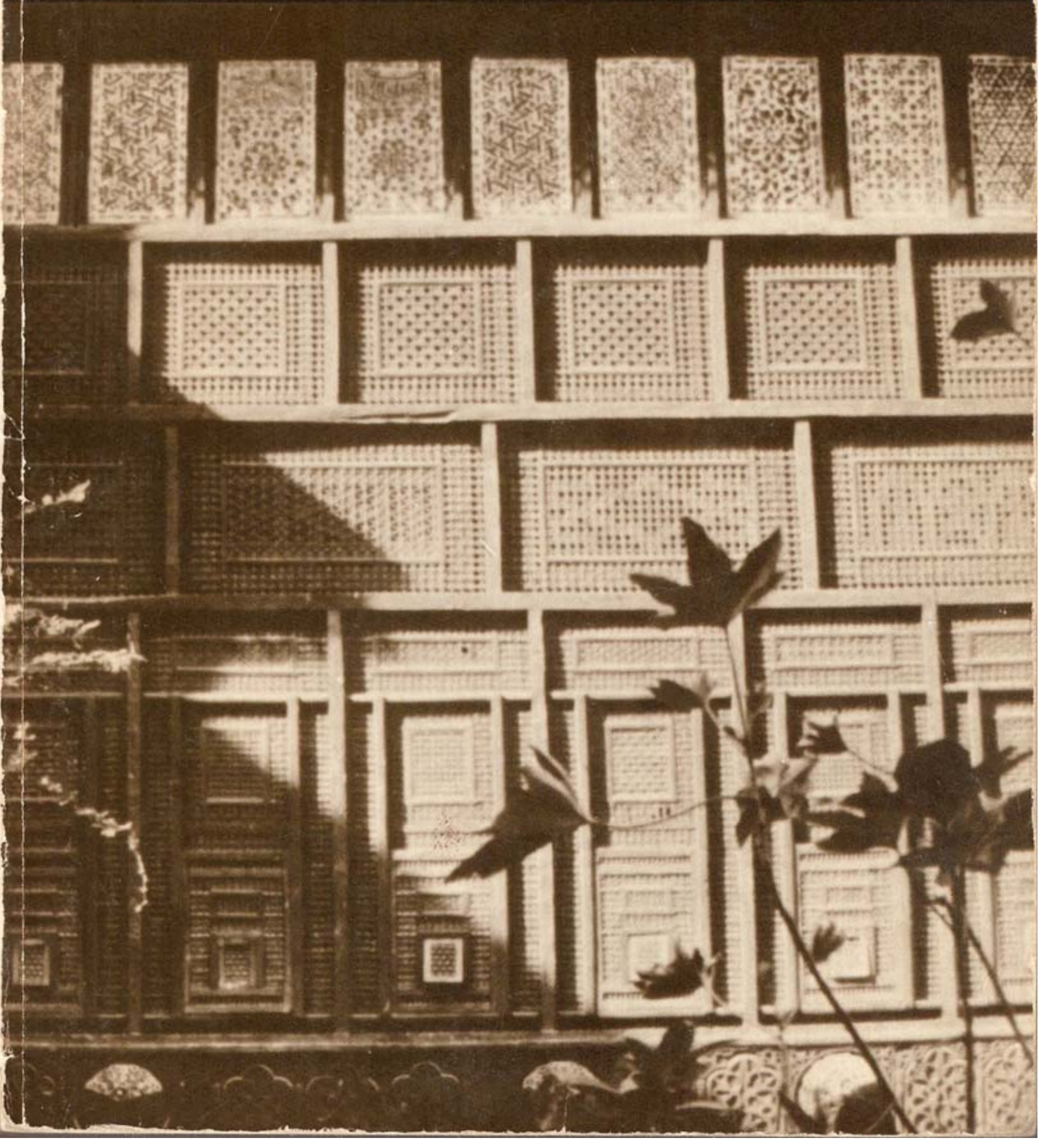
Natural Energy and Vernacular Architecture

Principles and Examples with Reference to Hot Arid Climates

Hassan Fathy



Architecture

The culmination of a lifetime's design practice and environmental study, *Natural Energy and Vernacular Architecture* presents a master architect's extraordinary insights into the vernacular wisdom of indigenous architectural forms that have evolved in hot arid climates. Hassan Fathy draws on his extensive research on climate control, particularly in the Middle East, to demonstrate the advantages of many locally available building materials and traditional building methods. Ultimately, Fathy suggests improved uses of natural energy that can bridge the gap between traditional achievements and modern needs.

Fathy argues that various architectural forms in these climates have evolved intuitively from scientifically valid concepts. Such forms combine comfort and beauty, social and physical functionality. Fathy shows that in substituting modern materials, architects sometimes have ignored the environmental context of traditional architecture. As a result, individuals may find themselves physically and psychologically uncomfortable in modern structures, and whole cultures may feel challenged by contemporary building conventions that often emphasize the latest technique or design concept at the expense of social needs. Fathy's approach, informed throughout by a sensitive humanism, demonstrates the ways in which traditional architectural forms can be of use in solving problems facing contemporary architecture, in particular the critical housing situation now facing millions in the Third World.

Natural Energy and Vernacular Architecture includes examples of both vernacular buildings and modern structures drawn from Fathy's own architecture as well as from that of other architects. The text is complemented by a selected bibliography and a glossary of terms with English equivalents. Bringing together design philosophy and on-site research, this volume will be of exceptional value to architects and students of architecture, environmentalists and policymakers on energy and conservation, and those interested in developing areas and the Third World.

Hassan Fathy, an Egyptian architect, has taught on the Faculty of Fine Arts in Cairo and served as head of its architectural section. In 1984 he received the first Union of International Architects Gold Medal. He is the author of *Architecture for the Poor: An Experiment in Rural Egypt*, also published by the University of Chicago Press.

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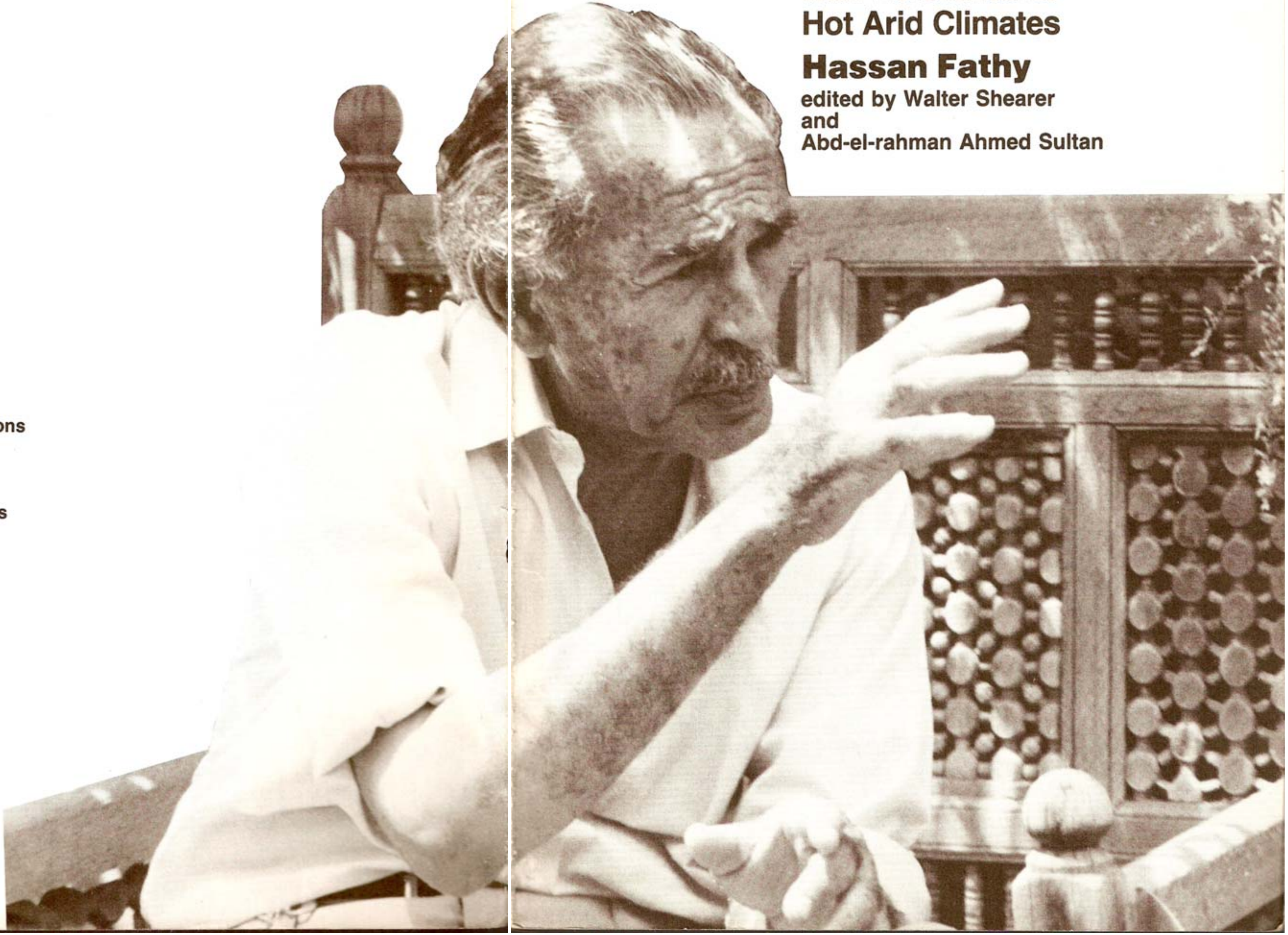
Hassan Fathy

edited by Walter Shearer
and
Abd-el-rahman Ahmed Sultan



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HASSAN FATHY, an Egyptian architect, has taught on the Faculty of Fine Arts in Cairo and served as head of its architectural section. He has received the Union of International Architects Gold Medal, the Egyptian Government's National Prize for Arts and Letters, and the Aga Kahn Award for Architecture. He is the author of *Architecture for the Poor*, also published by the University of Chicago Press.

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Foreword

Hundreds of millions of people in the world today live in poor housing under adverse climatic conditions that stress their undernourished bodies toward the limits of human endurance and occasionally beyond. The poverty of these people severely restrains their ability to procure the energy required to provide healthful climatic conditions within their homes. Yet their ancestors survived, and often lived comfortably, for centuries under the same climatic conditions in dwellings of traditional design. They were able to do so because they made use of the energy available locally in the environment. Many traditional societies in climates with cold seasons relied on firewood and organic waste to provide them with the heat they needed. People living in the hot, arid climates, however, were faced with a different problem: high daytime and cool nighttime temperatures with very little humidity. More than firewood is needed to solve climatic problems of this type. The solutions that were found relied on energy from the sun and wind and the innovative, architectural structures and forms that were developed to make use of this natural energy. The vernacular architecture of the Arab World and neighboring regions not only solved the climatic problems but did so with a combination of beauty and physical and social functionality. This book describes some elements of the vernacular architecture developed by these societies over many generations to provide a comfortable microclimate using natural energy.

Yet, there is much more to be acquired than scientific understanding and aesthetic appreciation of the vernacular architecture of a people. A topic such as this can open the door to a recognition of the contribution traditional knowledge can make to the solution of many contemporary problems. The fact that most traditional societies, in the developing as well as in pockets within the industrialized nations, have not been able to maintain the economic pace set by the industrialized societies has led to their generally being viewed as backward, primitive, unsophisticated, irrational, naive, and, at best, perhaps quaint communities. They are seen as having little knowledge of the "real" world about them with which they seem largely unable to cope, as manifested by their poverty.

It is rarely remembered that, at some time in the past, most of these societies or those from which they are derived were among the most sophisticated of their time, greatly surpassing their contemporaries, some of which have since become the industrialized societies of today. The survival of traditional societies over hundreds and thousands of years indicates that they surely possess knowledge that can still be of great value either in its original form or as the basis for new developments.

Ironically, in general, it is the poorer societies that are the custodians of this important knowledge which could do so much to relieve their poverty. The traditional techniques employed are rarely costly in terms of materials or energy and are thus not only largely within the economic grasp of such people but are often directly within the realm of their understanding. Thus it is these societies that should logically, as well as morally, benefit first from this knowledge. But much remains to be done to convince the populations of poorer societies to look to tradition for the solutions to many of their problems. It is important that they be encouraged to do so by their political, economic, and social leaders and by those governments, organizations, and individuals wishing to assist them. It is wise to remember that not only will modern solutions be frequently out of their economic reach but that these solutions may not in fact be relevant to the local climatic, ecological, social, cultural, and economic conditions.

In trying to look realistically at the conditions of many poor societies, it can be argued that they are poor for the very reason that they have relied upon traditional knowledge, which has proven largely inadequate to the task of improving their economic conditions. There is some truth to this argument. Many of the situations under which traditional techniques were effective have now changed to the point where the original techniques are no longer appropriate. Populations may have become too large to be sustained by traditional methods, climates and ecologies may have changed (often through overexploitation) producing a situation unfamiliar to the original society, and markets for traditional products or goods produced by traditional techniques may no longer be viable. Rather than develop a new solution rooted in tradition, societies often opt for a modern answer. Unfortunately, in far too many cases, the traditional devices, methods, and systems have thus been supplanted by modern solutions that are inappropriate to and untried under the local conditions.

What appears to be needed, therefore, is an appraisal of the conditions under which the traditional solutions are technically, environmentally, socially, and economically valid, so that use can be made of this knowledge in appropriate situations. It would be of great benefit also if societies with similar conditions could share their traditional solutions to specific problems. Following appraisal, some solutions may be rejected as inappropriate, but a scientific understanding of the principles upon which they are based could serve as a useful foundation upon which to develop new solutions more in keeping with the local economics, environment, and society than those that have replaced the traditional ones. Many traditional techniques could be improved, using new materials and knowledge, rather than totally abandoned.

Fortunately, recent "discoveries" of the value of traditional forms of medicine, technology, and agriculture have led to a revived interest in preindustrial knowledge. This information, which is an important part of the human heritage, is the focus of a new project of the United Nations University, the Archive of Traditional Knowledge.

The field of vernacular architecture offers an abundance of concepts that can be of use today in solving the critical housing situation now facing millions in the Third World. The example chosen to illustrate this by the UNU Energy Subprogramme covers the vernacular architecture of the hot, arid zones of the Arab World and neighboring regions.

It was felt that the person best suited to prepare a monograph on this subject was Professor Hassan Fathy. Not only is Professor Fathy a master architect and an expert in the area of traditional architecture, especially in the Arab World, but he has been so for more than half a century. His work has also demonstrated the value that traditional architecture can have in improving the housing and living environments of the poor of the Third World. As a theoretician and practitioner of environmental planning design, Dr. Fathy's approach is based on a set of principles that are useful in opening the mind to the value of vernacular architecture and to adapting it to the situation in which a large fraction of the world's population find themselves today.

Professor Fathy's approach is based on the concept that architectural form should be determined by spiritual, artistic, climatic, and social considerations as well as function, material, and structure. He emphasizes that due consideration must be given to a number of elements including harmony.

One principle of this approach requires the adoption of designs appropriate to local conditions, thereby eliminating the possibility of settling on universal or international designs for buildings that must be used in all countries and all climates. Another rule is the use of natural locally available materials to the maximum extent possible, traditional building methods with adaptation appropriate to the demands and conditions of modern life, and the use of climate-oriented design. Building techniques, methods, and material costs are to be tailored to the economy and capabilities of the people for whom the structure is intended rather than matching the tenants to the techniques, methods, and costs of the intended structure. Thus, citizens must participate in the design of buildings, thereby leading to a triangular relationship between the citizen, the architect, and the builder. This means that the task of the architect is not to express his own ideas in the building but those of the locale, the people, and the culture. Finally, Professor Fathy insists that architects must thoroughly analyze traditional building methods and forms using scientific principles and an understanding of social and cultural requirements before discarding any of them. At the same time, however, an equally thorough analysis is required of modern architectural techniques and forms using the same considerations before adopting any of them.

Professor Fathy's work demonstrates the application of these principles and has shown how useful they can be in the development of viable solutions to the problems of contemporary architecture, especially to that of adequately housing the people of the Third World.

In an effort to further the understanding of these principles and promote sharing of traditional solutions developed by the Arab World and neighboring areas with peoples in other hot, arid regions, as well as to show the ingenuity and beauty with which these solutions were executed, the United Nations University presents this volume.

The editing of this book afforded not only an extremely pleasant opportunity to work with the author but also with one of his disciples, Dr. Abd-el-rahman Ahmed Sultan. His long association with the author and intimate knowledge of the author's work made Dr. Sultan's contribution to the meticulous editing process invaluable. In addition to his generous donation of time and knowledge, Dr. Sultan has provided many photographs from his personal collection and prepared the drawings for publication.

Walter Shearer
Senior Programme Officer
United Nations University

Preface

Since antiquity, man has reacted to his environment, using his faculties to develop techniques and technologies, whether to bake bread or make brick, in such internal psychological balance with nature that humanity historically lived attuned to the environment. Man's creations were natural when built of the materials offered by the landscape.

Learning to manipulate clay, stone, marble, and wood, man penetrated their properties, and his techniques gave expression to his aspirations toward the divine. In architecture, environmental harmony was known to the Chinese, the Indians, the Greeks, and others. It produced the temples of Karnak, the great mosques of Islam, and the cathedral of Chartres in France.

With the advent of the industrial revolution, the inherited techniques and perfected knowledge of creating, using handmade tools, were lost and are now forgotten. Energy-intensive mechanized tools have diminished man's personal, cellular contribution to the fabrication of objects, the building of structures, and the growing of food. The lesser the challenge for man to imprint his genius, the less artistic is the product.

The resulting economic and political disturbances are visible today. Production of beauty, once the prerogative of millions, is replaced by industrialization—even of bread—under the control of a minority of owners. The negative consequences of the industrial revolution have disturbed the natural organization of the divine concept for humanity.

Sixty years of experience have shown me that industrialization and mechanization of the building trade have caused vast changes in building methods with varying applications in different parts of the world. Constant upheaval results when industrially developed societies weaken the craft-developed cultures through increased communications. As they interact, mutations create societal and ecological imbalance and economic inequities which are documented to be increasing in type and number.

Profoundly affected is the mass of the population, which is pressured to consume industrially produced goods. The result is cultural, psychological, moral, and material havoc.

Yet it is this population that has an intimate knowledge of how to live in harmony with the local environment. Thousands of years of accumulated expertise has led to the development of economic building methods using locally available materials, climatization using energy derived from the local natural environment, and an arrangement of living and working spaces in consonance with their social requirements. This has been accomplished within the context of an architecture that has reached a very high degree of artistic expression.

At all costs, I have always wanted to avoid the attitude too often adopted by professional architects and planners: that the community has nothing worth the professionals' consideration, that all its problems can be solved by the importation of the sophisticated urban approach to building, If possible, I want to bridge the gulf that separates folk architecture from architect's architecture. I always wanted to provide some solid and visible link between these two architectures in the shape of features, common to both, in which the people could find a familiar point of reference from which to enlarge their understanding of the new, and which the architect could use to test the truth of his work in relation to the people and the place.

An architect is in a unique position to revive people's faith in their own culture. If, as an authoritative critic, he shows what is admirable in local forms, and even goes so far as to use them himself, then the people at once begin to look on their own products with pride. What was formerly ignored or even despised becomes suddenly something to be proud of. It is important that this pride involves products and techniques of which the local people have full knowledge and mastery. Thus the village craftsman is stimulated to use and develop the traditional local forms, simply because he sees them respected by a professional architect, while the ordinary person, the client, is once more in a position to understand and appreciate the craftsman's work.

In spite of this, we are witnessing a change that is now forcing a complete rupture with the past; every concept and every value has been reversed. For house design in the Middle East, the introverted plan wherein family life looked into the courtyard was changed to a plan with family life looking out upon the street. The cool, clean air, the serenity and reverence of the courtyard were shed, and the street was embraced with its heat, dust, and noise. Also, the *qā'a* was supplanted by the ordinary salon, and all such delights as the fountain, the *salsabīl*, and the *malqaf* were discarded in the name of progress and modernity.

It may seem that, from the functional point of view, mechanical air-conditioning was made possible by modern technology; but we must recognize that such technologies also have a cultural role. In fact, this role may be even more important than the function it serves, considering the special place occupied by the decorative arts in many cultures.

Thus when the modern architect replaced these decorative elements with air-conditioning equipment, he created a large vacuum in his culture. He has become like a football player playing football with a cannon. If the purpose of the game is scoring goals, then assuredly he can score a goal with every shot. But the game itself will disappear, and so will any diversion for the spectators, except perhaps in the killing of the goalkeeper.

Every advance in technology has been directed toward man's mastery of his environment. Until very recently, however, man always maintained a certain balance between his bodily and spiritual being and the external world. Disruption of this balance may have a detrimental effect on man, genetically, physiologically, or psychologically. And however fast technology advances, however radically the economy changes, all change must be related to the rate of change of man himself. The abstractions of the technologist and the economist must be continually pulled down to Earth by the gravitational force of human nature.

Unhappily, the modern architect of the Third World, suddenly released from this gravity, and unable to resist temptation, accepts every facility offered to him by modern technology, with no thought of its effect on the complex web of his culture. Unaware that civilization is measured by what one contributes to culture, not by what one takes from others, he continues to draw upon the works of Western architects in Europe and North America, without assessing the value of his own heritage.

In order to assess the value of our heritage in architecture and to judge the changes that it has undergone, there is a need to analyze scientifically the various concepts of design, and to clarify the meaning of many terms that the modern architect uses freely in his professional jargon, such as "contemporaneity." The role architecture and town-planning play in the progress of civilization and culture must be grasped. While change is a condition of life, it is not ethically neutral. Change that is not for the better is change for the worse, and we must continually judge its direction. Architecture concerns not technology alone but man and technology, and planning concerns man, society, and technology.

In architectural criticism, the concepts of past, present, and future are used capriciously, and the present is extended to mean the whole modern epoch. To avoid being arbitrary, we must establish some standards of reference that involve the concept of contemporaneity.

The word "contemporary" is defined as meaning "existing, living, occurring at the same time as." The word implies a comparison between at least two things, and it conveys no hint of approval or disapproval. But as used by many architects, the word does carry a value judgment. It means something like "relevant to its time" and hence to be approved, while "anachronistic" means "irrelevant to its time" and is a term of disapproval. This raises the two questions of what we mean by time and what we mean by relevance—and to what.

Now, if we are to reconcile chronological time with the artist's definition of contemporaneity, we may say that to be relevant to its time, to be contemporary, a work of architecture must be part of the bustle and turmoil, the ebb and flow of everyday life; it must relate harmoniously to the rhythm of the universe, and it must be consonant with man's current stage of knowledge in the human and the mechanical sciences, and in their inseparable relationship within planning and architectural design.

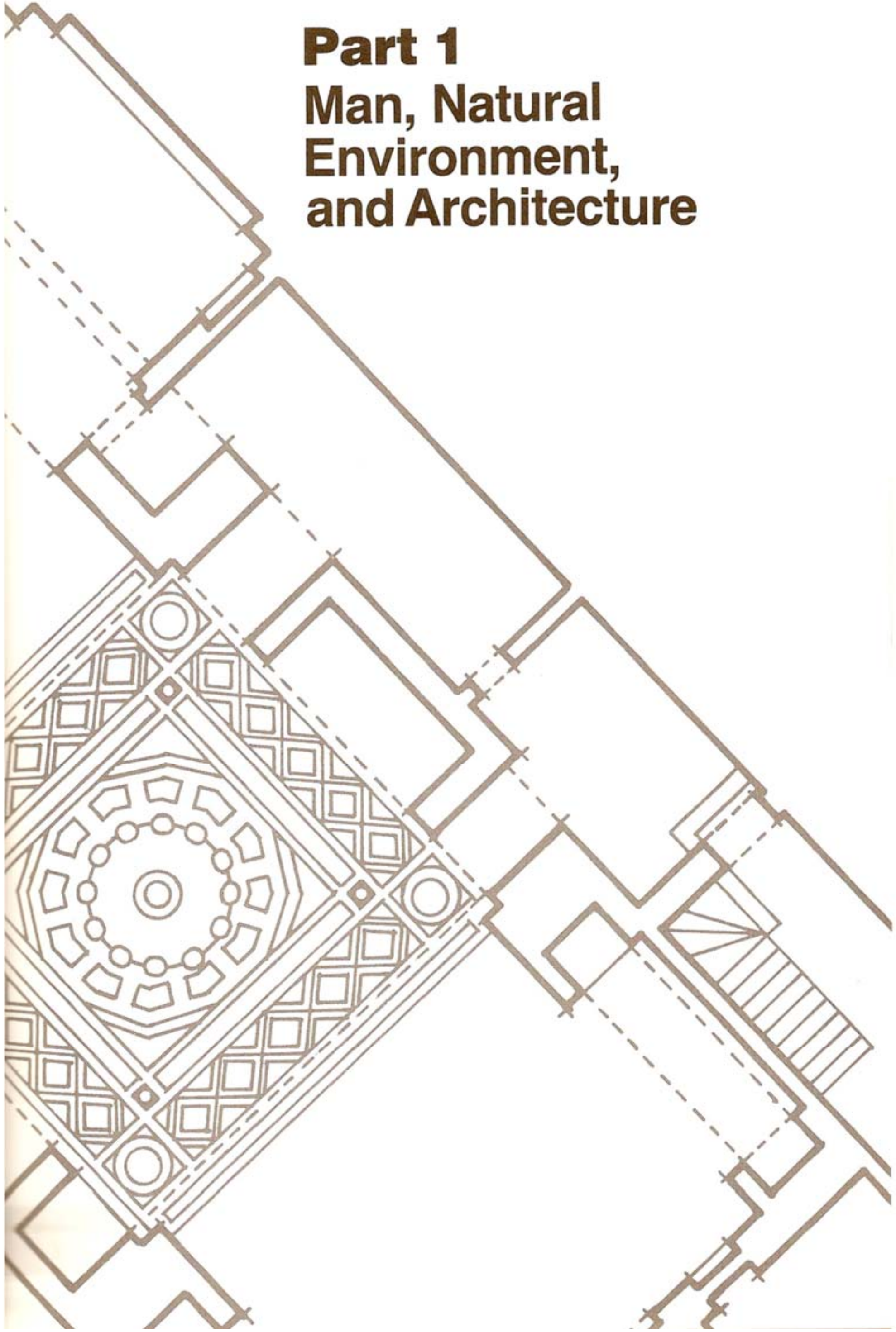
To judge the criterion of contemporaneity, we must sense the forces that are working for change, and must not passively follow them but rather control and direct them where we think they should aim. Physical and aerodynamic analysis has shown that many of the concepts embodied in the design of houses of the past remain as valid today as they were yesterday and that, judged by the same standards, much of what is called modern is in fact anachronistic. We must determine what is basic and constant and thus worth keeping, and what is ephemeral and transient and can be discarded.

Looking to the future, we see that the situation at any given time largely determines the coming stage in development and change. Thus there would be no problem were the present situation of architecture normal, that is to say, truly contemporary. The future would then take care of itself. But unfortunately that is not the case, and it is the responsibility of the modern architect to find a remedy. He must renew

architecture from the moment when it was abandoned; and he must try to bridge the existing gap in its development by analyzing the elements of change, applying modern techniques to modify the valid methods established by our ancestors, and then developing new solutions that satisfy modern needs.

Part 1

Man, Natural Environment, and Architecture



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Environment and Architecture

When an engineer designs a machine, a bridge, or a regulator, each line in his drawings is the result of a great accumulation of laws and principles from a dozen different mechanical sciences. He designs the machine to withstand a certain amount of strain and to do a particular job. In both these aspects he must consider and apply all that he has been taught in such fields as physics, dynamics, structural mechanics, and the resistance of materials, and must put into each line a whole library of expertise.

Similarly, when an architect designs a town or a building, every line is determined by the application of the same complex set of mechanical laws, with the addition of a whole collection of other sciences whose provinces are less well defined: the sciences that concern man in his environment and society. These sciences—sociology, economics, climatology, theory of architecture, aesthetics, and the study of culture in general—are no less important to the architect than are the mechanical sciences, for they are directly concerned with man, and it is for man that architecture exists.

The mechanical side of an architect's work—ensuring that his building will stand and provide protection against the elements, or that the street pattern of a town performs its function efficiently—is no more than a preliminary to his real creation. Only when he has provided these mechanical prerequisites, which should be incorporated without question or argument, can he begin to consider the real problem of designing a building. He is rather like the pianist who can start to interpret the music he plays only after he has mastered the technique of piano playing.

A machine is independent of its environment. It is little affected by climate and not at all by society. A person, however, is a member of a living organism that constantly reacts to its environment, changing it and being changed by it.

A plant provides a good example of the mutual interaction between a living organism and its environment. It possesses its own heat and water economies. Its respiratory heat is the result of metabolism which tends to raise its temperature, just as with animals. It perspires, and the evaporation of this perspiration leads to cooling, since every gram of water given off requires between 570 and 600 calories from the plant, depending on the air temperature. Consequently, plants exert a reaction on the microclimate of their environment and to some extent adjust their own temperature to their particular needs.

In the same way, a building is affected by its environment. The climate of the locality and the buildings around it mold the building, so that, even though social, cultural, and economic aspects are important, it owes much of its shape to these factors.

Effect of Climate on Architectural Form

Climate, in particular, produces certain easily observed effects on architectural forms. For example, the proportion of window area to wall area becomes less as one moves toward the equator. In warm areas, people shun the glare and heat of the sun, as demonstrated by the decreasing size of the windows. In the subtropical and tropical zones, more distinctive changes in architectural form occur to meet the problems caused by excessive heat. In Egypt, Iraq, India, and Pakistan, deep loggias, projecting balconies, and overhangs casting long shadows on the walls of buildings are found. Wooden or marble lattices fill large openings to subdue the glare of the sun while permitting the breeze to pass through. Such arrangements characterize the architecture of hot zones, and evoke comfort as well as aesthetic satisfaction with the visible endeavors of man to protect himself against the excessive heat. Today a great variety of devices such as sun-breakers or brise-soleil have been added to the vocabulary of architectural features in these zones.

Notice, too, how the gabled roof decreases in pitch as the rate of precipitation decreases. In Northern Europe and most districts subjected to heavy snow, gables are steep, while in the sunnier lands of the south, the pitch steadily decreases. In the hot countries of the North African coast the roofs become quite flat, in some areas providing a comfortable place to sleep. Still further south, in the tropical rainfall zone, the roofs are again steep to provide protection from the torrential downpours typical of the region.

It is worth noting that so long as the people of the humid tropical regions built their huts with reeds and grass, which allowed air to pass through the walls, the steeply pitched roof was a useful device. However, once they began to use more sophisticated materials like cement block and the common gabled roof topped with corrugated iron sheets, the houses became unbearably hot and stuffy. This kind of roof prevents the catching of draughts at the very level where they prevail, and the solid walls prevent the passage of air.

The traditional flat roof and the brise-soleil of recent tropical architecture, with its modern feel, have attracted the imagination of architects in colder regions who are continuously searching for something different and exotic. The result is that in some northern cities thoroughly inappropriate examples of architecture, with shapes suitable to an alien climate, have succeeded in making the neighboring buildings look old-fashioned without responding to the needs of the people in their climate. The temptation to create up-to-date designs which assails a modern architect prevents him from achieving the chief aim of architecture: to be functional. He forgets the environment into which he will implant his buildings because he is attracted by new and modern innovations and gadgetry. He fails to realize that form has meaning only within the context of its environment.

Environment

The techniques and equipment available to the architect today free him from nearly all material constraints. He has the run of centuries of styles and can choose his plans from every continent on earth. But he must remember that he is not building in a vacuum and placing his houses in empty space, as mere plans on a blank sheet of paper. He is introducing a new element into an environment that has existed in equilibrium for a very long time. He has responsibilities to what surrounds the site, and, if he shirks this responsibility and does violence to the environment by building without reference to it, he is committing a crime against architecture and civilization.

What constitutes the environment of a building? Briefly, it is all that surrounds the site on that part of the Earth, including the landscape, be it desert, valley, mountain, forest, seaside, or riverside, and what is above the surface with its seven zones that envelop the Earth and influence terrestial life. The zone most concerned here is the first, the atmosphere. This zone rises to an average height of 10 kilometers and reaches 20 kilometers in the Tropics. It contains the humidity on which human, animal, and plant life depend. In the six zones above the atmosphere, oxygen, ozone, and hydrogen are present in different concentrations that affect the cosmic radiation reaching the surface of the earth. In the natural order prevailing in the environment, there has always existed a continuous balanced flow of cosmic radiation within which all living organisms and even minerals have been created and evolved.

Some materials are transparent and some are opaque to the various components of this radiation. Man should be careful not to disturb the natural electromagnetic balance by improperly selecting the material he uses for his dwelling. Thus wood is a more desirable material for man's surroundings than reinforced concrete. Aesthetically, man appears to prefer wood within his dwelling in the form of furniture and structural elements, which he often describes as warm, contrary to steel or other metals, which he describes as cold. This psychological effect can be explained in part scientifically by the physical properties of both materials, including their heat conductivities and insulation characteristics.

These details demonstrate that the architect has a moral responsibility to consider whatever may affect the efficiency of the building and the well-being of the people whom he is housing. Besides the tangible and measurable features of the environment, there exist intangible elements, but insufficient scientific information prevents their use in town planning and architectural design. Therefore, this discussion is limited to the tangible and measurable elements of the environment, mainly the climate.

The importance of climate is clear. All living organisms depend entirely on climate for their existence and adapt themselves to this environmental influence. Plants that live in the Tropics cannot live in the Arctic, nor can arctic plants live in the Tropics, unless of course the immediate local conditions—the microclimate—are arctic, as at the top of a high equatorial mountain. Most organisms, in fact, are limited to a habitat of narrow climatic range.

Conscious Modification of the Microclimate

Yet not all species are so limited. Many animals can regulate their own internal body temperature and can maintain it at a constant value even during considerable fluctuations of the air temperature. Man has an elaborate and very sensitive mechanism involving the secretion of sweat and the distribution of blood that keeps him at about 37 °C at all times. In general, warm-blooded animals can survive wider variations than cold-blooded ones. Some species manipulate their environment to produce a favorable microclimate: the tortoise does so when it hibernates for the winter. Man, too, does this in a variety of ways. He can change his microclimate by changing his clothes, building a house, burning fuel, planting trees, digging artificial lakes, and using machines to heat, cool, moisten, or dry the air around him.

A principal purpose of building is to change the microclimate. Early men built houses to keep out the elements—rain, wind, sun, and snow. Their purpose was to produce an environment favorable to their comfort and even to their survival. The microclimate on each building site is changed into several different microclimates as the result of the construction of the house itself. The microclimate adjacent to the south wall is quite different from that at the north wall, and the climates at the east and west walls are again different. Inside the building, each room has its own microclimate which is a modification of one or more of the outdoor microclimates.

Before the advent of the industrial era and mechanization, man depended on natural sources of energy and available local materials in forming his habitat according to his physiological needs. Over many centuries, people everywhere appear to have learned to interact with their climate. Climate shapes the rhythm of their lives as well as their habitat and clothes. Thus, they build houses that are more or less satisfactory in providing them with the microclimate that they need. In the warm humid lands of East Asia, the local inhabitants live in huts with flimsy, loosely woven walls that allow the slightest breeze to pass through. The people who live under the blazing sun of the desert construct houses with thick walls to insulate themselves from the heat, and with very small openings to keep out hot air and the glare of the sun.

These successful solutions to the problems of climate did not result from deliberate scientific reasoning. They grew out of countless experiments and accidents and the experience of generations of builders who continued to use what worked and rejected what did not. They were passed on in the form of traditional, rigid, and apparently arbitrary rules for selecting sites, orienting the building, and choosing the materials, building method, and design.

In any approach prescribed by tradition, it is essential that every injunction of the tradition be strictly observed. Thus, if one element were changed in a traditional building method, that change, though small, could destroy the entire validity of the building as a satisfactory solution to the local climatic problems. In this sense, both the material and the way it is used are very important. For example, if mat screens are replaced by corrugated iron or some other solid wall material, then even though the building may appear more substantial, the lack of ventilation could make the interior intolerably hot and stuffy. Modern architects have attempted to solve this problem with modern technology, for instance, introducing the vented screen-wall, using unshaded concrete or brick *claustra*-work to replace the objectionable solid wall. Many different examples of this can be seen in entire elevations of modern buildings in tropical zones. While such a solution is a definite improvement over the solid wall, careful investigation reveals that it is not as efficient as the humble mat screen. When the sun-breaking or brise-soleil elements of the *claustra*-work are not shaded, they heat up and then transmit this heat to the air flowing into the building through the *claustra*-work, as well as reflecting warming solar radiation into the interior.

Every substance that has formed part of a living organism will retain some of its original qualities of climatic response as long as its original structure is not destroyed or significantly modified. Wood, hair, grass, leaves, reeds, cotton, hemp, and other organic materials are sensitive to air humidity. When increased ventilation and humidity are required, matting responds to its climate by absorbing moisture from the air passing through it into the building, thereby reducing the degree of humidity in the room. In contrast, *claustra*-screen walls can breathe, but they do not perspire. A mat, being porous, is a poor heat conductor, and cools to below air temperature by evaporating the moisture it has captured from the air. Thus it cools the air passing through it. Furthermore, a closely woven mat with loose fibers and bristles around the ropes will intercept dust as well.

Trends in International Architecture

Changing a single item in a traditional building method will not ensure an improved response to the environment, or even an equally satisfactory one. Yet change is inevitable, and new forms and materials will be used, as has been the case throughout history. Often the convenience of modern forms and materials makes their use attractive in the short term. In the eagerness to become modern, many people in the Tropics have abandoned their traditional age-old solutions to the problems presented by the local climate and instead have adopted what is commonly labeled "international architecture," based on the use of high-technology materials such as the reinforced-concrete frame and the glass wall. But a 3 × 3-m glass wall in a building exposed to solar radiation on a warm, clear tropical day will let in approximately 2000 kilocalories per hour. To maintain the microclimate of a building thus exposed within the human comfort zone, two tons of refrigeration capacity are required. Any architect who makes a solar furnance of his building and compensates for this by installing a huge cooling machine is approaching the problem inappropriately and we can measure the inappropriateness of his attempted solution by the excess number of kilocalories he uselessly introduces into the building. Furthermore, the vast majority of the inhabitants of the Tropics are industrially underdeveloped and cannot afford the luxury of high-technology building materials or energy-intensive systems for cooling. Although traditional architecture is always evolving and will continue to absorb new materials and design concepts, the effects of any substitute material or form should be evaluated before it is adopted. Failure to do so can only result in the loss of the very concepts that made the traditional techniques appropriate.

Only a scientific approach to the evaluation of such new developments can save the architecture of the Tropics and Subtropics. The thoughtless application of modern methods in this region is seldom successful. A thorough understanding of the climatic environment and developments based thereon is essential for appropriate solutions. Although traditional architecture was evolved intuitively over long periods, it was based primarily on scientifically valid concepts. The modern academic world of architecture does not emphasize the value of investigating and applying concepts scientifically and, therefore, has no respect for vernacular architecture. Now is the time to bridge the gap between these widely different approaches.

All traditional solutions should be evaluated scientifically before they are discarded or substitutes proposed. The phenomena of the microclimate must be analyzed and new building materials, methods, and designs must be tested until the complex relationships among buildings, microclimate, and human beings are fully understood. Fortunately, agriculture is perhaps even more intimately affected by the microclimate than architecture, and agricultural scientists have long made careful observations of the climate near the ground and in small localities. Their findings are available to those interested in tropical and subtropical architecture.

Another science to which architecture is indebted is aerodynamics. The methods of investigating airflow around the wings and bodies of aircraft are now being used to study airflow through, over, and around buildings. Scaled and full-size models can be tested in wind tunnels to determine the effect of the size, location, and arrangement of openings on the airflow through individual buildings, as well as the nature of wind patterns and forces between groups of buildings.

Today more attention is being given to the relationship between climate and architecture, and several building research organizations are beginning to examine this relationship.

Various disciplines, including aerodynamics and meteorology, provide an impressive stock of facts that are extremely useful to architecture. The architect is responsible for interpreting these facts and applying them to his designs. In this respect, he resembles the attending physician, who, though using the expertise of the physiologist, radiologist, or bacteriologist, is the only person who can actually undertake the treatment of a case.

2

Architectural Thermodynamics and Human Comfort in Hot Climates

The properties of matter and energy must be considered in order to fully understand climatic phenomena. Heat, radiation, pressure, humidity, and wind, among other factors, interact mutually to establish climate conditions near the Earth's surface.

In this environment of continuously changing pressure, wind movement, temperature, humidity, and cloud cover, an architect places a fixed building. Such a rigid structure is intended to provide a comfortable internal environment over a wide range of these external variables. Two factors facilitate this task: first, in temperate and subtropical zones, ordinary buildings offer fair protection from climatic extremes, and, second, the human body has a considerable margin of tolerance for these variables. However, special treatment is required, particularly in tropical zones.

When considering the architectural design of a building, as well as in town and regional planning, other elements should be considered. The continuous daily motion of the population, which has properties analogous to the humidity concepts of saturation, evaporation, and condensation, must be accommodated in houses, towns, and regions.

Any living organism continuously adapts itself to the flux of its environment. Once constructed, however, a man-made object can no longer adjust itself. This inflexibility of human creation is at once its weakness and its strength. A design can succeed in uniting the particular and permanent with the universal and continuously changing. Yet another design, by failing to sense the forces at work or to create a harmonious union, can isolate and alienate human life.

Before considering the application of scientific concepts to architectural design and town planning, it is useful to briefly examine some basic concepts of architectural thermodynamics and human comfort.

Temperature

The concept of *temperature* describes the degree of heat contained in a body or a fluid medium or some region thereof, but a clear definition usually is a description of the operations performed in its measurement. Since heat flows from hotter to colder bodies or substances, temperatures can be measured by bringing a thermometer into intimate contact with the body or substance. The thermometer is then assumed to acquire the same temperature.

Scientists use two conveniently reproducible temperatures, the freezing and boiling points of water, to establish temperature scales. On the Celsius scale, the first was taken to be 0° and the second 100°. On the Fahrenheit scale, these values are 32° and 212°, respectively. The temperature of a body so cold that it is incapable of giving up any heat is called absolute zero, −273.15 °C or −459.67 °F. However, no limit for maximum temperature is known to exist.

The air temperature range of interest here is that of the extremes in the usual human habitats. Meteorologists have observed air temperatures of −93 °C (−135 °F) and 57 °C (135 °F) at the Earth's surface, a range of merely 150 C° or 270 F°. But narrow though this range may be, it is enormous in comparison with the variation of temperature that the human body can endure within itself. The body maintains a constant temperature of about 36 °C (98.6 °F) at the mouth, increasing to about 37.2 °C (99 °F) in the deep tissues, and can rarely survive if this temperature varies even by 1 C° (about 2 F°) for prolonged periods.

Thermal Conduction and Resistance

The concepts of thermal conduction and resistance are important in attempting to provide a comfortable environment for the inhabitants of hot, arid regions. These heat-flow concepts are based on the movement of a *quantity of heat*.[1]

The *specific heat* of a substance is the quantity of heat energy required to raise the temperature of one unit mass of the substance by one degree of temperature.[2]

When considering heat-flow concepts, the notion of *rate of heat flow* is useful. It equals the rate of displacement of a quantity of heat.[3]

Conduction is the process by which heat flows through a material, or from one material to another with which it is in contact. Some materials, such as metals, are good thermal conductors, while others, like air, are poor thermal conductors. *Thermal conductivity* is a specific property of a material and is a measure of the rate at which heat will flow through a material when a difference in temperature exists between its surfaces. It is defined as the quantity of heat that will flow through a unit area in a unit time, or equivalently, as the rate of heat flow through a unit area, when a unit of temperature difference exists between the faces of the material of unit thickness,[4] such as the wall

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[1] The symbol for quantity of heat is q. In the metric system, the joule (J) and the kilocalorie (kcal) are used to measure the quantity of heat; in the British system, the British thermal unit (Btu) is used. One kilocalorie is defined as the quantity of heat energy required to raise 1 kilogram of water at 15 °C by 1 Celsius degree, or as 4186.8 J. One Btu is defined as the quantity of heat energy required to raise 1 pound of water at 60 °F by 1 Fahrenheit degree, or as 0.252 kcal or 1055 J.

[2] The symbol for specific heat is c. In the metric system, specific heats are measured in joules/kilogram · Celsius degree $[\mathrm{J} \cdot \mathrm{kg}^{-1} \cdot (\mathrm{C\ deg})^{-1}]$ or in kilocalories/kilogram · Celsius degree $[\mathrm{kcal} \cdot \mathrm{kg}^{-1} \cdot (\mathrm{C\ deg})^{-1}]$. In the British system, specific heat is measured in British thermal units/pound · Fahrenheit degree $[\mathrm{Btu} \cdot \mathrm{lb}^{-1} \cdot (\mathrm{F\ deg})^{-1}]$. Owing to the definitions of the kilocalorie and the Btu above, the units of specific heat determined using these quantity-of-heat units are identical, and thus the numerical value of the specific heat is the same in either of these units, i.e.:

$$1\ \frac{\mathrm{kcal}}{\mathrm{kg} \cdot \mathrm{C\ deg}} = 1\ \frac{\mathrm{Btu}}{\mathrm{lb} \cdot \mathrm{F\ deg}}.$$

However, since 1 kcal = 4186.8 J, this is not true for the specific heat measured in $\mathrm{J} \cdot \mathrm{kg}^{-1} \cdot (\mathrm{C\ deg})^{-1}$, which is

$$1\ \frac{\mathrm{kcal}}{\mathrm{kg} \cdot \mathrm{C\ deg}} = 4186.8\ \frac{\mathrm{J}}{\mathrm{kg} \cdot \mathrm{C\ deg}}.$$

Thus, the quantity of heat necessary to raise the temperature of a mass, m, of a substance by a temperature difference ΔT is obtained using the equation,

$$q = cm\Delta T. \tag{1}$$

[3] The symbol for rate of heat flow is Q. This is expressed in joules/second (J/s), defined as watts (W) or kilocalories/second (kcal/s) in the metric system, and in British thermal units/second (Btu/s) in the British system.

[4] Thermal conductivity is commonly expressed by the symbol k and is measured, in metric units, in joules/second · meter · Celsius degree $[\mathrm{J} \cdot \mathrm{s}^{-1} \cdot \mathrm{m}^{-1} \cdot (\mathrm{C\ deg})^{-1}]$, equivalent to watts/meter · Celsius degree $[\mathrm{W} \cdot \mathrm{m}^{-1} \cdot (\mathrm{C\ deg})^{-1}]$, in kilocalories/second · meter · Celsius degree $[\mathrm{kcal} \cdot \mathrm{s}^{-1} \cdot \mathrm{m}^{-1} \cdot$ (C

shown in figure 1. The thermal conductivity varies with the density, porosity, and moisture content of the material and also with the absolute temperature. The quantity of moisture contained in a material can have a considerable effect on the thermal conductivity of the material; the higher the moisture content, the greater the thermal conductivity. This is important because rain penetration, high humidity within a building, and condensation may result in an appreciable amount of moisture in the building structure. The average temperature of a material is another factor influencing the rate of heat flow; the thermal conductivity may be considerably greater at high than at low temperatures. However, the variation of the thermal conductivity over the range of temperatures commonly occurring in buildings is comparatively small, and thus the thermal-conductivity values measured at normal atmospheric temperature are generally used when considering structural insulation.

In calculations, it is often convenient to use the reciprocal of the thermal conductivity which is called the *thermal resistivity*.[5] The thermal resistivity may be regarded as either the time required for the transmission of one unit of quantity of heat through one unit area of a rectangular solid material of unit thickness, when the difference between the temperatures of the surfaces perpendicular to the direction of heat flow is one degree of temperature; or the number of degrees difference between these surfaces of the material of unit thickness when one unit of quantity of heat flows through one unit area in one unit of time. Thus resistivity, like conductivity, is a property inherent to a material and is independent of its thickness.

The *thermal resistance* is a measure of the resistance to heat flow of a

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deg)$^{-1}$], or in British thermal units/second · foot · Fahrenheit degree [Btu · s^{-1} · ft^{-1} · (F deg)$^{-1}$]. Therefore, k can be determined by

$$k = \frac{Q\ L}{A\,\Delta T}, \tag{2}$$

where L is the thickness of the material, and A is its area.

5. For a constant flow of quantity of heat, the thermal resistivity, $1/k$ is

$$\frac{1}{k} = \frac{tA\,\Delta T}{qL} = \frac{A\,\Delta T}{QL}. \tag{3}$$

Thermal resistivity is measured in units of C deg · m · s · J^{-1} or C deg · m · W^{-1}, C deg · m · s · kcal^{-1}, or F deg · ft · s · Btu^{-1}.

material or a combination of materials.[6] The thermal resistance may be regarded as either the time required for the transmission of one unit of quantity of heat through one unit area of material when the temperature difference between surfaces perpendicular to the direction of heat flow is one degree of temperature; or the number of degrees difference in temperature between these surfaces when one unit of quantity of heat flows through one unit area in one unit time. If the thickness of the material is increased there is a corresponding proportional increase in its thermal resistance. If several materials are placed together in layers, as, e.g., in a plastered and rendered solid brick wall, as illustrated in figure 2, the total thermal resistance of the wall may be obtained by adding the resistances for each component, i.e., of the plastering, rendering, and brick masonry.[7]

The *thermal conductance* is the rate of heat flow through a material or a combination of materials and is therefore the reciprocal of the thermal resistance.[8] The thermal conductance is the quantity of heat that will flow per unit time per unit area of a material for a one degree temperature difference between its surfaces. If the thickness of the material is increased, its conductance decreases proportionately.

The thermal conductance and resistance and thermal conductivity and resistivity already considered have been related to the tempera-

6. Thermal resistance, R, is defined as

$$R = \frac{L}{k}. \tag{4}$$

However, substituting for the resistivity from eq. (3) in fn. 5 gives

$$R = \frac{tA\,\Delta TL}{qL} = \frac{tA\,\Delta T}{q} = \frac{A\,\Delta TL}{QL} = \frac{A\,\Delta T}{Q}. \tag{5}$$

This is measured in units of C deg · m^2 · s · J^{-1} or C deg · m^2 · W^{-1}, C deg · m^2 · s · kcal^{-1}, or F deg · ft^2 · s · Btu^{-1}.

7. The total thermal resistance of the 1, 2, . . . , n components of a wall with thermal resistances of R_1, R_2, . . . , and R_n, respectively, will then be

$$R = R_1 + R_2 \ldots + R_n. \tag{6}$$

8. Thermal conductance, C, is thus

$$C = \frac{1}{R} = \frac{k}{L} = \frac{q}{tA\,\Delta T} = \frac{Q}{A\,\Delta T}, \tag{7}$$

and is measured in J · s^{-1} · m^{-2} · (C deg)$^{-1}$ or W · m^{-2} · (C deg)$^{-1}$, kcal · s^{-1} · m^{-2} · (C deg)$^{-1}$, or Btu · ft^{-2} · s^{-1} · (F deg)$^{-1}$.

tures at the material surfaces. The surface temperatures of a building usually are not known. For purposes of heat-loss calculations, therefore, the inside and outside air temperatures are used. In this situation, heat transfer from the warmer to the cooler air mass occurs in three steps: first from the warmer air to the structure, then through the structure, and finally from the structure to the cooler air. Both the inside and outside air-surface interfaces provide some resistance to heat flow.

The *thermal transmittance* includes these surface resistances and is the rate per unit area at which heat will flow from the air on one side of the structure to the air on the other side. It may be defined as the quantity of heat that will flow per unit time per unit area through the material when one unit of temperature difference exists between the air on each side.[9] In fact, the thermal transmittance may be regarded as the overall air-to-air conductance, which is the reciprocal of the overall air-to-air resistance.[10] The thermal transmittance is of considerable practical importance. It provides a basis both for comparing the insulating capabilities of different wall, floor, and room constructions; and for calculating heat loss from a building for heating purposes in cold climates, and heat gain for cooling purposes in hot climates.

Radiation

All matter emits electromagnetic waves which are generated by the thermal motion of molecules composing the material. Such radiation is called thermal radiation. The intensity and wavelength distribution of this radiation depend on the nature and temperature of the material.

A perfectly opaque material with a totally absorbing and therefore totally nonreflecting surface, which is usually called a black body, emits radiation at the maximum possible rate for any given temperature. This black body is a convenient concept used as an idealized standard, but which should not be confused with an actual object with a black-colored surface. For such an object, the rate of radiation

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[9] Thermal transmittance, U, is thus measured in the same units as thermal conductance.

[10] Thus, following relation (6) in fn. 7, with all these components included in the summation, the total air-to-air thermal transmittance is

$$U = \frac{1}{R_1 + R_2 + \ldots + R_n}. \tag{8}$$

emission depends only on the fourth power of its absolute temperature.

As the temperature of the radiating object increases, the wavelength of maximum radiation intensity becomes shorter, and the distribution changes so that a greater proportion of the energy is radiated at shorter wavelengths (i.e., with higher energy). At temperatures below about 500 °C (about 900 °F), the emission consists almost entirely of wavelengths too long to be observed as light. At about 700 °C (about 1300 °F), the object glows with a dull red color. As the temperature increases further, the wavelength of maximum emission decreases, and the color shifts successively to bright red, yellow, and white.

The energy emitted by a radiating body ultimately impinges on other matter, which absorbs it, reconverting the energy into heat. In this way heat is transferred from one place to another by radiation.

At ordinary temperatures, most nonmetallic surfaces, including painted surfaces, radiate virtually as black bodies—their emissivity is high, and they are good absorbers for long wavelength radiation. Thus, various paints ranging from black to white are found to be indistinguishable as regards heat radiation at temperatures up to 100 °C (212 °F). However, whereas dark paints absorb most of the short wavelength radiation received from the sun, white pigments reflect most of it. And, at temperatures up to 100 °C (212 °F) aluminum and other metallic paints have an emissivity only about one-half that of a black surface. On the other hand, highly polished metals are strong reflectors of radiation, and many such surfaces are almost perfect reflectors of the long wavelength (low-energy thermal) radiation emitted by bodies at ordinary room temperature.

Emissivity, Absorptivity, and Reflectivity

Reference has been made to the importance of surfaces for heat transfer by radiation. To evaluate their emissive, absorptive, and reflective properties, surfaces can be compared with the properties of a black body, which absorbs all radiation falling on its surface and therefore reflects none.

The emissivity of a surface at a given temperature is equivalent to its absorptivity for radiation from another body at the same temperature, since two bodies at the same temperature will remain in thermal equilibrium with each other. The emissivity, and hence the absorptivity, of a black body has by definition, a value of unity, with the values of all real surfaces being in practice less than this value. Radiation falling on an opaque surface is partly absorbed, and the remainder is reflected. Since the incoming radiation can only be absorbed or reflected, the sum of the absorptivity and reflectivity must equal unity. For example, at normal temperatures, an aluminum foil may have an emissivity of 0.05, and thus its absorptivity will also be 0.05, but its reflectivity will be 0.95. This means that it emits by radiation only 5% of the amount a black body emits at normal temperatures. Also, it absorbs only 5% of the radiant energy falling on it (from another body at normal termperatures), and it reflects the other 95%.

The emissivity of a surface at normal temperatures (10–38 °C or 50–100 °F) is not necessarily the same as its absorptivity for radiation received from the sun. Emissivities at normal temperatures are important when considering heat losses from buildings through cavity-wall, floor, or roof constructions. For external surfaces, the absorptivity for solar radiation is important when considering heat gain from the sun. Table 1 gives these characteristics for some common surfaces.

Table 1 shows that the emissivities of white and dark paints are about equal at normal temperatures but that white paint has a much lower absorptivity for solar radiation. A roof coated externally with white paint gains less heat from the sun than if it were a dark color.

Table 1. Average emissivities and absorptivities for some common building surfaces under relevant conditions

Surface	Emissivity or Thermal Absorptivity at 10–38 °C (50–100 °F)	Absorptivity for Solar Radiation
Black nonmetallic surfaces	0.90–0.98	0.85–0.98
Red brick, concrete, and stone, dark paints	0.85–0.95	0.65–0.80
Yellow brick and stone	0.85–0.95	0.95–0.70
White brick, tile, paint, whitewash	0.85–0.95	0.30–0.50
Window glass	0.90–0.95	Transparent
Gilt, bronze, or bright aluminum paint	0.40–0.60	0.30–0.50
Dull copper, aluminum, galvanized steel	0.20–0.30	0.40–0.65
Polished copper	0.02–0.05	0.30–0.50
Highly polished aluminum	0.02–0.04	0.10–0.40

Source: *Heating and Air Conditioning Guide*, American Society of Heating and Ventilating Engineers.

Table 2. Reflectivities of various materials and paints

Material or Paint	Reflectivity (%)
Red brick or stone	30–50
Slate	10–20
Asphalt bituminous felt	10–20
Galvanized metals (new)	36
Dark paints	10–20
Aluminum paints	40–50
Polished metals	60–90
Whitewash or white paints	80–90

Source: N. S. Billington, *Journal of the Institute of Heating and Ventilating Engineers* 19, no. 190 (June 1957).

Table 2 gives the reflectivities of various materials and paints.

Transparency

Some substances, such as glass, rock salt, liquids, and gases, are more or less transparent to radiation of certain wavelengths. Glass is transparent to wavelengths within the visible range of the spectrum, but absorbs radiation in the infrared or thermal region, while rock salt transmits a high percentage of infrared radiation. Most solids, however, are opaque to thermal radiation, and in such cases the emission and absorption of radiation are surface phenomena. Thus, the low emissivity of a burnished metal surface depends on the cleanliness of the surface. A very thin film of nonmetallic material, e.g., transparent varnish or grease, will increase the emissivity of the metal surface almost to that of a black body.

Clothing and human skin radiate virtually as black surfaces. For radiation at the wavelengths encountered in buildings and other living spaces, the absorption of clothing and skin approximates that of a black object. Indoors, white clothing has no advantage over black. But outdoors in the sun, although both materials radiate heat freely, white clothing reflects most of the solar radiation, while black clothing absorbs the sun's rays.

If the human body emits more radiant energy than it receives from its surroundings, it is, on balance, losing heat by radiation. If, on the other hand, the radiation received exceeds that emitted, there is a net heat gain by the body.

Thermal Convection

Natural or free convection is the process whereby a fluid moves because of differences in its density resulting from temperature changes. If the fluid is moved by mechanical means, e.g., by pumps, fans, or wind, the process is called forced convection. Heat may be transferred by convection between a surface and a liquid or a gas.

Discussions of thermal comfort involve the heat transfer between a surface and the neighboring air. When the surface is at a temperature above that of the air, heat is transferred from the surface to the adjacent air by conduction, thereby changing the density of the heated air. Then, even in otherwise still air, air currents result from the gravitational effects due to the differences in density. These natural convection currents cause much greater heat transfer from the surface than would result from conduction in a perfectly still atmosphere. Obviously, the rate of heat transfer by natural convection depends on the temperature difference between the surface and the neighboring air.

Perfectly still air is rare. Even in a closed compartment, variations in the temperature of the walls and other surfaces set up air currents, so that there is some air movement. If fans are employed or if there are openings to the outside, the air movement may be considerable. These currents increase heat transfer by convection. The speed of the air current and the temperature difference affect the rate of heat transfer by convection.

Air is a gaseous fluid containing by volume (excluding the water vapor content) 21% oxygen, 78% nitrogen, and a remaining 1% consisting of traces of rare gases (argon, neon, and krypton), carbon dioxide (from 0.3 to 0.4 liters per m^3), and carbon monoxide (about 0.03 liters per m^3 in urban areas and much less in the countryside). Air also contains water vapor from four parts per thousand to two parts per hundred. Dust and soot particles in air are visible as motes in a sunbeam. The oxygen, nitrogen, and other rarer gases are called permanent gases because they only become liquids at temperatures approaching absolute zero, whereas water undergoes continuous change between its gaseous and liquid states within the common range of air temperatures encountered in human climatic zones.

Atmospheric Pressure

Air exerts a pressure on any surface in the atmosphere which corresponds to the weight of the column of air that it supports. Every surface in the neighborhood of sea level carries a load of about 1 kg per cm^2, or 1 ton per ft^2. As the altitude increases above sea level, the atmosphere below no longer contributes to the pressure, which is correspondingly reduced.

Using this concept, atmospheric pressure can be expressed as the height of a column of mercury in a barometer, in millimeters or inches, with the pressure at sea level being 760 mm or 29.9 inches of mercury at a standard temperature of 0 °C (32 °F). The barometer reading must be corrected for the temperature of the mercury as well as for the latitude.

The bar is the unit of pressure in an absolute system of measurement adopted for scientific use to replace the arbitrarily chosen column of mercury. Atmospheric-pressure measurements in meteorological work are normally expressed in units of one millibar. One bar corresponds very nearly to 750 mm or 29.5 inches of mercury at 0 °C (32 °F), or 1019 cm or 401 inches of water, which is the atmospheric pressure a little above sea level.

Water Vapor

At temperatures throughout the climatic range of the normal human habitat, water can exist as solid ice, liquid water, and gaseous water vapor. At the freezing point, ice and water can exist together. Above this temperature ice is completely converted to water, and below it, only ice exists. However, regardless of whether the water is solid or liquid, the air above it contains a certain amount of water vapor.

Generally speaking, the permanent gases in the air produce the pressure indicated by a barometer. However, if water is present at the base of the column of air, that water partially evaporates (becomes water vapor) and contributes to the atmospheric pressure. This share depends on the temperature. Air containing the maximum possible amount of water vapor for its temperature is said to be saturated. The temperature at which condensation begins in a mixture of air and water is termed the dew point.

There are several ways to express the relation between humidity and temperature. The amount of water vapor that a volume of air can support at saturation can be expressed as grams or grains of vapor per volume of air, or as the portion of the total atmospheric pressure that the water vapor contributes. Similarly, the water-vapor content of unsaturated air can always be expressed as the portion of the total pressure that the water vapor contributes, called the vapor pressure, or as the amount of atmospheric water vapor in grams per m^3 or grains per ft^3. These values can also be determined with respect to the dew point, which is the temperature to which air must be reduced, without altering its barometric pressure, to reach saturation. In this way, the water-vapor content of air at a given temperature can be expressed as the ratio of the portion of the total atmospheric pressure contributed by water vapor to the portion necessary to cause saturation at that air temperature. This ratio, most often expressed as a percentage, is called the relative humidity.

Appendix 1 gives the values of water-vapor density and pressure for saturated water vapor over the range of temperatures from −10–34 °C (14–93 °F).

A given volume of water vapor is lighter than the same volume of air at the same temperature and pressure. In the atmosphere, therefore, saturated air is lighter than dry air of the same temperature and pressure. When water evaporates, the vapor simply rises into the air. If this process occurs in open air where there is freedom of motion, the water vapor can displace the equivalent volume of dry air without affecting the atmospheric pressure. Near water surfaces, therefore, rising water vapor is continuously replaced by dry air, which in its turn dampens and rises into the air. This water vapor eventually reaches a certain height, condenses on the floating particles always present in air, and becomes visible as clouds.

The processes involved in weather phenomena are not so simple. Such factors as heat, radiation, pressure, and wind interact to establish relative balances in the atmosphere, resulting in the constant recycling of water by evaporation, cloud formation, cloud motion, and precipitation.

Water vapor and temperature, pressure, and air movement are very important to the study of the climate and the microclimate both outside and inside buildings. They are key to an understanding of the formation of clouds, rain, dew, frost, and nearly all other meteorological phenomena. The behavior of water vapor must be understood to comprehend the physical and physiological processes of cooling by evaporation—the phenomenon upon which thermal comfort in hot climates largely depends. If air in a room is saturated with water vapor and its temperature decreases, then some water vapor will condense, leaving in the air only the amount that can be accommodated at the new temperature. However, if the air temperature rises, the air can accommodate additional water vapor and is called "dry air." This air can be described as "thirsty" until its temperature falls or it encounters water from which it can absorb vapor.

In winter, a dry feeling in the throat can result when moisture from the human body evaporates in a room overheated by a stove. A heated kettle of evaporating water can reestablish the moisture content of the air, corresponding to its increased temperature. The same feeling of dryness occurs in hot weather when evaporation of perspiration is necessary to lower body temperature. Here a parched throat indicates the need to drink water to maintain the supply of perspiration.

When air temperature drops below the saturation point, water collects in droplets on the dust particles always floating in the air. Or, if the air is in contact with a sufficiently cold surface, water vapor will condense on that surface. Thus water condenses on cold walls just as on a drinking glass containing a liquid cooled by ice. Similarly, when an amount of water vapor exceeding the saturation limit is introduced into air in an enclosed space, the excess vapor will condense, as on a bathroom mirror in winter or on the inner surfaces of the windows of a closed automobile with many people.

Cooling by Evaporation

Water will evaporate from a wet surface if it is exposed to air with a dew point lower than the surface temperature. The rate at which water evaporates from the surface depends on the relative humidity of the neighboring air, the surface temperature, and the velocity of air movement. Thus, for a wet surface at a given temperature, a reduction in relative humidity or an increase in air velocity both increase evaporation.

Energy is needed to convert water from liquid to vapor. This latent heat of evaporation must be supplied by the wet surface, which thus loses heat or is cooled. This process is called adiabatic cooling, because it does not involve a transfer of heat to or from the air participating in the process. Therefore, the air is allowed to cool as it expands and to heat as it contracts, and the temperature, pressure, and relative humidity of the air change without varying the total heat content.

This phenomenon is used for cooling in hot dry areas such as in Iraq, where the people place against the windows panels of dried desert plants, which are kept moist by water dripping from perforated pipes positioned above them. In the grasslands of Australia, where farmers cannot obtain ice, butter is kept cool in food chests with sides of chicken-wire netting filled with charcoal. When the chests are placed in the shade outside and their sides are kept moist with occasional sprinkles, a sufficiently cool environment is maintained in the chest.

Thermal Gain

The various ways in which the interior of a building can gain heat without recourse to internal heating devices can be examined. Solar radiation is the principal source of heat in hot arid zones, and this heat can be transmitted during the day to the building interior in a number of ways.

The most important is by conduction of the absorbed solar radiation through the walls or roof at a rate determined by the thermal conductance (or thermal resistivity) of the building material used, the surface area receiving solar radiation, and the properties of the surface, principally its color and texture. The relationship involving the incoming and reflected solar radiation, absorbed and reemitted heat and heat gain is shown in figure 3 for the case of a typical white painted surface. In this case, it is seen that 3% of the incident energy is transformed into heating the structure. Obviously, shading can be used to prevent solar radiation from directly falling on building surfaces.

If any openings permit the solar radiation to penetrate into the interior, then heat gain results from the direct heating of internal air, surfaces, and objects. The heat gain is proportional to the area of insolated internal surfaces. This mode of heat gain can be easily avoided by obstructing the passage of light.

Heat gain can also be caused by ventilation, which results when warm outside air flows into the building replacing the cooler interior air that escapes to the outside and by external air exchanging heat with the internal air. The rate of gain is dependent on the ventilation rate. Ventilation heat gain can be avoided by restricting the size of openings, especially during the heat of the day.

The other sources of heat gain are the inhabitants of the building themselves and household equipment such as electric lights and appliances. These sources, unlike the solar radiation, can contribute heat even at night.

Figure 4 illustrates these modes of heat gain.

Thermal Loss

The difference between diurnal and nocturnal heat losses in a building when not considering artificial cooling devices, is not marked as in the case of heat gain. Heat is lost by conduction through the walls, by exactly the same process that it is gained from the direct solar radiation once it has been absorbed by the surface, or through the roof by a combination of convection and conduction.

Ventilation is also another mode of heat loss which occurs when hot air escapes through an opening in the roof or a wall to be replaced by cooler air from outside. Nocturnal heat losses can be retarded by closing vents.

Evaporation from the surface of the building or from objects within the interior can produce a cooling effect on the building which acts as a source of heat loss. In hot arid climates, this can be a particularly effective cooling mechanism since the rate of evaporation in dry air is very high.

Figure 4 also shows the modes of heat loss.

Dynamic Thermal Equilibrium

At any particular time, the heat gained by the building can be expected to be balanced by the heat lost and an internal temperature distribution thus established. These temperatures are dependent on the outside (ambient) temperature and the ratio of the heat gained to the heat lost and can be adjusted by regulating the sources of heat gain and loss. For example, if one were to reduce to a minimum the heat losses of an insolated building, the internal temperature would rise, much as in the case of an automobile left in the sun with its windows closed. This is called greenhouse gain. On the other hand, a very cool internal temperature could be obtained by shading the insolated surface, obstructing direct penetration of solar radiation, enhancing a flow of cool air, using thick light-colored walls made of a low thermal-conductivity material, using high ceilings provided with roof ventilation, and providing sources of evaporation including possibly a roof pond and an internal fountain.

However, in fact, the temperature situation within a building changes slowly throughout the day for two important reasons. First, the solar radiation and external temperatures vary slowly, and the internal temperatures are constantly adjusting to the changing rates of heat gain and loss. Second, the mass of the building structure does not react instantaneously to external changes but has a thermal inertia requiring from many minutes to hours to adjust to a temperature change. The principle of thermal inertia can be used advantageously to provide dynamic heating and cooling of a building by selecting the wall material and its thickness such that the warmth of the day penetrates the building only after nightfall when it would be welcomed and is dissipated before morning.

Thus, it is seen that the microclimatic situation of a building is in a constant state of flux and that the equilibrium that is established is a dynamic one. When providing a comfortable microclimate, it is necessary to reduce the extreme fluctuations to within the range of human comfort by regulating the various parameters that govern heat gain and loss.

Before examining the systems and devices that have been developed to do this in the hot arid zones, it is first necessary to have an idea of the heat-regulating mechanism of the human body and the microclimatic conditions for human comfort.

Heat-regulating Mechanisms of the Human Body

As discussed earlier, the human body must maintain a fairly constant temperature over a considerable range of external air temperatures. The human body is subject to the same laws of physics as other objects, gaining and losing heat by the processes described above, namely: radiation through space; conduction between bodies and/or substances in contact; convection involving the transfer of heat from a warm body to a body of air above it, which then rises to be replaced by cooler air; and evaporation, which requires that the evaporating surface give up some heat. However, the human body is not simply a passive object warmed or cooled like metal or water. Its metabolic processes generate its own heat as well, similar to a heat-producing engine. Like any other engine, it burns fuel, in the form of food, and converts this into heat and work. As with an engine, work cannot be generated without producing some heat—even if unwanted—which must be dissipated just as for an automobile.

In a hot environment, the heat generated by the human body must be dissipated. Body heat regulation is essentially the maintenance of a balance between heat gains and losses. The body has an excellent heat-regulating mechanism, which under normal conditions can adjust its temperature to maintain the appropriate heat balance. Only when it is exposed to prolonged severe conditions do serious difficulties arise.

The metabolic processes of the living human body continuously generate heat. Even at complete rest, an important quantity of heat is produced. This basal heat production amounts to 73 kcal/h (290 Btu/h) for an average adult male. For a short time he can increase this rate eightfold through violent exercise, although over 24 hours the average heat production would not amount to more than 130% of the basal rate for sedentary work and 300% for heavy manual labor.[11]

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[11] Douglas H. K. Lee. *Physiological Objectives in Hot Weather Housing: An Introduction to Hot Weather Housing Design* (Washington, D.C.: Government Printing Office, 1953).

Table 3. Heat gain and loss processes for the human body

Mechanism	Gain Process	Loss Process
Metabolism	Basal heat production Digestion Activity Muscle tensing and shivering in response to cold	
Radiation	From solar radiation—direct and reflected From radiation by radiators	To surrounding air
Conduction	From air above skin temperature (increased by air movement) From warmer bodies in contact	To air below skin temperature To cooler bodies in contact
Evaporation		From respiratory tract From skin covered with perspiration or applied water

Table 3 shows the modes of heat gain and loss between the human body and its surroundings for the metabolic activities and three mechanisms of physical heat exchange, namely, radiation, conduction, and evaporation.

Air movement has a significant influence on the heat transfer between the skin and air and will increase the transfer rate in whichever direction it is proceeding, i.e., either to or from the body. Air movement increases the rate of heat loss by evaporation. For continued heat loss, the evaporated water vapor must be free to move away from the site of evaporation. Thus the difference between the vapor pressure at the skin surface and that of the surrounding air controls the ease with which evaporation cools the skin. The vapor pressure at the skin surface results largely from the extent to which a water film covers the skin, which may vary from less than 10% of the skin area on a cool, dry day, to 100% when the skin is bathed in perspiration.

The consequences of heat stress can be important. When the human body has difficulty losing heat, the blood vessels of the skin dilate, allowing much more blood to circulate and cooling by heat loss through any of the processes discussed above. But this increase in blood-vessel volume may exceed the body's ability to provide a corresponding amount of blood. To compensate, other blood vessels in the internal organs may receive less blood, although this still may not yield sufficient blood. During such a relative blood shortage, the brain, located at the highest part of the body, may be deprived of an adequate supply. Brain tissue is most sensitive to the shortage of oxygen and quickly produces the characteristic symptoms of "heat exhaustion": lassitude, headache, nausea, dizziness, uneasiness, and ultimately fainting. However, a wide range of lesser disturbances probably interfere with efficiency without resulting in total exhaustion. In addition, the human body has a remarkable sweating capability. With moderately hard work under hot dry conditions, a man can produce about 1.5 liters (3 pt) of perspiration per hour. Although he probably would not keep this up for more than two or three hours, he could lose as much as 8 liters (4 gal) in one day, which must be compensated for by drinking water. Eight liters is a large quantity of water for the body to handle, and even at lower sweating rates there probably will be periods when water loss exceeds supply. Then the already precarious blood supply is depleted still further and the risk of heat exhaustion is increased. Further indirect consequences of heat stress are lowered alimentary activity due to the insufficient blood supply, discomfort from hot and moist skin, the risk of skin disturbances when moist skin is chafed, possible salt deficiencies due to sweat loss, and perhaps urinary stones from reduced urine flow.[12]

Thus it is important to avoid conditions that stress human heat-regulatory processes until they interfere with normal body functions or health. A permanent state of human comfort need not be guaranteed, but there is a range of microclimatic conditions that can be maintained with an effort that is more than recovered by the saving in human efficiency. Securing this degree of climatic improvement should be the aim of tropical architecture.

Measurement of Conditions of Human Comfort

A convenient standard for thermal comfort is required. Analysis shows that a variety of factors can be involved in situations of discomfort. For example, temperature alone does not determine discomfort. In Athens, 32 °C (90 °F) is quite bearable, but it is generally intolerable in Bahrain. The difference is due entirely to the relative humidity of the atmosphere. In Bahrain the air is very humid and perspiration evaporates slowly, decreasing the body's ability to lose heat. In Athens, with its dry air, the evaporation rate is high and perspiration evaporates quickly, lowering body temperature.

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[12] Ibid.

The factors that have been identified as standard for thermal comfort within buildings are: air temperature, air humidity, rate of air movement, level of radiation, and rate of heat production by the bodies of people in the building. Extensive studies have established representative physiological scales that take into account all of these variables. An index used in the United States, and which with one limitation appears to provide an adequate measure of environmental warmth, is *effective temperature*. This takes into account temperature, humidity, and airspeed, but not radiation. Introduced by Houghton and Yaglou, this measure of heat sensation is defined as the temperature of saturated motionless air that would produce the same sensation of heat or cold as the combination of temperature, humidity, and air motion under consideration. An improvement on this measurement by Vernon and Warner uses the temperature given by the *globe thermometer* instead of the dry-bulb air temperature and thus includes an approximation of the radiation component. This standard is known as the *corrected effective temperature* and is the most useful scale of thermal sensation now available for the Tropics.

The effective temperature scale is in fact a physiological temperature scale. To establish it, a large number of people were exposed to wide ranges of temperature, humidity, and airspeed, and their sensations recorded. Later it was determined that the physiologically objective reactions of the subjects, such as pulse and perspiration rates, were in agreement with this effective temperature scale. However, it must not be assumed that this scale can be indiscriminately applied throughout the world with equal accuracy. Its American originators were the first to point out the limitations imposed by the fact that the scale was established from experiments on American subjects wearing clothing of American style and material. To establish an accurate, effective temperature scale for, say, Pakistan, a complete investigation using Pakistani subjects and clothing would be necessary.

The physical parameters to be measured and the instruments needed are shown in table 4.

Measurements made using a globe thermometer include the heating effects of infrared radiation emitted by warm flooring, roofing, and walls. The dry-bulb thermometer of a whirling psychrometer permits a nearly accurate evaluation of the basic air temperature; its speed through the air is sufficient to eliminate radiation effects. The Kata thermometer is superior to the usual type of vane anemometer. It indicates the sum of the effects of variable draughts to which a vane anemometer is not sensitive but which are physiologically important.

Table 4. Parameters to be measured for establishing an effective temperature scale and the corresponding instruments required

Parameter	Instrument
Air temperature	Silvered thermometer or whirling (dry-bulb) psychrometer
Air temperature including approximation of radiant heat contribution	Globe thermometer
Air humidity	Whirling wet-bulb psychrometer
Air movement	Kata thermometer

It also records velocities lower than most anemometers, and it needs no calibration.

Table 5 gives some examples of effective temperatures for different combinations of air temperature, relative humidity, and airspeed. For optimal comfort in air-conditioned buildings, the recommended range of effective temperatures is 22.2–23.3 °C (72–74 °F), corresponding to dry-bulb temperatures of 25.6–26.7 °C (78–80 °F), at 50% relative humidity.

Such physiological scales are useful when comparing the relative comfort of different sites. It should be remembered, however, that buildings can reduce the free wind speed. Studies in London have shown that wind speed at street level is generally about one-third of the unimpeded wind speed.

To subjectively compare human reactions to various conditions of heat, humidity, and airspeed, several microclimatic comfort sensation scales have been established. An example of such a scale and instructions for its use are given in Appendix 2.

At the London School of Hygiene and Tropical Medicine, a group of 32 students were asked to record their sensations of comfort under precise air-temperature, humidity, and airspeed conditions. They included approximately equal numbers of students from Great Britain and the United States, and from tropical countries. A summary of the student responses at 22.2 °C (72 °F) dry-bulb temperature, 16.1 °C (61 °F) wet-bulb temperature, 56% relative humidity, and 0.25–0.38 m/s (50–75 ft/min) airspeeds is given in table 6. Although this is a preliminary, and by no means conclusive, experiment with only a small number of subjects, it indicates some fundamental difference between people from tropical and temperate countries with regard to comfort sensation.

Table 5. Examples of effective temperatures for different combinations of air temperature, relative humidity, and airspeed

		Effective Temperature at Airspeeds of:			Effective Temperature Difference for
Shaded Dry Bulb Temperature	Relative Humidity (%)	0.1 cm/s (0.33 ft/s)	0.5 cm/s (1.64 ft/s)	22.5 m/s (73.8 ft/s)	Airspeed Increase from 0.1 to 22.5 m/s (0.33 to 73.8 ft/s)
40.6 (105)	75	36.7 (98)	36.7 (98)	36.1 (97)	−0.6 C° (−1 F°)
	40	32.8 (91)	32.2 (90)	31.4 (88.5)	−1.4 C° (−2.5 F°)
	20	30.6 (87)	30.0 (86)	29.2 (84.5)	−1.4 C° (−2.5 F°)
35 (95)	90	33.9 (93)	33.3 (92)	32.2 (90)	−1.7 C° (−3 F°)
	75	31.7 (89)	31.4 (88.5)	30.0 (86)	−1.7 C° (−3 F°)
	40	28.9 (84)	28.3 (83)	26.9 (80.5)	−2.0 C° (−3.5 F°)
29.4 (85)	90	28.6 (83.5)	27.7 (82)	25.6 (78)	−3.0 C° (−5.5 F°)
	75	27.2 (81)	26.7 (80)	24.4 (76)	−2.8 C° (−5 F°)
	40	24.4 (76)	23.9 (75)	22.2 (72)	−2.4 C° (−4 F°)

Note: All absolute temperatures are in °C (°F).

Table 6. Summary of the comfort sensation of two groups of students exposed to 22.2 °C (72 °F) dry-bulb temperature, 16.1 °C (61 °F) wet-bulb temperature, 56% relative humidity, and 0.25–0.28 m/s (50–75 ft/min) airspeeds

Comfort Sensation	Students from Temperate Zone (%)	Students from Tropical Zone (%)
Comfortable temperature	36	7
Too warm	14	0
Too stuffy	30	0
Comfortably cool	7	36
Comfortably dry	0	31
Air fresh	30	50

Table 7. The values for the ambient and most appreciated air-conditioning temperatures and humidities in four tropical cities

	Dry Bulb Temperature	Wet Bulb Temperature	Dew Point	Relative Humidity	Effective Temperature
Ambient conditions:					
Delhi, India	43.3 (110)	24.4 (76)	16.1 (61)	21%	30.4 (86.8)
Abadan, Iran	46.1 (115)	26.7 (80)	19.4 (67)	22%	31.9 (89.5)
Bombay, India	32.2 (90)	27.7 (82)	26.7 (80)	72%	29.0 (84.2)
Lagos, Nigeria	35.0 (95)	28.3 (83)	27.8 (82)	62%	30.2 (86.3)
Most desired conditions	25.6 (78)	19.4 (67)	15.6 (60)	55%	22.5 (72.5)

Note: All temperatures are in °C (°F).

Table 8. Comparison of outdoor and indoor temperature and humidity conditions provided by a continuous airspeed of 0.3 m/s (60 ft/min) over a wet surface

Location	Dry Bulb Temperature	Wet Bulb Temperature	Dew Point	Relative Humidity	Effective Temperature
Outside	43.3 (110)	24.4 (76)	16.1 (61)	21%	29.5 (85.2)
Inside	32.2 (90)	26.1 (79)	24.4 (76)	65%	27.2 (81.0)

Note: All temperatures are in °C (°F).

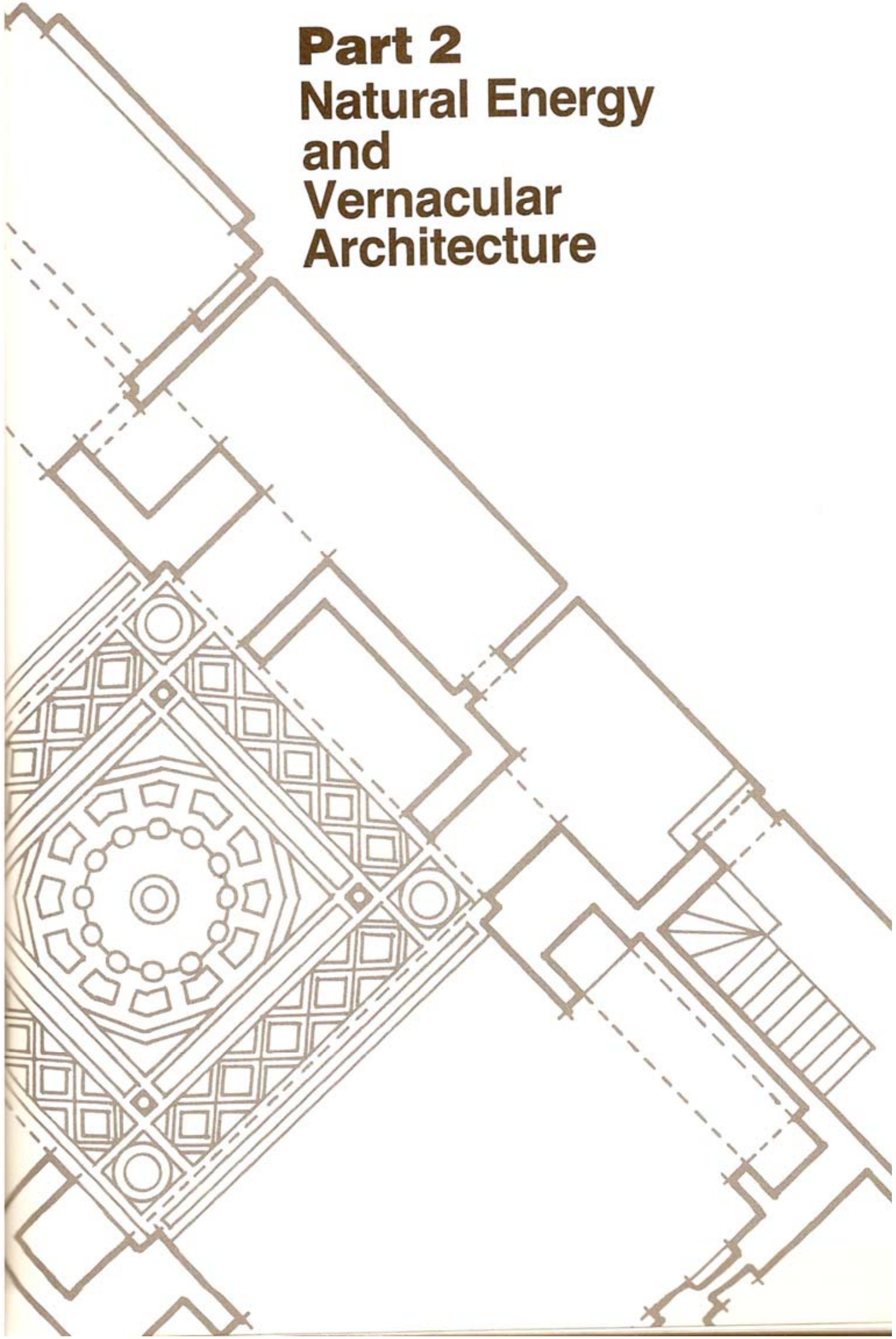
Table 7 shows values for air-conditioning that were found to be generally favored by the occupants of buildings in tropical countries. The airspeed was taken to be 0.3 m/s (60 ft/min) in these effective temperature calculations.

Table 8 shows that it may not be necessary to use powered air-conditioning, an expensive expedient in places where ambient conditions are hot and dry, as in Delhi or Lahore. The inside effective temperature can be reduced using only evaporation in such climates, merely by ensuring a continuous air speed of 0.3 m/s (60 ft/min) over a continuously wet surface. Thus a reduction in effective temperature of 2.3 C° (4.2 F°) can be achieved.

With this understanding of the physical principles affecting human comfort, it is now possible to examine the applications of scientific concepts to architectural design and town planning in hot arid regions.

Part 2

Natural Energy and Vernacular Architecture



3

Architecture and Comfort

Before the advent of modern mechanical means for obtaining thermal comfort, people in the hot arid and warm humid zones were forced to devise ways to cool their houses with only natural sources of energy and physical phenomena. Generally, these solutions have been found to be much more in harmony with the human physiological functions than such modern means as electrically powered desert coolers and air-conditioners.

This situation is unchanged for the majority of people in the industrially developing countries, where the conventional energy sources of the industrialized world are not readily available at affordable prices. There is a clear need to further develop the traditional systems based on natural resources. Before inventing or proposing new mechanical solutions, traditional solutions in vernacular architecture should be evaluated, and then adopted or modified and developed to make them compatible with modern requirements. This process should be based on modern developments in the physical and human sciences, including the fields of materials technology, physics, aerodynamics, thermodynamics, meteorology, and physiology.

Architectural Design for a Comfortable Microclimate

In designing and planning for the hot arid and warm humid zones, two of the main problems confronting the architect are to ensure protection against heat and provide adequate cooling. The Earth's major source of heat and light, the sun, also creates the secondary climatic elements of wind and humidity that affect physiological comfort. These are caused by the configuration and nature of the local surface, such as the mountains, plains, oceans, deserts, and forests. The interplay between this astronomical source of energy with the effects it causes and the landscape creates the microclimate, which is the concern of the science of meteorology.

However, the built environment produces changes in the microclimate. The configuration of buildings, their orientations, and their arrangement in space create a specific microclimate for each site. To this must be added the building materials, surface textures and colors of exposed surfaces of the buildings, and the design of open spaces, such as streets, courtyards, gardens, and squares. These man-made elements interact with the natural microclimate to determine the factors affecting comfort in the built environment: light, heat, wind, and humidity.

There is no doubt that certain configurations create better microclimates than others. For each site, there is an optimum arrangement in space that the designer should seek and use as a standard of reference in the process of deciding upon a certain design. Where it can be avoided, it is inappropriate and irresponsible to implement a design that adds even one degree of temperature or reduces air movement by one centimeter per second, if this would negatively affect thermal comfort. This obviously includes defective designs which require energy-intensive mechanical means for their rectification.

Building Materials

The materials surrounding the occupants of a building are of prime importance for protection against heat and cold. Great care must be taken in the choice of the wall and roof materials and their thicknesses with respect to their physical properties, such as thermal conductivity, resistivity and transmission, and optical reflectivity.

Considering an external wall exposed to a high outside air temperature and a lower inside air temperature (see fig. 1), the rate of heat flow transmitted through the wall from the outside air to the inside air is proportional to the air temperature difference, area of the wall, and rate of global heat transmittance that can be determined from an analysis of the components of the total resistance to heat flow.[1] The

total resistance is composed of the resistance to heat flow through the material, the interfacial resistance at the external surface, and the interfacial resistance at the internal surfaces.[2] Since the interfacial resistances are determined primarily by temperature conditions over which the builder has little control, his principal effect on the heat transmittance is on changing the resistance to heat flow through the wall material.[3] To reduce the heat transmission from one side of a wall to the other, the thermal transmittance must be reduced as much as possible by either increasing the thickness of the wall or using materials of lower thermal conductivity and therefore of higher resistance. Often walls composed of several materials, as shown in figure 2, are used to provide the desired thermal and aesthetic wall characteristics.[4] Coefficients of thermal transmittance for a variety of wall materials and of combinations of such materials are provided in Appendix 3. These coefficients are given in the practical units commonly used: kcal/hm²C° and Btu/hft²F°.[5]

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[1] If the wall is of thickness L, area A, and exposed to an outside air temperature T_1 and an inside air temperature T_2, with T_1 greater than T_2, the rate of heat flow, Q, transmitted through the wall can be calculated using the formula:

$$Q = UA(T_1 - T_2) \tag{9}$$

where Q is given in kcal/h and U is the rate of global heat transmittance.

[2] Representing these resistances by R_M, R_1, and R_2, respectively, the total resistance is

$$R = R_M + R_1 + R_2. \tag{10}$$

[3] Using eq. (8) of fn. 10, eq. (10) gives the following expression for the rate of global heat transmittance:

$$\frac{1}{U} = \frac{L}{k} + \frac{M_1}{M_1} + \frac{M_1}{M_2}, \tag{11}$$

where R_M is obtained from eq. (4) of fn. 6, M_1 is a constant for the external surface which was empirically found to be 18 kcal/hm²C° (3.69 Btu/hft²F°), and M_2 is a constant for the internal surface which was empirically found to be 7 kcal/hm²C° (1.4 Btu/hft²F°).

[4] If the wall is composed of n different materials of thickness $L_1, L_2, \ldots,$ and L_n that have, respectively, the thermal conductivities $k_1, k_2, \ldots,$ and k_n, the formula for heat transmission becomes

$$\frac{1}{U} = \left(\frac{L_1}{k_1} + \frac{L_2}{k_2} + \ldots + \frac{L_n}{k_n} + \frac{1}{M_1} + \frac{1}{M_2}\right). \tag{12}$$

[5] Two examples demonstrate how this information is used.

Example 1 (see fig. 1): an external brick wall of thickness 0.11 m (4.3 inch) and thermal conductivity 0.6 kcal/hmC° (0.12 Btu/hft²F°) gives

$$\frac{1}{U} = \frac{0.11\ \text{m}}{0.6\ \text{kcal/hmC°}} + \frac{1}{7\ \text{kcal/hm}^2\text{C°}} + \frac{1}{18\ \text{kcal/hm}^2\text{C°}} = 0.382\,\frac{\text{hm}^2\text{C°}}{\text{kcal}}$$

resulting in

$$U = 2.62\ \text{kcal/hm}^2\text{C° } (0.537\ \text{Btu/hft}^2\text{F°}).$$

In hot arid climates, the coefficient of thermal transmittance should be about 1.1 kcal/hm^{2}C° (0.225 Btu/hft^{2}F°) for an outer wall to have an appropriate thermal resistance. Table 9 lists the thicknesses of walls composed of various construction materials needed to achieve coefficients of approximately 1.1 kcal/hm^{2}C° (0.225 Btu/hft^{2}F°).

These tables do not contain data for mud-brick walls. However, experiment has proved that mud brick is most appropriate for achieving thermal comfort in addition to being widely available to all segments of the population.

In 1964, six small experimental buildings were built on the grounds of the Cairo Building Research Centre, using different materials. They were used to evaluate cost, local availability, and thermal comfort. Two modes of these six represented extremes. One was built entirely of mud brick with the 50-cm (20-inch) thick walls and roof in the shape of a combined dome and vault. The other was built of 10-cm (4-inch) thick prefabricated concrete panels for both the walls and the roof. Plans and sections of these buildings are given in figures 5 and 6, respectively.

These models were examined on a day in March when external air temperature varied from 12 °C (53.6 °F) at 6 A.M. to 28 °C (82.4 °F) at 2 P.M. and back to 12 °C (53.6 °F) at 4 A.M.[6] As shown in figure 7, the air-temperature fluctuation inside the mud-brick model did not exceed 2 C° (3.6 F°) during the 24-hour period, varying from 21–23 °C (69.8–73.4 °F), which is within the comfort zone. However, the maximum air temperature inside the prefabricated model reached 36 °C (97 °F), or 13 C° (23 F°) higher than in the mud-brick model and 9 C° (16 F°) higher than the outdoor air temperature. It fell within the comfort zone for only one hour in the morning (9–10 A.M.) and between 8:40 P.M. and 12:20 A.M., as recorded in figure 8. The contrast can be explained by the fact that concrete has a thermal conductivity of 0.9, while that of mud brick is 0.34, and that the mud-brick wall is five times thicker than the prefabricated panels. Thus, the mud-brick wall has a thermal resistance more than 13 times greater than the prefabricated concrete wall. Unfortunately, these models were not evaluated for the salient dates of the equinoxes and solstices, which would have provided complete information, especially about the lag effect and heat storage.

Table 9. Thicknesses of walls of different material that give coefficients of thermal transmittance of approximately 1.1 kcal/hm^{2}C° (0.225 Btu/hft^{2}F°)

Wall Material	Wall Thickness (in m)	(in in)	Thermal Transmittance (in kcal/hm^{2}C°)	(in Btu/hft^{2}F°)
Hollow brick block	0.30	12	1.10	0.225
Double-wall brick with holes and 8-cm cavity	2 × 0.12	2 × 4.7	1.12	0.229
Brick wall with holes	0.38	15	1.03	0.211
Sand-lime brick	0.51	20	1.25	0.256
Hollow block sand-lime brick	0.51	20	1.16	0.238
Lime	0.51	20	1.10–1.35	0.225–0.277
Concrete	1.00	39	1.20	0.246

Example 2 (see fig. 2): the same brick wall with inside and outside layers of plaster of paris with 0.6 kcal/hmC° (0.12 Btu/hft^{2}F°) thermal conductivity and 2-cm (0.8-inch) thickness on both sides gives

$$\frac{1}{U} = \frac{0.11\ \text{m}}{0.6\ \text{kcal/hmC°}} + \frac{0.04\ \text{m}}{0.6\ \text{kcal/hmC°}} + \frac{1}{7\ \text{kcal/hm}^2\text{C°}}$$

$$+ \frac{1}{18\ \text{kcal/hm}^2\text{C°}} = 0.448\,\frac{\text{hm}^2\text{C°}}{\text{kcal}}$$

resulting in

$$U = 2.23\ \text{kcal/hm}^2\text{C° } (0.457\ \text{Btu/hft}^2\text{F°}).$$

[6] Omar El-Farouk, John Norton, Wendy Etchells, Jocelyn Levaux, Allan Cain, and Farroukh Afshar, *Climate Study—Traditional Houses*. Third World Studies (London: Architectural Association School of Architecture, 1974). (Measurements made 25 March to 10 May 1973.)

4

The Sun Factor

Orientation

In hot climates, the sun is the major source of heat. To plan any site, the position of the sun must be determined for all hours of the day at all seasons as well as the direction of the prevailing winds, especially during the hot season. For the direct rays of the sun, it is sufficient to know the angles of declination and altitude for the summer and winter solstices (21 June and 21 December, respectively) and the autumnal and vernal equinoxes (21 September and 21 March, respectively), from which the position of the sun at any time of day on any intermediate date can be deduced. These dates, rather than averages, represent the extreme cases which the architect must consider. Appendix 4 gives this information for the city of Cairo, Egypt, which is located at latitude 30° N. Similar tables for any city can be obtained from the local meteorological office. In addition, for an ensemble of buildings forming a sector, there will be reflection from adjacent buildings and wind screening by clusters of buildings, which contribute to a specific microclimate for each location in the sector. Wind movement and humidity also are important and should be considered simultaneously with the direct and indirect effects of the sun.

The main objective is to establish the optimum orientation with regard to the sun and the prevailing wind. The problem is complex, and it is useful to begin by considering the simple case of a block consisting of a single row of buildings. On the basis of this, more complex cases can be understood.

Appendix 4 indicates that the optimum orientation of the building block with regard to the sun factor is east-west. In this case, the north facade is exposed to the sun's rays at the summer solstice from sunrise at 5:00 A.M. to about 9:00 A.M. These rays have an angle of altitude of 0° at 5:00 A.M., but at 9:00 A.M. the angle of altitude is 49°30′, the angle of declination 88°13′, and the rays hit the facade at an angle of only 1°03′. For the south facade, the angle of altitude is 83°36′ at noon, which is 6°24′ off the vertical. Solar radiation does not penetrate the south facade openings, and a slight overhang properly positioned could easily shade the openings and wall surface. The east and west facades constitute the end walls of the entire row and are not provided with openings. In winter, the angle of altitude at noon is 36°34′, which allows the sunlight to penetrate into the interior for warmth.

Meteorological records show that the cool wind in Cairo blows from the northwest. Thus the optimal orientation with regard to wind is such that the long side of the row is aligned northeast to southeast so the wind can be as normal to the long surface as possible.

At first glance, the obvious solution to the requirements of these two factors would be to orient the row from northeast-east to southwest-west, bisecting the angle between the two optimal orientations as shown in figure 9. This solution would be correct if the windows were to serve as wind inlets and outlets to ensure air movement indoors. However, people in the hot arid and warm humid zones devised the *malqaf* or wind-catch, whereby air high above a building can be captured and forced through the interior, as explained in the next chapter. With the wind problem solved with the *malqaf*, the row can be aligned east-west, which is optimal for the sun, as indicated in figure 10. This innovation permits flexibility in design with regard to the wind factor and makes it possible for the designer to concentrate on orienting his buildings with respect to the sun factor.

Shading

Although the optimal orientation for single buildings and blocks of row houses is with the long side aligned from east to west, for many reasons this cannot always be applied so simply over the entire plan of a city or sector. Some single buildings or row houses must face streets and squares that may be oriented at any angle from the north, with each case requiring an appropriate means of shading, depending on its orientation.

Generally, a building with a facade opening to the west is the worst case encountered, owing to the heat gain of the surrounding environment during the day and the angle of altitude, which allows the sun's rays to penetrate into the interior. However, for a sector with the long facade facing west and east, blocks of buildings can themselves shade one another. To ensure this, the height of the blocks must be designed according to the width of the street and the angle of altitude of the sun, which can be obtained from data like that contained in Appendix 4 for any geographical site. In this way, areas that will be exposed to the sun can be defined, either for the facades or for street surfaces, and the duration of exposure can also be calculated.

Facades

Northern Facade

This facade is least exposed to the sun. In fact, exposure occurs only in the early and late hours of summer days when the angle of altitude is low and the angle of declination is such that the sun's rays are almost tangential to the surface of the wall, as illustrated in figure 11. An advantage to rooms opening on this facade is that their illumination is always evenly distributed, making them ideal for hospital operating rooms and for school classrooms.

Southern Facade

With regard to the sun factor, an advantage of southern exposure in the Tropics and Subtropics is that the sun is high over the horizon in summer and can be shaded using a relatively small overhang. In winter it is low, allowing the sunshine to penetrate when it is most desirable. This situation is outlined for a particular case in figure 12. However, with regard to the wind factor, a disadvantage of the southern exposure is that it receives no wind, since the cool prevailing winds generally blow from a northerly direction in the Northern Hemisphere.

Although the sun's rays cannot be manipulated and directed at will, there are ways of directing airflow to rooms with a southern exposure, either by architectural design or by such devices as the *malqaf*, the wind-escape, and even the indoor *mashrabīya* as seen in some traditional houses in Jeddah, Saudi Arabia.

Eastern and Western Facades

The eastern facade is exposed to the sun's rays only from sunrise to noon. The walls cool down considerably by evening, making this exposure more suitable for bedrooms than the western exposure.

Shading of the facades of buildings can be achieved by covering the streets, as is often found in older cities and oasis villages of West Asia and North Africa, examples of which are illustrated in figures 13–15. For a single building, shade can be provided by architectural elements such as balconies, covered loggias or open galleries, and verandas to shield the facade, or by introducing special devices such as the venetian blind, the brise-soleil, and the *mashrabīya* to shield the openings. In Iraq, walls ventilated and cooled by surrounding the rooms with an outside corridor with arcades and colonnades, as shown in figure 16.

Openings

Window openings normally serve three functions: to let in direct and indirect sunlight, to let in air, and to provide a view. In the temperate zones these functions are conveniently combined together in the window, the size, form, and location of which are determined by local climatic conditions. However, since in hot arid climates it is rarely possible or desirable to combine these three functions in a single architectural solution, several solutions were developed which concentrate on each function separately.

The Venetian Blind

One device which can be added directly to the window is the venetian blind. This blind is made of small slats, about 4–5 cm (1.6–2 inches) wide, closely set in a wooden frame at an angle that will intercept the sun's rays. The slats are often movable so the angle can be changed. This feature of adjustability renders venetian blinds very useful in regulating solar radiation and wind flow into rooms. Using the venetian blind, the sun's rays can be blocked out without obstructing the breeze, which generally blows from the northwest in most hot arid areas, including Egypt, Iraq, and North Africa. When the blinds are drawn, they completely obstruct the view to the outside as well as considerably dim the light reaching the interior.

However, sometimes the venetian blind is not a satisfactory solution to the problem of adjusting radiation and airflow. In summer, the blind can be adjusted to deflect the wind downward onto the occupants, but this permits the sun to shine directly into the room, as shown in figure 17a. Alternatively, by changing the position of the blind to block the direct sunlight, the wind is redirected uselessly over the heads of the occupants, as figure 17b illustrates. Also, if the slats are made of metal, they then absorb some incoming radiation and reradiate it into the room as heat.

The Brise-soleil

The brise-soleil or sun-breaker is a new shading device that requires a special sophisticated support. It is generally used to shield entire facades of glass-wall and concrete or steel frame buildings. Originally, the glass-wall concept was introduced to provide an outside view through the entire side of a room. Standard glass is transparent to ultraviolet radiation and opaque to infrared or heat radiation. Therefore, when a glass wall of a room measuring, say, 3 × 3 m (about 10 × 10 ft) is exposed to the sun's rays, it lets in 2000 kcal (nearly 8000 Btu) per hour throughout most of the day. This light strikes the solid material inside, including the walls, floor, and furniture, and is transformed into infrared radiation to which the glass is opaque. The glass wall thus traps the heat, creating a phenomenon known as the greenhouse effect, and two tons of refrigeration per hour are required. Thus additional energy, and therefore cost, is required to maintain a comfortable microclimate in the room.

A brise-soleil properly designed to intercept the sun's rays reduces this heat gain to at most one-third, which although an improvement is still inadequate. Furthermore, there is the additional disadvantage of using the brise-soleil with regard to the view to the outside, which was the original purpose for using the glass wall. The brise-soleil is in fact a transposition of the venetian blind, with the slat width increased from 4 to about 40 cm (1.6 to about 16 inches) to suit the scale of the entire facade instead of just the window opening in a solid wall. When the angles of altitude and declination for screening direct sunlight are calculated, the required space between the slats is much larger than for the venetian blind. The result is a view slashed by large dark stripes interspersed by offensive glare. This is why photos showing the brise-soleil in architectural magazines and books are always taken from the outside and never from the inside looking out, as in figure 18. Nevertheless, the brise-soleil concept need not be discarded. It may be used advantageously in some cases of modern architecture if comprehensively articulated in the facade with due regard for reduction of physical glare and for aesthetics.

The *Mashrabīya*

The name *mashrabīya* is derived from the Arabic word "drink" and originally meant "a drinking place." This was a cantilevered space with a lattice opening, where small water jars were placed to be cooled

by the evaporation effect as air moved through the opening. Now the name is used for an opening with a wooden lattice screen composed of small wooden balusters that are circular in section and arranged at specific regular intervals, often in a decorative and intricate geometric pattern. Figure 19 shows such a *mashrabīya*, that of the As-Suḥaymī house in Cairo.

The *mashrabīya* has five functions. Different patterns have been developed to satisfy a variety of conditions that require emphasis on one or more these functions. These functions involve: (1) controlling the passage of light, (2) controlling the air flow, (3) reducing the temperature of the air current, (4) increasing the humidity of the air current, and (5) ensuring privacy. Each *mashrabīya* design is selected to fulfill several or all of these functions. In the design, it is the sizes of the interstices (spaces between adjacent balusters) and the diameter of the balusters that are adjusted. Different names identify certain of these patterns.

Daylight entering a room with an opening facing south has two components, the direct high-intensity sunlight that enters at very large angles normal to the plane of the opening, and the lower-intensity reflected glare, which can enter nearly normal to the opening. Since direct sunlight passing through the opening will heat surfaces in the room, it is best to block such radiation. The reflected glare, while less intense and not very effective in heating room surfaces, does produce uncomfortable visual effects.

The sizes of the interstices and the balusters of a *mashrabīya* placed in such an opening are adjusted to intercept direct solar radiation. This requires a lattice with small interstices. The balusters, round in section, graduate the light reaching their surfaces, thus softening the contrast between the darkness of the opaque balusters and the brightness of the glare entering through the interstices, as illustrated in figure 20. Therefore, with the *mashrabīya* the eye is not dazzled by the contrast as in the case of the brise-soleil. Figures 21 and 22 show the effect of a *mashrabīya* under conditions of severe glare. The characteristic shape of the lattice with its lines interrupted by the protruding sections of the balusters produces a silhouette which carries the eye from one baluster to the next across the interstices, vertically and horizontally. This design corrects the slashing effect caused by the flat slats of the brise-soleil and harmoniously distributes the outside view over the plane of the opening, superposing it on the decorative pattern of the *mashrabīya* so that it resembles a darkened glass made of lace. This effect is shown in Figure 19.

At eye level, the balusters of the *mashrabīya* are set close together with very small interstitial spacing both to intercept direct sunlight and to reduce the dazzle of contrasting elements in the pattern. But to compensate for the accompanying dimming effect, the interstices are much larger in the upper part of the *mashrabīya*, as in the example from the Jamāl Ad-Dīn Adh-Dhahabī house in Cairo, shown in figure 23. Figure 24 shows the striking effect that can be achieved for a room with a high ceiling. This arrangement permits reflected light to brighten the upper part of the room, while an overhang at the top of the opening, as seen in the outside view of a second story *mashrabīya* in figure 25, prevents direct sunlight from entering. Similarly, in openings on a northern facade, where direct sunlight is no problem, the interstices are quite large, to provide adequate room lighting.

To provide airflow into a room, a *mashrabīya* with large interstices will ensure as much open area in the lattice as possible, as shown in figure 26. Where sunlight considerations require small interstices and thus sufficient airflow is not provided, an open, large-interstice pattern can be used in the upper part of the *mashrabīya* near the overhang. For this reason, a typical *mashrabīya* is composed of two parts: a lower section with fine balusters in close mesh, and an upper section filled with a wide mesh grill of turned wood in a pattern called *sahrīgī*, as shown in figures 23 and 25. If this solution still does not provide sufficient air movement due to the small interstices required to reduce the glare, the dimensions of the *mashrabīya* can be increased to cover any size opening, even to the point of filling up the entire facade of a room. Figures 27 and 28 show inside and outside views of a facade-sized *mashrabīya* designed to solve this problem in the As-Suḥaymi house in Cairo. The very large size of such a *mashrabīya* also helps to compensate for the dimming effect of the screen. In some places, the *mashrabīya* is used indoors between rooms for cross-ventilation, as in some houses in Jeddah, Saudi Arabia. The *mashrabīya* concept has been universally used in hot arid areas, particularly throughout the Middle East and North Africa, but even in India, where it is called the *jālī*.

Its cooling and humidifying functions are closely related. All organic fibers, such as the wood of a *mashrabīya*, readily absorb, retain, and release considerable quantities of water. Plants can provide some regulation of their skin temperatures by the successive processes of transpiration and evaporation (called evapo-transpiration). Thus, the sap flows through the fibers to the plant surfaces, where it evaporates and cools the skin. Wood fibers retain this ability even after they are cut from the tree and used in buildings, as long as the pores are not covered by an impervious paint.

Wind passing through the interstices of the porous-wooden *mashrabīya* will give up some of its humidity to the wooden balusters if they are cool, as at night. When the *mashrabīya* is directly heated by sunlight, this humidity is released to any air that may be flowing through the interstices. This technique can be used to increase the humidity of dry air in the heat of the day, cooling and humidifying the air at a time when most needed. The balusters and interstices of the *mashrabīya* have optimal absolute and relative sizes that are based on the area of the surfaces exposed to the air and the rate at which the air passes through. Thus if the surface area is increased by increasing baluster size, the cooling and humidification are increased. Furthermore, a larger baluster has not only more surface area to absorb water vapor and serve as a surface for evaporation but also more volume, which means that it has more capacity and will therefore release the water for evaporation over a longer period of time.

In addition to these physical effects, the *mashrabīya* serves an important social function: it ensures privacy from the outside for the inhabitants while at the same time allowing them to view the outside through the screen. Therefore, a *mashrabīya* covering an opening that overlooks the street has small interstices except at the top far above eye level. A striking example of the feeling of security and external view a *mashrabīya* can provide is shown in figures 29 and 30. With the focus on the lattice, the *mashrabīya* appears as a lighted wall. When focusing beyond the lattice, the external view is quite clear and only slightly obstructed.

Figure 31 shows how *mashrabīya* can be used in the design of a modern villa. This design for Saudi Arabia includes *mashrabīya* high in the top of the *dur-qā'a* and others at a lower level in adjacent rooms, as well as a *malqaf* on the right.

The Roof

If the outdoor air temperature is higher than the indoor temperature, the outer surface of the roof exposed to the sun is heated as it absorbs radiation, and, being in contact with the outside hot air, also is heated by conduction. The roof then transmits this heat to the inner surface, where it raises the temperature of the air in contact with it by conduction. At the same time, it radiates heat that is absorbed by people and objects indoors, thereby affecting thermal comfort.

Therefore, the reflectivity of the outer surface of the roof and the thermal resistivity of its materials are of primary importance. Shade can be achieved by using a double roof with a layer of air between or by covering the roof surface with hollow bricks. Insulating materials such as fiberglass, styrofoam, and lightweight blocks are often used. This solution, however, requires special commercial materials and increases the cost of the building beyond the means of most inhabitants in hot arid zones.

The idea of using a roof with a lightweight cover as a living space has been further developed in the modern example of the roof garden with a trellis. Soil is a good heat insulator, and plants can provide shade. Plants also transpire and cool the air in contact with the roof. Again, this idea requires special structures to ensure a strong and waterproof roof, and is also too costly for most inhabitants of these regions. Psychologically and aesthetically, people appear to prefer to live on the level of tree trunks, branches, leaves, and flowers, rather than to feel as if they were living under the roots.

A useful idea is to shade the roof more naturally by designing it to suit popular traditions. In hot arid countries, since the air temperature drops considerably during the night, the inhabitants have arranged the roof architecturally into loggias or open galleries and lightweight roof covers. These loggias and roof covers have the double function of shading the roof during the day and providing physiologically comfortable living and sleeping spaces at night. Examples from Iraq and Rosetta, Egypt, are shown in figures 32 and 33, respectively.

The shape of the roof is also of considerable importance in a sunny climate. A flat roof receives solar radiation continuously throughout the day, at a rate that increases in the early morning and decreases in the late afternoon due to changes in both solar intensity and angle of the sun.

Pitching or arching the roof has several advantages over a flat structure. First, the height of part of the interior is increased, thereby providing a space far above the heads of the inhabitants for warm air that rises or is transmitted through the roof. Second, the total surface area of the roof is increased with the result that the intensity of solar radiation is spread over a larger area and the average heat increase of the roof and heat transmission to the interior are reduced. Third, for most of the day, part of the roof is shaded from the sun, at which time it can act as a radiator, absorbing heat from the sunlit part of the roof and the internal air, and transmitting it to the cooler outside air in the roof's shade.

This latter effect is particularly effective for roofs vaulted in the form of a half-cylinder and those domed in the form of a hemisphere since at least part of the roof is always shaded except at noon when the sun is directly overhead. Domed and vaulted roofs also increase the speed of any air flowing over their curved surfaces due to the Bernoulli effect, discussed in the next chapter, rendering cooling winds more effective at reducing the temperature of such roofs.

5

The Wind Factor in Air Movement

When skin is wet with perspiration and is exposed to the air with a dew point below skin temperature, the perspiration evaporates. The skin temperature is lowered because energy is needed to convert the perspiration into water vapor. However, the air in contact with the skin soon becomes saturated, and evaporation stops. For the evaporation process to continue, this air must be removed either mechanically, using a fan, e.g., or naturally by air movement and drafts.

The architectural design can ensure such natural air movement through two principles. In the first, differences in wind velocity produce a pressure differential which results in air flowing from the higher to the lower air pressure region. In the second, air is warmed, causing convection, with the warm air rising and being replaced by cooler air. A cool draft is created in the space between the warm area and the cool-air intake opening. The rate of airflow caused by convection in buildings is determined by the difference in the level of openings, with greater airflow resulting from a greater difference in the heights of the openings. It is most important when the outside air is still and yet the interior requires ventilation to achieve comfort. Both these principles have been used in architectural design and town planning in many ways using several innovations. Air movement by pressure differential and cooling systems based primarily on this principle will be discussed in the present chapter, while the following chapter will concentrate on the air movement by convection which requires the effect of the sun.

Air Movement by Pressure Differential

An important concept in understanding how wind-generated pressure differentials produce air movement is "Venturi action," which is based on the Bernoulli effect. From Bernoulli's theorem, the pressure of a moving fluid decreases as its velocity increases. Figure 34 shows a funnel-shaped tube that opens to a side tube. When air is channeled into the larger end of the funnel, it accelerates as it passes through, owing to the reduced open area through which the same volume of air must pass in the same period. This increased airspeed lowers the pressure in the airstream at *A* with respect to the atmospheric pressure at *B* in the lower part of the side tube. Thus air is drawn up the side tube by the pressure difference which is proportional to the square of the velocity. This concept can be used in a variety of ways to provide steady streams of air through buildings.

For indoor air movement caused by a pressure differential, the airflow is steadier in cases that depend more on the suction resulting from low air pressure than on the high air pressure caused by wind force. Obviously, a window or an opening will not create the desired air movement in a room unless an air outlet of some sort is also provided. Experience has shown that air movement is faster and steadier when the area of the openings on the leeward side of a structure is larger than the inlets on the windward side.

An important example is illustrated by the loggia in a guest house in Gourna village near Luxor, Egypt, shown in figure 35. Even on an uncomfortably hot day, the shaded area of the loggia is provided with a cool and refreshing breeze, a result of intelligent architectural design following the principles of aerodynamics. The loggia opens onto a courtyard on the leeward side and is nearly closed to the prevailing wind by a wall pierced with two rows of small openings. The airflow over and around the building produces a zone of low pressure on the leeward side, and thus inside the loggia as a result of the Bernoulli principle. This ensures steady airflow due to suction through the small openings. Figure 36 shows schematically the airflow and pressure changes for this loggia. Variations of this effective method of climatization are widely used for many types of buildings in the hot arid regions. This example shows that a detailed analysis of the aerodynamic lines of air movement is essential to a clear understanding of how architectural devices can ensure optimized thermal comfort.[1]

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[1] The effectiveness of this technique depends very much on the areas of the inlet (A_I) and outflow (A_O) vents and the wind velocity, v. Assuming that the direction of the wind in fig. 33 is normal to the surface of the wall in the vicinity of the inlet, the rate of airflow, F, through the building is

Other applications of this principle can provide valuable practical information. In the region of Al-Hilla in Iraq, the villagers adopted the arrangement for creating air movement by suction shown in figure 37. However, the inlet vents on the windward side are placed low. The reason for this is that the indoor space is used for sleeping when the roof is unsuitable, and the air temperature near the ground drops considerably at night. By placing the door, which is considerably larger in area than the inlet vents, on the leeward side, a draft is created by suction, causing air to flow through the room at the level of the sleepers. In addition, with the top of the inlet vents considerably lower than the top of the door, the hot air escaping through the open door is accelerated by convection and replaced by cooler air drawn in through the inlet vents.

Vents also can be used as outlets for hot air. An example can be seen in the exterior of a traditional building in Najd, Saudi Arabia, shown in figure 38. Here the triangular vents are positioned on the wall just under the roof to evacuate hot air collected in the higher parts of the room by convection. The air passing through these outlet vents is then replaced with air drawn from cooler parts of the building.

The *Claustrum*

Often a multitude of small vents is preferable to a few large openings for purposes of privacy, security, uniform distribution of air flow, blocking of direct solar rays, and decoration. Large openings, used mainly for ventilation and lighting and set at specific places in the building, can then be filled with lattice work, in the form of a pierced screen wall. These lattices, called *claustra*, were originally used in large openings at high levels in the Roman baths. In vernacular architecture, they generally are made in different decorative patterns of carved plaster plates, unlike the *mashrabīya*, which are wooden. *Claustra* are mainly used to evacuate the hot air collected in the higher parts of the room, or in parapet walls, the low walls around roof edges, to produce drafts over people sleeping on the roofs in summer. Examples of various *claustra* designs are shown in figures 39 and 40, from Dubai, United Arab Emirates, and figures 41 and 42, from Oman.

$F = CA_I v$

A_I/A_O	C
0.25	.208
0.5	.379
0.75	.511
1.0	.597
2.0	.758
3.0	.805
4.0	.824
5.0	.833

with C dependent on the ratio A_I/A_O in the following manner: (C is dimensionless if uniform units are used throughout the equation, i.e., if F is in m^3/s, A in m^2, and v in m/s; or if F is in ft^3/s, A in ft^2, and v in ft/s.) If the wind direction is not normal to the surface of the wall, the airflow is reduced in proportion to the angle between the wind and normal directions.

In modern architecture, *claustra* are sometimes used inappropriately over the entire facade of a building to serve as a brise-soleil. In fact, the *claustrum* is a screen to be set in an opening of proper size and should not be used as a bearing wall. In extending it beyond its frame and scale to cover an entire facade, the structural scale and aesthetic rules of architecture are disturbed. Furthermore, when *claustra* are set at eye level, they annoy the eye with dazzling contrasts of light and shade, resulting from the inappropriate relative and absolute sizes of the solid and void lattice components and the lack of graduation caused by the rectangularity of the bars. When a *claustrum* is used as a brise-soleil, it shares with the latter many defects which are overcome by the *mashrabīya*. Figure 43 illustrates inappropriate use of a *claustrum* in a facade in Kuwait. However, the *claustrum* is effective at eye level in infrequently used indoor spaces, such as in a staircase wall, or in outdoor spaces, like courtyards or roofs, where the play of light and shade does not dazzle the eye when looking outward.

The Wind-Escape

The technique of using the suction caused by low air-pressure zones to generate steady air movement indoors is used in the design of the wind-escape. The funnel and side tube used to illustrate the Bernoulli effect or Venturi action (see fig. 34) are transposed into the structural elements of an architectural design in order to accelerate air movement and to create drafts in places with no exposure to the outside, such as basements in Iraq.

An interesting example occurred by accident in the design of a pump room for an artesian well in Alexandria, Egypt. The pump room was located about 6 meters below ground level because the underground water level was 12 meters deep. The room had an opening overlooking the well for the passage of piping and for inspection, and it was covered with a slanting-vault roof with the higher end toward the leeward side, as shown in figures 44 and 45. It was feared that the pump-engine exhaust gases would pollute the air in this very small chamber. However, the vaulted-roofing arrangement of the pump room created a strong air current, which drew air through the well-shaft opening at ground level.

This concept can be applied more advantageously in designs for use above ground. The wind-escape can accelerate effective ventilation and air circulation when used with other devices for air movement such as windows, doors, and the *malqaf* or wind-catch, described in detail below.

The *Malqaf*

In hot arid zones, a difficulty is found in combining the three functions of the ordinary window: light, ventilation, and view. If windows are used to provide for air movement indoors, they must be very small, which reduces room lighting. Increasing the size to permit sufficient lighting and an outside view lets in hot air as well as strong offensive glare. Therefore, it is necessary to satisfy the three functions ascribed to the window separately.

To satisfy the need for ventilation alone, the *malqaf* or wind-catch was invented. This device is a shaft rising high above the building with an opening facing the prevailing wind. It traps the wind from high above the building where it is cooler and stronger, and channels it down into the interior of the building. The *malqaf* thus dispenses with the need for ordinary windows to ensure ventilation and air movement. The *malqaf* is also useful in reducing the sand and dust so prevalent in the winds of hot arid regions. The wind it captures above the building contains less solid material than the wind at lower heights, and much of the sand which does enter is dumped at the bottom of the shaft.

The value of the *malqaf* is even more obvious in dense cities in warm humid climates, where thermal comfort depends mostly on air movement. Since masses of buildings reduce the wind velocity at street level and screen each other from the wind, the ordinary window is inadequate for ventilation. This situation can be corrected by using the *malqaf*.

The *malqaf* is much smaller than the building facade and therefore offers less surface area to screen the *malqaf* of buildings downwind. The example shown in figure 46 is from Sind, Pakistan, where the *malqaf* is universally used and can be seen rising above the houses like sails capturing the wind.

In Egypt the *malqaf* is very developed and has long been a feature of vernacular architecture. The excellent example of the Qā'a of Muḥib Ad-Dīn Ash-Shāf'ī Al-Muwaqqī, known as Othmān Katkhudā, in Cairo dates from the fourteenth century A.D. The plan and a section of this *qā'a* are shown in figures 47 and 48.

The *qā'a* is a central upper-story room for receiving guests, usually a living room in a residence or a meeting room in a formal hall. It is traditionally composed of three connected spaces: a central part called the *dur-qā'a*, an uncarpeted high-roofed circulation area which provides light and ensures ventilation; and two closed, raised, and carpeted recesses called *īwānāt* (singular: *īwān*). The walls of the *qā'a*, being very high, are stiffened by buttresses to provide rigidity with lightness of structure. The spaces between these buttresses are used as sitting alcoves called *kunja*. The floors of the *kunja* are usually more elevated than the adjacent spaces, the *dur-qā'a* and *īwān*. Access to the *qā'a* is through the *dur-qā'a*, which is in fact a covered courtyard or *ṣaḥn* that has retained the paved floor and marble mosaics characteristic of an open courtyard.

A simplified section through the Qā'a Muḥib Ad-Dīn is shown in figure 49. This example demonstrates the operation of the *malqaf* as part of a complete climatization system. As shown, the *malqaf* is a large shaft rising high above the roof of the northern *īwān*. If an appreciable amount of air is to flow into the *malqaf*, a wind-escape must be provided, and, as for the loggia, airflow will be faster if the air can be strongly drawn out through the air escape by suction. The system of climatization developed depends primarily on air movement by pressure differential, but also secondarily on air movement by convection, producing the stack effect (discussed in more detail below). The ceiling of the *dur-qā'a* rises far above the ceilings of the *īwānāt* and is equipped with high clerestory windows in its upper structure which are covered with *mashrabīya*. In addition to diffused and agreeable lighting, these openings provide the required air escape. Thus the *malqaf* in the northern *īwān* channels the cool breeze from the north down into the *qā'a*, due to the increased air pressure at the entrance of the *malqaf* caused by the wind. Once inside the *īwān*, the air slows down, flows through the *īwān*, rises into the upper part of the *dur-qā'a*, and escapes through the *mashrabīya*. Outside wind blowing over the *dur-qā'a* is accelerated owing to the shape of the *dur-qā'a* roof. From the Bernoulli or Venturi-action effect, the air pressure in the outside wind is lower than that in the *qā'a*. Air from the region of the *dur-qāʻa* escapes into the wind, to be continuously replaced by inside air. Thus, complete circulation through the *qāʻa* is effected.

Figure 49 shows the results of airflow-rate and direction measurements made on 2 April 1973 by scholars from the Architectural Association School of Architecture in London, which substantiate the airflow pattern described. The lengths of the arrows in the figure are proportional to the measured airspeeds, some of which are indicated in units of meters per speed.

But this is not the entire situation. Convection is also important because warm air in the *qāʻa* rises naturally to the upper part of the *dur-qāʻa*. This air movement is accelerated because the flat upper part of the *qāʻa* is exposed to the sun. The upper air inside it heats even more, rises even faster into the upper part of the *dur-qāʻa*, and thus escapes through its *mashrabīya* openings. Heating the air in the upper part of the *qāʻa* does not disturb the thermal comfort due to its extremely high ceiling. Air is drawn from below and ultimately from the *malqaf*, which contributes toward the total air movement. In fact, this arrangement of openings ensures the circulation of air indoors even when the air outside is still. Thus, it is important that the *qāʻa* is placed in the middle of the building and surrounded by rooms that protect the sides from external heat, thus ensuring a maximal temperature difference between the lower and upper parts of the *qāʻa* to promote air circulation.

The idea of the *malqaf* dates back to very early historical times. It was used by the ancient Egyptians in the houses of Tal Al-Amarna and is represented in wall paintings of the tombs of Thebes. One example, shown in figure 50, is the Pharaonic house of Neb-Amun depicted on his tomb, which dates from the Nineteenth Dynasty (1300 B.C.). It has two openings, one facing windward and the other leeward, to evacuate the air by suction. It is interesting to find the same concept applied in the modern design of the workshop at the University of Science and Technology in Kumasi, Ghana, as shown in figure 51, where a *Y*-beam system is used for routing the air circulation.

The *malqaf* can be incorporated into modern buildings aesthetically, as in one of the preliminary designs made by architect Paul Rudolph for the School of Architecture building at Yale University, shown in figure 52. Some of the forms he chose for ventilation can be successfully used as *malqaf*. Thus some of the traditional functional elements of vernacular architecture may enrich the otherwise bare products of modern architecture.

In planning for a *malqaf*, it is important to locate and orient its opening in the direction facing the on-coming wind. The surrounding buildings, and indeed even the new building that includes the *malqaf*, can significantly alter the direction of the prevailing winds. The aerodynamic flow of the new building in its surroundings should be studied to ensure that the *malqaf* is properly positioned. As shown in figure 53, a *malqaf* on the left side of the building facing the prevailing wind would be well placed to capture the airflow. But another on the right side, facing the same direction, would become a wind-escape due to the suction caused by the airflow pattern unless its opening was far above the low-pressure zone.

The size of a *malqaf* is determined by the external air temperature. A larger size is required where the air temperature at the intake is low, and a smaller size where the ambient air temperature is higher than the limit for thermal comfort, provided that the air flowing through the *malqaf* is cooled before it is allowed to circulate into the interior. In Iraq, where the air temperature in summer rises to 45°C (113°F), the typical *malqaf* shaft is very narrow. It is placed in the northern wall with a small inlet allowing the air to cool before it flows into the interior, as illustrated in figure 54. This is very similar to the shape of human nostrils, which are narrower in colder countries so that cold air will not reach the lungs before it has been heated by contact with the trachea, which is at body temperature.

In the areas of An-Najf and Al-Kūfa in Iraq, where air temperature is very high in summer, people live in basements ventilated by small holes in the ceiling and a *malqaf* with a very small inlet. Figure 55 shows the plans and the section of a residence with a basement from this region. However, as the airflow is small and the air circulation is insufficient, this design is unhealthy and a possible cause of lung diseases.

In some designs, the drafts from the *malqaf* outlet are cooled by passing over water in the basement. However, this method is not very effective, and some other device is required to provide air cooling, at increased rates of airflow, sufficient to meet the conditions of both hygiene and thermal comfort.

By increasing the size of the *malqaf* and suspending wetted matting in its interior, the airflow rate can be increased while providing effective cooling. People in Iraq hang wet mats outside their windows to cool the wind flowing into the room by evaporation. The matting can be replaced by panels of wet charcoal held between sheets of chicken wire. Evaporation can be further accelerated by employing the Bernoulli effect or Venturi action with baffles of charcoal panels placed inside the *malqaf*, as shown in figure 56. The wind blowing down through the *malqaf* will decrease the air pressure below the baffle, which increases airflow and thus accelerates evaporation. Metal trays holding wet charcoal can be advantageously used as baffles. As shown in figure 56, air can be directed over a *salsabīl*, a fountain or a basin of still water, to increase air humidity. These components are discussed in Chapter 7. The baffles are also effective in filtering dust and sand from the wind.

Examples of *malqaf* placed directly over a roof opening and without a shaft to channel the airflow into the room are found in nineteenth-century Turkish-style houses in Cairo, illustrated in figure 57.

Figures 58 and 59 show the design for a neighborhood in Bārīs Oasis, Egypt, illustrating how the *malqaf* principle can be incorporated into new architectural designs. Other modern examples of the use of the *malqaf* are the villa designed for Saudi Arabia in figure 60 and the Fu'ad Riyaḍ house in Cairo, shown in detail in figures 61–63.

The *Bādgīr*

In Iran and the countries of the Gulf, a specific type of *malqaf* called the *bādgīr* was developed. It has a shaft with the top opening on four sides (occasionally only two), and with two partitions placed diagonally across each other down the length of the shaft to catch breezes from any direction. This shaft extends down to a level that allows the breeze to reach a seated or sleeping person directly. An example from Dubai, United Arab Emirates, is shown in detail in figures 64–66. The *bādgīr* is usually treated decoratively as an architectural element, as shown in figure 67. In addition to ventilation, the *bādgīr* can be used in pairs or four at a time to cool underground water tanks, as shown in figure 68.

A great advantage of the *malqaf* and the *bādgīr* is that they solve the problem of screening resulting from the blocking of buildings in an ordinary town plan. Several research centers have been working to develop the best configuration for the implantation of blocks of buildings, while avoiding screening of blocks by those upwind. But after six or seven blocks, no configuration will solve the problem of screening. The *malqaf* and the *bādgīr*, however, being smaller in size than the buildings themselves, do provide an effective solution.

When designing the *malqaf* and the *bādgīr*, it is important to determine the airflow pattern around the house, following the principles of aerodynamics, and to orient the inlet appropriately in the airflow. Generally, a building placed in the wind will create a zone of compression to the windward side and a low-pressure zone to the leeward side. This low-pressure zone continues a certain distance beyond the building, depending on the wind velocity, as illustrated in figure 53. The faster the wind velocity, the shorter the low-pressure zone extends, because of eddies created on the leeward side which disrupt the smooth airflow pattern. For normal wind velocities, the length of the low-pressure zone can be taken to be five times the height of the building.

6

The Sun Factor in Air Movement

Under some circumstances, judicious architectural designs can be used to take advantage of the sun factor as a driving force for maintaining air movement. Generally, this technique is applied where large areas are available and is based on the principle of convection.

Air Movement by Convection

Warm air is less dense than cool air and therefore will rise in an environment of cool air. This movement is called convection and can lead to the phenomenon called the stack effect. As the warm air rises, it must be replaced by cooler air from the surroundings. If a heat source exists below the initial pocket of warm air, the cooler air replacing it will also be warmed and will rise. Using a continuous heat source, a steady flow of air is generated. In vernacular architecture, this effect has been exploited to produce small areas with cool breezes, using the ground heated by the sun as the heat source. As long as a large volume of cooler air is available and is unaffected by heat from the sun, the hotter the sun heats the ground, the stronger will be the breeze.

The Courtyard House

The relatively static cooling system used in a courtyard house can provide the basis for understanding modifications that can generate air movement by convection. In hot dry zones, air temperature drops considerably after sunset from re-radiation to the night sky. The air is relatively free of water vapor that would reflect the heat or infrared radiation back toward the ground, as occurs in warm humid regions.

To enhance thermal comfort, this phenomenon has been used in the architectural design of houses by employing the courtyard concept.

Nature is hostile at ground level in these zones, especially in the deserts. People learned to close their houses to the outside and open them inwardly onto internal courtyards called *ṣaḥn*, which are open to the sky. This arrangement provides drops in air temperature of 10–20 C° (18–36 F°) at night. This might explain why the lunar crescent as a symbol of the night sky is so meaningful to Arab people and ultimately to all Muslims, to the point of appearing on the flags of eight predominantly Muslim nations.

As evening advances, the warm air of the courtyard, which was heated directly by the sun and indirectly by the warm buildings, rises and is gradually replaced by the already cooled night air from above. This cool air accumulates in the courtyard in laminar layers and seeps into the surrounding rooms, cooling them. In the morning, the air of the courtyard, which is shaded by its four walls, and the surrounding rooms heat slowly and remain cool until late in the day when the sun shines directly into the courtyard. The warm wind passing above the house during the day does not enter the courtyard but merely creates eddies inside, unless baffles have been installed to deflect the airflow. In this way, the courtyard serves as a reservoir of coolness.[1] The courtyard concept is universally applied in the traditional architecture of countries in hot arid regions stretching from Iran in the East to the shores of the Atlantic Ocean in the West, and in both rural and urban housing design. Examples from Egypt, Tunisia, and Iraq are shown in figures 69, 70, and 71, respectively. Figure 72 shows a view of the courtyard of the As-Suḥaymī house in Cairo, illustrating the pleasant atmosphere that can be created within the courtyard and the arrangement of the surrounding spaces, some with *mashrabīya*-filled openings.

The *Takhtabūsh*

Modifications of the courtyard concept have been developed to ensure a steady flow of air by convection. The vernacular architecture of the Arab house includes an element called the *takhtabūsh*, a type of loggia. This is a covered outdoor sitting area at ground level, located between the courtyard and the back garden, opening completely onto

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[1] Daniel Dunham, "The Courtyard House as a Temperature Regulator," *New Scientist* (8 September 1960): 659–666.

the courtyard and through a *mashrabīya* onto the back garden. Since the back garden is larger and thus less shaded than the courtyard, air heats up more readily there than in the courtyard. The heated air rising in the back garden draws cool air from the courtyard through the *takhtabūsh*, creating a cool draft, as in the As-Suḥaymī house and the Qā'a of Muḥib Ash-Shāf'ī Al-Muwaqqī in Cairo, shown in figures 73 and 74. A similar arrangement can be found in the *tablinum* of the ancient Roman villas of Pompeii.

This concept can be used in the town plan of a village or a residential sector from which automobile traffic is excluded, to provide a cool and agreeable meeting place for the inhabitants. In this case, the *takhtabūsh* can be set between two squares, one larger than the other. The larger square is on the leeward side to help in creating drafts by pressure differential. This design is illustrated in the village of Bārīs, Egypt, shown in figure 75.

The people of a village or a residential quarter often gather in certain agreeable places, in addition to parks, which were created unintentionally by the configuration of the buildings. Some of these places are well oriented to receive sunlight and are protected against wind, places elderly people would choose in the winter. Other places are shaded from the sun, have elements like the *takhtabūsh* to produce drafts, and are sought in the summer. It is important that the architect note this need and, based on a scientific understanding of the situation, consciously create agreeable public places that reintroduce human scale and aesthetics to townscapes.

Traditional City Layout and Climate

As climate is a dominant factor in traditional town planning, a marked uniformity in urbanization is found in all hot arid zones. The layouts of almost all traditional cities in the area are characterized by two features: narrow winding streets, and large open courtyards and internal gardens.

Typically, large courtyards serving as reservoirs of cool, fresh air dominate a city plan, as seen in examples from Marrakech, Morocco; Tunis, Tunisia; and Damascus, Syria; shown in figures 76, 77, and 78, respectively. At first sight, this arrangement appears far superior to the gridiron layout with wide boulevards of Washington, D.C., shown in figure 79, that is often held up as a model for city planning, even in hot arid climates. The narrow meandering streets with closed vistas perform the same function as a courtyard. They retain any cool air that may be deposited during the night from being swept out by the first puff of wind as would occur in a gridiron plan with wide boulevards.

But to objectively judge this matter, a comprehensive comparison between the two design concepts is required, based on measurements of the open courtyards, internal gardens, and external streets and squares, and their corresponding air quality and temperatures.

While traditional layouts may not be designed to accommodate motor traffic, solutions to this problem exist. One alternative is to encircle the residential quarter with a ring road for cars, with cul-de-sac streets branching off into the interior as suggested by the Radburn Plan.[2] Another solution is the Dynopolis concept launched by Doxiadis,[3] which assumes that the characteristic traditional layout can be preserved within the quarter.

With regard to a gridiron town plan, buildings crowded in the city center affect wind movement in that quarter, creating eddies and lowering the wind velocity by friction and change of direction. Research in the Federal Republic of Germany showed that mean wind speed dropped from 5.1 to 3.1 m/s (16.7 to 10 ft/s) in one German town as it grew in size and expanded. In Detroit, Michigan, the wind speed dropped from 6.5 to 3.8 m/s (21.3 to 12.5 ft/s) over a period of 20 years. And in Stuttgart, Federal Republic of Germany, the number of days in which the wind was stagnant increased from 1% in 1894 to 20% in 1923. It can be concluded that, when buildings are crowded into a small area, the wind velocity decreases markedly. Wind above the city is affected by three factors: (1) high winds, (2) microclimatic winds which are affected by the topography and the configuration of the city, and (3) the wind movement created by the city itself.

As the solar warming process is greatest at the center of a city, the hot air of this sector rises by convection and is replaced by air from the other quarters. When the city plan is a gridiron pattern with wide, straight streets, hot air laden with dust and fumes from automobile traffic collects from the surrounding quarters and from the industrial areas and forms a dome of polluted air above the city center. This phenomenon can be seen at night by observing the reflection of city lights on floating particles of dust suspended in the air, which take on the colors of advertisement illumination. However, if the architect must adopt a gridiron street pattern with wide avenues, then sufficient green areas should be spread over the geographical area in order to redistribute the heat evenly within the city and avoid its concentration in the center.

[2] Clarence Stein, *Toward New Towns for America* (New York: Reinhold Publishing, 1957).

[3] Constantinos A. Doxiadis, *Ekistics: An Introduction to the Science of Human Settlements*. (New York: Oxford University Press, 1968).

7

The Humidity Factor

In the name of Allah, The Beneficient, The Merciful. And "We sent down out of Heaven water in measure and lodged it in the earth and we are able to take it away" (18).—Book of *Al-Qur'ān*, "The Believer."

Water is scarce in desert lands, and people in the hot arid zones have always cherished water and tried to remain in contact with it as long as possible. Apart from its refreshing effect physically, it has always had a pleasing psychological effect. Furthermore, water is very important in increasing the humidity and thereby promoting thermal comfort in hot arid lands.

In the Arab house, the fountain plays a role equivalent to the fireplace in the temperate zones, although one is used for cooling and the other for heating. Thus, the fountain is an architectural feature occupying a privileged place in the house plan.

The Fountain

Originally in the Arab house the fountain was placed in the middle of the courtyard with the *īwānāt* or living spaces opened onto it. It always had a symbolic form, square in shape, with the inner basin in the form of an octagon or a hexadecagon as in the example of a fountain in a traditional house in Cairo shown in figure 80. From each of the triangles formed at the corners of the square, a semi-circle was scooped out, so that the entire basin appears as if it were a geometrical projection of a dome on squinches, symbolizing the sky as seen in figure 81. Thus the real sky is brought down into intimate contact with the *īwānāt* by the reflection in the symbolic sky of the water basin.

After further development of the Arab house, the concept of the courtyard with several *īwānāt* was transformed into the *qā'a* concept, composed of a *dur-qā'a*, which is a covered courtyard, with the *īwānāt* leading from it. In this arrangement, the fountain occupies a place in the center, displaying its water and mixing it with air to increase humidity.

The *Salsabīl*

In places where there was not enough pressure to permit the water to spout out of the fountainhead, architects frequently replaced the fountain with the *salsabīl*. The *salsabīl* is a marble plate, decorated with wavy patterns suggestive of water and wind, which is placed against the wall inside a niche on the opposite side of the *īwān* or sitting space. It is placed at an angle, as shown in figure 82, to permit the water to trickle over the surface, thus facilitating evaporation and increasing the humidity of the surrounding air. The water then flows into a marble channel until it reaches the fountain in the middle of the *dur-qā'a*. The *salsabīl* can be interpreted as a transposition of the fountainhead placed outside the fountain, which shows mental flexibility and freedom of inventiveness in design. It allows the architect to use his creativity and sensitivity in expressing his feelings through architecture. Of the two examples in figures 83 and 84, one can say that they provide tangible proof of Goethe's statement that "architecture is frozen music."

Postscript

People can beautify anything they do with their hands and can satisfy their physical and spiritual needs when they interact with the environment, using its natural materials and sources of energy. The result of the human-environment interaction constitutes culture and has led to the development of a multitude of cultures by different people in different environments. Vernacular architecture is one of the most concrete manifestations of this interaction.

The aesthetic aspect was given no less attention and importance than the functional aspect in the development and application of the *salsabīl*, the fountain, the *claustra*, and the architectural design concepts for shading and air movement, in spite of the fact that these appear to be losing ground to the apparent conveniences of mechanical solutions. The unrestrained use of the machine has resulted in the current energy problems in industrialized countries. As a result, a serious effort has been launched to return to natural energy sources such as solar and wind energy. In this effort, the solutions provided by generations of traditional societies, which used only natural sources of energy in their vernacular architecture, may be of great help in opening new fields for research and application.

Modern science can develop human capabilities to use natural sources of energy far beyond what has been achieved in vernacular architecture. This requires a systematic application of science and a comprehensive comparison of modern and traditional structures. But if modern science is to revitalize architecture in this way, the principles that produced the traditional solutions must be respected. This is the only way modern architecture can surpass, in human and ecological quality, the achievements of vernacular architecture in the hot arid regions of the world.

The examples presented here, some of which show opportunities available for the continuity of vernacular traditions, indicate the benefits of critically evaluating our heritage. We must determine which might serve as viable solutions to some of the current problems, not just of architecture in the hot arid zones but in all environments and cultures, and in many other fields. Such an effort can only enrich human thought and culture.

Illustrations

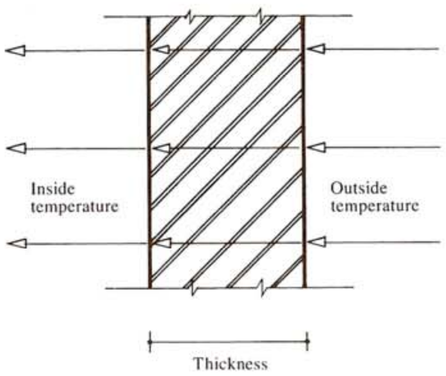


Fig. 1. Heat flow through an external wall of uniform material of given thickness. (See p. 14.)

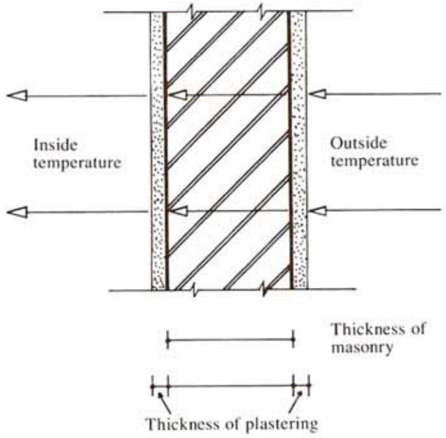


Fig. 2. Heat flow through an external wall of composite materials. (See p. 15.)

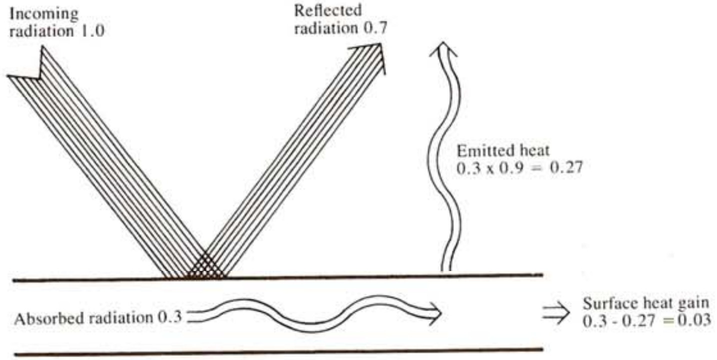


Fig. 3. Relationship between the radiation incident on a building surface and the heat gain of the structure. (See p. 24.)

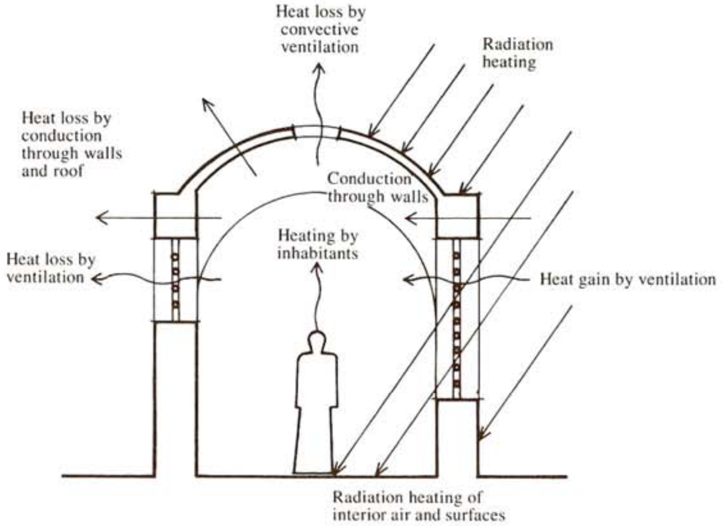


Fig. 4. Schematic diagram of the modes of heat gain and loss in a building. (See p. 24.)

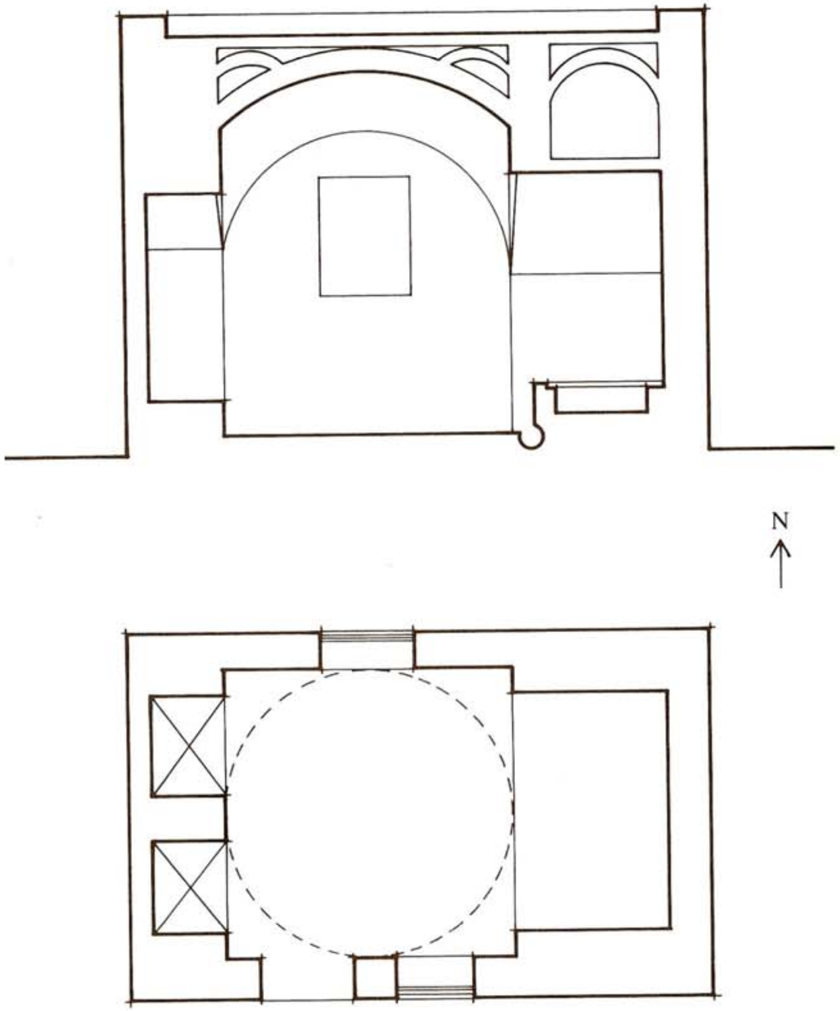


Fig. 5. Plan and section of the sun-dried mud-brick vault-and-dome test model used to observe diurnal temperature fluctuations. (See p. 40.)

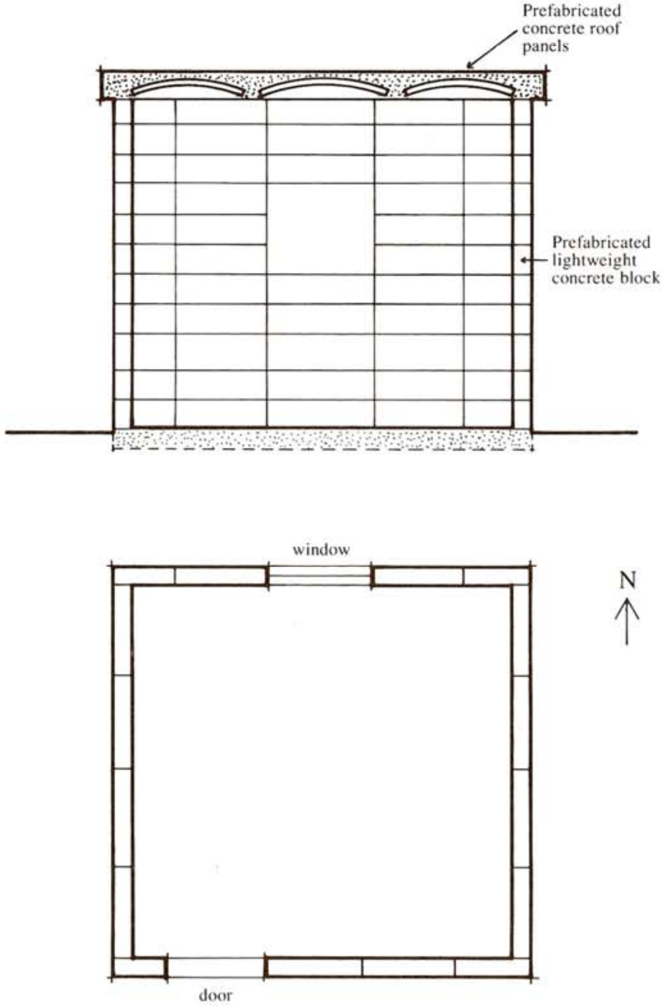


Fig. 6. Plan and section of the prefabricated concrete test model used to observe diurnal temperature fluctuations. (See p. 40.)

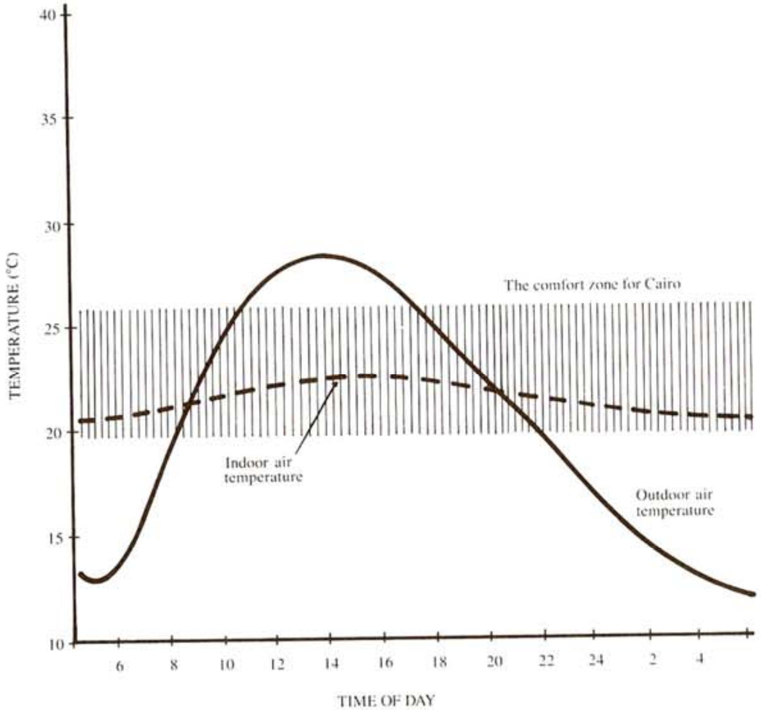


Fig. 7. Comparison of indoor and outdoor air-temperature fluctuations within a 24-hour period for the mud-brick vault-and-dome test model. (See p. 40.)

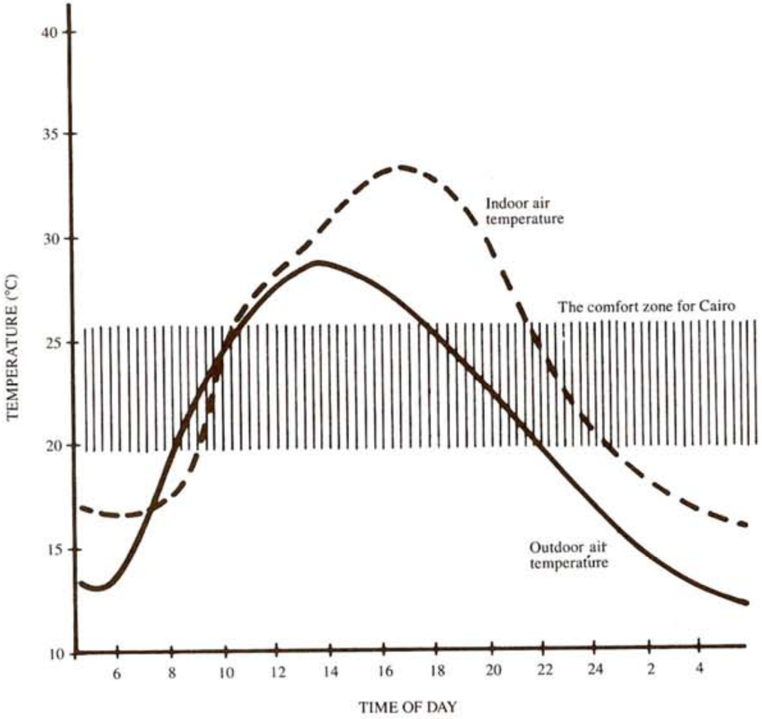


Fig. 8. Comparison of indoor and outdoor air-temperature fluctuations within a 24-hour period for the prefabricated concrete test model. (See p. 41.)

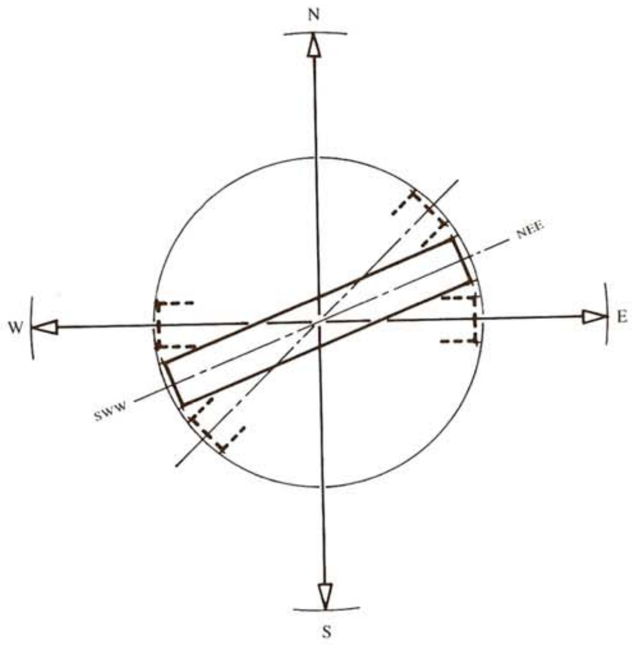


Fig. 9. Optimal orientation of a row of houses with regard to both sun and wind. (See p. 43.)

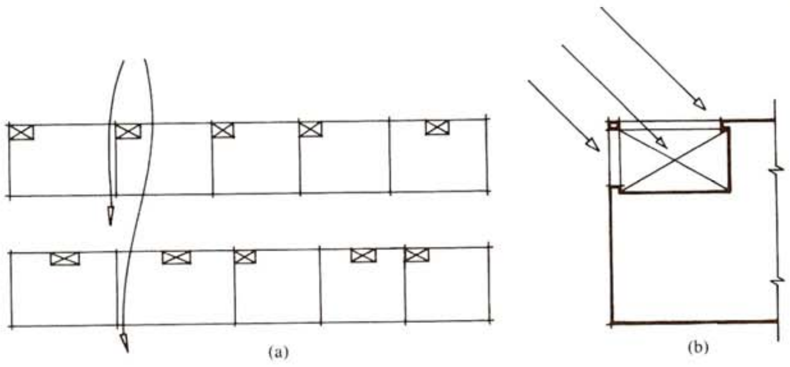


Fig. 10 Plan for two rows of houses showing the *malqaf* or wind catch of each arranged to bring wind to the dwelling *(a)*, and details of a *malqaf (b)*. (See p. 43.)

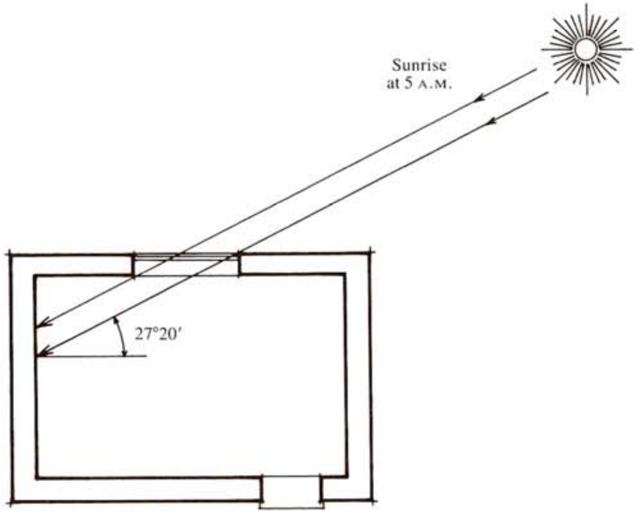
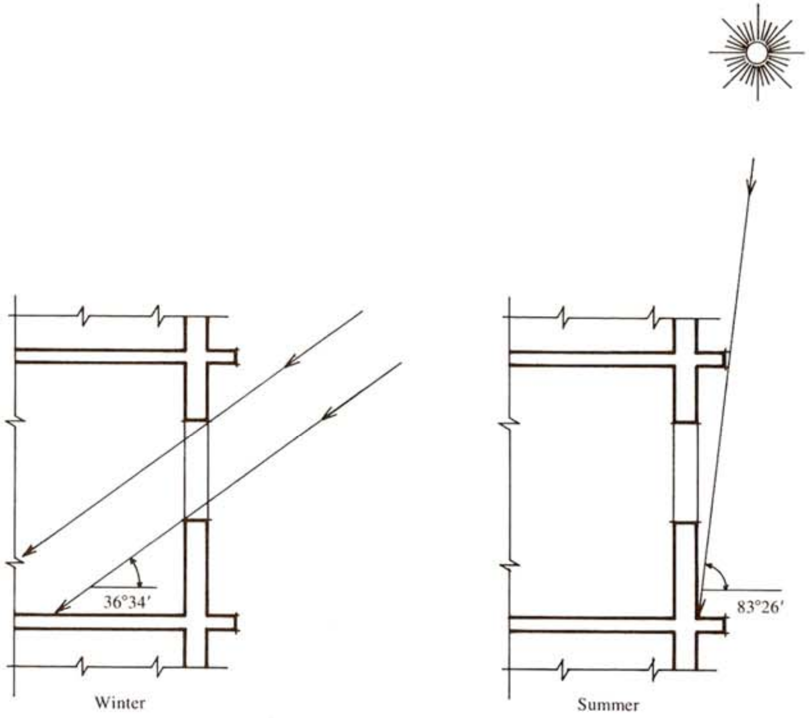


Fig. 11. Plan of a room in Cairo exposed to the north at sunrise on the summer solstice, with the sun's rays at declination angle of 27° 20′. (See p. 44.)



Winter

Summer

Fig. 12. Angle of altitude at noon for a southern facade in Cairo. (See p. 44.)

Fig. 13. Covered street in Cairo. (See p. 45.)

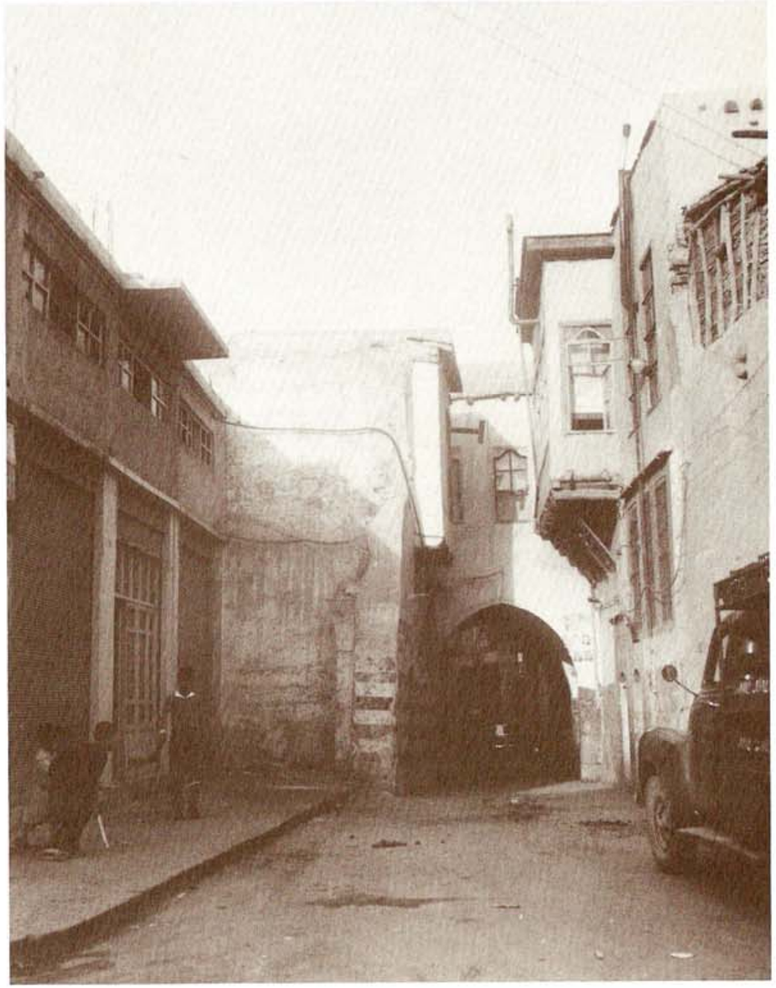


Fig. 14. Covered street in Damascus. (See p. 45.)

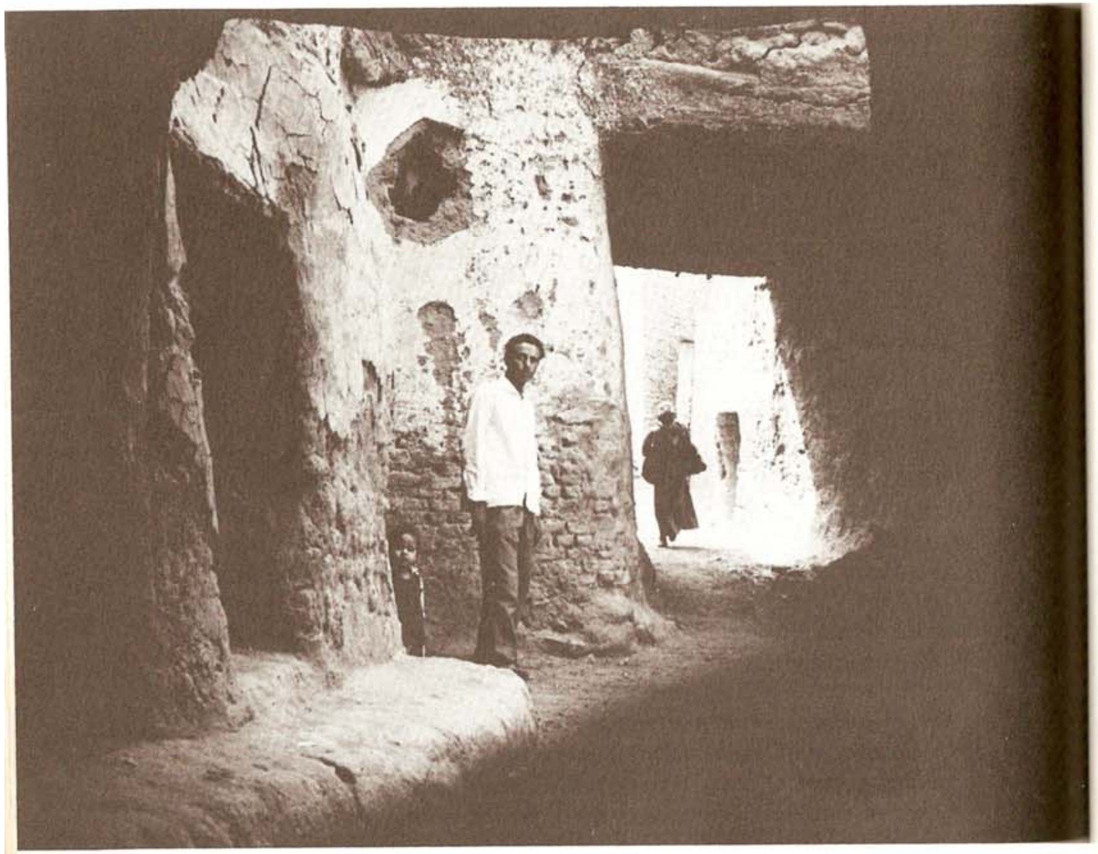


Fig. 15. Covered street in Kharga Oasis in the Western Desert of Egypt. (See p. 45.)

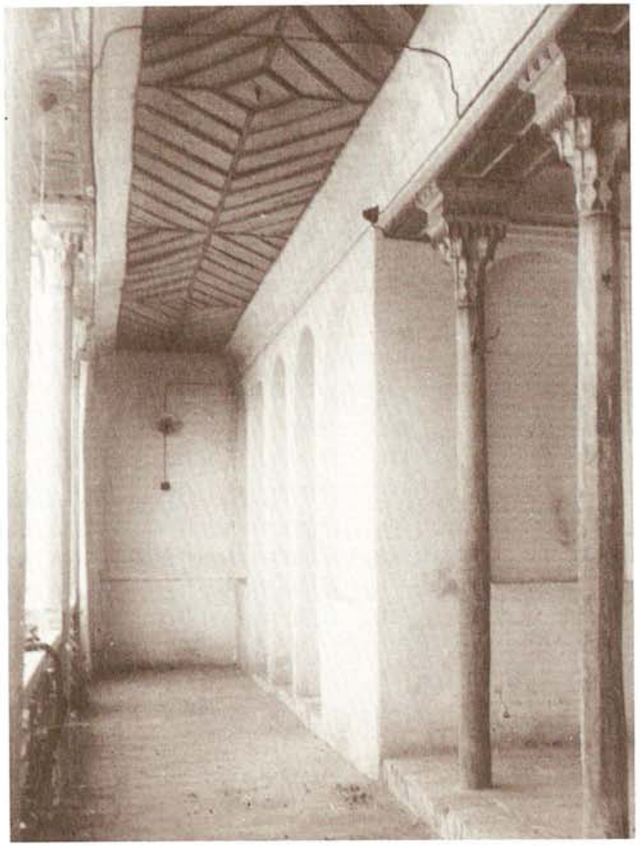


Fig. 16. Protective outer corridor in Iraq. (See p. 45.)

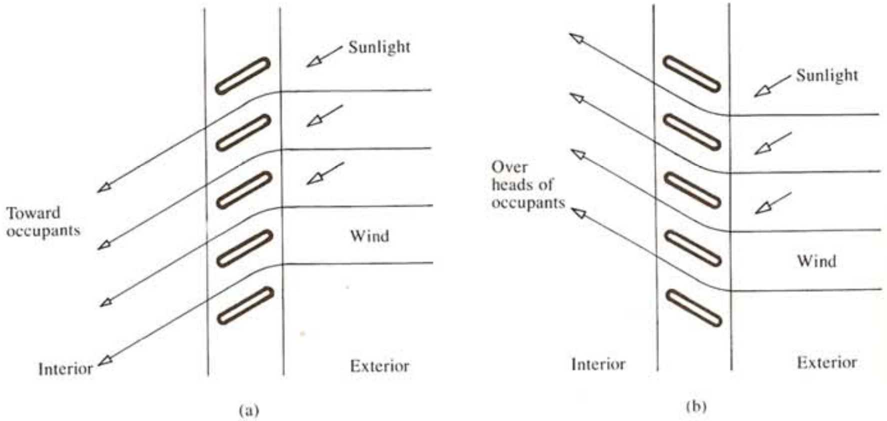


Fig. 17. Difficulty of adjusting venetian blinds in summer: *(a)* the position for the optimal direction of the air movement is undesirable with regard to sunshine; *(b)* the optimal position for blocking sunlight is undesirable with regard to the wind direction. (See p. 45.)

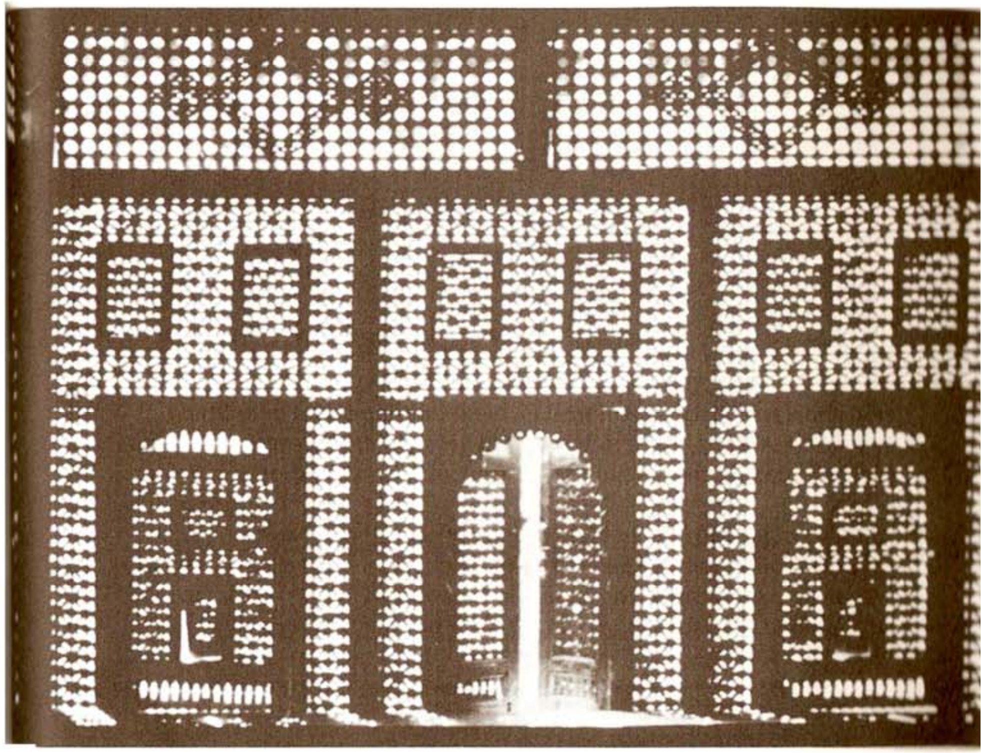


Fig. 18. Brise-soleil in Boiké, Ivory Coast. (See p. 46.)

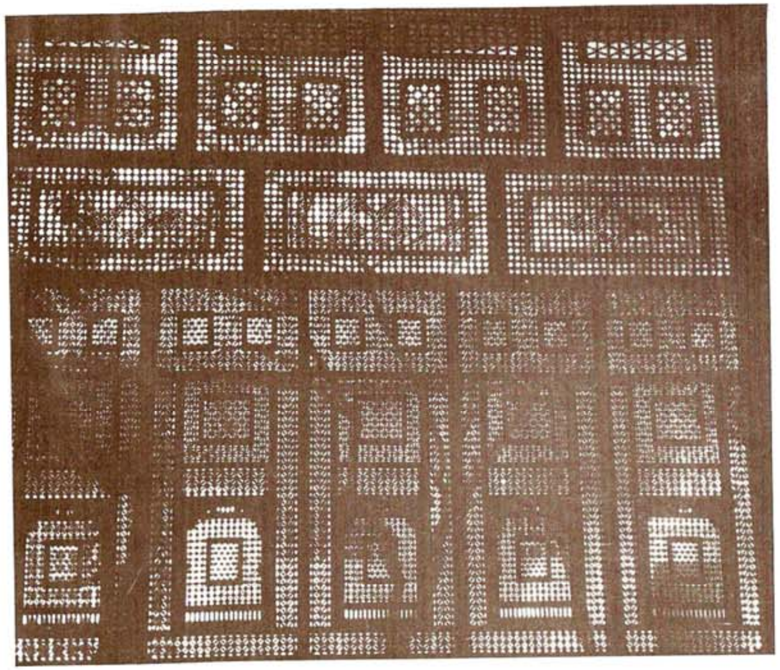
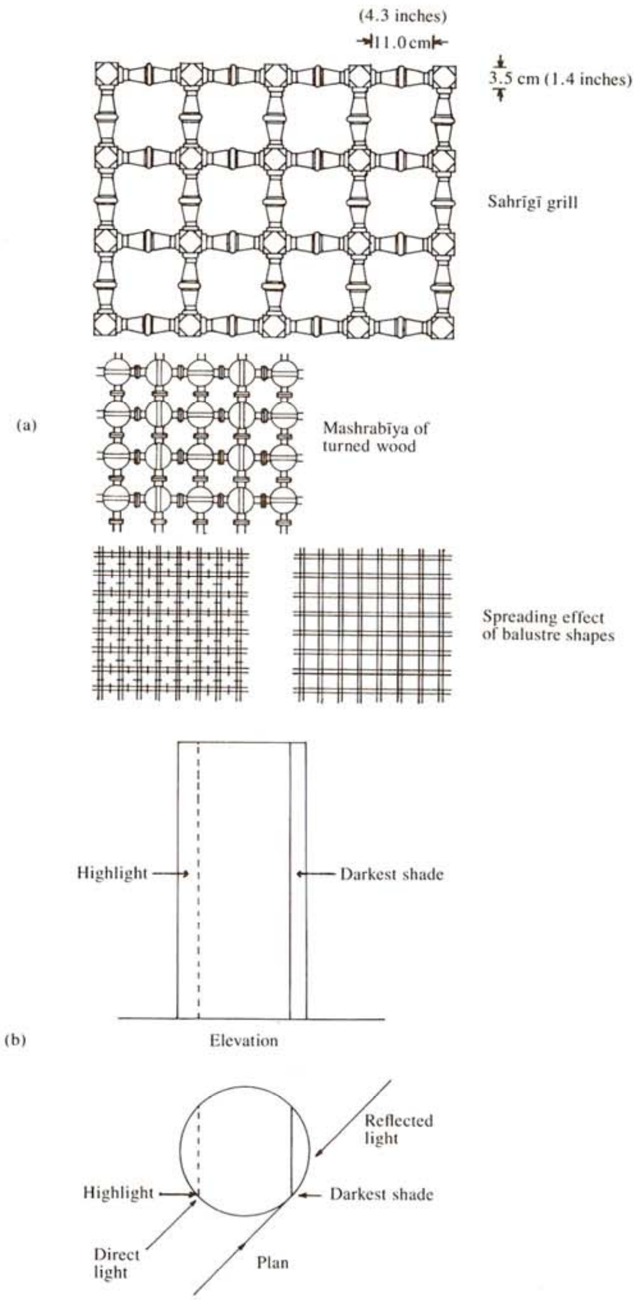


Fig. 19. (above) *Mashrabīya* in the As-Suḥaymī house, Cairo. (See p. 47.)

Fig. 20. (opposite) Analysis of light falling on a *mashrabīya: (a)* examples of lattice arrangements; and *(b)* the effect of light falling on a cylinder. The graduated light and shade of the cylinder subdue the dazzling effect of dark-light contrast which occurs when looking from the inside toward the light outside. (See p. 47.)



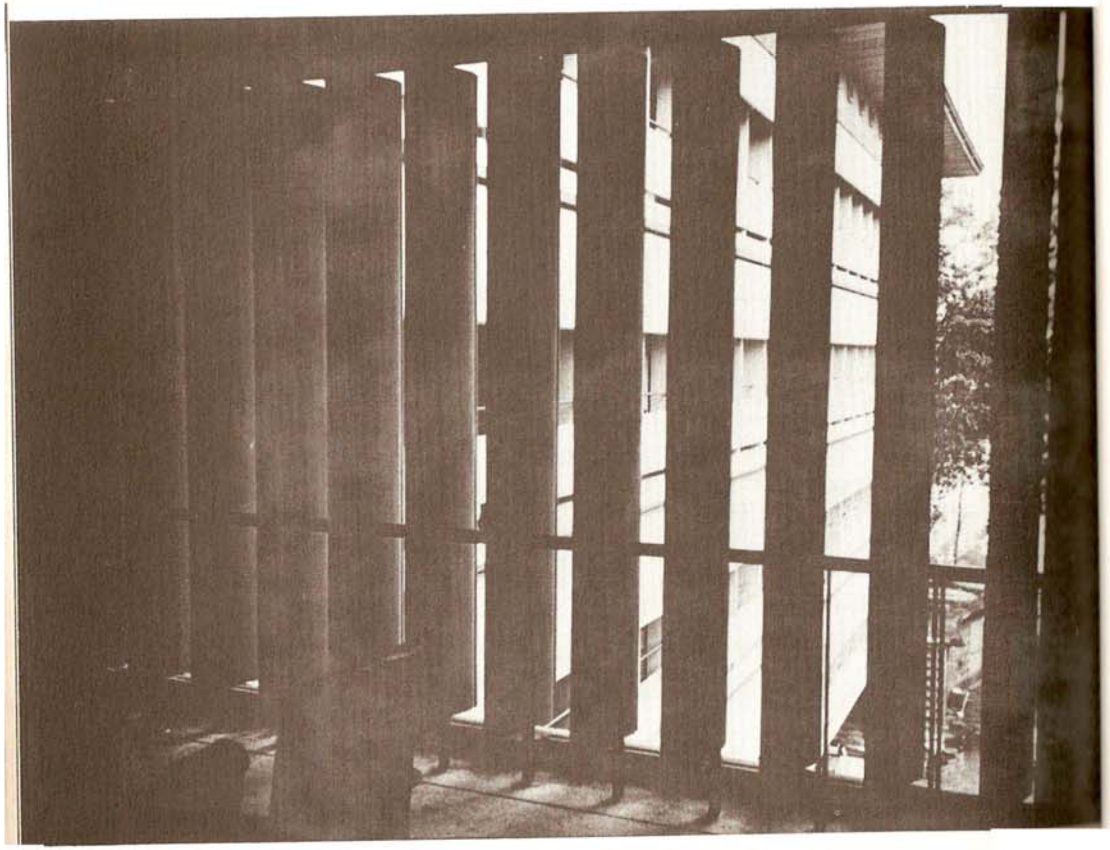


Fig. 21. *Mashrabīya* seen from inside. The lattice can be opened at the eye and hand level of a standing person when desired. Note the reduction in glare. (See p. 47.)

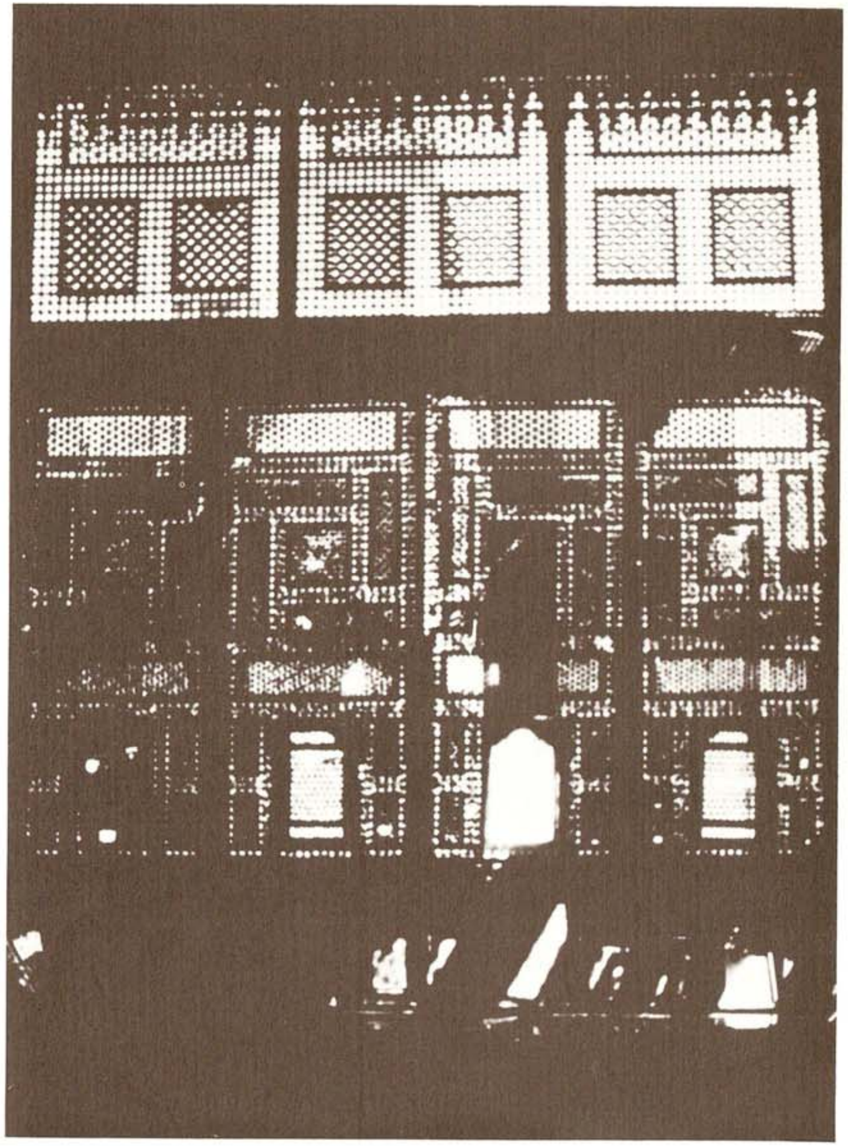


Fig. 22. View of *mashrabīya*, showing its effectiveness in reducing glare at eye level. Note the larger interstitial spacing of the upper part of the *mashrabīya*, which permits reflected light to brighten the room above eye level, thus compensating for the dimming effect. (See p. 47.)

Fig. 23. *Mashrabīya* of the Jamāl Ad-Dīn Adh-Dhahabī house, Cairo, showing increased interstitial spacing at high levels. (See p. 48.)

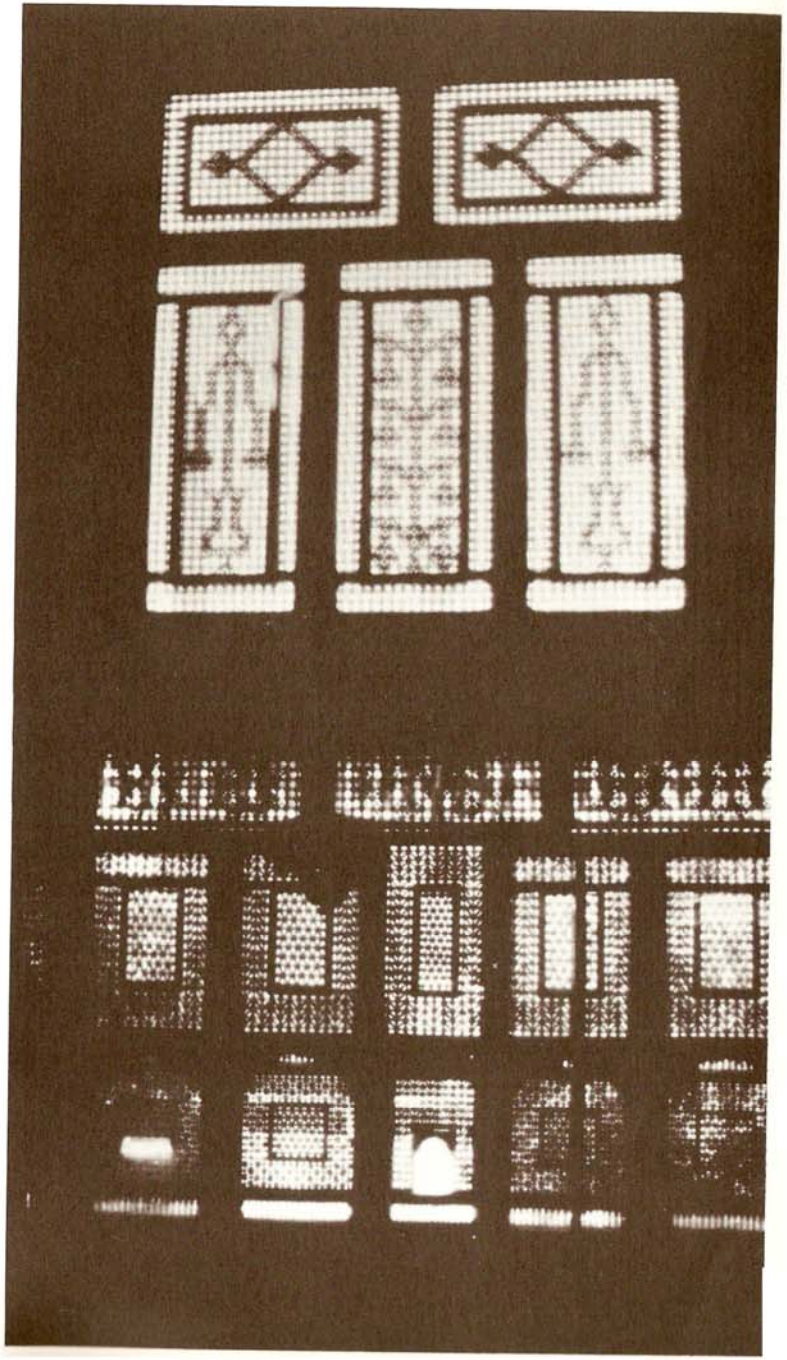


Fig. 24. (opposite) The lighting effect that can be achieved with *mashrabīya* in a room with a high ceiling. (See p. 48.)

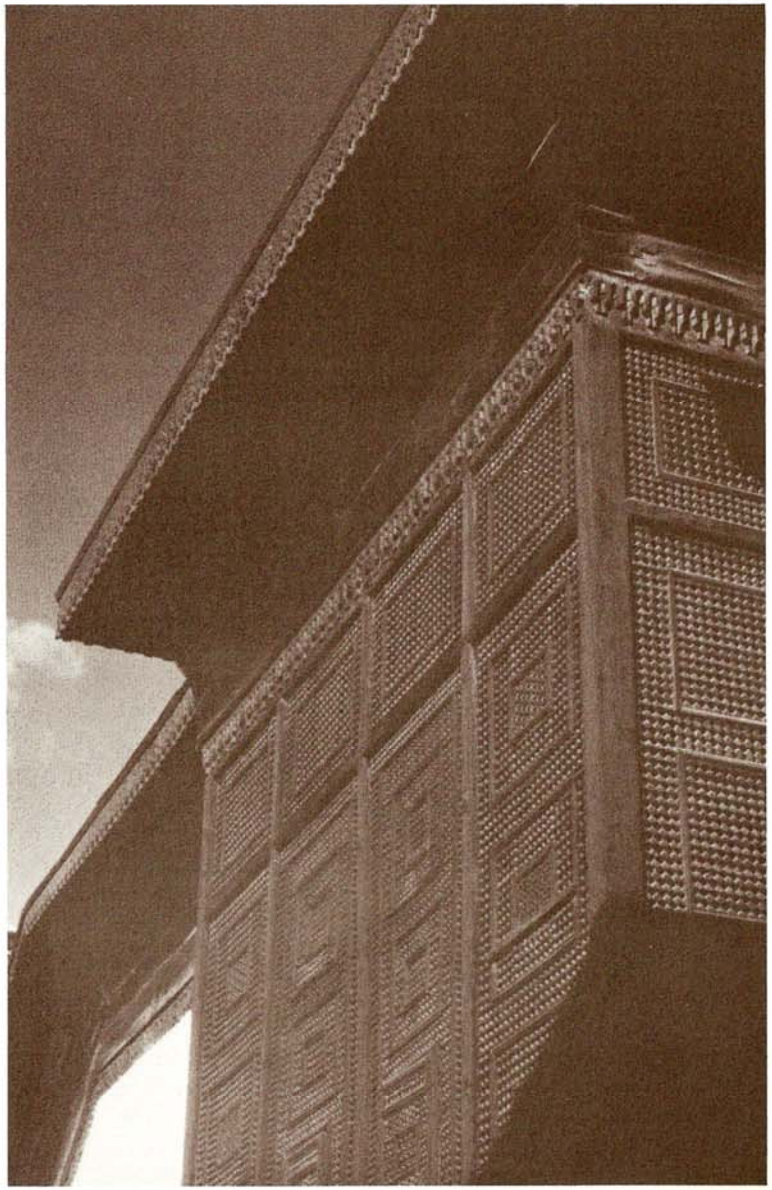


Fig. 25. Outside view of a *mashrabīya* in a second story of the As-Suḥaymī house, Cairo, showing the use of an overhang. The obstruction of the view to the inside ensures privacy. (See p. 48.)

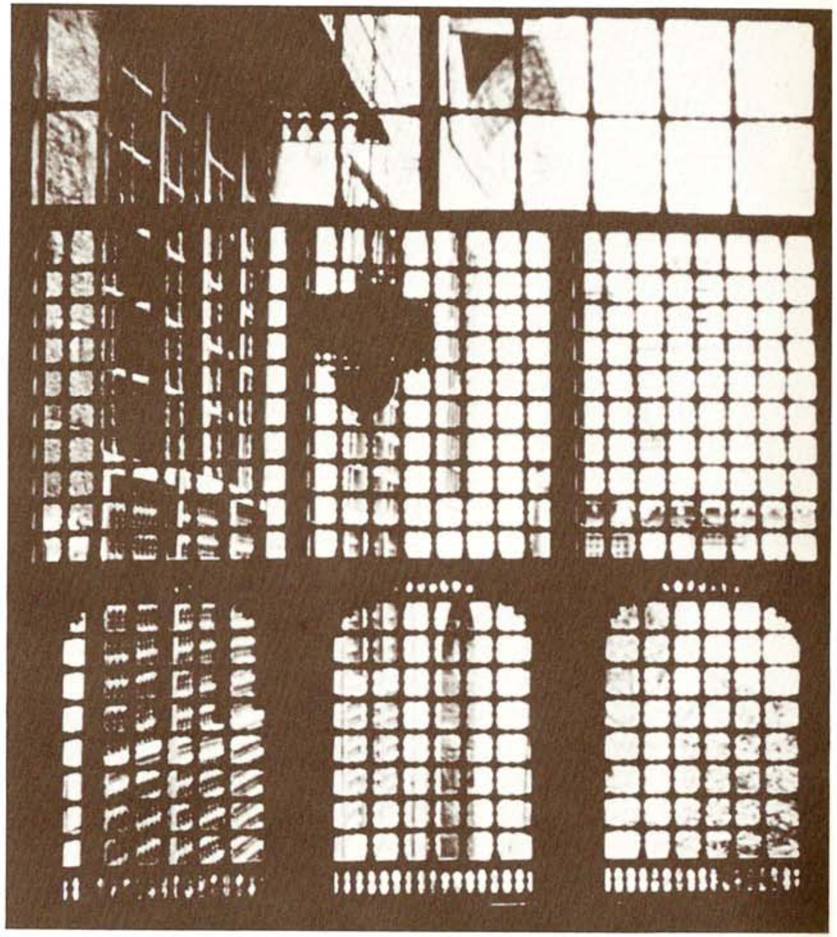
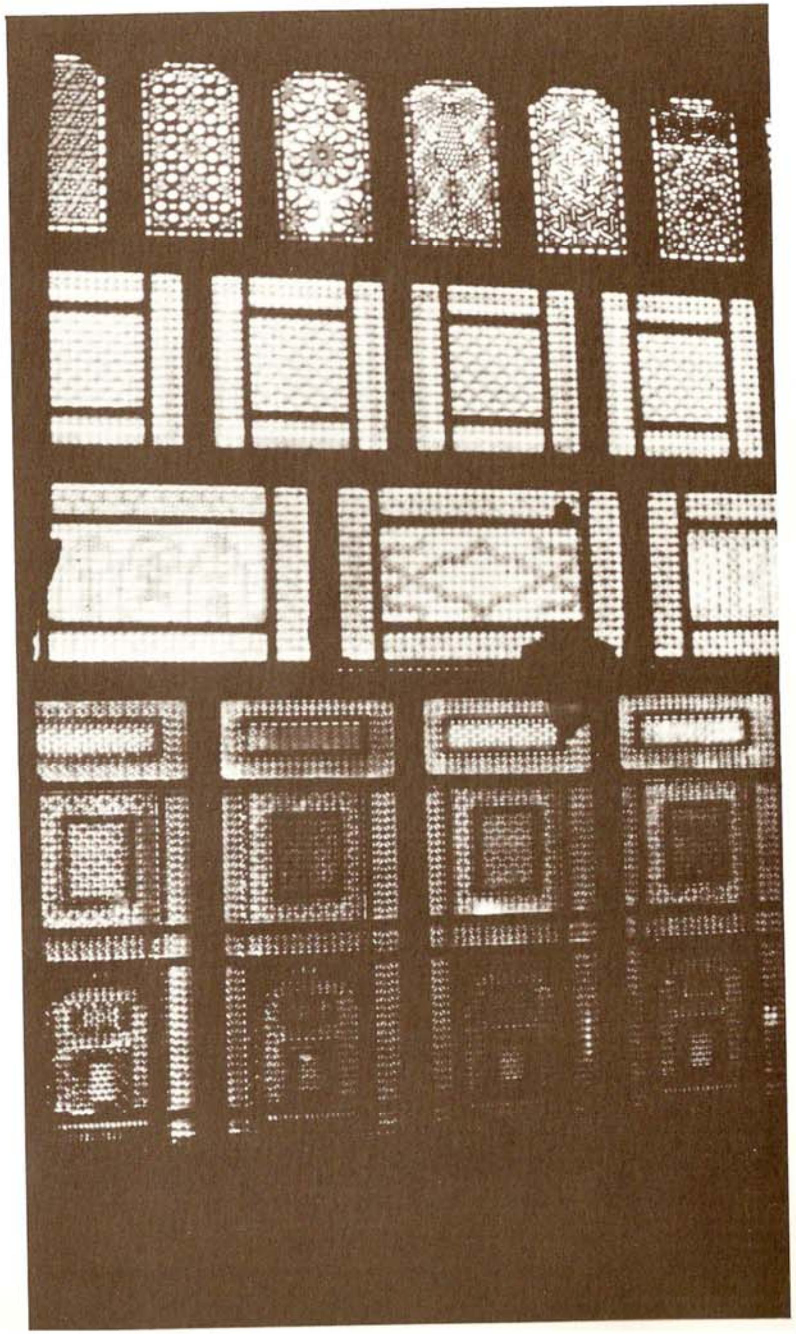


Fig. 26. *Mashrabīya* with large interstitial spacing to increase ventilation. (See p. 48.)



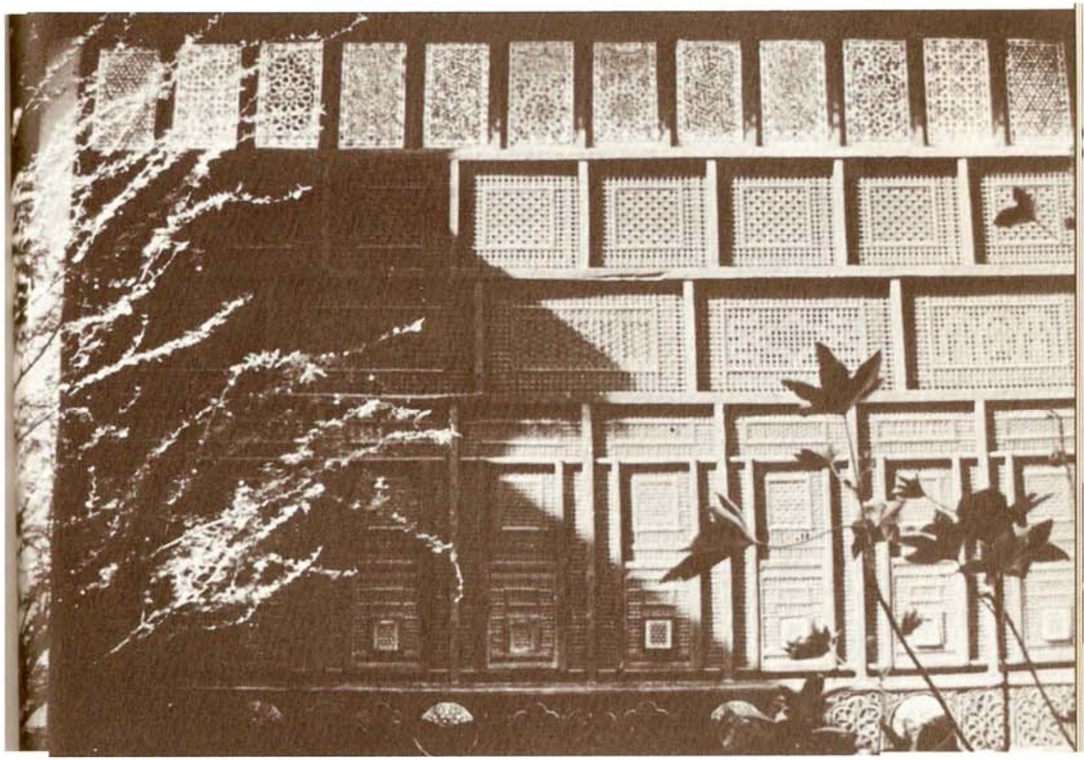


Fig. 27. (opposite) *Mashrabīya* covering the entire facade of a room to increase ventilation, the As-Suḥaymī house, Cairo. Note the variety of patterns and how the interstitial spacing changes with height. (See p. 48.)

Fig. 28. (above) An outside view of the *mashrabīya* shown in fig. 27. (See p. 48.)

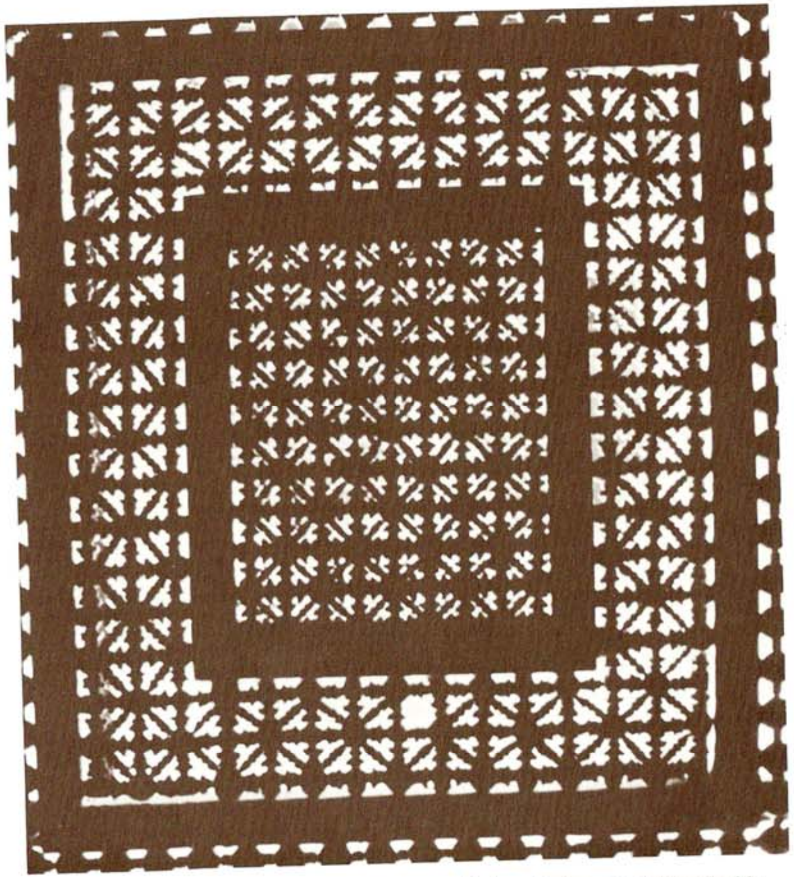


Fig. 29. *Mashrabīya* of the As-Suḥaymī house, Cairo, photographed from inside with the camera focused on the lattice. (See p. 49.)

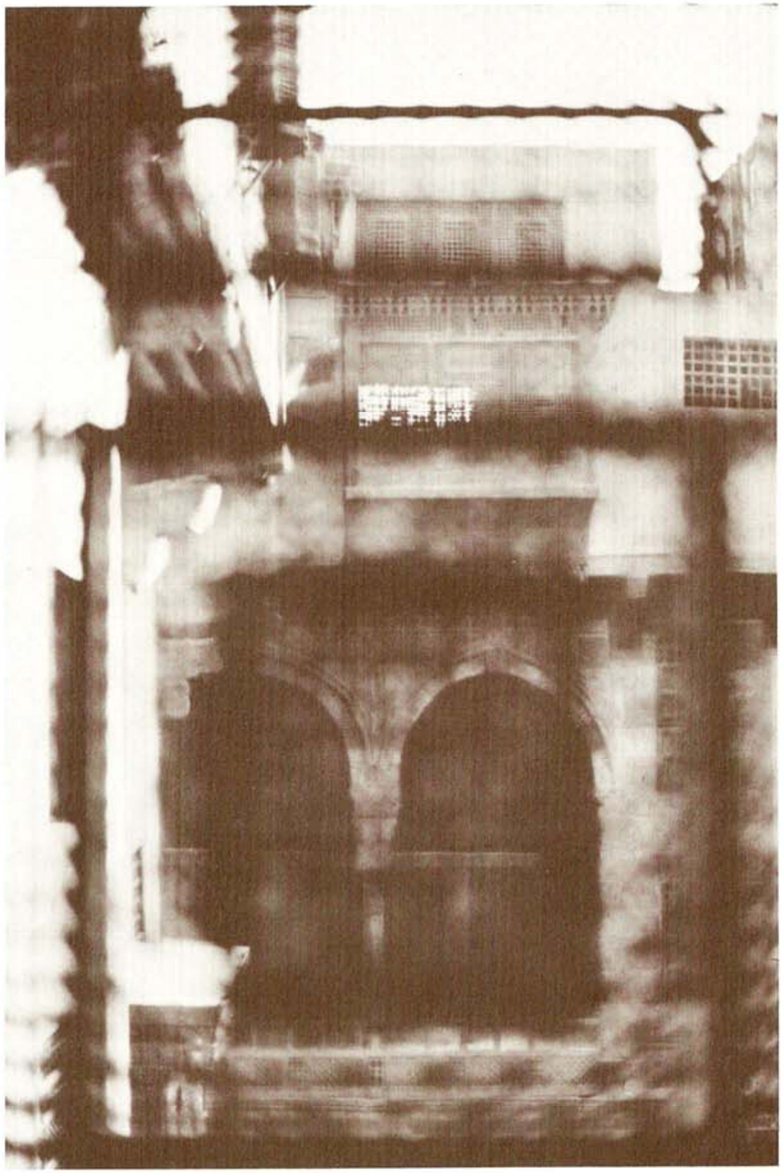


Fig. 30. View through the *mashrabīya* shown in fig. 29, with the camera in the same position but focused on the building across the courtyard. (See p. 49.)

Fig. 31. (above) Section through the reception room of a modern villa designed for Saudi Arabia showing the use of *mashrabīya*. This design incorporates a complete climatic system including *malqaf*, room, *dur-qā 'a* and *ṣaḥn* (courtyard). The decorations harmonize the scale of the imposing structure of which the *dur-qā 'a* is 13 m (43 ft) high. Design by Hassan Fathy. (See p. 49.)

Fig. 32. (top right) Roof-terrace loggia in Iraq. (See p. 50.)

Fig. 33. (bottom right) Roof-terrace loggia of a house in Rosetta, Egypt. The railing encloses an opening in the main roof through which hot air can escape from the lower floors during the day and cool air descends during the night. (See p. 50.)

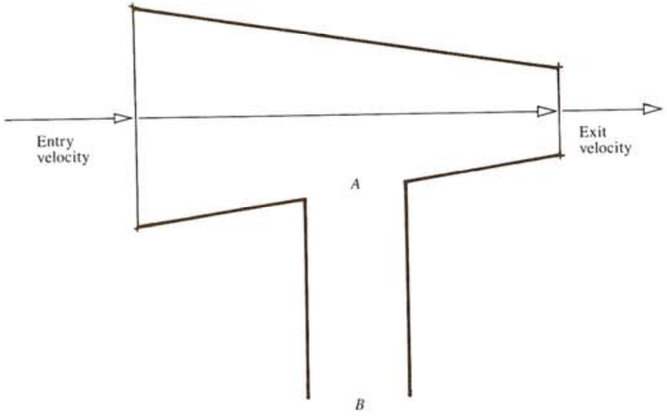


Fig. 34. (above) Funnel with a side tube to illustrate the Bernoulli effect. (See p. 53.)

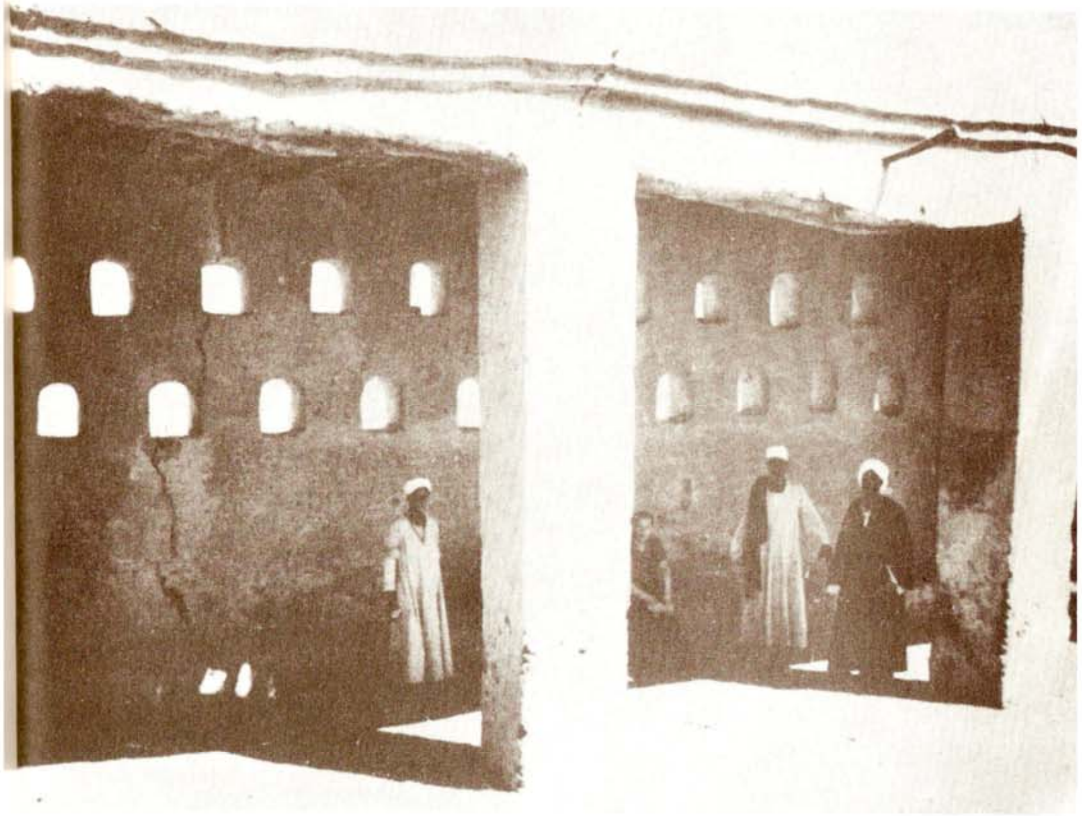
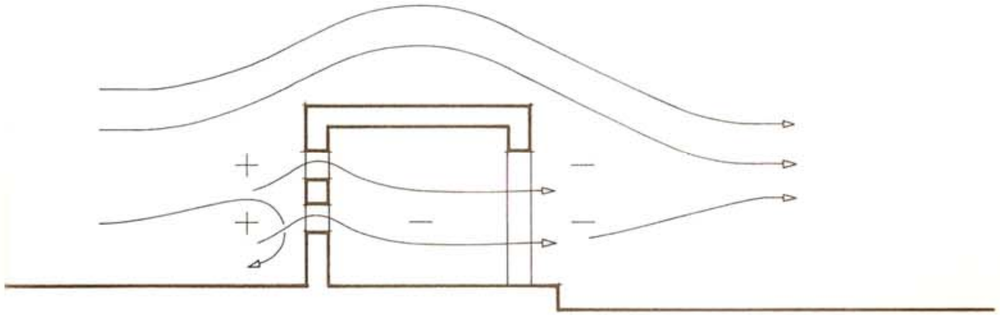
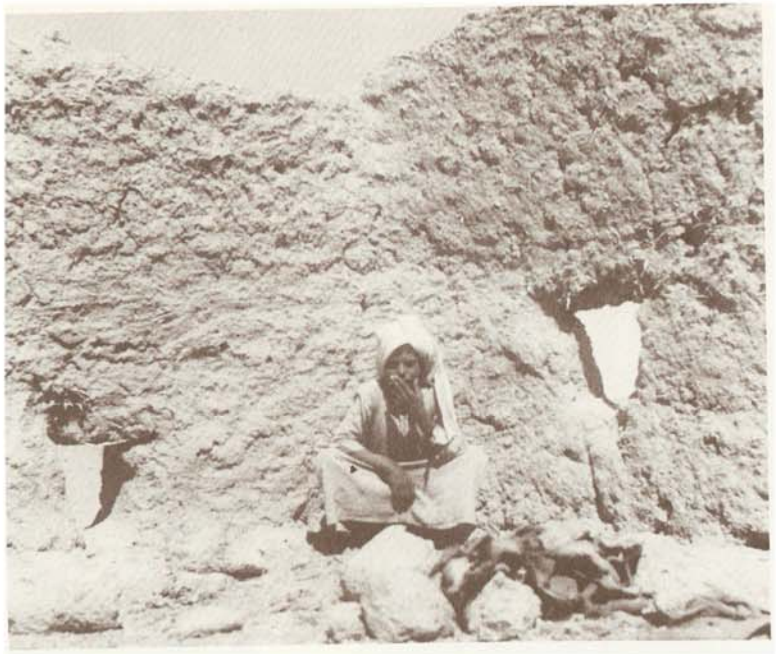
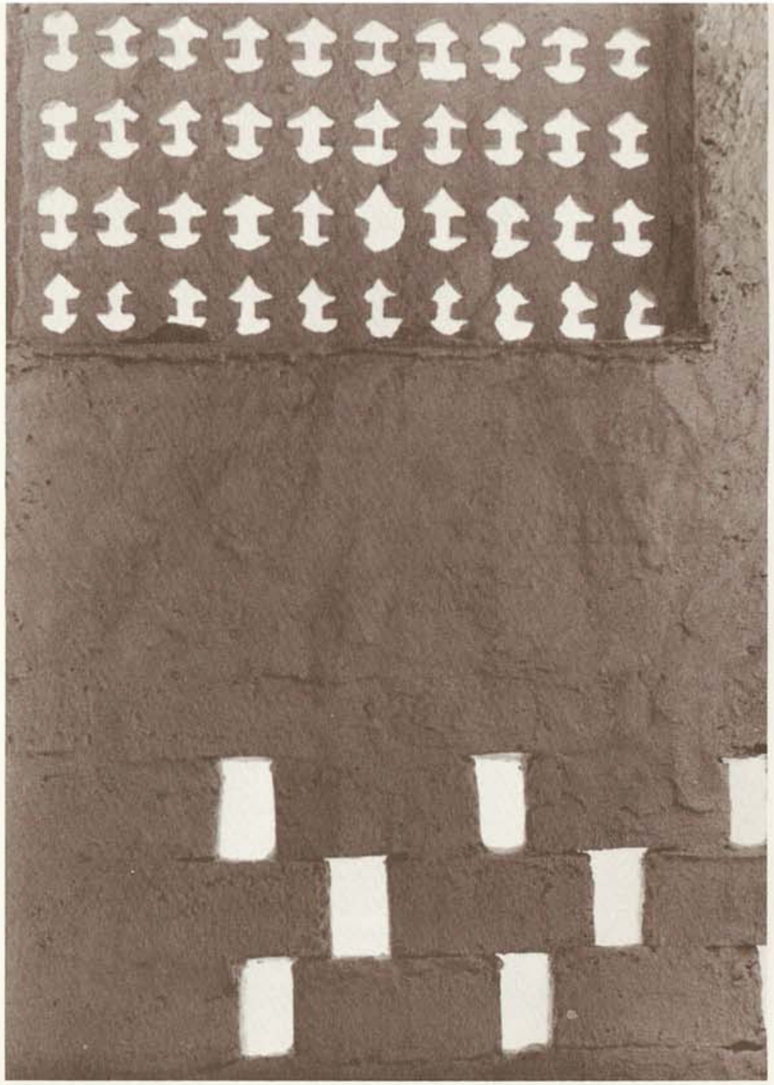


Fig. 35. (top right) Pierced wall in the windward side of the loggia of a *maḍyafa* or guest house, Gourna, Egypt. (See p. 53.)

Fig. 36. (bottom right) Schematic drawing, showing the aerodynamic principles that provide a comfortable breeze in a loggia of the type shown in fig. 35. The positive and negative signs indicate the regions of pressure build-up and deficiency, respectively. A detailed analysis of the aerodynamic lines of air movement is important when applying scientific principles to optimal thermal comfort. (See p. 53.)







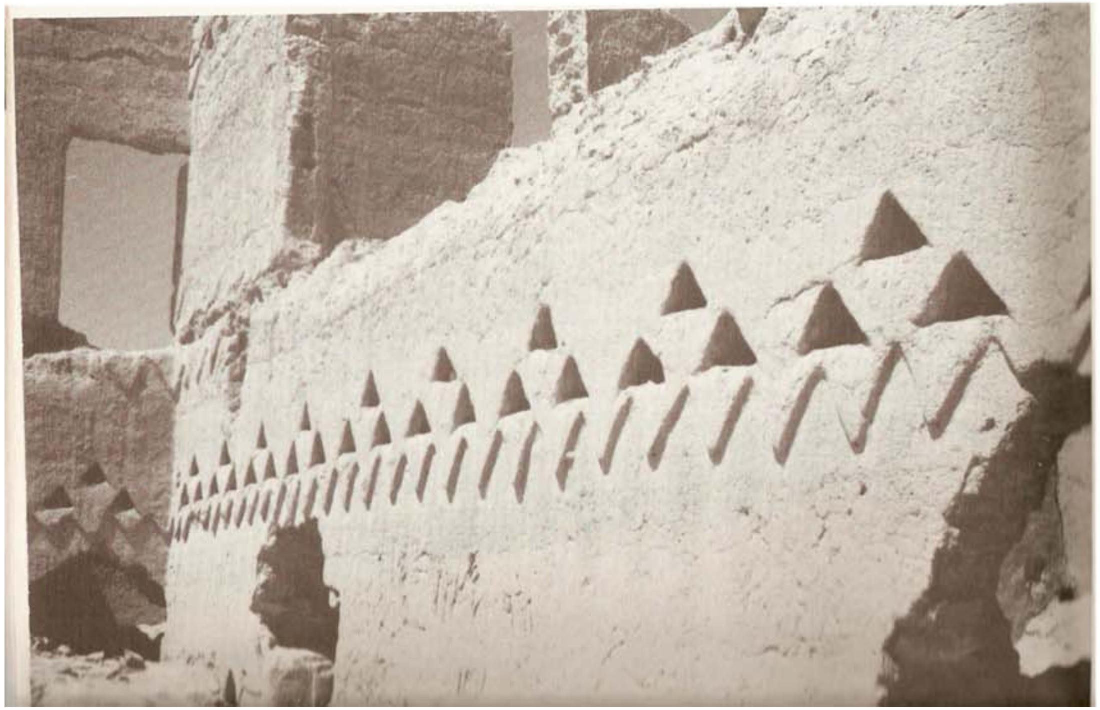


Fig. 37. (top left) Interior of a room in a village in the region of Al-Hilla, Iraq, with the palm-frond-stem roof removed, showing the low-level air vents used for indoor sleeping. (See p. 54.)

Fig. 38. (bottom left) Triangular outlet vents placed just below the roof in a house in Daniga village, Najd, Saudi Arabia. (See p. 54.)

Fig. 39. (above) *Claustra* in Dubai, United Arab Emirates. (See p. 55.)

Fig. 40. *Claustra* in Dubai, United Arab Emirates. The *claustrum* at sleeping level resulted in excessive draft and had to be closed. (See p. 55.)

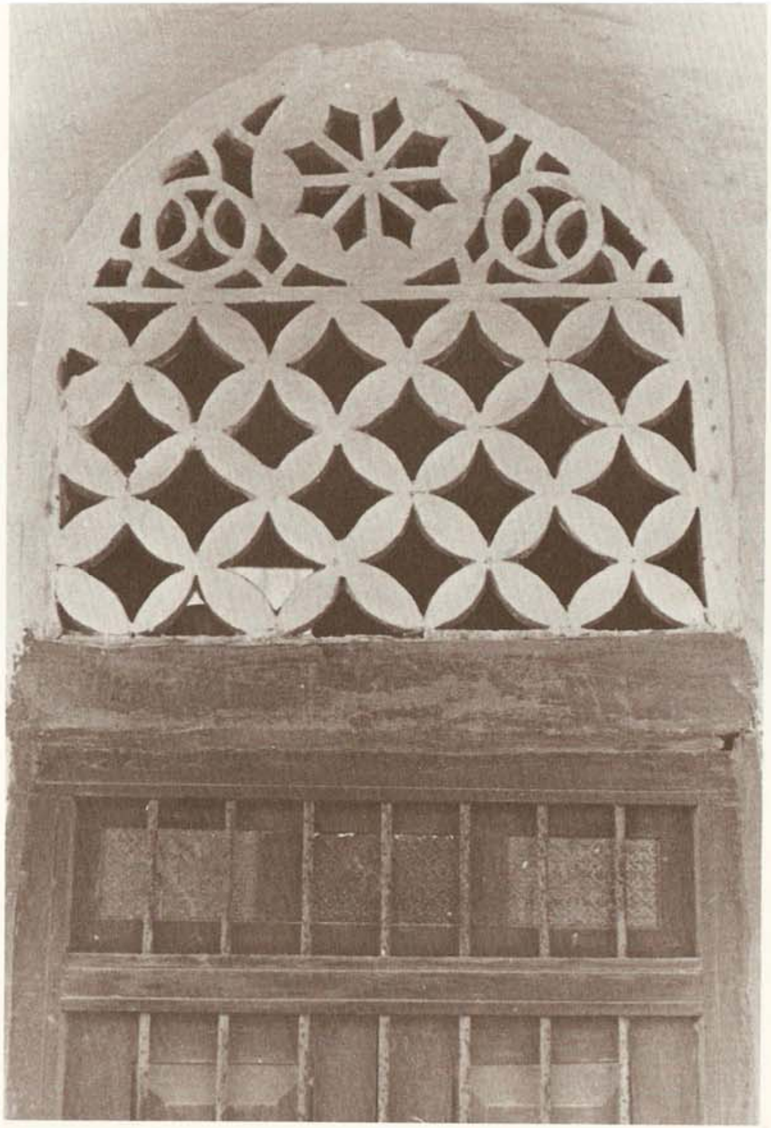


Fig. 41. *Claustrum* above the door of a building in Oman. (See p. 55.)

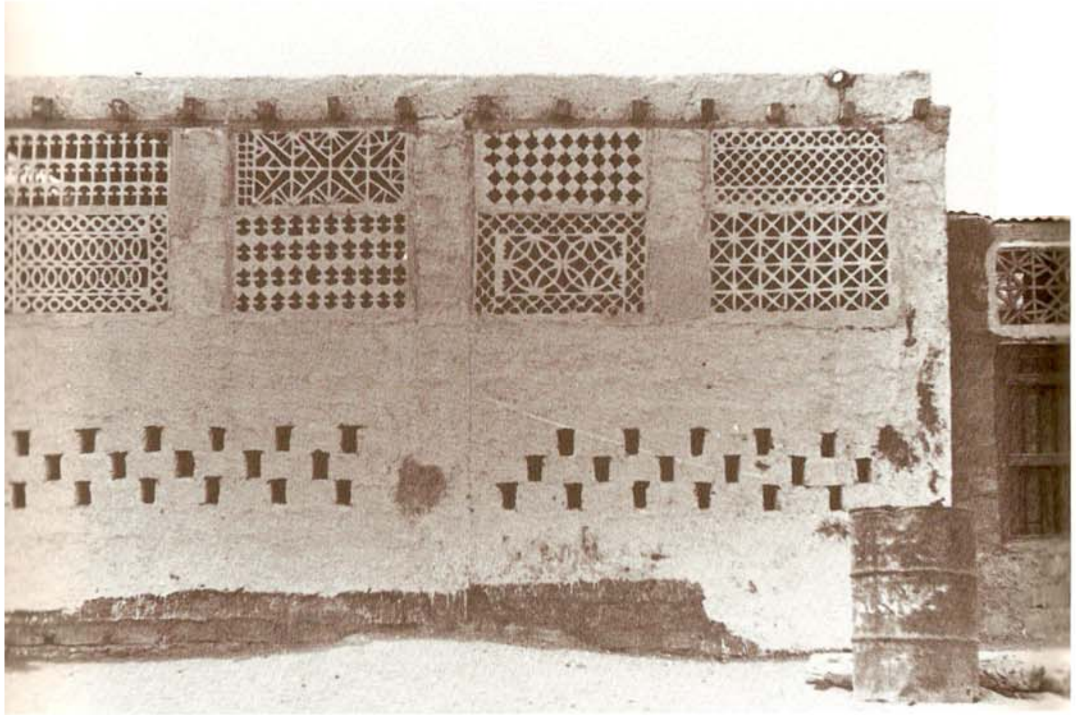


Fig. 42. *Claustra* in a parapet wall on the roof of a building in Oman. (See p. 55.)

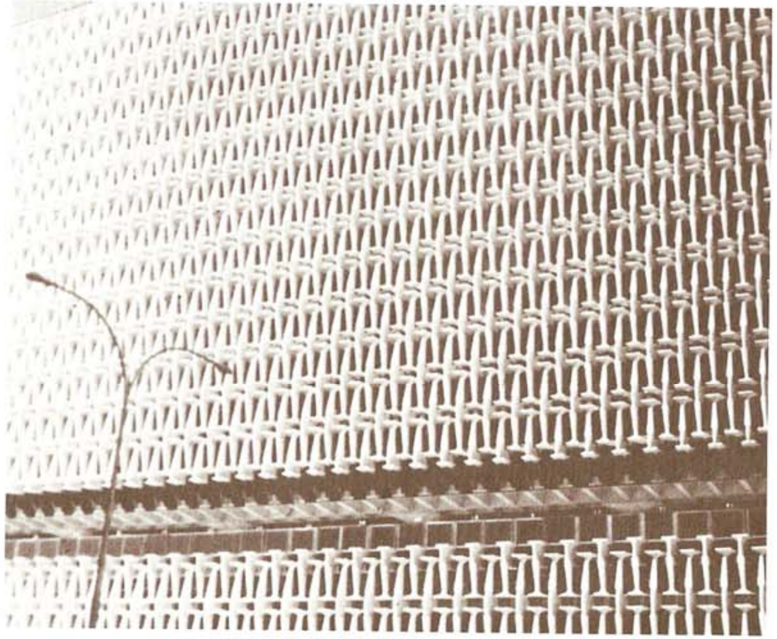


Fig. 43. Facade of a building in Kuwait, illustrating inappropriate use of a *claustrum* as a brise-soleil. (See p. 55.)

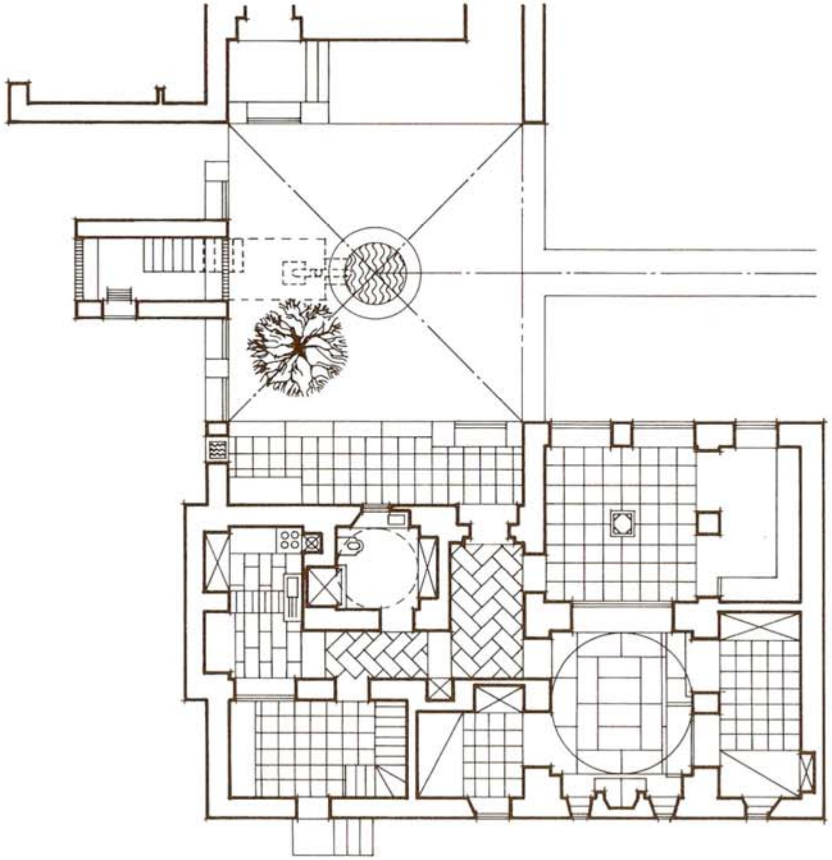


Fig. 44. Plan of part of the Sīdī Krēr house, Alexandria, Egypt, showing details for the pump room under the courtyard. Design by Hassan Fathy. (See p. 56.)

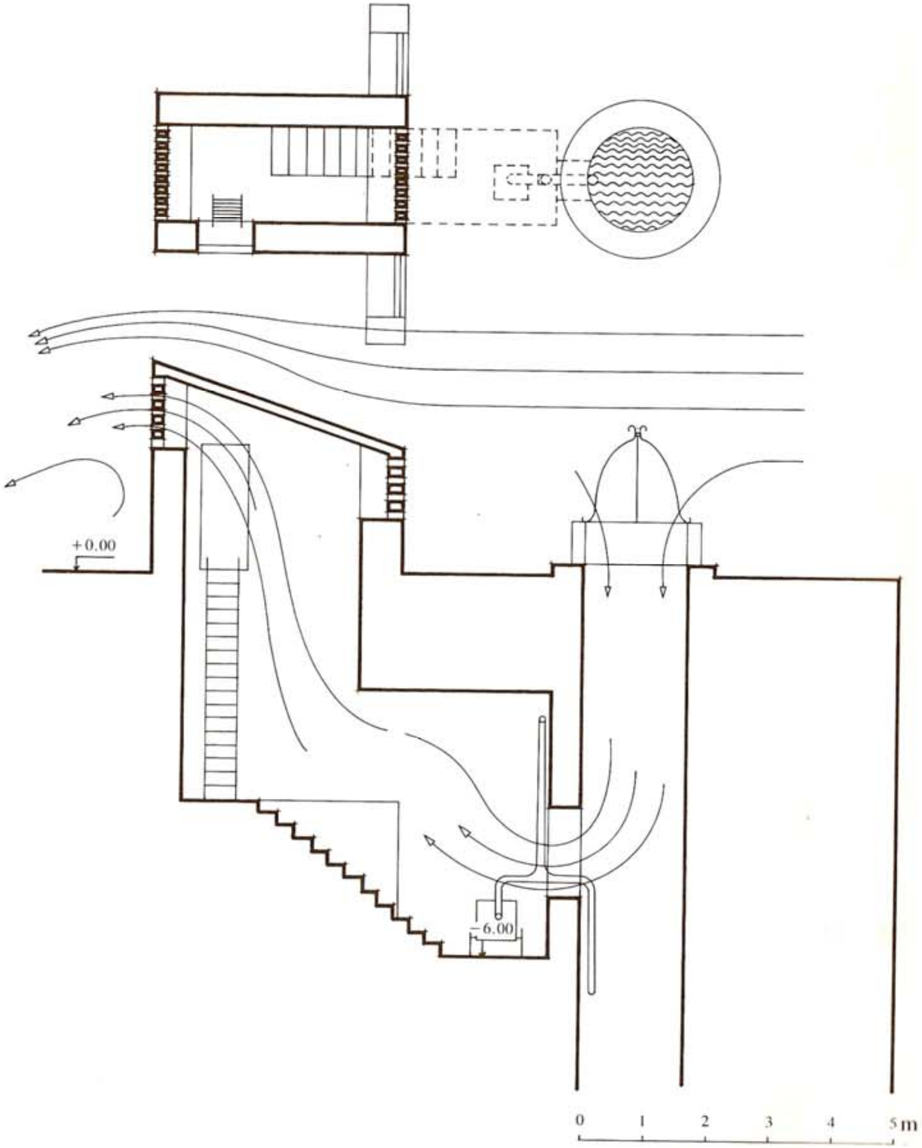
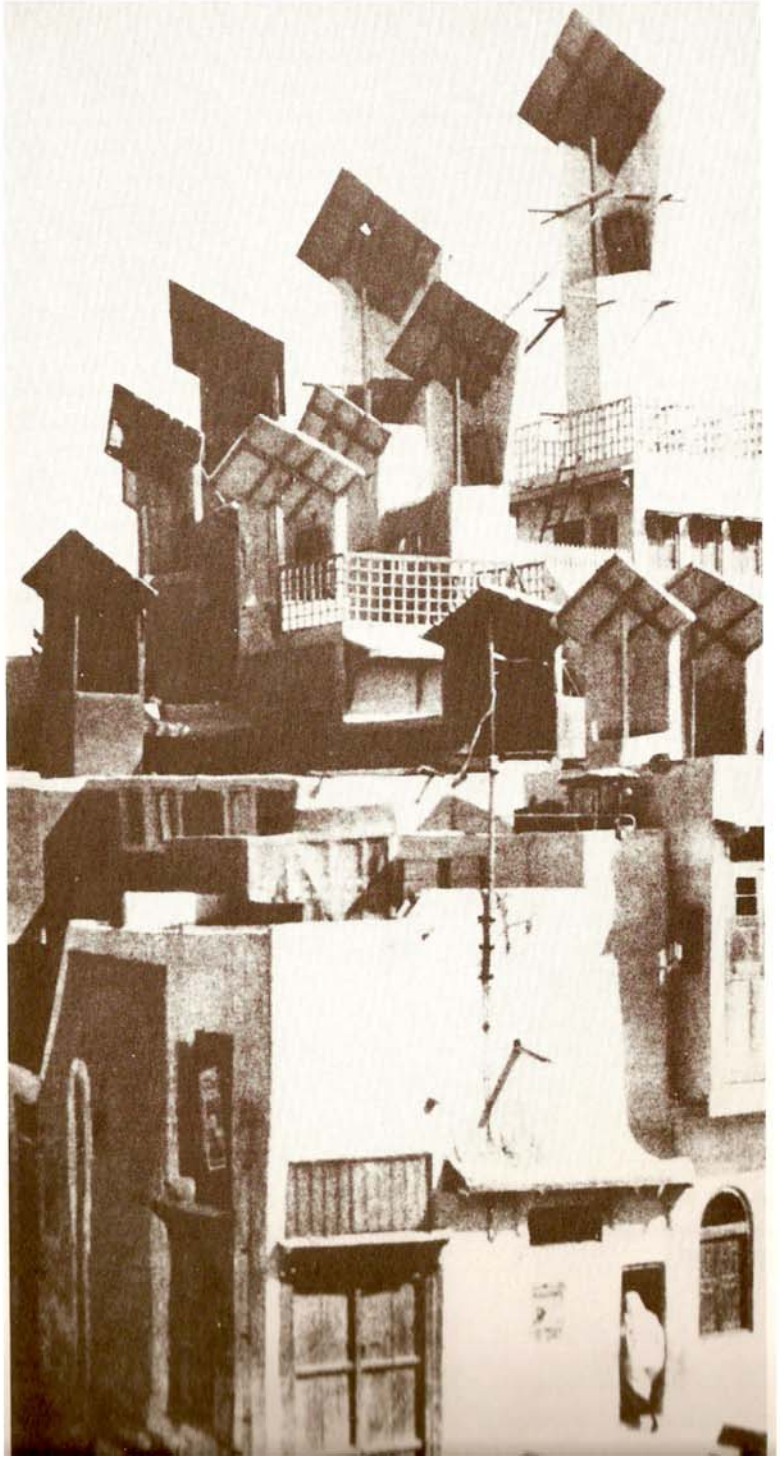


Fig. 45. Plan and section of the pump room of the Sīdī Krēr house, Alexandria, showing the ventilation generated by the wind-escape. Design by Hassan Fathy. (See p. 56.)



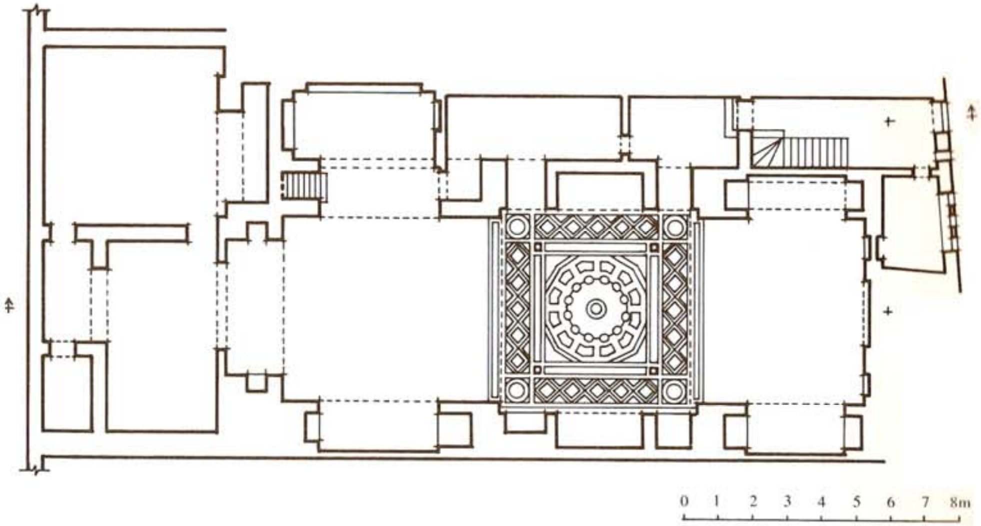


Fig. 46. (opposite) Use of the *malqaf* in a village in the Sind province of Pakistan. (See p. 56.)

Fig. 47. (above) Plan of the Qā 'a of Muhib Ad-Dīn Ash-Shāf 'ī Al-Muwaqqī, built in Cairo, about 1350. (See p. 57.)

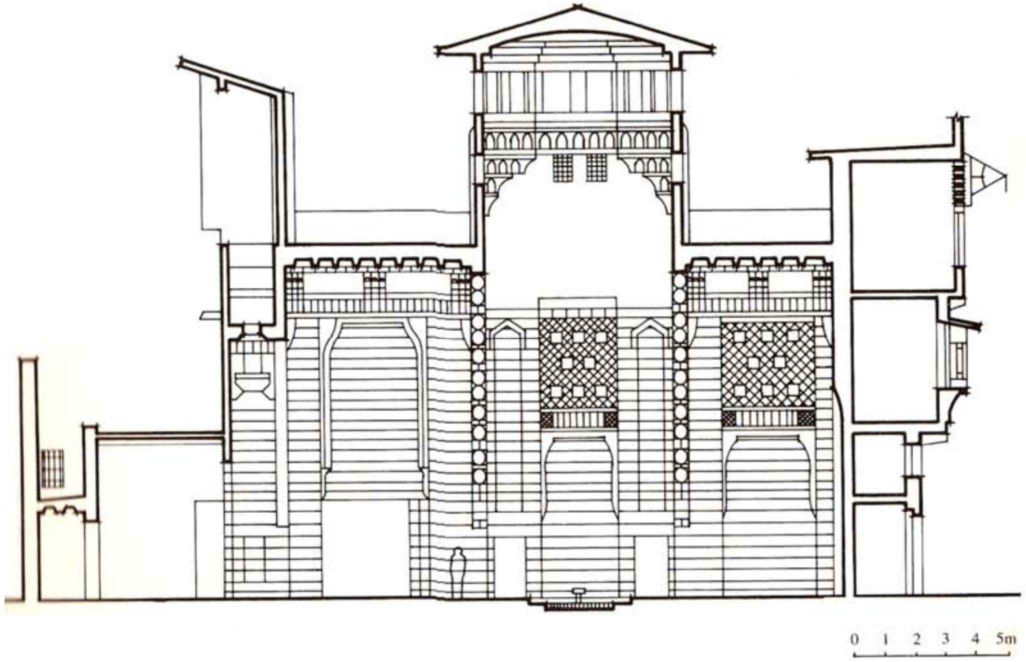


Fig. 48. Section through the Qā 'a of Muḥib Ad-Dīn Ash-Shāf 'ī Al-Muwaqqī, showing the *malqaf* and central location of the *qā 'a*. (See p. 57.)

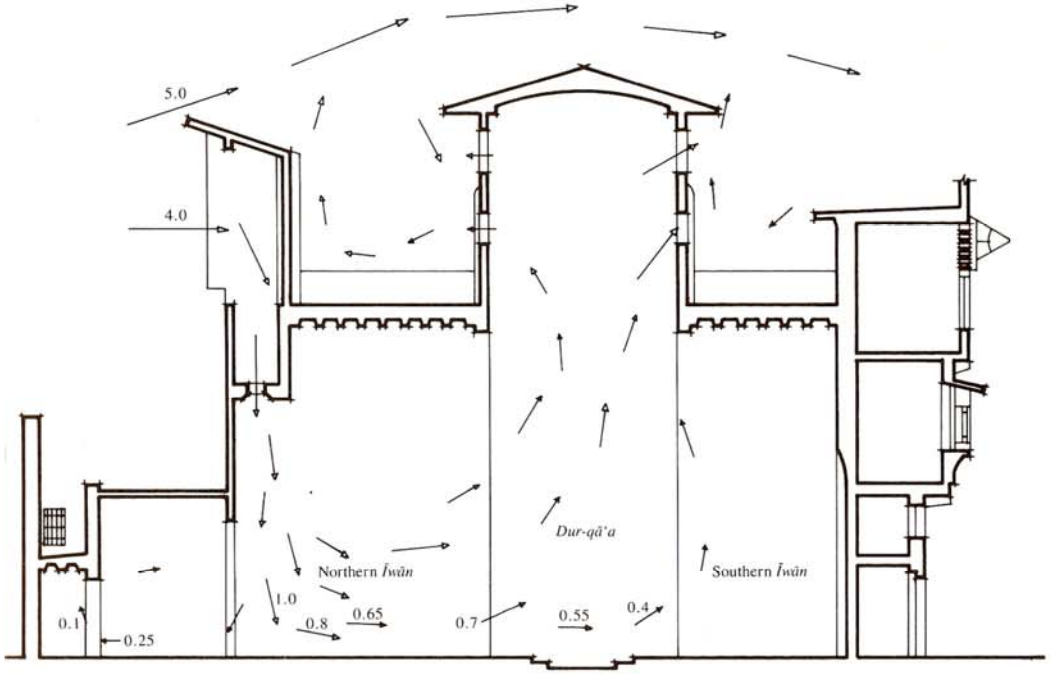


Fig. 49. Section through the Qā 'a of Muḥib Ad-Dīn Ash-Shāf 'ī Al-Muwaqqī, showing how the *malqaf* and wind-escape produce internal air movement. Arrows indicate the direction of airflow; arrow length corresponds to airspeed. The measurements were made on 2 April 1973 by scholars from the Architectural Association School of Architecture in London. All wind and airspeeds are given in meters per second. (See p. 57.)

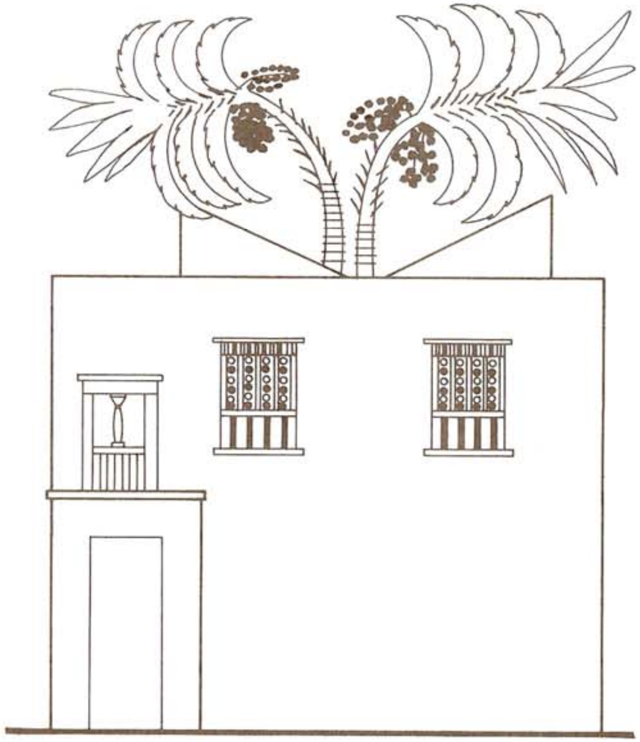


Fig. 50. *Malqaf* of the Pharaonic house of Neb-Amun, from a painting on his tomb, Nineteenth Dynasty (c. 1300 B.C.). (See p. 58.)

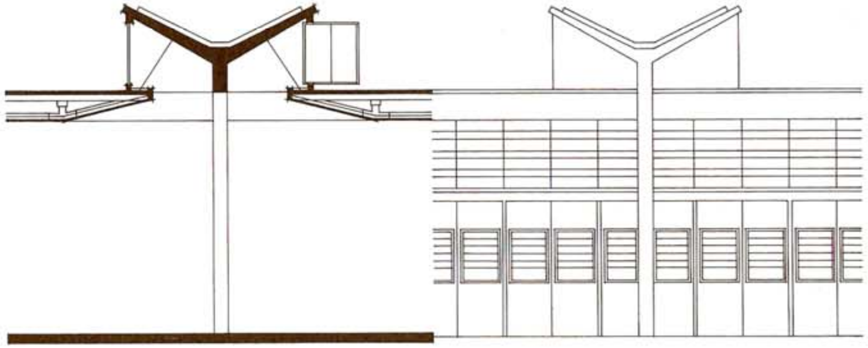


Fig. 51. Workshop at the University of Science and Technology, Kumasi, Ghana, showing how *Y*-beams route airflow through the work area. (See p. 58.)

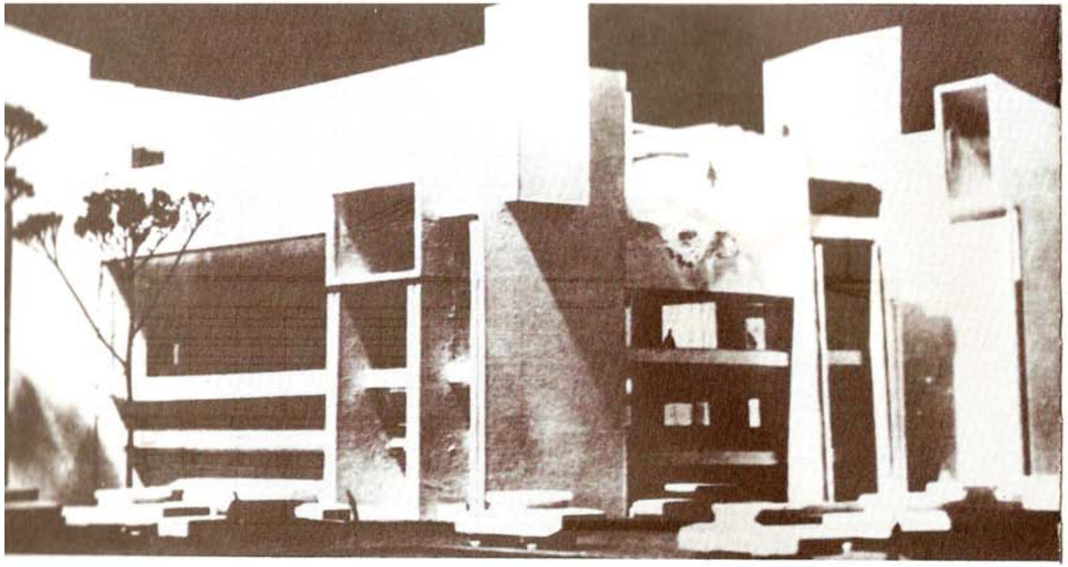


Fig. 52. Design for the Yale University School of Architecture by Paul Rudolph, showing that *malqaf* forms can be used in buildings of modern design. (See p. 58.)

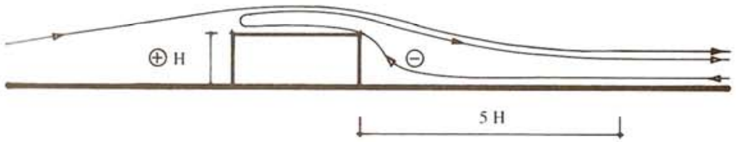
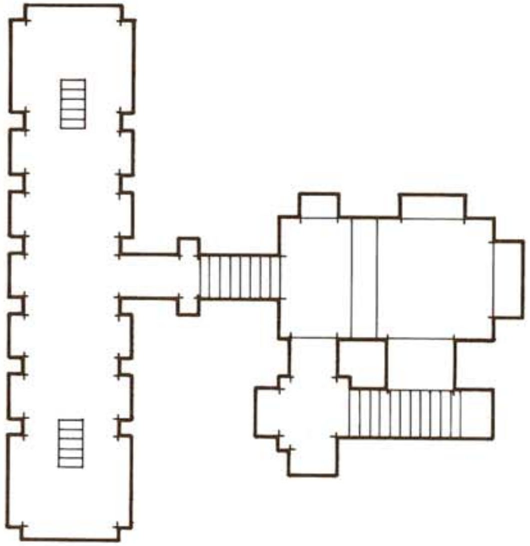


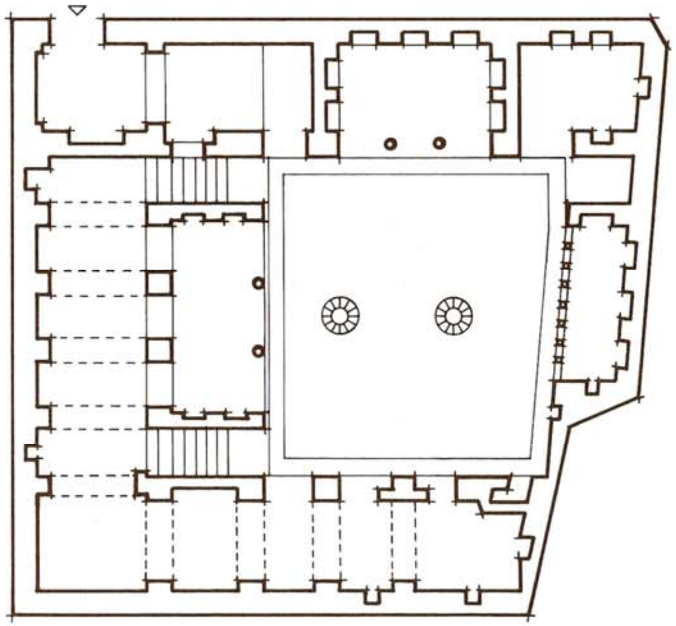
Fig. 53. Airflow pattern and pressure changes for a building placed in the wind. (See p. 59.)

Fig. 54. Residence in Baghdad, Iraq, with two small *malqaf* openings high on the side of the buildings, as typical in regions with very hot seasons. (See p. 59.)

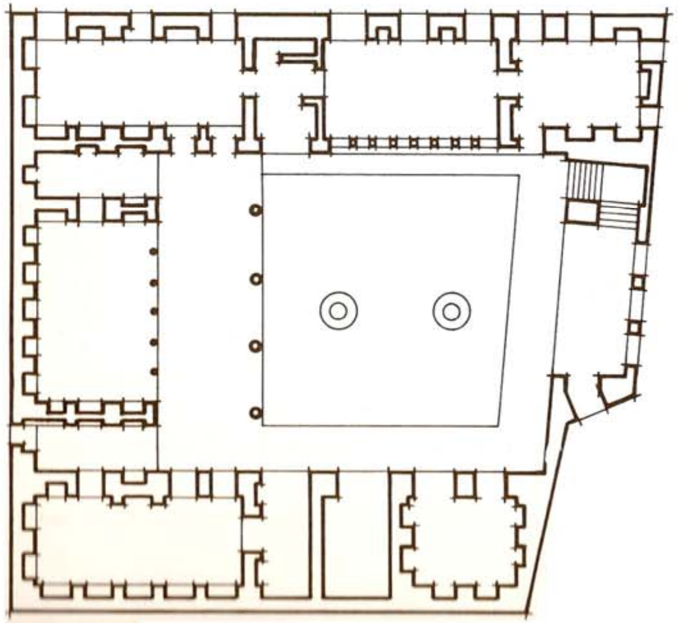


Basement plan

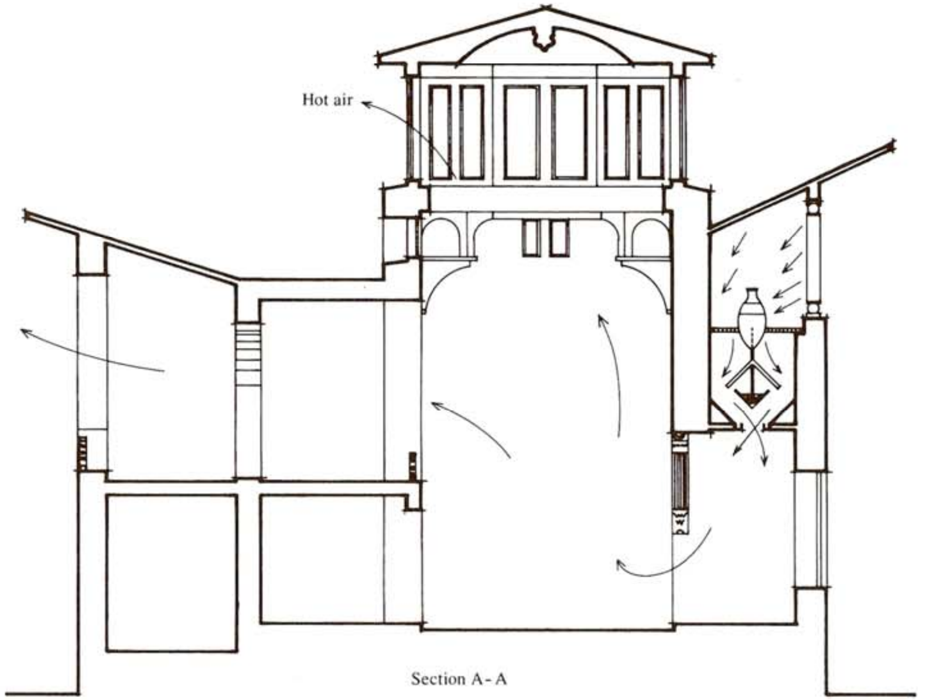
Fig. 55. Floor plans and section of a home with a basement living area in Al-Kūfa, Iraq, with a narrow *malqaf* and ceiling vents for ventilation. (See p. 59.)



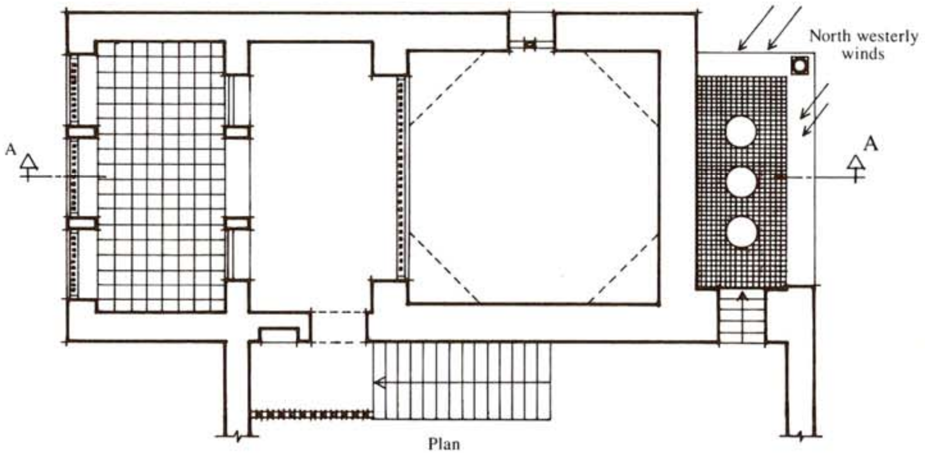
Ground floor plan



Upper floor plan

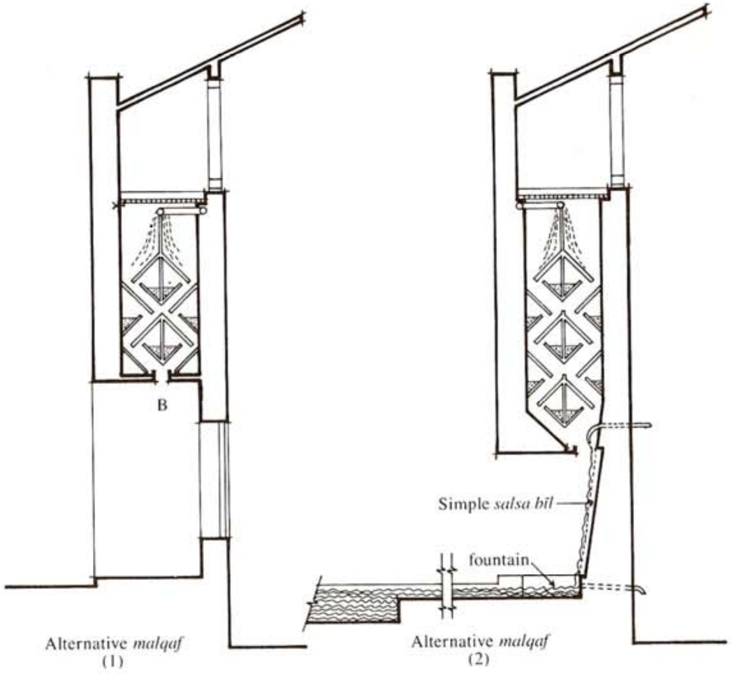


Section A-A



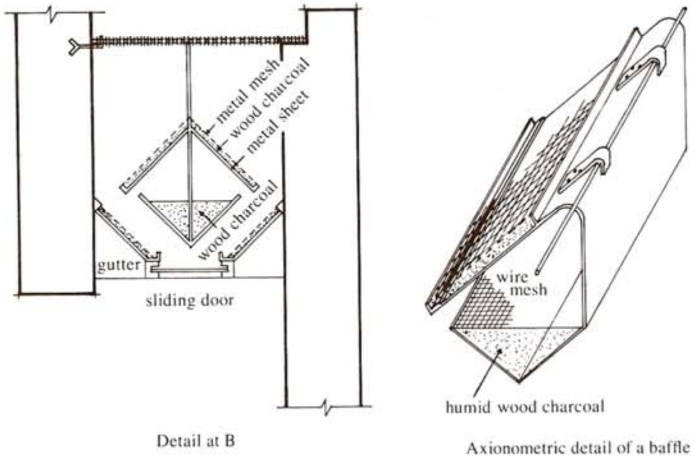
Plan

Fig. 56. *Malqaf* with wetted baffles and a wind-escape. Design by Hassan Fathy. (See p. 59.)



Alternative *malqaf* (1)

Alternative *malqaf* (2)



Detail at B

Axionometric detail of a baffle

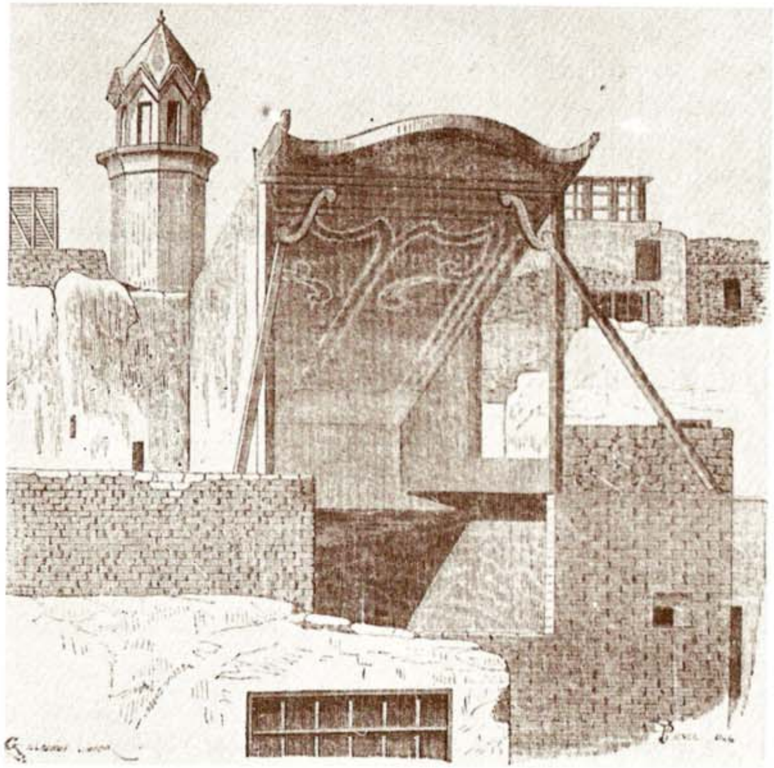


Fig. 57. (above) Turkish-style *malqaf,* Cairo. (See p. 60.)

Fig. 58. (top right) Sections and elevations of houses planned for the village of Bārīs, Al-Khārga Oasis, Egypt, showing the *malqaf* applied on a neighborhood scale. Design by Hassan Fathy. (See p. 60.)

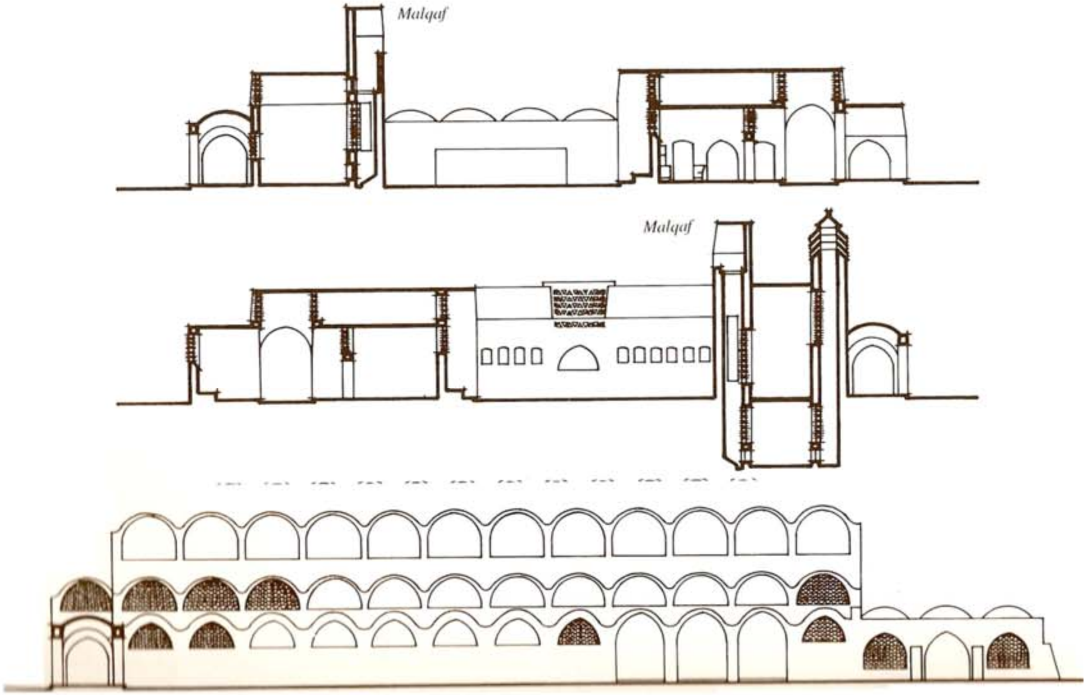


Fig. 59. (bottom right) Sections and elevations of a marketplace planned for the village of Bārīs, Al-Khārga Oasis, Egypt, showing application of the *malqaf.* Design by Hassan Fathy. (See p. 60.)

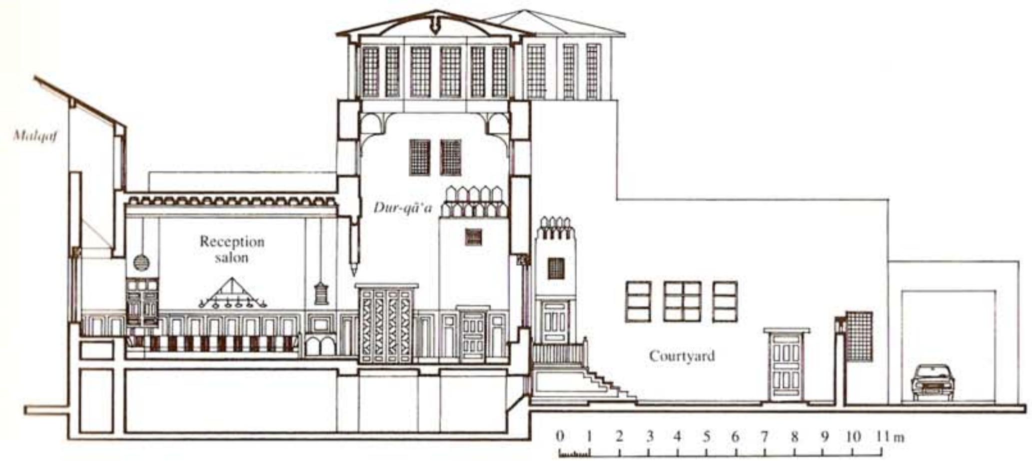


Fig. 60. Section of a modern villa designed for Saudi Arabia showing the use of a *malqaf.* This section is facing in the opposite direction from that shown in fig. 31. The 13-m (43-ft) high double *qā 'a* structure can be seen from the drawing. Design by Hassan Fathy. (See p. 60.)

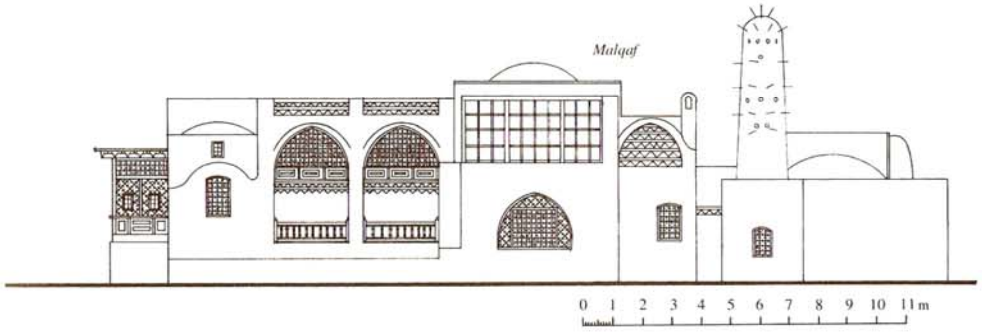


Fig. 61. Elevation of the Fu'ad Riyaḍ house built in the 1960s in Cairo, showing the *malqaf* entrance which is just below the dome. The tower is a pigeon roost. (See p. 60.)

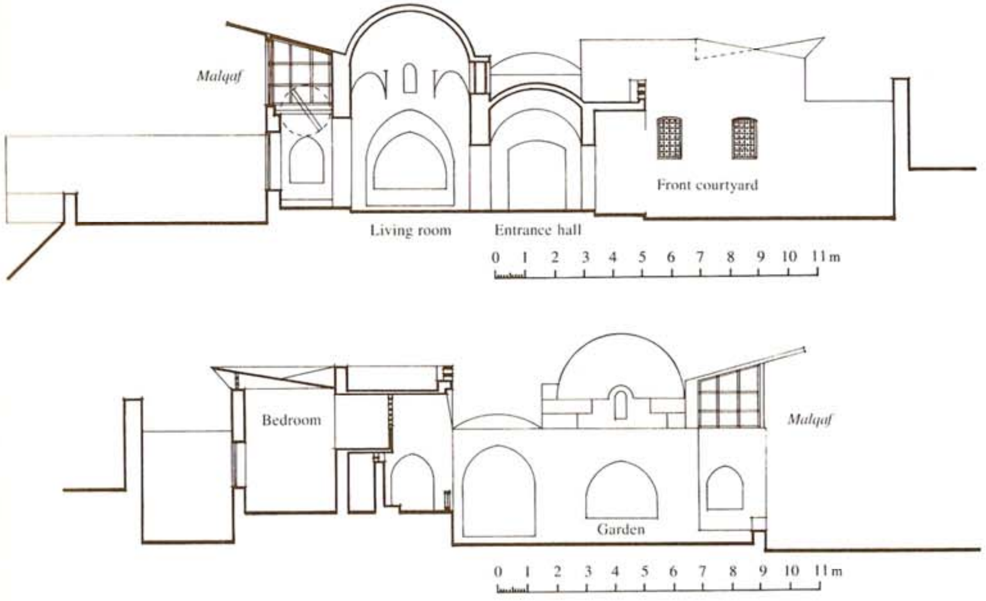


Fig. 62. Sections of the Fu'ad Riyad house showing the *malqaf.* (See p. 60.)

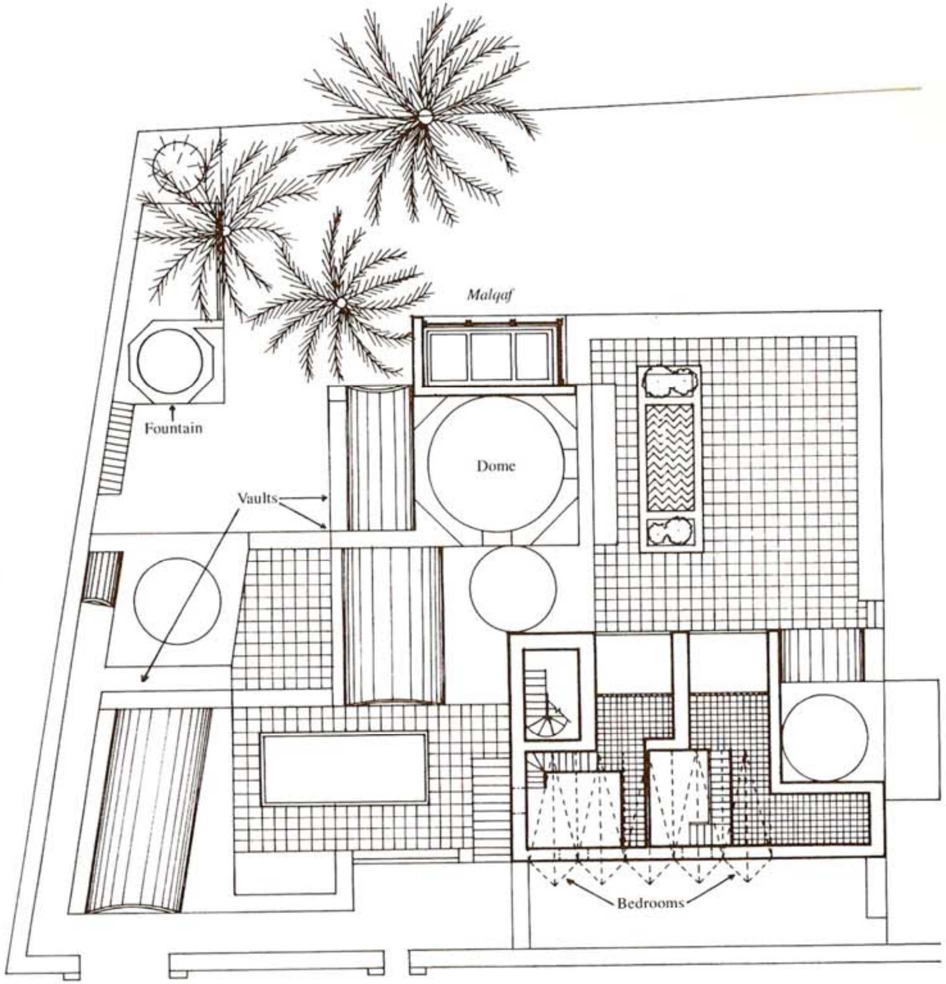


Fig. 63. Roof plan of the Fu'ad Riyaḍ house in Cairo, showing the *malqaf,* dome, vaults, and fountain, with sectional plan details. (See p. 63.)

Fig. 64. Tower of a *bādgīr,* Dubai, United Arab Emirates. (See p. 60.)

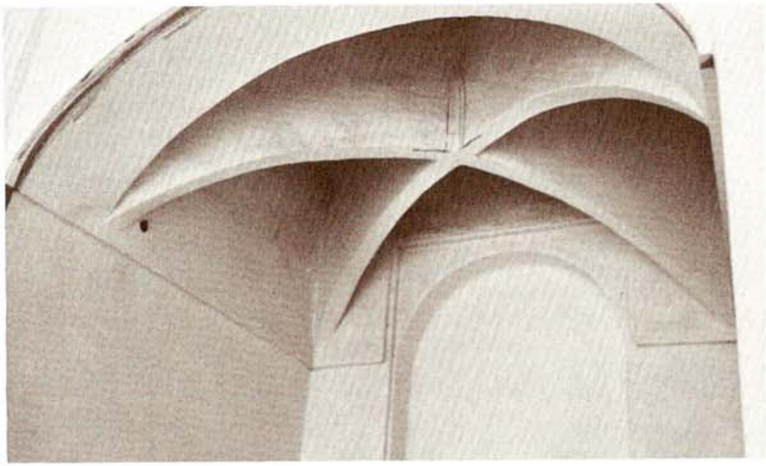


Fig. 65. Outlet of the *bādgīr* in fig. 64 with the diagonally crossing partitions visible at room level. (See p. 60.)

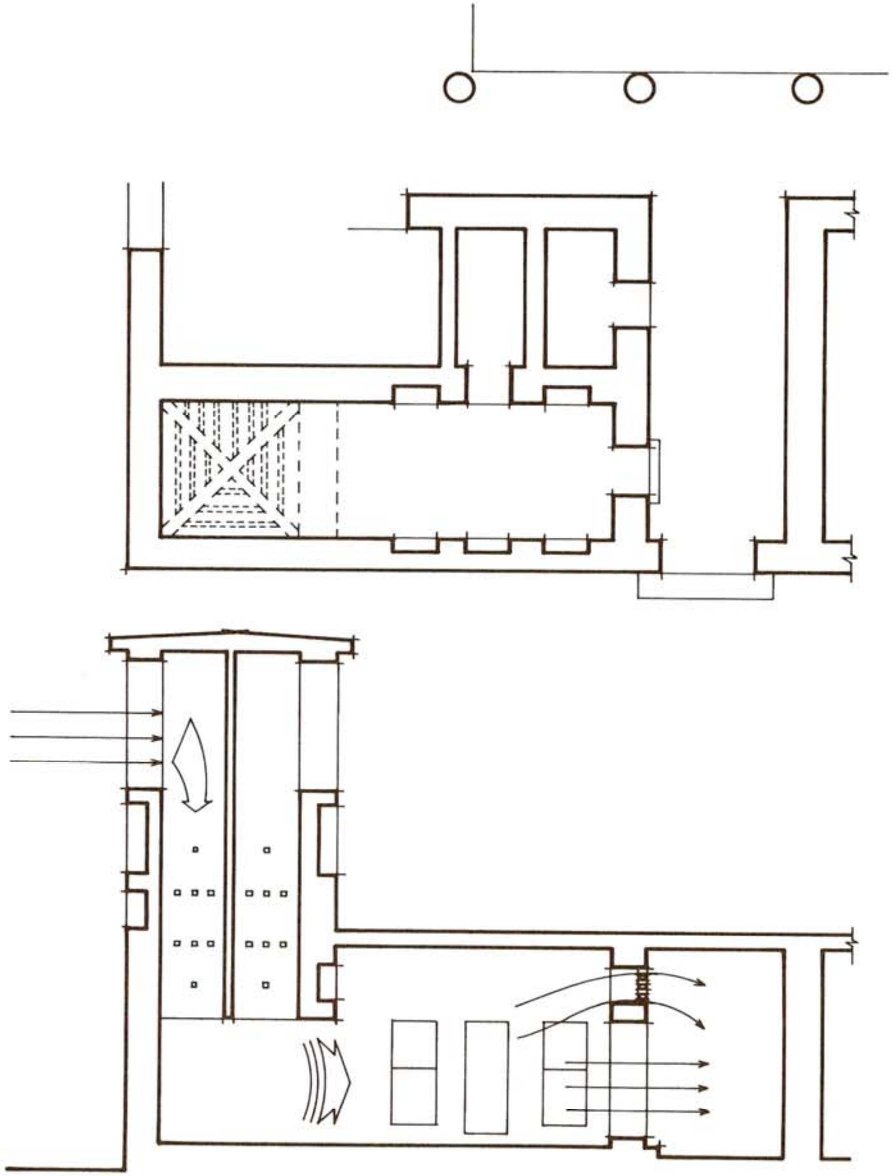


Fig. 66. Plan and section of the *bādgīr* in figs. 64 and 65. (See p. 60.)

Fig. 67. *Bādgīr* used as a decorative architectural element. (See p. 60.)

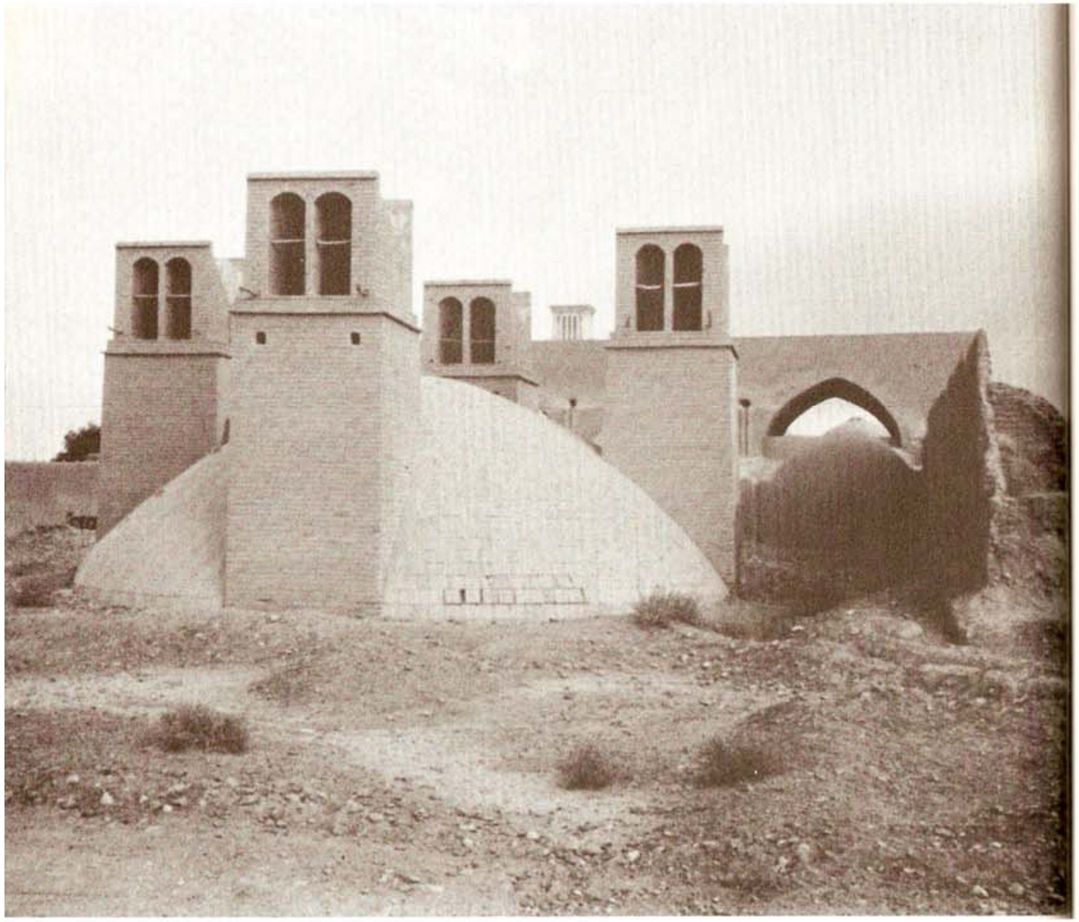


Fig. 68. Four *bādgīr* structures in Yazd, Iran, placed over an underground water reservoir to ensure cooling and ventilation. The *bādgīr* of another building in the distance is visible between two of the *bādgīr* structures. (See p. 60.)

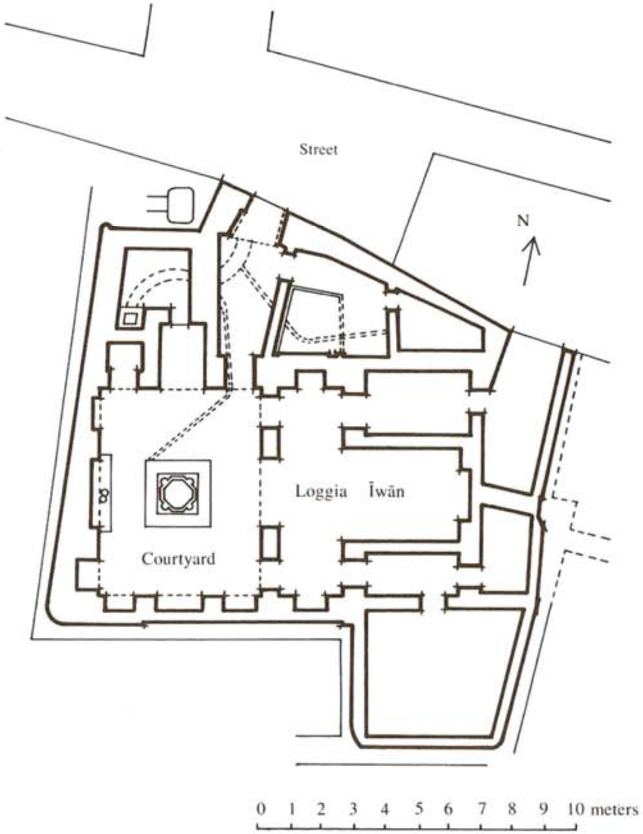


Fig. 69. Plan of the Al-Fusṭāṭ house, Cairo, showing the courtyard. (See p. 63.)

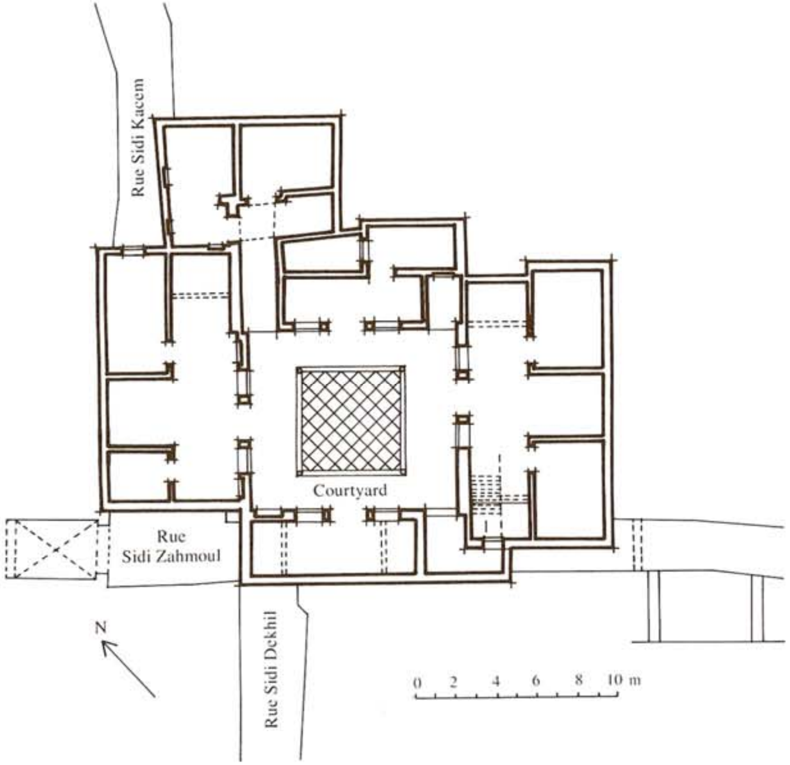


Fig. 70. Plan of Dar Lajimi, a courtyard house, Tunis. (See p. 63.)

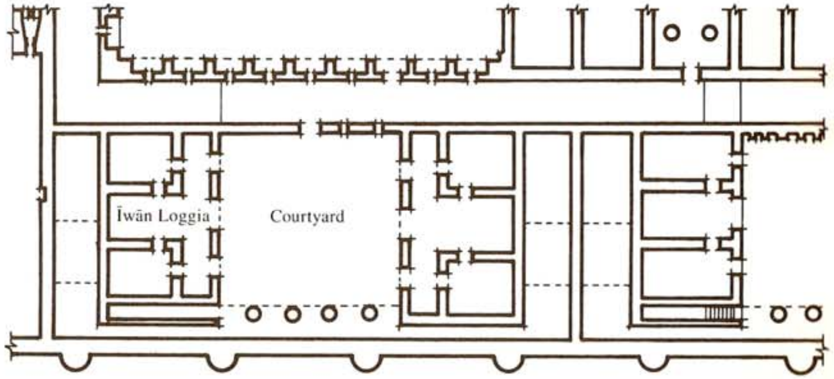


Fig. 71. Plan of the Al-Ukhaiḍar Palace in Iraq, showing a courtyard with a loggia. (See p. 63.)

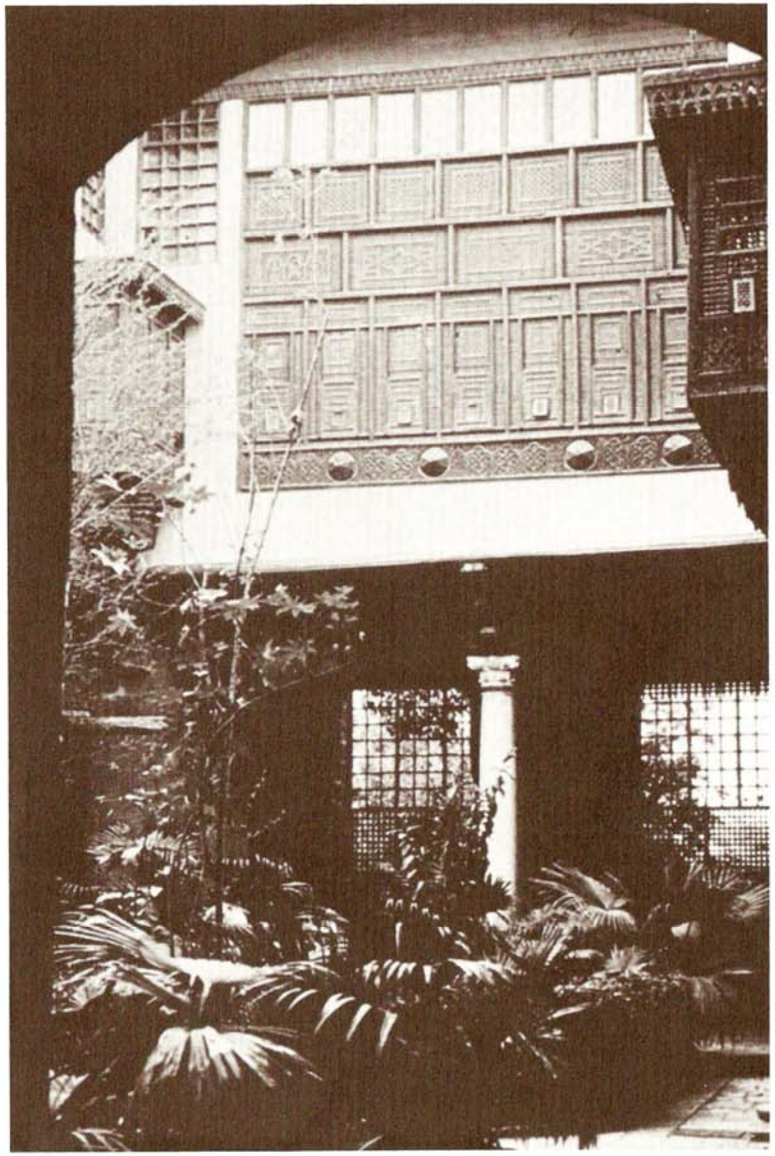
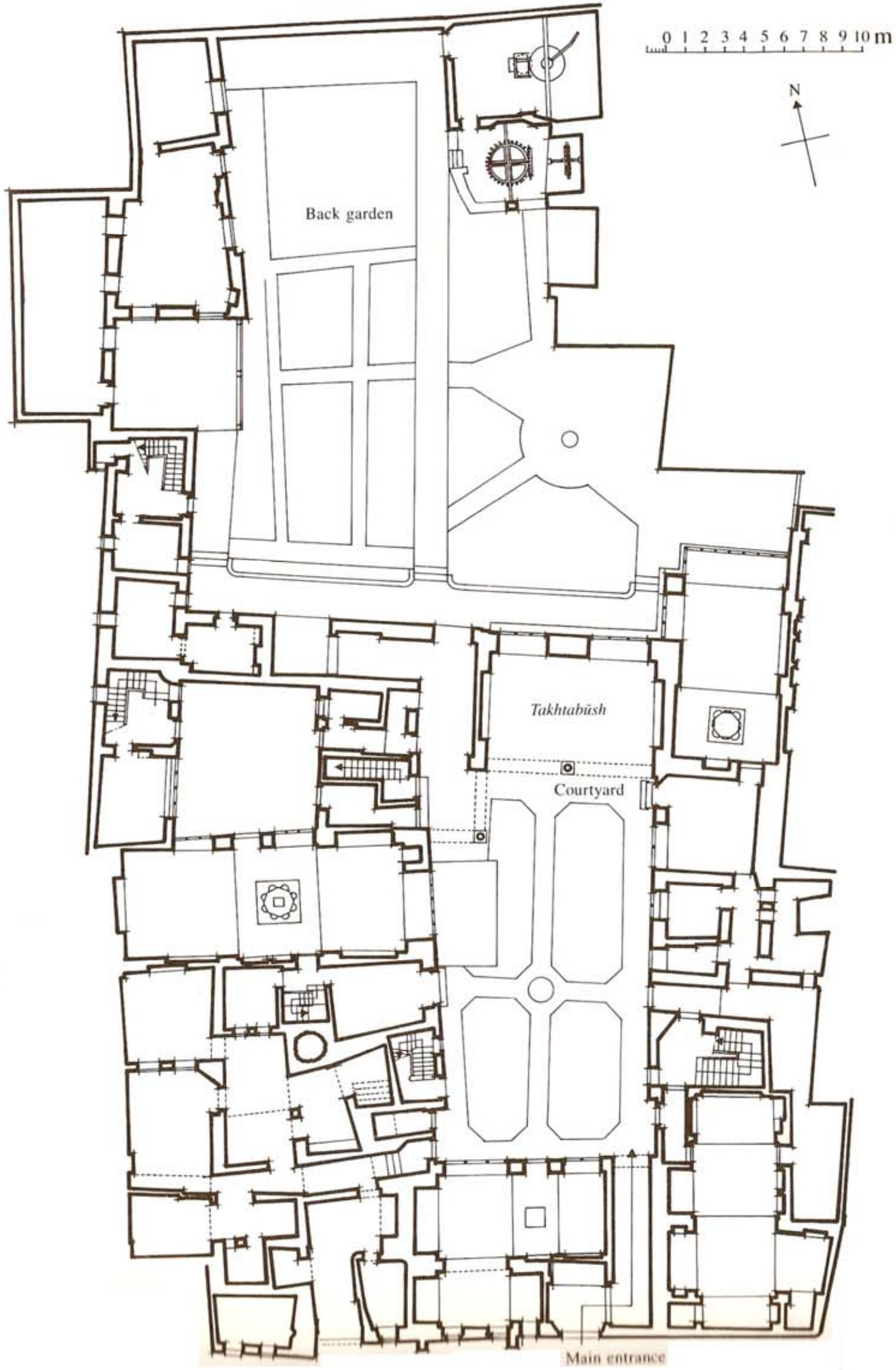


Fig. 72. View of the As-Suḥaymī house, Cairo, showing the courtyard and surrounding spaces with *mashrabīya*-filled openings. The recessed space behind the pillar is a *takhtabūsh*. (See p. 63.)

Fig. 73. (opposite) Plan of the As-Suḥaymī house at Darb Al-Asfār, Cairo, showing the courtyard, *takhtabūsh*, and back garden. (See p. 64.)



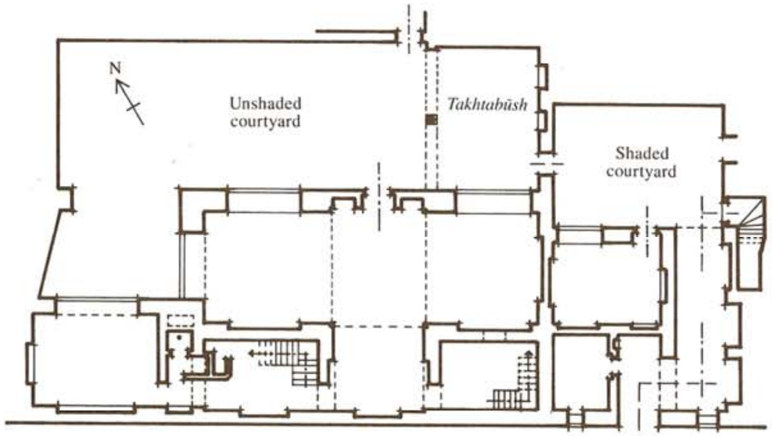
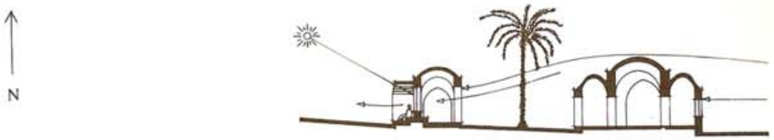
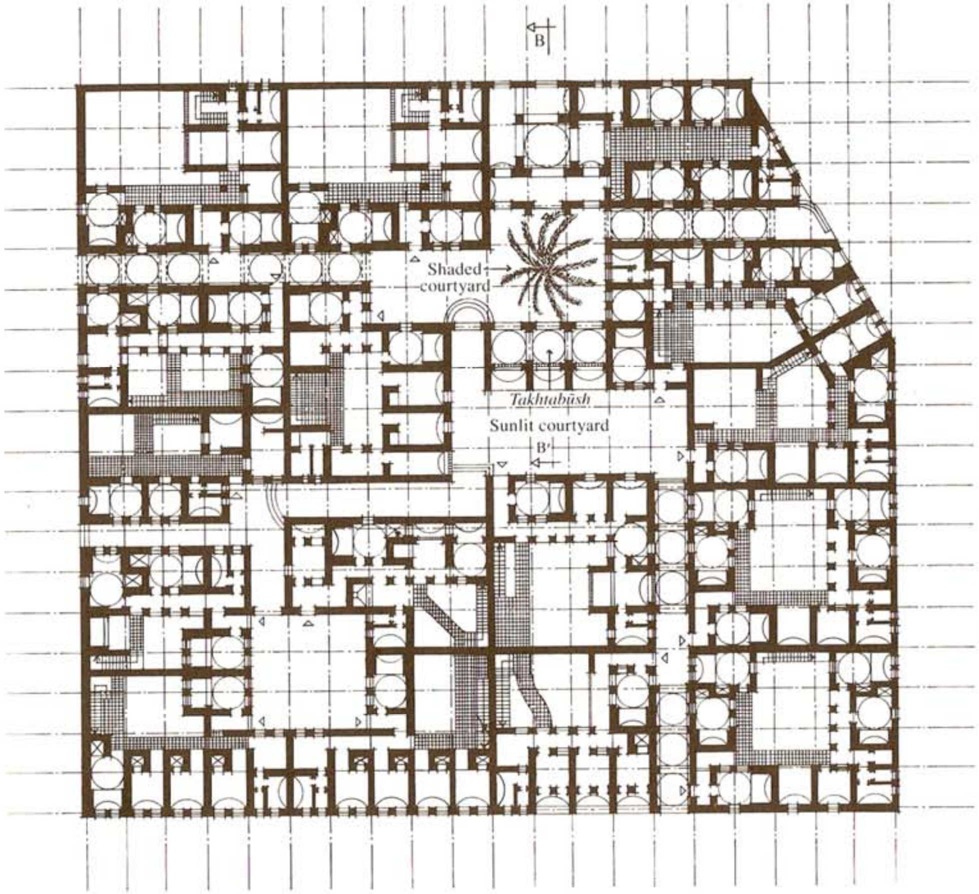


Fig. 74. Plan of the ground floor of the Qā ʻa of Muḥib Ad-Dīn Ash-Shāf ʻī Al-Muwaqqī at Darb Al-Usta, Cairo, showing two courtyards with a *takhtabūsh* between them. (See p. 64.)



Section B-B′



Ground floor plan

Fig. 75. Plan of a part of the village of Bārīs, Al-Khārga Oasis, Egypt, showing a *takhtabūsh* between a shaded and an exposed courtyard. Design by Hassan Fathy. (See p. 64.)

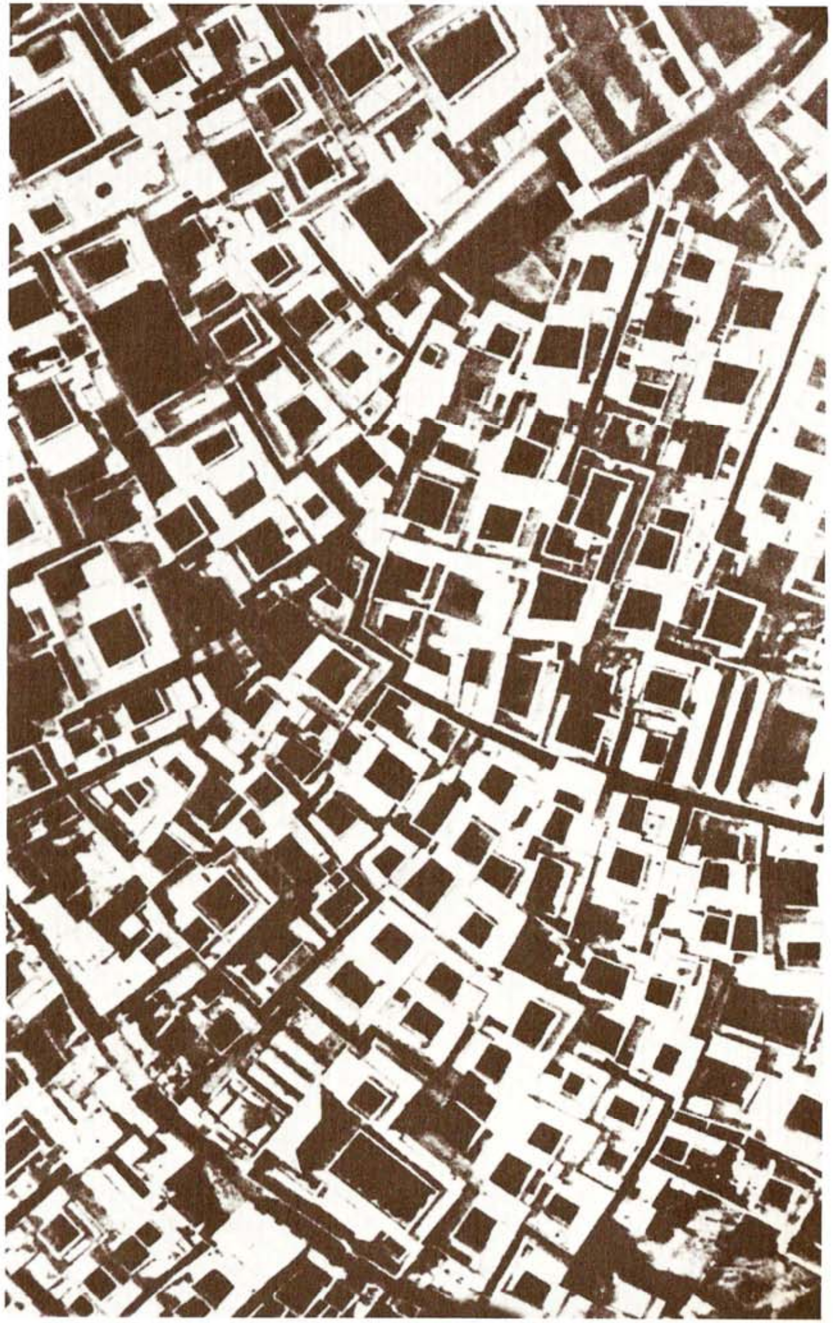


Fig. 76. (opposite) Part of the town plan of Marrakech, showing the abundance of courtyards. (See p. 64.)

Fig. 77. (above) Part of the town plan of Tunis, near Dar Lajimi, showing courtyards. (See p. 64.)

Fig. 78. Part of the town plan of Damascus, with courtyards unmarked. (See p. 64.)

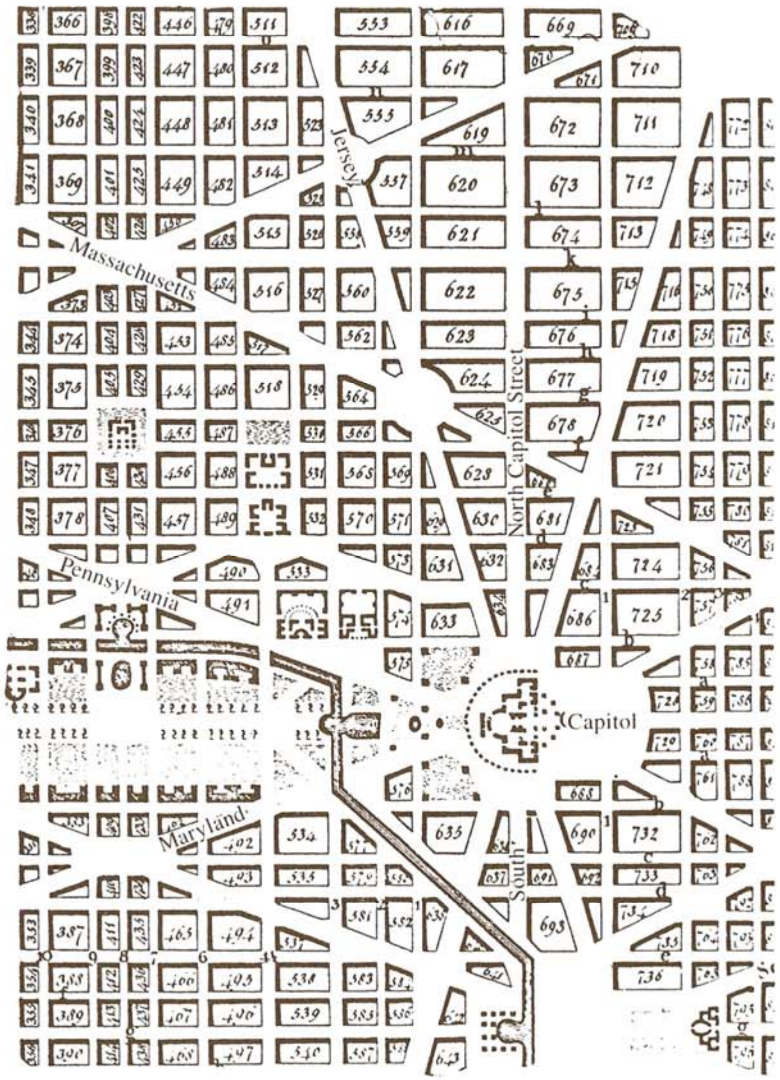
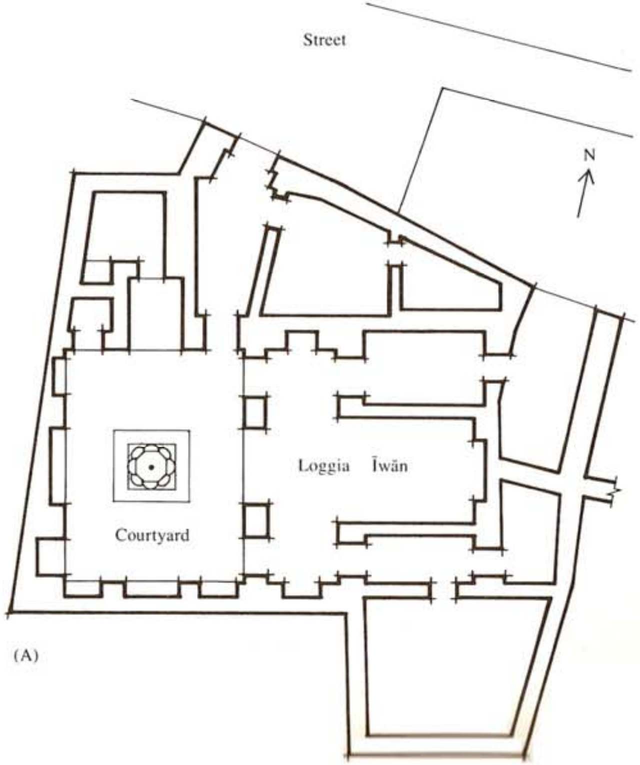


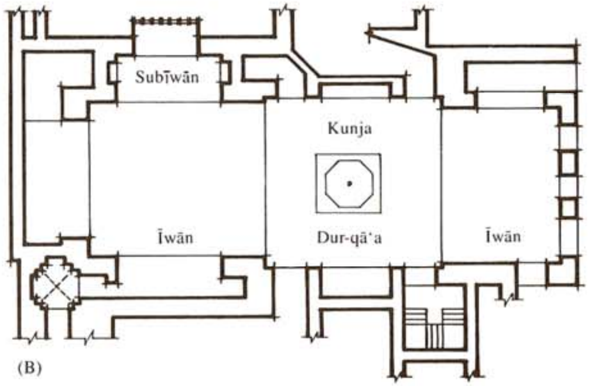
Fig. 79. Part of the town plan of Washington, D.C., showing the gridiron pattern. (See p. 64.)

Fig. 80. (top left) A view of a fountain in a traditional house in Cairo. (See p. 66.)

Fig. 81. (below left and right) *(a)* Plan of the Al-Fusṭāṭ house, Cairo, showing a fountain in the courtyard; *(b)* plan of the *qā ʻa* of Al-Ḥaramain in Saudi Arabia, showing a fountain in the *dur-qā ʻa; (c)* a view of a dome rising above squinches. (See p. 66.)



(A)



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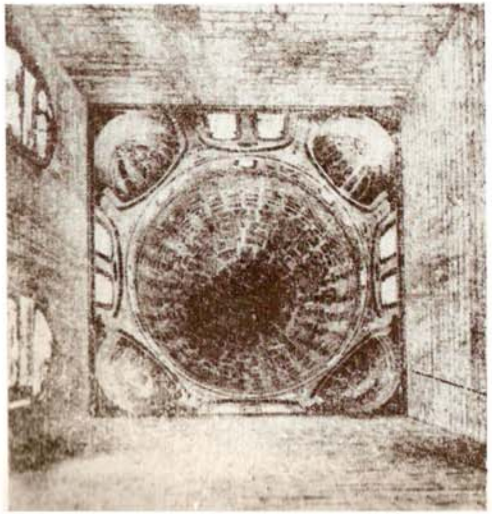

(C)

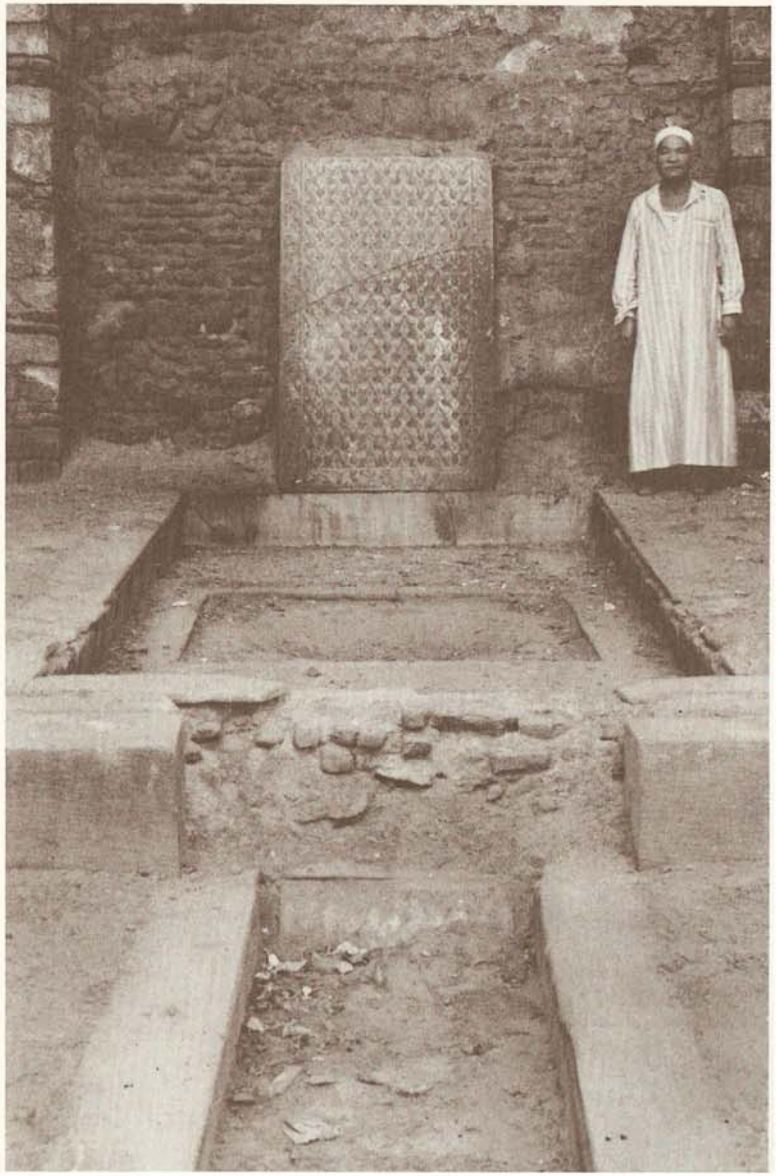

Fig. 82. An Egyptian *salsabīl*. (See p. 67.)

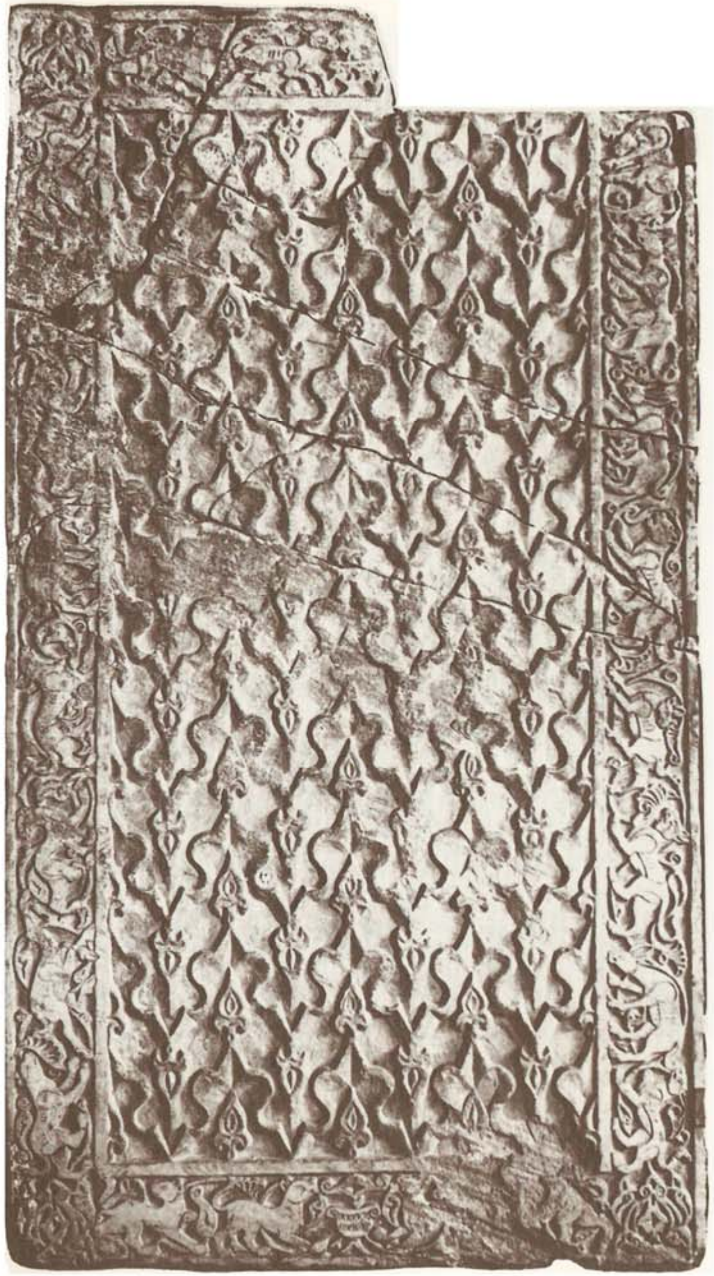

Fig. 83. A *salsabīl*. (See p. 67.)

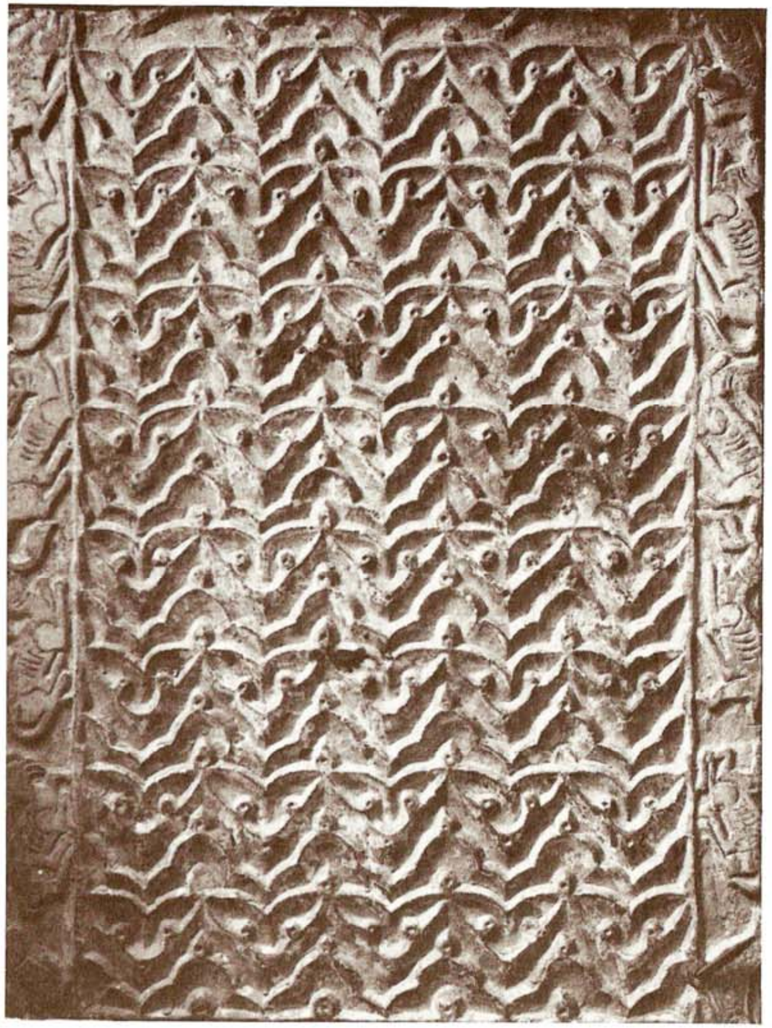

Fig. 84. A *salsabīl*. (See p. 67.)

Appendices

Appendix One

Data on Saturated Water Vapor

Table A1.1. Density and pressure of saturated water vapor at different temperatures at sea-level pressure (760 mm Hg or 14.7 psi).

Temperature		Density		Pressure		
°C	°F	g/m^3	grains/ ft^3	milli- bars	mm Hg	inches Hg
34	93.2	37.66	16.46	53.26	39.95	1.573
32	89.6	33.87	14.80	47.60	35.70	1.406
30	86.0	30.43	13.30	42.48	31.86	1.254
28	82.4	27.29	11.93	37.84	28.38	1.117
26	78.8	24.43	10.68	33.65	25.24	0.994
24	75.2	21.83	9.54	29.86	22.40	0.882
22	71.6	19.46	8.50	26.45	19.84	0.781
20	68.0	17.33	7.57	23.40	17.55	0.691
18	64.4	15.40	6.73	20.65	15.49	0.610
16	60.8	13.66	5.97	18.19	13.64	0.537
14	57.2	12.09	5.28	15.99	11.99	0.472
12	53.6	10.68	4.67	14.03	10.52	0.414
10	50.0	9.42	4.12	12.28	9.21	0.363
8	46.4	8.28	3.62	10.72	8.04	0.317
6	42.8	7.27	3.18	9.35	7.01	0.276
4	39.2	6.37	2.78	8.13	6.10	0.240
2	35.6	5.57	2.43	7.05	5.29	0.208
0	32.0	4.86	2.12	6.11	4.58	0.180
−2	28.4	4.15	1.81	5.18	3.89	0.153
−4	24.8	3.54	1.55	4.39	3.29	0.130
−6	21.2	3.01	1.32	3.70	2.78	0.109
−8	17.6	2.56	1.12	3.12	2.34	0.092
−10	14.0	2.16	0.94	2.62	1.96	0.077

Source: *Handbook of Chemistry and Physics*, ed. Robert C. Weast and Melvin J. Astle, 62d ed. (Boca Raton, Fla.: Chemical Rubber Co. Press, 1981).

Appendix Two

Thermal Comfort Sensation Scales

Many thermal comfort sensation scales have been established; one is presented as an example in table A-1 below. This scale recognizes 15 degrees of comfort and discomfort with regard both to heat and humidity and 5 degrees with respect to air freshness.

Table A2.1. Thermal comfort sensation scale

Heat		Humidity		Air Freshness	
Unbearably hot	+7	Unbearably moist	+7		
Much too hot	+6	Much too moist	+6		
Too hot	+5	Too moist	+5		
Hot	+4	Moist	+4	Very stuffy	+2
Too warm	+3	Too humid	+3		
Warm	+2	Humid	+2	Stuffy	+1
Comfortably warm	+1	Comfortably humid	+1		
Neutral	0	Neutral	0	Comfortable	0
Comfortably cool	−1	Comfortably dry	−1		
Cool	−2	Dry	−2	Fresh	−1
Too cool	−3	Too dry	−3		
Cold	−4	Parched	−4	Very fresh	−2
Too cold	−5	Too parched	−5		
Much too cold	−6	Much too parched	−6		
Unbearably cold	−7	Unbearably parched	−7		

In applying this scale to a practical situation, one determines the degrees that correspond to the sensation and notes down the corresponding code from table A-1 and the time of observation on a record sheet similar to the example shown in table A-2 along with other relevant data.

Table A2.2. Typical data sheet for environmental conditions and thermal comfort observation

Outdoor Weather Conditions — **Date**
Description of Room — **Location**

Instrument	Measurement	Observations		
		1	2	3
Time of observation				
Whirling hygrometer	°C Dry bulb			
	°C Wet bulb			
	°C Wet bulb			
	Temp. difference			
From tables or chart	% Relative Humidity			
From tables or chart	Dew Point			
Globe thermometer	G. T. °C			
Silvered thermometer	S. T. °C			
Kata thermometer	Cooling times			
Factor:				
Range:				
Glass or silvered				
From nomogram	Cooling power			
	Air velocity			
Effective temperature (Normal-scale nomogram)	E. T. °C			
Effective temperature (Basic-scale nomogram)	B.E.T.°C			
Corrected effective temperature (Basic-scale nomogram)	G.E.T. (B)°C			
Mean temperature of surroundings	M.T.S. °C			
Equivalent temperature nomogram	Equiv. Temp. °C			
Thermal comfort sensations				
Sensation	Time			
a. Heat				
b. Moisture				
c. Freshness				

Name______________ Posture or work__________ Weight______
Age and sex____________ Last meal: time__________
nature__________
Clothing______________

Appendix Three

Data on Thermal Transmittance

Table A3.1. Values of coefficients of thermal transmittance for different wall materials and combinations in kcal/hm^{2}C°.

	Wall Thickness (in m)						
Type of Masonry	**0.30**	**0.40**	**0.50**	**0.60**	**0.70**	**0.80**	**0.90**
Limestone masonry:							
External wall plastered on exterior	2.40	2.00	1.80	1.60	1.45	1.33	1.22
External wall plastered on both sides	2.30	2.00	1.80	1.60	1.41	1.30	1.19
Internal wall plastered on both sides	1.90	1.70	1.50	1.37	1.25	1.16	1.08
Dense stone, including marble and granite:							
External wall plastered on exterior	2.90	2.60	2.40	2.20	2.00	1.90	1.70
External wall plastered on both sides	2.80	2.50	2.30	2.10	1.90	1.80	1.70
Internal wall plastered on both sides	2.20	2.00	1.90	1.80	1.60	1.50	1.45

	Wall Thickness (in m)						
	0.05	**0.10**	**0.15**	**0.20**	**0.30**	**0.40**	**0.50**
Concrete masonry (gravel, cement, and sand):							
External wall without plaster	4.20	3.60	3.10	2.70	2.20	1.80	1.60
Internal wall without plaster	3.10	2.70	2.40	2.20	1.80	1.60	1.36
External wall plastered on both sides	3.50	3.00	2.70	2.40	2.00	1.70	1.44
Internal wall plastered on both sides	2.70	2.40	2.20	2.00	1.70	1.44	1.27

	Wall Thickness (in m)						
	0.12	**0.25**	**0.38**	**0.51**	**0.64**	**0.77**	**0.90**
Red brick:							
External wall plastered on exterior	2.60	1.80	1.37	1.11	0.93	0.80	0.70
External wall on both sides	2.50	1.70	1.34	1.09	0.91	0.79	0.69
External wall plastered on interior	1.90	1.33	1.04	0.85	0.71	0.62	0.55
Light concrete block:							
External wall plastered on both sides	2.00	1.25	0.93	0.73	0.60	. . .	. . .
Internal wall plastered on both sides	1.70	1.12	0.85	0.68	0.57	. . .	. . .
Sand-lime brick:							
External wall plastered on exterior	2.90	2.00	1.60	1.27	1.08	0.93	0.82
External wall plastered on both sides	2.70	1.90	1.50	1.23	1.05	0.91	0.81
Internal wall plastered on both sides	2.10	1.60	1.24	1.03	0.89	0.78	0.69

	Wall Thickness (in m)						
	0.12	**0.25**	**0.38**	**0.51**	**0.64**	**0.77**	**0.90**
Red-brick double wall plastered on both sides with 5–12 cm cavity	. . .	1.38	1.11	0.93	0.81	0.70	0.63
Ordinary red-brick wall insulated with cork sheeting on internal wall only for insulation:							
2-cm thick insulation	1.11	0.93	0.80	0.70	0.63	0.57	0.52
5-cm thick insulation	0.61	0.55	0.50	0.46	0.43	0.40	0.37
10-cm thick insulation	0.34	0.33	0.31	0.29	0.28	0.27	0.25

Table A3.2. Values of coefficients of thermal transmittance for different wall materials and combinations in Btu/hft^{2}F°.

	Wall Thickness (in in)						
Type of Masonry	4.7	9.8	15	20	25	30	35
Red brick:							
External wall plastered on exterior	0.533	0.369	0.281	0.227	0.190	0.164	0.143
External wall on both sides	0.512	0.348	0.274	0.223	0.186	0.162	0.141
External wall plastered on interior	0.389	0.272	0.213	0.174	0.145	0.127	0.113
Light concrete block:							
External wall plastered on both sides	0.410	0.256	0.190	0.150	0.123	...	...
Internal wall plastered on both sides	0.348	0.229	0.174	0.139	0.117	...	...
Sand-lime brick:							
External wall plastered on exterior	0.594	0.410	0.328	0.260	0.221	0.190	0.168
External wall plastered on both sides	0.553	0.389	0.307	0.252	0.215	0.186	0.166
Internal wall plastered on both sides	0.430	0.328	0.254	0.211	0.182	0.160	0.141

	Wall Thickness (in in)						
	12	16	20	24	28	31	35
Limestone masonry:							
External wall plastered on exterior	0.492	0.410	0.369	0.328	0.297	0.272	0.250
External wall plastered on both sides	0.471	0.410	0.369	0.328	0.289	0.266	0.244
Internal wall plastered on both sides	0.389	0.348	0.307	0.281	0.256	0.238	0.221
Dense stone, including marble and granite:							
External wall plastered on exterior	0.594	0.553	0.492	0.451	0.410	0.389	0.348
External wall plastered on both sides	0.573	0.512	0.471	0.430	0.389	0.369	0.348
Internal wall plastered on both sides	0.451	0.410	0.389	0.369	0.327	0.307	0.297

	Wall Thickness (in in)						
	2	4	6	8	12	16	20
Concrete masonry (gravel, cement, and sand):							
External wall without plaster	0.860	0.737	0.635	0.553	0.451	0.369	0.328
Internal wall without plaster	0.635	0.553	0.492	0.451	0.369	0.327	0.279
External wall plastered on both sides	0.717	0.614	0.553	0.492	0.410	0.348	0.295
Internal wall plastered on both sides	0.553	0.492	0.451	0.410	0.348	0.295	0.260

	Wall Thickness (in in)						
	4.7	9.8	15	20	25	30	35
Red-brick double wall plastered on both sides with 13–31 cm cavity	...	0.283	0.227	0.190	0.166	0.143	0.129
Ordinary red-brick wall insulated with cork sheeting on internal wall only for insulation:							
0.8-in thick insulation	0.227	0.190	0.164	0.143	0.129	0.117	0.107
2-in thick insulation	0.125	0.113	0.102	0.094	0.088	0.082	0.076
4-in thick insulation	0.070	0.068	0.063	0.059	0.057	0.055	0.051

Appendix Four

Angles of Declination and Altitude for Cairo, Egypt

Table A4.1. Angles of declination and altitude at latitude 30° N corresponding to Cairo

Time of Day	21 June Summer Solstice		21 March or 21 September Equinoxes		21 December Winter Solstice	
	Angle of Declination to the North	Angle of Altitude	Angle of Declination to the North	Angle of Altitude	Angle of Declination to the North	Angle of Altitude
5:03	62°40′	Sunrise-zero	. . .	. . .	. . .	. . .
6:00	69°24′	11°27′	90°00′	Sunrise-zero	. . .	. . .
7:00	75°42′	23°51′	97°24′	12°57′	117°20′	Sunrise-zero
8:00	81°48′	36°35′	106°53′	25°40′	125°50′	11°27′
9:00	88°13′	49°30′	116°27′	37°45′	135°24′	21°18′
10:00	96°34′	62°28′	130°00′	48°36′	148°36′	29°18′
11:00	112°34′	75°05′	151°11′	56°43′	163°15′	34°40′
12:00	180°00′	83°26′	180°00′	60°00′	180°00′	36°34′
13:00	247°56′	75°05′	208°49′	56°43′	196°45′	34°40′
14:00	263°56′	62°28′	230°00′	48°36′	211°24′	29°18′
15:00	271°77′	49°30′	243°33′	37°45′	224°06′	21°18′
16:00	278°12′	36°25′	253°07′	25°40′	234°10′	11°27′
17:00	284°18′	23°51′	262°36′	12°57′	242°40′	Sunset at 16:57
18:00	290°66′	11°27′	270°00′	Sunset-zero		
18:58	279°20′	Sunset-zero				

Glossary

Architectural Terminology of the Region

Bādgīr (بادجير): A type of wind-catch into which wind can flow from several directions, generally four, but also two. A septum that is the height of the vertical channel prevents wind from flowing in one entrance and out another. Highly developed in Iran and the Arab countries surrounding the Gulf. The word in Persian is بادگير (bādgīr), which appears to be the source of the word in Arabic.

Brise-soleil: A projection, louvers or a screen, used to block out unwanted sun rays.

***Claustrum* (pl. *Claustra*)**: Decorative moldings or tracery used for air passage.

Dur-qā'a (دور قاعة): The central space of the *qā'a*.

***Īwān* (pl. *Īwānat*)** (ايوان / ايوانات): A recessed covered space open to the center of a *qā'a*, the *dur-qā'a*, or, often through a loggia, to a courtyard.

Jālī: A lattice screen, used in South Asia for air passage. Also written *jally* or *jalee*. From the Hindi word जाली (jālī).

Kunja (كونجة): The space between buttresses in a *qā'a* used as a raised sitting alcove or built-in cupboards. Probably from the Persian word for corner or nook كنج (kunj).

Loggia: An open-roofed gallery or arcade on the side of a building with a height of one or more stories and not projecting from the surface of the building.

Maḍyafa (مضيفة): A guest house or guest room.

Malqaf (ملقف): A device for capturing wind at a high point of a building. The word literally means catcher.

Mashrabīya (مشربية): Wooden lattice screens which can be placed in the window of a *qā'a*, in a *dur-qā'a*, in an oriel window, or elsewhere.

Qā'a (قاعة): A main hall of a house or building, usually the reception area for receiving male guests.

Ṣaḥn (صحن): An internal courtyard.

Sahrīgī (صهريجي): A *mashrabīya* pattern with large lattice spacing, usually placed above another pattern to permit air circulation.

Salsabīl (سلسبيل): A type of fountain, consisting of a decorated sloping marble slab over which water flows.

Squinch: A support, usually an arch or a lintel, carried across the corner of a room below a superimposed mass.

Tablinum: A room or alcove between the atrium and the peristyle of an ancient Roman house.

Takhtabūsh (تختبوش): A covered outdoor sitting area at ground level located between the main courtyard and another courtyard, possibly the back garden.

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