend the comfort region somewhat, but for very high humidities or very high temperatures, comfort cannot be achieved. Air movement of above 300 fpm is considered annoying.

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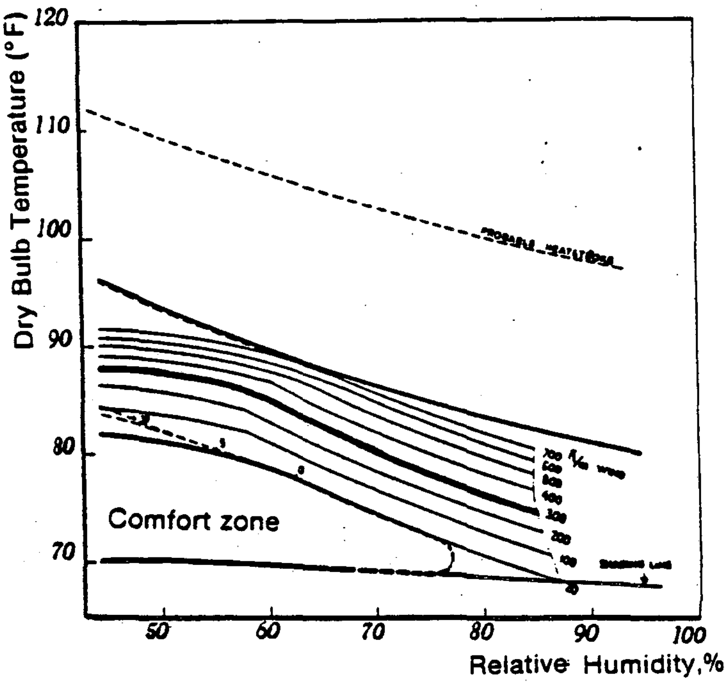

Fig. 1. Hot, humid quadrant of bio-climatic chart. Lines above comfort zone show air movement needed to achieve comfort at a given temperature and relative humidity. Source: Ref. 2.

With a liberal definition of comfort, Clark[3] has shown that a combination of night venting, air circulation during the day and passive sensible cooling may provide acceptable interior conditions for the severe climate of Miami, Florida. The worst conditions are during five hours in July when the indoor temperature is 80-81°F with 95-100% relative humidity and 83-84°F with 80-85% relative humidity. The dew point temperature for these conditions is 78-80°F; water would condense on any surface at these temperatures slightly below the indoor dry bulb temperature. It was claimed that comfort conditions are improved because the mean radiant temperature of the residence is 2°F below the indoor dry bulb temperature, which would be at, or very close to, the dew point. In fact, for 219 hours during July, the dew point temperature corresponding to the indoor conditions is less than 5°F below the indoor dry bulb temperature, and for 434 hours (64%) of the month, that difference is less than 7°F. Water would condense on any surface at the dew point temperature: for example, water pipes, the ceiling under the roof pond, or any surface that is used to cool the inside space.

If relatively low temperatures can be reached by the sensible cooling (under about 60°F), controlled condensation can result in dehumidification. In a few humid areas, the ground water is sufficiently cool. In some seasonally overheated climates seasonal storage of ice can yield cold water for both sensible cooling and dehumidification. This method is working successfully in Princeton, New Jersey[4]. Uncontrolled condensation on surfaces, however, is undesirable because it causes the degradation of building materials and the growth of mold and mildew.

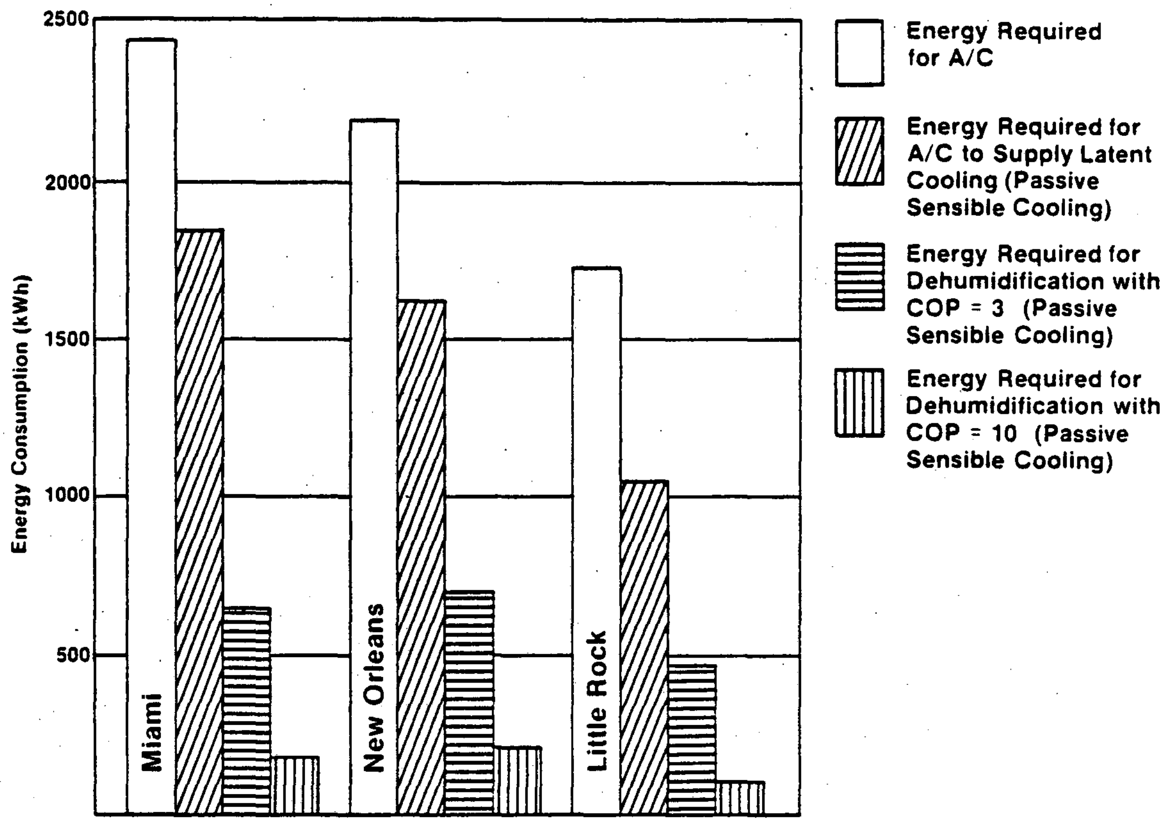

Fig. 2. Energy consumption for three southern cities for a typical cooling season (June, July, August). Adapted from Ref. 1.

In certain residential applications, where low ventilation rates are possible and the occupants are only engaged in sedentary activities, the passive cooling/air circulation scheme can provide an energy-conserving alternative to mechanical air-conditioning for a significant part of the cooling season. For the most severe days and for more demanding applications in both commercial and residential areas, some form of controlled dehumidification is required to maintain comfortable conditions and the integrity of building materials. A high-efficiency dehumidifier can be used when relative humidities are high (80-100%), provided that it is not used when venting of the building is taking place. If a good control scheme is not a part of this system, more energy can be used trying to dehumidify ten room-fuls of air per hour than was originally used to air-condition the house. An analogy is trying to cool your car as you are going down the highway with all the windows down.

The alternative to air circulation is dehumidification. It has been shown that air conditioning and mechanical dehumidification with currently available vapor compression dehumidifiers is inappropriate for use with passive sensible cooling techniques in hot, humid climates.[5] The results of the Trinity simulation have been adapted in Fig. 2 for three Southern cities. The first bar is the energy consumption for air-conditioning a standard

1,224 ft^2 house for a typical cooling season (June, July and August). The second bar represents a passively-cooled home with air-conditioning to meet the latent load only. The reduction in energy use is small because the air conditioner does both latent and sensible cooling. In order to meet a given latent load, the air conditioner must do double work, providing sensible cooling that the passive cooling methods can give. Vapor compression dehumidifiers give no better results. In fact, the energy consumption turns out to be even greater than that of the air conditioner because current dehumidifiers work with a COP* of less than 1, compared to 2-2.5 for an air conditioner. Significant energy savings are realized only when the passive sensible cooling is combined with a high-efficiency dehumidifier, represented by the third and fourth bars in Fig. 2. Future vapor compression dehumidifiers are likely to have COP's on the order of 3[6] and solar-regenerated desiccant dehumidifiers can have COP's (with respect to electrical input) of 10 or greater.

SOURCES OF LATENT LOADS AND LOAD REDUCTION

The size of the latent load that must be met by a dehumidifier will be reflected in energy consumption and the initial cost and size of the unit. Ideally, latent loads should be made as small as possible through good design and conservation techniques. The tradeoffs between the costs of reducing loads and the costs of removing the moisture with a dehumidifier must be considered.

Although an air conditioner works with a COP of 2.0-2.5, it uses electricity mostly generated with fossil fuels at an overall efficiency, including distribution, of about 25%. The efficiency of conversion of fossil fuel to cooling is then .25(2.5) = .63, which is approximately the efficiency of a furnace for heating. The greatest demand also occurs during the day, which makes cooling a severe peak demand problem for the utilities. Although the temperature difference between the house and the ambient is usually small (10-30°F), the additional latent load in humid climates and prevalent poor construction mean a total load that is often comparable to heating loads in cold climates. The cost to the consumer is also comparable. This should tell us that the priority for reducing energy use for cooling should be equal to that for reducing heating energy use in relatively severe climates. Unfortunately, little conservation work has been done for cooling, and even less has distinguished between sensible and latent load reduction.

With care, we can extend many of the conclusions of conservation work in heating to cooling, but first it is necessary to know the sources of the cooling loads. Sensible heat gain is discussed in other papers;[7] here we will dwell on latent heat gain.

The latent load that a dehumidifier must meet is comprised of moisture from internal and external sources. Some of the internal sources are occupants, cooking, appliances and showers. The external sources of humidity are the water vapor that permeates the building materials due to the water vapor gradient between the outside and the inside, and the vapor carried into the room through windows, doors, cracks and other openings. Table 1 shows approximate quantities of water vapor coming from each of these sources.

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*COP (coefficient of performance) is a dimensionless measure of the efficiency of an air-conditioner or dehumidifier. It is defined as cooling (dehumidification) output per energy input. EER is defined in the same way, except that the cooling output is Btu/hr and the energy input is given in Watts. To get EER from COP, multiply by 3.41.

Table 1. LATENT LOAD FROM INTERNAL AND EXTERNAL SOURCES

		Moisture released (lb/hr)
Internal		
Occupants:	adult at rest	.16
	light exertion	.43
	heavy exertion	.57
Appliances:	3 gallon coffee urn	.29
	cooking (dinner for 4):	
	from food	1.2
	from gas	1.5
		2.7
Shower:	(5 minutes)	.25-.50
Other:	house plants (7)	.04
	floor mopping (1 time)	2.4
External		
Permeation:	wood frame wall (1,000 ft^2)	.03
Infiltration/ ventilation:	(1 ACH, 10,000 ft^3 and conditions in Fig. 3)	4.4

Sources: Ref. 8, 9, 10.

Methods of reducing the moisture gain must be applied at the entry point: hoods for appliances or venting the bathrooms and kitchens will reduce some of the internally generated load, but may not be cost effective due to the small fraction of the total load that is affected. From Table 1 it seems that a good starting point would be to reduce infiltration or ventilation rates, or find an alternative that does not introduce as much water vapor into the building. The infiltration/ventilation rate is also a source of considerable sensible heat gain, and is, therefore, doubly important. Limited retrofits can reduce infiltration rates by 40%[11], and more extensive retrofits can reduce the rate to .15 ACH (air change per hour) or less. New buildings can be designed for almost any infiltration rate with little additional cost. Measures such as installing a polyethylene air-vapor barrier* to exterior walls and ceiling, caulking the sill plates and electrical and plumbing penetrations to the outside, and installing tight-fitting, weatherstripped doors and windows can bring the infiltration rate to 0.2 ACH and would add about $350 to the cost of a new home[12].

*This vapor barrier is far more useful for reducing cooling loads from infiltration rather than from moisture transfer through the wall.

For health reasons, however, one would not want to "tighten" buildings to a high degree (less than .6 ACH for residential buildings) unless some form of controlled ventilation is used to remove pollutants. Indoor pollution levels can exceed safe limits unless a mechanism is available to remove radon and aldehydes coming from building materials and noxious combustion gases[13]. Too-low ventilation rates also result in stale air, as kitchen and bathroom odors cannot be dissipated.

In new buildings and in old buildings that can be fairly easily retrofitted to very low infiltration rates, an air-to-air heat exchanger can be used to provide the necessary air exchange, without unduly penalizing performance. For example, Mitsubishi claims an efficiency of 70% for sensible heat exchange and 58% for latent heat exchange for its Lossnay total heat exchanger (70 cfm). Therefore, if the outdoor dry bulb temperature is 90°F and the humidity ratio is .018 lb water/lb dry air (60% relative humidity) and the room conditions are 77°F and .012 lb/lb (60% relative humidity), the condition of the air at the outlet of the heat exchanger is 80.9°F and .0145 lb/lb (Fig. 3). These conditions are plotted in Fig. 4 on the psychrometric chart, where we see that the cooling load is only a fraction of the original load from infiltration/ventilation (3.8 Btu/lb air processed versus 9.7 Btu/lb air processed, or 39%). This exchanger only consumes 46W, so we can calculate what the equivalent COP of this device is:

$$COP = \frac{\text{Cooling output}}{\text{Energy input}} = 12$$

This is the COP that an air conditioner would have to have to produce the same effect. The COP of a good air conditioner is 2.5.

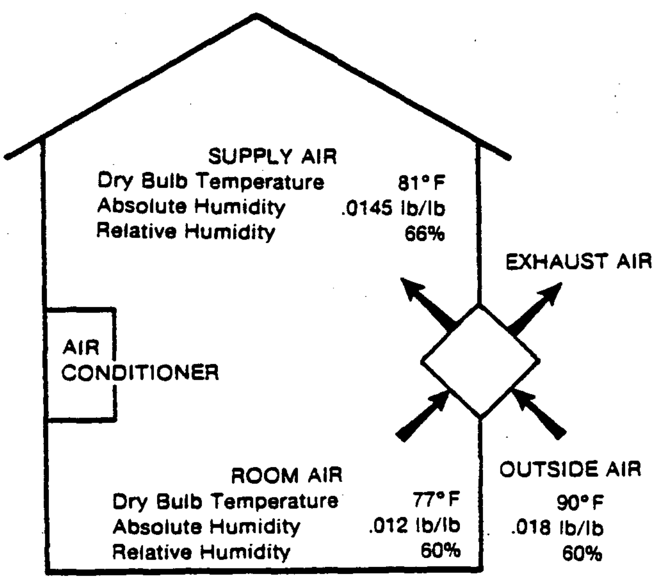

Fig. 3. Low-infiltration building with mechanical ventilation through a total heat exchanger. For the given room and ambient conditions, at the outlet of the heat exchanger the air is 81°F, with a humidity ratio of .0145 lb/lb.

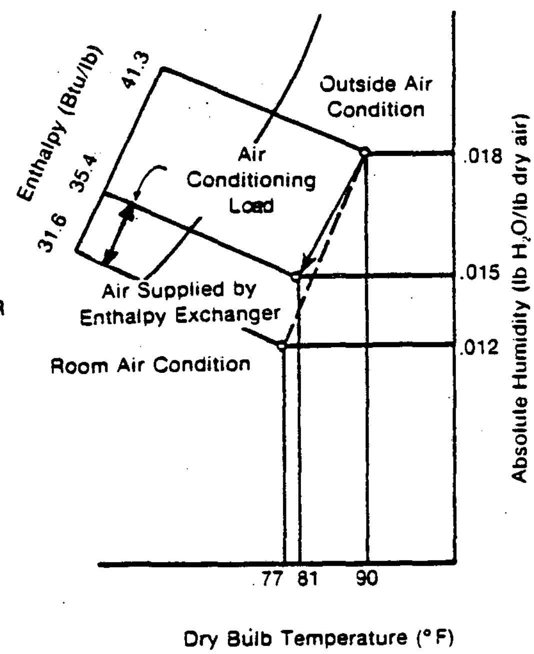

Fig. 4. Ambient, room and heat exchanger outlet conditions from Fig. 3 plotted on the psychrometric chart. A 39% reduction in the cooling load from ventilation is realized using a heat exchanger.

The water that must be removed from the interior space for different infiltration/ventilation schemes is shown below for a typical summer day in Miami. The internally generated water load is assumed to be 16 lb/day.

Infiltration	Mechanical Ventilation	Total water removal (lb/day)
1.0 ACH		120
.6 ACH		78
.1 ACH	+ .5 ACH	48

Reducing infiltration to low levels and using air-to-air heat exchangers for ventilation can reduce the total latent load by 60%. Large reductions in energy consumption can be realized with simple retrofits to reduce infiltration rates. Keep in mind that infiltration is important in determining the sensible load, and additional savings can be expected there.

Cost/benefit and net present value analyses for heat exchangers in new construction have shown them to be cost-effective for the heating season alone, even in mild climates like that of Atlanta, Georgia[14]. They would almost certainly be cost-effective for seasonally overheated climates, where they can reduce both heating and cooling loads. They would also be cost-effective for the severe hot and humid climate of the Gulf States.

The major problem with these heat exchangers is that any material that will allow the transfer of water will also allow the transfer of pollutants. There would probably have to be filters installed and regularly changed.

DESICCANT DEHUMIDIFICATION

Desiccant dehumidification is an attractive alternative to vapor compression dehumidification because it requires a low-temperature thermal input that can be easily supplied by low-cost solar collectors. Electricity is only needed to blow air through the desiccant bed. Electricity- and fossil fuel-regenerated desiccant dehumidifiers are already used in industry for very low humidity applications. Manufacturers are starting to show some interest in using waste heat and heat from renewable resources to regenerate the desiccant beds. In general, however, the parasitic power requirements are large, and regeneration is done at high temperatures (250–400°F) with little regard to energy efficiency.

This section on desiccant dehumidification is made up of an introduction, a short discussion of dehumidification cycles, and a few examples of solar dehumidifiers with a review of each. In the appendices you will find a short introduction to the psychrometric chart, a discussion of desiccant materials, a brief section on liquid desiccant dehumidifiers, dehumidifier design criteria, a sizing method for desiccant systems, and a description of the efforts underway at SERI to model the dynamic performance of desiccant beds.

Introduction to desiccant dehumidification

In a solar-regenerated desiccant dehumidifier, humid air is passed through a desiccant bed where water is adsorbed. Once the bed is loaded, solar-heated air is passed through it to drive out the water and regenerate the bed. In Fig. 5 we see that the wet air is used to dehumidify the indoor space. The room air is heated during the dehumidification process because energy is released during adsorption. This energy, the heat of adsorption, varies from material to material. A short discussion of the importance of the heat of adsorption is given in Appendix 2.

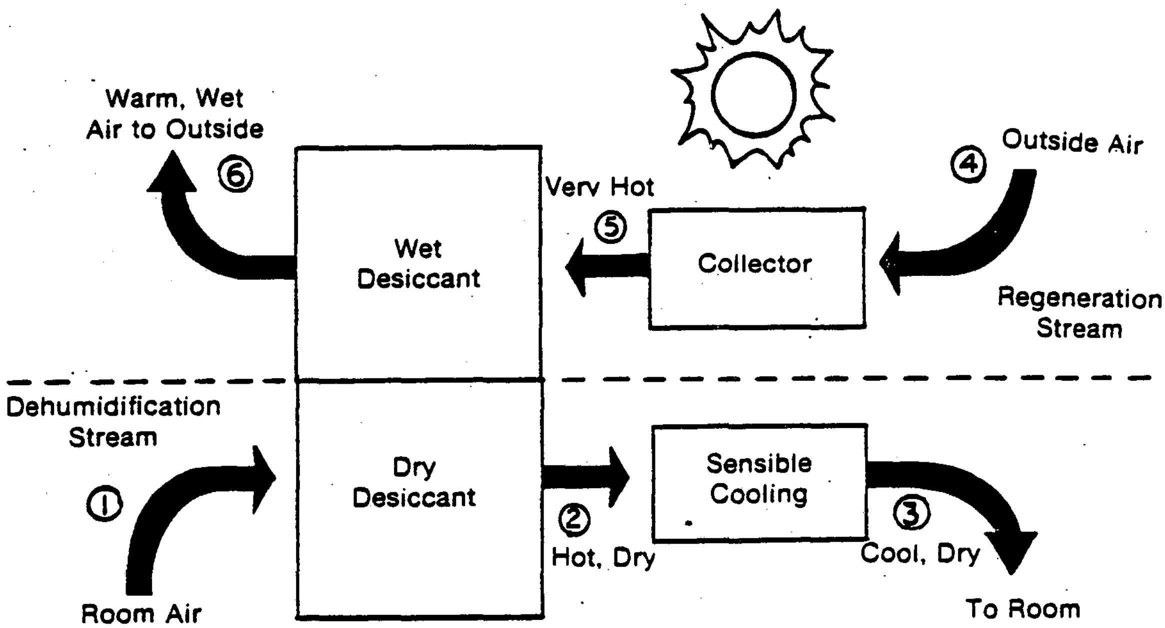

Fig. 5. Operation of a simplified desiccant dehumidifier.

The psychrometric chart is a very useful tool for illustrating the process of desiccant dehumidification. The chart is a graphical representation of the thermodynamic properties of air-water mixtures, and is widely used to plot air-conditioning processes. A short explanation of the psychrometric chart can be found in Appendix 1.

The psychometric chart in Fig. 6 shows a plot of the dehumidification process. These lines represent the conditions of air streams as they pass through a desiccant dehumidifier. Point 1 (77°F dry bulb and 60% relative humidity) corresponds to typical comfortable indoor conditions. As this air passes through the desiccant, it becomes progressively drier and warmer. Point 2 represents the air conditions at the outlet of the dehumidifier. With this line we can determine the outlet conditions of the air and, therefore, how much air must be processed to maintain comfort conditions in the living space. (Appendix 2 shows how this line is found for any given material.) From Fig. 6 we see that the moisture removed from the air stream during the dehumidification process is given by the moisture content of the inlet air at point 1 minus the moisture content of the air at the outlet, point 2. This difference is .012 - .006 = .006 lb water/lb dry air processed. If we wished to remove a total of 2 lb of water per hour from the room, then 2/.006 = 330 lb air/hour would have to be passed through the desiccant (74 cfm).*

Once the air is dehumidified, it must then be sensibly cooled before it can be returned to the room (point 3, Fig. 6). Methods of sensible cooling include heat exchange with precooled ambient air or with cool surfaces from passive cooling techniques (e.g., roof pond). Sensible cooling is discussed briefly in Appendix 4 along with dehumidifier design improvements.

*This is approximate because the humidity is given on a dry air basis. The error introduced by assuming that the basis is moist air is small, however.

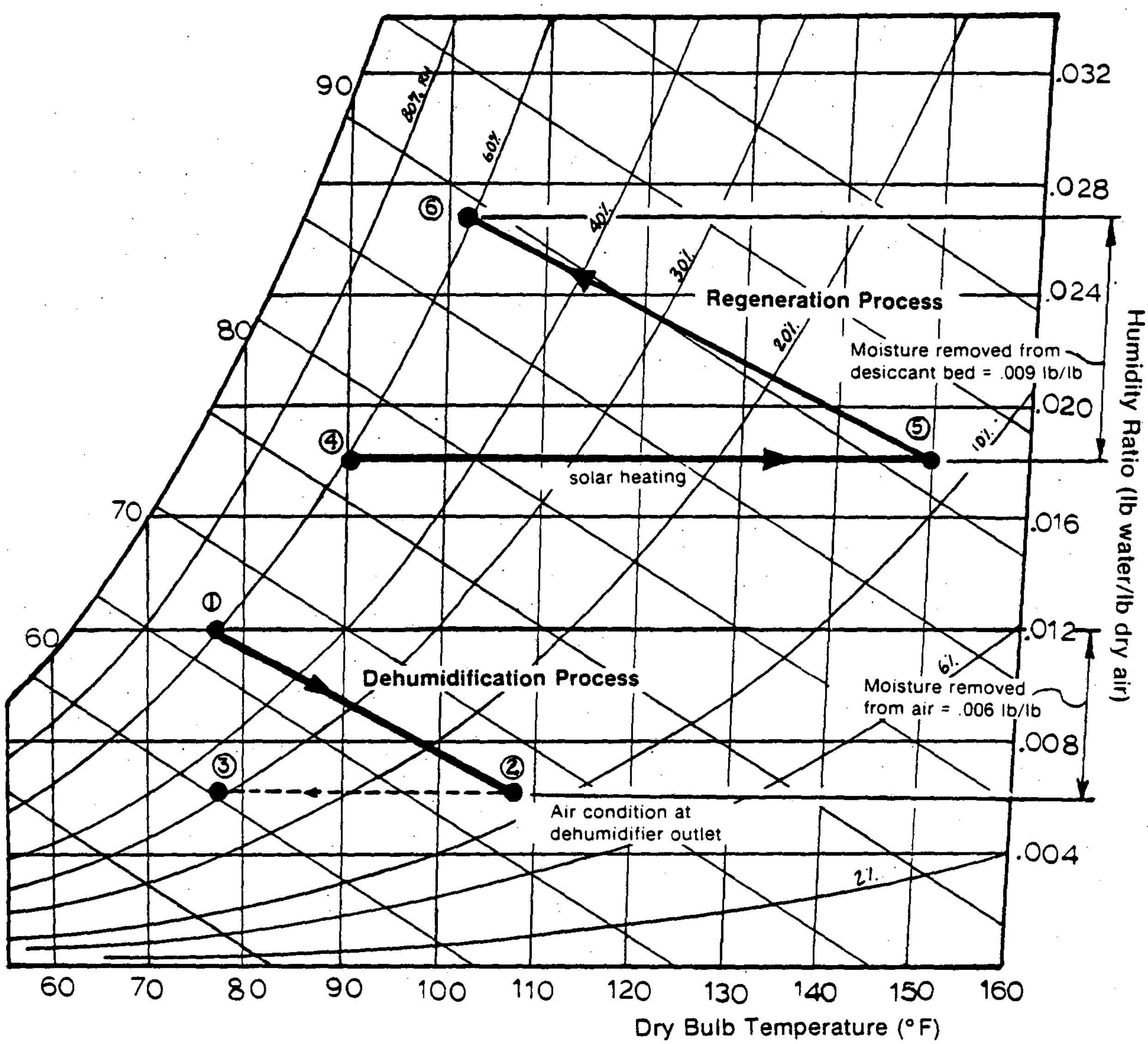

Fig. 6. Dehumidification and regeneration processes plotted on the psychrometric chart. Points on this chart represent the conditions of air streams in the desiccant dehumidifier. State points correspond to points on the block diagram of the dehumidifier in Fig. 5.

The regeneration portion of the cycle can also be plotted on the psychrometric chart, where we can see the water removed from the wet desiccant by the hot air stream. Ambient air (point 4) is heated to 150°F (point 5) and is then passed through the wet desiccant. The air picks up moisture from the desiccant and is cooled, as energy equaling the heat of adsorption is removed from the desiccant and air stream to vaporize the water.

Points 1, 4 and 5 are determined by the room conditions, the ambient conditions and the solar collector, respectively. Points 2 and 6 must be known in order to predict the performance of the desiccant dehumidifier. These points will be determined by the properties of the desiccant material and the conditions of regeneration. A method of estimating conditions at points 2 and 6 is given in Appendix 4.

Dehumidification cycles

Two basic dehumidification modes are possible: the recirculation mode and the ventilation mode. In the recirculation mode room air is processed through the dehumidifier, while in the ventilation mode ambient air is introduced into the building through the dehumidifier (Fig. 7). In general, in hot, humid climates where the indoor humidity levels are kept below the outdoor humidity levels, the best approach to dehumidification is to limit ventilation to the minimum necessary for removal of odor and pollutants and to use the dehumidifier in a recirculation mode. Bringing in more air from the outside than necessary increases both the sensible and latent loads that the cooling system must be designed to handle. For example, it can be shown that, for the conditions that make the latent load for the energy-conserving house 48 lb/day, the same dehumidifier working in the ventilation mode would have to remove three times as much water to maintain the same room conditions.

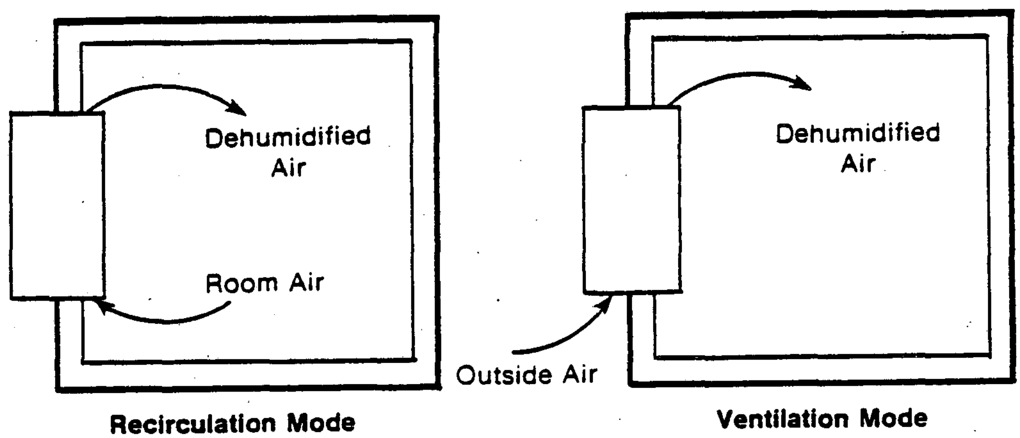

Fig. 7. a) Recirculation mode: room air is processed in the dehumidifier. b) Ventilation mode: air from the outside is processed in the dehumidifier.

Examples of desiccant dehumidifiers

The earliest solar solid desiccant dehumidification system is credited to Altenkirch[15]. A similar system was described by Dannies[16] in 1959. The original Dannies system is reviewed in Ref. 17 and 18, from which the improved, fan-assisted version in Fig. 8 has been taken.

This concept is attractive because it can be integrated in the building structure. The east-west orientation allows some passive regeneration control, but it appears that fans would be required to provide the necessary flow rates[17,18,19]. Desiccant material is packed in the east and west walls of the building. The sun heats the east wall in the morning, regenerating the desiccant that had adsorbed water the afternoon before. Meanwhile, the west wall is dehumidifying the room air. These processes are exchanged as the sun moves over to the west in the afternoon.

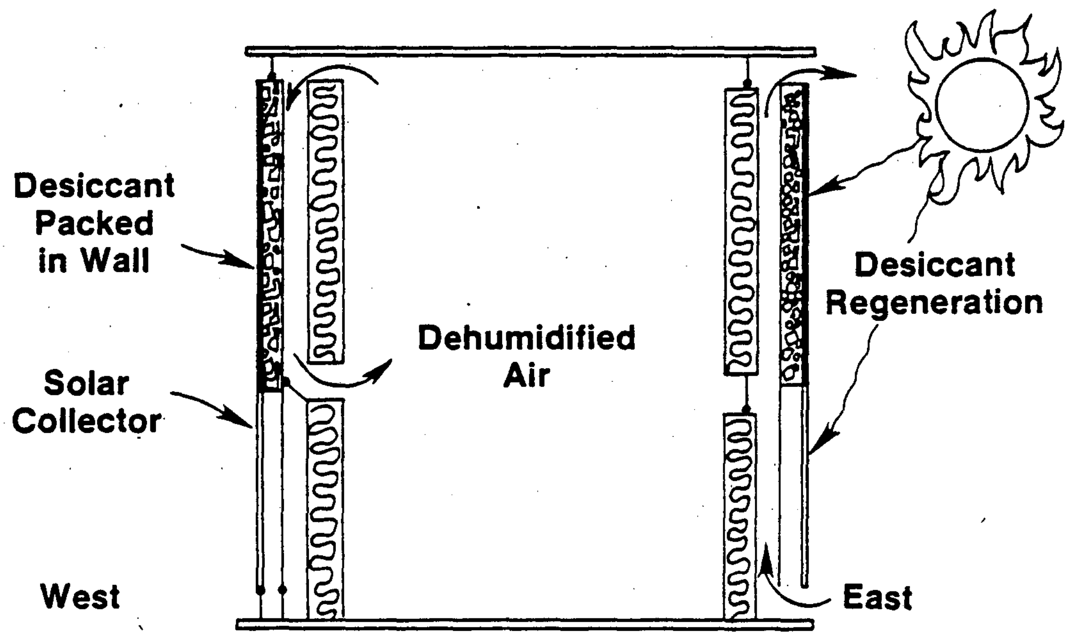

Fig. 8. Improved, fan-assisted Dannies wall dehumidification system. In the morning the sun heats the east wall, regenerating the desiccant that had adsorbed water the afternoon before. Meanwhile, air is being dehumidified in the west wall. These processes are exchanged as the sun moves over to the west in the afternoon. Source: Ref. 18, 19.

The original Dannies wall was a completely passive dehumidification scheme in which room air was heated for regeneration and then exhausted to the outside. Fresh air from the outside was to be drawn in through the other desiccant wall for dehumidification. This mode, the ventilation mode, is often inappropriate for very humid climates for the reasons mentioned in the section on dehumidification cycles. Furthermore, the dehumidification streams and regeneration streams flowed in the same direction through the desiccant, which would result in very little cycling of moisture. Natural convection flow rates are complicated because of the heating and cooling effects that accompany adsorption, and finally, the low temperatures in an unglazed wall will result in little moisture removal from the wet desiccant during regeneration. (See Appendix 4 for a more complete discussion of the effects of these parameters.) The addition of glazed collectors and fans to assist the flows through the system would greatly increase the performance of the east-west wall dehumidifier.

To estimate the size and performance parameters of the system in Fig. 8 we will use the room and outdoor conditions given in Fig. 3, and the dehumidification and regeneration processes plotted in Fig. 6 for silica gel. It is assumed that the desiccant bed is long enough to achieve equilibrium conditions at the bed outlet.* From Fig. 6 we see that .006 lb of water per lb air processed are removed during the dehumidification cycle. To remove 50 lb of water per day from the house requires 50/.006 = 8333 lb air to be processed per day. If dehumidification takes place over 24 hours** (some storage of solar energy for regeneration or storage of "dryness" in a regenerated desiccant bed would be required), then 8333/24 = 347 lb/hr (78 cfm) air must be passed through the bed. If equilibrium were obtained everywhere in the bed, then the cycled capacity of the silica gel would be 22%. For adiabatic operation, however, the cycled capacity is only about 1/2 the maximum. (Cycled capacity is explained in Appendix 4.) If we use 11% as the cycled capacity of the silica gel, then 50/.11 = 455 lb of silica gel would be necessary to remove 50 lb of water. If the desiccant is used in packed form, at a bulk density of 45 lb/ft^3, the total volume of silica gel needed is 10 ft^3.

If solar energy for regeneration is available from storage, then the desiccant can be used again for drying at night. A system that is cycled twice would require only 228 lb of silica gel. An alternative to the storage of heat for regeneration is the storage of drying potential in regenerated desiccant. Additional desiccant on south-facing tilted or horizontal surfaces can be dried all day to be used for dehumification at night. Since the desiccant is cycled only once, 455 lb are needed.

The collector area needed to supply the regeneration energy can be calculated using the information in Fig. 6. Here we see that during regeneration at 150°F, .009 lb of water can be removed from the desiccant per lb air processed. Therefore, to remove the 50 lb of water requires 60/.009 = 5556 lb of air. Once again, if regeneration takes place over 24 hours, the necessary flow rate is 52 cfm. The energy required for regeneration is simply the flow rate times the temperature difference across the collector and the heat capacity of air:

$$\text{Energy required (Btu/day)} = 5556 \text{ lb/day} \times .240 \text{ Btu/lb°F} \times (150 - 90)\text{°F} = 80{,}000$$

The collector area needed to deliver this much energy per day to the desiccant bed, assuming a 35% overall system efficiency and incident radiation of 900 Btu/day (Fig. 9), is

$$\frac{80{,}000}{.35\ (900)} = 254 \text{ ft}^2$$

*See Appendix 5.

**Of course, other dehumidification schemes can be envisioned. Perhaps the solar dehumidifier can be used during the day, with night-time conditions relying on venting with cooler ambient air or on backup dehumidification from a high-efficiency vapor compression machine. The assumption of constant dehumidification over 24 hours is the easiest to deal with and is good for illustrating desiccant dehumidifier parameters. If one is interested in dehumidifying over 12 instead of 24 hours, then the sensible heat gain, collector area and silica gel needed can be divided by 2.

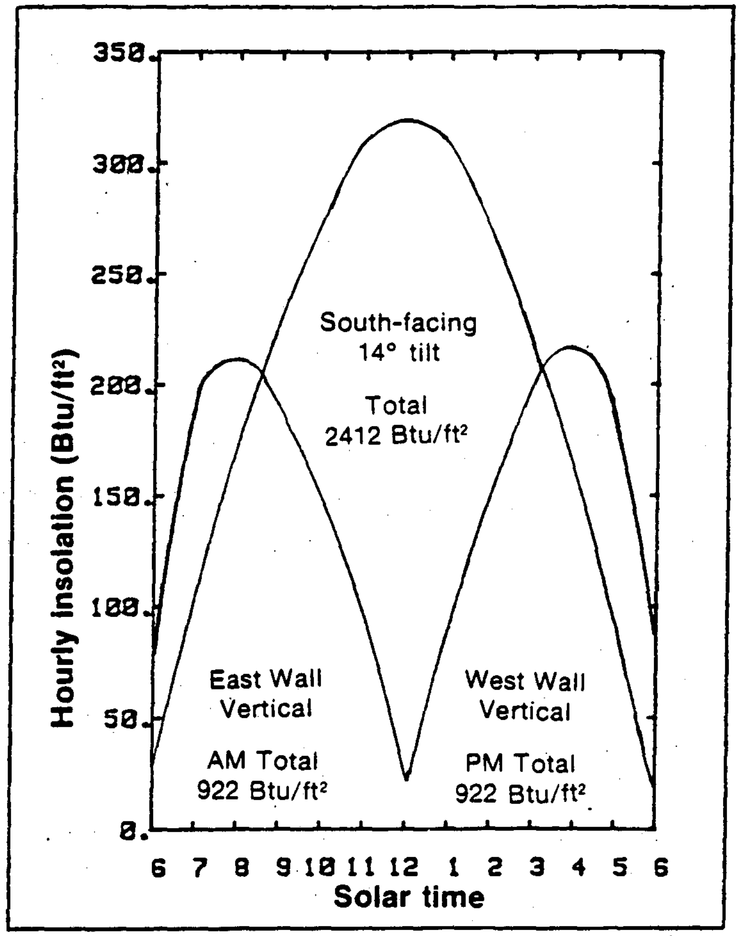

Fig. 9. Clear sky radiation on east-west vertical surfaces and south-facing surface with 14° tilt. 24°N latitude. Source: Ref. 20.

To be able to do these simple calculations, we have assumed that regeneration air is available at a constant temperature of 150°F. For most solar systems this temperature will vary, and the calculations should be made for every temperature. The numbers here will actually represent maximum performance if the maximum regeneration temperature is 150°F.

The next thing we must do is calculate the additional load on the sensible cooling system due to the hot, dehumidified air. For this system it is 8333 x .240 x (108 - 77) = 62,000 Btu/day. The parameters of the Dannies wall system are summarized in Table 2 (Case I).

We can now estimate the performance of this or similar dehumidification systems with some improvements, such as the addition of a heat exchanger and the use of precooled ambient air. (See Fig. 10.) Two important improvements are realized with the heat exchanger: (1) the amount of regeneration energy from the solar collectors is reduced and (2) the additional sensible cooling needed to bring the dehumidified air down to room temperature is reduced. Precooling the ambient air before it enters the heat exchanger (Fig. 10(b)) will increase the energy needed from the collectors, but it will reduce the additional sensible cooling load from the dehumidifier. Both of these improvements are discussed in Appendix 4.

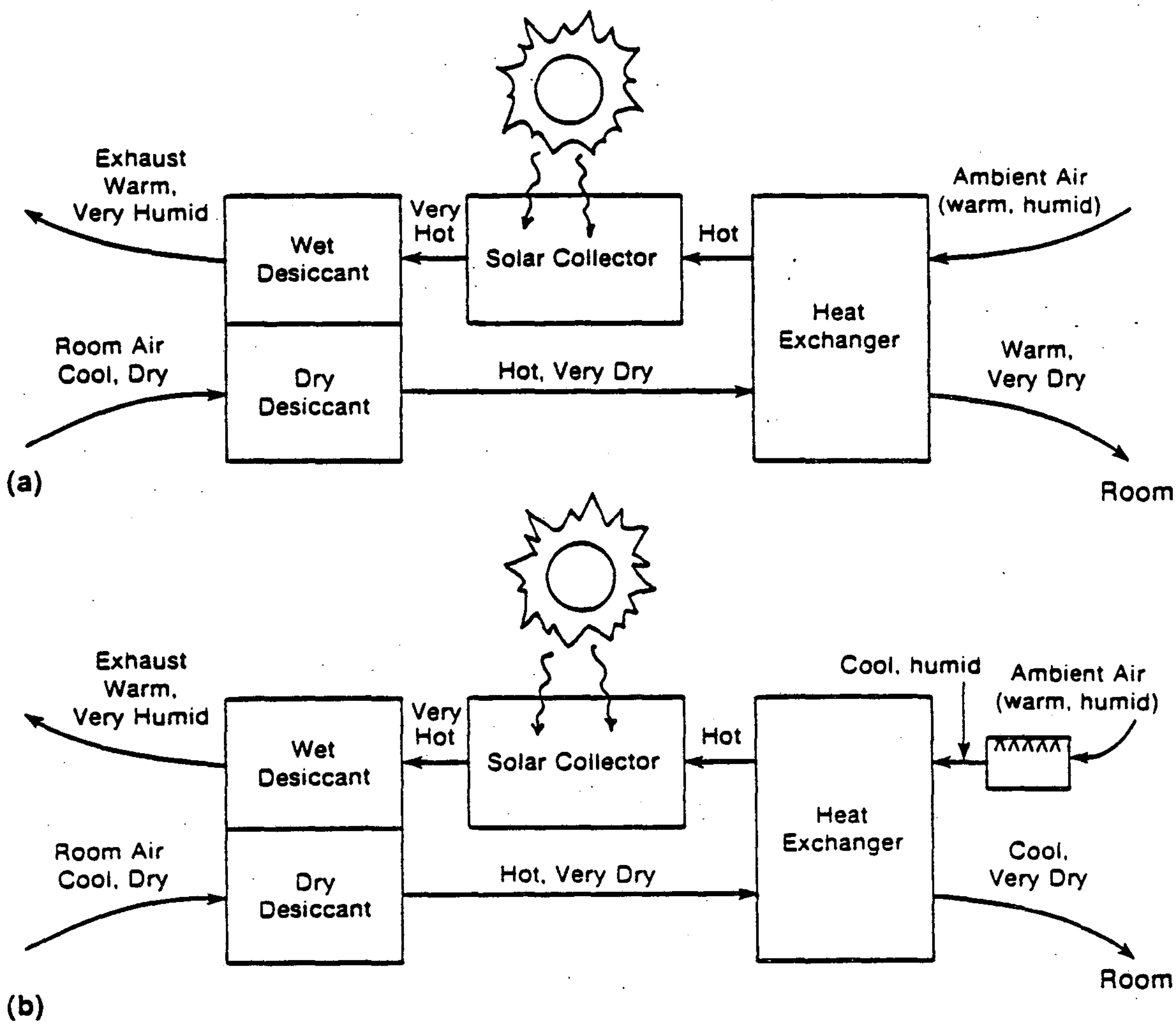

Fig. 10. Improvements to the desiccant dehumidifier. a) The addition of a heat exchanger to preheat the regeneration air using the hot dehumidified air stream. b) Precooling the ambient air by adiabatic humidification before it enters the heat exchanger will reduce the temperature of the dehumidified air entering the room.

If a heat exchanger is added to the Dannies or similar system, the collectors must heat the same amount of air as before, but from 106°F to 150°F, instead of from 90°F to 150°F. (See Fig. A-11.) There will be some decrease in the collector efficiency because of the higher average temperatures, but, with a good collector design, this decrease in performance should be small compared to the energy saved.

With the heat exchanger, the total amount of energy required for regeneration is

$$\text{Energy required (Btu/day)} = 5556 \text{ lb/day} \times .240 \text{ Btu/lb°F} \times (150 - 106)\text{°F} = 59{,}000$$

If we assume once again that 900 Btu/day is the incident insolation on an east or west wall and use a lower system efficiency for delivery of solar energy of 30%, then the collector area required is 59,000/(.3 x 900) = 219 ft^2. A 14% decrease in collector area is realized. The additional sensible cooling load is 8333 x .240 x (97 - 77) = 40,000 Btu—a 35% reduction. These parameters are summarized in Table 2 as Case II.

Table 2. DEHUMIDIFICATION SYSTEM PARAMETERS—DANNIES WALL

	Case I*	Case II**	Case III***
Flow Rate (cfm)			
Dehumidification	78	78	85
Regeneration	52	52	55
Total Desiccant Needed			
(LB)	228 (455)†	228 (455)	228 (455)
(ft^3)	5 (10)	5 (10)	5 (10)
Collector Area			
(ft^2)	254	219	240
Additional Sensible Cooling Load			
(Btu/day)	62,000	40,000	32,700

* Base case (Fig. 8)
** With heat exchanger
*** With heat exchanger and evaporatively cooled ambient air.
† Dehumidification for 24 hours, desiccant cycles once per day.
Latent load = 50 lb water/day

If pre-cooled ambient air is used to cool the dehumidified air in the heat exchanger (Fig. 10(b), plotted on the psychrometric chart in Fig. A-12), then a further decrease in sensible cooling load can be realized. A slight tradeoff in flow rates and collector area versus sensible cooling exists.* The results of this analysis are presented in Table 2, Case III.

If the collectors are inexpensive, the east-west wall dehumidification scheme may be attractive. However, a large part of the solar resource is wasted by collecting energy on the east and west walls rather than on horizontal surfaces or on slightly tilted south-facing surfaces (Fig. 9). Whereas 1 ft^2 of collector on an east or west wall will see only 900 Btu/day, the same collector would see 2400 Btu/day on a south-facing surface with a 14° tilt.

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*The sensible cooling load can be decreased even more by increasing the flow-rate of the pre-cooled air through the heat exchanger. For example, if the flows are equal in the heat exchanger (78 cfm), the outlet temperature of the dehumidified stream drops to 84°F, for an additional sensible cooling load of only 14,000 Btu/day.

If we go to an integrated desiccant/collector dehumidification scheme on the roof (Fig. 11), there is a significant decrease in necessary collector area. The results of a similar analysis for this system are shown in Table 3 for three corresponding cases. Although equilibrium probably could not be expected in such short beds, the analysis will give an upper limit on performance, and, therefore, a lower limit for the collector area.*

It is interesting to note that the desiccant/collector can also be used in the winter to heat (and humidify) the space, both day and night. During the day (Fig. 11(a)), the desiccant is regenerated, and the warm, humid air is introduced into the building instead of being exhausted to the outdoors. At night (Fig. 11(b)), the fully regenerated desiccant actually stores energy in the form of drying potential. The hot, dry outlet air can be used for heating. Recent work has shown this form of storage to have significant advantages over sensible heat storage.[21]

Finally, if the desiccant is separated completely from the collector, then the same collector can be used, without shading, to provide regeneration energy throughout the day. The collector area necessary for regeneration is essentially cut in half (Table 3).

Table 3. COLLECTOR AREA FOR IMPROVED DEHUMIDIFICATION SCHEMES

(South-facing surface, 14° tilt, 24°N Latitude)

	Case I*	Case II**	Case III***
1. Integrated Collector and Desiccant (ft^2)	191	164	180
2. Separated Collector and Desiccant (ft^2)	96	82	90

* Base case (Fig. 8)
** With heat exchanger
*** With heat exchanger and evaporatively cooled ambient air
Latent load = 50 lb water/day

*See Appendix 5.

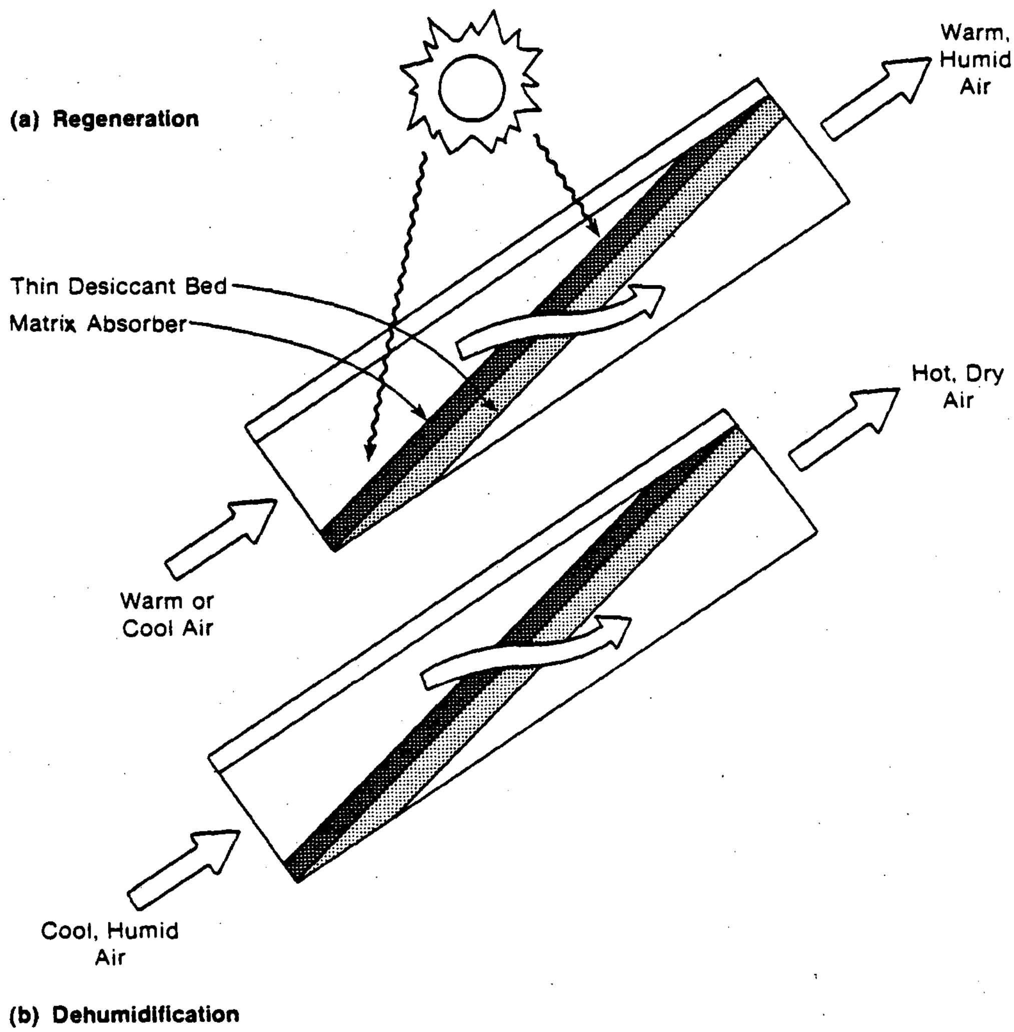

Fig. 11. Integrated desiccant/solar collector for south-facing tilted surfaces. a) Regeneration of desiccant. In the summer, the warm humid air is exhausted to outdoors, whereas in winter it can be used for heating. b) Dehumidification. In the summer the hot dry air must be sensibly cooled before it can be used in the building. In the winter, the hot dry air can be used for heating. (Low humidities may be a problem.) Energy can be stored in the form of dry regenerated desiccant, and heating or dehumidification can be continued into the night.

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APPENDIX 1: THE PSYCHROMETRIC CHART

The psychrometric chart is an extremely useful tool for illustrating the desiccant dehumidification process. A point on this chart (Fig. A-1) represents the conditions of an air-water vapor mixture at a given state. The axes of the psychrometric chart are the dry bulb temperature of the air and the humidity ratio, or moisture content of the air in lb of water per lb dry air. Relative humidity is a function of the temperature and the moisture content of the air. Constant relative humidity can be plotted on these axes as shown in Fig. A-1. For example, for a 77°F dry bulb temperature and a moisture content of .012 lb water/lb dry air, we can see that the relative humidity is 60%. Or for 77°F and 60% relative humidity, we can read off the humidity ratio of .012 lb water/lb dry air. The line of 100% relative humidity is known as the saturation line because any point along this line represents saturated air. The temperature scale along the saturation line is the dew point temperature. The significance of this temperature is that spontaneous condensation will occur at temperatures at or below this value. The dew point temperature is the dry bulb air temperature (horizontal axis) corresponding to 100% RH.

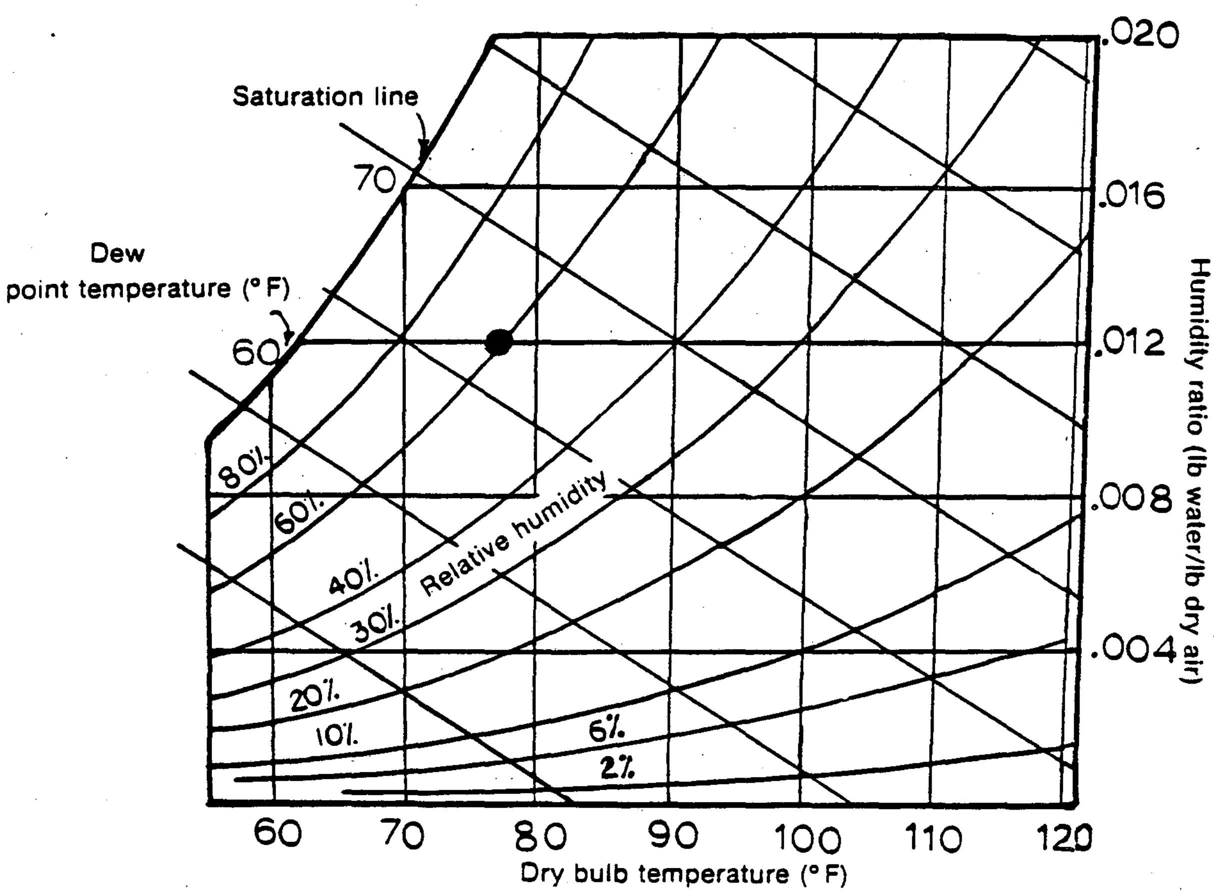

Fig. A-1. Basic psychrometric chart.

APPENDIX 2: DESICCANT MATERIAL PROPERTIES

The degree to which a desiccant will adsorb water is a function of the physical properties and chemical composition of the material. The adsorption properties of desiccants are most often presented as the amount of water contained in the desiccant as a function of the temperature and humidity of the air in equilibrium with the desiccant. The equilibrium properties of three solid desiccants are shown in Fig. A-2.

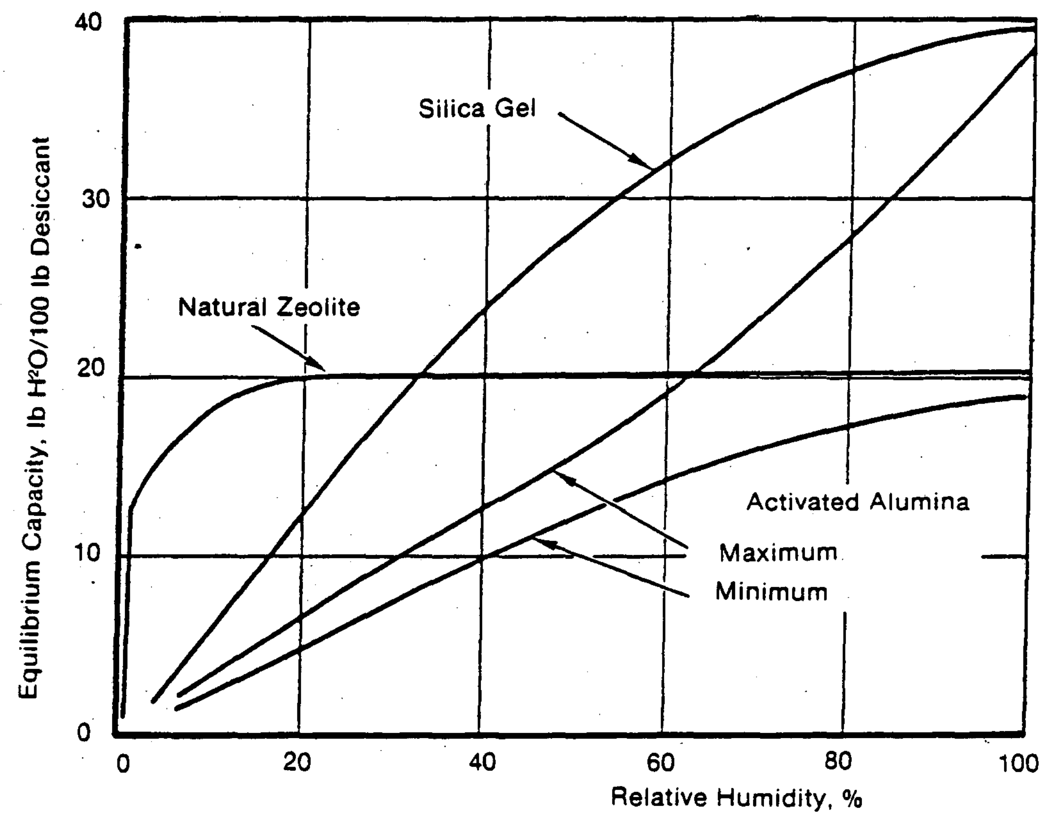

Fig. A-2. Equilibrium adsorption properties of three solid desiccants.

In general, the graph of capacity versus relative humidity is valid for only one temperature, usually 77°F. For silica gel, however, the plot is good for a range of temperature from 75°F to about 150°F. Other useful forms of presenting equilibrium data are isotherms (lines of loading versus water vapor pressure at a constant temperature), isobars (lines of loading versus temperature at a constant vapor pressure), and isosteres (lines of constant loading with temperature and vapor pressure as the axes). Equilibrium isobars for silica gel and natural zeolite are shown in Fig. A-3 and A-4.

We can use Fig. A-2 to do a first order comparison of the equilibrium properties of solid desiccants for dehumidification. A good desiccant will adsorb large amounts of water for the temperature and humidities of indoor conditions, and desorb large amounts at the

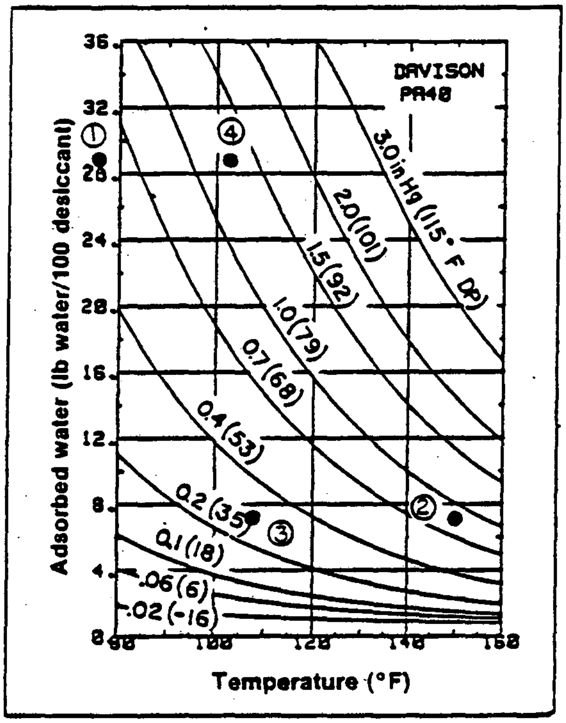

Fig. A-3. Equilibrium isobars for silica gel Davison PA40.

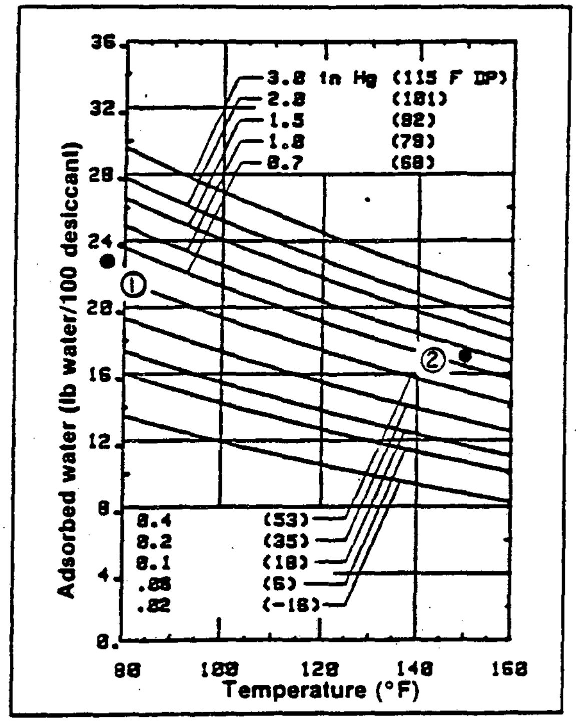

Fig. A-4. Equilibrium isobars for natural zeolite from Bowie, Arizona.

temperatures and humidities of regeneration conditions. The difference in capacities between the two states partly determines the cycled capacity of the desiccant and, therefore, the size and capacity of the dehumidifier.

If we take the conditions for the dehumidification stream and the regeneration stream from Fig. 6 (77° F and 60% relative humidity, and 150° F and 11% relative humidity, respectively), we can compare the performance of materials. At 60% relative humidity, the weight capacity of natural zeolite is 20%, and at 11% RH it is 17%. The difference is only 3%, which means that a maximum of 3 lb of water per 100 lb of desiccant can be cycled in this system. Activated alumina will cycle about 16 lb of water per 100 lb of material and silica gel will cycle the most water, 27 lb, of all three at the stated conditions.

During adiabatic dehumidification, however, this dependence on relative humidity becomes a disadvantage. As air is dried in the desiccant bed it is also heated, and its relative humidity is greatly reduced. The result is that the capacity of a silica gel bed is also greatly reduced. The natural zeolite, on the other hand, shows very little decrease in capacity over the relative humidity ranges that are of interest in dehumidification. Some researchers [A1,A2] have attempted the design of isothermal silica gel beds. Although significant improvements in performance can be realized through isothermal operation, the accompanying increase in system complexity has been unacceptable.

One must be very careful in using published equilibrium data in the design of dehumidifiers. Properties change from batch to batch for these desiccants, and within one group there can be many different sizes and types with correspondingly different properties. Equilibrium capacity will also often decrease with the first few cycles, although it generally evens out at about 90% of its original capacity. Contamination of the desiccant can also pose problems, especially for activated charcoals. These desiccants adsorb other molecules which may not be removed during regeneration, and which will eventually reduce water adsorption capacities.[A3]

The major problem in using equilibrium properties is that they are limited to equilibrium conditons, although the phenomenon of adsorption in a desiccant bed can be a non-equilibrium one. The rate of adsorption must also be taken into account in choosing a material. For the most widely-used desiccants (silica gel, molecular sieves and alumina), and for conditions in present desiccant dehumidifiers, the rates of adsorption are high and equilibrium closely approximates the real conditions. Equilibrium properties can be safely used to estimate the maximum performance of a dehumidifier design.

The importance of the heat of adsorption

When water is adsorbed on the surface of a material, heat is released. This heat, known as the heat of adsorption, is generally slightly greater than the heat of condensation. For silica gel, the heat of adsorption varies from about 1200-1400 Btu/lb water, while for the natural zeolite it is greater: 1200-1600 Btu/lb.

A good desiccant has a low heat of adsorption for two reasons: (1) the heat of adsorption increases the temperature of the desiccant and reduces its capacity and (2) the heat of adsorption heats the air stream and places the additional sensible cooling load on the system. The effect of the heat of adsorption can be shown by looking at the dehumidification process line (Fig. 6). The slope of this line is given by*

$$-\frac{\text{heat of condensation of water}}{\text{heat of adsorption}} \times \text{slope of constant enthalpy line}$$

$$= -.22/H_A \quad \frac{\text{lb/lb}}{°\text{F}}$$

where H_A = heat of adsorption (Btu/lb).

Obviously, a large slope is desirable because the outlet temperature will be lower and the heat effects on capacity will be minimized. An ideal desiccant would have a heat of adsorption of zero. Unfortunately, high loading capacity and heat of adsorption are not completely separable; all we can do is look for the best combination.

*This assumes adiabatic operation and that the heat capacity of the bed is small compared to that of the air processed, a good assumption for flow rates in solar dehumidification.

APPENDIX 3: LIQUID DESICCANT DEHUMIDIFICATION*

Dehumidifiers using liquid solutions as desiccants have also been used in industry and have shown promise for solar cooling and dehumidification. Figure A-5 shows the equilibrium capacities of several liquid desiccants and compares them to two solids, silica gel and activated alumina. These liquids have very large water absorption capacities—from 1 to 20 times greater than that of the solids over a range of humidities. The moisture cycled per solution weight, however, will be much lower than that for the dry weight. For example, if lithium chloride is regenerated to its loading at 10% relative humidity, it still contains 1 lb of water for every lb of desiccant. This is water that the desiccant is carrying around with it and never cycles. Nevertheless, even on a solution-weight basis, liquids can be very good desiccants.

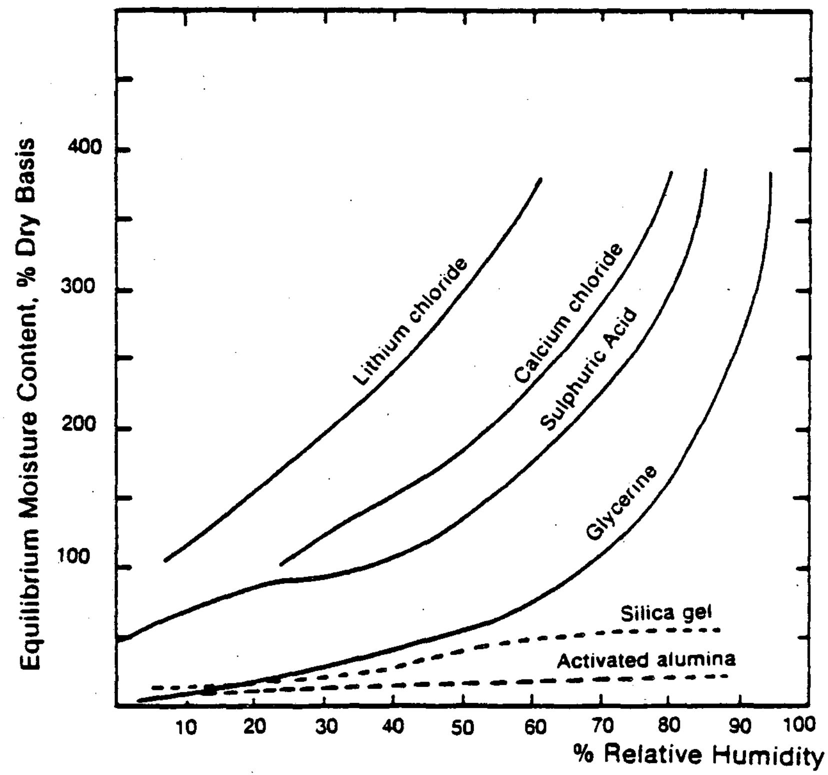

Fig. A-5. Equilibrium absorption properties of liquid desiccants. Two solid desiccants, silica gel and activated alumina, are included for comparison. Source: Ref. A4.

Figure A-6 is a schematic diagram of a typical commercial liquid desiccant dehumidifier. Moist air enters the dehumidifying section and loses water to the sorbent solution, which is sprayed onto cooling coils. The cooling medium in the coils carries away the

*Prepared by Kirk Collier, SERI.

heat of absorption and keeps the sorbent cool. This is necessary to maintain the high absorption capacity of the desiccant. Without this cooling, the mass transfer areas necessary would mean enormous spray chambers to achieve drying. Whereas the poor heat transfer in beds of solid desiccant makes non-adiabatic operation difficult, the cooling of the liquid is much easier because it is in intimate contact with the cooling coils.

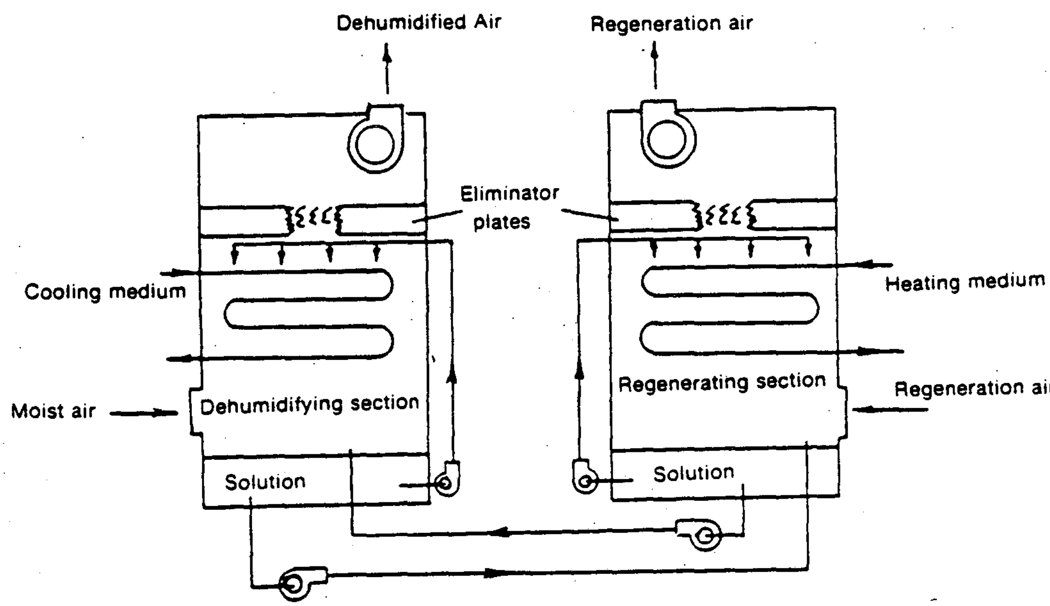

Fig. A-6. Commerical liquid desiccant dehumidifier. Moist air enters the dehumidifying section and loses water to the sorbent solution sprayed on the cooling coils. Regeneration is achieved by heating the liquid and causing it to desorb water. Eliminator plates are used to reduce the sorbent solution content of the air streams. Source: Ref. A4.

The machinery may be simple, but an external cooling medium such as cold water from a cooling tower or the ground is necessary. In most hot, humid climates the wet bulb and ground water temperatures are high enough to seriously affect the performance of these dehumidifiers. For many residential applications, a cooling tower just for dehumidification would probably not be justified.

Regeneration is accomplished by heating the sorbent solution, much like the regeneration of solid desiccants. In the commercial dehumidifiers, the heat source is commonly process steam. For solar regeneration, the solution can be heated directly in a plastic collector and sprayed through an air stream in a packed column. Alternatively, the unheated solution can be sprayed over the packed column through a solar-heated air stream.[A5] A third solar regeneration option is to flow the solution as a fluid film over an open, solar-absorbing surface. Water is released directly to the atmosphere as the solution is heated by the solar flux. This regneration scheme combines the solar collector and the desiccant regenerator into a single, low-cost unit. Black asphalt roll roofing for the absorber and plastic pipe for the delivery and return manifolds are all that are needed.

Studies by Collier[A6] indicate that 0.8 lb of water can be removed per square foot of unglazed collector over a typical July day in Miami, Florida. Only 62.5 ft^2 of collector is needed to remove 50 lb of water. For humid climates, however, these collectors must be 35-50 feet long and could pose problems for residential applications. Another problem in humid climates is the loss of salt left on absorber surfaces and washed away by frequent rains. Researchers[A7,A8] have proposed glazed versions of the combined collector and regenerator to avoid possible environmental problems and solution contamination. The absorber surface is protected from the environment by a glazing, and an external air stream is forced between the absorber and the glazing to remove the water vapor.[A8] Experiments are too preliminary to judge the effectiveness of this modification.

The physical nature of liquid desiccants will also determine their viability for open-cycle dehumidification systems. The two most common liquid pairs are lithium chloride/water and triethylene glycol/water. Lithium chloride is very corrosive, and the carryover of salt would be a serious problem without the eliminator plates shown in Fig. A-6. For passive applications requiring very large absorption surface areas, the salt carryover problem can be formidable. Triethylene glycol, although not as corrosive as lithium chloride, has much larger carryover rates due to the higher vapor pressure of the glycol. The prospect of a glycol film that covers all internal building surfaces, as in Lof's system, is not pleasant.

Lithium bromide and water is used widely in closed-cycle adsorption machines, and is attractive because the solution will remain a liquid at very low water vapor pressures. However, when combined with oxygen, this solution is extremely corrosive and is not practical for use in open-cycle systems.

APPENDIX 4: DEHUMIDIFIER DESIGN CRITERIA

This section presents some tools for the design of desiccant dehumidification systems. Before many of these considerations will make sense, it is useful to have an understanding of what is happening in the desiccant bed during adsorption and desorption. Humid air is entering the initially dry bed at point 1 in Fig. A-7. Water vapor from this air is adsorbed on the desiccant until the equilibrium concentration of water is reached. The loading of the bed at point 1 is given by the loading of the desiccant that is in equilibrium with the temperature and humidity of the air stream. If we go to Fig. A-3 we see that it is approximately 29% loading (point 1), for silica gel and about 23% for natural zeolite (point 1, Fig. A-4).

In Fig. A-7, we see that there is a moisture wave which travels through the desiccant as the bed becomes progressively more laden with water. Until this wave reaches the end of the bed, the air exiting the bed will be in equilibrium with the dry portion of the bed. If we can determine what this equilibrium condition will be, then we know the outlet conditions of the air from the dehumidifier and we can determine the end point of the dehumidification process line in Fig. 6. With the information in Fig. 6 we can then make estimates on the size of the dehumidifier.

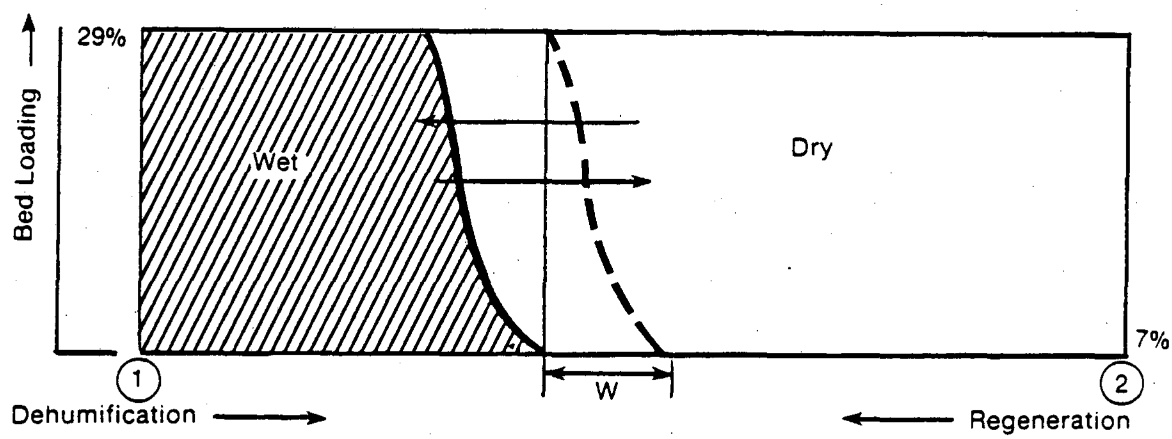

Fig. A-7. Moisture wave in a desiccant bed. Bed is either 29% loaded or 7% loaded, except for in the transition region of width W. Until the wave reaches the end of the bed, the exiting dehumidified air is in equilibrium with 7% loading.

The dryness of the bed at the exit point 2 in Fig. A-7 depends on what took place during regeneration. If, for example, we have solar-heated ambient air at 150°F available for regeneration, then the bed at point 2 should be at a loading that is in equilibrium with this regeneration stream.* From the isobars in Fig. A-3 and A-4 we see that point 2 corresponds to the 150°F, 74°F dew point of the regeneration air stream. At equilibrium, the loading in the bed is 7% for silica gel (17% for the natural zeolite). Therefore, the conditions of the dehumidified air at the outlet of the silica gel bed are those along the dehumidification process line that are in equilibrium with 7% loading. This point can be located on the psychrometric chart of Fig. 6 with a trial-and-error method, and can be shown to be point 3 on the isobar chart for silica gel. The air conditions at the outlet of this bed are 108°F dry bulb and 44°F dew point (.006 lb/lb).

The last thing we need to know is the end point of the regeneration stream, point 6 in Fig. 6. By a similar argument, this is the point along the regeneration process line that is in equilibrium with the loading at the entrance of the bed, 29%. The air conditions at the outlet of the regeneration stream are given on the isobars for silica gel as point 4.

It is important to clearly state the assumptions implicit in this model. By stating that the end point of the dehumidification process line is fixed and is given by the above method, we have assumed essentially that the wave width W shown in Fig. A-7 is small compared to the length of the desiccant bed or that the loading at the end of the bed, 7%, changes very little over the cycle. This means that, as the wave passes through the bed, the outlet conditions are steady at 108°F and 44°F dew point. If the width of this wave is on the order of the length of the bed, this no longer holds and the air at the outlet of the dehumidifier is no longer in equilibrium with the initial loading. Heat effects from the adiabatic operation of the bed may cause the wave to spread out, but it appears that for long beds the equilibrium assumption is pretty good. A valid picture of this wave shape cannot be had without detailed experiments or complicated computer models. This work is currently underway at SERI in order to determine how good the equilibrium assumption is for the flow rates and bed geometries of interest in desiccant dehumidification. Some results presented in Appendix 5 show equilibrium to be a good assumption for beds longer than about 2 1/2 inches.

A simplified method for silica gel

For silica gel, the equilibrium analysis is even simpler than what we have presented so far. Since the equilibrium properties of silica gel can be described in a single curve of loading versus relative humidity (Fig. A-8), then we need only the psychrometric chart to plot the entire dehumidification/regeneration cycle. From Fig. A-8 we see that for any one relative humidity there is a corresponding weight percent loading, and vice versa. Therefore, to find the point along the dehumidification process line that is in equilibrium with 7% loading, we need only know the relative humidity of the regeneration air stream. At 150°F and 74° dew point, the relative humidity is (from the psychrometric chart) 11%. From Fig. A-8 we see that at 11% relative humidity, the loading is approximately 7%. The dehumidification outlet air is in equilibrium with 7% loading, and therefore must be at 11% relative humidity. So the end point of the dehumidification process line is simply the intersection of the process line and the 11% relative humidity line.

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*This brings up an important point: the desiccant should be regenerated in the opposite direction (Fig. A-7). Then you will be guaranteed that the bed will be driest at the end and, therefore, that the dehumidified air will be as dry as possible. Regeneration in the same direction will only move the moisture wave further over in the bed, and will not remove moisture for some time, if the desiccant is not fully loaded.

Similarly, the end point of the regeneration stream is simply the intersection of the regeneration process line and the 60% relative humidity line.

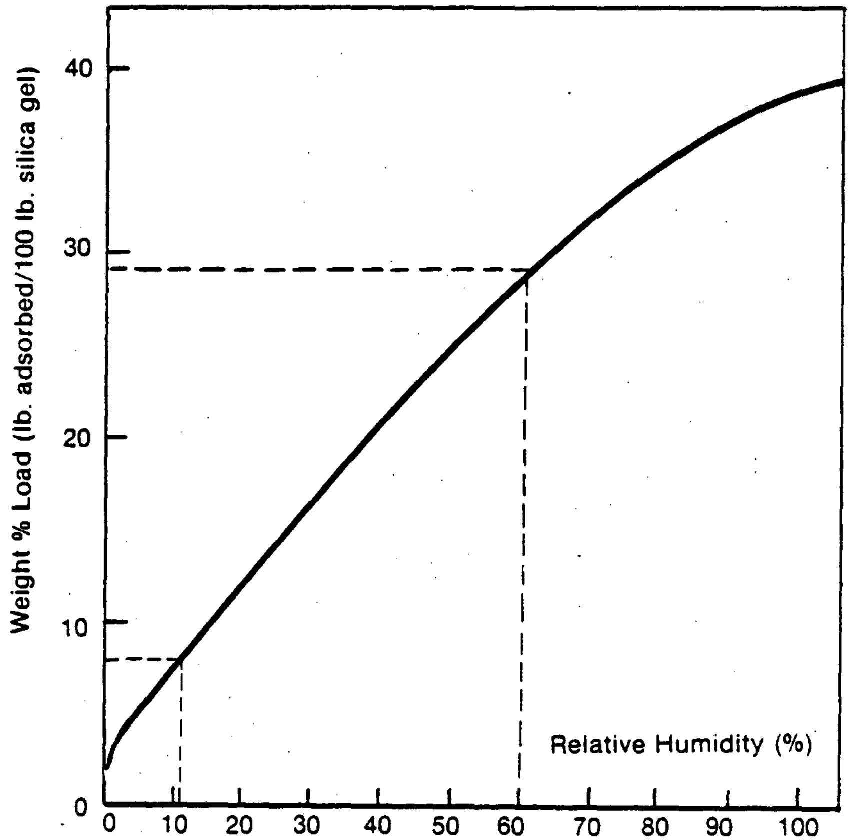

Fig. A-8. Equilibrium capacity of silica gel Davison PA40. Loading is plotted as a function of relative humidity of the surrounding air. (75°-150° F).

Solar dehumidifier design criteria

Using this simplified method for silica gel we can now illustrate the important aspects of solar dehumidifier design. First, let us list the qualities of a good solar dehumidifier:

1. High efficiency with respect to the electrical input. For solar dehumidifiers, this input is fan power to blow the air through the desiccant and the rest of the system.
2. High efficiency with respect to the solar input. A high solar COP means that less collectors are necessary and reduces the system cost.
3. High capacity will be reflected in the system size for a given application, and hence the system cost.

1. In order to achieve high efficiencies with respect to the parasitic power requirements (fan power), the pressure drop through the bed and the amount of air that must be drawn through the bed must be minimized. Pressure drops through packed beds can be considerable when the beds are long. Some industrial dehumidifier manufacturers have tried to overcome this problem by packing the desiccant material in

the walls of laminar flow channels in order to reduce the resistance to the flow. Some examples are the use of lithium-chloride-impregnated paper, silica gel glued to paper or metal foil, and teflon honeycombs impregnated with desiccant. The trade-offs between the good mass transfer in the packed bed and the lower pressure drop in channel flow have not yet been completely determined, and are being examined at SERI.

Another way of reducing the fan power requirement is to increase the dehumidification achieved per pound of air passed through the dehumidifier. In other words, we would like to maximize the humidity difference between the room and the dehumidified air, and between the air at the inlet and outlet of the regeneration streams (Fig. 6). If these differences are small, then the amount of air that must be processed and the corresponding fan power requirements become large.

Dehumidification achieved is reduced if the regeneration temperature is lowered. The effect of regeneration temperature is clearly shown in Fig. A-9. Whereas .006 lb of water are removed per lb air during the dehumidification process and .009 lb water during the regeneration process when the bed is regenerated at 150°F, this drops to .004 and .0055 at 125°F, and to .0015 and .0015 for regeneration at 100°F. In other words, the same amount of dehumidification would require a flow rate 4 to 6 times greater if the regeneration temperature is reduced from 150°F to 100°F. The corresponding parasitic power requirement can be up to 36 times as large.

Some people are interested in designing systems that rely on natural convection to provide the necessary flows. The driving force could be provided either by the solar input (during regeneration) or by the heat of adsorption released during the dehumidification process. Although it has not been conclusively shown that sufficient natural convection is impossible, there are a number of things that complicate the process:

a. The large pressure drop in packed beds.

b. The fact that the regeneration stream and the dehumidification stream should flow in the opposite direction for good performance.

c. During regeneration, the air stream is cooled because energy equal to the heat of the adsorption is used to vaporize the water. Unless there is a solar input to the bed itself greater than this energy loss, the final effect will be that the outlet temperature is lower than the inlet temperature, and a natural convection flow would be complicated.

2. The efficiency of the dehumidifier with respect to the solar input is defined as the dehumidification output per solar input. The solar heating process is shown in Fig. 6 as the line between points 4 and 5. A way to reduce the energy input required from solar without compromising performance is to add a heat exchanger in the system to recover the heat from the hot, dehumidified air stream and use it to preheat the air entering the solar collectors Fig. A-10(a). The process plotted on the psychrometric chart in Fig. A-11 clearly shows the advantages of adding a 90% effectiveness heat exchanger to our dehumidification cycle. The temperature at point 5 closely approximates the temperature at point 2, and the temperature difference across the collectors is reduced from 60°F to 44°F. Furthermore, the dehumidified outlet air (point 3) is no longer so hot—its temperature has been reduced to 97°F, which relieves the load on the sensible cooling system. The dehumidified air stream can be

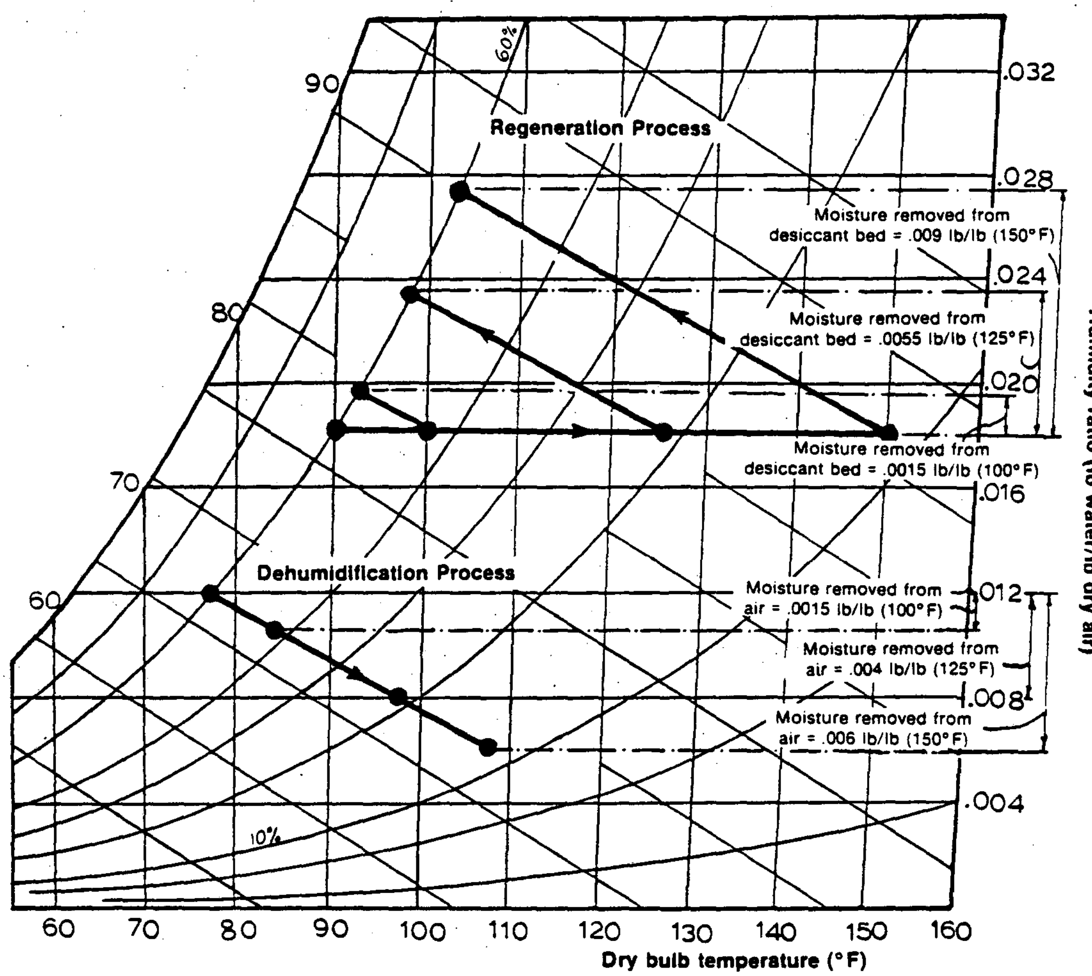

Fig. A-9. Dehumidification/regeneration process at 3 regeneration temperatures, 100°F, 125°F and 150°F. The higher the regeneration temperature, the greater the moisture cycled in the bed for a given flow rate.

cooled further if the ambient air in the regeneration stream is adiabatically humidified before it enters the heat exchanger Fig. A-10(b). This process is plotted in Fig. A-12, point 4-5. When the flowrate of the regeneration stream is less than that of the dehumidification stream (52 cfm vs. 78 cfm) the outlet temperature (point 3) is 92°F.* This temperature can be brought very close to that at point 5, 81°F, by increasing the flow rate of the cooler stream.

3. As seen before, the capacity of the system is increased by increasing the regeneration temperature of the desiccant. A rule-of-thumb is that 10 lb of silica gel is needed to remove 1 lb of water (the cycled capacity of the desiccant is 10%). Therefore, if the desiccant is cycled only once a day, 500 lb of silica gel would be needed in a system to remove 50 lb of water per day from the building. At a bulk density of 45 lb/ft^3, 11 ft^3 of desiccant would be needed. If this volume and the corresponding material cost are unacceptable, then cycling more than once can be considered.

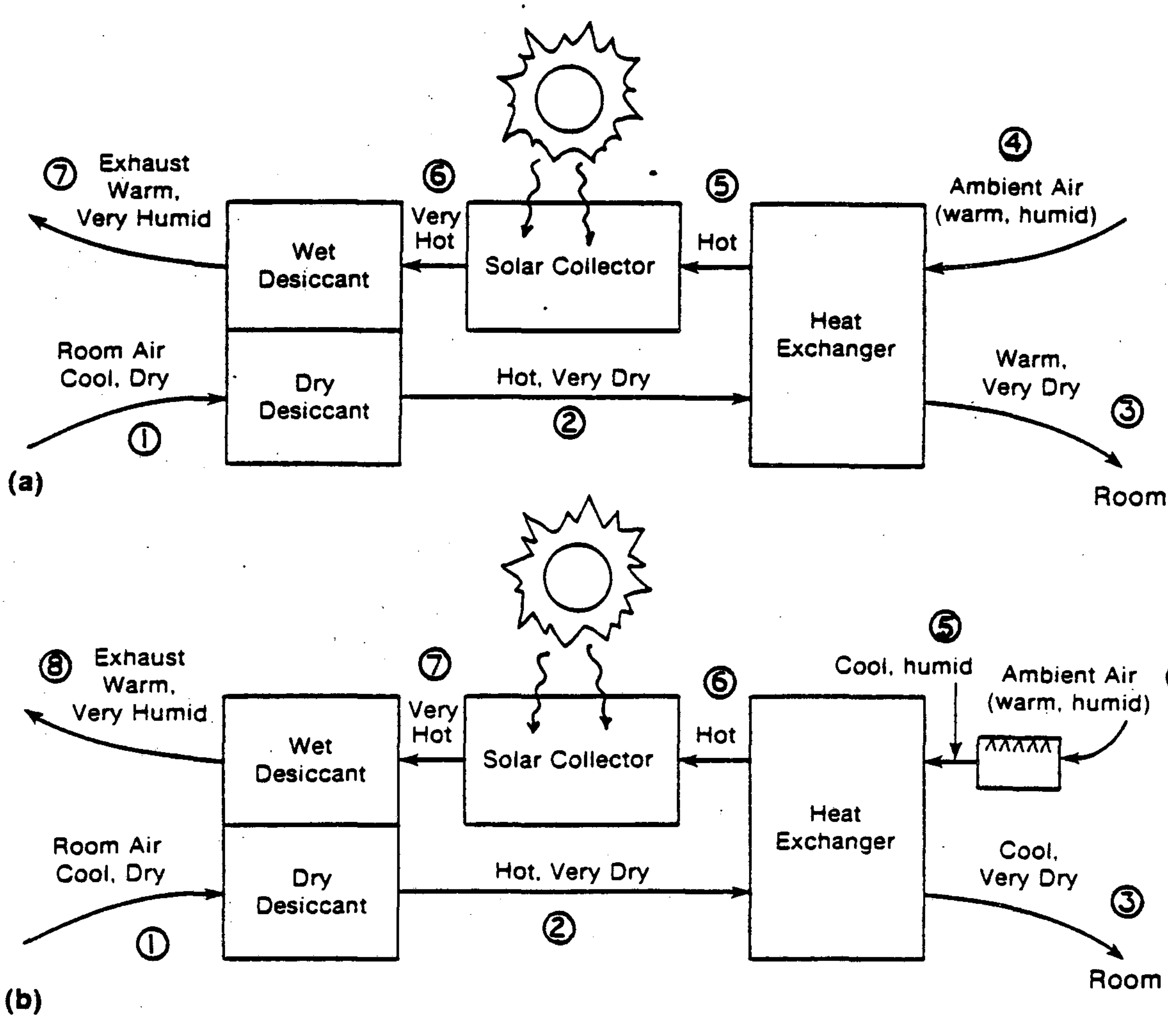

Fig. A-10. Improvements to the desiccant dehumidifier. a) The addition of a heat exchanger to preheat the regeneration air using the hot dehumidified air stream. b) Precooling the ambient air by adiabatic humidification before it enters the heat exchanger will reduce the temperature of the dehumidified air entering the room.

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*We have assumed a heat exchanger effectiveness of 90%.

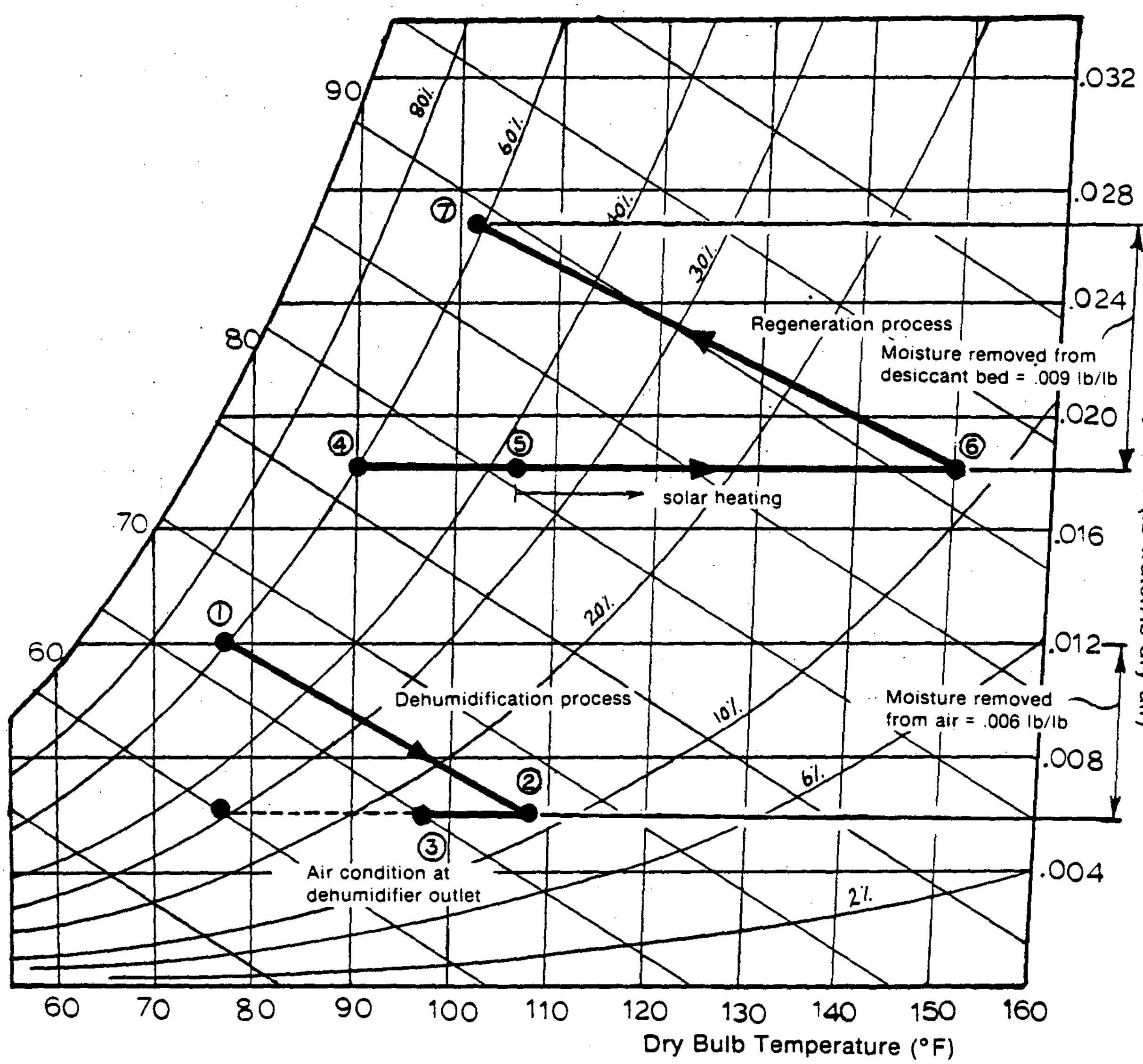

Fig. A-11. Dehumidification and regeneration process plotted on the psychrometric chart. The addition of a heat exchanger to preheat regeneration air (point 5-6) using the hot dehumidified air at point 2 increases the solar COP of the system and lowers the temperature of the dehumidified air (point 3). A block diagram of this machine is shown in Fig. 10(a).

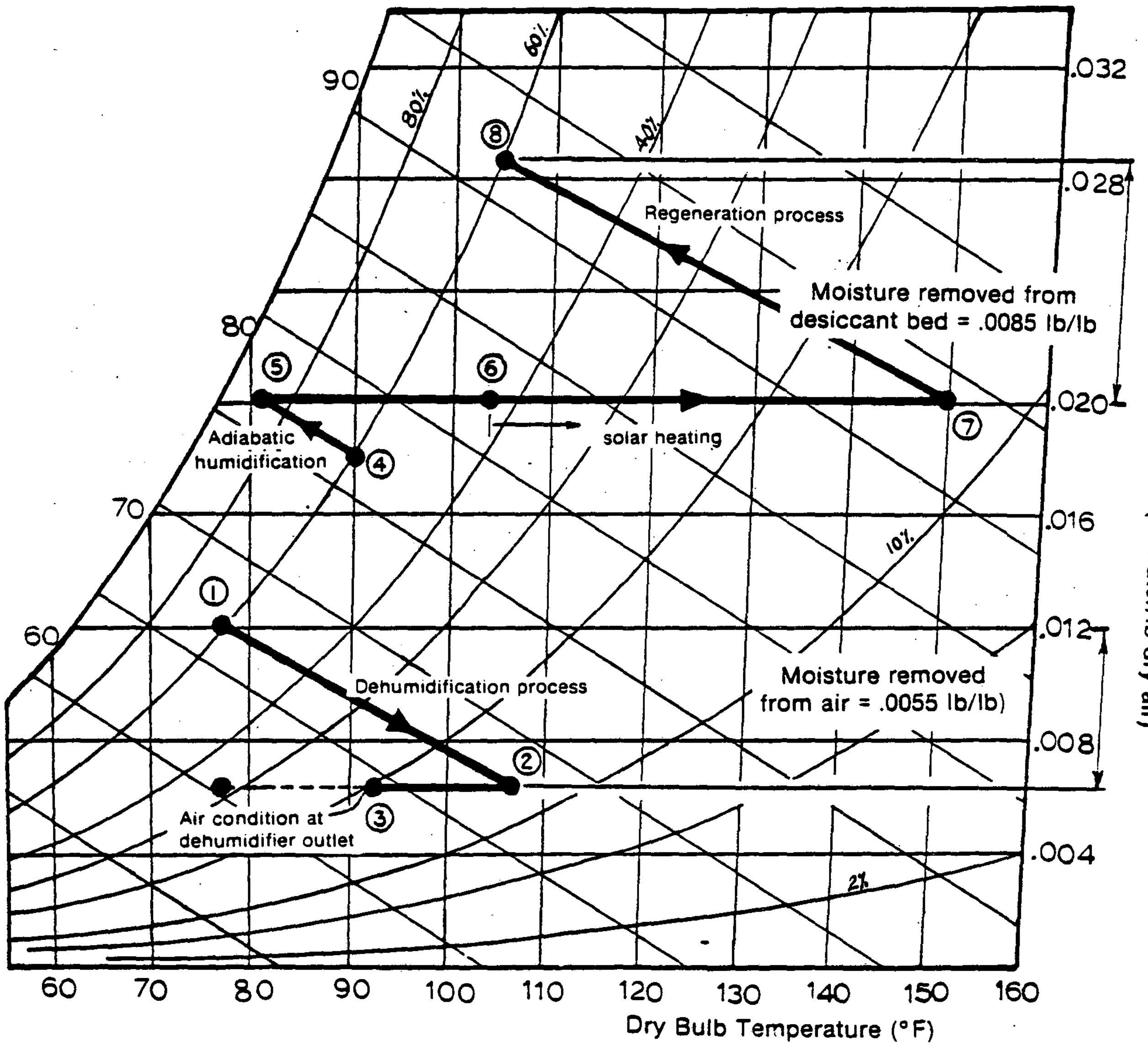

Fig. A-12. Adiabatic humidification of the ambient air stream (point 4-5) before it enters the heat exchanger will reduce the temperature of the dehumidified air at the outlet of the dehumidifier (point 3). A block diagram of this machine is shown in Fig. A-10(b).

APPENDIX 5: MODELING DESICCANT PERFORMANCE— A NONTECHNICAL OVERVIEW*

The primary goal in passive/hybrid cooling is to minimize the conventional energy requirements for air conditioning. This implies that systems must be optimized with respect to both cost and performance. As with many concepts, it is impractical to build and test all the possible designs for solar-regenerated desiccant dehumidifiers. Therefore, accurate analytical methods for predicting the performance of desiccant systems are essential if sound decisions are to be made regarding the design of pilot projects and the direction of future research into solar dehumidification and cooling concepts.

A solar-regenerated dehumidifier has several components, but the heart of the system, and the part that is most difficult to analyze, is the desiccant bed itself. Desiccants have been used for many years to dry air for industrial processes. The history of analytical models for the adsorption process is nearly as long, beginning in the mid-1940s. Unfortunately, none of the many adsorption models that have been developed for industry are directly applicable to solar-regenerated systems, simply because the solar problem contains more variables. Over the past decade, progress has been made in developing models for active solar desiccant systems using rotary wheels[A9] and cross-cooled laminar channel matrices[A10], but restrictions on these models preclude their application to the type of bed that would probably be used in a passive/hybrid system. It is likely that existing models could be adapted or expanded to encompass the passive/hybrid problem. This sort of adaptation is being investigated at SERI,** along with the development of a new modeling approach which will be described below. Nevertheless, the current state is that there are no proven models that can predict the long term performance of proposed passive/hybrid desiccant dehumidification systems.

The reason for this void is that adsorption, though it may seem simple at first, is a very complicated process. In the most general terms, the adsorption of water vapor by a bed of desiccant particles can be described as follows. When humid air is exposed to dry desiccant, water vapor is transported to the surface of the desiccant and then diffuses into the pores of the solid. Adsorption, which is somewhat similar to condensation, releases energy and heats the desiccant. Some of this heat is then transferred to the air. The amount of water that a given desiccant will hold is a function of its temperature and the humidity of the surrounding air. Thus, the mass transfer and heat transfer problems are coupled in the nonlinear way.

The approach to modeling has been to make some simplifying assumptions about the adsorption process or the desiccant properties, derive the system of differential equations for conservation of energy and mass, and then solve this system numerically on a computer. Even with simplifications, the mathematics of the problem can get very complicated, and most of the modeling efforts have been done as doctoral dissertations in chemical engineering. The purpose of the models is to predict the temperature and

*Prepared by Robert Barlow, SERI.

**Models being investigated include the Rosen model[A11] and adaptations by Carter[A12] and Liaw, et al.[A13]. These models include both a gas film resistance and a solid side diffusion resistance to mass transfer. In addition, models based on a single combined resistance, such as that presented by Chi and Wasan[A14], are being investigated.

humidity of the air leaving the desiccant bed as functions of time. This is exactly the information that would be needed to predict the performance of a solar dehumidifier. However, all the available models are based on the assumptions that the temperature and water content of the bed are uniform at the beginning of a run, and that the conditions of the inlet air stream remain constant. These assumptions are valid for most industrial processes, but not for passive/hybrid solar-regenerated dehumidification. In a passive/hybrid application, it is likely that a desiccant bed would only be cycled once a day. Conditions of the inlet air could vary considerably, especially during regeneration, since the temperature of regeneration air coming from solar collectors will vary throughout the day.

In industry, energy efficiency has not been a major concern, and ample energy is spent to completely regenerate a desiccant bed. In solar applications it is not practical to regenerate completely and therefore, a useful model must deal with nonuniform initial conditions as well as variable inlet conditions.

Modification of existing models to treat nonuniform initial bed profiles should not be a problem, but the inclusion of variable inlet air conditions presents considerable difficulty. For this reason, and because existing models are computationally expensive and impractical for long term performance prediction, an alternative approach to modeling in desiccant systems is being investigated at SERI. This approach is based on algebraic rate equations rather than differential equations. This greatly simplifies the mathematics, and allows one to keep better track of the actual physics of the dehumidification process. Most important, however, is the fact that the model can treat variable inlet conditions and nonuniform initial conditions without any difficulty. A nontechnical description of model follows, which should help to clarify the adsorption process itself, as well as illustrate the general concepts of modeling.

As is illustrated in Fig. A-13, the computer model can be though of as a conveyor belt that carries one chunk of air at a time through the desiccant bed. As the air chunk is exposed to each bed section, mass transfer and heat transfer calculations are preformed in an uncoupled manner. First, a mass transfer rate equation is used to determine the amount of water that is transfered to the desiccant. The temperature increase of the bed due to the heat of adsorption is calculated. Then a heat transfer rate equation is used to find the new temperatures of the air and bed section. Finally, the computer stores the conditions of the bed section and moves the air chunk to the next bed section.

Preliminary results using this approach have been very encouraging. Figures A-14 and A-15 show the type of graphical output that the computer model produces. The upper graphs show the temperature and humidity of the air leaving the desiccant bed as functions of time. The lower graphs give the temperature and loading profiles in the bed at times corresponding to the tic marks on the graph of outlet conditions. This format gives one a clear picture of how the bed behaves during cyclic operation. During adsorption (Fig. A-14) the moisture wave in the bed (dashed lines) moves to the right in the direction of flow. This moisture wave is coupled with a temperature wave (solid lines) which also moves to the right. During regeneration the waves move in the opposite direction.

These computer runs were based on the system parameters given in reference A15, except for increases in the flow rate and regeneration temperature to .038 m^3/s (80 cfm) and 70° C (158° F), respectively. Adsorption and regeneration periods were taken to be 12 hours and 6 hours, which correspond to a system using two beds to dehumidify 24 hours a day. A packed silica gel bed only 5 cm deep was specified in order to keep pressure drop down to .307 N/m^2 (.25" H_2O).

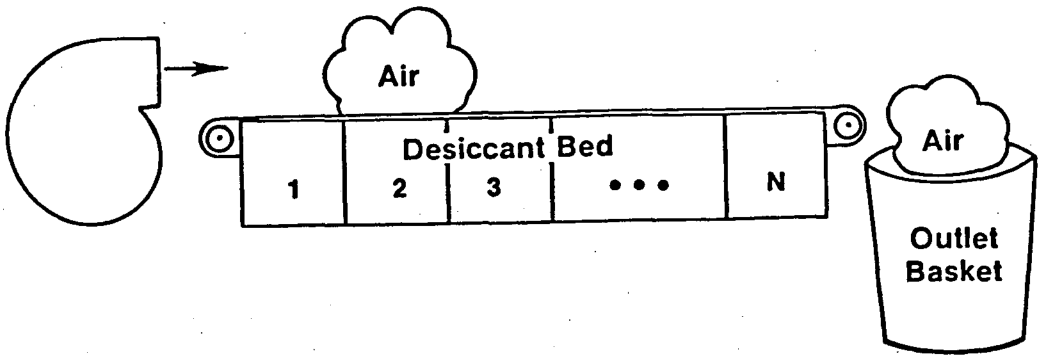

Fig. A-13. The conveyor belt model divides the desiccant bed into sections and exposes air chunks to one section at a time. Mass and heat transfer calculations are based on algebraic rate equations.

Since the model is still in developmental stages, only a few qualitative results will be discussed. First, during cyclic operation, the mass transfer zone extends across the entire thickness of the bed. Consequently, the outlet air conditions can change during adsorption, and the total water adsorbed will be less than the amount predicted using the simplified approach presented in Appendix 3. If the bed is fairly well regenerated, then the simplified approach will be nearly correct. However, if regeneration is not very complete and the steeper portion of the moisture wave reaches the outlet end of the bed during adsorption, performance may be considerably reduced. Once the model has been refined and predictions have been compared to experimental data from the SERI desiccant test facility, more quantitative results will be published. The modeling effort will also lead to confirmation or improvement of the approximate sizing procedures presented in this paper.

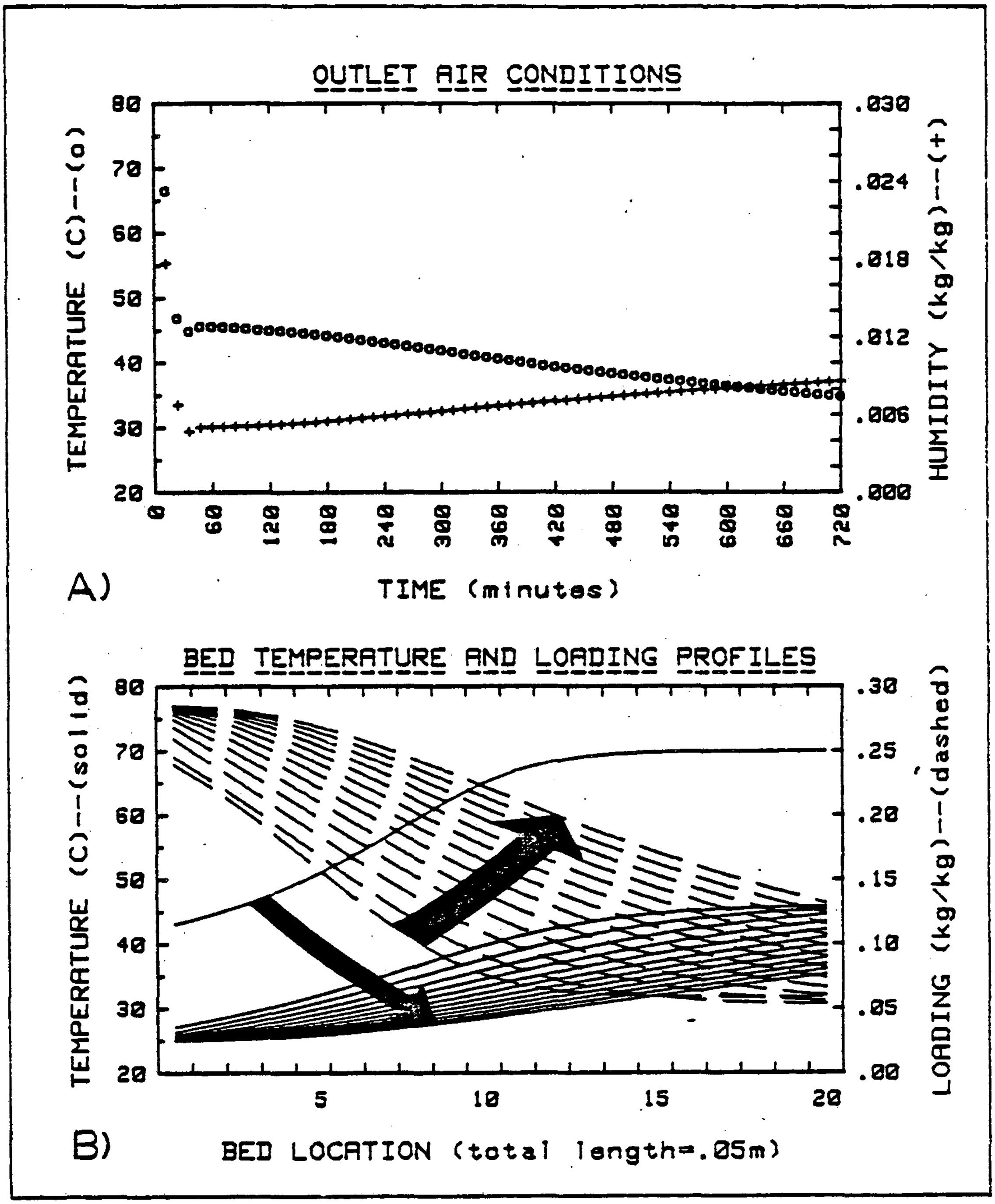

Fig. A-14. Outlet air and bed conditions during dehumidification. a) Temperature and outlet humidity of air as function of time. Over the first six hours of dehumidification the average air conditions are .006 kg/kg humidity ratio and 43° C (.006 lb/lb and 109° F), which correspond quite well to the conditions predicted using the equilibrium assumption (.0053 lb/lb and 113° F). After 12 hours, the outlet humidity is at .0084 kg/kg and 35° C. b) Bed temperature and loading profiles. The loading profiles show that for thin beds, the mass transfer zone is not small compared to the bed length. Over the first six hours, however, the change in loading at the end of the bed is within a few percent of the original loading.

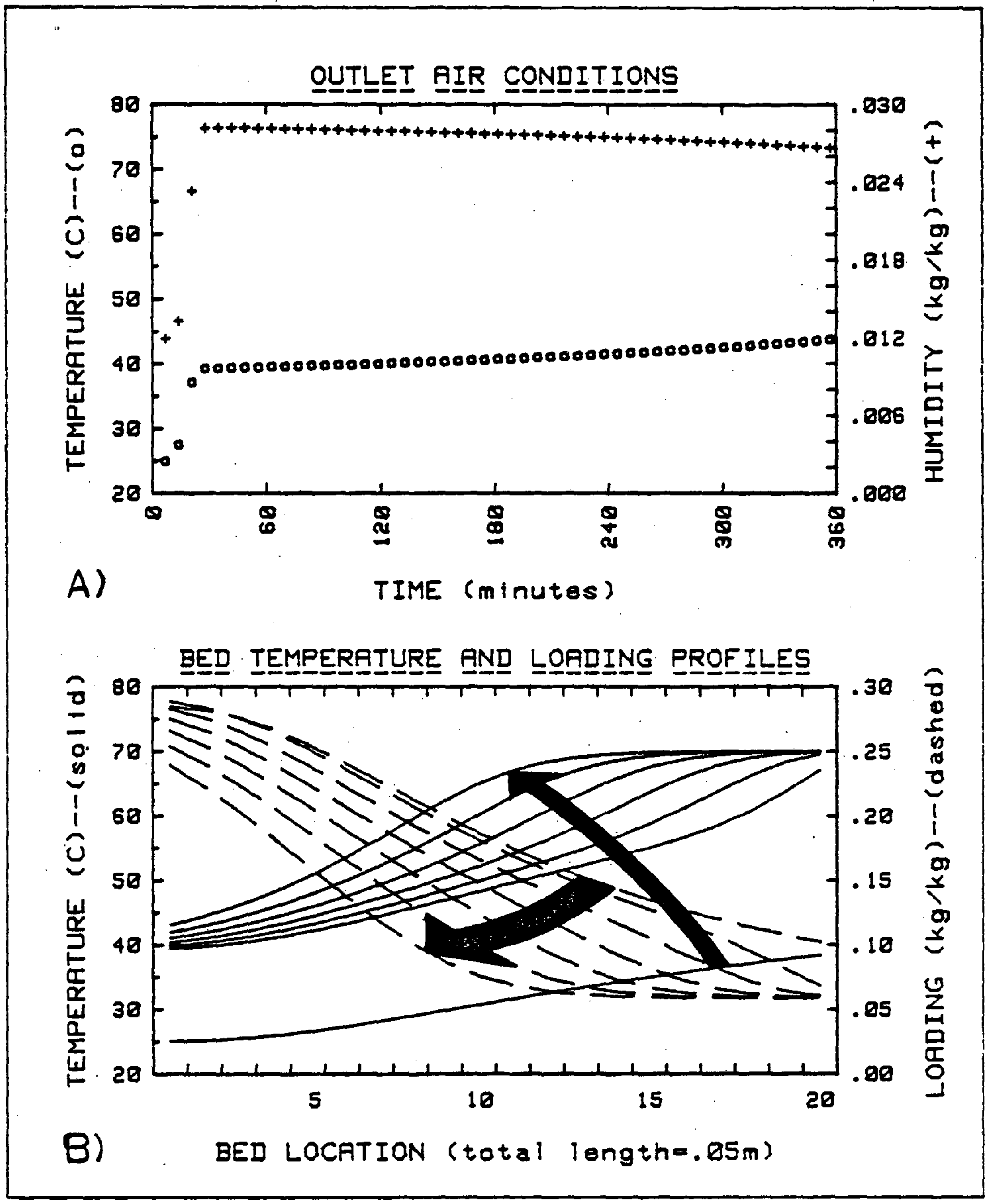

Fig. A-15. Outlet air and bed conditions during regeneration. a) Over 6 hours of regeneration, the outlet air conditions are relatively constant at 41°C and .027 kg/kg (106°F and .027 lb/lb). These correspond very well to the conditions predicted by the equilibrium analysis (104°F and .0285 lb/lb). b) Loading and temperature profiles are similar to those in Fig. A-14.

REFERENCES—APPENDICES

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LANDSCAPE PLANNING

Heating and Cooling of Buildings and Sites Through Landscape Planning and Design -- Harris J. Sobin

HEATING AND COOLING OF BUILDINGS AND SITES THROUGH LANDSCAPE PLANNING AND DESIGN*

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ABSTRACT

All too frequently architects, builders and engineers inherit a site or building alteration with disadvantages of undesired heating or cooling, which can be avoided at the initial planning stage. Preventive methods exist to provide a more acceptable site micro-climate, or to alter a punitive existing situation. Site choice, building location, building orientation, envelope design and judicious employment of landscape materials in and around buildings are major contributing factors to ammelioration. This paper is limited to the use of landscape material and site strategies to assist comfort levels and reduce the energy needs for heating and cooling buildings.

KEYWORDS

landscape planning and design; buildings, heating and cooling; landscape material; roof gardens; wind control around buildings; site planning and design; planting plans

INTRODUCTION

Human experience reveals that all animals, including humans, greatly benefit from live plantings, for food, visually and psychologically, cleaning the atmosphere, altering global, regional and micro-climate, including impacts on a personal scale. Although, much is known about the botanical and horticultural characteristics of plants, little is known of the manner and extent to which they can effect site and building climate. Plants, trees and shrubs need categorization and evaluation of their potentials to alter ambience. Additionally, many other materials, such as earth, stone, concrete, brick, water, wood, bamboo, etc. are used in landscape and gardening. Their bioclimatic effects need to be examined, individually and conjointly. The manner in which they may be deploy for benefit in different situations, needs to be explored.

LANDSCAPE MATERIALS

Landscape may be classified as natural and man-made. Natural landscapes are those

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resulting from an uninterrupted local eco-system, which falls into a regional classification governed by climate controls, determined by basic sun-earth relations. Plant life in these eco-systems is always hardy as it is a result of the survival of the fittest. Observation of these plants assists in the selection of appropriate species for a man-made situation. These landscapes result from human interference and have a range of characteristics from farmlands to manicured gardens, including urban and rural built environments, communication systems, etc. These man-made environments are constructed from all the materials of earth which possess known thermal characteristics. Orientation, materials choice, shape and envelope design effect the heating and cooling of buildings. Further ammelioration of extremes can be achieved through landscape use.

Landscape materials, then, can be regarded as living, non-living and dead. Examples of these are trees and shrubs, brick and concrete, lumber and coral stone, respectively. Earth, water and glass possess unique thermal properties that may be usefully employed in landscaping. Tables 1-3 illustrate the reaction of some typical materials to solar and thermal radiation. The selection of landscape materials is influenced by aesthetics, articulation, ecology, "genius loci" and site suitability. Landscape materials may also be selected for their heating or cooling effects according to need.

PLANT FACTORS AND CONTROLS

In landscaping an environment with living materials such as trees, shrubs and low growing plants (hereafter, all living materials used for landscaping will be referred to as plants), every aspect of the plant must be considered and dealt with individually:

- soil preference
- growth habit
- life expectancy
- sunlight or shade requirements
- moisture requirements
- hardiness to climate extremes
- reaction to transplanting and pruning
- atmospheric tolerance including salt spray
- resistance to susceptability to disease or pests
- symbiotic preferences for co-existence

PLANT TYPES

There are three types of plant materials:

1.) Trees: always stand on a stem or trunk, or a system of trunks, growing generally from a height of 15 feet to 80 feet, with various canopy structures capable of throwing a shadow some distance from their centers, allowing air to circulate under or over a canopy by deflection. (See Fig. 1)

2.) Shrubs: always hug the ground and grow from 4 feet to 12 feet. Always casting adjacent shadows and circulating air over and around them. Because of these char-

TABLE 1 Solar Reflectivity for Various Ground Surfaces

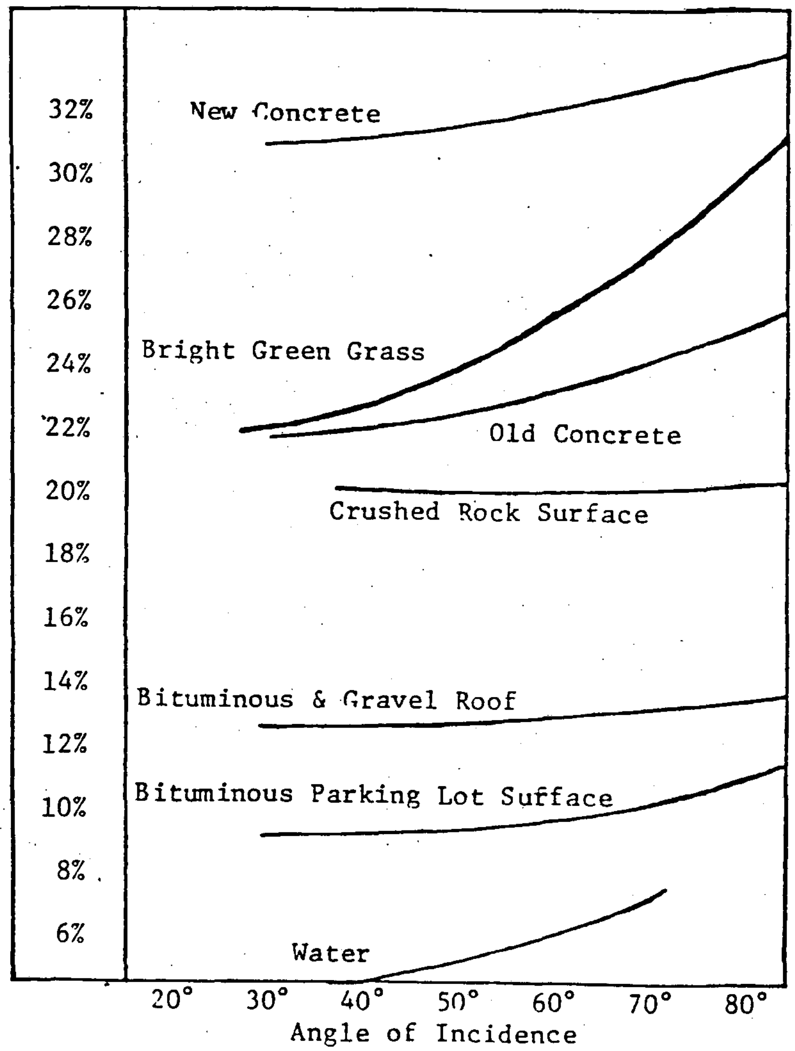


TABLE 2 Percentage of Incident Solar Radiation, Diffusely Reflected [3]

Nature of Surface	Estimate % Reflected
Bare ground, dry	10–25
Bare ground, wet	8–9
Sand, dry	18–30
Sand, wet	8–18
Mold, black, dry	14
Mold, black, wet	8
Rock	12–15
Grass, dry	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

TABLE 3 Reaction of Materials to Solar and Thermal Radiation [3]

Surface	% of Reflectivity		% of Emissivity
	Solar Radiation	Thermal Radiation	Thermal Radiation
Silver, polished	93	98	2
Aluminum, polished	85	92	8
Whitewash	80	-	-
Copper, polished	75	85	15
Chromium plate	72	80	20
White lead paint	71	11	89
White marble	54	5	95
Light green paint	50	5	5
Aluminum paint	45	45	55
Indiana limestone	43	5	95
Wood, pine	40	5	95
Asbestos cement, aged 1 yr	29	5	95
Red clay brick	23–30	6	94
Gray paint	25	5	95
Galvanized iron, aged (oxidized)	10	72	28
Black matte	3	5	95

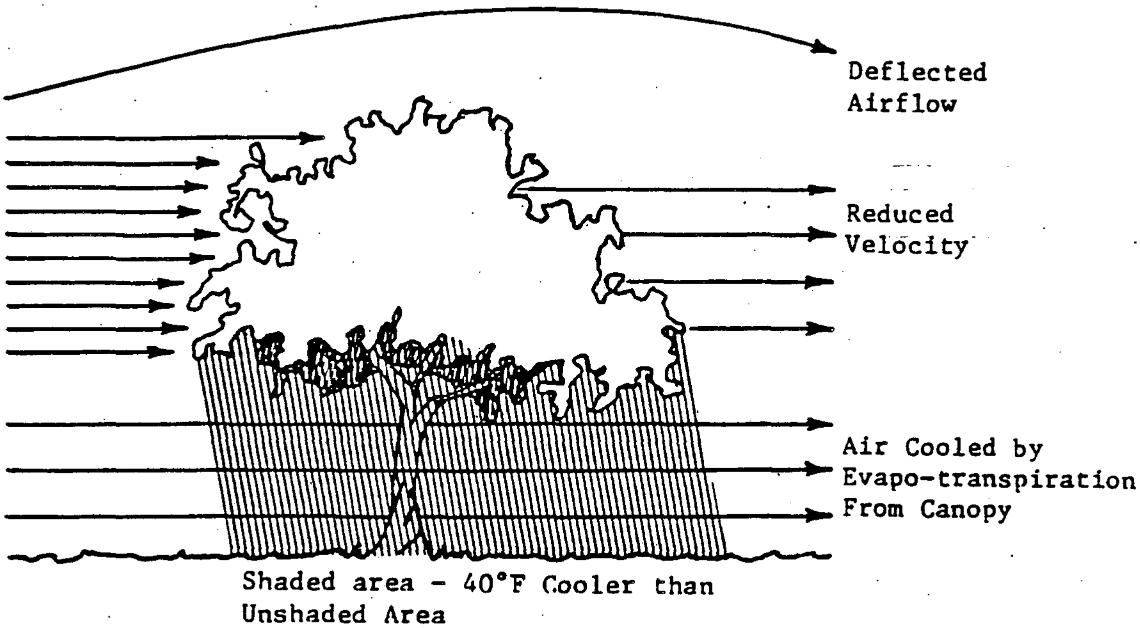


Fig. 1 - Trees have various canopy structures capable of throwing a shadow some distance from their centers, allowing air to circulation under or over a canopy by deflection.

acteristics, shrubs are generally used as privacy screens or wind barriers. (See Fig. 2)

3.) Low growing plants: always grow and spread close to the ground, reaching heights of 0 inches to 4 feet. Shadows cast by these plants cool the immediate earth below, thus cooling the wind which flows over them. (See Fig. 3)

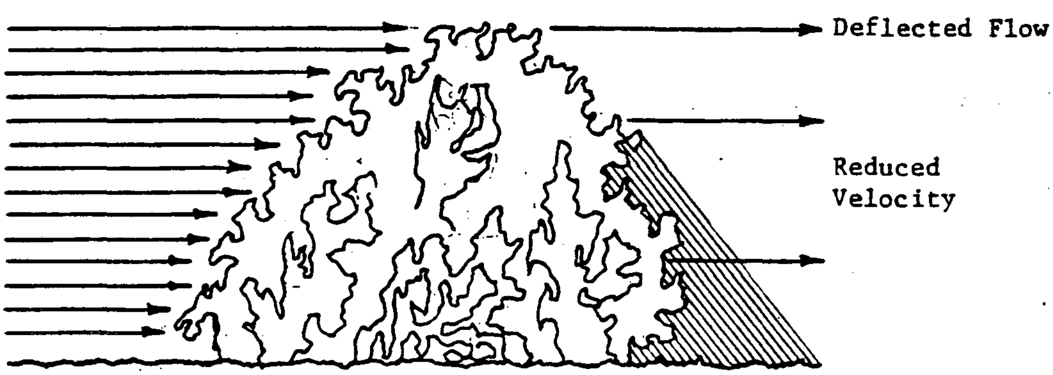


Fig. 2 - Shrubs cast adjacent shadows and circulating air over and around them.

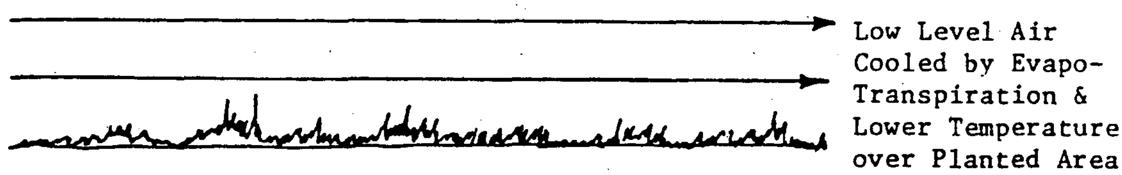


Fig. 3 - Low growing plants cast shadows that cool the immediate earth below, thus cooling the wind which flows over them.

PLANT STRUCTURES

Knowledge of the structure and characteristics of all types of plant materials is essential to enable the best selection related to the task requirements.

Structure and Characteristics of Plants

Form of mature tree (See Fig. 4):

a.) Fastigate - extremely narrow, tapering to a point (Lombardy poplar)

b.) Columnar - very narrow, but not possessing a pointed tip (Sentry maple, pines)

c.) Open-headed - loose branch structure, indistinguishable silhouette (Silk tree, orchid tree)

d.) Spreading - (Sugar maple, poinciana)

e.) Round Top - a distinctly rounded profile (White oak, Italian olive)

f.) Pyramidal - almost conical outline (Douglas fir)

g.) Weeping - pendulous branches (Weeping willow, bottle brush)

h.) Walking - horizontal spread resulting from aerial root growth (Banyan)

Textures:

Coarse - large leaves, heavy branches (Horse chestnut, ficus, scheffelaria)

Medium - less opaque and strong in outline (American elm, live oak, gumbo limbo)

Fine - a feathery appearance, providing light shade (Honey locust, olive, casaurina)

Vines - small leaves, lightweight, no trunk (ivy, thumbergia, morning glory)

Rate of growth:

Slow - under one foot per year under ideal conditions of growth (European birch, live oak)

Medium - one foot to two feet per year (Maples, gumbo limbo)

Fast - two or more feet per year (Lombardy poplar, ficus, scheffelaria)

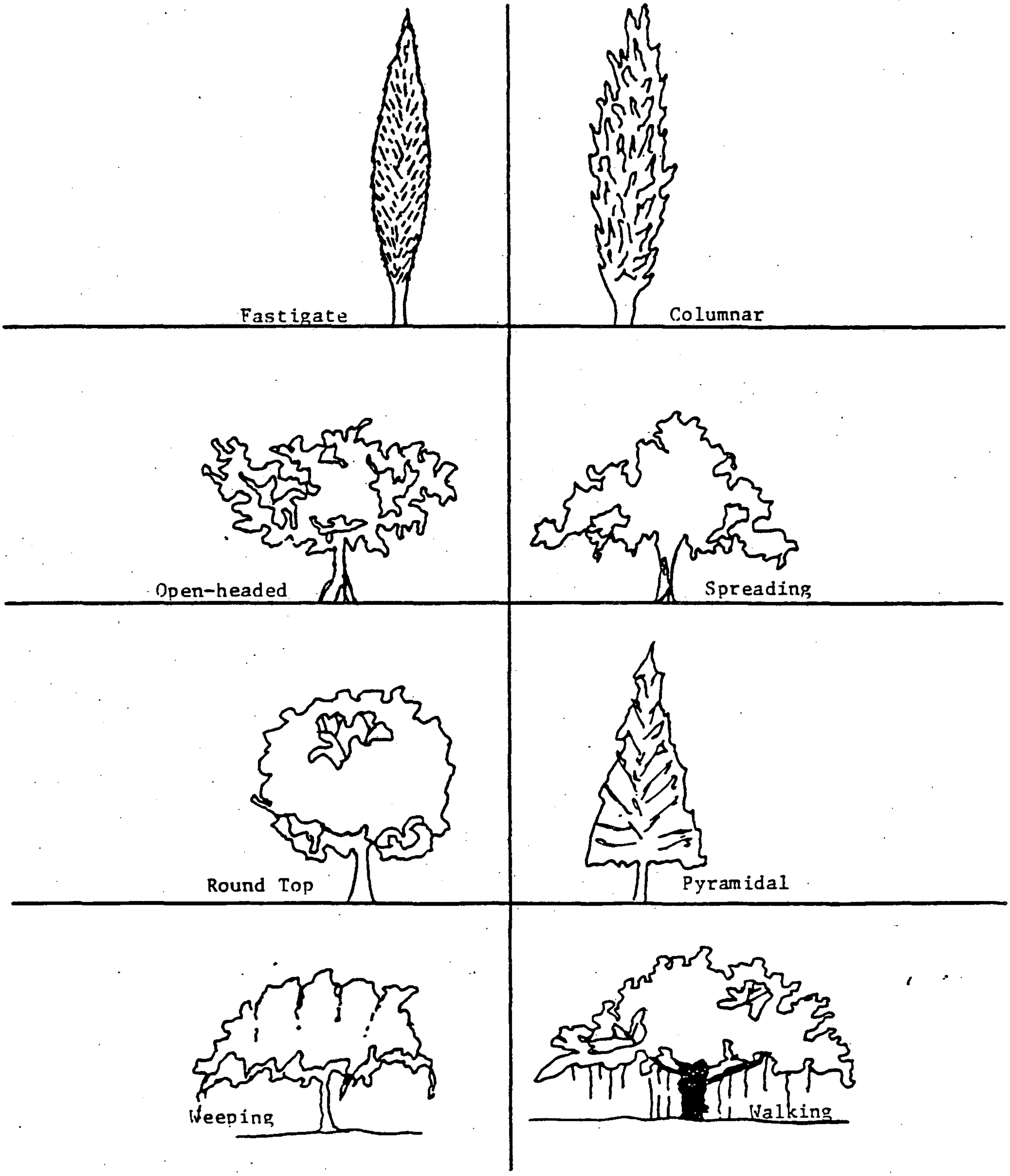


Fig. 4 - The Morphology of Trees

Blossom: color, period of bloom

Fruit: color, size and profusion, edible or poisonous

Fall foliage: color, prolific or moderate shed

Bark: special interest or undistinguished

The obvious structure and characteristics of shrubs and low growing plants are few and the most significant have been described above under plant types.

PRINCIPAL PLANT COMPONENTS

Understanding the functions and types of different plant components is also essential in the selection of plants. Because of general similarities between many components of shrubs and low growing plants with those of trees, tree components only will be discussed. It is appreciated that infinite intricacies exist between plants, but these are mainly botanical and not the subject of this paper.

Major tree components are: roots, trunk and canopy. The proximity of locations of a tree to a building or structure should be determined by the tree's root system, so as to avoid any physical damage to the structure. It usually follows that the larger the tree trunk and canopy, the larger the root system.

The roots of a tree spread radially from the trunk, seldom to a depth greater than four to six feet, except the tap root. A rich, moist soil will develop a shallow root system; while a dry soil will encourage a deep root system so as to obtain more moisture.

The heavy roots near the trunk serve principally for anchorage, while the root hairs that occur at the root tips are those that absorb the mineral solutions from the soil.

The trunk has two functions - to transport nutrients between the roots and the canopy and also to support the canopy.

Principal functions of the canopy are: (1) photosynthesis and (2) transpiration. There are many different types of canopies: round, vertical, oval, horizontal oval, vase, pyramidal; and each will perform differently in controlling solar radiation, wind and precipitation. The choice of one over the other will depend on the function that each canopy is to perform.

COMPARISON OF COOLING EFFECTS OF PLANTS AND MAN-MADE STRUCTURES

The most significant resulting difference between the cooling effects of plants and man-made structures, is that the structure is made of non-living (concrete) or dead (lumber) materials and, therefore, offers limited cooling capabilities determined by the thermal performance of the materials, while a plant - which is a living organism - will constantly position and arrange its canopy and leaves to take maximum advantage of the sun's rays, thus maximizing their cooling effects. A detailed examination of the different properties of each follow.

Plants

- provide shade by blocking the sun's rays.
- use solar radiation for growth and nourishment, so do not radiate any stored heat.
- the position of the leaves rotate with the solar beam to expose the broad side of the leaf to the sun, thus providing maximum shade.
- as a result of its nourishment, the plant discharges large amounts of water vapor, so cooling the air and breezes in its immediate surroundings.
- absorb and deaden sound as it passes through the plant system.
- absorb and retain precipitation as it passes through the plant system, thus cooling the air that will flow over and through it for some time after the precipitation stops.
- will provide a layer of decaying matter that will serve to insulate the ground.
- will obstruct, filter, deflect or guide airflow passing through it.
- absorb solar radiation for nourishment during the day, releasing this stored heat at night in order to minimize drastic temperature changes.
- at night the canopy will also serve to keep the escaping heat that was absorbed during the day near the soil by acting as an umbrella shield.

Man-Made Structures

- provide shade by blocking the sun's rays.
- collect thermal radiation from the sun, thus radiating stored energy in the form of heat.
- need to be operable to maximize cooling and heating efficiencies.

From this comparison it is evident that the cooling benefits from a tree versus a man-made structure are quite significant. But to fully understand how and why trees behave the way they do, a closer examination of the life cycle of a tree is necessary.

The main function of a tree is to take minerals from the soil and with solar radiation, transform it into nutrients. To allow photosynthesis to take place, large amounts of water vapor must escape through three types of structures in the leaves: the stomates, cuticles and lenticles. It is this water vapor that causes a cooling effect on the air flow as it passes under, through, over and around the plant. This process is known as evapo-transpiration.

FUNCTIONAL USES OF PLANTS

A primary purpose for using plant materials in our landscape is to solve environmental problems inherent in the built environment. They may additionally be employed to solve architectural and engineering problems, for their aesthetic qualities, to control the sun, wind, temperature and precipitation and humidity. (See Figs. 5 and 6) However, only the effects of plants on the cooling and heating of

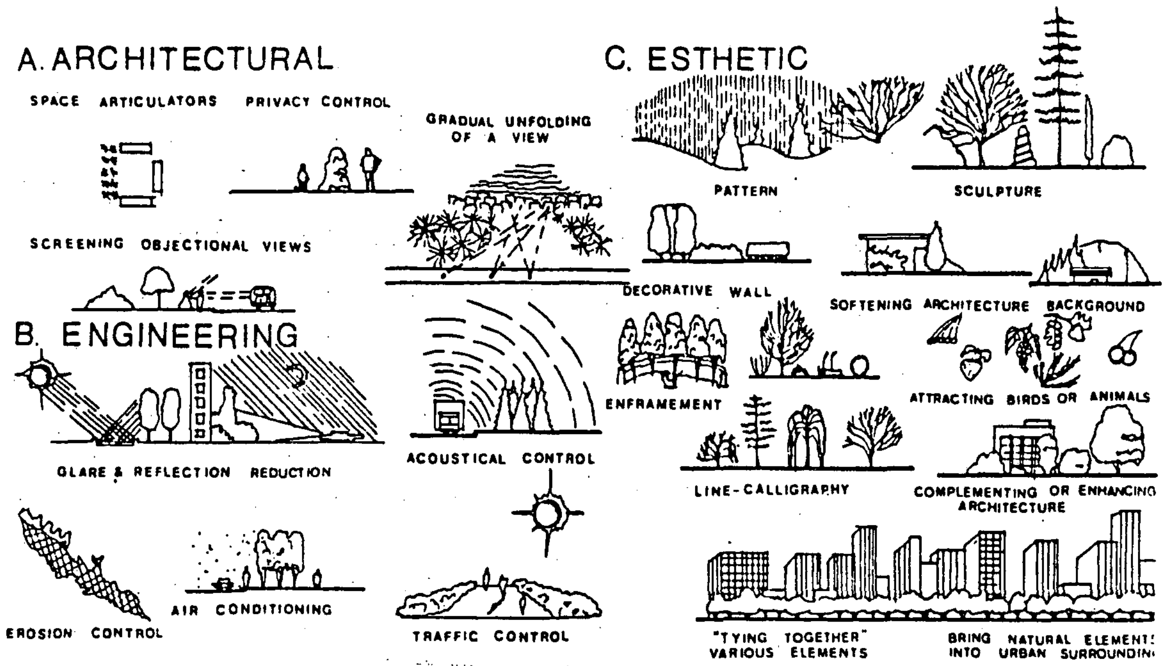


Fig. 5 - Functional Use of Plant Materials

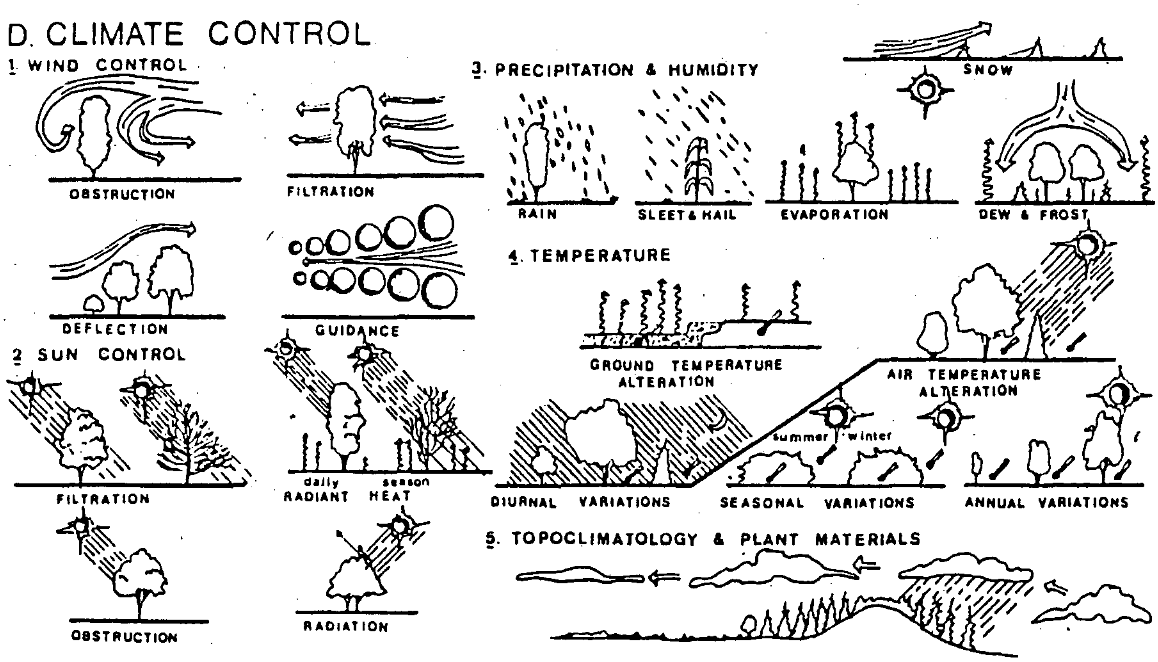


Fig. 6 - Functional Use of Plant Materials

micro-climates will be discussed in detail.

The control of the temperature is directly related to the amount of solar radiation, wind and humidity present at any point in time. Plants will affect all of these natural phenomena, and if used properly, the temperature may be modified to help keep the living environment at a comfortable level year-round.

According to Dr. Robert B. Deering [1] the following criteria are essential when landscaping a site, for either cooling or heating:

1.) In areas where the warm winter sun is desired, deciduous trees should be used. Even when leaves are not present thickness of branching and twigginess can screen out great quantities of radiation.

2.) The placement of trees and the use of grass near the house allows the heavier cool air to flow inside, providing low openings are present. High strip windows are not desirable in this respect.

3.) The greater the number and size of trees and square footage of lawn area the more cooling there is.

4.) Shrubs may even increase the heat, if the air circulation which aids transpiration is cut off. The use of very low specimens is suggested.

5.) Windbreaks, however, may be necessary in order to keep out hot-dry and winter winds.

6.) Keep sun off walls to prevent absorption and re-radiation, and off glass to prevent it from penetrating inside.

7.) Deciduous vines may be used on trellises over windows.

8.) Radiation may be partially stopped by the use of a wall cover of vines.

9.) Roofs may even be covered in the same manner as walls, resulting in a double roof; the upper one of living materials. Also roof gardens may be used.

10.) Keep lawns and trees well watered during dry weather.

11.) Shade as much paving as possible by trees and vines to prevent heat absorption. It may be well to keep paving to a minimum in hot climates.

12.) Large fans for outdoor use should be seriously considered in warm-humid climates to increase evaporation and transpiration.

PLANTS AND TEMPERATURE CONTROL

The sun, being our main energy source, effects our temperature and climate through several radiation channels. This heat may either be desirable or not, depending on geographic location, season, air temperature and the vapor pressure at any given time.

Radiant heat transfer as experienced by man can simply be categorized into four types: direct short wave radiation, diffused short wave radiation from the sky vault, short wave radiation reflected from surrounding buildings and terrain, long wave radiation from the heated buildings and terrain [2].

Trees, shrubs and low growing plants are among the best solar radiation controllers, this being one of their major functions. Plants can be used to control direct solar radiation by shading, or intercepting reflected radiation from a reflective surface; this interception may occur either before or after it strikes the surface. Plants used for shading may either completely block the sun's rays or filter them through the foliage.

As already indicated, a light smooth surface reflects more than a coarse, dark surface. Generally, plants have a darker surface than any man-made paving or architectural materials, thus reflecting less solar readiation. To minimize the heat and reflection from paving, sidewalks and walls, vines may be grown on the walls and as much of the ground as possible should be covered with low growing plants in order to provide a buffer against the heat and reflection.

It has been found that temperatures over grassy surfaces on sunny days are about 10°F to 14°F cooler than the temperature of exposed soil. (See Fig. 2) One important factor seldom considered is the movement of shadows over the ground and the speeds of cooling as the shadow moves over the new area. In experiments conducted by Kelly and Ittner at the University of California using artificial shades for livestock, it was found that bare ground temperatures cooled as much as 40°F in five minutes after arrival of the shadow line [1]. When considering the total ground area covered by the shade from a large tree during a day, one can well see the importance of shading on the temperature of the ground and the temperature of the adjacent air layers. Trellises with vines can also be used to achieve the same results, with the advantage that they can be added to a building where it would be hard to receive shade from a nearby tree or because of structural reasons. The lightness of trellises and vines is another advantage for their use.

During mid-July 1979, in Coral Gables, Florida, the author has recorded that under wood shaded air temperatures averaging 86°F at 2:00pm, temperatures twenty inches above:

1.) the grass in the shadow of a concrete building averaged 87°F.

2.) the concrete surface of a car park in the shadow of a concrete building averaged 89.5°F.

3.) the grass in the shadow under a concrete shelter averaged 91°F.

4.) the ground in a densely wooded sink-hole in deep shadow averaged 80°F.

To achieve efficient shading, trees should be strategically placed. As the sun passes in the morning and late afternoon at a low altitude, trees give their best performance on the east/southeast, and on the west/southwest elevations, in northern latitudes. Low sun rays cast long shadows, which can be utilized effectively on the elevations otherwise difficult to protect from the sun's heat. At mid-day the sun's path is high and the rays can be intercepted with an overhang or a vine-covered trellis or pergola [3].

PLANTS AND WIND CONTROL

In seasonal, climatic cycles, large volumes of air are moved above the surface of the earth at varying speeds, intensities and temperatures. Wind can control real or perceived temperatures. There are three types of airflow. They are:

1.) Laminar airflow - when streams of layered airflow are at equal momentum.

2.) Turbulent airflow - when air masses move generally in the same direction, but in a random and unpredictable pattern.

3.) Separated airflow - when layers of air vary in momentum [2].

The general character of airflow is laminar. Changes from laminar to turbulent flow are governed by turbulence within the airstream and the roughness of the surface over which it flows. The surface of buildings or any other landscape obstruction will always produce turbulent airflow [2].

Trees usually reduce wind velocity, which also lowers the rate of thermodynamic exchanges between the air layers resulting in warmer temperature in areas sheltered from the wind. Prevailing winds have a tendency to change direction seasonally. Therefore, planting materials must be placed so as to protect the building from undesirable winds and yet allow desirable winds to flow through the building. (See Fig. 7)

Plants may control wind by obstruction, guidance, deflection and filtration. Plant obstruction reduces wind speed by increasing the resistance to wind. Plants may be used in conjunction with landforms and architectural elements to alter and direct the airflow over, around or through a building or site.

Shelterbelts are commonly used to reduce or change the directional flow of the wind. Studies have shown that shelterbelts and windbreaks are most effective when placed perpendicular to the prevailing winds. A 5 to 7 mph wind force is substantially reduced within a distance of seven times the height or width of the protection, whichever is less. The degree of protection and wind reduction depends on the height, width, and penetrability of the plants used.

For cooling, wind should always approach a building via a shaded zone or planted surface and not a hot surface. Special types of trees with open, espalier-like spread can be used where the air velocity is not to be reduced.

PLANTS AND THE CONTROL OF PRECIPITATION AND HUMIDITY

Plants will gather rain as it falls through the canopy and branches, only allowing a reduced amount of rain to reach the soil and debris below thus preventing the runoff of nutrients. As the water passes through the tree it also absorbs heat from the leaves and branches and cools the whole tree along with the ground cover below. This water is transformed into vapor after the rain stops and the heat builds up again during the day, thus cooling the breezes flowing near the tree through evaporation.

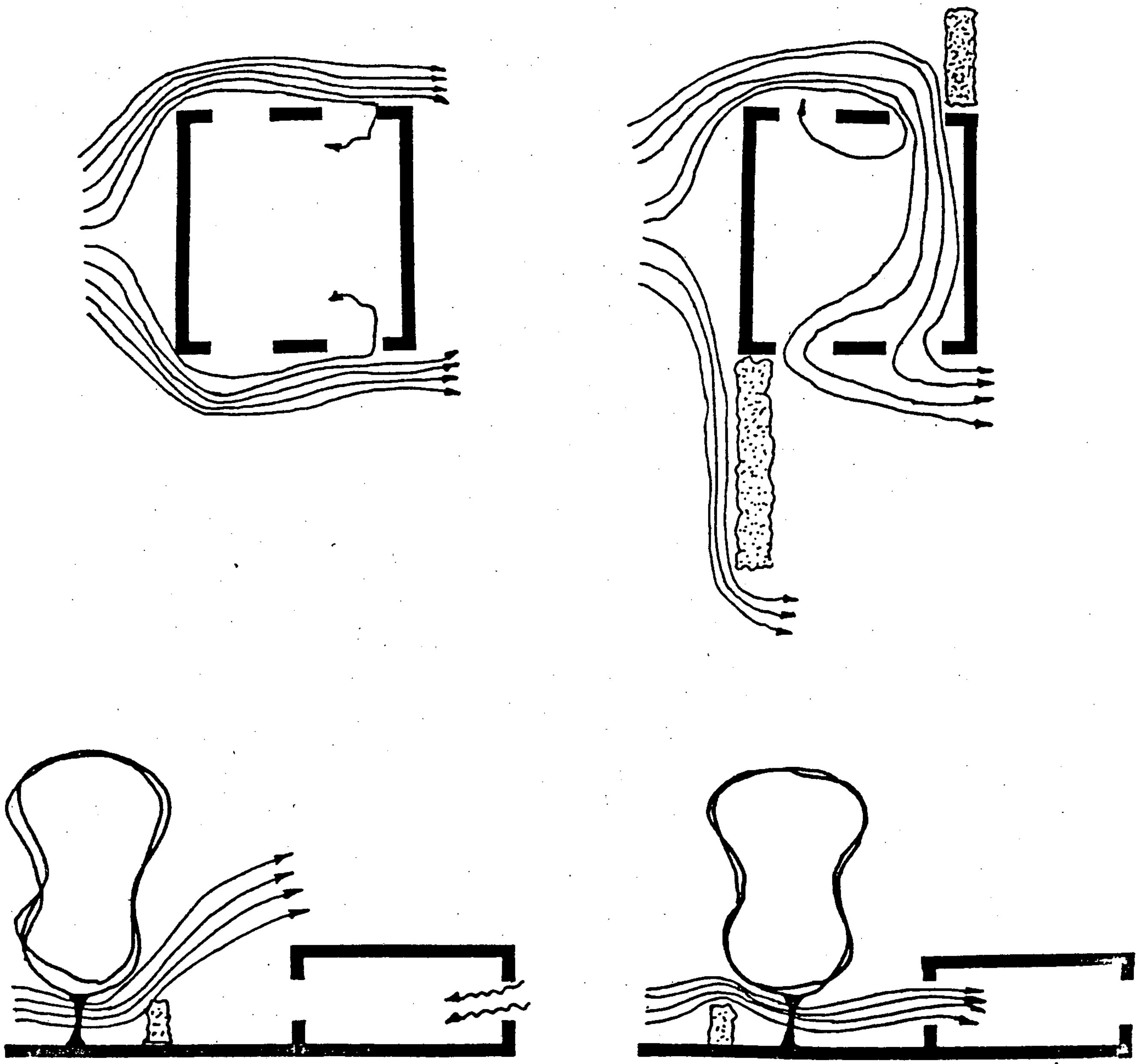


Fig. 7 - Living Landscape Materials Can Be Used to Create Desirable Wind Patterns

WATER AS A LANDSCAPE MATERIAL

Man has a great fascination towards water whether it be an ocean, lake, pond or fountain. Water, with its many uses, is a prime feature that can be used in the landscape wither as a focal point (pond) or to bring the landscape and building together as one with an artificial running stream). Furthermore, water is essential to plant growth.

Water, as a landscape element, could be used in two different ways: in its natural state or chlorinated to eliminate plant and animal life. When used without chemicals it provides an opportunity for an eco-system of living plants and animals adding interest to the body of water. Certain rules must be observed when attempting to create an eco-system:

1.) Water that does not circulate will become stagnant, thus inviting the infestation of mosquitoes and other pests.

2.) The water should be shaded at least partially to keep the algae to a minimum.

3.) Fish and snails can be introduced to both add interest and control the insect infestation and algae growth.

4.) Plants such as lily pads could be introduced to provide shade for fish and help keep the water temperature from fluctuating greatly between day and night.

5.) Waterfalls or fountains could be used for cooling and oxygenation.

EARTH AS A LANDSCAPE MATERIAL

While water is essential to <u>all</u> plant life, earth is essential to almost all plant life. The exceptions being aerobic and water plants, such as water hyacinths. The nutrients in the soil nourish plant growth and the large range of soils, coupled with climate conditions, results in an infinite variety of trees, shrubs and small plants spread all over the earth growing at a rate depending on these conditions. Some typical soils are loam, clay, marl, laterite and sand. The acid and alkalin content of the soil further dictates the selection of plant growth.

Thermal Performance of Soils

Soils will gather, retain and emit heat at a rate depending on:

a.) the thermal properties of the chemicals that compose the particular soil in question.

b.) the density of the soil.

c.) the moisture content of the soil.

d.) the color of the soil.

e.) the texture of the soil.

f.) the type of plant growth over the soil when this is applicable.

Earth In and Around Buildings

Because of its slow absorption rate, low emissivity rate and long time-lag, earth has historically been employed as a climatic extremes modifier in troglodytic settlements. Some notable settlements are located in Hunan in China, Matmata in Tunisia, Guadix in Spain and Cappadocia in Turkey. More recently, we have witnessed a rash of new underground and bermed buildings in the United States. Caution needs to be exercised when using these techniques.

Employment of Underground Structures and Berms

The very nature of the material - earth - requires a complete envelopment of the building and permits no 'leaks' or ventilation. So, unless a building is mechanically conditioned the burying or berming of structures in warm-humid conditions is a disaster and should be treated with great caution in temperate-humid conditions.

The greatest benefits from underground structures are to be experienced in situations that possess a large diurnal temperature range in the ambient atmosphere or within the building. Cold, cool and hot climates with arid rather than humid conditions are appropriate for these techniques.

However, in the cold-humid extreme there are far more positive than negative factors and troglogytic or bermed structures are recommended. Furthermore, in all mechanically heated or cooled systems, impressive results are experienced when using these principles.

Strategic berm placement on carefully selected orientations are always advantageous and may even be employed with extreme caution and discretion in warm-humid regions, under natural conditions, provided air will flow over human skin and interior space at a desirable velocity.

Planting on Berms

Planting of grass and ground cover, with water spraying facilities, advantageously cools the berm in hot conditions. In cold conditions the exterior surface should be designed for heat gain and the berm insulated against heat loss from the interior. Difficulties in mowing lawns is experienced.

SUN-EARTH GEOMETRY AND CONTROL OF SOLAR RADIATION

To control solar radiation by means of landscaping or other architectural controls, it is imperative to consider all the different sun angles throughout the year. The calculations and use of such angles is well documented and simple graphic tools are now available for easy assessment.

Of major concern in overheated regions is the maintenance of interior spaces of structures within the comfort zone. Depending on geographic location this may be accomplished by shading a structure heavily and providing enough ventilation or by cooling the interior spaces through mechanical means. It is not easy to remedy a problem after it has occurred (heavy shading of the whole structure is difficult in most retrofits), and since the maximum solar radiation a building receives is on the horizontal plane, cooling the roof, before the heat enters the building, will take care of most of the heat absorbed through the building envelope, as maximum solar gain is experienced on horizontal surfaces.

In Gainesville, Florida, George E. Sutton [4] experimented with the effects of roof spray on the cooling and economics of a building. Spraying of roofs is not new, but some aspects of temperature control are.

The system was set up as shown in Fig. 8. The two roof areas designated 'A' and 'B' were of the same roof construction. The sprays shown are ordinary rotating two-nozzle lawn sprays with adjustable throws. Throw was set at 18 feet on the 40 foot roof, leaving dry margins of 3 feet.

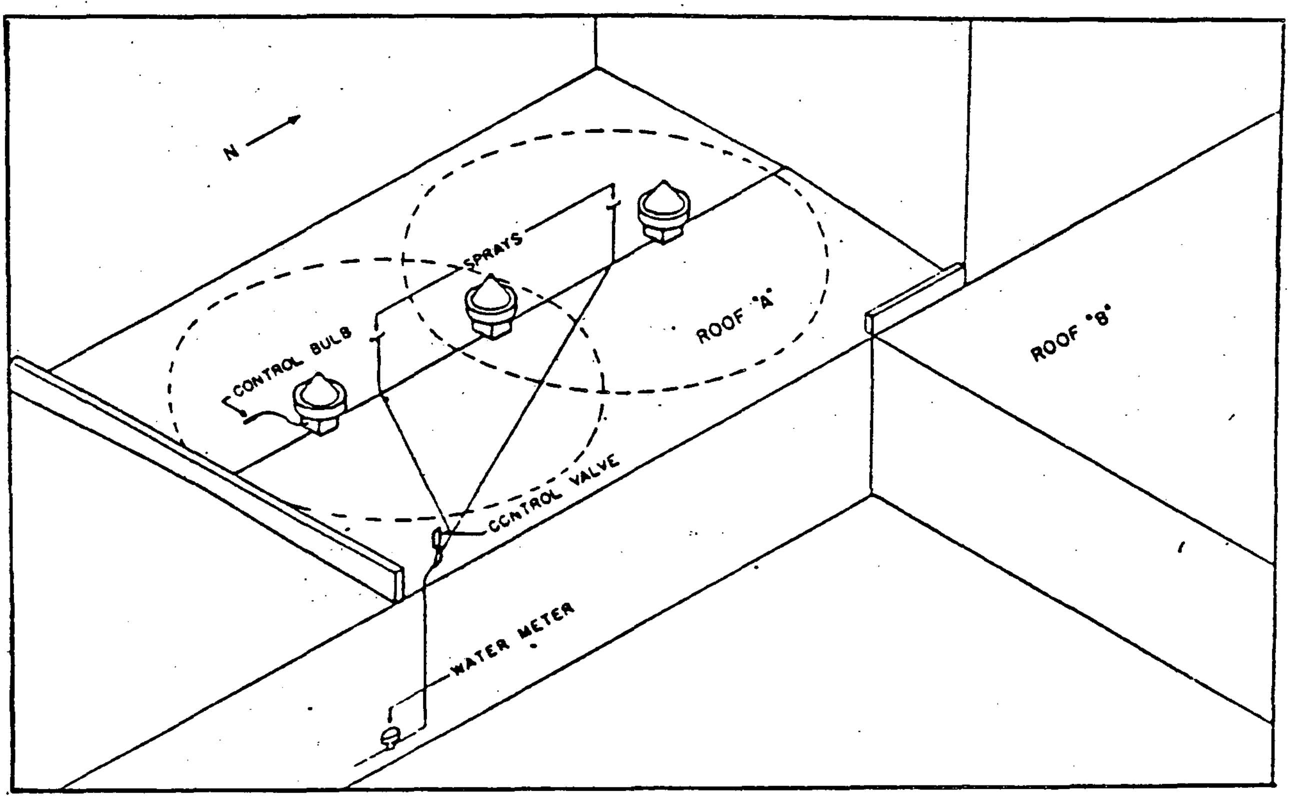


Fig. 8 - Evaporative Cooling of Roofs

Runs were made at three control settings: 95°, 100° and 105°F. At 95°F the sprays operated continuously creating a flooded roof with considerable runoff. The surface temperature maintained was not 95°F, but about 99°F. The efficiency of operation was about 26%, based on the amount of incident energy compared to the amount of latent heat of vaporization available in the water sprayed.

At 100°F control setting, operation of the sprays was intermittent. Very little run-off was observed and efficiency was about 49%.

At 105°F, run-off was negligible and efficiency approached 100%. However, heat transfer was higher because of the added temperature difference.

Obviously, then, a control temperature lower than 100°F is not practical, and the higher the temperature which may be tolerated, the more economical the operation.

Even with a control temperature of 100°F, the economics of operation appear very reasonable. In terms of dollars and cents, the economy of operation is impressive. Consider the roof used in the experiments, which has an area of 2400 ft^2. The difference in heat flows, between the sprayed and dry roofs for 9 August 1949, was 23,360 Btu/hr. This is the equivalent of practically two tons of refrigeration.

Due to the high cost of water in many areas, the roof should be designed to capture rain water and all the run-off and store it in a cistern so it could be re-used, or a well may be drilled and its water used for the roof spray. The use of either of these alternatives or combination thereof will make this system a feasible one as compared to the cost of having to cool the space mechanically. Comparison of the initial cost and maintenance of the two systems will hsow even greater reasons for use of spray systems.

The following conclusions gathered from literature and experimentation are offered as a summary:

1.) Roof spray of the rotating type can be made to maintain a surface temperature of about 100°F during the conditions of maximum incident solar energy.

2.) The higher the surface temperature that may be tolerated, the more efficicently will the spray system operate, since more of the evaporative effect may be utilized.

3.) Sprays are more effective than pooled water for cooling roofs.

4.) Some reduction in surface temperature of the walls of the building is produced by the spillage of cooled air from the roof.

5.) Spray water has a preservative effect on asphalt types of roofing by reducing temperature change and lowering surface temperatures. There is consequently, less thermal stress, less vaporization of volatile oils than for unsprayed roofs and there is no thermal shock from sudden thunderstorms.

6.) Addition of insulation will decrease heat transmission, but will cause an increase in surface temperature, thus adding a deteriorating effect to some types of roofing.

7.) Installation of sprays on conditioned buildings may serve to reduce the required refrigeration capacity, and thus present a saving in the cost of materials and installation, and energy used.

8.) Sprays offer the best means of distribution for all types of roofs.

9.) The spray system, though simple in design, presents an efficient and economical means of reducing the effects of incident solar radiation on roofs.

ROOF GARDENS

The major reason for a roof on a structure is to provide protection from the elements. Unfortunately, this is the only function given to nearly all the roofs, rather than treating them as another livable space of the building, especially in dense urban areas. Through the development of roof gardens this space may be used for a variety of functions. Depending on the geographical location, a roof garden may have to be designed either for its cooling, or heating capabilities.

Roof Gardens for Cooling in Overheated Areas

A roof garden designed to cool a building should use materials that are not heat retainers (lumber, grass, walking tiles) placed on a double sandwich screed to further keep out any stored heat from the roof slab and prevent water seepage. Planting materials should be used to provide shade and further insulate the roof slab, these should be placed strategically so as to shade as much of the garden as possible, to protect the garden from winter breezes and permit convective cooling in the summer. Vine-covered trellises can be used over paths so as to keep them shaded. A focal point in the form of a pond or fountain may be used to add interest. Sitting areas should mostly be provided in shaded zones and a sun bathing area may also be provided. The rest of the garden should be covered with grass or other low growing plants. All paths and resting areas should be made of wood decking or walking tiles, to keep heat absorption to a minimum.(See Fig. 9)

Roof Garden for Heating in Underheated Areas

A roof garden designed to heat a building may use many of the same elements used in the one for cooling. The difference is that all the materials should be chosen and placed so as to take maximum advantage of the sun's radiant heat. The roof slab should be covered with heat retaining materials such as concrete, brick, etc. and the plants located so the shadow falls off the garden edges and again, protection from winter breezes is necessary. Trellises can be used but not covered by a vine, or at best a deciduous vine could be used. Shaded areas should be kept to a minimun, placed only where seating is provided, and then umbrella-type shades that are closed when not in use will provide maiximum heat gain. (See Fig. 10)

Multiple Reasons for Roof Gardens

In May 1976, in Miami, Florida, the author found that in three buildings surveyed possessing R12 insulation on a flat concrete bituminised roof, the average ceiling temperatures of the roof slabs were 10.5°F to 12°F higher than the ceilings of the

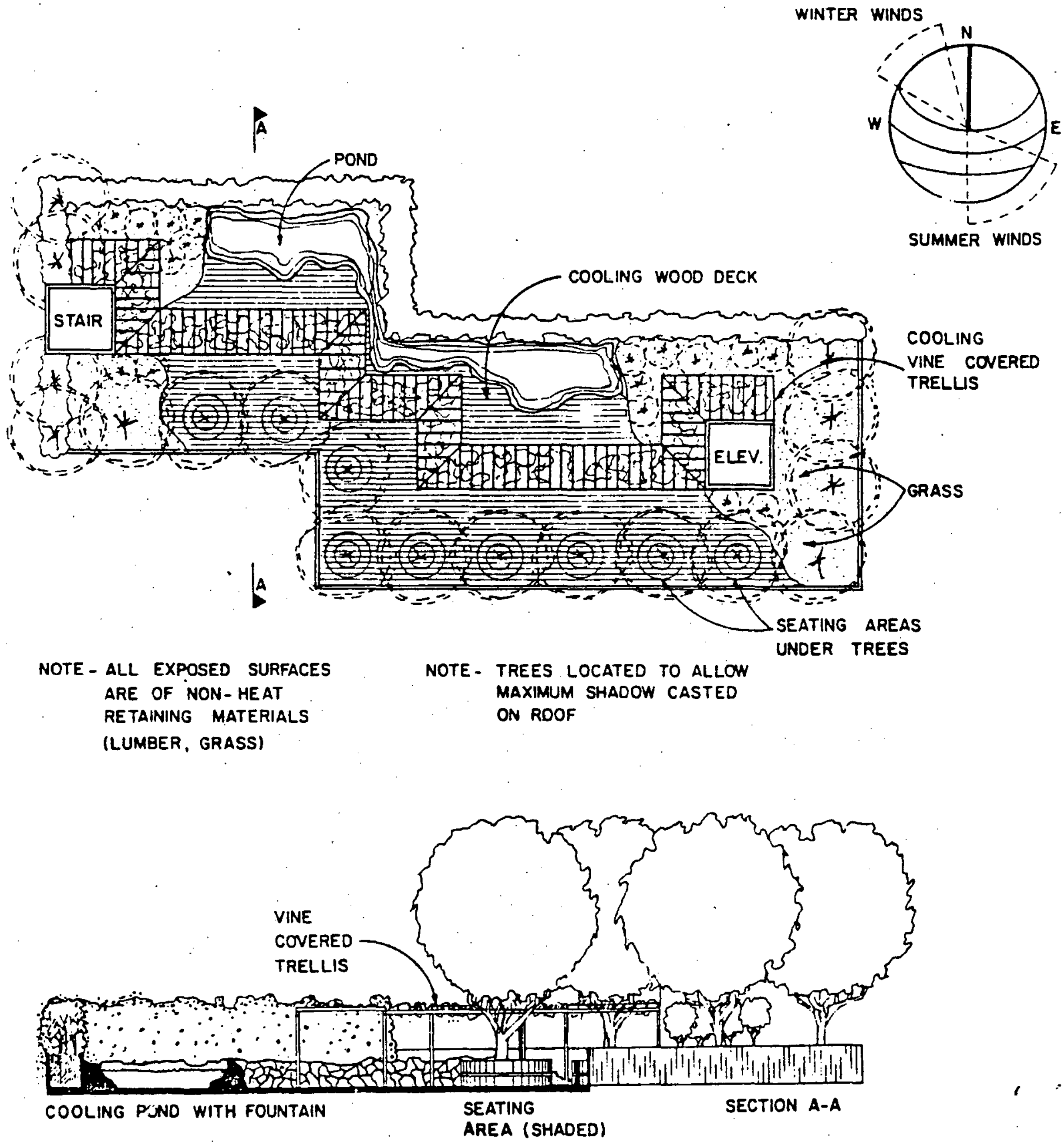


Fig. 9 - Cooling Roof Garden for Overheated Regions

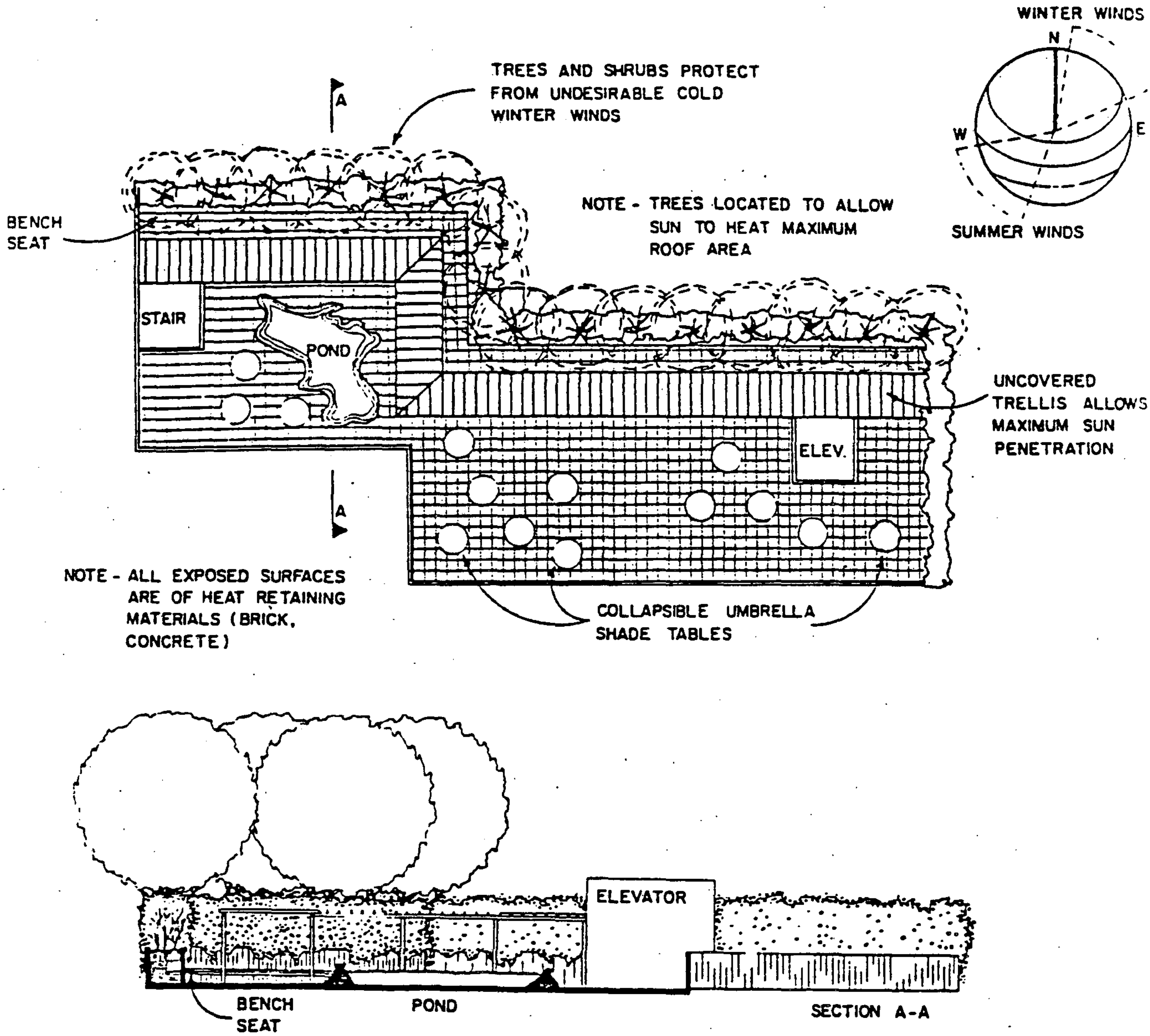


Fig. 10 - Heating Roof Garden for Underheated Regions

floor below.

Roof gardens will substantially increase the usable floor area of a building and in commercial buildings the garden will provide the employees a common area for congregation during lunch hours away from the bustle, noise and pollution of the street below. A well designed roof garden would assist in thermal flow in either direction - in or out.

COMPREHENSIVE PROBLEM IDENTIFICATION AND RESPONSE

The accepted convention to classify climate regions as hot-dry, temperate-humid, etc. is too simplistic as it describes an average annual condition. No earthly location possess a single annual climate regime and most experience three or four seasonal variations - for example, Miami, Flroida, is endowed with warm-humid summers, temperate-humid winter days and cool-humid winter nights. The intervening periods are short and transitionary. Other locations, such as Phoenix, Arizona, experience hot-dry summer days and moderate summer nights, cool-dry winter days and cold-moderately humid winter nights. The intervening seasons experience temperate days and cool-moderately humid nights. In some locations the seasonal and diurnal variations are even more diverse.

Effects of Temperature and Relative Humidity upon Problem Identification & Response

As temperature and relative humidity are the principal bioclimatic components - the impacts of solar radiation and air motion are recognized - these two co-ordinates are examined to dientify problems and responses that may be employed to provide human comfort conditions. The climate in any given location is a mixture of these variables.

Temperature

Hot - over 93°F (over 33.9°C)	Category	A
Warm - 80°F to 92°F (26.7°C to 33.3°C)	"	B
Temperate - 65°F to 79°F (18.3°C to 26.1°C)	"	C
Cool - 45°F to 64°F (7.2°C to 17.8°C)	"	D
Cold - below 44°F (below 6.7°C)	"	E

Relative Humidity

Arid - below 30%	Category	1
Moderate - 30% to 60%	"	2
Humid - over 60%	"	3

Four main comfort control factors are analysed because of close inter-relationship. However, only human, site and landscape are considered as relevant to the subject matter of this paper.

Category A
HOT - over 93°F (over 33.9°C) Problem Identification

HUMAN Very high level of solar and thermal radiation gains during the day. Moderate body heat loss to "sky" at night. Air temeprature above skin temperature. Metabolic heat loss retarded. Excessive perspiration. Air motion causes additional heat gain.

BUILDING Severe overheating experienced by incoming solar and thermal radiation. Difficulties encountered in releasing interior made heat, as external airflow could deposit heat. Outward conductive losses may be enhanced by convection. Glare encountered.

SITE Extremely high radiative gains. All live plantings need a very generous water supply to prevent dehydration. Occurrence of hot winds. High levels of daylight.

LANDSCAPE Scorching and dehydration of live plants. Very rapid evaporation of water. Extreme overheating of paved areas. Rapid growth rate.

Category A
HOT - over 93°F (over 33.9°C) Problem Response

HUMAN Prevent skin and body from severe radiation exposure, atmospheric heat gain, and burning, by using light color, lightweight, full-length cotton clothes and head gear. Protective shading at all times.

BUILDING Prevention of inward heat gain accomplished by use of long time-lag massive external fabric or materials possessing very high resistance to thermal flow. Small external openings are essential. High level exhaust of interior-made heat. Light, preferably white, external surface color. Domed, or vaulted roofs. Orientation for minimum gains. Night and outward radiative cooling essential. Wall shading.

SITE Oreintation for minimizing solar radiation gains and hot air motion. Extensive shading of surfaces. Glare prevention techniques. Ensure ample water supply. Thermal resistance materials to avoid heat accumulation.

LANDSCAPE Very generous watering of live plants. Plants with rapid transpiration rate provide beneficial evaporative cooling. Pools, fountains, waterfalls promote much needed evaporative cooling. Deep shade needed everywhere. Paths, decks and other hard surfaces should be constructed from wood or similar thermal resistor material. Use of vines, pergolas and water sprays are extremely effective. Earth berms and subterranean shelter are advantageous. Encourage airflow for convective cooling of land and building exterior surfaces.

Category B
WARM - 80°F to 92°F (26.7°C to 33.3°C) Problem Identification

HUMAN Moderate to high solar and thermal radiation gain. Moderate thermal exchange with ground. Small radiative loss to "sky". Small conductive loss to air temperature. Air motion promotes heat loss. Much perspiration.

BUILDING Overheating experienced by incoming solar and thermal radiation. Crucial to remove interior made heat: possible through natural convection and conduction. Daylight levels may bê high.

SITE High radiative gains. Generous water supply to live planting. Overheating of paved areas. Daylight levels may be high.

LANDSCAPE Dehydration of live plants. Rapid evaporation of water. Overheating of paved areas. Rapid growth rate.

Category B
WARM - 80°F to 92°F (26.7°C to 33.3°C) Problem Response

HUMAN Light color, lightweight cotton clothes designed for maximum skin exposure to airflow for cooling optimization. Protective body shading at all tiems to prevent excessive radiation gains.

BUILDING Preventation of inward heat gain by use of dense time-lag or high resistance to heat flow materials in external fabric. Large external openings to encourage convective losses. High level exhaust of interior made heat. Light external surface color. Curved or pole-ward pitched roofs. Orientation for minimum heat gains. Convective and outward radiative cooling necessary. Wall shading. Verandahs.

SITE Orientation to minimize solar radiation gains and maximize air motion. Generous shading of surfaces. Glare prevention techniques. Generous water supply. Employ heat resisting materials.

LANDSCAPE Generous watering of live plants. Plants with rapid transpiration rate, provide beneficial evaporative cooling. Pools, fountains, waterfalls promote evaporative cooling. Shade all surfaces. Construct paths, decks and other hard surfaces from thermal resistance materials, such as wood. Vines, pergolas and water sprays provide effective cooling. Earth berms are effective. Encourage airflow for convective cooling of land and building exterior surfaces.

Category C
TEMPERATE - 65°F to 79°F (18.3°C to 26.1°C) Problem Identification

HUMAN Moderate solar radiation gain. Moderate thermal radiation loss. Moderate metabolic heat loss to "sky" and exchange with ground. Desirable level of conductive loss to ambient air. Low level of perspiration. Air movement not critical.

BUILDING Slight overheating of external fabric in upper range. Interior-made heat will cause discomfort unless completely removed. Low levels of daylight may occasionally be experienced.

SITE Moderate radiative gains and losses. Steady plant growth. Air motion acceptable but not sought. Moderate daylight availability.

LANDSCAPE Moderate conditions permit many alternatives, as comfort components are not in critical range.

Category C
TEMPERATE - 65°F to 79°F (18.3°C to 26.1°C) Problem Response

HUMAN Moderate skin exposure or lightweight, medium color range, mixed materials, full-length clothing permissible, but not vital. Availability of low velocity air motion over skin not critical, but beneficial in upper range.

BUILDING Use small time-lag or thermal resistance materials in external fabric. Operable high level exhaust to remove interior heat as needed. Medium-sized exterior openings to permit convective cooling in high range and daylight receipt. Sun patios and porches. Medium color on external surface. Orientation not critical.

SITE Moderate shading needed in higher range. Hard surfaces from thermal capacity materials in lower range, otherwise resistors such as wood.

LANDSCAPE Very wide range of alternatives available as site temperature control is not critical. However, steps must be taken to assure partial shade only, of the building's surface. Exterior living on terraces and patios is desirable. Pergolas are found to be useful. Landscaping may be mainly decorative for social use. Deciduous trees are effective. Earth berms may be used when arid.

Category D
COOL - 45°F to 64°F (7.2°C to 17.8°C) Problem Identification

HUMAN Low solar radiation gains. High thermal radiation loss. High conductive loss to ambient air. No perspiration. Air motion promotes rapid metabolic heat loss.

BUILDING Underheating of building caused by moderate to low solar radiation gains and rapid outward conduction, convection and long wave radiation. Conservation of external gains and interior-made heat. Moderate to low daylight levels may be experienced.

SITE Low radiative gains, high losses. Air motion promotes excessive cooling. Moderately low daylight availability. Moderate plant growth.

LANDSCAPE Solar exposure to encourage plant growth. Heat retention in plant beds and hard surfaces. Possible damp conditions due to slow evaporation rate. Excessive deposits of falling leaves.

Category D
COOL - 45°F to 64°F (7.2°C to 17.8°C) Problem Response

HUMAN Complete skin cover with medium weight, wool clothing desirable to prevent metabolic heat loss by outward radiation, conduction and accelerated convective loss by air motion. Direct or indirect solar radiative gain desirable. Dark color range of clothing.

BUILDING Use thermal mass in exterior and interior fabric with medium time-lag. Generally, one medium size opening per room to discourage cross ventilation. Design envelope for warming. No high level ventilation of interior space or roof. Use dark colored, rough textured materials on exterior surface. Greenhouse and large glass exposures on equatorial elevation. Orientation for heat gain.

SITE Employ and expose thermal capacity materials to retain solar heat. Prevent airflow. Orientation for solar gains.

LANDSCAPE Provide wind barriers to divert unwanted cooling breezes. Expose site and buildings for maximum solar gain with precision planting. Earth berms and glass house winter gardens are effective. Use thermal capacity materials for all hard surfaces.

Category E
COLD - below 44°F (below 6.7°C) Problem Identification

HUMAN Very low solar radiation gains. Very high thermal radiation loss. Very high conductive loss to ambient air. No perspiration. Air motion promotes very rapid metabolic heat loss and wind chill.

BUILDING Serious underheating of building caused by very low solar radiation gains and severe outward conduction and long wave radiation losses. Conservation of external gains and interior-made heat. Low daylight levels.

SITE Very low radiative gains and very high losses. Air motion promotes excessive chilling. Low daylight availability. Slow plant growth. Frequent freezing of water. Bare ground surfaces.

LANDSCAPE Frost damage to plants and exposed materials. Freezing of pools and fountains. Difficult to grow deciduous plants and trees. Poor undergrowth and ground cover.

Category E
COLD - below 44°F (below 6.7°C) Problem Response

HUMAN Entire skin cover with heavy weight, cool clothing essential, to resist too rapid metabolic heat loss by outward radiation, conduction and accelerated loss by convective air motion. Maximize direct or indirect solar gain. Dark color range of clothing.

BUILDING Use high thermal mass materials throughout. Generally, one small external opening per room. Avoid openings on poleward elevations and encourage solar gain on equatorial elevations by employing greenhouse and larger windows. Design envelope for warming. No high level ventilation of interior space or roof. Use dark colored, rough textured materials on exterior surfaces. Maximize orientation for solar gain.

SITE Maximize use of thermal capacity materials. Maximize orientation and exposure for solar gain and daylight attainment. Prevent airflow.

LANDSCAPE Precision planting to miximize solar gains to building and site. Employ thermal capacitor materials everywhere. Strategically located wind breaks to prevent chilling. Earth berms and underground structures are very effective. Equatorward, attached greenhouses are effective in higher range only.

Category 1
ARID - below 30% relative humidity Problem Identification

HUMAN Air vapor pressure is usually low and is an important channel for metabolic heat loss, essential to restoring balance. Air motion varies and is, occasionally, high, accelerating heat loss through too rapid evaporation of perspiration.

BUILDING Dehydration of materials causes cracks and crazing. Dust. Occasional high winds. Glare. Extreme temperature differences in seasonal and diurnal ranges.

SITE Water scarcity. Soil parched and cracking. Lack of plant life. Dust and occasional sand storms. Impoverished soil. Severe glare problems. Rapid absorption of precipitants.

LANDSCAPE Difficult plant growing conditions resulting in slow rate of growth. Plants with very low transpiration rate may succeed, so shade trees, leafy shrubs and vines are difficult to nurture. Dry season abundance of deciduous leaf droppings.

Category 1
ARID - below 30% relative humidity Problem Response

HUMAN Protect skin and body from dehydration and harmful airflow. Voluminous, full-length clothes and head gear increases and preserves air vapor pressure at skin surface, near desirable comfort levels.

BUILDING Construct building fabric from favored time-lag materials. Small external openings. Encourage moisture preservation in interior spaces. Promote evaporative cooling techniques and interior courtyard design when overheated. Discourage air motion.

SITE Water conservation techniques are vital. Air/water contact only when evaporative cooling is needed. Occasional wetting of soil to control dust. Dark colors or shields to counteract glare.

LANDSCAPE Earth-sculptured landscape using sand, rocks, earth mounds, berms, etc. is effective with low maintenance needs. Select plants with low transpiration rate and water frequently. Encourage pools and fountains to promote evaporative cooling in overheated conditions. Man-made shading when needed.

Category 2
MODERATE - 30% to 60% relative humidity Problem Identification

HUMAN Air vapor pressure in comfortable range necessary to promote metabolic heat loss for all but the most strenuous tasks, to resotre heat balance. Air motion is variable and promotes heat loss.

BUILDING Preservation of acceptable vapor pressure conditions in building structure and interior. Daylight enhancement in large buildings and waning situations. Average precipitation, occasionally, seasonal.

SITE Micro-climate preservation. Drainage control to counter occasional heavy precipitation. Plant overgrowth control.

LANDSCAPE Orderly plant growth. Seasonal heavy leaf droppings. Average plant watering needs.

Category 2
MODERATE - 30% to 60% relative humidity Problem Response

HUMAN Skin exposure not critical factor in clothing design. Presence of lack of air motion over skin is not pertinent or crucial.

BUILDING Medium-sized openings located to permit ventilation of interior space to counter humidity increase. Moderate structure ventilation. Courtyards, patios and verandahs are effective when temperature permits.

SITE Orientation for sun and air motion to preserve desirable humidity. Ensure sufficient water conservation and drainage. Maximize daylight available.

LANDSCAPE Planting strategy to permit solar access for prevention of accelerating humidity. Medium time-lag materials for hard surfaces. Average transpiration planting. Evaporative cooling with pools and fountains, effective when hot.

Category 3
HUMID - over 60% relative humidity — Problem Identification

HUMAN Air vapor pressure is high and impedes opportunities for metabolic heat loss essential to restore heat balance. Air motion is variable, but essential for perspiration evaporation and heat loss.

BUILDING Exterior and rising damp. Mildew, fungus, vermin. Low to moderate levels of daylight. Seasonal to daily precipitation, moderate to high. Occasional high speed winds. Small seasonal and diurnal extremes of temperature.

SITE Drainage control to prevent flooding and erosion. Abundant plant growth. Daylight availability could be a problem.

LANDSCAPE Control of plant overgrowth and weeds. Low levels of daylight in deep shade. Water congestion after heavy rainfall. Obstruction of desirable cooling breezes. Prevention of radiative gains in underheated conditions. Seasonal abundance of deciduous tree leaf droppings.

Category 3
HUMID - over 60% relative humidity — Problem Response

HUMAN Clothing design permitting maximum skin exposure to assist perspiration evaporation is necessary and crucial in the higher range. Accelerated airflow over skin promotes perspiration evaporation as humidity increases. Skin-revealed clothing when hot.

BUILDING Ventilate building fabric, generously when hot and adequately when cold. Large openings throughout building when overheated under natural conditions. Size exterior windows to encourage daylight use and preserve warmth when underheated.

SITE Water control system to provide conservation for needs and drain off with sufficient outfalls to prevent erosion and flooding. Provide daylight access relative to conditions. Orientation for solar access when underheated and drying needs are established.

LANDSCAPE Strategic planning and precision planting to provide daylight access, heating or cooling of site and buildings as needed. Careful selection of rapid transpiration plants. Select trees with inherent minimum leaf fall. Discriminating use of non-living materials to control undesirable plant overgrowth.

SOME SITE PLANNING AND LANDSCAPE TECHNIQUES FOR SELECTED REGIONS

The evaluation of the climate of each region is essential in the design of both the landscape, and orientation of the building. (See Fig. 10)

The orientation must take into account the seasonal prevailing breezes, extreme temperatures, humidity and the seasonal and daily solar angles. In many cases, the building may be oriented and designed to take maximum advantage of these natural phenomena by aiding in the cooling or heating of the structure. The landscape should be designed in conjunction with the structure to assure a solution that will best suit each individual situation.

Landscape Techniques for Tucson, Arizona (Fig. 11)

Cool-moderate winters, Categories D & 2
Hot-arid summers, Categories A & 1

A look at the bioclimatic chart reveals that the annual temperature and humidity relationship is (See Fig. 12):

1.) Spring: temperate-arid days, cool-arid nights
2.) Summer: hot-arid days, temperate-moderate nights
3.) Autumn: temperate-arid days, cool-moderate nights
4.) Winter: cool-arid days, cold-moderate nights

The diurnal temperature range averages 30°F (16.7°C).

Under natural conditions, year-round aridity demands the prevention of airflow across human skin, building and site. Additionally, when considering temperature in the winter, airflow is harmful, while during spring and fall days it is beneficial and at nights harmful. The reverse is true in summer when airflow is undesirable during the day and very desirable at night. Under mechanically controlled conditions, air motion over site and the building face is always needed during the overheated summer days and nights and during spring and fall days only. Solar heating of the site and building should be aggressively promoted during the winter and moderately achieved during spring and autumn.

Along with the climate, the lack of natural vegetation and water, seasonal wind shifts and glare, indicate that the employment of earth berms, sod roofs, interior courtyards and south-facing greenhouses would make large contributions to the interior comfort of buildings. Water conservation is a key factor for its use in badly needed humidification and evaporative cooling during overheated periods. Roof spraying, both day and night, is found to be very effective during overheated periods. Earth berming is gainfully employed on east, west and north elevations, with the additional benefit of planting shrubs and vines on the east and west elevations to intercept low sun angles. The south-facing greenhouse and courtyard roof are designed to alternate glass and insulation to provide both summer shading and airflow, as well as winter heating. Rapid transpiration planting, under controlled interior conditions, would further improve interior humidity. All exterior surfaces should be rough textured and medium range color to reduce glare. When temperatures permit the poor rainfall experienced encourages outside living on terraces, patios, etc.

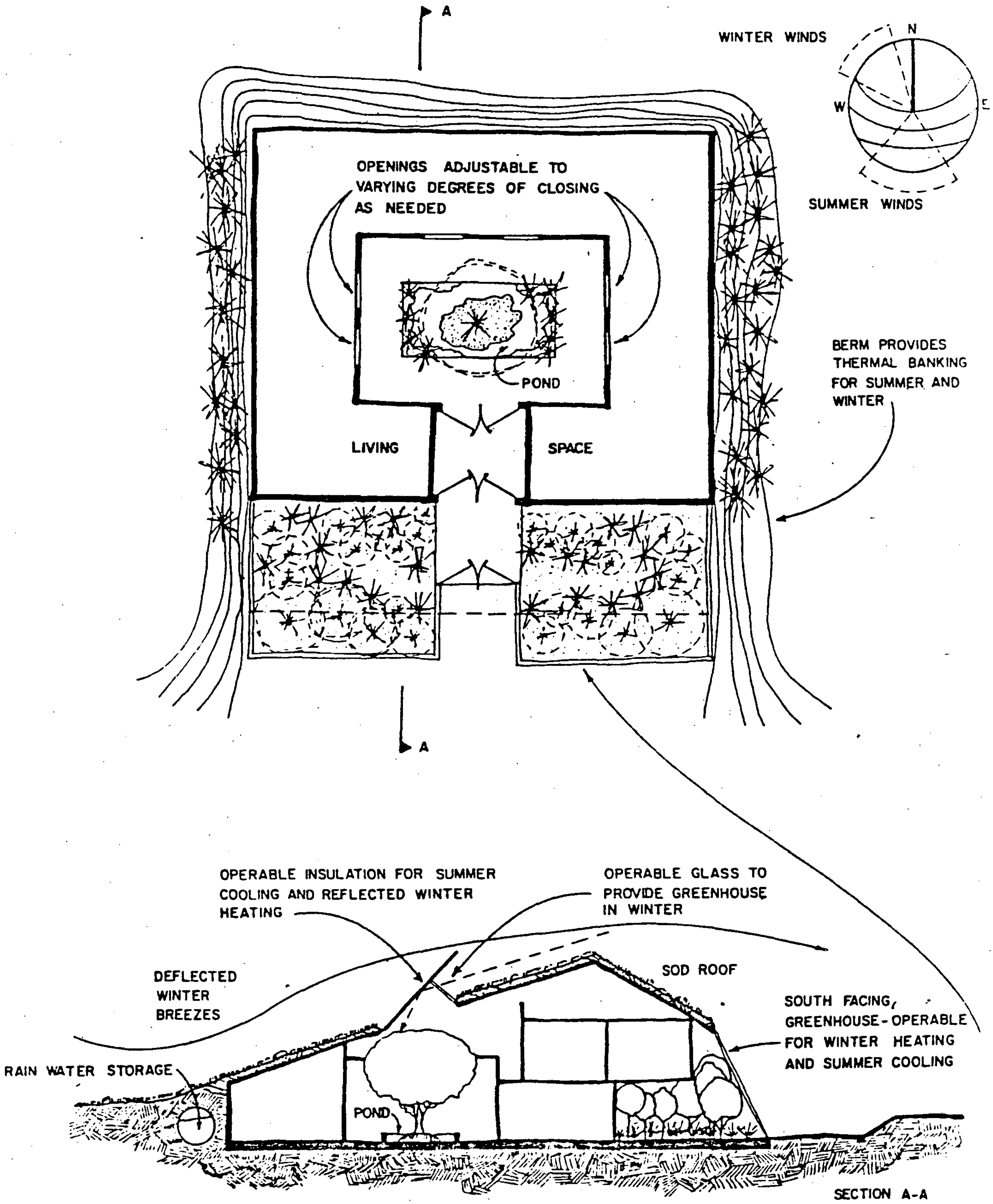
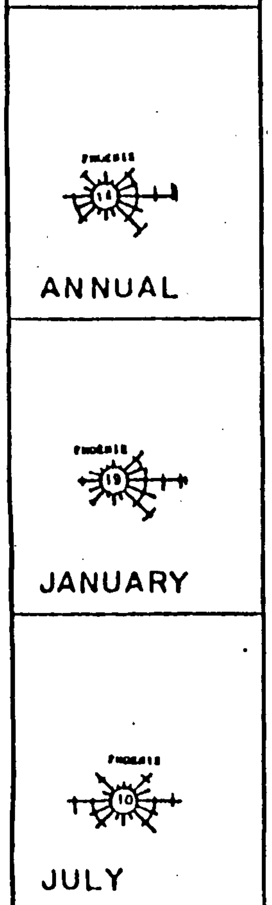


Fig. 11 - Landscape Techniques for Tucson, Arizona; A.1 Summers & D.2 Winters

WIND ROSES

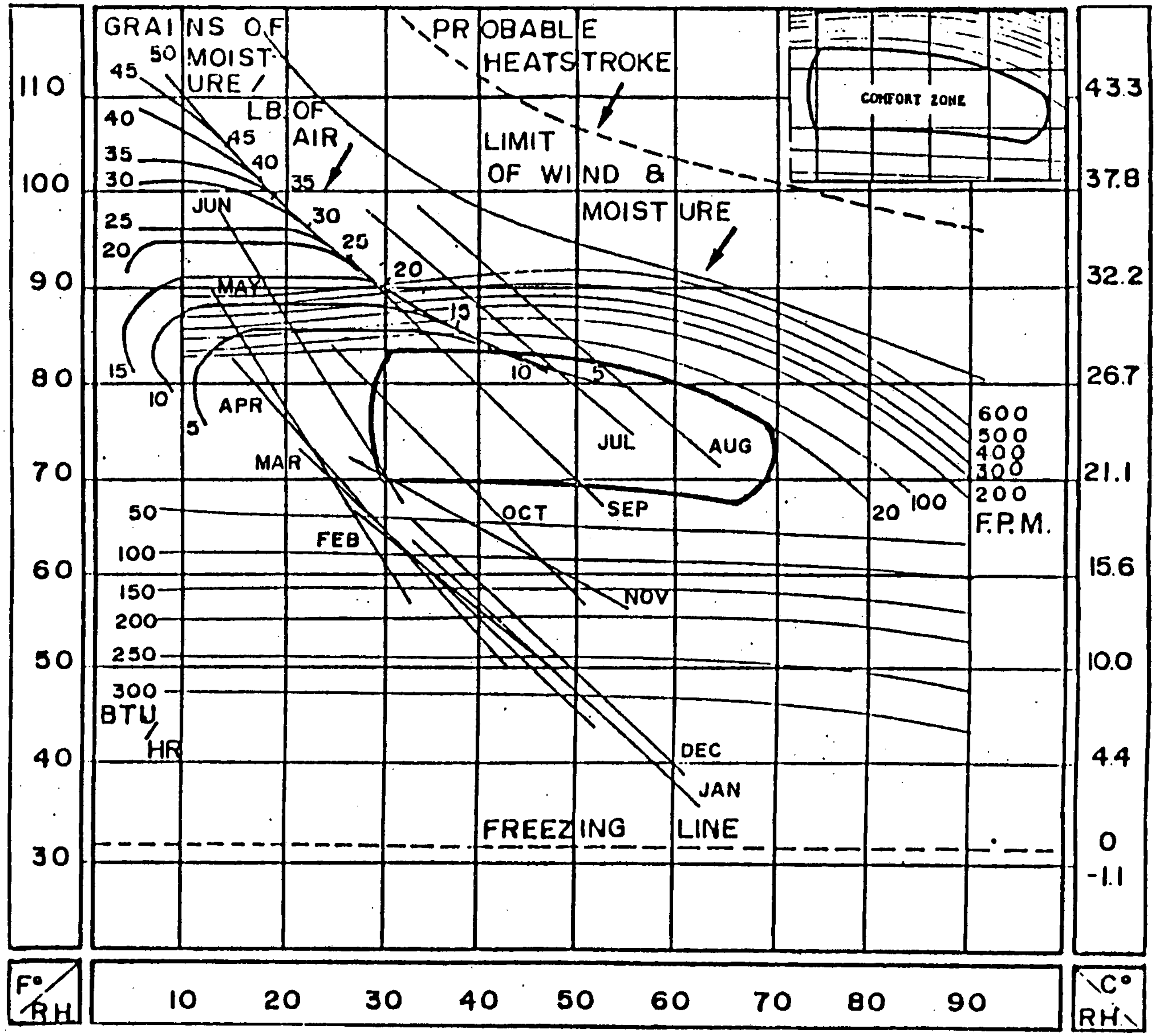


LATITUDE 32° 7' N
LONGITUDE 110° 56' W
ELEVATION 2584'

PRECIPITATION		
	NORMAL TOTAL	11.00"
	MAX. MONTHLY	7.93"
	MIN. MONTHLY	0.00"
	MAX. IN 24 HRS	3.93"

MEAN NO. OF DAYS		
	CLEAR	194
	PARTLY CLOUDY	91
	CLOUDY	80
	THUNDER-STORM	40
	HEAVY FOG	1
	PREC. OF 1.0" OR MORE	50
	DAYS ABOVE 90°F	144

SUN			
	DEGREE DAYS	HEAT	1800
	DEGREE DAYS	COOL	
	RADIAT.	BTU	
	RADIAT.	LANGLEY	513



HOT
DRY

WIND FROM SE ALL MONTHS BUT MARCH FROM SSE
AVG. SPEED 7.8 MPH

Fig. 12 - State of Bioclimatic Comfort - Annual - Tucson, Arizona

Note: Landscapes encompass any material in human vision, including concrete pavings, sand, earth, water, boardwalks, stonework and live plants. Landscapes are integrated into buildings, at the facade and internally. Glass houses are a common landscape feature.

Climatic Regions

A-1 Hot-Arid	A-2 Hot-Moderate	A-3 Hot-Humid	B-1 Warm-Arid	B-2 Warm-Moderate	B-3 Warm-Humid	C-1 Temperate-Arid	C-2 Temperate-Moderate	C-3 Temperate-Humid	D-1 Cool-Arid	D-2 Cool-Moderate	D-3 Cool-Humid	E-1 Cold-Arid	E-2 Cold-Moderate	E-3 Cold-Humid	Landscape Related Applications
						0	0	0	0	0	0	0	0	0	slope preference - equatorial
0	0	0	0	0	0										" " - poleward
															" " - easterly
															" " - westerly
	0	0	0	0	0	0	0	0							" " - windward
0									0	0	0	0	0	0	" " - leeward
0	0	0	0	0		0	0	0							location of water bodies to reduce specular heat and glare
									0	0	0	0	0	0	location of water bodies to maximize specular heat and glare
				0	0	0	0	0	0	0	0	0	0	0	siting of buildings as high as possible on sloping landmass
0	0	0	0												siting of buildings as low as possible on sloping landmass
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	siting of building as close as possible to poleward lot line to attain maximum solar control
		0	0	0	0			0							maximum ventilation of site
0	0					0			0	0	0	0	0	0	minimum ventilation of site
							0								ventilation of site not critical
0	0								0	0	0	0	0	0	employment of wind barriers
		0			0			0							employment of wind directing techniques
									0	0	0	0	0	0	greenhouse design for heating
0	0		0	0											" " " cooling
						0	0	0							" " " heating/cooling
0	0	0	0	0	0										employment of cooling terraces
									0	0	0	0	0	0	" " heating "
						0	0	0							" " cooling/heating terraces
0	0	0	0	0	0										" " cooling verandah
									0	0	0	0	0	0	" " heating "
						0	0	0							" " cooling/heating verandah
0	0		0	0		0	0								" " cooling patio or courtyard
									0	0	0				" " heating " " " (atrium)
						0	0	0							" " cooling/heating patio or courtyard
0	0		0	0					0	0		0	0	0	trogloditic structure design
									0	0	0	0	0	0	berming of poleward perimeter walls for thermal regulation

Climatic Regions															
A-1 Hot-Arid	A-2 Hot-Moderate	A-3 Hot-Humid	B-1 Warm-Arid	B-2 Warm-Moderate	B-3 Warm-Humid	C-1 Temperate-Arid	C-2 Temperate-Moderate	C-3 Temperate-Humid	D-1 Cool-Arid	D-2 Cool-Moderate	D-3 Cool-Humid	E-1 Cold-Arid	E-2 Cold-Moderate	E-3 Cold-Humid	Landscape Related Applications
0	0		0	0											berming of equatorial perimeter walls for thermal regulation
0	0		0	0								0	0	0	berming of easterly perimeter walls for thermal regulation
0	0		0	0								0	0	0	berming of westerly perimeter walls for thermal regulation
0	0								0	0	0	0	0	0	sod roof for thermal banking
0	0	0	0	0	0	0	0	0							airflow over exterior walls and roof
when diurnal range exceeds 30°F															deep still water layer on flat roof with operable insulating shutters
when diurnal range is between 20°F and 30°F															shallow still water layer on flat roof with operable insulating shutters
0	0	0	0	0	0										water spraying on roof and ground
						0	0	0							air intake through earth tunnel for cooling and heating
0	0	0	0	0	0										maximum shade of external surfaces exposed to radiant load
						0	0	0							partial shade of external surfaces exposed to radiant load
									0	0	0	0	0	0	minimum shade of external surfaces exposed to radiant load
0	0	0	0	0	0	0	0	0							external landscape shading devices
0	0	0	0	0	0	0	0	0							growth of deciduous vine on roof
0	0	0	0	0	0	0	0	0							growth of deciduous vine on walls exposed to radiant load
						0	0	0							deciduous trees on equatorial exposure
0	0	0	0	0	0										" " " poleward exposure
						0	0	0	0	0	0				" " " easterly exposure
						0	0	0	0	0	0				" " " westerly exposure
0	0	0	0	0	0										evergreen " " equatorial exposure
									0	0	0	0	0	0	" " " poleward exposure
0	0	0	0	0	0										" " " easterly exposure
0	0	0	0	0	0										" " " westerly exposure
									0	0	0	0	0	0	landscape use of thermal capacitor materials
0	0	0	0	0	0										" " " " resistor "

Climatic Regions															
A-1 Hot-Arid	A-2 Hot-Moderate	A-3 Hot-Humid	B-1 Warm-Arid	B-2 Warm-Moderate	B-3 Warm-Humid	C-1 Temperate-Arid	C-2 Temperate-Moderate	C-3 Temperate-Humid	D-1 Cool-Arid	D-2 Cool-Moderate	D-3 Cool-Humid	E-1 Cold-Arid	E-2 Cold-Moderate	E-3 Cold-Humid	Landscape Related Applications
						0	0	0							landscape use of thermal capacitor/resistor materials combination
									0	0	0	0	0	0	reflective ground surfaces on equatorial exposures
									0	0	0	0	0	0	" " " " poleward exposures
									0	0	0	0	0	0	" " " " easterly exposures
									0	0	0	0	0	0	" " " " westerly exposures
0	0	0	0	0	0	0	0	0							non-reflective ground surfaces on equatorial exposures
0	0	0	0	0	0	0	0	0							non-reflective ground surfaces on poleward exposures
0	0	0	0	0	0	0	0	0							" " " " easterly "
0	0	0	0	0	0	0	0	0							" " " " westerly "
0	0	0	0	0	0										paved areas located leeward and separated from building and outdoor living spaces
									0	0	0	0	0	0	paved areas located windward and connected to the building and outdoor living areas
0	0	0	0	0	0	0	0	0							use of light colors for surfaces exposed to radiant load
						0	0	0							use medium colors for surfaces exposed to radiant load
									0	0	0	0	0	0	use dark colors for surfaces exposed to radiant load
									0	0	0	0	0	0	use of rough textured surfaces exposed to radiant load
0	0	0	0	0	0	0	0	0							use of smooth textured surfaces exposed to radiant load

Landscape Strategies for Miami, Florida (Figs. 13)
Temperate-humid winters - Categories C.3
Warm-humid summers - Categories B.3

A look at the bio-climatic chart (Fig. 14) reveals that the annual temperature/humidity relationship is:

1.) Spring: temperate-moderate days, temperate-humid nights
2.) Summer: warm-humid days, warm-very humid nights
3.) Autumn: warm-humid days, warm-very humid nights
4.) Winter: temperate-moderate days, cool-humid nights

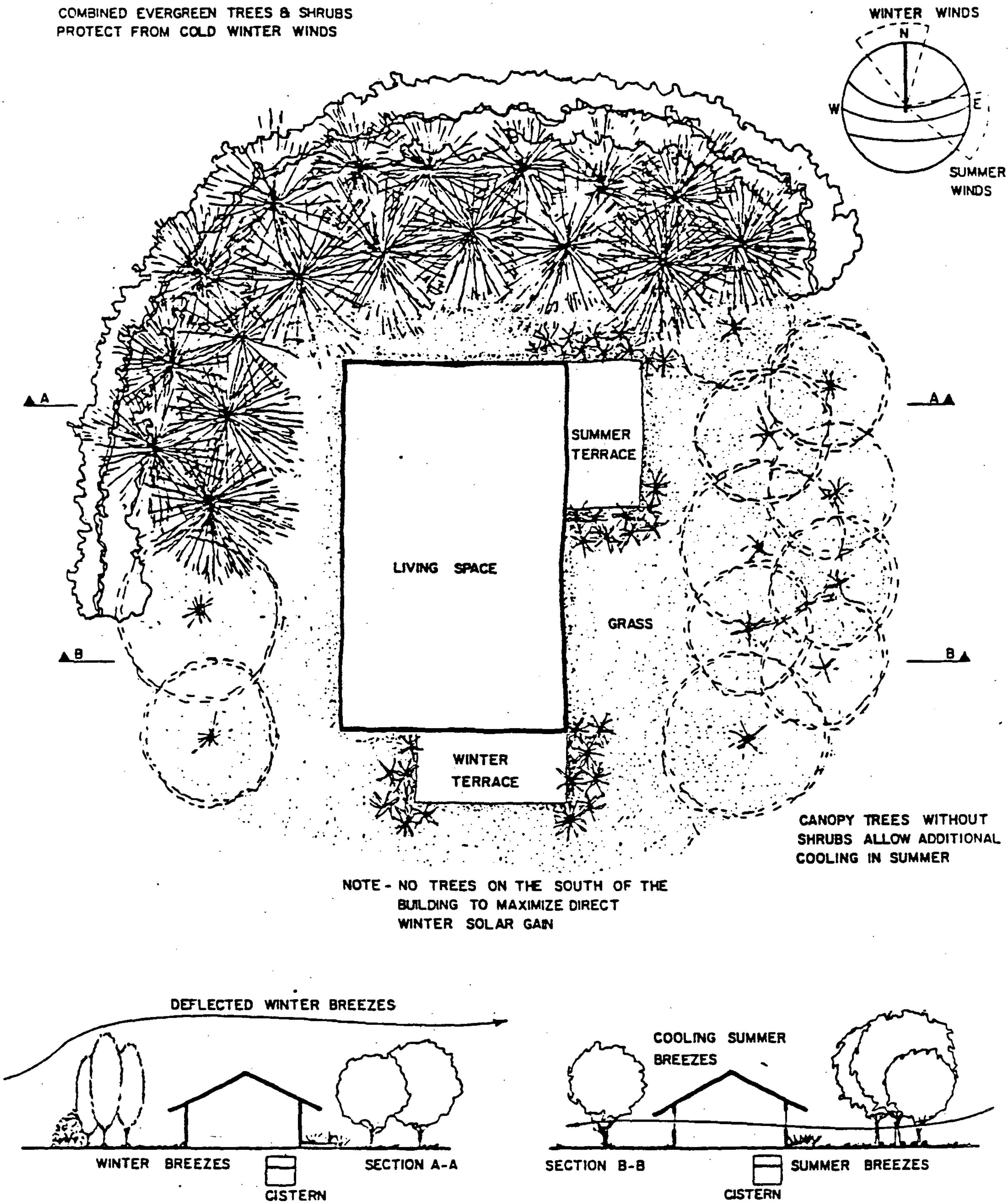


Fig. 13 - Landscape Techniques for Miami, Florida; B.3 Summers & C.3 Winters

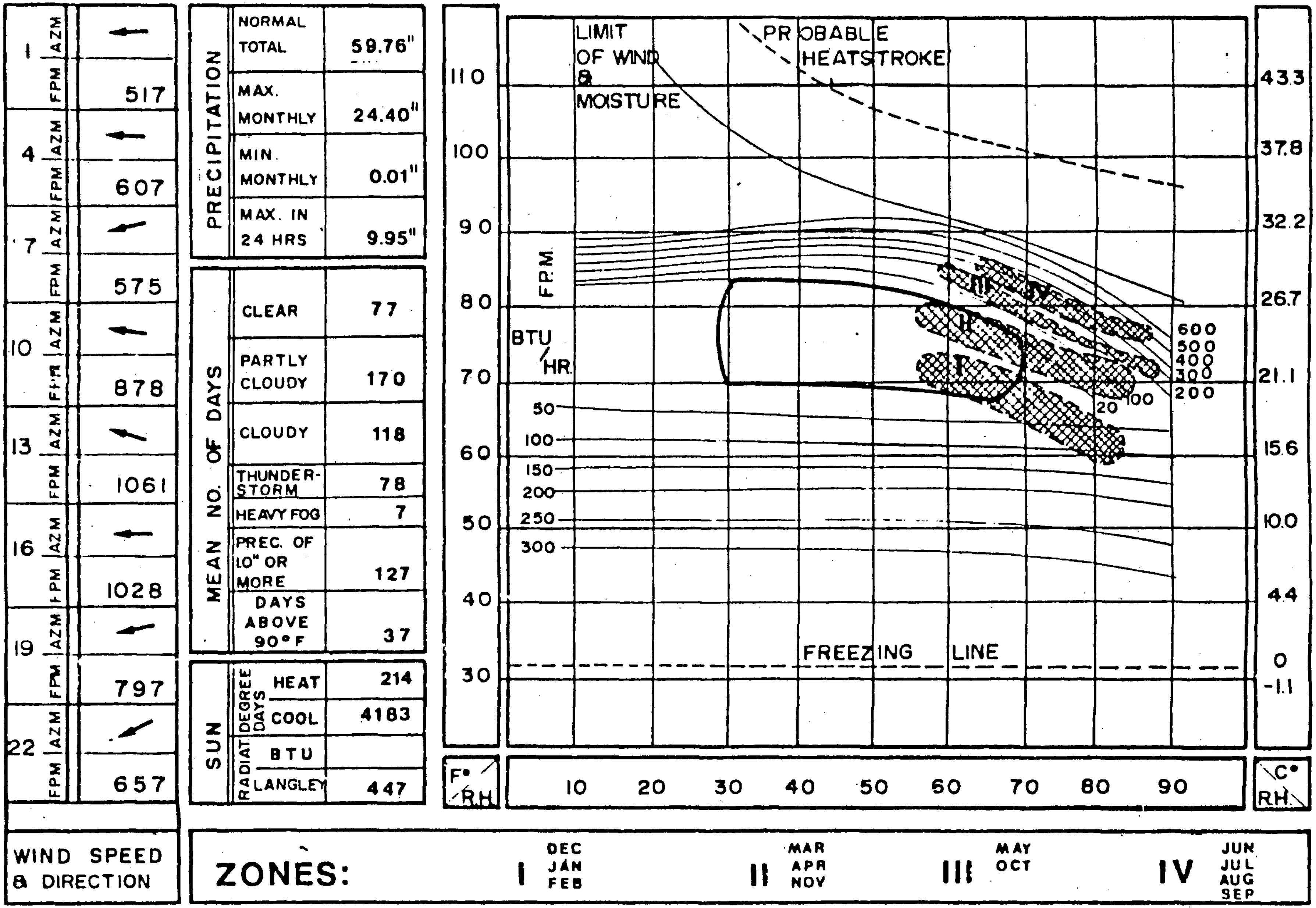


Fig. 14 - State of Biclimatic Comfort - Annual Average - Miami, Florida

The diurnal temperature range averages 11°F (6°C).

Under natural conditions, year-round humidity, demands airflow over human skin, building and site. Additionally, when considering temperature, this need is reinforced for all but winter nights. Generous shading is needed for all times of the year, except the winter, when moderate direct solar heating of the building is all that is required to attain interior comfort. Buildings should favor an east orientation to favor desirable prevailing breezes during the overheated seasons. Unwanted solar gain in east and west facades can be countered with appropriate shading devices. Under mechanically controlled conditions, the building should favor orientation for minimum solar gain. However, airflow over the building face should be encouraged during the overheated season.

Earth berms and enclosed patios discourage airflow and are to be avoided. Greenhouses encourage increase in humidity and heat and are to be avoided for all seasons. Precision planting is necessary. A combination of a triple row of conifer trees and shrubs to provide an effective wind break from the north, as a protection from undesirable winter winds. A generous arrangement of canopy trees, without shrubs on the east to allow undisturbed evapo-transpirative cooling from the desirable prevailing breezes and yet provide sufficient sun shading. A dense combination of trees and shrubs on the west exposure to counteract the summer, spring and autumn afternoon sun. The south orientation is without trees and shrubs to permit winter solar gain. At this latitude there is no direct solar gain on the south wall in the summer. Grass and ground cover is planted throughout the site to reduce ground temperature and long wave radiation. Weather permitting, winter and summer terraces are strategically located, to absorb winter sunshine and maximum shading and cooling breezes, respectively. Wrap-around verandahs are very effective in this climate and should be integrated with the landscape.

Landscape Strategies for Washington, D.C. (Fig. 15)

Cold-humid winters - Categories E.3
Temperate-humid summers - Categories C.3

A look at the bio-climatic chart (Fig. 16) reveals that the annual temperature/humidity relationship is:

1.) Spring: cool-moderate days, cool-humid nights
2.) Summer: warm-humid days, temperate-humid nights
3.) Autumn: temperate-moderate days, cool-humid nights
4.) Winter: cool-moderate days, cold-humid nights

The diurnal temperature range averages 20°F (11°C)

Under natural conditions, year-round humidity prevails at night and during summer days. For the remaining period moderately humid conditions are experienced. Solar gain is needed for the winter and spring seasons. Airflow across skin, building and site are imperative during summer days and nights and autumn days. In this location the building orientation, facing south, would satisfy both cooling and heating needs. Under mechanically controlled conditions, orientation for building and site heating and cooling needs is paramount. In these circumstances airflow over the building face is encouraged during the overheated season only.

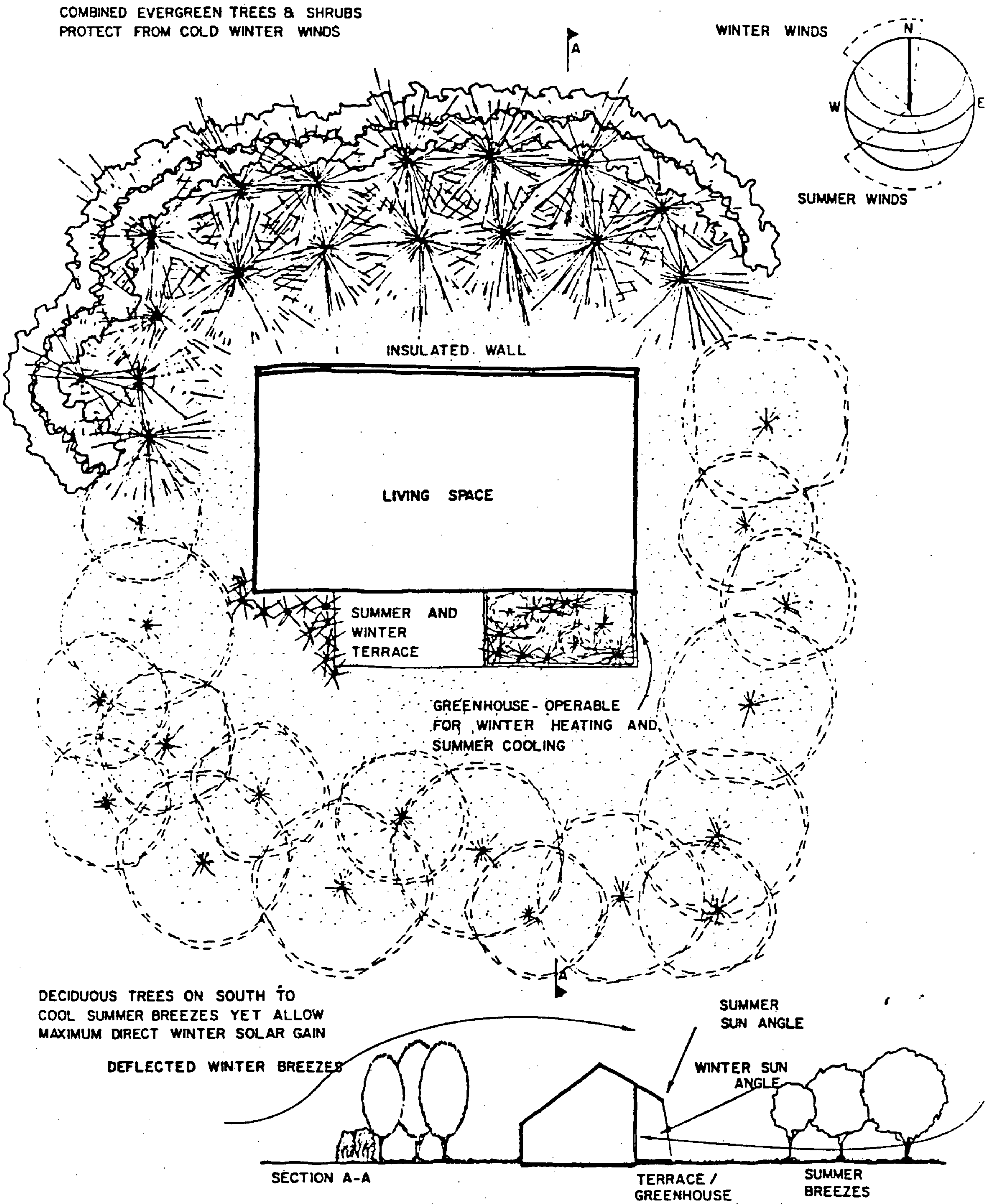
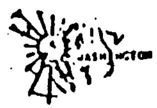


Fig. 15 - Landscape Techniques for Washington, D.C.; B.3 Summers & D.2 Winters

WIND ROSES



ANNUAL

JANUARY

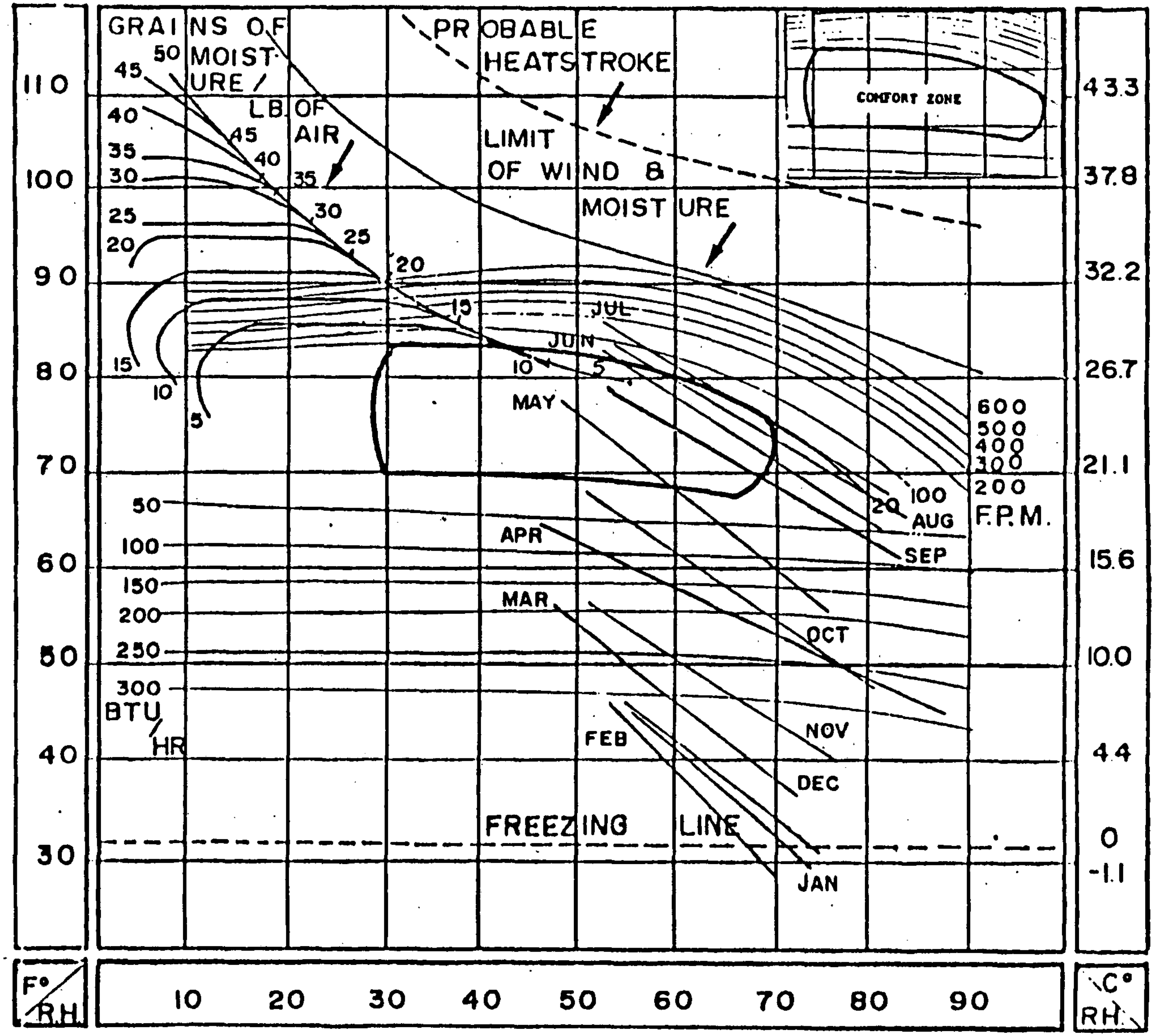
JULY

LATITUDE 38° 54' N
LONGITUDE 77° 03' W
ELEVATION 72'

PRECIPITATION	NORMAL TOTAL	41.44"
	MAX. MONTHLY	17.45"
	MIN. MONTHLY	0.14"
	MAX. IN 24 HRS.	7.31"

MEAN NO. OF DAYS	CLEAR	124
	PARTLY CLOUDY	118
	CLOUDY	123
	THUNDER-STORM	33
	HEAVY FOG	12
	PREC. OF 1.0" OR MORE	124
	DAYS ABOVE 90°F	28

SUN	DEGREE DAYS	HEAT	4224
		COOL	
	RADIAT.	BTU	
		LANGLEY	356



TEMPERATE — WIND FROM S IN SUMMER, WINTER FROM NW
AVG. SPEED 7.1 MPH

g. 16 – State of Bioclimatic Comfort – Annual – Wa ington, D.C.

Combination of a triple row of evergreen trees and shrubs provide an effective wind barrier for undesirable northerly winter winds. Desirable southwesterly breezes are allowed to collect evapo-transpirative cooling during the overheated seasons. The location of an adaptable greenhouse on the south facade permits sheltered exterior living in spring and fall and contributes generously to provide additional winter warmth. The opposing directions of the winter and summer winds allow one terrace to serve year-round functions. Ground surfaces are covered with grass or plants and time-lag terraces and paths are carefully located.

Landscape Strategies for Grand Junction, Colorado (Fig. 17)

Cold-humid winters - Categories E.3
Warm-moderate winters - Categories B.2

A look at the bio-climatic chart (Fig. 18) reveals that the annual temperature/relative humidity relationship is:

1.) Spring: cool-arid days, cool-moderate nights
2.) Summer: warm-arid days, temperate-arid nights
3.) Autumn: cool-moderate days,, cold-moderate nights
4.) Winter: cold-humid days, very cold-very humid nights

The diurnal temperature range averages 30°F (16.7°C).

Under natural conditions, summers only are comfortably tolerable, though slightly dry. During this period, air motion over human skin, through building interiors and across the site is desirable. At all other times air motion is undesirable. Humidification is needed in spring and summer and evaporative cooling is desirable during the summer only. Moderate solar gain is needed in the spring, with increasing needs for heat during the autumn and winter. Shading is needed in the summer. Under mechanically controlled conditions, the building must favor solar orientation needs only and be sheltered from chilling winds. Here there is a problem, as both summer and winter winds prevail from the southwest.

It is vital that the cold winter winds from the south are directed away from the building while still preserving the entire south facade for solar heating. As the cooling winds for the summer also come from the same direction, this requirement calls for no obstruction. Logically, the winter wind barrier must convert to a wind director for the summer. As no planting can perform this task, a man-made structure in the form of a collapsible screen, that can also be draped with vines, can be strategically located to answer these contrary needs. The summer terrace will need to be placed toward the south or west to utilize the seasonal breezes. A glass house should be attached to the south wall to optimize solar gain for extended spring and autumn operation. Additionally, winter warmth is enhanced with collapsible night insulation. (Adequate resistor insulation should be employed on north, east and west elevations, to prevent heat loss.) Alternatively, earth berms could be gainfully employed in these locations.

Landscape Strategies for Fairbanks, Alaska (Fig. 19)

Cold-humid winters - Categories E.3
Cool-moderate summers - Categories D.2

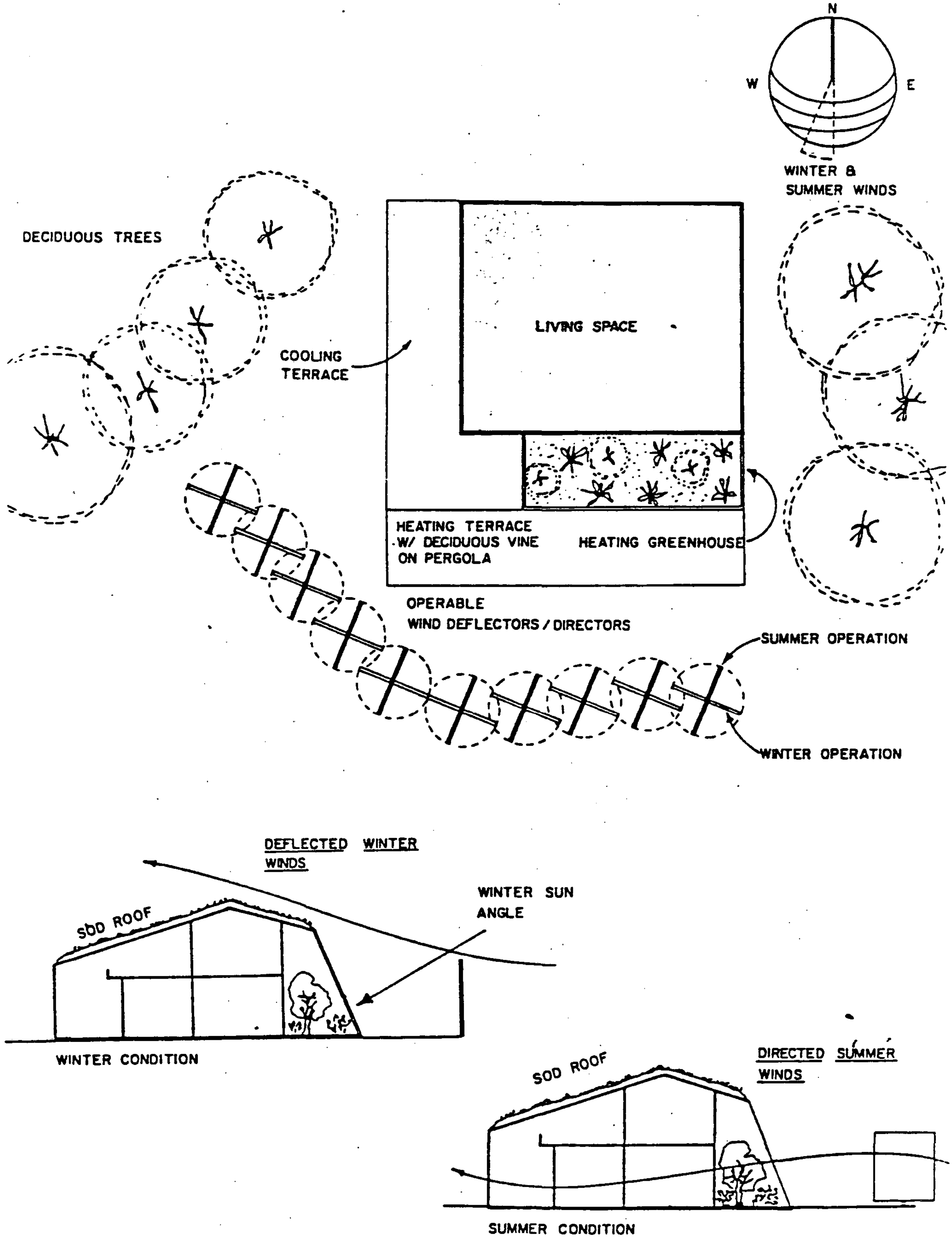


Fig. 17 - Landscape Techniques for Grand Junction, Colorado; B.2 Summers & E.3 Winters

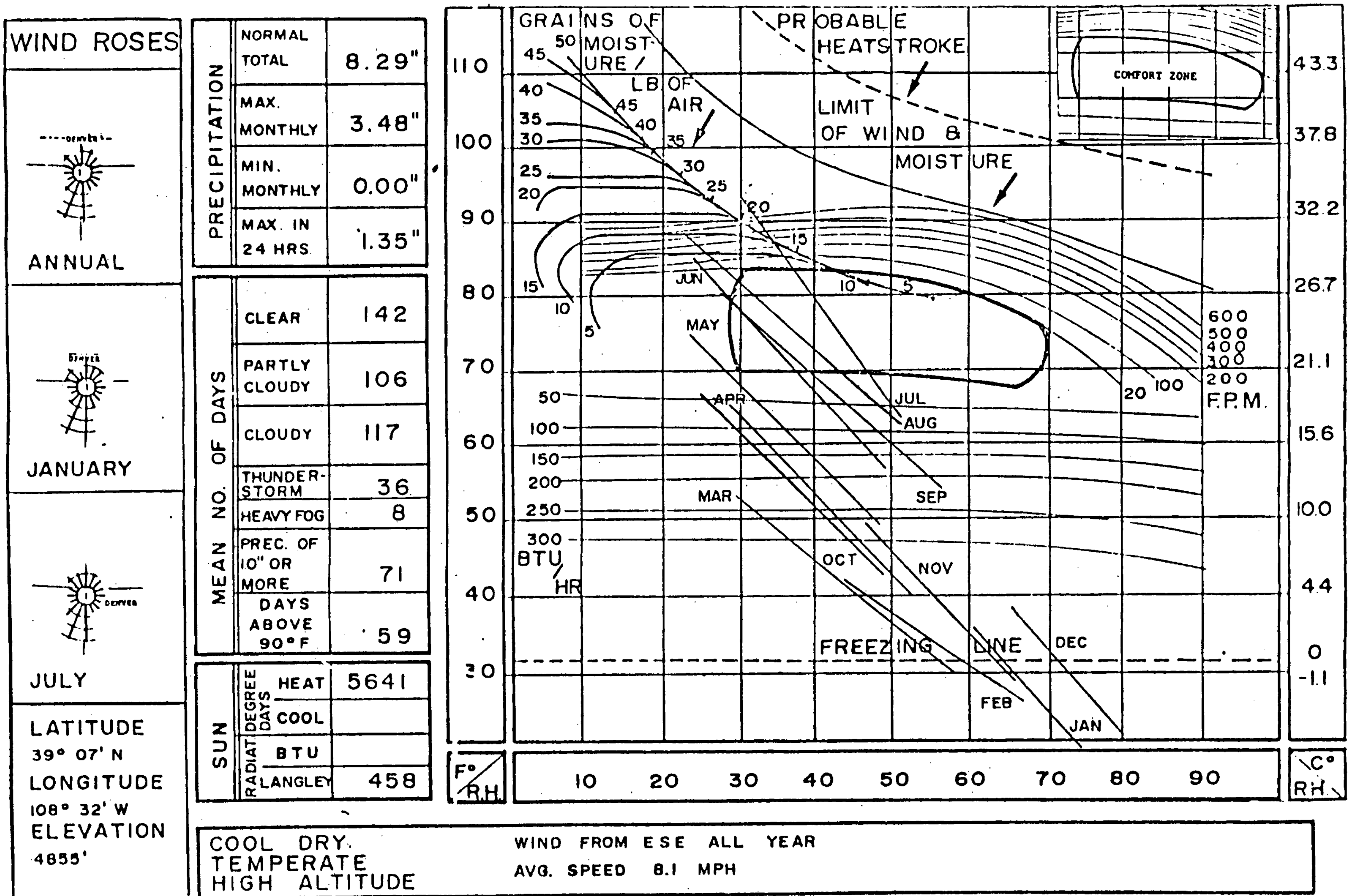


Fig. 18 - State of Bioclimatic Comfort - Annual - Grand Junction, Colorado

A look at the bio-climatic chart (Fig. 20) reveals that the annual temperature/relative humidity relationship is:

1.) Spring: cold-humid days, very cold-very humid nights
2.) Summer: temperate-moderate days, cool-humid nights
3.) Autumn: cool-humid days, cold-humid nights
4.) Winter: very cold-very humid days and nights

The diurnal temperature range averages 28°F (15°C).

Under natural conditions, airflow over human skin, through the building or across the site ranges from undesirable to extremely harmful. Only during summer days can a slight air movement be tolerated. Building and site orientation, therefore, must be geared to solar heating to the maximum extent available. The wind cooling of an overheated building does not arise in this case. Under mechanically controlled conditions, the criteria remains unchanged.

Triple planting of evergreen trees and shrubs provide an effective wind break from chilling northwesterly winds. Further protection can be provided with a berm on north and west walls. Precision tree planting in the east and southwest will permit desirable solar gain. Deciduous trees and shrubs on the south side to allow uninterrupted winter sun. An attached greenhouse on the south facade will allow protected exterior living conditions during spring and autumn days. Additionally, solar benefits are achieved for winter warmth, when night insulation is operated. A terrace of time-lag materials, facing south, could be well used during summer, spring and fall days.

LANDSCAPE INFLUENCES ON URBAN AND RURAL CLIMATE

Climate in urban areas is distinctly different from that in rural areas (See Table 4) in terms of temperature, air motion, precipitation, vapor pressure and radiative responses. Thermal mass materials in urban areas tend to absorb and re-radiate more heat than the soil and vegetal surfaces in rural locations. Additionally, urban forms act as absorbers, reflectors and/or concentrators directing solar and thermal radiation to other surfaces resulting in alterations to micro-climate with profound implications in terms of satisfying human comfort needs and energy utilization. In rural areas solar radiation is intercepted by only the tops of trees, shrubs and small scale plants, including grass, thereby keeping ground surfaces and air close to the ground, at relatively cool temperatures.

Hard surfaces are needed in urban settings for walking, traffic, etc. These surfaces replace live plantings with, generally, concrete or stone which are materials possessing a high thermal capacity, resulting in temperature rises of 10°F approximately in urbanizations as compared with surrounding countryside [5]. It follows, therefore, that the use of materials possessing thermal mass should be encouraged and strategically located in cities located in underheated regions. The reverse will be true in overheated regions when an abundance of live plantings will result in cool surfaces and a cooler urban atmosphere. Hard surfaces in overheated conditions, therefore, should minimize surface area, density and volume, of heat absorbing materials, and where possible, thermal resistor mater-

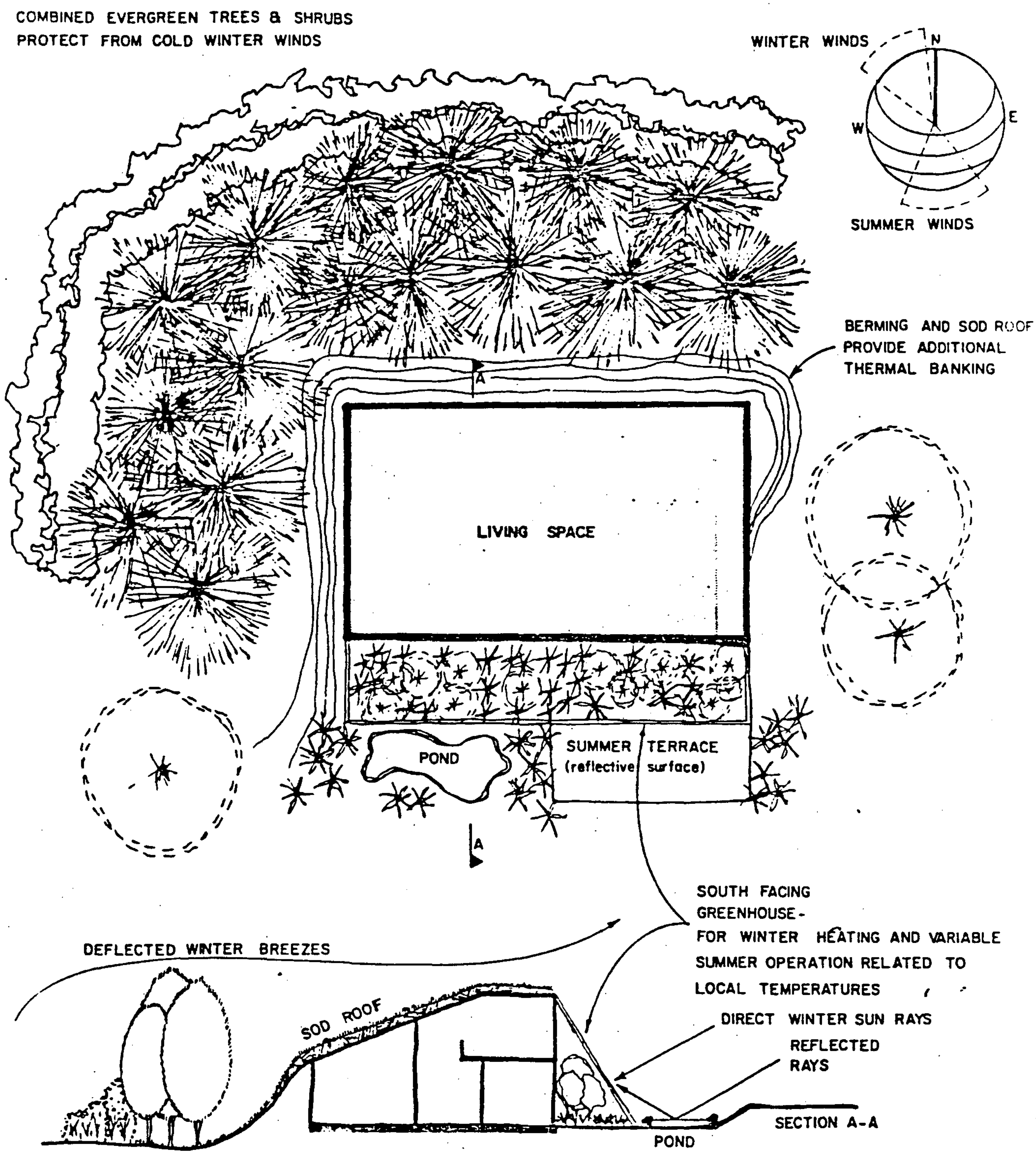
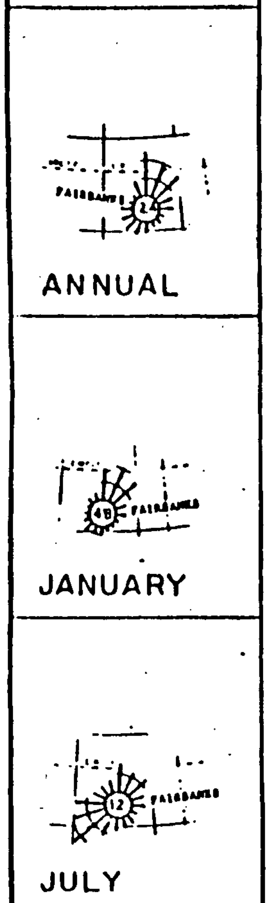


Fig. 19 - Landscape techniques for Fairbanks, Alaska; D.2 Summers & E.3 Winters

WIND ROSES

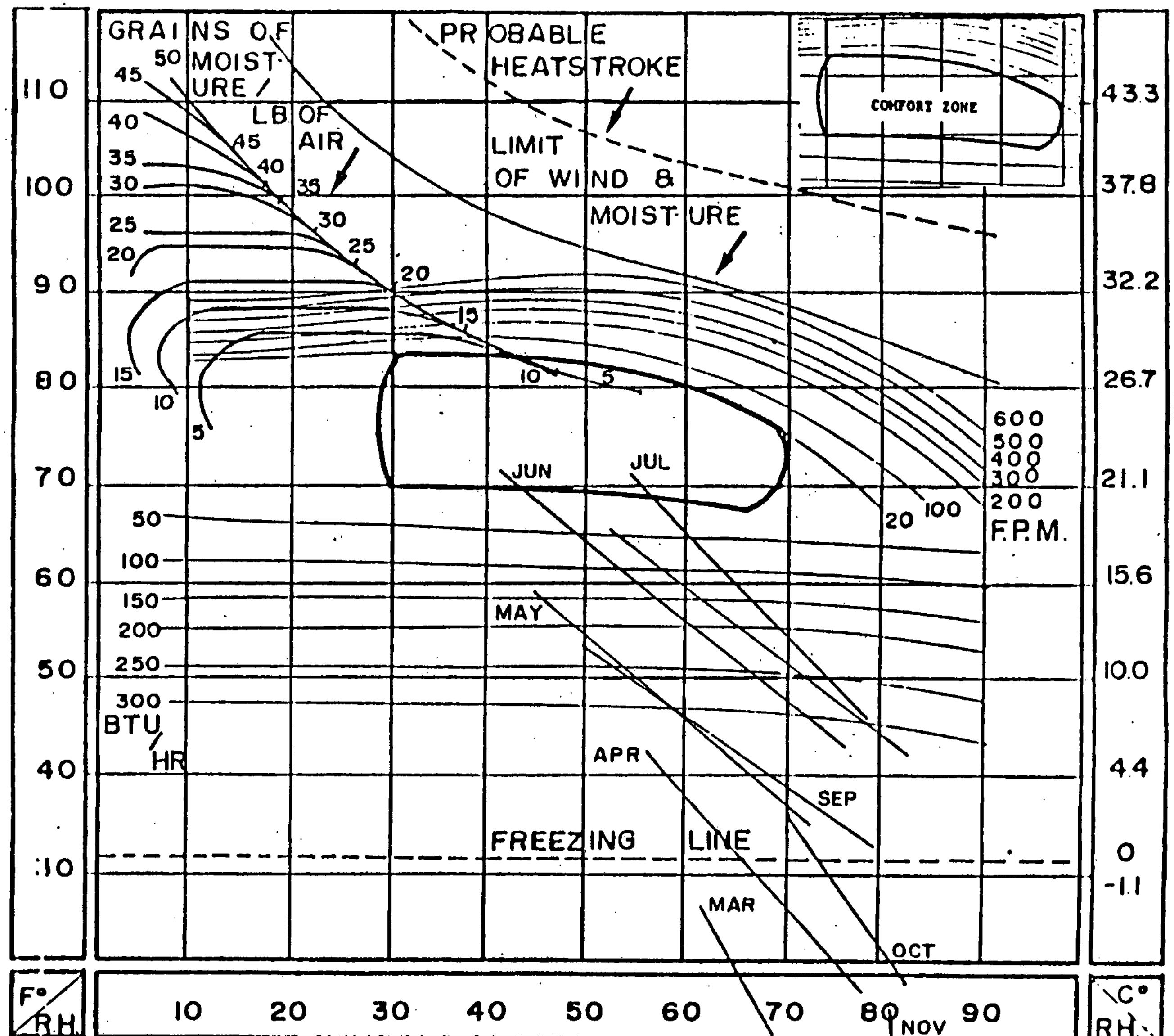


LATITUDE 64° 49' N
LONGITUDE 147° 52' W
ELEVATION 436'

PRECIPITATION		
	NORMAL TOTAL	11.29"
	MAX. MONTHLY	6.20"
	MIN. MONTHLY	0.04"
	MAX. IN 24 HRS.	3.42"

MEAN NO. OF DAYS		
	CLEAR	68
	PARTLY CLOUDY	81
	CLOUDY	216
	THUNDER-STORM	5
	HEAVY FOG	19
	PREC. OF 1.0" OR MORE	103
	DAYS ABOVE 70°F	50

SUN		
DEGREE DAYS	HEAT	14279
DEGREE DAYS	COOL	
RADIAT.	BTU	
RADIAT.	LANGLEY	227

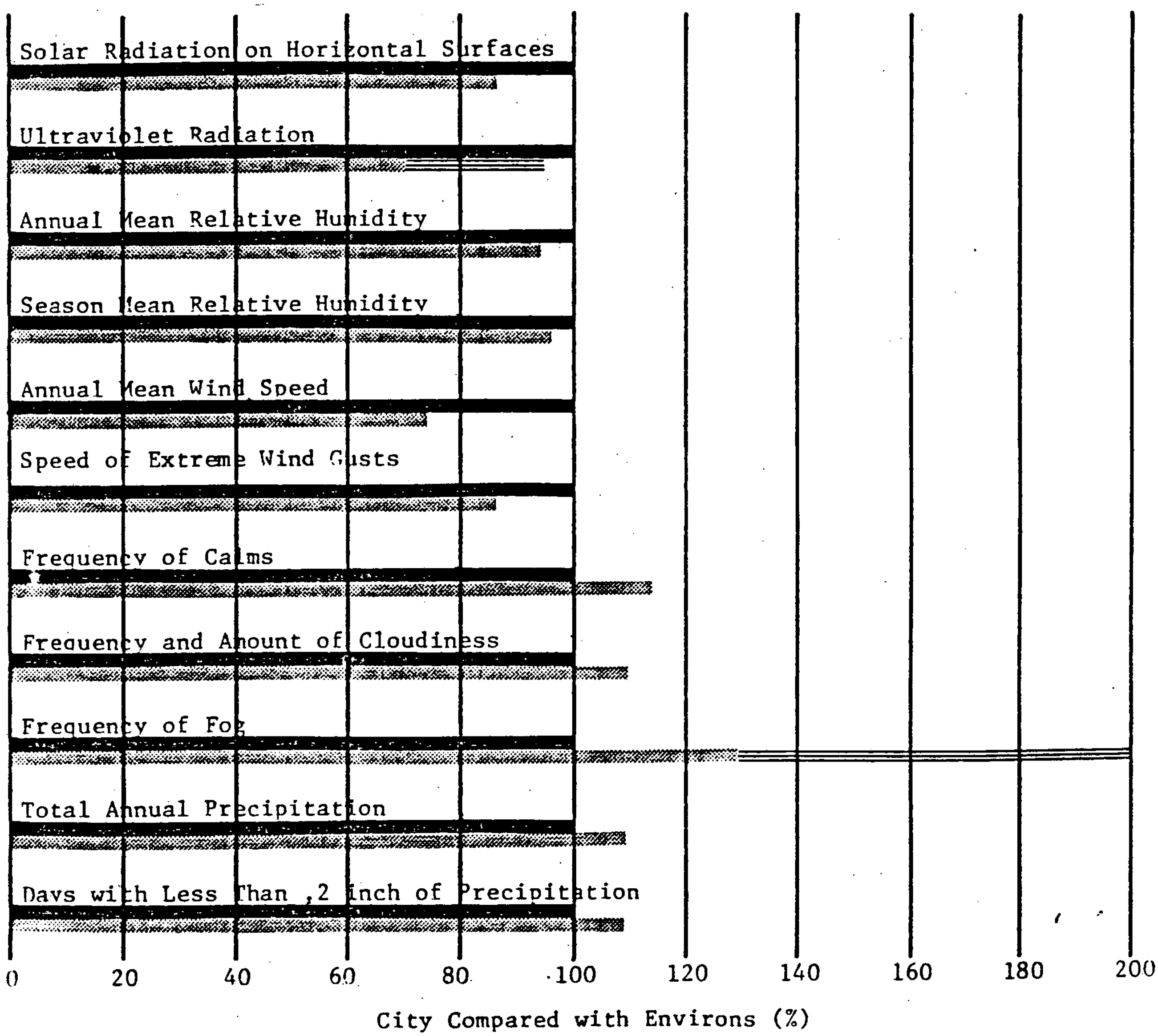


COLD HUMID

WIND FROM N EXCEPT JUN & JUL FROM SW
AVG. SPEED 5.0 MPH

20 - State of Bioclimatic Comfort - Annual - Fair' nks, Alaska

TABLE 4 Major Differences in Climate between a City (black) and Its Environs (gray) Are Set Out in Terms of the Percentage by which the City Has More or Less of Each Climatic Variable During a Year Than Is Experienced in the Countryside



ials, such as wood, should be employed. Furthermore, urban areas remove water through drains and sewage systems, resulting in a reduced ability for evaporative cooling. Artificial water bodies, such as streams, ponds, pools and fountains, will tend to rectify the position when appropriately employed.

Buildings, monuments and plantings, successfully impede and divert natural airflow. In underheated and hot-arid regions, the city-scape and its plantings can be employed, in a tight geometry, to eliminate "wind-chill" and "heat-gain", respectively. Whereas, in temperate and overheated humid conditons, an open or spread geometry of buildings and plants will encourage airflow to cool surfaces and human skin.

Urban areas, as they increase in scale and density, tend to produce "heat domes", with the warmest temperatures over the town center. Human activities, such as industry, automobile emissions, etc. and temperature inversions are prime causes. When urban heat is reduced by building morphology, materials choice and landscape techniques, the adverse micro-climate is ammeliorated. An analysis of the situation is suggested in Fig. 21.

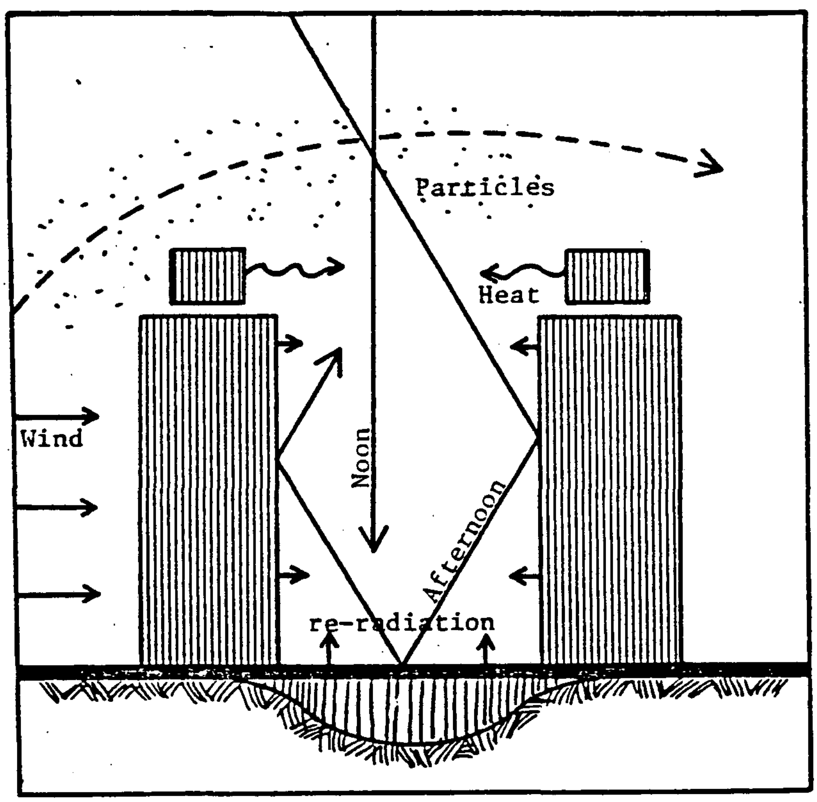


Fig. 21a - Solar Response in Urban Areas includes: (1) low & multiple reflections, (2) high absorption, (3) little moisture available for conversion of sensible to latent heat, (4) wind flow restrained, air stagnation, retarded cooling of heat producing sources, & (5) particles cause selective radiation & heat absorption.

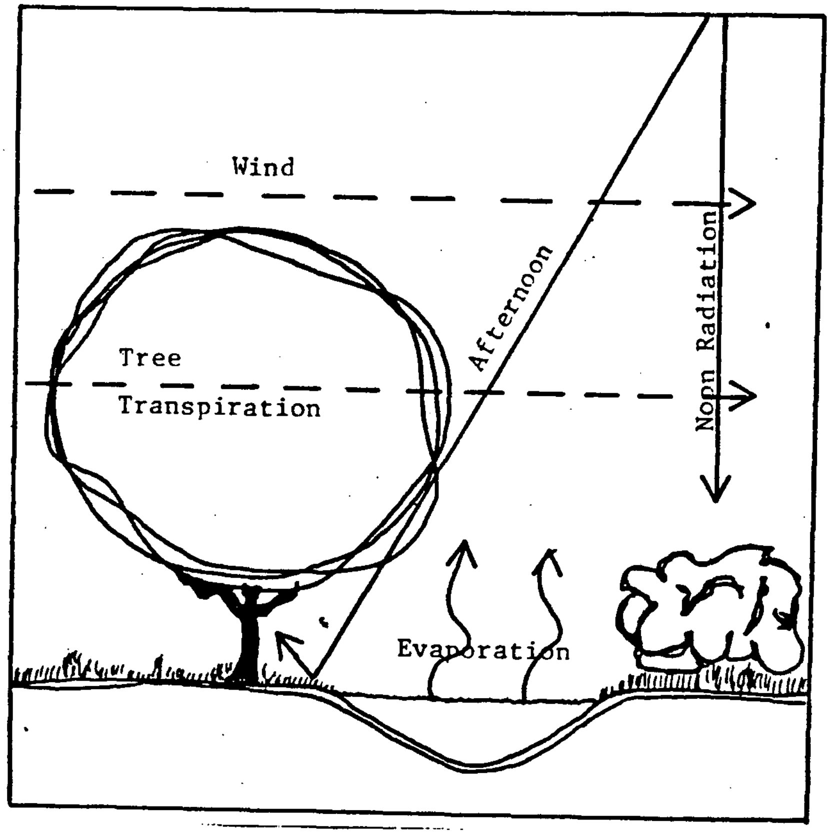


Fig. 21b - Solar Response in Rural Areas includes: (1) high degree of reflection, (2) low absorption, (3) moisture available for conversion of sensible to latent heat, (4) wind flow unrestrained. lower air temperatures due to vegetative surfaces, & (5) clean air.

PHASED PLANTING STRATEGIES

In discussing techniques above, for cooling and heating through landscape design, the schemes have envisaged matured planting. Depending on location and plantings used, these matured schematics, will occur from 20 to 50 years. Meanwhile, the project will be inadequately served with immature landscaping.

It is a standard practice in landscape design to provide temporary plantings, that will grow fast, or in portable boxes, etc. These staged designs frequently pass through two or three phases before the matured situation is reached. Normally, landscape architects are motivated by aesthetic and horticultural considerations when arriving at "Phased Planting Plans". Additional consideration must be given to the energy needs of a building or site in determining planting phases until final maturity is achieved.

CONCLUSION

Through this brief study of the effects of landscaping, it is hoped that the value of landscape conscious design has been exemplified. Simple considerations can make considerable improvements in the comfort of our built environment, and future building and site design needs to provide us with this comfort as well as an aesthetically pleasing situation. All of the suggestions brought forth are feasible alternatives to present day design methods. When used correctly throughout the design process, these will enable a final design to integrate both the natural and built environment into a symbiotic composition. It is clear that while general principles are now available for use, there is a need for the development of quantification data to assist in the derivation of design methods for easy understanding and implementation.

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Daylighting

Daylighting and Cooling -- Marietta Millet

DAYLIGHT AND COOLING

Marietta S. Millet[1]

"A great American poet once asked the architect, "What slice of the sun does your building have? What light enters your room?' - as if to say the sun never knew how great it is until it struck the side of a building."[2] ... Louis I. Kahn

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[1]Department of Architecture, University of Washington, Seattle, Washington 98105.

[2]R. Guirgola & J. Mehta, Louis I. Kahn, Artemis Nerlag fur Architektur, Zurich & Munich, 1975, p. 187.

Short Glossary of Daylighting Terms

CIE Standard Clear Sky - completely clear sky condition where the relative luminance of sections of the sky vault are defined according to their position in relation to the sun; the zenith luminance is held constant at one. The area around the sun is brightest, an area opposite the sun on the sky vault is darkest, and the horizon generally has low luminances.

CIE Standard Overcast Sky - complete overcast sky (sun position cannot be detected) producing an illumination on the unobstructed horizontal plane less than 2000 footcandles. The luminance of the zenith is approximately three times that at the horizon.

Contrast - the relationship between the luminance of an object or area of interest and that of its immediate background. Mathematically, the difference between the luminances divided by the luminance of the background.

Daylight Factor - ratio of the daylight illumination at a point inside to the illumination on an exterior horizontal plane from an unobstructed hemisphere of the sky. Direct sunlight is excluded for both values of illumination. The Daylight Factor comprises three components: the Sky Component, the Externally Reflected Component, and the Internally Reflected Compound.

$$DF = SC + ERC + IRC$$

Disability Glare - glare which reduces the ability to perceive the visual information needed for a particular activity.

Discomfort Glare - glare which is distracting or uncomfortable, which interferes with the perception of visual information required to satisfy biological needs, but does not significantly reduce the ability to see information needed for activities.

Efficacy (Luminous Efficacy of a Light Source) - the quotient of the total luminous flux emitted divided by the total lamp power input, expressed in lumens per watt.

Externally Reflected Component (ERC) - component of the Daylight Factor which consists of light reflected from obstructions exterior to the daylight opening which block direct light from the sky.

Footcandle - the English unit of light intensity (see Technical Section).

Footlambert - the English unit of luminance, or measured surface brightness (see Technical Section).

Glare - an interference with visual perception caused by an uncomfortably bright light source or reflection; a form of visual noise.

Illumination - quantity of light per unit of surface area; the intensity or "density" of light falling on a surface. (English unit: Footcandle. Metric unit: Lux.)

Internally Reflected Component (IRC) - component of the Daylight Factor which consists of light reflected from internal reflecting surfaces.

Light - visually evaluated radiant energy; also, a source of illumination such as the sun or an electric lamp, or the illumination received from such a source.

Luminance - the physical measure of brightness: luminous intensity per unit projected area of any surface, as measured from a specific direction. (English unit: Footlambert. Metric unit: Candela per square meter.

Sky Component - component of the Daylight Factor which consists of light received directly from the sky.

Work Plane - the horizontal Reference Plane located 30" above the floor and limited by the walls of the room.

Zenith - the point on the sky vault located directly above the observer.

Sources of Light & Strategies for their Use with Passive Cooling

The ultimate source of daylight is, of course, the sun, but much of the direct-beam radiation is diffused by the atmosphere and by intermittent cloud cover. Approximately half of the light received from sun and sky is in the visible part of the spectrum, the other half being in the infrared. (See Appendix.)

Sources of Light:

1) Direct sunlight through building aperture
2) Diffuse skylight through building aperture
3) Diffuse externally reflected light through building aperture
   a. sunlight
   b. skylight
4) Diffuse internally reflected light from interior room surfaces

Strategies

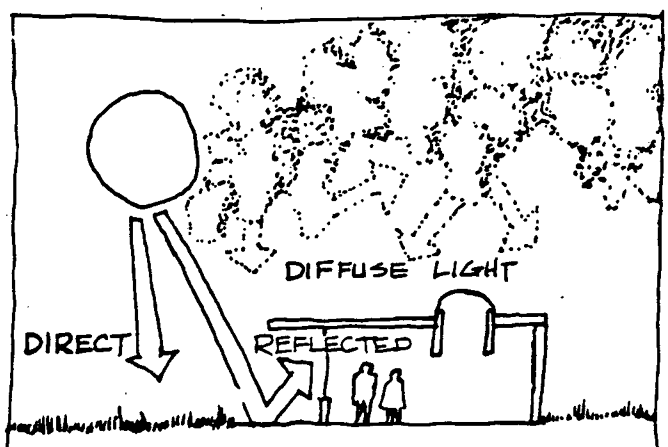
Hot-Dry Climate:

Exclude	1)	during overheated period
Use	2)	if sun can be excluded and field of view is not too bright or is restricted; or modify light
Use	3)	making sure sources are not too bright (opposite or adjoining walls) or not in field of view (ground); or modify light
Maximize	4)	making sure surfaces are matte finish and not so bright as to cause discomfort glare.

Hot-Humid Climate:

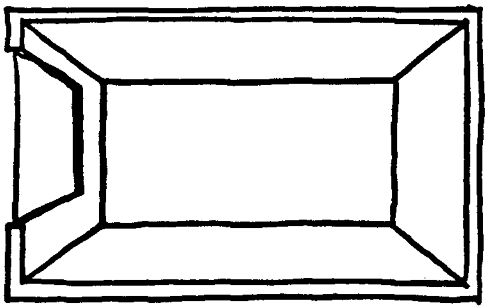
Exclude	1)	during overheated period
Use	2)	especially when skies are overcast; modify and control light without restricting air circulation.
Use	3)	if sun can be excluded and field of view is not too bright, or is restricted; modify and control light without restricting air circulation.
Maximize	4)	making sure surfaces are matte finish and not so bright as to cause discomfort glare.

Switch between overcast and clear sky conditions may indicate use of operable sun- and light-control devices.

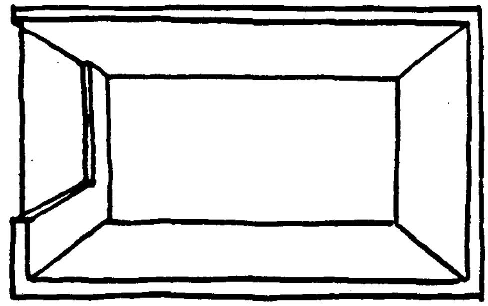


SOURCES OF SOLAR RADIATION

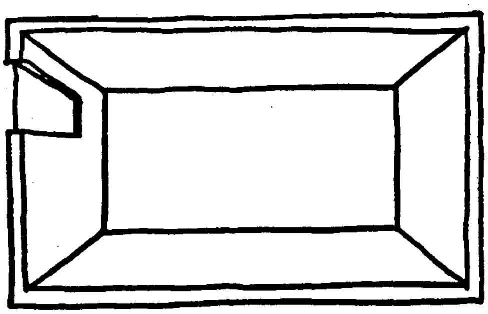
1. POSITION OF (GLAZED) OPENING



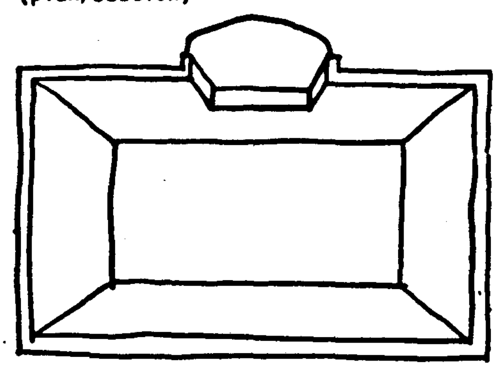
VERTICAL



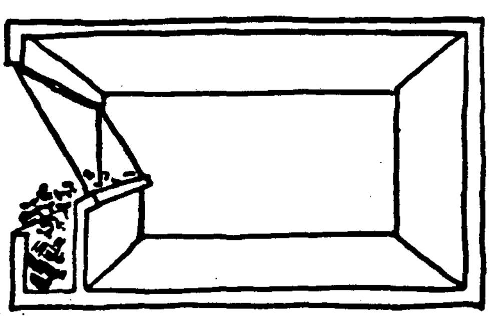
SURFACE WASH
(plan/section)



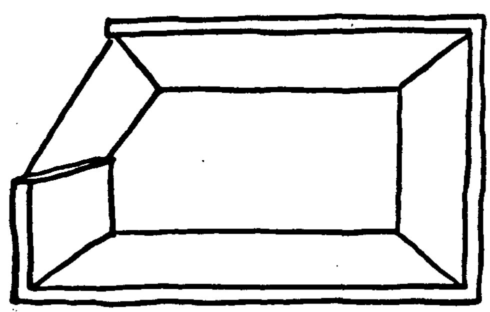
CLERESTORY



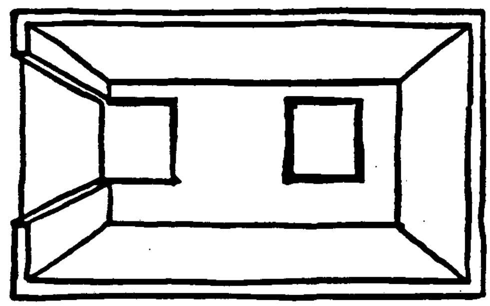
TOP-LIGHT

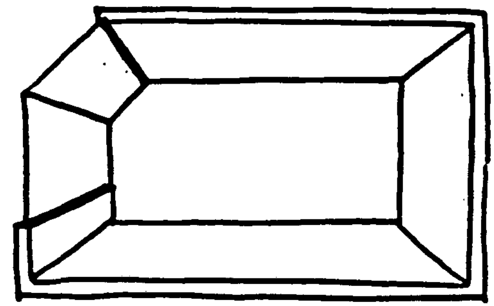


CUT-IN

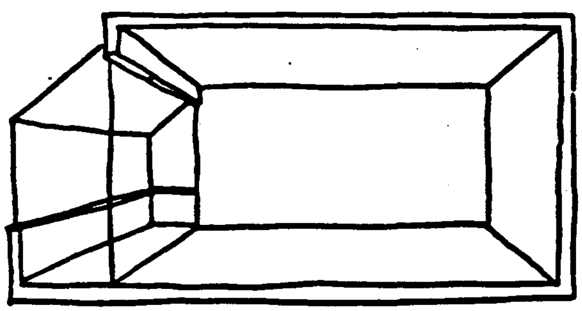


LEAN-TO

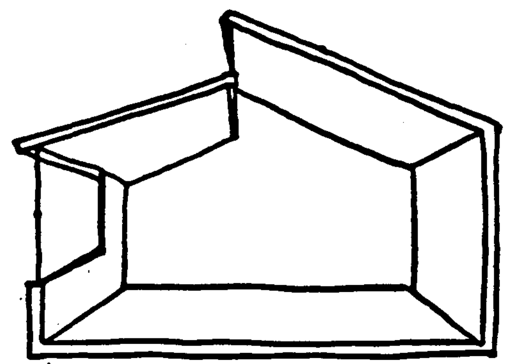




TWO-SIDED LIGHT
(plan/section)

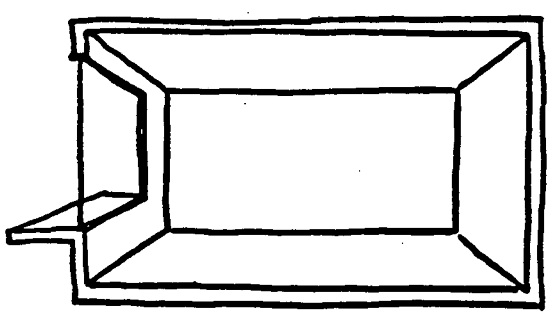


THREE-DIMENSIONAL
(plan/section)

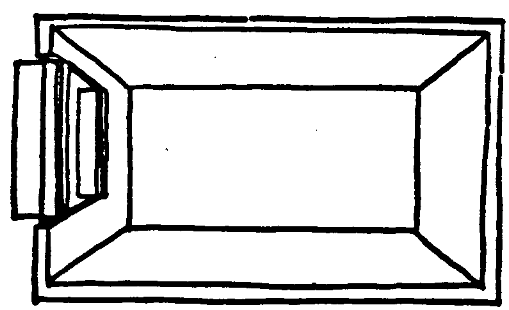


ADDITIVE DIRECTIONAL

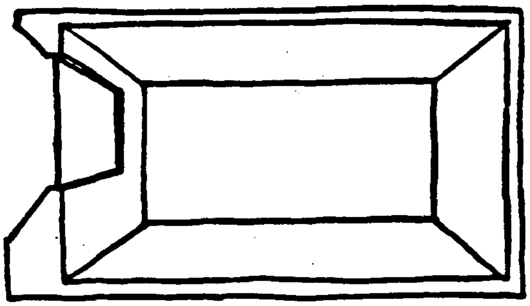
2. EXTERNAL CONTROL DEVICES



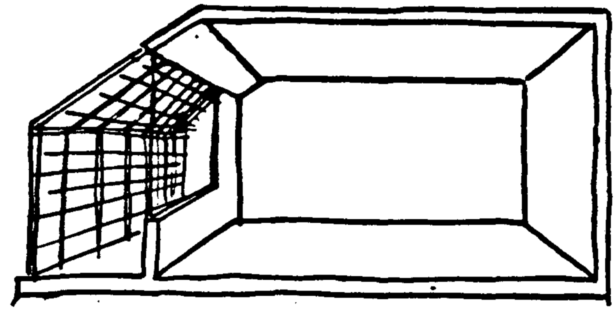
HORIZONTAL
(reflectors/shaders)



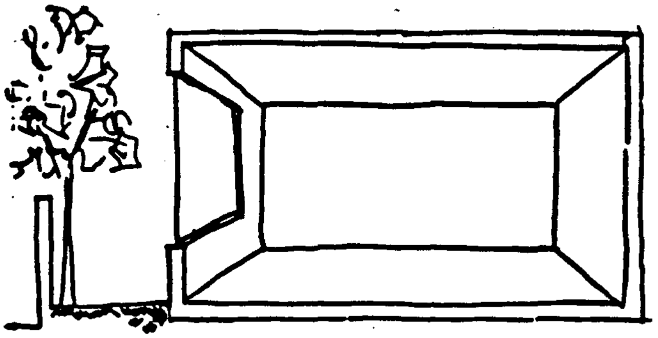
VERTICAL



SPLAYED
(plan/section)

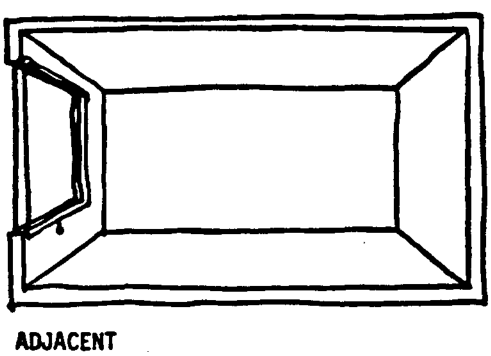


FRAMEWORK
(plan/section)

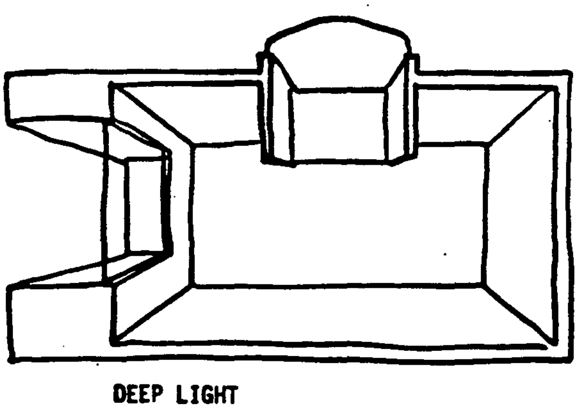


REMOVED

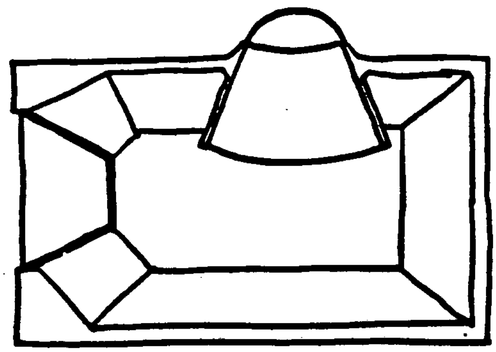
3. INTERNAL CONTROL DEVICES



ADJACENT



DEEP LIGHT



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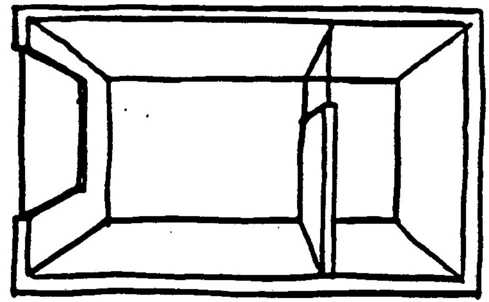


BORROWED LIGHT

4. MATERIAL CHARACTERISTICS

Building surfaces, exterior and interior:

- reflectance / value
- color
- finish (ranging from matte to specular)

Glazing:

- transparent
- translucent
- color
- relecting
- heat absorbing

(different characteristics of:
- transmission
- absorption
- reflection)

External control devices:

- solid
- screen / filter (i.e. brise soleil)

Internal control devices, adjacent:

- opaque (curtains, shades)
- louvers
- screen / filter ("casement" curtains)

Daylighting and Energy - Conscious Design

The role of daylighting in the total energy balance and performance of a building is a significant one. The admission of useful daylight means that electrical lighting fixtures can be turned off, saving electricity. (On the other hand, the electrical fixtures must be installed anyway for nighttime lighting, so little if any production energy can be saved.) The daylighting effects of glazing also have direct and indirect influence on the building thermal loads. The glazed area that lets in light is also going to either admit heat from insolation or lose it to the exterior through conduction, or both at the same time. Reduction in the use of electrical lighting will lower internal heat loads. Different types of buildings and building occupancies have different major mechanical loads, sometimes heating, sometimes cooling. In some cases minimizing heat gains and maximizing heat loss can be beneficial, but in any case a balance must be achieved to provide a habitable environment.

No one concern will determine totally the final fenestration design. It seems best, therefore, to evaluate each proposed building design according to its own significant features.

In any energy analysis, the final thermal balance of a proposed design will be compared to an alternate "standard" design in order to determine cost effectiveness. A cost analysis of an energy-conscious design includes operating costs as well as initial costs. The issues which must be considered in such an analysis are listed below.

1. Portion of occupied hours illumination is provided by daylight
   a. Required illumination level
   b. Hours of occupancy
   c. Availability of daylight
2. Electrical load of supplementary electrical lighting compared to electrical load of "standard" design lighting installation
3. Heat loss through building envelope with daylight openings compared to heat loss of "standard" design envelope
4. Heat gain through building envelope with daylighting openings compared to heat gain of "standard" design envelope
5. Reductions in electrical lighting load due to lighting control systems
6. Reductions in heat loss and heat gain due to insulating window treatments.

The building type and use will determine the required illumination and hours of occupancy. The climate will determine available daylight and quantities of heat loss and gain through the building envelope. Local electrical rates will determine the significance of electrical lighting fixture load. And design and operation of shading devices and lighting control systems will determine the probable reductions in operating load due to use of daylighting. Although general guidelines can be drawn up for typical skin-dominated and internal-load dominated buildings, the number of variables and the multitude of design decisions that affect them require individual analysis.

Influence of Climate

Daylight is a dynamic function of site, changing with the latitude, dominant weather patterns, the seasons, local atmosphere, the diurnal cycle, and specific site conditions. The relationship between daylight and useful interior illumination is affected by all these factors, the most important being weather. Daylighting techniques suitable for Santa Fe may not be suitable for Miami.

The weather is changing constantly. According to weather experts, there are no two days alike. The sky is likewise changing constantly. It is not possible to predict how many hours of sunshine we will have in a particular year or in a particular month. As the conformation of the sky varies, so does its daylight contribution. When the sky is clear, the sun's apparent movement causes the brightness distribution of the sky to change constantly. The "partly cloudy sky" covers myriads of combinations, ranging from 3/10 to 7/10 of the sky being covered with clouds. In addition, these clouds can be opposite the sun, reflecting light, or obscuring the sun and casting shadows. The fully overcase sky is likewise variable, with differing degrees of thickness of cloud cover and darkness. It is difficult to define design conditions among all these variables. There is not standard that exactly duplicates reality. Some assumptions must be made in order to test and compare design alternatives. In this case, a standard is extremely useful, allowing the comparison among alternatives on a base which represents known conditions.

Climate Data for Energy Calculations

Information on the average number of clear and cloudy days is necessary for total energy use calculations in order to compare average daylight availability to average yearly radiation data. The amount of illumination from the sky will vary according to season of the year and time of day, so information on the average number of clear and cloudy days per month and associated average illumination levels are both necessary for a detailed analysis. A general indicator of available illumination is the chart reproduced in the Appendix. The values shown are broad estimates based on location determined by latitude alone. The curves represent the minimum daylight illumination that can be expected for different portions of the "working hours" between 9 a.m. and 5 p.m.

Daylighting Design in Response to Climate

Since the climatic variations in the United States encompass most, if not all, of the distinct climate zones of the world, there is an extensive range of indigenous architecture to study to understand the interplay of light and climate characteristics. While it is possible to make generalizations about daylighting approaches in indigenous architecture in response to climate, there are no hard and fast rules. It must be recognized that many other factors enter in: available materials, social and organizational structure of the building occupants, use of the building, and cultural patterns, to name a few. In most indigenous architecture, windows tend to be few and small in hot arid regions and are often placed above eye level to block views of the bright ground. Or windows open onto shaded court yards where brightness can be controlled by vegetation and color. In hot humid areas, openings are large but shaded or shuttered to allow cross-ventilation and reduce light and heat penetration. In temperate regions, window areas are large or outdoor areas flow into the building, while in cold climates window openings are small and covered to reduce heat loss. But few regions are constantly the same throughout the seasons, so that seasonal variations will demand a building that responds to two or more climate "types".

Influence of Building Type

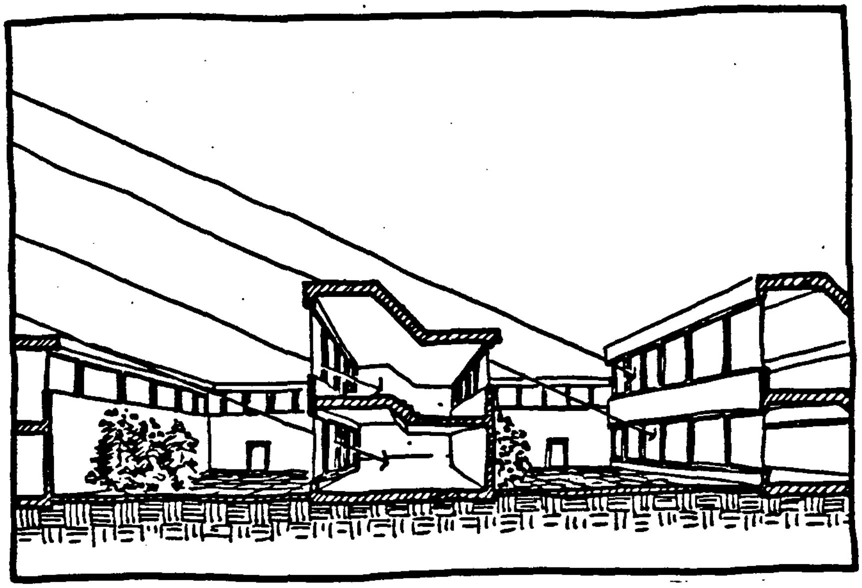
Lighting does not play a significant role in residential energy consumption patterns, but it is a prime contributor to energy consumption in office buildings, schools, commercial low-rise buildings, health-care facilities, and warehouses. As interest in energy-conscious building design grows to include medium and large-size structures, lighting and daylighting become important considerations in the overall energy balance of these buildings. The lighting load can account for as much as half of the total energy loads in an office building, for example, depending on building design and location. In addition, each watt of electric lighting requires approximately 1/2 watt of mechanical cooling to counteract its heat generation. Mechanical equipment and distribution systems are still considered a necessity in most of these building types. If energy conserving design efforts in large buildings are not limited to mechanical "fixes" only, then site and climate-responsive considerations such as passive solar heating and daylighting become critical design issues. Daylighting is an integral part of the balance equation, both for its ability to eliminate large parts of the electric lighting load and also for its intimate association with heat delivery and heat loss through glazing.

The first consideration in designing for daylight is occupancy of a building: who and when? It is important to determine if people inhabiting the building have special visual requirements that dictate certain lighting qualities or illumination levels (low or high), or if they will be restrained in their movement (in a hospital bed, at a desk all day, etc.) so that exposure to direct sunlight or harsh sky glare would cause discomfort.

Direct sunlight admitted to a space can have a very positive effect, but it should be restricted to ancillary areas, and places where people are free to move about, or sun controls should be provided. Several techniques are available for designing and evaluating sun control devices. The amount of illumination available from the clear sky alone even without direct sunlight is greater than that from an overcast sky in the same season. For this reason, calculating daylight illumination under overcast sky conditions alone is considered sufficient in most cases to provide an adequate quantity of daylight. In hot climates, however, care must also be taken that too high a level of illumination doesn't cause a sensation of a hot, rather than a cool, interior.

"When" the building is occupied determines the usefulness of daylight contribution, with major daytime occupancy providing the greatest opportunity for daylight utilization. Schools and offices are prime examples since their operating hours conincide with daylight hours. Some health care facilities, on the other hand, are operating day and night. In this case, daylight can reduce a major electrical load but cannot totally substitute for it. One of the large-scale results of effective utilization of daylight occurs in the summer when daylight is plentiful everywhere, and that is reduction of peak power demand on utilities.

In the schematic design phase, consideration of occupancy patterns and lighting requirements will help determine the general configuration of the building and the location of various functions. An overall building configuration which is divided into wings rather than lumped together provides more daylight accessibility and, if properly oriented, optimum heat gain or heat loss. As another example, attention to the lighting requirements of various staff members could lead to locating personnel with visually demanding jobs



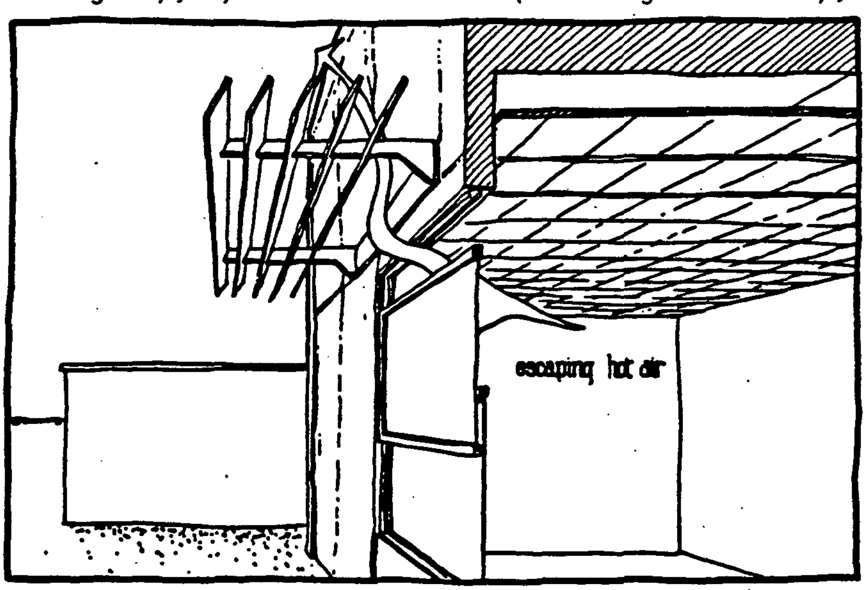
Building configuration to maximize admission of daylight

near daylight sources. Executives whose major office tasks are dictating, talking on the telephone, and holding conferences might be located in offices somewhat distant from the windows, while secretaries and clerks with predominantly visual tasks might have stations near the windows. The architect's imagination might then be stretched to find another status symbol to compensate for the executive's loss of view.

Another example of energy-conserving building layout is grouping together functions that are on the same time schedule, so that the lighting and ventilation systems for that entire section can be shut down when it is not operating. This capability assumes an appropriate control system.

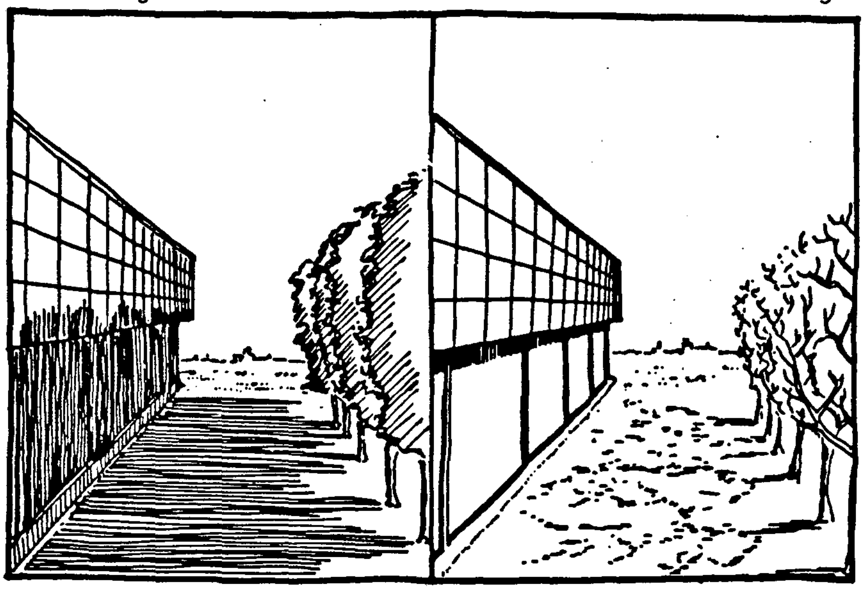
A Sampler of Design Guidelines

In considering daylighting along with passive cooling approaches, it is important not to focus on "devices", but rather to keep one's mind set on merging the building form with local environmental forces in order to minimize consumption of nonrenewable energy sources to satisfy comfort requirements of the inhabitants. Three issues must be considered: 1) solar control (preventing heat gain); 2) thermal balance (allowing heat loss); and 3) ventilation.



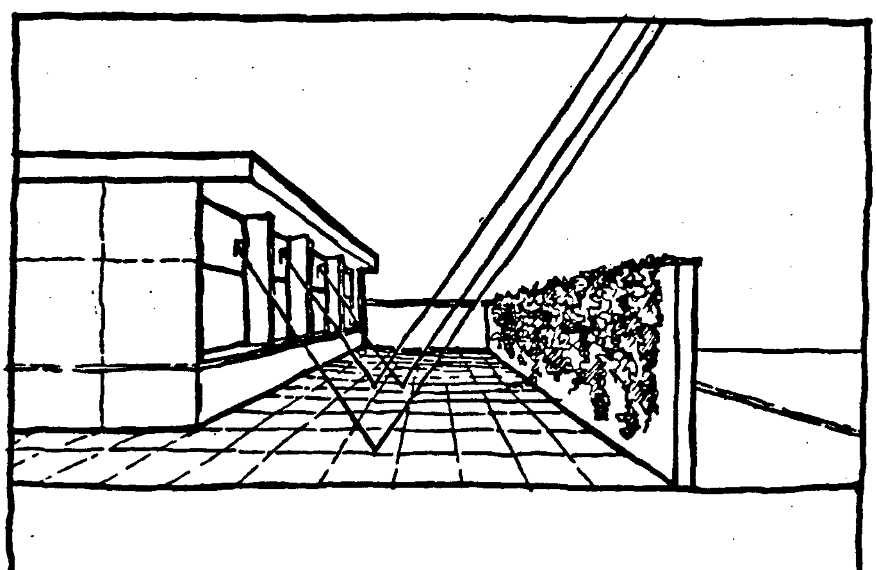
Shading devices and operable sash

The issue of solar control requires an evaluation of the role of the glazing as a heat and light transmitter. Heat gain control most often involves exterior shading devices for maximum effectiveness. The shading technique that allows daylight to be utilized without adverse heat gain is a combination of clear glazing with an exterior shading device, such as an open-work horizontal overhang. This technique proves more effective than using tinted or heat-absorbing glass which blocks much of the daylight (approximately 50% reduction factor). Deciduous trees are excellent shading devices, providing shade in the summer and access to the sun in winter. Their period of leafing should be matched to seasonal requirements for shade or insolation. Useful catalogues and workbooks of shading devices are References 17 and 18. Reference 11 includes a shading calculator and directions on constructing shading masks.



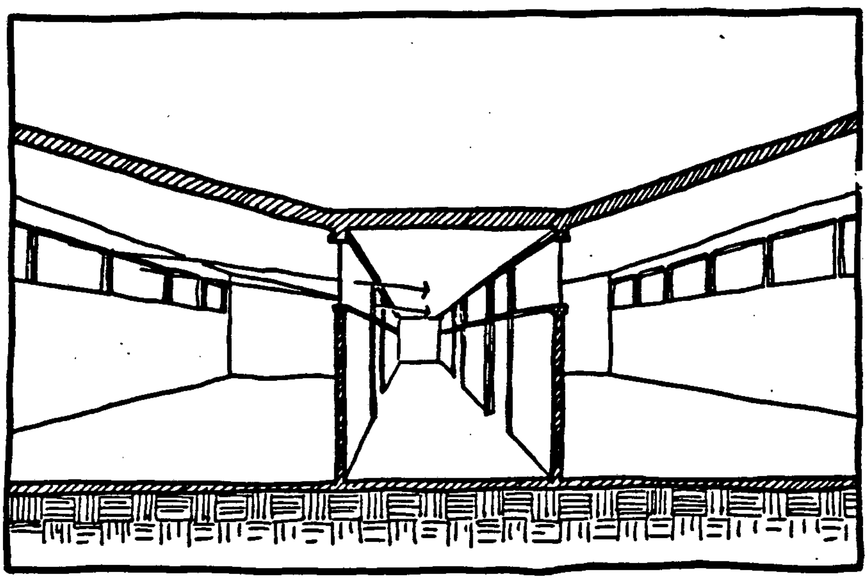
Trees as variable shading device and windbreak

Areas adjacent to the building affect the entry of light and heat into rooms through windows as well as creating microclimate effects at the building perimeter. These effects can be used to advantage, for instance reflecting sunlight off exterior light paving while using plants on walls to prevent glare from visible bright surfaces.



Exterior surfaces affect light delivery to room

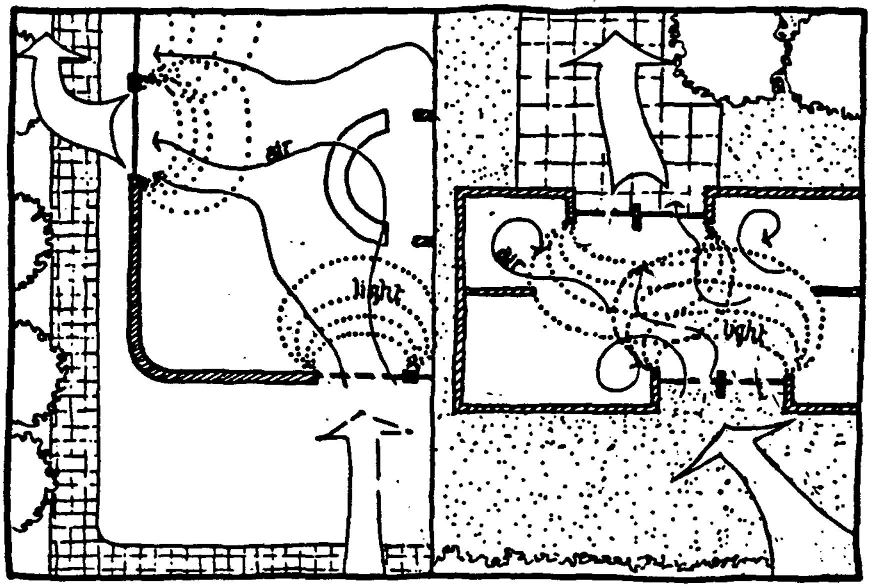
Thermal balance. In the category of thermal balance, which is here defined as allowing heat loss, we enter the area of window construction and management. When considering daytime balance between heat transfer and daylight admission, north glazing may provide helpful thermal transfer as well as high quality diffuse light for buildings where the dominant mechanical load is cooling, such as office buildings in temperate climates. The location of north glazing with regard to proximity to people is critical, however, since radiational heat loss from the body would be increased in underheated periods. These considerations might lead to north clerestory glazing in a corridor, as one isolated example. To carry this example further, clear transoms could then be used to admit "borrowed light" into inner working spaces. An opposite example is rooms where comfort levels are critical, such as hospital patient rooms. Both heat transfer and daylight admission must be carefully designed to avoid overheating or glare for the immobile patient. A high south-facing window with a deep sill, in combination with a low shaded window for view, can provide daylighting and work as a direct-gain collector in underheated periods.



Borrowed light

Ventilation. The third category, ventilation, is usually considered along with windows since they often provide the ventilating openings. Alternatives are possible, however, such as doors or hinged solid panels or louvers. In using the latter, the dynamic character of both light and ventilation are reinforced by the lighting changes that take place when the solid panels are opened. When considering windows for both daylighting and ventilating purposes, the effects of each must be weighed. Here it would seem that placement of windows for cross ventilation should receive priority, and that treatment of windows for daylight admittance and control should follow. With openings in opposite walls, good overall air circulation is achieved if the walls are slightly askew to the direction of the wind. In this case, windows on opposite sides will provide bilateral lighting, which can be varied by window height location. Bilateral lighting reduces contrast and makes a naturally balanced luminous environment. On the other hand, if prevailing winds during the cooling season are perpendicular to the building wall, then windows in adjacent walls provide good overall circulation and minimize stagnant air pockets.

Light from windows in adjacent walls also reduces contrast and provides balance in comparison to a unilateral daylighting scheme. In many cases, openings for daylight and for ventilation may be best kept separate.



Combinations of light and air distribution patterns

How to Handle Daylight

DAYLIGHT: No matter how much you have to work with it can be used.

I. Capture It.

1. Analyze site as to sources of light: sky, external reflectors (vertical, horizontal)
2. Analyze shading patterns
   - from existing obstructions
3. Orient building so that available light can be received
   - Consider different qualities of light from different directions
     - N. - no direct, uniform
     - S. - high direct, summer- mid-day
     - E. - morning, direct - low angle
     - W. - afternoon, direct - low angle
   - Consider elongating building along E-W axis
4. Use site and surrounds to direct lighting toward building
   - light-colored soffits
   - light-colored ground
   - light-colored exterior walls
   - adjacent water
   - adjacent reflective buildings
5. Open building to receive light
   - open sides (side windows effect of shape, size and locations of windows, greenhouse)
   - open roof (skylights, clerestories) Light from 2 sides minimum.
6. Shape building to maximize penetration
   - narrow wings
   - stepped back form
   - sawtooth roof
   - courtyards or atriums

II. Modify It.

1. Block direct sunlight
   - plantings
   - horizontal overhang on south facade
2. Selectively absorb it
   - exterior plantings
   - interior surfaces to delineate different areas
3. Reflect it
   - ground and other horizontal surfaces
   - skylight shading and reflecting devices
   - clerestory reflecting devices
   - side window devices bounce lighting deeper into room (beam sunlighting)
4. Direct, concentrate it
   - light shaft
   - slit opening
5. Selectively transmit it
   - neutral tinted glass
   - tilted glazing

FRAGILE
HANDLE WITH CARE

6. Re-reflect it
   - light-colored interiors: ceiling - 70% (Munsell Value 9)
     walls - 50%-70% (Munsell Value 7.5-9)
   - shape interiors to help spread daylight
7. Soften it
   - deep openings
   - splayed openings
   - surface parallel to light rays
   - light-colored window frames & mullions
8. Diffuse it
   - rough surfaces, matte surfaces
   - glass block
   - obscure glass
   - fine mesh curtains/shades
9. Filter it
   - exterior plantings or screens
   - interior plantings or screens
10. Play with it
   - color it: stained glass, colored shaft
   - fracture it with prism: chandelier for daylight , glass blocks

III. Control It

1. operable exterior shading devices to block heat without excluding light
2. operable interior shading devices to block heat without excluding light
3. operable electric lighting controls
   - switching: manual, photo-controlled, computer-controlled
   - dimming: photo-controlled

IV. Use it Wisely

1. Make sure no light source (daylight or electric light) is a source of glare. Modify and control direct sun and skylight admission into building.
2. Use plantings both to shade glazing and to provide views with low luminance, to counteract glare.
3. If direct sun is admitted, it should be confined to areas where it will not disturb (overheat or cause glare for) inhabitants of the building. Direct sunlight can be modified to act as a sparkling focus.
4. Keep overall energy use for electric lighting to below 2 w/sq. ft. installed lighting and to 1 w/sq. ft. where possible.
5. Use electric lighting fixtures to balance daylight as well as provide nighttime lighting.
6. Make sure that thermal insulating materials intended for daytime use do not block admission of daylight.
7. As a rough estimate, figure 1/2 watt of cooling load for each watt of electric lighting load.
8. In general, use efficient electric light sources (fluorescent & HID). However, match light source to its use. A low-wattage incandescent lamp may be more appropriate for lighting a task from close-up than the same wattage flourescent lamp which, emitting more light, might cause glare conditions or too high a contrast with surroundings.

9. Consider lighting and ventilation requirements separately at first. Openings to admit light need not be the same ones used for ventilation.
10. Shading devices placed outside the glazing block heat more effectively than ones placed inside the glazing.
11. Vertical glazing ("windows") is much preferable to horizontal glazing ("skylights") due to adverse heat gain and glare during overheated periods. Use skylights only if they can be fully shaded.
12. Plan for reasonable levels of illumination. Provide higher levels for specific uses only where needed. If possible group functions with similar illumination requirements together.
13. Place functions which require high levels of illumination near daylight openings.
14. Place some daylight openings (or all, if no view is required) high to let bright light wash to the ceiling and reflect into the room without the inhabitants viewing the bright light source.
15. Screen views of the sky or other possible sources of glare such as light-colored walls.
16. Admit daylight to as many interior spaces as possible by using transparent or translucent partitions.
17. Provide balanced daylighting and reduce contrast by admitting daylight from more than one side of a space.

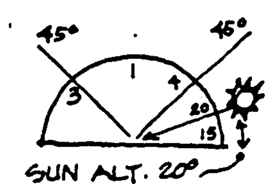
Daylighting Calculations

Many methods have been developed to calculate the amount of daylight to be expected in a room due to a given fenestration design. The major determinants are the sky conditions; the location, shape and size of the openings; the location, shape and size of exterior obstructions blocking direct skylight; and the interior surface reflectances. Different methods of calculation account for these factors in different ways.

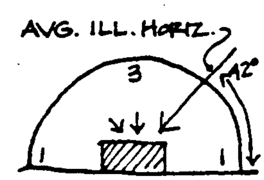
Daylight Factor Concept

The constant variation of sky conditions cannot be acknowledged in calculation procedures, which require standardized conditions. The two sky conditions that have been standardized are the completely overcast sky and the totally clear sky. Calculations involving the overcast sky are accomplished easily since variations are minimal. The C.I.E. Standard Overcast Sky is a close approximation to reality. Its luminance distribution as represented by a formula has been compared to several sets of luminance measurements of actual overcast skies and found to be in close agreement. Since the sky distribution pattern does not change with azimuth (direction), a window facing southeast will produce the same light distribution pattern as the same window facing west, or any other direction, all other factors being equal.

Since the clear sky luminance distribution depends on sun position, which changes constantly, it is a much more complicated matter to represent resulting interior light distribution under clear sky conditions.



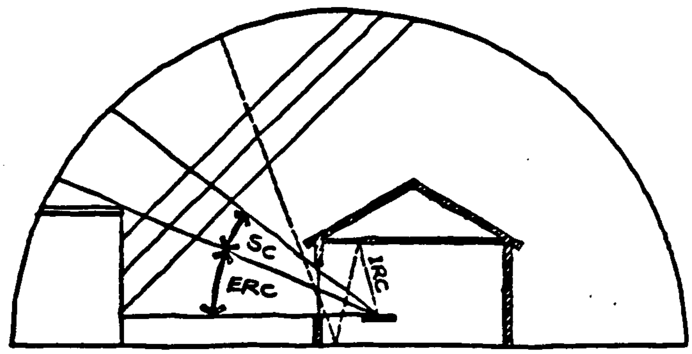
Relative Sky Brightness
Clear Sky



Relative Sky Brightness
Overcast Sky

The Daylight Factor calculation approach treats the illumination from daylight that occurs at a reference point inside a room as a percentage of the simultaneous illumination on a horiziontal plane from an unobstructed sky outdoors. This value is called the Daylight Factor and is composed of three different contributions of daylight to the room:

1. the Sky Component, or light received at the reference point directly from the sky;
2. the Externally Reflected Component, or light reflected from surfaces external to the room to the reference point; and
3. the Internally Reflected Component, which is light reflected from interior room surfaces to the reference point.

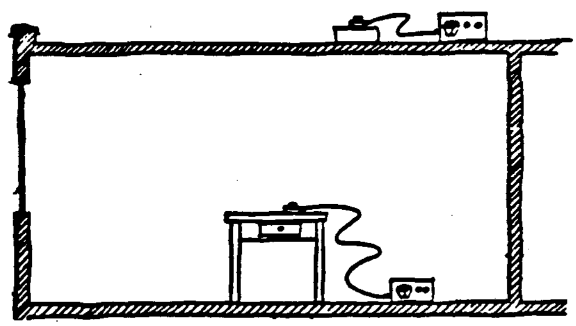


DF = SC + ERC + IRC

Components of Daylight Factor

For example, for a 1000 fc overcast sky (a completely overcast sky producing 1000 fc on the horizontal plane), a simultaneous interior measurement of 20 fc at a specific point is expressed as a Daylight Factor of 2%.

If the sky brightness changes, the amount of illumination measured at a point in the room will also change, but the Daylight Factor will remain the same. For example, for a 500 fc sky, the 2% Daylight Factor results in an illumination value of .02 x 500 = 10 fc.



Daylight Factor = 2%
fc on roof = 1000 fc (on horizontal plane
fc in room = .02 x 1000
= 20 fc (on horizontal plane)

Simultaneous interior & Exterior (unobstructed) measurements result in Daylight Factor

Different quantities of light will occur at different points in a room depending on its geometry and the placement of the openings; yet the relative pattern will remain the same as sky brightness changes as long as the Overcast Sky distribution is maintained. The pattern of light distribution is calculated once and then can be multiplied by data on daylight availability to get actual levels to be expected for the minimum, average, or maximum daylighting conditions in a particular locale.

The advantage of the Daylight Factor approach to daylighting calculations is that the pattern of light distribution in a room can be figured once and that pattern will not change. The disadvantage is that it only works simply for the Standard Overcast Sky where the luminance distribution of the sky vault is symmetrical about an axis through the zenith. Conditions of partly cloudy skies are so variable in distribution and occurrence as to make it pointless to try to predict exact effects, at least for purposes of design. The same conceptual approach of Daylight Factor calculation can also be followed for the clear sky since its luminance distribution has also been standardized, but it is a more complicated process due to the multiple conditions of sky luminance distribution as the sun changes positions in the sky. Since the effects of direct sunlight are not included in the Daylight Factor calculation, they must be figured separately in addition to illumination from the sky for clear sky conditions.

Preliminary Rough Estimates of Daylight Factor

It is possible to obtain a rough first approximation of the average Daylight Factor from overcast skies in a room by using some rules-of-thumb which relate glazing area to floor area. These guidelines are rough approximations only intended to start the process of selecting Patterns that will produce the desired illumination level. They are given for two conditions: side lighting (a window in one wall or a room); and top lighting (an even distribution of skylights or monitors in the roof).

For side lighting in a room with average room surface reflectances of 40% and no external obstructions, the following approximations can be used:

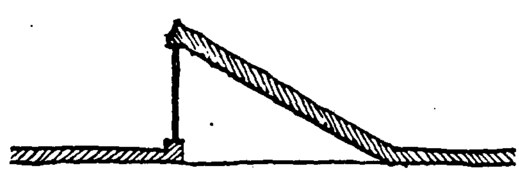
$$DF_{average} = .2 \frac{\text{net glazing area}}{\text{floor area}}$$

$$DF_{minimum} = .1 \frac{\text{net glazing area}}{\text{floor area}}$$

For top lighting, there are three glazing conditions for which the average Daylight Factor can be approximated: vertical monitors, sawtooth openings, and horizontal skylights. (Figure 2-3) If there is an even distribution of openings in the roof, there will be an even distribution of light in the room, so only the average Daylight Factor is considered.

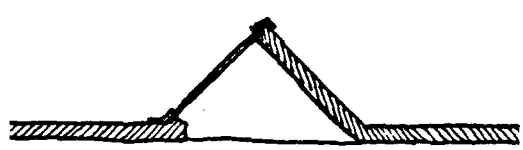
Vertical monitors:

$$DF_{average} = .2 \frac{\text{net glazing area}}{\text{floor area}}$$



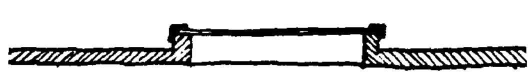
North facing sawtooth:

$$DF_{average} = .33 \frac{\text{net glazing area}}{\text{floor area}}$$



Horizontal skylights:

$$DF_{average} = .5 \frac{\text{net glazing area}}{\text{floor area}}$$



Summary of Calculation Methods

Sky Condition	Method
Any - record it!	1) Model measurements (see following pages) Ref: (4)
Overcast	2) Graphic methods
Overcast	a) Graphic Daylighting Design Method Ref: (4), (24), & (25)
Overcast (can be modified for clear)	b) BRS Daylight Factor Protractors Ref: (4), (7, Ch. 20), & (23)
	3) Calculation from prepared tables & graphs
Any, if illum. values on window known	a) LOF Lumen Method Ref: (4) & (22)
Clear	b) Simplified Clear Sky Ref: (4), (20), & (21)
Overcast, clear	4) Computer simulation programs

Models: Daylight

Daylight behaves identically in a scale model and in a full-size room, provided that the geometry is the same and the surface reflectances are the same. There is no need to use a correcting multiplier for scale. The scale of the model should depend on the type of study being undertaken. If you intend to take measurements, the size will depend on the size of the photometer cells with which the measurements will be made. The photometer cell should ideally cover about one square foot at model scale. Of course there are practical limits to the sizes of models. Building at the scale of 1/2" = 1'-0" represents a reasonable compromise and also allows easy viewing. Mirrors can be used to extend the perceived space of the model.

There are a number of factors, however, that will make measurements in a model differ from measurements in a real room. These factors are the transmission of the glass; the accumulation of dirt from the outside atmosphere on the glass; the presence of glazing bars or mullions in the window assembly (if not reproduced in the model); and the accumulation of dirt on the room surfaces. Typical ranges for each of these factors are shown below.

Glass transmission	.6 - 1.0
Exterior dirt	.5 - .9
Glazing bars	.65- .8
Interior dirt	.6 - .9

To correct model Daylight Factor measurements to approximate the built condition after a period of use, you can use the following assumed factors:

Glass transmission	.9 (clear glass)
Exterior dirt	.9 (non-industrial area, vertical glazing)
Glazing bars	.8 (metal windows)
Interior dirt	.9 (non-industrial area)

RULE-OF-THUMB CORRECTION FACTOR FOR MODEL DAYLIGHT MEASUREMENTS:

.9 x .9 x .8 x .9 = .58, or .6

INSTRUMENTATION*

There are a variety of photometers (light meters) and photocells available which are suitable for model studies. The discussion of instruments here will be limited to those which, in the opinion of the author, are suitable, sufficiently accurate, and in a reasonable price category for use in daylighting studies by architect's and engineer's offices.

Most modern illumination photometers make use of a photovoltaic cell. This cell has a chemically treated metallic plate, which when exposed to light, generates a small electromagnetic current. The current is conducted to a sensitive instrument (the "light meter") which measures this current and translates it into footcandles (or into lux which is the worldwide standard unit of illumination). However, there are several details regarding their performance characteristics which should be considered.

Photocells are not all identical and their current output is not always directly proportional to the illumination incident upon the surface of the cell. For this reason, cells must be calibrated at the factory or in the laboratory so that the photometer reading indicates the true illumination at all levels. Thus, the cell from one photometer cannot usually be used with another, although some manufacturers do offer equipment which is transferable within the line of their own products.

Also, photocells respond to the total energy spectrum differently than does the human eye whose response is to the "visible" portion of the spectrum. The photocell measures other areas of the energy spectrum as well. For comparative studies of models this discrepancy is not significant. The relative merits of two design schemes being compared are still valid. However, for absolute measurements (actual illumination levels) the photocell must be adapted with a color corrector (often referred to as a "Viscor Filter"). Since the addition of the <u>color correction device</u> seldom alters significantly the price to the purchaser, it is recommended that it be included in any new purchase.

Photocells are also subject to the "cosine law of illumination." That is, they are not as sensitive to light striking the cell from a low angle as from a high or more direct angle. This produces incorrect measurements which the instrument is used for general lighting studies. Most manufacturers of photometers can provide a cosine correction device for their photocells. It is absolutely <u>necessary</u> that photometers for lighting studies be equipped with a <u>cosine correction device</u>.

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*This section was prepared by Benjamin Evans under contract to the Lawrence Berkeley Laboratory. It will be used as part of their Daylighting Window Design Resource Package. This information is at the technical review draft stage and should not be copied or quoted.

Early model photometers used some type of galvanometer for measuring the current output of the photovoltaic cell. These galvanometers were extremely sensitive to shock and were frequently knocked out of calibration by rough handling. Some architects and engineers are still using this type of instrument. More recent photometers are a little more rugged and the best of the new equipment is transistorized and uses digital liquid crystal display units. Before purchasing a new photometer, read the manufacturer's specifications with regard to ruggedness.

Other characteristics to consider include the frequency of need for calibration and the range of illumination levels that can be measured. Good equipment will not need to be recalibrated more often than about once every two years with normal use. For daylighting studies, the photometer should provide a range of measurement from one to 12,000 footcandles. Usually, this range of response will require the user to switch ranges as necessary and mentally multiply the output by some correction factor (e.g., x1, x10, x100). However, it is possible to adapt most photometers which do not have this range so that they will measure high illumination levels by covering the cell with a cap which transmits a percentage of the incident light. For instance, if the maximum range of the scale is 1,000 footcandles and you wish to measure a light level of 2,000 footcandles, the cell can be covered with a cap allowing 50 percent of the light to penetrate. The indicator on the scale will then read 500 footcancles and can be multiplied by two to get the correct answer of 1,000. A cap for this purpose can be made by drilling holes that amount to 50 percent of the total cell area.

Photometers which have the photocell built into the display meter case (such as those normally used for photography) are not suitable for model studies since the light level indicator must be placed inside the model and cannot usually be seen from outside the model without influencing or blocking the incident light.

However, those meters which read in footcandles can be helpful for general measurements around the office.

<u>Available Light Meters</u> -- Choosing the right photometer will depend upon intended use (e.g., model studies, full scale measurements), the expertise of the purchaser and user, funds available, range of options needed, accuracy required, and so on. A survey of photometer manufacturers resulted in fewer responses than expected and only in England is a unit made especially for model studies. The units briefly described here appear suitable for model studies as well as general lighting measurements. While some of the manufacturer's more critical performance criteria are listed here, no attempt is otherwise made to evaluate quality in the instruments. Costs shown are based on information received for 1979-80, but may vary considerably with passing time.

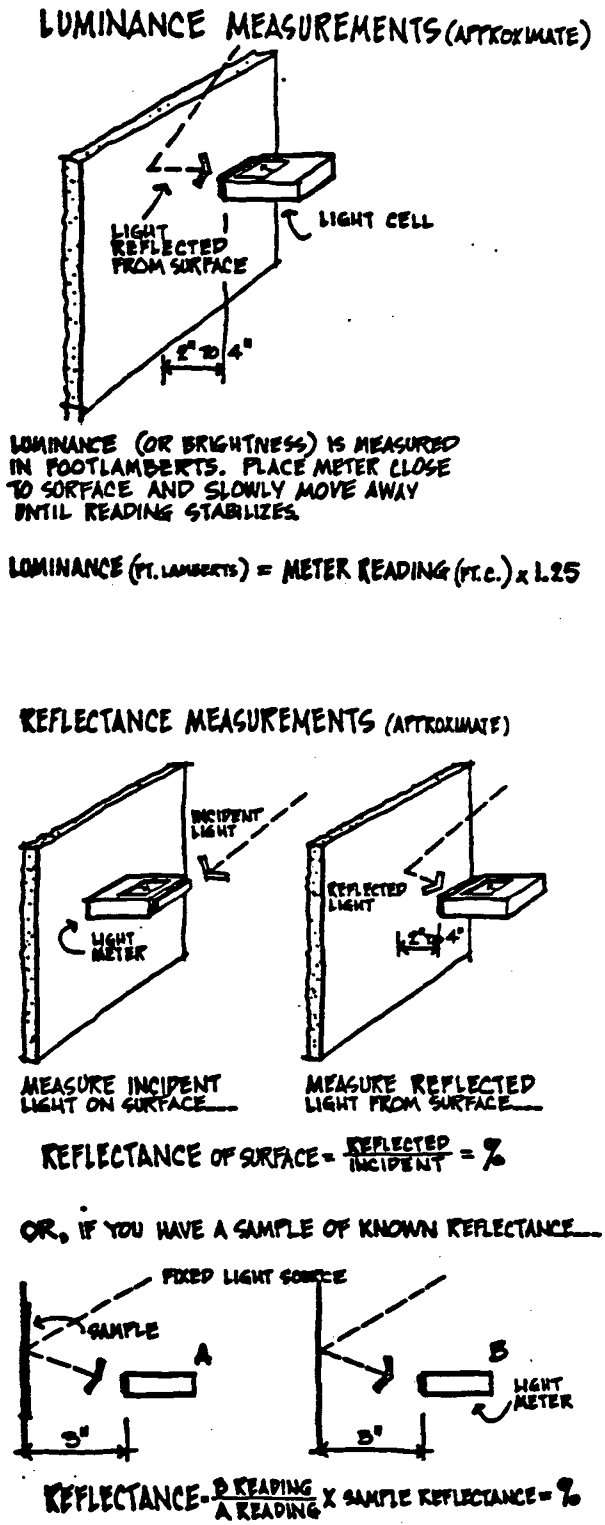
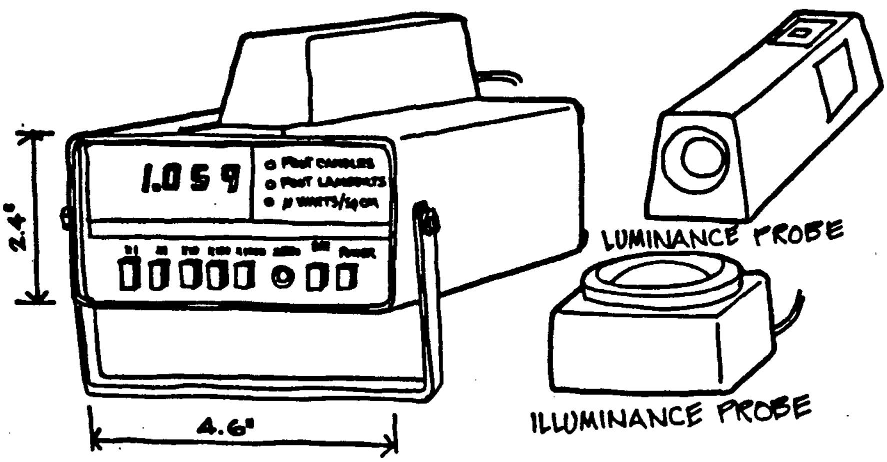

LUMINANCE MEASUREMENTS (APPROXIMATE)
LIGHT CELL
LIGHT REFLECTED FROM SURFACE
2" TO 4"
LUMINANCE (OR BRIGHTNESS) IS MEASURED IN FOOTLAMBERTS. PLACE METER CLOSE TO SURFACE AND SLOWLY MOVE AWAY UNTIL READING STABILIZES.
LUMINANCE (FT. LAMBERTS) = METER READING (FT.C.) x 1.25
REFLECTANCE MEASUREMENTS (APPROXIMATE)
INCIDENT LIGHT
LIGHT METER
REFLECTED LIGHT
2" TO 4"
MEASURE INCIDENT LIGHT ON SURFACE...
MEASURE REFLECTED LIGHT FROM SURFACE...
REFLECTANCE OF SURFACE = REFLECTED / INCIDENT = %
OR, IF YOU HAVE A SAMPLE OF KNOWN REFLECTANCE...
FIXED LIGHT SOURCE
SAMPLE
A
B
LIGHT METER
3"
3"
REFLECTANCE = B READING / A READING x SAMPLE REFLECTANCE = %

Figure A.

While the price of a good photometer may seem excessive, remember that the unit itself represents only a minor portion of the costs that may be devoted to a project -- personnel becoming familiar with the model-study process, model supplies and construction, and the time and energy contribution for meaningful studies. An appropriate, well-made photometer may save in the long run and one significant model study project may save thousands of dollars if it prevents a design error, thus offsetting the cost of the instrument.



TEKTRONIX
J16 PHOTOMETER

Tektronix, Inc.
P.O. Box 500
Beaverton, OR 97007
(503) 644-0161

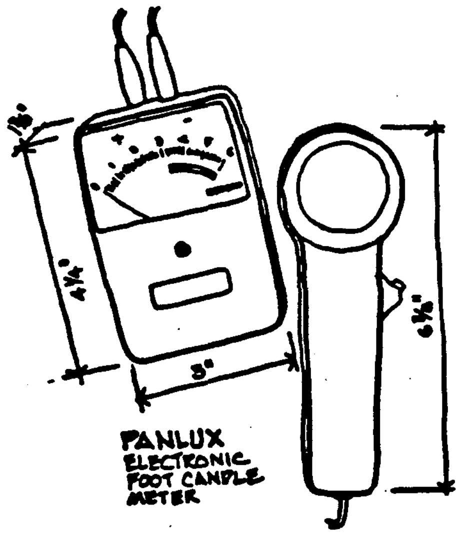
<u>The J16 Digital Photometer/Radiometer</u> (basic readout unit):
LED Digital display; 2.4 x 4.6 x 8 in.; 3.3 lbs.; rechargeable nickel-cadmium batteries and battery charger; Optional A/C power supply; Price $850.

> <u>J6511 Illuminance Probe</u> (for measuring illumination in footcandles): 0.001 to 1999 f.c. (to 199,900 f.c. on request); Cosine and color corrected; 2.5 x 2.5 x 1 in.; 12 to 25 ft. probe cable; Price $420.

> <u>J6503 8 Degree Luminance Probe</u> (for measuring luminance or "brightness" in footlamberts): 0.1 to 199,900 footlamberts; 2 x 1.5 x 8 in. (clips to photometer); 8 Degree = 1.7 inches per foot of distance from probe to target; Price $400.

Gossen Division
Berkey Marketing Companies
25-20 Brooklyn-Queens Expwy. West
Woodside, NY 11377
(212) 932-4040

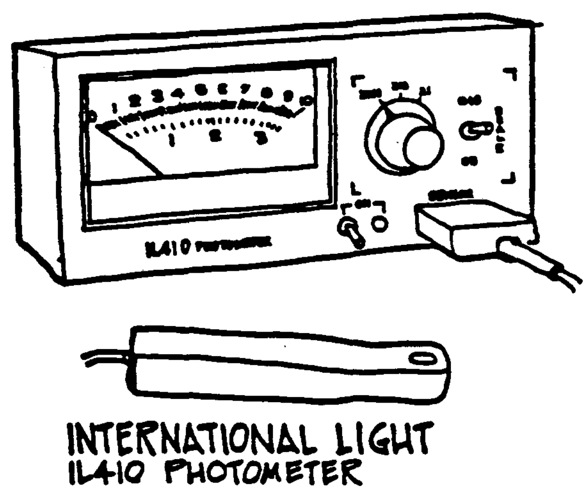
Panlux Electronic Foot Candle Meter
0.05 to 12,000 f.c.; 4.25 x 3 x 1.5 in. (probe 6 3/8 in.); 4.5 oz.; battery operated; Cosine corrected; 3-foot probe cord; Price $176 (for 10-foot cord add $25)



International Light, Inc.
Dexter Industrial Green
Newburyport, MA 01950
(617) 465-5923

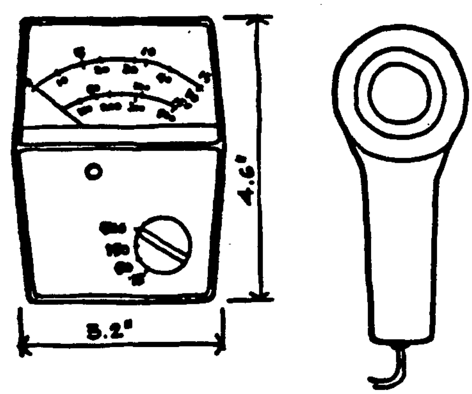
IL410 Photometer (for measuring footcandles):
0.3 to 1000 f.c.; 4.2 x 3.5 x 23.1 in.; 2.5 lbs; Cosine and color corrected; 7-foot probe cable; battery operated; Price $419.

SC110/CM219 Optional Illuminance Probe
0.8 to 10,000 f.c.; Price $177



Simpson Electric Company
853 Dundee Avenue
Elgin, IL 60120
(312) 697-2260

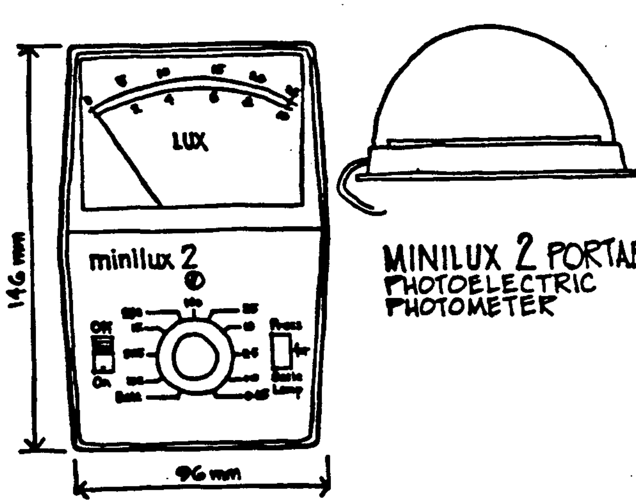
Simpson Illumination Level Meter (for measuring footcandles):
0 to 1,500 f.c.; 0 to 50,000 f.c. with optional filter; 1.8 in. cell diameter; 3.2 x 4.6 x 1.6 in.; less than 1 lb.; Cosine and color corrected; luminance x2 tube for luminance or "brightness" measurements - 0 to 10,000 f.l.; Price $199 complete with carrying case.



SIMPSON MODEL 408
ILLUMINATION LEVEL METER

Salford Electrical Instruments Ltd.
Peel Works
Barton Lane, Eccles
Manchester M30 OHL
England

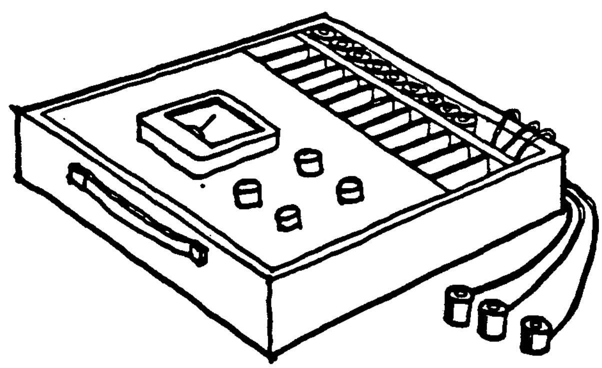
Minilux 2 Portable Photoelectric Photometer (for measuring illumination in lux: 10 lux = approx. 1 footcandle):
215 x 135 x 95 mm.; 440 grams; 0.25 to 10,000 lux; Cosine and color corrected; battery powered; 2 meter cord; Price 159 Pounds.



MINILUX 2 PORTABLE
PHOTOELECTRIC
PHOTOMETER

Megaton Ltd.
165 Marlborough Road
Hornsey Road
London N19 4NE
England

<u>Megatron Architectural Model Luxmeter</u> (for measuring illumination in lux): Utilizes 12 type M photocells through selective switching; 0 to 10,000 lux (1,000 f.c.); Cosine and color corrected; cell diameter 45 mm., other sizes available; 10-foot cables; Price 560 Pounds.



MEGATRON
ARCHITECTURAL MODEL LUXMETER

Survey of Light Measuring Instruments

June 1980

MANUFACTURER	MODEL	SENSITIVITY RANGE	COSINE CORRECTION	CIE PHOTOPIC % DEVIATION	SENSOR SIZE	SILICON SENSOR	SELENIUM SENSOR	DIGITAL DISPLAY	ANALOG DISPLAY	POWER SUPPLY	COMMENTS
EG & G ELECTRO - OPTICS 35 Congress Street Salem, MA 01970 (617) 745-3200	550-1 Radiometer/ Photometer	1.999×10^{-3}-1.999×10^{3} f.c 19.99×10^{-3} - 19.99×10^{3} fl		±2%	1 CM2					115V 220V	Multiprobe 550-2 provides photometric correction filter, flat radiometric filter and an 8° field of view lens
GOSSEN Berkey Marketing Companies P.O. Box 1102 Woodside, NY 11377 (212) 932-4040	Panlux Electronic	$10.^{0}$-1.2×10^{4} fc.	●						●	9V	
INTERNATIONAL LIGHT, INC. Dexter Industrial Green Newbury Port, MA 01950 (617) 465-5923	IL 410	10^{-3}-10^{-3} fc.	●	±3%		●			●	9V	Compact Low Profile Probe Available
	SC 110/CM 510A	10^{-1}-10^{4} fc.									High Illumination Probe with 7 foot cord
	IL 510A	2×10^{-2}-2×10^{4} fc.		±2%					●	95-135 VAC	Programming Switch Reads Currents in Amps
	IL 710A	2×10^{-3}-5×10^{4} fc.		±2%		●		●			Research Photometer Range As Low As 4×10^{-9} With Photomultiplier

*This chart was prepared by the Windows and Lighting Group at the Lawrence Berkeley Laboratory for their Daylighting Window Design Resource Package. This information is at the technical review draft stage and should not be copied or quoted.

Survey of Light Measuring Instruments

June 1980

MANUFACTURER	MODEL	SENSITIVITY RANGE	COSINE CORRECTION	CIE PHOTOPIC % DEVIATION	SENSOR SIZE	SILICON SENSOR	SELENIUM SENSOR	DIGITAL DISPLAY	ANALOG DISPLAY	POWER SUPPLY	COMMENTS
KRATOS/SCHOEFFEL 24 Booker Street Westwood, NJ 07675 (201) 644-7263	M 460			±2%					●	DC	
LICHTMESSTECHNIK BERLIN Helmholtzstrasse 9 D-1000 Berlin 10 (030) 393-4028	LMT Pocket Lux	10^{-1} - 10^{5} lux	●			●			●	6V DC	Automatic Ranging System Storage of Measured Display
MEGATRON LIMITED 165 Marlborough Road Hornsey Road London N19 4NE (01) 272-3739	Architectural Model Luxmeter	10^{-1} - 10^{4} lux	●	2.98%			●		●		12 Individually Operated Photocells Allows 12 Simultaneous Measurements Ideal For Model Work
	BRS Daylight Photometer	10^{0} - 10^{-5} lux	●	2.98%			●		●		Reads Daylight Factor Directly 0-5%, 1-10% 0-20%
	BRE Cyclindrical Illuminance Meter	10^{0} - 10^{4} lux	●	2.98%			●		●		Toggle Switch To Allow For Cyclindrical or Planar Measurement, Also Potentionmeter For Zero Drift Correction

Survey of Light Measuring Instruments

June 1980

MANUFACTURER	MODEL	SENSITIVITY RANGE	COSINE CORRECTION	CIE PHOTOPIC % DEVIATION	SENSOR SIZE	SILICON SENSOR	SELENIUM SENSOR	DIGITAL DISPLAY	ANALOG DISPLAY	POWER SUPPLY	COMMENTS
MEGATRON	DA 5 Luxmeter	$2.5x10^{1}$-$2.5x10^{-1}$	●		.7 CM		●		●	9V	Low Level Illuminance Meter Portable, Lt. Weight
OPTRONIC LABORATORIES, INC. 7676 Fenton Street Silver Spring, MD 20910 (301) 587-2255	730 A	10^{0} - 10^{6} fc.			1 CM^2	●		●		110V	Autoranging, Radiometer/ Photometer
	85 Cosine Receptor		●								Optional Receptor For Model 730A.
	80 Relay Lens	10^{0} - 10^{6} fL.									Optional Lens Enables Luminance Measurements.
PHOTODYNE INC. 5356 Sterling Center Dr. Westlake Village, CA 91361 (213) 889-8770	88 XL	10^{-6} - 10^{3} fc.		±5%		●		●		9V	Range Achieved Sensor Model 650/750
PHOTORESEARCH 3000 North Hollywood Way Burbank, CA 91505 (213) 849-6017	1980A	10^{-5} - 10^{7} fc. 10^{-5} - 10^{7} fL.	●					●		117V 220- 240V	Photometer Requires Accessories For Full Range Readings
	Litemate/Spotmate System 500	10^{-2} - $1.9x10^{4}$ fc. 10^{-2} - $1.9x10^{4}$ fL.	●			●		●		6V	Handheld photometer and a luminance spotmeter with a 1° acceptance angle.

Survey of Light Measuring Instruments

June 1980

MANUFACTURER	MODEL	SENSITIVITY RANGE	COSINE CORRECTION	CIE PHOTOPIC % DEVIATION	SENSOR SIZE	SILICON SENSOR	SELENIUM SENSOR	DIGITAL DISPLAY	ANALOG DISPLAY	POWER SUPPLY	COMMENTS
PHOTO RESEARCH	1605 - Sprd Specktra-Spot	10^{-1} - 2 x 10^{5} fc.					●			117V	Photometer/Radiometer ½° Measuring Field.
	1610 - Sprd.	10^{-1} - 2 x 10^{4} fc.					●				1° Measuring
	FC - 200	10^{-1}-3x10^{4} fc. 10^{-1}-3x10^{4} fL.	●						●		Low Cost Portable, Solid State, Multi-Ranging Photometer
	PR - 1000	10^{0}-1.9x10^{4} fc. 10^{0}-1.9x10^{4} fL.				●		●			Accessory Probe
TEKTRONIX P.O. Box 500 Beaverton, OR 97077 (503) 644-0161	J 16 J 6511	10^{-3} - 1.9 x 10^{3} fc.	±2%			●		●		115V	Digital Photometer Radiometer
	J 6503	10^{-1} - 1.9 x 10^{5} fL.	±2%			●		●			Luminance Probe 8°
	J 6523	10^{-1} - 1.9 x 10^{5} fL.	±2%			●		●			Luminance Probe 1°

Survey of Light Measuring Instruments

June 1980

MANUFACTURER	MODEL	SENSITIVITY RANGE	COSINE CORRECTION	CIE PHOTOPIC % DEVIATION	SENSOR SIZE	SILICON SENSOR	SELENIUM SENSOR	DIGITAL DISPLAY	ANALOG DISPLAY	POWER SUPPLY	COMMENTS
UNITED DETECTOR TECHNOLOGY, INC 2644 30th Street Santa Monica, CA 90405 (213) 396-3175	Opto-Meter UDT - 40X	10^{-3} - 10^{4} fc. 10^{-2} - 10^{5} fL.	●	±2%	1 CM2	●			●	126V	Model 113 Accessory Lens For Luminance
	PIC UDT - 181	10^{-5} - 10^{4} fc.	●	±2%	1 CM2	●		●		AC or Bat.	Offers Plug In Calibration Modules, With Programmable Decimal Points
	Laboratory Standard UDT - 111A	10^{-3} - 10^{3} fc.		±2%	1 CM2	●				115/230V	
	Digaphot 3300	10^{0} - 10^{3} fc.	●			●		●		9V	Rechargeable Battery Available.

Global State-of-the-Art of Passive Cooling and Dehumidification with Potential Applications for Overheated U.S. Conditions --

Arthur Bowen

Editor's Note: The following paper describes some research recommendations that were made at a meeting of International Cooling Experts. It is included to provide a starting point for an ongoing discussion of needs assessment for the Passive Cooling Program. Your input is solicited. Please forward your comments to: Don Elmer, Passive Cooling Program, Lawrence Berkeley Laboratory, Building 67A, University of California, Berkeley, CA 94720.

GLOBAL STATE-OF-THE-ART OF PASSIVE COOLING AND DEHUMIDIFICATION, WITH POTENTIAL APPLICATIONS FOR OVERHEATED U.S. CONDITIONS *

Professor Arthur Bowen
School of Engineering and Architecture
University of Miami
Coral Gables, Florida, U.S.A. 33124

BACKGROUND

Passive cooling and dehumidification, probably because of achievement difficulties, has not been funded or researched to the same extent as heating - particularly within the United States. Furthermore, the broad knowledge base is not established or generally known.

Historically, world-wide indigenous human shelter and settlement, have qualifed and established proven methods to optimize ambient conditions. Recent technological advances permit the emergence of new, and more effective, passive cooling techniques in buildings and communities. However, quantification of established and new cooling and dehumidification methods need to be accomplished before successful applications can be expected.

SUMMARY

Unlike the United States, most of the predominantly overheated regions of the world have, for economic and technical reasons, remained unhampered by the impact of conventional mechanical air conditioning. Consequently, the need to construct shelter and settlement so as to optimize ambient energy utilization for the purposes of achieving and maintaining human comfort, persists. Several significant passive cooling techniques are understood, and successfully employed through historical, vernacular responses, in a variety of overheated bioclimatic regions. Furthermore, some important work is being accomplished, by oversea research establishments, to quantify known methods and explore new potentials.

Within the United States, ambient cooling, once well understood by the builder, has all but vanished. However, recent experimentation in some locations of the sun-belt, has stimulated a revival.

To enable a survey to be completed and a report prepared within one year, an "International Expert Group Meeting on Passive and Low Energy Cooling, Heating and Dehumidification"(I.E.G.M.) was held in May 1980, to determine the global state-of-the-art. Eighteen carefully selected experts, from a wide range of topics and geographical regions, prepared thirty-six position papers. A further twenty-five invited observers and technical recorders,

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* Extracted from the paper presented at the U.S. Department of Energy Passive and Hybrid Solar Energy Program Update Meeting, 21-24 September 1980, Washington, D.C.

assisted in scrutinizing these papers and questioning the experts on pertinent matters. A "National Expert Group Meeting on Passive and Low Energy Cooling, Heating and Dehumidification" (N.E.G.M.) is to be held in November 1980. This second meeting will scrutinize the papers and recommendations of the International Meeting, and make recommendations for research, applications and implementation needs for cooling and dehumificiation in the United States.

ACCOMPLISHMENTS

The I.E.G.M. identified the global state-of-the-art and made these recommendations in the following areas:

Thermal Requirements of Occupants in Passive Buildings

- to determine the discomfort limits, using different age, sex and ethnic groups, for a broader sample.
- to study and determine the effects of the rate of change in thermal conditions on occupants. Also the combination of thermal and other factors.
- to investigate the influence of cultural factors and clothing habits.

Radiative Cooling

- collection and distribution of regional data on night sky radiation, from roofs and north walls.
- collection and distribution of regional data on panel cooling of interior spaces and exterior surfaces.
- research and develop materials of low absorption and high emission rates for exterior use. High absorption and low emission rates for internal use.
- determine the limits of cooling by radiation in humid conditions.

Convective Cooling

- to determine airflow rate for body cooling as a function of task and micro-climate conditions.
- based on meteorological data, established theory and experiments, to develop relationships which will allow prediction, at a given site, of windspeed and direction.
- develop algorithms, which describe the heat transfer rates caused by airflow, through buildings of various configurations. Suitable for insertion in detailed building energy analysis computer programs.
- determine the causes and effects of diurnal thermo-regulation on the stack-effect in buildings.
- using detailed building energy analysis tools, perform parametric sensitivity studies for many build-types, configurations and climates, so as to establish:
    - cooling load reductions

- expected level of indoor thermal comfort, based on climate parameters, assuming a purely passive strategy.

- from the above, develop designer-oriented rules of thumb, which suggest systems for various climates and provide simple methods for estimating the thermal benefits of these systems as a function of a few simple climate parameters.

Evaporative Cooling

- determine the extent to which, passive methods will provide body comfort related to task, in a range of climate conditions, governed by both temperature and vapor pressure.

- determine the limits to which, passive and hybrid methods will provide body comfort related to task, in a range of warm and humid conditions, seasonally and diurnally.

- determine the effects of various evaporative cooling methods on a building structure, under various overheated and vapor pressure conditions, seasonally and diurnally.

- determine the extent to which convection augments the evaporative cooling process.

Passive and Hybrid Dehumidification

- promote theoretical research and experimentation to characterize the heat transfer and heat generation processes involved in existing desiccant materials.

- promote research and development for new desiccant materials with low regeneration temperatures.

- promote demonstration projects for solar-induced passive dehumidification.

Earth Cooling

- meteorology data collection should be extended to include essential earth composition information, such as, soil moisture, regional water content, subterranean temperature profiles.

- determine the effects of soil composition, moisture content and ground cover on earth temperatures at various levels.

- provide accurate subterranean data and profiles in presently inaccurate areas, such as, coastal zones, lake and riverside.

- assemble data achieved into algorithms for regional dissemination through simple computer programs.

- determine the effects of surface evaporation and ground cover variations on subterranean climate.

- determine the effects of controlled added moisture on soil temperature profiles.

- expand research into the use of winter air to modify summer soil temperatures through earth heat exchangers.

- existing data on heat exchange with the ground should be collected and augmented with new performance data, for computer modelling and distribution of generic systems.
- explore chemical alteration to the soil and the effects of electric fields.
- develop regional guidelines for dehumidification, ventilation, daylighting, view, access, etc.
- develop design details for promising systems, especially waterproofing, insulation levels and location. Also, regional guidelines.
- obtain experimental data on sod roof design, moisture percolation, drainage, etc. Also, moisture removal from the interior.
- identify and resolve structural concerns such as expansion and contraction of soils, earthquakes and mechanical strength.

Daylight Controls in Buildings and Urban Areas

- obtain and distribute illumination data for C.I.E. and clear skies. Also, modification factors for cloud cover.
- effects of room geometry and openings on daylighting interiors.
- effects of building morphology on daylighting interiors and urban spaces.
- develop tools and prediction methods to ensure controlled levels of daylight in buildings.
- develop sunlight and daylight protractors and nomograms to ensure sunlight or shade in urban areas and the building's perimeter.
- develop and distribute guidelines for the employment of planned supplementary artifical lighting.

Thermal Regulation Through Site and Landscape Design

- establish and disseminate information on the thermal properties of typical landscape materials.
- quantify the cooling effects of various types of planting materials, in a wide range of combinations.
- quantify the cooling and heating effects of deciduous plants.
- identify the range of site planning and design techniques that may be employed to promote cooling.
- determine regional characteristics, classifications and guidelines for landscape and site planning cooling strategies.

Passive Energy Optimization Through Urban and Regional Planning

- establish genotype strategies by bio-climatic regions.
- establish phenotype methods and employment guidelines.
- provide controlled solar access or protection in the above.
- research and develop passive land and building zoning strategies for

cooling.

- provide guidelines for the integration of cooling needs in local building and planning regulations.
- provide guidelines for the employment of materials and methods to ensure cooling in urban spaces.
- research and develop methods for optimizing local ambient energy at all times.
- collect and disseminate all the above information.

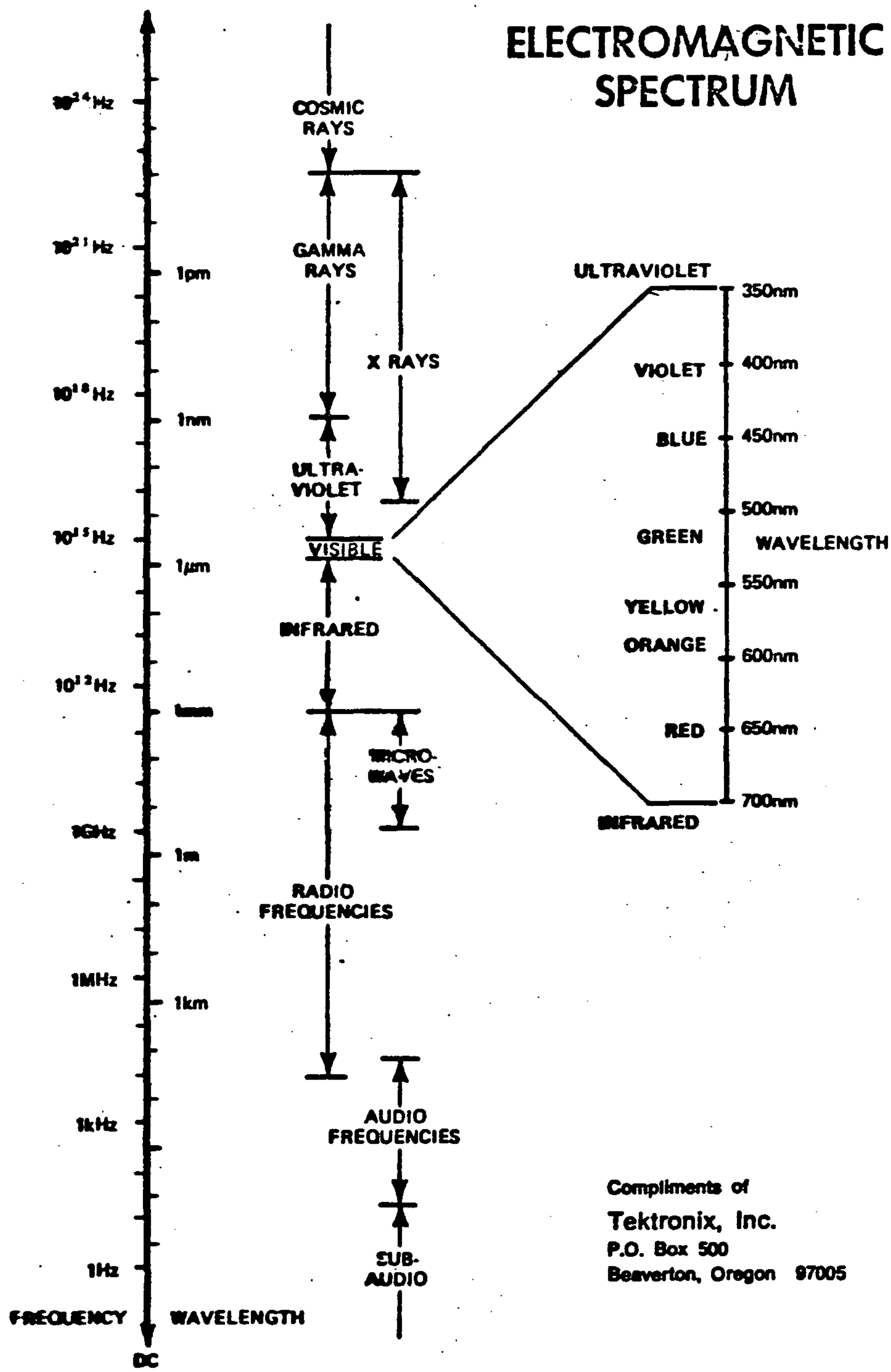
FUTURE ACTIVITIES

The immediate research topics have been identified above. A further list of additional items will be included in the final report. As the majority of passive cooling techniques are, as yet, not quantified, immediate demonstration projects are strongly recommended for evaluation.

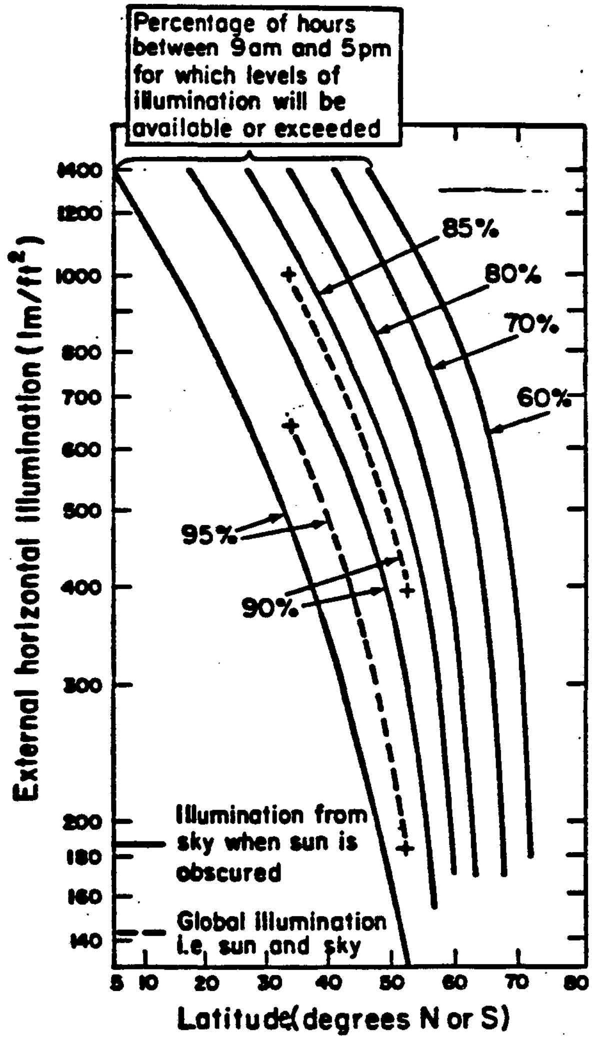
Annual update meetings of international and national experts will be continued to establish progress in scheduled research topics. Information dissemination on developments will be through national conferences and regional workshops. New literature, prediction tools, problem-solving methods and research results will be made available as they are developed.

APPENDICES

Visible Spectrum Within the Electromagnetic Spectrum



Available Illumination



Reference: (4)

Solar Illumination on a Surface Perpendicular to Sun's Rays
(in footcandles)

Latitude		Dec. 21			Mar. 21/Sept. 21			June 21		
		8am/4pm	10am/2pm	noon	8am/4pm	10am/2pm	noon	8am/4pm	10am/2pm	noon
30°	average*	2,898	5,565	6,020	5,250	6,503	6,769	6,020	6,811	6,986
	peak	4,140	7,950	8,600	7,500	9,290	9,670	8,600	9,730	9,980
40°	average	1,015	4,676	5,320	4,907	6,258	6,552	6,069	6,762	6,937
	peak	1,450	6,680	7,600	7,010	8,940	9,360	8,670	9,660	9,910
50°	average	--	2,980	3,980	4,360	5,870	6,200	6,040	6,660	6,820
	peak	--	4,260	5,680	6,230	8,380	8,850	8,630	9,510	9,750

*"average" - 70% of "peak"

Reference: (7) pp. 31-36

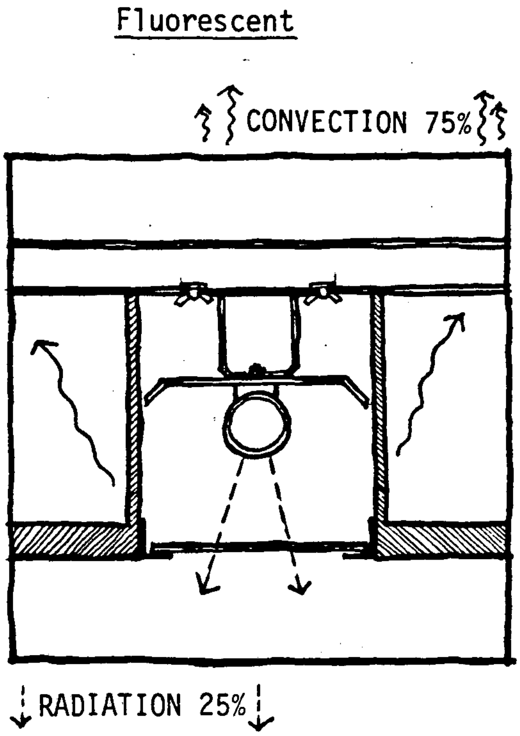
Efficacy of Light Sources

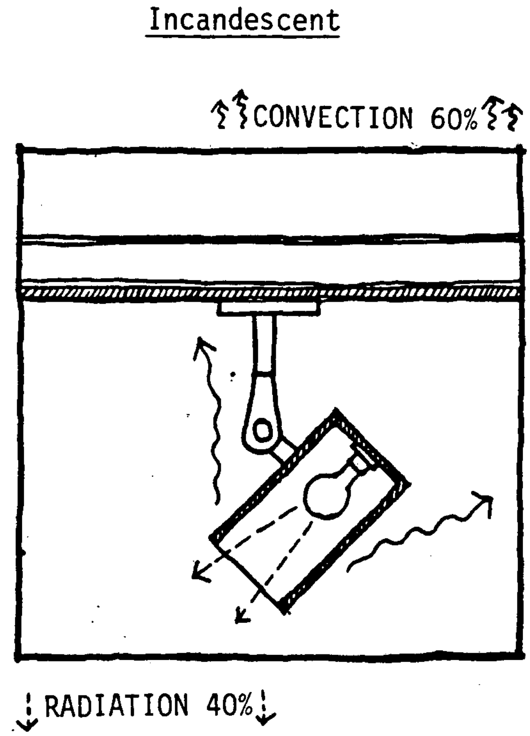
	Lumens/Watt
Daylight*	
Sun - (alt $7\frac{1}{2}^{o}$)	90
- (alt 25^{o})	117
- suggested mean	100
Sky (clear)	150
Sky (average)	125
Global (average)	115
Incandescent	5-25
Fluorescent	55-85
HID	
mercury	25-60
metal halide	85-100
high-pressure sodium	100-140

Note: These light sources all have different color-rendering properties. Our visual systems are adapted to the changing spectral distribution of daylight. All of the electric light sources do not blend well with daylight or with each other, however. It is good practice to test proposed combinations of electric light sources with daylight and with color samples of interior finishes and furnishings.

*Reference: (7), p. 51.

Heat Gain From Electric Lights





Reference: (1)

Recommended Levels of Illumination

Table 1: Recommended maximum lighting levels

Task or area	Footcandle levels	How measured
Hallways or corridors ------	10 ± 5	Measured average, minimum 1 footcandle.
Work and circulation areas surrounding work stations ------	30 ± 5	Measured average.
Normal office work, such as reading and writing (on task only), store shelves, and general display areas ------------	50 ± 10	Measured at work station.
Prolonged office work which is somewhat difficult visually (on task only) ----------	75 ± 15	Measured at work station.
Prolonged office work which is visually difficult and critical in nature (on task only)------	100 ± 20	Measured at work station.
Industrial tasks ---------	ANSI-A11.1-1973	As maximum.

Table 2: Relative visual task difficulty for common office tasks

Task description	Visual Difficulty Rating
Large black object on white background -----------------	1
Book or magazine, printed matter, 8 point type and larger ----------	2
Typed original ----------------------------	2
Ink writing (script) -------------------------	3
Newspaper text ---------------------------	4
Shorthand notes, ink ------------------------	4
Handwriting (script) in No. 2 pencil --------------------	5
Shorthand notes, No. 3 pencil --------------------	6
Washed-out copy from copying machine ------------------	7
Bookkeeping ---------------------------	8
Drafting -----------------------------	8
Telephone directory -------------------------	12
Typed carbon, fifth copy -----------------------	15

Reference: (6)

Table 1 shows levels for office work that are recommended when work stations are occupied; otherwise, consideration should be given to turning lights off or to switching to 30 footcandles if other workers remain nearby. For tasks requiring levels higher than 50 footcandles, switching to lower levels is desirable if the work changes to less critical tasks. Illumination at the task should be reasonably free of veiling reflections and body shadows. Refer to Table 2 for guidance in determining visual difficulty of office tasks. Levels for industrial work are from the American National Standards Institute A11.1-1973, June 1973, Practice for Industrial Lighting.

Table 2 may be used as a guide in evaluating the degress of visual difficulty for office work. It is based on the concept that visual difficulty for this kind of work is not only a function of the intrinsic characteristics of the task and the lighting system, but also of the length of time the task must be performed.

To use this table, multiply the difficulty rating, as shown in the table, for each task performed at a given work place by a single worker times the number of decimal hours per day it is performed, for example, 3 hours 15 minutes = 3.25 decimal hours. Add the products for each task. If the sum is greater than 40, provide 75 footcandles on the work station. If the sum is greater than 60, provide 100 footcandles on the work station. Multiply the difficulty factors by 1.5 if the operator is over 50 years of age, or if he has uncorrectable eyesight problems.

SOUTH OVERHANG DESIGN METHOD
FOR SEASONALLY OVERHEATED CLIMATES

Karen Crowther

The following method of designing south overhangs is based on the sun's altitude (the angle it makes with the horizon). Except at solar noon, the sun is to the east or west of due south. Unless the overhang extends over each side of the window the sun will strike the window on the side. (See Figure 1.) This design method does not address that problem.

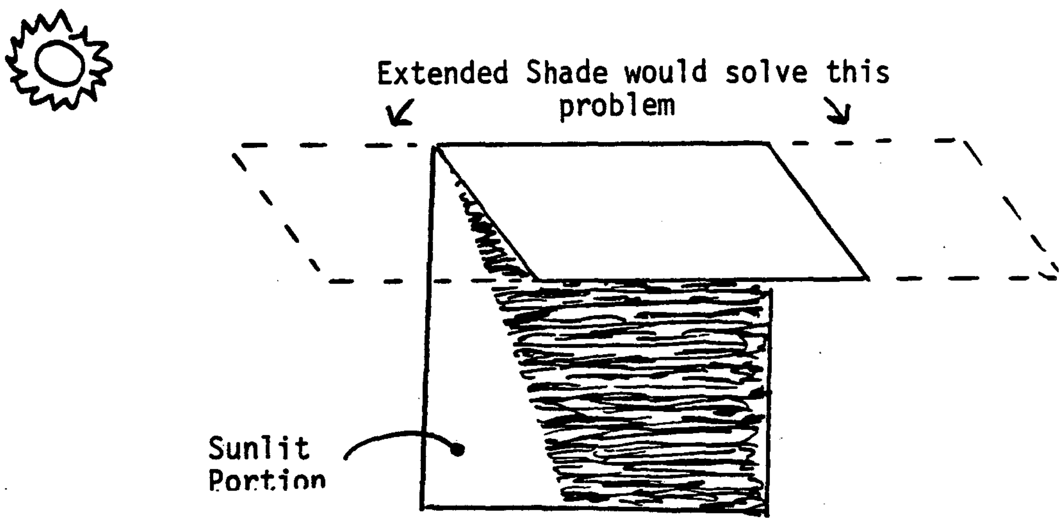
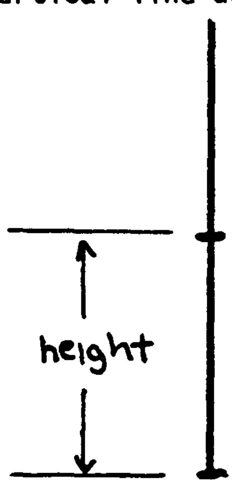
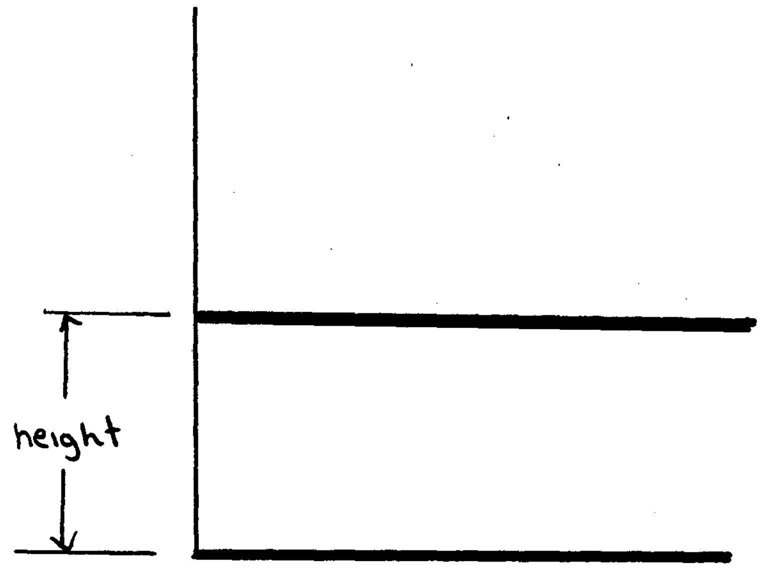


Figure 1.

STEP 1. Draw a vertical line and mark off the window height to scale.



STEP 2. Draw horizontal lines at the window top and bottom.



STEP 3. Choose the summer months during which the window should be shaded.

Look at Table I and find the sun angles which correspond to your latitude and summer shading months. Pick the smallest of these angles.

EXAMPLE: Your latitude. . . 39^{o}
Shaded months . . . July and August
Look in the 40^{o} latitude column (it's the closes to 39^{o}).
Find the July angle (57^{o}) and the August angle (51^{o}).
The August angle is the smallest so choose this as your summer angle.
Summer Angle . . . 51^{o}

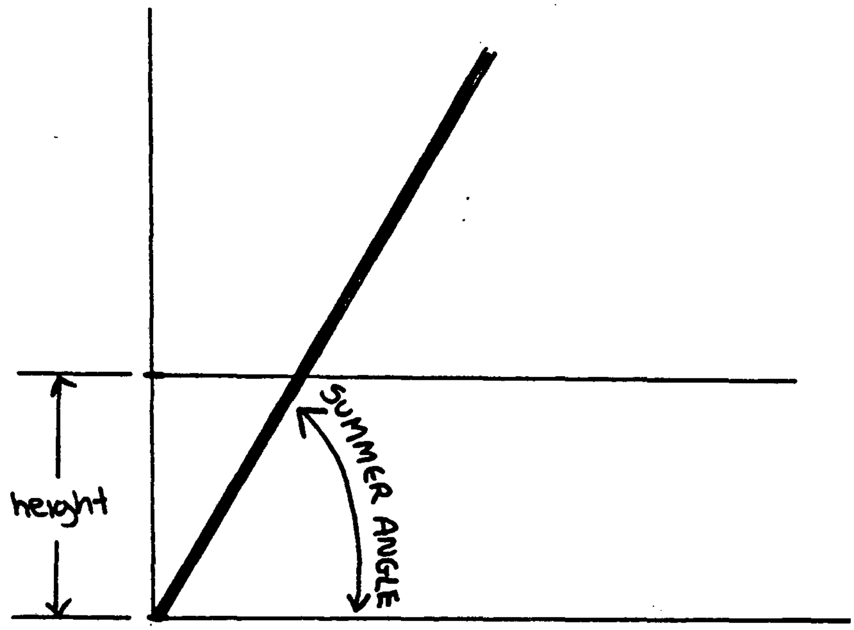
TABLE I

SUMMER ANGLE
Sun Altitude at 10AM and 2 PM

Latitude	24	28	32	36	40	44	48
Month							
Sept/Mar	52	50	47	44	42	39	35
Aug/Apr	59	58	56	54	51	49	46
Jul/May	62	62	61	60	57	56	53
June	63	63	62	61	60	58	56

Note: If the summer month you choose is not shown on this table, use one which does appear.

STEP 4. Draw the Summer Angle at the bottom of the window using a protractor.



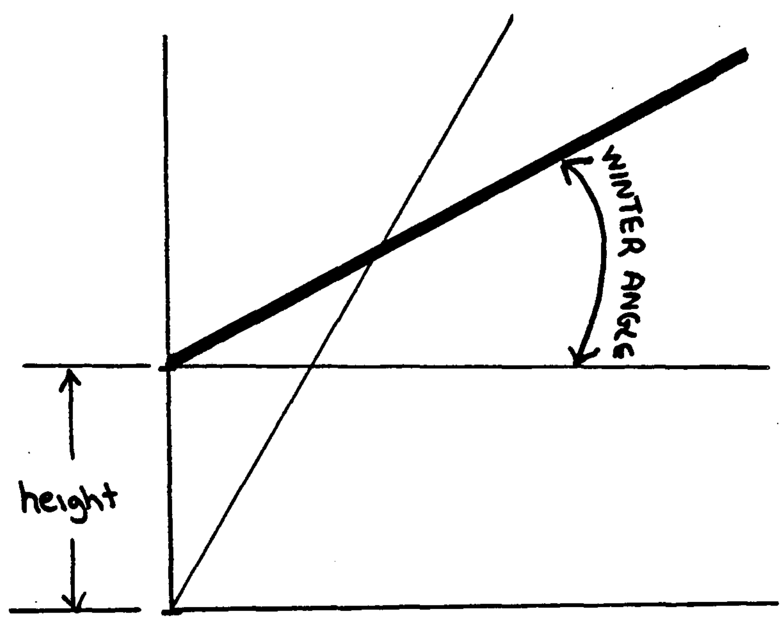
STEP 5. Find your Winter Angle for your latitude from Table II.

TABLE II

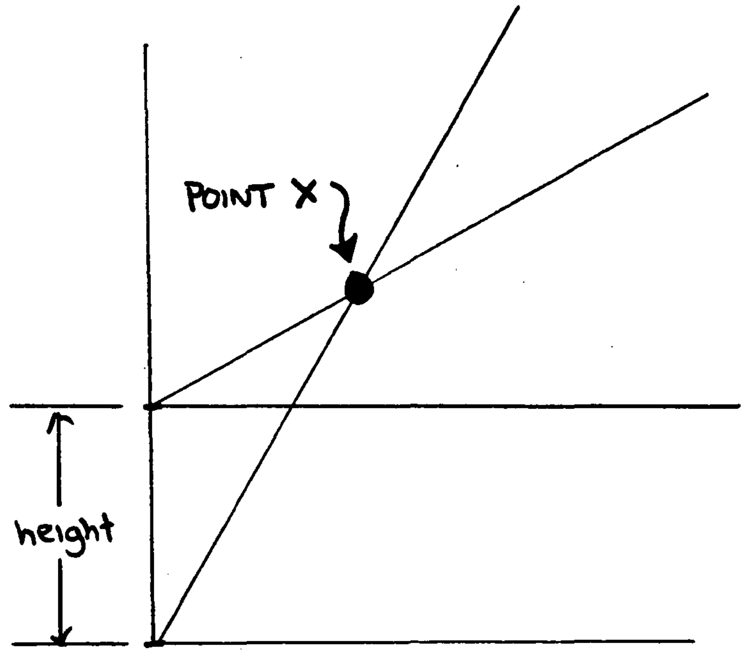
WINTER ANGLE
Sun Altitude at Noon on Dec. 21

Latitude	24	28	32	36	40	44	48
Sun Angle	43	39	36	31	27	23	19

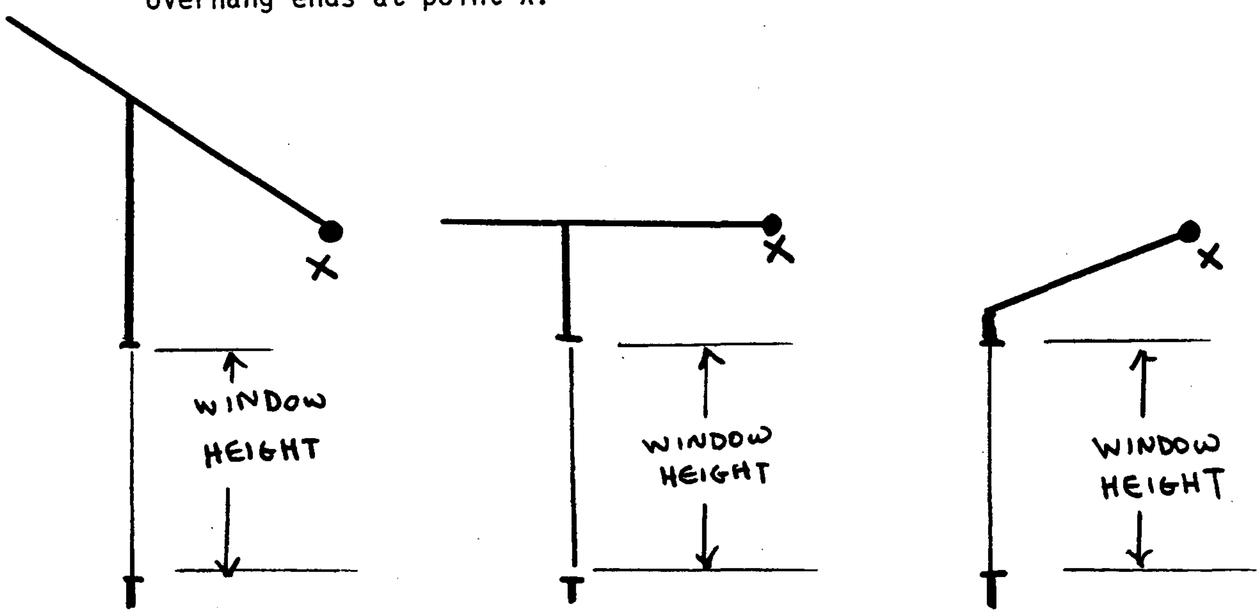
STEP 6. Draw the Winter Angle at the top of the window.



STEP 7. The overhang should extend out to the point at which the Winter Angle line crosses the Summer Angle line (point X).



Several possible overhang designs are shown below. Note that each overhang ends at point X.



STEP 8. If this drawing has been carefully drawn to scale it should be possible to measure the position of point X and determine the dimensions of the overhang.

ACKNOWLEDGMENTS

I would like to express my appreciation to Sue Slatkin who has been working with me on the development of daylighting design guidelines and has helped in preparing and editing this paper, among others. Portions of this workbook have been produced under a grant from the U.S. Department of Energy through Lawrence Berkeley Laboratory, University of California Purchase Order No. 4503310.

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DESIGN RESOURCES

Heat Gain Calculation

Psychrometric Chart

Analysis Methods

HEAT GAIN CALCULATION

Karen Crowther

Heat Gain Calculations should include:

1. Solar radiation through windows
2. Conduction/convection through walls and infiltration/ventilation based on outside air temperatures
3. Solar radiation on unshaded walls and roofs
4. Internal gains from appliances and machines
5. People heat generation

Calculation of these heat gain paths will be discussed for hourly and daily calculations. For a more sophisticated analysis see a text on Environmental Engineering or ASHRAE Fundamentals.

1. SOLAR RADIATION THROUGH WINDOWS

TABLE I

(1) window direction	(2) window area	X	(3) glazing factor	X	(4) shading factor	X	(5) solar radiation	=	(6) solar gain
North	______		______		______		______		______
South	______		______		______		______		______
East	______		______		______		______		______
West	______		______		______		______		______
							T O T A L. . .		______

COLUMNS 1 - 2: list window area for each direction (N, S, E, W) in square feet.

COLUMN 3: fill in glazing factor:

	for ASHRAE solar radiation data	Solar radiation from other sources
single glazed	1.0	.9
double glazed	.9	.81
triple glazed	.81	.73

COLUMN 4: fill in shading factor:

completely unshaded	1.0
partially shaded	.2 to 1.0
completely shaded	.2
shuttered	0

COLUMN 5: look up solar heat gain for clear skies for your Latitude in ASHRAE Fundamentals.

Hour-by-hour: fill in value for appropriate hour

Daily: fill in value for entire day

COLUMN 6: Multiply the numbers in columns 2 through 5 to get solar gain. Add all the figures in column 6 to get total hourly or daily gain.

2. CONVECTION/CONDUCTION AND INFILTRATION/VENTILATION

The building heat loss coefficient must be calculated. In this method the heat gain through the building envelope will be combined with the heat gain from infiltration or ventilation. The unshaded walls and roofs will be broken out so they will be available for calculation of the additional heat gain due to the sun (part 3).

TABLE II

	(1) Direction/ Tilt	(2) Area sq. ft.	X	(3) U-value BTUs/hr-°F-ft²	=	(4) UA-value BTU/hr-°F
unshaded walls	________	________		________		________
	________	________		________		________
	________	________		________		________
	________	________		________		________
unshaded roof	________	________		________		________
	________	________		________		________
windows		________		________		________
shaded walls		________		________		________
shaded roof		________		________		________
floor		________		________		________
doors		________		________		________
infiltration or ventilation						________
				Total UA-value . . .		________

COLUMN 1: The direction and tilt of unshaded walls and roofs is important in calculating heat gain from solar radiation. It is not needed for the other building components.

COLUMN 2: For wall areas do not include window area.

COLUMN 3: U-value. This is the inverse of the R-value. These values are tabulated for various building materials in ASHRAE <u>Fundamentals</u>.

COLUMN 4: Multiply Column 2 times Column 3 to get the UA-value. Then sum up all the figures in Column 4 to get the overall building heat loss (gain) coefficient.

FLOORS: If the building has a slab floor it is customary to assume that the heat loss or gain is a function of the perimeter rather than the area. It is not clear that the slab will experience a net gain of heat from the environment even in summer. It may be possible to ignore any heat gain to a slab floor. (Notice that this statement is surrounded by qualifiers.)

VENTILATION: Calculate the equivalent UA-value for ventilation as follows:

$$\left(\begin{matrix}\text{Ventilation Rate}\\ \text{cfm}\end{matrix}\right) \times 60 \times .018 = \text{UA value}$$

If there is no forced ventilation calculate the infiltration rate.

INFILTRATION:

$$\left(\begin{matrix}\text{Volume of Building}\\ [\text{cubic feet}]\end{matrix}\right) \times \left(\begin{matrix}\text{Air Changes}\\ \text{per hour}\end{matrix}\right) \times .018 = \text{UA value}$$

The air changes per hour can be roughly estimated as:

tightly sealed building.	.5
well built building.	.7
ordinary building	1.0
draughty building	1.5 and up

Now that the building UA-value has been calculated, the hourly or daily heat gain from conduction and infiltration can be calculated.

DAILY HEAT GAIN:

1. Look up monthly Cooling Degree Days (CDD) in ASHRAE or NOAA
2. Multiply:

$$(\text{Total UA-value}) \times \left(\frac{\text{CDD/month}}{\text{days/month}}\right) \times 24 = \text{DAILY HEAT GAIN}$$

This is the average daily heat gain through the building skin and from air changes. It does not include heat gain from solar radiation through windows.

HOURLY HEAT GAIN: Multiply:

$$(\text{Outside Temperature} - \text{Inside Temperature}) \times (\text{UA-value})$$

3. SOLAR RADIATION ON WALLS AND ROOFS

It is much easier to shade your building than to do this calculation! But solar gain on unshaded walls and roofs is significant. One method of calculating this gain is to figure the temperature that the outside air would have to be to give the same heat flow from convection alone as is given by combined convection and radiation. This is the Sol-Air temperature. The difference between the Sol-Air temperature and the actual outdoor temperature is the Temperature Differential. The temperature differential depends on the building orientation, material, and latitude. It is complicated by thermal lag (it takes longer for heat to get through a concrete wall because the wall must be warmed up).

These Temperature Differentials have been tabulated along with nine zillion schemes for correcting them. They can be found in Environmental Engineering by Jennings or in ASHRAE Fundamentals. Use the unshaded wall and roof values from Table II.

TABLE III

	Direction/ tilt	(1) UA-value	X	(2) Temperature Differential	=	(3) Solar Heat Gain
Unshaded walls	______	______		______		______
	______	______		______		______
Unshaded roof	______	______		______		______
	______	______		______		______
				TOTAL GAIN		______

COLUMN 1: Take the UA values listed in Column 4 of Table II.

COLUMN 2: Look up temperature differentials and apply the appropriate correction factors (see ASHRAE or Environmental Engineering).

COLUMN 3: Multiply Column 1 times Column 2.

Hour-by-hour: Add up figures in Column 3.

Daily: Fill out Table III for each sunlit hour and add up all figures from Column 4.

4. INTERNAL GAINS:

All energy used by machines or appliances winds up as heat unless the device is vented to the outside (as exterior compressors, air conditioning equipment, etc.).

For each device, calculate:

$$\left(\begin{array}{c}\text{time device is}\\ \text{operating in hours}\end{array}\right) \times \left(\begin{array}{c}\text{power device consumes}\\ \text{in kilowatts}\end{array}\right) \times (3412\ \text{BTU/KWH})$$

Hour-by-hour: For time use the fraction of an hour that the device will be operating.

Daily: Use the total number of hours that the device will be operating each day.

5. PEOPLE:

Heat generated by people is dependent on their activity level. Table IV gives some values for adults:

TABLE IV

Seated Resting	390 BTUs/hr
Standing at Rest	440
Active Dancing	1390

More values are listed in ASHRAE. To figure the load from people:

(Number of people-hours) X (Heat generated per person per hour)

TOTAL HEAT GAIN:

Add up the heat gains calculated in parts 1 through 5. This will give either the total hourly or daily heat gain depending on which figures were used.

PEAK HOURLY LOAD:

Air temperatures are usually highest around 3:00 p.m. solar time but, depending on window configurations, the peak heat gain could be almost any time during the day. Unless there is a lot of solar gain through East windows, the peak hour will probably occur in the afternoon.

1. Determine which hour has the most solar gain and calculate that gain (Parts 1 and 3).
2. Calculate the conduction-infiltration gain (Part 2) using the summer design temperature.
3. Calculate the other heat gains (Part 4 and 5) for hour.
4. Add up all these gains.

PSYCHROMETRIC CHART

Karen Crowther

The psychrometric chart displays the various properties of moist air. It is useful for two reasons:

1. If two air properties are known (say, wet bulb and dry bulb temperatures), then all the other properties (relative humidity, enthalpy, vapor pressure, etc.) can be read off the chart simply by locating the point defined by the two known properties.

2. Results of processes such as evaporative cooling, chilling, heating, etc., can be predicted by finding the original state of the air and then following the appropriate line to the final state. Thus, if the temperature and relative humidity is known before the air is evaporatively cooled and it is known that the swamp cooler is 70 percent efficient, then the air temperature and humidity of the cooled air can be found by following a Wet bulb temperature line 7/10ths along its length to the left.

The following is a discussion of the more widely used psychrometric properties:

DRY BULB TEMPERATURE: Figure 1 shows the lines of constant dry bulb temperature. This is the temperature measured by an ordinary thermometer.

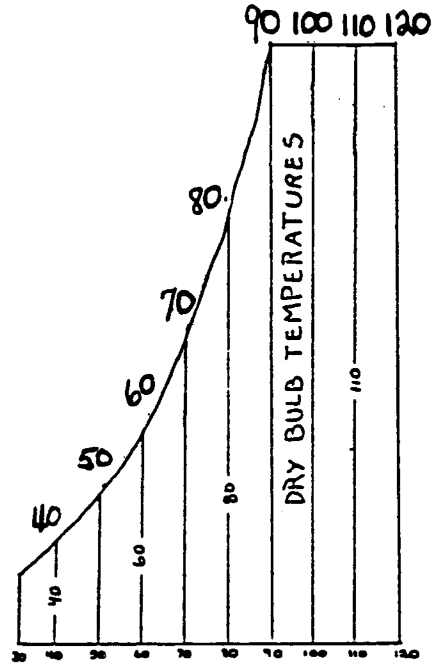

Figure 1
Constant Dry Bulb Temperature Lines

WET BULB TEMPERATURE: This temperature results when both convection and evaporation are at maximum rates. It is usually measured by covering a thermometer with a wetted wick and whirling it around so that evaporation will cool it. This is theoretically the lowest temperature that can be reached by an evaporative cooler. If the air is evaporatively cooled its properties will move to the left along a line of constant wet bulb temperature. Figure 2 shows lines of constant wet bulb temperature.

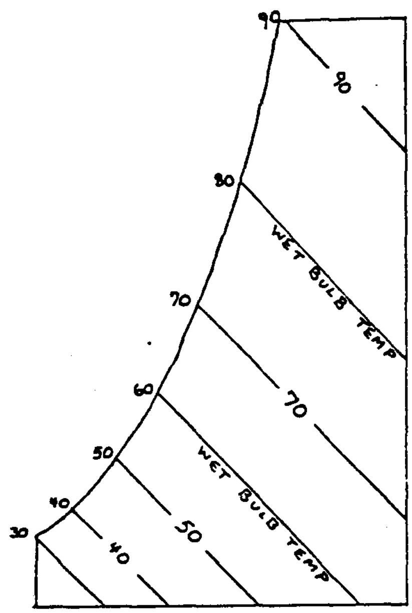

Figure 2
Constant Wet Bulb Temperature Lines

HUMIDITY RATIO: is the weight of water vapor (in pounds) per pound of air (or: kg. of water per kg. of air). When the air is heated or cooled the humidity ratio will remain constant (unless water vapor is added to the air by evaporation). The Humidity Ratio is often used to predict the amount of evaporative cooling. Water Vapor Pressure lines coincide with the constant Humidity Ratio lines and can also be used to predict evaporative cooling. Sometimes the water content of the air is expressed in grains of water per pound of air. This just changes the scale. (There are 7,000 grains in a pound.) Figure 3 shows lines of constant Humidity Ratio.

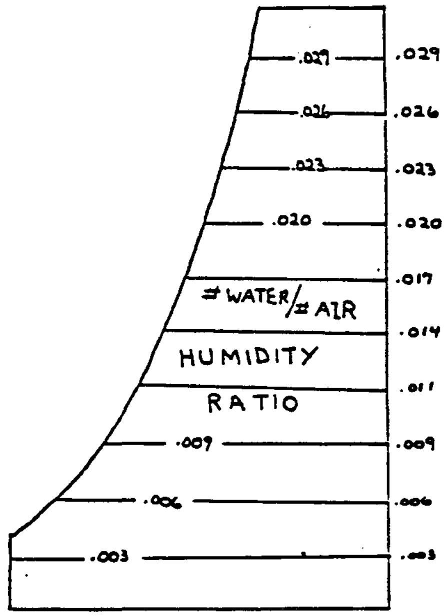

Figure 3
Constant Humidity Ratio Lines

DEW POINT TEMPERATURES: If a line of constant Humidity Ratio is followed to the left the Dew Point Temperature can be found. If the air is cooled below the Dew Point Temperature, the water vapor will start to condense out. At the Dew Point the air is completely saturated with water and has 100 percent Relative Humidity. Dew Point temperatures fall along the far left curved line which is also the 100 percent Relative Humidity line. Water will condense on a surface which is below the air's Dew Point Temperature. This is one way of removing water vapor from the air.

RELATIVE HUMIDITY: The water content of the air divided by the amount of water the air could hold if it were completely saturated. Relative Humidity is not that useful a property unless the air temperature is also known. It does indicate whether evaporation will result in cooling. (At 100 percent RH there will theoretically be no net evaporation from a surface.) Figure 5 shows lines of constant Relative Humidity.

Figure 4a shows a typical 24-hour Relative Humidity chart. Figure 4b shows the actual water content which remains nearly constant despite the wide Relative Humidity swing. Since the air can hold more water when it is warmer, the Relative Humidity will decline as the air warms even though the water content remains the same. For this reason a number for Relative Humidity is of little use unless the corresponding air temperature is known.

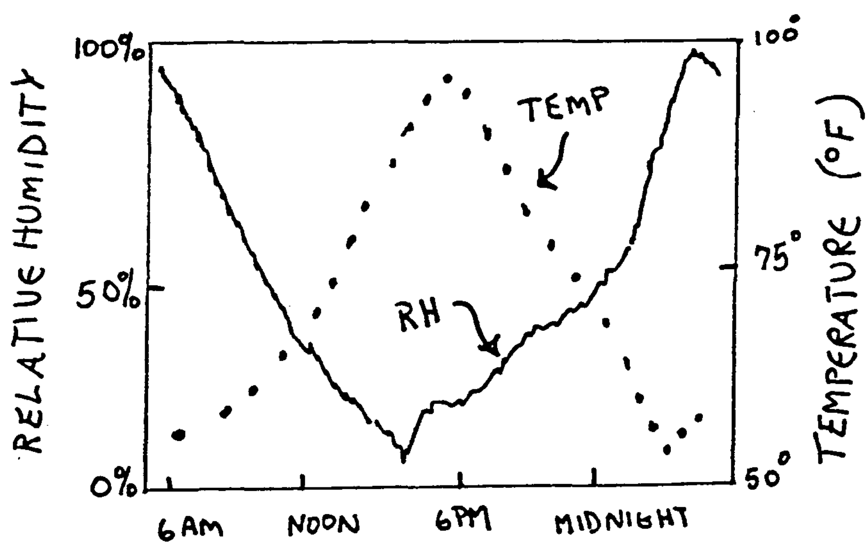

Figure 4a
Relative Humidity and Temperature vs. Time

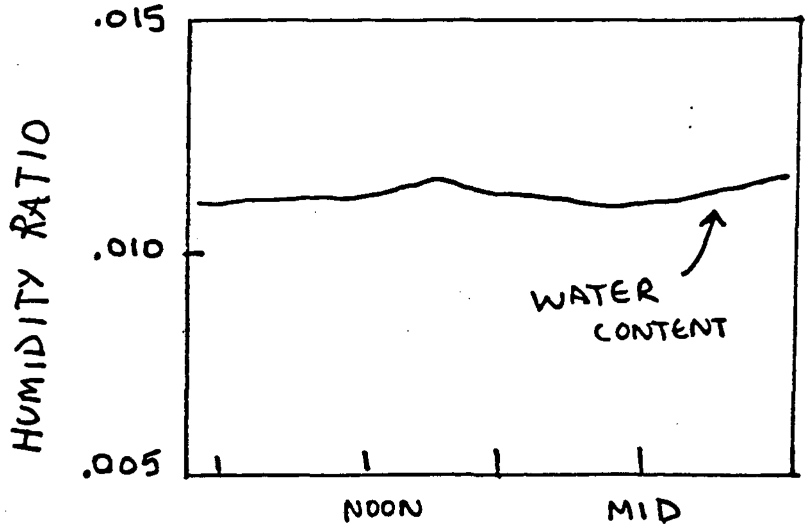

Figure 4b
Water Content vs. Time

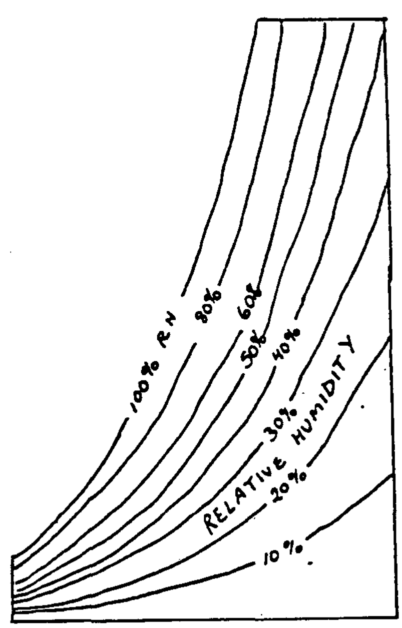

Figure 5
Constant Relative Humidity Lines

ANALYSIS METHODS

The following are descriptions of computer programs that are available to assist researchers and designers of passive cooling systems. Some of them were designed to deal primarily with heating analysis. Some are valuable for analysis of the cooling loads rather than simulation of the performance of cooling systems or techniques. The lists are not comprehensive, there are undoubtedly some useful programs that are not cited here. Also, each program makes certain assumptions that should be understood before using the results for design purposes. The editors would appreciate descriptions of any useful program not listed herein for a future version of the handbook.

Some of the descriptions were derived from the brochure, "Analysis Methods for Solar Heating and Cooling Applications," prepared by the Solar Energy Research Institute.

BLAST

The BLAST (Building Loads Analysis and System Thermodynamics) program, developed by the U.S. Army Construction Engineering Research Laboratory (CERL) with joint sponsorship by the U.S. Air Force and the U.S. Army, was released for public use in 1978. The program was written to permit analysis and design of energy conservation in new and existing buildings including application of liquid type active solar energy and total energy systems. Many of the methods used are based on the ASHRAE algorithms; however, new algorithms have been included relating to building shading, cooling coil modeling, and room heat balances. The program employs its own English-like input language and can perform two types of analyses: (1) Hourly energy analysis in which actual hourly weather data are used to calculate hourly heating and cooling loads for each zone of the building. Output from the hourly energy analysis is used as input to the system simulation subprogram. (2) Design day analysis in which user-supplied input weather data are used to calculate hourly heating and cooling loads for each zone of the building for the specified design days. Life-cycle costs are computed for each central plant option selected on the basis of user-supplied or default capital costs, maintenance costs, operating costs, and utility rate schedules. Output data provide monthly and daily loads and energy consumption with separate meters for different end uses. Both average and peak day load and energy profiles may be output.

References

"The Building Loads Analysis and System Thermodynamics (BLAST) Program, Vol. I, User's Manual," AD-A048 982/3ST, 1977.

"The Building Loads Analysis and System Thermodynamics (BLAST) Program, Vol. II, Reference Manual," AD-A048 734/8ST, 1977.

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CALPAS3

CALPAS3 is a computer program which analyzes the energy performance of passive solar residences. It is much easier to use than either hand-held calculator methods or large programs such as DOE-2. CALPAS3 produces report quality output of hourly, daily, monthly, and yearly heating and cooling loads, space and storage temperatures, heat gains and losses and annual operating costs. CALPAS3 will be available beginning October, 1980.

Buildings and Features Modeled

CALPAS3 can model conventional and passive solar residential buildings, including any of these features:

- Attached sun space, greenhouse or envelope
- Thermal mass in many forms, such as mass wall, water wall, slab, underslab rockbed
- Trombe walls
- Any wall and window orientation and type
- Seasonally variable shading from shutters, overhangs, fins
- Movable window insulation
- Wind, convective, and forced ventilation
- Evaporative cooling

Reporting Features

CALPAS3 prints reports describing building performance during the entire year, each month of the year, and for the days and hours you specify.

- Report-quality, 80-column format; fits easily on an 8 1/2" x 11" sheet.

- Annual report shows the total operating costs and total conventional energy used for the year, and peak heating and cooling hourly loads for the year.

- Monthly report: for each month and totaled for the entire year, CALPAS3 reports energy flows, such as conduction and infiltration gains and losses, south-window solar gain, non-south-window solar gain, storage gains and losses, venting losses, internal gain, conventional heating and cooling; the peak heating and cooling hourly loads and the days on which they occurred; total ventilation air changes; space and outdoor temperatures; insolation.

- Daily report: same quantities, calculated for each day you specify.

- Hourly report: same quantities, plus energy flows for each individual thermal mass element; storage temperatures; wind speed and direction.

CALPAS3 Modelling, Method, History, and Validation

CALPAS3 is an hour-by-hour thermal network simulation program using:

- ASHRAE heat transfer and ventilation algorithms.

- Backward (implicit) differencing equations for mode/ling transient heat conduction in mass elements (eliminates stability problems and allows consistent use of a one hour time-step).

- Combined radiant-convective coefficients (allows very fast execution with little loss of accuracy).

The program was originally developed at California Polytechnic State University by Phil Niles and collaborators for use in modelling the performance of passive homes for the California Passive Design Handbook, published in January, 1980, by the California Energy

Commission. Subsequent enhancements were implemented at BSG. Validation is currently underway using performance data from the Balcomb house in Santa Fe, New Mexico.

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DEROB

The DEROB (Dynamic Energy Response Of Buildings) programs have been under development since 1972 at the University of Texas as a research and design tool relating to heat flow in complex structures. In its current release, 1979, it is capable of simulation of a variety of passive solar system designs. The series consists of three main programs: (1) development of building geometric factors relating to radiation interchanges, (2) development of material properties for elements of the structures, and (3) calculations of hourly loads and interior distributions. Interior heat flow takes place by air circulation, conduction through opaque walls, and direct radiation via transparent walls. Interior temperature control is by passive means only. Input data consist of building geometry data, thermophysical property data, use factors, and hourly SOLMET weather data. Output data for daily, monthly, and peak day load profiles are available.

Reference

Arumi, F. and D. Northrup, "A Field Validation of the Thermal Performance of a Passively Heated Building as Simulated by the DEROB System," Energy and Buildings, Vol. 2, No. 1, January 1979, p. 65.

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DOE-2

DOE-2 is an energy-analysis tool that simulates the hourly heating and cooling loads for each space in the building; the operation of the HVAC (heating, ventilation, and air-conditioning) distribution systems; and the operation of the building's primary heating, cooling, and electrical plant. It then calculates the hourly, monthly, and yearly energy requirements for the building and the building's life-cycle cost. It will also execute a cost-benefit analysis, allowing the user to rank various design options on the basis of cost and energy use.

The addition of passive capabilities to DOE-2 requires the generation of "weighting factors" suitable for the materials used in typical passive systems. Weighting factors are used in the load-determining part of the program to account for the time delay between an instantaneous heat gain (i.e., a pulse of solar energy entering a zone) and its effect on the heating or cooling load. This work has been successful in a test version of DOE-2, where a simulation of the direct-gain test cell at the Los Alamos Scientific Laboratory has predicted cell temperatures that agree well with measured data. Future work will be directed at accommodating other passive designs.

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Lokmanheim, M. et al. "Doe-2: A New State-of-the-Art Computer Program for the Energy Utilization Analysis of Buildings." Lawrence Berkeley Laboratory report LBL-8974 (1979).

Schnurr, N. M. et al. "Applications of DOE-2 to Direct Gain Passive Solar Systems: Implementation of a Weighting Factor Calculative Technique." Proceedings of the 4th National Passive Solar Conference, American Section of the International Solar Energy Society, Newark, Delaware, 1979, p. 182.

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FREHEAT

FREHEAT was developed at Colorado State University (CSU) under funding from the Department of Energy, with its original release in 1978 and its current release in 1979. The program is intended as a research tool for the design of a passive solar heating system at CSU. A one-room system may be modelled with a simple mass wall or with an isothermal mass wall. Heat capacity may be added to the room and floor (either single node or multi-node), or an interior mass wall. Inputs to the system include hourly weather data, type of system, and thermodynamic properties. The outputs provided by the program are hourly room temperature, node temperatures, solar fraction, energy incident on wall, energy stored in wall, auxiliary energy required, and standard deviations in temperature, both daily and for the study period.

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SUNCAT

The SUNCAT program was developed by the National Center for Appropriate Technology (NCAT) to simulate the thermal performance of a passive solar structure. The program consists of two mainline programs which simulate the transmissivity and shading of a user-specified glazing system and the thermal performance of a user-specified passive solar structure. Input to the program consists of hourly radiation and temperature data files and a window and building description. The present version of the program allows for interactive creation of the window and building descriptions. The output of the program is a tabulation by zone and total building of the thermal characteristics of the passive system, including solar fraction and the useful heat delivered.

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TRACE

The first version of TRACE (Trane Air Conditioning Economics), developed by the Trane Company, was introduced in 1973 and intended as an aid to architects and engineers in comparing life-cycle costs of various HVAC systems for multizone structures. A third version of the program, released in 1978, incorporates a solar capability based on TRNSYS. Using the ASHRAE (1967) algorithms for calculating heat gains and losses by zone, the load phase prepared input for the design segment of the program. The system simulation phase translates design conditions into equipment loads taking into account part load operation of the HVAC systems. These equipment loads are converted to fuel and electrical usage rates in the equipment simulation phase where as many as four distinct (Trane manufacture) equipment alternatives may be considered simultaneously. Input for the program consists of a building description and operating schedules, design conditions for various zones, equipment selections, and various economic data. Weather data for a number of cities are included in TRACE's data base in the form of a "typical" 24-hour profile for each of the 12 months. The program output contains design loads for the HVAC equipment, monthly fuel and electrical usage by component, peak hourly loads, and economic comparisons of the selected equipment options.

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TWO-ZONE

Motivation for the development of this program in 1975 stemmed from a desire to analyze the collection efficiencies of windows in a residence. The program computes the hourly heating and cooling loads for the north and south zones ("two-zones") of a single-family dwelling and provides for thermal coupling between them through convective air exchange. Hourly weather data are used in the calculation in addition to various active controls such as thermostat setback, scheduled shade or curtain closings, and window opening for ventilation. In addition to these passive solar capabilities, the current program version (1977) provides for simulation of evaporative coolers and for some economic analysis. Program input consists of the hourly weather data, a description of the internal loads (appliances, occupants, etc.), schedules for active controls, and calculated transfer functions for the dynamic thermal response of the walls and roof. Output from the simulation includes monthly summaries of the total heating and cooling loads for the residence as well as a breakdown by contribution (windows, walls, infiltration, etc.). HVAC equipment simulation is limited to the evaporative cooler and a warm-air furnace with a fixed efficiency. No active solar systems are simulated by TWO-ZONE. Energy use by the auxiliary systems is reported in the output, and their life-cycle costs, based upon constant annual fuel or electric (energy/demand) rates, are included if desired.

Reference

A. G. Gadgil, G. Gibson, and A. H. Rosenfeld, "User's Manual," Lawrence Berkeley Laboratory, Report LBL-6840, March 1978.

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UWENSOL

The State of Washington's plans for construction of a series of buildings prompted funding of a team of architects and engineers at the University of Washington (Seattle) to develop energy conservation guidelines for those buildings. These guidelines were embodied in a pair of computer programs released in 1978 which were designed to be used in tandem to minimize the lighting and comfort maintenance requirements of a multizone structure. Reductions in these requirements are achieved by changing the building's architecture and fenestration to achieve passive control and augmentation of the two functions. Changes are directed at reducing the heating and cooling loads which would need to be met by an HVAC system selected for the building. Architectural changes which reduce these loads are feasible so long as the lighting levels and thermal insulation values stipulated in building codes are met, and there is an acceptable thermal comfort level maintained under all weather conditions. The lighting program UWLIGHT first determines the lighting distribution in the building and the steady-state heat transmission coefficients of its envelope to ensure code compliance. UWENSOL then performs a dynamic hour-by-hour simulation of the building using a finite-difference approximation of the zonal interactions and calculates the transient heating and cooling load requirements for the HVAC system. Architectural changes are then made to reduce these loads, and the attractiveness of the modifications is later checked by evaluating a thermal comfort level for each zone. Electrical load profiles or fuel requirements for the comfort control system are not determined by this program, and no active solar system (collectors) can be simulated. Input requirements for the program emphasize the passive aspects of the structure since its principal concern is with the building's reaction to solar input. Hourly data for ambient temperature and humidity, direct and diffuse solar radiation, etc., must be supplied by the user. Program output includes daily heating and cooling loads for the various thermal zones as well as average and peak day hourly load profiles.

Reference

Emergy, A. F., et al., "UWENSOL: A Computer Program for the Dynamic Simulation of the Thermal Response of Buildings with Emphasis on Human Comfort," University of Washington, 1978.

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Description	Author	Availability		
		Cost($)	Date	Reference/Source
A Simple Empirical Method for Estimating the Performance of a Passive Solar Heated Building of the Thermal Storage Wall Type	J.D. Balcomb & R. D. Farland		1978	Rept. No. LA-UR-78-1159. Available from NTIS 5258 Port Royal Road Springfield, VA 22161
Roof Overhang Design for Solar Control	Paul R. Barnes			Proceedings of the 4th National Passive Solar Conference, AS/ISES, 1979, pp. 153-157
The SEA-PASS Passive Simulation Program	J. R. Clinton			Proceedings of the 4th National Passive Solar Conference, AS/ISES, 1979, pp. 202-206
Predicting the Performance of Solar Energy Systems	U.S. Army Construction Engineering Research Lab		1977	Rept. No. AD-A035 608/9 ST (NTIS)
PEGFIX and PEGFLOAT	W. Glennie	75 both	1978	Princeton Energy Group 729 Alexander Road Princeton, NJ 08540

Description	Author	Availability		
		Cost($)	Date	Reference/Source
Solarcon Program ST33	R. W. Graeff	138	1979	Solarcon, Inc. 807 Church Street Ann Arbor, MI 48104
Modelling Passive Solar Buildings with a Small Computer System	William M. Kingrey			Proceedings of the 4th National Passive Solar Conference, AS/ISES, 1979, pp. 216-220
TEANET	J. T. Kohler and P. W. Sullivan	95	1978	Total Environmental Action, Inc. Church Hill Harrisville, NH 04350
A Design Handbook for Direct Heat Transfer Passive Solar Systems	R. M. Lebens	10	1978	New England Solar Energy Association P.O. Box 541 22 High Street Brattleboro, VT 05301
Two Simple Tools for Design of Fixed Shades	Dave Nawrocki, Brandt Andersson, and Ron Kammerud			Proceedings of the 5th National Passive Solar Conference, AS/ISES, 1980

Description	Author	Availability		
		Cost($)	Date	Reference/Source
SEEC VI -- Passive Solar Heating	C. B. Winn, D. Barley, G. Johnson, J. Leflar	125	1978	Solar Environmental Engineering Co., Inc. 2524 East Vine Drive Fort Collins, CO 80522
Sunshine Power Programs for Modelling Solar Energy Components and Systems	G. Shramek	30-60	1977	Sunshine Power Co. 1018 Lancer Drive San Jose, CA 95129

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