INCORPORATION
OF THE PRINCIPLES OF NATURE IN ARCHITECTURE;
SUN, SHADE AND TEMPERATURE CONTROL IN THE SONORAN DESERT

by

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A Thesis Submitted to the Faculty of the

COLLEGE OF ARCHITECTURE

In Partial Fulfillment of the Requirements
For the Degree of

MASTER OF ARCHITECTURE

In the Graduate College

THE UNIVERSITY OF ARIZONA

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UMI Number: 1382636

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ACKNOWLEDGEMENTS

Many people have contributed to the completion of my thesis in diverse ways. I would like to gratefully acknowledge them.

There are a number of professors who provided me with inspiration and guidance through the preparation of this thesis. My sincere appreciation and gratitude are extended to Professor Fred S. Matter, my thesis committee chairperson, for his continual encouragement, advice and guidance during the entire course of this study, and to Professor Martin R. Yoklic, professor of Planning, my boss and thesis committee member, for his willingness to listen to my thoughts and ideas and his ability to clarify and comprehend what I was trying to express, while providing a direction for me to follow. I would also like to thank Professors Susan K.E. Moody, Nader V. Chalfoun, Judith Chafee, Harris Sobin and A. Richard Williams, for their guidance.

My deepest gratitude go to my family and friends for their loving support and encouragement during the ebbs and flows of my thesis process. Many thanks to my parents for never doubting my abilities and for instilling in me a love for learning. I dedicate my thesis to them.

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ABSTRACT

"Incorporation of the Principles of Nature in Architecture; Sun, Shade and Temperature Control in the Sonoran Desert" is a study of the adaptations of selected plants and animals to the unique climatic features of the desert environment. The lessons learned from this study are abstracted from the natural setting and presented in a systematic way to illustrate the incorporation of their adaptive principles into architecture.

Living organisms continuously adapt to the changes of their environment and contribute a regenerative cycle of natural processes. Biotechnology adds important issues to the design process, including economy of resources, protection and thermal regulation in harmony with the fluctuations of the natural environment. The interaction of interior and exterior architectural space is a benefit, not a constraint, for the environment and its inhabitants. This biotechnological method can become a viable part of the traditional architectural design process.

CHAPTER 1

BACKGROUND INFORMATION

1.1 INTRODUCTION

The evolution of design for human habitation from indigenous through traditional built forms may be considered a human constructive parallel to the Darwinian evolutionary model of survival of the fittest. Survival and evolution in the biological world requires an environmental fitness in the Darwinian model. Similarly, Man's early survival was dependent upon his understanding and adaptation to the natural world, an intellectual fitness of sorts. This intellectual fitness is clearly expressed in indigenous architecture. Cook (1994) postulates that vegetation types and biological systems that have emerged in response to unique climatic situations may be an architectural analog to indigenous constructions for human habitation. Indigenous architecture, although based on local materials, is restricted by local resources and has emerged as an important creative expression of man's intimate knowledge of the environment, especially climate. Thus, it is suggested that the form and nature of buildings evolved through the continuous and consistent human engagement are influenced by the regional environment and climate. And because of intellectual fitness, man has been able to adapt the built form to ensure survival even in the harshest of climates.

In the highly stressed and exaggerated conditions of extreme climates, both indigenous vegetation and architecture can be highly informative in providing bio-technological solutions for contemporary architecture.

The modern architectural paradigm in its isolation from the environment and with its dependence on energy for accommodating human thermal comfort is often criticized as floundering - in search of a constituency, a purpose and a direction. The random play with forms, colors and materials as though they exist in defiance of the natural world are a common attribute of the contemporary building design process. Seldom are the regional character, climate and other analogous relationships with nature considered as rational options for an optimum solution to a design issue. The contemporary design process most frequently accepts the energy dependent mechanical solution over obvious natural or passive energy independent opportunities.

There are limitations. Many buildings are designed in defense of previously constructed "irresponsible" structures. Often, in tight urban situations, the architect must deal with the created constraints of lack of natural ventilation and sunlight and the overabundance of noise and air pollution. The logical response is to rely on mechanical systems to overcome the design limitations created through the evolution of the built form (Clark, 1980). However, due to inexpensive energy, market forces and engineering pragmatics, reliance on mechanical systems has become the norm.

McHarg succinctly summarizes both the dilemma and the opportunity in the following quote from Design with Nature (1969).

> "Clearly the problem with man and nature is not one of providing a decorative background for human plan, or even ameliorating the grim city: it is the necessity of sustaining nature as a source of life, milieu, teacher, sanctum, challenge and most of all of rediscovering nature's corollary of the unknown in the self, the source of meaning."

1.2 SCOPE OF STUDY AND METHODOLOGY

Can man be in a state of thermal balance and live in harmony with nature, of which he is a part? Can his thermal comfort be achieved in the extreme climate of the Sonora Desert, learning from and adapting his abode / mode of living to react to the climate in ways similar to the rest of the plant and animal life that also share and thrive in this arid region?

1.2.1 Hypothesis

This thesis will examine the plant and animal life in the Sonora desert, derive their underlying principles of adaptation to the climate and show that these principles reflect the key elements of passive design and are the same as that required by man for his comfort. Man can lead his modern lifestyle and still live passively in harmony with the Earth following the examples set forth by Nature.

1.2.2 Outline of thesis

How the scope of study will be accomplished is determined from the four-part outline that follows.

Part 1 CONTEMPORARY DESIGN AND SUSTAINABILITY

- Does architecture embrace sustainability and energy efficiency in building design?
- Does the contemporary architectural paradigm consider biological adaptation to environment and climate as a rational model for sustainable, energy efficient building design?
- How have modern architects included models from nature in design?
- What contemporary schools of thoughts within architecture embrace a world view that considers regional character and climate as critical to effective building design?
- Have these architects or movements considered biological adaptation models for the development of sustainable, energy efficient building?

Part 2 CLIMATIC ADAPTATIONS OF PLANTS AND ANIMALS

- What are the specific adaptive characteristics of selected plants and animals from the Sonoran Desert that allow them to survive and thrive in the harsh arid climate?
- Are these adaptations effective models for sustainable building design in the Sonoran desert?

Part 3 CLIMATIC ADAPTATIONS OF MAN

- What are the physiological adaptive characteristics of man?
- What are the essential precepts for bioclimatic architecture in the arid Southwest?
- Are these precepts consistent with the models identified from the selected adapted plants and animals of the Sonoran Desert?

Part 4 CASE STUDIES AND CONCLUSIONS

- What can the evolution of architecture in the Southwest, from indigenous to contemporary, tell architects about how our understanding of biological adaptations have influenced building design?
- What do the case studies illuminate about how buildings have responded to regional and environmental conditions and what are the implications of the socio - technological evolution expressed in the analysis of the case studies?
- What key precepts can be gleaned from the case studies that express a sustainable energy efficient ethos that can be associated with the biological adaptations?
- What are the implications of this study on the direction of building design in the Sonoran Desert?

1.2.3 Mode of inquiry

The mode of inquiry used to illustrate the validity of the thesis is that of the empirical-inductive type, whereby the research is set to:

- find the physiological modes of construction used by selected plants and animals that are bioclimatically responsive to the Sonora Desert.
- literatively collect information on the building techniques and issues of bioclimatically responsive design used by man in extreme climates.
- through the process of induction, illustrate the explanations of the phenomenon used to derive the principles of adaptations to the climate.
- development of a theory for this thesis.

1.2.4 Contents of thesis

This chapter provides the hypothesis of the thesis, the methodology used to present it, and a review of the literature and background information on which the thesis is based. It describes the meaning of architecture, mode of present construction and also thoughts on architecture. Discussed also is the comparison of the mode of construction / load bearing techniques utilized by man and selected forms of animal and plant life.

The second chapter attempts to fit information and fact into a general picture, to emphasize the simplicity of the underlying principles, and to illustrate the resourcefulness of biological adaptations to the Sonoran Desert. The seven elements under study have been carefully chosen to basically represent all forms of life. Namely: from the plant kingdom; a cactus - saguaro, and a tree - mesquite and from the animal kingdom; an insect - termite, a reptile - horned lizard, a bird - roadrunner, a small mammal - jack rabbit, and a large mammal - bighorn sheep.

The third chapter deals with the literature on the analysis and requirements of human thermal comfort, focusing on man's physiological responses to the thermal environment. The elements of this investigation will be used as the basis for critical review of passive solar and resource efficient strategies for building design in arid regions. From this review the critical issues of bioclimatic design will be listed, then summarized into design principles. These bioclimatic design principles will then be classified into a representation of an adaptive model for the Sonoran Desert.

The material presented in chapters two and three has largely been gathered from a number of non-architectural scientific sources and has been distilled and translated into a more palatable, verbal and graphic architectural terminology.

In the fourth chapter, the principles of nature derived from selected plants and animals in chapter two are compared to the principles derived from man in chapter three and translated into the human art of building design, to form an architectural synthesis. This material is then compared with various elements of architecture, to arrive at the conclusion of the need to enhance nature and utilize its set biological principles, with a special emphasis on the Sonora Desert.

1.3 ART, FUNCTION AND SUSTAINABILITY IN ARCHITECTURE

"The western assumption of superiority has been achieved at the expense of nature. The oriental harmony of man-nature has been achieved at the expense of the individuality of man. Surely a united duality can be achieved by accounting for man as a unique individual rather than as a species, man in nature" (Ian McHarg, 1969, p27).

Many architects and designers today would lead one to believe that their 'art' has to be sacrificed in order to attain energy efficiency in buildings, or alternatively that they have to sacrifice energy efficiency in order to attain 'art'. Neither of these statements should be regarded as being the truth (McDonald, 1980). Architecture is a complex undertaking involving technical, social, utilitarian and cultural issues. It is the systematic arrangement of knowledge, primarily aimed at providing comfort and convenience for its users and their activities, within a cultural and environmental context.

Architecture involves the ordering of space in a coherent manner, the use of materials in functional and efficient ways, and the making of beautiful forms.

To be successful, the architect must be able to effectively assess user need and organize space, form and materials in a manner which will produce a rational and balanced whole that is responsive to the social and physical context. If the architect neglects any one of the elements or overemphasizes one to the detriment of the others, he/she will, by definition, produce a flawed piece of architecture and will therefore have failed.

A building is not a living thing although it is sometimes said to have 'life' of a kind. It does no work and needs no muscle but it breaths through its ventilation system, has power in its veins, a body temperature, a circulation system, possibly a heart, and a skeleton covered and protected by a skin. It is however inanimate. Its 'life' is that of its occupants and it is that life which provides its reason for existence. All living things adapt to their surroundings and, although buildings are inanimate, it is on this point that nature and architecture may have the most in common.

The relationship of architecture to the physical environment is first of all defensive. A building must be designed to resist the onslaughts of nature - rain, wind, fire, snow, earthquake, etc. and also to resolve issues related to temperature extremes and user comfort.

"What is missing from our dwellings today are the potential transactions between body, imagination and environment. It is absurdly easy to build, and appallingly easy to build badly. Comfort is confused with the absence of sensation. The norm has become rooms maintained at a constant temperature without any verticality or outlook or sunshine or breeze or discernible source of heat or center or, alas, meaning. These homogeneous environments require little of us, and they give little in return besides the shelter of a cubical cocoon" (Kent Bloomer, 1977, p105).

"Nowadays you can design a building in one country to be built in another. No longer is it a case of famous European architects designing buildings for

America; now all over the world buildings designed out of one culture are placed in another. Such buildings typically have artificial indoor climate control and are reached by car. They can therefore be sited anywhere in the world, but they belong nowhere" (Christopher Day, 1990, p13).

1.4 SCHOOLS OF THOUGHTS ON NATURE IN ARCHITECTURE

Man has always, when confronted with extreme climatic conditions and particular environmental discomfort, at any latitude or in any geographic location, felt the necessity to struggle against nature to defend himself from extremes of hot and cold temperatures, wind, drought, poverty and disease.

To these problems the established and standard answers for the home have been sometimes brilliant and ingenious, at times attached only to a string with a dramatic minimal chance of survival; always man has revealed a commitment for superior to pure adaptation.

In the course of the history of architecture, many renowned architects have incorporated different physical aspects of Nature in their architectural practice, though none have applied a systematic approach to derive the underlying biological principles of nature, and then translate it into architecture. To name a few such architects and architectural movements:

1.4.1 As in naturally occurring forms **Alvar Aalto** believed in putting together smaller units to produce a large organic whole. "Nature, biology, offers profuse and luxuriant forms; with the same constructions, same tissues and same cellular structures it can produce millions and millions of combinations, each of which is an example of a high level of form" (Alvar Aalto, 1935). "I claimed once before that the best standardization committee in the world is nature herself, but in nature standardization occurs mainly - in fact almost solely - in connection with the smallest possible units, cells. The result is millions of flexible combinations in which one never encounters the stereotyped. Another result is that there is immense richness and an endless variation of organically growing forms. Architectural standardization must tread the same path" (Alvar Aalto, 1938).

1.4.2 Frank Lloyd Wright also sought his principles in nature, for, to him, they were not only organic, but eternal. "Design is abstraction of nature - elements in purely geometric terms" (Wright, 1923). His idea of organic structure is well illustrated by the proposed St. Mark's Tower for New York. From a central structural core, rooted deeply in the earth, radiated four bearing walls, with floors cantilevered out from these to a non-structural, external glass skin. Wright had reverted to nature for his vertical structure, employing the principle of the tree. In the case of Taliesin and Taliesin West, though designed for the same person, they have vastly different features. Taliesin in Wisconsin reflects the soft features of the eroded terrain, whereas Taliesin West in the Sonora Desert reflects the sharp, hard, clean and savage nature of the desert.

1.4.3 Frei Otto predicts that as our knowledge of nature progresses, human structures will more clearly approximate nature's structures. His column designs utilize the branching configuration of a tree to evenly support the roof structure. Otto's objective was to use the minimum amount of material to achieve maximum strength.

1.4.4 Louis Sullivan's love of delicate ornamentation of natural forms shows in the display windows at the ground level of his buildings, where it is appropriately related to a person's range of vision, and where a greater richness and intimacy is used to emphasize the principal entrance.

1.4.5 Malcolm Wells believed in merging buildings with the environment. Earth integration of a structure creates a nexus between site and structure to a degree which is simply not possible with a conventional, above ground building. He allowed landscape to surround and cover the structure, reducing its visibility and matching the existing landscape's color and character. His structures therefore blend in with the environment year round, even though there are seasonal changes of color. "When architecture draws its lessons from the wild, beauty will no longer have to be applied. That's an empty exercise. Organic rightness - appropriateness - will repair the broken connection between architecture and its roots" (Malcolm Wells, 1981).

1.4.6 Victor Olgyay proposed a method for working with, not against, the forces of nature and to make use of their potentials to create better living conditions. The tenets of his methods are: "Architectural expression must be preceded by the study of the variables in climate, biology, and technology. The first step toward environmental adjustment is a survey of climatic elements at a given location. However, each element has a different impact and presents a different problem. Since man is the fundamental measure in architecture and the shelter is designed to fulfill his biological needs, the second step is to evaluate each climatic impact in physiological terms. As a third step the technological solutions must be applied to each climate-comfort problem. At the final stage these solutions should be combined, according to their importance, in architectural unity" (Olgyay, 1963, p11).

1.4.7 With the advent of modern architecture the concept of **organic architecture** came into being, which involves the use of forms derived from living organisms, use of natural materials and cool, shaded interiors, and their close relationship with their sites. The term 'organic' was an expression coined by Xavier Bichat in 1800 to represent a synthesis of biology - the source of life, and morphology - the science of form. "By organic architecture I mean an architecture which develops from within outward in harmony with the conditions of its being as distinguished from one that is applied from without" (Frank Lloyd Wright, 1914). "In any good organic structure it is difficult to say where the house ends and the garden begins - and that is all as should be, because Organic architecture declares that we are by nature ground-loving animals, and insofar as we court the ground, know the ground and sympathize with what it has to give us and produce in what we do to it, we are utilizing practically our birth-right" (Frank Lloyd Wright, 1970, p12).

1.4.8 Geomorphic architecture concerns the fitting of buildings into the natural contours of the land. The most obvious manifestation of geomorphic architecture is the building that takes its imagery from the form of some natural geological feature. It is a phrase first coined by Sibyl Moholy-Nagy in her book, 'Matrix of Man'. Whereas geomorphic architecture has existed throughout history, its revolution occurred in the 20th century because the technical advances that make modern geomorphic buildings possible have been developed only recently. "The following list summarizes the ways in which a building can be considered geomorphic: 1) Takes its imagery from nature. 2) Takes its imagery from a natural process. 3) Provides an experiential equivalence to that found in nature. 4) Fits into the natural contour of the land. 5) Merges with the landscape to form a single entity. 6) Is partially or completely earth sheltered." (Edmund Burger, 1986, p22).

1.4.9 Green architecture is an ecologically sensitive method of design which seeks to serve natural ecosystems (Ian McHarg, 1969). The merging of ecology and architecture changed the course of organic architecture, giving it additional purpose and urgency. "Green architecture is the common ground between architecture and landscape and the familiar resemblance between formal agrarian gardens" (Barbara S. Solomon, 1988, p113). The following principles comprise green architecture: 1) Conserving energy by constructing buildings so as to minimize the need for fossil fuels to run them. 2) Working with climate by designing buildings to work with climate and natural energy sources. 3) Minimizing new resources by designing so as to minimize the use of new resources and at the end of its useful life, to form the resources for other architecture. 4) Respect for users by recognizing the importance of all the people involved with it. 5) Respect for site by constructing buildings that are in touch with the earth. 6) Holistic approach to the built environment by embodying all the green principles (Brenda Vale, 1991).

1.4.10 Sustainable design is by and large inseparable from social and economic sustainability. A cornerstone of sustainable development policy is the principle of community and regional control. The aim is to retain as many resources as possible within the community, to spur economic growth and increase community well-being (Andrew John, 1992). "Sustainability means providing for the needs of the present without detracting from the ability to fulfill the needs of the future" (Earth Summit). The question of sustainability or stewardship of the land is viewed as a forgotten way of the past and an imperative for the future. Sustainable communities have been achieved by civilized cultures on earth. In these settlements, supplies and demands are balanced and generated through renewable natural processes. A sustainable community exacts less of its inhabitants in time, wealth, and maintenance, and demands less of its environment in land, water, soil and fuel. Sustainability implies different solutions for different places and is quantified by context.

1.4.11 Bioclimatic design is the utilization of energy furnished by the sun and the environment to arrive as closely as possible to conditions of desirable comfort without the contribution of other forms of energy. The expression bioclimatic architecture comprehends various concepts. We could possibly define it, in a schematic way, as the whole ensemble of those design solutions that will create a satisfactory level of comfort within a specific building. This should involve a minimum of mechanical equipment needing non-renewable energy. The building in question should be designed such as to be able, in its interior, to modify the environmental conditions because of its morphological, dimensional, thermophysical, etc characteristics (ENEA, 1983).

Modern times have brought, however, a widespread demand for comfort, to a social question of prosperity, the answer to which cannot be spontaneous or entrusted to the geniality of a single daring arctic or rural community. The task of the contemporary builder has thus become that of producing homes that consider the bioclimatic problem in terms of the quality of life and reasonable installational and technical solutions.

Perhaps it will be in the blending of diverse technologies, of craftsmanship and industrialization, of individuals and groups, that future design will find advanced, but not sciencefictional solutions for environmental control.

1.5 USE OF ENERGY IN THE BUILT ENVIRONMENT

Our society is living beyond the means of the earth to sustain it. Our patterns of resource exploitation will dispossess the earth of its capital assets in the space of a few lifetimes. These patterns are devastating the natural environment upon which we depend for survival.

Until the end of the last century, architecture greatly took unto account bioclimatic and energy aspects, as can be deduced from the analysis of many examples. Prior to the 18th century, building services were very simple: buildings were daylit, artificial lighting was by candles and oil lamps, and heating was by open fires and solid-fuel stoves. There was no sound amplification, no cooling, no artificial ventilation, and no air filtering.

Pre-industrial architecture was often more responsive to nature because of the lack of mechanical backup systems; there was very little design margin of error. With the advent of the machine-age, coal and steam engines were used, which later led to the industrial revolution and a quest for technological advancement, with a total disregard to Nature.

During the late 19th century, new methods and equipment were developed, and it seemed possible that a perfect interior environment could be provided at a price, but a price that an effluent society could well afford. Then a period of waste began, with the construction of buildings no longer aware of energy consumption, for the problem became totally delegated to the 'plant', mythicized as capable of resolving everywhere and at any rate whatever problem of environmental comfort, without calculating the sometimes extremely high cost (Nancy Ruck, 1989).

Now, after the energy crises in the 1970's, the fall of blind faith in technological development and headway in the new dramatic awareness of the limits of nonrenewable resources, a similar irresponsible attitude can no longer be tolerated and the forgotten principles have to be rediscovered, the good and wise rules of the past, studying the remaining examples to extract the still valid teachings.

In the design of buildings and building services the human factor is of paramount importance. It is what people feel, not what instruments tell us they ought to feel, that matters. Consequently, human well-being and hence performance are of primary importance in the design of buildings from the energy viewpoint, in addition to the human need for an appropriate and simulating environment. It can be said that buildings do not consume energy, people do. At the same time, heating, cooling, lighting, and ventilation adjustments need to be made in response to people's needs and desires.

Human well-being and energy savings do not necessarily achieve their optimums simultaneously, however, in any design, basic human needs should have first priority.

1.6 ADAPTATION, SUSTAINABILITY AND LIFE

Long before the enterprising man bent some twigs into a leaky roof, many animals were already accomplished builders. It is quite unlikely that beavers got the idea of building dams by watching human dam-builders at work. It probably was the other way. Most likely, man got his first incentive to build up a shelter from his cousins, the anthropomorphous apes. Darwin observed that the orangutan in the islands of the Far East, and the chimpanzees in Africa, build platforms on which to sleep, and concluded that since both species follow the same habit, it might be due to instinct or it may be the result of both animals having similar wants, and possessing similar powers of reasoning.

A prominent theme in man's cultural evolution has been the creation and development of artifacts to shield him from the discomforts and hazards of life. The same has been true of the biological evolution and building behavior in animal species. These are; physical protection from danger of other animals and thermal protection from extremes of the physical environment.

Man also manipulates the environment in other ways; for example, to enhance his food-gathering ability. Artifacts with comparable functions are also built by some other animals, these are; cultivation, prey capture and feeding, and communication and display.

Both man and other animals have been building their abode using similar construction materials and building techniques, following the structural laws of tension and compression. The reaction forces that trees withstand are equivalent to those which man's buildings experience.

The materials used for construction by animals are ones which are either the same as, or comparable with, those used by man, so the constraints imposed by the materials on animal builders are very similar to those imposed upon craftsmen. The construction methods used by animals also have close parallels with human manufacture. These methods can be classified as:

Sculpting -It describes the formation of a structure by removal of material from the initial mass. In the case of animal builders, this mainly concerns the excavations of tunnels and chambers to provide a home for the miner, its off-spring or the whole family.

Piling up -The basic characteristics of this construction process are the picking up of building units, the carrying of them onto the existing structure. Typically, assembly takes place without the use of an adhesive to bind the elements together and the structure is entirely in compression.

Molding -The identifying feature of this method of construction is the working into shape of a plastic material. To achieve any precision in this technique an animal must be equipped both with delicate coordination and with precision tools.

Rolling and folding -The principle of this method of construction is the creation of a three-dimensional structure by rolling or creasing a flat plane. The plane material is usually a leaf.

Sticking together -Building is achieved by the combination of two distinct materials: discrete, more or less solid bricks or building blocks and an adhesive to fasten them together. The latter is initially plastic although it may later harden. Sand grain as the building blocks may be selected as ready made objects from the environment, lengths of plant stem may be cut from the environment or the material may be secreted by the animal itself. The adhesive is generally a secretion produced by the builder.

Weaving -of fabrics by humans typically involves the regular alteration of threads of weft over and under parallel threads of warp oriented at right angles to them. The threads available to animals are only rarely longer than two or three times the length of the animal itself, so in the structure there must be relatively more emphasis on knotting and fastening devices to prevent disintegration of the fabric.

Sewing -results in the formation of distinct stitches passing through some other material. The stitches are secured with the aid of an adhesive, spider silk. (Michael H. Hansen, 1984).

Angiosperms, like the Mesquite and Palo Verde, deposit tension reaction cells on the upper side of the branches holding them up in **tension**. Gymnosperms, like the Aleppo Pine, deposit compression reaction cells on the underside of the branches to resist **compression**. The woody ribs forming a hollow tubular column in the Saguaro provide it with greater **resistance to buckling** than it would if the central column was to be solid and having the same cross-sectional area. Correct placement of cells also insures that the weight of the tree is distributed evenly, reducing bending caused by **eccentric loading**. The tensile stresses created on one side of the tree trunk from the branches on the other, activate cells to grow an offsetting branch to equalize the load. The living cells are capable of renewal and able to respond to the changing needs of the tree. Overturning of the above ground cantilever is resisted by an anchoring **foundation system** provided by the roots of the tree. The roots, as well as the stem, can develop primary and secondary buttressing for **added structural support.**

1.7 SUMMARY

It is obvious that since time immemorial all animals, including man, have been building their abode using similar construction materials and building techniques. The reaction forces that trees withstand are equivalent to those which man's buildings experience.

In the course of the history of contemporary architecture, many renowned architects and architectural movements that have attempted to incorporate nature in building design have come and gone. Their architecture admired but no more practiced. They have set forth successful bioclimatically responsive building designs but modern man's ego to be superior to and his quest to conquer nature has prevented him from further developing these techniques or utilizing the benefits / lessons offered by nature.

CHAPTER 2

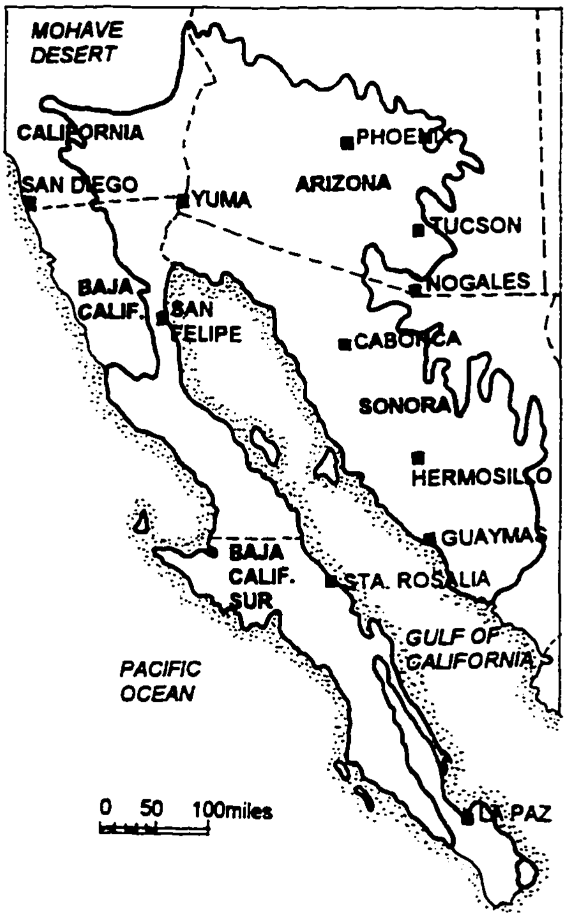
STUDIES IN NATURE AND THEIR ADAPTATIONS

2.1 THE SONORAN DESERT

The North American Desert system consists of some 440,000 square miles in the Western United states and northern Mexico. It is composed of four deserts which differ somewhat in climate and vegetation. Namely; Chihuahuan, Great Basin, Mojave, and Sonoran.

The Sonoran Desert, where my study is based, extends through southern Arizona; much of the state of Sonora, Mexico; across the peninsula of Baja, California; and the islands within the Sea of Cortez -a total of about 120,000 square miles. The elevation ranges from below sea level to nearly 3,500 feet, and annual rainfall varies from less than one inch to over twelve inches. The higher elevations commonly have freezing temperatures in winter, while the lower areas are generally frost-free. The eastern section has a summer rainy season, while the north-west receives winter rain. Summers, especially in the western parts are very hot.

Yet, it is quite lush in comparison with other deserts of the world and supports a wide range of animal life. While the plant and animal life in the Sonora Desert adapt to this harsh climate naturally, man tries to attain his physical comfort by forcefully using artificially created energy and consuming natural resources.



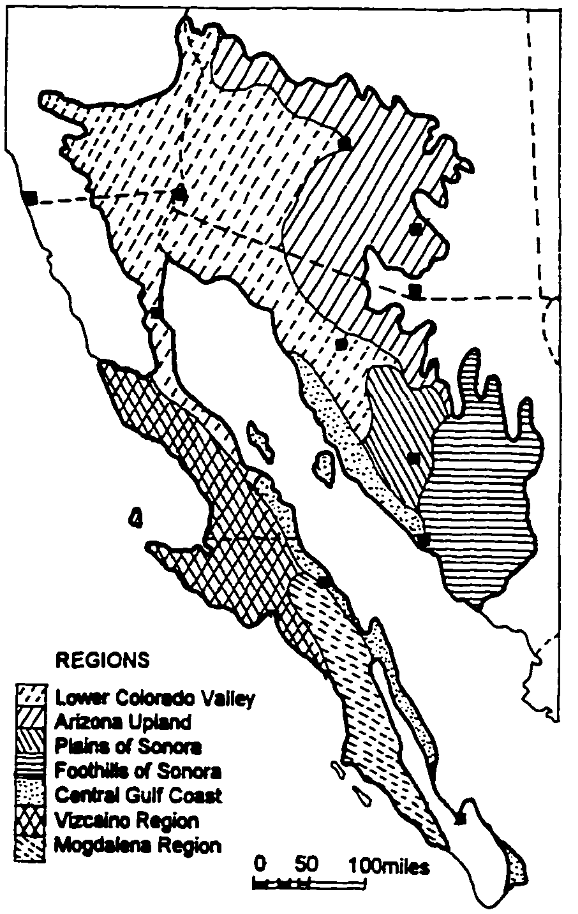


Figure 2.1 The Sonoran Desert covers much of Southern Arizona, southeastern California, Baja California peninsula and the Mexican state of Sonora.

Figure 2.2 The Sonoran Desert can be divided into seven distinct subdivisions on the basis of vegetation.

PLANT KINGDOM:

2.2 CACTUS COUNTRY

The Southwestern desert is a land of extremes: intense sun, rapid fluctuations in temperature, low humidity and sandy, rocky soils. Bordered and intersected with hills and mountains, climatic conditions also vary with altitude changes. Storms arise quickly, producing strong winds and sometimes more than an inch of water in minutes -easily a tenth (or more) of the annual rainfall.

Inhabitants of the desert must "outwit" this unusual region for survival. Among the most successful are cacti. The origin of cacti isn't completely known because there are few fossilized forms to study. It is thought that they developed about 65 million years ago, at the end of the dinosaur age when flowering plants were well established. Modern cactus ancestors were most likely small leafy trees with woody trunks, which dropped their leaves and became dormant during droughts, as many non-cactus desert plants do today. Two unearthed cactus fossils -one in Utah dated about 65 million years ago, the other dated from two million years ago in Arizona -were similar to Prickly Pears, with more primitive fruits, an indication that cacti were evolving toward desert adaptation at that time.

When cacti were first classified, their family was called *Cactaceae*, after the Greek word, *kaktos*, meaning thistle -a reference to the spines. But cacti are not thistles. Described as large, fleshy plants with usually leafless stems, they often have showy flowers and edible fruit. They are distinguished from other succulents (water-storing plants) by their areoles (round to oval spots on various parts of the plant, 1/16 to 1/2 inch), which produce flowers, fruits and spines.

2.2.1 Saguaro

This familiar symbol of the Southwest, the largest cactus in the United States, is aptly called the king of cacti. What better throne than the Sonora Desert of the Arizona and Mexico -the only place where this regal subject can be found? Saguaros can grow up to 50 feet tall and weigh 12 tons, reaching a possible life-span of 200 years. The clusters of white night-appearing blossoms on the branch tips, appearing / blooming in late spring comprise Arizona's state flower.

Saguaro seeds sprout in the shade of other desert plants or tall grasses, protected from intense sun and predators. They grow best on rocky slopes called *bajadas*, where they take advantage of well-drained soils. Saguaro's scientific name is Latin for "gigantic candle", and it certainly looks like this for the first portion of its life. Seedlings grow slowly, reaching a mere two feet after 25 years, six feet at 50 years. First branches develop at age 75, and height increases to 35 feet at the end of their first century. Over the next 100 years Saguaros may be veritable 50-foot towers with as many as 50 arms.

2.2.2 Saguaro's adaptations to the desert

The saguaro has evolved through natural selection, a set of adaptive strategies required to survive the irregular occurrence of climatic extremes that are a normal character of the saguaro environment.

A young saguaro seedling grows under the protection of a tree or shrub; like paloverde or creosote. These "**nurse plants**" branches and leaves hide the baby saguaro from animals that might eat it or step on it. The nurse plant also shades the young cactus from the burning sun, yet allowing enough sunlight through its branches for the seedling to grow. At night its branches blanket it, holding the warmth the soil absorbed during the long hot day.

The presence of **spines** is one way in which the saguaro adapts to its arid environment. Because plants lose moisture through their leaves, it is speculated that cacti have evolved reduced leaves, or spines, through which no water can evaporate. The straight ends of these spines function as "drip tips", quickly channeling any moisture into the roots (such as the minimal amount of humidity that naturally occurs when the hot desert cools down at night). Spines also cast small shadows which break up the sun's rays and provide water-saving shade in a shadow-scarce land. The density of the spines helps to diminish air currents by breaking the force of the moisture-sucking desert winds, cutting down on further moisture loss. Smaller hairs or **bristles** surrounding the spines function as insulators, keeping the plant from overheating or freezing. In addition, spines protect the saguaro from predators who want to draw precious water from their "storage tanks".

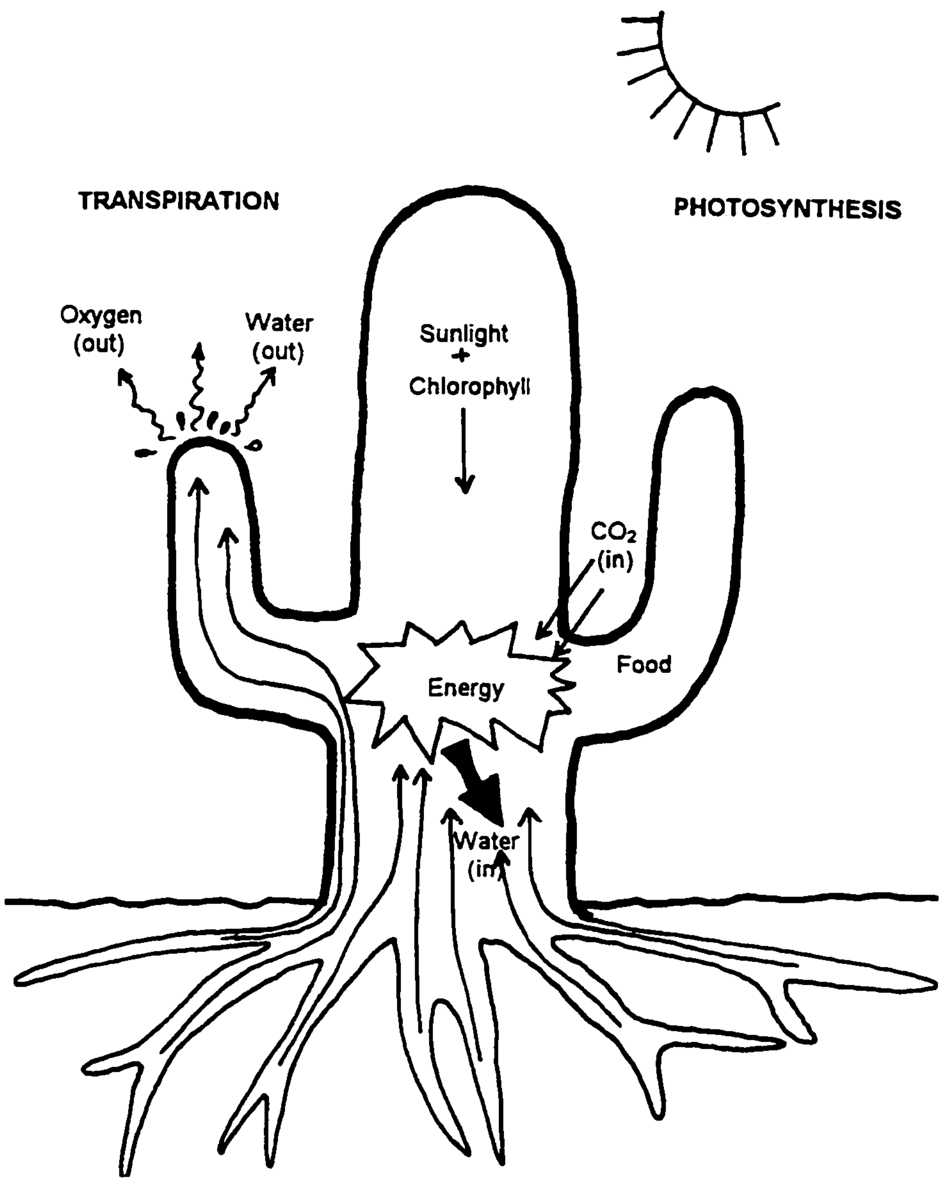


Figure 2.3 Energy transfer in a saguaro

Figure 2.4 Shadows cast on the saguaro by its spines and pleats

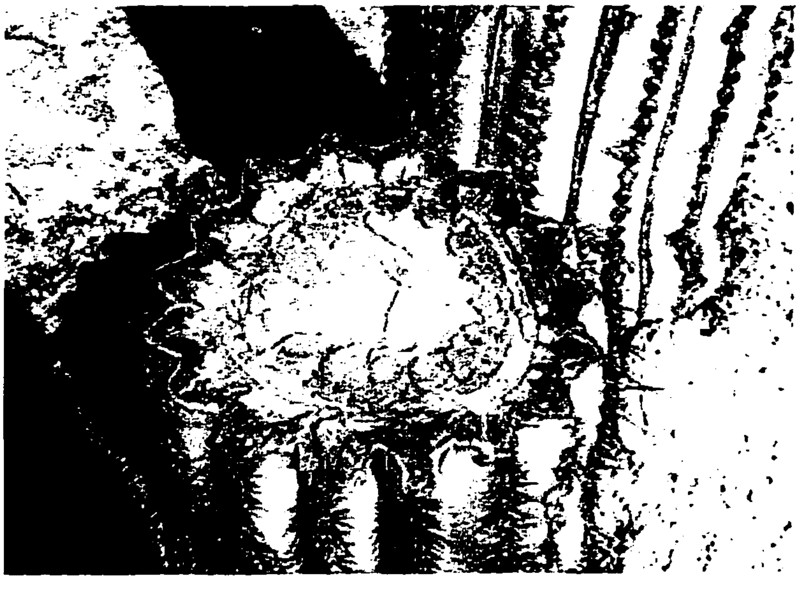


Figure 2.5 Cross-section of saguaro showing central ribs

To get enough water to survive in this arid region, Saguaro **root systems** are widespread, the taproot delving two to three feet underground. The rest of the roots snake 35-50 feet in all directions just below the ground's surface so that they can quickly lap up all rain and transport it to their stems. In this way it is possible for a plant weighing six to ten tons to absorb as much as a ton of water.

Sponge-like tissues in the **stem** possess an enormous capacity for holding water. Water is drawn up from the roots, changed to gelatin-like substances and stored within the plant tissue. During dry periods (which may last from five months to an year), Saguaros gradually consume their stored moisture and shrink in girth until "the well is dry" or the next drink is available. The trunk and branches have accordion-like pleats, to allow for such expansion/contraction. As the plant shrinks, the pleats become more pronounced, casting more shadow onto the saguaro, thus helping it remain cooler. Twelve to thirty woody rods arranged in a circle inside the trunk comprise saguaro "ribs", supporting the plant to keep it from breaking. Sturdy stem development is another method of adaptation. Being mostly rounded, there is no part that is exposed to the sun for any length of time, and only a small area of the plant faces the cooler north. Saguaros generally thrive on south facing slopes. Stems are protected with a thick, waxy **skin**, which discourages evaporation. Pores in the skin open during the cool of the night, allowing the entry of carbon dioxide which is stored and used for photosynthesis. Photosynthesis takes place in the stem of cacti, not in the leaves, to further reduce moisture loss. During transpiration a saguaro loses about a glassful of water each day, whereas some large plants can lose as much as a 100 gallons of water through their leaves and stem each day. Prominent tubercles or "ribs" act as enlarged leaf bases. The massiveness of the stem assists the plant in regulating an even internal temperature.

Saguaros even manage to produce **flowers and fruits** during long droughts. The waxy-white, funnel-shaped blossoms unfold in May or June. There are about 100 on larger plants, a few opening each night, so that flowers occur over a month's period. These white night-bloomers are strongly fragranced, an evolutionary development for attracting night-flying bats and insects who are important for pollination.

The Gila woodpecker pecks through the outer layer of the saguaro and makes a cavity within the soft, inner tissues. The saguaro responds by forming a tough, woody "scab" around the cavity, called "**saguaro shoes**". This prevents the cactus from drying out, just as our bodies produce scabs which keep us from losing blood after an injury.

2.3 TREES IN THE DESERT

The intense insolation, atmospheric drought, and high negative soil-water potentials of deserts pose severe constraints on the growth and maintenance of angiosperms. To overcome these strictures, plants may posses special features, especially in the morphology and physiology of their leaves, roots, and conducting systems. In order to absorb water from the soil, a plant exerts a "suction" force -that is, it produces a water potential within the root lower than the force with which water molecules adhere to the surrounding soil. The water potential within the root is negative relative to the soil, thus water moves into the root hair.

As a necessary part of the process of photosynthesis, a plant has to take in carbon dioxide from the air. As the carbon dioxide is used by photosynthetic (usually leaf) tissue, its concentration in the air spaces within the tissue drops to a very low level causing a gradient from inside the leaf to the outside air. Carbon dioxide consequently continues to diffuse into tissues through openings called stomates. While the stomates are open, and carbon dioxide is moving into the leaf, water vapor which has a higher concentration within the leaf than without, inevitably diffuses out. Water loss by this process, known as transpiration, can be sizable.

Water is constantly lost from leaves and must be replaced by water that has been absorbed by the roots and conducted up through the plant. As the soil around the root becomes drier, it becomes increasingly difficult for the plant to absorb water. What little moisture there is in the desert soil is held with increasingly stronger cohesive forces and the root has to exert a constantly greater negative water potential. However , most plant species can withstand only low to moderate negative water potentials. When a plant has extracted all the water it is physiologically capable of extracting (or reaching its maximum negative water potential) it is forced to close its stomates to stop water loss by transpiration or suffer irreversible damage by permanent wilting of its leaves.

In deserts, potential evaporation greatly exceeds rainfall for most of the year. Soils consequently become exceedingly dry, especially in the uppermost layers. Under such arid conditions, mesophytic plants soon wilt and die. The relatively small number of plants that survive in the desert do so because they have found solutions to the problem of severe water loss. Solution differ, but several major syndromes of drought avoidance or endurance have evolved in most warm desert regions.

2.3.1 Mesquite

Mesquite (*Prosopis spp.*) is a perennial belonging to the Mimosoideae subfamily of Leguminosae. Spiny plants of mesquite are among the most common plants along washes and canyons of the deserts of North and South America, northern Africa and the Middle East. They occur at elevations up to 4,500 feet where the average annual minimum temperature exceeds -5° F.

From early pre-historic times until recent years, mesquite has served native peoples in Southwestern North America as a primary resource for food, fuel, shelter, weapons, tools, fiber, medicine, and many other practical and aesthetic purposes. Every part of the plant is used. Utilization of mesquite was the common denominator among the diverse peoples of the arid southwestern low lands, agriculturists as well as nomadic hunters and gatherers. Because mesquite is such an important and unfailing resource, it came to figure in the everyday lives of these peoples from cradle to grave.

Their long tap roots reach to moisture. These hardy trees produce long, straight, non splitting seed pods relished by animals and historically collected as a basic food source by many native Americans. Their wood has brightened many a desert campfire, provided the posts for innumerable fences, and long served for construction in a wood-scarce land. Passed through the intestinal tract of cattle, the seeds immerge digested only sufficiently to promote immediate germination. Mesquites have thus been ready-planted in often over-grazed rangeland, further deteriorating it and arousing ranchers' ire. To animals, however, the mesquite is a blessing.

2.3.2 Adaptive principles of the mesquite

The physiological capabilities of mesquite (mesquite is a water-table-tapping plant which is known as a phreatophyte) for coping with drought are complex and, on a short-term basis, can rival those of xerophytes (plants adapted for life and growth with a limited water supply). Adaptations for acquiring and retaining moisture involve the root system, the leaf morphology, and the physiological tolerances of the plant.

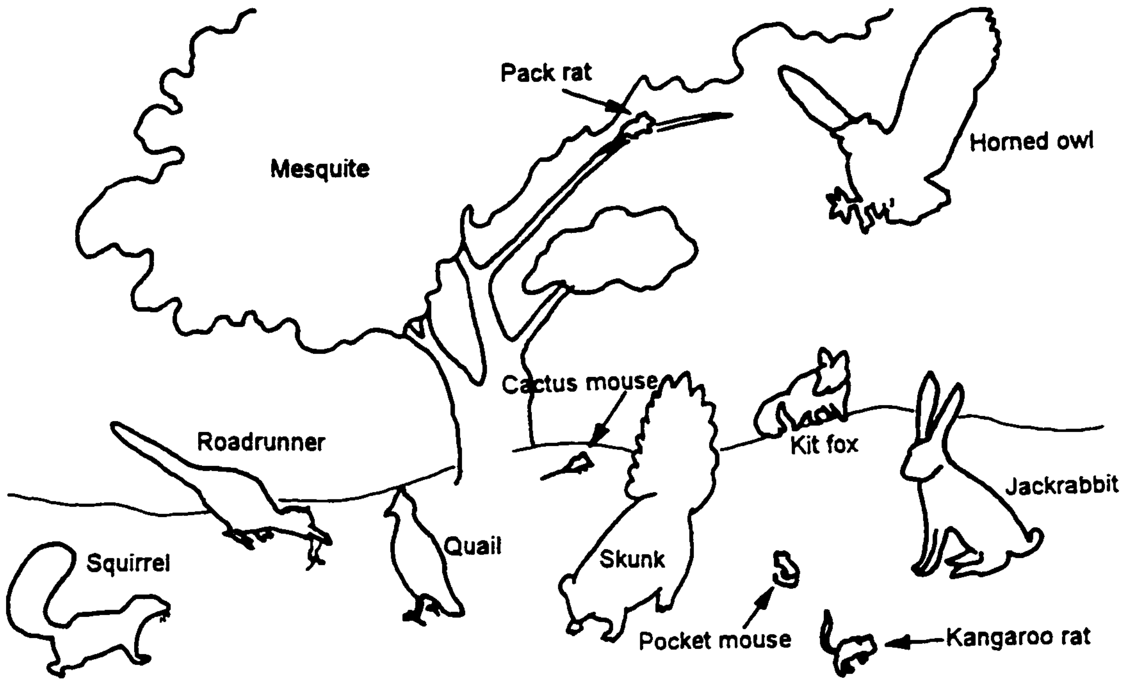


Figure 2.6 Common vertebrates of mesquite

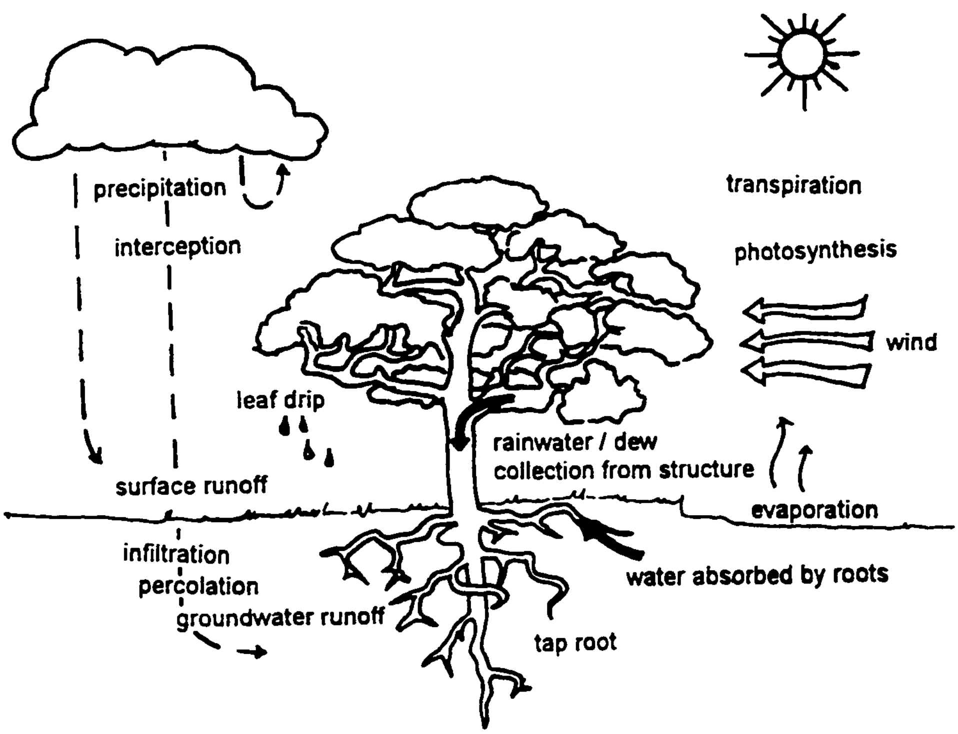


Figure 2.7 Evapotranspiration model of mesquite

The potential water reservoir available to *Prosopis* is large relative to that of other desert shrubs. Trees have **roots** deep enough (upto 160 feet) to tap ground water as well as a pronounced lateral root system extending over 60 feet from the tree. As soil moisture diminishes, a lower vapor pressure deficit produces a decrease in transpiration. In other words, if the evaporative demand of the air exceeds a certain level, *Prosopis* essentially becomes de-coupled from the atmospheric environment (transpiration is generally linearly related to the vapor pressure deficit assuming equal stomatal openings). The point at which this de-coupling occurs appears to shift with the amount of available soil moisture.

As the vapor pressure deficit increases to a point at which water loss would be so great as to result in a very high water stress, the **stomates** simply close. This stomatal closure results, of course, in a concomitant reduction in photosynthesis since it blocks the intake of carbon dioxide from the atmosphere into the leaf as well as the escape of water. The midday closure of the plant stomates in desert environments can enhance water use efficiently considerably because it increases the ratio of carbon fixation to water loss. Carbon is thus gained only during periods of low vapor pressure deficit which are also the periods of lowest potential water loss.

New **leaves** emerge in the spring after the soil moisture has been recharged. Photosynthetic rates are high during this period. As temperatures increase, plants transport increasing amounts of water from the soil to the atmosphere via transpiration and consequently come under continually increasing water stress. The leaves apparently adjust not only physiologically to this stress by means of the stomatal behavior, but also morphologically by increasing their cuticular thickness as the season progresses. The photosynthetic capacity in old leaves decreases with advanced leaf age and water stress. In drought conditions there is almost complete cessation of growth.

At the base of each leaflet, leaf, and petiole are pulvini that allow the pinnae and leaflets to droop and/or close. The leaflets close somewhat at night and the leaves tend to droop partially during the hottest part of the day in summer. The plant is capable of moving its leaves so that during the hottest time of day only its narrow edges are directed towards the sun, thereby reducing surface area and stomatal exposure. The stomates are not sunken or covered by trichomes as is often common in the leaves of xerophytic shrubs. However, the surface is covered with deposits of lipids, producing a waxy type layer that reduces moisture evaporation from their surfaces and which often forms characteristic patterns on the leaf surface. Small leaf size is advantageous in desert environments because it reduces the heat of the leaves although at the same time it causes increased evaporation.

Under certain conditions, dew is deposited in the desert at night; certainly some of this dew condenses on the mesquites. To a very limited extent the plant is capable of absorbing this moisture. However, the mere presence of the dew on the leaves in the early morning briefly reduces both the leaf temperature and transpiration from the plant itself. Hence the stomata may remain open to support photosynthesis for a time period ranging from a few minutes to an hour or more longer than would have been economically feasible without this moisture.

The most important feature afforded other plants and animals by individuals of mesquite is that of **shelter** -shelter from the sun, from soil draught, or, in some cases, from grazing animals. Shade affects soil temperatures, evaporation, and the amount of radiant energy impinging on understory vegetation. Mesquite which grows along washes and riparian systems provide a distinct micro-habitat for annuals and herbaceous perennials under their canopies. In addition to soil moisture, the cooler temperatures under the canopy provide an increased atmospheric moisture relative to surrounding areas. The combination of these factors prevents excessive transpiration. Soil under mesquite is more favorable for germination and establishment of understory vegetation than open soil. Higher organic matter and lower bulk density of mesquite soil would tend to reduce the rate of soil heating during the day and rate of cooling at night, thereby improving conditions for germination and growth of seeds of perennial grasses and large-leafed herbs.

One consequence of increased soil moisture on its root system is an increase in the development of the superficial root system. Leaf litter and other material that accumulates under the tree is a major contributor to the retention of soil moisture under the canopy because litter acts as a barrier to incoming solar radiation during the day and also conserve moisture in the soil.

The mature mesquite plant has tremendous ability to regrow following injury because of an accumulation of dormant buds along the trunks and stems. Lateral buds are produced in the axil of leaves along new stem growth. Following the juvenile stage, one of the axillary buds usually produces an inflorescence. If a new flush of foliar growth is stimulated by a wet period later in the season, both leaf and inflorescence may immerge from axillary buds.

ANIMAL KINGDOM:

2.4 Termites

The termites are a group of insects which comprise the order *Isoptra* with over 2200 species. The termites are unique in that all species are apparently social, in what are essentially family groups. These groups or "colonies", include individuals in different stages of development and of different morphological and functional types of "castes" (reproductives, soldiers and workers). The types of individuals present in the colony vary with the age of the colony and the particular species. The size of the mature colony also varies among the species, from several hundred individuals in some, to many hundreds of thousands of individuals in others. In general, the ultimate size of the colony is limited by: the egg laying capacity of the queen (or the combined egg-laying capacities of several queens);

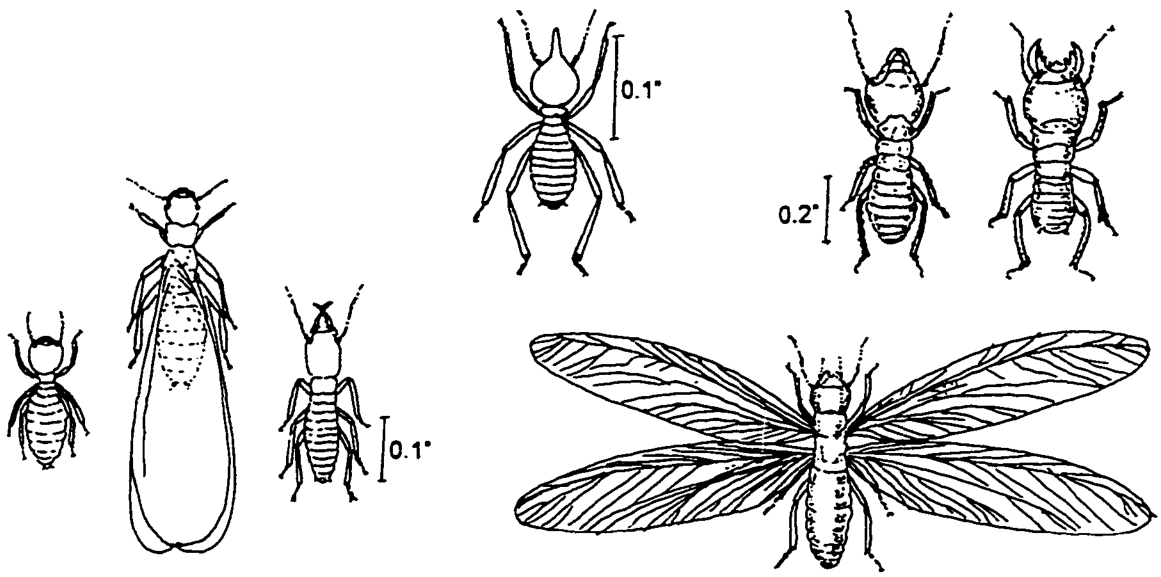


Figure 2.8 **Some termites of different castes. (Frisch, 1974)**

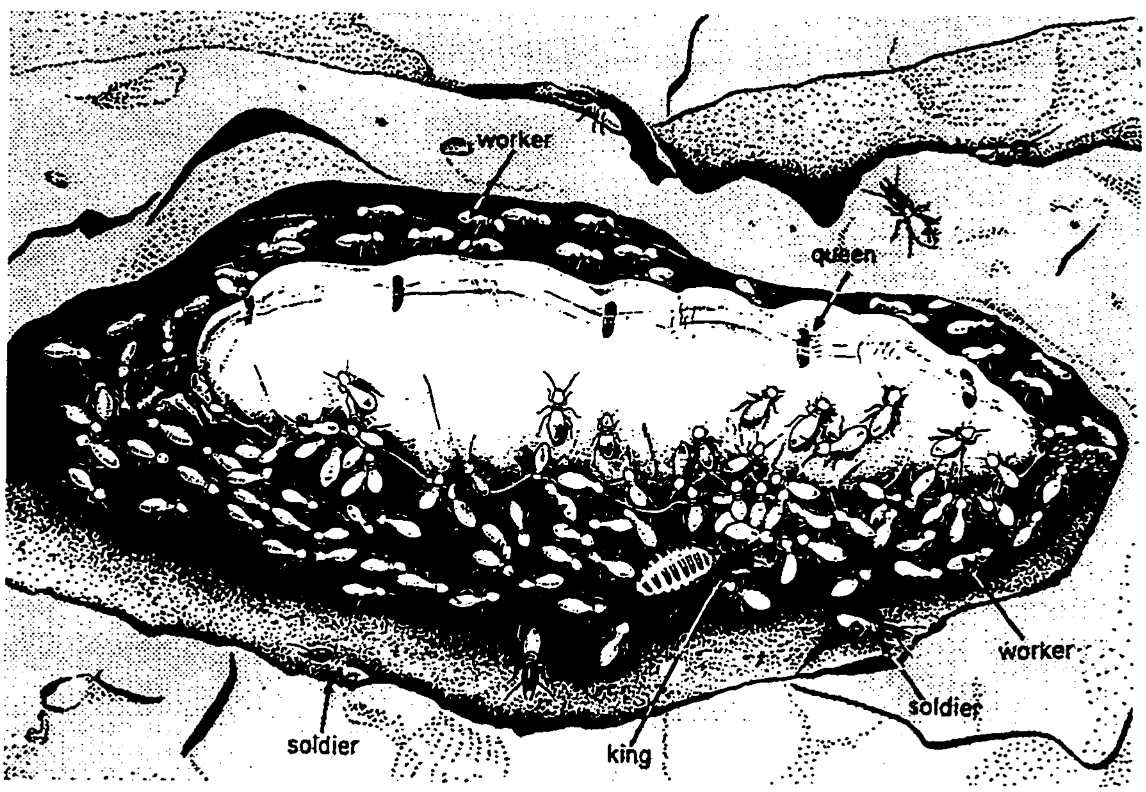


Figure 2.9 **The interior of a royal cell. (Frisch, 1974)**

the rate of development and longitivity of the individuals produced; and by loss from the colony of winged reproductive individuals termed alates.

The termites have long been of interest to man. Their attacks upon man-made structures and materials are matters of continuing economic concern. Their social habits have aroused the interested observer to speculations regarding the complex organization and functioning of the colonies. Their conspicuous, often complex, and diverse nest structures have attracted the attention of biologists and layman alike.

Termite dwellings represent an equilibrium of three forces -behavior, material and climate. Termites have developed the capacity to burrow and to mold structures from soil and organic matter to a level unknown in any other group of soil animals. Termite nests, mounds, and gallery systems are sealed off from the external environment except when they are deliberately opened by the termites to allow air to circulate or to permit the exit of foraging parties or flight of alates.

The workings of termites protect their inhabitants from the external environment. They exclude small predators such as ants, a primary enemy of the termites. They serve to maintain a rather constant humidity regardless of external conditions. Most termites require a very high environmental humidity. This is maintained within the workings which have a limited number of openings and are otherwise very carefully sealed. The tube-like extensions which form exploratory or connecting tunnels likewise aid in protection from small predators

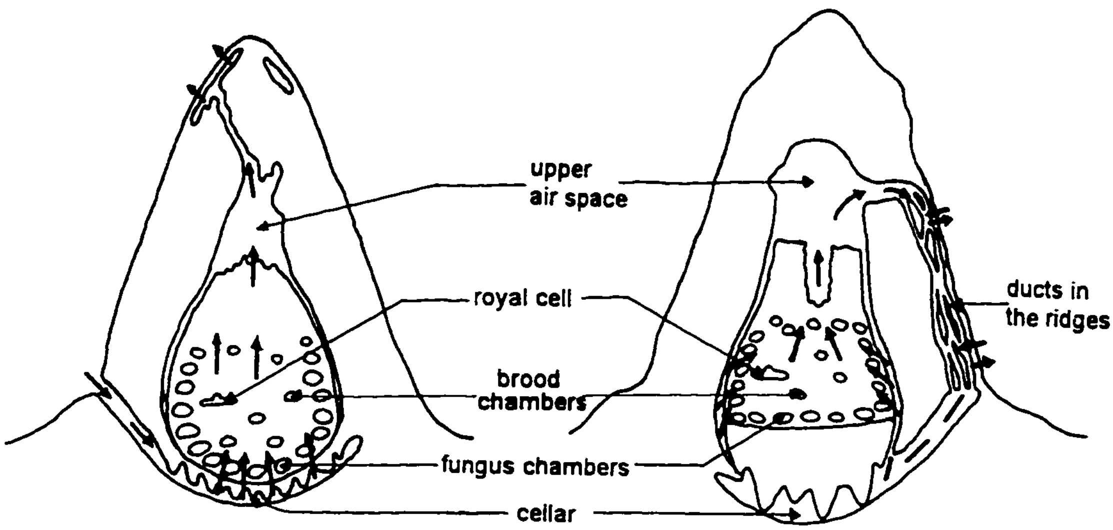


Figure 2.10 Circulation of air in the nests of *Macrotermes bellicosus*: right, in a nest from Ivory Coast; left, in a nest from Uganda. (Krishna, 1970)

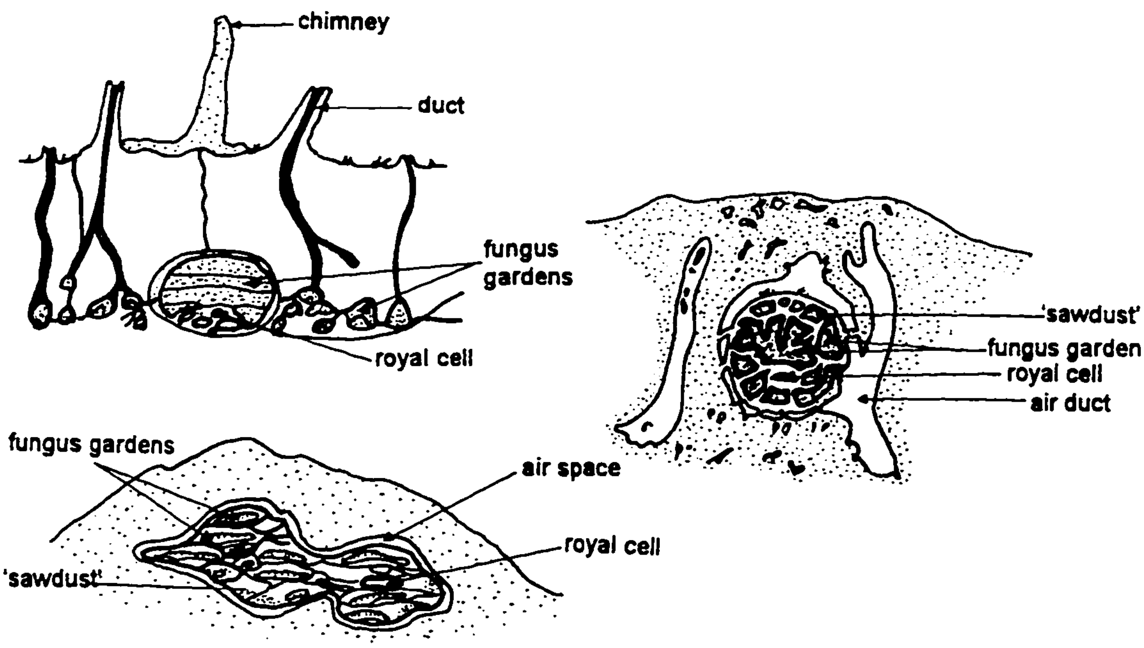


Figure2.11 Sections through nests of various species of termites. (Howse, 1970).

and desiccation. These tubes serve to channel subterranean moisture supplies into workings above ground. Soil-dwelling termites, living in arid regions, are likewise dependent upon a high environmental humidity. This they obtain from deeper layers of the soil.

In many instances the type of mound or nest constructed by a given species in one area is quite different from that of the same species in another area. These variations are due to differences between the structure of the soils or the climatic conditions in the different regions.

Termites were architects long before the advent of man on earth. In the tropics their hard, earthlike cartons or mound nests are built in trees (as the arboreal man built), or in excavations below ground (as the cave man built), or as low, hutlike mounds or lofty skyscrapers on and above the ground (as present man builds). Termites have not only constructed primitive rammed earth and adobe houses but well-ventilated and rain-shedding pagodas which afford proper ventilation and air conditioning.

2.4.1 The *Hodotermitidae*

The *Hodotermitidae* are harvesters that build nests entirely underground in semi-desert and desert areas. Although structurally primitive, these termites build a most peculiar and complex nest. The nests of *Hodotermes mossambicus* are compact and almost spherical, consisting of a surprisingly large cavity, two feet in diameter and eighteen inches high. These are divided into numerous chambers by layer upon layer of horizontal paperlike partitions, most of which are filled with grass that has been collected. These layers, three-eighths to five-eighths of an inch apart, are attached to the walls by clay supports and to each other by slender columns and by short ramps which allow the termites to pass from one level to another. There are also galleries leading to the surface and into cavities used as "granaries" located just around the nest where, again collected grass is stored.

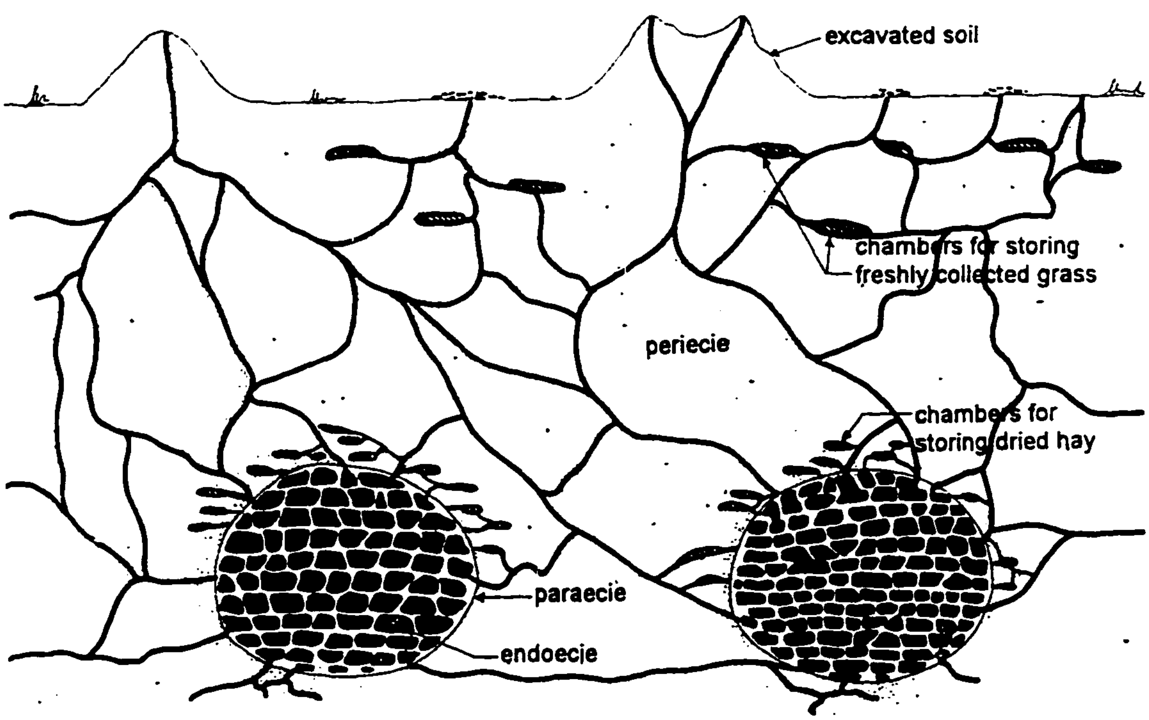


Figure 2.12 Cross-section through ground nests of *Hodotermitidae*. (Lee and Wood, 1970)

Unlike the common pale, thin-skinned, blind, slow and timid termites, the termites of this group have well-developed eyes and often forage in daylight in long trails, bringing back to the nest portions of the leaves of grasses and other plants which are first stored in cavities just below the surface. Storing the grass here protects the young brood in the nest from the gases that are given off as the grass starts to ferment. The nests are found at depths of 3-10 feet under the ground, occasionally much deeper, and the earth from the excavations is piled up in heaps above ground. The nests are interconnected with galleries where they come near to each other underground.

2.4.2 Adaptive principles of *Hodotermitidae*

Termites do not merely occupy a niche, but model it within the dimensions of their tolerances and preferences. The composition of the atmosphere within the nest, its temperature and moisture content, are related to those of the external environment, but Hodotermes exercise some control over them. Control results from the cumulative effects of various adaptations of behavior and methods of construction, and varies in its effectiveness. With respect to the microclimate within the nest, three important factors are: temperature, humidity and the internal atmosphere and ventilation.

Temperature regulation:

The temperature inside termite nests varies diurnally and from day to day. The temperature in the central nursery chamber is always higher than soil or air temperatures, but varies less than temperatures in other parts of the nest. The mean daily temperature in the nest does not vary more than 1°F throughout the year, but diurnal fluctuations parallel ambient temperature variations and sometimes exceed 5°F.

Hodoterms build **subterranean nests** with chambers deep in the soil to minimize the effects of diurnal temperature fluctuations.

Though the primary function of the nest is to provide a protected living and food storage space for the termites, it also insulates the central regions of the nest from variations in ambient temperature. An **insulating layer** is constructed around the periphery of the nest by filling the outer galleries with loosely packed fragments of grass, which provides insulation as well as food storage. This grass is first fermented and dried in special flat chambers situated close to the surface and then carried into chambers around the periphery of the nest.

Crowding together of large numbers of termites in the central portion of the nest during cold weather is a commonly used device for maintaining high nest temperatures. Constantly high temperature of the nursery is attributed to **metabolic heat**. The metabolic rate of individual termites is higher when ambient temperatures are high than when they are low, and fewer number of termites can maintain an elevated nursery temperature when ambient temperature is high than when it is low. Thus the nest temperature, particularly in the nursery, is buffered by movement of individuals between peripheral galleries and the nest.

Humidity:

Termites are very susceptible to desiccation, for their cuticle is exceptionally soft and its water retaining-properties are poor. The young larvae are particularly sensitive to dehydration. Thus maintaining high humidity in nests and galleries is an essential requirement for their survival.

Clay and carton are the two main types of **absorbent materials** used by the Hodotermes. Clay is used as a structural and cementing material, but its distribution in the nest is important for water conservation. Carton consists largely of the excreta of termites, usually incur incorporting some mineral particles and often undigested fragments of wood, grass or leaves of trees. It is formed into a labyrinth of laminar or alveolar structure and makes up the galleries of the central portion. The proportion of organic matter increases from 20% in the outer regions to about 75% in the inner portion, where the young are raised. The material of the central is more hygroscopic than that of the periphery. This serves both to prevent rapid desiccation during dry hot periods, and hinder the condensation of free water when cooling occurs.

Decomposition of cellulose, which is the principal food resource of termites, results in release of water. Most of the water required to maintain high humidity is produced from carbohydrate **metabolism**.

The absence of direct communication between the nest and the exterior obviously reduces the evaporation rate.

Internal atmosphere and ventilation:

The crowding of a great number of individuals into a limited space which is usually partitioned off within the nest produces the problem of a renewal of the gases. The level of oxygen which is necessary for respiration must be maintained and the carbon dioxide which is produced by the termites, and other gases arising from their intestinal symbiotes, must be eliminated.

As described earlier, the nests are enclosed and do not have any direct communication with the outside air. Temporary communication may be established as the nest is enlarged, at the time of emergence of the alates, and in order to permit the passage of the foragers into the colonies. However, these openings are immediately closed when they are no longer necessary. The renewal of the internal atmosphere therefore, must take place throughout the wall of the nest.

Like any tightly packed group of breathing animals, the termites themselves cause a rise in temperature. This hot air rises by way of the central spiral path and is forced by the pressure of the continuos stream of hot air causing an air circulation driven by convection currents.

2.5 THE HORNED LIZARDS

In the Sonoran Desert, lizards are particularly conspicuous to the casual observer, because so many species are diurnally active. Most of them are carnivorous, and the majority are important consumers of insects. A few like the common collared lizard and desert spiny lizard are omnivorous and a few like the common chuckwalla and desert iguana are primarily plant eaters.

Sonoran Desert lizards use various forms of behavior to achieve and sustain optimal metabolic body temperature without overheating. The majority depend primarily on the sun as a source of radiant heat to raise body temperatures to levels necessary for metabolic activity (heliothermia). When necessary, they can achieve body temperatures substantially higher than the surrounding air temperature.

Horned lizards are members of the family Iguanidae. Various species occur throughout Arizona and Sonora. These are short, squat lizards with very short tails. Undoubtedly the short rounded body shape accounts for the common misleading name "horned toad" which mistakenly implies some amphibious relationship. The horned lizard is, of course, a reptile. All have large protuberances on the head, some long and pointed, others short and blunt, from which the name is derived. In addition, most have fringes of spines on the sides of their bodies. Coloration varies with the species and the habitat. All species are remarkably cryptic in their natural habitat. Horned lizards are principally diurnal and crepuscular, feeding primarily on ants. They sometimes consume other insects and spiders, but their fundamental "sit and wait" feeding behavior is not effective with more elusive prey.

Horned lizards usually inflate their bodies and jab with their horns in defense. They occasionally squirt blood from a sinus behind the eyes, through a tiny pore at the corner of the eye. The blood may be projected several feet, and appears to be irritating to the eyes and mucous membranes of carnivore predators.

The unusual appearance of all horned lizards is due to their unique and integrated set of adaptations. Their camouflaging colors, flat forms, and sedentary nature make them difficult to see. Their horns and spiny scales make them difficult to swallow. Their pancake shape provides them with a large collecting surface which they can orient for rapid solar heating. Their spacious body provides room for development of numerous eggs or young and a large stomach. At the same time, their awkward shape limits their speed, both for hunting and for escaping predators. It also makes walking through dense stands of ground-level herbs and grasses difficult. These lizards look strange because some of their methods of survival are out of step with our stereotype of lizards. But for them this unorthodox strategy has worked, with the benefits outweighing the costs. They continue to survive and reproduce.

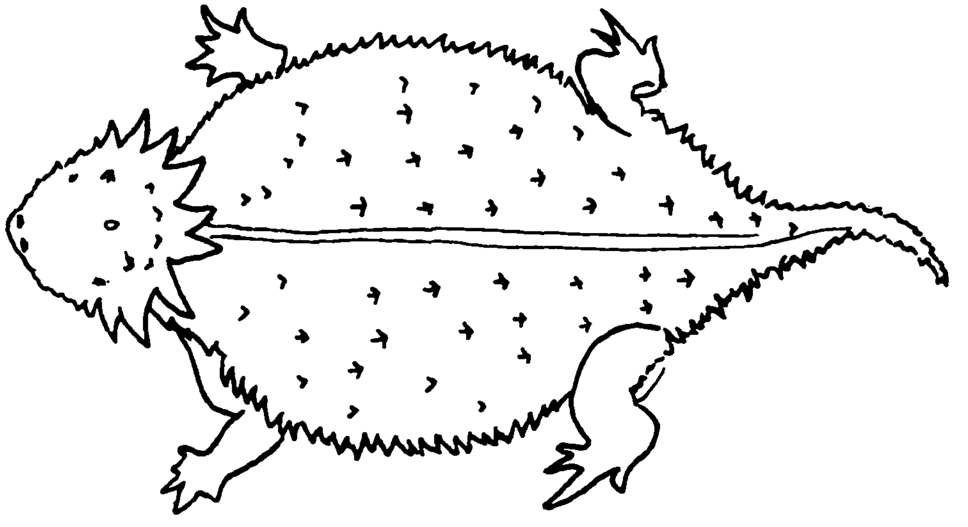


Figure 2.13 The regal horned lizard

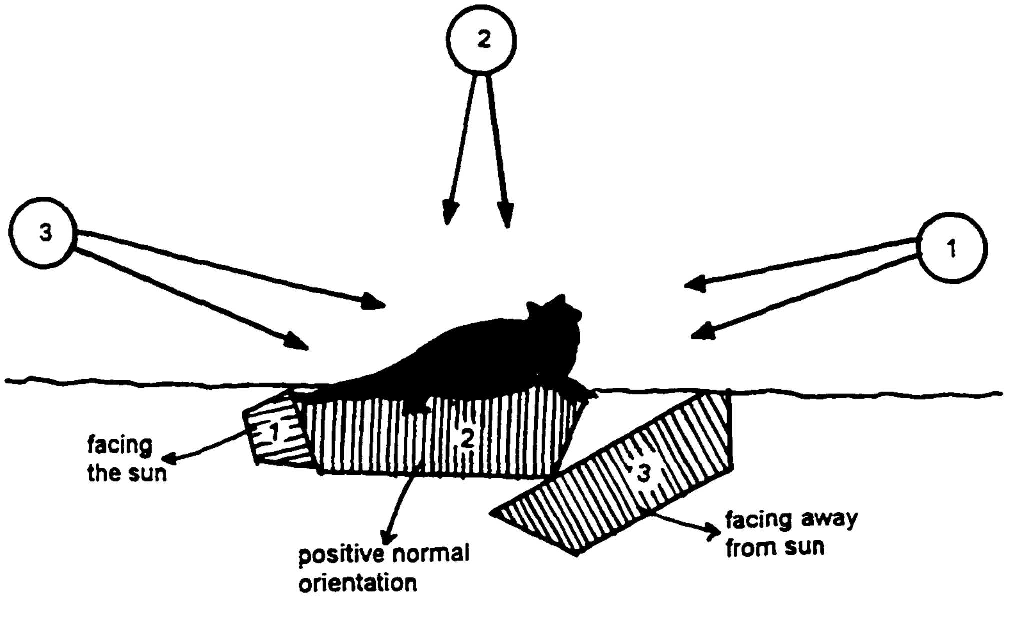


Figure 2.14 Orientation behavior of a horned lizard. Radiant heat load is proportional to the shadow cast. (Avery, 1979)

2.5.1 Adaptations of the regal horned lizard

The regal horned lizard, *Phrynosomatidae solare* (in Greek *phrynosoma* means "toad-bodied" and *solaris* means "belonging to the sun"), is common only in southern Arizona, within the vicinity of the warm Sonora Desert. It has the largest crown of "horns". It is the only species with four central horns, the bases of which are all in contact. These horns grade uniformly into adjacent horns, forming a regular, complete crown, thus giving the specie a regal appearance. The horns, rather flattened, are broader than they are high. A single row of large fringe scales extends along each side of the body. On the upper surface there are numerous large erect scales, giving these horned lizards a particularly spiny appearance.

The significant **regulatory movements and the temperature levels** triggering each response are presented for five methods of thermoregulation: shade-seeking, re-entry into the sun, burrowing, variation in body shape and color, and orientation movements. The horned lizard undergoes a regular sequence of behavior each day. This may be illustrated by following the idealized activity of the lizard through a typical summer day.

As the sun rises the regal horned lizard initially exposes only its head as it emerges out of the ground. The smaller head mass achieves higher temperature more quickly than would the unexposed body. The jugularis muscle constricts the jugular vein, slowing blood flow back to the body. Blood is thus warmed in the head and transferred to the body. The lizard is thus able to raise its body temperature to a metabolically efficient level with less risk of exposure to predators. When the head-body temperature reaches equilibrium, emergent activity begins. When the body temperature is low it has a dark **coloration** for increased heat absorption.

Once above ground the lizard begins **basking**. It tilts its body and turns its back toward the sun. It may face away from the rising sun while standing high on extended forelegs, or it may orient a lowered side toward the eastern horizon while elevating the opposite side by extending its legs on that side. Sometimes it stands with its forelegs on elevated objects or sits on steep east-facing slopes. All these tactics increase the angle between the rays of light arriving from the recently risen sun and the animal's back. This more direct exposure brings about a faster rise in body temperature as a surface held perpendicular to incoming rays absorbs more radiant heat. While basking, horned lizards increase the amount of blood circulating through the small capillary vessels in the skin on their back. Heat is rapidly taken up from the skin by the blood and dispersed throughout the body. They also spread their ribs and pull them forward, which increases efficiency of their solar heating by **increasing the area** exposed to sunshine.

Early in the morning horned lizards alternate between basking and other activities until finally basking is discontinued as surface and air temperatures rise and the higher angle of the sun in the sky enables the lizards to maintain warm body temperatures without basking.

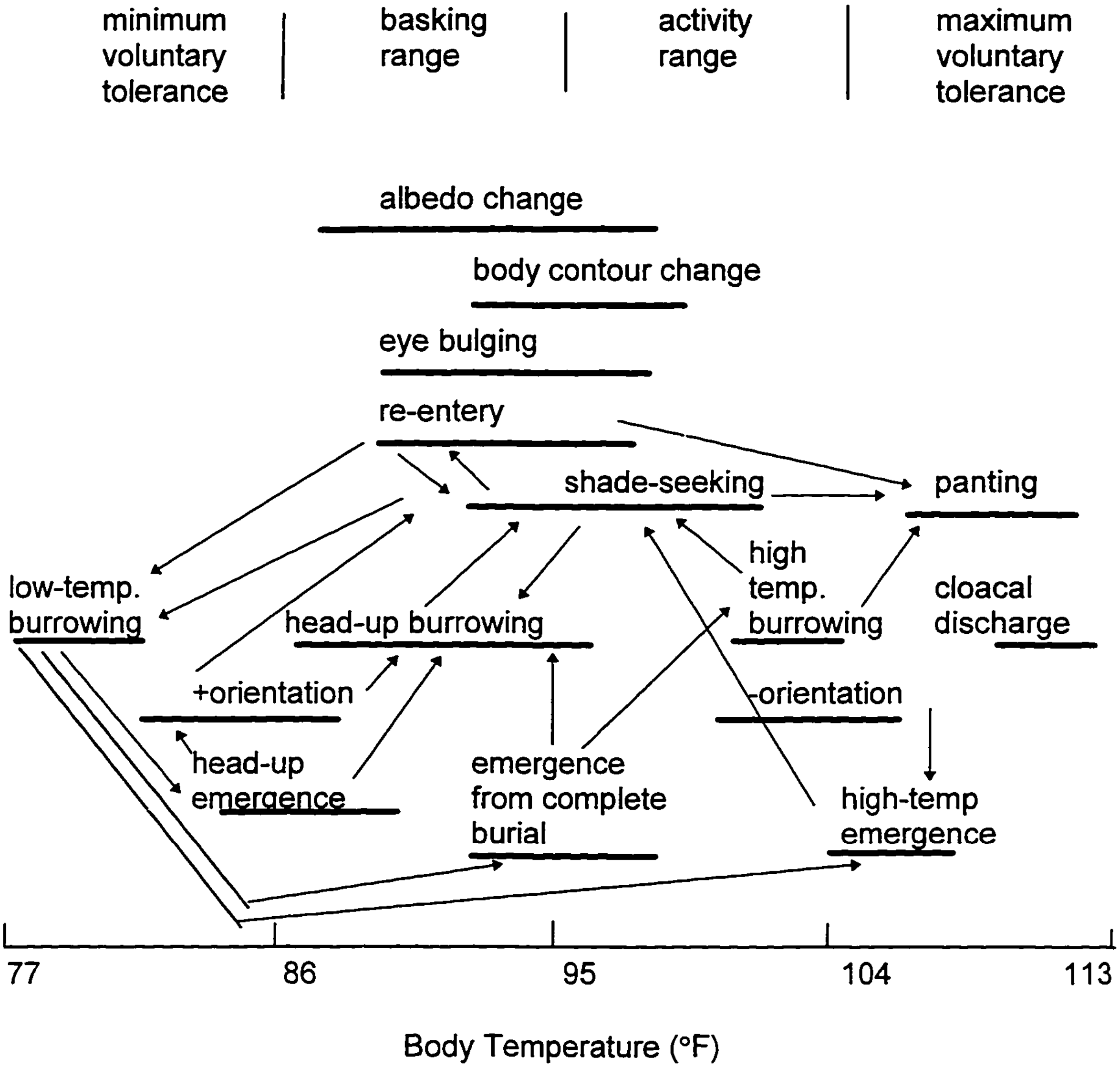


Figure 2.15 Behavior patterns of thermoregulation in the horned lizard

Later in the morning the ground becomes even warmer and the sun's rays are more direct. Now horned lizards must prevent body temperature from rising any higher; relatively slight increases could be fatal. At this point it will begin to shuttle back and forth between sunny and shady areas. In the shade it will flatten its body against the cooler ground, losing heat to it. When in the opensunshine it will face into the sun, so that its back is oriented away from it, and will pull its ribs backward so as to minimize the exposed surface area. Its color also lightens in order to reflect the solar radiation when little increase in body temperature is required.

By late morning a horned lizard finds that even shuttling behavior is ineffective for maintaining its body temperature safely below the lethal. It now retreats to the **shade** of a shrub.

Throughout midday, as the earth turns and the sun moves across the sky, patches of shade shift position. Horned lizards that had earlier burrowed in shaded areas may now find their underground retreats exposed to direct sunshine, and heating unbearably. They may burst from beneath the hot sand and run for shaded areas where they rapidly propel themselves into the cooler subsurface soil. Initially it **buries** itself an inch deep, moving deeper later as necessary.

By mid-afternoon there is a decrease in the angle of incidence with which the suns rays hit the earth, and the cooling surface soil again becomes tolerable for horned lizards. As they adjust to cooling surroundings their cycle of thermoregulatory behaviors is nearly the reverse of the morning cycle. Emerging lizards tend to remain in the shade at first. As the environment cools further they shuttle between sun and shade. Later they remain in the sun for longer periods of time and bask in the final rays of sunshine before burrowing again under the loose soil to pass the night.

Supplemental means of temperature regulation include panting and cloacal discharge.

Under extreme temperature conditions panting begins when the animal opens its mouth and slims its body by moving the distal ends of the ribs backward. Increased respiratory movements may accompany the initiation of panting. If the animal remains in an excessively warm environment, deep respiratory movements become apparent within a minute or so after the mouth opens.

If excessive high temperature prevails then the regal horned lizard produces a copious flow of clear fluid from the cloaca. The fluid moistens the vent and proximal end of the tail which acts as an accessory cooling mechanism. This response is dependent not only on temperature but also on the availability of water within the cloaca.

Obtaining and conserving water is important in the desert. Small amounts of water are constantly being lost through the skin and lungs. By burrowing underground, horned lizards help reduce these evaporative water losses. They replace lost water with water in foods and they drink on occasion. They lap up droplets of morning dew from plants, perhaps recognizing them by their metallic shine, and during a rain shower they take water from rock surfaces. If caught out in a rain storm, a Regal horned lizard will use its back as a water collecting surface. It arches and spreads it, while standing high off the ground and holding its head low. The scaly surface of the skin absorbs the droplets of rain which are then pulled toward the lizard's mouth by gravity. By slightly opening and closing the mouth, it can ingest the water gathering around its jaws.

Horned lizards conserve a great deal of water by not using it to flush nitrogenous wastes and salts from their bodies. Like most reptiles, they eliminate nitrogenous wastes in the form of uric acid. Uric acid is chemically similar to urine but is nearly insoluble in water and therefore can be excreted as a semi-solid with little water loss. Water carrying it from the kidney is reabsorbed in the cloaca.

They also conserve water by eliminating salts through nasal glands. These glands extract excess salts from the blood and secrete them, as a very concentrated brine, into the nasal passages. The brine is removed by sneezing.

2.6 THE ROADRUNNER

The roadrunner (*Geococcyx californianus*) is unique in many ways. It is also commonly known as *el paisano*, which means "fellow countryman", chaparral, lizard bird, war bird, snake killer, medicine bird, running cuckoo, and cock of the desert. Every early settler in the Sonora Desert was quickly informed of the *paisano*, a bird which could run faster than a horse, just as surely as he was informed of the "sacred toad" (horned lizard -discussed earlier), which wept tears of blood.

The vaquero whose horse was fast enough to overtake a roadrunner so that it could be lassoed boasted of the fact for weeks. In fact, the roadrunner adds interest and charm to every region where it is found. It is a bird that races freight trains and cars. Dead or alive, it brings luck to native American tribes and inspires legends and ceremonies. It challenges vipers and fights them to death. It will live in a busy telephone booth and eat bacon and eggs for breakfast.

The roadrunner is really a strange-looking bird. It might be compared to a tall, slim tramp in a swallow-tailed coat. This tramp has yellow or orange eyes. It also has bristle-tipped feathers on the top of its head which stand straight on end and looks like a head of hair. The roadrunners tail is narrow and as long as its body. The roadrunner can put on the brakes very suddenly by throwing its tail in the air. Or if it wants to change direction, it throws out one wing, turns about quickly, and then starts out again. The foot structure is different from that of other birds. The long sturdy legs have toes that make a track like an 'X'. From the tracks it is hard to tell which direction the roadrunner has gone. This gives them excellent balance in executing ground maneuvers and attributes to their remarkable agility in capturing food.

When running, its body becomes a straight line and it moves like an arrow without any bobbing or weaving. When standing still its head is erect and moves sideways in quick jerks to better see its prey. Its body slopes downward to the rear and wings hang limply, especially in warm weather. On cold days they are folded against its body. Its tail is tilted upward at a 45 degree angle and sways from side to side like a straw in the wind.

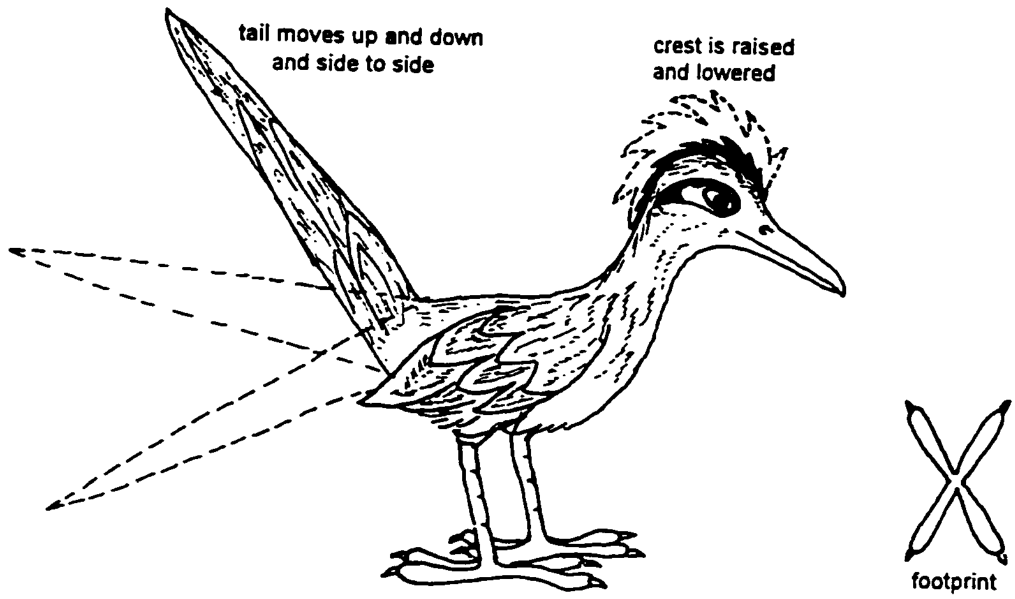


Figure 2.16 The roadrunner

Figure 2.17 The roadrunner builds a cholla prison around the sleeping rattle snake. (Waggin, 1982)

Underneath the feathers, a coarse furlike down enables the roadrunner to endure snow and cold weather. When animated or alarmed, the feathers press close to the body, the neck extends in the direction of flight, the headcrest rises to full height, and the vivid colors behind the eyes gleam in a band about the head. The roadrunner's strong legs flee from danger, and only if pressed or startled does it take wing, gliding for short distances with comparative ease and swiftness.

2.6.1 Adaptive principles of the roadrunner

On cold days you may see the roadrunner **sunning** itself in the warm early morning rays and also just before sunset. With its back to the sun, it holds out its wings and fluffs out its feathers, revealing an area of dark-colored skin that absorbs heat and raises the bird's temperature. This is essential since an internal thermostat permits the body's temperature at night to drop some seven degrees below daytime normals. **Fluffing** increases the insulative layer and reduces the heat loss to the environment or heat gain from the environment.

On the other hand, the roadrunner can stand terrific heat. During the desert summer, you may observe it standing with open beak and panting like a dog, though during the hottest daylight hours it will **seek shade** in trees/brush. **Panting** consists of rapid shallow breathing which greatly increases the ventilation of the upper respiratory tract. In open-mouth panting the countercurrent mechanism of heat conservation may not operate, and the number of breaths per minute is so large that heat loss is considerable.

Roadrunners also reduce their temperature by evaporative cooling, which takes place through the respiratory tract, as they have no sweat glands. **Gular flutter**, or the rapid fluttering of the skin on the ventral surface of the throat, is employed by the roadrunner in what is considered to be an energy-saving means of respiratory evaporative cooling.

Like other birds, roadrunners excrete uric acid rather than urea with a consequent impressive saving in moisture in comparison to mammals. Normal bird temperatures are considerably elevated above those of mammals, being in the 104°-108°F range. Thus the bird is much delayed in starting to build a heat load under high temperatures. Additionally, the birds' body is capable of **storing heat gained**, to the extent of an elevation in body temperature of 4 to 6°F, without ill effect. This stored heat can later be radiated back to the surrounding air as temperatures cool at night. This amount of heat gain is therefore dessipated without loss of costly water.

2.7 JACK RABBITS

One of the most conspicuous animals of the Sonora Desert is the jack rabbit, an animal which in spite of its common name is a hare. Jack rabbits

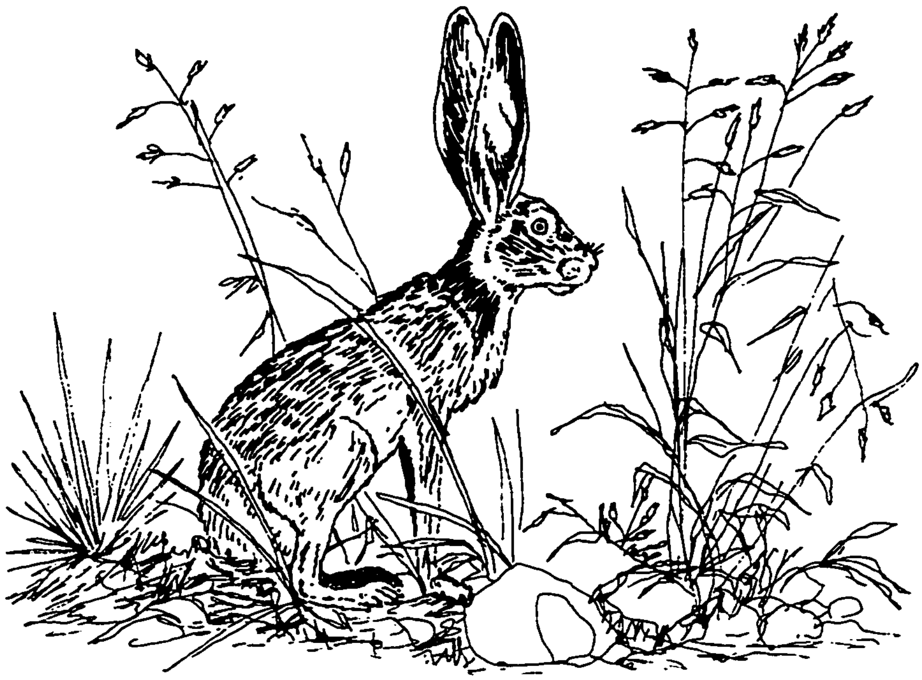


Figure 2.18 The jackrabbit

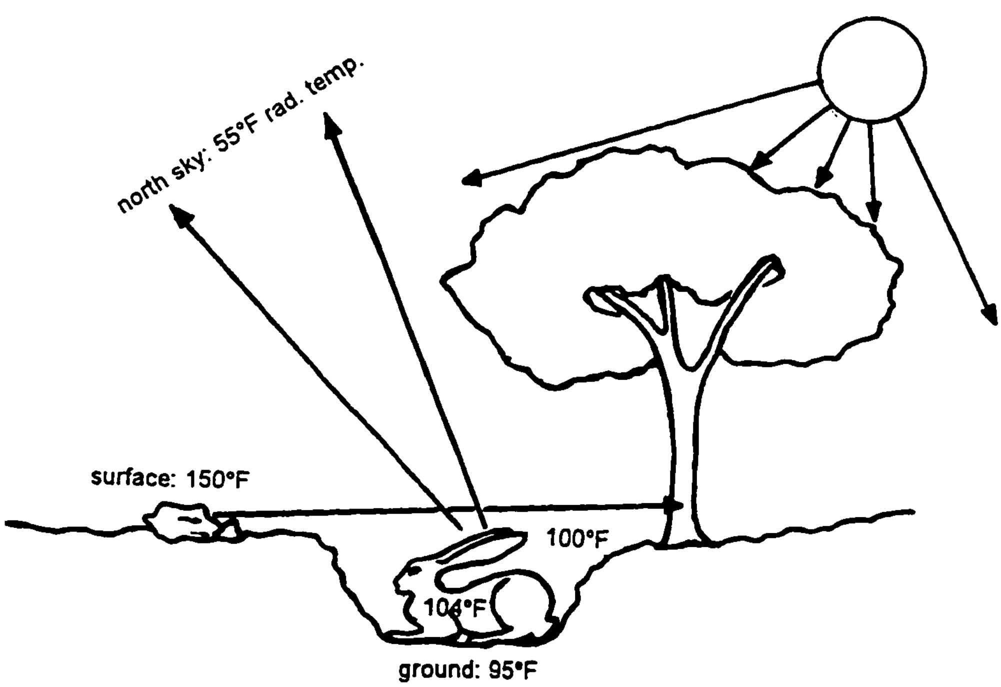


Figure 2.19 Thermal situation for the jackrabbit

(*Lepus alleni*) pretty much blanket the west. Fossils have proved that jackrabbits are among the oldest known land mammals. They are surface dwelling and heat-enduring mammals. They do not have burrows and may be seen in the desert at any time of the day, although on hot days they are more inactive and tend to rest in shade. The most prominent feature of the jack rabbit is its tremendously large ears, which are completely out of proportion, even for a hare.

Jack rabbits eat a fair amount of green and succulent food. After rain, when there is fresh grass, this constitutes the major part of the diet. At other times of the year they eat the green leaves of the mesquite and other shrubs, and during the dry part of the year cactus is of importance as a source of water. Plant eaters, they cannot subsist on dry food alone, but are able to live on vegetation without free drinking water. They rest in shade during the hot days, seeking food nocturnally.

2.7.1 Adaptive principles of the jack rabbit

During the hot season jack rabbits are invariably found in the shade during the day-time, frequently in a depression near a mesquite bush. If they are chased from their resting place they will rapidly run for a short distance and seek out a new place under a bush, behind a rock, or in a depression in the ground. One advantage of sitting in the shade is that the ground and air temperatures in and near desert shrub vegetation is lower than in the open desert. We may have a situation whereby the animal lies resting his form, his ears lie flat, spread along his back, in a slight hollow in the shade on the north side of a bush. The ground surface is never exposed to the sun, and is therefore appreciably cooler than the surface in the open, and even cooler than the day-time air temperature. Its temperature instead approaches the mean air temperature. The radiation from the sun is screened out by the bush, and the re-radiation from the hot desert surface does not reach the animal in the depression. The huge, lightly haired, almost bare-skinned ears will be in radiation exchange with the visible surroundings. In the bush the surface temperatures on the shade side are close to air temperatures, or perhaps a little lower due to evaporation, and in the sky the temperature is assumed to be 25 degrees lower than the ears. These ears display a high reflectivity to light. The blood vessels in the ears are greatly dilated when conditions are propitious for heat loss from the ears to the environment and are severely constricted when the opposite condition prevails (that is , heat gain from the environment).

2.8 DESERT BIGHORN SHEEP

The desert bighorn sheep, *Ovis canadensis*, is one of the largest mammals which inhabits the Sonora Desert. This animal is successful in dealing with the desert environment. Living gregariously, the bighorn sheep primarily inhabit rugged mountain ranges where their jumping and climbing abilities are impressively put to use. These heavy-bodied animals may weigh 150 to 200 or more pounds, are approximately three feet tall at the shoulder, may be upto five feet in length, and are a pale tan in color. The males have immense, curling horns; the females' considerably smaller horns do not curl as impressively as the males'. The desert bighorns are non choosy vegetarians. Living in some of the most desolate and arid areas of the desert these animals generally must have access to free water, at least during certain times of the year, but derive a considerable amount of moisture from their diet. Successful as sheep have been in coping with the desert environment, unfortunately they have not been so successful in their confrontation with man, who has hunted them severely, reduced their access to water sources with agriculture and highways, and released burros which have severely pressured the sheep in terms of water and forage availability.

2.8.1 Physiological characteristics

Water retention and cooling are important to desert animals. The following characteristics may play an important role in the survival of desert bighorn:

- The animals retain their thick pelage during the heat of the summer.
- The rams usually go into the summer with a good amount of fat, presumably in preparation for the rut season.
- The rams may go for 5 to 7 days without water during dry hot weather.
- Studies of the shedding pattern show that hair and wool over the chest is the last to be lost.

- The animals seek shade, higher elevations, cool soil or rocks, and breezes that are cooling.
- They can drink large amounts of water in a short time.
- Their internal organs are adapted to withdraw liquids from their foods and conserve body moisture.
- Three water retention organs (the reticulum in the stomach, the enteric caecum and the colon) in the desert bighorn are enlarged and modified for greater water retention when compared to those same organs in domestic sheep.
- Cooling appears to be achieved mainly by evaporation and by direct conduction to ground and rocks when the animals are in caves or other shades.
- Desert bighorn can withstand changes in body temperature from 102°F to 107°F without apparent ill effect.
- The kidney eliminates excreta with a relatively small amount of water.
- Bighorn can withstand a certain amount of dehydration, perhaps exceeding the 30% weight loss reported in domestic sheep.
- Desert bighorn exhibit a tolerance to heat and water depletion that exceeds the norm for most animals, while showing a decrease in plasma volume that appears to be extreme.

Figure 2.20 The desert bighorn sheep

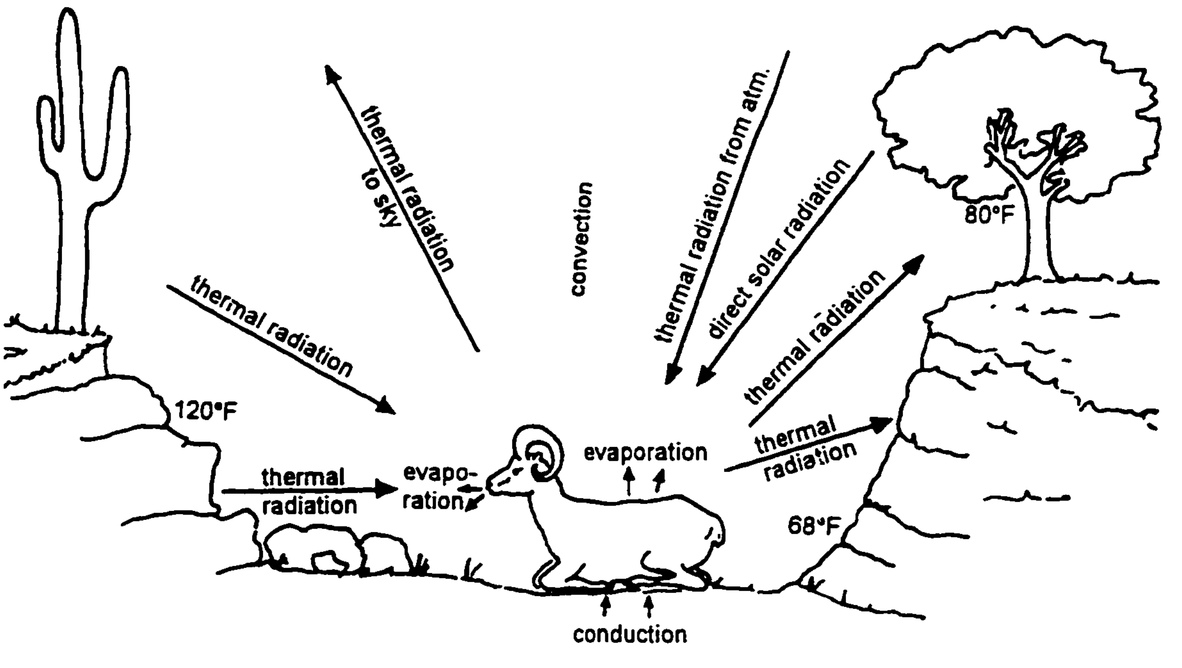


Figure 2.21 Heat exchange for the bighorn sheep

2.8.2 Thermal adaptive principles of the desert bighorn sheep

Sweat glands scattered over the body aid somewhat in maintaining the body temperature. Hair and wool act as **insulation** against heat as well as cold. Heat is also lost through **respiration**, which may be the principal system that regulates body heat in these animals.

The hair exposed to the desert heat acts as a heat shield, preventing an impressive percentage of possible environmental heat gain from reaching the animal's skin. It allows evaporation of perspiration from the skin, but slows this process, preventing a too-rapid wasteful evaporation from taking place. In this regard it acts in a manner similar to man's clothing, which serves the same useful purpose.

Within this "heat shield" certain "windows" occur. These more open areas, largely **without fur** or only lightly haired, are located on the ventral portions of the animal's body. As the bighorn sheep is standing, these areas are directed downward toward the shade formed by its body; heat is thus lost by convection from these body sites to the shade.

2.9 SUMMARY OF ADAPTIVE PRINCIPLES

Saguaro:

- Nurse plant provides protection to the young saguaro in the form of shade in the daytime and warmth in the night.

- Spines cast shadow on the saguaro and help to diminish air currents.
- Bristles surrounding spines function as insulators.
- Rounded nature of stem allows minimal surface area exposed to the sun at any one time.
- Mass of stem allows for an even internal temperature regulation.
- Waxy surface prevents water loss.
- Vertical pleats cast shadows on the plant's surface.
- Ability to shrink in girth, allows more shadows to be cast.
- Avoids cooler northern exposure.

Mesquite:

- Deep tap root obtains moisture from the water table and wide spread lateral roots quickly absorb moisture from rain.
- Leaflets close at night to reduce water loss by transpiration and close during hottest part of day in summer to reduce water loss during photosynthesis.
- During hot parts of day leaves move to orient the narrow edges towards the sun, reducing exposed surface area.
- Ability of the stomata to close during increased vapor pressure deficit, reduces water loss while increasing carbon fixation.
- During summer the cuticle thickness of the leaves increases, thus reducing water loss.

- Provides shelter for other plants and animals by providing shade which affects soil temperature, evaporation and amount of radiant energy impinging on understory vegetation.

Termites:

- Builds underground to minimize effect of diurnal temperature fluctuations.
- Constructs insulating layer around periphery of nest.
- Living close together in large numbers during winter is a device used for maintaining high nest temperatures.
- Different proportions of building materials used controls the humidity content in different parts of the nest.
- Nest is cooled and ventilated by induced convection currents.

Horned lizard:

- It basks in the sun to raise body temperature.
- Can vary its coloration; dark for increased heat absorption and light for less heat absorption.
- Tilts its body and turns its back towards the sun in order to increase the angle between the rays of light and the lizard's body, bringing about a faster rise in body temperature.
- Increases efficiency of solar heating by spreading its ribs and pulling them forward to increase the area exposed to sunshine.
- Seeks shade to dessipate excess heat.

- Burrows under cooler subsurface soil.
- Heat is also dessipated by panting, initiated by increased respiratory movement.
- Water is harvested on its broad back.

Roadrunner:

- Dark colored skin under wings absorbs heat when sunning.
- Fluffing of feathers increases insulative layer and reduces heat loss or gain to or from the environment.
- Seeks shade during hottest part of day.
- Heat loss by open-mouth panting.
- Employs respiratory evaporative cooling by gullar flutter.
- Its body is capable of storing heat and later radiating it back to the surrounding air as temperatures cool at night.

Jack rabbit:

- Seeks shade in a depression near a tree where temperatures are considerably lower than air temperatures.
- The large ears have blood vessels that are greatly dilated as heat is radiated to the environment and severely constricted when heat gain is required.

Bighorn sheep:

- Evaporation of sweat somewhat aids in maintaining body temperature.
- Wool acts as insulation against heat and cold.
- Heat is also lost through respiration.
- Heat is lost by convection from the lightly haired ventral portion of the sheep's body to the shade cast by it.
- Cooling by conduction to the ground and rocks occur when it is resting in caves or other shades.

A wide range of plant and animal life in the Sonora Desert have undergone evolutionary changes in numerous ways in order to adapt effectively to the climate, both physiologically and behaviorally for their survival, to encertain that their specie may continue to live.

CHAPTER 3:

THE HUMAN ELEMENT

Man is the most intelligent of creatures, but like all living things he is highly sensitive to his physical surroundings, so much so that both natural and man-made environments have a great impact on his productivity and well-being. Adverse weather conditions diminish health and productivity in man. Although some reactions of a human being to a given physical setting may be labeled psychological, there are often physiological bases for such behavior. For instance, although working in an office without windows can have a negative psychological effect on an individual, his low spirits may well be due in part to the physical and psychological effects of poor lighting and inadequate ventilation.

3.1 MAN IS A TROPICAL ANIMAL

A distinguished biologist, Peter Scholander, coined the phrase - 'man is a tropical animal' -many years ago. He was emphasizing that man almost certainly originated in East Africa in a hot, possibly rather dry, savannah environment, conditions for which man is well adapted. He is extremely well-endowed with sweat glands and has more than any other mammal; because of the ability to sweat at a high rate man can obtain body temperature in hot climates without difficulty. Though, there is a price to pay, requiring the replacement of water and salt lost. Man is also almost hairless, which is not a great advantage in any climate but is less of a disadvantage in hot climates than it is in cool or cold regions. If man were to live naked and maintain a body temperature close to 98.6°F he must have a climate where the temperature is of the order of 82-86°F. Otherwise he has to have artificial means of insulation from the environment or suffer the discomforts and physiological cost of increasing heat production by shivering, or by active muscular movements. For all of these and many other reasons, man has the characteristics of a tropical animal.

Although man can penetrate and sometimes prosper in deserts, he does so only because of cultural adaptations -he depends on water that he brings with him or obtains by digging or drilling. It is man's technological culture, not his physiology, that permits him to live there.

3.2 MAN AND ARCHITECTURE

It is said that architecture lives in 3-dimensional space -"lives" because that space, designed and built by man, also includes man himself -his comings and goings, his actual presence -throughout time and in ever-changing patterns (Bennett, 1977). Man himself, therefore, is the quality peculiar and unique to architecture, the dimension that distinguishes architecture from all other arts. It is man who calls forth the kinds of spaces he needs, desires and enjoys. It is man who by his actions becomes part of buildings, moving about, around and inside them.

Architecture creates for man a second skin. It is revealing that the word "house" often symbolizes "body" in the Bible and some other spiritual and religious writings.

3.3 MAN AS THE THERMAL MACHINE

It is understood but perhaps not always remembered, that the first "thermal machine" is man: he transforms chemical energy into mechanical energy with the accompanying dispersion of heat (metabolism). One could even assert, in a certain sense, that all the bioclimatic story of architecture is the story of how man has sought to meet the need of his body to remain at an approximately constant temperature, no matter the temperature of the external environment. Eating, muscular activity, sweating and clothes are, as physics explains, various natural or artificial means used by man to maintain the equilibrium of his thermal machine. Viewed this way, the habitation itself is - or should be - the most complete and intelligent "clothing", good for all seasons (ENEA, 1983).

The thermal difference between the exterior and interior conditions of the building, and the requirements for internal thermal comfort constitute the basic problem. The greater the difference, the more difficult is the job of the designer who wants to achieve a thermal comfort level with a minimum of energy consumption.

Obviously, external conditions vary from site to site and in time; consequently, an 'ideal bio-climatic building' should be able to react to those conditions by absorbing a maximum of solar energy during daytime in winter, while releasing as little as possible heat. On the other hand, during summer the same building should reject the solar radiation and disperse as much heat as possible.

Man's first environmental problem was to shelter and protect himself physically against both the elements and other animals and men. Primitive man did this in two ways, either by finding ready-made shelter in the form of caves, or by constructing little shelters or huts out of available materials. In some areas the huts were made of trees or reeds. In other areas, where stones were available, these were piled up to form little dwelling of a different type. Other groups of people learned to make simple frames and cover them with thatch, animal skins, or bark, thus producing tents or teepees. In the Arctic, people constructed igloos out of the only available material, ice. These various forms of shelter could be called the first "architectural styles". They were all intended to solve the same need and to express the same idea - that of providing physical protection in the simplest possible way. However, the reason a stone hut, a native American teepee, and an Eskimo igloo all look so different is that each is made of entirely different material and located in different bioclimatic regions.

A re-examination of the primitive building technique is a practical journey, seeking to strip architecture of preconceived vocabularies, to determine timeless principles, not by imitation of nature, but through a greater understanding of the inner workings of nature.

For researchers and designers of architecture intended to fit its climate there are many lessons to be derived from the study of indigenous architecture. Especially where extreme climates have stretched human ingenuity we may find appropriate models to address today's problems. We should have no illusions of returning to the folk culture that through time developed local traditional architectural expressions including climatic response. But there are many concepts that may be useful and even necessary in an industrial and post-industrial society that is now searching for models of sustainability (Jeffery Cook, 1994).

3.4 EVOLUTION AND VERNACULAR ARCHITECTURE

Architecture is considered one of the "arts" or human created artifact. Human invention, from shelter through civilization, can be traced to its roots of inspiration from natural sources. At the origin of human artifact for shelter, nature was the singular, tangible, inspirational model. The architectural concept of the primitive hut explains how the theoretical beginnings of architectural form and function are based upon nature and motivated by necessity.

"Vernacular architecture does not go through fashion cycles. It is nearly immutable, indeed unimprovable, since it serves its purpose to perfection" (Rudofsky, 1964).

Not only do our surroundings affect us, but we can affect and control them. Man is the only animal that can adapt his environment to his needs. While giraffes have developed longer necks with which to reach and be able to eat tree leaves, we have developed shorter fruit trees and ladders to simplify the problem. Whereas polar bears developed heavier fur coats, we developed clothing, shelter and heating systems.

The cultural evolution of the human race has occurred through artificial selection, invention, and adaptation. Architecture as a human creation has also evolved. Vernacular traditions are an example of 'evolution' in architectural design. Examination of these traditions and 'taking them to the next higher level' of development is an architectural evolution analogy. Through evolutionary process, layers of meaning and symbolism have been applied to the original concept of the need-based dwelling

3.5 ENERGY AND WATER BALANCE IN THE SONORA DESERT

The Sonora Desert is the classic example of a thermally extreme climatic environment.

As a result of the lack of moisture, and the concentration of heat in the uppermost sand layer, the daytime surface temperature of the desert is high. The nocturnal temperature profile over and beneath the surface of a desert is similar to that above bare soil. As the surface cools an inversion develops and the lower levels become stable. The relatively unrestricted radiative cooling often causes temperatures to drop markedly, and in terms of human comfort the Sonora desert distinctly becomes a cold environment at night.

Thus another important feature of the desert is its large diurnal range of temperature. At weather screen height of 5 feet the diurnal range is commonly 40°F, and has been found to be as great as 56°F at Tucson, Arizona. At ground surface the range may even approach 80°F (Oke, 1987).

Plants and animals able to survive such extreme thermal shifts usually exhibit physiologic /behavioral adaptations. Humans feel overheated by day and chilly at night. During a really hot day in the Sonora Desert, a man may produce as much as 12 liters of sweat, giving an average rate of over a liter per hour.

3.6 THERMAL COMFORT OF MAN

The subject of thermal comfort is not only of physiological interest but is of practical importance in specifying and providing satisfactory conditions inside the built environment.

The concept of comfort is an abstract one which does not coincide with any specific physiological sensation. Thermal comfort zone can be defined as a thermal condition within which little or no effort is needed for the human body to adjust to the surrounding environmental conditions. In a state of thermal comfort we are generally unaware of any temperature sensation and there are no parts of the body feeling either too hot or too cold.

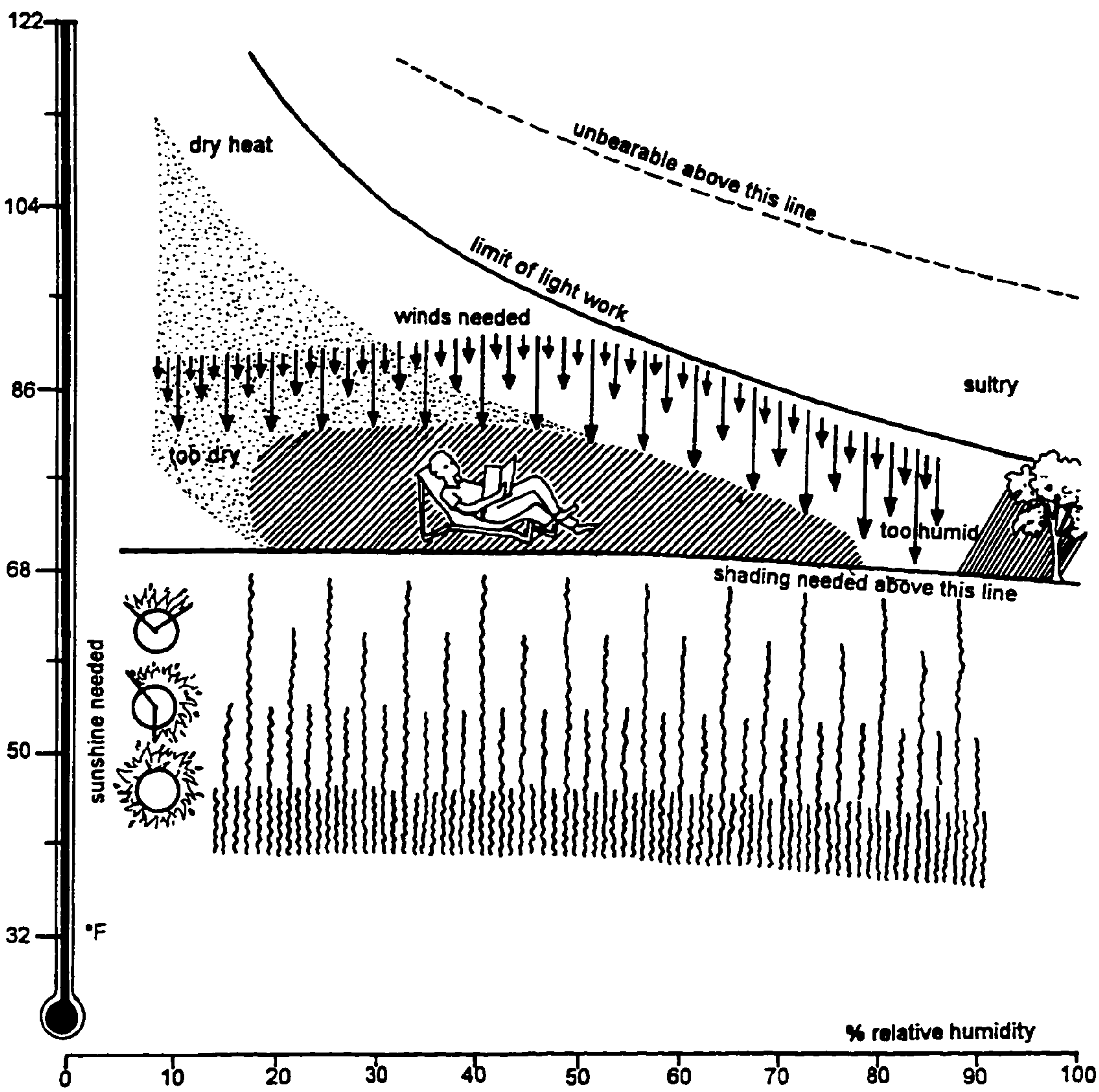


Figure 3.1 Schematic diagram of Victor Olgyay's bioclimatic chart

There are a number of physiological factors which affect thermal comfort. Our sensations are primarily determined by the skin and deep body temperatures, which are both sensed in the hypothalamus. It is here that the temperature regulating center uses the information to control the various mechanisms of heat loss and heat gain. Both skin and deep body temperatures give rise to sensations in the sensory cortex; however, we are not in general aware of our deep body temperature unless it is changing fairly rapidly, although this temperature comes into our overall appreciation of thermal appreciation and comfort.

3.7 TEMPERATURE REGULATION IN MAN

Man has to maintain a constant body temperature close to 98.6°F, and this is achieved even with wide variations of climatic conditions and of the heat produced in the body. All the tissues of the body are metabolically active; they consume oxygen and produce carbondioxide and water as the end result of complex chains of chemical reactions.

3.7.1 Heat balance

A heat balance has to be maintained between production and loss. The heat produced by metabolism (M) equals heat loss by evaporation (E), convection (C), conduction (K), and radiation (R), and a positive or negative storage (S) according to excess heat loss or heat gain (see figure 3.2).

$M = E \pm C \pm K \pm R \pm S$

Metabolic rate. The total sum of all the chemical reactions in the body is exothermic; that is, heat is released. The overall rate of these reactions is termed the metabolic rate and is usually expressed in terms of units of heat. The metabolic rate varies with activity, essentially muscular activity. The maximum rate which can be achieved depends on the individual and his muscular development and training. Most people have at least ten-fold range of oxygen consumption or heat output between rest and the hardest physical work of which they are capable.

Evaporation. Heat is required to convert water into water vapor. At rest, heat is lost from the surface of the body by the evaporation of water passing through the skin in what is know as insensible perspiration. Skin, which separates the tissues of the body with their high water content from air, is remarkably waterproof. Water vapor is also lost in the expired air. These two sources of heat loss by evaporation are not controlled in man by the temperature regulating system. The important role of evaporation in temperature regulation is the evaporation of sweat, produced from the sweat glands in the skin.

Convection. Heat is lost by convection in the same way in which any hot body loses heat: the air in contact with the surface of the body is warmed, becomes lighter and so rises to be replaced by cooler air. The temperature of the rate of blood flow through it can be regulated by changing the diameter of the blood vessels to the skin, constricting or dilating them. The amount of heat lost by convection will depend upon the temperature difference between the skin and the air, and also on the rate of air movement. Heat can be gained by convection when the air temperature is higher than skin temperature; the heat gain will increase as the air movement increases.

Conduction. Heat loss or gain due to the direct conduction of heat by contact with a solid body at a temperature above or below skin temperature is of relatively little importance in the heat balance of the body. Contact is usually limited to the feet with the ground.

Radiation. The phenomenon of thermal radiation forms part of the electromagnetic spectrum. The wavelengths concerned range from the visible spectrum (short-wave radiation) to the long-wave infra-red radiation, which is invisible to the human eye. The exchange of heat by radiation between two objects is not affected by air temperature or air movement but depends upon the difference in surface temperature of the two objects. As heat loss or gain depends upon surface temperature, there is some physiological control of this channel since skin temperature can be varied by altering the rate of blood flow through it. The individual sitting at rest in a room will radiate heat to those surfaces of the room which are at a lower temperature than their own surface, clothed or bare.

Storage. If heat loss and heat production are not equal, then the human body either gains or loses heat. Even with the body resting, heat production is not constant; someone sitting in a chair will make variable movements, turning his head, moving his hands, so changing heat production. The rate of blood flow through the skin is not constant, but varies, and hence heat loss varies. It is a dynamic equilibrium.

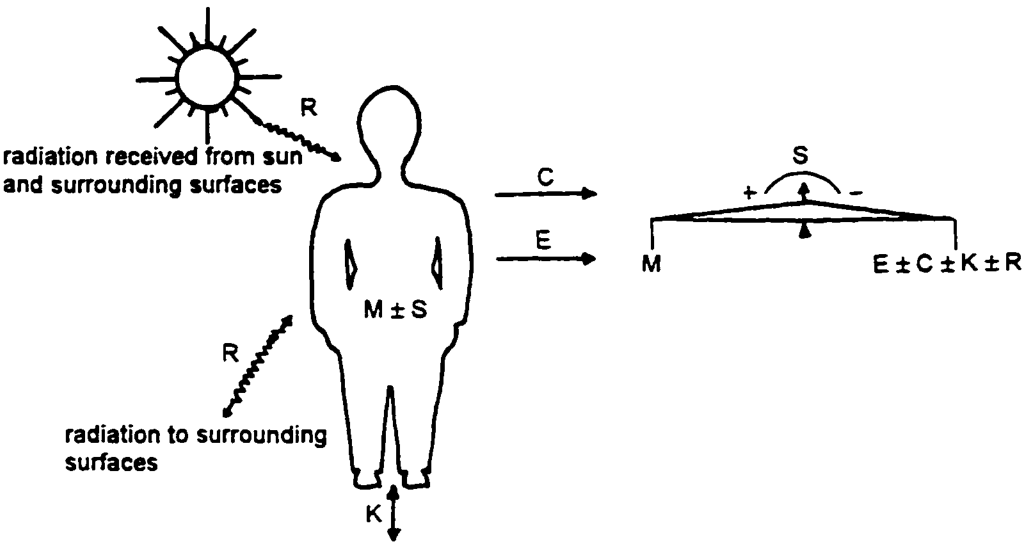


Figure 3.2 Channels of heat flow to and from the human body

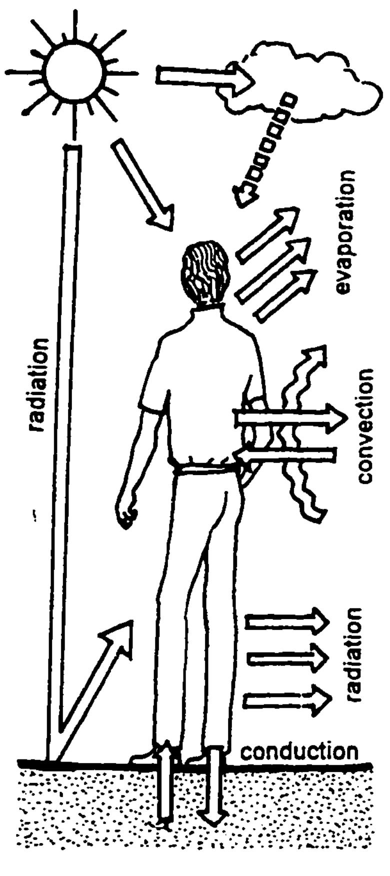


Figure 3.3 Thermal exchange between human body and its environment

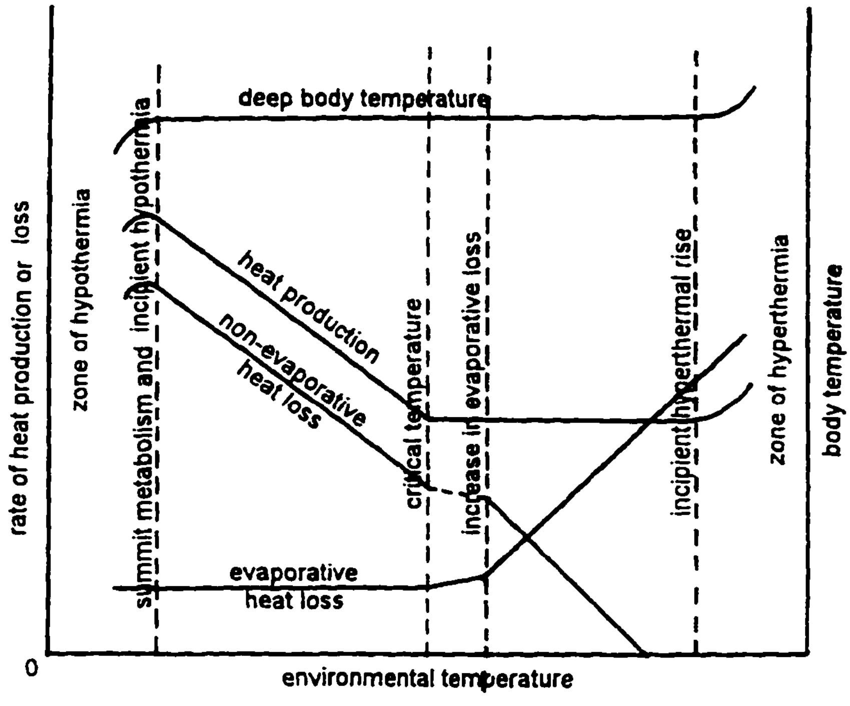


Figure 3.4 Diagrammatic representation of relations between heat production, evaporation and non-evaporative heat loss and deep body temperature in man. (Stanier, 1984)

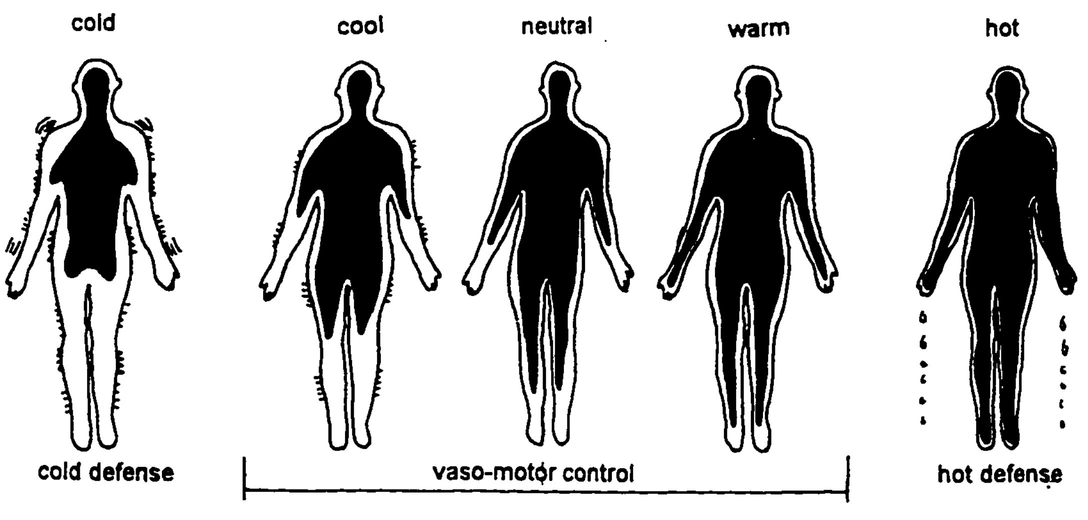


Figure 3.5 Representation of the size of the central constant temperature 'core' in conditions ranging from hot to cold. (Clark, 1985)

3.7.2 Body temperature

The usual statement about body temperature of man is that it is maintained at 98.6°F or close to this level. However, there is a temperature difference between deep tissues and the surface of the body, heat flowing down a gradient to the skin and hence by convection, or evaporation, to the air surrounding the body and by radiation to surfaces 'seen' by the body. In a state of thermal comfort skin temperature will be between 91-93°F; there is a moderate steep gradient until a temperature of approximately 98.6°F is reached at a depth of about an inch in the vital 'core' of the body.

3.7.3 The regulation of body temperature

The concept of a constant body temperature is not strictly accurate, even when 'body' means the core. It is quite easy to raise body temperature to 100°F, by having a hot bath, but it is not so pleasant to increase body temperature much higher. However, energetic muscular exercise can increase body temperature to 102°F or even higher. The increase in body temperature with exercise is proportional to the oxygen consumption involved, which means the amount of muscular activity and hence the quantity of heat produced.

3.7.4 The effector mechanisms

The skin of the body has many functions, one being temperature regulation. The word 'skin' includes the structure in the skin such as blood vessels, sweat glands, hairs and sensory nerve endings.

Blood vessels. The amount of blood flowing through the blood vessels of the skin affects the temperature of the skin. When there is no blood flow the surface of the skin will come close to the temperature of the surrounding air; as flow increases skin temperature rises rapidly, but gradually levels off as maximal blood flow is reached. Blood temperature cannot exceed body temperature.

Sweat glands. The sweat glands are situated in the deeper layers of the skin, in the dermis, and sweat secreted by each gland reaches the surface of the skin via a tube or duct. The passage of impulses is controlled by the temperature regulating centers; sweat rate is precisely regulated in terms of heat balance.

The hairs. Fur is most important in animal temperature regulation, as air is trapped between the hairs; since air is a poor conductor of heat, heat loss from the body surface is diminished. The thicker the layer of hairs, the greater the layer of insulation and the effective thickness can be increased by altering the angle of the hair to the skin. There is a small muscle attached to the root of each hair, and when this contracts the hair stands up. In man this mechanism persists, and in cold conditions the muscles contract, giving the puckered appearance called 'goose-flesh'. The effect of this mechanism on heat loss in man is very small.

Nerve endings. There are a variety of sensory nerve endings sensitive to touch, temperature and pain. These nerve endings are highly specialized in the sense that sensations of hot and cold are only obtained when specific nerve endings are stimulated.

Muscles and shivering. There is also control of heat production, primarily by alteration of muscular activity. Shivering is a specialized form of muscular activity which is evoked by cooling the body. The usual way by which muscles contract and relax results in a smooth movement. Shivering consists of an uncoordinated pattern of activity in which groups of muscle fibers within a muscle contract and relax out of phase with each other. Apart from the use of muscles in shivering, muscular activity is the main variable in heat production. Such activity can play a part in temperature regulation when behavioral responses are examined. In cold weather most people walk briskly, in warm weather they stroll.

3.8 MAN'S ADAPTATION TO THE SONORAN DESERT

Perhaps the main physiologic difference between man and other forms of life relates to man's erect posture, lack of significant insulating coat and the extent to which he employs sweating as a means of cooling. In terms of distinctive behavioral practices the provision of elaborate means of insulation (clothing) and shelter (housing) are the most notable.

The human body has two main **physiologic** means of combating increasing heat load. Initially it can decrease internal insulation by dilating blood vessels in the skin. The increased blood flow to the periphery causes the skin temperature to rise, thereby increasing the skin-to-air temperature gradient, and aiding non-evaporative loses, but this is limited to skin temperatures below 95°F.

The second most powerful response is to increase evaporative cooling by sweating. Below 77°F evaporative cooling is due to losses from the lungs, and by diffusion through the skin, but above 82°F true sweating occurs wherein water is excuded onto the skin, and then evaporated.

The main **physical** feature of humans to help in minimizing heat gain is his erect posture. At the times when solar radiation is most intense the body presents its smallest area.

The primary thermoregulatory role of **clothing** is insulation (that is, giving a greater peripheral thermal resistance). In cold climates it prevents heat loss from the body and in hot climates excess heat gain. As with an animal's coat the degree of insulation depends upon the structure of the clothing, including not only its thickness but also the amount of air it encloses. The insulating quality is also dependent upon the amount of moisture contained, and the wind speed. If the clothing becomes wet, either as a result rain or snow, or by perspiration, the thermal resistance drops sharply.

In hot, dry climates clothing remains important but mainly to provide body shade, and to reflect solar radiation. The fabric should be closely-woven to prevent radiation penetrating to the skin, yet thick enough to provide some insulation against conductive gains. All clothes must be loose thereby allowing sufficient circulation for sweating (Oke, 1987).

3.9 THERMAL BALANCE IN THE BUILT ENVIRONMENT

Whatever heating system is used, from coal fire to air-conditioning, the building itself is critical for the success or failure of the system. Heat is lost from external surfaces; most is lost by convection, some by conduction to the ground on which the building is constructed, and some escapes through chimneys and open windows. Heat loss from buildings is obviously affected by climatic conditions, including wind, which has become more important with the construction of high-rise buildings.

The two essential features of the building which affect heat balance with external conditions are the thermal capacity and the thermal insulation. Light-weight buildings, for example thin concrete slabs with wood and glass, heat up quickly and cool down quickly. Heavy-weight brick or stone buildings take much longer both to heat and to cool. These differences are due to contrasting thermal capacities of the two types of building. Thermal insulation depends both on the materials used in the construction of a building and on its design. It is quite possible to design a light-weight building with good thermal insulation by utilizing the low thermal conductivity of still air. The light-weight materials can be separated by an air gap of about a centimeter; this will ensure that there is little or no air movement due to convection, and will provide effective insulation.

Solar radiation affects buildings, most of all by the glass-house effect of windows. Glass excludes the shortest waves, ultraviolet, but long waves also are not transmitted. The greater part of the energy in sunlight is transmitted, warms surfaces inside the room which in turn re-radiate, but at wavelengths which cannot penetrate glass. This is the origin of the glass-house effect, and accounts for the uncomfortable conditions which can be experienced inside buildings with extensive areas of windows. The glass-house effect is an energy trap; radiant energy can enter but not escape.

Glass has another characteristic, a fairly high thermal conductivity. The effect of this is that in the absence of sunlight the surface temperature of a glass window on the inside will be close to the outside air temperature. Hence, any one inside will lose heat by radiation to the glass surface.

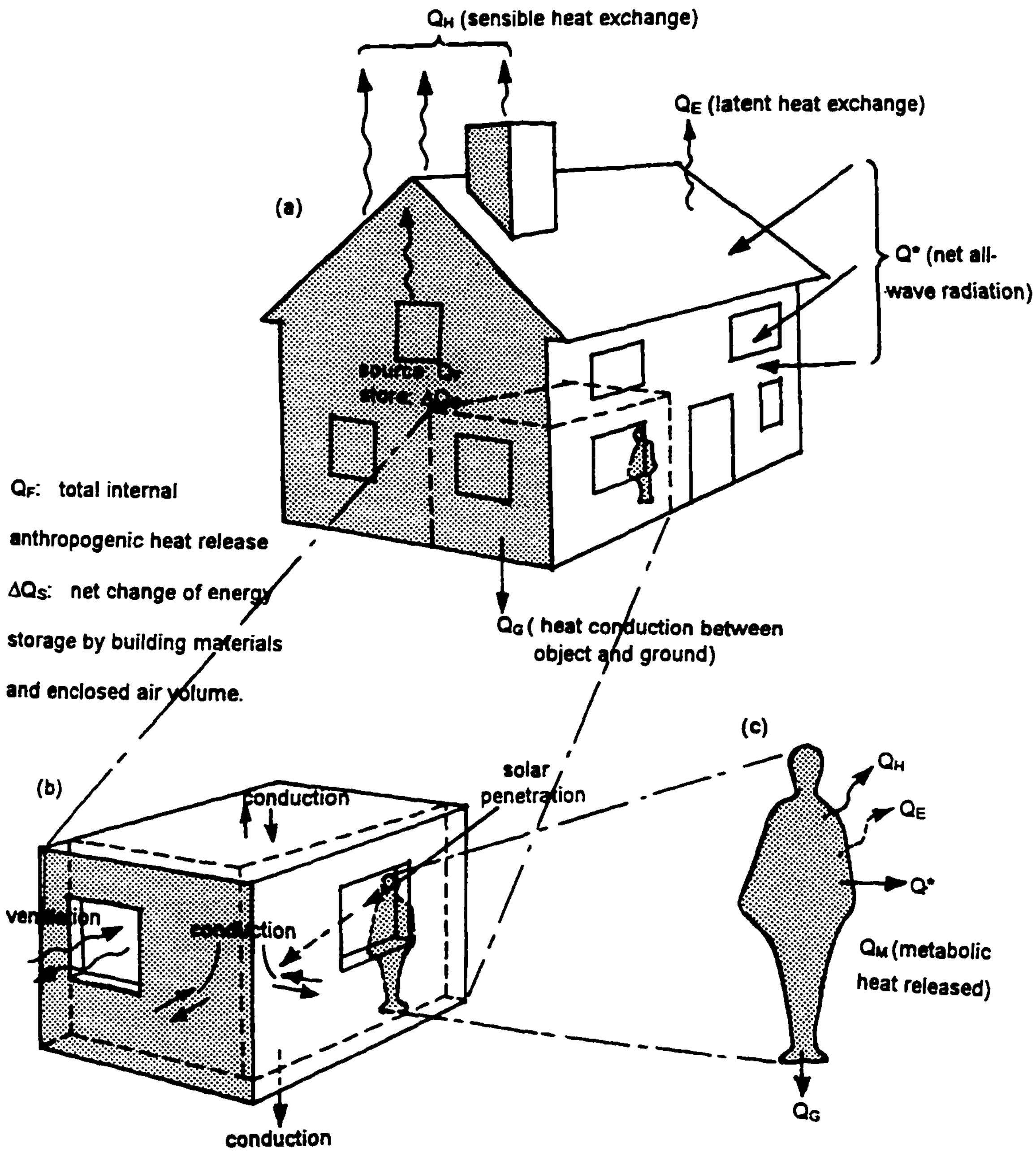


Figure 3.6 Schematic depiction of the fluxes involved in the energy balance of (a) a complete building volume, (b) a room in a building, (c) a person in a room. (Oke, 1987)

During hot seasons fans are used to increase air movement. In the absence of any devices for promoting the movement of air, and assuming there is no effect of wind, air will be almost still, about 0.05 ms^{-1}. Air movement only becomes perceptible at speeds of 0.2 - 0.25 ms^{-1}, and in a hot room speeds up to 0.5 ms^{-1} are increasingly comfortable. At greater speeds, papers on a desk will flutter and may be blown on to the floor. The effect of air movement on thermal comfort will depend on air temperature and humidity. If the air temperature exceeds body temperature then moderate air movement up to 0.5 meters per second increases thermal comfort by increasing the evaporation of sweat and heat loss by convection. But at high air speeds the body will gain heat from the hot moving air, and this heat gain will more than balance the increased heat loss from the evaporation of sweat.

Cooling the indoor atmosphere is not too difficult in a hot, dry, typically desert climate where the evaporation of water can lower air temperature, and a variety of techniques have been developed in different parts of the world. Before air-conditioning, architects dealt with this problem by building houses with massive insulation, usually by having very thick walls, small windows and high ceilings to help keep the buildings cool. Other features included building round a central courtyard so providing shelter from the sun, and constructing chimneys for warm air to escape, bringing in cooler air at ground level as well as providing an effective means of air movement. It is important to shade outside walls of a building in a hot climate with high levels of sunlight. This can be done by planting trees or shrubs or erecting permanent screens. These are particularly effective if they shade the east and west walls of the building which are exposed to morning or evening low-level sunlight. It is only now being realized that many features of traditional architecture in hot countries were both effective and attractive, as compared with imported western architecture.

The techniques of air-conditioning involve the provision of air in sufficient volume at a desired temperature and humidity. The air has to be distributed throughout the building, using ducts to deliver air and remove air. Amongst other problems, there are many difficulties in designing a system for delivering air to and removing it from a particular room to ensure that the conditioned air is properly distributed, without any uncomfortable draughts or regions of dead air and with a minimum of noise. Since there are individual differences regarding preferred conditions, most people want to have some control, by opening or closing windows, changing thermostats or putting up screens.

Since warm air rises it is not surprising to find that there is normally a gradient of temperature from floor to ceiling, which may be as much as 20°F over a height of 10 feet during a cold winter. Occupants would have cold feet and a hot head, which is an unpleasant combination. A gradient of 6-8°F is, in general, associated with comfort. When there is likely to be considerable variation in the number of people in a room, a high ceiling provides greater comfort, since hot air accumulates at levels above head height.

There are many problems associated with the thermal control of the built environment. Some have been solved, but it is a field of research which will continue for a long time, since the problems change with alterations in expectation and demand.

3.10 SUMMARY OF ADAPTIVE PRINCIPLES

- Evaporative cooling by sweating helps in maintaining body temperature.
- Non-evaporating cooling by dilating blood vessels in the skin helps in releasing excess heat.
- Erect posture of man presents smallest area when solar radiation is most intense, thereby minimizing heat gain.
- Shivering provides temporary / emergency heat production in the body.
- Hair acts as insulation against heat and cold.
- Clothing provides additional insulation against heat and cold.
- Construction of buildings provides maximum flexibility for insulation against heat and cold, and also protection against other natural elements like wind, rain, etc.

CHAPTER 4

SYNTHESIS OF CASES

4.1 INTRODUCTION

The synthesis of biological principles and architecture involves the determination of the objectives and technics which are common to both. This chapter synthesizes the information gathered in the previous chapters to arrive at a basis for comparison that shows the general biological principles of the eight selected life forms in the Sonora Desert, with its translation into architecture. The case studies that follow have been chosen from the Sonora Desert and demonstrate the architectural synthesis of the biological principles.

4.2 ADAPTIVE PRINCIPLES OF EXAMPLES UNDER STUDY

The biological adaptive principles derived in chapters two and three are listed below. The life forms are numbered from 1 to 8 and their subsequent principles lettered from a to i. This numbering is used in the summary of the adaptive principles to group the like principles together.

1 Saguaro:

1a Nurse plant provides protection to the young saguaro in the form of shade in the daytime and warmth in the night.

1b Spines cast shadow on the saguaro and help to diminish air currents.

1c Bristles surrounding spines function as insulators.

1d Rounded erect (columnar) nature of stem allows minimal surface area exposed to the sun at any one time.

1e Mass of stem allows for an even internal temperature regulation.

1f Waxy surface prevents water loss to the surroundings.

1g Vertical pleats cast shadow on the plant's surface.

1h Ability to shrink in girth, allows more shadows to be cast when needed.

1i Avoids cooler northern exposure.

2 Mesquite:

2a Deep tap root obtains moisture from the water table and wide spread lateral roots quickly absorb moisture from rain.

2b Leaflets close at night to reduce water loss by transpiration and close during hottest part of day in summer to reduce water loss during photosynthesis.

2c During hot parts of day leaves move to orient the narrow edges towards the sun, reducing exposed surface area.

2d Ability of the stomata to close during increased vapor pressure deficit, reduces water loss while increasing carbon fixation.

2e During summer the cuticle thickness of the leaves increases, thus reducing water loss.

2f Provides shelter for other plants and animals by providing shade which affects soil temperature, evaporation and amount of radiant energy impinging on understory vegetation.

3 Termites:

3a Builds underground to minimize effect of diurnal temperature fluctuations.

3b Constructs insulating layer around periphery of nest.

3c Living close together in large numbers during winter is a device used for maintaining high nest temperatures. The population is more spread out in the summer to reduce chances of heat accumulation.

3d Different properties of building materials used controls the humidity content in different parts of the nest.

3e Nest is cooled and ventilated by inducing convection currents.

4 Horned lizard:

4a It basks in the sun to raise body temperature.

4b Can vary its coloration; dark for increased heat absorption and light for less heat absorption.

4c Tilts its body and turns its back towards the sun in order to increase the angle between the rays of light and the lizard's body, bringing about a faster rise in body temperature.

4d Increases efficiency of solar heating by spreading its ribs and pulling them forward to increase the area exposed to sunshine.

4e Seeks shade to dessipate excess heat.

4f Burrows under cooler subsurface soil.

4g Heat is also dessipated by panting, initiated by increased respiratory movement.

4h Water is harvested on its broad back.

5 Roadrunner:

5a Dark colored skin under wings absorbs heat when sunning.

5b Fluffing of feathers increases insulative layer and reduces heat loss or gain to or from the environment.

5c Seeks shade during hottest part of day.

5d Heat loss by open-mouth panting.

5e Employs respiratory evaporative cooling by gullar flutter.

5f Its body is capable of storing heat and later radiating it back to the surrounding air as temperatures cool at night.

6 Jack rabbit:

6a Fur acts as insulation against heat and cold.

6b Seeks shade in a depression near a tree where temperatures are considerably lower than air temperatures.

6c The large ears have blood vessels that are greatly dilated as heat is radiated to the environment and severely constricted when heat gain is required.

7 Bighorn sheep:

7a Evaporation of sweat somewhat aids in maintaining body temperature.

7b Wool acts as insulation against heat and cold.

7c Heat is also lost through respiration.

7d Heat is lost by convection from the lightly haired ventral portion of the sheep's body to the cooler shade cast by it.

7e Cooling by conduction to the ground and rocks occur when it is resting in caves or other shades.

7f During the summer months the bighorn sheep moves to regions of higher and cooler elevations to avoid heat, and moves to regions of lower elevations during winter to avoid the cold.

8 Man

8a Evaporative cooling by sweating helps in maintaining body temperature.

8b Radiative cooling by dilating blood vessels in the skin helps in releasing excess heat.

8c Erect posture of man presents smallest area when solar radiation is most intense, thereby minimizing heat gain.

8d Shivering provides temporary / emergency heat production in the body.

8e Hair acts as insulation against heat and cold.

8f Clothing provides additional insulation against heat and cold.

8g Construction of buildings provides maximum flexibility for insulation against heat and cold for the human body, and also protection against other natural elements such as wind, rain, etc.

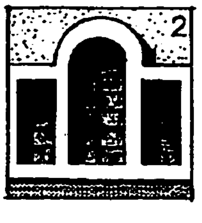
4.2.1 Summary of adaptive principles derived

The above 50 principles derived from the selected life forms found in the Sonora Desert can be further summarized into 20 principles by grouping the like / similar principles together. These strategies are categorized under five group headings, namely; shade/shadow, insulation, water, active thermal and movement, and listed below. An icon has been developed for each biological principle which represents its equivalent in the field of architecture, as practiced by man. These principles have further been summarized into the comparative table that follows the summary.

I. Shade / shadow

1.  *As exhibited by: 1a, 2f, 4e, 5c, 7d*

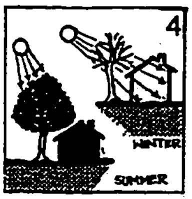
Seek shelter to dessipate heat by: casting its own shadow or seeking shade provided by other natural elements.

2.  *As exhibited by: 1b, 1g*

Elements cast shadow onto the surface of the subject itself.

3. *As exhibited by:* *1d, 8c*

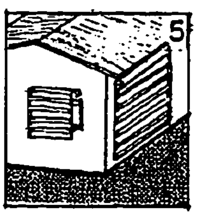
Smallest surface area of the subject is exposed to the sun when solar radiation is most intense.



4. *As exhibited by:* *1h, 4d*

Ability to control amount of radiation received by: shrinking of the subject to cast more shadow on its surface or increase area exposed to the sun to increase solar heating.

II. Insulation



5. *As exhibited by:* *1c, 3b, 5b, 6a, 7b, 8e*

Outer layer of subject provides insulation against heat and cold.

6. *As exhibited by:* *1f, 2e, 8f, 8g*

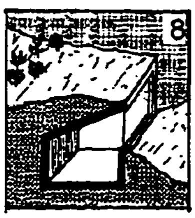
Additional insulative material used on periphery, as and when required.

7.

As exhibited by: *1i*

Avoids exposure to the freezing north breeze by flourishing on southern slopes of mountains.

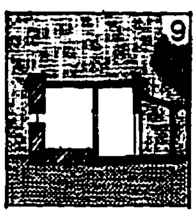
8.



As exhibited by: *3a, 4f, 6b, 7e*

Partial or full subterranean shelter.

9.

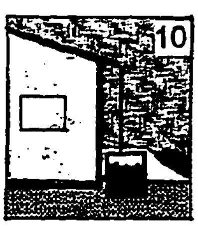


As exhibited by: *3d.*

Use of building materials with differing properties as and where needed.

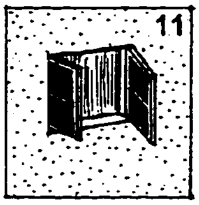
III. Water

10.



As exhibited by: *2a, 4h*

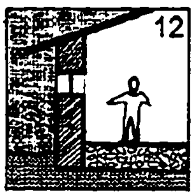
Harvesting water from all available sources.

11. 

As exhibited by: *2b, 2d*

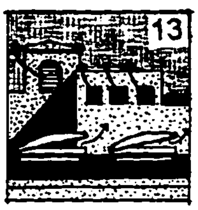
Elements close to reduce waterloss and open for exchange of gases.

IV. Active thermal

12. 

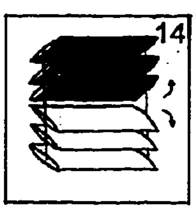
As exhibited by: *1e, 5f*

Body stores heat in daytime and radiates it back at night.

13. 

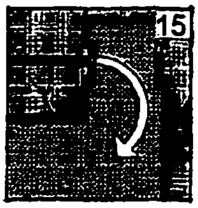
As exhibited by: *3e*

Cooling and ventilating by inducing convection currents to pass through building structure.

14. 

As exhibited by: *4b, 5a*

Exposure of dark color for increased heat absorption and light color for less heat absorption or reflection of heat.

15. 

As exhibited by: *4g, 5d, 5e, 7a, 7c, 8a*

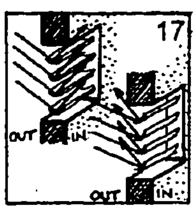
Evaporative cooling through respiratory system or skin surface.

16. 

As exhibited by: *6c, 8b*

Radiative cooling from circulatory system.

V. Movement

17. 

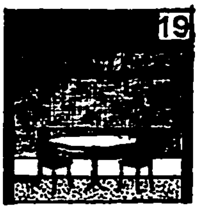
As exhibited by: *2c, 4c*

Ability to move element to change the incident angle of the sun by: orienting narrow edges towards the sun to reduce exposed surface area or tilting body towards sun to increase rate of heat absorption.

18. 

As exhibited by: *3c*

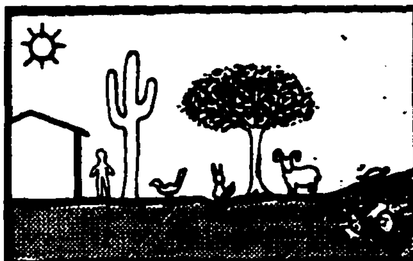
Clustering / dispersing in winter / summer.

19.  *As exhibited by:* *4a, 7f*

Moves seasonally to regions of higher or lower sun exposure.

20.  *As exhibited by:* *5e, 8d*

Temporary heat production through movement of body.



		saguaro	mesquite	termites	horned lizard	roadrunner	jack rabbit	bighorn sheep	man
SHADE	seek/provide shade	●	●	○	○	○	○	○	○
	cast shadow on itself	●						●	○
	least surface area exposed	●							●
	reducing/exposing area	●			●				○
INSULATE	outer insulative layer	●		○		●	●	●	○
	add insulation as required	●	●			●			●
	avoid northern breezes	●						○	○
	earth shelter			○	○		○	○	○
	differing building materials			○					○
WATER	harvest water		●		●				○
	close to reduce water loss		●						○
ACTIVE THERMAL	store/radiate heat	●	●			●			○
	convective ventilation			○					○
	change color				●	●			
	evaporative cooling				●	●		●	●
	radiative cooling						●		●
MOVEMENT	move to change sun angle		●		●				○
	clustering/dispersing			●					
	seasonal/daily movement				●			●	
	heating through movement					●			●

KEY
● physiological response
○ architectural response

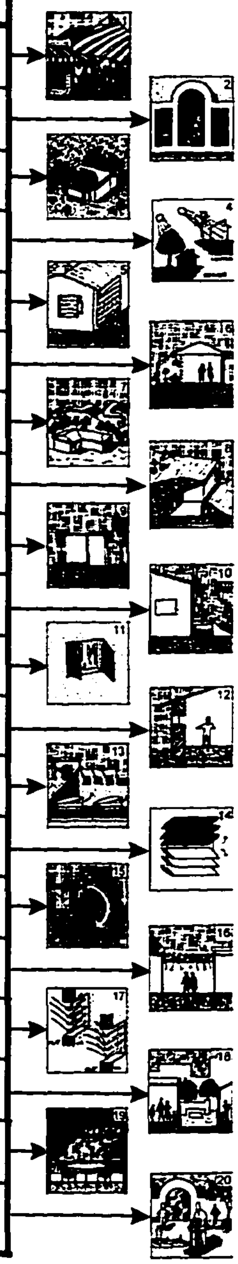


Figure 4.1a Comparison of selected life forms to their adaptive principles

4.4 CASE STUDIES

In order to have an equitable / objective comparison the following case-studies have been chosen from the Sonora Desert and demonstrate the adaptive principles of the plant and animal life in the Sonora Desert, listed above (see pages 108-112). These photographs by no means record the complete projects / buildings, but show only those portions of the structure that can visually describe the biological principles exhibited in Nature.

Icons developed earlier in the chapter (see pages 113-118) have been superimposed onto the photographs in order to show / indicate where a translation of the adaptive principles used by the plants and animals of the Sonora Desert is demonstrated in man's built environment. The principles have then been explained below each illustration, using the same numbering system as in the summary of adaptive principles (see section 4.2.1, pages 113-119) and the strategies categorized under the same five group headings.

4.3.1 Coleman Residence, Tucson

Les Wallach, Line and Space Design, Tucson, 1979

Figure 4.1 Side view, Coleman Residence

I. Shade / shadow

2 Large roof overhangs provide shade onto the building.

3 Overhangs and earth berm leave least surface area exposed to sun.

II. Insulation

8 Earth berm provides thermal insulation.

4.3.2 Taliesin West, Phoenix

Frank Lloyd Wright, 1938

Figure 4.2 Front view, Taliesin West

I. Shade / shadow

1 Canopy provides shade over entranceway.

2 Concrete and wooden fins provide shadows over walls and roofs.

3 Numerous shading devices leave least surface area of living space exposed to the sun.

4 Seasonal vegetation reduces/exposes the surface area.

II. Insulation

7 The building is oriented towards true south

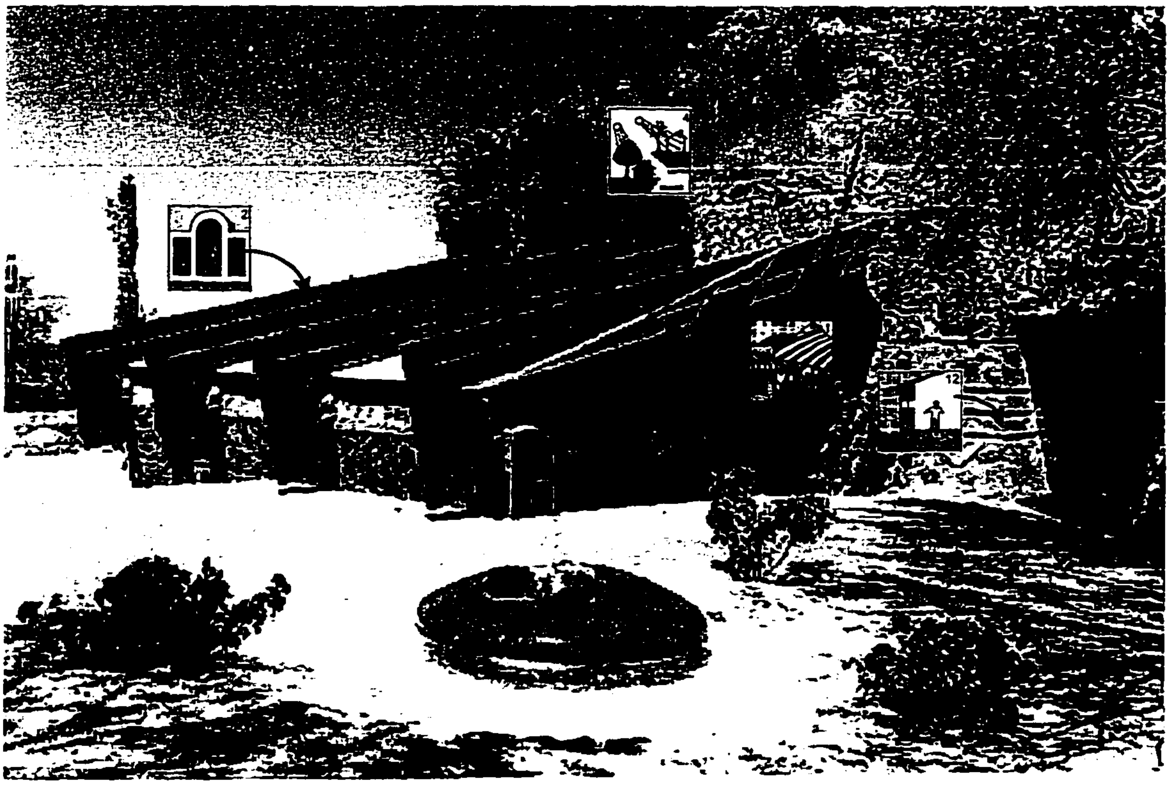


Figure 4.3 Side view, Taliesin West

8 Kiva/private dining is partially subterranean (not shown in photographs).

9 Building materials with differing properties are used.

III. Water

11 Windows can be opened for ventilation

IV. Active thermal

12 Stone thermal mass wall for coolth during day and warmth at night.

4.3.3 Boyce Thompson Southwestern Arboretum Visitors Center, Superior

Les Wallech, Line and Space Design, Tucson

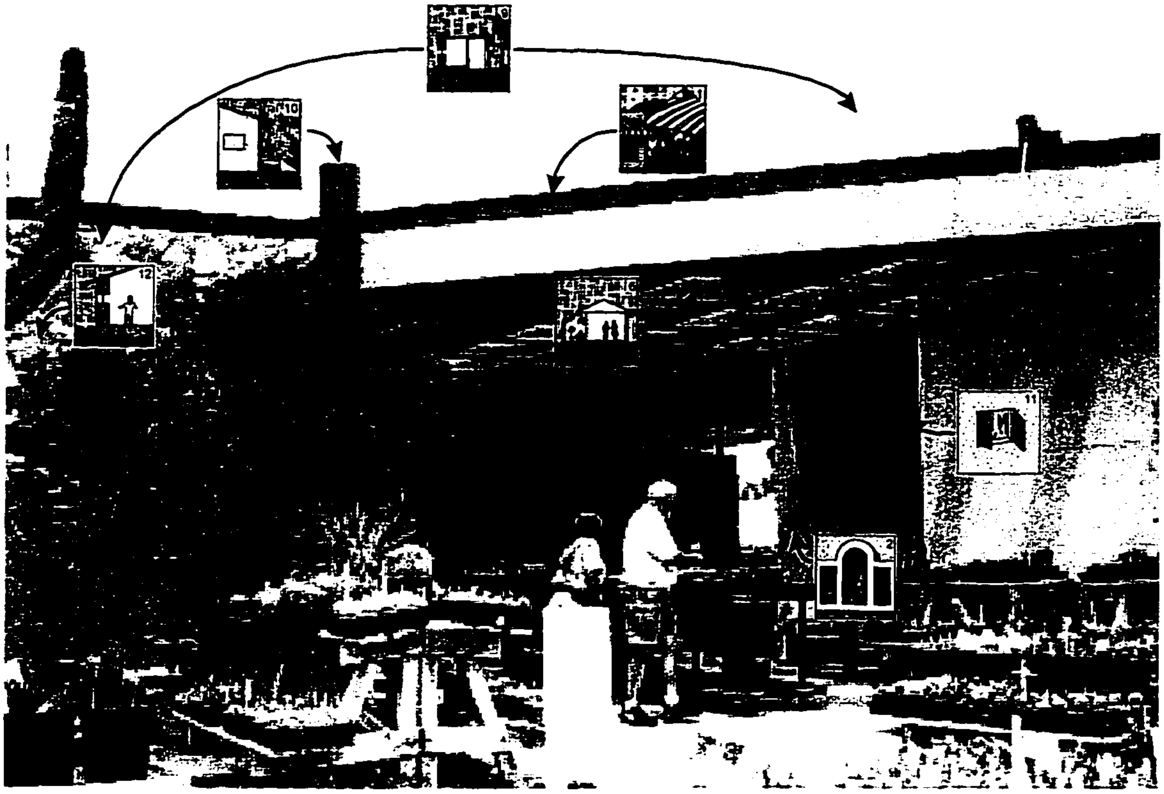


Figure 4.4 Rear view, Boyce Thompson Arboretum

I. Shade / shadow

1 The concrete roof grid shades other functions underneath.

2 The texture of the exterior rock walls and concrete fins provide shade on the building.

II. Insulation

5 Venetian blinds and vegetation around the building provide insulation.

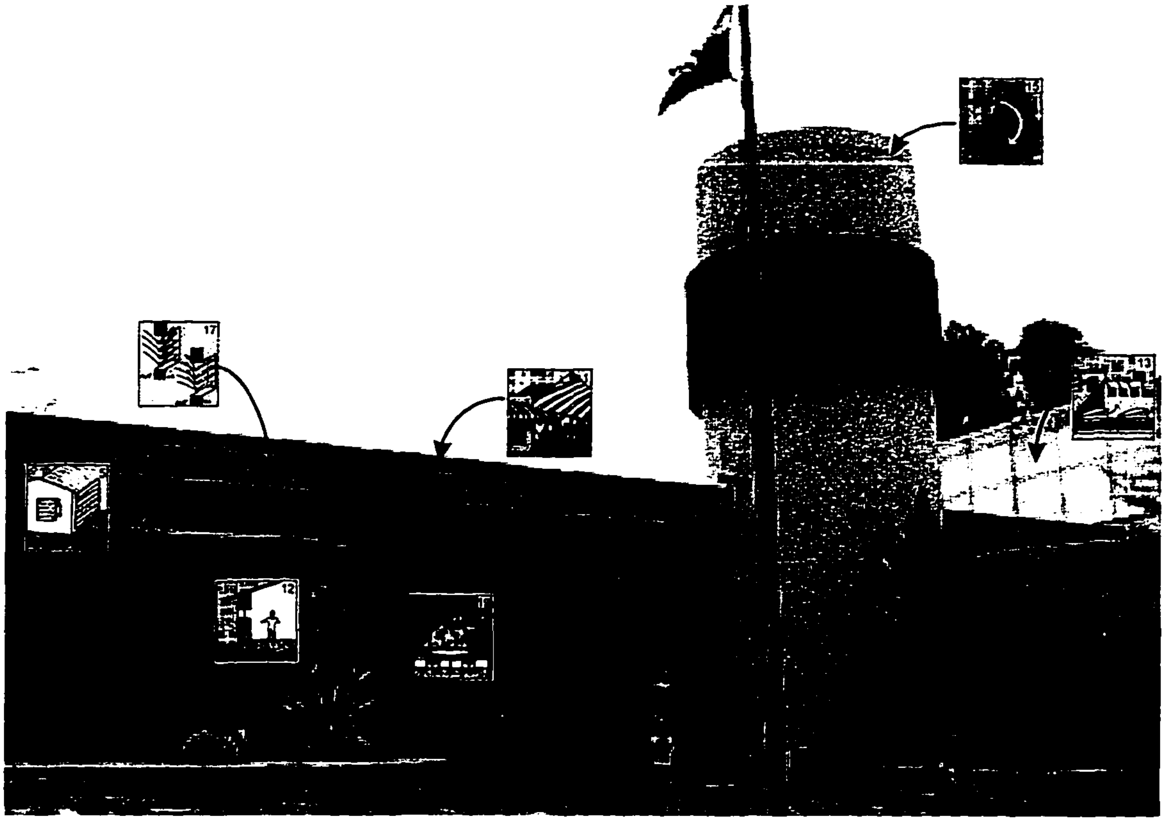


Figure 4.5 Front view, Boyce Thompson Arboretum

6 The grid roof offers variable insulation by having some cells that are open while others have clear or frosted acrylic domes.

7 The surrounding mountains provide insulation from breezes.

9 Building materials with varitable properties are used.

III. Water

10 Roof water is harvested in large tubes.

Low water demanding plants are used.

Parking lot runoff used in Demonstration Garden (not in photograph).

11 Greenhouse windows are operable, night time ventilation.

IV. Active thermal

12 Exterior rock thermal walls for heat storage.

13 Ventilation through clearstory windows and fan under cool tower to direct cool air under the patio floor.

15 Air is drawn past water-soaked pads for evaporative cooling in the cool tower.

V. Movement

17 Venetian blinds can be operated according to the sun's angle.

19 Central breezeway cooled by the cool tower is a gratifying resting place.

4.3.4 SunTran Bus Stop, Tucson

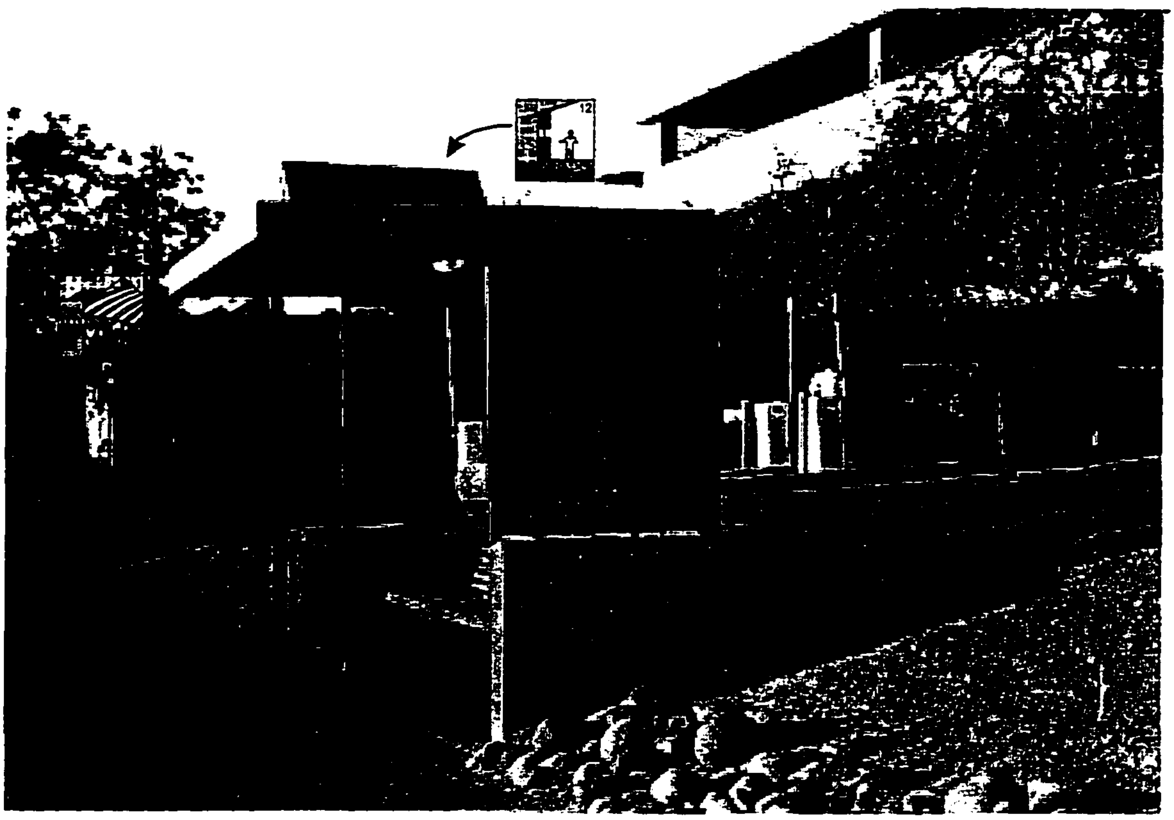


Figure 4.6 SunTran bus stop

I. Shade / shadow

1 Shade for waiting passengers.

IV. Active thermal

12 Photovoltaic stores energy during the day to light the bulb at night.

4.3.5 Hynes Residence, Tucson

Patrick Hynes, Tucson. 1982

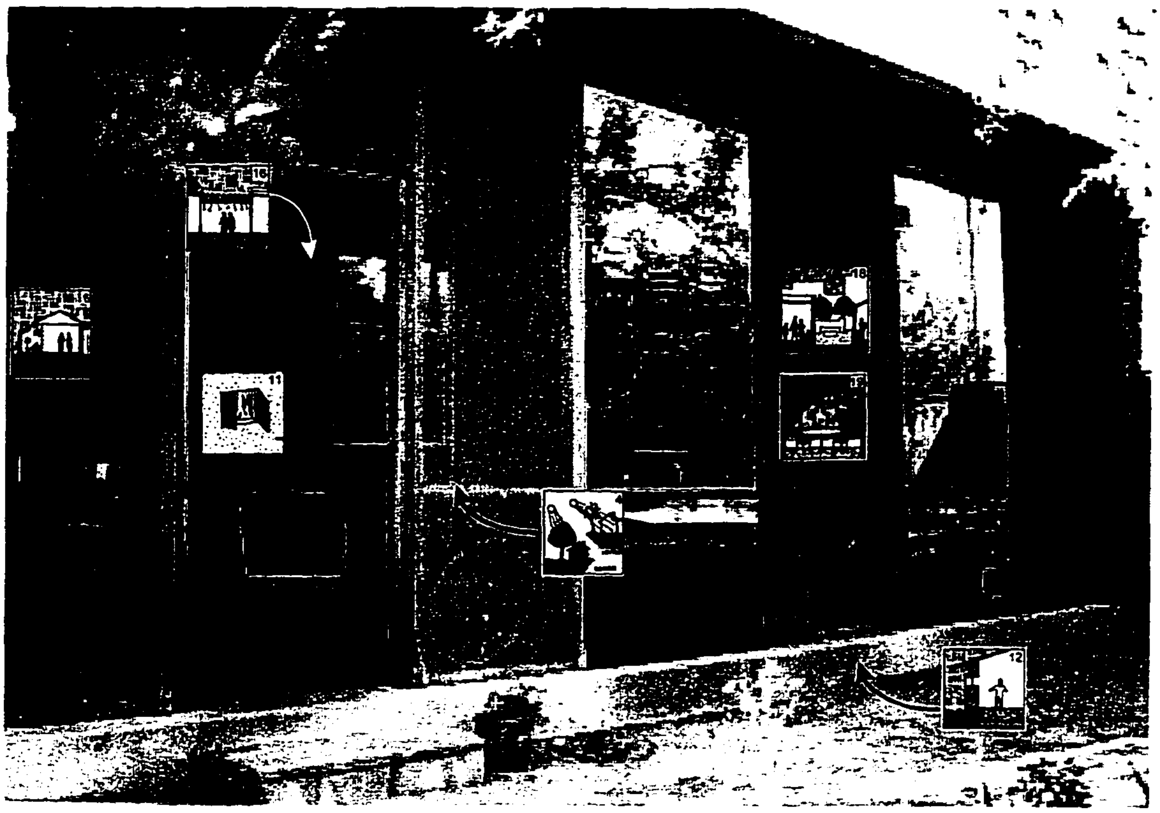


Figure 4.7 Sunspace, Hynes Residence

I. Shade /shadow

2 Summer shading is provided by roof overhangs on all sides of building.

4 Sunspace / screened porch in winter / summer exposes / reduces the surface area.

II. Insulation

6 Screened porch acts as additional insulation for the house.

III. Water

11 operable double hung windows and clearstory .

Figure 4.8 Roof detail, Hynes Residence

IV. Active thermal

12 Adobe walls and concrete floor act as thermal mass.

13 Roof vents. Heat transferred into living space from sunspace through transom windows and high and low vents.

16 Heat transferred by radiation through thermal wall.

V. Movement

18 Sunspace converted into living space in winter.

19 Screen porch used for evening relaxation in summer.

4.3.6 Broadway Village, shopping complex, Tucson

Josai Josler, 1930's

Figure 4.9 Broadway Village (shopping complex)

I. Shade / shadow

2 Reveals and balconies cast shadows onto the structure.

3 Courtyards and vegetation reduce exposed surface area.

III. Water

10 Water is harvested from the roofs.

11 Windows can be operated when needed.

IV. Active thermal

12 Brick thermal mass wall.

13 Wind tower causes a hot air draft from the building.

V. Movement

18 Courtyards and breezeways attract clustering of people outdoors.

19 Outdoor eating area encourages periodical movement.

20 Movement of people between various functions of the shopping complex generates heat.

4.3.7 Two Pesos, Mexican Restaurant, Tucson

Figure 4.10 Outdoor dining porch of Two Pesos

I. Shade / shadow

1 Porches provide shade for outdoor activities.

II. Insulation

5 Cooler air under porches provides insulation for the building.

III. Water

11 Windows can be opened when desired.

V. Movement

18 Large porch allows people to disperse outside when needed.

19 Daily / seasonal indoor / outdoor movement as desired.

4.3.8 The Josler House, Tucson

Figure 4.11 Josler House

I. Shade / shadow

1 Ramada and breezeway provide shade for outdoor activities.

II. Water

11 All windows are operable.

IV. Active thermal

12 Thermal mass wall.

13 Breezeway and high windows help in convective ventilation.

V. Movement

19 Second floor has a sleeping porch for summer use.

4.3.9 Fraternity House, University of Arizona, Tucson

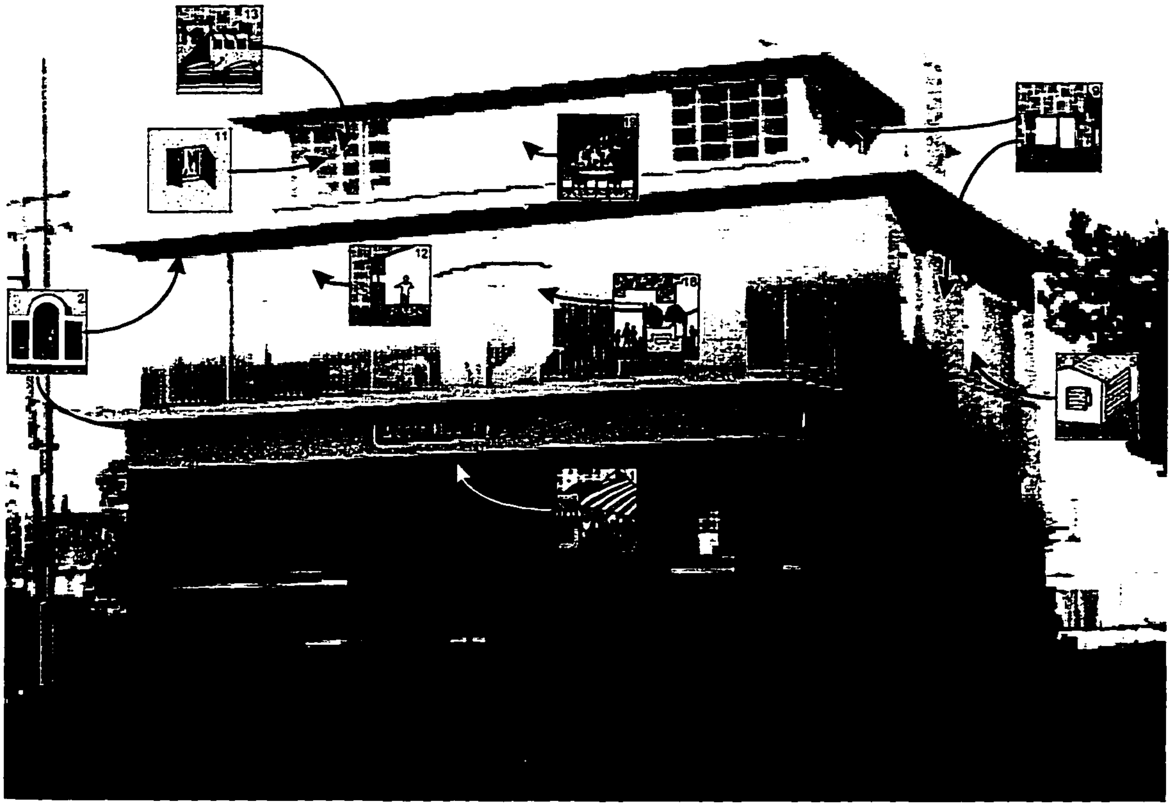


Figure 4.12 Aggie House (Fraternity building)

I. Shade / shadow

1 Porch provides shade for the entire front facade.

2 Roof overhangs cast shadows on the building.

II. Insulation

5 Screens over doors and windows provide insulation.

9 Different building materials are used for the construction of main building and sleeping porch.

III. Water

11 Windows can be left open or closed as desired.

IV. Active thermal

12 Brick thermal mass wall.

13 Windows on sleeping porch allow for convective ventilation.

V. Movement

18 Balcony and porches allow for opening up of building when desired. During winter only the rooms on the first and second floors are used as living quarters, while in the summer all three floors, including balconies are used.

19 Third floor is used as sleeping porch in the summer.

4.3.10 Chapel of San Pedro at Fort Lowell, Tucson

The Men of El Fuerte, 1915.

Figure 4.13 Chapel of San Pedro

I. Shade / shadow

2 Reveals and recesses cast shadows on the structure.

III. Water

11 Operable windows. Night time ventilation.

IV. Active thermal

12 Thick adobe walls provide thermal insulation.

13 Convective ventilation through windows and roof vents.

4.3.11 Solomon Residence

Judith Chafee, Architect, Tucson.

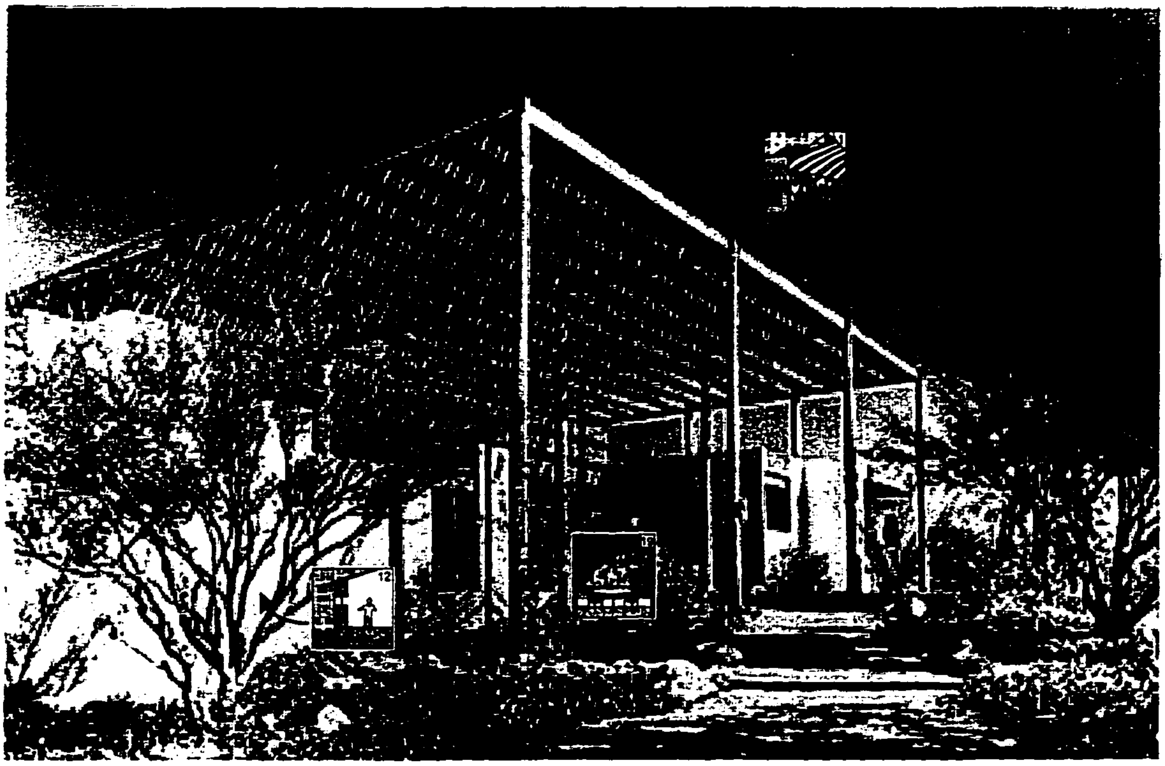


Figure 4.14 Solomon Residence

I. Shade / shadow

1 Ramada over building provides shade to the structure.

IV. Active thermal

12 Thick adobe wall acts as thermal mass storage.

V. Movement

19 Shaded outdoor area promotes indoor / outdoor activity.

4.3.12 College of Architecture, University of Arizona, Tucson

University of Arizona, Tucson, 1980.

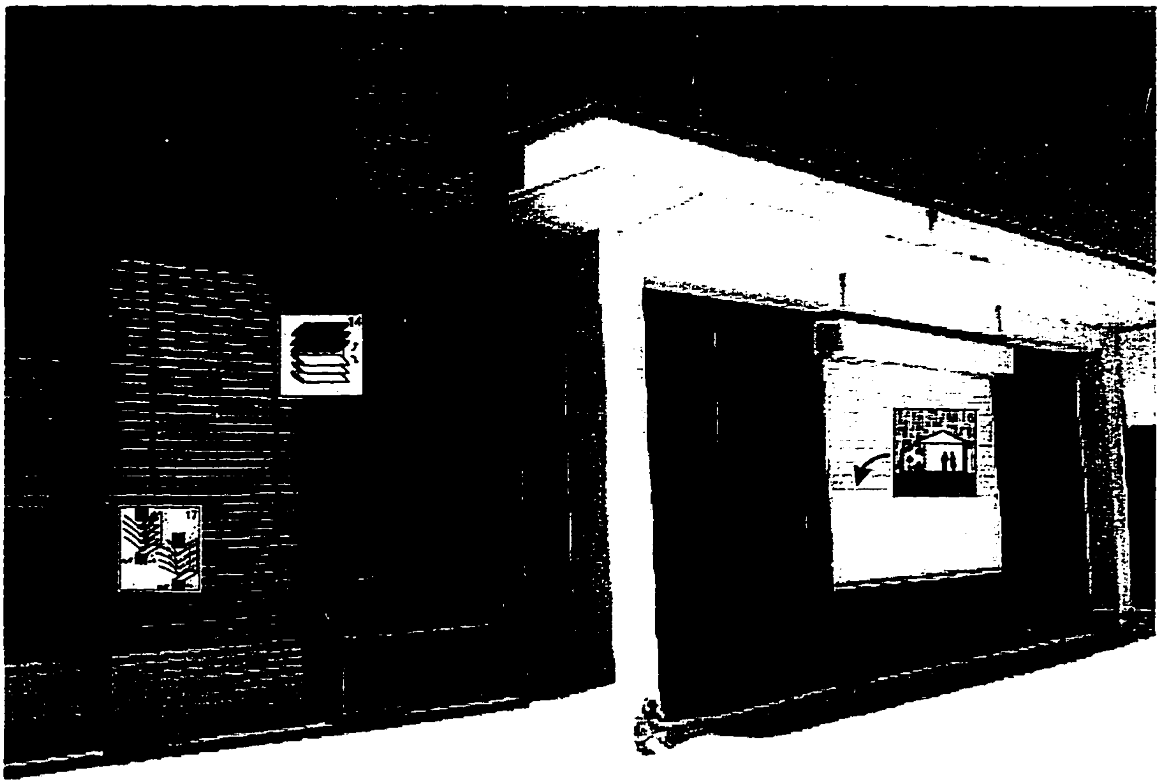


Figure 4.15 South view solar collector, College of Architecture

II. Insulation

6 White insulation is added on glass panel when needed.

IV. Active thermal

14 Venetian blinds in the windows are black on one side to absorb heat and white on the other to reflect solar radiation.

V. Movement

17 Blinds are electronically controlled to move according to the sun's angle.

4.3.13 The Passive Cooling and Heating Experimental Facility, Tucson

Environmental Research Laboratory, University of Arizona, Tucson.

This has been an ongoing research since 1977. The laboratory has been involved in solar energy research and applications since the 1950's, when it developed a technique for the solar distillation of sea water. With the petroleum crises in the 1970's it developed the ClearView® collector for residential and light commercial space heating.

Figure 4.16 Structure One, ERL

I. Shade / shadow

4 Opening / closing of blinds reduces / exposes surface area.

II. Insulation

5 Venetian blinds on windows provides insulation.

7 Klos windows and greenhouse are situated on the south side of building.

9 Walls of varying thicknesses used.

III. Water

11 Windows can be opened to gain or loose heat as needed.

IV. Active thermal

12 Adobe wall acts as thermal mass storage.

Photovoltaics stores energy to be used at a later time.

13 Attic ventilation to remove hot air.

14 Venetian blinds in windows and green house are black on one side to absorb heat and white on the other to reflect solar radiation.

V. Movement

17 The blinds and solar panels are electronically controlled to move according to the sun's angle.

18 Greenhouse provides heat in winter days and becomes a screen porch for lounging during summer evenings.

19 People can move seasonally / daily between greenhouse / screened porch and the main building.

20 Solar panels move to collect more heat.

Figure 4.17 Structure Two, ERL

I. Shade / shadow

1 Porch provides shade for rooms below.

II. Insulation

8 44% of the structure is underground, basement and half basement.

III. Water

10 Water is harvested from the roof porch.

11 Natural ventilation through operable windows.

IV. Active thermal

12 Interior and exterior block walls filled with cement mortar act as thermal mass.

V. Movement

17 The blinds and solar panels are electronically controlled to move according to the sun's angle.

19 Daily / seasonal movement between basement, upperstory and roof porch.

20 Movement between various levels of building produces temporary heat.

Figure 4.18 Structure Three, ERL

I. Shade / shadow

2 Porch provides shade on part of building

II. Insulation

6 ClearView collector operated when needed.

9 Walls and floors of materials with varying properties.

III. Water

10 Water is harvested from the roof porch.

IV. Active thermal

12 Rock bed under floor stores heat in winter and coolth in summer (not shown in photograph).

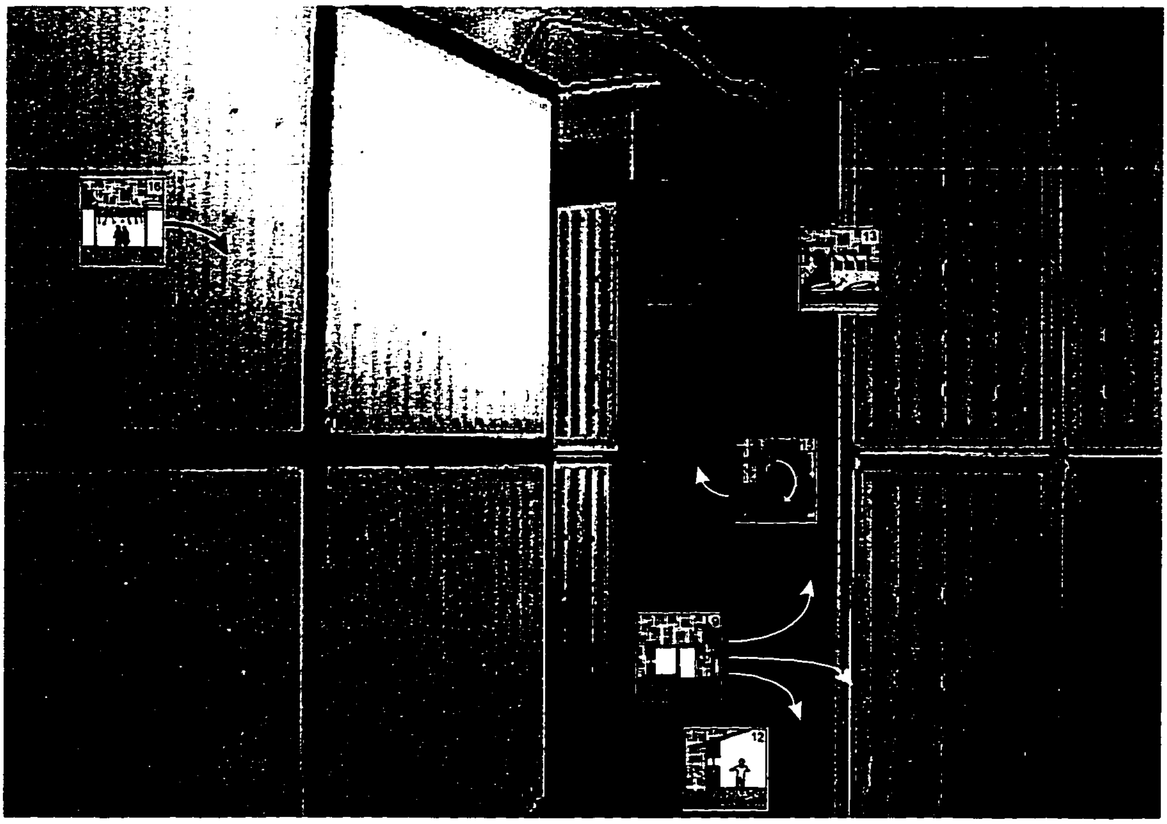


Figure 4.19 Water walls in Structure Three

13 Attic collector on west side of building has black colored absorbers to assist in convecting the hot air out of the roof attic.

14 Venetian blinds in windows and green house are black on one side to absorb heat and white on the other to reflect solar radiation.

15 Cool tower passes hot air through wet pads, evaporating water which cools the air, becomes heavier and by convection moves down into the building.

16 Interior water walls radiate stored coolth.

V. Movement

18 People can disperse to the porch when it is comfortable.

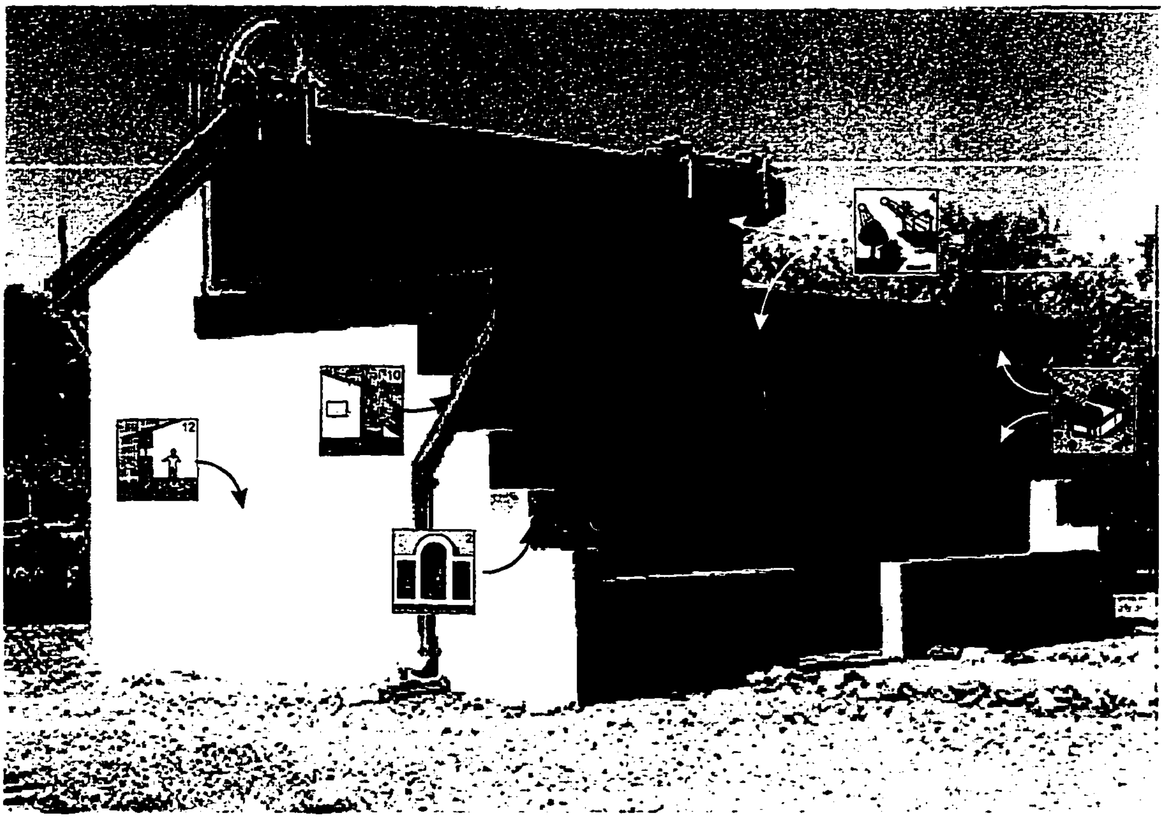


Figure 4.20 Data Acquisition Building

I. Shade / shadow

2 Porch shades the entire south facade.

3 Overhangs and dwarf walls protect the building from exposure to the sun when solar radiation is most intense.

4 Roof overhang is deep enough to provide shade during summer when the sun's angle is high, and exposure during winter when sun's angle is low.

III. Water

10 Water is harvested from the roof porch

IV. Active thermal

12 Block walls filled with cement mortar act as thermal mass.

4.4 CONCLUSIONS

By trial and error, mostly after observing other living forms, early man found what would work and what would not, resulting in a vernacular historical tradition that we greatly admire today but do not allow ourselves to make use of. Vested interests in the manufacture of cement, blocks, bricks, and lumber have made it possible to prohibit the use of many old, simple, less costly materials that work. While use of most of these old materials is labor intensive, our building industry is dedicated to the minimization of labor in the use of materials. In view of the continuing energy shortages, unemployment problems, and an increasing labor force, however, it is, perhaps, time to re-evaluate material / labor cost ratios before many of the old skills are lost for good through specialization.

Borrowing technology from nature has played an important role throughout the history of architecture and continues to be a source of inspiration as scientific research reveals more information about our environment and various forms of life that share it. This biotechnology offers a systematic way to study and incorporate the principles of natural organisms into architecture. Biotechnology is also defined as a general category of all studies and techniques that combine the ideas and needs of biology and medicine with engineering.

Design in the desert should aim at fulfilling the basic human requirements for comfort by providing an indoor environment and, to a certain extent also, a man-made out-door environment which mitigates the harshness of nature and enables rest and recuperation. In view of the world's energy situation this objective should be accomplished with minimum expenditure of non-renewable energy resources and maximum utilization of the natural, renewable, energies available for heating and cooling of buildings. Thus an energy conscious / nature respecting building industry in the Sonora Desert could be achieved by the complementary effects of two lines of action in architectural design: minimizing the energy needs by proper building design learning from various biological and biotechnological examples found in nature, and maximizing the use of available natural resources for heating and cooling as the plants and animals thriving in the same desert shared by man, have done.

Energy, in all its forms, is vital to sustain life. It is also fundamentally important in man's attempt to control nature. It is obvious that it would be unthinkable to return to handicraft work of a mason and a stubble roof, as well as a return to the use of a fireplace for microclimatic comfort. But, as demonstrated by the case-studies, human thermal comfort in the Sonora Desert can be achieved by following the unique adaptive principles set forth by nature.

Since man is a part of the Sonora Desert and no different from the other plants and animals that thrive in this region, it is also logical to conclude that man can achieve his thermal comfort biotechnologically. In order for man to thrive and flourish till the end of the life of the solar system and not terminate the life of the earth prematurely he must follow / respect the biological laws set forth by Nature, instead of the breach that man is creating between himself and Nature.

What could be a better way to achieve this natural balance than through the use of biologically derived strategies that are conducive to nature, in our buildings?

Thus the architects philosophy should be to design in a comprehensive manner, taking account of all the multivarious aspects of his art. He must utilize intelligently the possibilities that a computer offers, the new building materials, every valid innovation in construction technology and the suggestions that come from other fields, up to now largely neglected, such as the wonders of biological complexity and diversity, anthropology, psychology, etc. He must explore new technology and take account of past technology and natural resources. He must also study the meaning of good desert citizenship and the adaptive principles of the vegetation types and biological systems that have emerged in response to the unique climatic situations, and then apply the results in a manner which produces a coherent whole.

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