AN ENERGY EFFICIENT SOLAR GREENHOUSE FOR COLD CLIMATIC CONDITIONS

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BY
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CERTIFICATE

This is to certify that the thesis entitled "An Energy Efficient Solar Greenhouse for Cold Climatic Conditions" submitted in partial fulfillment of the requirement for the degree of Doctor of Philosophy in Agricultural Engineering of the Post Graduate School, Indian Agricultural Research Institute, New Delhi, is a record of bona fide research carried out by Ms. Mathala J. Gupta under my guidance and supervision and that no part of the thesis has been submitted for any other degree or diploma. The assistance and help received during the course of investigation has been truly acknowledged by her.

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Abstract

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Abstract

A generalized mathematical model of the greenhouse thermal environment has been developed. Thus, the model can serve as an effective tool of design of greenhouse for any location given the climatic conditions of the place.

The model was used to predict the effect of shape, orientation, thermal insulation, night curtains; air inflated double walled glazing and rockbed thermal storage on the heating requirements of a greenhouse. The results indicated that a gothic arch greenhouse requires the least heating energy i.e. 2.6 per cent and 4.2 per cent less as compared to gable and quonset greenhouses. Under north Indian cold climatic conditions, an east-west oriented greenhouse requires about 2 per cent less heating in comparison to a north-south oriented greenhouse. The proposition of north wall insulation is more effective in an east-west oriented greenhouse as compared to a north-south oriented gothic arch greenhouse, saving 30 per cent of heating energy. The use of night curtains in an east west oriented greenhouse can save 71 per cent of the night heating requirements and 61 per cent of the daily energy requirements. The use of air inflated double wall glazing on the south side of the greenhouse reduces the heating requirement by 23 per cent. In an east-west oriented gothic arch greenhouse with all above mentioned energy conservation measures with a rockbed of adequate size has no heating requirement.

Thus, the results suggested that an ideal design of a greenhouse for cold climatic conditions of India should have the following design features:

i) East-west orientation
ii) Gothic arch shape
iii) North wall insulation
iv) Use of a night curtain
v) Air inflated double wall glazing
An internal / external solar thermal storage system

An experimental solar greenhouse was constructed based on the above-mentioned criteria and tested under winter conditions of New Delhi. The results indicated that the designed greenhouse could maintain favorable thermal environment for crop growth as compared to the ambient and a quonset greenhouse. Night temperatures in the solar greenhouse were 13.2 °C and 9.1 °C higher than the ambient and the control greenhouse respectively. The heat storage factor and the heat recovery factor for the solar greenhouse were 12.9 per cent and 65.6 per cent. However, there is scope for improvement of the thermal performance of the solar greenhouse system.

The model was used to simulate the performance of the designed greenhouse under Leh conditions and the results indicated that the designed solar greenhouse could save the daily heating requirements by 78 per cent for a cold sunny day in Leh as compared to the traditional lean-to greenhouse. Comparison of the cost economics of a lean-to and the designed greenhouse under the environmental conditions of Leh indicates that the extra cost of installation of the designed greenhouse is paid back in 2 to 3 months.

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LIST OF SYMBOLS

Symbol	Description	Units
A	Area, m^2	
A_g	Greenhouse surface area,	m^2
Bi	Biot number, dimensionless	
C_p	Specific heat at constant pressure,	J/kg°K
De	Equivalent diameter,	m
Dk	Coefficient of condensation,	kg/m^2 s
ds	Differential surface area	
dv	Differential element volume	
dx	Differential length in x direction	
dy	Differential length in y direction	
F	Radiation shape factor	
HW	Enthalpy of water vapor at 0°C,	J/kg
HTC	Lumped heat transfer parameter, dimensionless	
HTC_m	Modified lumped heat transfer parameter, dimensionless	
h	Convection heat transfer coefficient,	W/m^2°K
h_v	Volumetric convection surface coefficient,	W/m^2°K
k	Thermal conductivity of a material,	W/m^2°K
L	Length,	m
M	Rate of moisture transfer,	kg/s
M_{bal}	Moisture balance of a greenhouse,	kg/hr
M	Air flow rate through rockbed,	kg/hr
N	Finite element shape function	
n	Number of surfaces in an enclosure	
P	Perimeter,	m
P	Total atmospheric pressure,	kPa
Pe	Peclet number, dimensionless	
Pw	Partial water vapor pressure,	kPa
Q	Coefficient in heat load vector	

Q'	Rate of internal heat generation,	W/m^2
Q_{bal}	Heat balance of a greenhouse,	J/hr
q	Heat flux,	W/m^2
Q_{net}	Daily solar radiation measured inside the greenhouse,	kWh/m^2
RH	Relative humidity, decimal fraction	
R_p	Plant resistance to water vapor diffusion per unit leaf area,	sm^{-1}/m^2
S	Coefficient in heat capacity matrix	
s	Surface area,	m^2
T	Temperature,	°C
TI	Temperature of greenhouse air,	°C
TO	Temperature of outside air,	°C
TP	Plant canopy temperature,	°C
t	Time,	s
U	Coefficient in effective global conductivity matrix	
U	Overall heat loss coefficient,	W/m^{2}°K
v	Volume,	m^3
VR	Ventilation rate,	m^3/s
W	Humidity ratio, kg/kg of dry air	
WI	Humidity ratio of the greenhouse air, kg/kg of dry air	
WO	Humidity ratio of the outside air, kg/kg dry air	
WP	Humidity ratio of saturated air at plant temperature kg/kg of dry air	
x	Spatial variable in x-direction	
y	Spatial variable in x-direction	
Greek		
α	Thermal radiation absorptivity	
Δ	Area of a triangular element,	m^2
Δt	Period of data recording,	hr

ε	Thermal radiation emissivity	
γ	Thermal radiation reflectivity	
χ	Variational functional	
η_s	Storage performance coefficient	
η_r	Heat recovery factor	
ρ	Mass density,	kg/m^3
σ	Stefen-Boltzmann constant,	$W/m^2\ °K$
τ	Thermal radiation transmissivity	
Subscript		
a	Air	
amb	Ambient	
b	Rockbed	
c	Conduction	
co	Condensation	
dp	Dewpoint	
db	Dry bulb	
f	Greenhouse floor	
g	Internal heat generation	
h	Heater	
h	Convection	
i	Index to represent a point in space	
in	Inside	
j	Index to represent a point in space	
k	Index to represent a point in space	
ou	Outside	
P	Plants	
V	Normal flux	
r	Radiation	
rok	Rockbed	
S	Heat capacity	
s	Structural cover surface	
sat	Saturation	

sky	Sky
T	Transpiration
x	x-coordinate
y	y-coordinate
-	Bar under a letter indicates the matrix denoted by the letter
∞	Ambient
*	Overall system matrix
·	Time derivative
T	Transpose of a matrix
e	Related to element
K	Absolute temperature

Introduction

Chapter 1

Introduction

Humankind developed agriculture for their survival against hunger. Crops were selected to suit different seasons under favourable climatic condition. However, harsh climates did not let crops survive in the open field. The need to protect the crops against unfavorable environmental conditions led to the development of protected cultivation practices. Greenhouse technology is the most practical way of achieving the goal of protected cultivation. A greenhouse is a framed or inflated structure covered with a transparent or translucent material in which crops could be grown under the conditions of atleast partially controlled environment and which is large enough to permit a person to work within it to carry out cultural operations. Glasshouses, rain shelters, shade houses, melon houses are all different names given to greenhouses depending upon the type of material used and the ability of the facility.

In India, although the situation with respect to the production of foodgrains has reached self-sufficiency, it is not so with regards to some other sectors including horticulture. Agricultural planners are emphasizing the use of advanced biotechnology for enhanced crop production. At the same time, there is an emphasis to improve the efficiency of agricultural inputs in the farming systems, which includes the search for improved and even alternate technologies for intensive agriculture within the socio-economic constraints of the nation. Every unit area of cultivable land must grow manifolds with cropping or land use intensities much higher than the present. This extreme and unutilized agro-climatic regions would have to be harvested as a part of this strategy. Greenhouse technology is highly relevant under Indian conditions keeping in view the extreme variations in the climate of the country and an uphill task of higher production to feed the burgeoning population.

Present Status of Greenhouse Technology in India

Commercial greenhouse technology in India at present is in its infancy. Although a few commercial greenhouse units in India existed even in the sixties, the impetus for greenhouse area expansion came in the mid eighties with the development of low cost greenhouse structures and the manufacture of U.V. stabilized LDPE. Components of six pipe framed low cost greenhouse of IARI design were fabricated in Delhi and were transported by road to Leh by IPCL for installation there. Today, Leh alone can boast of more than 14,000 small units of greenhouses. These greenhouses attached to houses or located nearby permit convenient access to the growing area during severe winters. The transparent cover during night is often supplemented with an insulated sheet from within the greenhouse to reduce heat losses. The low cost greenhouses in Leh have permitted the expansion of growing season from four months to more than eight months. Mostly, fresh vegetables are grown in these greenhouses.

Another important application for which greenhouses have been installed is nursery raising. Both low cost and medium cost greenhouses have been employed depending upon the requirements. Naturally ventilated greenhouses without any environmental control equipment are termed as low cost greenhouses. Whereas, those with some environmental control to permit round the year utilisation are termed as medium cost greenhouses. Low cost greenhouses have permitted vegetable farmers in northern plains to prepare seedlings for early transplantation during spring season to capture early markets and, thereby, obtain higher prices. Medium cost greenhouses have been used to raise healthy seedlings with higher germination percentage from expensive seeds of flowers and vegetables. These greenhouses are also being used extensively for vegetative propagation of chrysanthemum, carnation, grapes, roses, etc. Strawberry cultivation in low and medium cost greenhouses is gaining popularity.

Greenhouse frames of steel, wood and bamboo have been developed for use in different places. Evaporative cooling systems have been developed for greenhouse temperature control during summers. Exhaust fans of upto 135 cm diameter have been used for moving air out of the greenhouse. However, fans of bigger capacities for greenhouse use are not widely manufactured at present in India. While wood wool cooling pads can be assembled locally, the cellulose cooling pads are largely imported. Some efforts have recently been made to manufacture cellulose pads indigenously. Thermostats for controlling the fans and pumps are indigenously available. High quality fogging systems are not yet manufactured in the country.

Greenhouse heating system poses a challenge, mainly, due to the relative non-availability of conventional fuels in the country. No serious effort has gone into developing light control, CO_2 enrichment, and other environmental control systems for commercial greenhouses in India yet.

Ultra violet stabilized polyethylene film for glazing is manufactured in India. Besides, some PVC based films and FRP sheets are locally available. Twin-wall polycarbonate sheets for greenhouse glazing are also being manufactured. Micro irrigation systems are available for irrigation of greenhouse crops. Some of the plant protection devices available for open field crops could also be used effectively in greenhouses. Both bench and floor operations are prevalent.

Future Potential

A lot of efforts have to be made by all concerned to bring the technology level up to date. Globalization and economic liberalization promise faster developments.

Energy efficient and environmentally safe greenhouse systems and practices must be evolved. Greenhouse structures with locally available materials must be developed with emphasis on the energy conservation principals. Adequate environmental controls based on natural processes need to be evolved for sustainability. Use of renewable energy resources for meeting greenhouse energy needs is appropriate. Even more important is the determination of precise requirements of the plants for best productivity coupled with energy conservation.

Low-grade heat rejected from thermal power plant, geothermal energy, and energy from solar thermal storage systems has been used successfully for greenhouse environmental control elsewhere in the world. Special glazing materials with appropriate strength, cost, radiation properties and thermal properties are being sought.

Environmental considerations will demand that the greenhouse technology of tomorrow is a closed system with complete recycling of everything other than the intended produce. Plant protection will rely more on biological route. Future may belong to technological cascading with greenhouses of different levels coexisting with some degree of interdependence. Gadgets to help greenhouse workers in their cropping operations will be developed. Intelligent knowledge based control systems will come to exist in near future. An interactive relationship between control system and the plant will become imperative to maximise the profit.

Keeping in view the scope of greenhouse technology in Indian agriculture, adequate research efforts are needed to adopt the promising technology in the various agro-climatic regions of India. Greenhouse environment control, especially temperature and humidity control could be most energy-intensive operation in certain situations. While there is minimum requirement of active temperature control requiring the need of heating/ cooling equipment in places like Bangalore and Pune, the requirement is substantial when greenhouse cultivation is practiced in either extremely cold climatic conditions of northern region or extremely hot climate of western India. The cost of temperature control in these extreme climatic conditions could form almost half of the total operating cost.

The cold climatic regions of India are being targeted for popularising greenhouse technology because the greenhouse would permit the extension of the growing season in those areas. For example, the crop growing season in the northern hilly regions of India is limited to 4-8 months because of low temperature during the rest of the year. The use of greenhouses could permit more favourable microclimate for crop growth when the open field conditions are not suitable. More agricultural activity in the hills means better economic condition of the people of the hilly regions and hence, their reduced migration to the plains. The Kargil war has shown the need for greater presence of army personnel in these extreme climatic conditions. A better food production there would reduce army outlay on supply of food to them.

Greenhouses suitable for cold climatic regions should not only be energy efficient but also enable the use of renewable energy resources to meet the environmental control requirements as the availability of fossil fuels in the hills is severely constrained. Higher operating costs have constrained the popularization of greenhouses in these conditions. Hence, there is a need to study the greenhouse cultivation in cold climatic condition of India from the point of view of energy requirement for environmental control and to design an energy efficient solar greenhouse for these conditions. The specific objectives of the present study are:

1. To develop a generalised computer model of greenhouse thermal energy exchanges for the design of solar greenhouses.
2. To design an optimum low-cost solar greenhouse for the cold climatic regions of India using the computer model.
3. To study the adequacy of the designed solar greenhouse by using it for growing vegetable crops and monitoring energy expenses.
4. To study the economic feasibility of the proposed solar greenhouse system.

Chapter II

Review of Literature

The basic criterion for designing a greenhouse has been that the structure should admit the maximum possible amount of sunshine during the months of lowest light. The structural system must have minimum opaque area and maximum transparent area, yet be strong enough to support itself and predicted wind and snow loads. The structure must be made of a transparent material such as glass or plastic to transmit the necessary light for plant growth (Aldrich and White, 1973).

Unfortunately, these materials have poor thermal resistance characteristics. As a result, a great deal of heat is required to maintain the necessary temperature inside the structure in most cold climatic conditions. Excessive heating costs render the whole greenhouse operation uneconomical during the most severe part of the winter, as fossil fuels are scarce and expensive. Hence, it is very important to research ways to reduce the energy intensiveness of greenhouse cultivation.

2.1 Techniques of energy conservation in Greenhouse

Various techniques to reduce heat losses from greenhouses in order to make them energy efficient have been developed all over the world.

2.1.1 Orientation

Brun *et al.* (1974) have studied the effect of greenhouse orientations on the growth of tomato and capsicum in a large scale trial in the Mediterranean zone in an area receiving intense solar energy early in

Review of Literature

the season. They found that the north-south orientation contributed to the homogenity of microclimatic conditions in the greenhouse. East-west orientation, on the other hand, was not favourable for early growth. Yield and income were greater from plants grown in north-south oriented greenhouses. This orientation also allowed better utilization of the soil and also helped to support the greenhouse against the prevailing northwest winds.

It had been observed by Chandra (1976) that an east-west oriented free standing gothic arch shaped greenhouse required about 20 per cent less heating as compared to a greenhouse of the same size oriented north-south at the latitudes of 49.25^{o} N.

Harnett *et al.* (1979) compared various greenhouse types and orientations and concluded that there was a consistent advantage in terms of light transmission and crop yield from orienting a multi span structure east west as compared to north south.

For a greenhouse with length to width ratio of more than one, the orientation of the greenhouse can affect the amount of solar energy available in this enclosed space (Chandra *et al.*, 1982). Except at the equator, more solar energy is usually incident on a surface facing south in Northern Hemisphere. Therefore, more solar heat could be admitted to a greenhouse by providing more area facing south. This can be accomplished by orienting the long axis of the greenhouse in east-west direction. While constructing a series of greenhouse at one place, the spacing between the greenhouses should be adjusted for minimum mutual shading.

Facchini *et al.* (1983) conducted experiment on solar greenhouses with low energy consumption and concluded that in north Italy greenhouses should have the longest side facing south.

Kurata (1993) studied the effect of greenhouse orientation, number of spans, time of year and latitude on the direct solar radiation transmissivity into greenhouses using a mathematical model and found that at low latitudes, the effects of the above factors are less significant than at high latitudes. However, spatial irregularities of irradiance with east-west oriented greenhouses could be a problem at all latitudes.

2.1.2 Greenhouse Shape

Facchini *et al.* (1983) conducted experiments on solar (heated) greenhouses with low energy consumption and concluded that greenhouse shape is an important factor in maximizing the use of solar energy.

Zamir *et al.* (1984) measured the temperatures, RH, wind direction and velocities, and quantities of heat supplied to greenhouses during winter. They observed that when there is no wind and RH is 100 per cent, 5.6 Kcal/h/m^2 of cover is needed for every 1^{o}C difference to overcome the heat losses from the greenhouse. This value rises as RH decreases and wind speed decreases. Hence, they concluded that a greenhouse that followed the shape of the surrounding area, such as a sloping greenhouse could save upto 15 per cent of heat requirements as compared to regular multispan structures under the same climatic condition.

Kurata *et al.* (1991) studied direct light transmissivities during cold seasons using numerical calculations. Results showed that optimal tunnels had non-symmetric cross-sections with steep south surfaces and direct light transmissivities in cold seasons could be improved by approximately 10 per cent over semi-circular cross-sections. Further in 1995, Kurata and Kamo recalculated the optimum shape of parallel east west oriented single span tunnels with respect to direct solar radiation transmissivity in cold season for middle latitude countries. The calculated optimum tunnel shape gave about 3 per cent higher transmissivity than that previously found and 12 per cent higher transmissivity than conventional semi-circular tunnels.

Malquori *et al.* (1993) evaluated various cross-sectional shapes for incoming solar radiation in greenhouses. Results showed that asymmetrical roof with a shallow pitch performed better than standard roofs.

2.1.3 North wall insulation

Chandra (1976) observed that the transparent north side in an east-west oriented greenhouse contributed very little to greenhouse solar gain during winters (almost 3 per cent in December).

Hartz *et al.* (1981) compared the performance of a prototype greenhouse (5.5 X 9.0 m) with a reflective wall (Plywood painted with a highly reflective white coating capable of reflecting 93 per cent of incident radiation) with a conventional greenhouse. The prototype required 14 per cent less energy for heating between October and March.

Tiwari and Dhiman (1985) developed a mathematical model for a greenhouse thermal environment and found that the system performance was improved when the north wall was opaque.

Nilsson (1986) carried out light and energy measurements in ⅓ scale greenhouses. Light measurements showed that for asymmetric greenhouses, a non-transparent, high reflecting north wall was more profitable than a transparent wall, whereas there was no difference for symmetric greenhouses.

Li *et al.* (1995) investigated the characteristics of solar radiation transmissivity with an east-west oriented lean-to greenhouse, widely in use in China. Experimental observations showed that a large amount of solar radiation was incident on the inside of the north wall in winter and could be used to improve the radiative environment on the floor by reflection.

2.1.4 Double Wall Glazing

Landgren (1985) studied the greenhouse climate related to various glasses and plastic covers for greenhouse. A heat saving of 35-40 per cent for double cladded house was observed.

Mielsch (1986) studied various energy saving techniques and products and summarized that 38 per cent energy saving could be achieved with a double-glazing.

Christensen (1986) studied the energy consumption in various types of greenhouses and concluded that energy consumption per plant in houses with double glazing was 25 per cent lower than in a single glazed greenhouse with thermal screens.

Gonzales and Hanan (1988) studied the natural gas consumption of greenhouses of double-layer air inflated polyvinyl fluoride and a single layer fibre reinforced plastic. They found that under standard conditions at night a double rather than single cover reduced gas consumption by 40 per cent.

Kang *et al.* (1991) conducted experiments to determine appropriate wall and insulation materials for optimum heat conservation in a solar greenhouse by monitoring temperatures of different layers of the wall. Results indicated that perlite was the best insulator followed by coal cinder, saw dust and air.

2.1.5 Thermal Screens

Night curtains or thermal screens are drawn below or over the greenhouse cover during night time to reduce the thermal radiation loss to the night sky. Various researchers have worked on the effect of thermal screens on energy efficiency of greenhouses and the development of appropriate materials suitable for use as thermal screens. A few efforts are listed below:

Coulon and Wacquant (1984) conducted experiments on the greenhouse climate with a permeable thermal screen (isotex 60) and in a greenhouse with an aluminized thermal screen. The total consumption of fuel oil was 16.72 litres/m^2 and 12.64 litres/m^2, respectively, as compared with 22.14 litres/m^2 for the control greenhouse with no thermal screen.

Fuller *et al.* (1984) reported a saving of 30 per cent in energy in a greenhouse fitted with a commercially available moulded polyester screen into which aluminum had been crushed.

Meyer (1984) compared the energy savings of 12 screen materials in a single glazed greenhouse with reference to an unscreened house. The greatest savings of (more than 50 per cent at night) were obtained using a double layer of the non-woven polyester material, floratex 80, aluminum backed air cap (bubble film) and a double layer of black polyester film.

Jolliet *et al.* (1985) has reported 35 per cent and 47 per cent reductions in the nighttime thermal transmittance through the roof by the use of ethylene thermal screen and chrome coated one respectively, and 52 per cent reduction if used simultaneously. He has predicted that the resulting 0.4 K temperature rise of plants below screen may lead to a variation of more than 50 per cent in energy requirement.

Arinze *et al.* (1986) experimentally evaluated greenhouse thermal screen system where heavily insulated and relatively thick screens operate between the glazings of a double glazed greenhouse to avoid exposure to weather. Results indicated that the thermal screen heating requirements could be reduced by as much as 60 to 80 per cent.

Newell (1986) reviewed the performance of new plastics and fabrics that could be used as greenhouse covers. They were opaque to IR radiation and resulted in energy savings in the range of 20 to 40 per cent. New materials for thermal screens (from Ludwig Svensson International) gave energy reduction from 45 to 75 per cent.

Short *et al.* (1990) have reported based on experimental results that the night time heat loss from a double acrylic greenhouse could be reduced by 60-70 per cent with a polystyrene pellet shading system.

Abak *et al.* (1994) reported that the minimum night temperatures inside (1) a double skinned greenhouse, (2) a double skinned greenhouse with a aluminized polyester (LS-17) screening and (3) a single skinned greenhouse with PE screening were 2.5, 3.4 and 3.4 ^{0}C higher, respectively, than that in an unscreened single skinned control greenhouse.

Pirard *et al.* (1994) tested five types of thermal screens and compared them to a control greenhouse with no screen. Results showed that there was no difference in performance of the screens but just drawing any screen during the night resulted into energy saving of at least 20 per cent. They reported that it was preferable to delay the opening of the screen after sunrise and to close it earlier at sunset.

2.2 Solar Greenhouses

Many techniques to reduce heat losses in a greenhouse have been reviewed in the above section. Researchers have adopted some or all of the above techniques to make their greenhouses energy efficient. In addition, efforts to replace direct heating of greenhouses by inexpensive alternatives, especially the abundantly available winter solar radiation, have also been carried out. Thus, the concept of solar greenhouses has essentially been developed. A review of some solar greenhouse experiments is presented below:

Brundrett and Brundrett (1984) designed and constructed an energy efficient solar greenhouse with three quarter span, a 45 degree slope for the south facing glazing, a 26 degree slope for the north glazing and vertical east and west sides. Winter heating was augmented by 70 tonnes of gravel stored below the growing benches. Circulating hot air that collected at the peak of the greenhouse on sunny days, using a simple direct system and thermostatically controlled fans warmed the gravel. At night, air was forced through the gravel beds and warmed gravel beds and warmed by the natural chimney effect of the gravel. Heating costs were reduced by installing thermal curtain under south and north glazing. In addition, 6 mm double walled polycarbonate glazing was used on the south and north slopes and two layers on the east and west sides. Experiment confirmed that the greenhouse operates at one fifth of the fuel costs of a single glass greenhouse.

Adam and West (1989) designed, constructed and tested the Talura solar greenhouse which had a cladding of 6 mm double skin poly carbonate, a vertical flow rockpile and a roof mounted solar air heater for night heating of the greenhouse. A thermal screen made of 6 mm strips of alternating aluminum foil and clear polyethylene was drawn in two layers across the ceiling and in one layer on the walls to reduce heat losses from the greenhouse. Thus, supplementary heating using electric radiators or fuel-fired boilers was reduced. However, detailed performance data regarding supplementary heating has not been reported.

Brendenbeck (1989) carried out experiments on two simple plastic film heat exchange systems for solar heating of greenhouses. It was observed that the system employing external solar collectors and vertical plastics film heat exchangers supplied 73 per cent of the annual heat load, while the system employing internal plastic film heat exchangers inside the greenhouse contributed 44 per cent of the annual heat load.

Connellan (1989) studied the performance aspects of an open floor solar water heated greenhouse under Australian conditions and found that an open floor was able to provide adequate heating (50 per cent of heating load) during autumn and spring periods, however the performance of the collector was very dependent on the temperature of the storage water.

Kozai (1989) analysed the thermal performance of a solar greenhouse with an underground heat storage system widely used commercially in the region along the pacific coasts of Central and Western Japan. The experimental greenhouse was oriented north-south, fitted with withdrawable double layer thermal screens under the roof. Vertical fixed double layer thermal screens were fitted inside the side walls; a vertical fixed single layer thermal screen and a vertical withdrawable double layer thermal screen insulated the gable ends. Eight electric fans circulated air for heat exchange between greenhouse air and soil through PVC pipes buried underground at depth of 0.5 m and 0.9 m. The average oil reduction factor was about 27 per cent.

McCarney (1989) reported work on planted earth commercial solar greenhouse at Colarado. To operate greenhouse successfully it had an integrated design and business approach. Heat loss was minimized by making the greenhouse airtight using continuous double inflated polyethylene glazing and closed ventilation (minimum outside air). External surfaces were well insulated (R30, R20 and R10). A shed roof, which resulted in reduced net glazing area when compared to conventional greenhouses and infrared radiation inhibitors to reduce radiant loss, was incorporated into the glazing. Solar heat was actively collected, stored, controlled and distributed in two rockbeds and four subsurface soil beds. The projected energy cost was $\$0.25/ft^2/yr$ as compared to $\$1.25\ /ft^2/yr$ of conventional local greenhouses. The payback period was estimated to be three to four years.

Sorensen (1989) conducted experiments with energy storage in a high latitude greenhouse. The greenhouse was furnished with a 0.8 m^3 water store and solar absorber in the form of four black-painted oil drums. The system was able to prolong the growing season by lifting the greenhouse temperature by about 5^0C and extreme diurnal temperature variations were damped. At temperatures below 0 ^{0}C, the water store behaved as a phase change storage system for a period of several months.

Amor *et al.* (1990) conducted experiments on passive solar heating using water extracted from a deep well and circulating through black radiant mulch or small EVA plastic tubes of 320 mm diameter. Results showed a gain of 5 to 9^0 C in the minimum temperature.

Grafiadellis (1990) has reviewed the use of solar energy for heating greenhouse and has summarised based on experiments and experience of greenhouse growers that it can cover a percentage of fuel ranging from 20-80 per cent and is useful for frost control in greenhouses.

Kauranen (1991) studied the use of an organic PCM storage system with adjustable temperature for passive solar heating of greenhouses by impregnating the material in greenhouse wall. Based on hourly energy balance simulations, he has shown that the PCM will add to both energy savings and thermal comfort in framed solar greenhouse.

De-laCruz *et al.* (1992) have evaluated the degree of self-sufficiency of the 'INSOLE' buried solar greenhouse and found that due to thermal inertia of the wall and floor the greenhouse has good for growing sub-tropical plants under Spain's climatic conditions.

Santamouris *et al.* (1994) designed, constructed and operated a prototype 1000 m^2 passive solar agricultural greenhouse which had a 30 cm thick thermal mass wall on the north side made of cement blocks and filled with concrete, external side of the wall was insulated using 5 m of polyurethane insulation. While internal side was painted black. Due to thermal inertia, the wall discharged the collected energy during night by radiative and convective processes, thus reducing the required backup heating load. Monitoring the greenhouse for two year period showed that the system reduce energy requirement by 35 per cent of the heating requirement of an identical conventional greenhouse.

Seki and Komari (1995) have studied the possibility of using the heat generated in the composting as an alternative energy source for heating greenhouses and have found that under poor thermal insulation conditions of the experiment 16-22 per cent of the whole heat generated could be recovered.

Bouhdjar *et al.* (1996) studied the performance of sensible heat storage in a rockbed used in a tunnel greenhouse under Algerian climatic conditions. They found that heat provided by the storage, expressed through an elevation of temperature upto 7 ^{0}C above the out door temperature, was enough to protect plants from damaging low temperatures which occurred during the cold season.

Oiang *et al.* (1999) conducted studies on energy conservation of Huaboi type multispan plastic greenhouses which had a double walled insulation with a plastic film roof, thermal screens, earth pipe heat exchanging system and energy storage gable. The temperature in the greenhouse was more than 8 ^{0}C in winter and the temperature difference between outside and inside was more than 11 ^{0}C.

Lau and Staley (1987) have summarised various greenhouses solar heating systems as given in table no 2.1., and providing a comparison of the various options.

Table 2.1: Greenhouse solar heating system

Greenhouse	Cover	Collection	Storage	Solar fraction*	Authors
Brace-style	Double polyethylene	Internal (Q-mats with water)	-	10%	Albright *et al.,* (1979)
Hemispheric	Polyethylene	-	-	93% (estimated)	Begin *et al.,* (1984)
Quonset	Corrugated fibreglass/ plastic	External air solar collector with reflective wings	Soil	4%	Dale *et al.,* (1980)
Shed-type	Corrugated fibreglass/ Tedlar	External (flat plate air collector)	Soil	43%	Dale *et al.,* (1984)
Quonset	Double polyethylene	Solar pond (brine solution)	Solar pond	62%	Fynn *et al.,* (1980)
Semi-cylindrical	Double acrylic	Internal (solar air heater and fan)	Rock	84%	Garzoli and Shell (1984)
Quonset	Double polyethylene	External (plastic film solar collector)	Rock and water	5%	Ingratta and Blom (1981)
Gutter-connected	Glass	Internal (fan)	$CaCl_2.10H_2O$	60%	Jaffrin and Cadier (1982)
Brace-style	Double polyethylene	-	-	35%	Lawand *et al.,* (1975)
Quonset	Double polyethylene	External (plastic film solar collector)	Gravel and water	53%	Mears *et al.,* (1980)
Venlo-type	Glass	Internal (fan)	$Na_2SO_4.10H_2O$ with additives	100%	Nishina and Takakura (1984)
Shed-type	Glass	Internal (solar air heater and fan)	Rock	35%	Staley and Monk (1984)
Conventional	Glass	Internal (fan)	Soil	25%	Staley and Monk (1984)
Quonset	Fibreglass	Internal (fan)	Rock	33%	Willits *et al.,* (1980)

*Measured over a period (month, season or annual).

2.3 Greenhouse models for Energy Conservation

As evident from literature reviewed in the earlier section a number of possibilities exist to make greenhouse energy efficient. In order to design a greenhouse suitable for the cold climatic conditions of India, there is a necessity to synthesize the available information on greenhouse thermal behavior, energy conservation practices and solar energy use techniques in the form of a model. This model could, in turn, be used to arrive at optimum solution for a given set of operating conditions.

Earlier efforts for model development of greenhouse thermal environment were mainly to determine heater and fan sizes (Walker, 1965; Morris, 1956; McCune and Stipe). They were generally simple steady state heat balances, often neglecting components of the thermal environment, which supposedly contributed little error.

Another category of models concentrated on studying the effect of variations like structure, location, orientation, heating and cooling alternatives etc. (Chandra, 1976; Chandra and Albright, 1978; Simpkins *et al.,* 1975). These were also steady state models.

Steady state models, though adequate for above applications, are not accurate in their predictions, as they do not account for heat storage. Hence came the need for time-dependent predictions and, consequently, time dependent or periodic models, which are useful for environmental control of greenhouses and simulation of plant growth. Several authors (Takakura *et al.,* 1971; Selcuk, 1970; Seginar and Levav, 1971; Froehlich, 1976; Kimball, 1973; Soribe and Curry, 1973; Chandra, 1979; Sutar and Tiwari 1995 and Tiwari *et al.,* 1997).

Models to analyze various options of energy conservation and thermal storage have been developed to reduce the expenditure on cost prohibitive experimental evaluation of system performance at specific locations and to extend the analysis to any location or climatic condition. These models have also been used to evaluate long-term system behavior.

Lau and Staley (1987) developed a design procedure for greenhouse space heating and a simulation model that described the greenhouse thermal environment and thermal storage. The model was then used for evaluating long-term system performance using monthly average meteorological data as input.

Garzoli (1989) developed mathematical expressions that described heat transfer processes for greenhouse heat gain and used it as a basis for calculating the collector efficiency for a range of conditions.

Boulard *et al.,* (1990) developed a soil storage system model for dynamic simulation of heat and water transfers in the storage. The model operated in two steps. In the first step, heat and water balances at the pipe wall surfaces were solved for deduction of the pipe wall temperature and different heat and water fluxes. In the second step, the pipe wall temperature was considered as boundary condition for the heat transfers in the soil and three-dimensional heat conduction was modeled by a scheme. The model was experimentally validated using two types of greenhouse with solar energy storage. The experimental measurement and simulation result showed good agreement and the simulation helped the authors to understand the thermal performance of the soil storage system and PCM heat storage system under Mediterranean climate.

Kurata and Takakura (1991) investigated the possibility of seasonal storage of solar energy in the soil under a greenhouse and compared it with that of a daily storage. A numerical model of the system was developed. Predictions showed that electric energy consumed for operation of the seasonal storage system was greater than the energy saved in greenhouse heating (6.54 MJm^{-2}), resulted in a negative net energy saving, while the energy saving in a daily storage was positive (6.52 MJm^{-2}).

Xie *et al.*, (1991) developed a dynamic mathematical model based on heat and humidity balances to predict the environmental variables in a greenhouse with subsoil heat storage. Regression equations describing interactions between moisture and thermal performance parameter were derived to evaluate the effects of soil moisture on its thermal performance. The greenhouse floor and soil beneath were divided into a series of layers and the soil moisture was assumed to be homogenous for each layer. Thus the soil variables in one layer could be considered to be constant for temperature and heat flow through the floor cover. A comparison of the measured variables in the greenhouse with model predictions showed a high degree of correlation. The dynamic model was also used by the author to simulate the thermal performance of the greenhouse as affected by greenhouse structural parameters and environmental factors. The results for thermal performance of 3 types of heat storage pipe material (common brick, hollow brick and earthenware pipe) showed that hollow bricks had the highest efficiency of heat storage.

Levit *et al.,* (1994) simulated the performance of greenhouse heated by means of horizontally laid underground pipe heat exchanger. The system exploits the inertia of the soil when the temperature is constant at a certain depth. The model was developed by joining together 2 systems, the first consisting of a one-dimensional dynamic model of the greenhouse with a thermal screen, and the second of a two-dimensional model of the pipe. The simulation and experimental results were compared and the results demonstrated the energy conservation and good thermal performance of the system.

Nava *et al.,* (1998) developed a dynamic greenhouse climate model with 5 system components (growing medium, soil, crop, cover and inside air) by formulating the balance equation of energy and mass of each component. A set of differential equations, thus obtained, was numerically solved by means of computer program. The program asked the user for the physical variables (temperatures of growing medium and soil, temperature of the crop and cover, temperature and humidity of the inside air) to predict the climate of a specific greenhouse. The predicted dynamics of all the simulated variables was correct.

The experiences of these researchers positively supports the need for energy conservation practices in the greenhouses that the study aims to design for cold climatic conditions of India. However, what set of options would best suit the location will have to be studied by a simulation model initially to reduce the expenses on costly and time consuming experimental study. The proposed design features for the greenhouse will then need field-testing.

Greenhouse Thermal Environment Model

Chapter III

Greenhouse Thermal Environment Model

In the previous chapter, a number of possibilities have been found to exist in order to make greenhouse energy efficient. However, it is not possible at present to assert if a certain combination of options would be better than other combinations in a given set of situations. Hence, there is a need for a mathematical model to synthesize the available information on greenhouse thermal behavior, energy conservation practices and renewable energy resources. The model could be used to arrive at an optimum solution for a given set of operating conditions.

In this chapter, the formulation of a suitable greenhouse thermal environment model will be discussed to predict the energy balance of the greenhouse air and hence subsequently its temperature and humidity conditions given the required ambient, initial and boundary conditions. The finite element method will be applied to predict the various surface temperatures that appear in the heat and moisture balance of greenhouse air. Several assumptions were required for the analysis.

General Assumptions

1. The greenhouse air is well mixed at all times so that no temperature or moisture gradients exist in the air.
2. The temperature and relative humidity of the greenhouse air are specified at all times; the objective is to determine the heat and moisture fluxes.
3. The greenhouse floor does not participate in water vapor diffusion; that is, condensation and evaporation on the floor are negligible.

4. Thermal properties of the materials of construction, and convective heat transfer coefficients do not change with time.
5. Greenhouse cover surfaces are thin enough so that heat transfer through them is essentially one-dimensional.

The major component of greenhouse thermal environment, are schematically represented in Fig no. 3.1

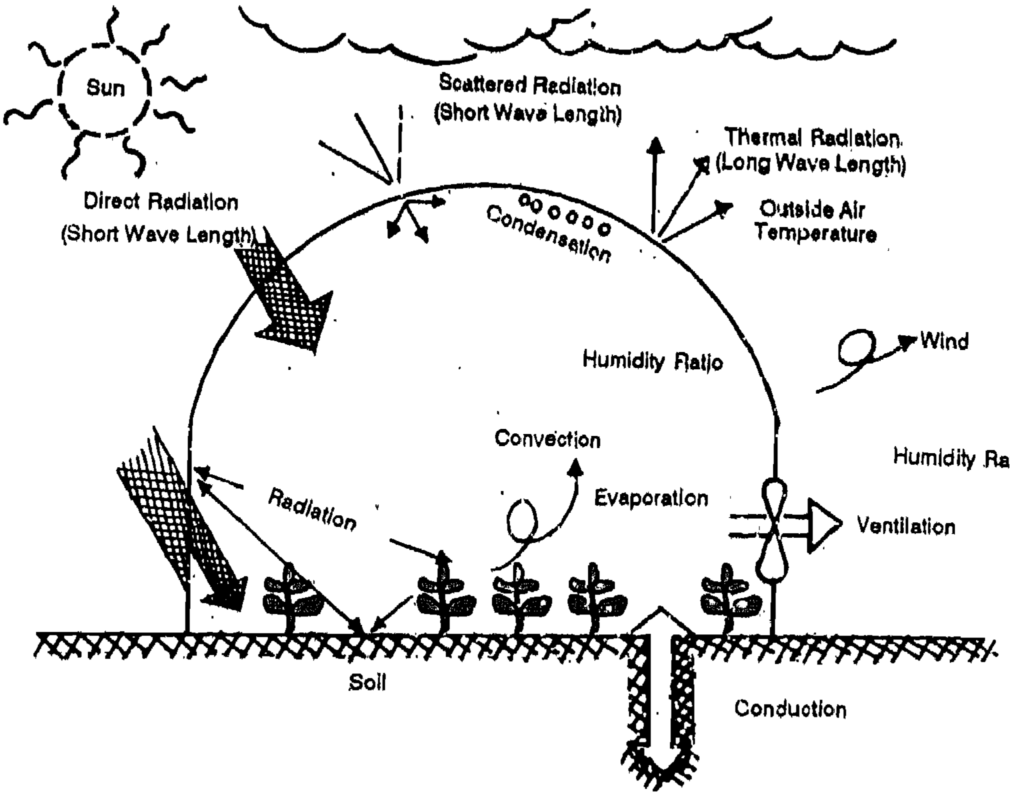

Fig.no. 3.1. Schematic of Greenhouse thermal environment

Heat Balance of the Greenhouse Air:

The air exchanges heat with the solid structure, plants, and floor surfaces by convection. In addition, infiltration-exfiltration and ventilation influence the energy budget of the greenhouse air at any instant of time, the heat balance of the greenhouse air is given as:

$$Q_{bal}(t) = \sum_{s} A_s h_s (TI(t) - T_s(t)) + 2A_p h_p (TI(t) - T_p(t)) + A_f h_f (TI(t) - T_f(t)) \\ + \rho_a C_{pa} VR(t)(TI(t) - TO(t)) \qquad (3.1)$$

Symbols are defined in the list of symbols. The first term on the R.H.S.

of the equation represents the heat exchange with the structural cover. The summation sign indicates that there may be more than one type of surface in the structural cover. The second term is convective heat exchange with the crop canopy within the greenhouse. Since, convection is from both sides of a leaf, a factor of 2 appears in that term. The third term is heat exchange with the greenhouse floor and the fourth term is the contribution from infiltration-exfiltration and ventilation. Both infiltration-exfiltration and ventilation are included in VR.

The quantity expressed by Q_{bal} is the net heating or cooling requirement for the greenhouse in order to maintain its air temperature at the desired level.

In case of using night curtain, the above equation has an extra term for convective heat exchange with the night curtain $A_{c_2}h_{c_2}(TI(t) - T_{c_2}(t))$ on the RHS

When the above greenhouse has a rockbed attached to it the heat balance equation is further modified by incorporating $q_{rok}(t)$. The modified equation is as follows:

$$\begin{aligned} Q_{bal}(t) = {} & \sum_s A_s h_s (TI(t) - T_s(t)) + 2A_p h_p (TI(t) - T_p(t)) + A_f h_f (TI(t) - T_f(t)) \\ & + A_{c_1} h_{c_1} (TI(t) - T_{c_1}(t)) + A_{c_2} h_{c_2} (TI(t) - T_{c_2}(t)) + \rho_a C_{pa} VR(t)(TI(t) - TO(t)) \\ & - q_h(t) + q_{rok}(t) \end{aligned} \tag{3.2}$$

These equations can be solved to determine the steady-state heat balance of the greenhouse air at a time t when the terms on the R.H.S. of the equations are known at that time as follows:

$$\begin{aligned}\rho_a C_{pa} V \frac{\partial T}{\Delta t} = & \sum_s A_s h_s (T_s(t) - TI(t)) + 2A_p h_p (T_p - TI(t)) + A_f h_f (T_f(t) - TI(t)) \\ & + \rho_a C_{pa} VR(t)TO(t) + A_{c_1} h_{c_1} (T_{c_1}(t) - TI(t)) + A_{c_2} h_{c_2} (T_{c_2}(t) - TI(t)) \\ & + q_h(t) - q_{rok}(t)\end{aligned} \tag{3.3}$$

The above differential equation can be solved for TI at a time t if the surface temperatures and heat fluxes on the right hand side of the equation are known at that time. This analysis along with the other known conditions at time t is used to predict the greenhouse air temperature by employing finite difference approximation for the time derivative in equation 3.3. The following result is obtained:

$$\begin{aligned}TI(t) = & \left(\frac{V\rho_a C_{pa}}{\Delta t} TI(t-1) + \sum_s A_s h_s T_s(t) + A_f h_f T_f(t) + A_{c_1} h_{c_1} T_{c_1}(t) + A_{c_2} h_{c_2} T_{c_2}(t) \right. \\ & \left. + \rho_a C_{pa} VR(t)TO(t) + q_h(t) - q_{rok}(t) \right) \Big/ \left(\frac{V\rho_a C_{pa}}{\Delta t} + \sum_s A_s h_s + 2A_p h_p \right. \\ & \left. + A_{c_1} h_{c_1} + A_{c_2} h_{c_2} + \rho_a C_{pa} VR(t) \right)\end{aligned} \tag{3.4}$$

Temperatures of the structural cover, plants, and floor surfaces are unknowns in the above equation. Beside the thermal properties of the materials, which constitute these surfaces, their temperatures at any instant of time are also influenced by the environmental factors at those surfaces shown in Fig.no.3.1.

Moisture Balance of the Greenhouse Air

The amount of moisture to be added or to be removed from the greenhouse air to maintain its desired relative humidity is calculated as follows:

$$M_{bal}(t) = \rho_a VR(t)(WO(t) - WI(t)) + M_T(t)_s - \sum_s M_{co}(t)_s - \sum_{co} M_{co}(t)_{co} \tag{3.5}$$

A positive value for M_{bal} indicates that excess moisture exists in the air, and moisture must be removed to maintain the proper humidity condition. The second and the third and fourth terms represent the moisture fluxes due to transpiration from the plant canopy, condensation on the structural cover surfaces and thermal curtain surfaces, respectively. These fluxes depend on the temperature of the respective surfaces, which must be determined.

To determine the relative humidity of the greenhouse air the above equation has to be restructured as follows:

$$\rho_a V \frac{\partial WI}{\partial t} = \rho_a VR(t)(WO(t) - WI(t)) + \frac{2\,A_p \rho_p}{R_p}(W_p(t) - WI(t)) + \sum_{co} A_{co} D_k (W_{co}(t) - WI(t)) - M_{bal}(t) \tag{3.6}$$

The relative humidity was solved using finite difference approximation for the time derivative term and the following result was obtained.

$$WI(t) = \frac{\left\{ \frac{\rho_a V}{\Delta t} WI(t-1) + \rho_a VR(t)WO(t) + \frac{2\,A_p \rho_p}{R_p} W_p(t) + \sum_{co} \left(A_{co} D_k W_{co}\right)_t - M_{bal}(t) \right\}}{\left\{ \frac{\rho_a V}{\Delta t} + r_a VR(t) + \frac{2\,A_p \rho_p}{R_p} + \sum_{co} \left(A_{co} D_k\right)_t \right\}} \tag{3.7}$$

Once the humidity ratio of the greenhouse air is calculated using the above relationship, the partial vapor pressure is given as:

$$P_h = \left(\frac{WIP_{atm}}{WI + 0.622} \right) \tag{3.8}$$

Saturation vapor pressure, P_s for the greenhouse air is calculated using psychometric equations (Wilhelm, 1975). Finally, the relative humidity of the greenhouse air is given as:

$$\mathrm{RHI} = P_h / P_{sat} \tag{3.9}$$

Consideration of heat transfer for the rockbed is necessary to specify its interaction with the greenhouse thermal environment.

Heat Transfer in the Rockbed

Though Schumann's model (Schumann, 1929) is widely used to describe the heat transfer process in a rockbed with forced air, the rockbed thermal storage model of Hughes *et al.* (1976) was chosen in the present study to analyse the sensible heat exchange because the model included the use of more readily available volumetric heat transfer coefficient, consideration of the effect of internal rock temperature gradients, axial conduction and dispersion within the bed, and heat loss to the environment. The basic equations of the model are:

$$\frac{\partial T_{a_b}}{\partial X} = \frac{\mathrm{NTCm}}{L}(T_b - T_{a_b}) + \frac{U_b P_b}{\rho_{a_b} C_{a_b} \overline{V}_{a_b} A_b (To_b - T_{a_b})} \tag{3.10}$$

$$\text{and} \quad \frac{\partial T_b}{\partial t} = \frac{\mathrm{NTCm}}{T}(T_{a_b} - T_b) \tag{3.11}$$

where,

$$\frac{1}{\mathrm{HTCm}} = \frac{D_e}{L_b(P_e)} + \frac{(1 + B_i/5)}{\mathrm{HTC}} \tag{3.12}$$

$$\mathrm{HTC} = \frac{h_v L_b}{\rho_a V C_{p_a}} \tag{3.13}$$

$$\mathrm{Pe} = \frac{\rho_a \overline{V} D_e C_{p_a}}{K_a} \tag{3.14}$$

$$T = \frac{\rho_b C_{p_b} (1-\in) L_b}{\rho_a C_{p_a} \overline{V}} \tag{3.15}$$

$$\text{and } B_i = \frac{h_v De^2}{12(1-\in) K_b} \tag{3.16}$$

Here, Biot number is defined in terms of volumetric heat transfer coefficient. The experimental correlation of Chandra and Willits (1980) was used for h_v:

$$\frac{h_v De^2}{Ka} = 1.45 \left(\frac{\rho_a \overline{V}_a De}{\mu_a} \right)^{0.7} \tag{3.17}$$

The coefficient of heat loss from the rockbed to the surrounding, U was estimated for the rockbed based upon the temperature delay of the passively cooling rockbed and assuming that the heat from the rockbed was lost to the outside air of temperature TI in case of an internal rockbed.

For a given time interval t, q represents the heat lost from the passively cooling rockbed to the inside air. It is computed as the difference in the heat content of the rockbed at the beginning and at the end of the time interval, i.e.

$$q = \rho_b A_b L'_b C_{pb} (\overline{T}_b|_t - \overline{T}_b|_{t+\Delta t}) \tag{3.18}$$

$$\text{also, } q = U_b P_b L_b (\overline{T}_b - \overline{T})|_{t+\Delta t/2} \tag{3.19}$$

The value of U_b can then be obtained by solving the above equation and averaging the value over several time steps. It is realized that this estimate of U_b neglects the thermal inertia effect and serves as a representative value only.

The solution of equation 3.10 requires the initial temperature field in the rocked and one boundary condition at the bed inlet. The fact that the greenhouse air enters the rocked inlet permits the following boundary condition:

$$T_{a\,i,\,j}\big|_{x=0} = TI \tag{3.20}$$

The partial differential equation 3.10 and 3.11 were solved using finite differences for the derivation terms (Larsen, 1967). The result is a set of coupled algebraic equation; one each for the air and the rocks in the rocked, which should be simultaneously solved for solution at each time step.

Equation 3.10 is applicable when the rockbed is in active operation. At those times when the rockbed is being neither charged nor discharged the bed passively exchanges heat with the surrounding environment only. In this mode, both air and rockbed temperatures can be assumed equal and the heat transfer for the rockbed is described as:

$$\frac{\partial Tc}{\partial t} = \frac{U_b P_b}{\rho_c A_b C_{p_c}}(TI - T_c) \tag{3.21}$$

Net heat in the rockbed at the beginning of a simulation is arbitrarily assumed to be zero, $Q_{tot}|_{t=0}=0$, and the net heat balance of the rockbed at the subsequent time step, Δt, becomes

$$Q_{tot}|_{t=\Delta t} = Q_{tot}|_{T=0} + \Delta t\,(q_{rok} + q_{env})|_{t+\Delta t} \quad (3.22)$$

where $$q_{env}|_{t=\Delta t} = \sum_{i=1}^{N} U_b P_b \Delta x\,(TI - Ta_{b}i)|_{t=\Delta t} \quad (3.23)$$

and $$q_{rok}|_{t=\Delta t} = \rho_a C_{pa} \overline{V} A_b (T_{a_b,in} - T_{a_b,out})|_{t=\Delta t} \quad (3.24)$$

q_{rok} assumes non-zero values only when the rockbed is being neither charged or discharged. Q $_{tot}$, at the end of a time period, represents the net heat balance of the rockbed as a result of its interaction with the greenhouse and surroundings.

Taking into consideration, the condensation that takes place in the rocked when warm, moist air from the greenhouse passes through the cool rocked during day time and returns the most of the moisture at night when cool, unsaturated air from the greenhouse passes through the warm moist rockbed, the approximation of the physical situation latent heat exchange was handled in two parts. First the temperature of the air having each of the rockbed was calculated via sensible exchange using equation 3.10 and 3.11. If the temperature of air leaving was below saturation, condensation was assumed to have occurred. The amount of water condensed was calculated by

$$dW_{a_b} = (W_{a_b} - W_{a_b s}) \quad (3.25)$$

and the energy released was used to raise the temperature of that particular rock layer. The amount of water condensed in each layer was assumed to remain in the layer, although it reality does not. Under conditions of possible evaporation, a check was made to determine that if water remained in the layer being examined. If it indeed was the case then, air was assumed to leave at saturation. The energy required to evaporate the water was taken from the rock layer and the amount of water subtracted from the total for that layer. When no more water remained in particular layer, evaporation was not permitted from that layer.

Solution of the Heat and Moisture Balances

To calculate the heat and moisture balances of the greenhouse air at any given time, the temperature of the various surfaces in contact with the air must be determined at that time. To determine temperatures at any time in a region of interest, initial conditions, boundary conditions, and a principle of energy conservation for the region are required.

Initial Conditions

The temperature field in a time-dependent heat transfer problem at any time depends, among other things, on the temperature field at a previous time, t-Δt. Regions of small thermal capacity respond quickly to time dependent conditions so that the initial conditions are quickly forgotten. For regions of high thermal capacity, the effect of boundary condition variations may be very slow, letting the residual effects of initial conditions to persist for a long time.

Boundary Conditions

The effects of all environmental thermal forces can be conveniently separated into three categories:

1. specified temperature condition
2. normal flux condition
3. convection

In greenhouses there are usually no specified boundary temperatures except at a sufficient depth in the ground beneath the greenhouse. At a depth in the ground where yearly environmental fluctuations do not penetrate and also where the thermal influence due to the greenhouse presence is not present, an isothermal boundary can be assumed.

Heat is transferred from solid surfaces to a surrounding fluid by both conduction and the fluid motion. The overall heat transfer effect is represented by the convection heat transfer coefficient, h. This boundary condition is represented as:

$$q_{conv} = h_s (T_s - T_{amb}) \tag{3.26}$$

Transpiration from the plant canopy, condensation on greenhouse cover surfaces, and thermal radiation fluxes may be included in normal flux boundary conditions. Absorbed solar radiation fluxes for opaque surfaces are also part of normal flux boundary condition. Solar radiation absorbed by translucent materials is distributed throughout their thickness, suggesting it is more appropriate to consider it as internal heat generation by the material. Solar radiation flux absorbed by a translucent material, when divided by the thickness of the material, changes into uniform volumetric heat generation for that material. Determination of the quantities, which constitute the normal flux boundary condition, will now be presented.

Solar Radiation

The solar radiation absorbed by a material at any time depends upon the quality of the irradiation, material radiation properties and the influence of surroundings. At present there are several schemes available to determine the absorbed solar radiation flux for a surface either from completely theoretical consideration or from some measured quantity (Morris et al., 1969, ASHRAE, 1976). Froehlich (1976) developed a procedure to compute absorbed solar radiation fluxes for various structural covers, plant, and floor surfaces in a greenhouse assuming that hourly total solar radiation fluxes incident on a horizontal surface on the earth are known. He considered single glazed and double glazed translucent cover and opaque cover surfaces in his development. Also, the radiation properties of the translucent materials for direct solar radiation were considered to depend on the incidence angle. His procedure was adopted for the present model development.

The total absorbed hourly solar radiation quantities determined using Froehlich's development were converted for unit surface areas and represented by the exponential form of Fourier series. The Fourier series representation of these quantities permitted their estimation at any time.

Thermal Radiation Exchange

Analysis of thermal radiation exchange for greenhouses developed by Chandra (1979) was adopted for the present study.

McAdam *et al.,* (1971) have presented plotted results for estimating shape factors required in the above analysis for common greenhouse geometries. Simple expressions and/or plotted results for other generally encountered configurations are also available in literature (Sparrow and Cess, 1978; ASHRAE, 1976; Seigel and Howel, 1972). In special cases, the shape factors can also be determined from the definition (Sparrow and Cess, 1978). It is essential that the shape factors for a surface i with respect to the other surfaces in the enclosure satisfy the following equation:

$$\sum_{j=1}^{n} F_{i-j} = 1 \tag{3.27}$$

This is necessary to satisfy the energy conservation requirement. The reciprocity relationship stated in the following equation must also be observed.

$$A_i F_{i-j} = A_j F_{j-i} \tag{3.28}$$

Transpiration

The diffusion of water vapor from a plant canopy to the surrounding air-water vapor mixture was modeled according to Nobel (1973) as:

$$M_T = 2A_p \alpha_a (WP - WI)/R_p \tag{3.29}$$

Assuming the rate of transpiration to be the same from both the upper and lower sides of a leaf, A_p is multiplied by 2. The plant resistance to water vapor diffusion, R_p, is the sum of the stomatal resistance on the surface of the leaves. The stomatal resistances on both sides of a leaf are assumed to be the same. The value of R_p varies from crop to crop and with time. The time-dependence is caused by a variety of environmental factors such as sunlight and moisture stress. No general equations for a variety of crops relating R_p to environment factors are available although the general effects of these environmental factors are fairly well understood (Kuiper, 1961). It is assumed that in a well-managed greenhouse, the value of R_p is influenced only by sunlight. In sunlight, stomata open and the resistance to transpiration decreases. In the dark, stomata close, resulting in high transpiration resistance.

Heat flux due to transpiration was calculated as

$$q_T = M_T\,(HW + C_{pw}(TI + TP)/2)/2A_p \tag{3.30}$$

Humidity ratios as used above were calculated using relationships from the psychometrics section.

Condensation

When the temperature of a surface in contact with moist air drops below the dew point temperature of the moist air, some of the moisture from the air condenses on the cool surface. The rate of condensation is (ASHRAE, 1977):

$$M_{co} = A_{co} D_k\,(W_a - W_{co}) \tag{3.31}$$

The mass transfer coefficient, D_k, is related to the heat transfer coefficient, h_{co} for small condensation rates by the Lewis relation:

$$D_k \cong h/C'_{pa} \tag{3.32}$$

where,

$$C'_{pa} = (1 + W_a)C_{pa} \tag{3.33}$$

Heat flux due to condensation was calculated as follows:

$$q_{co} = M_{co}(HW + C_{pw}\,(TI + T_{co})/2)/A_{co} \tag{3.34}$$

The humidity ratios to calculate M_{co} were determined using relationships from the psychometrics section.

Psychrometry

Wilhelm (1975) has presented relationship to calculate moist air properties in SI units. The equations for saturation vapor pressure as a function of dry bulb temperature are

$$\ln(pw_{sat}) = 24.2779 - 6238.64/T_{db}^{k} - 0.3444381n\,(T_{db}^{k}) \qquad 233.16 \leq T_{db}^{k} \leq 273.16 \tag{3.35}$$

$$\begin{aligned} \ln(pw_{sat}) = &-7511.52/T_{db}^{k} + 89.63121 + 0.02399897\ 0T_{db}^{k} \\ &-1.1654551 \times 10^{-5}(T_{db}^{k})^{2} - 1.2810336 \times 10^{-8}(T_{db}^{k})^{3} + \\ &2.0998405 \times 10^{-11}(T_{db}^{k})^{4} - 12.1507991\ n(T_{db}^{k}) \\ &273.16 \leq T_{db}^{k} \leq 393.16 \end{aligned} \tag{3.36}$$

The actual vapor pressure for an air-water vapor mixture is given by

$$pw = pw_{sat}RH \tag{3.37}$$

and the actual humidity ratio by

$$W = 0.62198pw/(p - pw) \tag{3.38}$$

The humidity ratio of air saturated with water vapor is, however,

$$W_{sat} = 0.62198pw_{sat}/(p - pw_{sat}) \tag{3.39}$$

Dew point temperature as related to actual vapor pressure is

$$T_{dp} = 5.994 + 12.41A + 0.4273A^{2} \qquad (-50 \leq T_{db} \leq 0^{0}C) \tag{3.40}$$

$$T_{dp} = 7.024 + 13.561A + 1.416A^{2} \qquad (0 \leq T_{db} \leq 110^{0}C) \tag{3.41}$$

Where, $A = \ln(pw)$ (3.42)

Principle of Energy Conservation

Temperatures in solid regions, for which the initial and boundary conditions have been defined, can be determined by using an energy conservation principle along with Fourier's law of conduction (Eckert and Drake, 1959). The partial differential equation that represents temperatures in an orthotropic material along with appropriate initial and boundary conditions in two dimensions is,

$$\frac{\partial}{\partial x}(k_x \frac{\partial T}{\partial x}) + \frac{\partial}{\partial y}(k_y \frac{\partial T}{\partial y}) + Q' = \text{œ} C_p \frac{\partial T}{\partial t} \tag{3.43}$$

For a one-dimensional problem, one of the spatial derivatives in equation (3.43) is omitted. Some of the boundary conditions, e.g., thermal radiation, condensation, and transpiration, are nonlinear functions of temperature. Further, greenhouse geometry may not be represented in analytical form. Under these conditions, a general solution of equation (3.43) is not feasible.

An alternate formulation of the problem of temperature determination is suggested by Calculus of Variation. For a two-dimensional problem, minimization of the following functional with respect to the dependent variable, T, yields a differential equation of temperature T in time t.

$$\begin{aligned} &= \int_v [\frac{1}{2} k_x \left(\frac{\partial T}{\partial x}\right)^2 + \frac{1}{2} k_y \left(\frac{\partial T}{\partial y}\right)^2 - Q' T + C_p T \frac{\partial T}{\partial t}] \, dv \\ &+ \int_s [qT + \frac{1}{2} h(T - T_\infty)^2] \, ds \end{aligned} \tag{3.44}$$

The differential equation is integrated with respect to time to obtain the desired temperatures. For a one-dimensional problem, one of the spatial derivative terms in the volume integral of equation (3.44) is omitted. An explicit formulation of T is required to minimize the functional.

The procedure involved in the minimization of the functional is better known as a Finite Element Method. In order to obtain an explicit formulation of T, the region of interest is subdivided into a finite number of elements. The temperature in an element is expressed in terms of the temperatures of the nodes of the element. Using this explicit representation for the temperature, the functional is minimized for one element. The result is a differential equation in time for the element temperature. After performing the process of minimization for all the elements in the region of interest, a set of simultaneous differential equations is obtained. As mentioned before, these equations involve time derivatives of temperature. These time derivatives can be represented by a suitable finite difference. By doing so, the set of simultaneous differential equations is converted to a set of simultaneous algebraic equations. The solution of this set of simultaneous equations yields the desired temperatures.

The minimization procedure for the functional, χ has been presented in several finite-element textbooks (Huebner, 1975; Segerlind, 1976). The procedure was used to develop the finite-element heat equilibrium equations using linear one-dimensional line segments.

Depending upon the boundary condition(s) for a one-dimensional problem, individual components of the functional can be assembled for each element and equated to zero to obtain minimization of the element functional.

Stability

Polivka and Wilson (1976) have shown that the integration scheme assuming a linear variation of temperature over the time step Δt, is unconditionally stable for all positive values of the selected time step.

Using too large a time step might result in oscillations of temperature predictions due to thermal radiation, condensation, and transpiration terms, which need to be evaluated using the temperature predictions from the previous time step. That is, a large time step may result in a large temperature change, which in turn may underestimate or overestimate the fluxes for the next time step, causing the temperatures to oscillate. But this restriction on the time step to avoid oscillations does not appear to be of serious concern in the case of greenhouse thermal environment study. The environmental changes in general are not very fast, thereby, permitting one to select reasonably large time steps.

Development of Computer Program

It is not possible to perform hand calculations on the basis of the analysis presented in the earlier section. Therefore, a computer program was developed to obtain the time dependent temperatures and humidity fields.

General description

A computer program developed by Chandra *et al.* (1981) for predicting the greenhouse hourly heat and moisture balance was available. The program was in FORTRAN IV language. The program performs the majority of steps involved in the analysis of the greenhouse thermal environment. The finite element analysis to solve time-dependent heat conduction problem forms the core of the program. The remaining part of the program arranges boundary conditions, performs input and output functions, and performs additional computation required in the simulation.

In addition to the specified temperature, convection, and specified normal flux boundary conditions, the program also considers non-linear thermal radiation and evaporation boundary conditions. The non-linear boundary conditions are quasi-linearized by using the predicted temperatures from the present time step to compute the boundary condition values for temperature prediction at the next time step. The assumption is reasonable if the selected time step is such that the temperature changes during that time step do not cause appreciable change in the values of the nonlinear boundary conditions (Heuser, 1973).

The computer program had the option to analyze either one-dimensional or two-dimensional heat conduction problem. In the present analysis one-dimensional heat conduction was considered adequate in view of the conclusions of Chandra (1979). The skeletal outline of the above mentioned greenhouse thermal model was adapted for the present analysis with appropriate modifications and additions to account for the energy conservation practices and rockbed thermal energy storage.

The computer program for the greenhouse environment simulation was written in two stages; first one was SOLFOR and the second ROCK. The SOLFOR output forms a part of input data for ROCK.

The SOLFOR program requires the following information:

1. Geometry of the region of interest,
2. Radiation properties of the materials constituting the region of interest,
3. Boundary and initial conditions details, and
4. Solar-radiation, air temperature and relative humidity of atmosphere around the greenhouse structure.

The required atmospheric conditions should be measured values (ASHRAE, 1976) for higher level of accuracy in thermal environment predictions.

The SOLFOR program, after getting the hourly solar radiation, temperature and relative humidity along with other data, computes the absorbed solar radiation fluxes for the participating surfaces of the greenhouse. Finally, it represents the digital exponential series of the absorbed fluxes and other hourly measurements with respect to time. This output forms a part of input for the ROCK program.

SOLFOR program

The main program is assisted by three subroutine subprograms. The main program follows the sequence mentioned below:

1. Read the input data and print the same on unit (printer) in the same format. It is useful to check for any error in preparation of input data.
2. Compute absorbed solar radiation balances for the participating surfaces in the greenhouse. Check if it is a sunshine period. If it is not, set the absorbed solar radiation balance equal to zero and proceed to step three. If it is sunshine period.
    i) Compute the solar incidence angle of the surface. Also, compute the absorbed and reflected radiation by plant and

floor surfaces from the transmitted solar radiation by the cover surface. Repeat this step for all the cover surfaces.

ii) By adding the contributions from all the cover surfaces, compute the total absorbed and reflected solar radiation balances (assumed all diffuse) for the plant surfaces and floor surfaces. Some of the solar radiation reflected by plant and floor surfaces is absorbed by the greenhouse cover surfaces. The absorbed solar radiation portions for the greenhouse cover surfaces are determined and added to their balances of absorbed solar radiation from previous step. The absorbed solar radiation balances are converted to fluxes by dividing the balances by the corresponding incidence surface areas.

3. Compute the parameters (average, moduli, and phase angles) of the exponential Fourier series used to represent absorbed solar radiation fluxes.

4. Compute the coefficients of the exponential Fourier series for the out side air temperature and relative humidity.

5. Write all the computed Fourier series coefficients to a file, which would be added to the input data stream of ROCK.

ROCK program

Both, steady state and time-dependent problems could be solved with the help of this program. Step-by-step solution method for time-dependent problem is given as time independent steps:

i) Form effective global conductivity matrix, $\underline{U}$ and heat capacity matrix, $\underline{S}$; initialize temperature matrix, $\underline{T}$.

ii) Modify $\underline{U}$ for convection boundary conditions

iii) Modify $\underline{U}$ for known temperature boundary conditions

iv) Compute the effective system matrices

$$\underline{U}^* = \underline{U} + \underline{S}^*$$

$$\underline{S}^* = \underline{S} / \Delta t,$$

v) Triangularize $\underline{U}^*$

For each solution Time Increment,

1. Compute the resistance vector
2. Determine the absorbed solar radiation fluxes at time t + Δt,
3. Determine the fluid (air) temperature to which the elements convert at time t+Δt,
4. Compute and add the contributions of convective boundary conditions to $Q_{t+\Delta t}$,
5. Determine the fluxes for the elements with normal flux boundary conditions at time t+Δt,
6. Determine the condensation rates on the inside and outside of the greenhouse cover surfaces by using the predicted temperatures at time t and add the resultant heat fluxes to the flux matrix from step five,
7. Determine the transpiration rate for the plant canopy by using the predicted leaf temperatures at time t and add the resultant heat flux to the corresponding coefficient in the flux matrix from step five.
8. Determine thermal radiation fluxes by using the predicted temperatures of time t and add them to the flux matrix from step five,
9. Add the contribution of the normal flux boundary condition to $Q_{t+\Delta t}$,
10. Determine the rate of internal heat generation for the affected elements at time, t+Δt, and add the contribution to $Q_{t+\Delta t}$,
11. Modify Q for constant temperature boundary conditions, t+Δt,
12. Add $\underline{R}$ to $Q_{t+\Delta t}$,
13. Add the heat contribution or deduct the heat discharge. Q_{ok} to the rockbed to $Q_{t+\Delta t}$
14. Solve the effective heat flow equilibrium equation for

$$T_{t+\Delta t}, \underline{U}^{*} T_{t+\Delta t} = Q_{t+\Delta t} + \underline{R}$$

15. Compute temperature and relative humidity of greenhouse air and temperature of all the elements

16. Repeat for the next time step. For steady-state problem, step number four from the time dependent step is eliminated, and in step number five $\underline{U}$ is triangularized. The steps for each time increment are executed only once without step 1, 13, and 16. The effective heat flow equilibrium equation in case of a steady-state problem becomes

$$\underline{U}\,\underline{T} = Q$$

Capabilities of the Computer Model

The model in its present form predicts the thermal environment for the greenhouses consisting of one dimensional heat conduction regions. The boundary conditions include specified temperature, convection, transpiration, thermal radiation, condensation, and solar radiation. Internal heat generation of heat may exist.

The model was developed in modular fashion, with particular tasks accomplished by separate subprograms. The main program coordinates the function of the subprograms. This structure lends itself to convenient modification of the model for specific problems. Therefore, in future when new information about a particular component of the greenhouse thermal environment becomes available, it can be incorporated into the model. Thus, the model can be up dated without extensive program reformulation whenever new information becomes available.

The model stores global conductivity and heat capacity matrices more efficiently. For such matrices, only the terms in their half bandwidths are stored, thereby reducing the computer storage requirement significantly. Thus, the model can accept problems with a large number of elements before computer storage limits are exceeded.

Limitations of Computer Model

Only one-dimensional line segments and two dimensional linear triangular elements can be used to model one and two dimensional line segments and two dimensional heat transfer regions. While for most greenhouse problems this is considered adequate, higher order elements may be more desirable for complex geometry.

1. Temperature dependence of the material thermal properties is neglected. As the temperature range encountered in greenhouse thermal environment studies is relatively small (about 50°K), thermal properties may be assumed constant over this temperature range.

2. Time-dependence of convective heat transfer coefficients cannot be easily considered. It is because the convective heat transfer coefficients appear in global conductivity matrix. It would be a major computational effort to recompute the matrix at each time increment.

3. Some of the input data requirement for ROCK is contained within some of the subprograms. Although this reduces the amount of input data, increased user familiarity with the program is required to accomplish the modifications necessary to study variety of problems.

Greenhouse details

The experimental greenhouse geometry, shown in Fig. 5.1 was used for preparing input data for the computer program. The greenhouse enclosure (Fig.3.2) consists of UV-Stabilized polyethylene (single and double wall), insulated north wall, night curtain, plant canopy, floor surface. Radiation shape factors, mentioned earlier for the enclosure were determined by using information from Sparrow and Cess (1978).

The shape factor matrix containing the shape factors for the surfaces within the enclosure is given by equation 3.45 for the greenhouse with night curtain and equation 3.46 without night curtain.

Parameter selection

Geometric parameters associated with the experimental greenhouse and needed for the solar radiation exchange are given in Table 3.1. To consider the solar radiation reflected from the surrounding ground to the outside of the greenhouse enclose, appropriate shape factors between the ground and structural cover surfaces were included in the table.

Convective heat transfer coefficients for heat transfer between various solid surfaces inside and outside the greenhouse and surrounding air were chosen from ASHRAE Handbook of Fundamentals (1977). A list of values (Refer Fig. 3.2 for surface identification) is given in Table 3.2. The effect of ventilation rate on convective heat transfer coefficients is neglected and hence it is assumed as a constant parameter.

Several other parameters required in the computation are given in Table 3.3 and 3.4.

Table 3.1: **Geometric parameters of cover surface for use in solar radiation exchange (Fig.5.1)**

Surface	Area(m^2)	Azimuth*	Tilt**	Shape factors			
				F_{s-a}	F_{s-p}	F_{s-f}	F_{s-g}
1	7.46	1.57	1.57	0.5	0.15	0.35	0.5
2	12.00	0.00	0.8901	0.83	0.249	0.581	0.17
3	5.55	0.00	0.5236	0.94	0.282	0.658	0.06
4	5.55	3.14	0.5236	0.94	0.282	0.658	0.06
5	12.00	3.14	0.8901	0.83	0.249	0.581	0.17
6	7.46	4.71	1.57	0.5	0.15	0.35	0.5

* Measured from south going westward. **Measured from horizontal.

$$\begin{bmatrix} F_{2-2} & F_{2-4} & F_{2-6} & F_{2-8} & F_{2-10} & F_{2-12} & F_{2-p} & F_{2-f} & F_{2-C1} & F_{2-C2} \\ F_{4-2} & F_{4-4} & F_{4-6} & F_{4-8} & F_{4-10} & F_{4-12} & F_{4-p} & F_{4-f} & F_{4-C_1} & F_{4-C_2} \\ F_{6-2} & F_{6-4} & F_{6-6} & F_{6-8} & F_{6-10} & F_{6-12} & F_{6-p} & F_{6-f} & F_{6-C_1} & F_{6-C_2} \\ F_{8-2} & F_{8-4} & F_{8-6} & F_{8-8} & F_{8-10} & F_{8-12} & F_{8-p} & F_{8-f} & F_{8-C_1} & F_{8-C_2} \\ F_{10-2} & F_{10-4} & F_{10-6} & F_{10-8} & F_{10-10} & F_{10-12} & F_{10-p} & F_{10-f} & F_{10-C_1} & F_{10-C_2} \\ F_{12-2} & F_{12-4} & F_{12-6} & F_{12-8} & F_{12-10} & F_{12-12} & F_{12-p} & F_{12-f} & F_{12-C_1} & F_{12-C_2} \\ F_{p-2} & F_{p-4} & F_{p-6} & F_{p-8} & F_{p-10} & F_{p-12} & F_{p-p} & F_{p-f} & F_{p-C_1} & F_{p-C_2} \\ F_{f-2} & F_{f-4} & F_{f-6} & F_{f-8} & F_{f-10} & F_{f-12} & F_{f-p} & F_{f-f} & F_{f-C_1} & F_{f-C_2} \\ F_{C_1-2} & F_{C_1-4} & F_{C_1-6} & F_{C_1-8} & F_{C_1-10} & F_{C_1-12} & F_{C_1-p} & F_{C_1-f} & F_{C_1-C_1} & F_{C_1-C_2} \\ F_{C_2-2} & F_{C_2-4} & F_{C_2-6} & F_{C_2-8} & F_{C_2-10} & F_{C_2-12} & F_{C_2-p} & F_{C_2-f} & F_{C_2-C_1} & F_{C_2-C_2} \end{bmatrix} = \begin{bmatrix} 0.0 & 0.165 & 0.165 & 0.0 & 0.0 & 0.016 & 0.114 & 0.210 & 0.0 & 0.33 \\ 0.066 & 0.0 & 0.092 & 0.0 & 0.0 & 0.096 & 0.356 & 0.255 & 0.0 & 0.164 \\ 0.066 & 0.093 & 0.0 & 0.0 & 0.0 & 0.066 & 0.361 & 0.171 & 0.0 & 0.244 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 1.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 1.0 & 0.0 \\ 0.016 & 0.165 & 0.165 & 0.0 & 0.0 & 0.0 & 0.114 & 0.210 & 0.0 & 0.33 \\ 0.009 & 0.071 & 0.07 & 0.0 & 0.0 & 0.009 & 0.4 & 0.3 & 0.0 & 0.141 \\ 0.033 & 0.067 & 0.1 & 0.0 & 0.0 & 0.033 & 0.6 & 0.0 & 0.0 & 0.167 \\ 0.0 & 0.0 & 0.0 & 0.5 & 0.5 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.033 & 0.061 & 0.041 & 0.0 & 0.0 & 0.033 & 0.1795 & 0.1063 & 0.0 & 0.5462 \end{bmatrix} \qquad \ldots\ldots(3.45)$$

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$$\begin{bmatrix} F_{2-2} & F_{2-4} & F_{2-6} & F_{2-8} & F_{2-10} & F_{2-12} & F_{2-p} & F_{2-f} \\ F_{4-2} & F_{4-4} & F_{4-6} & F_{4-8} & F_{4-10} & F_{4-12} & F_{4-p} & F_{4-f} \\ F_{6-2} & F_{6-4} & F_{6-6} & F_{6-8} & F_{6-10} & F_{6-12} & F_{6-p} & F_{6-f} \\ F_{8-2} & F_{8-4} & F_{8-6} & F_{8-8} & F_{8-10} & F_{8-12} & F_{8-p} & F_{8-f} \\ F_{10-2} & F_{10-4} & F_{10-6} & F_{10-8} & F_{10-10} & F_{10-12} & F_{10-p} & F_{10-f} \\ F_{12-2} & F_{12-4} & F_{12-6} & F_{12-8} & F_{12-10} & F_{12-12} & F_{12-p} & F_{12-f} \\ F_{p-2} & F_{p-4} & F_{p-6} & F_{p-8} & F_{p-10} & F_{p-12} & F_{p-p} & F_{p-f} \\ F_{f-2} & F_{f-4} & F_{f-6} & F_{f-8} & F_{f-10} & F_{f-12} & F_{f-p} & F_{f-f} \end{bmatrix} = \begin{bmatrix} 0.0 & 0.165 & 0.165 & 0.165 & 0.165 & 0.016 & 0.114 & 0.210 \\ 0.066 & 0.0 & 0.092 & 0.088 & 0.156 & 0.66 & 0.361 & 0.171 \\ 0.066 & 0.093 & 0.0 & 0.076 & 0.088 & 0.066 & 0.356 & 0.255 \\ 0.066 & 0.088 & 0.076 & 0.0 & 0.093 & 0.066 & 0.356 & 0.255 \\ 0.066 & 0.156 & 0.088 & 0.092 & 0.0 & 0.066 & 0.361 & 0.171 \\ 0.016 & 0.165 & 0.165 & 0.165 & 0.165 & 0.0 & 0.114 & 0.210 \\ 0.009 & 0.071 & 0.07 & 0.07 & 0.071 & 0.009 & 0.4 & 0.3 \\ 0.033 & 0.067 & 0.1 & 0.1 & 0.067 & 0.033 & 0.6 & 0.0 \end{bmatrix}$$

....(3.46)

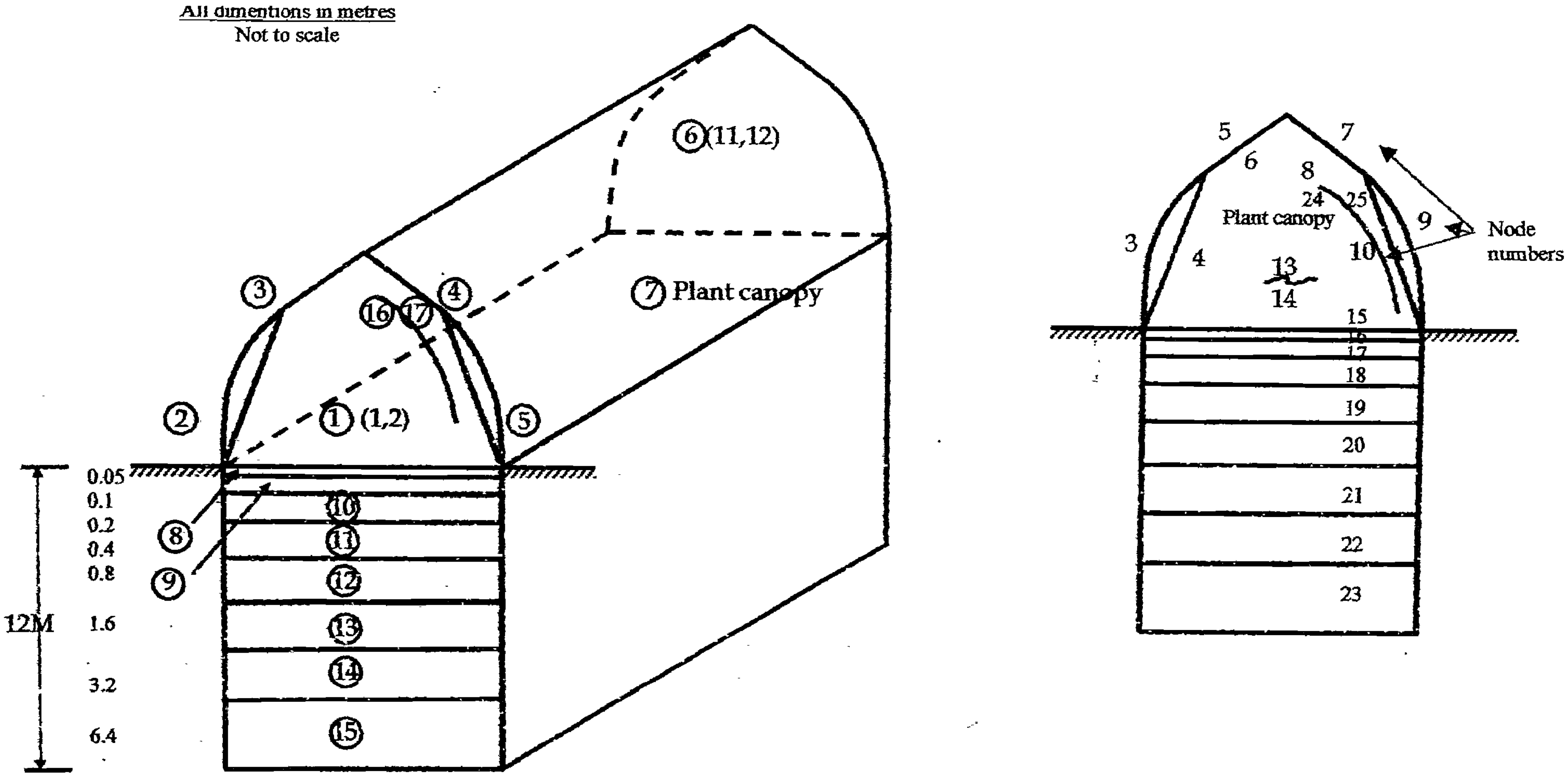


Fig3.2: Schematic diagram of Greenhouse showing element number, ⓘ, and nodes, (i,j), used for the finite element analysis

Table 3.2: **Convective heat transfer coefficients between the solid surfaces and the surrounding air (Fig.3.2)**

Node No.	Convective heat transfer coefficient, W/m^2 ^{O}K
1	35.00
2	8.08
3	35.00
4	8.08
5	35.00
6	8.08
7	35.00
8	8.08
9	35.00
10	8.08
11	35.00
12	8.08
13	13.00
14	13.00
15	17.00
24	1.0
25	8.08

Table 3.3: **Constant parameters used in numerical solution**

Computer notations	Chosen value	Units
AHF	0.7	-
AHP	0.95	-
DF	17.0	m^2
DK	0.008	Kg/m^{3}s
DP	6.0	m^2
FFP	0.005	-
FRF	0.8	-
FRP	0.1	-
FPF	0.23	-
FPP	0.5	-
HW	2.502x10^6	-
RHF	0.3	-
RHG	0.3	-
RHP	0.05	-
VOLUME	37.3	m^3
VER	0.01- 0.9	m^3/s

Table 3.4: Material Properties

	U-V stablized polyethylene	Air inflated double glazing	Night curtain	Insulated north wall	Greenhouse floor	Plant	Units
AH(M)	0.1	0.25	0.1	0.8	0.7	0.95	
AL(M)	0.0002	0.1	0.05	0.05	-	0.001	m
AN(M)	1.526	1.526	10000.0	-	-	-	
AX(M)	6.85	6.85	10000.0	-	-	-	m^{-1}
COND(M,2)	0.865	0.44	0.44	0.027	0.42	1.00	W/m°K
ET(M)	0.25	0.5	0.1	0.8	0.94	0.9	
PC(M)	2.27 x10^6	2.27 x10^6	2.27 x10^6	2.27 x10^6	1.73 x10^6	2.00 x10^6	J/m^3°K
TH(M)	0.8	0.64	-	0.0	0.0	0.0	
TT(M)	0.5	0.25	0.33	0.0	0.0	0.0	

Finite element model of the greenhouse

The finite element representation of the greenhouse (Fig.3.4) was similar to that of Chandra *et al.* (1981) except for one-dimensional representation of heat transfer in the ground and taking into account the ends thermal gradient. Chandra *et al.* (1981) observed that the heat transfer through the ground constituted only about five per cent of the total heat balance for the greenhouse. Hence, use of two-dimensional grid may not be essential. Further more, one-dimensional representation allows approximately 75 per cent reduction in computation time. The perimeters of the one-dimensional element in the ground are assumed to be insulated. A constant temperature boundary condition was assumed in the ground at a depth of 12.0 m. This constant temperature was chosen as 20.0°C.

Design of the Solar Greenhouse

CHAPTER IV

Design of The Solar Greenhouse

In order to fulfil the objectives of the present study, the model developed in the previous chapter was used to study the effects of various shapes, orientation and energy conservation measures on the energy balance of a simulated 12m×200m greenhouse situated at 28^0 35′ N latitude and 77^0 12′ E longitude. Commercial greenhouses, generally, have floor area of 1,000 m^2 to 50,000 m^2. The relative humidity of the greenhouse was assumed to be 80 per cent and night and day temperatures were 15 ^{0}C and 20 ^{0}C, respectively. The environmental conditions in a greenhouse are crop specific. However, the selected values of temperature and relative humidity represent the conditions required for many temperate crops. The simulations were conducted for an average sunny day in December. The input parameters for the model included hourly data of

a) ambient air relative humidity,

b) ambient air temperature,

c) solar radiation incident on a horizontal surface outside the greenhouse.

The behavior of the above greenhouse under following modes of operation were predicted:

a) Various shapes of greenhouse structure

b) East-west and north-south oriented gothic arch greenhouse

c) A east-west oriented gothic arch greenhouse with 5cm thick north wall with glasswool filling between two layers of black polyethylene, thermal properties given in table of parameters and a north-south oriented gothic arch greenhouse with same level of insulation on north wall

d) An east-west oriented gothic arch greenhouse with thermal curtain having properties listed in table of parameters

e) An east-west oriented greenhouse with air inflated double glazing on southern wall.

Table 4.1(a) Parameters used for simulation

Quantity	Value	Unit
C_{pa}	1004.0	J/kg°K
D_k	0.008	Kg/m^{2}s
h_c	1.0(outside)	W/m^2°K
	10.0(inside)	W/m^2°K
h_f	17.0	W/m^2°K
h_{ins}	35.0(outside)	W/m^2°K
	8.08(inside)	W/m^2°K
h_p	13.0	W/m^2°K
h_s	35.0(outside)	W/m^2°K
	8.08(inside)	W/m^2°K
HW	2.502X10^6	J/kg
K_c	0.05	W/m°K
K_f	0.42	W/m°K
K_{ins}	0.05	W/m°K
K_p	1.00	W/m°K
K_s	0.865(single wall)	W/m°K
	0.44(double wall)	W/m°K
PC_c	1.65X105	J/m^3°K
PC_f	2.27X106	J/m^3°K
PC_{ins}	1.3X105	J/m^3°K
PC_p	2.00X106	J/m^3°K
PC_s	1.73X106	J/m^3°K
		J/m^3°K
TH_c	0.05	m

TH_{ins}	0.05	m
TH_p	0.001	m
TH_s	0.0002(single wall)	m
	0.1(double wall)	m
ε_c	0.1	
ε_f	0.9	
ε_{ins}	0.8	
ε_p	0.8	
ε_s	0.25	
τ_c	0.0	
τ_f	0.0	
τ_{ins}	0.0	
τ_p	0.0	
τ_s	0.5	
V	7836.0	m^3
VER	2.18	m^3/s

4.1 Effect of shape on heating energy requirement of a greenhouse

Three shapes of greenhouse were considered for the simulation:

i. Quonset

ii. Gable

iii. Gothic Arch

These shapes were chosen because they are common in commercial use. The simulation could be easily extended to any other shape.

4.1.1 Description of the Greenhouse

(i) Quonset greenhouse

The basic shape of a quonset greenhouse is illustrated in Fig.4.1. An end section of this greenhouse is a semi-circle with a diameter equal to the width of the greenhouse. The surface areas related to this shape of greenhouse are given in Table 4.1(b).

Table 4.1(b): Areas of the surfaces in Quonset greenhouse

Surface	Area (m^2)
Ground surface	2400
One end wall area	56.55
One side wall	1884.0

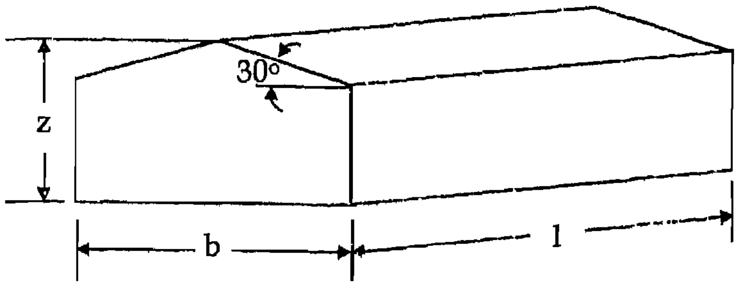
(ii) Gable greenhouse

The basic shape of a gable greenhouse is illustrated in Fig. 4.1. The roof slope was chosen as 30 degrees on the basis of published literature. Surface areas were calculated based on ground bed dimensions and assumed height of vertical section of the side wall. Table 4.2 gives the calculated surface area parameters that were used in the heat balance analysis.

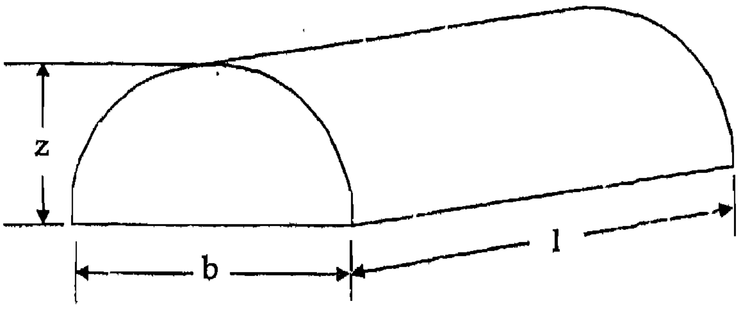
Table 4.2: Areas of the surfaces in gable greenhouse

Surface		Area (M^2)
Ground surface		2400
End walls		41.5
Side walls	a) 30^0 inclined surface	1386.0
	b) Vertical surface*	340.0

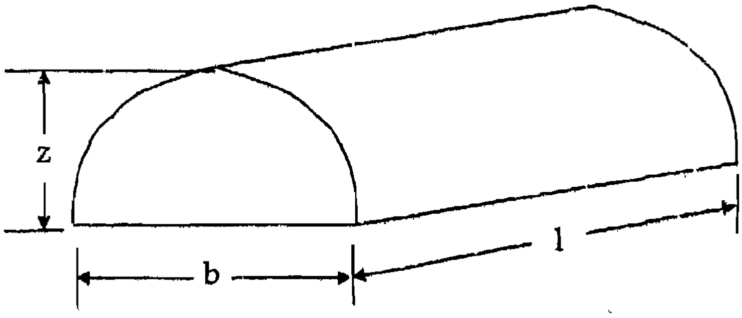
*Height of the vertical section of the side wall was assumed as 1.7 M.



GABLE GREENHOUSE



QUONSET GREENHOUSE



GOTHIC ARCH GREENHOUSE

Fig 4.1 Different Shapes of Greenhouses used for analysis

(iii) Gothic arch

The basic shape of a gothic arch greenhouse is illustrated in Fig. 4.1. This is not a classic gothic arch shape. In this case, the arch was assumed to consist of a lower curved portion and an upper straight portion. The straight portion was assumed to be inclined at 30 degrees with the horizontal and to begin at the point where a tangent to the lower curved portion was inclined at 30 degrees with the horizontal. The curved portion was approximated by an area of a circle with a radius equal to

$$r = \frac{b/2}{\text{Cos } (20)} \qquad (1)$$

The tangent at the bottom of the arch made a 70 degree angle with the horizontal. Table 4.3 gives the necessary parameters for the gothic arch greenhouse.

Table 4.3: Areas of the surfaces in gothic arch greenhouse

Surface	Area (M^2)
Ground surface	2400
One end wall area	39.18
One side wall a) curved portion	892.0
b) straight portion	692.0

4.1.2 Energy Balances for Gothic Arch, Gable and Quonset Shapes of Greenhouse

Energy balances for the three shapes are summarized in Table 4.4 and presented in Fig. 4.2.

Table 4.4: Energy balance for different shapes of greenhouses

Shape	Daily energy balance(MJ)
Gothic arch	21699.9
Gable	22240.2
Quonset	22237.6

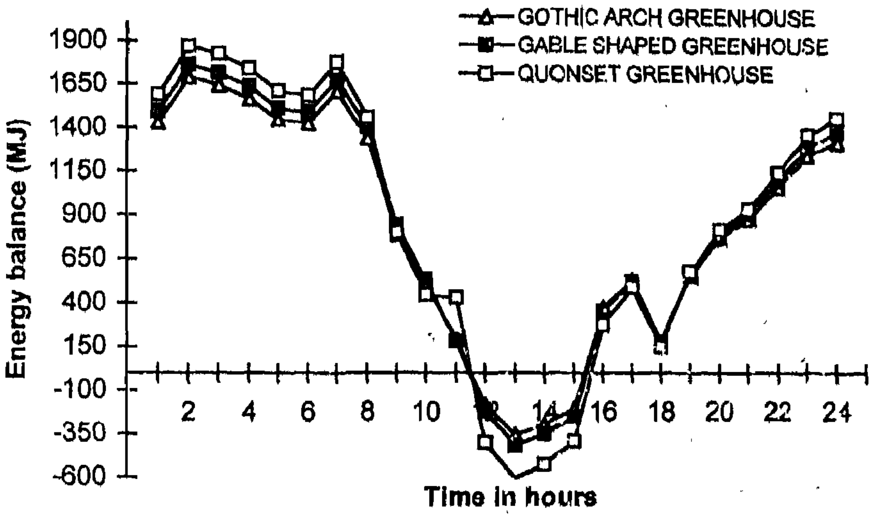


Fig. 4.2 Hourly Energy Balance for Different Shapes of Greenhouses

It is observed that the gothic arch shaped greenhouse requires 2.6 and 4.2 per cent less heating as compared to gable and quonset shapes respectively. The heating requirement per square metre floor (MJ/m^2) for the three shapes are gothic arch 8.15, gable, 8.37 MJ/m^2 and Quonset, 8.51 MJ/m^2.

In view of the above results, the effects of orientation and various energy conservation measures viz. double wall glazing, north-wall insulation, movable night curtains on the energy balance of a gothic arch greenhouse were studied.

4.2 Effect of Orientation on Heating Energy Requirement of a Gothic Arch Greenhouse

Orientation of a greenhouse affects its thermal energy balance by altering the structure's ability to admit solar energy. The difference in solar energy transmission qualities of north-south and east-west oriented greenhouse is clear from Table 4.5 which summarizes the hourly heat energy balances for a Gothic arch shaped greenhouse. It is evident from the figure that an east-west oriented greenhouse requires less heating i.e. around 2 per cent in this case. This difference could be specifically visualized with the help of daily energy profiles in Fig. 4.3.

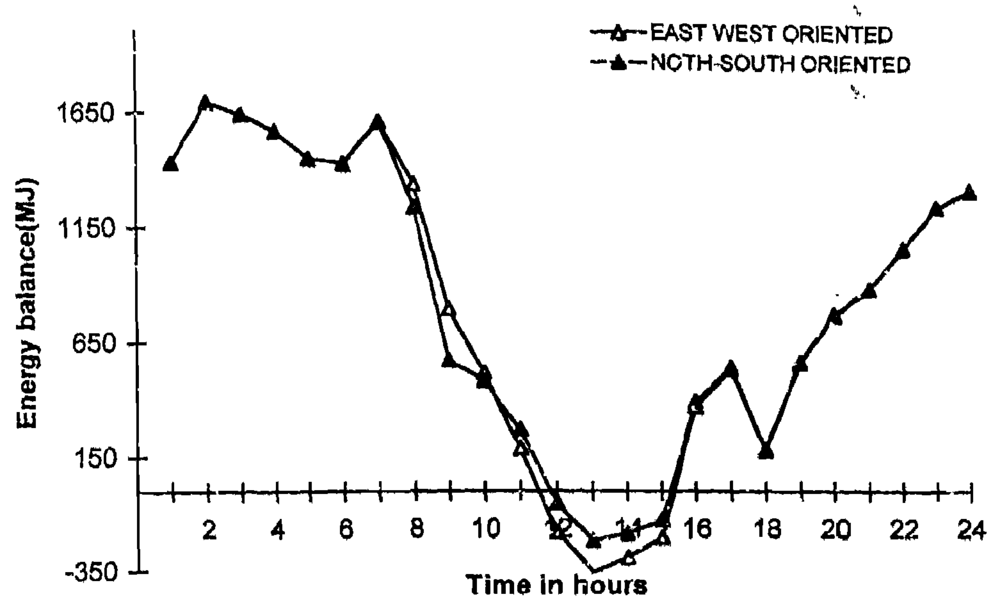


Fig. 4.3 Hourly energy balances for different orientations

It was observed by Chandra (1976) that an east-west oriented gothic arch greenhouse required around 20 per cent less heating as compared to a greenhouse of the same size oriented north-south at high latitudes of 49.25⁰ N. One of the reasons for this difference may be the latitude of the location for which the study has been conducted. When the present analysis was used for a hypothetical location at 50⁰ N latitudes, the

Table 4.5 Hourly energy balances for east west and north south oriented gothic arch greenhouses

Time of day (hrs.)	Hourly energy balance(MJ)	
	East-west	North-south
1	1429.8	1431.5
2	1692.7	1694.3
3	1642.1	1643.5
4	1567.8	1569.1
5	1446.9	1447.4
6	1426.4	1427.4
7	1608.5	1609.5
8	1339.6	1240.9
9	795.4	573.3
10	518.3	479.9
11	189.7	272.3
12	-181.3	-50.7
13	-357.1	-220.1
14	-294.6	-186.5
15	-206.1	-127.0
16	373.8	393.4
17	534.4	543.4
18	179.8	189.4
19	562.0	568.7
20	770.5	775.5
21	883.3	887.2
22	1065	1067.9
23	1247	1249.5
24	1322	1323.9

difference in the energy requirement of east west oriented and north-south oriented greenhouse was noted to be 28 per cent. The analysis has, therefore, permitted to assert that under north Indian conditions an east-west oriented greenhouse may require only about 2 per cent less heating in comparison to a north-south oriented greenhouse.

4.3 Effect of North-wall Insulation on Heating Energy Requirement of the Greenhouse

It can be seen from Table 4.6 that at the given location the transparent north side in a greenhouse contributes very little to the greenhouse solar heat gain during winters as the percentage of total solar radiation incident on it is small (0.11-13 per cent). This is because during winters, in the Northern Hemisphere, the sun stays on the south side of the greenhouse. As a result, the transparent north side contributes little to the total solar heat gain of a greenhouse. But, depending upon the fraction of the total surface area constituted by the surface, heat lost from it may amount to almost half of the total heat lost from the greenhouse. It is, therefore, undesirable to maintain the north side of the greenhouse transparent. It has been suggested that a greenhouse for colder regions should have opaque and insulated north side to reduce heating requirement.

Table 4.6: Percentages of Solar radiation incident on the transparent north-facing surface in greenhouses

Time of day	N-S Orientation	E-W Orientation
8:00	0.099	9.3
9:00	0.19	5.6
10:00	0.398	7.6
11:00	0.305	8
12:00	0.308	8.9
13:00	.308	12.99
14:00	.302	7.8
15:00	0.28	6.3
16:00	0.18	5.3

4.3.1 Hourly Energy Balance for Gothic Arch Greenhouse with Transparent and Insulated North Side Oriented East-West and North-South

Figure. 4.4 and Table 4.7 show energy profiles of hourly heat balances for both transparent and north side insulated greenhouse oriented east-west and north-south. The thermal and radiation properties of the material used are presented in table 4.1. The results indicate that the north wall insulation in a north-south oriented greenhouse results in a little reduction in the heating requirements (approx. 5 per cent) whereas, the reduction is about 30 per cent in an east-west oriented greenhouse. This difference in the reduction for east-west and north-south oriented greenhouses is a direct consequence of the area available for insulating. While north wall area in a north-south oriented greenhouse was only 39.18 sq. m. the area available in an east-west oriented greenhouse was 1584.0 sq. m.

Table 4.7 Hourly energy balance for a gothic arch greenhouse with insulated and transparent north wall

Time of day (hrs.)	Hourly energy balance(MJ)			
	East-west		North-south	
	Transparent North wall	Insulated North wall	Transparent North wall	Insulated North wall
1	1429.8	954.7	1431.5	1367.9
2	1692.7	1184.2	1694.3	1627
3	1642.1	1116.1	1643.5	1575.1
4	1567.8	1058.8	1569.1	1502.3
5	1446.9	953.1	1447.4	1382.3
6	1426.4	946.1	1427.4	1363.5
7	1608.5	1111.3	1609.5	1543.5
8	1339.6	931.8	1240.9	1192.1
9	795.4	509.8	573.3	539.4
10	518.3	313.5	479.9	452.9
11	189.7	35.6	272.3	250.2
12	-181.3	-239.6	-50.7	-66.49
13	-357.1	-331.5	-220.1	-231.2

14	-294.6	-233.6	-186.5	-196.4
15	-206.1	-119.2	-127.0	-137.3
16	373.8	411.3	393.4	379.1
17	534.4	488.8	543.4	526.1
18	179.8	597.2	189.4	156.4
19	562.0	355.5	568.7	529
20	770.5	518.5	775.5	731.8
21	883.3	620.7	887.2	842.3
22	1065.0	740.9	1067.9	1018.2
23	1247.0	854.6	1249.5	1193.6
24	1322.0	927.6	1323.9	1262.9
Total	19555.9	13706.2	19803.7	18804.2

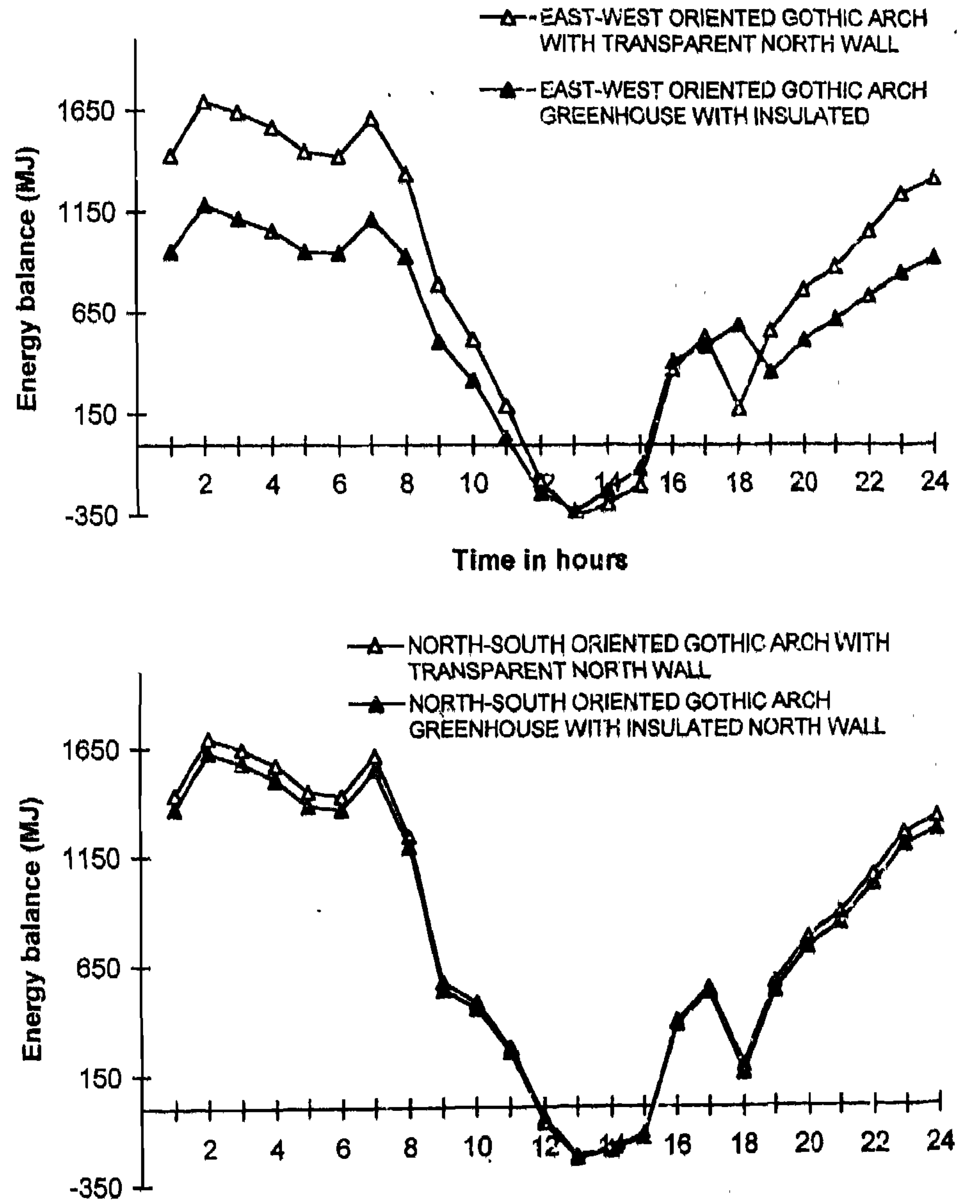


Fig 4.4 Hourly energy balances for a gothic arch greenhouse with insulated and transparent north wall

Thus based on the above results two observations can be made regarding the heat balances in Fig. 4.3 & 4.4.

i. An east-west oriented greenhouse requires less heating under cold climatic condition.

ii. While the effect of insulating the north side of a greenhouse in reducing the structures heating and ventilation requirements are prominent in east-west orientation, the effects are relatively small in north-south orientations.

Thus clearly the advantage of an east-west oriented greenhouse over that of a north-south oriented greenhouse is established by the above two observations. Hence further analyses will be restricted to only east-west orientation gothic arch greenhouse.

4.4 Effect of Movable Night Curtain on the Heating Energy Requirement of a Greenhouse

Use of thermal screens at night considerably reduces the heat losses in greenhouses (S.M. Nijskins *et al.,* 1985; Chandra and Albright, 1980). Since radiation losses depend on the radiometric properties of those materials in the thermal infrared wavelength range, ideally zero transmittance and absorptance are desired. In the present our analysis it was assumed that during nighttime, 7.00 p.m. to 8.00 a.m., a thermal screen of high thermal reflectivity was used below the greenhouse cover on the transparent south side of the greenhouse. The thermal screen/ night curtain reduced the nighttime heating requirement significantly as presented evident from by result in Table 4.8 and Fig. 4.5. The radiation and thermal properties of the night curtain are presented in table 4.1

Table 4.8 Hourly energy balance for a gothic arch greenhouse with and without night curtain

Time of day (hrs.)	Hourly energy balance(MJ)	
	Without night curtain	With night curtain
1	1429.8	366.8
2	1692.7	526.9
3	1642.1	400.8
4	1567.8	354.9
5	1446.9	258.8
6	1426.4	272.0
7	1608.5	430.6
8	1339.6	331.6
9	795.4	677.5
10	518.3	447.1
11	189.7	130.6
12	-181.3	-232.9
13	-357.1	-403.7
14	-294.6	-337.8
15	-206.1	-246.9
16	373.8	334.9
17	534.4	496.4
18	179.8	141.5
19	562.0	139.1
20	770.5	161.1
21	883.3	244.6
22	1065	283.1
23	1247	298.0
24	1322	216.3
Total	19555.9	5291.3

Clearly, the nighttime heating requirements have been reduced by 70.8 per cent. The reduction in daily requirement is 60.6per cent. The results make it clear that the installation of night curtain is highly desirable from the point of view of energy conservation.

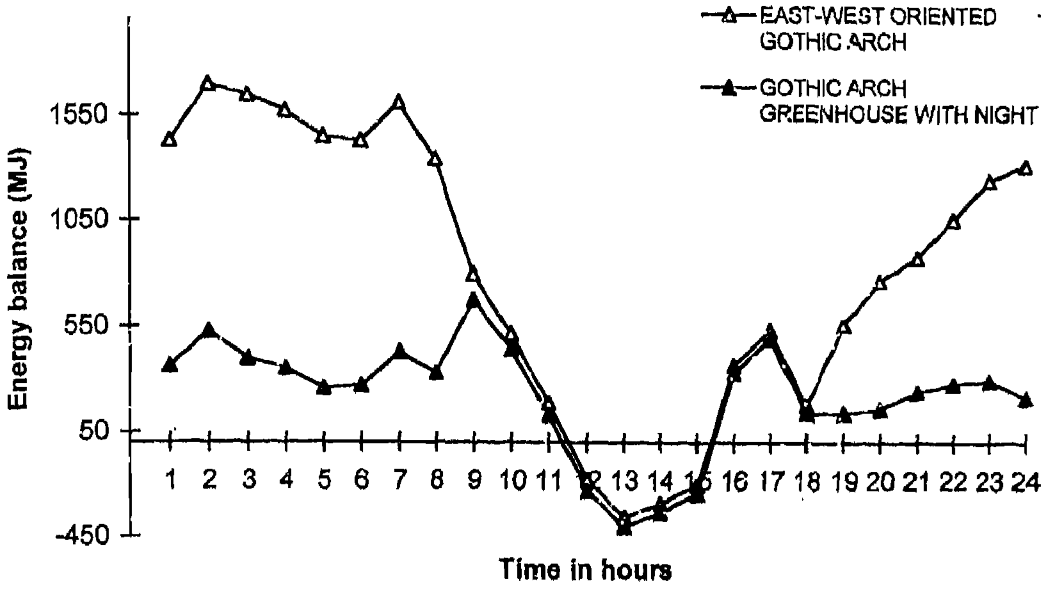


Fig. 4.5 Hourly energy balance for a gothic arch greenhouse with and without night curtain

4.5 Effect of Double Walled Glazing on Heating Energy Requirement of a Greenhouse

The effect of replacing the single transparent glazing on the south side of an east-west oriented greenhouse with air inflated double-glazing

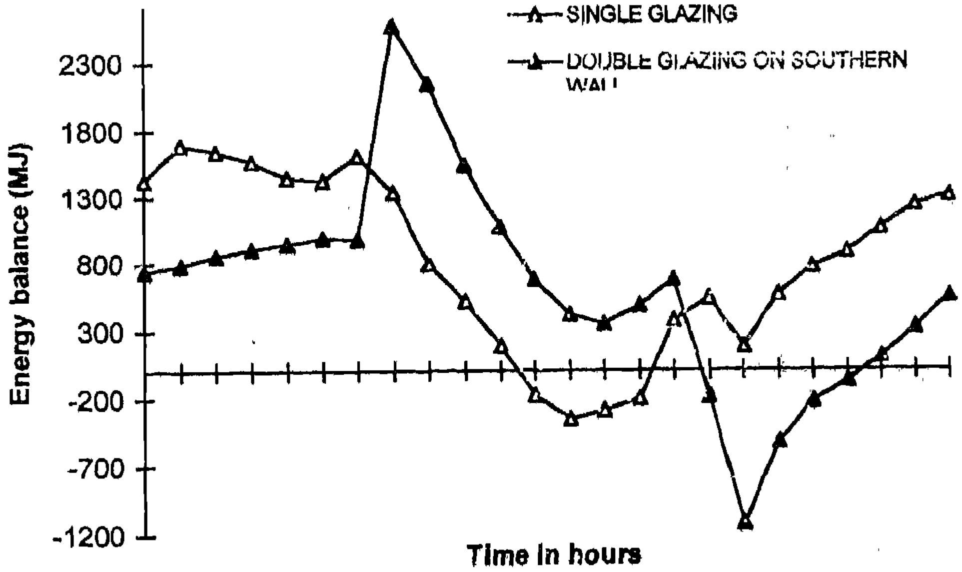


Fig 4.6 Hourly energy balance for a gothic arch greenhouse with and without double wall

was analyzed using the model. The results are presented in Table 4.9 and Fig. 4.6. The daily energy requirement could be reduced by about 23.4 per cent as compared to gothic arch greenhouse with no energy conservation measures.

Table No. 4.9 Hourly energy balance for a gothic arch greenhouse single and double glazing

Time of day (hrs.)	Hourly energy balance(MJ)	
	Single glazing	Double glazing on southern wall
1	1429.8	736.8
2	1692.7	786.4
3	1642.1	859.3
4	1567.8	904.9
5	1446.9	944.3
6	1426.4	990.4
7	1608.5	980.6
8	1339.6	2579.8
9	795.4	2148.4
10	518.3	1542.4
11	189.7	1075.1
12	-181.3	675.3
13	-357.1	417.0
14	-294.6	347.5
15	-206.1	483.6
16	373.8	674.9
17	534.4	-191.6
18	179.8	-1133.4
19	562.0	-528.2
20	770.5	-232.0
21	883.3	-77.9
22	1065	101.8
23	1247	318.8
24	1322	550.0
Total	19555.9	14954.2

4.6 Effect of an Internal Rockbed on the Heating Requirements of a Greenhouse

Since the objective of this study was to replace the use of conventional fuels with solar energy an analysis was carried out to study the effect of a 350 m^3 capacity internal rockbed with graded gravel of 2″ diameter.

Table no 4.10 Effect of an Internal Rockbed on the Heating Requirements of a Greenhouse

Time of day (hrs.)	Hourly energy balance(MJ)	
	With rockbed	Without rockbed
1	0	1431.5
2	0	1694.3
3	0	1643.5
4	0	1569.1
5	0	1447.4
6	0	1427.4
7	0	1609.5
8	0	1240.9
9	0	573.3
10	0	479.9
11	0	272.3
12	0	0
13	0	0
14	0	0
15	0	0
16	0	393.4
17	0	543.4
18	0	189.4
19	0	568.7
20	0	775.5
21	0	887.2
22	0	1067.9
23	0	1249.5
24	0	1323.9
Total	0.0	20388

The night time temperature was maintained at 15° C and day time temperature at 25° C. A blower was assumed to circulate the greenhouse air through the rockbed and back. The results are summarized in Fig. 4.7. and table no. 4.10. All values below zero are assumed to be zero. The saving in heating energy requirement was 100 per cent as compared to north south oriented normal greenhouse.

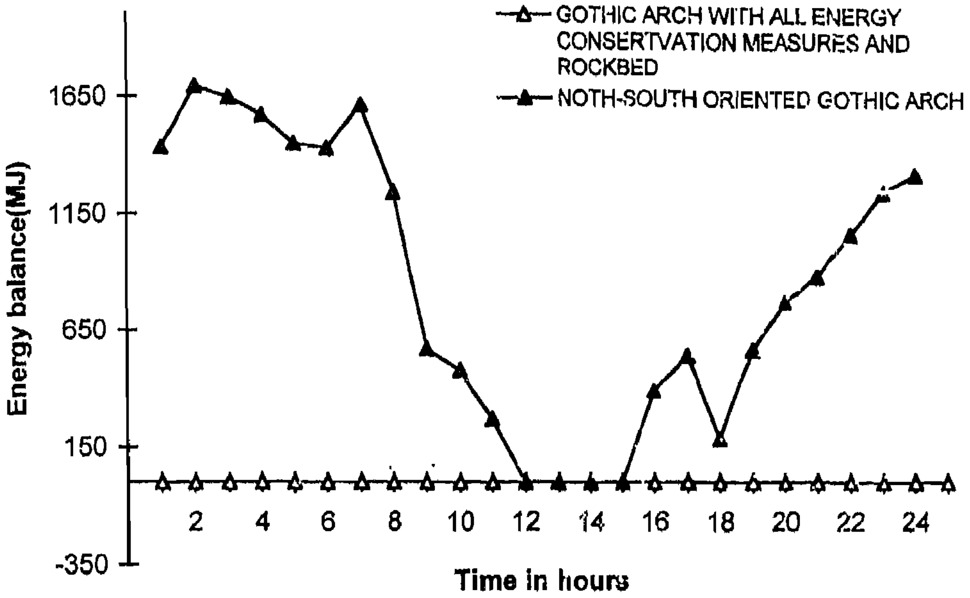


Fig. 4.7 Hourly energy balance for a gothic arch greenhouse with and without rockbed thermal storage

Thus, the above results suggest that an ideal design of a greenhouse for cold climatic condition of India should include the following design features:

i. East-west orientation

ii. Gothic arch shape

iii. North-wall insulation

iv. Use of a Night curtain

v. Air inflated double walled glazing

vi. An internal/external solar thermal storage system

Testing of the Designed Solar Greenhouse

Chapter V

Testing of the Designed Solar Greenhouse

Design of a solar greenhouse suitable for cold climatic conditions has been presented in the previous chapter. In order to test the adequacy of the designed greenhouse to maintain favorable conditions for plant growth, an experimental greenhouse based on the design was constructed and tested.

5.1 The Test Greenhouse

The studies were conducted in a 5m X 4m single span gothic arch greenhouse (Plate no.1 a & b) The cross-section was symmetrical with a ridge height of 2.6 m. The areas of the floor and walls are given in Table. 5.1. The greenhouse was oriented along the east-west direction at the Division of Agricultural Engineering, I.A.R.I., New Delhi (28^0 35′N latitude, 77^0 12′E longitude). Details of greenhouse geometry are given in fig.5.1. The greenhouse has the following design features:

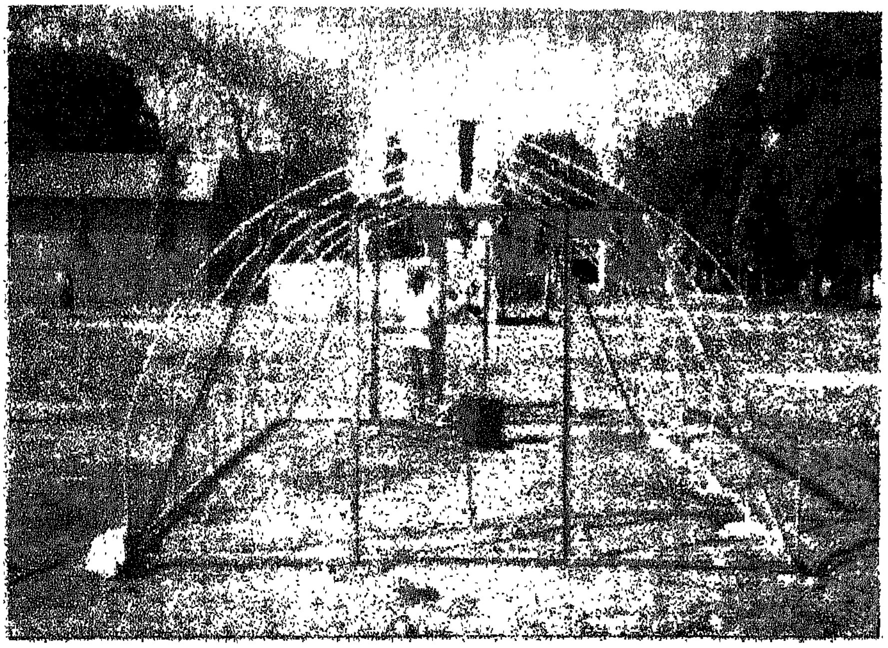


Plate No.1 a: Gothic arch shaped frame of the test greenhouse

Greenhouse cover: The greenhouse has a double layer of 200μm polyethylene cover which is air inflated using a 0.1 hp blower on the southern side and a single layer polyethylene of 200μ on the end walls.

Plate No. 1 b: The test greenhouse

North wall insulation: The north wall of the greenhouse is double layer

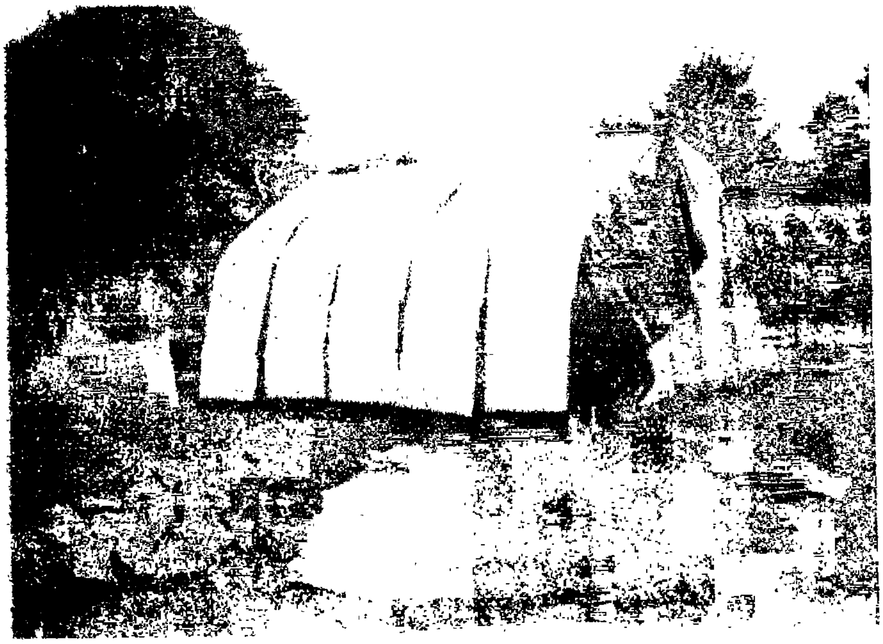


Plate No. 2 a: Thermocole insulation of north wall of 200 μm thick black polyethylene which has a layer of 50 mm thick thermocole insulation in between (Plate no. 2 a & b).

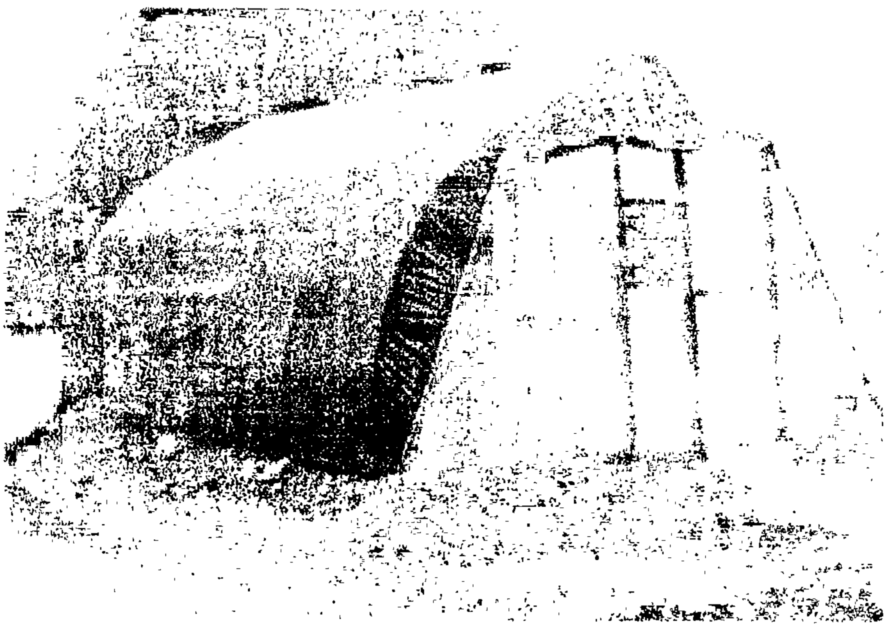


Plate No. 2 b: Insulated opaque north wall

Night curtain/thermal screen: There was difficulty in the procurement of appropriate thermal curtains locally. Nijskins *et al* (1985) has stated that shading materials, which reflect the sun's infrared outward rather

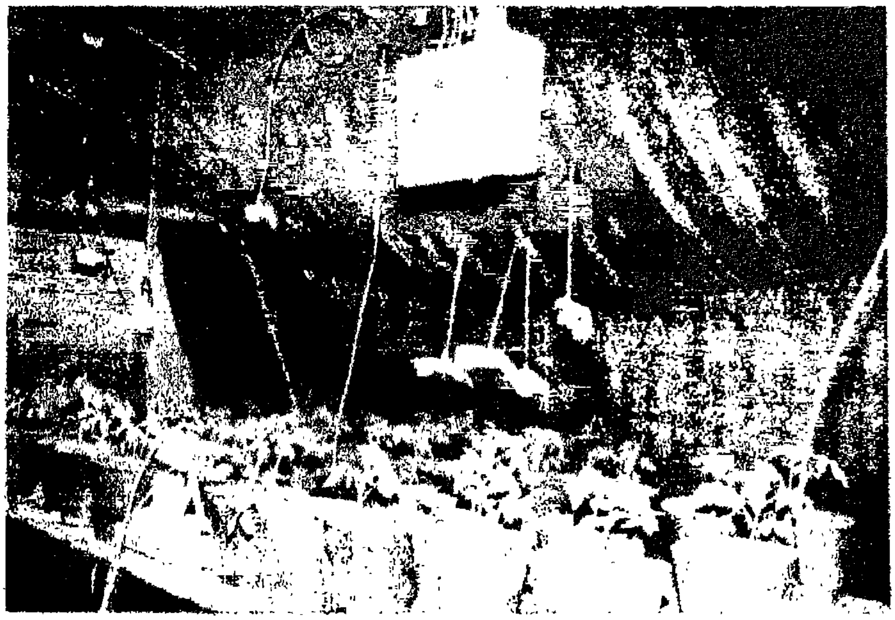


Plate No. 3: Night curtain

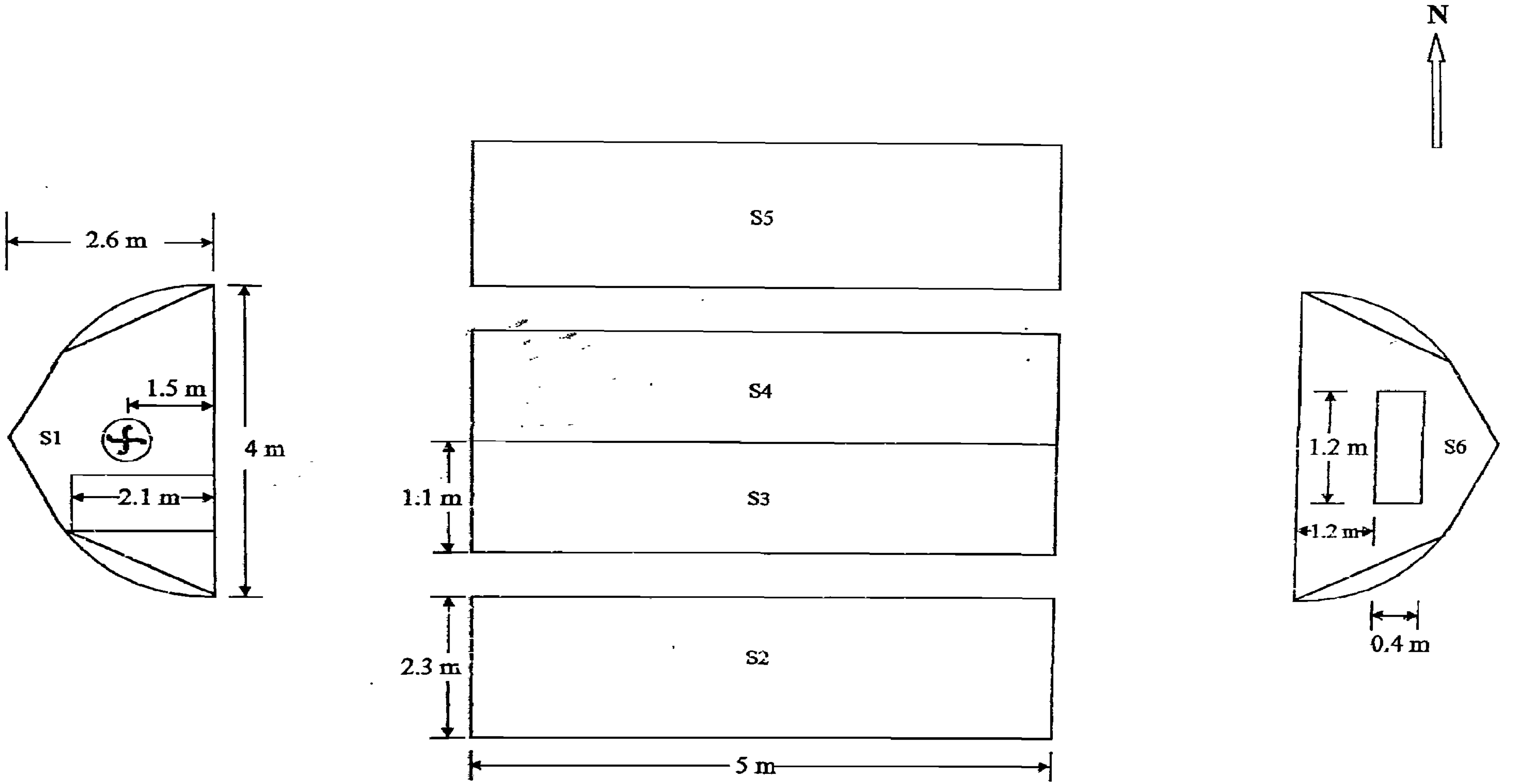


Fig. No.5.1 DETAILS OF TEST GREENHOUSE

than absorb and transmit the far infrared minimally could also be used as thermal screens during night. Hence a 50 percent shade net of woven polyester (2 mm thick) was drawn below the transparent southern side to serve as a thermal screen between 5:30 p.m. and 8:00 a.m. (Plate no.3).

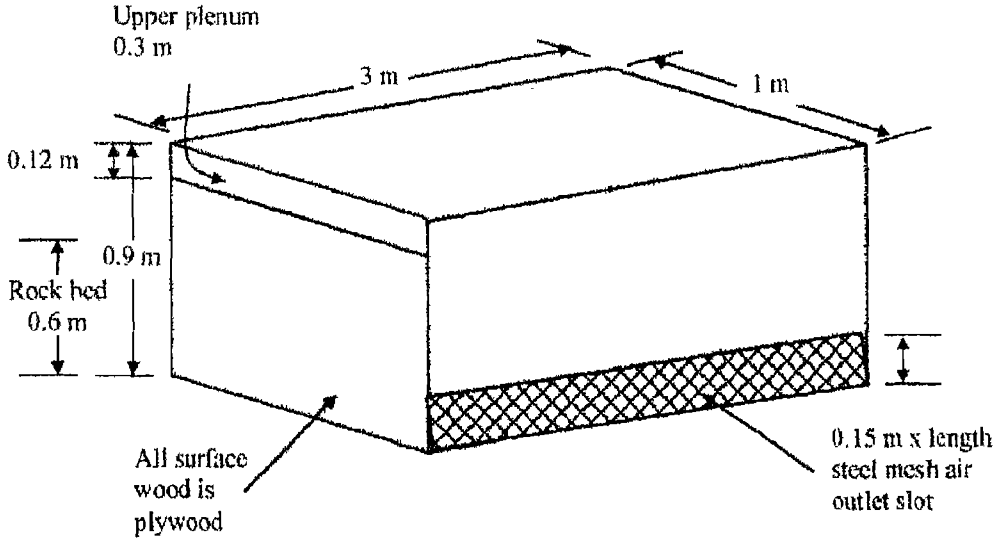


Fig.5.2 Schematic of design selected for rock storage bed modules

Rockbed thermal storage system: A wooden bench of 3m X 1m X 0.9m (Fig.5.2, Plate no.4) housing 1.8 metric ton of 7.5cm size gravel placed

Plate No. 4: Rockbed thermal storage system inside the greenhouse served as a thermal heat storage system. Rocks were filled to a height of 60 cm in the bench providing an upper plenum of 30 cm. The volume of rockbed was calculated based on energy requirement predicted by the simulation model for solar greenhouse. While the design of the rockbed was based on the design developed by Wilson *et. al.* (1977). Schematic representation of the system in presented in fig. 5.3. The space at the top allows a free passage from the inlet at one end of the bench to the far end. Laboratory tests have shown that air introduced in this way will distribute itself uniformly within 10% for downward travel through the rocks at the maximum flow rate. The air exits through steel mesh slots located along the bottom edge of the benches.

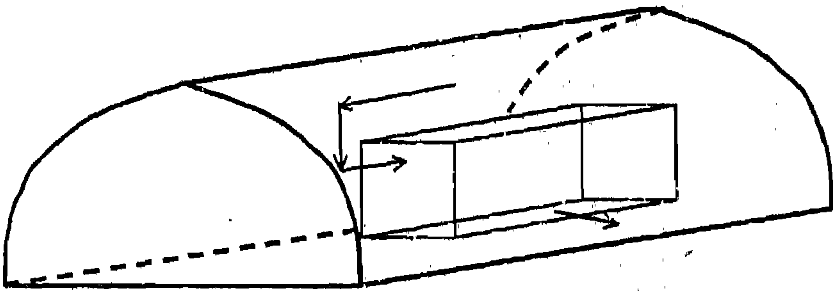


Fig.5.3: Schematic Diagram of the Greenhouse Thermal Storage / Discharge System

Environmental Control: The air temperatures in the greenhouse were controlled in the range of 25-30°C during daytime and 10-15°C during nighttime. If the greenhouse air temperature exceeded 25°C during daytime a thermostat switched on the blower which circulated warm air through the rocks in the rockbed. If the temperature exceeded 30°C, another thermostat switched on the fan that was used to cool the greenhouse by ventilation as the blower alone could not cool the greenhouse air. During nighttime if the greenhouse temperature dropped below 15^{0}C a third thermostat switched on the blower which now circulated the cool greenhouse air through the warm rockbed, thus heating it. If the temperature dropped below 10^{0}C a fourth thermostat switched off the blower and simultaneously switched on the auxiliary heater to heat the greenhouse air.

Greenhouse crop: A tomato crop was transplanted in pots on 10th December 1999 and the crop environment was monitored for validation of the greenhouse model and the adequacy of the design features (Plate no 5). Tomato was selected, as this crop require fairly high temperatures of 22-28^{0}C for its growth. Low night temperatures of winter adversely affect flowering and fruit setting of the crop. The need for the crop was basically to see if with a transpiring crop in the greenhouse the crop environment could be favorably maintained without any supplementary heating.

Plate No.5: Tomato crop in the test greenhouse

Auxiliary heater: An air heater of 4 KwH was fixed at one end of the greenhouse to supplement the greenhouse heating if the greenhouse temperature could not be maintained by the rockbed heat storage.

5.2 Experimental set-up and instrumentation: Sixteen copper-constantan thermocouples were used to measure the temperature of air at the greenhouse ridge, near plants, outside greenhouse, at rockbed inlet and outlet and temperatures of rock at inlet and outlet. Aspirated psychrometers were used to measure wet bulb temperatures of greenhouse and ambient air. A sixteen-channel datalogger of Campbell Scientific Inc. (Plate no.6) was used to record the hourly data. The ambient environmental data of temperature, relative humidity and solar radiation were measured using a weather station and recorded on a Sunitron datalogger. Airflow rate through rockbed was measured using a hot-wire anemometer. An energy meter was used to measure the energy consumed by the air heater for supplementary heating.

Plate No.6: Sixteen-channel datalogger of Campbell Scientific Inc.

The study variables are summarized as below:

Table 5.1 Study variables

S.No.	Parameters	Units
1	Total solar radiation outside the greenhouse	W/m^2
2	Ambient air temperature	^{0}C
3	Ambient air relative humidity	%
4	Greenhouse air temperature	
	a) near ridge	^{0}C
	b) near plants	^{0}C
5	Rockbed air temperature	
	a) at inlet	^{0}C
	b) at outlet	^{0}C
6	Rock temperature	
	a) at inlet	^{0}C
	b) at outlet	^{0}C

Performance of the Solar Greenhouse

Chapter VI

Performance of the Solar Greenhouse

An experimental solar greenhouse described in chapter V with a floor area of 20 m^2 was used for testing the feasibility of the design developed for maintaining favorable environmental conditions for crop growth under cold climate. The air temperature in the solar greenhouse was compared with that of the ambient air and the air in a quonset shaped greenhouse of the same floor area. The measured data was also compared with the predictions of the simulation model. The model was then used to predict the energy requirements of the designed greenhouse and the commonly used lean-to greenhouse under the environmental conditions of Leh using weather recorded at Leh. Cost economics of the designed greenhouse, viz. operating cost, was compared with that of the traditional lean-to greenhouse using Leh weather data.

6.1 Comparison of air temperature in the solar greenhouse, quonset greenhouse and ambient

A qualitative idea about the potential of the designed solar greenhouse to maintain favorable environmental conditions for crop growth could be obtained by comparing the environment inside and outside the solar greenhouse. Total solar radiation, air temperatures and relative humidity values for five of the experimental days are presented in Fig. 6.1. Representative data are appended in Annexure-C. The data indicated that there was an increase of upto 13.2 ^{o}C in the night time temperature.

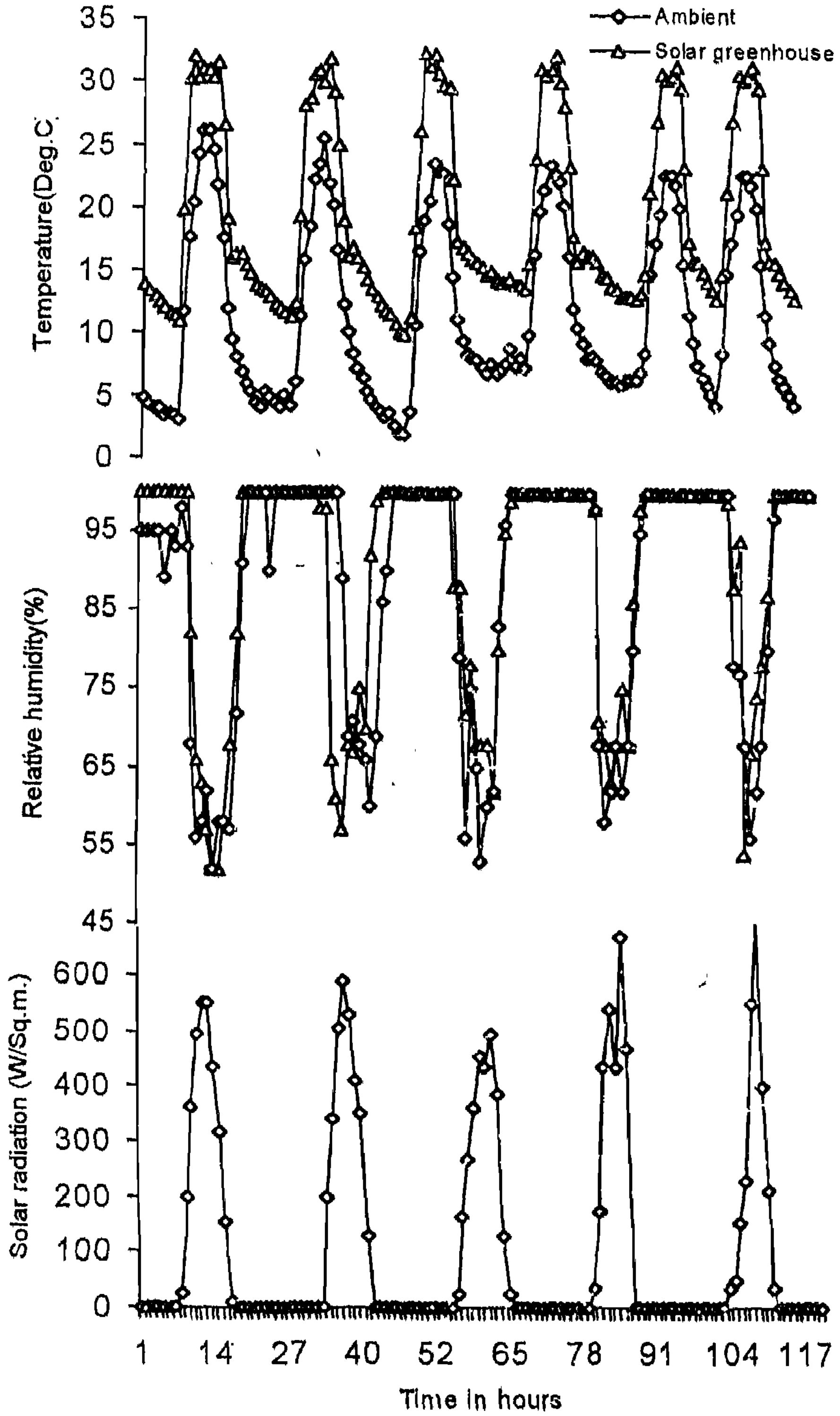


Fig. 6.1 Comparison of thermal environment outside and inside the solar greenhouse for Dec.19-23, 1999

Considering that the test greenhouse was ventilated mechanically only if the temperature exceeded 30°C, evidently, a reduction in the greenhouse air was achieved by using it to heat the rocks in the rockbed. The above fact is evident from fig. 6.2, which summarizes the air temperatures at inlet and outlet of the rockbed. Corresponding data is recorded in Annexure-D. The comparison of temperatures in the control greenhouse and the solar greenhouse is presented in Fig. 6.3 for December 23, 1999, and its tabulated data is presented in Annexure E. It can be inferred that, the crop environment was more favorable in the solar greenhouse as there was a reduction in the peak temperature during daytime, imparting a cooling effect, and an increase in the night time temperature as compared to the control greenhouse due to the rockbed storage. The maximum temperature in the solar greenhouse was 9.4°C lower and the minimum night time temperature was 9.1°C higher as compared to the control greenhouse.

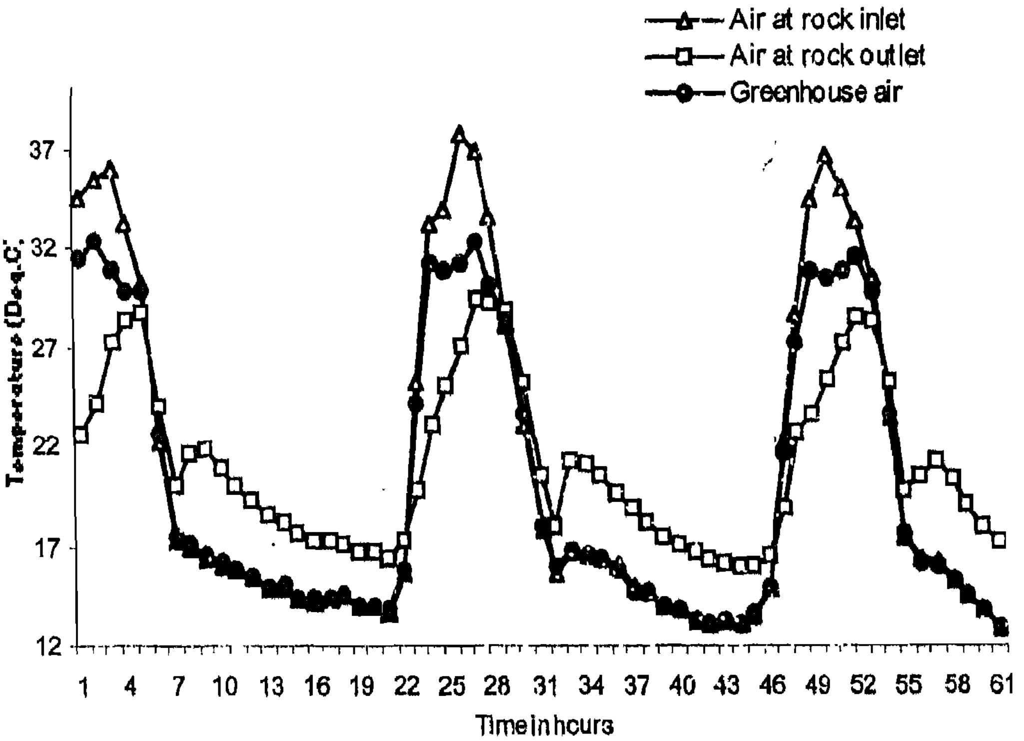


Fig. 6.2 Temperature of air in rockbed

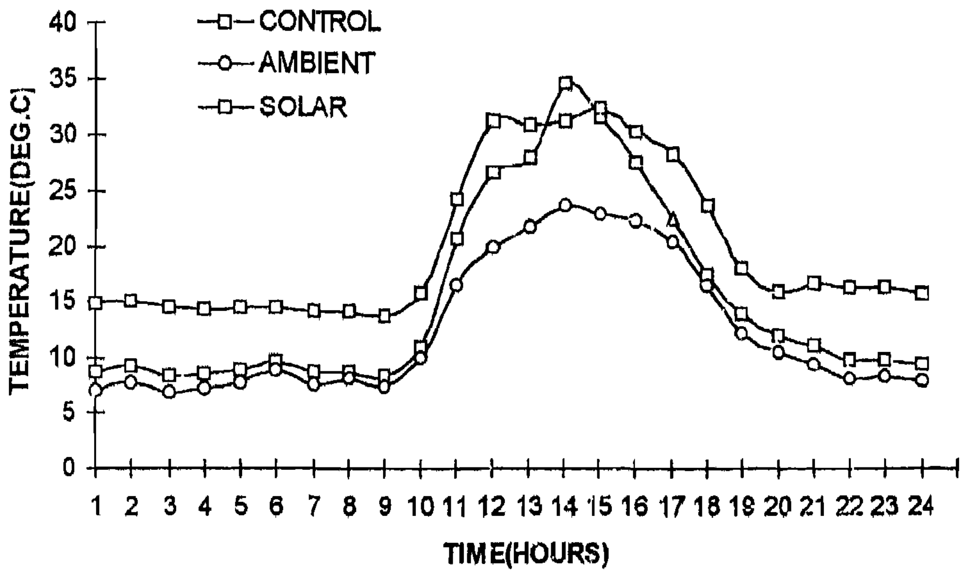


Fig 6.3 Comparison of air temperatures in the solar greenhouse, control greenhouse and ambient for Dec. 23, 1999

6.2 Comparison of model predictions with measured data:

The time dependent model, as discussed in chapter 3, was used to simulate the energy balances in the solar greenhouse with rockbed thermal storage and tomato crop. The model at any time predicted the temperature and relative humidity of the greenhouse air along with energy balances. The results are being discussed using the data for only two days. The results are graphically presented in Fig. 6.4-6.5. The comparison between predicted temperatures and measured temperatures in the solar greenhouse is good. The average deviation for the two days is 1.4°C, the maximum deviation being 5.5°C. The model tends to underestimate the daytime temperatures and overestimate the night time temperatures. A part of the reason could be that the fan and blower flow rates were assumed to be constant. However, it was noticed that due to voltage fluctuations the flow rates were varying considerably. Another reason could be lower flow rate of the rockbed blower which, possibly, did not permit adequate storage/ retrieval of energy. Hence, the rockbed system could not lower the daytime temperatures to the designed value and also could not raise the night time temperatures as much and as fast as predicted by the model.

The comparison between the predicted and measured relative humidities was influenced even more by the above factors. The mean deviation was 10.01 % with the maximum deviation as high as 27.6%. The model tended to underestimate the night time relative humidities. Infiltration-exfiltration in the structure was far more than the estimated value, which influenced the small air mass of the greenhouse. A more realistic record of air exchanges, which needed more sophisticated instrumentation, could have improved the relative humidity predictions. The comparison of the model predictions with the measured data suggests that the mathematical model used for the study is generally capable of simulating the thermal environment of the solar greenhouse. There is a need for improving the model accuracy by selecting more appropriate heat and mass transfer parameters for the analysis. Although the model has been tested using limited experimental data of fifteen days during Dec. 10-25, 1999, the model is quite general in its capabilities. Any reasonable modifications or variations in the structure of the greenhouse and operating conditions can be conveniently handled by suitably modifying the input data. The model accepts the measured data and converts them into Fourier series. Hence, it is possible to provide the environmental parameters for any intended location to evaluate its performance, thus, minimizing the cost of experimental investigations. The model can also be modified to study the feasibility of using any other non-conventional energy resource and any thermal storage/retrieval system.

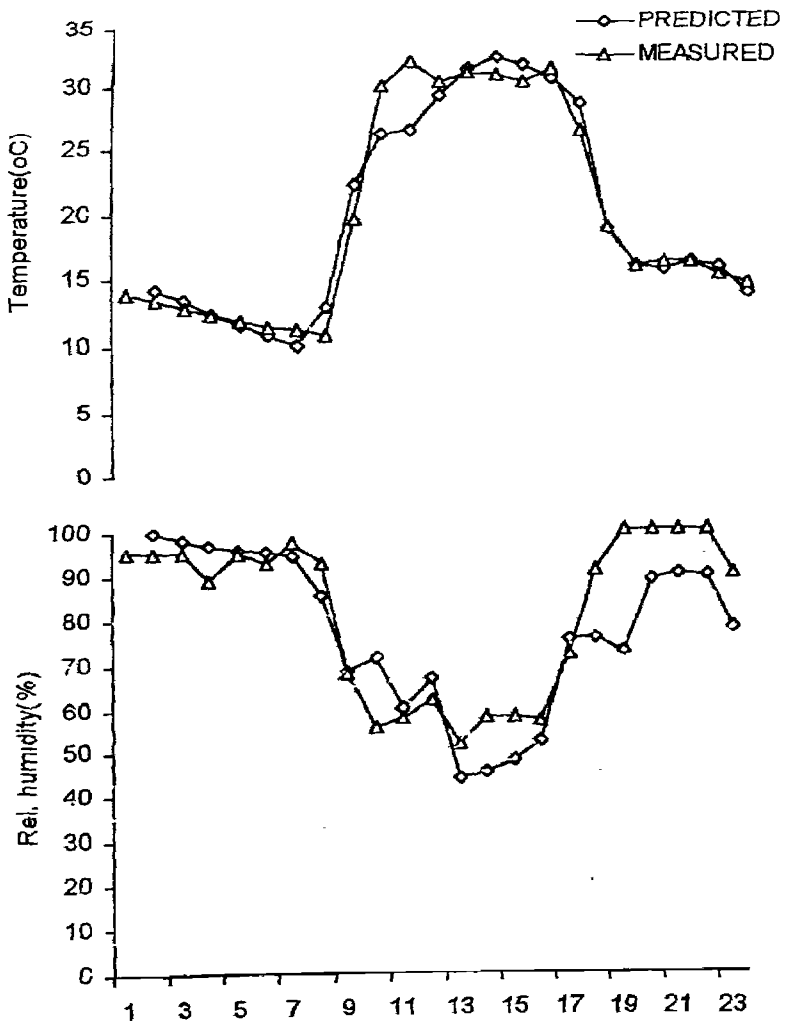


Fig. 6.4 Comparison of measured and predicted data for Dec. 19, 1999

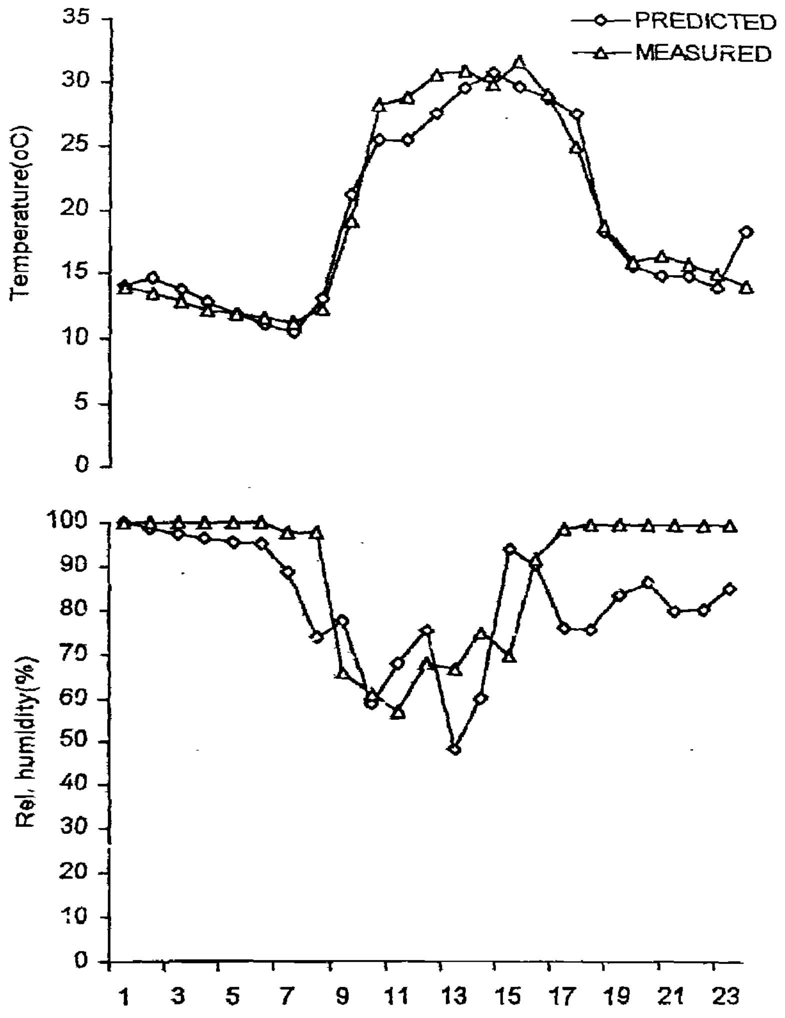


Fig. 6.5 Comparison of measured and predicted data for Dec. 21, 1999

6.3 Thermal performance of the system:

Bouhdjar *et al* (1996) tested the performance of sensible heat storage in a underground rockbed used in a tunnel greenhouse and developed a relationship to define the performance of the storage process on a daily basis. It represented the ratio of heat available in the greenhouse to the heat transferred by air to the rockbed,

$$\eta_s = \frac{\Sigma\, m\, C_{p_a} \,(\, Ta_{b_{in}} - Ta_{b_{ou}})\, \Delta t}{Q_g . A_g - Q_{loss}} \tag{6.1}$$

Where Q_{loss} is heat loss through the covers, to the soil and through air leakage. In order to calculate the thermal efficiency of the solar greenhouse system as a whole, the expression 6.1 was modified as

$$\eta_s = \frac{\Sigma\, m\, Cp_a \,(\, Ta_{b_{in}} - Ta_{b_{ou}})\Delta t}{Q_{net} \cdot A_g} \tag{6.2}$$

The term in the denominator represents the heat available in the greenhouse over a day. In order to appreciate the impact of the storage system on the greenhouse, a heat recovery factor for the storage system defined by Bouhdjar *et al.* (1996) was used. It represents the ratio of the amount of heat delivered by the storage during one night to the amount of heat which was stored during the previous day. It was expressed as

$$\eta_r = \frac{\text{Restituted energy}}{\text{Stored energy}} = \frac{\Sigma\, mCp_a(\, Ta_{b_{in}} - Ta_{b_{ou}})\Delta t \;\; \text{during discharge}}{\Sigma\, mCp_a(Ta_{b_{in}} - Ta_{b_{ou}})\Delta t \;\; \text{during storage}} \tag{6.3}$$

The above formula neglects evaporation and condensation during storage and heat restitution. Both the values were calculated using data presented in Annexure-D.

For an average clear, sunny and cold day the values approximated as summation of hourly values are as follows:

Solar radiation measured outside the greenhouse in a day
= 3.048 kWh/m^2

The average global transmissivity of the greenhouse was found to be 0.500.

Hence, solar radiation available inside the greenhouse for one day
= 1.524 kWh/m^2.

The surface area of the greenhouse = 50.02 m^2

Stored energy = 9.84623 kWh

Restituted = 6.46172 kWh

Hence the storage efficiency

$$\eta_s = \frac{9.84623}{1.524 \times 50.02} \times 100 \quad = 12.92\%$$

Thus, the performance of the designed greenhouse system is better than that described by Bouhdjar *et al.* (1996) as their storage efficiency was reported to be 8 per cent.

The heat recovery factor was found to be

$$\eta_r = \frac{6.46172}{9.84623} \times 100 = 65.63\%$$

The system performance factors found above indicate that the storage efficiency of the designed thermal solar greenhouse system could be increased by better design of the thermal storage system. There have been more radiation and infiltration-exfiltration losses, which could have been reduced by using a better thermal screen and a more airtight structure.

6.4 Simulated performance of designed solar greenhouse under climatic conditions of Leh:

One of the most important utilities of a simulation model of any system is to predict the behavior of the system under a different set of operating conditions for which no experimental data might be available.

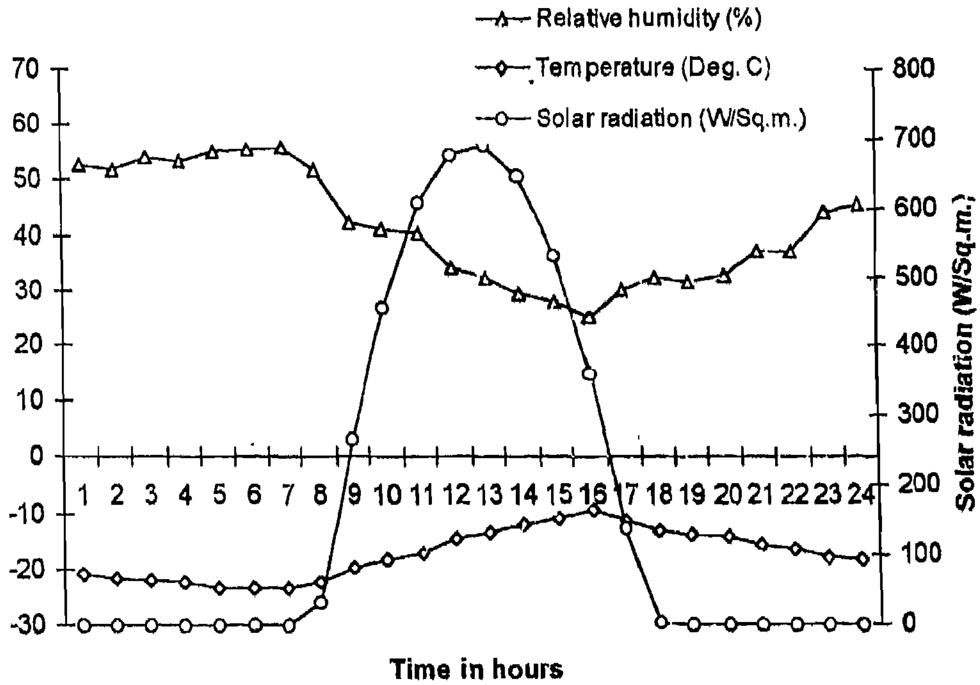


Fig. 6.6 Environmental conditions of Leh for Jan. 1, 1998

Consequently, the effort in the present context is to predict the behavior of the system under a different set of operating conditions not covered by experimental efforts. India has harsh cold climatic conditions for a major part of the year in its hilly region. The model could be used to study the performance of the solar greenhouse under these conditions. For limiting the scope of our present effort, it was assumed that the solar greenhouse designed was used to grow crops under the cold climatic conditions of Leh.

The environmental conditions for Jan. 1, 1998, used for the study, are summarized in Fig. 6.6. The computed energy balances were calculated and are summarized in Fig. 6.7 and Table 6.1. The results suggest that use of the solar greenhouse under cold climatic conditions of Leh could result in 78.3% decrease in energy requirement.

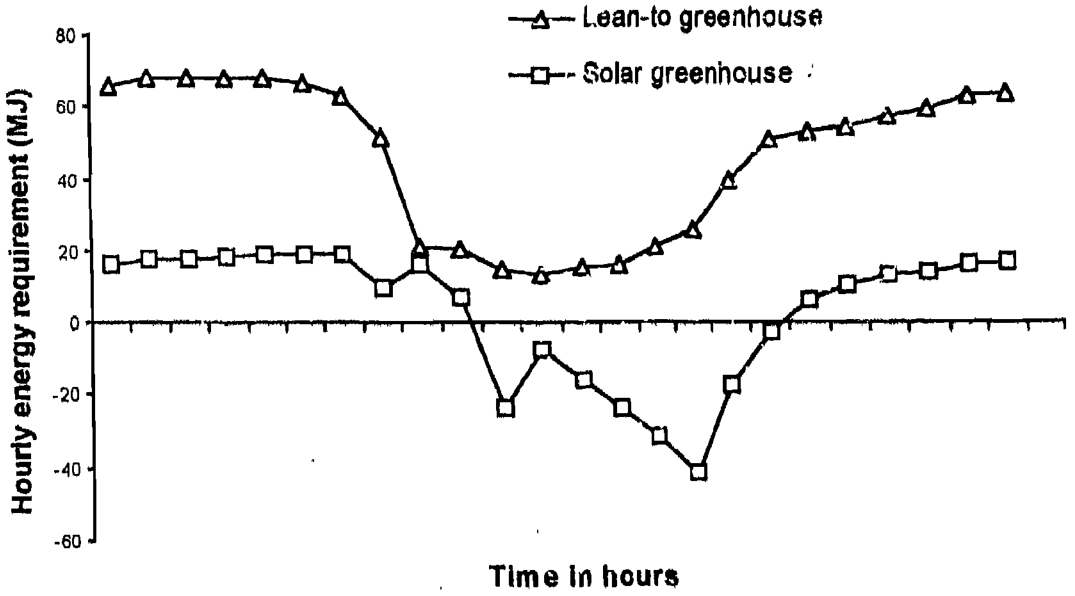


Fig. 6.7 Simulated hourly energy balances for lean-to and solar greenhouses

Table 6.1 Simulated hourly energy balances of Lean-to and Solar greenhouse

Time (Hrs.)	ENERGY REQUIREMENT (MJ)	
	Lean-to greenhouse	**Designed solar greenhouse**
1	65.99	16.54
2	67.75	17.43
3	67.64	17.99
4	68.32	18.47
5	67.72	18.84
6	66.29	19.04
7	62.85	18.95
8	51.43	9.95
9	21.5	16.45
10	20.31	7.24
11	15.16	0
12	13.51	0
13	15.54	0
14	16.3	0
15	21.26	0
16	25.97	0
17	39.66	0
18	50.87	0
19	52.99	6.6
20	54.84	10.78
21	57.42	13.66
22	59.2	14.51
23	62.75	16.48
24	63.6	17.42
Total	1108.87	240.35
% saving in energy		78.32%

6.5 Economic Analysis of Solar Greenhouse

The aim of the study was to design an energy efficient solar greenhouse for the cold climatic conditions of India. Therefore, the comparison of cost economics was carried out for the climatic conditions of Leh. The environmental data for Leh was obtained from automatic data recording station at Indian Astronomical Observatory, Mount Saraswati, Digpa-rtsa-rec, Halec- Ladakh maintained by Indian Institute of Astrophysics, Block II, Koramangala, Banglore, 560 034.

Since, the returns in cash from both the greenhouses were assumed to be the same, a comparison of the fixed and operating costs was carried out. While determining the BEP (break even point), it was found that the total cost of the traditional greenhouse exceeded that of the experimental greenhouse within a year. Hence, it was not necessary to consider maintenance cost for the purpose of comparison as there would be no such cost incurred on this aspect.

The monthly energy requirements of a 100 m^2 designed greenhouse and a traditional lean-to greenhouse to maintain a temperature of 15 ^{o}C at night and 20 ^{o}C during daytime were determined using the simulation model. The environmental data for a representative day of the corresponding month was used to calculate monthly energy requirement. Following assumptions were made for the economic analysis, comparing performances of the lean-to and solar greenhouses.

1. The energy requirement is met using a Kerosene based heating system with an efficiency of 80 per cent
2. The cost of fuel per litre was Rs.3.
3. The electricity charges were Rs.2 per kWh.
4. The labour charges for maintaining the greenhouse were Rs.2500 per month.

The results are summarised in fig 6.8, and table 6.2

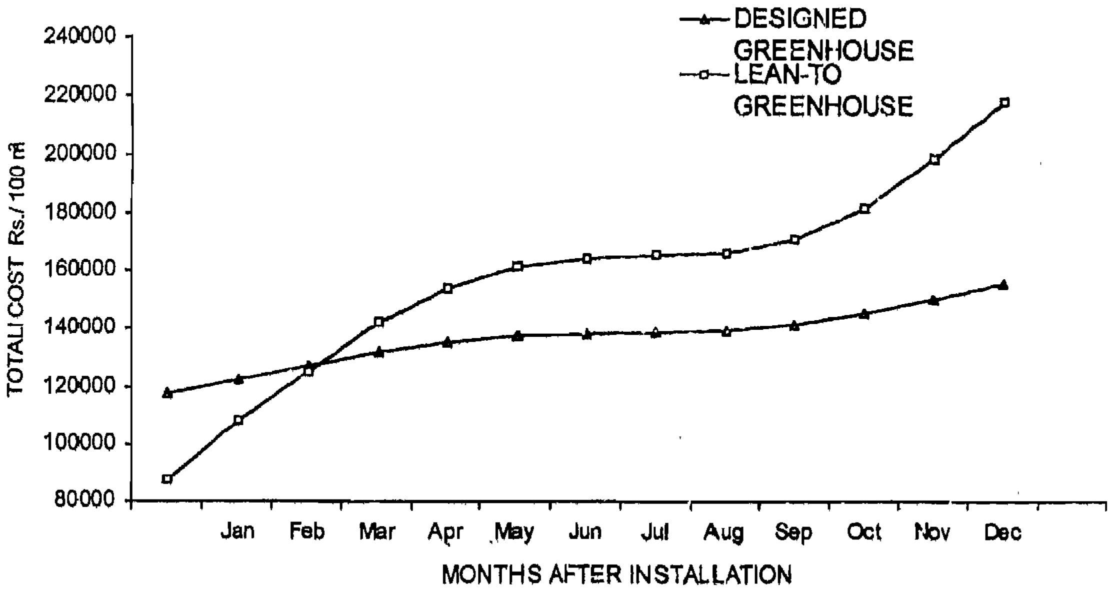


Fig. 6.8 **Simulated monthly total costs for a Lean-to and the solar greenhouse**

Table 6.2: Costs of designed greenhouse and traditional lean-to greenhouse for first year of instalation

Costs	Designed Greenhouse	Lean-to greenhouse
Fixed costs		
Frame	40,000.00	40,000.00
Fans	7,000.00	7,000.00
Blowers	5,500.00	
Rockbed	5,000.00	
Night Curtain	10,000.00	
Thermostat	5,000.00	
North wall Insulation	1,500.00	
Misc.	6,000.00	3,000.00
Total	80,000.00	50,000.00
Annual Operating costs		
Labour cost	30,000.00	30,000.00
Electricity- Fan	7,300.00	7,300.00
Electricity- Blowers	8,560.00	
Fuel cost for heating	38,695.00	1,31,526.00
Grand Total	1,64,555.00	2,18,826.00

It is evident from the above table that the cost of maintaining the desired thermal environment in case of traditional lean-to greenhouse by using conventional heating sources is exorbitantly high and hence not being practiced. On the other hand, the benefits from designed greenhouse is so high that the break even point is achieved during second month of installation.

The performances of both the greenhouses were further compared by reducing the nighttime temperature to 5 °C, so as to reduce the heating cost. As a result, the annual cost of heating with fuel was reduced to Rs.81,059 and Rs.9,908 for lean-to and the designed greenhouses respectively. However, the BEP was pushed by only one month(fig.6.9).

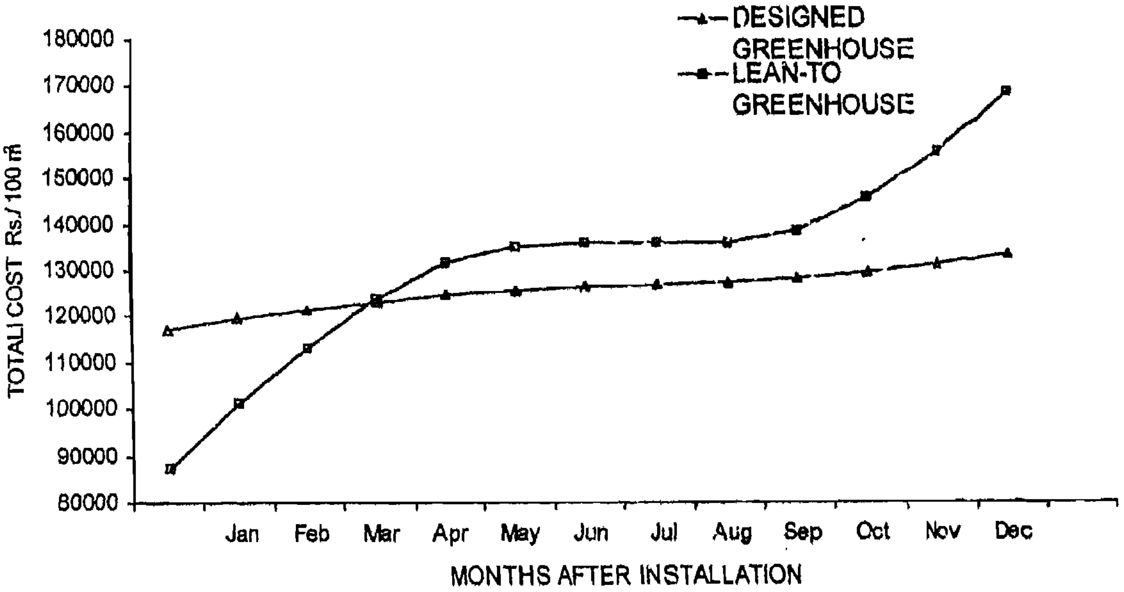


Fig. 6.9 **Simulated monthly total costs for a Lean-to and the solar greenhouse**

Summary and Conclusions

Chapter VII

Summary and Conclusions

A time dependent mathematical model has been developed to simulate the thermal environment of a greenhouse. The model was used to study the effects of different shapes, orientation and various energy conservation measures viz., north wall insulation, double wall glazing and night curtains on the heating requirements of a 12m X 200m greenhouse situated at Delhi under the environmental conditions of a cold sunny day. The model predicted that

1) a gothic arch shaped greenhouse required 2.6 per cent and 4.2 per cent less heating as compared to gable and quonset shapes, respectively,
2) an east-west oriented gothic arch greenhouse required 2 per cent less heating as compared to a greenhouse of the same size oriented north-south,
3) north wall insulation of a gothic arch greenhouse reduced the structure's heating requirements in east-west orientation by 30 per cent as compared to around 5 per cent in north-south orientation. This was because the north wall area in a north-south oriented greenhouse was only 39.18 m^2, while the area available in an east-west oriented greenhouse was 1584.0 m^2,
4) the use of night curtain with high thermal reflectivity below the greenhouse cover reduced the night time heating requirements by 70.8 per cent. The daily heating requirement was reduced by 60.6 per cent,
5) the effect of replacing the single cover on the southern side with air inflated double wall glazing was a reduction in the heating requirement of the gothic greenhouse by 23 per cent,
6) a 350 m^3 internal rockbed thermal storage/retrieval system with gravel of 5 cm dia. could completely meet the heating energy requirements of an east-west oriented gothic arch greenhouse with all above mentioned energy conservation measures.

Thus, the results suggested that an ideal design of a greenhouse for cold climatic conditions of India should have the following design features:

i) East-west orientation
ii) Gothic arch shape
iii) North wall insulation
iv) Use of a night curtain
v) Air inflated double wall glazing
vi) An internal / external solar thermal storage system

Based on the above design a 4m X 5m gothic arch greenhouse with a ridge height of 2.6 m oriented east-west with a 5cm thick thermocole insulation on the north wall and air inflated double wall glazing on the south side was constructed at the division of Agril. Engineering, I.A.R.I., new Delhi - 12. A woven polyester shade net was used on the south side as an internal night curtain between 5 p.m. and 8 a.m. The greenhouse had an internal rockbed to supply the heating requirements of the greenhouse to maintain its temperature between 10-15 °C during night time and 20-25 °C during day time. The charging of the rockbed was started at a temperature of 25°C.

The designed greenhouse was tested for its capability to maintain suitable thermal environment for crop growth. The data for testing was recorded between December 10-25, 1999. The data was also used to test the ability of the model to predict the thermal environment in the solar greenhouse.

The results indicated that the thermal environment in the solar greenhouse was more favorable for crop growth as compared to the ambient and a control quonset shaped greenhouse of the same size. The air temperatures during night in the solar greenhouse were 13.2 °C and 9.1 °C higher than the ambient and the control greenhouse. The thermal performance of the model was evaluated using hourly temperatures of air in the rockbed. The heat storage efficiency and the heat recovery factor of the greenhouse were 12.9 per cent and 65.6 per cent, respectively.

The comparison between the predicted and measured parameters suggested that the model could be used to simulate the performance of the solar greenhouse under different operating conditions. For the representative test days used the average deviation in temperature comparisons was 1.6 °C. The comparison between the predicted and measured relative humidities indicated the mean deviation to be 10.2 per cent.

The simulation model was used to predict the energy balances for the designed solar greenhouse and a traditional lean-to greenhouse of the same area under the environmental conditions of Leh on January 1, 1998. The model predicted that 78 per cent energy could be saved using the solar greenhouse with rockbed thermal storage/retrieval system to maintain the night time temperature of 15 °C and the day time temperature of 20 °C.

A comparison of the cost economics of the designed greenhouse and that of the lean-to greenhouse was carried out for the cold climatic conditions of Leh. To maintain a temperature of 15 °C during night time and 20 °C during day time, the cost of conventional fuel was so high that the break even point was achieved during the second month itself. If the night time temperatures were maintained at 5 °C instead of 15 °C, the BEP was achieved in the third month after installation.

On the basis of the present study the following conclusions are being drawn:

(1) A generalised mathematical model of the greenhouse thermal environment has been developed. The model predicts the effect of shape, orientation, thermal insulation, night curtains, air inflated double walled glazing and rockbed thermal storage on the heating requirements of a greenhouse.

(2) A gothic arch greenhouse requires the least heating energy i.e. 2.6 per cent and 4.2 per cent less as compared to gable and quonset greenhouses.

(3) Under north Indian cold climatic conditions an east-west oriented greenhouse requires about 2 per cent less heating in comparison to a north-south oriented greenhouse.

(4) The proposition of north wall insulation is more effective in an east-west oriented greenhouse as compared to a north-south oriented gothic arch greenhouse, saving 30 per cent of heating energy.

(5) The use of night curtains in an east-west oriented greenhouse can save 71 per cent of the night heating requirements and 61 per cent of the daily energy requirements.

(6) The use of air inflated double wall glazing on the south side of the greenhouse reduces the heating requirement by 23 per cent.

(7) In an east-west oriented gothic arch greenhouse with all above mentioned energy conservation measures with a rockbed of adequate size has no heating requirement.

(10)The experimental solar greenhouse designed on the basis of the above mentioned criteria could maintain favorable thermal environment for crop growth as compared to the ambient and a quonset greenhouse. Night time temperatures in the solar greenhouse were 13.2 °C and 9.1 °C higher than the ambient and the control greenhouse respectively.

(11)The heat storage factor and the heat recovery factor for the solar greenhouse were 12.9 per cent and 65.6 per cent. However, there is scope for improvement of the thermal performance of the solar greenhouse system..

(12)The simulation model indicates that the designed solar greenhouse could save the daily heating requirements by 78 per cent for a cold sunny day in Leh as compared to the traditional lean-to greenhouse.

(13)Comparison of the cost economics of a lean-to and the design greenhouse under the environmental conditions of Leh indicates that the extra cost of installation of the design greenhouse is paid back in 2 to 3 months.

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Annexure

ANNEXURE -A

INPUT DATA FOR SOLFOR

The input data for SOLFOR should be prepared as described below:

1. CONTROL LINE (615), one line

Columns	Variables	Description
1-5	NP	Number of hourly data points available for computing the Fourier series
6-10	NH	Number of harmonics desired
11-15	NS	Number of single layer translucent* cover surfaces in the greenhouse
16-20	ND	Number of double layer translucent* cover surfaces in the greenhouse
21-25	NM	Number of opaque* cover surfaces in the greenhouse
26-30	NG	Number of ground surfaces** which surround the greenhouse

*The translucent and opaque covers refer to the solar radiation spectrum

**If the ground surface surrounding the greenhouse has uniform reflectivity for solar radiation, then NG equals 1.

2. GENERAL DATA (5F10.4), one line

Columns	Variables	Description
1-10	ALAT	Latitude of the greenhouse location (radian) (+ north, - south)
11-21	ALONG	Longitude of the greenhouse location (radian) (+ west, - east)
21-30	TZN	Time zone number (hours west of (0° meridian)
31-40	DELTA	Declination angle of the sun (radian)
41-50	EQT	Equation of time (hour)

3. TEMPERATURE & RELATIVE HUMIDITY FOR OUTSIDE TOTAL SOLAR RADIATION INDICENT ON A HORIZONTAL SURFACE IN THE VICINITY OF THE GREENHOUSE (8F10.4), as many lines as necessary for 5*NP values. Each variable starts on a new line.

Variables	Description
TO (I)	NP values of the outside air temperature (°C)
RHO (I)	NP values of the outside air relative humidity (fraction)
SWM (I)	NP values of total sol. rad. incident on a horizontal surface (W/m^2)

4. SURFACE DATA (4F10.4), one line

Columns	Variables	Description
1-10	FRF	Floor angle factor for direct solar radiation
11-20	FRP	Plant angle factor for direct solar radiation
21-30	AHF	Floor absorptivity for solar rad.
31-80	RHG (K)	Reflectivities (solar radiation) for different ground surfaces surrounding the greenhouse (up to a maximum of five)

5. SURFACE DATA (8F10.4), one line

Columns	Variables	Description
1-10	RHF	Greenhouse floor reflectivity for solar radiation
11-20	DF	Greenhouse floor area (m^2)
21-30	FFP	Shape factor of the floor w.r.t. the plants
31-40	AHP	Solar absorptivity for the plant canopy
41-50	RHP	Solar reflectivity for the plant canopy
51-60	DP	Plant canopy area, m^2
61-70	FPP	Shape factor of the plants w.r.t. the plants
71-80	FPF	Shape factor of the plants w.r.t. the floor

There are (NS + ND + NM) sets of the following categories of the input data.

6. SURFACE DATA (8F10.4), one line

Columns	Variables	Description
1-10	AH (K)	Solar absorptivity for the cover surface
11-20	TH (K)	Solar transmittance for the cover
21-30	AL (K)	The cover thickness, m
31-40	AX (K)	Solar rad. extinction coefficient for the cover (m^{-1})
41-50	AN (K)	Cover index of rafraction for sol. rad. spectrum
51-60	AREA (K)	Cover area receiving sol. rad. (m^2)
61-70	WA (K)	Azimuth for the cover measured from south going westwards (radian)
71-80	WT (K)	Tilt angle for the cover measured from horizontal (radian)

7. SHAPE FACTORS (8F10.4), one line

Columns	Variables	Description
1-10	SFA (K)	Shape factor of a cover surface w.r.t. sky
11-20	SFP (K)	Shape factor of a cover surface w.r.t. plant canopy
21-30	SFF (K)	Shape factor of a cover surface w.r.t. the greenhouse floor
31-80	SFG (K,KG)	KG values of the shape factors of a cover surface w.r.t. the surrounding ground surfaces

ANNEXURE - B

INPUT DATA FOR ROCK

Input data preparation for ROCK is divided into three categories.

Direct Data Input:

Data in this category is directly supplied to the program by the user. Description of the data, in sequence, is given below. Units for the variables are mentioned for convenience.

1. PROBLEM TITLE (A80), one line

2. DESCRIPTION OF PROBLEM PARAMETERS(12I5, F8.1), one line

Columns	Variables	Description
1-5	NIDIM	Number of one-dimensional elements
6-10	NEL	Total number of elements
11-15	NODES	Total number of nodes
16-20	NMAT	Number of different materials involved
21-25	NCONST	Number of specified temperature nodes
26-30	NCONV	Number of elements with convection B.C.
31-35	NRAD	Number of surfaces involved in thermal radiation exchange
36-40	NFLUX	Number of elements with normal flux B.C.
41-45	NHEAT	Number of elements with internal heat generation
46-50	INDIC	Steady-state or time-dependent analysis (0=steady-state, 1-time-dependent)
51-55	NOIT	Number of time increments for time dependent analysis
56-60	IPRINT	Number of time increments after which the computation of results should be printed
61-68	DELTA	Time increment (s)

3. ROCKBED PARAMETERS (8f10.4), one line

Columns	Variables	Description
1-10	RBL	Length of the rockbed
11-20	RBA	Rockbed area normal to the airflow
21-30	RBP	Bulk density of the rockbed
31-40	CB	Specific heat capacity of the rocks
41-50	RK	Thermal conductivity of the rocks
51-60	U	Rockbed perimeter heat loss factor

61-70	RBP	Effective perimeter of the rockbed
71-80	DE	Equivalent rock particle diameter

4. ROCKBED PARAMETERS CONTD. (8f10.4), one line

Columns	Variables	Description
1-10	E	Porosity of the rockbed
11-20	DT	Differential rockbed length
21-30	DX	Differential rockbed length
31-40	FRBLO	Flow rate of the blower
41-50	FRFAN	Flow rate of the ventilation fan
51-60	TLIM1	Base temperature for heat collection
61-70	TLIM2	Temperature for switching on fan in SUBR. ROCKBED

5. SOME GENERAL DATA (10x, 7F10.2), one line

Columns	Variables	Description
11-20	GLENTH	Length of the greenhouse along its axis (m)
21-30	VOLUME	Volume of the structure (m^2)

6. MATERIAL PROPERTIES (10X, 2F10.2), NMAT lines

Columns	Variables	Description
11-20	COND (M,1)	Thermal conductivity of material M in x-direction (W/(m°K)
21-30	COND (M,2)	Thermal conductivity of material M in y direction (M/(m°K)
31-40	PC (M)	Volumetric heat capacity of material M (J/m$^{3\circ}$K))

7. NODAL INFORMATION (10X, 2F10.5), NODES lines

Columns	Variables	Description
11-20	X (K, 1)	x-coordinate of the node K (m)
21-30	X (K, 2)	y-coordinate of the node K (m)

8. SPECIFIED TEMPERATURE NODES (25I3) As many lines as necessary for NCONST numbers

Columns	Variables	Description
1-75	MCONST(J)	Mode numbers with specified temperature condition

9. ELEMENTS WITH INTERNAL HEAT GENERATION (25I3) As many lines as necessary for NHEAT numbers

Columns	Variables	Description
1-75	MHEAT (I)	Element numbers with internal heat generation

10. THERMAL RADIATION INFORMATION

The following two lines are required for each of the NRAD surfaces participating in thermal radiation exchange:

FIRST LINE (10x, 2F5.3, 12I2)

Columns	Variables	Description
11-15	ET (I)	Emissivity for thermal radiation
16-20	TT (I)	Transmissivity for thermal radiation
21-22	KC (I)	Surface number of the other side of a translucent surface. Leave blank for an opaque surface
22-24	KT (I)	Total number of surfaces (up to 10) with whom this surface directly exchanges radiation
25-44	(KS (I, J), J=1, 10)	Surface number of those surfaces directly exchanging radiation with this surface

SECOND LINE (10X, 10F5.3)

Columns	Variables	Description
11-60	SF (I, J)	Shape factors of surface I w.r.t. to the surfaces it sees. Sequence of the shape factors coincides with KS (I, J) from previous card

11. NORMAL FLUX BOUNDARY CONDITION (6 I 5)

NFLUX lines are required.

Columns	Variables	Description
1-5	LFLUX (I)	Element number with normal flux boundary condition
6-10	MFLUX (I)	A code to indicate if the b.c. exists on sides, and surfaces or both (1=sides,, 2=end surfaces, 3=both)
11-20	ISIDEF (I, J)	Sides (at the most two) on which this b.c. exists
21-30	IENDF (I, J)	End surfaces* of the element with this b.c. (1=yes, blank=no)

*One dimensional elements have two end surfaces. For 1-D elements, end surface on node I occupies the first space and the end surface on node I occupies the first space and the end surface on node J the second space.

12. CONVECTION BOUNDARY CONDITION (6I5, 4F10.3)

NCONV lines are required

Columns	Variables	Description
1-5	LCONV (I)	Element number with convection b.c.

6-10	MCONV (J)	A code to indicate if the b.c. exists on sides, end surfaces, or both (1=sides, 2=end surfaces, 3=both)
11-20	ISIDEC (I, J)	Sides (at the most two) on which this b.c. exists
21-30	IENDC (I, J)	End surfaces* of the element on which this b.c. exists (1=yes, 0=no)
31-50	HCONVB (I, J)	Convective heat transfer coefficient of sides I and J (31-40) (41-50)
51-70	HCONVE (I, J)	Convective heat transfer coefficient of erds I and J (51-60) (61-70)

*See the footnote * (above) for normal flux b.c.

13. ELEMENT INFORMATION

First N1DIM 1-D elements (10X, 4I5, 2F10.2) N1DIM Lines

Columns	Variables	Description
11-25	INDEX	I, J, and K, node numbers counterclockwise. Leave blank in place of K for 1-D elements
26-30	MMAT (I)	Material number constituting the element
31-40	AREA (I)	End area (m^2)
41-50	P (I)	Perimeter of the element (m)

14. INITIAL TEMPERATURE FIELD (8F10.5)

As many lines as necessary for NODES values.

Columns	Variables	Description
1-80	T(K)	Initial temperature of the nodes (°C)

II.SOLFOR Output:

The portion of SOLFOR output directed to unit 11 forms the part of ROCK input. The following information is sought:

1. CONTROL CARD (5I5), one line

Columns	Variables	Description
1-5	NP	Number of data points used in constructing the Fourier series for a function
6-10	NH	Number of required harmonics
11-15	NS	Number of single layer translucent cover surfaces in the greenhouse

16-20	ND	Number of double layer translucent cover surfaces in the greenhouse
21-25	NM	Number of opaque cover surfaces in the greenhouse

All the remaining information follows the (5E15.6) for mat. Each category starts on a new line and requires as many lines as necessary for the number of values indicated with each category.

2. AQA (K)

Average of the Fourier series used to represent absorbed solar radiation fluxes for the greenhouse surfaces (NS + ND + NM + 2 values)

The following two categories are repeated for NH number y harmonics.

3. QAM (J, K)

Modulli of the Fourier series for greenhouse surfaces (NS + ND + NM + 2 values) for jth harmonics.

4. GA (J, K)

Phase angles of the Fourier series for greenhouse surfaces (NS + ND + NM + 2 values) for jth harmonics.

5. Coefficients of the Fourier series for solar radiation incident on a horizontal surface. (2*NH +1) values.

ASW	Average
SWP (J)	NH values of the modulli
GSW (J)	NH values of the phase angles

6. Coefficients of the Fourier series for outside air temperature. (2*NH +1) values.

ATO	Average
TOM (J)	NH values of the modulli
PSIO (J)	NH values of the phase angles

7. Coefficients of the Fourier series for ralative humidity of the outside air. (2*NH + 1) values.

ARHO	Average
RHOM (J)	NH values of the modulli

XIO (J) NH values of the phase angles

III. Subprogram modification:

Depending upon the problem under consideration, some or all of the following subroutines may need to be modified.

1. AIRBAL (CONRAT)
2. AMBI (NCONV, TIME)
3. CONDEN (RHO, RHI, CONRAT)
4. CONST (TC, NCONST, TIME)
5. FLUX (NFLUX, TIME)
6. QGEN (QP, NHEAT, TIME)
7. RADF
8. RADT
9. ROCKBED(TDSIRE, TIME, I1, BALANS)
10. SOLRAD (T, QP)
11. TIN
12. TRANSP

Functions of each of the above mentioned subroutines is explained in the ROCK listing (Appendix B). Portions of these subroutines needing modifications are also stated there.

APPENDIX B-1

LISTING OF SOLFOR PROGRAM

```
C       SOLFOR.FOR SOLAR RADIATION
        REAL HS(24),VER(24),VERM(10),HSM(10),PSII(10),SWP(10),GSW(10)
        REAL TO(24),RHO(24),SWM(24),AH(15),TH(15),AL(15),AN(15),AX(15)
        REAL AREA(15),WA(15),WT(15),SFA(15),SFG(15,5),SFP(15),SFF(15)
        REAL RH(15),RHG(5),RG(15),QA(24,15),QAF(24),QAP(24),XII(10)
        REAL AQA(15),QAM(10,15),GA(10,15),QAPM(10),QAFM(10),GAP(10)
        REAL GAF(10)
        REAL TOM(10),PSIO(10),A1(24),B1(10),C1(10),RHOM(10),XIO(10)
        REAL QAS(15)
        COMPLEX EYE,ZERO,CMPLX,PQA(15)
        DATA QA/360*0./
        OPEN(5,FILE='SOLFOR.DAT',STATUS='OLD')
        OPEN(6,FILE='SOLFOR1.OUT')
        OPEN(7,FILE='SOLFOR2.OUT')
        WRITE(6,59)
   59   FORMAT('0',20X,'THE FOLLOWING IS YOUR INPUT DATA SET',/)
        READ(5,5)NP,NH,NS,ND,NM,NG
        WRITE(6,69)NP,NH,NS,ND,NM,NG
   69   FORMAT(' ',6I5)
    5   FORMAT(7I5)
        READ(5,15)ALAT,ALONG,TZN,DELTA,EQT
   15   FORMAT(8F10.4)
        WRITE(6,79)ALAT,ALONG,TZN,DELTA,EQT
   79   FORMAT(' ',8F10.4)
        READ(5,15) (TO(I),I=1,NP),(RHO(I),I=1,NP)
        WRITE(6,79) (TO(I),I=1,NP),(RHO(I),I=1,NP)
c       READ(5,15) (HS(I),I=1,NP),(VER(I),I=1,NP)
c       WRITE(6,79) (HS(I),I=1,NP),(VER(I),I=1,NP)
        READ(5,15) (SWM(I),I=1,NP)
        WRITE(6,79) (SWM(I),I=1,NP)
        READ(5,15) FRF,FRP,AHF,(RHG(K),K=1,NG)
        WRITE(6,79) FRF,FRP,AHF,(RHG(K),K=1,NG)
        READ(5,15) RHF,DF,FFP,AHP,RHP,DP,FPP,FPF
        WRITE(6,79) RHF,DF,FFP,AHP,RHP,DP,FPP,FPF
        NT=NS+ND+NM
        DO 2 K=1,NT
        READ(5,15) AH(K),TH(K),AL(K),AX(K),AN(K),AREA(K),WA(K),WT(K)
```

```
      WRITE(6,79) AH(K),TH(K),AL(K),AX(K),AN(K),AREA(K),WA(K),WT(K)
      RH(K)=1.-AH(K)-TH(K)
      READ(5,15) SFA(K),SFP(K),SFF(K),(SFG(K,KG),KG=1,NG)
      WRITE(6,79) SFA(K),SFP(K),SFF(K),(SFG(K,KG),KG=1,NG)
    2 CONTINUE
      DRC=0.1
      DO 4 K=1,NT
      RG(K)=0.
      DO 4 KG=1,NG
    4 RG(K)=RG(K)+RHG(KG)*SFG(K,KG)
      HH=ACOS(-TAN(ALAT)*TAN(DELTA))
      TR=TAN(DELTA)/TAN(ALAT)
      SRT=12.-HH*3.82-EQT-TZN+ALONG*3.82
      SST=24.-SRT
      DO 6 I=1,NP
      DNSW=0.
      QHF=0.
      QHP=0.
      TIME=I
      EST=TIME
      IF (EST.LT.0.) EST=EST+24.
      H=0.261799*(EST-12.+TZN+EQT)-ALONG
      IF(ABS(H).LE.ABS(HH)) GO TO 3
      GO TO 7
    3 Z=ACOS(SIN(ALAT)*SIN(DELTA)+COS(ALAT)*COS(DELTA)*COS(H))
      W=ACOS(COS(DELTA)*SIN(H))
      DNSW=(1.-DRC)*SWM(I)/COS(Z)
      IF(COS(H).GT.TR) GO TO 9
      S=ACOS(-SQRT(1.-COS(Z)*COS(Z)-COS(W)*COS(W)))
      GO TO 11
    9 S=ACOS(SQRT(1.-COS(Z)*COS(Z)-COS(W)*COS(W)))
   11 IF(NS.EQ.0) GO TO 13
      DO 8 K=1,NS
      CALL THETA(WA(K),WT(K),S,W,Z,R6)
      CALL AR(R6,AX(K),AN(K),AL(K),SS4,SS5)
      IF (R6.LE.0.01) GO TO 17
      IF (R6.GT.1.570796) GO TO 17
      QTH=AREA(K)*SS4*DNSW*COS(R6)
      QTD=AREA(K)*TH(K)*SWM(I)*(DRC*SFA(K)+RG(K))
      GO TO 27
   17 QTD=AREA(K)*TH(K)*SWM(I)*(DRC*SFA(K)+RG(K))
      QTH=0.
```

```
27   QA(I,K)=QTH*SS5/SS4+QTD*AH(K)/TH(K)
     QHF=QHF+QTH*FRF+QTD*SFF(K)
     QHP=QHP+QTH*FRP+QTD*SFP(K)
 8   CONTINUE
13   IF(ND.EQ.0)GO TO 19
     N1=NS+1
     N2=NS+ND
     DO 10 K=N1,N2,2
     K1=K+1
     CALL THETA(WA(K),WT(K),S,W,Z,R6)
     CALL AR(R6,AX(K),AN(K),AL(K),SS4,SS5)
     CALL AR(R6,AX(K1),AN(K1),AL(K1),U4,U5)
     IF(R6.LE.0.01) GO TO 21
     IF(R6.GT.1.570796) GO TO 21
     QTHU=AREA(K)*SS4*DNSW*COS(R6)
     QTDU=AREA(K)*TH(K)*SWM(I)*(DRC*SFA(K)+RG(K))
     K1=K+1
     QTHL=U4*QTHU*AREA(K1)/AREA(K)
     QTDL=TH(K1)*AREA(K1)*QTDU/AREA(K)
     GO TO 29
21   QTDU=AREA(K)*TH(K)*SWM(I)*(DRC*SFA(K)+RG(K))
     QTHU=0.
     QTHL=0.
     QTDL=AREA(K1)*TH(K1)*QTDU/AREA(K)
29   QA(I,K)=QTHU*SS5/SS4+QTDU*AH(K)/TH(K)
     QA(I,K1)=QTHL*U5/U4+QTDL*AH(K1)/TH(K1)
     QHF=QHF+QTHL*FRF+QTDL*SFF(K1)
     QHP=QHP+QTHL*FRP+QTDL*SFP(K1)
10   CONTINUE
19   IF(NM.EQ.0) GO TO 23
     N1=NS+ND+1
     N2=NS+ND+NM
     DO 12 K=N1,N2,2
     CALL THETA(WA(K),WT(K),S,W,Z,R6)
     IF(R6.LE.0.01) GO TO 31
     IF(R6.GT.1.570796) GO TO 31
     QA(I,K)=AREA(K)*AH(K)*(DNSW*COS(R6)+SWM(I)*(DRC*SFA(K)+RG(K)))
     GO TO 12
31   QA(I,K)=AREA(K)*AH(K)*SWM(I)*(DRC*SFA(K)+RG(K))
12   CONTINUE
23   QAP(I)=AHP*QHP
     QAF(I)=AHF*QHF
```

```
      IF(NS.EQ.0) GO TO 37
      DO 16 K=1,NS
      AA=0.
      IF(DP.GT.0.) AA=RHF*SFP(K)*QHP/DP
      BB=RHP*SFF(K)*QHF/DF
16    QA(I,K)=QA(I,K)+AH(K)*AREA(K)*(AA+BB)
37    IF(ND.EQ.0) GO TO 39
      N1=NS+1
      N2=NS+ND
      DO 18 K=N1,N2,2
      K1=K+1
      AA=0.
      IF(DP.GT.0.) AA=RHP*SFP(K1)*QHP/DP
      BB=RHF*SFF(K1)*QHF/DF
      QA(I,K1)=QA(I,K1)+AH(K1)*AREA(K1)*(AA+BB)
 18   QA(I,K)=QA(I,K)+AH(K)*TH(K1)*AREA(K1)*(AA+BB)
 39   IF(NM.EQ.0) GO TO 6
      N1=NS+ND+1
      N2=NS+ND+NM
      DO 20 K=N1,N2,2
      K1=K+1
      AA=0.
      IF(DP.GT.0.) AA=RHP*SFP(K1)*QHP/DP
      BB=RHF*SFF(K1)*QHF/DF
 20   QA(I,K1)=QA(I,K1)+AH(K1)*AREA(K1)*(AA+BB)
      GO TO 6
 7    DO 14 K=1,NT
 14   QA(I,K)=0.
      QAP(I)=0.
      QAF(I)=0.
 6    CONTINUE
      DO 40 I=1,NP
      DO 50 K=1,NT
 50   QA(I,K)=QA(I,K)/AREA(K)
      QAP(I)=QAP(1)/DP
      QAF(I)=QAF(1)/DF
 40   CONTINUE
      DO 24 K=1,NT
      DO 26 I=1,NP
 26   A1(I)=QA(I,K)
      CALL FOURIE(A1,NP,NH,AQA(K),B1,C1)
      DO 28 J=1,NH
```

```
      QAM(J,K)=B1(J)
 28   GA(J,K)=C1(J)
 24   CONTINUE
 109  FORMAT(5E15.6)
      CALL FOURIE(QAP,NP,NH,AQAP,QAPM,GAP)
      CALL FOURIE(QAF,NP,NH,AQAF,QAFM,GAF)
      CALL FOURIE(TO,NP,NH,ATO,TOM,PSIO)
C     CALL FOURIE(HS,NP,NH,AHS,HSM,PSII)
      CALL FOURIE(SWM,NP,NH,ASW,SWP,GSW)
      CALL FOURIE(RHO,NP,NH,ARHO,RHOM,XIO)
C     CALL FOURIE(VER,NP,NH,AVER,VERM,XII)
      WRITE(7,119) NP,NH,NS,ND,NM,SRT,SST
 119  FORMAT(5I5,2F10.5)
      WRITE(7,109) (AQA(K),K=1,NT),AQAP,AQAF
      DO 30 J=1,NH
      WRITE(7,109) (QAM(J,K),K=1,NT),QAPM(J),QAFM(J)
      WRITE(7,109) (GA(J,K),K=1,NT),GAP(J),GAF(J)
 30   CONTINUE
      WRITE(7,109) ASW,(SWP(J),J=1,NH),(GSW(J),J=1,NH)
      WRITE(7,109) ATO,(TOM(J),J=1,NH),(PSIO(J),J=1,NH)
C     WRITE(7,109) AHS,(HSM(J),J=1,NH),(PSII(J),J=1,NH)
      WRITE(7,109) ARHO,(RHOM(J),J=1,NH),(XIO(J),J=1,NH)
C     WRITE(7,109) AVER,(VERM(J),J=1,NH),(XII(J),J=1.NH)
      T=0.
      OMEGA=6.2831/NP
      EYE=CMPLX(0.0,1.0)
      ZERO=CMPLX(0.0,0.0)
      DO 200 I=1,288
      T=T+1/12.
      NT=NM+ND+NS+2
      DO 1 K=1,NT
   1  PQA(K)=ZERO
      DO 111 K=1,NT
      DO 211 J=1,NH
      PQA(K)=PQA(K)+QAM(J,K)*CEXP(EYE*(J*OMEGA*T+GA(J,K)))
      IF(K.EQ.7) PQA(K)=PQA(K)+QAPM(J)*CEXP(EYE*(J*OMEGA*T+GAP(J)))
  211 IF(K.EQ.8) PQA(K)=PQA(K)+QAFM(J)*CEXP(EYE*(J*OMEGA*T+GAF(J)))
      QAS(K)=AQA(K)+2.*REAL(PQA(K))
      IF(K.EQ.7)QAS(K)=AQAP+2.*REAL(PQA(K))
  111 IF(K.EQ.8)QAS(K)=AQAF+2.*REAL(PQA(K))
      IF(I-((I/12)*12).EQ.0.) WRITE(7,215) T,(QAS(K),K=1,NT)
  215 FORMAT('TIME=',F10.2,/,8F10.2)
```

```
200   CONTINUE
      STOP
      END
      SUBROUTINE AR(P,Q,R,S,T,U)
      V=S/SQRT(1.-SIN(P)*SIN(P)/(R*R))
      W=EXP(-Q*V)
      X=ASIN(SIN(P)/R)
      Y=P-X
      Z=P+X
      A=SIN(Y)*SIN(Y)/(SIN(Z)*SIN(Z))
      B=TAN(Y)*TAN(Y)/(TAN(Z)*TAN(Z))
      C=0.5*(A+B)
      D=1.-C
      T=D*D*W/(1.-C*C*W*W)
      U=1.-C-D*D*W/(1.-C*W)
      RETURN
      END
      SUBROUTINE FOURIE(A,NP,NH,B,V,W)
      REAL A(24),H(10),D(10),E(15),F(15),V(10),W(10)
      NN=NH+1
      X=NP
      C1=COS(6.283185/X)
      S1=SIN(6.283185/X)
      C=1.
      S=0.
      DO 8 J=1,NN
      U2=0.
      U1=0.
      N=NP
9     U0=A(N)+(2.*C)*U1-U2
      U2=U1
      U1=U0
      N=N-1
      IF(N.GT.1) GO TO 9
      E(J)=(2./X)*(A(1)+C*U1-U2)
      F(J)=(2./X)*(S*U1)
      Q=C1*C-S1*S
      S=C1*S+S1*C
8     C=Q
      B=E(1)/2.
      DO 7 J=2,NN
      H(J-1)=E(J)
```

```
7    D(J-1)=F(J)
     DO 5 J=1,NH
     V(J)=0.5*SQRT(H(J)*H(J)+D(J)*D(J))
     W(J)=0.
 5   IF (V(J).GT.0.) W(J)=ATAN2(-D(J),H(J))
     RETURN
     END
     SUBROUTINE THETA(A,B,C,D,E,F)
     AA=COS(B)
     BB=SIN(A)*SIN(B)
     G=COS(A)*SIN(B)
     F=ACOS(AA*COS(E)+BB*COS(D)+G*COS(C))
     RETURN
     END
```

APPENDIX B-2

SAMPLE INPUT DATA FOR SOLFOR PROGRAM

```
 24   10    4    0    2    1
  0.4989    4.9358   18.5      -0.3970    -0.0705
  7.06      6.564     5.429     4.979      4.44       4.137      5.145      4.276
  6.267    11.40     15.91     18.52      22.37      23.55      25.52      21.95
 20.23     16.8      12.32     10.18       8.52       7.21       6.44       5.38
  1.0       1.0       1.0       1.0        1.0        1.0        1.0        1.0
  1.0       0.89      0.69      0.71       0.68       0.66       0.60       0.69
  0.86      0.90      1.0       1.0        1.0        1.0        1.0        1.0
  0.0000    0.0000    0.0000    0.0000     0.0000     0.0000     0.0000    36.0000
200.0000  342.0000  506.0000  588.0000   530.0000   412.0000   352.0000   130.0000
 24.0000    0.0000    0.0000    0.0000     0.0000     0.0000     0.0000     0.0000
  0.8       0.1       0.7       0.3
  0.3      20.0       0.005     0.05       0.95       6.0        0.5        0.23
  0.1       0.8       0.0002    6.85       1.526      7.46       1.57       1.57
  0.5       0.15      0.35      0.5
  0.25      0.64      0.1       6.85       1.526     12.00       0.0        0.9425
  0.7       0.3       0.49      0.21
  0.25      0.64      0.1       6.85       1.526      5.55       0.0        0.5236
  0.94      0.282     0.658     0.06
  0.1       0.8       0.0002    6.85       1.526      7.46       4.71       1.57
  0.5       0.15      0.35      0.5
  0.8       0.00      0.05  10000.000110000.0001      5.55       3.14       0.5236
  0.94      0.282     0.658     0.06
  0.8       0.00      0.05  10000.000110000.0001     12.00       3.14       0.9425
  0.7       0.3       0.49      0.21
```

APPENDIX B-3

SAMPLE OUTPUT DATA OF SOLFOR PROGRAM WHICH FORMS PART OF INPUT FOR ROCK PROGRAM

```
  24    10     4     0     2   5.53169  18.45831
 0.177961E+02   0.174803E+03   0.219791E+03   0.176242E+02   0.271358E+03
 0.555203E+02   0.607375E+01   0.165619E+03
 0.121173E+02   0.136132E+03   0.165702E+03   0.120184E+02   0.188764E+03
 0.358576E+02   0.403318E+01   0.104079E+03
 0.308113E+01  -0.308164E+01  -0.309329E+01   0.311646E+01   0.311637E+01
 0.303893E+01   0.307066E+01   0.300555E+01
 0.215773E+01   0.579608E+02   0.595507E+02   0.216906E+01   0.421017E+02
 0.291134E+01   0.524771E+00   0.649917E+01
-0.169897E+00   0.141723E+00   0.949495E-01  -0.244528E-01  -0.145837E-01
-0.602592E+00  -0.236478E+00  -0.150462E+01
 0.172288E+01   0.372624E+01   0.729400E+01   0.170551E+01   0.190487E+02
 0.753598E+01   0.698613E+00   0.259149E+02
-0.722972E-01   0.304066E+01   0.633341E+00  -0.489556E-01  -0.149926E+00
-0.148746E+00  -0.113629E+00  -0.174439E+00
 0.363903E+00   0.118476E+02   0.151820E+02   0.453563E+00   0.361933E+01
 0.142043E+01   0.135811E+00   0.522848E+01
-0.169187E+01  -0.233540E+01  -0.242598E+01  -0.179854E+01  -0.113222E+01
-0.943695E+00  -0.133016E+01  -0.674718E+00
 0.976364E+00   0.832625E+01   0.560796E+01   0.900695E+00   0.125897E+02
 0.423718E+01   0.390715E+00   0.146225E+02
 0.210270E+01   0.102379E+01   0.127060E+01   0.213349E+01   0.243562E+01
 0.204840E+01   0.207467E+01   0.202934E+01
 0.844138E+00   0.265823E+01   0.299111E+01   0.776523E+00   0.913312E+01
 0.404041E+01   0.357923E+00   0.143366E+02
-0.292703E+01   0.266657E+01   0.207858E+01  -0.297639E+01  -0.303931E+01
-0.291816E+01  -0.293201E+01  -0.290877E+01
 0.792251E+00   0.463464E+01   0.399962E+01   0.726606E+00   0.101811E+02
 0.340460E+01   0.314832E+00   0.117329E+02
-0.802329E+00  -0.159786E+01  -0.131302E+01  -0.741459E+00  -0.720801E+00
-0.880909E+00  -0.839142E+00  -0.911326E+00
 0.779354E+00   0.295217E+01   0.349005E+01   0.718794E+00   0.950940E+01
 0.359815E+01   0.323830E+00   0.126291E+02
 0.117817E+00  -0.244918E+00  -0.531216E+00   0.791632E-01   0.106653E+00
 0.133526E+00   0.120923E+00   0.142298E+00
 0.774296E+00   0.546121E+01   0.566631E+01   0.701020E+00   0.942494E+01
 0.327190E+01   0.303952E+00   0.112306E+02
 0.209646E+01   0.166793E+01   0.179709E+01   0.212990E+01   0.217572E+01
 0.204653E+01   0.207321E+01   0.202692E+01
 0.838640E+00   0.458054E+01   0.511691E+01   0.783555E+00   0.107308E+02
 0.359302E+01   0.334108E+00   0.123303E+02
-0.268527E+01  -0.248707E+01  -0.251040E+01  -0.268743E+01  -0.266722E+01
-0.277955E+01  -0.274068E+01  -0.280813E+01
 0.392000E+03   0.294493E+03   0.104058E+03   0.122179E+02   0.179753E+02
 0.548696E+01   0.216346E+01   0.576367E+01   0.175593E+01   0.484479E+01
 0.632911E+01  -0.309180E+01   0.830635E-01   0.617260E+00  -0.252514E+01
```

```
 0.272548E+01    0.129779E+01    0.190629E-01   -0.964906E+00    0.266131E+01
-0.198251E+01
 0.159417E+02    0.290255E+01    0.304499E+00    0.175844E+00    0.146302E+00
 0.119314E+00    0.127090E+00    0.962894E-01    0.126713E+00    0.127829E+00
 0.129477E+00    0.240360E+01   -0.571885E+00    0.761568E+00    0.272786E+01
 0.149826E+01   -0.302658E+01   -0.441308E-01   -0.229507E+01   -0.157550E+01
-0.251391E+01
 0.270833E+00    0.704093E-01    0.135724E-01    0.637001E-02    0.500925E-02
 0.596135E-02    0.615200E-02    0.179844E-02    0.666659E-02    0.133565E-02
 0.720423E-02   -0.895843E+00   -0.203516E+01   -0.673500E+00   -0.128976E+01
-0.140230E+01   -0.493944E+00   -0.831871E+00    0.104720E+01    0.876865E+00
-0.285879E+00
```

APPENDIX B-4

LISTING OF ROCK PROGRAM

```
C       ROCK.FOR (PREDICTION OF GREENHOUSE THERMAL STORAGE REQUIREMENT)
        CHARACTER*80 TITLE
        COMMON/BAS1/INDEX(50,7),X(50,7),AREA(50),AL(50),N1DIM
        COMMON/BAS2/COND(5,2),PD(5),AMBB(50,7),AMBE(50,7),MCONV(50),DELTA
        COMMON/BAS4/T(50),MHEAT(50),MFLUX(25),MMAT(50),MCONST(25)
        COMMON/BAS5/NEL,NODES,NMAT,NCONST,NCONV,NFLUX,NHEAT,NOIT,IPRINT
        COMMON/BAS6/LCONV(50),LFLUX(25)
        COMMON/FLXN/FLUXB(50,7),FLUXE(50,7),ISIDEF(50,7),IENDF(50,7)
        COMMON/CONV/HCONVB(50,7),HCONVE(50,7),ISIDEC(50,7),IENDC(50,7)
        COMMON/RAD1/ET(35),TT(35),SF(35,35),KC(35),KT(35),KS(35,10),NRAD
        COMMON/RAD2/TR(35),QR(35),AT(35,35),BT(35),RT(35)
        COMMON/SR1/AQA(15),QAM(10,15),GA(10,15),ASW,SWP(10),GSW(10),QA(15)
        COMMON/SR2/NP,NH,NS,ND,NM,SRT,SST
        COMMON/INP1/ATO,TOM(10),PSIO(10),ARHO,RHOM(10),XIO(10)
        COMMON/INP2/AHS,HSM(10),PSII(10),AVER,VERM(10),XII(10)
        COMMON/BALA/GLENTH,VOLUME,PA,CPA,WI,WO,TI,TO,WATER
        COMMON/PLHU/PLC,PLV,CONDC,CONDV
        COMMON/ROK1/RBL,RBA,PB,CB,RK,U,RBP,DE,E,DT,DX
        COMMON/ROK2/TA(50),TB(50),FRBLO,FRFAN,TLIM1,TLIM2
        COMMON/ROK3/KODE,FRAT,ISIG,QROK,QROKS,QTOT,WIROK,WTOT
        REAL H(30,40),SP(30,40),F(50),CONRAT(15)
        REAL FS(50),QP(50),P(50),TC(25)
        DATA MAXNE,MAXNOD,MAXMAT,MAXBW/50,30,7,40/
        OPEN(5,FILE='ROCK.DAT',STATUS='OLD')
        OPEN(7,FILE='SOLFOR2.OUT',STATUS='OLD')
        OPEN(6,FILE='ROCK.OUT')
        TI = 14.0
        RHI=1.0
        READ(5,10) TITLE
  10    FORMAT(A80)
        WRITE(6,5) TITLE
   5    FORMAT('0',20X,A80)
        MAXDIF=0
        INS=0
        READ(7,100) NP,NH,NS,ND,NM,SRT,SST
 100    FORMAT(5I5,2F10.5)
        NT=NS+ND+NM+2
        READ(7,90) (AQA(K),K=1,NT)
  90    FORMAT(5E15.6)
        DO 9  J=1,NH
        READ(7,90) (QAM(J,K),K=1,NT)
        READ(7,90) (GA(J,K),K=1,NT)
   9    CONTINUE
        READ(7,90) ASW,(SWP(J),J=1,NH),(GSW(J),J=1,NH)
        READ(7,90) ATO,(TOM(J),J=1,NH),(PSIO(J),J=1,NH)
```

```
      READ(7,90) ARHO,(RHOM(J),J=1,NH),(XIO(J),J=1,NH)
16    CALL PUTIN1(MAXNE,MAXNOD,MAXMAT,ISTOP,MAXDIF,TC,P,INDIC)
      IF(HOUR.LT.8.)GOTO 13
      IF(HOUR.EQ.17.)GOTO 337
17    CALL PUTIN2(MAXNE,MAXNOD,MAXMAT,ISTOP,MAXDIF,TC,P,INDIC)
      IF(HOUR.EQ.8.) GOTO 3
13    CALL TIN
      PA=1.201
      CPA=1004.0
      IF(ISTOP.EQ.0) GO TO 2
      STOP
 2    IBAND=MAXDIF+1
      IF(IBAND.LE.MAXBW) GO TO 12
      WRITE(6,15) IBAND,MAXBW
15    FORMAT('0',10X,'BANDWIDTH=',I4,'EXCEEDS MAX.ALLOWABLE=',I4,//)
      STOP
12    WRITE(6,25) IBAND
25    FORMAT('0',9X,'SEMI-BANDWIDTH FOR THE GRID IS:',I4,/)
      DO 1 I=1,NODES
      F(I)=0.
      DO 1 J=1,IBAND
      H(I,J)=0.
      SP(I,J)=0.
 1    CONTINUE
      DO 121 I=1,NFLUX
      IL=MFLUX(I)
      IF(IL.NE.2) GO TO 152
      FLUXE(I,1)=0.
      FLUXE(I,2)=0.
      GO TO 121
152   FLUXB(I,1)=0.
121   CONTINUE
      DO 11 I=1,NEL
      CALL CONDUC(I,MMAT(I),H)
      IF(INDIC.EQ.0) GO TO 11
      CALL SPECIF(I,MMAT(I),SP)
 11   CONTINUE
      IF(NCONV.EQ.0) GO TO 72
      DO 101 I=1,NCONV
      N=LCONV(I)
101   CALL CONVEC(N,I,P,H)
 72   CONTINUE
      IF(NCONST.EQ.0) GO TO 22
      DO 21 I=1,NCONST
      I2=MCONST(I)
 21   H(I2,1)=H(I2,1)+1.0E+10
      IF(INDIC.EQ.0) GO TO 82
 22   DO 31 I=1,NODES
      DO 31 J=1,IBAND
      H(I,J)=H(I,J)+SP(I,J)/DELTA
      SP(I,J)=SP(I,J)/DELTA
```

```
 31  CONTINUE
 82  CALL DECOM(H,NODES,IBAND,MAXNOD,MAXBW)
     CALL FIXED(HOUR,C1,C2)
     IF(INDIC.EQ.0) NOIT=1
     TIME=0.
     KOUNT=0
     HOUR=0.
     DO 81 I1=1,NOIT
     IF(INDIC.EQ.0) GO TO 122
     TIME=TIME+DELTA
     HOUR=TIME/3600.
     KOUNT=KOUNT+1
     IF(HOUR.EQ.24.)TIME=0.0
     CALL MULPLY(SP,T,FS,NODES,IBAND,MAXNOD,MAXBW)
     DO 131 II=1,NHEAT
131  QP(II)=0.
122  CALL SOLRAD(HOUR,QP)
     IF(NCONV.EQ.0) GO TO 32
     CALL AMBI(NCONV,HOUR)
     DO 41 II=1,NCONV
     N=LCONV(II)
 41  CALL CONVEF(N,II,P,F)
 32  IF(NFLUX.EQ.0) GO TO 42
     CALL FLUX(NFLUX,TIME)
     CALL RELHUM(HOUR,RHO)
     CALL CONDEN(RHO,PHI,CONRAT)
     CALL TRANSP(EP,HOUR)
     IF(NRAD.LE.1) GO TO 132
     CALL RADT(HOUR)
     CALL TRADP(INS)
     CALL RADF(HOUR)
     INS=1
132  DO 51 II=1,NFLUX
     N=LFLUX(II)
 51  CALL FLUXN(N,II,P,F)
     DO 111 I=1,NFLUX
     IM=LFLUX(I)
     IL=MFLUX(I)
     IF(IL.NE.2) GO TO 142
     FLUXE(I,1)=0.
     FLUXE(I,2)=0.
     GO TO 111
142  FLUXB(I,1)=0.
111  CONTINUE
 42  IF(NHEAT.EQ.0) GO TO 52
     CALL QGEN(QP,NHEAT,TIME)
     DO 61 II=1,NHEAT
     N=MHEAT(II)
 61  CALL HETGEN(N,II,QP,F)
 52  CONTINUE
     IF(NCONST.EQ.0) GO TO 62
```

```
      CALL CONST(TC,NCONST,HOUR)
      DO 71 I=1,NCONST
      I2=MCONST(I)
   71 F(I2)=H(I2,1)*TC(I)
   62 CONTINUE
      DO 91 I2=1,NODES
      IF(INDIC.EQ.0) GO TO 92
      FS(I2)=FS(I2)+F(I2)
      GO TO 91
   92 FS(I2)=F(I2)
   91 F(I2)=0.
      CALL SOLVE(H,FS,T,NODES,IBAND,MAXNOD,MAXBW)
C UPDATE THE TEMPERATURE AND RELATIVE HUMIDITY FOR THE GREENHOUSE AIR
C
      VER = VENT(HOUR)
      HS = HEAT(HOUR)
      CALL AIRTEM(C1,C2,VER,HS,HOUR,TDSIRE,BALANCE)
      CALL AIRHUM(VER,TIME,RHI)
      CALL ROCKBED(TIME,TDSIRE,I1,TEXT)
      IF(INDIC.EQ.0) KOUNT = IPRINT
      IF(KOUNT.NE.IPRINT) GO TO 81
      KOUNT=0
      WRITE(6,35) TIME/3600.,TO,TI,RHI,KODE,TEXT,QTOT,WTOT,BALANce
   35 FORMAT('0','*TIME=',F11.1,'*',2X,'TO=',F7.2,'TI=',F7.2,5X,'RHI=',
     &F5.3,5X,'KODE=',I4,5X,'TEXT=',F7.2,5X,'QTOT=',E14.6,5X,'WTOT=',
     1E14.6,5X,'Q=',E14.6)
      WRITE(6,*)(T(I),I=1,25)
      balance=0.
      IF(HOUR.EQ.8.)GO TO 17
    3 IF(HOUR.EQ.8.) GOTO 332
      IF(HOUR.EQ.17.)GOTO 336
      GO TO 81
  332 CALL FIXED(HOUR,C1,C2)
      H(4,1)=H(4,1)+HCONVE(2,2)*AREA(2)
      H(6,1)=H(6,1)+HCONVE(3,2)*AREA(3)
      INS=0
      GO TO 81
  336 INS=0
      H(4,1)=H(4,1)-HCONVE(2,2)*AREA(2)
      H(6,1)=H(6,1)-HCONVE(3,2)*AREA(3)
      GO TO 16
  337 CALL FIXED(HOUR,C1,C2)
   81 CONTINUE
      STOP
      END
C ---------------------------------------------------------------------
      SUBROUTINE AIRHUM(VR,TIME,RHI)
      COMMON/BAS2/COND(5,2),PD(5),AMBB(50,7),AMBF(50,7),MCONV(50),DELTA
      COMMON/BALA/GLENTH,VOLUME,PA,CPA,WI,WO,TI,TO,WATER
      COMMON/RLHU/PLC,PLV,CONDC,CONDV
      COMMON/ROK2/TA(50),TB(50),FRBLO,FRFAN,TLIM1,TLIM2
```

```
      COMMON/ROK3/KODE,FRAT,ISIG,QROK,QROKS,QTOT,WIROK,WTOT
      REAL H(30,40),SP(30,40),F(50),CONRAT(15)
      REAL FS(50),QP(50),P(50),TC(25)
      VER = VOLUME/3600.
      IF(TI.GT.30.) VER=VER+FRFAN
C
C COMPUTE SOME COEFFICIENTS
      C1 = (PA*VOLUME)/DELTA
      C2 = PA*VER
C
C WAOUT IS THE AMOUNT OF WATER REMOVED FROM THE GREENHOUSE AIR BY
C ARTIFICIAL MEANS.
      WAOUT = WIROK
C COMPUTE THE NEW VALUE OF THE GREENHOUSAE AIR HUMIDITY RATIO
C
      U = C1+PLC+CONDC+C2
      V = C2*WO + PLV + CONDV +WAOUT
      WI = (C1*WI + V)/U
      IF(WI.LT.0.) WI = 0.
C
C PH IS THE ACTUAL PARTIAL VAPOUR PRESSURE
C
      PH = WI*101.325/(WI+0.622)
C
C PS IS THE SATURATION VAPOUR PRESSURE
C
      TIK = TI+273.16
      PS = PRES(TIK)
C
C THEREFORE, THE NEW RELATIVE HUMIDITY OF THE GREENHOUSE AIR IS:
C
      RHI =PH/PS
      IF(RHI.GT.1.0)RHI=1.0
C
      RETURN
      END
C ---------------------------------------------------------------------
      SUBROUTINE AIRTEM(C1,C2,VR,HS,HOUR,TINEW,BALANCE)
      COMMON/BAS1/INDEX(50,7),X(50,7),AREA(50),AL(50),N1DIM
      COMMON/BAS4/T(50),MHEAT(50),MFLUX(25),MMAT(50),MCONST(25)
      COMMON/CONV/HCONVB(50,7),HCONVE(50,7),ISIDEC(50,7),IENDC(50,7)
      COMMON/BALA/GLENTH,VOLUME,PA,CPA,WI,WO,TI,TO,WATER
      COMMON/RLHU/PLC,PLV,CONDC,CONDV
      COMMON/ROK2/TA(50),TB(50),FRBLO,FRFAN,TLIM1,TLIM2
      COMMON/ROK3/KODE,FRAT,ISIG,QROK,QROKS,QTOT,WIROK,WTOT
C
      VER =VOLUME/3600.
      IF(TI.GT.30.)VER=VER+FRFAN
      TIOLD = TI
      TINEW = 15.
      IF(HOUR.GT.8.0.AND.HOUR.LE.17.0) TINEW = 20.
```

```
      COMMON/SR2/NP,NH,NS,ND,NM,SRT,SST
      COMMON/INP1/ATO,TOM(10),PSIO(10),ARHO,RHOM(10),XIO(10)
      COMPLEX EYE,ZERO,CMPLX,CEXP,PTO,PTI
      ZERO=CMPLX(0.0,0.0)
      EYE=CMPLX(0.0,1.0)
      OMEGA=6.283285/NP
      PTO=ZERO
      DO 11 J=1,NH
      PTO=PTO+TOM(J)*CEXP(EYE*(J*OMEGA*TIME+PSIO(J)))
   11 CONTINUE
      TO=ATO+2.*REAL(PTO)
      DO 1 I=1,6
      AMBE(I,1)=TO
      AMBE(I,2)=TI
    1 CONTINUE
      AMBE(7,1)=TI
      AMBE(7,2)=TI
      AMBE(8,1)=TI
      AMBE(9,1)=0.
      AMBE(9,2)=0.
      IF(TIME.LE.8..OR.TIME.GT.17.)GO TO 3
      GOTO 4
    3 AMBE(9,2)=TI
      AMBE(9,1)=TI
    4 RETURN
      END
C-------------------------------------------------------------
      SUBROUTINE CONDEN(RHO,RHI,CONRAT)
      COMMON/BAS1/INDEX(50,7),X(50,7),AREA(50),AL(50),N1DIM
      COMMON/BAS4/T(50),MHEAT(50),MFLUX(25),MMAT(50),MCONST(25)
      COMMON/FLXN/FLUXB(50,7),FLUXE(50,7),ISIDEF(50,7),IENDF(50,7)
      COMMON/BALA/GLENTH,VOLUME,PA,CPA,WI,WO,TI,TO,WATER
      COMMON/RLHU/PLC,PLV,CONDC,CONDV
      REAL CONRAT(15)
      DK = 0.008
      DO 1 I=1,10
 1    CONRAT(I)=0.
      CALL HUMIDT(TO,RHO,TDP1,PW1,WO)
      CALL HUMIDT(TI,RHI,TDP2,PW2,WI)
      J=1
      DO 11 I=1,11,2
      IF(T(I).GT.TDP1) GO TO 11
      TK=T(I)+273.16
      PS=PRES(TK)
      WS=0.62198*PS/(101.325-PS)
      CONRAT(I)=DK*AREA(J)*(WO-WS)
      HFG=2.502E6+1880.*((TO+T(I))/2.)
      FLUXE(J,1)=HFG*CONRAT(I)/AREA(J)+FLUXE(J,1)
 11   J=J+1
      CONDC = 0.
      CONDV = 0.
```

```
      J=1
      DO 21  I=2,12,2
      IF(T(I).GT.TDP2) GO TO 21
      TK=T(I)+273.16
      PS=PRES(TK)
      WS=0.62198*PS/(101.325-PS)
      CONRAT(I)=DK*AREA(J)*(WI-WS)
      CONDC  = AREA(J)*DK+CONDC
      CONDV  = AREA(J)*DK*WS+CONDV
      HFG=2.502E6+1880.*((TI+T(I))/2.)
      FLUXE(J,2)=HFG*CONRAT(I)/AREA(J)+FLUXE(J,2)
   21 J=J+1
      RETURN
      END
C-------------------------------------------------------------
      SUBROUTINE CONDUC(N,M,H)
      REAL H(30,40),AK(3,3)
      COMMON/BAS1/INDEX(50,7),X(50,7),AREA(50),AL(50),N1DIM
      COMMON/BAS2/COND(5,2),PD(5),AMBB(50,7),AMBE(50,7),MCONV(50),DELTA
      I=INDEX(N,1)
      J=INDEX(N,2)
      XI=X(I,1)
      XJ=X(J,1)
      IF(N.GT.N1DIM) GO TO 2
      AL(N)=ABS(XJ-XI)
      CF=COND(M,1)*AREA(N)/AL(N)
      AK(1,1)=CF
      AK(1,2)=-CF
      AK(2,1)=-CF
      AK(2,2)=CF
      GO TO 12
    2 K=INDEX(N,3)
      XK=X(K,1)
      YI=X(I,2)
      YJ=X(J,2)
      YK=X(K,2)
      AREA(N)=ABS(XJ*YK-XK*YJ-XI*(YK-YJ)+YI*(XK-XJ))/2.
      BI=YJ-YK
      BJ=YK-YI
      BK=YI-YJ
      CI=XK-XJ
      CJ=XI-XK
      CK=XJ-XI
      CX=COND(M,1)/(4.*AREA(N))
      CY=CX*COND(M,2)/COND(M,1)
      AK(1,1)=CX*BI*BI+CY*CI*CI
      AK(1,2)=CX*BI*BJ+CY*CI*CJ
      AK(1,3)=CX*BI*BK+CY*CI*CK
      AK(2,2)=CX*BJ*BJ+CY*CJ*CJ
      AK(2,3)=CX*BJ*BK+CY*CJ*CK
      AK(3,3)=CX*BK*BK+CY*CK*CK
```

```
      AK(2,1)=AK(1,2)
      AK(3,1)=AK(1,3)
      AK(3,2)=AK(2,3)
   12 H(I,1)=H(I,1)+AK(1,1)
      H(J,1)=H(J,1)+AK(2,2)
      IF(I.GT.J) H(J,I-J+1)=H(J,I-J+1)+AK(2,1)
      IF(J.GT.I) H(I,J-I+1)=H(I,J-I+1)+AK(1,2)
      IF(N.LE.N1DIM) RETURN
      H(K,1)=H(K,1)+AK(3,3)
      IF(I.GT.K) H(K,I-K+1)=H(K,I-K+1)+AK(3,1)
      IF(I.LT.K) H(I,K-I+1)=H(I,K-I+1)+AK(1,3)
      IF(J.GT.K) H(K,J-K+1)=H(K,J-K+1)+AK(3,2)
      IF(J.LT.K) H(J,K-J+1)=H(J,K-J+1)+AK(2,3)
      RETURN
      END
C-----------------------------------------------------
      SUBROUTINE CONST(TC.NCONST,HOUR)
      REAL TC(25)
      DO 10 I=1,NCONST
   10 TC(I)=20.
      RETURN
      END
C-----------------------------------------------------
      SUBROUTINE CONVEC(II,N,P,H)
      REAL H(30,40),P(50)
      COMMON/BAS1/INDEX(50,7),X(50,7),AREA(50),AL(50),N1DIM
      COMMON/BAS2/COND(5,2),PD(5),AMBB(50,7),AMBE(50,7),MCONV(50),DELTA
      COMMON/CONV/HCONVB(50,7),HCONVE(50,7),ISIDEC(50,7),IENDC(50,7)
      I=INDEX(II,1)
      J=INDEX(II,2)
      IF(II.GT.N1DIM) GO TO 2
      IF(MCONV(N).EQ.2) GO TO 12
      CF1=HCONVB(N,1)*P(II)*AL(II)/6.
      CF2=CF1+CF1
      H(I,1)=H(I,1)+CF2
      H(J,1)=H(J,1)+CF2
      IF(I.GT.J) H(J,I-J+1)=H(J,I-J+1)+CF1
      IF(I.LT.J) H(I,J-I+1)=H(I,J-I+1)+CF1
      IF(MCONV(N).NE.3) RETURN
   12 IF(IENDC(N,1).EQ.0) GO TO 22
      H(I,1)=H(I,1)+HCONVE(N,1)*AREA(II)
   22 IF(IENDC(N,2).EQ.0) RETURN
      H(J,1)=H(J,1)+HCONVE(N,2)*AREA(II)
      RETURN
    2 CONTINUE
      K=INDEX(II,3)
      IF(MCONV(N).EQ.2) GO TO 32
      DO 1 I1=1,2
      IJ=ISIDEC(N,I1)
      IF(IJ.EQ.0) GO TO 1
      GO TO(42,52,62),IJ
```

```
   42 L1=I
      L2=J
      GO TO 72
   52 L1=J
      L2=K
      GO TO 72
   62 L1=K
      L2=I
   72 D1=SQRT((X(L1,1)-X(L2,1))**2+(X(L1,2)-X(L2,2))**2)
      CF1=HCONVB(N,I1)*D1/6.
      CF2=CF1+CF1
      H(L1,1)=H(L1,1)+CF2
      H(L2,1)=H(L2,1)+CF2
      IF(L1.GT.L2) H(L2,L1-L2+1)=H(L2,L1-L2+1)+CF1
      IF(L1.LT.L2) H(L1,L2-L1+1)=H(L1,L2-L1+1)+CF1
    1 CONTINUE
      IF(MCONV(N).NE.3) RETURN
   32 CF1=(HCONVE(N,1)+HCONVE(N,2))*AREA(II)/12.
      CF2=CF1+CF1
      H(I,1)=H(I,1)+CF2
      H(J,1)=H(J,1)+CF2
      H(K,1)=H(K,1)+CF2
      IF(I.GT.J) H(J,I-J+1)=H(J,I-J+1)+CF1
      IF(I.LT.J) H(I,J-I+1)=H(I,J-I+1)+CF1
      IF(I.GT.K) H(K,I-K+1)=H(K,I-K+1)+CF1
      IF(I.LT.K) H(I,K-I+1)=H(I,K-I+1)+CF1
      IF(J.GT.K) H(K,J-K+1)=H(K,J-K+1)+CF1
      IF(J.LT.K) H(J,K-J+1)=H(J,K-J+1)+CF1
      RETURN
      END
C-----------------------------------------------------
      SUBROUTINE CONVEF(N,II,P,F)
      REAL F(50),P(50)
      COMMON/BAS1/INDEX(50,7),X(50,7),AREA(50),AL(50),N1DIM
      COMMON/BAS2/COND(5,2),PD(5),AMBB(50,7),AMBE(50,7),MCONV(50),DELTA
      COMMON/CONV/HCONVB(50,7),HCONVE(50,7),ISIDEC(50,7),IENDC(50,7)
      I=INDEX(N,1)
      J=INDEX(N,2)
      IF(N.GT.N1DIM) GO TO 2
      IF(MCONV(II).EQ.2) GO TO 12
      CFA=HCONVB(II,1)*P(N)*AL(N)*AMBB(II,1)/2.
      F(I)=F(I)+CFA
      F(J)=F(J)+CFA
      IF(MCONV(II).NE.3) RETURN
   12 IF(IENDC(II,1).EQ.0) GO TO 22
      F(I)=F(I)+HCONVE(II,1)*AREA(N)*AMBE(II,1)
   22 IF(IENDC(II,2).EQ.0) RETURN
      F(J)=F(J)+HCONVE(II,2)*AREA(N)*AMBE(II,2)
      RETURN
    2 CONTINUE
      K=INDEX(N,3)
```

```
      IF(MCONV(II).EQ.2) GO TO 32
      DO 1 I1=1,2
      IJ=ISIDEC(II,I1)
      IF(IJ.EQ.0) GO TO 1
      GO TO (42,52,62),IJ
   42 L1=I
      L2=J
      GO TO 72
   52 L1=J
      L2=K
      GO TO 72
   62 L1=K
      L2=I
   72 D1=SQRT((X(L1,1)-X(L2,1))**2+(X(L1,2)-X(L2,2))**2)
      CFA=HCONVB(II,I1)*D1*AMBB(II,I1)/2.
      F(L1)=F(L1)+CFA
      F(L2)=F(L2)+CFA
    1 CONTINUE
      IF(MCONV(II).NE.3) RETURN
   32 CFA=(HCONVE(II,1)*AMBE(II,1)+HCONVE(II,2)*AMBE(II,2))*AREA(N)/3.
      F(I)=F(I)+CFA
      F(J)=F(J)+CFA
      F(K)=F(K)+CFA
      RETURN
      END
C--------------------------------------------------------------------
      SUBROUTINE DECOM(GSM,NP,NBW,M1,M2)
      REAL GSM(M1,M2)
      NP1=NP-1
      DO 226 I=1,NP1
      MJ=I+NBW-1
      IF(MJ.GT.NP) MJ=NP
      NJ=I+1
      MK=NBW
      IF((NP-I+1).LT.NBW) MK=NP-I+1
      ND=0
      DO 225 J=NJ,MJ
      MK=MK-1
      ND=ND+1
      NL=ND+1
      DO 225 K=1,MK
      NK=ND+K
  225 GSM(J,K)=GSM(J,K)-GSM(I,NL)*GSM(I,NK)/GSM(I,1)
  226 CONTINUE
      RETURN
      END
C--------------------------------------------------------------------
      SUBROUTINE FIXED(HOUR,C1,C2)
      COMMON/BAS1/INDEX(50,7),X(50,7),AREA(50),AL(50),N1DIM
      COMMON/BAS2/COND(5,2),PD(5),AMBB(50,7),AMBE(50,7),MCONV(50),DELTA
      COMMON/CONV/HCONVB(50,7),HCONVE(50,7),ISIDEC(50,7),IENDC(50,7)
```

```
      COMMON/BALA/GLENTH,VOLUME,PA,CPA,WI,WO,TI,TO,WATER
C
      C1 =PA*CPA*VOLUME/DELTA
      C2=0.0
      DO 1 J=1,6
    1 C2=C2+HCONVE(J,2)*AREA(J)
      IF(HOUR.EQ.8.0) GO TO 3
      C2=C2+AREA(7)*(HCONVE(7,1)+HCONVE(7,2))+AREA(8)*HCONVE(8,1)+
     1AREA(16)*(HCONVE(9,1)+HCONVE(9,2))
      GO TO 4
    3 C2=C2+AREA(7)*(HCONVE(7,1)+HCONVE(7,2))+HCONVE(8,1)*AREA(8)
    4 DO 11 I=10,20
      J=INDEX(I,2)
      K=INDEX(I,3)
      XJ=X(J,1)
      XK=X(K,1)
      ALL=ABS(XJ-XK)
   11 SUM=SUM+HCONVB(I,1)*ALL
      SUM=SUM+SUM*GLENTH*2.
      C2=C2+SUM
      RETURN
      END
C ------------------------------------------------------------------------
      SUBROUTINE FLUX(NFLUX,TIME)
      COMMON/FLXN/FLUXB(50,7),FLUXE(50,7),ISIDEF(50,7),IENDF(50,7)
      DO 1 I=1,7
      FLUXE(I,1)=FLUXE(I,1)+0.
    1 FLUXE(I,2)=FLUXE(I,2)+0.
      FLUXE(8,1)=FLUXE(8,1)+0.
      IF(TIME.LT.6..OR.TIME.GT.17.)GOTO 3
      GO TO 4
    3 FLUXE(9,1)=FLUXE(9,1)+0.
      FLUXE(9,2)=FLUXE(9,2)+0.
    4 RETURN
      END
C-------------------------------------------------------------------
      SUBROUTINE FLUXN(II,N,P,F)
      COMMON/BAS1/INDEX(50,7),X(50,7),AREA(50),AL(50),N1DIM
      COMMON/FLXN/FLUXB(50,7),FLUXE(50,7),ISIDEF(50,7),IENDF(50,7)
      COMMON/BAS4/T(50),MHEAT(50),MFLUX(25),MMAT(50),MCONST(25)
      REAL F(50),P(50)
      I=INDEX(II,1)
      J=INDEX(II,2)
      IF(II.GT.N1DIM) GO TO 2
      IF(MFLUX(N).EQ.2) GO TO 12
      CF=FLUXB(N,1)*AL(II)*P(II)/2.
      F(I)=F(I)+CF
      F(J)=F(J)+CF
      IF(MFLUX(N).NE.3) RETURN
   12 IF(IENDF(N,1).EQ.0) GO TO 22
      F(I)=FLUXE(N,1)*AREA(II)+F(I)
```

```
   22 IF(IENDF(N,2).EQ.0) RETURN
      F(J)=FLUXE(N,2)*AREA(II)+F(J)
      RETURN
    2 CONTINUE
      K=INDEX(II,3)
      IF(MFLUX(N).EQ.2) GO TO 32
      DO 1 I1=1,2
      IJ=ISIDEF(N,I1)
      IF(IJ.EQ.0) GO TO 1
      GO TO(42,52,62),IJ
   42 L1=I
      L2=J
      GO TO 72
   52 L1=J
      L2=K
      GO TO 72
   62 L1=K
      L2=I
   72 D1=SQRT((X(L1,1)-X(L2,1))**2+(X(L1,2)-X(L2,2))**2)
      F(L1)=F(L1)+FLUXB(N,I1)*D1*0.5
      F(L2)=F(L2)+FLUXB(N,I1)*D1*0.5
    1 CONTINUE
      IF(MFLUX(N).NE.3) RETURN
   32 CF=(FLUXE(N,1)+FLUXE(N,2))*AREA(II)/3.
      F(I)=F(I)+CF
      F(J)=F(J)+CF
      F(K)=F(K)+CF
      RETURN
      END
C------------------------------------------------------------
      SUBROUTINE HETGEN(II,N,QG,F)
      REAL F(50),QG(50)
      COMMON/BAS1/INDEX(50,7),X(50,7),AREA(50),AL(50),N1DIM
      I=INDEX(II,1)
      J=INDEX(II,2)
      IF(II.GT.N1DIM) GO TO 2
      CF=QG(N)*AREA(II)*AL(II)/2.
   12 F(I)=F(I)+CF
      F(J)=F(J)+CF
      RETURN
    2 CONTINUE
      K=INDEX(II,3)
      CF=QG(N)*AREA(II)/3.
      F(K)=F(K)+CF
      GO TO 12
      END
C------------------------------------------------------------------
      SUBROUTINE HUMIDT(TDB,RH,TDP,PW,W)
      TDBK=TDB+273.16
      PSDB=PRES(TDBK)
      PW=RH*PSDB
```

```
      W=0.62198*PW/(101.325-PW)
      ALFA=ALOG(PW)
      IF(PW.GT.0.611) GO TO 220
      TDP=5.994+12.41*ALFA+0.4273*ALFA**2
      GO TO 230
 220  TDP=7.024+13.561*ALFA+1.416*ALFA**2
 230  CONTINUE
      RETURN
      END
C------------------------------------------------------------------
      SUBROUTINE MULPLY(GSM,GF,RF,NP,NBW,M1,M2)
      DIMENSION GSM(M1,M2),GF(M1),RF(M1)
      DO 277 I=1,NP
      SUM=0.0
      K=I-1
      DO 276 J=2,NBW
      M=J+I-1
      IF(M.GT.NP) GO TO 275
      SUM=SUM+GSM(I,J)*GF(M)
 275  IF(K.LE.0) GO TO 276
      SUM=SUM+GSM(K,J)*GF(K)
      K=K-1
 276  CONTINUE
 277  RF(I)=SUM+GSM(I,1)*GF(I)
      RETURN
      END
C--------------------------------------------------------------
      SUBROUTINE PUTIN1(MAXNE,MAXNOD,MAXMAT,ISTOP,MAXDIF,TC,P,INDIC)
      COMMON/BAS1/INDEX(50,7),X(50,7),AREA(50),AL(50),N1DIM
      COMMON/BAS2/COND(5,2),PD(5),AMBB(50,7),AMBE(50,7),MCONV(50),DELTA
      COMMON/BAS4/T(50),MHEAT(50),MFLUX(25),MMAT(50),MCONST(25)
      COMMON/BAS5/NEL,NODES,NMAT,NCONST,NCONV,NFLUX,NHEAT,NOIT,IPRINT
      COMMON/BAS6/LCONV(50),LFLUX(25)
      COMMON/FLXN/FLUXB(50,7),FLUXE(50,7),ISIDEF(50,7),IENDF(50,7)
      COMMON/CONV/HCONVB(50,7),HCONVE(50,7),ISIDEC(50,7),IENDC(50,7)
      COMMON/RAD1/ET(35),TT(35),SF(35,35),KC(35),KT(35),KS(35,10),NRAD
      COMMON/SR1/AQA(15),QAM(10,15),GA(10,15),ASW,SWP(10),GSW(10),QA(15)
      COMMON/SR2/NP,NH,NS,ND,NM,SRT,SST
      COMMON/INP1/ATO,TOM(10),PSIO(10),ARHO,RHOM(10),XIO(10)
      COMMON/INP2/AHS,HSM(10),PSII(10),AVER,VERM(10),XII(10)
      COMMON/BALA/GLENTH,VOLUME,PA,CPA,WI,WO,TI,TO,WATER
      COMMON/ROK1/RBL,RBA,PB,CB,RK,U,RBP,DE,E,DT,DX
      COMMON/ROK2/TA(50),TB(50),FRBLO,FRFAN,TLIM1,TLIM2
      REAL H(30,40),SP(30,40),F(50),CONRAT(15)
      REAL FS(50),QP(50),P(50),TC(25)
      ISTOP=0
      READ(5,10)N1DIM,NEL,NODES,NMAT,NCONST,NCONV,NRAD,NFLUX,NHEAT,INDIC
     &,NOIT,IPRINT,DELTA
   10 FORMAT(12I5,F8.1)
      WRITE(6,15)N1DIM,NEL,NODES,NMAT,NCONST,NCONV,NRAD,NFLUX,NHEAT,
     &NOIT,IPRINT,DELTA,INDIC
```

```
   15 FORMAT('0',9X,'THE PROBLEM HAS',I2,1X,'1-D ELEMENTS',/,
     110X,'NUMBER OF ELEMENTS=',11X,I4,/,
     210X,'NUMBER OF NODES=',14X,I4,/,
     310X,'NO. OF MATERIALS=',10X,I4,/,
     410X,'NO. OF CONST. TEMP. NODES=',1X,I4,/,
     510X,'NO. OF ELEMENTS WITH CONVECTION=',10X,I4,/,
     610X,'NO. NODES WITH THERM.RAD.EXCHANGE=',2X,I4,/,
     710X,'NO. OF ELEMENTS WITH NORMAL FLUX=',9X,I4,/,
     810X,'NO. OF ELEMENTS WITH INT.HEAT GEN.=',8X,I4,/,
     910X,'NO. OF TIME INCR.FOR TRANS.ANALYSIS=',5X,I4,/,
     &10X,'PRINTING INTERVAL FOR TEMP.FIELDS=',7X,I4,/,
     &10X,'TIME INCREMENT FOR TRANS.ANALYSIS=',F12.4,/,
     &10X,'INDIC(1=TRANSIENT,0=STEADY)=',12X,I1,/)
      IF(NEL.LE.MAXNE) GO TO 2
      ISTOP=ISTOP+1
      WRITE(6,25) MAXNE
   25 FORMAT('0',9X,'ERROR:MAXIMUM OF',I4,'ELEMENTS ARE ALLOWED')
    2 IF(NODES.LE.MAXNOD) GO TO 12
      ISTOP=ISTOP+1
      WRITE(6,35) MAXNOD
   35 FORMAT('0',9X,'ERROR:MAXIMUM OF',I4,'NODES ARE ALLOWED')
   12 IF(NMAT.LE.MAXMAT) GO TO 22
      ISTOP=ISTOP+1
      WRITE(6,45) MAXMAT
   45 FORMAT('0',9X,'ERROR:MAXIMUM OF',I4,'MATERIALS ARE ALLOWED')
   22 IF(ISTOP.NE.0) WRITE(6,55)
   55 FORMAT('0',9X,'EXECUTION HALTED BECAUSE OF THE EXCESSIVE
     &MEMORY REQUIREMENT EVIDENCED BY INPUT DATA')
      IF(ISTOP.NE.0) STOP
      READ(5,110)RBL,RBA,PB,CB,RK,U,RBP,DE
      READ(5,110)E,DT,DX,FRBLO,FRFAN,TLIM1,TLIM2
      WRITE(6,245)RBL,RBA,RBP,DE,E,DX,DT,U
  245 FORMAT('0',9X,'LENGTH OF THE ROCKBED',19X,F10.2,/,
     110X,'ROCKBED AREA NORMAL TO THE AIRFLOW',6X,F10.4,/,
     210X,'EFFECTIVE PERIMETER OF THE ROCKBED',6X,F10.4,/,
     310X,'EQUIVALENT ROCK PARTICLE DIAMETER',7X,F10.4,/,
     410X,'POROSITY OF THE ROCKBED',17X.F10.4,/,
     510X,'DIFFERENTIAL ROCKBED LENGTH',13X,F10.5/,
     610X,'SOLUTION TIME STEP',22X,F10.2,/,
     710X,'ROCKBED PERIMETER HEAT LOSS FACTOR',6X,F10.2,/)
      WRITE(6,255) PB,CB,RK,FRBLO,FRFAN,TLIM1,TLIM2
  255 FORMAT('0',9X,'BULK DENSITY OF THE ROCKBED',13X,F10.2,/,
     110X,'SPECIFIC HEAT OF THE ROCKS',14X,F10.4,/,
     210X,'THERMAL CONDUCTIVITY OF THE ROCKS',7X,F10.4,/,
     310X,'FLOW RATE FOR LOW VENT FAN',14X,F10.4,/,
     410X,'FLOW RATE FOR HIGH VENT FAN',13X,F10.4,/
     510X,'BASE TEMPERATURE FOR HEAT COLLECTION',4X,F10.2,/,
     610X,'KODE 3 TEMPERATURE IN SUBR. ROCKBED',6X,F10.2,/)
      READ(5,110) GLENTH,VOLUME
  110 FORMAT(8F10.4)
      WRITE(6,225) GLENTH,VOLUME
```

```
225  FORMAT('0',9X,'LENGTH OF THE STRUCTURE=',16X,F10.5,/,
    110X,'VOLUME OF THE STRUCTURE=',16X,F10.2)
     WRITE(6,65)
 65  FORMAT('0',9X,'MATERIAL INFORMATION:',/,
    19X,'M',10X,'KX',10X,'KY',10X,'PC')
     DO 1 M=1,NMAT
     READ(5,20) (COND(M,I),I=1,2),PD(M)
 20  FORMAT(7F10.2)
  1  WRITE(6,75) M,COND(M,1),COND(M,2),PD(M)
 75  FORMAT(6X,I4,3F12.3)
     WRITE(6,85)
 85  FORMAT('0',9X,'NODAL INFORMATION:',/,
    &9X,'N',17X,'X',14X,'Y'/)
     DO 11 K=1,NODES
     READ(5,30) (X(K,I),I=1,2)
 30  FORMAT(3F10.5)
 11  WRITE(6,95) K,X(K,1),X(K,2)
 95  FORMAT(5X,I5,3X,3F15.5)
     IF(NCONST.EQ.0) GO TO 32
     READ(5,40) (MCONST(I),I=1,NCONST)
 40  FORMAT(25I3)
     WRITE(6,105)
105  FORMAT('0',10X,'CONST.TEMP.NODES ARE:',/)
     WRITE(6,115) (MCONST(I),I=1,NCONST)
115  FORMAT(6X,25(I3,','))
 32  IF(NHEAT.EQ.0) GO TO 42
     READ(5,40) (MHEAT(I),I=1,NHEAT)
     WRITE(6,125)
125  FORMAT('0',10X,'ELEMENTS WITH INTERAL HEAT GEN.ARE:',/)
     WRITE(6,115) (MHEAT(I),I=1,NHEAT)
 42  IF(NRAD.LE.1) GO TO 52
     DO 101 I=1,35
     DO 101 J=1,35
101  SF(I,J)=0.
     DO 61 I=1,NRAD
     READ(5,80) ET(I),TT(I),KC(I),KT(I),(KS(I,J),J=1,10)
  80 FORMAT(2F5.3,12I2)
     KR=KT(I)
 61  READ(5,70) (SF(I,KS(I,J)),J=1,KR)
 70  FORMAT(10F6.4)
     WRITE(6,135)
135  FORMAT('0',10X,'THERMAL RADIATION INFORMATION:',/,4X,
    &'SURFACE',4X,'ET',4X,'TT',3X,'KC',3X,'KT',10X,'(KS(I,J),J=1,10)')
     DO 71 I=1,NRAD
 71  WRITE(6,205) I,ET(I),TT(I),KC(I),KT(I),(KS(I,J),J=1,10)
205  FORMAT(3X,I5,3X,2F6.3,12I5)
     WRITE(6,235)
235  FORMAT('0',10X,'SHAPE FACTOR MATRIX FOR THERMAL RADIATION',
    &'EXECHANGE(FORMAT F5.3):',/)
     DO 81 I=1,NRAD
 81  WRITE(6,215) (SF(I,J),J=1,NRAD)
```

```
215   FORMAT(' ',25F5.3)
 52   IF(NFLUX.EQ.0) GO TO 62
      WRITE(6,145)
145   FORMAT('0',10X,'NORMAL FLUX B.C. INFORMATION:',/,
     &9X,'ELEM',3X,'CODE',2X,'SIDE1',2X,'SIDE2',3X,'END1',3X,'END2')
      DO 21 I=1,NFLUX
      READ(5,50)LFLUX(I),MFLUX(I),(ISIDEF(I,J),J=1,2),(IENDF(I,J),J=1,2)
 21   WRITE(6,155)LFLUX(I),MFLUX(I),(ISIDEF(I,J),J=1,2),
     &(IENDF(I,J),J=1,2)
155   FORMAT(6X,6I7)
 62   IF(NCONV.EQ.0) GO TO 72
      WRITE(6,165)
165   FORMAT('0',10X,'CONVECTION B.C. INFORMATION:',/,
     &9X,'ELEM',3X,'CODE',2X,'SIDE1',2X,'SIDE2',3X,'END1',3X,'END2',
     &1X,'HCONVB1',1X,'HCONVB2',1X,'HCONVE1',1X,'HCONVE2')
      DO 31 I=1,NCONV
      READ(5,50)LCONV(I),MCONV(I),(ISIDEC(I,J),J=1,2),
     &(IENDC(I,J),J=1,2),(HCONVB(I,J),J=1,2),(HCONVE(I,J),J=1,2)
 50   FORMAT(6I5,4F10.3)
 31   WRITE(6,175)LCONV(I),MCONV(I),(ISIDEC(I,J),J=1,2),
     &(IENDC(I,J),J=1,2),(HCONVB(I,J),J=1,2),(HCONVE(I,J),J=1,2)
175   FORMAT(6X,6I7,4F8.2)
 72   WRITE(6,185)
185   FORMAT('0',10X,'ELEMENT INFORMATION:',/,'0',39X,'GENERAL DATA:',
     &/,13X,'ELE',4X,'I',4X,'J',4X,'K',1X,'MMAT',6X,'AREA',7X,'P')
      DO 41 J=1,NEL
      IF(J.GT.N1DIM) GO TO 92
      READ(5,60) (INDEX(J,I),I=1,3),MMAT(J),AREA(J),P(J)
 60   FORMAT(4I5,2F10.2)
      GO TO 102
 92   READ(5,60) (INDEX(J,I),I=1,3),MMAT(J)
102   WRITE(6,195) J,(INDEX(J,I),I=1,3),MMAT(J),AREA(J),P(J)
195   FORMAT(' ',10X,5I5,2F10.3)
 41   CONTINUE
      DO 51 I=1,NEL
      IF(I.GT.N1DIM) GO TO 82
      N1=IABS(INDEX(I,1)-INDEX(I,2))
      IF(MAXDIF.LT.N1) MAXDIF=N1
      GO TO 51
 82   N1=IABS(INDEX(I,1)-INDEX(I,2))
      N2=IABS(INDEX(I,2)-INDEX(I,3))
      N3=IABS(INDEX(I,1)-INDEX(I,3))
      IF(MAXDIF.LT.N1) MAXDIF=N1
      IF(MAXDIF.LT.N2) MAXDIF=N2
      IF(MAXDIF.LT.N3) MAXDIF=N3
 51   CONTINUE
      RETURN
      END
C----------------------------------------------------------------------
      SUBROUTINE PUTIN2(MAXNE,MAXNOD,MAXMAT,ISTOP,MAXDIF,TC,P,INDIC)
      COMMON/BAS1/INDEX(50,7),X(50,7),AREA(50),AL(50),N1DIM
```

```
      COMMON/BAS2/COND(5,2),PD(5),AMBB(50,7),AMBE(50,7),MCONV(50),DELTA
      COMMON/BAS4/T(50),MHEAT(50),MFLUX(25),MMAT(50),MCONST(25)
      COMMON/BAS5/NEL,NODES,NMAT,NCONST,NCONV,NFLUX,NHEAT,NOIT,IPRINT
      COMMON/BAS6/LCONV(50),LFLUX(25)
      COMMON/FLXN/FLUXB(50,7),FLUXE(50,7),ISIDEF(50,7),IENDF(50,7)
      COMMON/CONV/HCONVB(50,7),HCONVE(50,7),ISIDEC(50,7),IENDC(50,7)
      COMMON/RAD1/ET(35),TT(35),SF(35,35),KC(35),KT(35),KS(35,10),NRAD
      COMMON/SR1/AQA(15),QAM(10,15),GA(10,15),ASW,SWP(10),GSW(10),QA(15)
      COMMON/SR2/NP,NH,NS,ND,NM,SRT,SST
      COMMON/INP1/ATO,TOM(10),PSIO(10),ARHO,RHOM(10),XIO(10)
      COMMON/INP2/AHS,HSM(10),PSII(10),AVER,VERM(10),XII(10)
      COMMON/BALA/GLENTH,VOLUME,PA,CPA,WI,WO,TI,TO,WATER
      REAL H(30,40),SP(30,40),F(50),CONRAT(15)
      REAL FS(50),QP(50),P(50),TC(25)
      ISTOP=0
      READ(5,10)N1DIM,NEL,NODES,NMAT,NCONST,NCONV,NRAD,NFLUX,NHEAT,INDIC
     &,NOIT,IPRINT,DELTA
 10   FORMAT(12I5,F8.1)
      WRITE(6,15)N1DIM,NEL,NODES,NMAT,NCONST,NCONV,NRAD,NFLUX,NHEAT
 15   FORMAT('0',9X,'THE PROBLEM HAS',I2,1X,'1-D ELEMENTS',/,
     110X,'NUMBER OF ELEMENTS=',11X,I4,/,
     210X,'NUMBER OF NODES=',14X,I4,/,
     310X,'NO. OF MATERIALS=',10X,I4,/,
     410X,'NO. OF CONST. TEMP. NODES=',1X,I4,/,
     510X,'NO. OF ELEMENTS WITH CONVECTION=',10X,I4,/,
     610X,'NO. NODES WITH THERM.RAD.EXCHANGE=',2X,I4,/,
     710X,'NO. OF ELEMENTS WITH NORMAL FLUX=',9X,I4,/,
     810X,'NO. OF ELEMENTS WITH INT.HEAT GEN.=',8X,I4,/)
      IF(NEL.LE.MAXNE) GO TO 2
      ISTOP=ISTOP+1
      WRITE(6,25) MAXNE
 25   FORMAT('0',9X,'ERROR:MAXIMUM OF',I4,'ELEMENTS ARE ALLOWED')
  2   IF(NODES.LE.MAXNOD) GO TO 12
      ISTOP=ISTOP+1
      WRITE(6,35) MAXNOD
 35   FORMAT('0',9X,'ERROR:MAXIMUM OF',I4,'NODES ARE ALLOWED')
 12   IF(NMAT.LE.MAXMAT) GO TO 22
      ISTOP=ISTOP+1
      WRITE(6,45) MAXMAT
 45   FORMAT('0',9X,'ERROR:MAXIMUM OF',I4,'MATERIALS ARE ALLOWED')
 22   IF(ISTOP.NE.0) WRITE(6,55)
 55   FORMAT('0',9X,'EXECUTION HALTED BECAUSE OF THE EXCESSIVE
     &MEMORY REQUIREMENT EVIDENCED BY INPUT DATA')
      IF(ISTOP.NE.0) STOP
      WRITE(6,65)
 65   FORMAT('0',9X,'MATERIAL INFORMATION:',/,
     19X,'M',10X,'KX',10X,'KY',10X,'PC')
      DO 1 M=1,NMAT
      READ(5,20) (COND(M,I),I=1,2),PD(M)
 20   FORMAT(7F10.2)
  1   WRITE(6,75) M,COND(M,1),COND(M,2),PD(M)
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```
 75   FORMAT(6X,I4,3F12.3)
      WRITE(6,85)
 85   FORMAT('0',9X,'NODAL INFORMATION:',/,
     &9X,'N',17X,'X',14X,'Y')
      DO 11 K=1,NODES
      READ(5,30) (X(K,I),I=1,2)
 30   FORMAT(3F10.5)
 11   WRITE(6,95) K,X(K,1),X(K,2)
 95   FORMAT(5X,I5,3X,3F15.5)
      IF(NCONST.EQ.0) GO TO 32
      READ(5,40) (MCONST(I),I=1,NCONST)
 40   FORMAT(25I3)
      WRITE(6,105)
105   FORMAT('0',10X,'CONST.TEMP.NODES ARE:',/)
      WRITE(6,115) (MCONST(I),I=1,NCONST)
115   FORMAT(6X,25(I3,','))
 32   IF(NHEAT.EQ.0) GO TO 42
      READ(5,40) (MHEAT(I),I=1,NHEAT)
      WRITE(6,125)
125   FORMAT('0',10X,'ELEMENTS WITH INTERAL HEAT GEN.ARE:',/)
      WRITE(6,115) (MHEAT(I),I=1,NHEAT)
 42   IF(NRAD.LE.1) GO TO 52
      DO 101 I=1,35
      DO 101 J=1,35
101   SF(I,J)=0.
      DO 61 I=1,NRAD
      READ(5,80) ET(I),TT(I),KC(I),KT(I),(KS(I,J),J=1,10)
  80  FORMAT(2F5.3,12I2)
      KR=KT(I)
 61   READ(5,70) (SF(I,KS(I,J)),J=1,KR)
 70   FORMAT(10F6.4)
      WRITE(6,135)
135   FORMAT('0',10X,'THERMAL RADIATION INFORMATION:',/,4X,
     &'SURFACE',4X,'ET',4X,'TT',3X,'KC',3X,'KT',10X,'(KS(I,J),J=1,10)')
      DO 71 I=1,NRAD
 71   WRITE(6,205) I,ET(I),TT(I),KC(I),KT(I),(KS(I,J),J=1,10)
205   FORMAT(3X,I5,3X,2F6.3,12I5)
      WRITE(6,235)
235   FORMAT('0',10X,'SHAPE FACTOR MATRIX FOR THERMAL RADIATION',
     &'EXECHANGE(FORMAT F5.3):',/)
      DO 81 I=1,NRAD
 81   WRITE(6,215) (SF(I,J),J=1,NRAD)
215   FORMAT(' ',25F5.3)
 52   IF(NFLUX.EQ.0) GO TO 62
      WRITE(6,145)
145   FORMAT('0',10X,'NORMAL FLUX B.C. INFORMATION:',/,
     &9X,'ELEM',3X,'CODE',2X,'SIDE1',2X,'SIDE2',3X,'END1',3X,'END2')
      DO 21 I=1,NFLUX
      READ(5,50)LFLUX(I),MFLUX(I),(ISIDEF(I,J),J=1,2),(IENDF(I,J),J=1,2)
 21   WRITE(6,155)LFLUX(I),MFLUX(I),(ISIDEF(I,J),J=1,2),
     &(IENDF(I,J),J=1,2)
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155   FORMAT(6X,6I7)
 62   IF(NCONV.EQ.0) GO TO 72
      WRITE(6,165)
165   FORMAT('0',10X,'CONVECTION B.C. INFORMATION:',/,
     &9X,'ELEM',3X,'CODE',2X,'SIDE1',2X,'SIDE2',3X,'END1',3X,'END2',
     &1X,'HCONVB1',1X,'HCONVB2',1X,'HCONVE1',1X,'HCONVE2')
      DO 31 I=1,NCONV
      READ(5,50)LCONV(I),MCONV(I),(ISIDEC(I,J),J=1,2),
     &(IENDC(I,J),J=1,2),(HCONVB(I,J),J=1,2),(HCONVE(I,J),J=1,2)
 50   FORMAT(6I5,4F10.3)
 31   WRITE(6,175)LCONV(I),MCONV(I),(ISIDEC(I,J),J=1,2),
     &(IENDC(I,J),J=1,2),(HCONVB(I,J),J=1,2),(HCONVE(I,J),J=1,2)
175   FORMAT(6X,6I7,4F8.2)
 72   WRITE(6,185)
185   FORMAT('0',10X,'ELEMENT INFORMATION:',/,'0',39X,'GENERAL DATA:',
     &/,13X,'ELE',4X,'I',4X,'J',4X,'K',1X,'MMAT',6X,'AREA',7X,'P')
      DO 41 J=1,NEL
      IF(J.GT.N1DIM) GO TO 92
      READ(5,60) (INDEX(J,I),I=1,3),MMAT(J),AREA(J),P(J)
 60   FORMAT(4I5,2F10.2)
      GO TO 102
 92   READ(5,60) (INDEX(J,I),I=1,3),MMAT(J)
102   WRITE(6,195) J,(INDEX(J,I),I=1,3),MMAT(J),AREA(J),P(J)
195   FORMAT(' ',10X,5I5,2F10.3)
 41   CONTINUE
      DO 51 I=1,NEL
      IF(I.GT.N1DIM) GO TO 82
      N1=IABS(INDEX(I,1)-INDEX(I,2))
      IF(MAXDIF.LT.N1) MAXDIF=N1
      GO TO 51
 82   N1=IABS(INDEX(I,1)-INDEX(I,2))
      N2=IABS(INDEX(I,2)-INDEX(I,3))
      N3=IABS(INDEX(I,1)-INDEX(I,3))
      IF(MAXDIF.LT.N1) MAXDIF=N1
      IF(MAXDIF.LT.N2) MAXDIF=N2
      IF(MAXDIF.LT.N3) MAXDIF=N3
 51   CONTINUE
      RETURN
      END
C-----------------------------------------------------------------
      SUBROUTINE QGEN(QP,NHEAT,TIME)
      REAL QP(50)
      DO 1 I=1,NHEAT
  1   QP(I)=QP(I)+0.
      RETURN
      END
C-----------------------------------------------------------------
      SUBROUTINE RADF(HOUR)
      COMMON/RAD1/ET(35),TT(35),SF(35,35),KC(35),KT(35),KS(35,10),NRAD
      COMMON/RAD2/TR(35),QR(35),AT(35,35),BT(35),RT(35)
      COMMON/FLXN/FLUXB(50,7),FLUXE(50,7),ISIDEF(50,7),IENDF(50,7)
```

```
      N=NRAD-1
      DO 1 I=1,6
      FLUXE(I,1)=FLUXE(I,1)-QR(2*I-1)
    1 FLUXE(I,2)=FLUXE(I,2)-QR(2*I)
      FLUXE(7,1)=FLUXE(7,1)-QR(13)/2.
      FLUXE(7,2)=FLUXE(7,2)-QR(13)/2.
      FLUXE(8,1)=FLUXE(8,1)-QR(14)
      IF(HOUR.LE.8..OR.HOUR.GT.17.)GO TO 3
      GO TO 4
    3 FLUXE(9,1)=FLUXE(9,1)-QR(16)
      FLUXE(9,2)=FLUXE(9,2)-QR(17)
    4 RETURN
      END
C-----------------------------------------------------------------
      SUBROUTINE RADT(HOUR)
      COMMON/RAD2/TR(35),QR(35),AT(35,35),BT(35),RT(35)
      COMMON/BAS4/T(50),MHEAT(50),MFLUX(25),MMAT(50),MCONST(25)
      COMMON/BALA/GLENTH,VOLUME,PA,CPA,WI,WO,TI,TO,WATER
      DO 1 I=1,12
    1 TR(I)=T(I)
      TR(13)=(T(13)+T(14))/2.
      TR(14)=T(15)
      TR(15)=0.0552*(TO+273.16)**1.5-273.16
      IF(HOUR.LE.8..OR.HOUR.GT.17.)GO TO 3
      GO TO 4
    3 TR(16)=T(24)
      TR(17)=T(25)
    4 RETURN
      END
C-----------------------------------------------------------------
      SUBROUTINE RELHUM(TIME,RHO)
      COMMON/INP1/ATO,TOM(10),PSIO(10),ARHO,RHOM(10),XIO(10)
      COMMON/BALA/GLENTH,VOLUME,PA,CPA,WI,WO,TI,TO,WATER
      COMMON/SR2/NP,NH,NS,ND,NM,SRT,SST
      COMPLEX PRHO,ZERO,EYE,CMPLX,CEXP
      ZERO = CMPLX(0.0,0.0)
      EYE = CMPLX(0.0,1.0)
      PRHO = ZERO
      OMEGA=6.283185/NP
      DO 1 J=1,NH
      PRHO=PRHO+RHOM(J)*CEXP(EYE*(J*OMEGA*TIME+XIO(J)))
    1 CONTINUE
      RELHUM = ARHO + REAL(PRHO)*2.
      IF(RELHUM.LE.0.0) RELHUM=0.5
      RHO=RELHUM
      RETURN
      END
C-----------------------------------------------------------------
      SUBROUTINE ROCKBED(T,TDSIRE,K1,TEXT)
      COMMON/BAS2/COND(5,2),PD(5),AMBB(50,7),AMBE(50,7),MCONV(50),DELTA
      COMMON/BALA/GLENTH,VOLUME,PA,CPA,WI,WO,TI,TO,WATER
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      COMMON/ROK1/RBL,RBA,PB,CB,RK,U,RBP,DE,E,DT,DX
      COMMON/ROK2/TA(50),TB(50),FRBLO,FRFAN,TLIM1,TLIM2
      COMMON/ROK3/KODE,FRAT,ISIG,QROK,QROKS,QTOT,WIROK,WTOT
      REAL UA(50),UB(50)
C
      AK = 0.0262
      CA = CPA
      NX = IFIX(RBL/DX+1.1)
      NT = IFIX(DELTA/DT)
      ISIG = 0
C
C INITIALIZE THE ROCKBED TEMPERATURES
C
      IF(K1.GT.1) GO TO 21
      DO 20 I=1,NX
      TA(I) =  21.0
  20  TB(I) =  21.0
  21  CONTINUE
C
      QROK = 0.0
      QROKS = 0.
      WIROK = 0.
      DO 30 J=1,NT
C
C UPDATE THE TEMPERATURE DISTRIBUTION IN THE ROCKBED.
C
      IF(KODE.EQ.0) GO TO 45
      V=FRAT/RBA
      RE=PA*V*DE/(1.819E-5)
      H=(1.52*AK*RE**0.69)/(DE*DE)
      PE=PA*CA*V*DE/AK
      BI=H*DE*DE/(12.*(1.-E)*RK)
      TAU=PB*CB*RBL/(PA*CA*V)
      HTU=H*RBL/(PA*CA*V)
      HTUC=1./(DE/(RBL*PE)+(1.+BI/5.)/HTU)
      PC=HTUC/TAU
      PCD=HTUC/RBL
      PCDD=U*RBP/(PA*V*CA*RBA)
      PCS=PCD+PCDD
      B1=(2.-PC*DT)/(2.+PC*DT)
      B2=PC*DT/(2.+PC*DT)
      A=1.+PCS*DX/2.-PCD*PC*DX*DT/(4.+2.*PC*DT)
      A1=(1.-PCS*DX/2.)/A
      A2=PCD*DX/(2.*A)
      A3=PCD*DX*(2.-PC*DT)/(A*(4.+2.*PC*DT))
      A4=PCD*PC*DX*DT/(A*(4.+2.*PC*DT))
      A5=PCDD*DX/A
  45  CONTINUE
      C1=1./(1.+U*RBP*DT/(PB*CB*RBA))
      DO 10 I=1,NX
      UA(I)=TA(I)
```

```
   10 UB(I)=TB(I)
      IF(KODE.EQ.0) GO TO 33
      TA(1)=TI
      TB(1)=B1*UB(1)+2.*B2*TA(1)
      DO 40 I=2,NX
      TA(I) = A1*TA(I-1)+A2*TB(I-1)+A3*UB(I)+A4*UA(I)+A5*TO
      TB(I) = B1*UB(I) + B2*(TA(I)+UA(I))
   40 CONTINUE
      GO TO 35
C     TA(NX)=TI
C     TB(NX)=B1*UB(NX)+2.*B2*TA(NX)
C     DO 50 I=2,NX
C     K=NX-I+1
C     TA(K) = A1*TA(K+1)+A2*TB(K+1)+A3*UB(K)+A4*UA(K)+A5*TO
C     TB(K) = B1*UB(K) + B2*(TA(K)+UA(K))
C 50  CONTINUE
C     GO TO 35
   33 CONTINUE
      DO 70 I=1,NX
      TB(1) = C1*UB(I)+(1.-C1)*TO
      TA(I) = TB(I)
   70 CONTINUE
      GO TO 35
C
C COMPUTE INCREMENTAL AND NET SENSIBLE & LATENT HEAT STORED.
C
   35 CONTINUE
      ATEXT = (UA(NX)+TA(NX))/2.
      ATIN = (UA(1)+TA(1))/2.
      DO 80 I=1,NX
   80 QROKS=QROKS+U*RBP*DX*DT*(TI-TA(I))
      QROK=QROK+PA*CA*FRAT*(ATIN-ATEXT)
C     IF(KODE.EQ.0)  QROK=QROK-PA*CA*FRAT*(ATIN-ATEXT)
      IF(KODE.EQ.-1) QROK=QROK+PA*CA*FRAT*(ATIN-ATEXT)
      ATEXTK = ATEXT+273.16
      ATINK = ATIN+273.16
      WRS = PRES(ATEXTK)
      WRS=0.622*WRS/(101.325-WRS)
      IF(WRS-WI) 150,160,170
  150 WIROKS = -PA*FRAT*(WI-WRS)*DT
      GO TO 180
  170 WIROKS = -PA*FRAT*DT*(WI-WRS)
      GO TO 180
  160 WIROKS = 0.
  180 WIROK = WIROK+WIROKS
C
C THE FOLLOWING SEGMENT DETERMINES THE MODE OF ROCKBED OPERATION.
C
      IF(TI-TDSIRE) 100,200,300
  100 FRAT = FRBLO
      KODE = -1
```

```
      GO TO 310
300   IF(TI.LT.TLIM1) GO TO 200
      IF(TI.GE.TLIM2) GO TO 400
      FRAT = FRBLO
      KODE = 1
      GO TO 310
400   KODE = 2
      FRAT = FRBLO
      GO TO 310
200   FRAT = 0.
      KODE =0.
310   CONTINUE
 30   CONTINUE
      TEXT = TA(NX)
      QROK = QROK/NT
      QTOT = QTOT+QROKS+QROK*DELTA
      QROKS = QROKS/DELTA
      WTOT = WTOT+WIROK
      WIROK=WIROk/DELTA
      RETURN
      END
C -----------------------------------------------------------------------
      SUBROUTINE SOLRAD(T,QP)
      REAL QP(50)
      COMMON/SR1/AQA(15),QAM(10,15),GA(10,15),ASW,SWP(10),GSW(10),QA(15)
      COMMON/SR2/NP,NH,NS,ND,NM,SRT,SST
      COMMON/BAS1/INDEX(50,7),X(50,7),AREA(50),AL(50),N1DIM
      COMMON/FLXN/FLUXB(50,7),FLUXE(50,7),ISIDEF(50,7),IENDF(50,7)
      COMPLEX EYE,ZERO,CMPLX,CEXP,PSW,PQA(15)
      OMEGA=6.283185/NP
      EYE=CMPLX(0.0,1.0)
      ZERO=CMPLX(0.0,0.0)
      NT=NS+ND+NM+2
      IF(T.LE.SRT) GO TO 2
      IF(T.GT.SST) GO TO 2
      DO 1 K=1,NT
  1   PQA(K)=ZERO
      DO 11 K=1,NT
      DO 21 J=1,NH
 21   PQA(K)=PQA(K)+QAM(J,K)*CEXP(EYE*(J*OMEGA*T+GA(J,K)))
 11   QA(K)=AQA(K)+2.*REAL(PQA(K))
      PSW=ZERO
      DO 31 J=1,NH
 31   PSW=PSW+SWP(J)*CEXP(EYE*(J*OMEGA*T+GSW(J)))
      SW=ASW+2.*REAL(PSW)
      GO TO 12
  2   DO 71 K=1,NT
 71   QA(K)=0.
      SW=0.
 12   DO 41 I=1,6
      FLUXE(I,1)=FLUXE(I,1)+QA(I)/2.
```

```
      FLUXE(I,2)=FLUXE(I,2)+QA(I)/2.
   41  QP(I)=0.
      FLUXE(7,1)=FLUXE(7,1)+QA(7)/2.
      FLUXE(7,2)=FLUXE(7,2)+QA(7)/2.
      FLUXE(8,1)=FLUXE(8,1)+QA(8)
      RETURN
      END
C-----------------------------------------------------------------
      SUBROUTINE SOLUTN
      COMMON/RAD1/ET(35),TT(35),SF(35,35),KC(35),KT(35),KS(35,10),NRAD
      COMMON/RAD2/TR(35),QR(35),AT(35,35),BT(35),RT(35)
      REAL AP(35,35)
      DO 1 I=1,NRAD
      DO 1 J=1,NRAD
    1 AP(I,J)=AT(I,J)
      DO 11 K=1,NRAD
      AKK=AP(K,K)
      IF(AKK.EQ.0.) STOP
      DO 21 J=K,NRAD
   21 AP(K,J)=AP(K,J)/AKK
      BT(K)=BT(K)/AKK
      DO 11 I=1,NRAD
      IF(I.EQ.K) GO TO 11
      AIK=AP(I,K)
      DO 31 J=K,NRAD
   31 AP(I,J)=AP(I,J)-AIK*AP(K,J)
      BT(I)=BT(I)-AIK*BT(K)
   11 CONTINUE
      RETURN
      END
C-----------------------------------------------------------------
      SUBROUTINE SOLVE(GSM,GF,X,NP,NBW,M1,M2)
      DIMENSION GSM(M1,M2),GF(M1),X(M1)
      NP1=NP-1
      DO 250 I=1,NP1
      MJ=I+NBW-1
      IF(MJ.GT.NP) MJ=NP
      NJ=I+1
      L=1
      DO 250 J=NJ,MJ
      L=L+1
  250 GF(J)=GF(J)-GSM(I,L)*GF(I)/GSM(I,1)
      X(NP)=GF(NP)/GSM(NP,1)
      DO 252 K=1,NP1
      I=NP-K
      MJ=NBW
      IF((I+NBW-1).GT.NP) MJ=NP-I+1
      SUM=0.0
      DO 251 J=2,MJ
      N=I+J-1
  251 SUM=SUM+GSM(I,J)*X(N)
```

```
  252 X(I)=(GF(I)-SUM)/GSM(I,1)
      RETURN
      END
C-------------------------------------------------------------------
      SUBROUTINE SPECIF(N,M,SP)
      REAL SP(30,40)
      COMMON/BAS1/INDEX(50,7),X(50,7),AREA(50),AL(50),N1DIM
      COMMON/BAS2/COND(5,2),PD(5),AMBB(50,7),AMBE(50,7),MCONV(50),DELTA
      I=INDEX(N,1)
      J=INDEX(N,2)
      IF(N.GT.N1DIM) GO TO 2
      CF=PD(M)*AREA(N)*AL(N)/6.
      CF2=CF+CF
      SP(I,1)=SP(I,1)+CF2
      SP(J,1)=SP(J,1)+CF2
      IF(I.GT.J) SP(J,I-J+1)=SP(J,I-J+1)+CF
      IF(I.LT.J) SP(I,J-I+1)=SP(I,J-I+1)+CF
      RETURN
    2 K=INDEX(N,3)
      CF=PD(M)*AREA(N)/12.
      CF2=CF+CF
      SP(I,1)=SP(I,1)+CF2
      IF(I.GT.J) SP(J,I-J+1)=SP(J,I-J+1)+CF
      IF(I.LT.J) SP(I,J-I+1)=SP(I,J-I+1)+CF
      IF(I.GT.K) SP(K,I-K+1)=SP(K,I-K+1)+CF
      SP(J,1)=SP(J,1)+CF2
      IF(I.LT.K) SP(I,K-I+1)=SP(I,K-I+1)+CF
      IF(J.GT.K) SP(K,J-K+1)=SP(K,J-K+1)+CF
      IF(J.LT.K) SP(J,K-J+1)=SP(J,K-J+1)+CF
      SP(K,1)=SP(K,1)+CF2
      RETURN
      END
C-------------------------------------------------------------------
      SUBROUTINE TIN
      COMMON/BAS4/T(50),MHEAT(50),MFLUX(25),MMAT(50),MCONST(25)
      COMMON/BAS5/NEL,NODES,NMAT,NCONST,NCONV,NFLUX,NHEAT,NOIT,IPRINT
      READ(5,10) (T(I),I=1,NODES)
   10 FORMAT(8F10.5)
      RETURN
      END
C-------------------------------------------------------------------
      SUBROUTINE TRADP(INS)
      COMMON/RAD1/ET(35),TT(35),SF(35,35),KC(35),KT(35),KS(35,10),NRAD
      COMMON/RAD2/TR(35),QR(35),AT(35,35),BT(35),RT(35)
      REAL AP(35,35)
      IF(INS.EQ.1) GO TO 2
      DO 1 I=1,NRAD
    1 RT(I)=1.-ET(I)-TT(I)
      DO 11 I=1,NRAD
      IF(TT(I).NE.0.) GO TO 12
      DO 21 J=1,NRAD
```

```
      AT(I,J)=-RT(I)*SF(I,J)
   21 IF(I.EQ.J) AT(I,J)=1.+AT(I,J)
      GO TO 11
   12 X=ET(I)/2.+RT(I)
      Y=ET(I)/2.+TT(I)
      DO 31 J=1,NRAD
      AT(I,J)=-X*SF(I,J)
   31 IF(I.EQ.J) AT(I,J)=1.+AT(I,J)
      I1=KC(I)
      DO 41 J=1,NRAD
      IF(SF(I1,J).EQ.0) GO TO 41
      AT(I,J)=-Y*SF(I1,J)
   41 CONTINUE
   11 CONTINUE
    2 DO 51 I=1,NRAD
      BT(I)=5.67E-8*ET(I)*(TR(I)+273.16)**4
   51 IF(TT(I).NE.0.) BT(I)=0.
      CALL SOLUTN
      DO 61 I=1,NRAD
      SUM=0.
      DO 71 J=1,NRAD
   71 SUM=SUM+BT(J)*SF(I,J)
   61 QR(I)=BT(I)-SUM
      RETURN
      END
C-----------------------------------------------------------------------
      SUBROUTINE TRANSP(EP,HOUR)
      COMMON/BAS1/INDEX(50,7),X(50,7),AREA(50),AL(50),N1DIM
      COMMON/BAS4/T(50),MHEAT(50),MFLUX(25),MMAT(50),MCONST(25)
      COMMON/FLXN/FLUXB(50,7),FLUXE(50,7),ISIDEF(50,7),IENDF(50,7)
      COMMON/BALA/GLENTH,VOLUME,PA,CPA,WI,WO,TI,TO,WATER
      COMMON/SR2/NP,NH,NS,ND,NM,SRT,SST
      COMMON/RLHU/PLC,PLV,CONDC,CONDV
C THE FOLLOWING ONE STATEMENT MAY VARY WITH THE PROBLEM
      TP = (T(13)+T(14))/2.
      RP = 50000.
      IF(HOUR.GT.SRT.AND.HOUR.LT.SST) RP=500.
      DP=AREA(7)
      TK=TP+273.16
      PS=PRES(TK)
      HFG=2.502E+06 + 1880.0*((TP+TI)/2.)
      WP=0.62198*PS/(101.325-PS)
      PLC = 2.*PA*DP*(WP-WI)/RP
      EP=2.*PA*DP*(WP-WI)/RP
      PLV = 2.*PA*DP*WP/RP
C THE FOLLOWING TWO STATEMENTS MAY VARY ACCORDING TO THE PROBLEM
      FLUXE(7,1)=-0.5*HFG*EP/DP+FLUXE(7,1)
      FLUXE(7,2)=-0.5*HFG*EP/DP+FLUXE(7,2)
      RETURN
      END
C-----------------------------------------------------------------------
```

```
      FUNCTION HEAT(TIME)
C THIS SUBROUTINE COMPUTES THE INSTANTANEOUS VALUE OF THE ALGEBRAIC HEAT
C SUPPLIED TO THE GREENHOUSE AIR BY EVALUATING ITS EXPONENTIAL FOURIER
C SERIES

C TIME  TIME AT THE CURRENT TIME STEP
C HS    HEAT SUPPLIED TO THE GREENHOUSE AIR
C ------------------------------------------------------------------------
      COMMON/SR2/NP,NH,NS,ND,NM,SRT,SST
      COMMON/INP2/AHS,HSM(10),PSII(10),AVER,VERM(10),XII(10)
      COMPLEX EYE,ZERO,CMPLX,CEXP,PHS
      ZERO = CMPLX(0.0,0.0)
      EYE = CMPLX(0.0,0.0)
      OMEGA = 6.283285/NP
      PHS = ZERO
      DO 11 J=1,NH
   11 PHS = PHS + HSM(J)*CEXP(EYE*(J*OMEGA*TIME+PSII(J)))
      RETURN
      END
C-----------------------------------------------------------------------
      FUNCTION PRES(T)
      IF(T.GT.273.16) GO TO 30
      PRES=EXP(24.2779-6238.64/T-0.344438*ALOG(T))
      RETURN
   30 PRES=(-7511.52/T+89.63121+0.023999*T-1.1654551D-5*T**2-
     &1.2810336D-8*T**3+2.0998405D-11*T**4-12.150799*ALOG(T))
      PRES=EXP(PRES)
      RETURN
      END
C------------------------------------------------------------------------
      FUNCTION VENT(TIME)
      COMMON/SR2/NP,NH,NS,ND,NM,SRT,SST
      COMMON/INP2/AHS,HSM(10),PSII(10),AVER,VERM(10),XII(10)
      COMPLEX EYE, ZERO, CMPLX, CEXP, PVER
      ZERO = CMPLX(0.0,0.0)
      EYE = CMPLX(0.0,1.0)
      OMEGA = 6.283285/NP
      PVER = ZERO
      DO 11 J=1,NH
   11 PVER = PVER+VERM(J)*CEXP(EYE*(J*OMEGA*TIME+XII(J)))
      VENT = AVER+2.*REAL(PVER)
      VENT=0.009
      IF(TIME.GT.11.0.AND.TIME.LE.17.0) VENT =.009
      RETURN
      END
C-------------------------------------------------------------------------
```

APPENDIX B-5

SAMPLE INPUT DATA FOR ROCK PROGRAM

```
SAMPLE SIMULATION
   16   16   25     6    1    9  17    9    6    1  288   12    300.0
    0.6       3.0    1000.0     900.0      2.7       0.0191  13.00      0.075
    0.46    300.00     00.30      0.175    0.900    25.0     30.0
    5.00     37.3
     0.865      0.0   2.27E+06
     0.44       0.0   2.27E+06
     1.000      0.0   2.00E+06
     0.420      0.0   1.73E+06
     0.027      0.0   2.27E+06
     0.44       0.0   2.27E+06
   0.0       0.0
   0.0002    0.0
   0.0       0.0
   0.1       0.0
   0.0       0.0
   0.1       0.0
   0.0       0.0
   0.0002    0.0
   0.0       0.0
   0.05      0.0
   0.0       0.0
   0.05      0.0
   0.0       0.0
   0.001     0.0
   0.0       0.0
   0.05      0.0
   0.15      0.0
   0.35      0.0
   0.75      0.0
   1.55      0.0
   3.15      0.0
   6.35      0.0
  12.00      0.0
   0.0       0.0
   0.05      0.0
  23
   1  2  3  4  5  6
 0.2500.500 2 115
 1.0
 0.2500.500 1 6 81012131417
 0.01600.16500.16500.11400.21000.3300
 0.5000.250 4 115
 1.0
 0.5000.250 3 116
 1.0
 0.5000.250 6 115
 1.0
 0.5000.250 5 116
 1.0
```

```
0.2500.500 8 115
1.0
0.2500.500 7 6 21012131417
0.01600.16500.16500.11400.21000.3300
0.8000.00010 115
1.0
0.8000.000 9 6 2 812131417
0.06600.06600.09200.36100.17100.2440
0.8000.00012 115
1.0
0.8000.00011 6 2 810131417
0.06600.06600.09300.35600.25500.1640
0.9000.000   7 2 81012131417
0.00900.00900.07100.07000.40000.30000.1410
0.9000.000   6 2 810121317
0.03300.03300.06700.10000.60000.1670
0.9400.000   115
1.0
0.1000.33017 2 4 6
0.50000.5000
0.1000.33016 7 2 81012131417
0.03300.03300.06100.04100.17950.10630.5462
    1    2    0    0    1    1
    2    2    0    0    1    1
    3    2    0    0    1    1
    4    2    0    0    1    1
    5    2    0    0    1    1
    6    2    0    0    1    1
    7    2    0    0    1    1
    8    2    0    0    1    0
   16    2    0    0    1    1
    1    2    0    0    1    1        0.0        0.0      35.00       8.08
    2    2    0    0    1    0        0.0        0.0      35.00       0.00
    3    2    0    0    1    0        0.0        0.0      35.00       0.00
    4    2    0    0    1    1        0.0        0.0      35.00       8.08
    5    2    0    0    1    1        0.0        0.0      35.00       8.08
    6    2    0    0    1    1        0.0        0.0      35.00       8.08
    7    2    0    0    1    1        0.0        0.0      13.00      13.00
    8    2    0    0    1    0        0.0        0.0      17.00      00.00
   16    2    0    0    1    1        0.0        0.0       1.00       8.08
    1    2         1      7.46       0.0
    3    4         2     12.00       0.0
    5    6         2      5.55       0.0
    7    8         1      7.46       0.0
    9   10         5      5.55       0.0
   11   12         5     12.00       0.0
   13   14         3      6.0        0.0
   15   16         4     17.000      0.0
   16   17         4     17.000      0.0
   17   18         4     17.000      0.0
   18   19         4     17.000      0.0
   19   20         4     17.000      0.0
   20   21         4     17.000      0.0
   21   22         4     17.000      0.0
   22   23         4     17.000      0.0
   24   25         6     17.500      0.0
```

```
  14.00     14.00     14.00     14.00     14.00     14.00     14.00     14.00
   9.92     14.00     14.00     14.00     14.00     14.00     14.00     14.962
  10.046    10.214    10.55     11.22     12.57     15.25     20.0      14.00
   9.92
   15   15   23    5    1    8   15    8    6    1  288   12    300 0
     0.865       0.0    2.27E+06
     0.44        0.0    2.27E+06
     1.000       0.0    2.00E+06
     0.420       0.0    1.73E+06
     0.027       0.0    2.27E+06
   0.0        0.0
   0.0002     0.0
   0.0        0.0
   0.1        0.0
   0.0        0.0
   0.1        0.0
   0.0        0.0
   0.0002     0.0
   0.0        0.0
   0.05       0.0
   0.0        0.0
   0.05       0.0
   0.0        0.0
   0.001      0.0
   0.0        0.0
   0.05       0.0
   0.15       0.0
   0.35       0.0
   0.75       0.0
   1.55       0.0
   3.15       0.0
   6.35       0.0
  12.00       0.0
 23
  1  2  3  4  5  6
0.2500.500 2 115
1.0
0.2500.500 1 71012 4 6 81314
0.16500.16500.16500.16500.01600.11400.2100
0.5000.250 4 115
1.0
0.5000.250 3 7 21012 6 81314
0.06600.15600.08800.09200.06600.36100.1710
0.5000.250 6 115
1.0
0.5000.250 5 7 21012 4 81314
0.06600.09300.07600.08800.06600.35600.2550
0.2500.500 8 115
1.0
0.2500.500 7 7 21012 4 61314
0.01600.16500.16500.16500.16500.11400.2100
0.8000.00010 115
1.0
0.8000.000 9 7 212 4 6 81314
0.06600.08800.07600.09300.06600.35600.2550
0.8000.00012 115
```

```
1.0
0.8000.00011 7 210 4 6 81314
0.06600.15600.08800.09200.06600.36100.1710
0.9000.000   8 21012 4 6 81314
0.00900.07100.07000.07000.07100.00900.40000.3000
0.9000.000   7 21012 4 6 813
0.03300.06700.10000.10000.06700.03300.6000
0.9400.000   115
1.0
    1    2    0    0    1    1
    2    2    0    0    1    1
    3    2    0    0    1    1
    4    2    0    0    1    1
    5    2    0    0    1    1
    6    2    0    0    1    1
    7    2    0    0    1    1
    8    2    0    0    1    0
    1    2    0    0    1    1       0.0       0.0     35.00      8.08
    2    2    0    0    1    1       0.0       0.0     35.00      8.06
    3    2    0    0    1    1       0.0       0.0     35.00      8.08
    4    2    0    0    1    1       0.0       0.0     35.00      8.08
    5    2    0    0    1    1       0.0       0.0     35.00      8.08
    6    2    0    0    1    1       0.0       0.0     35.00      8.08
    7    2    0    0    1    1       0.0       0.0     13.00     13.00
    8    2    0    0    1    0       0.0       0.0     17.00     00.00
    1    2         1     7.46       0.0
    3    4         2    12.00       0.0
    5    6         2     5.55       0.0
    7    8         1     7.46       0.0
    9   10         5     5.55       0.0
   11   12         5    12.00       0.0
   13   14         3     6.0        0.0
   15   16         4    17.000      0.0
   16   17         4    17.000      0.0
   17   18         4    17.000      0.0
   18   19         4    17.000      0.0
   19   20         4    17.000      0.0
   20   21         4    17.000      0.0
   21   22         4    17.000      0.0
   22   23         4    17.000      0.0
   16   16   25    6    1    9   17    9     6    1   288   12    300.0
     0.6       3.0    1000.0     900.0      2.7      0.0101   13.00     0.075
     0.46    300.00     00.30      0.175     0.900     25.0     30.0
     5.00     37.3
      0.865      0.0   2.27E+06
      0.44       0.0   2.27E+06
      1.000      0.0   2.00E+06
      0.420      0.0   1.73E+06
      0.027      0.0   2.27E+06
      0.44       0.0   2.27E+06
    0.0        0.0
    0.0002     0.0
    0.0        0.0
    0.1        0.0
    0.0        0.0
    0.1        0.0
```

```
   0.0        0.0
   0.0002     0.0
   0.0        0.0
   0.05       0.0
   0.0        0.0
   0.05       0.0
   0.0        0.0
   0.001      0.0
   0.0        0.0
   0.05       0.0
   0.15       0.0
   0.35       0.0
   0.75       0.0
   1.55       0.0
   3.15       0.0
   6.35       0.0
  12.00       0.0
   0.0        0.0
   0.05       0.0
 23
  1  2  3  4  5  6
0.2500.500 2 115
1.0
0.2500.500 1 6 81012131417
0.01600.16500.16500.11400.21000.3300
0.5000.250 4 115
1.0
0.5000.250 3 116
2.0
0.5000.250 6 115
1.0
0.5000.250 5 116
1.0
0.2500.500 8 115
1.0
0.2500.500 7 6 21012131417
0.01600.16500.16500.11400.21000.3300
0.8000.00010 115
1.0
0.8000.000 9 6 2 812131417
0.06600.06600.09200.36100.17100.2440
0.8000.00012 115
1.0
0.8000.00011 6 2 810131417
0.06600.06600.09300.35600.25500.1640
0.9000.000   7 2 81012131417
0.00900.00900.07100.07000.40000.30000.1410
0.9000.000   6 2 810121317
0.03300.03300.06700.10000.60000.1670
0.9400.000   115
1.0
0.1000.33017 2 4 6
0.50000.5000
0.1000.33016 7 2 81012131417
0.03300.03300.06100.04100.17950.10630.5462
     1     2     0     0     1     1
```

```
 2   2   0   0   1   1
 3   2   0   0   1   1
 4   2   0   0   1   1
 5   2   0   0   1   1
 6   2   0   0   1   1
 7   2   0   0   1   1
 8   2   0   0   1   0
16   2   0   0   1   1
 1   2   0   0   1   1      0.0      0.0    35.00     8.08
 2   2   0   0   1   0      0.0      0.0    35.00     0.00
 3   2   0   0   1   0      0.0      0.0    35.00     0.00
 4   2   0   0   1   1      0.0      0.0    35.00     8.08
 5   2   0   0   1   1      0.0      0.0    35.00     8.08
 6   2   0   0   1   1      0.0      0.0    35.00     8.08
 7   2   0   0   1   1      0.0      0.0    13.00    13.00
 8   2   0   0   1   0      0.0      0.0    17.00    00.00
16   2   0   0   1   1      0.0      0.0     1.00     8.08
 1   2       1    7.46      0.0
 3   4       2   12.00      0.0
 5   6       2    5.55      0.0
 7   8       1    7.46      0.0
 9  10       5    5.55      0.0
11  12       5   12.00      0.0
13  14       3    6.0       0.0
15  16       4   17.000     0.0
16  17       4   17.000     0.0
17  18       4   17.000     0.0
18  19       4   17.000     0.0
19  20       4   17.000     0.0
20  21       4   17.000     0.0
21  22       4   17.000     0.0
22  23       4   17.000     0.0
24  25       6   17.500     0.0
```

APPENDIX B-6

SAMPLE OUTPUT FROM ROCK PROGRAM

```
0                              SAMPLE SIMULATION
0          THE PROBLEM HAS16 1-D ELEMENTS
           NUMBER OF ELEMENTS=              16
           NUMBER OF NODES=                 25
           NO. OF MATERIALS=              6
           NO. OF CONST. TEMP. NODES=    1
           NO. OF ELEMENTS WITH CONVECTION=            9
           NO. NODES WITH THERM.RAD.EXCHANGE=     17
           NO. OF ELEMENTS WITH NORMAL FLUX=           9
           NO. OF ELEMENTS WITH INT.HEAT GEN.=          6
            NO. OF TIME INCR.FOR TRANS.ANALYSIS=       288
           PRINTING INTERVAL FOR TEMP.FIELDS=          12
           TIME INCREMENT FOR TRANS.ANALYSIS=     300.0000
           INDIC(1=TRANSIENT,0=STEADY)=            1

0           LENGTH OF THE ROCKBED                         0.60
           ROCKBED AREA NORMAL TO THE AIRFLOW          3.0000
           EFFECTIVE PERIMETER OF THE ROCKBED         13.0000
           EQUIVALENT ROCK PARTICLE DIAMETER           0.0750
           POROSITY OF THE ROCKBED                     0.4600
           DIFFERENTIAL ROCKBED LENGTH                 0.30000
           SOLUTION TIME STEP                          300.00
           ROCKBED PERIMETER HEAT LOSS FACTOR            0.02

0           BULK DENSITY OF THE ROCKBED                1000.00
           SPECIFIC HEAT OF THE ROCKS                 900.0000
           THERMAL CONDUCTIVITY OF THE ROCKS           2.7000
           FLOW RATE FOR LOW VENT FAN                  0.1750
           FLOW RATE FOR HIGH VENT FAN                 0.9000
           BASE TEMPERATURE FOR HEAT COLLECTION         25.00
           NODE 3 TEMPERATURE IN SUBR. ROCKBED           30.00

0           LENGTH OF THE STRUCTURE=                   5.00000
           VOLUME OF THE STRUCTURE=                     37.30
0           MATERIAL INFORMATION:
          M          KX          KY          PC
          1        0.865       0.000 2269999.980
          2        0.440       0.000 2269999.980
          3        1.000       0.000 2000000.020
          4        0.420       0.000 1729999.920
          5        0.027       0.000 2269999.980
          6        0.440       0.000 2269999.980
0           NODAL INFORMATION:
          N                  X               Y

          1               0.00000         0.00000
                          0.00020         0.00000
                          [illegible]     0.00000
                          0.10000         0.00000
                          [illegible]     0.00000
```

```
           6             0.10000          0.00000
           7             0.00000          0.00000
           8             0.00020          0.00000
           9             0.00000          0.00000
          10             0.05000          0.00000
          11             0.00000          0.00000
          12             0.05000          0.00000
          13             0.00000          0.00000
          14             0.00100          0.00000
          15             0.00000          0.00000
          16             0.05000          0.00000
          17             0.15000          0.00000
          18             0.35000          0.00000
          19             0.75000          0.00000
          20             1.55000          0.00000
          21             3.15000          0.00000
          22             6.35000          0.00000
          23            12.00000          0.00000
          24             0.00000          0.00000
          25             0.05000          0.00000
0           CONST.TEMP.NODES ARE:

        23,
0           ELEMENTS WITH INTERAL HEAT GEN.ARE:

         1,  2,  3,  4,  5,  6,
0           THERMAL RADIATION INFORMATION:
      SURFACE    ET     TT    KC   KT          (KS(I,J),J=1,10)
         1     0.250 0.500    2    1    15    0    0    0    0    0    0    0    0    0
         2     0.250 0.500    1    6     8   10   12   13   14   17    0    0    0    0
         3     0.500 0.250    4    1    15    0    0    0    0    0    0    0    0    0
         4     0.500 0.250    3    1    16    0    0    0    0    0    0    0    0    0
         5     0.500 0.250    6    1    15    0    0    0    0    0    0    0    0    0
         6     0.500 0.250    5    1    16    0    0    0    0    0    0    0    0    0
         7     0.250 0.500    8    1    15    0    0    0    0    0    0    0    0    0
         8     0.250 0.500    7    6     2   10   12   13   14   17    0    0    0    0
         9     0.800 0.000   10    1    15    0    0    0    0    0    0    0    0    0
        10     0.800 0.000    9    6     2    8   12   13   14   17    0    0    0    0
        11     0.800 0.000   12    1    15    0    0    0    0    0    0    0    0    0
        12     0.800 0.000   11    6     2    8   10   13   14   17    0    0    0    0
        13     0.900 0.000    0    7     2    8   10   12   13   14   17    0    0    0
        14     0.900 0.000    0    6     2    8   10   12   13   17    0    0    0    0
        15     0.940 0.000    0    1    15    0    0    0    0    0    0    0    0    0
        16     0.100 0.330   17    2     4    6    0    0    0    0    0    0    0    0
        17     0.100 0.330   16    7     2    8   10   12   13   14   17    0    0    0
0           SHAPE FACTOR MATRIX FOR THERMAL RADIATIONEXECHANGE(FORMAT F5.3):

 0.0000.0000.0000.0000.0000.0000.0000.0000.0000.0000.0000.0000.0000.0001.0000.0000.000
 0.0000.0000.0000.0000.0000.0000.0000.0160.0000.1650.0000.1650.1140.2100.0000.0000.330
 0.0000.0000.0000.0000.0000.0000.0000.0000.0000.0000.0000.0000.0000.0001.0000.0000.000
 0.0000.0000.0000.0000.0000.0000.0000.0000.0000.0000.0000.0000.0000.0000.0001.0000.000
 0.0000.0000.0000.0000.0000.0000.0000.0000.0000.0000.0000.0000.0000.0001.0000.0000.000
 0.0000.0000.0000.0000.0000.0000.0000.0000.0000.0000.0000.0000.0000.0000.0001.0000.000
 0.0000.0000.0000.0000.0000.0000.0000.0000.0000.0000.0000.0000.0000.0001.0000.0000.000
 0.0000.0160.0000.0000.0000.0000.0000.0000.0000.1650.0000.1650.1140.2100.0000.0000.330
 0.0000.0000.0000.0000.0000.0000.0000.0000.0000.0000.0000.0000.0000.0001.0000.0000.000
```

```
 0.0000.0660.0000.0000.0000.0000.0000.0660.0000.0000.0000.0920.3610.1710.0000.0000.244
 0.0000.0000.0000.0000.0000.0000.0000.0000.0000.0000.0000.0000.0000.0001.0000.0000.000
 0.0000.0660.0000.0000.0000.0000.0000.0660.0000.0930.0000.0000.3560.2550.0000.0000.164
 0.0000.0090.0000.0000.0000.0000.0000.0090.0000.0710.0000.0700.4000.3000.0000.0000.141
 0.0000.0330.0000.0000.0000.0000.0000.0330.0000.0670.0000.1000.6000.0000.0000.0000.167
 0.0000.0000.0000.0000.0000.0000.0000.0000.0000.0000.0000.0000.0000.0001.0000.0000.000
 0.0000.0000.0000.5000.0000.5000.0000.0000.0000.0000.0000.0000.0000.0000.0000.0000.000
 0.0000.0330.0000.0000.0000.0000.0000.0330.0000.0610.0000.0410.1790.1060.0000.0000.546
0          NORMAL FLUX B.C. INFORMATION:
        ELEM    CODE  SIDE1  SIDE2    END1    END2
           1       2      0      0       1       1
           2       2      0      0       1       1
           3       2      0      0       1       1
           4       2      0      0       1       1
           5       2      0      0       1       1
           6       2      0      0       1       1
           7       2      0      0       1       1
           8       2      0      0       1       0
          16       2      0      0       1       1
0          CONVECTION B.C. INFORMATION:
        ELEM    CODE  SIDE1  SIDE2    END1    END2 HCONVB1 HCONVB2 HCONVE1 HCONVE2
           1       2      0      0       1       1    0.00    0.00   35.00    8.08
           2       2      0      0       1       0    0.00    0.00   35.00    0.00
           3       2      0      0       1       0    0.00    0.00   35.00    0.00
           4       2      0      0       1       1    0.00    0.00   35.00    8.08
           5       2      0      0       1       1    0.00    0.00   35.00    8.08
           6       2      0      0       1       1    0.00    0.00   35.00    8.08
           7       2      0      0       1       1    0.00    0.00   13.00   13.00
           8       2      0      0       1       0    0.00    0.00   17.00    0.00
          16       2      0      0       1       1    0.00    0.00    1.00    8.08
0          ELEMENT INFORMATION:
0                                          GENERAL DATA:
             ELE     I     J     K MMAT      AREA         P
               1     1     2     0    1     7.460     0.000
               2     3     4     0    2    12.000     0.000
               3     5     6     0    2     5.550     0.000
               4     7     8     0    1     7.460     0.000
               5     9    10     0    5     5.550     0.000
               6    11    12     0    5    12.000     0.000
               7    13    14     0    3     6.000     0.000
               8    15    16     0    4    17.000     0.000
               9    16    17     0    4    17.000     0.000
              10    17    18     0    4    17.000     0.000
              11    18    19     0    4    17.000     0.000
              12    19    20     0    4    17.000     0.000
              13    20    21     0    4    17.000     0.000
              14    21    22     0    4    17.000     0.000
              15    22    23     0    4    17.000     0.000
              16    24    25     0    6    17.500     0.000
0          SEMI-BANDWIDTH FOR THE GRID IS:    2

0*TIME=         2.0*  TO= -21.76TI=  14.64     RHI=0 095     KODE=    0     TEXT=    0.00
QTOT=  0.000000E+00     WTOT=  0.000000E+00     Q=  0.134974E+08
 -14.947764 -14.862230 -13.488540  24.070937 -13.488540  24.070931 -14.947764
 -14.862230 -21.016699  17.891006 -20.825126  19.065481  13.286392  13.[illegible]77561
  13.951930  14.254781  10.538402  10.135779  10.5[illegible]3461  11.217637  1[illegible].5[illegible]0449
```

```
  15.249833  20.000307  10.275089  15.144924
0*TIME=          3.0*  TO= -22.27TI=  14.72      RHI=0.066      KODE=   0      TEXT=    0.00
QTOT=  0.000000E+00       WTOT=  0.000000E+00      Q=  0.177677E+08
 -15.345790 -15.261003 -16.548700  19.939145 -16.548703  19.939140 -15.345790
 -15.261004 -22.883093  12.282283 -22.825886  13.081428  12.954202  12.942729
  13.224232  13.564521  10.913354  10.089962  10.570770  11.216388  12.570674
  15.249803  20.000307  10.359676  15.114027
0*TIME=          4.0*  TO= -23.21TI=  14.69      RHI=0.054      KODE=   0      TEXT=    0.00
QTOT=  0.000000E+00       WTOT=  0.000000E+00      Q=  0.195025E+08
 -16.112877 -16.027000 -18.129429  15.566180 -18.129432  15.566165 -16.112877
 -16.027000 -24.198210  10.262586 -24.174535  10.939606  12.787844  12.775428
  12.913747  13.066136  11.152943  10.076177  10.572202  11.216188  12.570706
  15.249805  20.000307  10.415009  15.124262
0*TIME=          5.0*  TO= -23.39TI=  14.68      RHI=0.048      KODE=   0      TEXT=    0.00
QTOT=  0.000000E+00       WTOT=  0.000000E+00      Q=  0.202604E+08
 -16.268537 -16.182635 -19.207924  11.525156 -19.207927  11.525138 -16.268537
 -16.182635 -24.745108   9.291830 -24.731615   9.930779  12.704347  12.691505
  12.724784  12.736852  11.297984  10.083474  10.569892  11.216652  12.570622
  15.249826  20.000307  10.451155  15.130373
0*TIME=          6.0*  TO= -23.24TI=  14.68      RHI=0.044      KODE=   0      TEXT=    0.00
QTOT=  0.000000E+00       WTOT=  0.000000E+00      Q=  0.205482E+08
 -16.147418 -16.061952 -19.740515   7.854883 -19.740526   7.854862 -16.147416
 -16.061951 -24.704624   9.823133 -24.694213   9.448687  12.670858  12.657821
  12.619702  12.522634  11.382801  10.103403  10.565465  11.217480  12.570475
  15.249860  20.000307  10.484842  15.132124
0*TIME=          7.0*  TO= -22.26TI=  14.59      RHI=0.042      KODE=   0      TEXT=    0.00
QTOT=  0.000000E+00       WTOT=  0.000000E+00      Q=  0.204396E+08
 -15.348901 -15.265241 -19.814081   4.577625 -19.814090   4.577600 -15.348801
 -15.265241 -24.100160   8.482309 -24.090310   9.100500  12.676540  12.663465
  12.566861  12.384841  11.430160  10.130409  10.559980  11.218488  12.570293
  15.249899  20.000307  10.524056  15.125401
0*TIME=          8.0*  TO= -19.53TI=  14.74      RHI=0.274      KODE=   0      TEXT=    0.00
QTOT=  0.000000E+00       WTOT=  0.000000E+00      Q=  0.121822E+08
 -11.949157 -11.862824 -16.680392   4.642727 -16.877382   4.260651 -11.927956
 -11.841563 -21.616497   8.306326 -21.170087   9.877965  10.194130  10.164453
  19.534000  12.132395  11.465989  10.159883  10.554250  11.219532  12.570108
  15.249940  20.000307  10.621531  15.104499
0           THE PROBLEM HAS15 1-D ELEMENTS
           NUMBER OF ELEMENTS=             15
           NUMBER OF NODES=                23
           NO. OF MATERIALS=             5
           NO. OF CONST. TEMP. NODES=    1
           NO. OF ELEMENTS WITH CONVECTION=             8
           NO. NODES WITH THERM.RAD.EXCHANGE=    15
           NO. OF ELEMENTS WITH NORMAL FLUX=            8
           NO. OF ELEMENTS WITH INT.HEAT GEN.=           6

0           MATERIAL INFORMATION:
          M        KX          KY          PC
          1        0.865       0.000 2269999.980
          2        0.440       0.000 2269999.980
          3        1.000       0.000 2000000.020
          4        0.420       0.000 1729999.920
          5        0.027       0.000 2269999.980
0           NODAL INFORMATION:
          N                  X                 Y
          1              0.00000           0.00000
```

```
     2             0.00020          0.00000
     3             0.00000          0.00000
     4             0.10000          0.00000
     5             0.00000          0.00000
     6             0.10000          0.00000
     7             0.00000          0.00000
     8             0.00020          0.00000
     9             0.00000          0.00000
    10             0.05000          0.00000
    11             0.00000          0.00000
    12             0.05000          0.00000
    13             0.00000          0.00000
    14             0.00100          0.00000
    15             0.00000          0.00000
    16             0.05000          0.00000
    17             0.15000          0.00000
    18             0.35000          0.00000
    19             0.75000          0.00000
    20             1.55000          0.00000
    21             3.15000          0.00000
    22             6.35000          0.00000
    23            13.00000          0.00000
0         CONST.TEMP.NODES ARE:

       23,
0         ELEMENTS WITH INTERAL HEAT GEN.ARE:

       1,  2,  3,  4,  5,  6,
0         THERMAL RADIATION INFORMATION:
   SURFACE    ET    TT    KC   KT           (KS(I,J),J=1,10)
      1    0.250 0.500   2    1   15    0    0    0    0    0    0    0    0    0
      2    0.250 0.500   1    7   10   12    4    6    8   13   14    0    0    0
      3    0.500 0.250   4    1   15    0    0    0    0    0    0    0    0    0
      4    0.500 0.250   3    7    2   10   12    6    8   13   14    0    0    0
      5    0.500 0.250   6    1   15    0    0    0    0    0    0    0    0    0
      6    0.500 0.250   5    7    2   10   12    4    8   13   14    0    0    0
      7    0.250 0.500   8    1   15    0    0    0    0    0    0    0    0    0
      8    0.250 0.500   7    7    2   10   12    4    6   13   14    0    0    0
      9    0.800 0.000  10    1   15    0    0    0    0    0    0    0    0    0
     10    0.800 0.000   9    7    2   12    4    6    8   13   14    0    0    0
     11    0.800 0.000  12    1   15    0    0    0    0    0    0    0    0    0
     12    0.800 0.000  11    7    2   10    4    6    8   13   14    0    0    0
     13    0.900 0.000   0    8    2   10   12    4    6    8   13   14    0    0
     14    0.900 0.000   0    7    2   10   12    4    6    8   13    0    0    0
     15    0.940 0.000   0    1   15    0    0    0    0    0    0    0    0    0
 0          SHAPE FACTOR MATRIX FOR THERMAL RADIATIONEXECHANGE(FORMAT F5.3):

  0.0000.0000.0000.0000.0000.0000.0000.0000.0000.0000.0000.0000.0000.0001.000
  0.0000.0000.0000.1650.0000.1650.0000.0160.0000.1650.0000.1650.1140.2100.000
  0.0000.0000.0000.0000.0000.0000.0000.0000.0000.0000.0000.0000.0000.0001.000
  0.0000.0660.0000.0000.0000.0920.0000.0660.0000.1560.0000.0880.3610.1710.000
  0.0000.0000.0000.0000.0000.0000.0000.0000.0000.0000.0000.0000.0000.0001.000
  0.0000.0660.0000.0880.0000.0000.0000.0660.0000.0930.0000.0760.3560.2550.000
  0.0000.0000.0000.0000.0000.0000.0000.0000.0000.0000.0000.0000.0000.0001.000
  0.0000.0160.0000.1650.0000.1650.0000.0000.0000.1650.0000.1650.1140.2100.000
  0.0000.0000.0000.0000.0000.0000.0000.0000.0000.0000.0000.0000.0000.0001.000
```

```
 0.0000.0660.0000.0760.0000.0930.0000.0660.0000.0000.0000.0880.3560.2550.000
 0.0000.0000.0000.0000.0000.0000.0000.0000.0000.0000.0000.0000.0000.0001.000
 0.0000.0660.0000.0880.0000.0920.0000.0660.0000.1560.0000.0000.3610.1710.000
 0.0000.0090.0000.0700.0000.0710.0000.0090.0000.0710.0000.0700.4000.3000.000
 0.0000.0330.0000.1000.0000.0670.0000.0330.0000.0670.0000.1000.6000.0000.000
 0.0000.0000.0000.0000.0000.0000.0000.0000.0000.0000.0000.0000.0000.0001.000
0          NORMAL FLUX B.C. INFORMATION:
        ELEM    CODE  SIDE1   SIDE2    END1     END2
           1       2      0       0       1        1
           2       2      0       0       1        1
           3       2      0       0       1        1
           4       2      0       0       1        1
           5       2      0       0       1        1
           6       2      0       0       1        1
           7       2      0       0       1        1
           8       2      0       0       1        0
0          CONVECTION B.C. INFORMATION:
        ELEM    CODE  SIDE1   SIDE2    END1     END2 HCONVB1 HCONVB2 HCONVE1 HCONVE2
           1       2      0       0       1        1    0.00    0.00   35.00    8.08
           2       2      0       0       1        1    0.00    0.00   35.00    8.08
           3       2      0       0       1        1    0.00    0.00   35.00    8.08
           4       2      0       0       1        1    0.00    0.00   35.00    8.08
           5       2      0       0       1        1    0.00    0.00   35.00    8.08
           6       2      0       0       1        1    0.00    0.00   35.00    8.08
           7       2      0       0       1        1    0.00    0.00   13.00   13.00
           8       2      0       0       1        0    0.00    0.00   17.00    0.00
0          ELEMENT INFORMATION:
0                                       GENERAL DATA:
             ELE     I     J     K MMAT       AREA       F
               1     1     2     0    1      7.460    0.000
               2     3     4     0    2     12.000    0.000
               3     5     6     0    2      5.550    0.000
               4     7     8     0    1      7.460    0.000
               5     9    10     0    5      5.550    0.000
               6    11    12     0    5     12.000    0.000
               7    13    14     0    3      6.000    0.000
               8    15    16     0    4     17.000    0.000
               9    16    17     0    4     17.000    0.000
              10    17    18     0    4     17.000    0.000
              11    18    19     0    4     17.000    0.000
              12    19    20     0    4     17.000    0.000
              13    20    21     0    4     17.000    0.000
              14    21    22     0    4     17.000    0.000
              15    22    23     0    4     17.000    0.000
0*TIME=         9.0*  TO= -18.37TI=  20.00      RHI=0.260      KODE=    0      TEXT=    0.00
QTOT=  0.000000E+00      WTOT=  0.000000E+00      Q=  0.125805E+08
   -9.533424   -9.435455 -14.608763  17.528218 -15.334360  16.683988  -9.514171
   -9.416149 -20.198099  12.898012 -19.277462  15.000064  14.466960  14.430996
   27.457940  14.691747  11.129204  10.249145  10.538400  11.222350  12.569607
   15.250040  20.000307  10.621531  15.104499
0*TIME=        10.0*  TO= -17.14TI=  20.00      RHI=0.271      KODE=    0      TEXT=    0.00
QTOT=  0.000000E+00      WTOT=  0.000000E+00      Q=  0.607852E+07
   -8.493855   -8.397305 -1[illegible].539548  25.995257 -12.039987  25.067481  -8.478943
   -8.382352 -18.580448  15.420655 -17.904001  17.077194  14.673062  14.638456
   27.936702  17.631225  11.064664  10.281334  10.533197  11.223254  12.569448
   15.250079  20.000307  10.621531  15.104499
```

```
0*TIME=        11.0*  TO= -14.62TI=  20.34     RHI=0.292      KODE=   0     TEXT=   0.00
QTOT=  0.000000E+00      WTOT=  0.000000E+00      Q= -0.113653E+07
  -6.329311  -6.236179  -7.261210   32.63845  -7.855497  31.537336  -6.328053
  -6.234918 -15.778174  17.096203 -15.363813  18.017320  15.234555  15.202493
  29.817795  19.542858  11.365824  10.252986  10.538647  11.222277  12.569621
  15.250055  20.000307  10.621531  15.104499
0*TIME=        12.0*  TO= -13.31TI=  21.73     RHI=0.295      KODE=   0     TEXT=   0.00
QTOT=  0.000000E+00      WTOT=  0.000000E+00      Q= -0.582307E+07
  -4.987768  -4.894095  -4.589762   37.55560  -5.129224   36.45617  -4.990991
  -4.897327 -14.051160  19.022001 -13.922275  19.139494  16.200333  16.165168
  29.609102  21.104654  11.836403  10.205075  10.547274  11.220745  12.569889
  15.250013  20.000307  10.621531  15.104499
0*TIME=        13.0*  TO= -12.23TI=  25.39     RHI=0.270      KODE=   0     TEXT=   0.00
QTOT=  0.000000E+00      WTOT=  0.000000E+00      Q= -0.181007E+08
  -3.188006  -3.087908  -2.508719   42.18640  -3.143381   40.99711  -3.209347
  -3.109304 -13.308887  20.659431 -12.752534  21.484169  18.783612  18.743401
   34.87449  22.002358  12.437167  10.149619  10.556805  11.219080  12.570184
  15.249967  20.000307  10.621531  15.104499
0*TIME=        14.0*  TO= -10.75TI=  28.23     RHI=0.271      KODE=   0     TEXT=   0.00
QTOT=  0.000000E+00      WTOT=  0.000000E+00      Q= -0.276468E+08
 -1.2857043 -1.1801059 -9.8013257E-01   46.42841 -1.7007574   45.03652 -1.3057255
 -1.2001757 -12.270700  22.824512 -11.347997  24.750620  20.962375  20.915417
   37.45120  24.443681  12.846791  10.140514  10.557912  11.218907  12.570218
  15.249961  20.000307  10.621531  15.104499
0*TIME=        15.0*  TO=  -9.68TI=  30.10     RHI=0.069      KODE=   0     TEXT=   0.00
QTOT=  0.000000E+00      WTOT=  0.000000E+00      Q= -0.339529E+08
  1.9398407E-02  1.2698072E-01  2.5957080E-01   48.08316 -6.0843127E-01
   46.46506 -1.8356522E-02  8.9141803E-02 -11.110173  23.925252  -9.918562
  26.468273  22.204142  22.155599   40.29515  25.952118  13.544814  10.093700
  10.565523  11.217530  12.570451  15.249931  20.000307  10.621531  15.104499
0*TIME=        16.0*  TO= -11.21TI=  32.26     RHI=0.049      KODE=   0     TEXT=   0.00
QTOT=  0.000000E+00      WTOT=  0.000000E+00      Q= -0.411924E+08
 -1.4219865 -1.3126966  1.2942127   51.52580 -4.5660191E-01   48.26529 -1.4835640
 -1.3744318 -12.031266  23.801764 -10.017508  28.309014  23.991657  23.955267
   45.45215  28.359654  14.135311  10.083277  10.566432  11.217471  12.570467
  15.249940  20.000307  10.621531  15.104499
0*TIME=        17.0*  TO= -13.16TI=  24.34     RHI=0.062      KODE=   0     TEXT=   0.00
QTOT=  0.000000E+00      WTOT=  0.000000E+00      Q= -0.145739E+08
  -6.023307  -5.932902  -3.319619   46.37563  -5.136442   43.20445  -6.023305
  -5.932899 -13.977226  22.730542 -13.199178  25.252652  23.605722  23.596850
  28.071591  30.760174  14.932309  10.049611  10.571458  11.216624  12.570615
  15.249922  20.000307  10.621531  15.104499
0 ..       THE PROBLEM HAS16 1-D ELEMENTS
          NUMBER OF ELEMENTS=               16
          NUMBER OF NODES=                  25
          NO. OF MATERIALS=              6
          NO. OF CONST. TEMP. NODES=     1
          NO. OF ELEMENTS WITH CONVECTION=              9
          NO. NODES WITH THERM.RAD.EXCHANGE=     17
          NO. OF ELEMENTS WITH NORMAL FLUX=             9
          NO. OF ELEMENTS WITH INT.HEAT GEN.=            6
           NO. OF TIME INCR.FOR TRANS.ANALYSIS=       288
          PRINTING INTERVAL FOR TEMP.FIELDS=          12
          TIME INCREMENT FOR TRANS.ANALYSIS=     300.0000
          INDIC(1=TRANSIENT,0=STEADY)=              1

           LENGTH OF THE ROCKBED                             0.60
          ROCKBED AREA NORMAL TO THE AIRFLOW              3.0000
```

```
          EFFECTIVE PERIMETER OF THE ROCKBED          13.0000
          EQUIVALENT ROCK PARTICLE DIAMETER            0.0750
          POROSITY OF THE ROCKBED                      0.4600
          DIFFERENTIAL ROCKBED LENGTH                 0.30000
          SOLUTION TIME STEP                           300.00
          ROCKBED PERIMETER HEAT LOSS FACTOR             0.02

0          BULK DENSITY OF THE ROCKBED                1000.00
          SPECIFIC HEAT OF THE ROCKS                 900.0000
          THERMAL CONDUCTIVITY OF THE ROCKS            2.7000
          FLOW RATE FOR LOW VENT FAN                   0.1750
          FLOW RATE FOR HIGH VENT FAN                  0.9000
          BASE TEMPERATURE FOR HEAT COLLECTION          25.00
          KODE 3 TEMPERATURE IN SUBR. ROCKBED            30.00

0          LENGTH OF THE STRUCTURE=                   5.00000
          VOLUME OF THE STRUCTURE=                      37.30
0          MATERIAL INFORMATION:
         M        KX          KY           PC
         1        0.865       0.000 2269999.980
         2        0.440       0.000 2269999.980
         3        1.000       0.000 2000000.020
         4        0.420       0.000 1729999.920
         5        0.027       0.000 2269999.980
         6        0.440       0.000 2269999.980
0          NODAL INFORMATION:
         N               X              Y

         1             0.00000        0.00000
         2             0.00020        0.00000
         3             0.00000        0.00000
         4             0.10000        0.00000
         5             0.00000        0.00000
         6             0.10000        0.00000
         7             0.00000        0.00000
         8             0.00020        0.00000
         9             0.00000        0.00000
        10             0.05000        0.00000
        11             0.00000        0.00000
        12             0.05000        0.00000
        13             0.00000        0.00000
        14             0.00100        0.00000
        15             0.00000        0.00000
        16             0.05000        0.00000
        17             0.15000        0.00000
        18             0.35000        0.00000
        19             0.75000        0.00000
        20             1.55000        0.00000
        21             3.15000        0.00000
        22             6.35000        0.00000
        23            12.00000        0.00000
        24             0.00000        0.00000
        25             0.05000        0.00000
0             CONST.TEMP.NODES ARE:

        23,
```

```
0          ELEMENTS WITH INTERAL HEAT GEN.ARE:

       1,   2,   3,   4,   5,   6,
0          THERMAL RADIATION INFORMATION:
    SURFACE     ET     TT     KC     KT          (KS(I,J),J=1,10)
        1     0.250 0.500     2      1    15     0     0     0     0     0     0     0     0     0
        2     0.250 0.500     1      6     8    10    12    13    14    17     0     0     0     0
        3     0.500 0.250     4      1    15     0     0     0     0     0     0     0     0     0
        4     0.500 0.250     3      1    16     0     0     0     0     0     0     0     0     0
        5     0.500 0.250     6      1    15     0     0     0     0     0     0     0     0     0
        6     0.500 0.250     5      1    16     0     0     0     0     0     0     0     0     0
        7     0.250 0.500     8      1    15     0     0     0     0     0     0     0     0     0
        8     0.250 0.500     7      6     2    10    12    13    14    17     0     0     0     0
        9     0.800 0.000    10      1    15     0     0     0     0     0     0     0     0     0
       10     0.800 0.000     9      6     2     8    12    13    14    17     0     0     0     0
       11     0.800 0.000    12      1    15     0     0     0     0     0     0     0     0     0
       12     0.800 0.000    11      6     2     8    10    13    14    17     0     0     0     0
       13     0.900 0.000     0      7     2     8    10    12    13    14    17     0     0     0
       14     0.900 0.000     0      6     2     8    10    12    13    17     0     0     0     0
       15     0.940 0.000     0      1    15     0     0     0     0     0     0     0     0     0
       16     0.100 0.330    17      2     4     6     0     0     0     0     0     0     0     0
       17     0.100 0.330    16      7     2     8    10    12    13    14    17     0     0     0
0          SHAPE FACTOR MATRIX FOR THERMAL RADIATIONEXECHANGE(FORMAT F5.3):

  0.0000.0000.0000.0000.0000.0000.0000.0000.0000.0000.0000.0000.0000.0001.0000.0000.000
  0.0000.0000.0000.0000.0000.0000.0000.0160.0000.1650.0000.1650.1140.2100.0000.0000.330
  0.0000.0000.0000.0000.0000.0000.0000.0000.0000.0000.0000.0000.0000.0001.0000.0000.000
  0.0000.0000.0000.0000.0000.0000.0000.0000.0000.0000.0000.0000.0000.0000.0001.0000.000
  0.0000.0000.0000.0000.0000.0000.0000.0000.0000.0000.0000.0000.0000.0001.0000.0000.000
  0.0000.0000.0000.0000.0000.0000.0000.0000.0000.0000.0000.0000.0000.0000.0001.0000.000
  0.0000.0000.0000.0000.0000.0000.0000.0000.0000.0000.0000.0000.0000.0001.0000.0000.000
  0.0000.0160.0000.0000.0000.0000.0000.0000.0000.1650.0000.1650.1140.2100.0000.0000.330
  0.0000.0000.0000.0000.0000.0000.0000.0000.0000.0000.0000.0000.0000.0001.0000.0000.000
  0.0000.0660.0000.0000.0000.0000.0000.0660.0000.0000.0000.0920.3610.1710.0000.0000.244
  0.0000.0000.0000.0000.0000.0000.0000.0000.0000.0000.0000.0000.0000.0001.0000.0000.000
  0.0000.0660.0000.0000.0000.0000.0000.0660.0000.0930.0000.0000.3560.2550.0000.0000.164
  0.0000.0090.0000.0000.0000.0000.0000.0090.0000.0710.0000.0700.4000.3000.0000.0000.141
  0.0000.0330.0000.0000.0000.0000.0000.0330.0000.0670.0000.1000.6000.0000.0000.0000.167
  0.0000.0000.0000.0000.0000.0000.0000.0000.0000.0000.0000.0000.0000.0001.0000.0000.000
  0.0000.0000.0000.5000.0000.5000.0000.0000.0000.0000.0000.0000.0000.0000.0000.0000.000
  0.0000.0330.0000.0000.0000.0000.0000.0330.0000.0610.0000.0410.1790.1060.0000.0000.546
0          NORMAL FLUX B.C. INFORMATION:
        ELEM    CODE   SIDE1   SIDE2    END1     END2
          1       2       0       0       1        1
          2       2       0       0       1        1
          3       2       0       0       1        1
          4       2       0       0       1        1
          5       2       0       0       1        1
          6       2       0       0       1        1
          7       2       0       0       1        1
          8       2       0       0       1        0
         16       2       0       0       1        1
0          CONVECTION B.C. INFORMATION:
        ELEM    CODE   SIDE1   SIDE2    END1     END2 HCONVB1 HCONVB2 HCONVE1 HCONVE2
          1       2       0       0       1        1    0.00    0.00   35.00    8.08
          2       2       0       0       1        0    0.00    0.00   35.00    0.00
```

```
            3      2      0      0      1      0     0.00      0.00     35.00      0.00
            4      2      0      0      1      1     0.00      0.00     35.00      8.08
            5      2      0      0      1      1     0.00      0.00     35.00      8.08
            6      2      0      0      1      1     0.00      0.00     35.00      8.08
            7      2      0      0      1      1     0.00      0.00     13.00     13.00
            8      2      0      0      1      0     0.00      0.00     17.00      0.00
           16      2      0      0      1      1     0.00      0.00      1.00      8.08
0           ELEMENT INFORMATION:
0                                            GENERAL DATA:
              ELE      I      J      K MMAT       AREA          P
                1      1      2      0    1      7.460      0.000
                2      3      4      0    2     12.000      0.000
                3      5      6      0    2      5.550      0.000
                4      7      8      0    1      7.460      0.000
                5      9     10      0    5      5.550      0.000
                6     11     12      0    5     12.000      0.000
                7     13     14      0    3      6.000      0.000
                8     15     16      0    4     17.000      0.000
                9     16     17      0    4     17.000      0.000
               10     17     18      0    4     17.000      0.000
               11     18     19      0    4     17.000      0.000
               12     19     20      0    4     17.000      0.000
               13     20     21      0    4     17.000      0.000
               14     21     22      0    4     17.000      0.000
               15     22     23      0    4     17.000      0.000
               16     24     25      0    6     17.500      0.000
 0*TIME=          18.0*  TO= -13.52TI=  14.32      RHI=0.084     KODE=    0      TEXT=    0.00
 QTOT=  0.000000E+00      WTOT=  0.000000E+00      Q=  0.628128E+07
   -8.326374  -8.257188  -6.080741   39.57878  -6.638358   36.57871  -8.326374
   -8.257189 -14.046080  14.889481 -13 864600  16.218578  13.344262  13.338562
   18.240310  27.030709  16.499947   9.914643  10.593607  11.212781  12.571288
   15.249808  20.000307  10.944601  15.275779
 0*TIME=          19.0*  TO= -14.51TI=  14.59      RHI=0.069     KODE=    0      TEXT=    0.00
 QTOT=  0.000000E+00      WTOT=  0.000000E+00      Q=  0.109178E+08
   -9.064499  -8.994099  -7.723652   37.37442  -8.163300  30.794188  -9.064499
   -8.994095 -15.504160  11.902543 -15.437203  12.757357  13.294886  13.286520
   16 509513  23.022983  17.517727   9.910920  10.591971  11.213171  12.571212
   15.249827  20.000307  10.923504  15.167948
 0*TIME=          20.0*  TO= -15.29TI=  14.63      RHI=0.062     KODE=    0      TEXT=    0.00
 QTOT=  0.000000E+00      WTOT=  0.000000E+00      Q=  0.131440E+08
   -9.688831  -9.617425  -9.359678  27.990180  -9.731894  25.788399  -9.688830
   -9.617424 -16.577269  10.698907 -16.548325  11.389130  13.152036  13.142430
   15.480136  20.444352  17.896071  10.032566  10.568679  11.217369  12.570463
   15.249970  20.000307  10.896748  15.149788
 0*TIME=          21.0*  TO= -16.48TI=  14.63      RHI=0.057     KODE=    0      TEXT=    0.00
 QTOT=  0.000000E+00      WTOT=  0.000000E+00      Q=  0.145881E+08
  -10.654860 -10.581453 -10.972287  23.324169 -11.289473  21.446621 -10.654860
  -10.581453 -17.676660  10.247606 -17.661088  10.879442  13.036496  13.026139
   14.802467  18.751592  17.911295  10.216031  10.535657  11.223234  12.569420
   15.250166  20.000307  10.869368  15.151789
 0*TIME=          22.0*  TO= -17.66TI=  14.61      RHI=0.055     KODE=    0      TEXT=    0.00
 QTOT=  0.000000E+00      WTOT=  0.000000E+00      Q=  0.156779E+08
  -11.622154 -11.546678 -12.746933  19.290924 -13.017375  17.689937 -11.622154
  -11.546678 -18.952013   9.981379 -18.941271  10.594660  12.938235  12.927357
   14.330343  17.598776  17.729941  10.424077  10.499785  11.229536  12.568309
   15.250374  20.000307  10.825791  15.158094
```

```
0*TIME=         23.0*  TO= -18.56TI=  14.61      RHI=0.055     KODE=   0      TEXT=   0.00
QTOT=  0.000000E+00      WTOT=  0.000000E+00      Q=  0.165220E+08
 -12.351496 -12.274448 -14.114519  15.565691 -14.345128  14.200547 -12.351496
 -12.274448 -19.812206   9.716929 -19.803127  10.324537  12.878659  12.867379
  14.010950  16.780880  17.448543  10.635907  10.464818  11.235612  12.567239
  15.250574  20.000307  10.789644  15.157991
0*TIME=          0.0*  TO= -20.56TI=  14.57      RHI=0.054     KODE=   0      TEXT=   0.00
QTOT=  0.000000E+00      WTOT=  0.000000E+00      Q=  0.174609E+08
 -13.984251 -13.903528 -16.066621  12.532114 -16.263259  11.368068 -13.984254
 -13.903529 -21.566320   9.771221 -21.558496  10.382779  12.784209  12.772580
  13.749720  16.178615  17.122794  10.840222  10.432724  11.241120  12.566266
  15.250760  20.000307  10.722204  15.175226
0*TIME=          1.0*  TO= -21.65TI=  14.57      RHI=0.051     KODE=   0      TEXT=   0.00
QTOT=  0.000000E+00      WTOT=  0.000000E+00      Q=  0.182752E+08
 -14.874722 -14.792053 -17.817819   9.630068 -17.985492   8.637496 -14.874722
 -14.792053 -22.913597   9.477898 -22.905749  10.096230  12.727390  12.715426
  13.550320  15.706421  16.786211  11.030982  10.404467  11.245892  12.565428
  15.250918  20.000307  10.654146  15.175066
```

Annexure-C

Table C-1 Comparison of environment outside and inside the solar greenhouse data for Dec. 19, 1999

Time (hours)	Air temperatures		Air Relative Humidity (%)		Ambient solar radiation (W/Sq.m.)
	Ambient	Inside greenhouse	Ambient	Inside greenhouse	
1	4.41	13.49	100	95	0.0
2	4.03	13.01	100	95	0.0
3	3.98	12.53	100	95	0.0
4	3.46	12.06	100	95	0.0
5	3.54	11.62	100	89	0.0
6	3.44	11.40	100	95	0.0
7	3.131	11.03	100	93	0.0
8	11.84	19.82	100	98	24.0
9	17.64	30.17	100	93	200.0
10	20.4	32.11	82	68	364.0
11	24.36	30.36	66	56	494.0
12	26.25	31.19	63	58	552.0
13	26.23	30.99	57	62	552.0
14	24.68	30.40	52	52	436.0
15	21.85	31.55	52	58	318.0
16	17.59	26.57	58	58	152.0
17	12.12	19.15	68	57	12.0
18	9.62	16.18	82	72	0.0
19	8.24	16.45	100	91	0.0
20	6.954	16.37	100	100	0.0
21	6.105	15.44	100	100	0.0
22	5.382	14.79	100	100	0.0
23	4.457	14.01	100	100	0.0
24	4.221	13.58	100	90	0.0

Table C-2 Comparison of environment outside and inside the solar greenhouse data for Dec. 21, 1999

Time (hours)	Air temperatures		Air Relative Humidity (%)		Ambient solar radiation (W/Sq.m.)
	Ambient	Inside greenhouse	Ambient	Inside greenhouse	
0	7.06	14.75	100	100	0.0
1	6.56	14.07	100	100	0.0
2	5.43	13.53	100	100	0.0
3	4.98	12.98	100	100	0.0
4	4.44	12.39	100	100	0.0
5	4.14	12.05	100	100	0.0
6	5.15	11.75	100	100	0.0
7	4.28	11.46	100	100	36.0
8	6.27	12.48	100	98	200.0
9	11.40	19.30	89	98	342.0
10	15.91	28.23	69	66	506.0
11	18.52	28.84	71	61	588.0
12	22.37	30.71	68	57	530.0
13	23.55	31.00	66	68	412.0
14	25.52	30.04	60	67	352.0
15	21.95	31.88	69	75	130.0
16	20.23	29.28	86	70	24.0
17	16.80	25.15	90	92	0.0
18	12.32	19.03	100	99	0.0
19	10.18	16.27	100	100	0.0
20	8.52	16.81	100	100	0.0
21	7.21	16.16	100	100	0.0
22	6.44	15.32	100	90	0.0
23	4.221	13.58	100	100	0.0

Table C-3 Comparison of environment outside and inside the solar greenhouse data for Dec. 22, 1999

Time (hours)	Air temperatures		Air Relative Humidity (%)		Ambient solar radiation (W/Sq.m.)
	Ambient	Inside greenhouse	Ambient	Inside greenhouse	
0	4.79	13.68	100	100	0.0
1	4.13	12.95	100	100	0.0
2	3.87	12.43	100	100	0.0
3	3.37	11.86	100	100	0.0
4	3.67	11.56	100	100	0.0
5	2.64	10.84	100	100	0.0
6	2.019	10.26	100	100	0.0
7	1.99	10.01	100	100	24.0
8	3.92	11.43	100	88	164.0
9	10.77	18.56	79	88	270.0
10	16.79	26.27	56	72	364.0
11	19.24	32.47	75	36	458.0
12	20.82	31.44	65	57	436.0
13	23.73	32.30	53	68	494.0
14	23.00	30.88	60	67	388.0
15	22.97	29.89	62	75	130.0
16	18.97	29.80	86	70	24.0
17	14.72	22.49	90	92	0.0
18	11.35	17.54	100	99	0.0
19	9.53	17.01	100	100	0.0
20	8.56	16.53	100	100	0.0
21	8.20	16.15	100	100	0.0
22	8.00	15.81	100	90	0.0
23	7.49	15.41	100	100	0.0

ANNEXURE-D

Date	Time(hrs.)	Air Temperature ^{O}C		
		Greenhouse air	Rockbed inlet	Rockbed outlet
22/12/99	12:00 pm	31.44	34.62	22.48
	1:00 pm	32.30	35.40	24.15
	2:00 pm	30.88	35.94	27.27
	3:00 pm	29.89	33.19	28.44
	4:00 pm	29.80	30.25	28.80
	5:00 pm	22.49	22.23	23.97
	6:00 pm	17.54	17.19	20.02
	7:00 pm	17.01	16.83	21.67
	8:00 pm	16.53	16.41	21.73
	9:00 pm	16.15	16.00	20.94
	10:00 pm	15.81	15.75	20.05
	11:00 pm	15.41	15.40	19.31
23/12/99	12:00 am	14.88	14.87	18.54
	1:00 am	15.12	15.00	18.26
	2:00 am	14.43	14.37	17.72
	3:00 am	14.29	14.15	17.35
	4:00 am	14.44	14.28	17.24
	5:00 am	14.55	14.50	17.15
	6:00 am	14.09	13.95	16.80
	7:00 am	14.05	13.95	16.67
	8:00 am	13.83	13.64	16.44
	9:00 am	15.84	15.61	17.27
	10:00 am	24.19	25.20	19.88
	11:00 am	31.22	33.20	23.11
	12:00 pm	30.87	33.94	25.02
	1:00 pm	31.28	37.83	27.08
	2:00 pm	32.32	36.87	29.52
	3:00 pm	30.27	33.58	29.30
	4:00 pm	28.32	28.22	28.99
	5:00 pm	23.55	23.09	25.29
	6:00 pm	18.04	17.91	20.47
	7:00 pm	15.93	15.62	18.09
	8:00 pm	16.69	16.77	21.19
	9:00 pm	16.46	16.61	21.11
	10:00 pm	16.36	16.37	20.55
	11:00 pm	15.89	15.94	19.65
24/12/99	12:00 am	14.80	14.88	18.82
	1:00 am	14.68	14.65	18.17
	2:00 am	13.97	14.03	17.55
	3:00 am	13.83	13.90	17.12
	4:00 am	13.21	13.28	16.66
	5:00 am	13.17	13.18	16.38
	6:00 am	13.24	13.30	16.14
	7:00 am	13.07	13.02	15.93
	8:00 am	13.55	13.45	15.97

	9:00 am	14.98	14.90	16.48
	10:00 am	21.56	22.17	18.88
	11:00 am	27.28	28.67	22.65
	12:00 pm	30.91	34.49	23.69
	1:00 pm	30.52	36.66	25.48
	2:00 pm	30.88	35.15	27.34
	3:00 pm	31.63	33.51	28.49
	4:00 pm	29.84	30.48	28.44
	5:00 pm	23.56	23.37	25.25
	6:00 pm	17.71	17.47	19.86
	7:00 pm	16.18	16.30	20.50
	8:00 pm	15.97	16.10	21.20
	9:00 pm	15.21	15.29	20.31
	10:00 pm	14.46	14.48	19.14
	11:00 pm	13.76	13.79	18.09
	12:00p.m.	12.95	12.99	17.25

ANNEXURE F

Table F-1 Comparison of predicted and measured data for Dec. 19, 1999

Time (hrs.)	Greenhouse air temperatures (^OC)			Greenhouse relative humidity (%)		
	Predicted	Measured	Deviation	Predicted	Measured	Deviation
1	- -	13.96	-	-	95	
2	14.37	13.49	0.88	100	95	5
3	13.48	13.01	0.47	98.3	95	3.3
4	12.49	12.53	0.04	96.9	89	7.9
5	11.79	12.06	0.27	96	95	1
6	10.93	11.62	0.69	95.5	93	2.5
7	10.16	11.40	1.24	94.8	98	3.2
8	13.11	11.03	2.08	85.7	93	7.3
9	22.37	19.82	2.55	68.6	68	0.6
10	26.39	30.17	3.78	71.8	56	15.8
11	26.58	32.11	5.53	60.2	58	2.2
12	29.37	30.36	0.99	66.8	62	4.8
13	31.44	31.19	0.25	44.2	52	7.8
14	32.37	30.99	1.38	45.5	58	12.5
15	31.75	30.40	1.35	48.0	58	10
16	30.76	31.55	0.79	52.3	57	4.7
17	28.78	26.57	2.21	75	72	3
18	18.95	19.15	0.2	75.5	91	15.5
19	16.13	16.18	0.05	72.4	100	27.6
20	15.76	16.45	0.69	88.7	100	11.3
21	16.42	16.37	0.05	89.9	100	10.1
22	15.91	15.44	0.47	89.5	100	10.5
23	14.05	14.79	0.74	77.9	90	12.1
24	18.39	14.01	4.38	80.1	100	19.9
Mean			1.36			8.63
S.D.			1.44			6.62

ANNEXURE F

Table F-1 Comparison of predicted and measured data for Dec. 19, 1999

Time (hrs.)	Greenhouse air temperatures (°C)			Greenhouse relative humidity (%)		
	Predicted	Measured	Deviation	Predicted	Measured	Deviation
1	-	13.96	-	-	95	
2	14.37	13.49	0.88	100	95	5
3	13.48	13.01	0.47	98.3	95	3.3
4	12.49	12.53	0.04	96.9	89	7.9
5	11.79	12.06	0.27	96	95	1
6	10.93	11.62	0.69	95.5	93	2.5
7	10.16	11.40	1.24	94.8	98	3.2
8	13.11	11.03	2.08	85.7	93	7.3
9	22.37	19.82	2.55	68.6	68	0.6
10	26.39	30.17	3.78	71.8	56	15.8
11	26.58	32.11	5.53	60.2	58	2.2
12	29.37	30.36	0.99	66.8	62	4.8
13	31.44	31.19	0.25	44.2	52	7.8
14	32.37	30.99	1.38	45.5	58	12.5
15	31.75	30.40	1.35	48.0	58	10
16	30.76	31.55	0.79	52.3	57	4.7
17	28.78	26.57	2.21	75	72	3
18	18.95	19.15	0.2	75.5	91	15.5
19	16.13	16.18	0.05	72.4	100	27.6
20	15.76	16.45	0.69	88.7	100	11.3
21	16.42	16.37	0.05	89.9	100	10.1
22	15.91	15.44	0.47	89.5	100	10.5
23	14.05	14.79	0.74	77.9	90	12.1
24	18.39	14.01	4.38	80.1	100	19.9
Mean			1.36			8.63
S.D.			1.44			6.62

Table F-2 Comparison of predicted and measured data for Dec. 21, 1999

Time (hrs.)	Greenhouse air temperatures (^{O}C)			Greenhouse relative humidity (%)		
	Predicted	Measured	Deviation	Predicted	Measured	Deviation
1	-	14.75	-	-	100	-
2	14.15	14.07	0.08	100	100	0
3	14.7	13.53	1.17	98.9	100	1.1
4	13.88	12.98	0.9	97.5	100	2.5
5	12.9	12.39	0.51	96.3	100	3.7
6	12.02	12.05	0.03	95.8	100	4.2
7	11.33	11.75	0.42	95.4	100	4.6
8	10.67	11.46	0.79	88.7	98	9.3
9	13.19	12.48	0.71	73.6	98	24.4
10	21.28	19.30	1.98	77.8	66	11.8
11	25.55	28.23	2.68	58.8	61	2.2
12	25.56	28.84	3.28	68.1	57	11.1
13	27.71	30.71	3	75.4	68	7.4
14	29.67	31.00	1.33	48.3	67	18.7
15	30.84	30.04	0.8	60.3	75	14.7
16	29.82	31.88	2.06	94.2	70	24.2
17	28.96	29.28	0.32	90.8	92	1.2
18	27.66	25.15	2.51	76.6	99	22.4
19	18.53	19.03	0.5	75.9	100	24.1
20	15.95	16.27	0.32	83.9	100	16.1
21	15.25	16.81	1.56	87.1	100	12.9
22	15.18	16.16	0.98	80.3	100	19.7
23	14.37	15.32	0.95	80.9	100	19.1
24	18.75	14.40	4.35	85.5	100	14.5
Mean			1.36			11.73
S.D.			1.14			8.31