APPLICATION OF TRELLISES IN RETROFITTING BUILDINGS IN HOT DRY CLIMATES

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1. Introduction

In hot dry climates, as of central and southern Iraq, characterised by long hot summers and a wide daily temperature variation between dawn and the warmest part of the afternoon, the main concern is with the control of solar radiation. One passive cooling alternative intending to overcome the natural heat flow into the building lies in interrupting and delaying solar radiation before it reaches the building shell. This is achieved by creating a secondary shell, partially or entirely enclosing the building, and thus reducing insolation and the consequent heat buildup on the building surfaces (1). Trellises supporting climbing plants are one option for such double shell systems ; they are simple in construction, low in cost, and can be designed to be aesthetically appropriate (2).

Trellises can be added in retrofitting existing buildings, ill adapted to their climatic environment, due to bad building orientation, or because of poorly insulated walls and roofs. Their shading effect can improve the thermal performance of the building. This improvement can be observed and quantified, as this study proposses, through the comparison of actual temperature readings for two buildings, identical in building materials and in orientation, one of which is enclosed by a plant trellis.

2. Experimental setup

In choosing the building to be retrofitted, three criteria were observed :

- that the building should be detached, to allow an evaluation of all orientations.
- that it should be a low building, to allow the climbing plant to cover the structure within one summer season.
- the availability on the same site of a second building, identical to the first in form, orientation, and building materials, to allow for the temperature measurements.

The building chosen is the club house of a housing compound serving the resident engineering staff of the Dora Public Housing construction site in Baghdad, (lattitude 33 N). The club house and all the other houses are layed out in a grid pattern, with their longer sides facing north-east and south-west. The buildings are partially prefabricated. Wall pannels consist of .07 m mineral wool , sandwiched between sand rendered plywood to the exterior, and painted chipboard to the interior, providing a total wall thickness of .09 meters. The roof consists of the same pannel, covered by corrugated galvanised metal sheet.

Lightweight galvanised steel piping was used to construct a trellis completely enclosing the building , excluding the parts facing window openings. Wire mesh was layed over the piping to ensure a more uniform growth for the climbing plants.

The plant selected ,luffa cylindrica, (cucurbitaceae), is a cheap, and readily available, fast growing annual. Its luxuriant green leaves provide dense and efficient shading. Planting commenced with the completion of the trellis supportive structure, on the 22nd of June . Figure 1 shows the trellis on the north-east facade, and the climber in an advaced stage of growth.


Fig. 1. General view, and detail of the north-east facade.

3. Experimental data

The 21st of September was chosen to conduct the field measurements, as plant coverage of the trellis was not acheived before the first half of this month. A digital surface temperature sensor, (thermo-couple) was employed for measuring external wall and roof temperatures, and internal wall and ceiling temperatures, simultaneously, for the two buildings.

Local climatic data was obtained from the Central Meteological Station, in Baghdad , and is as follows :

- the average maximum temperatures for the five critical summer months of May, June, July, August, and September, 46 C, the average minimum for the same months, 39.6 C, the average relative humidity, 23 %.
- the average maximum and minimum temperatures for the 21st of September, were 40.5 C and 31.35 C respectively, the average humidity 27 %.

Results of the field measurements are presented in Figure 2.

4. Findings

The experimental data fall into three setts of findings ; the thermal performance of walls and roofs of the shaded and unshaded buildings; thermal performance and wall orientation ; calculation of the instantaneous solar heat gain.

4.1. The thermal performance of walls and roofs :

4.1.1. The reduction in the external surface temperature measurements , due to trellis shading is appreciable , averaging 8.2 C, reaching a maximum reduction of 17 C, for the south-west wall. This reduction in surface temperatures for the retrofitted building is not only the result of plant trellis shading, but is also due to the evaporative air cooling caused by the plants, and the buffer space between the plant and the wall , which creates a blanket of cool air adjacent to the building wall, increasing the initial cooling effect of plant shading.

4.1.2. diurnal variations in the internal wall temperatures , for either building are smaller than those for the external ones. An average difference of 2-3 C is recorded for the internal wall surface temperatures for the shaded and unshaded buildings.

4.1.3. When comparing the peak surface temperatures, a time lag of two to three hours is recorded between the occurance of this peak for the two buildings ; that is the peak for the shaded building occurs two to three hours after that of the exposed one. A similar time lag occurs for the internal surface temperatures ,but is less pronounced. A more accurate estimation of the occurance of temperature peaks would have been achieved, had hourly temperature readings been recorded instead of three hour intervals.

4.1.4. A maximum external surface temperature difference of 7 C was recorded for the roofs of both buildings. However, the temperature drop following the maximum reading differs , and is more rapid for the exposed building; more gradual for the shaded one. The reason lies in that the double shell presented by the trellis acts as a barrier hindering the outgoing long wave radiation . In contrast, the exposed roof heats up and cools down rapidly:

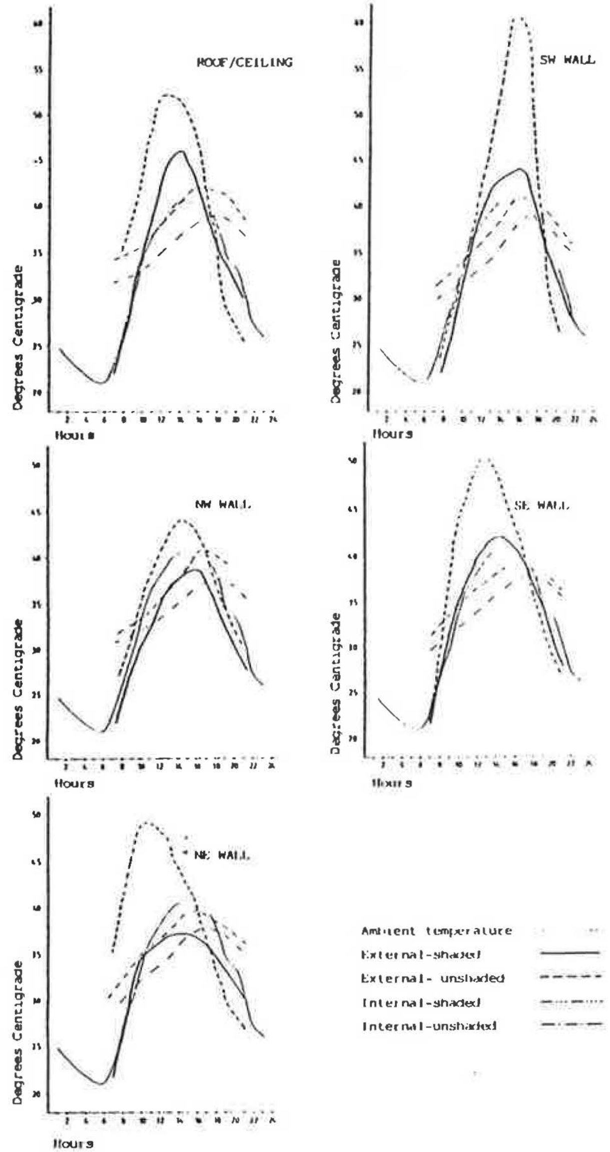

Fig. 2. The thermal performance of walls and roofs (ceilings), for the retrofitted and exposed Buildings.

4.2. Thermal performance and wall orientation :

4.2.1. When observing the thermal performance of the wall as a determinant of orientation, the highest external wall temperatures are recorded at the south-west wall, and to a lesser extent the south-east wall. It is these two orientations in a building that seem to profit most from retrofitting.

4.2.2. The thermal performance for the north-west, when comparing the shaded and unshaded buildings, shows the least variation, thus, eliminating the need to include this facade in the retrofitting.

4.2.3. Although the pattern of solar radiation around noon is symmetrical, south-west, and west facades are more critical than their corresponding south-east, and east facades, because of the thermal storage capacity of both the building and its surroundings.

4.3. Periodic solar heat gain :

In calculating the solar heat gain, the periodically varrying temperature was assumed on the outside, while the inside temperature was assumed constant. The instantaneous solar heat gain for both buildings, at 1600 hr. on September the 21st, was obtained, following the equation, (3) :

$$Q = A \times U[(T_{sam} - T_i) + \delta (T_{sa(t-\phi)} - T_{sam})]$$

Where U = transmittance, calculatted for wall,glass,or roof.
A = area of the component
T_{sam} = mean value of the sol-air temperature, as an average over a 24 hour period.
T_i = indoor air temperature, constant at 22 C
δ = decrement factor,calculated as the ratio of the maximum internal and external surface temperatures of the building component.
$T_{sa(t-\phi)}$ = the value of sol-air temperature hours before t; the time lag ϕ is defined as the difference in time between the time of maximum outdoor surface temperature and maximum indoor surface temperature.

The results of the calculations are presented in Table 1. given as a breakdown for the different building components (walls, roof,)and as a total for each of the two buildings (calculated by adding up the heat gain for all five building components.

4.3.1. The total instantaneous solar heat gain for the retrofitted building, given in watt per unit volume, was 7.57 w/m^3, thus approaching half the value of solar heat gain for the unsheltered building, 12.18 w/m3

4.3.2. The south-west facade contributes to over 50 % of the total periodic heat gain in both buildings. However, when comparing the

ORIENTATION	NORTHEAST			SOUTHEAST			SOUTHWEST			NORTHWEST			ROOF			TOTAL		
PERIODIC HEAT GAIN / BUILDING TYPE	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
SHADED	201.7	11	5	100.5	5.48	5	927	50.58	32.2	101.2	5.52	5.3	502	27.39	5	[illegible]	100	7.57
EXPOSED	288	13.02	13.5	147.5	6.57	7.3	[illegible]	53.5	54.86	[illegible]	[illegible]	6	475.3	21.54	5.3	[illegible]	[illegible]	[illegible]

Table 1. The instantaneous solar heat gain values for the shaded and exposed buildings, at 1600hr. on the 21st of September.

heat gain per unit area, the effect of the plant trellis become evident; 32.2 w/m3 for the shaded south-west wall ,compared to 54.86 w/m3 for the unshaded one.

4.3.3. The instantaneous heat gain for the north-west facades for the two buildings is similar in value ; the reduction in surface temperatures due to the trellis is almost negligable. Furthermore, had it not been for the fenestration in the north-east facade, constituting 20 % of the wall area, the instantaneous heat gain for this facade would have been close in value to that of the north-west wall.

4.3.4. The solar heat gain for the roof in the retrofitted building, given per unit area, was only slightly smaller in value than that of the exposed one. However, had the climber been planted earlier, as early as April, it would have provided a much more efficient and dense coverage.

5. Conclusion

In designing the field experiment, the aim has been to provide quantifiable data illustrating the role of plant trellises in improving the thermal performance of the primary building shell. At minimal initial and running costs, plant trellises can be successfully employed in retrofitting existing one to two storey structures. They can also be included in the initial design, forming part of the architectural expression, and amplifying the energy conservation of better insulated walls and roofs.

The findings indicate considerable reduction in the external and internal surface temperatures, due to the combined effect of plant shading and evaporative cooling. A similar reduction was also noted in the instantaneous heat gain for the retrofitted building. The reduction in solar heat gain were more prominent for the south-west facade, thus achieving saving in cooling energy for the peak-load time of the building, and for the same time of day , late afternoon, energy saving for the peak-period for electricity utility. Such reductions in both peak load, and utility peak load, result in a possitive environmental impact, beyond the boundaries of the individual building.

Although plant trellises posses several advantages over tree shading,mainly, shorter and faster growth characteristics, and a higher shading efficiency due to their proximity to the building facade, they cannot be utilised in shading fenestration areas, since their proximity would negate the basic function of the window. In the course of the field experiment, it was noticed that trellises adjacent to windows provide considerable shading of the glass, depending on the trellis-wall distance and wall orientation. Investigating the varying trellis-wall distance, as a determinant of the window shading coefficient , is one aspect to be researched, in order to provide the additional data necessary for the design of architectural trellises.

6. References

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A LARGE CLIMATE-MODERATING ENCLOSURE SUITABLE FOR HOT ARID CLIMATES

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The purpose of this work is to design a large volume (>10^5 m^3) climate-moderating enclosure suitable for hot arid climates. Without air-conditioning or any other powered mechanical cooling device it is to maintain an internal temperature significantly cooler than outside ambient. The interior is to be naturally lit. Potential uses of such an enclosure include agriculture, shopping centres, office parks and manufacturing.

The background to this work is diverse: Buckminster Fuller's one mile diameter dome over Manhattan (3); the one hundred acre roof of the Haj Terminal at Jeddah airport; the visionary ideas of Nikolaus Laing (6); and the pioneering computations of a group at the Oak Ridge National Laboratories (8).

A mathematical model has been constructed on a Macintosh microcomputer of the energy flows within a hypothetical large climate-moderating enclosure (LCME) situated near Tucson, Arizona. The LCME is very simple and is shown in Figure 1. It consists of a shallow depression in the ground surrounded by tall earth walls. The roof canopy is made of a durable and reflective architectural fabric arranged in large scale louvres, supported by a widely spaced regular grid of steel or timber masts.

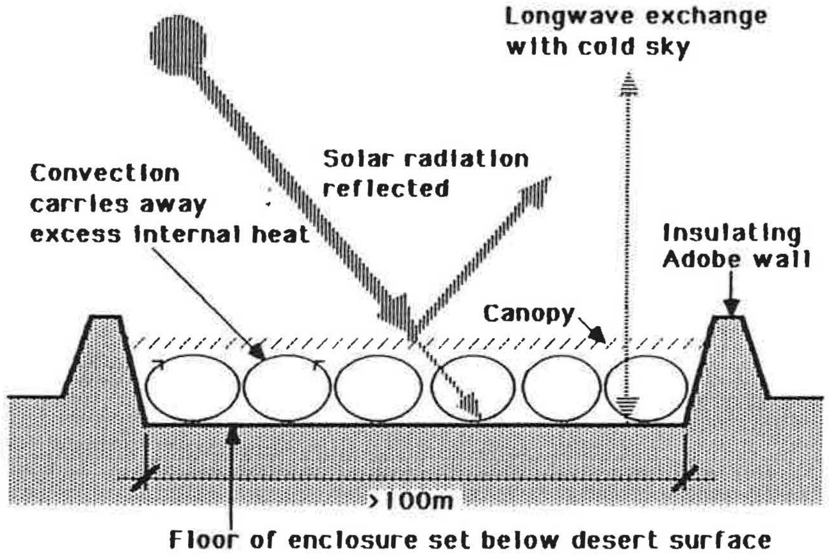


Fig. 1. Prototype Large Climate-Moderating Enclosure

The principles behind the design are also very simple. The canopy reflects most of the incident solar radiation. At the same time it is also open to the sky which permits an exchange of longwave radiation between the interior of the enclosure and the sky, which acts as a radiative sink. The massive earth walls insulate the sides of the enclosure. The roof is set below the top of the walls to discourage the mixing of wind-driven hot outside air with the cooler air within the enclosure. In this way a pool of cool air is maintained at the bottom of the enclosure. Natural convection ensures that the bottom of the enclosure tends to remain its coolest part.

The energy flows that are accounted for in the model are as follows:

1.Longwave and shortwave radiation, both inside and outside. The basic radiative exchanges are shown in figure 2. The symbol R means either longwave or shortwave radiation. R14, R15 and R16 represent emissions from the upper and lower surfaces of the canopy and from the ground and are therefore only longwave. R1 represents either shortwave radiation from the sun or longwave radiation from the sky. The radiative temperature of the sky is calculated using relationships devised by Berdahl and Fromberg (2). The dewpoint temperature is calculated from the dry bulb air temperature and relative humidity.

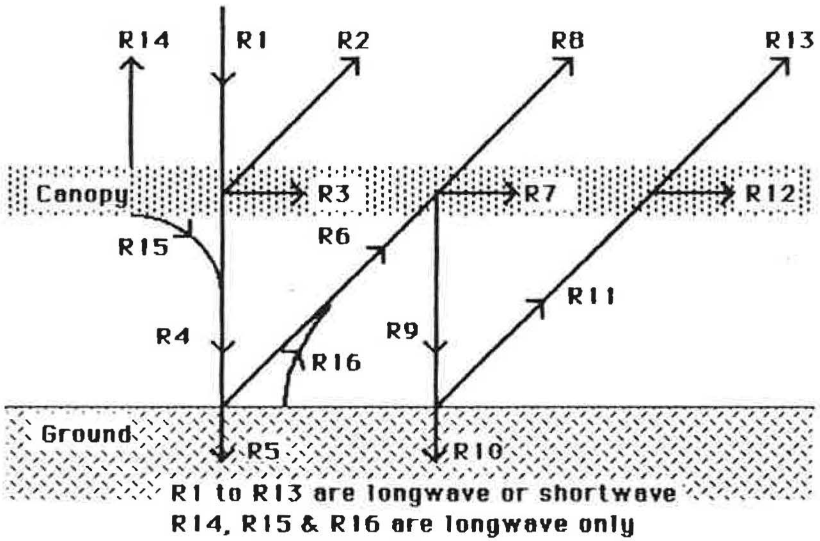


Fig. 2. Basic Radiation Exchanges

2.Convection from ground to air and from canopy to air. The basic convective exchanges are shown in figure 3. These are based upon correlations established by Alamdari and Hammond (1).

3.Conduction of heat in the soil beneath the floor of the enclosure. The sub-soil conduction of heat is calculated using the layered model shown in figure 4, taken from Ingersoll, Zobell and Ingersoll (4).

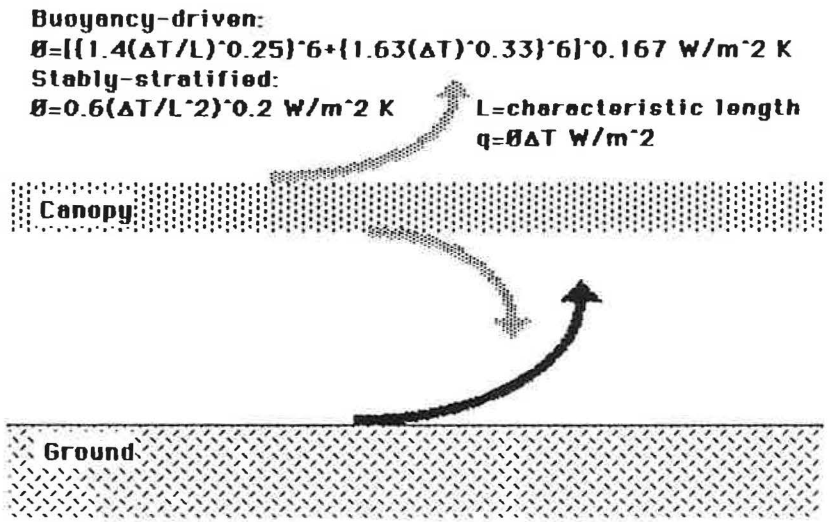


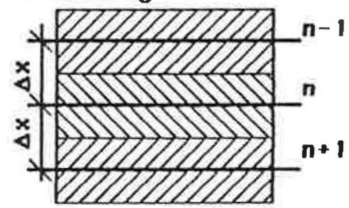
Fig. 3. Basic Convection Model.

During time Δt :

k: thermal conductivity
C: heat capacity
d: density

Heat flow from plane n-1
to plane n =
Δt(Temp[n-1]-Temp[n])k/Δx

Heat flow from plane n
to plane n+1 =
Δt(Temp[n]-Temp[n+1])k/Δx



Net flow of heat into plane n =
Δt(Temp[n-1]-2Temp[n]+Temp[n+1])k/Δx

Rise in temperature of plane n =
Δt(Temp[n-1]-2Temp[n]+Temp[n+1])k/((Δx^2)dC)

Fig. 4. Basic Soil Conduction Model.

The model also takes account of the following:

1.Soil Properties.

The soil beneath the floor of the LCME is divided into 10 layers, and each layer may be assigned its own thickness, conductivity, density and thermal capacity. The surface of the soil is assigned reflectivity and absorbtivity in the shortwave and longwave. It is also assigned a longwave emissivity.

2.Canopy Properties.

The roof canopy is assumed to have no thermal capacity. It does have both long- and shortwave reflectivity, absorbtivity, transmissivity and longwave emissivity.

3.Solar and other Weather Input (5,9).

The solar intensity on a horizontal surface can be specified at hourly intervals throughout the day. Dry bulb air temperature and relative humidity are assumed to vary sinusoidally. The program user supplies the lowest and highest daily values and the time at which the lowest value occurs.

4.Heat Sources and Sinks.

a.Infiltration of outside air.

b.Artificial sources of power at floor and canopy levels.

c.Absorbtion of specified fractions of long- and shortwave radiation inside the enclosure by plants.

5.Sequence of Calculations.

The program performs its calculations at regular time steps throughout the day and night, typically hourly or half hourly. Before it can begin these calculations it must 'initialise' the soil, that is to say it must establish realistic temperatures in each of the soil layers. This it does based upon the user's guessed range of soil surface temperature variations. At any depth the temperature range is calculated from (7):

$$\Delta T_z = \Delta T_0 \, e^{-z\sqrt{(\pi/KP)}}$$

where ΔT_z is the surface wave amplitude, ΔT_0 is the wave amplitude at depth z, K is the thermal diffusivity of the soil and P is the wave period in seconds (86400 in the case of diurnal cycles). The time lag is calculated from:

$$t = (z/2)\sqrt{(\pi/KP)}$$

where t is the time lag. The canopy temperature is initialised by searching for a temperature at which radiative and convective fluxes are in equilibrium. Initialisation and analysis begin at a time chosen by the user. Checks have shown that the predictions of the model are not sensitive to the choice of time.

Once conditions have been initialised, it is possible to proceed with the main analysis. The sequence of events is shown in figure 5. At each time step the results of the calculations are plotted graphically on the screen of the computer and are also printed in tabular form. The graphical output of a typical run is shown in figure 6.

The temperature of the surface of the ground represents the conditions at the floor of the enclosure, which are always cooler than the outside air. During the daytime the canopy heats up to much higher than the air in order to find equilibrium between its solar gains and its longwave and convective losses. At night the opposite occurs and the canopy reaches equilibrium at temperatures between the ground and the air, with longwave radiative losses balancing small convective gains. The small steps in the sky temperature are a feature of the model used, which changes slightly at dawn and dusk.

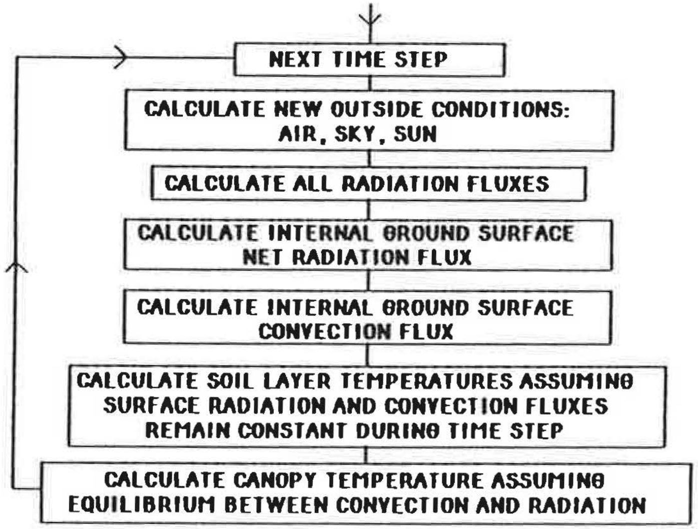


Fig. 5. Analysis Sequence.

Table 1 lists all the parameters used in the run presented in figure 6.

Analysis Begins at 6am. No infiltration or artificial power input.

Radiative Properties (%).

	Absorbed	Reflected	Transmitted	Emitted
Canopy Short	25	25	50	0
Canopy Long	15	75	10	15
Soil Long	85	15	0	85
Soil Short	65	35	0	0

Soil Conductive Properties

Thickness	Conductivity	Capacity	Density
m	W/m/K	J/m3/K	kg/m3
0.05	0.3	1280000	1600

Outside Air

Lowest Temp	Highest Temp	Lowest RH	Highest RH
21°C at 5am	37°C	13%	36% at 2pm

Solar Input.

Time	5am	6am	7am	8am	9am	10am	11am	12
	7pm	6pm	5pm	4pm	3pm	2pm	1pm	
W/m2	0	150	300	500	700	800	850	900

Table 1 Basic Parameters

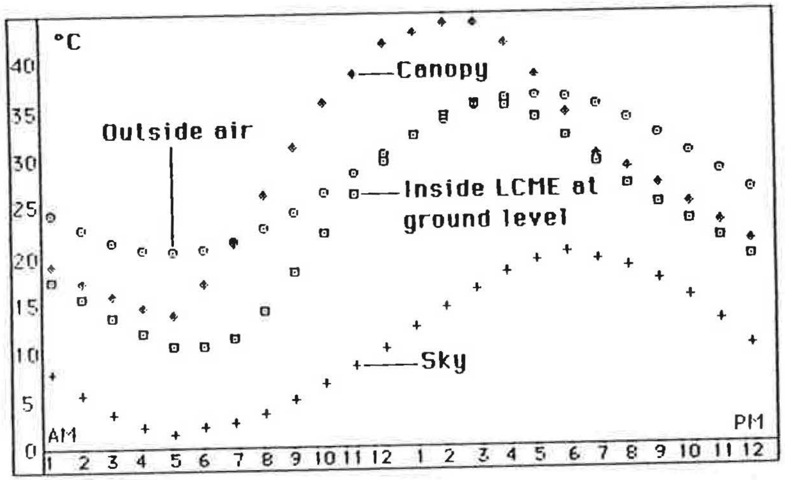


Fig. 6. Typical Daily Cycle Of LCME

The results presented in figure 6 are for just one of 45 combinations of canopy radiative properties that have been examined. The range of radiative properties are given in tables 2 and 3.

	Absorbed	Reflected	Transmitted	Emitted
A)	0	0	100	0
B)	0	25	75	0
C)	0	50	50	0
D)	0	75	25	0
E)	0	100	0	0
F)	25	0	75	0
G)	25	25	50	0
H)	25	50	25	25
I)	25	75	0	25
J)	50	0	50	50
K)	50	25	25	50
L)	50	50	0	50
M)	75	0	25	75
N)	100	0	0	100

Table 2 Canopy Longwave Properties (%)

	Absorbed	Reflected	Transmitted	Emitted
1)	10	70	20	0
2)	15	75	10	0
3)	20	75	5	0

Table 3 Canopy Shortwave Properties (%)

Table 4 summarises the results of these runs. The conclusions that can be made from these results are, perhaps, not surprising and therefore encouraging. It is clear that significant reductions in temperature are possible by passive means alone. There are at least three basic conclusions to be drawn from these analyses. The first is that the longwave absorbtivity of the LCME's canopy should be as low as possible. The second is that its longwave reflectivity should be as low as possible. The third is that absorbtivity is more crucial than reflectivity. These can be summarised by saying that longwave transmissivity should be as high as possible.

Shortwave:	1	2	3
Longwave			
A)	37.3°C	27.3	22.4
B)	40.9	28.6	22.4
C)	43.8	29.0	21.0
D)	47.5	27.2	13.4
E)	48.3	*	*
F)	42.8	32.9+	28.6
G)	47.4	35.9	30.6
H)	52.9	38.8	32.1
I)	58.3	40.3	31.0
J)	46.0	37.2	33.2
K)	51.7	41.5	36.4
L)	58.2	45.9	40.9
M)	48.7	40.3	36.5
N)	56.2	45.6	41.7
O)	51.5	43.0	39.8

* Did not converge to a solution after 48 hrs   + Illustrated in Figure 6

Table 4 Summary of Maximum Internal Ground Level Temperatures For Different Combinations of Canopy Short- and Longwave Properties.

Extensive runs have been carried out to make sure that the results being obtained are not sensitive to any of the assumptions made or particular values of parameters chosen. These are summarised in Table 5. The parameter that has the most marked effect on peak internal temperature is the assumed absorbtion of longwave radiation within the LCME by, for example, vegetation. Leaves are very good absorbers of longwave radiation (95% is a typical figure). However the behaviour of a plant stand is different from the behaviour of its individual leaves (7). A more realistic model of plant behaviour would have daytime shortwave and longwave absorbtion by the stand partly offset by convection and longwave emission; at night it is quite likely that convection would partly compensate net longwave heat loss by the leaves. The next stage in the development of this program is to construct a simple model of plant stand behaviour.

Apart from the absorbtion of longwave radiation by plants, the parameter that has the most marked effect on the model's predictions is the thickness of the soil layers. This is not surprising because it can easily be shown that with a dry sandy soil (the kind of soil whose properties have been assumed) daily temperature fluctuations penetrate to a depth of less than 0.5m. Even annual fluctuations reach only about 5m. It is therefore important to have thin enough upper layers in the soil so that the model can perform appropriately.