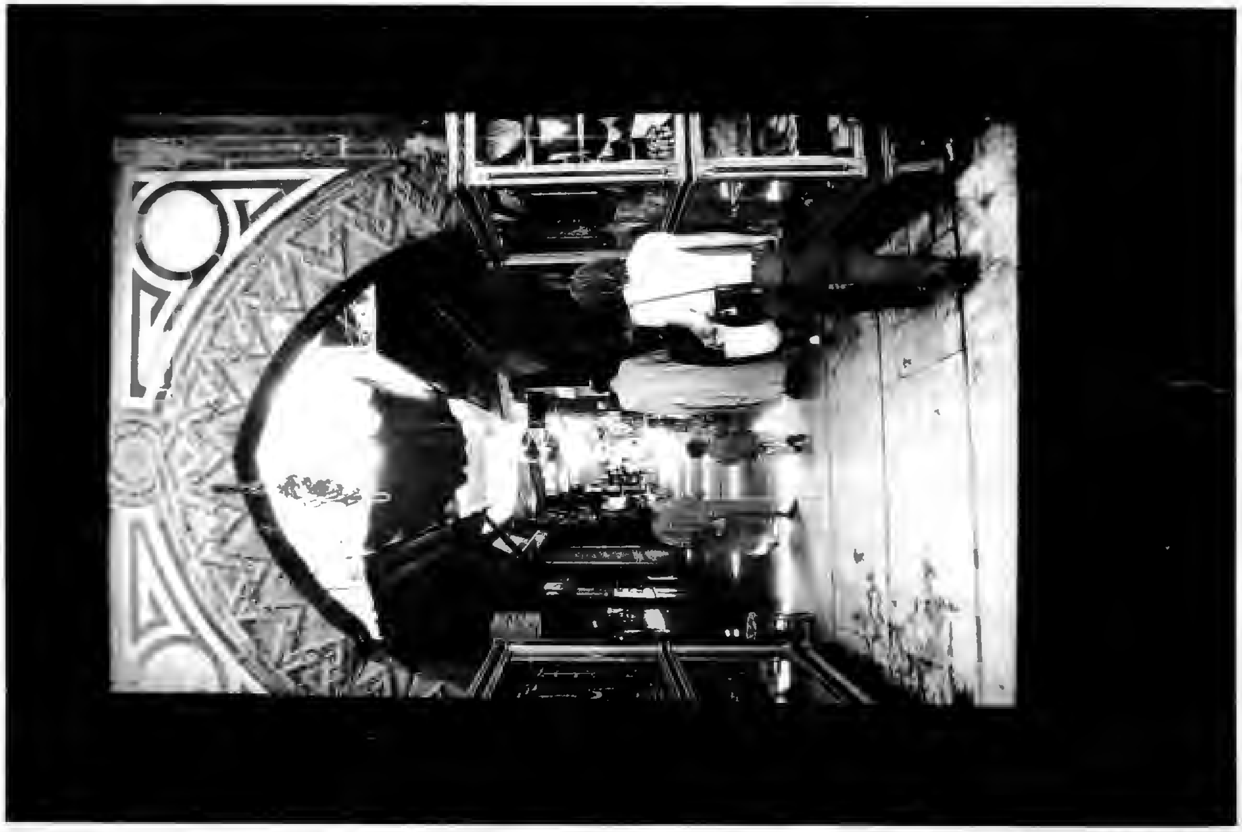
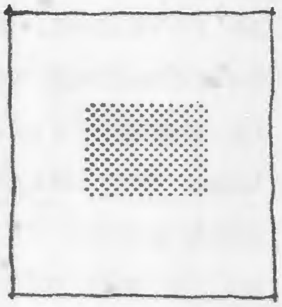
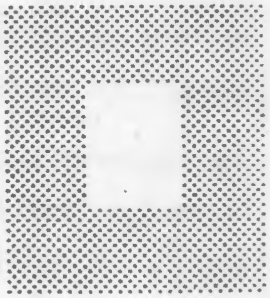


The Courtyard Form

The courtyard form developed in Mediterranean and Middle Eastern regions to meet the requirements of defence against the often hostile external physical environment. There was a need to protect living spaces from dry dusty winds and intense solar radiation. While the temperate climate dwelling looks outward onto green surroundings, shelter in arid regions looks inward to a protected space, or courtyard.

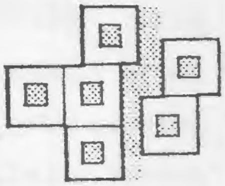


Western Model
Outward Facing
Centered on
Site



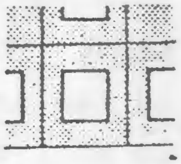
Courtyard Model
Inward Looking
Against Harsh
External
Environment

Living spaces clustered around the courtyard allowed extended families of several generations to live together with a degree of privacy and interaction. In most warm climates much of the day-to-day activities take place out of doors. Inward looking courtyard units could be built back to back and clustered to attain very high urban densities, without a loss of private open space.



boxlike form

A study of the old quarter of Delhi in India indicates that despite the high population density and close packing of housing units, 25% of the urban area is actually open courtyard space. 10-12 % streets
compare to Garden City Planning - Extroverted
30-40% open space



courtyard form

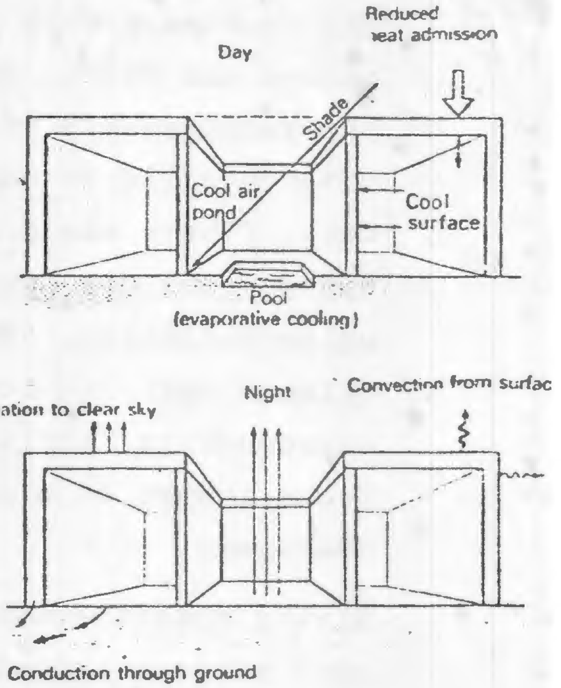
from Mohsen

Close urban clustering results in mutual shading and a decrease in heat gains on external walls. The courtyard if properly designed functions as a climatic modifier. Here a pool of cool night air can be retained, as it is heavier than the surrounding warm air. If the courtyard is small (i.e. the width is not greater than the height) even breezes will leave such pools of cool air undisturbed. High walls cut off the sun, and large areas of the inner surfaces and courtyard floor are shaded during the day. Cooler air, cooler surfaces, and the earth beneath the courtyard will draw heat from the surrounding areas, re-emitting it to the open sky during the night.

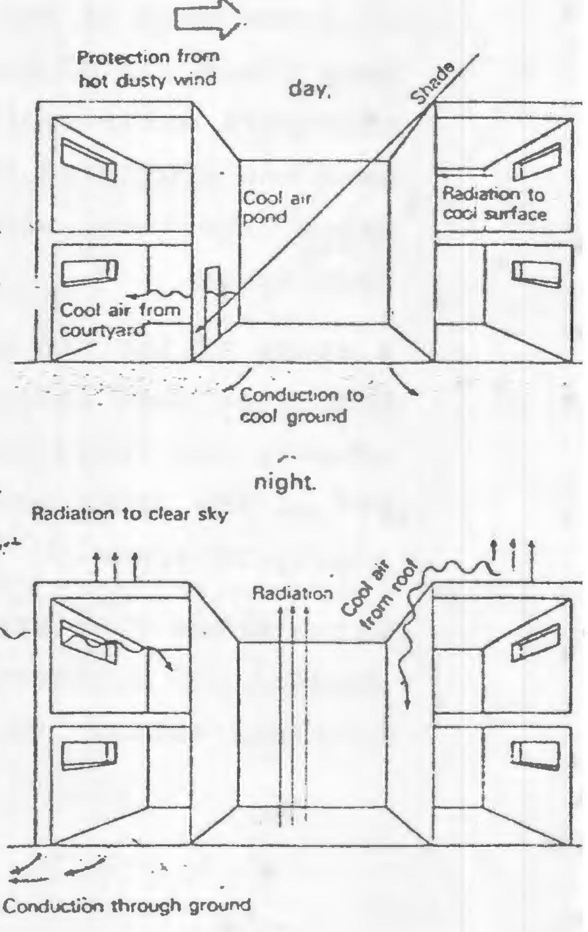
An interesting adaptation of the typical form is the two courtyard house. One court is small and deep and therefore generally shaded and cool; the other is wide and open to the heating of the sun's radiation. Air in the small courtyard, being cool and dense, has a higher pressure than the warm air of the large courtyard, which tends to be lighter and therefore rises. If an opening or passageway connecting the two courtyards is well positioned, there will be air movement induced by convection from the cool courtyard through the passage to the warm courtyard. The air's velocity is controlled by the size and nature of the passageway, as well as the temperature and pressure

from Koenigsberger→

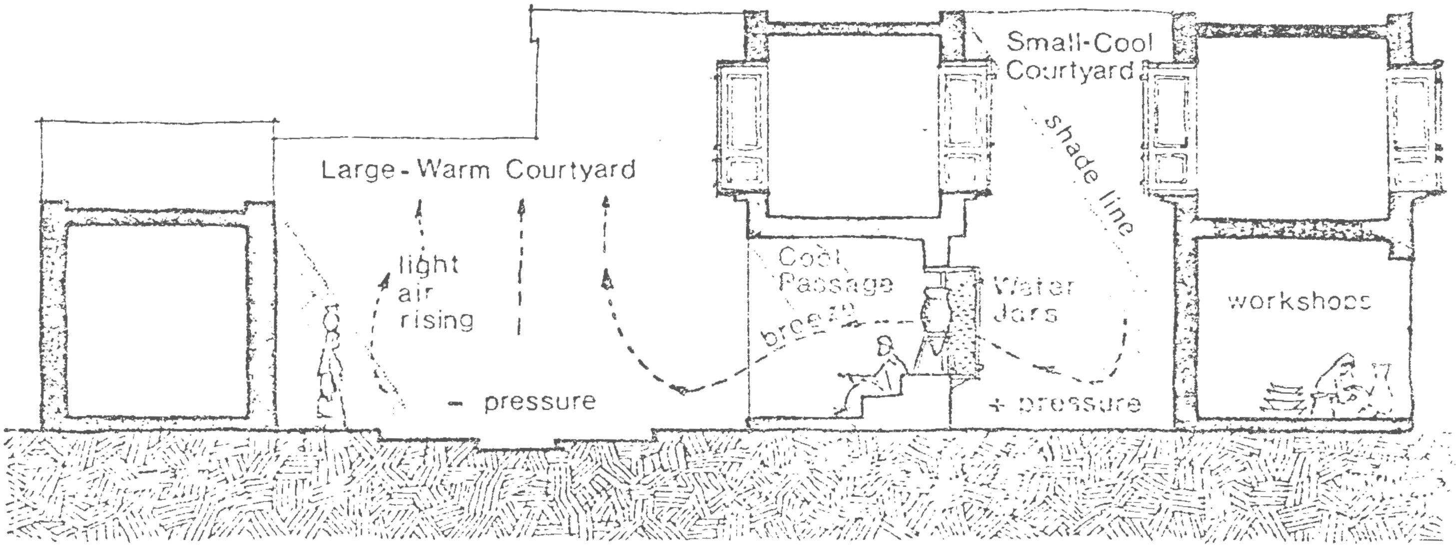
The thermal system of a small courtyard house



The thermal system of a larger courtyard house



differences between the two courtyards. In houses where this feature is employed, the inhabitants spend the hottest hours of the summer days in this cooled space between the courtyards.



Convection system between courtyards
from Development Workshop

Environmental Planning and Indigenous Urban Settlements
Case Study of Old Cairo

Old cities were of a manageable scale and functioned well. Even today the traditonal areas in cities such as Tunis, Cairo, Yazd and Delhi hold many lessons for urban planning in the Third World. Today ~~superficially~~ they are in bad physical condition because of the poverty of their inhabitants, intense overcrowding and official neglect. Detailed examination however, shows a layout of streets and blocks that are based on sound local, economic, social and environmental conditions. Solutions for accomodating dense populations without resorting to high-rise towers have evolved. Traditional centres such as Old Cairo have, using the courtyard house model, in the past comfortably supported population densities between 300-400 people per hectare. Post war high-rise tower residential neighbourhoods in London were zoned for about 250 people per hectare. Elsewhere planners have had to resort to building 10 to 15 story blocks side by side in order to increase densities above that which was found in the indigenous middle eastern city.

Although ringed by endless urban expansion and ignored by economic planners, these old quarters still today support a wide range of commercial and small-scale industrial activities, employing significant sectors of the labour force and housing many of the poorer classes.

Not only the peripheral squatter settlements, but the traditional city centre accomodates the rural and unskilled migrant. In the old city quarters he finds casual employment in the unmechanised traditional sector.

Old quarters have been adapted to accomodate much higher densities than those mentioned above. For instance, Old Cairo before 1800 and colonial contact with first France then Britain, housed about 250,000 people within its walls. Despite the growth of the European city and suburban areas around it, by 1947 the population of the old city was 665,000; in 1960 it had reached 850,000 and is now probably well over a million. At the same time metropolitan Cairo has grown from ½ million to 8 million people with population densities in some areas of 1500 persons per hectare. Every day about 500 new migrants enter Cairo.

~~one-family courtyard houses now accomodate 5 or more people in each room.~~

Many of these urban problems of overcrowding and unemployment of course can be traced to the & imbalance of investment. ~~So~~ ~~Them~~ Capital goes into urban rather than rural industrialisation & services. And the solution to the problems of ~~the~~ city are likely to

The old quarter of Cairo remains today a vital and productive sector of the city. Though containing a population well above the optimum and showing the effects of over taxation of municipal services, it still illustrates the principals of the indigenous city.

There exist a hierarchy of functions which have a rationale on many levels, social and economic as well as environmental.

ettlement to House form - structure of study.

The pattern shows a hierarchy of large and small squares ~~and~~ wide pedestrian streets on a north-south axis and narrow streets running east-west, ~~from intersections, off the main street.~~

The prinicpal municipal square is bounded by civic buildings such as the mosque and educational and cultural buildings. Running north or south from the square are the large pedestrian traffic routes. Commercial activity occurs along this artery, in the form of shops, beginning with those selling goods related to the mosque, bookshops through cloth and rugs, and further away, everyday domestic goods. The main street opens out at points where the smaller east-west streets intersect. These are usually places where street sellers set up their carts in the daytime to sell perishable or seasonal goods.

The narrow east-west streets (Atfa) contain much of the small-scale industrial activity; this now extends into the residential areas behind. Industries are grouped in sectors: weaving and leather work near the mosque to heavier and noisier trades such as metal working at the peripheries of the old settlement.

Residential areas are subdivided into cells or blocks (Hara). Access to residential areas is through a narrow passage off the secondary streets. The neighbourhood residential block, usually inhabited by a single family or tribal group, focused around a common square (Saha). Ten or twenty houses grouped together to form this cell, each house being itself based on the courtyard plan.

Now overcrowding has meant that extended family houses have been divided into one room units each containing a family group. House extension has resulted in encroachment into the already narrow streets, and a gneral neglect of once very efficient municipal services.

(13)

Old Cairo

The old quarter of Cairo remains today a vital and productive sector of the city. Though containing a population well above the optimum and showing the effects of over taxation of municipal services, it still illustrates the principals of the indigenous city.
There exist a hierarchy of functions which have a rationale on many levels, social and economic as well as environmental.

Settlement to House form - structure of study.

The pattern shows a hierarchy of large and small squares ~~and~~ Wide pedestrian streets on a north-south axis and narrow streets running east-west, ~~from intersections, off the main street.~~

The prinicpal municipal square is bounded by civic buildings such as the mosque and educational and cultural buildings. Running north or south from the square are the large pedestrian traffic routes. Commercial activity occurs along this artery, in the form of shops, beginning with those selling goods related to the mosque, bookshops through cloth and rugs, and further away, everyday domestic goods. The main street opens out at points where the smaller east-west streets intersect. These are usually places where street sellers set up their carts in the daytime to sell perishable or seasonal goods.
The narrow east-west streets (Atfa) contain much of the small-scale industrial activity; this now extends into the residential areas behind. Industries are grouped in sectors: weaving and leather work near the mosque to heavier and noisier trades such as metal working at the peripheries of the old settlement.
Residential areas are subdivided into cells or blocks (Hara). Access to residential areas is through a narrow passage off the secondary streets. The neighbourhood residential block, usually inhabited by a single family or tribal group, focused around a common square (Saha). Ten or twenty houses grouped together to form this cell, each house being itself based on the courtyard plan.
Now overcrowding has meant that extended family houses have been divided into one room units each containing a family group. House extension has resulted in encroachment into the already narrow streets, and a gheral neglect of once very efficient municipal services.

The indigenous hierarchy of open spaces and pedestrian ways also has a very clear environmental rationale.

North-south running street can be allowed to be wide and will still remain shaded. Since the sun's path runs at right angles, the street will be shaded by buildings on either side for most of he day. Only at noon when the sun is directly overhead will radiation penetrate down to street level.

On the other hand, east-west running parallel to the sun path streets are narrow and have many bends, overhangs and covered places. They are therefore kept shaded most of the time. The narrow streets and the courtyards of the old city trap cool night-time air and retain it well into the day.

The city pattern is also a response to the seasonal fluctuations of wind. Most of the year a cooling northern breeze blows, drawn up the Nile from the Mediterranean. The principal north-south streets help to channel this breeze through the old quarter, providing welcome ventilation and cooling in the late afternoon. As the breeze passes along the length of the street it creates negative pressure differentials at openings at intersections of the small east-west streets, which in turn draw air by suction through these alleys as well.

Hot dry south-east winds (Khamsin) blow off the desert during the spring. The maze of streets impede winds from this direction, and moderate their affect at ground level.

form

The courtyard house itself provides a cool green contrast to the hot arid climate. Its properties of trapping cool air at night and retaining it for daytime comfort are well known.

The two-courtyard house in Cairo is an interesting adaptation, which uses different size spaces to produce cooling air movement through convection. The large courtyard traps the sun and heats up, producing a low pressure area. The smaller courtyard remains shaded, keeping the air within it cooler and therefor of a higher pressure. Cool air moves through a passage from the high pressure area to the low pressure area. (Within the passageway we recorded a velocity of .5 m/sec.)

The same principals appled to the street pattern produce air movement during the hot times of day, even when no wind is evident. Openings at street intersections heat up and create pockets of low pressure which draw cooler air from the shaded streets.

Environmental Design

The indigenous hierarchy of open spaces and pedestrian ways also has a very clear environmental rationale.

North-south running street can be allowed to be wide and will still remain shaded. Since the sun's path runs at right angles, the street will be shaded by buildings on either side for most of the day. Only at noon when the sun is directly overhead will radiation penetrate down to street level.

On the other hand, east-west running parallel to the sun path streets are narrow and have many bends, overhangs and covered places. They are therefore kept shaded most of the time. The narrow streets and the courtyards of the old city trap cool night-time air and retain it well into the day.

The city pattern is also a response to the seasonal fluctuations of wind. Most of the year a cooling northern breeze blows, drawn up the Nile from the Mediterranean. The principal north-south streets help to channel this breeze through the old quarter, providing welcome ventilation and cooling in the late afternoon. As the breeze passes along the length of the street it creates negative pressure differentials at openings at intersections of the small east-west streets, which in turn draw air by suction through these alleys as well.

~~The~~ [illegible] Hot dry south-east winds (Khamsin) blow off the desert during the spring. The maze of streets impede winds from this direction, and moderate their affect at ground level.

The courtyard house itself provides a cool green contrast to the hot arid climate. Its properties of trapping cool air at night and retaining it for daytime comfort are well known.

House form

The two-courtyard house in Cairo is an interesting adaptation, which uses different size spaces to produce cooling air movement through convection. The large courtyard traps the sun and heats up, producing a low pressure area. The smaller courtyard remains shaded, keeping the air within it cooler and therefor of a higher pressure. Cool air moves through a passage from the high pressure area to the low pressure area. (Within the passageway we recorded a velocity of .5 m/sec.)

The same principals appled to the street pattern produce air movement during the hot times of day, even when no wind is evident. Openings at street intersections heat up and create pockets of low pressure which draw cooler air from the shaded streets.

References

1. Al Azzawi, S.H.
"Oriental Houses in Iraq"
Shelter and Society -ed. P.Oliver; ch.6 pg.91-102
Praegar, N.Y. 1969

2. Development Workshop
"Indigenous Building and the Third World"
Architectural Design; April 1975 pg.209-210
London, U.K.

3. Development Workshop
"Traditional Cooling Systems in the Third World"
Ecologist; vol.6#2 February 1976 pg.63
London, U.K.

4. Dunham, D.
"The Courtyard as a Temperature Regulator"
New Scientist; Sept.8th 1960
London, U.K.

5. Fathy, H.
"The Arab House in the Urban Setting: Past, Present and Future"
The Fourth Carreras Arab Lecture of the Univ. of Essex
Longmans, U.K. 1972

6. Fonseca, R.
"The Walled City of Old Delhi"
Shelter and Society -ed. P.Oliver; ch.7 pg.103-126
Praegar, N.Y. 1969

7. Koenigsberger and others
"Manual of Tropical Housing and Building - Part 1 Climatic Design"
Longmans, U.K. 1974 pg.205

8. Monsen, M.
"Solar Radiation and Courtyard House Forms"
Built Environment; vol.14, 1979 pg.89-106 & 185-201

References

1. Al Azzawi, S.H.
"Oriental Houses in Iraq"
Shelter and Society -ed. P.Oliver; ch.6 pg.91-102
Praegar, N.Y. 1969

2. Development Workshop
"Indigenous Building and the Third World"
Architectural Design; April 1975 pg.209-210
London, U.K.

3. Development Workshop
"Traditional Cooling Systems in the Third World"
Ecologist; vol.6#2 February 1976 pg.63
London, U.K.

4. Dunham, D.
"The Courtyard as a Temperature Regulator"
New Scientist; Sept.8th 1960
London, U.K.

5. Fathy, H.
"The Arab House in the Urban Setting: Past, Present and Future"
The Fourth Carreras Arab Lecture of the Univ. of Essex
Longmans, U.K. 1972

6. Fonseca, R.
"The Walled City of Old Delhi"
Shelter and Society -ed. P.Oliver; ch.7 pg.103-126
Praegar, N.Y. 1969

7. Koenigsberger and others
"Manual of Tropical Housing and Building - Part 1 Climatic Design"
Longmans, U.K. 1974 pg.205

8. Mohsen, M.
"Solar Radiation and Courtyard House Forms"
Built Environment; vol.14, 1979 pg.89-106 & 185-201

The courtyard house as a temperature regulator

Houses with central courtyards are traditional in many tropical countries. Besides being aesthetically pleasing they give protection against the environmental temperature. The style evolved from an apparently intuitive application of the principles of radiant heat and cooling

---

by DANIEL DUNHAM

Fulbright Scholar, Department of Tropical Architecture,
The Architectural Association, London

THE visitor to the hot, dry regions bordering the Mediterranean Sea becomes acquainted with one of the most charming traditional features of domestic architecture in those countries: the type of house in which all rooms adjoin a central courtyard, open to the sky.

Traditional housing all over the world has evolved through a system akin to natural selection: the fittest type survives. The courtyard house (also known as the *atrium* or *patio* house) owes its survival and popularity to its special suitability to the climate in which it is found. The internal court encourages heat loss from the living parts of the house in the form of outgoing radiant heat. This application of the radiant heat principle contributes to the relative comfort of these buildings during the hottest season.

Variations on the courtyard house have been built on both sides of the Mediterranean; indeed, it is traditional in a geographical belt from the shores of the Atlantic, across North Africa, through the Near East, well into the plains of India. It can be found transcending national and cultural boundaries, but following a zone of similar climate. In these arid and semi-arid regions, at least for a large part of the year, exclusion of heat from buildings is a major problem. Fires can provide extra heat to the rooms in winter, but most buildings must rely on natural cooling to achieve a temperate indoor climate in summer. The features which protect the interiors against high temperatures account for many of the special characteristics of this architec-

In extremely hot climates the phenomenon of outgoing radiation whereby the Earth and the buildings on it lose heat, becomes important. Although radiation from the Earth is far less dramatic in nature than that from the much hotter Sun, nevertheless it amounts on average to the same quantity of energy as that reaching the Earth from the Sun (Figure 1). If this were not the case there would be a gradual rise or fall in temperature of the Earth's surface over the years.

The quality of the radiation from the Earth is quite different from that arriving from the Sun. The Earth radiates long infra-red waves, while the Sun's radiation ranges from X-rays to infra-red. The intensity of radiant energy from the Earth is also much smaller than that from the Sun. The total radiation intensity from a hot body is given by the Stefan Boltzmann law, and is proportional to the fourth power of the absolute temperature of the radiating surface. The Sun's surface temperature is about 6,000° absolute, the Earth's about 300°, so that the radiant energy emitted per unit area of the Sun is about 160,000 times that emitted by the Earth.

So far we have thought of the Earth only as a "black body". Other factors affect the amount of heat that is radiated into space. The atmosphere is not completely transparent to these long waves, and this limits the net heat loss. A large part of the radiation is absorbed by atmospheric water vapour, carbon dioxide or dust, according to the wavelength, and reradiated partly into space and partly back to Earth. A complete cloud cover cuts the outward radiation from the Earth's surface to zero.

In hot, arid climates the magnitude of heat exchange between Earth, Sun and space is greater than elsewhere. Cloud cover is slight, and the increased transparency of the air allows the maximum amount of heat to reach the surface from the Sun during the day and to leave it into space during the night. The result is that these regions have the biggest range of air temperature between day and night, amounting to

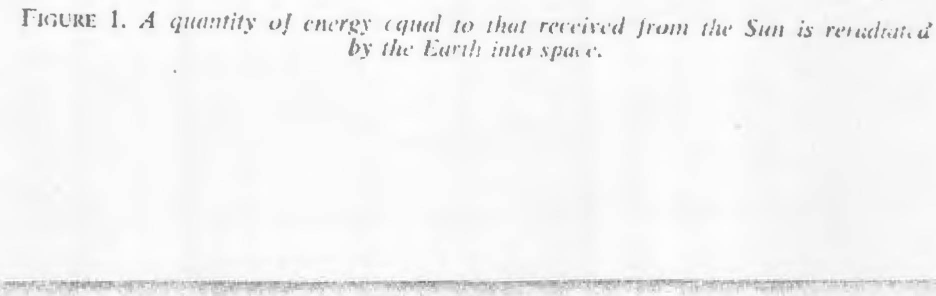


FIGURE 1. *A quantity of energy equal to that received from the Sun is reradiated by the Earth into space.*

approximately 20° to 40° F during the summer months.

The surfaces which actually receive and emit the radiation, of course, undergo much larger changes than the air above them. The highest temperatures during the day are found on the surface of the ground, and the same surface becomes the coolest place during the night. The air above the cool surface is cooled in successive layers upwards by conduction and "radiative pseudo-conduction", which is a process of internal radiation within layers of the atmosphere itself. As the cool air forms, surface winds drop and the heavier cold layers descend slowly to the lowest levels. Here they remain until the rising Sun's light raises the surface temperatures and reverses the process again.

Data on the magnitude of nocturnal radiation are not as complete as might be desired. Readings from arid regions are especially inadequate, and records from temperate regions are not directly applicable because of the higher cloud and pollution ratios there. In fact, over the range of temperatures normally found in architectural practice, so marked is the effect of water vapour in the air that outgoing radiation is related more closely to relative humidity than to temperature.

Because of the uncertainties of the data available it is difficult to calculate the heat balance of a house with any degree of accuracy. It is not only necessary to know the quantity of radiation absorbed by and emitted by a square foot of horizontal surface of the house during each day; other factors come into the equation. The house may lose heat by evaporation of moisture and by conduction and convection into the air above the surface. And part of the heat will be conducted into or up from the material below the surface. Thus, when the surface is being heated by the Sun its temperature will be lower than it would otherwise be if part of the arriving heat is conducted into a structure with large heat capacity and at a lower temperature. At night the reverse is true. The flow of heat from the structure to the surface means that the latter is rather warmer than it would otherwise be. This effect is very useful in places where the air temperature varies markedly during the course of a day. The materials from which the house is made can be chosen to have a large "thermal inertia" so that it provides an interior air temperature close to the daily mean at all times of the day.

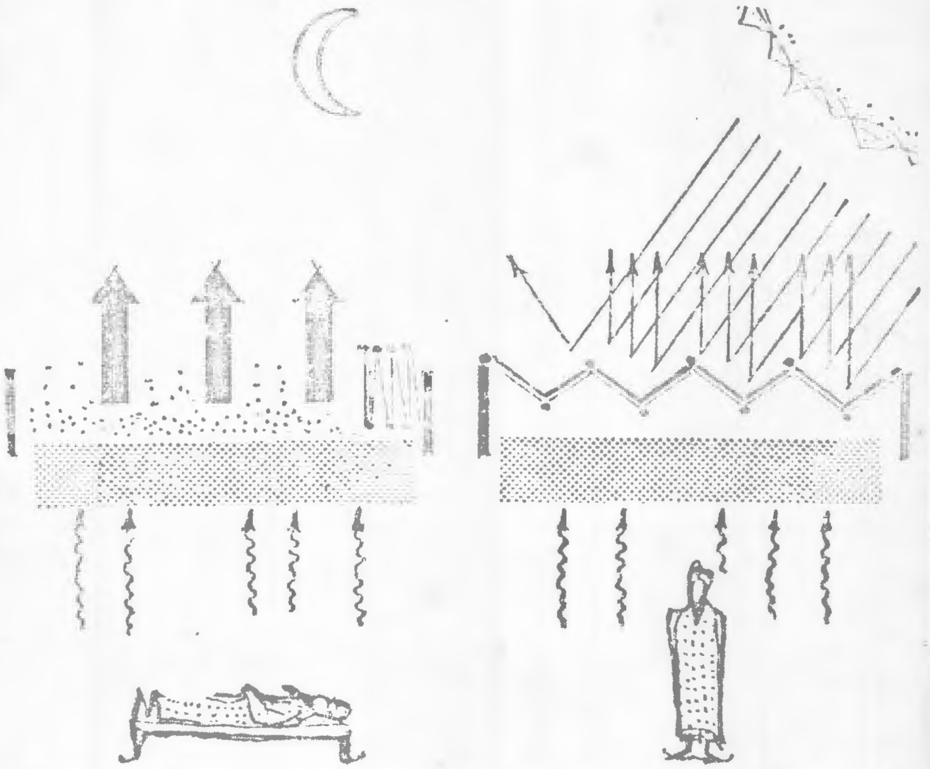


FIGURE 2. *A combinated radiating and storage unit protected from heat gain but allowed to emit radiation freely would act as a cooling element.*

Just as in cold climates it is possible to design structures to absorb, store and utilize what heat is available from the Sun to maintain interior temperatures above the daily mean, so it is possible in hot climates to augment heat losses through outgoing radiation and obtain

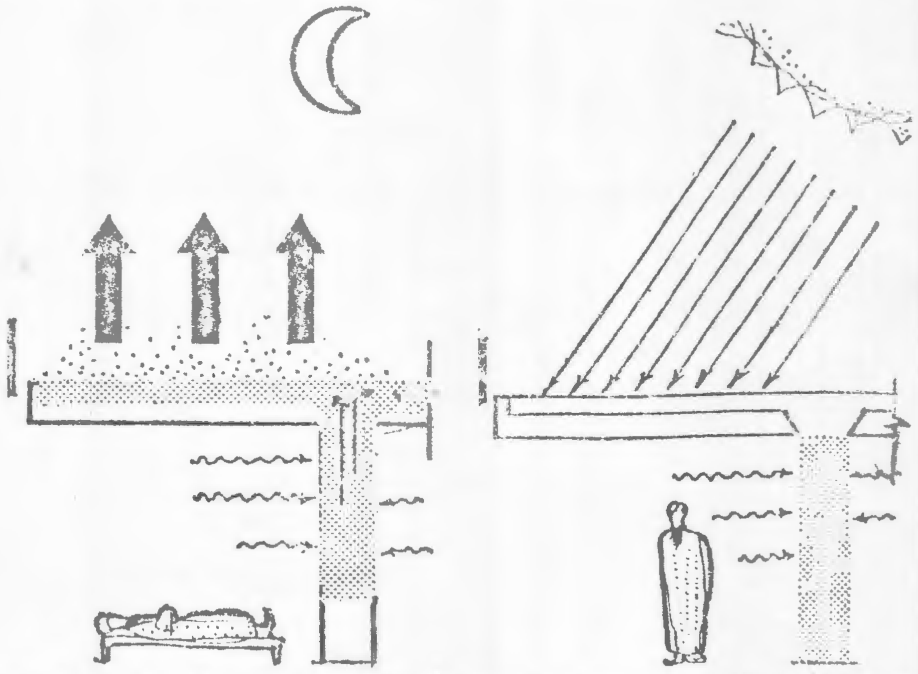


FIGURE 3. *A fluid cooled by radiating heat from the surface at night could be used to remove heat from other parts of the building during the day.*

interior environments in which the temperature is lower than the daily mean. For example, approximately 100,000 British Thermal Units are dissipated during the night from a roof 25 feet square. This is equivalent in heat loss, if stored and used efficiently, to the cooling power of a one ton air conditioning unit.

Two elements are needed to make use of this heat loss in practice: a surface from which the outgoing radiant heat could be emitted freely and an appropriate mass from which sufficient quantities of heat could be removed. This mass needs to be so placed that it, in turn, could remove unwanted heat from the interior of the structure and return it to the radiating surface. These elements could be devices specially designed for the purpose (as in the opposite case, where solar heat is absorbed and stored) or they could be the architectural elements of the building itself.

One simple arrangement would be to combine the radiating and storage unit. It would then be necessary to protect the surface from some or all of the incoming radiation during the day, while allowing it to reradiate freely during the hours when outgoing radiation is dominant (Figure 2). The effect of this would be to decrease the amount of absorbed radiant heat while allowing the outgoing radiant loss to remain as great as possible. A heavy roof or floor element treated in this fashion and protected from heat gain, while allowing radiant heat loss, would tend to equalize the net loss by withdrawing more heat from the surroundings. This is, of course, the desired result, for if the surroundings from which the heat is withdrawn are within the building, the effect is that of cooling the environment.

A second method would entail transferring heat from a protected storage area to a permanently exposed radiating surface by means of a fluid. In this case, radiation would be gained and lost from the same unprotected surface. A restricted heat exchange would take place during the period of incoming radiation, but during the period of outgoing radiation the heat lost would be transferred from some other area by means of air or water.

In the case of water, it could be cooled at night on the roof and transferred to heat exchangers within the building during the day. The following evening the warmed water would be returned to the roof by convection or mechanical means (Figure 3). In the case of air, it could be cooled by exposure to the radiating surface then transferred to interior protected elements to effect cooling during the day. We find natural examples of air transfer in the tendency of cooled night air to slide down slopes and collect permanently in depressions in the Earth. Certain kettle holes in the landscape of Central Europe have freezing temperatures even in midsummer. Here the collected cold air more than offsets the heat gain from the Earth itself and from the daily warming; and the daily mean temperature is considerably less than in exposed areas.

The traditional Moorish house of North Africa serves as an example in which the principles of radiant cooling are employed. This house, with its central court, is similar to most traditional urban dwellings in hot dry regions. It is, in essence, a square box open to the sky, with high narrow rooms on the perimeter (Figures 4 and 5). Exterior windows are lacking or of minimal size, but most rooms have large windows or doors on to the court.

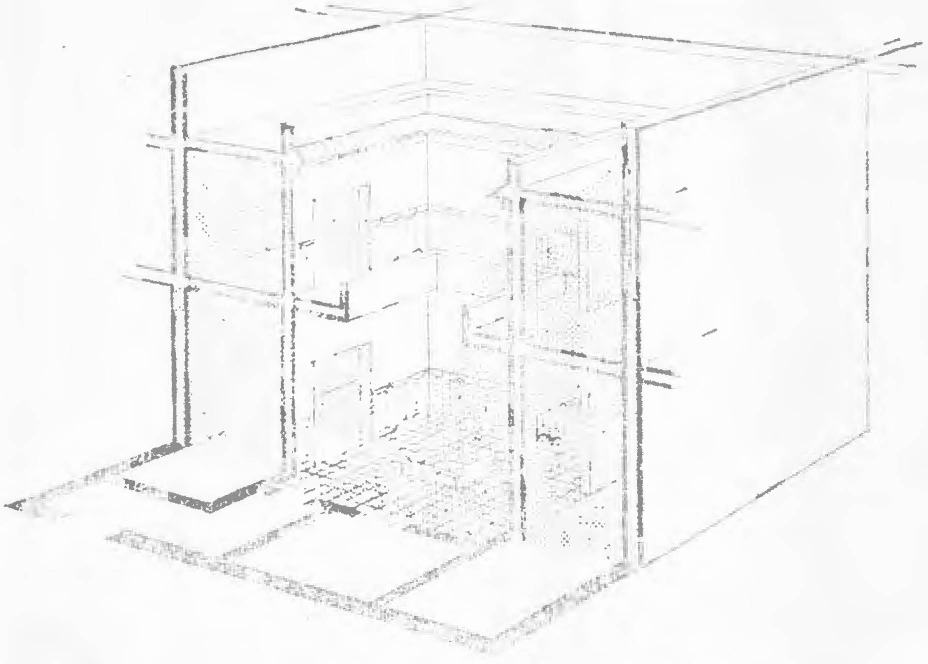


FIGURE 4. *Cross Section through a typical Moroccan courtyard house.*

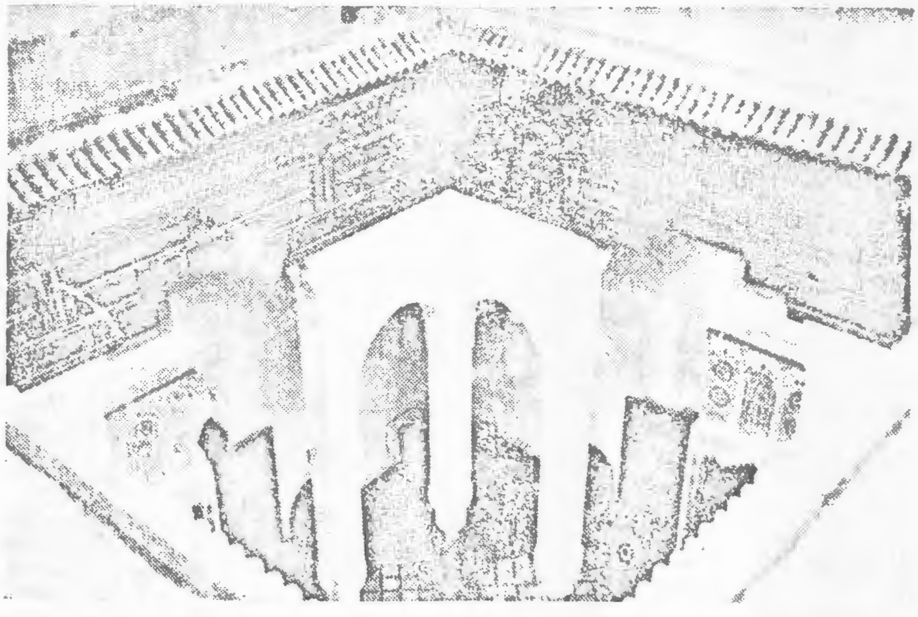


FIGURE 5. *A courtyard viewed from the roof. The daily extremes take place above the living area; the courtyard enjoys a more moderate climate.*

THE COURTYARD HOUSE AS A TEMPERATURE REGULATOR *continued*

Here the courtyard floor and earth beneath act as a combined radiation and storage unit. The high walls on all sides shade the court and protect it from direct sunlight during the greater part of the day, but leave it open to the "coldest" part of the sky (the zenith), to which it loses heat both day and night. The greatest radiation loss occurs towards the zenith because the thickness of atmosphere to be traversed is a minimum. The earth beneath the courtyard becomes a heat sink, which in turn receives heat from the surrounding areas in contact with it (Figure 6).

This process is reinforced by the unidirectional heat transfer that occurs on the rooftop. During the day, the air heated there rises, but during the cooling hours of the night the benefit of the heat exchange is transferred by convection to the lower regions of the house as the newly-formed layers of cooled air sink through the courtyard. The collected cold air flows into the rooms surrounding the courtyard and withdraws heat from the massive interior wall and floor elements. These elements are protected from incoming radiant heat by being in shade, and from the rising temperature of the air outside by the resistance of the structure to the effects of exterior air movement. By remaining cool, walls and floors help to reduce the interior air temperature as well as the mean radiant temperature of the living areas.

These traditional courtyard houses are held within fairly strict limits of size because only a small courtyard can be protected from the Sun. If a larger house is required, two or more of these units are joined rather than a larger one being created. They are closely grouped, covering large areas, and provide thermal protection to each other. Historically, protection for houses on the edges of cities was provided by the city wall, which gave climatic as well as physical protection from the conditions in the surrounding countryside. From the air these cities look like a raised platform pierced with courtyard holes (Figure 7). Life in a courtyard house can best be imagined as life at the bottom of a rather comfortable and sometimes very elegant well, where the coolness and stillness are in delightful contrast to the dust, wind and heat of the surroundings.

The value of folk solutions to traditional problems is often tempered by new conditions or solutions developed in other parts of the world. Universal air conditioning may some day simplify the task of builders in tropical areas. However, in most buildings in the arid tropics the architect and engineer face the same limitations which confronted the traditional builder: limited money, lack of skilled labour, difficulty in obtaining imported materials and, above all, the inhospitable climate. These conditions make the simple, apparently intuitive applications of climatic principles interesting and as valuable today as they were in the past.

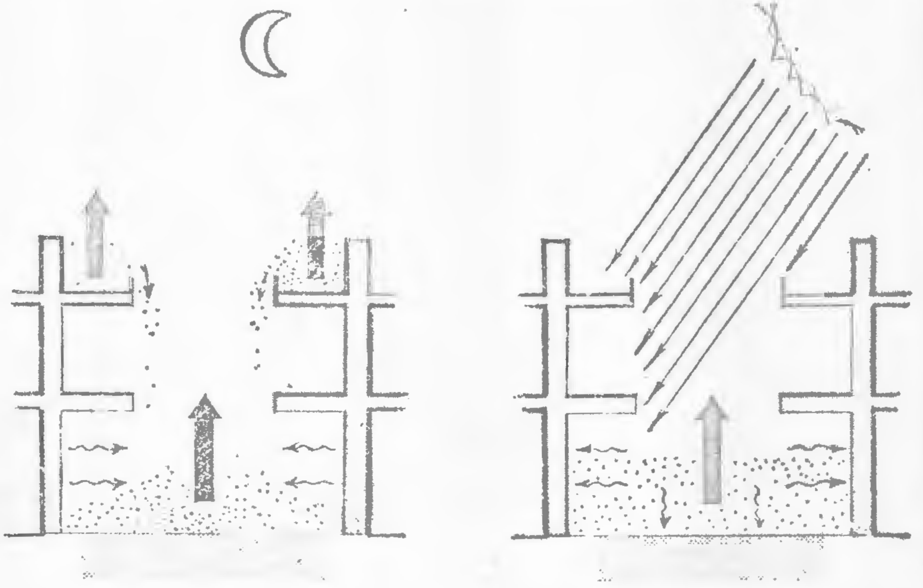


FIGURE 6. *During the night cold air formed on the roof sinks into the courtyard. Radiation from the protected courtyard surface helps cool the house during the day.*

FIGURE 7. *An air view of Marrakesh showing the close grouping of courtyard units. Several of these units may make up one dwelling. (Photograph by Lucien Vogel from* Le Jardin et la Maison Arabes au Maroc, *by Jean Galloti, Editions Albert Levy, Paris.)*

LEARNING FROM THE PAST: PASSIVE COOLING STRATEGIES IN TRADITIONAL AND CONTEMPORARY ARCHITECTURE

FULLER MOORE

INTRODUCTION:

Until the late 1960's, man has relied increasingly on the use of energy-consuming mechanical systems to achieve thermal comfort in buildings. In the wake of increasing shortages of energy, architects are re-examining traditional approaches to thermal comfort that used energy-conservative "passive" means to achieve this thermal comfort. The study of ancient structures is providing a fertile source of solutions to the heating and cooling of buildings. The state of the art in "passive" (use of natural heat transfer without mechanical equipment) heating and cooling has advanced significantly on the last decade, and it is economically feasible to reduce energy consumption for comfort conditioning by a factor of 4 using these passive techniques, as based on the author's experience.

ARID REGIONS:

In any overheated location, protection from direct solar gain becomes important in maintaining thermal comfort.

The relative dryness of air in arid regions makes a number of cooling techniques feasible. They are evaporation, nocturnal radiation, nocturnal mass cool-down, earth/air heat exchange, and exterior wall mass. Where air movement is required to accomplish the above, solar induced convection or winds can be employed. However, because of the high ambient daytime air temperatures present and the tendency of air movement to effect excessive skin evaporation (resulting in excessive drying and dehydration), ventilation alone is not an effective cooling choice.

TRADITIONAL EXAMPLES:

Ancient Arab houses used a curved marble slab adjacent to exterior window openings to effect evaporative cooling as the warm outside air passed across. Similar effects were achieved using a porous clay water vessel placed in windward wall openings; as moisture wicked to the outer surface, it cooled the air as it passed around the vessel and simultaneously cooled the liquid within.

Windcatches were often employed to direct winds above the surface down into residences where they were evaporatively cooled by central pools, or fountains. In his design for a girl's school in Gourna, Egypt, Architect Hassan Fathy employed the same principle using a bed of charcoal kept saturated with water to effect the evaporation (Fathy 1969).

In arid regions, the clear atmosphere conditions allow rapid radiation to the night sky. This radiation effect (not to be confused with the convective cooling effect of the ambient night air) allows surfaces to be chilled significantly lower than the ambient air temperature. This effect is most pronounced under still air conditions and is enhanced when radiating surfaces can be protected from the warming effect of night winds. In Iran, this phenomenon allowed ice to be produced passively when ambient night temperatures were above freezing. Bahadori (1978) has described the process whereby shallow trenches are dug along an east-west direction and filled with water, with an adjacent adobe shielding wall erected along the south edge of trench. At night the radiative heat loss from the surface of the water will exceed the convective gain from ambient air and conductive gain from surrounding earth. The ice is removed and stored the following morning. The wall serves not only as a wind barrier, but as a shading device.

Because the inherent mass of traditional adobe construction possesses a large thermal storage capacity, it has been used effectively as a cooling strategy in arid regions that experience large diurnal temperature swings. The thick exterior walls and roofs slowly absorb heat from direct solar radiation, both diffusing and delaying its impact on interior spaces. A significant amount of heat is retained by the adobe until it can be released back to the outside at night by radiation and convection. The remainder is delayed as much as 12 hours and radiated into the interior at a time when ambient air temperatures are lowest. If outside air is introduced at this time, even this delayed heat gain can be minimized. It is necessary to halt this ventilation during the day as outside air temperatures exceed those of the interior.

"Flushing" out the structure with this cool air has the additional effect of cooling isolated interior masses to evacuate heat absorbed during the day. Numerous examples of this strategy can be found in traditional Middle Eastern housing, as well as the Pueblo structure of the south-western United States. Many such structures provided for outdoor sleeping courts where occupants could be directly cooled by night convection and radiation, while the interior activity spaces thermally prepare themselves for the following day.

This mass cooling effect is maximized below the surface of the ground where the mean annual temperature is approached about six meters below the surface. In Matmata, Tunisia, living spaces were excavated below the surface, surrounding a sunken courtyard. This not only afforded thermal comfort, but freed the surface above for other activities including agriculture.

This underground cooling effect can be used remotely by drawing air outside through underground tunnels where it is cooled. Often, as in buildings in Yazd, Iran, a wind tower is used to direct air flow down, through underground tunnels, past a fountain where it is further cooled by evaporation before being introduced into inhabited spaces. The tower which is of masonry construction delays the heating effect of the sun on the air intake; at night, when the winds die down, the heat absorbed by the tower during the day effects it to act as a chimney, reversing the air flow. This allows the cool night air to be drawn directly into the living spaces and carried through the underground tunnels, before being exhausted by the convection of the tower. This not only cools the living spaces, but "backflushes" the heat absorbed by the tunnels during the day. (Bahadori, 1978).

CONTEMPORARY ADAPTATIONS:

The roof pond system developed by Harold Hay combines many of these traditional methods into a single passive system capable of maintaining year-round thermal comfort in regions of moderate to low humidity. The system is comprised of plastic bags of water covering the roof supported by an uninsulated metal roof structure. The roof is equipped with a set of horizontally sliding insulating shutters over the water bags. During summer nights the shutters are slid away, exposing the water bags, which lose heat to the clear night sky by radiation,to cool air by convection, and when the tops of the bags are flooded with water, by evaporation. During the day, the shutters are closed to minimize solar gain, while heat from interior spaces radiates to the cool metal ceiling which conducts the heat to the water bags above.

During the winter, the shutter sequence is reversed, allowing the bags to absorb and store solar heat during the day, while insulating them from the outside at night. Daytime heat loss is minimized by adding air to the bags, creating an insulating dead air space above the water.

Another strategy (Crowther and Melzer, 1979) uses a shallow pool of water on the roof with a pipe connection to a series of vertical water tubes in the space below. During the day, the water tubes collect heat from the interior by radiation and convection. At night the shallow roof pond loses heat by radiation, convection, and evaporation. As this water is cooled, convection is set up in the water system, and the pond water is replaced by the warmer water from the storage tubes below. The process continues as long as the roof pond is cooler than the storage tubes, and stagnates during the day as the pond temperature rises. The pond is shielded from the sun by a south-sloped shading device, which leaves the pond exposed to the north sky.

Pliny Fisk (University of Texas in Austin) has designed several projects that utilize a glazed solar chimney (which enhances the heating effect and thence the induced convection) to draw outside air through underground earth tubes.

HUMID REGIONS:

As humidity increases, the previously discussed methods become less effective. Evaporation is slowed, moisture in the air increases "greenhouse" effect, reducing radiation to the night sky, and daily temperature variations are considerably reduced making building mass ineffective in diurnal shifting of thermal loads. Often annual temperature variations are less, reducing the effect of earth-air heat exchange (this would use the sub-surface temperature of the earth — which approaches the average annual air temperature as a depth of 6 meters is reached).

Traditionally, the vernacular buildings in these regions have minimized mass, maximized elevational openness and perimeter area to promote ventilation, and maximized shading to reduce solar impact.

The author's recent research and architectural projects have addressed the problems of heating and cooling in southwestern Ohio, U.S.A. using many of the previously discussed principles.

The H.U.D. Competition:

One design is this author's entry in a passive solar design competition sponsored by the U.S Department of Housing and Urban Development. It won a design award in the competition and received construction funding to assist in the construction of six variations by local builders. The cooling system employed in the latest variation is a combination of several historic precedents.

The spaces occupied during the day (living, dining, kitchen, study) are located at grade level, while sleeping areas are located below grade. During mild cooling seasons, during the day outside air is drawn into the lower level through small exterior windows. Because of sub-surface earth contact, these areas remain cool and thereby cool the incoming air. This cooled air is drawn up the stairwell through the living space by convection induced by a low mass solar chimney (used as a heater during the winter) and finally exhausted to the exterior at the roof peak. At night, the solar chimney action ceases, and the cool air settles into the lower sleeping areas.

During extremely hot periods, a separate system is used. A series of six 15 cm plastic pipes are installed 2m. below grade. The pipes rise to grade level at each end and are connected to a plenum box attached to each end of the house. Each plenum opens both into the house and to the outside. During the winter, cold outside air is drawn through these pipes and exhausted to the outside using a low power fan (a solar chimney could have been used); this "super-cools" the earth mass surrounding the pipes to a temperature about 15°F colder than normal.

During the summer, the same fan is used to circulate interior room air down through the tubes where it is chilled before being returned to the interior at the opposite end of the house in a closed loop cycle. It is expected that the air can be chilled below the dew point resulting in not only sensible cooling but a modest amount of dehumidification.

DUAL DESICCANT BED DEHUMIDIFICATION:

Because of the difficulty in dealing with the humidity problems using traditional cooling methods the author and two colleagues (J. Cantrell and G. Willeke) have been working on a completely passive solar dehumidifier for summer use in humid areas, that would also provide heat during the winter.

The system utilizes low-cost desiccant materials for dehumidification, and solar heat for regeneration and convective air circulation. It consists of two identical adjacent arrays of desiccant, each alternately used for dehumidification or regeneration/convection. An apparatus model has been constructed and successfully tested to verify air flow. Several desiccant materials have been tested and evaluated for use in the system.

PRINCIPLES OF OPERATION:

This system consists of two identical, adjacent solar collector arrays of horizontal screen trays filled with a dark, granular desiccant material.

Figure 1

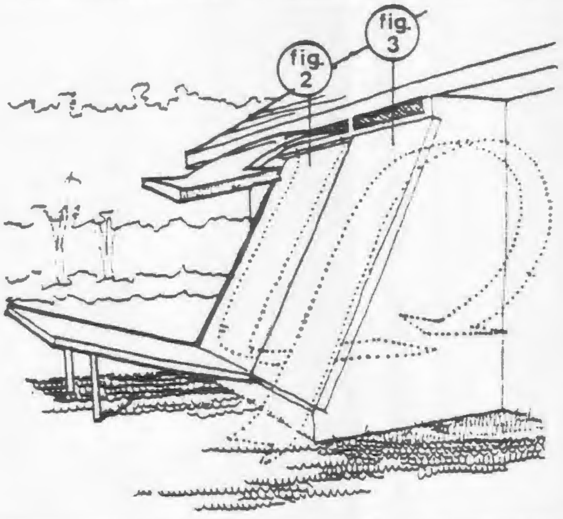


Fig. 1: AIR PATH THROUGH SYSTEM

One collector array is covered with a glazing material and is exposed to solar radiation which heats, dries, and regenerates the desiccant material. The array of horizontal trays is arranged in a "stair-step" configuration to maximize solar exposure and to allow solar-induced convective air flow to pass through the desiccant screens, enhancing the drying process. This heated, moist air is then vented to the exterior. A reflective horizontal panel below enhances solar collection.

The opposite array is covered with a reflective, insulating, bottom-hinged panel (for insulation from solar effects). Cool, moist air (from some external sensible cooling source; e.g., an earth-air heat exchanger or evaporative cooler) is drawn through the desiccant screens, and its specific humidity is lowered. This cool, dehumidified air can be used for building air conditioning.

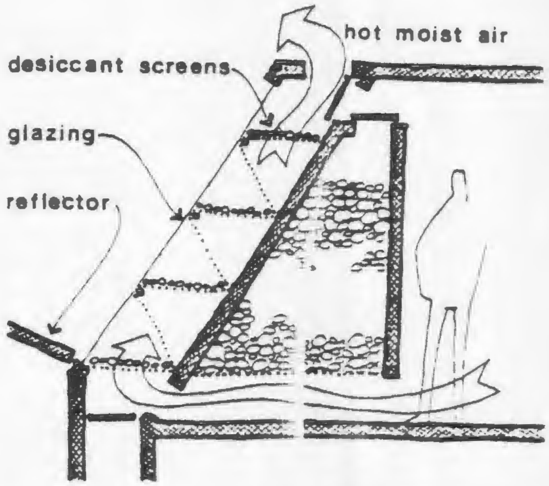


Figure 2

Fig. 2: DESICCANT REGENERATION

Air movement through the entire system (i.e., the sensible cooling device, the drying array, the building, and finally the regenerating array) is induced by the solar-heated convection in the regenerating array. When the desiccant is

Figure 3

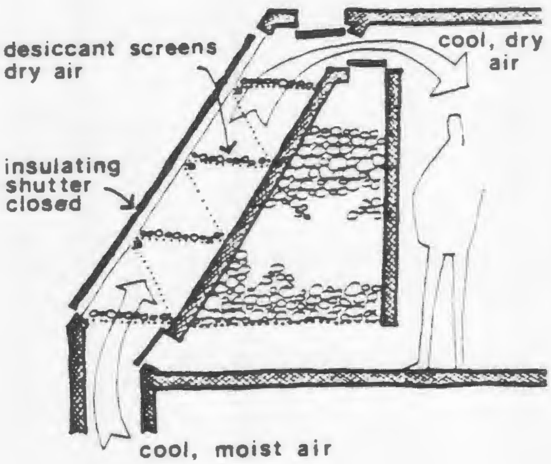


Fig. 3: DESICCATION MODE

exhausted, the roles of the two arrays are reversed by moving the insulating covers/reflectors and changing damper configurations.

Figure 4
Figure 5
During the winter, both arrays could be used for solar collection; heat would be stored in an adjacent rock storage bin.

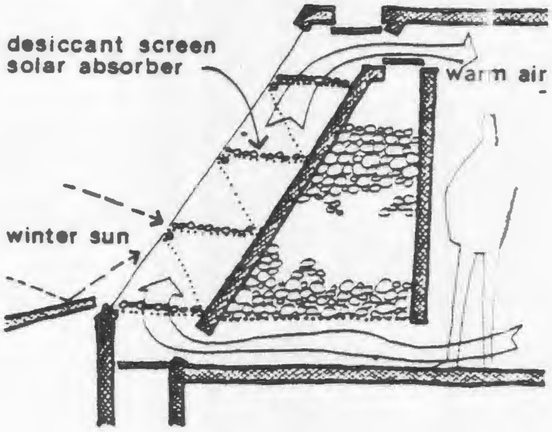


Fig. 4: HEATING FROM COLLECTOR

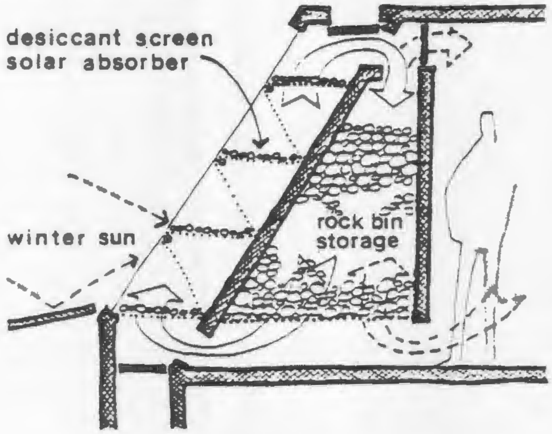


Fig. 5: STORING HEAT;
HEATING FROM STORAGE

The authors feel that, of the desiccants studied so far, the activated charcoal is preferable for the present system. It regenerates readily in the pertinent relative humidity and temperature ranges, can be recycled indefinitely, has inherent deodorization properties and is readily available at relative low costs ($1.24/pound; approximately $250 worth of charcoal would suffice for a collection area of 400 sq. ft. as of 1980). It is interesting that charcoal is an excellent solar absorber and proved superior in this regard to all other samples tested. These characteristics make the system not only attractive for summer dehumidification but also for winter heating. Although not the subject of the present study, it is speculated that performance might be enhanced with the addition of a fan unit.

ACKNOWLEDGEMENT:

The author wishes to acknowledge the support of Miami University in the preparation of this paper.

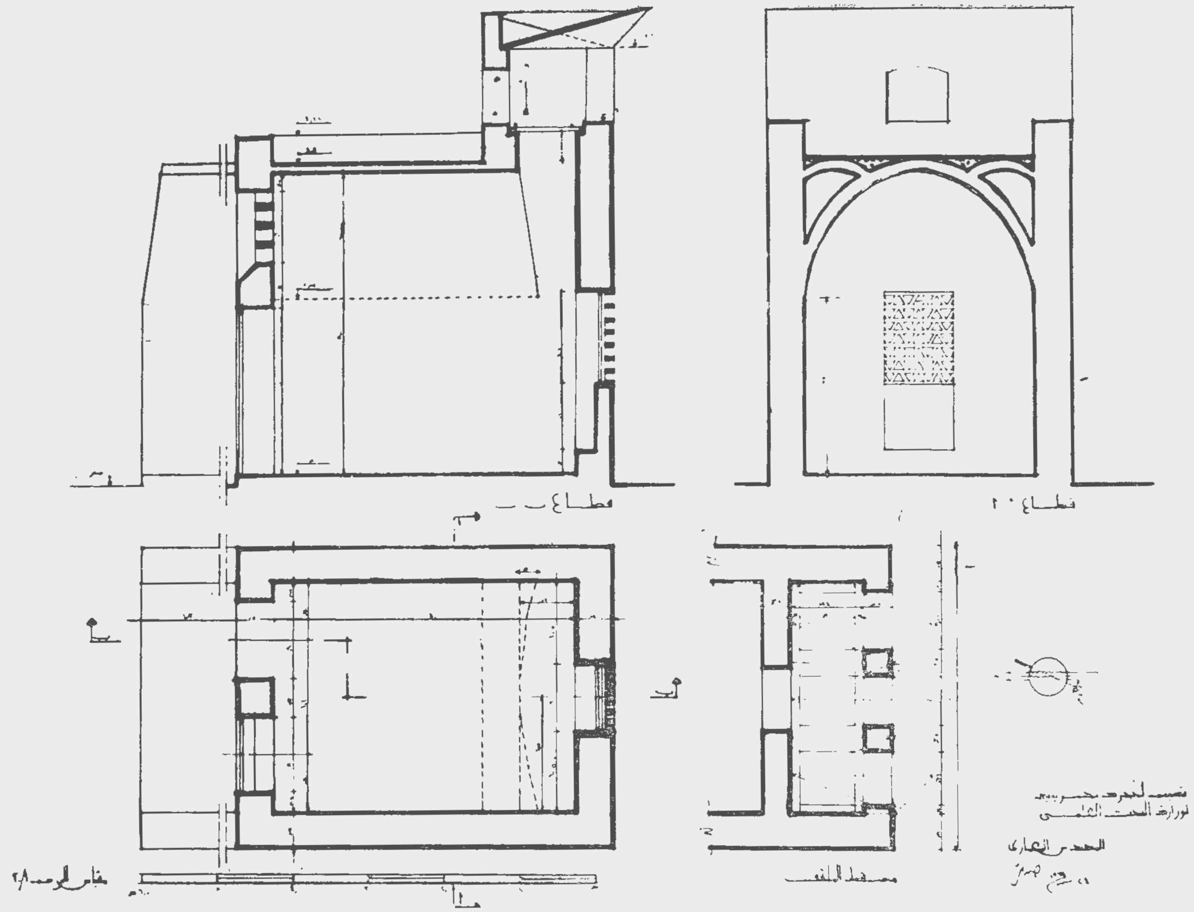
REFERENCES:

Fathy, H. *Architecture for the Poor.* Chicago: University of Chicago Press, 1973.

Crowther, K. and Melzer, B., "The Thermosiphoning Cool Pool" *Proceedings, Third National Passive Solar Conference,* San Jose, CA. 1979, pp. 448-452.

Bahadori, M. N., "Passive Cooling Systems in Iranian Architecture," *Scientific American,* February 1978, pp. 144-154.

1. Löf, G.O.G., "House Heating and Cooling with Solar Energy," *Solar Energy Research,* Madison: University of Wisconsin Press, 1955, p. 33.
2. Dunhe, R. V., "A Method of Solar Air Conditioning," *Mechanical and Chemical Engineering Transactions.* Australia: MCI, 1965, p. 73.
3. Scott, N. R., "Preliminary Report of Earth — in Heat Exchanger Studies," Paper No. NA-64-503, American Society of Agricultural Engineers, North Atlantic Regional Meeting, New Brunswick N. J., August 1964.
4. Hiramatsu, Y., et al., "Estimation of Temperature and Humidity of Underground Air Current," Kyoto University, Faculty of Engineering Memoirs,. Vol. 24, pp. 377-8, Dec., 1962.
5. Davis, P., "Thermosiphon Air Heaters," *Proceedings of the Passive Solar-Heating and Cooling Conference.* Albuquerque: E.R.D.A., 1976, pp. 40-41.
6. Morris, Scott, "Natural Convection Passive Solar Collectors," Proceedings of the Second Annual Passive Solar Conference. Philadelphia, March 1978.
7. Lunde, Peter, "Solar Desiccant System Analysis and Materials," *Solar Cooling for Buildings Workshop Proceedings.* Los Angeles: 1974, pp. 139-144.
8. Wellesley-Miller, S., "A Retrofittable Solar Dehumidifier," *Solar Cooling for Buildings Workshop Proceedings.* Los Angeles: 1974, pp. 145-150.
9. Rush, William, "Solar Desiccant Systems," *Solar Cooling for Buildings Workshop Proceedings.* Los Angeles: 1974, pp. 151-155.



شكل (٢٥) نموذج (أ) من الحجرات التجريبية لوزارة البحث العلمى

Fig. (25) Experimental Mide Room A
Ministry of Scientific Research

Fig. (25) Chambre Modèle Expérimentale A
Ministère des Recherches Scientifiques .