THE UNIVERSITY OF MANITOBA

PREDICTING THE EFFECTS OF GREENHOUSE ORIENTATION AND INSULATION ON ENERGY CONSERVATION

by

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ABSTRACT

Vegetable greenhouses in the province of Manitoba are usually constructed as transparent structures with a double layer of plastic covering materials so that necessary illumination can be made available to the plants. These covering materials have poor thermal resistance characteristics and the local climate is such that greenhouse operation has to be abandoned for a period in winter because high heating costs make production uneconomic. Greenhouse heating is probably one of the most inefficient uses of fuel for heating applications.

A number of studies have been conducted in different parts of the world with a view to reducing heating costs for greenhouse structures and a number of different schemes have been proposed. A solution valid for the cold Canadian climate is yet to be obtained. It has been observed that at northernly latitudes, the north side of a greenhouse receives little illumination during winter months. Insulating the north side of the structure could result in a substantial saving in heat lost from the greenhouse with little change in natural illumination available to the plants.

This theoretical study was undertaken to investigate the effect of insulating the north side of a greenhouse. A mathematical model was developed to study the effect of specific changes in greenhouse design on the greenhouse heat balance. In this model a more accurate method to determine solar radiation incident on a surface was incorporated. Variables studied were orientation, shape, size, and different levels of north-side insulation. Winnipeg was assumed as the location of the greenhouses and heat balance in greenhouses was studied for two arbitrarily selected summer and winter conditions. Gothic arch, gable, and circular shapes were analysed with two ground-bed sizes (15 m x 10 m and 200 m x 12 m). The greenhouses were assumed to be oriented either east-west or north-south. The necessary climatic data were obtained from the local meteorological office for December 21, 1974 and June 21, 1974 representing winter and summer conditions, respectively. The three levels of fiberglass insulation assumed in the insulated north side of greenhouses were R = 0.70, 1.41, and 2.11 $(m^2 \cdot K)/w$.

In most cases, the north side of a greenhouse was found to be contributing less than 3.0 percent to the total solar heat gain of a greenhouse on December 21. A gothic arch greenhouse was found to be superior to gable and circular greenhouses with respect to heating and ventilation requirements. An east-west oriented greenhouse maintained greater thermal environment efficiency in comparison to a north-south oriented greenhouse. Reductions of almost 50 percent in heating requirements on December 21, 1974 and at least 15 percent in ventilation requirements on June 21, 1974 were predicted when the north side of a greenhouse was insulated.

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LIST OF SYMBOLS

A	Area, m^2
A_z	Solar-azimuth angle (measured from South), rad
a	Atmospheric extinction coefficient
B	Ratio of the instantaneous diffuse solar radiation on horizontal surface to the instaneous direct normal solar radiation
b	Width, m
C_o	Conductance, $w/(m^2 \cdot K)$
C_p	Specific heat, $J/(kg \cdot K)$
C_a	Air conductance, $w/(m^2 \cdot K)$
D	Day of a year ($1 \leq D \leq 365$)
d	Solar declination angle, rad
de	Solar declination angle on June 21, rad
FS	Shape factor
f	Edge-loss factor
H	Solar hour angle, rad
HO	Daily total extraterrestrial solar radiation, w/m^2
h	Surface heat transfer coefficient, $(w/(m^2 \cdot K)$
I	Intensity of solar radiation, $w/(m^2 \cdot h)$
IO	Apparent solar constant, $w/(m^2 \cdot h)$
JC	Cloudless radiation index
KC	Cloud cover coefficient
KD	Ratio of daily direct solar radiation to daily direct extraterrestrial solar radiation
KS	Percent of possible sunshine expressed in fraction

KT	Daily cloudiness index
k	Thermal conductivity, w/(m • K)
L	Latitude of a place, rad
ℓ	Length, m
MH	Ratio of the hemispherical diffuse radiation on a surface to the hemispherical diffuse radiation on a horizontal surface
MS	Ratio of the circumsolar diffuse radiation on a surface to the circumsolar diffuse radiation on a horizontal surface
N	Number of days from January 1 to the desired date
n	Number of surfaces in a greenhouse
P	Perimeter, m
pw	Atmospheric vapour pressure, m Hg
pws	Atmospheric saturation vapour pressure at a given temperature, m Hg
Q	Rate of heat transfer for a whole greenhouse, w/h
q	Rate of heat transfer for a part of greenhouse, w/h
R	Resistance to heat transfer, $(m^2 \cdot K)/w$
RA	Actual solar constant, $w/(m^2 \cdot h)$
RH	Relative humidity expressed as fraction
r	Radius, m
S	Number of transparent surfaces
sw	Area of structural members in a wall section expressed as a decimal fraction of the area of the wall section
T	Local civil time
TL	Local watch time
TR	Sunrise time (local civil time)
t	Temperature, C
X	Value of rectangular coordinate in horizontal direction
XY	A point in rectangular coordinate

Y	Values of rectangular coordinate in vertical direction
z	Height, m
α	Wall-azimuth angle (measured from South), rad
β	Solar-altitude angle, rad
Δ	Curtain factor
δ	Stefan-Boltzmann constant, $w/(m^2 \cdot K^4)$
ε	Emissivity
γ	Wall-solar azimuth angle, rad
ω	Absorptance
ϕ	Surface inclination angle (measured from horizontal), rad
ψ	Transmittance
ρ	Reflectivity
σ	Curtain effect
τ	Atmospheric transmission coefficient for solar radiation
θ	Incidence angle i.e., angle between incident solar beam and the normal to the surface, rad

SUBSCRIPTS

A	Absorbed component of solar radiation
a	Air
c	conductive heat transfer
D	Direct component of solar radiation
DH	Direct component of solar radiation incident on a horizontal surface
DN	Direct normal component of solar radiation
d	Diffuse component of solar radiation

db	Dry-bulb temperature
dh	Diffuse component of solar radiation incident on a horizontal surface
dp	Dew-point temperature
e	Equipment
f	Floor level
g	Ground
h	Furnace
i	Indoor
ins	Insulation
j	Index to indicate surface number in a greenhouse
o	Outdoor
p	Photosynthetic
ply	Plywood, 1 cm thick
r	Respiratory
s	Surface
T	Transmitted component of solar radiation
t	Thermal radiation
u	Solar radiation
v	Ventilation
w	Wood
x	Lateral direction
y	Vertical direction
1	Clear sky
2	Cloudy sky

CHAPTER I

INTRODUCTION

Greenhouses are a means of assuring year-round production of certain agricultural products in areas of severe climate. For any given region, design should consider the local climate so that the greenhouse operation can be kept within permissible limits of economy.

The climate in most parts of western Canada is such that greenhouse operation has to be abandoned for a period in winter because high heating costs make production uneconomic. Vegetable greenhouses in the province of Manitoba are usually constructed as transparent structures with a double layer of plastic-covering materials. A number of studies have been conducted in different parts of the world with a view to reducing heating costs for greenhouse structures and a number of different schemes have been proposed to achieve this goal (23, 32, 35, 36, 42). An amicable solution valid for the cold Canadian climate is yet to be obtained.

A greenhouse is built using transparent materials, such as glass or plastic, to admit the light necessary for plant growth. These materials exhibit poor thermal resistance characteristics and thus tremendous heat losses occur, especially at night. From a study of the contribution of natural illumination from the various sides of a transparent greenhouse structure, it is inferred that the north side of the structure contributes little illumination during winter months (16) while the heat loss to the atmosphere from this side is comparable to any other side of the structure. Insulating the north side of the structure could result in a substantial saving in heat lost from the greenhouse with little change in natural illumination available to the plants.

For a greenhouse with a length-to-width ratio greater than one, the fraction of the surface area in the most favourable position to receive incoming solar energy depends upon the orientation, therefore, the surface area facing north is also dependent on it. Thus, the magnitude of the effect of insulating the north side of a greenhouse will depend upon the orientation of the greenhouse.

A theoretical study was proposed to investigate the effect of insulating the north side of a greenhouse on its thermal balance. A mathematical model was developed to study the effect of specific changes in greenhouse design on the greenhouse heat balance. Intended variables for study were orientation, shape, size, and levels of north-side insulation of greenhouse. Climatic conditions were arbitrarily selected for the model.

The specific objectives of this thesis were:

1. to develop a mathematical model which would adequately account for specific changes in greenhouse design on the thermal balance of the structure,
2. to determine the contribution of solar radiation from the north side of a greenhouse,
3. to compare gothic arch, gable, and circular greenhouse shapes for their heat loss property,
4. to compare north-south and east-west orientations of greenhouses with and without insulating the north side, and
5. to study thermal balance of greenhouses with and without insulating the north side in both winter and summer conditions.

CHAPTER II

REVIEW OF LITERATURE

2.1 System of Units

SI (Systems International d' unites) units have been used in this thesis as far as possible. Where the cgs system is more understandable, i.e., degrees Celsius (C) for temperature, this substitution has been made. A table for quantities used in this investigation is given for the convenience of the reader with conversion factors from the British system of units to the SI, Table 2.1.

TABLE 2.1

Conversion Factors

Quantity	Unit in British System	Conversion Factor	Unit in SI
Length, ℓ	ft	0.3048	m
Area, A	ft^2	0.0920	m^2
Temperature, t	F	(F-32·0)(5/9)	C
Coeff. of Heat Transfer, U,			(K=C+273.16)
and Conductance, C_o	Btu/(hr·ft^2·F)	5.6783	w/(m^2·K)
Res. to Heat Transfer, K	(hr·ft^2·F)/Btu	0.1761	(m^2·K)/w
Thermal Conductivity, k	Btu/(hr·ft·F)	1.7296	w/(m·K)
Rate of Heat Transfer, Q	Btu/hr	0.2929	w
Specific Heat, C_p	Btu/(lb · F)	4184.0	J/(kg·K)
Intensity of Radiation, I	Btu/(hr · ft^2)	3.152	w/m^2
(Stefan-Boltzmann	Btu/(hr·ft^2·R^4)	33.0788	w/(m^2·K^4)
constant, δ)	(0.1714×10^{-8})		(5.6697×10^{-8})

2.2 Necessity of Reducing Energy Intensiveness of Greenhouse Operation

A 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 a minimum opaque area and a maximum transparent area, and yet be strong enough to support itself and predicted wind and snow loads. The structure must be made of transparent material such as glass or plastic to supply the necessary light for plant growth (2). Unfortunately, these materials have poor thermal resistance characteristics. As a result, a great deal of heat will be required to maintain the necessary temperature inside the structure in most regions of Manitoba. Excessive heating will render the whole greenhouse operation uneconomical during the most severe part of the winter. Greenhouse heating is probably the most inefficient use of fuel of most heating applications (36).

During summer, a transparent greenhouse admits more sunlight than necessary and, therefore, increases the ventilation requirements. At a time when energy is becoming more costly and scarce, it is very important to research ways so that the energy intensiveness of the greenhouse industry is reduced.

2.3 Techniques to Reduce Heat Losses from Greenhouses

Price et al. (36) have laid guidelines to minimize thermal wastage from greenhouses. Their most critical recommendations include leak-proof greenhouse construction, using a double layer in plastic-covered greenhouses, and drawing a black curtain between the greenhouse covering and the plant canopy at night. Substantial savings (20 to 25 percent) in fuel are projected if these guidelines are followed. They have presented other suggestions which would reduce the energy demand of greenhouses such as insulating the greenhouse during the night and removing the insulation during sunshine hours; or using an opaque, insulated structure with artificial lighting.

The use of curtains in greenhouses at night to reduce heat losses has also been studied by Amsen (3) and Simpkins et al. (42). Amsen mathematically evaluated the effect of using curtains in greenhouses on radiative heat loss to the atmosphere at night. He introduced the 'curtain effect' which is defined as: the radiative difference in net heat radiation from a plant canopy before and after a curtain, with a specified 'curtain factor' ($\Delta = \psi_t - \rho_t$), is placed between the plant canopy and the greenhouse roof. Mathematically, the 'curtain effect' is:

$$\sigma = 1.0 - 2.0 \left(\frac{1 + \Delta}{3 + \Delta}\right) \tag{2.1}$$

Using the above formula, it is possible to evaluate and compare the effect of using curtains of different materials on radiative heat loss from the plant canopy to the atmosphere. An aluminum curtain would give a curtain effect as high as 90 percent because of its high reflectance, 0.9.

Simpkins et al. (42) conducted experimental studies to determine the coefficients of heat transfer through the walls and roof of a double-layer air-inflated polyethylene greenhouse with an internal curtain added. Various materials and installation techniques were studied and several proposed curtain materials evaluated. Tests were conducted in an environmental chamber and in a small prototype greenhouse. Based on the results of their tests, they observed that conduction due to thin curtains depends, primarily, upon the method and position of fastening and not upon the curtain material. A curtain fastened horizontally from eave to eave was more effective than one fastened from eave to peak. Installing a curtain with the edges sealed with no contact between the curtain and the greenhouse structure, except at the edges, maximized the added resistance to heat transfer by conduction. It was also observed that a curtain with higher reflectivity saved more radiation heat loss. A highly reflective curtain fastened tightly from gutter to gutter, with similar side wall and end wall curtains, could save half of the energy currently required to heat a double-layer air-inflated multi-span polyethylene greenhouse.

Both Amsen (3) and Simpkins et al. (42) assumed that the curtains were thin and, therefore, offered no appreciable conductive resistance in themselves. The observation of Simpkins et al., that a curtain with higher reflectivity saves more radiative heat loss, is consistent with Amsen's prediction of curtain effect. The former researchers also note the importance of the method and position of fastening the curtain to achieve better results.

Perry (35) has developed a 'clicon' system consisting of pairs of mylar tubes. Half of the outer surface of each pair is aluminized for light and radiation control. These tubes can be inflated to make contact as a ceiling at night or be partially or fully deflated and hung vertically in the day. The 'clicon' system has been reported to have reduced night roof heat losses by 48 percent. It minimum light obstruction is 15 percent at solar noon. It should be noted that the 'clicon' system was adopted taking into consideration, the climatic conditions at 34°

latitude where a 15 percent reduction in sunlight could be tolerated. Applying the 'clicon' system at 50° or higher latitudes, common in Canada. would probably result in an intolerable loss of sunlight during winter and early spring. Daily operation of either 'clicon' or night curtain would also add to the responsibilities of the operator.

Lawand et al. (23) developed an environmentally designed greenhouse for colder regions, Fig. 2.1. The east-west oriented greenhouse has its inclined north-facing wall insulated with a reflective cover on the interior face. The angles of each inclined roof were designed to permit optimum transmittance of solar radiation and maximum reflection of this radiation on the plant canopy. The shape of such a greenhouse is very different from the traditionally built symmetrical (about the ridge line) greenhouse shapes. Heat loss savings reported are promising in this greenhouse, but adoption by growers would require assessment of structural and economic performance of this greenhouse, relative to traditional shapes.

Musard (32) has carried out experimental trials with discontinuous fixed transparent screens located between the plants and the ceiling of the greenhouse. These screens must be discontinuous to allow for ventilation. They could, however, be continuous in a greenhouse fitted with a forced ventilation system. The screens in the trial were 1.5 m wide cut from 50 micron thick polyethylene film placed across the greenhouse span. Separation between screens varied from 10 to 15 cm. Installation of the discontinuous screens is shown in Fig. 2.2. Recorded temperatures under the screens were 0.7 C higher than those recorded above the screens when the control temperature was set at 13 C and 1.2 C with the control temperature set at 15 C. In the middle of the gaps

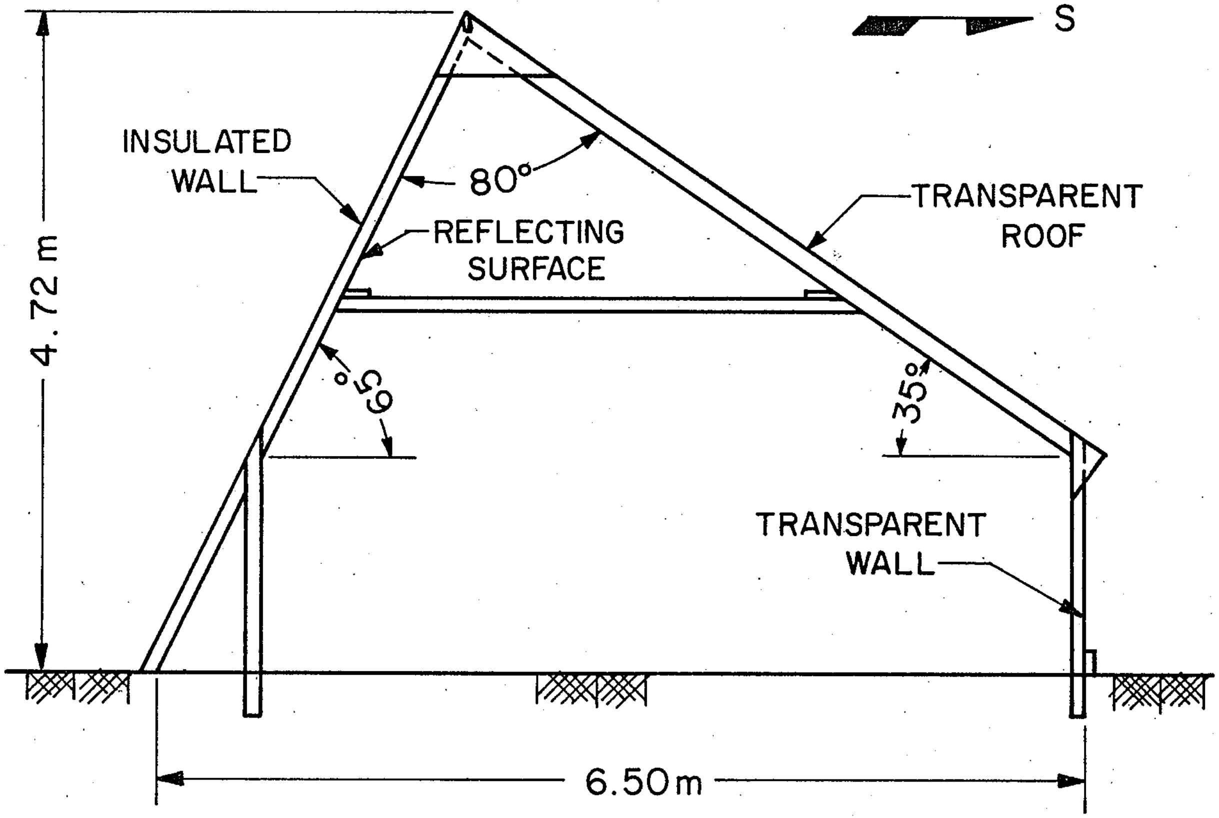

Fig. 2.1 Greenhouse for colder regions designed by Lawand *et al*. (23)

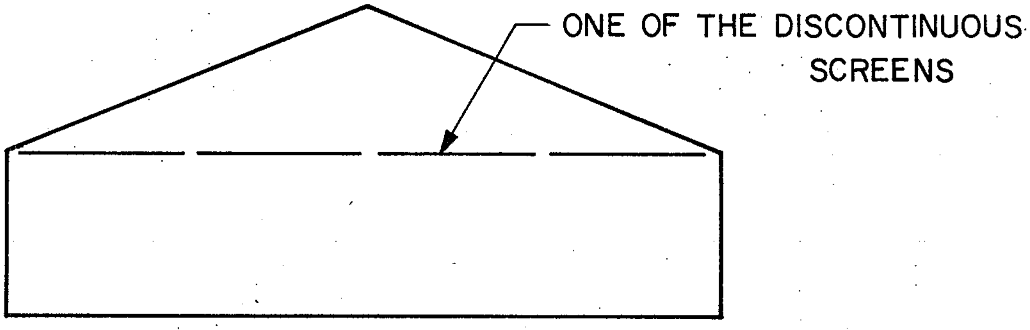

Fig. 2.2 Position of the discontinuous screens in a greenhouse as suggested by Musard (32)

between the films, a difference of 0.5 C between the temperature taken at 0.5 m below the level of screen and at 0.5 m above had been observed. These trials, carried out in glasshouses in France, showed that in spite of the reduction in luminosity there was some saving in heating and an improvement in the yield of early tomatoes. The author suggested that three to four percent energy savings were possible with such an arrangement.

Use of screens, as suggested by Musard (32) results in a reduction in solar radiation intensity at crop level that may not be tolerated in Canadian winter conditions. As well, these screens when installed would also restrict the cultural operation inside the greenhouse. Musard also noted that the improvement in the insulation of the walls exposed to the north or to the prevailing wind will result in a saving of energy. The suggested use of a double layer of plastic materials having low transmission to longwave radiation for greenhouse walls and the use of carbon dioxide between the two films of plastic instead of air should result in a better greenhouse effect.

According to trials carried out in Great Britain (7), using black polyethylene screens during nocturnal periods results in energy consumption savings of 33 percent. Taken over the total cultivation period this saving becomes 20 percent. If the screen is not continuous and has a gap of even one metre, the effect is almost completely lost.

2.4 Previous Studies on Greenhouse Thermal Environment

An analysis of greenhouse thermal environment was done by Morris (31) as early as 1956. Using a simple calculation procedure and a number of simplifying assumptions he computed design ventilation requirements for various sizes of gable greenhouses. Since this initial work, there have been a number of studies which have resulted in more accurate and complete analysis of greenhouse thermal environment.

Results of their experimental work on the glasshouse climate in Britain were reported by Whittle and Lawrence in a series of four papers (52, 53, 54, 55). They stressed the need to site, orient, and design the glasshouses so that the maximum available natural light would be admitted during winters. Two important observations were stated by the authors.

1. an east-west oriented glasshouse admitted 25 percent more winter light than a north-south oriented glasshouse, and
2. winter temperatures were consistently higher in an unheated unventilated east-west oriented glass house than in a north-south oriented glasshouse.

In the discussion, the second observation was considered to be a result of the first observation. As a result of their work, an east-west oriented glasshouse was recommended over a north-south oriented one in order to get a more favourable climate in a glasshouse. Adequate ventilation was recommended to reduce temperature fluctuations and also, in summer, to reduce the peak temperature.

Jenkins and Walker (22) prepared nomographs to determine heat and ventilation requirements and estimating annual heat cost for greenhouses. Heat requirements were determined by neglecting all but conduction losses through the exposed greenhouse because other heat losses were considered to be small compared to the surface heat losses. Ventilation requirements were determined by the rate of air change depending upon the crop to be grown and the highest temperature that could be tolerated in the greenhouse on a clear day.

McCune and Stipe (26) proposed rule-of-thumb values for determining heating requirements in single and double wall plastic greenhouses as 4.47 w/m^2 and 3.29 w/m^2, respectively, per degree Celsius temperature difference maintained. Heating requirements of a plastic greenhouse are influenced by such factors as size, type of construction, orientation and location of greenhouse, temperature to be maintained, and the outside climatic conditions.

Walker's (49) steady-state heat balance of a heated and ventilated greenhouse sums all the major components of the heat balance. Greenhouse temperatures predicted with this heat balance were found to be reasonably consistent with observed temperatures. Statistical analysis indicated that there was no significant difference between predicted and observed values. The analysis thus permits the determination of heating and ventilation requirements in greenhouses and the study of the total greenhouse heat balance with varying inside and outside climatic condictions. Walker's analysis, in general, is found satisfactory for representing energy balance in greenhouses (5).

Further studies in the control of greenhouse environment reveal that it is not sufficient to maintain a specified temperature inside a greehouse because plant leaf temperature can differ from inside air temperature appreciably on a sunny day or on a clear sky night. Plant performance is related to leaf temperature more than to air temperature (45). A good air circulation system is, therefore, very necessary in order to minimize this temperature difference (50).

Shaw (40) employed Walker's analysis to design greenhouse heating and ventilation systems under Manitoba conditions. Design values were reliable when compared to measured fuel consumption.

There have been recent studies of greenhouse thermal environment which consider transient heat transfer (43, 45). These advanced studies are primarily utilized for predicting crop response to various environmental parameters. It is possible with this approach to predict temperatures inside a greenhouse more accurately at any point in time. The complexity involved may not be justifiable for studies on the effect of structural alterations in a greenhouse on its heat balance or determining heating and ventilation requirements. An approach similar to that used by Walker (49) may be more practical for the intended applications. Information is available to determine accurately all components of greenhouse heat balance in Walker's analysis except solar radiation.

Barbee _et al_. (8) have reviewed the work done over the past 30 years in the field of plant environment simulators and have categorized engineering design techniques. This reference can serve as a starting point in most of the studies related to environmental control in greenhouses.

2.5 Solar Radiation in Greenhouses

Solar radiation constitutes a very important part of the total greenhouse thermal environment (48), therefore, a reasonably accurate method for predicting it is necessary. Several analyses are available which predict, with varying success, the quantity of solar energy incident on a given surface. Most of these methods are restricted to clear sky conditions (6, 28, 34, 44, 46, 47) and only a few have considered the diffuse component of solar radiation (6, 34, 44, 46).

Moon (28), in 1940, published proposed standard solar radiation curves for engineering use. He presented a method of calculating direct solar radiation on a surface normal to the sun's rays during cloudless days for any elevation and for varying amounts of water vapour and dust in the atmosphere. The basic atmosphere considered by Moon for the purpose of calculation consisted of ozone, water vapour, and dust particles. The effects of other atmospheric constituents on the reduction of solar radiation passing through it was neglected because of their small magnitude. Obviously, Moon's curves are not applicable under conditions other than clear-sky. Also, these curves do not account for the monthly variations in solar intensity caused by changes in the earth-sun distance and by the varying average moisture content of the atmosphere.

G. V. Parmelee (34) was one of the first investigators to develop curves to predict both diffuse and direct solar radiation for cloudless days. These curves were based on experimental data. His data indicated a relationship exists between clearness of the atmosphere and direct and diffuse components of solar radiation. More recent analytic solutions of Moon's equations have been carried out by Threlkeld and Jordan (47) using a redefined basic atmosphere. ASHRAE (6) has adopted these data for calculating the value of average direct solar radiation under cloudless day time conditions.

It is extremely difficult to approximate the cloud variables as the clouds are nonhomogenous by nature. It seems reasonable to correlate the solar radiation measurements with a parameter such as percent possible sunshine (9).

Morris and Lawrence (29) presented a mathematical model to predict total solar radiation incident on any surface. Percent of possible sunshine, which is generally recorded at weather stations, has been used as the parameter for specifying atmospheric sky conditions. In this model determination of diffuse solar radiation on inclined surfaces considers the isotropic nature of the diffuse radiation. Results of investigations by Norris (33) indicate that the distribution of diffuse radiation probably averages, over a long period of time, to near isotropic conditions. In a further study, Morris and Lawrence (30) invalidated the assumption of the isotropic intensity distribution of diffuse radiation for actual weather conditions. Drummond (14) has stated that true isotropic sky conditions practically never occur even with the densest clouds.

Investigation by Morris and Lawrence (30) revealed that clear-sky intensity distribution of diffuse radiation could be represented as emission from two superimposed sources. The sources have been defined as (i) the circumsolar region centred about the sun and extending radially outward, and (ii) the total hemisphere of the sky vault. Because the sun must be the ultimate origin of energy in both cases, these two sources are not completely independent of one another. The diffuse radiation available from each source, regardless of the directional nature of the radiation or its ultimate incidence angle is 43 percent from the hemispherical diffuse component and 57 percent from the circumsolar diffuse component.

Most researchers in the greenhouse industry have used either a rule-of-thumb (49) or a semiemperical approach (37) to determine the contribution of solar radiation to the greenhouse thermal environment. Manbeck and Aldrich (24) developed an analytical approach to determine direct visible solar energy transmitted by rigid plastic greenhouses. This approach, though quite precise, is valid only for clear sky conditions and computes only the direct component of the solar radiation. It relies on Moon's solar radiation curves and, therefore, the inherent limitations of Moon's analysis are present. The approach does not appear to be suited to determine total solar irradiation in greenhouses.

An important factor in computing solar irradiation in a greenhouse is the optical properties of the greenhouse-covering surface. Part of the total solar radiation incident on any surface is reflected, part is absorbed and the rest is transmitted either directionally as in clear glass or diffusely as in most plastics. The solar heat gain through a greenhouse surface consists of the transmitted component of the incident solar radiation and the part of the solar radiation absorbed by the surface which is conducted into the greenhouse (6). The optical properties of greenhouse-covering materials are a function of incidence angle. Walker (51) evaluated the transmission versus incidence angle characteristics of commonly used greenhouse-covering materials.

Gopffarth (19) used the following relationship to estimate transmittance of a system consisting of more than one layer of a transparent material when the reflectivity of the material is known:

$$\psi = \frac{1 - \rho}{1 + (2S - 1)\rho} \qquad (2.2)$$

where S is the number of the transparent material surfaces.

A mathematical model to compute total solar radiation incident on a surface, like that proposed by Morris and Lawrence (29), combined with the optical properties of the surface should adequately predict the solar heat gain through the surface. With this type of model, the solar heat gain in a greenhouse consisting of a finite number of such surfaces can be determined.

Aldrich and White (2) experimentally determined relationships between structural form and quality and quantity of transmitted solar energy in rigid plastic greenhouses. The greenhouse shapes studied were: (a) multibarrel cylindrical vault, (b) hyperbolic paraboloid, (c) segmental dome, (d) single-barrel vault, (e) gothic arch, and (f) gable greenhouse. There appeared to be a correlation between solar energy transmission and building shape. The gothic arch shape was observed to have transmitted maximum solar energy during the period near the winter solstice.

The quantity of solar light is quite often the limiting factor for plant growth in greenhouses during winter months above about 40 degrees north latitude (1). Friend (17) found that at 51 degrees north latitude, east-west orientation of a large span greenhouse resulted in more even transmission of direct radiation in winter than north-south orientation of a similar structure.

CHAPTER III

THERMAL BALANCE OF GREENHOUSES

3.1 Overall Thermal Balance of a Typical Greenhouse

Fig. 3.1 represents, schematically, the thermal environment of a greenhouse. All the components of the thermal environment can be expressed by the following equation (49):

$$Q_h + Q_u + Q_e + Q_r = Q_c + Q_t + Q_p + Q_g + Q_v \qquad (3.1)$$

At any given time, one or more of the terms in equation 3.1 may be equal to zero.

3.2 Basic Assumptions

The following assumptions were made in determining the thermal balance of greenhouses:

1. there is no crop in the greenhouse; therefore, heat transfer due to photosynthesis and respiration can be neglected,
2. there is negligible evaporation from the soil surface in the greenhouse,
3. there is no condensation on the inside of the transparent covering; therefore, transmittance of the covering will be constant,
4. atmospheric emissivity is a function of dewpoint temperature only,
5. heat lost from the greenhouse is positive,
6. boundaries of the greenhouse are assumed to be perfectly sealed; therefore, the infiltration loss is neglected,
7. thermal storage in the greenhouse structure and the ground bed is ignored to allow steady-state heat transfer calculation,

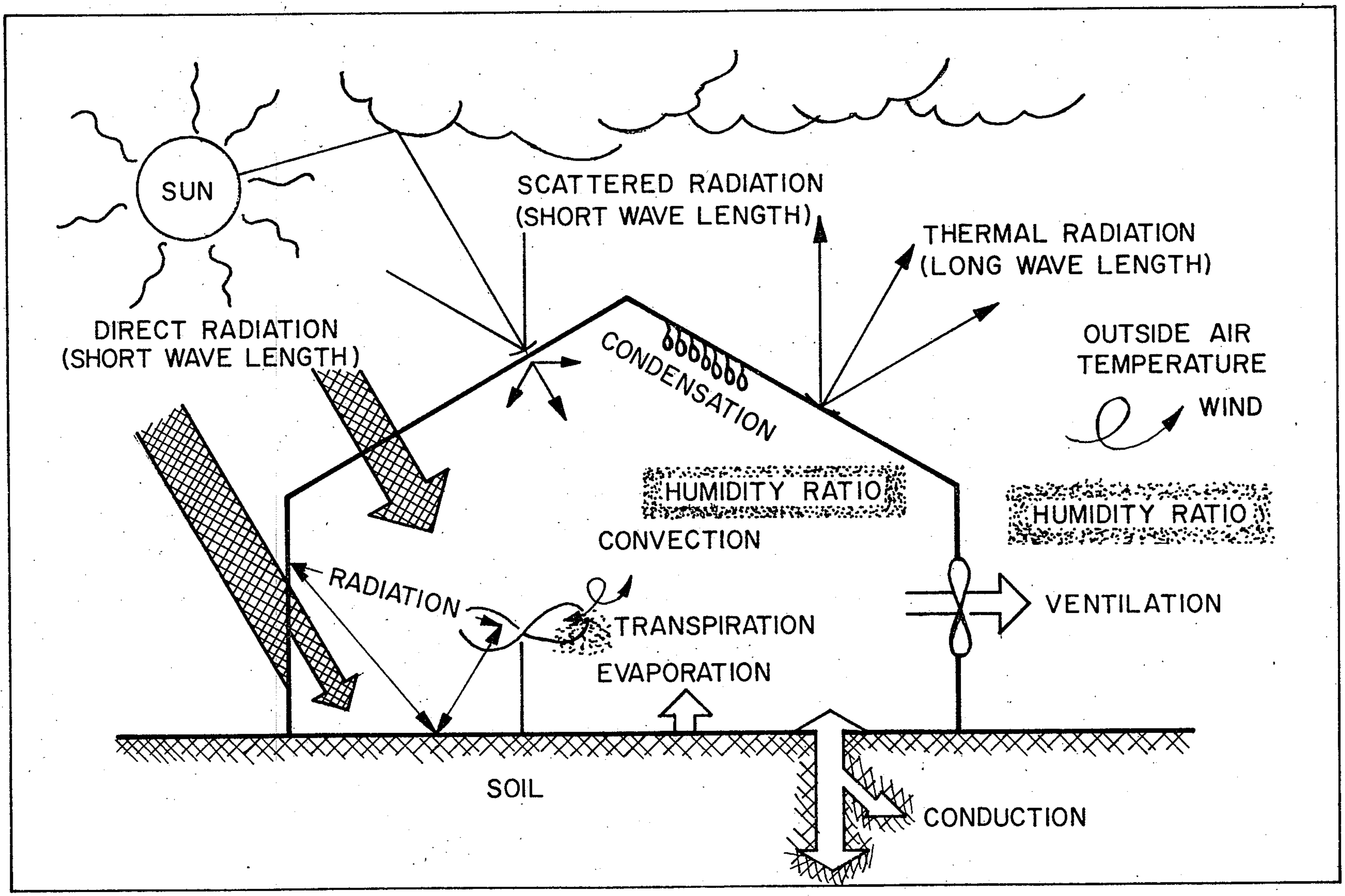

Fig. 3.1 Schematic representation of thermal environment of greenhouse (45)

8. reflection and reradiation from the surroundings are neglected,

9. homogeneous and isotropic temperature regimes exist in the structure at all times,

10. there is no mechanical operation going on inside the greenhouse; therefore, the heat released by equipment can be neglected, and

11. solar radiation transmitted by the greenhouse plastic surfaces is in the form of diffused radiation; therefore, the whole transmitted solar radiation becomes a part of the greenhouse thermal environment.

3.3 Steady-state Consideration

The main limitation of a steady-state approach in heat transfer is its inability to account for thermal storage in the system (45). There are two effects of thermal storage in a system:

1. a reduction in the peak amplitude of the thermal wave entering into the system, and

2. a phase difference occurring between the two thermal waves outside and inside the system.

Heat storage in greenhouses has been taken into account by a number of investigators (43, 45) in their bid to simulate plant growth. The resulting models have been quite complex. The heat storage consideration is unavoidable when the thermal environment in greenhouses is analysed from the point of view of optimization or simulating plant growth, but it would be a luxury when the effects of various design alternatives of greenhouse components on the thermal balance are to be studied.

Steady-state heat transfer models have been reported to be adequate in the analysis of greenhouse design (5). Carson et al. (13) found a steady-state model to be adequate in the analysis of swine performance. The steady-state approach was adopted, in this study, for the analysis of heat balance in greenhouses.

3.4 Modified Thermal Balance Equation

Walker (49) discussed the contribution of the heat of respiration and the heat utilized in photosynthesis to the total heat balance. The magnitude of these components was found to be negligible compared to that of other components of the heat balance. Morever, in the study of the effect of greenhouse design change on the total thermal balance, presence or absence of a crop should not make a significant difference. Therefore, it was assumed that no crop was present for purposes of this study. It was further assumed that no mechanical operation was going on inside the greenhouse under consideration thereby eliminating the heat released by equipment from the analysis.

Either heating requirement Q_h or ventilation requirement Q_v of a greenhouse will be zero at any instance depending on whether the greenhouse is being ventilated or heated. The sign of any component in the heat balance equation will be negative or positive according to assumption no. 5 in Section 3.2. With these considerations, Equation 3.1 can be rewritten as:

$$\begin{pmatrix} Q_h \\ Q_v \end{pmatrix} = Q_u + Q_t + Q_g + Q_c \qquad (3.2)$$

Individual components on the right hand side of Equation 3.2 can be evaluated using appropriate relationships.

3.5 Solar Heat Gain Determination

For this investigation, a mathematical approach was required which would predict the total solar heat gain through a surface under any amount of cloud cover. The surfaces to be considered may have any set of optical properties, may have any inclination and wall azimuth, and may be located on any latitude. Input quantities should be easily accessible and few in number. Accordingly, the model presented by Morris and Lawrence (29, 30) which allows consideration of the anisotropic nature of diffuse solar radiation was adopted to predict solar radiation incident on any surface. The following modifications were made to the above-mentioned model:

1. a simpler and more accurate equation, used by Ari Rabl et al. (4), was adopted for computing the solar declination angle on a particular day. The sun's declination angle does not change significantly during a day, and

2. the actual and apparent values of extraterrestrial solar radiation intensities normal to the sun's rays, RA and IO, respectively, were expressed in the form of equations so as to minimize the input data while programming the total analysis.

Solar transmittance of the greenhouse transmitting surfaces as a function of incidence angle were experimentally determined. Reflectance and transmittance of a surface were related as follows (19):

$$\rho_u = \frac{1 - \psi_u}{1 + \psi_u} \tag{3.3}$$

and, absorptance of the surface becomes:

$$\omega_u = 1 - \psi_u - \rho_u \tag{3.4}$$

As diffuse solar radiation appears to be coming from all points of the sky, a single value of incidence angle cannot be assigned to the diffuse solar radiation incident on a surface at any time. Therefore a constant transmittance of a transmitting surface, irrespective of the solar incidence angle, was assumed for the diffuse solar radiation. The value of the constant transmittance was chosen to be equal to the normal transmittance of direct solar radiation.

Total solar heat gain through a transmitting surface is given (10) by:

$$q_u(j) = I_T(j) + I_A(j) \times N_i \qquad (3.5)$$

where,

$$N_i = h_i/(h_i + h_o) \qquad (3.6)$$

Therefore, total solar heat of the whole greenhouse structure is,

$$Q_u = \sum_{j=1}^{n} q_u(j) \qquad (3.7)$$

The set of equations used to compute transmitted and absorbed components of solar radiation for a surface is given below:

Required input:

$D, L, KS, T, \alpha, \phi, \psi_u(\theta)$

Equation:

$$\sin(d) = \sin(de) \cdot \cos(2\pi \cdot N/365) \qquad (3.8)$$

$$H = \pi \cdot T/12 \qquad (0 \leq T \leq 24) \qquad (3.9)$$

$$\sin(\beta) = \sin(L) \cdot \sin(d) - \cos(L) \cdot \cos(d) \cdot \cos(H) \qquad (3.10)$$

$$(\beta_{max} = \pi/2 - L + d)$$

$$\sin(A_z) = \cos(d) \cdot \sin(-H)/\cos(\beta) \tag{3.11}$$

$$\gamma = |A_z - \alpha| \tag{3.12}$$

$$\cos(\theta) = \cos(\beta) \cdot \cos(\gamma) \cdot \sin(\phi) + \sin(\beta) \cdot \cos(\phi) \tag{3.13}$$

$$TR = (12/\pi) \cdot \cos^{-1} [\{\sin(L) \cdot \sin(d)\}/\{\cos(L) \cdot \cos(d)\}] \tag{3.14}$$

$$RA = 1353.0\{1.0 + 0.0335 \cdot \cos (2\pi \cdot N/365)\} \tag{3.15}$$

$$IO = 1160\{(1.0 + 0.033 \cos (2\pi N/365)\}^2 \tag{3.16}$$

$$JC = 0.37 + 0.622\ KS \tag{3.17}$$

$$KT = 0.28 + 0.45\ KS \tag{3.18}$$

$$KC = 1.6(1 - KT) \tag{3.19}$$

$$\begin{aligned} KD_1 &= 1.415JC - 0.384; && (0.38 \leq JC \leq 0.80) \\ &= 0.75; && (JC > 0.80) \end{aligned} \tag{3.20}$$

$$\begin{aligned} KD_2 &= 1.492\ KT - 0.492; && (0.60 \leq KT \leq 0.83) \\ &= \exp \{0.935(KT)^2\} - 1\ ; && (KT < 0.6) \end{aligned} \tag{3.21}$$

$$\begin{aligned} HO = (24/\pi) \cdot RA\ \{&\cos(L) \cdot \cos(d) \cdot \sin(\pi \cdot TR/12) + \\ &(\pi - \pi \cdot TR/12) \cdot \sin(L) \cdot \sin(d)\} \end{aligned} \tag{3.22}$$

$$I_{DH1} = \{KD_1 \cdot HO\}/\{2(12 - TR)\} \tag{3.23}$$

$$I_{DH2} = \{KD_2 \cdot HO\}/\{2(12 - TR)\} \tag{3.24}$$

$$a_1 = -\sin (\beta_{max}) \cdot \log_e \{I_{DH1}/0.6\ IO \cdot \sin (\beta_{max})\} \tag{3.25}$$

$$a_2 = -\sin (\beta_{max}) \cdot \log_e \{I_{DH2}/0.6\ IO \cdot \sin (\beta_{max})\} \tag{3.26}$$

$$I_{DN1} = IO \cdot \exp \{-a_1/\sin (\beta)\} \tag{3.27}$$

$$I_{DN2} = IO \cdot \exp \{-a_2/\sin (\beta)\} \tag{3.28}$$

$$I_{D1} = I_{DN1} \cdot \cos(\theta) \tag{3.29}$$

$$I_{D2} = I_{DN2} \cdot \cos(\theta) \tag{3.30}$$

$$I_D = (1 - KC) \cdot I_{D1} + KC \cdot I_{D2} \tag{3.31}$$

$$I_{DT} = (1 - KC) \cdot I_{DN1} \cdot \psi_u(\theta) + KC \cdot I_{DN2} \cdot \psi_u(\theta) \tag{3.32}$$

$$\omega_u(\psi_u) = \psi_u(\theta)\,\{1 - \psi_u(\theta)\} / \{1 + \psi_u(\theta)\} \tag{3.33}$$

$$I_{DA} = (1 - KC) \cdot I_{DN1} \cdot \omega_u(\psi_u) + KC \cdot I_{DN2} \cdot \omega_u(\psi_u) \tag{3.34}$$

$$\tau_{D1} = I_{DN1}/RA \tag{3.35}$$

$$\tau_{D2} = I_{DN2}/RA \tag{3.36}$$

$$\tau_{d1} = 0.2710 - 0.2939\,\tau_{D1} \tag{3.37}$$

$$\begin{aligned} \tau_{d2} &= 0.33\,(1 - \tau_{D2}) \qquad (0.45 \le \tau_{D2}) \\ &= \sqrt{1.07 \log_e(\tau_{D2} + 1)} - \tau_{D2} \end{aligned} \tag{3.38}$$

$$B_1 = (\tau_{d1}/\tau_{D1}) \cdot \sin(\beta) \tag{3.39}$$

$$B_2 = (\tau_{d2}/\tau_{D2}) \cdot \sin(\beta) \tag{3.40}$$

$$I_{dh1} = B_1 \cdot I_{DN1} \tag{3.41}$$

$$I_{dh2} = B_2 \cdot I_{DN2} \tag{3.42}$$

$$MS = F(\theta) \tag{3.43}$$

$$MH = F(\phi) \tag{3.44}$$

$$I_{d1} = (0.43\,MH + 0.57\,MS)\,I_{dh1} \tag{3.45}$$

$$I_{d2} = (0.43\,MH + 0.57\,MS)\,I_{dh2} \tag{3.46}$$

$$I_d = (1 - KC) I_{d1} + KC \cdot I_{d2} \tag{3.47}$$

$$I_{dT} = \psi_u(\theta = 0) \cdot I_d \tag{3.48}$$

$$I_{dA} = \omega_u(\psi_u) \cdot I_d \tag{3.49}$$

$$I = I_D + I_d \tag{3.50}$$

$$I_T = I_{DT} + I_{dT} \tag{3.51}$$

$$I_A = I_{DA} + I_{dA} \tag{3.52}$$

3.6 Thermal Radiation Exchange Between Greenhouse and the Atmosphere

The net thermal radiation balance between a greenhouse and the atmosphere will be equal to the summation of the thermal radiation emitted by each body with proper sign:

$$Q_t = A_s \cdot \delta \cdot FS \cdot \psi_t [\varepsilon_s \cdot t_s^4 - \varepsilon_a \cdot t_a^4] \tag{3.53}$$

Because the greenhouse was assumed to contain no crop, A_s was simply the greenhouse ground-bed area. It was assumed that in case of multiple layers of covering material, the successive layers would transmit the same percentage of radiation striking it as the first layer (49). A quadratic equation fit was obtained for the effective atmospheric emissivity values suggested by Bliss (10) as a function of atmospheric dew-point temperature.

The ASHRAE Handbook (6) lists equations to calculate dew-point temperature of atmospheric air numerically, if the air temperature and relative humidity are known. The equations in the ASHRAE Handbook are in the British system of units. After converting into SI units, the equations are:

$$pws = 0.76 \exp [2.3026 \{10.79586 (1 - x) + 5.02808 \log_{10}(x) + 1.50474 \times 10^{-4} (1 - 10^{-8.29692(1/x-1)}) + 0.42873 \times 10^{-3} (10^{4.76955(1-x)} - 1) - 2.2195983\}] \tag{3.54}$$

where pws is in the temperature range of -50C to 100C.

$$x = 273.16/(273.16 + t_{dp}) \tag{3.55}$$

$$pw = RH \times pws \tag{3.56}$$

Then, for a temperature range of 0 C to 65.5 C

$$t_{dp} = 102.6956 + 24.6988 \log_e(pw) + 1.0496 \{\log_e(pw)\}^2 \tag{3.57}$$

and, for a temperature range of -50 C to 0 C

$$t_{dp} = 79.6565 + 17.4615 \log_e(pw) + 0.4959 \{\log_e(pw)\}^2 \tag{3.58}$$

The structural frame of a greenhouse makes up approximately seven percent of the total covering surface area. It is difficult to account for this area when calculating the shape factor of the greenhouse in relation to the atmosphere as it requires integration of involved functions. It was decided that the structural frame of the greenhouse would be excluded from the calculation of shape factor.

When no wall is insulated, no part of the greenhouse radiating surface, the ground, is obscured from the atmosphere. The value of shape factor for this case will be 1.0. Under conditions other than this i.e., when some part of the greenhouse covering surface is opaque, exact determination of shape factor requires the evaluation of double integrals (15) which is often tedious. Shape factors for a large number of geometrical arrangements have been evaluated and can be found in various texts dealing with heat transfer. One such arrangement is shown in Fig. 3.2. Use of this type of design aid allows shape factors to be determined for a greenhouse with any of its sides insulated. The expression for evaluating the shape factor of this arrangement is (15):

$$\begin{aligned} FS_{2-3} = {} & (A_2/A_3)(1/\pi)[\tan^{-1}(b/z) + (\ell/z)\tan^{-1}(b/\ell) - \\ & (\sqrt{\ell^2 + z^2}/z)\tan^{-1}(b/\sqrt{\ell^2 + z^2}) + (z/4b)\log_e\{(\ell^2+b^2+z^2)z^2/ \\ & (\ell^2 + b^2)\cdot(b^2 + z^2)\} + (\ell^2/4b \cdot z)\log_e\{(\ell^2 + b^2 + z^2)\cdot \ell^2/ \\ & (\ell^2 + b^2)\cdot(\ell^2 + z^2)\} - (b/4z)\log_e\{(\ell^2 + b^2 + z^2)\cdot b^2/ \\ & (\ell^2 + b^2)\cdot(b^2 + z^2)\}] \qquad (3.59) \end{aligned}$$

This expression gives the shape factor of the end surface in relation to the base. For an end surface which is not rectangular, A_2 is the area for that particular end surface. In a symmetrical greenhouse construction, i.e. opposite sides of greenhouse are equal, the shape factor should be equal for both ends and also for both sides. Since the sum of shape factors of all the four sides of a greenhouse is equal to unity; by knowing the shape factor for one side, corresponding shape factors can be determined for any of the other three sides.

3.7 Heat Transfer with Greenhouse Ground Bed

Heat transfer with the greenhouse ground bed consists of heat transfer in vertical direction Q_y and lateral heat transfer Q_x.

The lateral heat transfer component depends upon the type of foundation construction and is directly proportional to the inside-outside air temperature difference (44). Deep insulated foundations can result in reduced heat transfer. This heat transfer through the green-

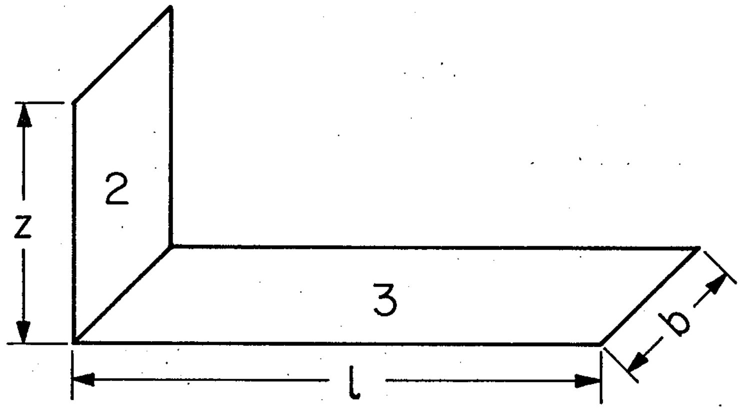

Fig. 3 . 2 A Geometric Configuration to Evaluate the Shape Factors for Symmetrical Greenhouse

house foundation walls can be represented as:

$$Q_x = P \cdot f \cdot (t_f - t_o) \tag{3.60}$$

The value of f was adopted from the Canadian Farm Building Code (12).

Steady-state heat transfer with the greenhouse floor in a vertical direction is given by:

$$Q_y = A_y\ (t_f - t_g)/R_y \tag{3.61}$$

where A_y is the area of the greenhouse floor after excluding a 1.0 m wide strip along the edges. This is because it is assumed that this 1.0 m of ground bed area contributes to the lateral heat transfer component through the foundation walls. Total heat transfer with the greenhouse ground bed is then:

$$Q_g = Q_x + Q_y \tag{3.62}$$

3.8 Heat Transfer From the Covering Surface of the Greenhouse

Heat may be transferred from the greenhouse surface by all three mechanisms; conduction, convection, and radiation. The surface heat transfer coefficient values given by ASHRAE (6) include the effects of both convective and radiative heat transfer. An expression for the heat transfer from the covering surface of a greenhouse under steady-state conditions is,

$$Q_c = \frac{A_s(t_i - t_o)}{R_s} \tag{3.63}$$

Values of R_s for various greenhouse surface constructions are calculated by the expressions given in Appendix 3.

CHAPTER IV

EXPERIMENTAL DETERMINATION OF SOLAR TRANSMITTANCE VERSUS INCIDENCE ANGLE CHARACTERISTICS FOR COMMON GREENHOUSE COVERINGS

4.1 Initial Preparation

4.1.1 Determination of Geographic Directions at the Experimental Site

The experiment was conducted in an open space south of the research greenhouse at the University of Manitoba. No shadows were present to interfere with the experiment and observations could be taken from sunrise to sunset without disturbance. A temporary platform was set up as a work bench to support the instruments and allow observed data to be recorded in the field. A geographic meridian was established on the platform with the procedure given below (11).

A pole with a pointed end was erected on the levelled platform and the endpoint of the pole's shadow was marked on the platform at approximately 20 minute intervals from 10.0 a.m. to 2.0 p.m. The point where the pole stood was marked on the platform. A smooth curve was sketched through the shadow marks. With the pole mark as centre and with an appropriate radius, a circular arc was swung to obtain two intersections, p_1 and p_2 (Fig. 4.1), with the shadow curve. A line from the pole mark through p_0, the midpoint of p_1p_2 will approximate the geographic meridian. Other directions were determined with this meridian as the reference base.

4.1.2 Experimental Equipment

A model SR spectroradiometer (21) was available to take observations in this experiment. A frame was fabricated to tilt the spectroradio-

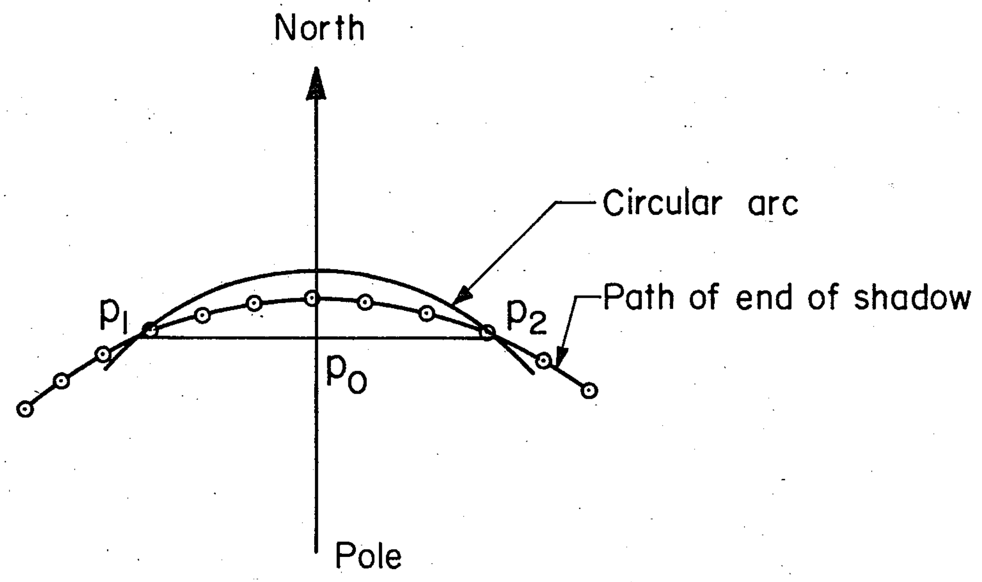

Fig. 4.1 Determining Geographical Meridian by Shadow Method (II)

meter at any inclination angle ranging from 0 to 90 degrees and to hold the spectroradiometer at that particular tilt angle. The frame was calibrated over the range of 0 to 90 degrees in five degree intervals. A frame and slide arrangement made it possible to hold the covering plastic films parallel to the diffusing screen. Location of the diffusing screen on the spectroradiometer is shown in Fig. 4.2. With this arrangement, greenhouse-covering plastic films could be tilted at a particular inclination angle and the observations could be recorded.

4.1.3 To Compute Solar Incidence Angle on a Surface at any Time

Incidence angles of the sun on a surface were computed with the following inputs:

- i) date of the observations
- ii) local watch time at which the incidence angle is to be computed
- iii) wall-azimuth of the surface
- iv) inclination angle of the surface

Local watch time had to be converted to the local civil time which in turn was used to compute the incidence angles. The following set of equations was programmed on the computer for the computation (Appendix 1.3):

$$T = F(TL) \tag{4.1}$$

$$H = \pi \cdot T/12 \tag{4.2}$$

$$\sin(d) = \sin(de) \cdot \cos(2\pi \cdot N/365) \tag{4.3}$$

$$\sin(\beta) = \sin(L) \cdot \sin(d) - \cos(L) \cdot \cos(d) \cdot \cos(H) \tag{4.4}$$

$$\sin(A_z) = \cos(d) \cdot \sin(-H)/\cos(\beta) \tag{4.5}$$

Fig. 4.2 A Model SR Spectroradiometer

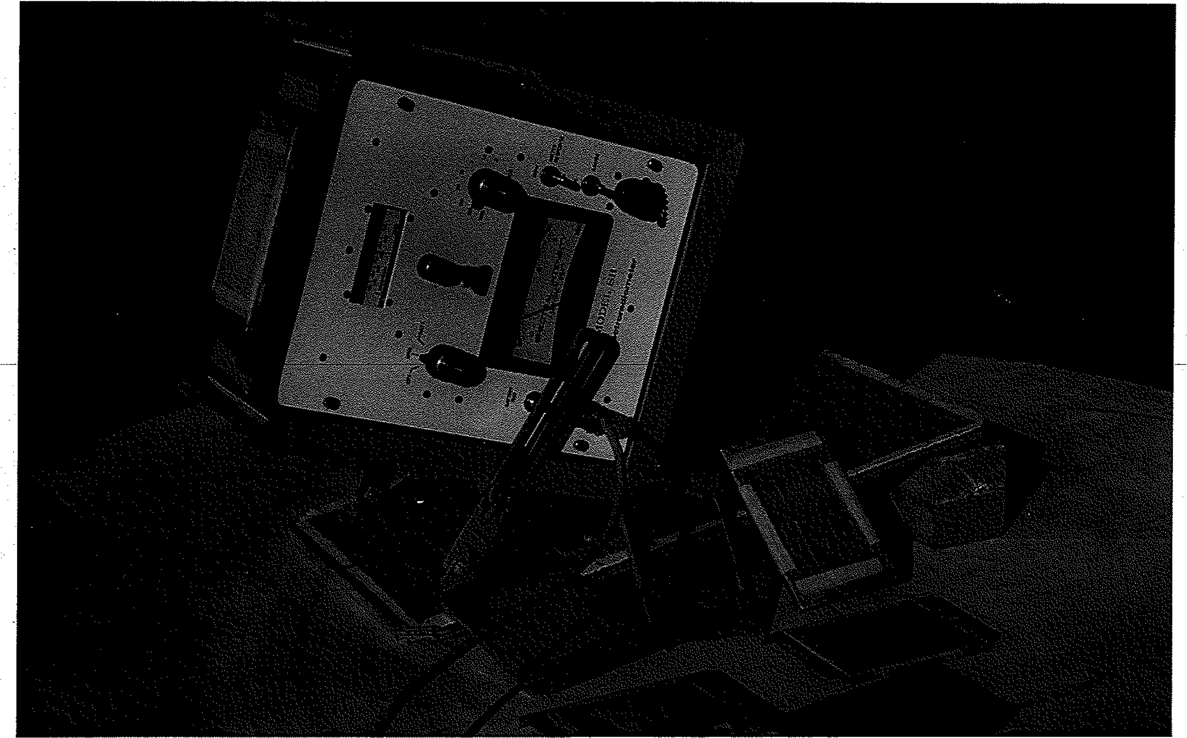

Fig. 4.3 The Experimental Set-up to Determine Solar Transmittance Versus Incidence Angle Characteristics

$$\gamma = |A_Z - \alpha| \qquad (4.6)$$

$$\cos(\theta) = \cos(\beta) \cdot \cos(\gamma) \cdot \sin(\phi) + \sin(\beta) \cdot \cos(\phi) \qquad (4.7)$$

$$TR = (12/\pi) \cdot \cos^{-1}[\{\sin(L) \cdot \sin(d)\}/\{\cos(L) \cdot \cos(d)\}] \qquad (4.8)$$

4.1.4 Greenhouse Coverings to be Tested

Seven greenhouse covering systems using three different plastic materials were used in the experiment. They were:

i) U.V. Polyethylene, 102 μ (Canadian Industies Limited),
ii) Fabrene-TM (Dupont of Canada Limited),
iii) Filon (Atlas Asbestos Company),
iv) two layers of U.V. Polyethylene,
v) two layers of Fabrene - TM ,
vi) top layer of Fabrene-TM and a lower layer of U.V. Polyethylene, and
vii) top layer of Filon and a lower layer of U.V. Polyethylene.

Slides of these seven systems were prepared to fit in the frame and slide arrangement described in Section 4.1.2.

4.2 Experimental Procedure

The spectroradiometer mentioned in Section 4.1.2 indicates the intensity of solar radiation at a preset wavelength in the range of 380 nm to 1550 nm. It was assumed that solar transmittance of greenhouse plastic coverings remains constant with respect to change in wavelength. This assumption was based on the observation of curves of incident and transmitted solar radiation for several plastic materials (18). This facilitated the experiment with the spectroradiometer as incident and transmitted intensities at a particular wavelength for a surface azimuth and inclination were the only data required.

Fig. 4.3 shows the scheme by which the data were recorded. The experiment was conducted on sunny days under cloudless sky conditions. The spectroradiometer and the tilting frame assembly were set in a predetermined direction which corresponded to the wall azimuth of the plastic surfaces to be tested. The direction was determined from the point of view of getting a wide range of incidence angles as the spectroradiometer was tilted from 0 to 90 degrees.

To take a set of observations, the spectroradiometer was set to read at a particular wavelength. Local watch time was noted at the beginning of the experiment. The incident and transmitted intensities of solar radiation for a particular inclination angle of a greenhouse covering system were recorded as follows. The incident intensity was recorded with the slide of greenhouse covering material off the diffusing screen and the transmitted intensity was recorded by placing the slide over the diffusing screen. The inclination angle of the surface was changed from 0 degrees through 90 degrees at definite intervals. It was assumed that the intensity of solar radiation and the solar incidence angle did not change appreciably during one set of observations, an elapsed time of about five minutes. Table 4.1 shows one such set of observations. The procedure was repeated for different systems of covering materials and different wavelengths (400 nm, 600 nm and 1250 nm).

4.3 Data Processing

Transmittance values were computed by taking a ratio of the transmitted solar intensity and the solar intensity at normal incidence. Incidence angles for a set of data were computed as described in Section

TABLE 4.1

A Set of Observations for the Experiment

Date: June 18, 1975; Wall-Azimuth: 250 degrees

Wavelength: 600 nm

1	2	3	4
9.43 a.m.	0.0	138.0	122.0
	10.0	190.0	175.0
	20.0	203.0	188.0
	30.0	212.0	199.0
	40.0	218.0	205.0
	50.0	214.0	200.0
	60.0	206.0	193.0
	70.0	190.0	173.0
	80.0	164.0	146.0
	90.0	130.0	114.0

Code:
1 Local watch time
2 Inclination angle of the test surface
3 Intensity of solar radiation with the test surface off the diffusing screen mw/(cm^2·nm)
4 Intensity of solar radiation transmitted through the test surface (U.V. Polyethylene in this case), mw/(cm^2·nm)

4.1.3. The transmittance values were then correlated with the computed incidence angles. These correlated transmittance and incidence angle values at different wavelengths were grouped for each system of covering surface and a polynomial fit was obtained for the transmittance as a function of incidence angle. The third-order polynomial fit obtained for the Filon and U.V. Polyethylene combination was

$$\psi_u(\theta) = 0.3571340 \times 10^{-3}(\theta^3) - 0.4347968 \times 10^{-1}(\theta^2) + 0.4119053(\theta) + 78.9124 \qquad (4.9)$$

where the transmittance (ψ_u) is in percent and the incidence angle (θ) is in degrees. Detailed results of the experiment are given in Appendix 2. It was observed that at incidence angles greater than approximately 70 degrees, the output from the spectroradiometer became constant. It was assumed that this was due to the fact that diffuse radiation incidence on the surface was dominant beyond about 70 degrees incidence. As discussed in Section 3.5, it is not possible to assign as single value of incidence angle to the diffuse solar radiation falling on a surface. Therefore, it did not appear possible to correlate the transmission of diffuse solar radiation through a surface with incidence angle. As a result of the above discussion, it was assumed that a constant fraction of the incident diffuse solar radiation, equal to the transmittance at normal incidence indicated by the transmission characteristics for a particular surface, would be transmitted by the surface.

CHAPTER V

ANALYSIS AND COMPUTATION

5.1 Scope of Analysis

In order to fulfill the objectives established in Chapter I, the analysis of heat blance was restricted to the following cases only.

Three shapes of greenhouses were considered in the analysis:

i) Circular
ii) Gable
iii) Gothic Arch

These shapes were chosen because they are common in commercial use. The methods of the analysis could easily be extended to other shapes.

Two different sizes of greenhouses were considered:

i) 15.0 m x 10.0 m
ii) 200.0 m x 12.0 m

The sizes are referred to as small and large, respectively, in the text. Heat balance calculations were carried out for completely transparent greenhouses, and greenhouses with their north side insulated. Three levels of insulation were considered in the north side.

Two weather conditions, winter (December 21) and summer (June 21), were considered to allow evaluation of the model under extremes of weather and at minimum and maximum solar radiation. The required weather data used for the two conditions were for the year 1974 and were acquired from the Atmospheric Environment Service, Winnipeg (27). These data were, by no means, exceptional based on a record of the past 30 years and, therefore, were representative of the weather conditions under consideration.

The greenhouses were considered to be oriented either east-west or north-south. Further, either clear sky or completely overcast sky conditions were assumed. The greenhouses were assumed to be located at Winnipeg, Manitoba.

5.2 Description of Greenhouses for Analysis

(i) Circular Greenhouse

The basic shape of a circular greenhouse is illustrated in Fig. 5.2 An end section of this greenhouse is a semicircle with a diameter equal to the width of the greenhouse. The surface areas related to this shape of greenhouse are given in Table 5.1.

TABLE 5.1

Area of the Surfaces in Circular Greenhouse

Surface	Area, m^2	
	Small	Large
Ground surface	150.00	2400.00
One end wall area	39.27	56.55
One side wall area	117.75	1884.00

(ii) Gable Greenhouse

The basic shape of a gable greenhouse is illustrated in Fig. 5.1. The roof slope was arbitrarily chosen as 30 degrees. Surface areas were calculated based on ground bed dimensions and assumed height of vertical section of the side wall. Table 5.2 gives the calculated parameters that were used in the heat balance analysis.

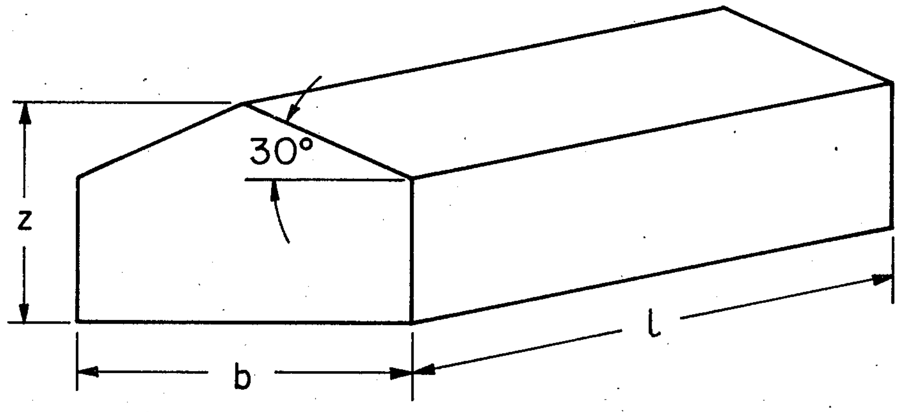

Fig. 5 . 1 Gable Greenhouse

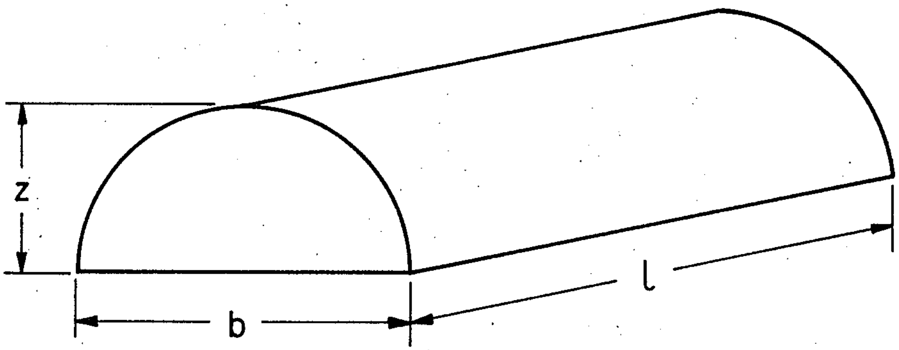

Fig. 5 . 2 Circular Greenhouse

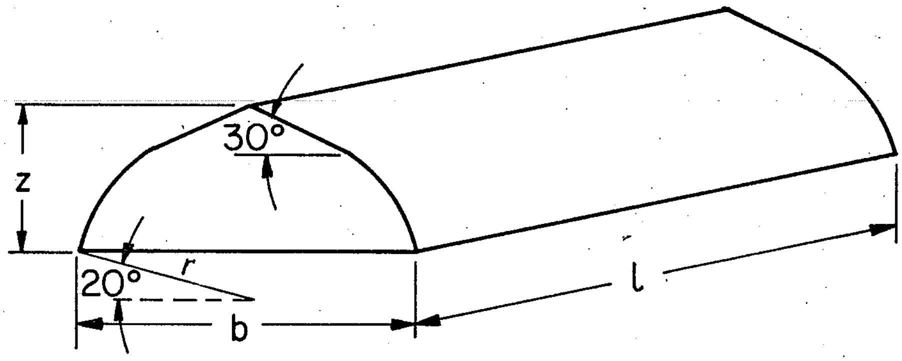

Fig. 5 . 3 Gothic Arch Greenhouse

TABLE 5.2

Area of the Surfaces in Gable Greenhouse

Surface	Area, m^2	
	Small*	Large**
Ground surface	150.00	2400.00
One end wall area	28.50	41.50
One side wall area: a) 30" inclined surface	86.55	1386.00
b) vertical surface	21.00	340.00

*height of the vertical section of the side wall was assumed as 1.4 m.

**height of the vertical section of the side wall was assumed as 1.7 m.

(iii) Gothic Arch Greenhouse

The basic shape of a gothic arch greenhouse is illustrated in Fig. 5.3 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 flat portion. The flat 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 arc of a circle with a radius equal to,

$$r = \frac{b/2}{\cos(20)} \tag{5.1}$$

The tangent at the bottom of the arc made a 70 degree angle with the horizontal. Table 5.3 gives the necessary parameters for the gothic arch greenhouse.

TABLE 5.3

Area of the Surfaces in Gothic Arch Greenhouse

Surface		Area, m^2 Small	Area, m^2 Large
Ground surface		150.00	2400.00
One end wall area		27.21	39.18
One side wall area:	(a) curved portion	55.72	892.00
	(b) flat portion	43.30	692.00

5.3 Greenhouse Construction and Assumptions for Analysis

The greenhouse construction was assumed to meet the following constraints:

i) foundation walls are of normal concrete and are uninsulated,

ii) structural members of 5 cm x 10 cm size spaced at 60 cm constitute the supporting structure of the greenhouse,

iii) transparent covering is composed of a layer of filon on the weather side and a layer of ultraviolet resistant polyethylene on the inner side of the greenhouse. Still air was held at atmospheric pressure in between the plastic layers,

iv) for opaque north walls, 1.0 cm (3/8") plywood sheets were used on both inside and outside surfaces, and

v) all insulation was fiberglass. Three levels of insulation are assumed in the analysis; R = 0.70, R = 1.41, and R = 2.11 $(m^2 \cdot K)/w$.

The following assumptions were made in the analysis:

i) the inside surface heat transfer coefficient is for zero air velocity,

ii) the outside surface heat transfer coefficient is for an air velocity of 12 kmph in summers and 24 kmph in winters,

iii) inside temperature of the greenhouse is 21 C throughout the year,

iv) thermal resistance of air spaces of 2.5 cm or greater in thickness is constant at 0.158 $(m^2 \cdot K)/w$ for all situations, and

v) solar absorptivity of a single skin plywood surface is 0.9.

5.4 Computation of the Individual Heat Balance Components

5.4.1 Solar Heat Gain

A computer program was written in WATFIV using the equations in Section 3.5 to compute incident solar radiation on a flat surface. A polynomial equation of solar transmittance versus incidence angle for the assumed greenhouse covering (Filon and ultraviolet resistant polyethylene) as determined experimentally, was included in the computer program. Solar heat gain through a transparent surface was calculated as:

$$q_u = I_T + I_A \cdot N_i \cdot A \tag{5.2}$$

The transmitted component for an insulated surface becomes zero and, therefore, solar heat gain for this surface is:

$$q_u = I \cdot \omega_u \cdot N_i \cdot A \tag{5.3}$$

To be used for curved surfaces, the above mentioned computer program was modified. A curved surface was assumed to consist of a number of equal arcs. The slope of the tangent to each arc at its midpoint was used to designate the inclination angle. Thus, the curved surface was approximated by a series of flat surfaces each inclined at the inclination angle of the corresponding arc tangent. If the equation of a curve is,

$$Y = F(X) \tag{5.4}$$

then the slope of the tangent at a specified point (XY) on this curve is found as:

$$\left.\frac{dY}{dX}\right|_{X=XY} = \tan(\theta) \tag{5.5}$$

The curves used in this investigation were segments of a circle, therefor, the equation of the curve:

$$X^2 + Y^2 = r^2 \tag{5.7}$$

and

$$\phi = \tan^{-1}(-X/\sqrt{r^2 - X^2}) \tag{5.8}$$

These equations were programmed along with some other necessary arguments and are given in Appendix 1.2. For the circles with 10-12 m diameter, used in this analysis, arcs of 10 to 15 degrees arc angle were assumed to be straight lines. This assumption resulted in reduced computer execution time.

5.4.2 Thermal Radiation Exchange

Equation 3.53 was used to determine the thermal radiation exchange between a greenhouse and the atmosphere,

$$Q_t = A_s \cdot \delta \cdot FS \cdot \psi_t[\varepsilon_s \cdot t_s^4 - \varepsilon_a \cdot t_a^4] \tag{3.53}$$

Shape factors were evaluated using the information given in section 3.6 (see Table 5.4). Thermal transmittance of the greenhouse plastic covering was approximated as (49):

TABLE 5.4

Shape Factors for Greenhouses with North Side Insulated

Shape of Greenhouse	Shape Factor, FS			
	E-W Orientation		N-S Orientation	
	Small Size	Large Size	Small Size	Large Size
Circular	0.582	0.508	0.918	0.992
Gable	0.560	0.506	0.940	0.994
Gothic arch	0.557	0.506	0.943	0.995

$$\psi_t = (\psi_{t\ \mathrm{Filon}}) \cdot (\psi_{t\ \mathrm{U.V.\ Poly.}}) \tag{5.9}$$

where $\psi_{t\ \mathrm{Filon}} = 0.12$ and $\psi_{t\ \mathrm{U.V.\ Poly}} = 0.708$ (51). Therefore,

$$\psi_t = 0.12 \times 0.708 = 0.085$$

A value of 0.95 was adopted for thermal emissivity of the greenhouse emitting surface, the ground bed in this analysis (38).

The average value for the effective atmospheric emissivity for a 24 hour period was calculated based on average atmospheric dew point temperature. This results in:

$\varepsilon_a = 0.836$ for June 21, 1974 under clear sky conditions

$\varepsilon_a = 0.746$ for December 21, 1974 under clear sky conditions

$\varepsilon_a = 1.0$ for all dates under overcast conditions

The daily value of t_a^4 was calculated by summing the fourth power of hourly absolute temperature values for that day,

$t_a^4 = 0.1742 \times 10^{12}\ K^4$ for June 21, 1974

$t_a^4 = 0.1096 \times 10^{12}\ K^4$ for December 21, 1974

Temperature of the emitting surface t_s was assumed equal to the temperature maintained inside the greenhouse itself, i.e. 294.16 K.

5.4.3 Heat Transfer With Greenhouse Ground Bed

Heat transfer with greenhouse ground bed consists of heat transfer through greenhouse foundation walls Q_x and vertical heat transfer with greenhouse bed Q_y.

To evaluate heat transfer through greenhouse foundation walls, a value of 1.42 w/(m•K) was adopted for the edge loss factor as in equation 3.60 (12). Perimeter P for small and large greenhouses were 50 m and 424 m, respectively. Hourly values of this heat transfer based on the hourly outside temperatures were summed to give daily heat transfer values.

The soil resistance to heat transfer was chosen as 1.76 $(m^2 \cdot K)/w$ in order to calculate the vertical heat transfer component (39). Deep soil temperature t_g was taken at 10 C year round based on the measurements by Shaw (40) under Winnipeg conditions. Ground bed areas were set at,

$$A_g = (15 - 2) \cdot (10 - 2) = 104 \text{ m}^2 \quad \text{for small greenhouses}$$

$$A_g = (200 - 2) \cdot (12 - 2) = 1980 \text{ m}^2 \quad \text{for large greenhouses.}$$

5.4.4 Heat Transfer from Greenhouse Covering Surface

Thermal resistance values for different wall constructions encountered in this investigation were calculated as shown in Appendix 3, and are listed in Table 5.5. The following values were assumed for the quantities used in the above mentioned equations (6).

k_w = 0.12 w/(m • K)

c_a = 6.31 $w/(m^2 \cdot K)$

h_o (winter) = 34.07 $w/(m^2 \cdot K)$

h_o (summer) = 22.71 $w/(m^2 \cdot K)$

h_i = 9.08 $w/(m^2 \cdot K)$

$$R_{ply} = 0.08\ (m^2 \cdot K)/w$$

$$R_{ins} = 0.22\ (m^2 \cdot K)/(w \cdot cm)$$

Thermal resistance of plastic films was neglected in calculating the overall thermal resistance of the greenhouse wall section. The three levels of fiberglass insulation assumed in insulating the north side of a greenhouse were 0.70, 1.41 and 2.11 $(m^2 \cdot K)/w$. For the convenience in reporting, the insulated wall sections have been referred to in the text by the amount of fiberglass insulation they have. An insulated wall section having 0.70 $(m^2 \cdot K)/w$ of fiberglass insulation, for example, has been referred as R = 0.70 section.

Thermal resistance of an air space depends mainly upon:

i) thickness of the air space,
ii) position of the air space (horizontal or sloping),
iii) direction of heat flow,
iv) mean temperature of the air space,
v) temperature gradient across the air space, and
vi) thermal emissivity of the enclosing surfaces.

Detailed qualitative descriptions of thermal resistance of air spaces are given by ASHRAE Handbook and Shirtliffe (6, 41). The tables listed in the ASHRAE Handbook (6) are only applicable for the specific cases described. This information is not sufficient to deal with the entire range of cases encountered in this analysis. Extrapolation or interpolation of the available values would involve a considerable amount of computation without much improvement in accuracy relative to the accuracy of other assumptions. It has been reported that the thermal resistance of air spaces, both reflective and nonreflective, becomes practically independent of thickness for air spaces thicker than 2.5 cm (41). Therefore, considering the magnitude of the thermal emissivity of the enclosing surfaces, the range of temperature difference, and the mean temperature of air spaces, a fixed value of 0.16 $(m^2 \cdot K)/w$ ($c_a = 6.31$ $w/m^2 \cdot K$) was assumed for all cases of air spaces thicker than 2.5 cm.

Heat transfer from greenhouse covering surfaces can then be computed by summing the heat transfer values for different wall sections of the covering surface calculated with the help of Equation (3.63).

$$Q_c = A_s(t_i - t_o)/R_s \tag{3.63}$$

TABLE 5.5

Summary of Resistance to Heat Transfer from Greenhouse Covering Surfaces

Climatic Condition	Type of Wall-section	Heat Transfer Resistance, $(m^2 \cdot K)/w$			
		Transparent	Insulated		
			R=0.70	R=1.41	R=2.11
Winter	End wall	0.31	1.19	1.85	2.44
	Side wall:				
	Circular	0.31	1.19	1.83	2.43
	Gable	0.31	1.18	1.84	2.43
	Gothic arch	0.31	1.19	1.84	2.43
Summer	End wall	0.32	1.20	1.86	2.45
	Side wall:				
	Circular	0.33	1.20	1.85	2.44
	Gable	0.33	1.19	1.85	2.45
	Gothic arch	0.33	1.20	1.86	2.45

5.5 Economic Considerations

The following approximate analysis has been performed to determine the economics of insulating the north side of a greenhouse with respect to its energy saving capacity. The period from October to April in any year was assumed to be the heating period and from May to September the ventilation period. A small size gothic arch greenhouse with the north side insulated (R = 0.70) was arbitrarily chosen for the analysis. The insulated area for the chosen greenhouse is 99.0 m^2.

On December 21, 1974:

Heating requirement for the insulated greenhouse	=	398.47 kwh
Heating requirement for the transparent greenhouse	=	187.82 kwh
Therefore, the heat saving due to insulated north side	=	210.65 kwh
Heat saving for unit insulated area	=	210.65/99.0
	=	2.12 kwh/m^2

If only 50 percent of this heat saving was achieved throughout the heating period, then,

Heat saving in one year = (2.12 x 212)/2 = 225.5 kwh/m^2

Similiarly, ventilation saving on June 21, 1974 = 953.24 - 791.62 = 161.62 kwh

Ventilation saving for a unit insulated area = 161.62/99.0 = 1.61 kwh/m^2

If only 50 percent of this ventilation saving was achieved throughout the ventilation period. Then,

yearly ventilation saving = (1.61 x 153)/2

= 124.9 kwh/m^2.

If the costs of heating and ventilation are assumed equal at 1.5¢/kwh, then yearly saving in heating and ventilation due to insulating the north side is,

$$\{(225.5 + 124.9) \times 1.5\}/100 = \$5.25/m^2$$

Additional cost of insulating 1.0 m^2 of north side may be distributed over the 10 years of its assumed life span. Considering fall 1975 prices of the building materials, it is found that almost no additional cost is involved in insulating the greenhouse surface instead of making it transparent. Thus, the $\$5.25/m^2$ of energy saving itself becomes the net saving due to an insulated north side.

CHAPTER VI

RESULTS AND DISCUSSION

6.1 Daily Heat Balance for Gothic Arch, Gable, and Circular Shapes of Greenhouses

Daily heat balances for the three shapes are summarized in Table 6.1. It is obvious that the three shapes differ with respect to their heat transfer properties. The gothic arch shape requires the least heat of the three shapes in all cases except when the small greenhouse is oriented north-south. In this case, the gothic arch shape requires the maximum heating of the three shapes. Relative heating requirements of the other two shapes are not consistent with a change in size or orientation. These variations are probably caused by an interaction of the following factors:

i) solar heat gain of a greenhouse, and

ii) amount of heat transfer from the covering surface of a greenhouse.

As the size of greenhouse increases, a gothic arch greenhouse oriented north-south becomes more efficient in admitting solar energy in comparison to the other two shapes in the same orientation. It is observed that a large size gothic arch greenhouse requires 15 to 25 percent less heating compared to gable and circular shapes. During summer conditions, a saving of three to ten percent in ventilation requirement is evident for the gothic arch shape compared to the other two shapes. Therefore, a properly sized gothic arch greenhouse can be expected to give better energy economy than a gable or a circular greenhouse would give. Moreover, surface area needed to cover a given ground bed area is minimum for a gothic arch greenhouse (proportion of surface area for gothic arch, gable, and circular greenhouse are 1:1.09:1.19), thereby reducing the material cost to construct a gothic arch greenhouse.

TABLE 6.1

Daily Heat Balance for Transparent Greenhouses under Clear Sky Condition

Size	Shape	Daily Heat Balance, kwh			
		December 21, 1974		June 21, 1974	
		east-west	north-south	east-west	north-south
Small	Gothic Arch	398.47	585.44	-953.24	-1,061.06
	Gable	463.33	548.59	-1,023.93	-1,097.45
	Circular	479.10	583.55	-1,064.07	-1,194.72
Large	Gothic Arch	3,249.30	6,130.14	-13,382.03	-16,561.01
	Gable	4,212.30	6,911.91	-14,431.72	-17,144.88
	Circular	3,881.35	7,375.86	-14,151.62	-18,340.88

6.2 Computation of Heat Transfer Resistances

In evaluating the rate of heat transfer from the curved surface of gothic arch and circular greenhouses, computation of thermal resistance for those sections was more involved than for flat sections. Considering the accuracy of other assumptions in this analysis, it was considered useful to determine the difference in accuracy that would result if the formulae for flat sections were used in evaluating the thermal resistance of curved sections. Besides, would there be a significant difference if the structural frame work was excluded from the calculation of thermal resistance? It was noted previously that the structural frame work in the conventional plastic covered greenhouses constitutes about seven percent of the total greenhouse covering surface area. Table 6.2 contains the results of thermal resistance calculations for flat and curved surfaces of a gothic arch greenhouse with and without the structural frame work considered.

Comparing the values of heat transfer resistance for end surface (flat) and side surface (flat and curved) in Table 6.2, it can be observed that both the surfaces have comparable resistance values. Deviation of no more than 0.5 percent is apparent. Probably with a sufficiently large radius of curvature, a curved surface behaves like a flat surface. This suggests that the heat transfer resistances for curved surfaces could be computed without any significant error even by ignoring the effect of curvature.

The percentage error column in Table 6.2 indicates the effect of neglecting the structural frame work in the calculation of thermal resistance. A minimum of 1.1 percent error is observed in this comparison, but the magnitude of the error is a direct function of the difference in the thermal resistance of the structural frame components and the insulating medium. Therefore, it appears that if the thermal resistance of the structural frame is comparable to the thermal resistance of the insulating medium between the frames, the structural frame work could be excluded from the analysis without much error. If there is a large difference between these resistance values, the structural frame work should be included.

TABLE 6.2

Heat Transfer Resistances (R) for various sections of Gothic Arch Greenhouse Covering Surface

Climatic Conditions	Wall-section Description	Heat Transfer Resistances $(m^2 \cdot K)/w$ Approximate*	Exact**	Percent*** Error
Winter	End wall: transparent	0.30	0.31	+3.2
	Insulated,			
	R = 0.70	1.17	1.19	+1.7
	R = 1.41	1.87	1.85	-1.1
	R = 2.11	2.57	2.44	-5.3
	Side wall: transparent	0.30	0.31	+3.2
	Insulated,			
	R = 0.70	1.17	1.19	+1.7
	R - 1.41	1.87	1.84	-1.6
	R = 2.11	2.58	2.43	-6.2
Summer	End wall: transparent	0.31	0.32	+3.1
	Insulated,			
	R = 0.70	1.18	1.20	+1.7
	R - 1.41	1.89	1.86	-1.6
	R = 2.11	2.59	2.45	-5.7
	Side wall: transparent	0.31	0.33	+6.1
	Insulated,			
	R = 0.70	1.18	1.20	+1.7
	R = 1.41	1.89	1.86	-1.6
	R - 2.11	2.59	2.45	-5.7

*values calculated by neglecting the structural frame work

**values calculated with the help of the equations given in Appendix 3

***percent error = 100 (exact-approximate)/exact

6.3 Contribution of Solar Energy from the North-facing Surface in Greenhouses

It can be seen, from Table 6.3, that at 49.25 degree latitute (Winnipeg) the transparent north side in an east-west oriented greenhouse contributes very little to the greenhouse solar heat gain during winters (almost three percent in December). However, the contribution from such a surface increases to as much as 40 percent during summers. The contribution in a north-south oriented greenhouse remains below three percent throughout the year. During winter, the transparent north side contributes little to the total solar heat given 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. Also, during summer, the large contribution of solar heat through the north side may be regarded as undesirable because it adds to the ventilation requirement of the greenhouse. Based on these conditions, an opaque north side in a greenhouse could result in a reduction in the energy intensiveness of the structure.

6.4 Hourly Heat Balance for Greenhouses With Transparent and Insulated North Sides

Gothic arch greenhouses were found to give maximum energy savings of all greenhouse shapes analysed in Section 6.1, therefore, hourly heat balances were computed for only gothic arch greenhouses. Fig. 6.1 shows daily profiles of hourly heat balance for both transparent and north side insulated greenhouse of large size. These profiles were plotted for December 21, 1974 under assumed clear and completely overcast sky conditions and east-west orientation. One of the observations from these profiles is that a reduction of about 170 kwh in the required

TABLE 6.3

Contribution of Solar Energy from the Transparent North-facing Surface in Greenhouses

Size	Shape	Percent*			
		December 21		June 21	
		East-West	North-South	East-West	North-South
Small					
	Gothic Arch	2.8	1.0	31.3	2.0
	Gable	2.7	0.7	33.7	2.0
	Circular	2.5	0.9	30.3	2.6
Large					
	Gothic Arch	3.1	0.1	36.7	0.2
	Gable	3.0	0.1	39.3	0.2
	Circular	2.8	0.1	37.4	0.2

*Percent = 100 (solar heat gain through the north facing surface/solar heat gain for the whole greenhouse).

capacity of the heating system for a greenhouse can be achieved by insulating its north side. An increase of 150 kwh in the ventilation requirement due to insulating the north side is also evident from the profile for clear sky conditions. This apparent increased ventilation requirement is mostly taken care of by heat storage capacity of the greenhouse ground bed. The advantage of insulating the north side of a greenhouse can be well realized by observing the profiles under overcast sky conditions.

Daily profiles in Fig. 6.2 represent all the cases of Fig. 6.1 under summer conditions (June 21, 1974). The peak ventilation requirement was reduced by about 250 kwh in greenhouses with their north side insulated under both clear and overcast sky conditions. This reduction is achieved because the solar heat gain through the north side is practically eliminated. Therefore, the capacity of the ventilation system in a greenhouse can be reduced by insulating its north facing surface.

Hourly heat balances during hight hours are equal for both east-west and north-south orientations of transparent greenhouses, Fig. 6.3, but the difference between the heat balances becomes pronounced during sunshine hours especially under clear sky conditions. During winter, the increased admission of solar energy by an east-west oriented greenhouse is a desirable property in the sense that more sunlight is assured to the plants. The apparent increase in ventilation requirement of an east-west oriented greenhouse is taken care of, as explained earlier, by heat storage capacity of the greenhouse ground bed. The difference of orientation becomes distinct under overcast sky conditions where an east-west oriented greenhouse requires much less heating as compared to

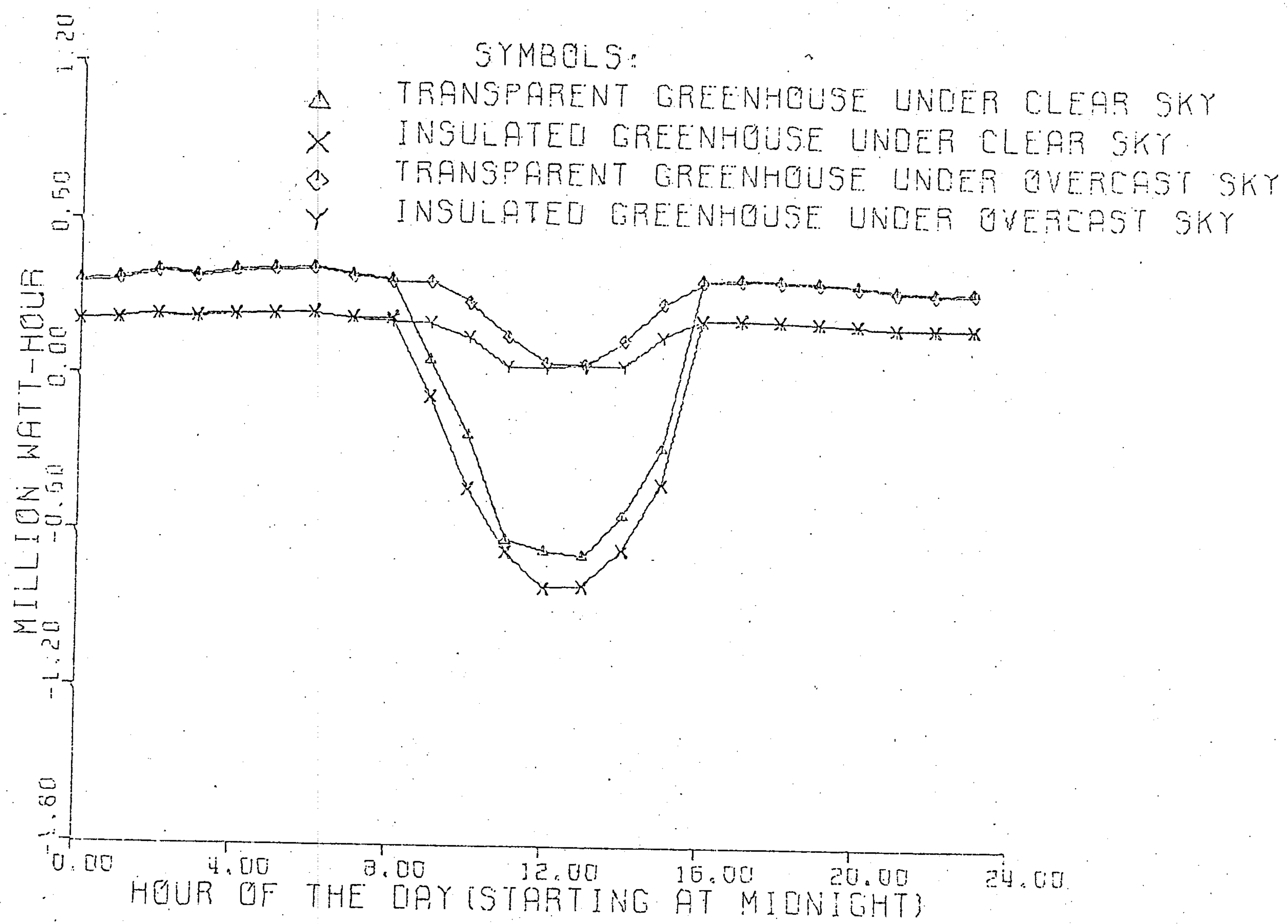

Fig. 6.1 Profiles of Hourly Heat Balance for East-west Oriented Large Gothic Arch Greenhouses on December 21, 1974

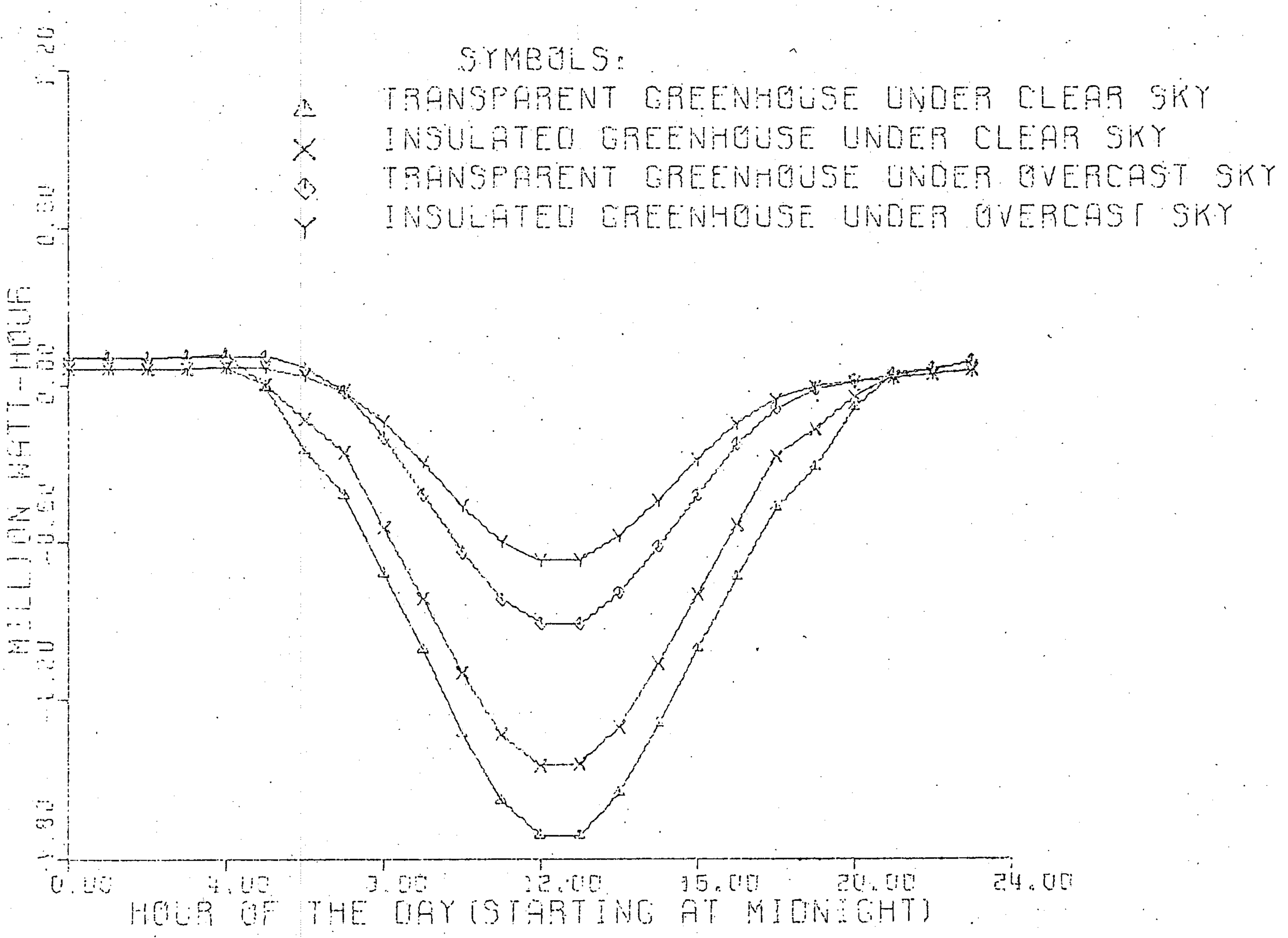

Fig. 6.2 Profiles of Hourly Heat Balance for East-west Oriented Large Gothic Arch Greenhouses on June 21, 1974

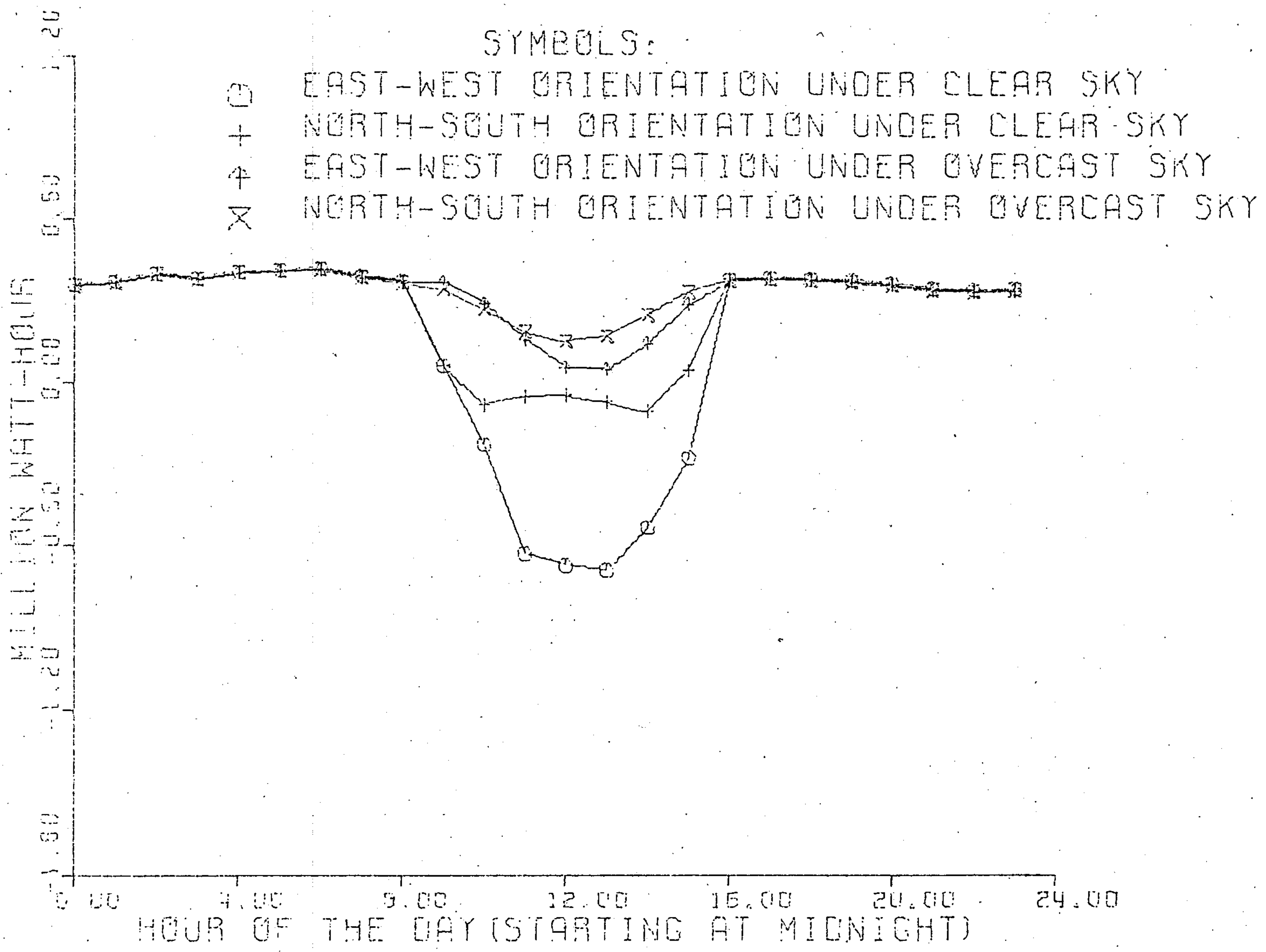

Fig. 6.3 Profiles of Hourly Heat Balance for Both East-west and North-south Oriented Large Gothic Arch Greenhouses on December 21, 1974

a north-south oriented one. The importance of an east-west oriented greenhouse in relation to its capacity to admit solar energy can still better be realised under much lower temperatures which occur during the later part of winter. Orientation of a greenhouse in relation to its heat balance is further discussed in the next section.

6.5 Daily Heat Balance for East-west and North-south Orientations of Greenhouse

Orientation of a greenhouse affects its heat balance, primarily, by way of altering the structure's ability to admit solar energy. The difference in the solar energy admitting qualities of north-south and east-west oriented greenhouses is clear from Table 6.4. At 49.25 degrees north latitude (Winnipeg) in winter a north-south oriented greenhouse admits less solar energy than an east-west oriented greenhouse does by a minimum of 20 percent (small gable). In summers, a north-south oriented greenhouse admits more solar energy than an east-west oriented greenhouse by at least seven percent (small gable).

Daily heat balances are summarized in Tables 6.5 and 6.6 for various cases in order to compare east-west and north-south orientations. Two observations can be made regarding the daily heat balance figures in Tables 6.5 and 6.6.

i) An east-west oriented greenhouse requires less heating during winter and less ventilation during summer than a north-south oriented greenhouse does. This difference could be specifically visualized with the help of daily profiles of hourly heat balance similar to those in Figure 6.3.

ii) While the effects of insulating the north side of a greenhouse

TABLE 6.4

Daily Solar Heat Gain for Transparent
Greenhouses under Clear Sky Condition

Size	Shape	Daily Solar Heat Gain, kwh			
		December 21		June 21	
		East-West	North-South	East-West	North-South
Small					
	Gothic Arch	-402.31	-215.30	-1,036.63	-1,144.45
	Gable	-395.05	-309.78	-1,111.02	-1,184.54
	Circular	-482.05	-377.60	-1,158.47	-1,289.12
Large					
	Gothic Arch	-5,815.27	-2.934.44	-14,151.55	-17,330.53
	Gable	-5,693.25	-2,993.62	-15,256.91	-17,970.07
	Circular	-6,817.89	-3,323.38	-15,033.41	-19,222.67

TABLE 6.5

Daily Heat Balance for Greenhouses on December 21, 1974 under Clear Sky Condition

Size	Shape	Daily Heat Balance, kwh Transparent East-West	 Transparent North-South	 North side insulated (R=2.11) East-West	 North side insulated (R=2.11) North-South
Small					
	Gothic Arch	398.47	585.49	152.93	519.92
	Gable	463.33	548.59	195.19	480.54
	Circular	479.10	583.55	191.15	489.78
Large					
	Gothic Arch	3,249.31	6,130.14	-372.33	6,036.22
	Gable	4,212.27	6,911.91	204.04	6,785.30
	Circular	3,881.35	7,375.86	-441.64	7,240.30

TABLE 6.6

Daily Heat Balance for Greenhouses on June 21, 1974 under Clear Sky Condition

Size	Shape	Daily Heat Balance, kwh			
		Transparent		North side insulated (R=2.11)	
		East-West	North-South	East-West	North-South
Small	Gothic Arch	- 953.24	-1,061.06	-793.57	-1,053.90
	Gable	- 1,023.93	-1,097.45	-832.03	-1,083.71
	Circular	- 1,064.07	-1,194.72	-891.02	-1,141.38
Large	Gothic Arch	-13,382.03	-16,561.01	-10,742.16	-16.550.80
	Gable	-14,431.72	-17,144.88	-11,272.42	-17,134.05
	Circular	-14,151.62	-18,340.88	-11,302.04	-18,326.14

in reducing the structure's heating and ventilation requirements are prominent in east-west orientation, the effects are relatively small in north-south orientation.

The latter observation can be attributed to the difference in greenhouse surface areas being insulated in the two orientations. The advantages of an east-west oriented greenhouse increase over a north-south oriented one with an increase in the size of greenhouses. It was not possible to project quantitative differences in heating and ventilation requirements caused by orientation from daily heat balance figures because both heating and ventilation were required on the days under consideration. Heating and ventilation cannot be separated from the daily heat balance without additional analysis.

A negative daily heat balance for large size gothic arch and circular greenhouses during winter (Table 6.5), indicating ventilation, may be misleading. These cases can be explained with the help of daily profiles of hourly heat balance. A negative number during winter express the excessive solar heat gain of the structure during the day which, if it could be stored, could be used during night hours to heat the structure. In practice, this excess solar heat gain is removed by ventilation.

6.6 Daily Heat Balance for Greenhouses with Different Levels of Insulation in their North facing Surface

Three levels of fibre glass insulation were assumed to observe the effect of increasing the thermal resistance of the north side in a greenhouse on the structure's heat balance. The three levels of insulation were R = 0.70, 1.41, and 2.11 $(m^2 \cdot K)/w$. The results are compared in Table 6.7.

TABLE 6.7

Daily Heat Balance for Gothic Arch Greenhouses With Different Levels of Insulation in their North Side

Date	Orientation	Size	Daily Heat Balance, kwh			
			Transparent	North Side Insulated		
				R = 0.70	R = 1.41	R = 2.11
Dec. 21, 1974	East-West	Small	398.47	187.82	163.67	152.93
		Large	3,249.31	185.85	- 200.56	- 372.33
	North-South	Small	585.49	530.15	523.34	519.92
		Large	6,130.14	6,050.08	6,040.43	6,036.22
June 21, 1974	East-West	Small	- 953.24	- 791.62	- 792.82	- 793.57
		Large	-13,382.03	-10,702.39	-10,730.05	-10,742.16
	North-South	Small	- 1,061.06	- 1,053.22	- 1,053.69	- 1,053.90
		Large	-16,561.01	-16,549.82	-16,550.50	-16,550.80

The effect of increasing insulation level in the north-side of a greenhouse appears to be an asymptotic decrease in the heating requirement of the greenhouse during winter. Looking at the December 21 daily heat balances for an east-west oriented small gothic arch greenhouse, it can be seen that first application of insulation (R = 0.70) reduced the heating requirement by almost 50 percent. Additional applications reduced the heating requirement by 15 and six percent, respectively. In summer, the effect of insulating the north side of a greenhouse is to reduce its total daily ventilation requirement. As the level of insulation is increased, the ventilation requirement also increases. This increase in ventilation requirement due to increased insulation also appears to be asymptotic. For the same east-west oriented small gothic arch greenhouse, on June 21, 1974, increase in ventilation, when insulation is increased from R = 0.70 to R = 1.41 is 0.15 percent but for an increase in insulation from R = 1.41 to R = 2.11 the consequential increase in ventilation is only 0.11 percent. The observed asymptotic nature of the effects due to increased levels of insulation are predicted by the discussion on economic thickness of insulation in the ASHRAE Handbook (6).

It would appear from the above discussion that there exists an optimum level of insulation, considering the cost of insulation, which should be provided in the north-side of a greenhouse to achieve optimum reductions in heating and ventilation requirements. No attempt was made to predict this optimum insulation level.

6.7 Daily Heat Balance for Greenhouses in Winter and Summer Conditions

Effects of the insulated north side in a greenhouse on its daily heat balance can be observed by considering Tables 6.5 and 6.6. In winter conditions (Table 6.5), the tendency of the insulated north side in a greenhouse is to reduce heating requirement of the structure over a transparent greenhouse. Reductions in the heating requirement are about 50 percent and five percent for east-west oriented and north-south oriented greenhouses, respectively. Ventilation requirements are reduced, during summers, by the insulated north side in a greenhouse. The reductions are 15 to 30 percent for east-west oriented greenhouses and only about one percent in the case of north-south oriented ones.

Clearly, both the above mentioned effects during winters and summers are desirable. Therefore, it can be projected that by insulating the north side in a greenhouse, energy requirements of the structure throughout a year can be reduced.

6.8 Economic Feasibility of Insulating the North-facing Surface in Greenhouses

Considering the fall 1975 prices of building materials, no appreciable additional cost was found to be required in insulating the greenhouse covering surface instead of making it transparent (Section 5.5) Therefore, the amount of energy saved by virtue of insulating the north side in a greenhouse will be the net saving. Based on the approximate analysis carried out in Section 5.5, a yearly saving of $5.25 per square metre of the insulated north side was obtained.

CHAPTER VII

CONCLUSIONS

The following conclusions can be drawn for plastic covered greenhouses under Manitoba climatic conditions:

[i] east-west orientation of a greenhouse is advantageous over north-south orientation,

[ii] a gothic arch shaped greenhouse is more efficient in maintaining desirable inside thermal environment as compared to a circular or a gable shaped greenhouse,

[iii] little solar radiation is incident on the north side of a greenhouse at southern Manitoba latitudes during winter,

[iv] a significant reduction in heating requirement of a greenhouse is obtained during winter by insulating its north side. The ventilation requirement is also reduced considerably during summer,

[v] insulating the north side in a greenhouse oriented north-south results in little effect on the heating and ventilation requirements,

[vi] there exists an economic level of insulation that should be provided in insulating the north side of a greenhouse to obtain optimum benefits, and

[vii] insulating the north side in an east-west oriented greenhouse appears to be economically feasible for the conditions analysed.

CHAPTER VIII

RECOMMENDATIONS FOR FURTHER STUDY

[i] The resultant illumination levels in a north side insulated greenhouse with a reflective coating on its inner side should be compared with the illumination levels in a completely transparent greenhouse;

[ii] Additional studies should be undertaken to determine the most suitable greenhouse orientation on the basis of local climatic conditions.

[iii] The proposition of insulating the north side of a greenhouse reported in this investigation should be experimentally verified.

[iv] Use of carbon dioxide in place of air between the two transparent covering layers to modify thermal environment in a greenhouse should be investigated.

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APPENDIX 1

Computer Programs

1.1 To Compute Solar Radiation for Flat Surfaces

```
$JOB  WATFIV   PITAM CHANDRA
C        MAIN LINE PROGRAM
       IMPLICIT REAL (I,K)                                          SR  0001
C SUFFICS NUMERAL CODE:
C 1      CLEAR SKY CONDITION
C 2      CLOUDY SKY CONDITION
C 3      DIRECT COMPONENT OF SOLAR RADIATION
C 4      TRANSMITTED DIRECT SOLAR RADIATION
C 5      TRANSMITTED DIFFUSE SOLAR RADIATION
C 6      DIFFUSE COMPONENT OF SOLAR RADIATION
C 7      ABSORBED DIRECT SOLAR RADIATION
C 8      ABSORBED DIFFUSE SOLAR RADIATION
       INTEGER DAY,MONTH,YEAR                                       SR  0011
C DAY,MONTH AND YEAR ARE TO REPRESENT DATE IN NUMERALS
       REAL I(800),I3(800),I4(800),I5(800),I6(800)                  SR  0021
C I      SOLAR RADIATION ON A SURFACE FOR ONE TIME INCREMENT
       REAL A(800),B(800),C(800),D(800)                             SR  0031
C A      SOLAR AZIMUTH ANGLES AT SPECIFIED TIME INTERVALS
C B      SOLAR ALTITUDE ANGLES AT SPECIFIED TIME INTERVALS
C C      HOURLY SOLAR AZIMUTH ANGLES
C D      HOURLY SOLAR ALTITUDE ANGLES
       REAL HTOT(800),HTOT3(800),HTOT4(800),HTOT5(800),HTOT6(800)   SR  0041
C HTOT AND DTOT ARE HOURLY AND DAILY TOTALS OF SOLAR RADIATION
       PI= 3.141593                                                 SR  0051
       READ, NJ                                                     SR  0061
       DO 499 JD=1,NJ                                               SR  0071
       READ,DAY,MONTH,YEAR,IL,KS                                    SR  0081
C IL     LATITUDE OF THE PLACE
C KS     PERCENT OF POSSIBLE SUNSHINE FOR  THE DAY
       CALL DAYA(DAY,MONTH,YEAR,NTOT,DT)                            SR  0091
       DA=ARSIN(SIN(23 .45*PI/180.)*COS(2.*PI*DT))                  SR  0101
C DA     DECLINATION ANGLE OF THE SUN FOR THE DAY
       CA   =   DA*180.0/PI                                         SR  0111
       R= 1353.0*(1.0+0.0335*COS(2.0*PI*NTOT/365.0))                SR  0121
       IO = 1160.0*(1.0+0.033*COS(2.0*PI*NTOT/365.0))**2            SR  0131
C R&IO   ACTUAL & APPARENT EXTRATERRESTRIAL SOLAR RADIATION INTENSITIES
       TR=ARCOS((SIN(IL)*SIN(DA))/(COS(IL)*COS(DA)))*(12./PI)       SR  0141
C TR     LOCAL SOLAR TIME OF SUNRISE FOR THE  DAY
       IJ=0.37+0.622*KS ; KT=0.28+0.45*KS ; KC=1.6*(1.-KT)          SR  0151
C IJ     CLOUDLESS RADIATION INDEX FOR THE DAY
C KT     DAILY CLOUDINESS INDEX
C KC     CLOUD COVER COEFFICIENT
       IF(KC.GT.1.0) KC= 1.0                                        SR  0161
       IF(IJ.GT.0.8)GOTO  101                                       SR  0171
       KD1= 1.415*IJ- 0.384                                         SR  0181
C KD     DAILY DIRECT SOLAR RADIATION/DAILY DIRECT EXTRATERR. SOLAR RAD.
       GOTO  102                                                    SR  0191
101    KD1= 0.75                                                    SR  0201
102    IF(KT.LT.0.6) GOTO  103                                      SR  0211
       KD2= 1.492 *KT- 0.492                                        SR  0221
       GOTO  104                                                    SR  0231
103    KD2= EXP(0.935*KT*KT)- 1.0                                   SR  0241
104   0HO= 24./PI*R*(COS(IL)*COS(DA)*SIN(PI*TR/12.)                 SR  0251
     1 +(PI-PI*TR/12.)*SIN(IL)*SIN(DA))                             SR  0261
C HO     DAILY TOTAL EXTRATERRESTRIAL SOLAR RADIATION
       IDHA1=KD1*HO/(2.*(12.-TR)) ; IDHA2=KD2*HO/(2.*(12.-TR))      SR  0271
C IDHA   AVERAGE DIRECT SOLAR RADIATION ON HORIZONTAL SURFACE
       BTM= PI/2. - IL+ DA                                          SR  0281
C BTM    MAXIMUM SOLAR ALTITUDE ANGLE FOR THE DAY
       ECO1=-SIN(BTM)*ALOG(IDHA1/(0.6*IO*SIN(BTM)))                 SR  0291
C ECO    ATMOSPHERIC EXTINCTION COEFFICIENT
       ECO2=-SIN(BTM)*ALOG(IDHA2/(0.6*IO*SIN(BTM)))                 SR  0301
       ILT= IL*180.0/PI                                             SR  0311
       PRINT5                                                       SR  0321
5      FORMAT('1',38X,'SOLAR RADIATION FOR A FLAT SURFACE')         SR  0331
       PRINT15, ILT                                                 SR  0341
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```
      15    FORMAT('0',45X,'LATITUDE',5X,F6.2)                                  SR  0351
            PRINT 25                                                            SR  0361
      25    FORMAT(20X,'DAY',10X,'MONTH',10X,'YEAR',10X,'R',10X,'IO',10X,'KS')SR  0371
            PRINT 35,DAY,MONTH,YEAR,R,IO,KS                                     SR  0381
      35    FORMAT(20X,I2,12X,I2,12X,I4,7X,F7.2,5X,F7.2,7X,F4.2 )               SR  0391
            PRINT45,CA,TR                                                       SR  0401
      45    FORMAT(31X,'DECLINATION',4X,F6.2,5X,'SUN RISE',4X,F5.2,'A.M.')      SR  0411
            N = TR                                                              SR  0421
            HB  =  TR*PI/12.0                                                   SR  0431
            BO=ARSIN(SIN(IL)*SIN(DA)-COS(IL)*COS(DA)*COS(HB))                   SR  0441
            AO=ARSIN((COS(DA)*SIN(-HB))/COS(BO))                                SR  0451
     C HB,BO AND AO ARE VALUES OF HA,B AND A AT SUNRISE
            NL=10*(TR+0.1)  ;  NM=10*(24.0-TR)                                  SR  0461
            READ, NK                                                            SR  0471
            DO 299 JT= 1,NK                                                     SR  0481
            READ, PH,AL                                                         SR  0491
     C PH     INCLINATION ANGLE OF A SURFACE
     C AL     WALL AZIMUTH OF A SURFACE
            TILT=PH*180.0/PI ; WAAZ=AL*180.0/PI                                 SR  0501
            PRINT 55, TILT, WAAZ                                                SR  0511
      55    FORMAT('-',31X,'SURFACE TILT',4X,F5.2,4X,'WALL AZIMUTH',4X,F6.2 )  SR  0521
            DO 99 J= NL,NM                                                      SR  0531
            T = J/10.0                                                          SR  0541
     C T      LOCAL SOLAR TIME
            HA = PI*T/12.                                                       SR  0551
     C HA     SOLAR HOUR ANGLE
            BT=ARSIN(SIN(IL)*SIN(DA)-COS(IL)*COS(DA)*COS(HA))                   SR  0561
            B(J) = BT*180.0/PI                                                  SR  0571
            AX=ARSIN((COS(DA)*SIN(-HA))/COS(BT))                                SR  0581
            IF(AX.LT.0.0)  GOTO  16                                             SR  0591
            IF(AX.GT.AO)  GOTO  26                                              SR  0601
            AZ  =  PI-AX                                                        SR  0611
            GOTO  36                                                            SR  0621
      26    AZ  =  AX                                                           SR  0631
            GOTO  36                                                            SR  0641
      16    IF(AX.GT.AO)  GOTO  26                                              SR  0651
            AZ  =- PI-AX                                                        SR  0661
      36     AO  =  AX                                                          SR  0671
            A(J) = AZ*180.0/PI                                                  SR  0681
            GA= ABS ( AZ- AL)                                                   SR  0691
     C GA     WALL - SOLAR AZIMUTH ANGLE
            TH=ARCOS(COS(BT)*COS(GA)*SIN(PH)+SIN(BT)*COS(PH))                   SR  0701
     C TH     INCIDENCE ANGLE OF THE SUN'S RAYS ON A SURFACE
            IF(ECO1/SIN(BT).GT.140.0) GOTO 121                                  SR  0711
            IDN1= IO*EXP(-ECO1/SIN(BT))                                         SR  0721
     C IDN    NORMAL SOLAR RADIATION INTENSITY
            GOTO 124                                                            SR  0731
      121   IDN1= 0.00                                                          SR  0741
      124   IF(ECO2/SIN(BT).GT.140.0) GOTO 123                                  SR  0751
            IDN2= IO*EXP(-ECO2/SIN(BT))                                         SR  0761
            GOTO 122                                                            SR  0771
      123   IDN2= 0.00                                                          SR  0781
      122   ID1=IDN1*COS(TH)  ; ID2=IDN2*COS(TH)                                SR  0791
     C ID     SOLAR RADIATION INTENSITY ON A SURFACE
            IT3 = (1.0-KC)*ID1 + KC*ID2                                         SR  0801
     C IT     TOTAL SOLAR RADIATION INTENSITY ON A SURFACE
            IF(IT3.LT.0.0)  IT3=0.0                                             SR  0811
            I3(J) = IT3/10.0                                                    SR  0821
            TRAN=TRA(0.0)                                                       SR  0831
     C TRAN  SOLAR TRANSMITTANCE AT NORMAL INCIDENCE
            ABTN=TRAN*(1.-TRAN)/(1.+TRAN)                                       SR  0841
     C ABTN  SOLAR ABSORPTANCE AT NORMAL INCIDENCE
            IT4=(1.-KC)*IDN1*TRA(TH)+KC*IDN2*TRA(TH)                            SR  0851
            IF(IT4.LT.0.0)  IT4=0.0                                             SR  0861
            ABT=TRA(TH)*(1.-TRA(TH))/(1.+TRA(TH))                               SR  0871
     C ABT   SOLAR ABSORPTANCE AT A PARTICULAR INCIDENCE ANGLE
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          IT7=(1.-KC)*IDN1*ABT+KC*IDN2*ABT                            SR  0881
          TD1=IDN1/R ; TD2=IDN2/R                                     SR  0891
C TD        ATMOSPHERIC TRANSMISSION COEFFICIENT FOR DIRECT SOLAR RADIATION
          TSD1=0.2710-0.2939*TD1                                      SR  0901
C TSD       ATMOSPHERIC TRANSMISSION COEFFICIENT FOR DIFFUSE SOLAR RADIATION
          IF(TD2.LT.0.4)GOTO107                                       SR  0911
          TSD2=0.33*(1.-TD2)                                          SR  0921
          GOTO108                                                     SR  0931
   107    TSD2=SQRT(1.07*ALOG(TD2+1.))-TD2                            SR  0941
   108    IF(TD1.EQ.0.0)  GOTO  109                                   SR  0951
          DIFCO1 = TSD1/TD1*SIN(BT)                                   SR  0961
C DIFCO RATIO OF INSTANTANEOUS DIFFUSE SOLAR RADIATION ON HORIZONTAL-
C           SURFACE TO THE INSTANTANEOUS DIRECT NORMAL SOLAR RADIATION
          IF(DIFCO1.LT.0.0) DIFCO1 = 0.0                              SR  0971
          GOTO 112                                                    SR  0981
   109    DIFCO1 = 0.0                                                SR  0991
   112    IF(TD2.EQ.0.0)  GOTO  110                                   SR  1001
          DIFCO2 = TSD2/TD2*SIN(BT)                                   SR  1011
          IF(DIFCO2.LT.0.0) DIFCO2 = 0.0                              SR  1021
          GOTO 114                                                    SR  1031
   110    DIFCO2  =  0.0                                              SR  1041
   114    ISDH1=DIFCO1*IDN1 ; ISDH2=DIFCO2*IDN2                       SR  1051
C ISDH  INTENSITY OF DIFFUSE SOLAR RADIATION ON A HORIZONTAL SURFACE
          ISD1  =   (0.43*HM(PH)+0.57*SM(TH))*ISDH1                   SR  1061
C ISD     DIFFUSE SOLAR RADIATION ON A SURFACE
          ISD2  =   (0.43*HM(PH)+0.57*SM(TH))*ISDH2                   SR  1071
          IT6 = (1.0-KC)*ISD1 + KC*ISD2                               SR  1081
          I6(J) = IT6/10.0                                            SR  1091
          IT = IT3 + IT6                                              SR  1101
          I(J) = IT/10.0                                              SR  1111
          IT5 = IT6*TRAN                                              SR  1121
          IT8 = IT6*ABTN                                              SR  1131
          I4(J)=(IT4+IT5)/10.00                                       SR  1141
          I5(J)=(IT7+IT8)/10.00                                       SR  1151
   99     CONTINUE                                                    SR  1161
          JI=1                                                        SR  1171
          SUM=0.0 ; SUM3=0.0 ; SUM4=0.0 ; SUM5=0.0 ; SUM6=0.0         SR  1181
          DTOT=0.00 ; DTOT4=0.00 ; DTOT5=0.00                         SR  1191
          DO 399 JK = NL,NM                                           SR  1201
          SUM=SUM+I(JK) ; SUM3=SUM3+I3(JK) ; SUM6=SUM6+I6(JK)         SR  1211
          SUM4=SUM4+I4(JK) ; SUM5=SUM5+I5(JK)                         SR  1221
          IF((JK/10)*10.EQ.JK)  GOTO 398                              SR  1231
          IF(JK.EQ.NM)  GOTO 397                                      SR  1241
          GOTO  399                                                   SR  1251
   397    HTOT(JI)=SUM ; HTOT3(JI)=SUM3 ; HTOT4(JI)=SUM4 ; HTOT5(JI)=SUM5  SR  1261
          HTOT6(JI)=SUM6 ; C(JI)=A(JK) ; D(JI)=B(JK)                  SR  1271
          DTOT=DTOT+HTOT(JI) ; DTOT4=DTOT4+HTOT4(JI) ; DTOT5=DTOT5+HTOT5(JI) SR  1281
          GOTO  399                                                   SR  1291
   398    HTOT(JI)=SUM ; HTOT3(JI)=SUM3 ; HTOT4(JI)=SUM4 ; HTOT5(JI)=SUM5  SR  1301
          HTOT6(JI)=SUM6 ; C(JI)=A(JK) ; D(JI)=B(JK)                  SR  1311
          DTOT=DTOT+HTOT(JI) ; DTOT4=DTOT4+HTOT4(JI) ; DTOT5=DTOT5+HTOT5(JI) SR  1321
          SUM=0.0 ; SUM3=0.0 ; SUM4=0.0 ; SUM5=0.0 ; SUM6=0.0         SR  1331
          JI =JI + 1                                                  SR  1341
   399    CONTINUE                                                    SR  1351
          IF(JI/2*2.EQ.JI)  JI=JI-1                                   SR  1361
          PRINT65                                                     SR  1371
   65     FORMAT(9X,'NO.',1X,'SOL.TIME',2X,'SOL.ALT.', 2X,'SOL.AZIM.',  SR  1381
         1 3X,'DIRECT', 5X,'DIFFUSE', 5X,'TOTAL',6X,'TRANS.',6X,'ABSOR.')  SR  1391
          DO 199  JC = 1,JI                                           SR  1401
          T = N+JC                                                    SR  1411
          PRINT75,JC,T,D(JC),C(JC),HTOT3(JC),HTOT6(JC),HTOT(JC),      SR  1421
         1HTOT4(JC),HTOT5(JC)                                         SR  1431
   75     FORMAT('0',8X,I2,2X,F5.2,4X,F6.2,4X,F8.2,3X,F9.2,3X,F8.2,3X,F9.2, SR  1441
         13X,F9.2,2X,F8.2)                                            SR  1451
   199    CONTINUE                                                    SR  1461
          PRINT 85, DTOT,DTOT4, DTOT5                                 SR  1471
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```
 85   FORMAT('0',20X,'DAILYTOT',F11.3,4X,'TRANSMITTED',F11.3,4X,          SR  1481
     1'ABSORBED',F11.3)                                                   SR  1491
 299  CONTINUE                                                            SR  1501
 499  CONTINUE                                                            SR  1511
      STOP                                                                SR  1521
      END                                                                 SR  1531
C        SUBPROGRAMS

      FUNCTION  TRA(TH)
C POLYNOMIAL RELATING SOLAR TRANSMITTANCE OF THE GREENHOUSE PLASTIC
C COVERING AND INCIDENCE ANGLE
      PI=3.141593
       THI=TH*180./PI
      TRA=(.3571340E-03*THI**3-.4347968E-01*THI**2+.4119053*THI+
     1 78.91238)/100.00
      IF(THI.GT.73.5)   TRA= 0.0
      RETURN
      END

      FUNCTION HM(PH)
C POLYNOMIAL RELATING HEMISPHERICAL DIFFUSE RADIATION AND INCLINATION-
C ANGLE OF THE SURFACE
      PI = 3.141593
      PHI = PH*180./PI
     0HM= .1172939E-08*PHI**5- .9023824E-07*PHI**4- .1507936E-04*PHI**3
     1+ .1290145E-02*PHI**2- .2234817E-02*PHI+ .1003143E01
      RETURN
      END

      FUNCTION SM(TH)
C POLYNOMIAL RELATING CIRCUMSOLAR DIFFUSE RADIATION AND INCIDENCE ANGLE
      PI = 3.141593
      THI = TH*180./PI
      IF(THI.GT.130.0) GOTO 100
     0SM=- .2546665E-07*THI**4+ .8287272E-05*THI**3- .8206838E-03*THI**2
     1+ .1552951E-01*THI+ .9326270E00
      RETURN
 100  SM= 0.00
      RETURN
      END

      SUBROUTINE  DAYA (DAY,MONTH,YEAR,NTOT,DT)
C COMPUTES PERIOD IN DAYS FROM JAN.1 TO THE DESIRED DAY(NTOT)AND
C PERIOD IN DAYS FROM JUNE 21 TO THE DESIRED DAY/NUMBER OF DAYS IN YEAR.
C DAY,MONTH AND YEAR ARE TO REPRESENT DATE IN NUMERALS
C NDAY  NUMBER OF DAYS IN A PARTICULAR MONTH
      INTEGER DAY, MONTH, YEAR
      INTEGER NDAY(12)/31,28,31,30,31,30,31,31,30,31,30,31/
      KT  =  172
      IF(YEAR/4*4.EQ.YEAR)GOTO  12
 14   NTOT  =  DAY
      J  =  MONTH-1
      IF(J.EQ.0)  GOTO  15
      DO  11  I  =  1,J
 11   NTOT = NTOT+NDAY(I)
 15   DT= (NTOT-KT)/(KT+193.)
      RETURN
 12   KT = 173  ;  NDAY(2) = 29
      GOTO 14
      END

$ENTRY                                                                    SR  1541
```

TABLE A.1

```
                          SOLAR RADIATION FOR A FLAT SURFACE

           DAY          MONTH       LATITUDE      49.25
           21             6           YEAR          R            IO            KS
                                      1975       1308.41       1085.91        1.00
                        DECLINATION   23.45      SUN RISE      3.98A.M.

                          SURFACE TILT    30.00    WALL AZIMUTH       0.00
NO. SOL.TIME  SOL.ALT.    SOL.AZIM.     DIRECT     DIFFUSE     TOTAL        TRANS.      ABSOR.
 1   4.00       0.12      -127.39        0.00        0.03        0.03         0.02        0.00
 2   5.00       8.42      -116.39        0.00       12.42       12.42         9.80        1.16
 3   6.00      17.55      -105.81       28.27       35.29       63.56        27.85        3.28
 4   7.00      27.16       -95.15      187.49       51.73      239.22        91.84       41.14
 5   8.00      36.93       -83.70      382.50       67.96      450.46       239.89      121.87
 6   9.00      46.46       -70.35      570.59       86.58      657.17       393.83      152.56
 7  10.00      55.09       -53.28      727.97      105.33      833.30       579.12      148.02
 8  11.00      61.63       -29.98      839.98      119.87      959.85       739.61      117.08
 9  12.00      64.20        -0.00      896.85      124.76     1021.61       817.53       94.65
10  13.00      61.63        29.98      893.82      124.74     1018.56       814.41       95.67
11  14.00      55.09        53.28      831.14      118.77      949.91       726.40      120.41
12  15.00      46.46        70.35      714.07      103.56      817.63       560.72      150.12
13  16.00      36.93        83.70      552.89       84.66      637.55       376.19      150.84
14  17.00      27.16        95.15      363.36       66.24      429.59       228.38      118.04
15  18.00      17.55       105.81      168.71       50.22      218.93        77.10       31.49
16  19.00       8.42       116.39       19.62       33.33       52.95        26.30        3.10
17  20.00       0.12       127.39        0.00       10.07       10.07         7.95        0.94
          DAILYTOT     8372.813   TRANSMITTED   5716.941   ABSORBED   1350.382
```

Note: Solar radiation is expressed as $w/(m^2 \cdot h)$

1.2 To Compute Solar Radiation for Curved Surfaces

```
    TO COMPUTE SOLAR RADIATION FOR CURVED SURFACE:-
FOLLOWING CARDS REPLACE THEIR COUNTERPARTS INDICATED BY CARD NUMBERS IN PROGRAM
FOR FLAT SURFACES
5     FORMAT('1',38X,'SOLAR RADIATION ON A CURVED SURFACE')             SR  0331
      READ,AL                                                           SR  0491
      WAAZ=AL*180.0/PI                                                  SR  0501
      PRINT55,WAAZ                                                      SR  0511
55    FORMAT('-',40X,'WALL AZIMUTH',4X,F6.2)                            SR  0521
      I3(J)=I3(J)+IT3/10.0                                              SR  0821
      I6(J)=I6(J)+IT6/10.0                                              SR  1091
      I(J)=I(J)+IT/10.0                                                 SR  1111
      I4(J)=I4(J)+ (IT4 + IT5)/10.0                                     SR  1141
      I5(J)=I5(J)+(IT7+IT8)/10.0                                        SR  1151
FOLLOWING CARDS ARE ADDED IN THE PROGRAM FOR FLAT SURFACES
         BETWEEN CARD NUMBERS SR  0691   AND   SR  0701
      I(J)=0.0 ; I3(J)=0.0 ; I4(J)=0.0 ; I5(J)=0.0 ; I6(J)=0.0          SR  0692
       RA = 5.0                                                         SR  0693
      PHP= PI/6.0                                                       SR  0694
599   PHPH= PHP- PI/36.0                                                SR  0695
      AB= RA*COS(PHPH)                                                  SR  0696
      OT=SQRT(RA*RA-AB*AB)                                              SR  0697
      PH=ATAN2(AB,OT)                                                   SR  0698
       PHI=PH*180.0/PI                                                  SR  0699
         BETWEEN CARD NUMBERS SR  1151   AND   SR  1161
      PHP=PHP+PI/18.00                                                  SR  1152
      IF(PHP.LE.1.048) GOTO599                                          SR  1153
```

TABLE A.2

SOLAR RADIATION ON A CURVED SURFACE

DAY	MONTH	LATITUDE 49.25 YEAR	R	IO	KS
21	12	1975	1397.66	1236.65	1.00
	DECLINATION	-23.45	SUN RISE	8.02A.M.	

WALL AZIMUTH 0.00

NO.	SOL.TIME	SOL.ALT.	SOL.AZIM.	DIRECT	DIFFUSE	TOTAL	TRANS.	ABSOR.
1	9.00	7.01	-40.81	1334.35	57.45	1391.80	755.36	369.98
2	10.00	12.54	-28.03	2698.41	109.06	2807.47	1751.40	623.06
3	11.00	16.08	-14.31	3396.11	135.86	3531.96	2481.65	608.18
4	12.00	17.30	-0.00	3723.89	148.98	3872.86	2879.29	548.75
5	13.00	16.08	14.31	3706.72	148.32	3855.04	2858.18	552.61
6	14.00	12.54	28.03	3343.94	133.76	3477.70	2420.97	614.44
7	15.00	7.01	40.81	2604.02	105.66	2709.68	1666.05	615.10

DAILYTOT 22815.850 TRANSMITTED 15441.540 ABSORBED 4246.164

Note: This table is computed for a south facing curved surface of a gothic arch greenhouse. The solar radiation values listed in the table are per 4.0 m^2 of the curved surface. Devide the solar radiation values by 4.0 to convert them into $w/(m^2 \cdot h)$.

1.3 To Compute Solar Incidence Angles

```
C       . MAIN LINE PROGRAM
      IMPLICIT REAL (I,K)
      INTEGER DAY,MONTH,YEAR
      PI= 3.141593
      READ,NJ
      DO 71 J3=1,NJ
      READ, DAY,MONTH,YEAR,IL
C IL      LATITUDE OF THE PLACE
      ILI = IL*180.0/PI
      PRINT 15,ILI
15    FORMAT('0',40X,'LATITUDE',5X,F5.2)
      CALL DAYA(DAY,MONTH,YEAR,NTOT,DT)
      DA=ARSIN(SIN(23 .45*PI/180.)*COS(2.*PI*DT))
C DA      DECLINATION ANGLE OF THE SUN FOR THE DAY
      CA  =  DA*180.0/PI
      TR=ARCOS((SIN(IL)*SIN(DA))/(COS(IL)*COS(DA)))*(12./PI)
C TR      LOCAL SOLAR TIME OF SUNRISE FOR THE  DAY
      HB  =  TR*PI/12.0
      BO=ARSIN(SIN(IL)*SIN(DA)-COS(IL)*COS(DA)*COS(HB))
      AO=ARSIN((COS(DA)*SIN(-HB))/COS(BO))
C HB,BO AND AO ARE VALUES OF HA,B AND A AT SUNRISE
      DO 70 J2=1,20
      READ,AL,T1
C AL      WALL AZIMUTH OF A SURFACE
C T1      LOCAL CLOCK TIME
      IF(T1.EQ.0.0) GO TO 71
      T=T1-1.5
C T       LOCAL SOLAR TIME
      PRINT32,AL,T1
32    FORMAT(' ',F8.6,10X,F5.2)
      PRINT40
40    FORMAT(28X,'TILT ANG',9X,'INCI.ANG')
      PH = 1.570796
C PH      INCLINATION ANGLE OF A SURFACE
31    HA = PI*T/12.
C HA      SOLAR HOUR ANGLE
      BT=ARSIN(SIN(IL)*SIN(DA)-COS(IL)*COS(DA)*COS(HA))
C BT      SOLAR ALTITUDE ANGLE
      AX=ARSIN((COS(DA)*SIN(-HA))/COS(BT))
      IF(AX.LT.0.0)  GOTO  16
      IF(AX.GT.AO)  GOTO  26
      AZ  =  PI-AX
      GOTO  36
26    AZ  =  AX
C AZ      SOLAR AZIMUTH ANGLE
      GOTO  36
16    IF(AX.GT.AO)  GOTO  26
      AZ  =- PI-AX
36     AO  =  AX
      GA= ABS ( AZ- AL)
C GA      WALL - SOLAR AZIMUTH ANGLE
      TH=ARCOS(COS(BT)*COS(GA)*SIN(PH)+SIN(BT)*COS(PH))
C TH      INCIDENCE ANGLE OF THE SUN'S RAYS ON A SURFACE
      P=TH*180.0/PI
      PRINT50,PH,P
50    FORMAT(30X,F7.5,10X,F9.4)
      PH = PH- 0.087266
      IF (PH.GE.0.00) GOTO 31
70    CONTINUE
```

```
 71   CONTINUE                                                          IA  0451
      STOP                                                              IA  0461
      END                                                               IA  0471
C       SUBROUTINE SUBPROGRAM
      SUBROUTINE  DAYA (DAY,MONTH,YEAR,NTOT,DT)
C COMPUTES PERIOD IN DAYS FROM JAN.1 TO THE DESIRED DAY(NTOT)AND
C PERIOD IN DAYS FROM JUNE 21 TO THE DESIRED DAY/NUMBER OF DAYS IN YEAR.
      INTEGER DAY, MONTH, YEAR
C DAY,MONTH AND YEAR ARE TO REPRESENT DATE IN NUMERALS
      INTEGER NDAY(12)/31,28,31,30,31,30,31,31,30,31,30,31/
C NDAY  NUMBER OF DAYS IN A PARTICULAR MONTH
      KT  =  172
      IF(YEAR/4*4.EQ.YEAR)GOTO  12
 14   NTOT  =  DAY
      J  =  MONTH-1
      IF(J.EQ.0)  GOTO  15
      DO  11  I  =  1,J
 11   NTOT = NTOT+NDAY(I)
 15   DT= (NTOT-KT)/(KT+193.)
      RETURN
 12   KT = 173  :  NDAY(2) = 29
      GOTO 14
      END
```

APPENDIX 2

Results of the Experiment to Evaluate Solar Transmittance versus Incidence Angle Characteristics

Following are the equations of solar transmittance versus incidence angle for the seven systems of plastic greenhouse coverings tested.

1. U.V. Polyethylene

$$\psi_u(\theta) = 0.3730878 \times 10^{-3}(\theta)^3 - 0.3830469 \times 10^{-1}(\theta)^2 - 0.1690454(\theta) + 93.7490 \quad \text{(A1)}$$

2. Filon

$$\psi_u(\theta) = 0.3722545 \times 10^{-3}(\theta)^3 - 0.3798616 \times 10^{-1}(\theta)^2 - 0.1716681(\theta) + 91.9575 \quad \text{(A2)}$$

3. Fabrene-TM

$$\psi_u(\theta) = 0.3777347 \times 10^{-3}(\theta)^3 - 0.3412366 \times 10^{-1}(\theta)^2 - 0.2702923(\theta) + 75.6601 \quad \text{(A3)}$$

4. U.V. Polyethylene + U.V. Polyethylene

$$\psi_u(\theta) = 0.3416329 \times 10^{-3}(\theta)^3 - 0.4012758 \times 10^{-1}(\theta)^2 + 0.2287912(\theta) + 82.0346 \quad \text{(A4)}$$

5. Fabrene-TM + Fabrene-TM

$$\psi_u(\theta) = 0.2854941 \times 10^{-3}(\theta)^3 - 0.3113431 \times 10^{-1}(\theta)^2 + 0.1622342(\theta) + 55.4789 \quad \text{(A5)}$$

6. Fabrene-TM + U.V. Polyethylene

$$\psi_u(\theta) = 0.3207908 \times 10^{-3}(\theta)^3 - 0.3551286 \times 10^{-1}(\theta)^2 + 0.1678648(\theta) + 66.6152 \qquad \text{(A6)}$$

7. Filon + U.V. Polyethylene

$$\psi_u(\theta) = 0.3571340 \times 10^{-3}(\theta)^3 - 0.4347968 \times 10^{-1}(\theta)^2 + 0.4119053(\theta) + 78.9124 \qquad \text{(A7)}$$

The incidence angles (θ) in these equations are in degrees and the solar transmittance (ψ_u) values computed are in percent. These equations were obtained as a result of the least-square polynomial fit to the experimental data (Section 4.3). Graphical representation of these equations is made in Fig. A.1. and Fig. A.2.

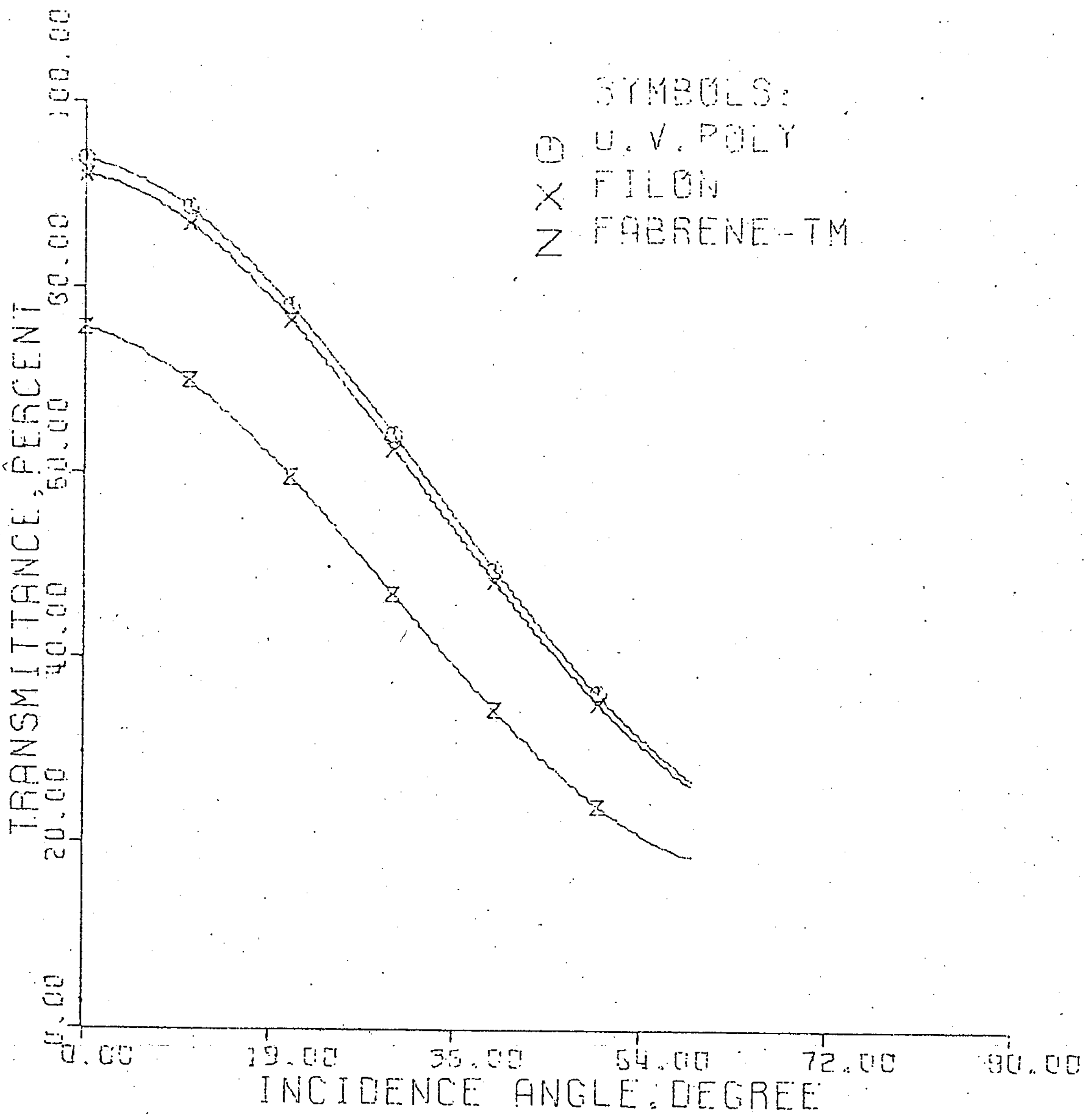


Fig. A.1 Experimental Solar Transmittance Versus Incidence Angle Characteristics for Single-layer Greenhouse Coverings

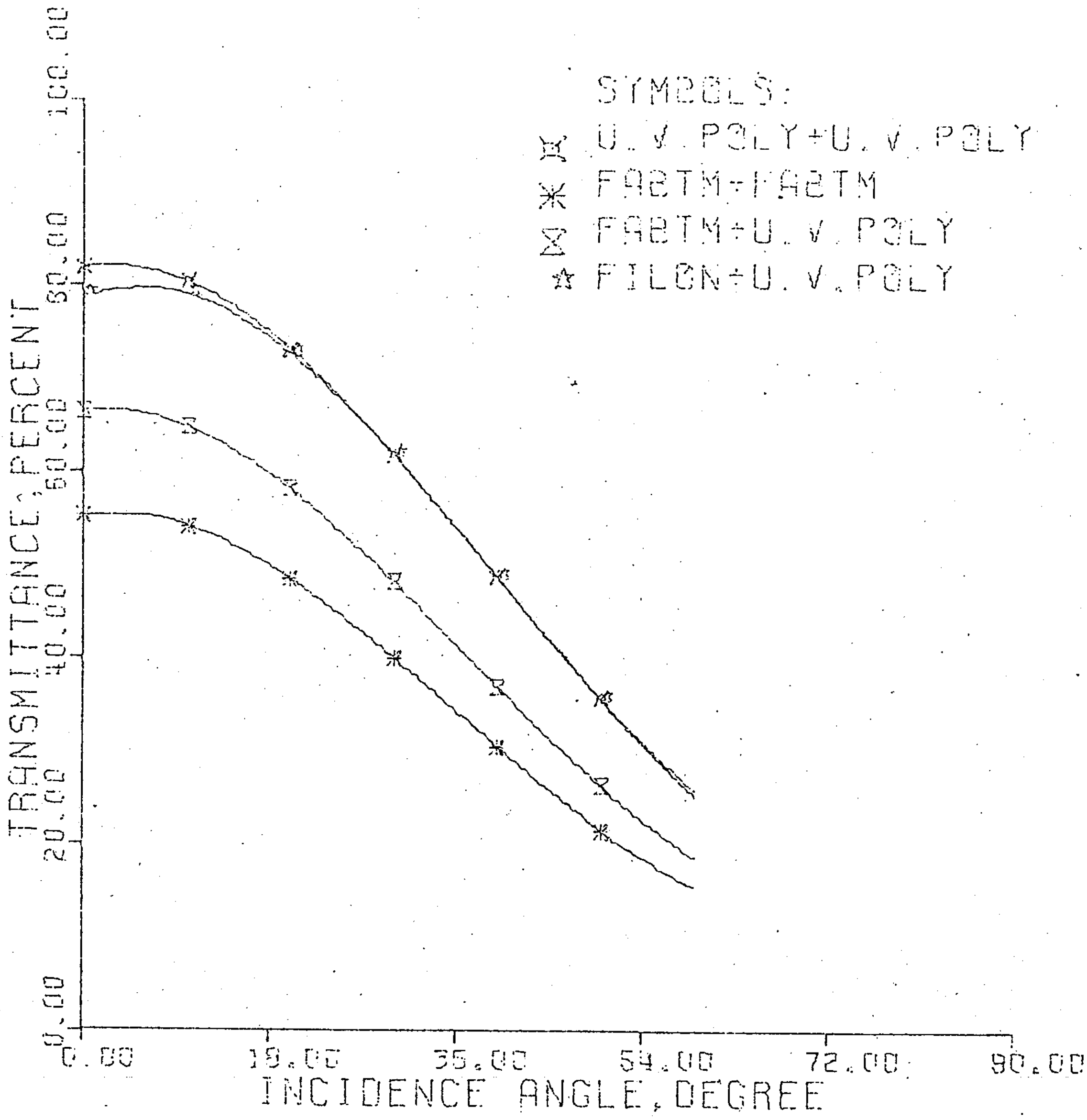


Fig. A.2 Experimental Solar Transmittance Versus Incidence Angle Characteristics for Double-layer Greenhouse Coverings

APPENDIX 3

Equations for Calculating Thermal Resistance of Various Greenhouse Wall-Sections

Fig. A.3 shows some of the wall sections. Minor constructional details like braces and ridge caps have been omitted. In the following equations ℓa refers to the length of a wall excluding structural members and ℓ is the total length of the wall.

I Thermal Resistance of Flat Sections

[i] Uninsulated Flat Section

$$R = 1/h_o + 1/h_i + [1/\{Sw \cdot k_w/b + (1 - Sw)/(1/C_a)\}] \qquad (A8)$$

[ii] Insulated Flat Section

$$R = 1/h_o + 1/h_i + 2\,R_{ply} + [1/\{Sw \cdot k_w/b + (1 - Sw)/(1/C_a + R_{ins})\}] \qquad (A9)$$

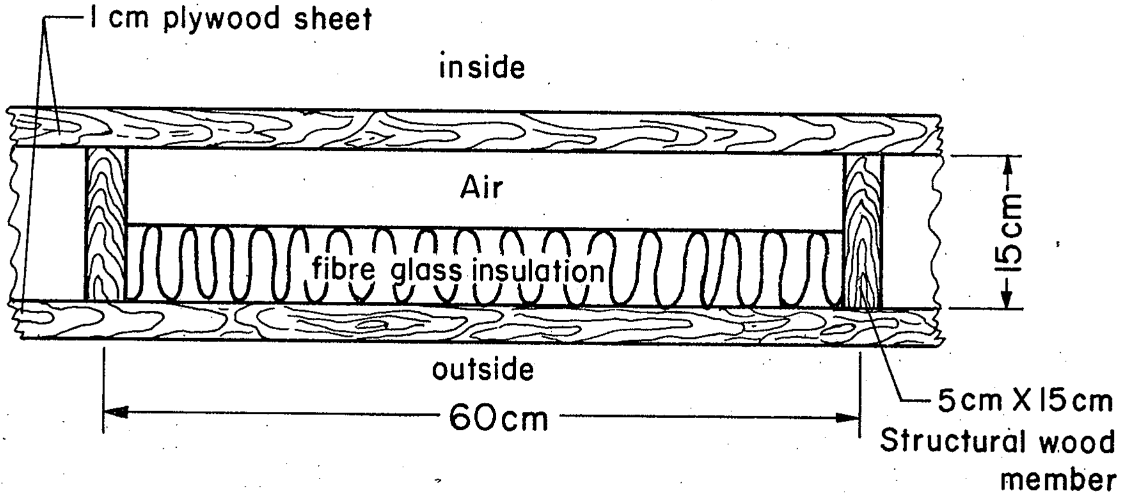
II Thermal Resistance of Curved Sections

[i] Uninsulated Curved Section

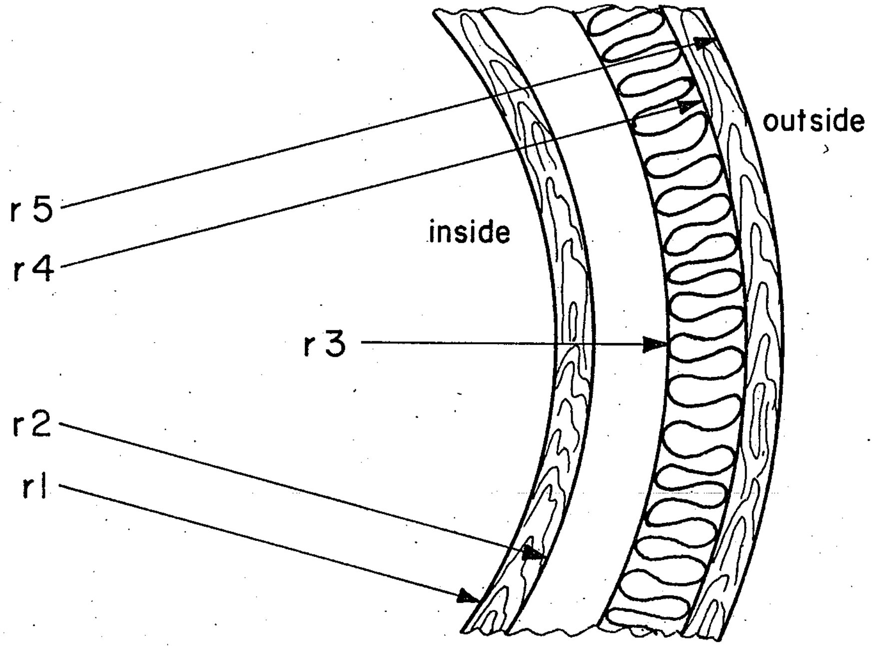
$$R = 1/h_o + (r_s/r_1)/h_i + \{r_5 \cdot \log_e(r_5/r_1)\} / \{(1 - \ell a/\ell) \cdot k_w + (\ell a/\ell) \cdot k_a\} \qquad (A10)$$

[ii] Insulated Curved Section

$$\begin{aligned} R = {} & 1/h_o + (r_5/r_1)/h_i + (\ell a/\ell)/[r_5 \cdot \log_e(r_5/r_4)/k_{ply} + \frac{r_5 \cdot \log_e(r_4/r_3)}{K_{ins}} \\ & + r_5 \cdot \log_e(r_3/r_2)/k_a + r_5 \cdot \log_e(r_2/r_1)/k_{ply}] + (1 - \ell a/\ell)/ \\ & [r_5 \cdot \log_e(r_5/r_4)/k_{ply} + r_5 \cdot \log_e(r_4/r_2)/k_w + r_5 \cdot \log_e(r_2/r_1) k_{ply}] \end{aligned} \qquad (A11)$$



(a) A typical horizontal cross section through an insulated wall



(b) A vertical cross section through an insulated curved wall

Fig. A.3 Details of the insulated greenhouse wall sections

The above equations were used in order to obtain thermal resistance values for individual surfaces of the greenhouses. A single side of either gable or circular greenhouses is either flat or curved, so the above equations would give the R values for the surfaces directly. The side surfaces of gothic arch greenhouses are composite surfaces, in the sense that both curved and flat sections exist in each side surface. Therefore, the law of combining parallel resistances was used to calculate the value of overall resistance for a side surface:

$$R = (A_{flat} + A_{curved})/\{(A_{flat}/R_{flat}) + (A_{curved}/R_{curved})\} \qquad (A12)$$

APPENDIX 4

Calculation for Daily Greenhouse Heat Balance

Type of greenouse:	Gable Greenhouse
Size:	15m x 10m
Orientation:	East-West
Date:	December 21, 1974
Sky Condition:	Clear Sky

North side of the greenhouse is insulated with fiberglass (R = 0.70).

Ground bed area = 15 x 10 = 150 m^2

From Table 5.2:

One end wall area = 28.50 m^2

One side wall area:

i) 30 degrees inclined surface = 86.55 m^2

ii) vertical surface = 21.0 m^2

I Solar Heat Gain (Section 5.4.1)

q_u for a transparent surface = $[I_T + I_A \cdot N_i]A$

q_u for a insulated surface = $I \cdot \omega_u \cdot N_i \cdot A$

The surface facing north or south consists of two surfaces, one inclined at 30 degrees and the other vertical. Therefore, q_u for surface facing north or south will be the sum of q_u for both 30 degrees inclined and vertical surfaces. Daily total of solar radiation for a surface facing east is equal to that for a west facing surface. Therefore, q_u for sections facing east and west will be equal because both surfaces have similar area and construction.

q_u for north facing surface = -[(101.62x0.9x0.21x21.0) +
(129.14x0.9x0.21x86.55)]
= -2,515.74 wh

q_u for south facing surface = -[(4466.07+992.74x0.21)21.0 +
(2549.67+1146.03x0.21)86.55]
= -339,669.18 wh

q_u for east facing surface = -(712.45+341.20x0.21)28.5
= -22,346.84 wh

q_u for west facing surface = -22,346.84 wh

Q_u for the whole greenhouse = -386,878.60 wh

II Thermal Radiation Exchange (Section 5.4.2)

$$Q_t = \psi_t \cdot FS \cdot \delta \cdot A_s \, (\varepsilon_s \cdot t_s^4 - \varepsilon_a \cdot t_a^4)$$

$\psi_t = 0.08496$

$A_s = 150 \text{ m}^2$

$\varepsilon_s = 0.95$

$\varepsilon_a = 0.746$

$FS = 0.56$

$t_s^4 = 0.1797 \times 10^{12} \text{ K}^4$

$t_a^4 = 0.1096 \times 10^{12} \text{ K}^4$

$\delta = 5.6697 \times 10^{-8} \text{ w/(m}^2 \cdot \text{K}^4)$

Therefore,

$Q_t = 35,992.1$ wh

III Heat Transfer With Greenhouse Ground Bed (Section 5.4.3)

[i] $Q_x = \{P \cdot f\ (t_i - \bar{t}_o)\}\ 24.0$

$P = 50$ m

$f = 1.418$ w/(m · K)

$t_i - \bar{t}_o = 34.24$C

therefore,

$Q_x = 58{,}275.1$ wh

[ii] $Q_y = \{A_g(t_i - t_g)/R_g\}\ 24.0$

$A_g = 104\ m^2$

$R_g = 1.7612\ (m^2 \cdot K)/w$

$t_i - t_g = 11.0$C

therefore,

$Q_y = 15{,}589.44$ wh

and

$Q_g = Q_x + Q_y$

$= 73{,}864.54$ wh

IV Heat Transfer from Greenhouse Covering Surface (Section 5.4.4)

$$Q_c = [(q_c)_{\text{end surface}} \times 2 + (q_c)_{\text{north surface}} + (q_c)_{\text{south surface}}] \times 24.0$$

$$= [2\{A(t_i - \bar{t}_o)/R\}_{\text{end surface}} + \{A(t_i - \bar{t}_o)/R\}_{\text{north surface}} +$$

$$\{A(t_i-\bar{t}_o)/R\}_{\text{south surface}}]\ 24.0$$

$$= 24[\{(2 \times 28.5)/0.31 + 108/1.18 + 108/0.31\}34.24]$$

$$= 510{,}807.20 \text{ wh}$$

Total Heat Balance of the Greenhouse:

$$\left|\begin{matrix} Q_f \\ Q_v \end{matrix}\right| = Q_u + Q_t + Q_g + Q_c$$

$$= -386{,}878.6 + 35{,}992.1 + 73{,}864.54 + 510{,}807.2$$

$$= 233{,}885.24 \text{ wh}$$

or,

$$Q_f = 233{,}885.24 \text{ wh}$$

Therefore, the calculated total heat balance for a 24 hour period on December 21, 1974 is 233,885.24 wh or, the heating requirement should have been 233.9 kwh on December 21, 1974.