C. 1

SOLAR HEATING OF INTEGRATED GREENHOUSE-ANIMAL SHELTER SYSTEMS

BY

NOUREDDINE BEN-ABDALLAH

B.Sc. Texas A & M University, 1969
M.A.Sc. The University of British Columbia, 1974

A Thesis submitted in partial fulfilment
of the requirements for the degree of
Doctor of Philosophy
(Interdisciplinary)

We accept this thesis as conforming to the required standard

THE UNIVERSITY OF BRITISH COLUMBIA
SEPTEMBER, 1983

Department of Agricultural Engineering

The University of British Columbia
2075 Wesbrook Place
Vancouver, Canada
V6T 1W5

Date 3 Oct. 1983

ABSTRACT

An analytical procedure to determine the effectiveness of greenhouses as solar collectors was presented. This procedure was used to predict the effect of several construction parameters on solar radiation input to greenhouses. The orientation of the greenhouse was found to be the most effective construction parameter controlling solar radiation input to greenhouses. The effective albedo of the plant canopy was also found to be a significant factor.

A new solar greenhouse design, suitable for high latitude regions was developed. The results showed that an internal solar collector could be incorporated as an integral part of the greenhouse design. The concept developed could be used as a free-standing greenhouse or in a combination with livestock building.

The efficiency of the solar input was investigated for the conventional and the shed greenhouses, both as a free-standing unit and a greenhouse-animal shelter system, using computer simulation analyses. The results indicated that the efficiency of solar input is highly dependent on location; the effect of location on the shed type design is more profound.

A typical case of a greenhouse-hog barn production system was investigated using computer simulation analyses. The results showed that such a food production system achieves a significant reduction in conventional fuel consumption due to both animal waste heat recovery and solar energy utilization.

TABLE OF CONTENTS

Page

Page

Page

Page

Page

Page

LIST OF TABLES

Table | Page

CHAPTER 5

Table Page

CHAPTER 6

Table

Page

APPENDIX L

LIST OF FIGURES

Figure | Page

CHAPTER 1

Figure		Page

CHAPTER 4

CHAPTER 5

CHAPTER 6

Figure Page

Figure | Page

APPENDIX K

APPENDIX L

ACKNOWLEDGEMENTS

The author wishes to express his sincere thanks and appreciation to Professor L.M. Staley, the research supervisor, for his guidance, encouragement and constructive criticism throughout the period of this study.

Sincere thanks are due to Dr. M. Iqbal of the Department of Mechanical Engineering for helping me understand the science of solar energy and heat transfer. Without the background gained from his excellent graduate courses, this study would not have been possible.

Thanks are extended to Dr. T.A. Black of the Department of Soil Science, Dr. P.A. Jolliffe of the Department of Plant Science and Dr. J.W. Zahradnik and Dr. N.R. Bulley of the Department of Bio-Resource Engineering for their invaluable suggestions.

The author expresses his sincere appreciation to Mrs. D. Chong and Ms. V. Ellis for their efficiency and co-operation in typing and editing some parts of the thesis.

Finally, the financial assistance of British Columbia Hydro and Power Authority through the Graduate Research and Engineering Technology Awards program is gratefully acknowledged.

INTRODUCTION

GREENHOUSE INDUSTRY IN CANADA*

Greenhouse production of flowers, nursery plants and vegetable crops is a significant component of Canadian agriculture. The 1980 total surface area under glass and plastic was estimated at 382.76 hectares, with the province of Ontario accounting for 60 percent of the total, followed by British Columbia with less than 14 percent and Quebec with slightly over 11 percent. The total sales value of flowers, ornamentals, bedding plants and vegetables was estimated at over 216 million dollars in 1980; while the total fuel cost used by the greenhouse industry was over 25 million dollars, or 11.6 percent of the sales value.

In 1980 the annual fuel costs per unit area under cover ranged between 5.53 $\$/m^2$ in the province of Quebec to 9.60 $\$/m^2$ in Nova Scotia. The national average was estimated at 6.63 $\$/m^2$. Unit fuel cost in Ontario was closest to the national average at 7.07 $\$/m^2$ because of its large contribution in surface area under cover; while in British Columbia, due to relatively warm climate, the unit fuel cost was only 5.70 $\$/m^2$.

The low fuel costs per unit area in Quebec may be attributed to the fact that some greenhouses in the province do not operate for the entire year. In Nova Scotia, the high

---

* All the statistical information in this section is derived by the author from Statistics Canada, Greenhouse Industry, Catalogue 22-202, 1979-1980.

fuel costs per unit greenhouse area could be explained by higher fuel prices and colder climate than in southern Ontario.

NEED FOR ENERGY CONSERVATION

The need for energy conservation and renewable sources of energy utilization for greenhouse heating was a result of the continuous increase, for the last decade, of conventional fuel costs.

The increase in energy costs have focused the attention of greenhouse operators on conservation methods such as installation of thermal curtains, use of double covers and more efficient greenhouse designs, planting late in the season, or growing plants requiring lower temperatures. In conjunction with applying conservation techniques, some growers went into fossil fuel substitution programs. These included waste heat utilization, combustion of wood and wood residues, and solar energy utilization. However, much more research, development and demonstration projects are needed to keep a viable greenhouse industry operating in adverse climatic conditions.

Obviously there is no single solution to the energy dilemma facing the greenhouse industry today. However, the author believes a combination of new energy conserving ideas and concepts, solar energy utilization and waste heat recovery and re-use may alleviate the burden of high fuel costs for greenhouse operators.

The work presented in this study on internal solar energy collection and utilization, and animal waste heat recovery and use for greenhouse heating, is only one of the many possible concepts which might prove reasonably efficient in reducing the dependence of the greenhouse industry on non-renewable energy sources. Therefore, the following proposed concept should be taken as a partial solution and should be applied in combination with other energy conservation methods for greenhouses.

In this study, it is proposed that animal heat from livestock buildings be used in conjunction with solar energy to heat adjacent greenhouses. Two situations need to be investigated: retrofit of existing structures and incorporation of a new and efficient design for expansions and new operations.

The criteria for the new design were: ease of construction and improvement of the internal solar radiation collection efficiency of the attached greenhouse. Obviously, for ease of construction a standard gable structure, with the long-axis oriented east-west, divided by a vertical wall at the ridge giving two shed sections, was proposed. One section is an animal shelter and the other a greenhouse. This design would permit the installation of a solar collector inside the greenhouse, on the upper portion of the dividing wall on the south-facing side. The placement of the collector, in this manner, is not expected to interfere with plants or normal operations within the greenhouse. However, it remained to be seen if the shed-shaped greenhouse would perform at least as well as a conventional gable greenhouse having identical floor area, orientation and construction materials. Surprisingly enough, theoretical analyses indicated that its performance as a solar collector was significantly better than a gable shape greenhouse under Vancouver climatic conditions. Therefore, it was then decided that the shed-shaped greenhouse could also be used efficiently as a free-standing structure. This new design was then called by the author as a "solar-shed greenhouse" and was analysed, in this study, separately and in combination with a livestock building.

In 1980, a solar-shed greenhouse was constructed at the Agriculture Canada Research and Plant Quarantine Station in Saanichton on Vancouver Island, British Columbia. Its performance is being compared to a conventional gable glasshouse located at the same site. Preliminary results were presented by Staley et al.(1981).

It is hoped that the data collected from the experimental greenhouse at Saanichton would be used for calibration of the mathematical model developed in this study. This would make it possible to predict its performance accurately at other locations in Canada and elsewhere.

PROPOSITIONS

The following propositions were considered to apply to this study:

1. High costs of energy are plaguing the producers of greenhouse crops, even though the growers are taking steps to conserve fuel by installing night heat saving curtains, using double layers of plastic with an air space between the layers, planting crops late in the season and growing plants which have lower temperature requirements (Baird et al.(1977)).

2. Greenhouses waste substantial amounts of heat by ventilation during the day while they consume large amounts of supplemental heat at night (Chandra and Willits(1980), Brundrett and Turkewitsch(1979), Baird et al.(1977), Short et al.(1976), McCormick(1976), Liu and Carlson(1976), Price et al.(1976), Willits et al. (1979), Simpkins et al.(1979)).

3. External solar collectors for greenhouses require a large amount of additional space, thus resulting in a waste of valuable land (Brundrett and Turkewitsch(1979)).

4. Internal solar collectors located in the ridge area of conventional greenhouses will cast a shadow on the plant canopy, thus reducing crop productivity (Wiegand(1976)).

5. Internal solar collectors located on the north wall of conventional greenhouses will be shaded by the plants, thus reducing the collection efficiency of the solar collector (Wiegand(1976)).

6. Ventilation and supplemental heat is required, even during cold weather periods, to keep the humidity within the livestock buildings at acceptable levels (Bon et al.(1981), Stauffer and Vaughan(1981), Sokhansanj et al.(1981), Spillman et al.(1981)).

OBJECTIVES OF THE STUDY

The principle aim of this study was to reduce the dependence of greenhouse operations on fossil fuels.

The following were the main objectives:

1. To develop a simple mathematical model which would predict the solar radiation capture of greenhouses as a function of measured insolation and greenhouse construction parameters.

2. To develop a computer simulation model for estimating potential energy savings due to the utilization of waste animal heat from livestock buildings to supplement greenhouse heating demand in a greenhouse-animal shelter combination.

3. To develop a suitable system for improving internal solar energy capture by the greenhouse in an integrated greenhouse-livestock building.

ASSUMPTIONS

The major assumptions underlying objectives 2 and 3 were as follows:

1. Livestock producers are willing to operate greenhouses or vice versa, or a cooperative between a livestock producer and a greenhouse operator could be organized.
2. Exhaust air from the livestock building does not have a detrimental effect on the growth of greenhouse crops.

INFERENCES

The major inferences related to this study were the following:

1. Daytime waste heat from a greenhouse can be stored for night use.
2. A significant amount of surplus animal waste heat is available to justify its recovery for greenhouse usage.
3. The shape of the greenhouse can be altered from the conventional in order to accommodate for an efficient internal solar collection system without seriously affecting the availability of light to the plant canopy.
4. An integrated greenhouse-livestock operation is more energy efficient than a separate greenhouse production system.

SCOPE OF THE STUDY

The scope of this study was limited to investigations using computer simulations. The study consisted of four stages. In the first stage, the effect of greenhouse construction parameters including shape and energy conservation measures on the solar radiation captured by the greenhouse were studied theoretically. In the second stage, mathematical models were developed for the different subsystems of the greenhouse-livestock combination. These subsystems included; a livestock building, a conventional greenhouse and a solar-shed greenhouse. In the third stage, a computer simulation model was developed based upon the mathematical models of the second stage. The computer model was kept as general as possible such that it could be used to analyse a single greenhouse, a single livestock building, a conventional greenhouse-animal shelter combination, and a solar-shed greenhouse either free-standing or attached to a livestock building. The complete computer program was written in the FORTRAN language. In the fourth stage, the computer simulation model was used to investigage the feasibility of a conventional greenhouse-hog barn combination, and a solar assisted greenhouse-swine finishing house combination. The feasibility study was based on energy savings only.

ORGANIZATION OF THE MANUSCRIPT

For the convenience and clarity of presentation, this manuscript is presented in three separate parts. Part I deals with the effectiveness of greenhouses as solar collectors, where the solar radiation input and then the solar energy capture by greenhouses are covered in Chaper 1 and Chapter 2, respectively. Part II investigates the feasibility of a retrofit situation of a conventional greenhouse-livestock building combination. In this part, Chapter 3 is devoted to the livestock subsystem, Chapter 4 to the greenhouse subsystem, while the combination of the subsystems is treated in Chapter 5. Finally, solar energy utilization in a greenhouse-livestock building combination is investigated in Part III. This part includes Chapter 6 where the development of the solar-shed greenhouse concept is given in detail, and Chapter 7 where the combination of this new greenhouse design to an animal shelter is investigated.

Each of the three parts could be read separately with the exception of Section B of Chapter 2, where the calculation of diffuse radiation configuration factors for gable greenhouses is needed for full understanding of the material in Chapter 4. Also, the mathematical model for a livestock building developed in Chapter 3 is a requirement for Chapter 7.

LITERATURE REVIEW

GREENHOUSE THERMAL ENVIRONMENT MODELS

Most of the existing mathematical models are based on the energy balance method. This method consists of dividing the greenhouse into different components; cover, plant canopy, ground and greenhouse air mass. The heat and mass fluxes among these components are modeled mathematically thus obtaining an energy balance for each component of the greenhouse system. The result is the generation of a system of simultaneous algebraic equations to yield the temperatures of the components.

Several models are discussed in this section whose major objective is the prediction of temperature and humidity inside the greenhouse. The differences between these models are the assumptions underlying their development and the boundary conditions chosen to arrive at a final solution.

Probably the most important assumption, where discrepancies between models occur, is the treatment of the heat capacity of the greenhouse. Some of the models, either explicitly or implicitly, treat all components of the greenhouse system as having a negligible heat capacity; while others, single out the soil component as having a significant heat capacity. However, some of the authors of these models have also expressed concern about treating the plant canopy component as having a negligible heat capacity, but none has considered it otherwise.

Obviously, the choice of the assumptions with respect to the system component's heat capacity depends on the intended use of the model. If the determination of psychrometric properties of the air within the greenhouse is the objective of the model development, then the heat capacity of the soil and perhaps that of the plant canopy (i.e. tall plants at full stage of growth) should be considered. On the other hand, if the objective of the model is the prediction of greenhouse heating requirements, then the steady state analyses are adequate (Kindelan, 1980).

Other discrepancies between the existing models are the selections of the boundary conditions. Primary boundary conditions, that is climatic variables that are easily obtainable, would be preferred. For example, the use of net radiation into the greenhouse or the ground temperature as inputs to the model is not recommended. Preferably, these variables should be determined by the mathematical model from primary boundary conditions such as solar radiation incident on a horizontal surface and ambient air temperature.

Brief descriptions follow of the most recent and frequently referred to mathematical models for the prediction of a greenhouse thermal environment:

Walker (1965) presented an analytical procedure for predicting temperatures within both heated and ventilated greenhouses. A heat balance in a greenhouse was expressed mathematically involving solar heat gain, conduction heat loss, thermal radiation heat loss to atmosphere, ventilation heat loss, evapotranspiration heat loss, and furnace heat.

Experimental tests were conducted to determine the applicability of the analytical procedure for the prediction of greenhouse temperatures. They found a mean difference between the predicted and observed temperature of 1.4°C for periods of high solar radiation input when ventilation was required. The analytical procedure was reported suitable for predicting the greenhouse heat requirement during cold weather periods but test results were not included.

Selçuk (1970) used unsteady state heat and mass balance equations for controlled-environment greenhouses yielding 24 simultaneous non-linear differential equations. These equations were solved numerically using the finite difference method. A greenhouse analysis which included the effects of soil water evaporation, plant transpiration, and condensation on the cover was presented.

Formulations of the heat balance on the cover, heat and mass balance on the airstream, heat balance over the plant canopy and heat balance on moist soil were given in detail. greenhouse. The model was found to predict temperatures of plant, cover, soil surface, and inlet and outlet air within 1.5°C. A five percent difference between predicted and measured air humidity ratios was reported.

Takakura et al.(1971) presented probably the most detailed computer simulation model available for predicting temperature variations of the soil-plant canopy-greenhouse system components. The analysis included soil water evaporation, plant transpiration, condensation on the glass cover, and heat storage in the soil. A two-dimensional heat conduction equation was used to model the soil. The solution requires the temperature at a certain depth as a boundary condition. Beam and diffuse components of solar radiation were considered separately.

Heat balance equations were given for plant surface, soil surface, glass surface and air within the greenhouse.

The model was tested for specific days and found to give reasonably accurate values for temperature variations.

Duncan et al.(1976) reported on the development and use of a greenhouse simulation model for predicting winter heating loads and evaluating the potential storage and reuse of excess solar energy in a greenhouse with a rock bed. The greenhouse energy balance model accounted for solar radiation input, thermal radiation heat loss, conduction heat loss, ventilation heat loss, evapotranspiration heat loss and heat loss to the ground. The thermal radiation and conduction heat losses were combined using the overall heat transfer coefficient method. The solar heat gain within a greenhouse was taken as equal to solar radiation incident on an outside horizontal surface multiplied by two constants, one representing the transmittance of the greenhouse covering material and the other the absorptivity of the plant canopy. The absorptivity of plants and other objects in the greenhouse to solar radiation was taken as 0.70 to 0.85. Detailed analysis of heat loss to the ground was not given, but each unit length of greenhouse perimeter was assumed to have an equivalent overall heat transfer coefficient equal to that of one unit area of wall.

Calibration and validation of the model was accomplished using 3-day measured data in April within an experimental greenhouse located at Lexington, Kentucky. They found a mean temperature difference between simulated and measured values of less than $1^{o}C$. Analyses using the rock bed simulation were performed for two 9-day winter heating periods representing cold January weather and milder March weather for an under-bench rock storage system. Their results showed little potential for excess solar energy storage in January but potentially 11.1% reduction in heating requirement in March.

Froehlich et al. (1979) developed a mathematical model for predicting the steady-periodic thermal behavior of greenhouses. The temperature of internal greenhouse air, plant canopy, floor surface and covering surfaces were predicted in closed form. The model also predicts the humidity of the greenhouse air. Testing of the model was found to predict the temperatures with reasonable accuracy. But a significant difference occurred between the measured and predicted humidity ratios at low ventilation rates.

Kindelan(1980) described a model to simulate the internal greenhouse environment by the energy balance method. The system was divided into four components similar to the model presented by Takakura et al.(1971). The soil, plant, internal air and cover were modeled by heat and mass balances.

For the soil heat flow analysis, unlike Takakura's model, the deep ground temperature was not given as a boundary condition but obtained as an additional result of the simulation.

It was stated in the paper that testing of the greenhouse model was carried out by predicting the ambient conditions in a small hydroponic greenhouse, but only predicted values were reported. Therefore, the prediction accuracy of the model could not be evaluated.

Chandra et al.(1981) improved on the model represented by Froehlich et al.(1979) by incorporating a detailed analysis of thermal radiation exchange between plants and greenhouse surfaces. The surfaces were assumed gray, isothermal, and perfectly diffuse.

When the greenhouse air temperature and relative humidity are given, the model predicts the heat and moisture balances of the greenhouse air.

The model was tested using measured greenhouse data reported by Froehlich(1976). The data were gathered in a

22 m x 11 m east-west oriented single-glazed glasshouse located at Cornell University. Hourly data for outside air temperature and humidity ratio, greenhouse air temperature and humidity ratio, plant canopy and floor surface temperatures in the greenhouse, and the total hourly solar radiation on a horizontal surface outside the greenhouse were used as inputs in the model. Five test days (2 in August, 1 in November and 2 in December) were selected representing summer and winter conditions. Comparison of model predictions and measured greenhouse data indicated that the mathematical model can predict the greenhouse thermal environment with reasonable accuracy.

Brundrett and Abbot (1981) developed a thermal model for predicting hourly or daily averaged heating or ventilating loads of greenhouses. During the development of the model the following factors were considered; covering material, passive solar contribution, air infiltration or ventilation rate, temperature stratification within the greenhouse and variation in the outside air temperature. The model is also capable of predicting heating loads for greenhouses equipped with thermal curtains. The thermal model has been extensively tested using an experimental greenhouse located in southern Ontario. They found that monthly average weather conditions are suitable for predicting annual fuel consumption by greenhouses.

SOLAR HEATING OF GREENHOUSES

During daylight hours when solar energy is available, the supplemental heat requirement for the greenhouse is zero or small. Most of the fossil fuel for greenhouse heating is used at night. Therefore, heat storage is a necessary part of a solar energy collection system.

With respect to solar energy applications to greenhouse heating, solar collection systems can be divided into "integral" and "non-integral" collectors depending on whether the collector is contained inside the greenhouse, or is a separate construction outside the greenhouse. Furthermore, integral solar collection systems can be classified as "active" or "passive".

A comparison of integral versus non-integral collectors for greenhouses is given in a list of advantages and disadvantages by Price et al.(1976). An integral solar collection system in a greenhouse will save on the cost of collector construction and on equipment that would be needed to transfer externally collected heat to the greenhouse. In addition, heat losses inherent in external collectors would be eliminated or at least reduced by integral collectors. However, internal greenhouse collection systems usually have a low efficiency and give lower operating temperatures than external collectors. Also, an existing greenhouse may have a poor orientation and configuration for installing internal solar collectors. External collectors usually give higher collection efficiency. They can be installed at optimum orientation and tilt for solar energy collection. The size of integral solar collectors within the greenhouse is limited by availability of suitable space since care must be taken not to shade plant growing areas while the size of external collectors is usually optimized by making use of appropriate economic analyses.

NON-INTEGRAL SOLAR COLLECTORS

A number of researchers have developed low-cost, external solar collectors for greenhouse applications using clear plastic covers and a black plastic absorber sheet. Much of this work was done at Rutgers University, New Jersey.

Mears and Baird (1976) described the development and testing of this type of collector coupled with a water heat storage reservoir underneath benches in an adjoining greenhouse. The collectors were 1.52 m x 2.44 m and 3.96 m x 5.49 m with adjustable legs that allowed for different slope angles. All tests were carried out with collectors at a 40^{o} tilt angle. The frames had a plywood back over which two sheets of polyethylene plastic were laid and separated by air to support a black polyethylene absorber sheet. At the bottom the black polyethylene was pulled up over the frame to provide a return gutter for the heated water. Water flow over the black sheet was maintained by a 31.75 mm PVC header pipe at the top of the frame with 0.79 mm holes drilled on 152.4 mm centers. A clear plastic sheet was used as a cover.

Initially the authors found that water flow over the black plastic sheet was uneven forming rivulets. This reduced the possible efficiency of the collector since large areas were not behaving as a collector. Water coverage was improved by adding detergent to the water supply and efficiency was improved. A further improvement to sheeting action of water was obtained by adding a second clear sheet over the collector and using air inflation to separate these two sheets and force one clear sheet against the black collector sheet. This also improved the insulation of the collector. Light absorbed by the second plastic sheet does not create an efficiency loss since this sheet is in contact with the water and any heat it collects is transferred to the water. Final improvements were addition of insulation to the back of the collectors and addition of a polypropylene mesh shade cloth over the black polyethylene collector sheet to improve the evenness of water flow. Under their test conditions the authors found that for temperature differences up to 22^{o}C the low cost plastic design compared favorably with conventional collectors. At 33^{o}C temperature difference the efficiency fell to about one-third that of a conventional collector. These units can provide large amounts of low quality heat, but to be well utilized they should be coupled to large heat storage units with high capacity heat transfer units.

Roberts et al.(1976) designed a plastic film solar collector similar in many respect to the one described by

Mears and Baird (1976). This collector has done away with the plywood back and used two air-inflated, clear polyethylene tubes with a black polyethylene absorber sheet sandwiched between them. A 31.75 mm header pipe with holes on 101.6 mm centers distributes water from the top of the frame to flow over the absorber sheet to the return gutter at the bottom. Detergent was added to the water supply to achieve good sheeting action of water over the black layer. Also, the pressure of the clear top sheet touching the black absorber helped to produce an even flow of water. These collectors were constructed 3.05 m high and 7.32 m long with easily adjustable supports to vary the collector tilt angle. The authors reported these collectors have withstood 96 km/h winds and snow storms without damage. These researchers also pointed out that efficiency decreased at higher collection temperatures. At the time of writing their paper initial construction costs for this design were 5.38 dollars per square metre. The plastic would have to be replaced annually at a cost of 1.61 dollars per square metre. To gain benefit from this type of low cost solar collector the greenhouse system should include: low-cost, large storage; heat conservation measures; and low-cost, high capacity heat exchangers.

Further modifications and improvements to this collector system were reported by Mears et al. (1977). Four plastic layers were used instead of five. The collectors had a clear, inflated tube for the front layers and a black tube to act as the absorber plate, support, and back insulation. Also, it was found that an aluminized layer inserted between the absorber plate and back inflated cushion reduced the heat loss coefficient by 10 percent due to reflective insulation. The authors caution that in direct sunlight with no water flowing the black plastic collector sheet can become warm enough to permanently stick to the front clear sheet. The collector efficiency ranged between 40 and 60 percent with best efficiency on warm days. On the coldest days efficiency fell to 35 percent. This collector system was constructed on a commercial site in 1978 at the Kube Pak Corporation, Allentown, New Jersey.

Mears et al.(1978) reported on the construction of a 0.54 hectare greenhouse with thermal storage and vertical vinyl curtain heat exchanger coupled to 1000 square metres of the Rutgers' design, non-integral, inflated-plastic-film solar collectors. Further information concerning the performance of the Rutgers system for other solar heating of greenhouse applications can be found in publications by Mears et al.(1979) and Simpkins et al. (1979).

Milburn et al. (1977) at Pennsylvania State University designed a low-cost, air-heating solar collector with a flat fiberglass glazing for greenhouse applications. Construction was simple and the cost was one-half to one-third that of a conventional solar collector. The absorber plate was made of 28 gauge sheet steel painted flat black. The framing was wood and the sides and back were insulated with foil faced polyurethane board. A rock bed storage system was used. The system for collecting and storing heat, and heating the greenhouse was fully automated by use of differential thermostats to operate the appropriate fans for heating or collecting mode.

Another type of solar collector which may be classified under non-integral systems is the solar pond. Researchers at the Ohio State University and the Ohio Agricultural Research and Development Center have done experiments using 'Solar ponds' for greenhouse heating. The solar pond may act both as a solar energy collector and a heat storage. Long term storage of summer heat for winter heating requirements can be achieved.

Short et al.(1976) designed an experimental solar pond; 3.6 m deep, 8.5 m wide, and 18.3 m long. The pond was lined with two 30-mil chlorinated-polyethylene liners over a sand bottom and insulated side walls. A salt concentration gradient was established in the pond so that the bottom 1.8 m had a 20 percent salt solution convective zone. The top 1.8 m of the pond had a concentration gradient of 20 percent salt to zero percent salt at the surface. This top layer was non-convective, since the specific gravity increases with increasing salt concentration in the zone from 0 - 2.8m depth. Solar radiation passes through the salt water and heats the black pond liner; this heats the 20 percent salt concentration gradient at the bottom of the pond. The non-convective upper layer is essentially transparent to incoming ultraviolet and visible radiation and opaque to reradiated thermal energy. The non-convective top layer also provides good insulation against conductive losses.

Solar ponds of this type must be leak-proof or the hot brine will be lost, as well as the insulation effectiveness of dry soil around the pond. Initial operation showed that the pond had a good potential to perform as expected, but several operating problems were observed: wind causes surface mixing of the salt gradient; rain water dilutes the proper gradient at the surface; and organic debris can collect in the pond and obstruct incoming solar radiation. To overcome some of the problems caused by wind, rain and debris and also to study insulating benefits of the cover, Husseini et al. (1979) constructed a polyethylene cover over the solar pond designed by Short et al.(1976). They also installed a reflector on the north wall with a tilt angle of 75° over the pond in an attempt to increase the solar radiation input. Their tests showed that the plastic cover was of questionable benefit. The cover and supporting frame decreased the radiation to the pond's surface by about 10 percent. They also found that the maximum benefit of the reflector occurred in the winter months. The annual energy gain of the pond with a reflector was 12 percent for a slope of 75°, and 14 percent for slope equal to 90°.

Shah et al.(1981) added another refinement to the solar pond concept by using a heat pump that uses a solar pond as its heat source for heating the greenhouse. This increases the effectiveness of the heat pump as well as the solar pond. A heat pump designed for a source temperature of 5°C to 40°C in the pond has greater stability and higher efficiency than a heat pump that uses the ambient air as its heat source. Also, the energy storage and availability of stored energy is increased by a heat pump. Energy can be efficiently extracted down to lower temperatures in the heat source even when the solar pond temperature is below that of the greenhouse.

EXCESS INTERNAL HEAT COLLECTION

An excess amount of heat from the collected and trapped solar radiation within greenhouses is usually available around noon hours. This excess heat must be eliminated by either natural or forced ventilation. Many design concepts have been proposed to collect this excess heat and store it for later use (Wilson et al.(1977), Baird et al.(1977), Rotz and Aldrich(1978), Milburn and Aldrich(1979), Albright et al.(1979) and Chandra and Willits(1980)).

Wilson et al.(1977) adopted the notion of the greenhouse as a solar collector; they attempted to determine its solar energy collection efficiency and ways to increase this efficiency. In their analysis, they considered the greenhouse as a horizontal flat plate solar collector of surface area equal to its floor area. The greenhouse solar collection efficiency was then calculated by dividing the solar component of daytime heating load by the measured insolation as given by weather data. They found that for the greenhouse under study, located at Cornell University, the greenhouse solar collection efficiency, as defined above, was about 32 percent.

Among the methods Wilson et al. have proposed to improve the greenhouse solar collection efficiency were: addition of a second cover, insulation of the north wall, insulation of a portion or all of the north roof, and modifying the greenhouse shape to maximize solar radiation input.

Baird et al.(1977) described the design and operation of a greenhouse solar heating system that uses partial shading in the greenhouse attic as the solar collector and an underbench rock thermal storage. The partial shading is accomplished by a layer of polypropylene shade cloth and a layer of clear polyethylene which constitute the only additional cost of the solar collector. The authors hope this system would be suitable for ornamental foliage producers, where a 50 percent reduction in light will probably be acceptable. The system has been tested in a glasshouse located at Bradenton, Florida. Their results showed that this solar heating system provides enough heat to maintain a minimum greenhouse temperature at least 14^{o}C above ambient. For reason of light availability, the above described system obviously is not applicable under Canadian conditions.

Rotz and Aldrich (1978) attempted to predict, through computer simulations, the possible fuel savings and cost benefits for the use of thermal insulation (double glazing and/or thermal blankets) and solar heat utilization (internal or external collection) in a commercial-sized greenhouse at eight locations across the United States. Their conclusions indicated that all these systems were able to reduce the fuel requirement substantially at all locations except the internal collection system. This system only performed well in the mild climatic regions (i.e. California, Florida). In cold climate regions of the U.S., internal solar energy collection in greenhouses was predicted to result in less than 5 percent fuel saving.

Milburn and Aldrich (1979) studied the effectiveness of collecting the excess heat generated by solar radiation in a greenhouse by circulating the warm air as it is collected under the roof ridge of the greenhouse through a rock heat storage unit. In particular, they compared a system using a plastic tube with inlet holes placed along the ridge of the greenhouse with a fan and ducting to circulate the warm air from the ridge to the heat storage units with a similar system minus the plastic tubing. In their conclusion to the study, the authors found that with this method of collection of excess internal heat in a single cover greenhouse, located in Pennsylvania, 10 to 20 percent of the annual heating load could be met. The performance of this system was found to be dependent on ambient temperature, crop zone temperature and air flow rate. The use of the perforated collection duct in the ridge improved the collection efficiency of the system.

Chandra and Willits (1980) developed a computer simulation model to predict the thermal behavior of a greenhouse attached to a rock bed thermal storage situated outside the greenhouse. The rock storage is charged from excess solar energy collected in the greenhouse.

The model as presented in the paper was intended to predict temperatures, relative humidities, and heat balances for the greenhouse air and the rock bed.

The model was tested using measured data from a prototype operating system located in Raleigh, North Carolina. The predicted values of temperatures and humidities were reasonably close to the measured data. However, an estimate for the system efficiency, either predicted or calculated from experimental data, was not given.

Albright et al.(1979) tested yet another method of improving the greenhouse as a passive solar collector. This method consisted of laying flat wide polyethylene tubing, filled with water, on the benches or ground between the rows of pots or plants. These tubes are usually referred to as Q-mats*. The purpose of these Q-mat tubes is to increase the thermal mass within the greenhouse. Tests performed with the Q-mats indicated that approximately 55 percent of the incident solar radiation was absorbed when they were used with the absence of plant canopy. However, when the Q-mat

---

* Trade name.

tubes were placed under a thick canopy (chrysanthemums in the bud stage), only 25 percent of the solar radiation above the canopy was absorbed by the tubes.

Experiments with Q-mats performed by the authors at Cornell University during the winter indicated a contribution of about 10 percent to the night heating requirement of a Brace Institute style greenhouse.

Lawand et al.(1973, 1975) proposed an unconventionally shaped greenhouse for colder regions. The basis for the new design was to maximize solar radiation input and reduce heat losses associated with conventional greenhouse designs.

The proposed greenhouse has a long-axis oriented east-west, the south-facing roof and wall are transparent, and the insulated north-facing wall is inclined toward the south and covered with solar radiation reflective material on the interior face. The angle of the transparent roof, and the inclined wall are location specific. These angles are chosen to optimize both the solar radiation transmission by the south roof, and the reflection of this radiation by the rear wall on the plant canopy. This type of design became to be known as the Brace Institute greenhouse.

An experimental Brace Institute greenhouse having the transparent surfaces covered with a double layer of polyethylene was tested during a cold winter in Quebec City. The authors claimed a reduction in heating requirements of 30 to 40 percent compared to a conventional, double layered plastic covered greenhouse. They also reported an increase in crop yields (tomatoes and lettuce) grown in the new greenhouse. The improved crop production was attributed to increased light availability in the Brace Institute greenhouse during the winter period.

INTEGRAL SOLAR COLLECTORS

Very little research has been done on integral solar collectors for greenhouses because of their limited applications. Integral solar collectors are likely to be limited to relatively small greenhouses. As a general rule, the size of collector required for solar heating of greenhouses should be approximately equal to the floor area of the greenhouse. It is impossible to install a collector system of this size within the greenhouse without shading the plants and interfering with normal greenhouse operations.

Recognizing the above limitations, researchers who attempted to apply integral solar collectors to greenhouse heating have concentrated on the use of the north-facing wall of the greenhouse. Previous studies showed that insulation of the north wall had no effect on plant yield (Willits et al. 1979).

Light levels in insulated greenhouses such as the Brace design were investigated by Turkewitsch and Brundrett(1979) for Toronto and Winnipeg, using a computer simulation model.

Four greenhouses were chosen for study; a N-S oriented gable, an E-W oriented gable, a Brace type and a Greensol type. The latter is a modified Brace design, developed by the authors. Both the Brace and the Greensol have an insulated and reflective north wall.

Floor level radiation in the four greenhouses were computed. When the results of the two gable greenhouses were compared, the N-S ridge was found to collect more solar radiation in the summer months, and less in the winter months than the one with an E-W ridge orientation. However, when the results of the four greenhouses were compared, the authors found that the Brace type has the highest winter solar radiation collection efficiency and the lowest summer collection efficiency of all the greenhouses in both locations.

Liu and Carlson(1976) have proposed a greenhouse design using a flat place collector facing south at a tilt angle of 60°. It would be located on the roof of an A-frame head house built inside the north wall of the greenhouse. The authors recommended that a single-plate, corrugated aluminum collector be used. The aluminum should be dark coated, and a copper tube manifold, with holes drilled to match the valleys in the aluminum corrugations, suspended over the top of the collector to supply water flow. A gutter at the bottom would collect the heated water. A selective reflecting collector cover may be used to enhance the radiation for crop growth in the planting area.

Calculations for this design are presented for Beltsville, Maryland at 40°N latitude for a greenhouse 7.32m long by 6.1m wide. The integral solar collector has a surface area of $36m^2$. The authors estimated that the solar collector and storage system could account for 78 percent of the greenhouse heating load.

A $46.47m^2$ greenhouse with a flat plate solar collector as a part of the north-facing wall with a crushed rock thermal storage located underneath the concrete floor was designed and tested by Click and Pile(1980). The greenhouse was built with one-quarter circle pipe frame members to form the south wall and roof. The north wall was an insulated wood frame construction The covering was two air separated layers of polyethylene sheeting.

The $28m^2$ flat plate collector on the interior of the north-facing wall used 26 guage, corrugated metal roofing painted flat black, fastened over a system of wooden spacers that formed air-flow channels behind the black metal collector. A fan in the bottom of the wall pulled air through a plenum at the top of the wall and then forced the heated air through the rock storage. The cooled air exited the rock storage at the front inside wall of the greenhouse. A differential thermostat controlled the circulating fan moving air through the solar collector. When the air behind the collector place was 10°C higher than the rock storage temperature, air was circulated through the system.

Data collected during the winter of 1979-1980 indicated that a greenhouse of this type, located in Cookeville, Tennessee, could realize significant energy savings up until late November and beginning again in late February. The authors found that this system could reduce heating costs or extend growing seasons in unheated greenhouses.

The Boeing Company has introduced an interesting approach to integral solar collectors for greenhouse use (Deminet, 1976). The glass collectors function both as the greenhouse glazing and as a solar collector. This concept would increase the ratio of collector to greenhouse floor area. As stated earlier, low ratios are the major constraints to efficient use of integral solar collectors for greenhouses. The Boeing dual greenhouse cover-solar collector system is basically a sandwich construction with three layers of glass forming two spaces. The top space is empty with a partial vacuum. The bottom layer is designed to conduct the flow of circulating collector fluid. Ideally, the collector fluid can be chosen to transmit only selected portions of the solar spectrum so that the most useful portion of insolation for plant growth (photosynthetically active radiation) is transmitted to the crop. The portion of the solar spectrum at other wavelengths is absorbed and transformed to heat in the collector fluid. It appears that this technology might have application in warm climates where midday screening of some direct insolation is necessary anyway. At the time Deminet(1976) presented his paper, the system was not tried in a practical application and suitable collector fluids had not been chosen.

Recently, van Bavel and Sadler(1979) at Texas A & M University, experimented with what they have called fluid-roof greenhouse concept. The tests were performed in a small, specially designed greenhouse. No crops were grown in the greenhouse, but the floor was covered with a standard St. Augustine turf. The main objectives of these preliminary tests were to find solutions to some construction engineering problems, rather than to conduct a detailed study on plant behavior in the different environment created by the fluid-filter roof. Experience gained by the authors from these preliminary tests suggested that the plumbing and circulation of the copper chloride solution, used as infrared absorbing fluid, present problems that must be solved prior to any practical application.

It is doubtful that the fluid-roof greenhouse concept would be applied in colder regions. Therefore, no further discussions of this system will be given during this study. The interested reader is referred to publications by van Bavel (1978), van Bavel and Damagnez(1978), and van Bavel et al.(1980).

GASES IN TOTAL CONFINEMENT ANIMAL HOUSING UNITS

Gaseous contaminants found in confined animal buildings originate not only from manure decomposition but also from the animals themselves. Metabolic processes by the housed animals constitute the main source of carbon dioxide in barns, while decomposition of manure is the chief contributor to ammonia, methane and hydrogen sulfide concentrations found in animal barns.

Application of the greenhouse-livestock building combination concept requires the knowledge not only of the gases present in the ventilated air from the livestock building but also their concentrations. Unfortunately, actual data on gas concentrations in exhaust air from animal barns under Canadian conditions are not readily available. However, recent information given by McQuitty and Feddes (1982) and van Dalfsen and Bulley (1982) could be used as a guideline to estimate the expected concentrations in the exhaust air.

AMMONIA

A literature review undertaken by McQuitty and Feddes (1982) revealed that NH_3 concentrations vary considerably in animal barns. In a well ventilated building, expected concentrations appear to lie in the 5 to 30 ppm range. Values of 50 ppm however, are not uncommon during periods of winter minimum ventilation rates.

McQuitty and Feddes (1982) recorded NH_3 concentrations in the range of 5 to 12 ppm in four swine buildings; 2 to 12 ppm in two broiler houses; and less than 2 ppm in four dairy barns. van Dalfsen and Bulley (1982) reported a range between 1 to 7 ppm in four dairy units with subfloor manure storage. During agitation of manure, higher NH_3 concentrations can be anticipated, possibly in the range of 100 to 200 ppm (McQuitty and Feddes, 1982).

HYDROGEN SULFIDE

Values of H_2S concentrations have been found to be undetectable to low in many total confinement animal buildings. Concentrations in swine barns tend to be somewhat higher than in buildings housing other types of animals. McQuitty and Feddes (1982) found mean H_2S concentrations under winter conditions of less than 10 ppb in two broiler houses and four dairy barns. In four swine barns, the authors found mean H_2S concentrations of 70 ppb just above the slotted-floor while less than 10 ppb was measured in the exhaust air.

van Dalfsen and Bulley (1982) found that H_2S was undetectable in the four dairy units during normal operating conditions. However, when manure is disturbed, particularly by agitation, an immediate release of the gas in large quantities will occur resulting in considerable increase in concentrations. They reported a concentration of 2.7 ppm during agitation of the manure in the four dairy barns.

METHANE

McQuitty and Feddes (1982) stated that CH_4 concentrations likely to be encountered in ventilated animal buildings would not be a direct health hazard, even under winter minimum ventilation rates. Expected concentrations were not reported.

CARBON DIOXIDE

CO_2 is normally present in fresh air at a concentration in the order of 300 ppm. Concentrations in the range of 500 to 3000 ppm were experienced in ventilated animal buildings. During winter conditions, McQuitty and Feddes(1982) found concentrations of CO_2 to be less than 4000 ppm in four swine buildings, two broiler houses and four dairy barns in Alberta.

CARBON DIOXIDE ENRICHMENT OF GREENHOUSES

The effect of CO_2 enrichment on greenhouse crop production was recently investigated by Willits and Peet (1981) in Raleigh, North Carolina. Greenhouse crops tested were tomatoes, cucumbers and bedding plants. Average concentrations of CO_2 within the greenhouse ranged between 1000 and 1050 ppm when the set point was established at 1000 ppm.

Their experimental results indicated an average increased yield of 14.6 percent for tomatoes, 42 percent for cucumbers and 104 percent for bedding plants. For cucumbers, the percentage increase ranged between 32.2% to 60.7% depending on the cultivar with Vetomil giving the greatest increase in production. Among the bedding plants tested, pepper plants were heavier in the CO_2 enriched greenhouse by 135 percent, followed by regular tomatoes, then cherry tomatoes which showed increases in harvest weights of 123 percent and 69 percent, respectively. No attempt was made to "grow out" these plants to determine CO_2 enrichment effect on fruit yields in the field.

Obviously, the increased yields due to greenhouse CO_2 enrichment found by Willits and Peet (1981) could only be taken as a representative case due to the complexity of the interactions between CO_2 concentrations and other environmental factors including light intensity and temperature.

In any event, the study by the above mentioned authors showed the beneficial effects of CO_2 enrichment on greenhouse crop. Since the actual CO_2 concentrations in exhaust air from livestock building is not well defined, the potential increase in yields of crops grown in a greenhouse-animal shelter combination could not be determined without experimentation. In addition, exhaust air from animal barns contains other gases than CO_2, including high concentrations of water vapour which may have an adverse effect on greenhouse crop productivity.

GREENHOUSE-LIVESTOCK BUILDING COMBINATION

An extensive review of the literature, undertaken for the present research project, revealed that neither theoretical nor experimental information on the concept of combined greenhouse-livestock building systems was available. However, the literature search indicated a significant amount of research, development and demonstration projects were performed on greenhouse-residence combinations by engineers, architects and ecologists. The greenhouse is mainly used in this case as a solar collector partially to provide the heating load of the attached house.

In a greenhouse-livestock combination, the basic approach is totally different than that used with respect to the greenhouse-residence combination, since the concept of the former combination is to use animal heat to supply some of heating requirements of the attached greenhouse. Therefore, the information on greenhouse-residence combination is somewhat irrelevant to this study and will not be discussed further. The interested reader is referred to the many excellent papers published in the Proceedings of the annual conferences on Solar Energy for Heating Greenhouses and Greenhouse-residence combinations*.

---

* Available from National Technical Information Service
U.S. Department of Commerce
Springfield, VA 22161

In 1980, researchers at Kansas State University published a study dealing with a greenhouse-animal shelter combination (Spillman et al. 1980). The main objectives of the research underway at Kansas State University were to evaluate yield and quality of greenhouse crops supplied with exhaust air from a hog house, and to compare the amounts of fossil fuel requirements of a conventional greenhouse to those of a greenhouse using exhaust air from animal buildings with solar energy storage.

The Kansas State University experimental facility unit consisted of an experimental greenhouse attached to the south-facing wall of a swine finishing barn and a conventional greenhouse for control. Both greenhouses have the same dimensions of 6 m by 7.3 m and were covered by air inflated double polyethylene film. The air flow rate from the hog barn was introduced to the experimental greenhouse either at 680 m^3 per hour or 1200 m^3 per hour. In addition the experimental greenhouse had 7.25 m^3 vertical rock bed thermal storage for excess internal solar heat collection.

Spillman et al (1980) dealt exclusively with the effects of supplying the greenhouse with animal produced carbon dioxide on crop production.

Air samples taken within the attached greenhouse indicated a carbon dioxide concentration of 1500 ppm when both hoghouse and greenhouse were unventilated, and 450 ppm to 600 ppm when both were ventilated. In addition to ventilation rates, CO_2

concentrations in the greenhouse depend upon the number and weights of the animals in the barn; 124 to 202 hogs averaging 30 to 135 kg were present during the experiments.

Plant growth studies were performed on tomatoes, cucumbers and broccoli. Tomato plants in the attached greenhouse were stockier with darker green colored leaves than plants in the control greenhouse during the first three months. Then apparently, they developed interveinal chlorosis and drying and curling of the lower leaves. A week later, the fruits were discovered to have blossom end rot. About three weeks later, these symptoms also appeared in the control greenhouse. Average production was very low in both greenhouses. The authors attributed the disease and eventually the poor yield to unbalanced fertilization.

Analysis of the yield data for cucumbers grown in both greenhouses showed that marketable fruit in the CO_2 house was 31 percent more than from the control house. Also, the marketable fruit in the experimental greenhouse weighed 40 percent plant more than those grown in the control house.

Broccoli transplants grown in the attached greenhouse had tops weight (above ground) more than 2 1/2 times when compared to the broccoli plants grown in the control house. A surprising result was nitrogen content in the broccoli tops, which was over 3 times as much for plants grown in the CO_2 house compared to those grown in the control greenhouse.

PART I

ANALYSIS OF THE EFFECT OF SEVERAL CONSTRUCTION PARAMETERS ON THE SOLAR RADIATION INPUT INTO GREENHOUSES

CHAPTER 1

SOLAR RADIATION TRANSMISSION FACTORS OF GREENHOUSES

INTRODUCTION

To compare greenhouses from a solar energy standpoint, a standard or bench mark is required so that the effect of latitude, solar radiation availability, size, orientation, shape and covering material can be estimated. A term which the author calls "a greenhouse transmission factor" is defined, then used to compare greenhouses with different construction parameters and at different locations for their solar radiation input efficiency.

This chapter is divided into three sections. The first describes a method for estimating the monthly average daily beam, diffuse and total transmittance of the greenhouse transparent surfaces. The second section gives the mathematical expressions for the solar radiation transmission factors of greenhouses. Also, the relative contribution to beam, diffuse and total solar radiation by the different surfaces of the greenhouse are investigated. In the last section, the total transmission factor concept is used to investigate the effect of several energy conservation strategies on the solar radiation input into greenhouses leading to a new design which the author calls "a solar-shed" greenhouse.

SECTION A

ESTIMATION OF THE MONTHLY AVERAGE DAILY BEAM, DIFFUSE AND TOTAL TRANSMITTANCE OF THE GREENHOUSE TRANSPARENT SURFACES

TRANSMITTANCE OF THE GREENHOUSE TRANSPARENT SURFACES

The following section describes the method used to calculate the monthly average beam and total transmittance of the greenhouse covering material to solar radiation. These average values are required to estimate the beam and total greenhouse transmission factors as indicated in Section B of this chapter by equations (13) and (15) respectively.

ASSUMPTIONS

The following assumptions are made in order to calculate the weighted average daily beam and total transmittance for the greenhouse covering materials.:

i) No condensation or dust accumulation on the greenhouse covering such that the transmittance is for the covering material only. However, absorption and reflection losses are accounted for.

ii) The transmittance of the greenhouse covering material to the diffuse component of radiation is independent of the orientation and tilt of the surface. It is assumed to be constant and equal to that of the beam.

THEORETICAL FORMULATION *

The instantaneous beam solar radiation flux transmitted through a greenhouse transparent cover is,

$$I_{b,t} = \tau_b I_b \qquad (1)$$

then, the daily energy weighted beam transmittance of the surface to the direct component of solar radiation may be calculated by integrating equation (1) from sunrise to sunset as follows:

$$\tau_{b,day} = \int_{\omega_{sr}}^{\omega_{ss}} \tau_b I_b d\omega \Bigg/ \int_{\omega_{sr}}^{\omega_{ss}} I_b d\omega . \qquad (2)$$

Since solar radiation data are usually available on an hourly basis, the daily beam transmittance of the greenhouse covering material may be approximated by:

$$\tau_{b,day} \cong \sum_{\omega_{sr}}^{\omega_{ss}} \dot{\tau}_b \dot{I}_b \Bigg/ \sum_{\omega_{sr}}^{\omega_{ss}} \dot{I}_b . \qquad (3)$$

* The definition of symbols used in this section can be found on Pages 89 and 90.

For feasibility studies of solar energy applications to greenhouses, it is more important to be able to estimate monthly average daily beam and total transmittance for each of the transparent greenhouse surfaces which are location dependent.

For locations where both monthly average daily diffuse and total insolation on a horizontal surface are known, the monthly average hourly diffuse and total insolation may be estimated using the Liu and Jordan method (1960).

Since most widely available solar radiation data are in the form of monthly average total insolation on a horizontal surface, correlation equations must be used to separate the monthly average daily total solar radiation into its two components. Many empirical equations have been proposed for such a purpose (Liu and Jordan (1960), Page (1961), Tuller (1976) and Iqbal (1978). Iqbal (1978) gives a detailed discussion of these correlations, including a comparison of the results obtained by each of these methods.

Here, Iqbal's correlation equation,

$$\overline{H}_d/\overline{H} = 0.958 - 0.982\ \overline{K}_T \qquad (4)$$

is used throughout the analysis.

When the monthly average hourly diffuse and total insolation on a horizontal surface are known, then the monthly average hourly beam solar radiation incident on a tilted surface "i" of the greenhouse is determined as follows:

$$\bar{I}_{b,i} = (\bar{I} - \bar{I}_d)\bar{R}_{b,i} \; , \qquad (5)$$

where $$\bar{R}_{b,i} = \cos\theta_i/\cos\theta_h \qquad (6)$$

where $$\cos\theta_h = \cos\phi \, \cos\delta \, \cos\omega + \sin\phi \, \sin\delta \quad (7)$$

and
$$\begin{aligned} \cos\theta_i = {} & \cos\beta_i \sin\delta \sin\varphi \\ & - \sin\delta \cos\varphi \sin\beta_i \cos\gamma_i \\ & + \cos\delta \cos\varphi \cos\beta_i \cos\omega \\ & + \cos\omega \cos\delta \sin\beta_i \cos\gamma_i \sin\varphi \\ & + \cos\delta \sin\beta_i \sin\gamma_i \sin\omega \, . \end{aligned} \qquad (8)$$

Also, the monthly average daily diffuse solar radiation on the tilted surface is,

$$\bar{H}_{d,i} = (1/2)(1 + \cos\beta_i)\,\bar{H}_d + (1/2)\,\alpha(1 - \cos\beta_i)\bar{H} \, . \; (9)$$

In this equation, the sky-diffuse radiation $\bar{H}_d$, and the ground reflected radiation $\alpha\bar{H}$ are assumed isotropic. Knowing the different components of the radiation on the tilted surface, the monthly average daily beam transmittance of greenhouse surfaces may be estimated as follows:

$$\bar{\tau}_{b,i} = \sum_{\omega_{sr}}^{\omega_{ss}} \dot{\tau}_{b,i} \, \bar{I}_{b,i} \Big/ \sum_{\omega_{sr}}^{\omega_{ss}} \bar{I}_{b,i} \qquad (10)$$

and for the monthly average daily total transmittance,

$$\bar{\tau}_i = (\bar{\tau}_{d,i}\bar{H}_{d,i} + \sum_{\omega_{sr}}^{\omega_{ss}} \tau_{b,i}\ \bar{I}_{b,i})/\bar{H}_i \qquad (11)$$

where

$$\bar{H}_i = \bar{H}_{d,i} + \sum_{\omega_{sr}}^{\omega_{ss}} \bar{I}_{b,i} \qquad (12)$$

is the daily total solar radiation incident on the greenhouse transparent surface, i.

The beam and diffuse transmittance for the glass as a function of the angle of incidence and the optical properties of the glass and its thickness are calculated using the method described by Duffie and Beckman (1974). This method takes into account both reflection and absorption losses. For the diffuse transmittance the angle of incidence is assumed to be constant and taken to be equal to 58°. A summary of the above method is included in Appendix A for the sake of completeness.

SECTION B

ESTIMATION OF THE MONTHLY AVERAGE DAILY BEAM, DIFFUSE AND TOTAL TRANSMISSION FACTORS OF GREENHOUSES

SOLAR RADIATION TRANSMISSION FACTORS OF GREENHOUSES

DEFINITIONS OF TRANSMISSION FACTORS *

The greenhouse transmission factor is defined as the ratio of the solar energy transmitted through the greenhouse covering system to that incident on a horizontal surface area equal to the floor surface area of the greenhouse with the absence of the greenhouse covering. As solar radiation incident of the greenhouse surfaces is composed of beam and diffuse radiation and the transparent covering has a different transmittance value for each of the two components of radiation, then we have two distinct transmission factors which could be defined as follows:

BEAM TRANSMISSION FACTOR (BTF)

$$\text{BTF} = \frac{\text{Beam solar radiation transmitted through the translucent greenhouse covering}}{\text{Outside beam solar radiation incident on a horizontal surface equal to the floor of the greenhouse}}$$

$$\text{BTF} = \frac{\sum_{i=1}^{n} A_i \bar{\tau}_{b,i} \bar{H}_{b,i}}{A_f \bar{H}_b} \; . \qquad (13)$$

* The definition of symbols used in this section can be found on Pages 89 and 90.

DIFFUSE TRANSMISSION FACTOR (DTF)

$$\text{DTF} = \frac{\text{Diffuse solar radiation transmitted through the translucent greenhouse covering}}{\text{Outside diffuse solar radiation incident on a horizontal surface equal to the floor of the greenhouse.}}$$

$$\text{DTF} = \frac{\sum_{i=1}^{n} A_i \bar{\tau}_{d,i} \bar{H}_{d,i}}{A_f \bar{H}_d}. \qquad (14)$$

TOTAL TRANSMISSION FACTOR (TTF)

Knowing the beam and diffuse transmission factors, a total transmission factor for the greenhouse may also be defined in a similar manner.

$$\text{TTF} = \frac{\text{Total solar radiation transmitted through the translucent greenhouse covering}}{\text{Outside total solar radiation incident on a horizontal surface equal to the floor of the greenhouse}}$$

$$\text{TTF} = \frac{\sum_{i=1}^{n} A_i \bar{\tau}_i \bar{H}_i}{A_f \bar{H}} = \frac{\sum_{i=1}^{n} A_i \bar{\tau}_{b,i} \bar{H}_{b,i} + \sum_{i=1}^{n} A_i \bar{\tau}_{d,i} \bar{H}_{d,i}}{A_f \bar{H}}. \qquad (15)$$

DESCRIPTION OF THE COMPUTER MODEL FOR TRANSMISSION FACTORS

A computer program was written in FORTRAN to compute the solar energy transmitted through each of the surfaces of a greenhouse, their percent contribution to solar input, and the greenhouse transmission factors. The program was originally written for monthly average daily values, but with minor modifications it could be used for specific days. The program will also handle any number of surfaces per greenhouse as long as they are flat, any number of covers as long as they are of the same material for any particular surface. Different covering materials for different surfaces are permitted.

Input variables:

1. Monthly average daily total insolation on a horizontal surface.
2. Reflectivity of surrounding surfaces to solar radiation.

Input parameters:

1. Location of the greenhouse (latitude)
2. Number of surfaces which make up the greenhouse
3. Orientation, tilt and number of covers for each of the surfaces
4. Optical properties (index of refraction and extinction coefficient) and thickness

of greenhouse covering material for each of the surfaces

Outputs:

1. Average daily beam, diffuse and total transmittance of each of surfaces making up the greenhouse.
2. Average daily beam, diffuse and total solar energy transmitted through various surfaces.
3. Contribution of each surface to beam, diffuse and total solar energy inputs.
4. Daily beam, diffuse and total solar energy transmitted through the greenhouse covering.
5. Average daily beam, diffuse and total transmission factors for the greenhouse.

SAMPLE OUTPUT: RESULTS AND DISCUSSION

A 500 square metre gable glasshouse was used as an example. The greenhouse length and width are 50m and 10m respectively, with a wall height of 2m and an 18° roof slope. The long-axis of the greenhouse is east-west oriented. The cover is single glass with the following characteristics;

Thickness	3.0 mm
Extinction Coefficient	0.161 cm^{-1}
Index of Refraction	1.526
Location	Vancouver, B.C. (49.25°N)

The monthly average daily total insolation on a horizontal surface and the monthly average ground cover reflectivity for solar radiation (albedo) used as input to the program are indicated in Table 1.1.

The calculated monthly average daily diffuse transmittance for the single glass cover was 0.818, which is independent of orientation and tilt angles. The monthly average daily beam transmittance and total transmittance for the various surfaces of the greenhouse are shown in Figures 1.1 and 1.2, respectively.

A sample of results of the other outputs of the computer model are shown for December and for July in Tables 1.2 and 1.3, respectively. These two tables are included here for discussion purposes. Appendix B gives a complete computer output for a greenhouse having construction parameters as described above. The transmission factors for the beam, diffuse and total solar radiation are shown in Figure 1.3

It is important to notice that the greenhouse diffuse transmission factor (DTF) remains fairly constant over the

Month	MONTREAL (45.5°N)			WINNIPEG (50°N)			EDMONTON (53.5°N)			VANCOUVER (49.25°N)			TUSCON (32.5°N)	
	$\overline{H}$ kJ.m^{-2}day^{-1}	α	$\overline{H}_d/\overline{H}$	$\overline{H}$ kJ.m^{-2}day^{-1}	α	$\overline{H}_d/\overline{H}$	$\overline{H}$ kJ.m^{-2}day^{-1}	α	$\overline{H}_d/\overline{H}$	$\overline{H}$ kJ.m^{-2}day^{-1}	α	$\overline{H}_d/\overline{H}$	$\overline{H}$ kJ.m^{-2}day^{-1}	$\overline{H}_d/\overline{H}$
Jan	5 272	0.32	0.52	5 230	0.32	0.39	3 682	0.32	0.44	2 970	0.18	0.65	13 180	0.30
Feb	8 870	0.33	0.45	9 247	0.33	0.33	6 987	0.33	0.40	5 565	0.17	0.59	16 359	0.30
Mar	14 058	0.25	0.40	14 226	0.25	0.33	12 678	0.25	0.35	10 502	0.12	0.50	22 394	0.23
Apr	16 192	0.20	0.47	27 447	0.22	0.41	17 615	0.22	0.38	15 188	0.14	0.48	27 425	0.21
May	20 167	0.20	0.45	20 794	0.20	0.42	20 711	0.20	0.42	20 502	0.14	0.43	30 501	0.20
Jun	22 092	0.20	0.43	22 259	0.20	0.43	22 259	0.20	0.42	22 845	0.14	0.41	29 246	0.26
Jul	21 297	0.20	0.44	23 012	0.20	0.39	22 886	0.20	0.39	23 179	0.14	0.38	26 192	0.32
Aug	17 581	0.20	0.47	10 497	0.20	0.39	18 033	0.20	0.42	19 121	0.14	0.41	24 602	0.31
Sep	12 975	0.20	0.46	13 472	0.20	0.44	13 054	0.20	0.42	13 682	0.14	0.44	23 849	0.23
Oct	8 954	0.20	0.50	8 494	0.20	0.46	8 075	0.20	0.42	7 280	0.14	0.54	18 493	0.26
Nov	4 268	0.23	0.64	4 644	0.23	0.51	4 100	0.23	0.47	3 766	0.15	0.61	14 895	0.25
Dec	3 891	0.28	0.59	3 766	0.28	0.47	2 678	0.28	0.49	2 385	0.18	0.67	12 761	0.27

Table 1.1 Monthly average daily total insolation on a horizontal surface, ground albedo and ratio of diffuse to total radiation for the locations selected for this study.

Note: The values for H are taken from "World Survey of Climatology", see reference Hare and Hay (1974).

- $\overline{H}_d/\overline{H}$ are calculated.

- For source of the ground albedo "α" refer to the text, pages 72 & 74

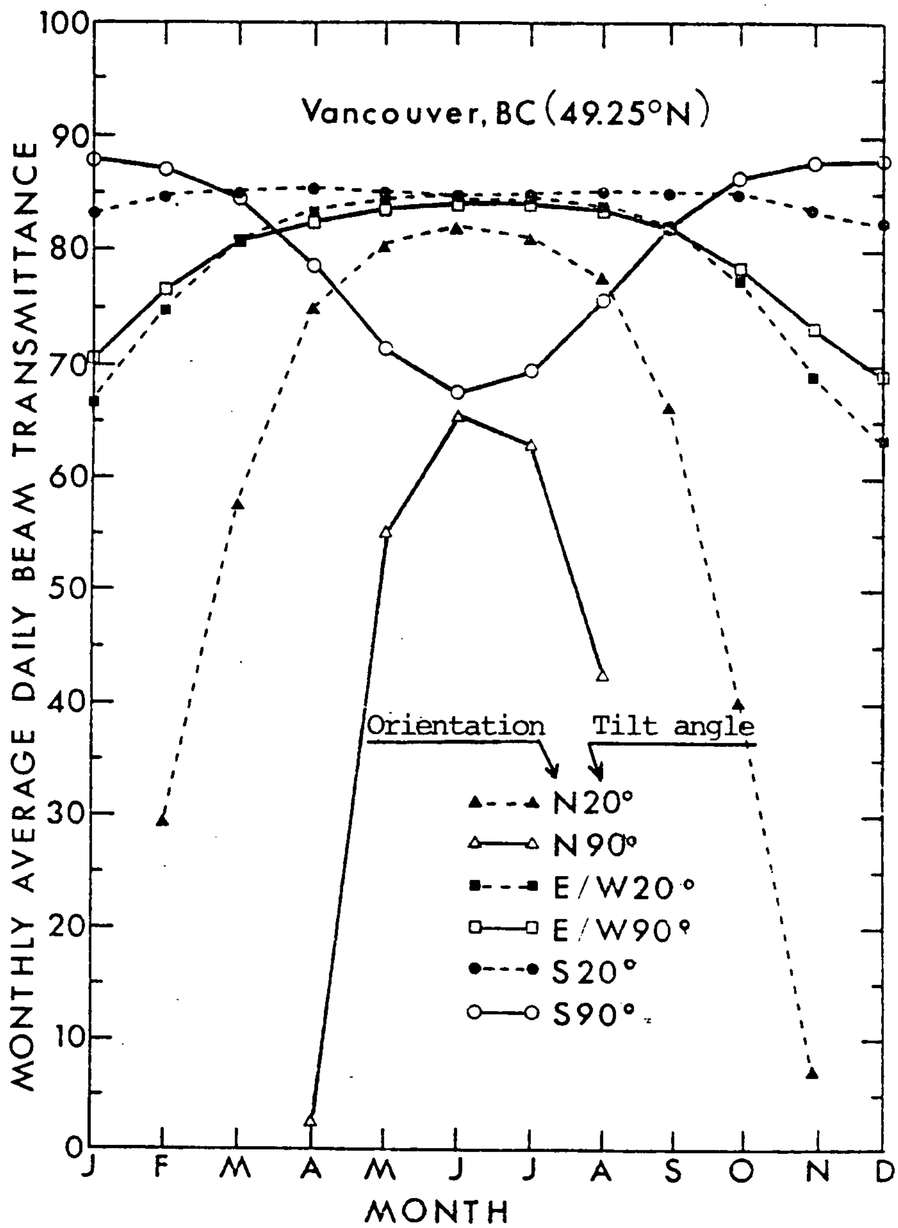


FIGURE 1.1 MONTHLY AVERAGE DAILY BEAM TRANSMITTANCE ($\bar{\tau}_b$) FOR VARIOUS SURFACES OF A GREENHOUSE WITH SINGLE GLASS COVER.

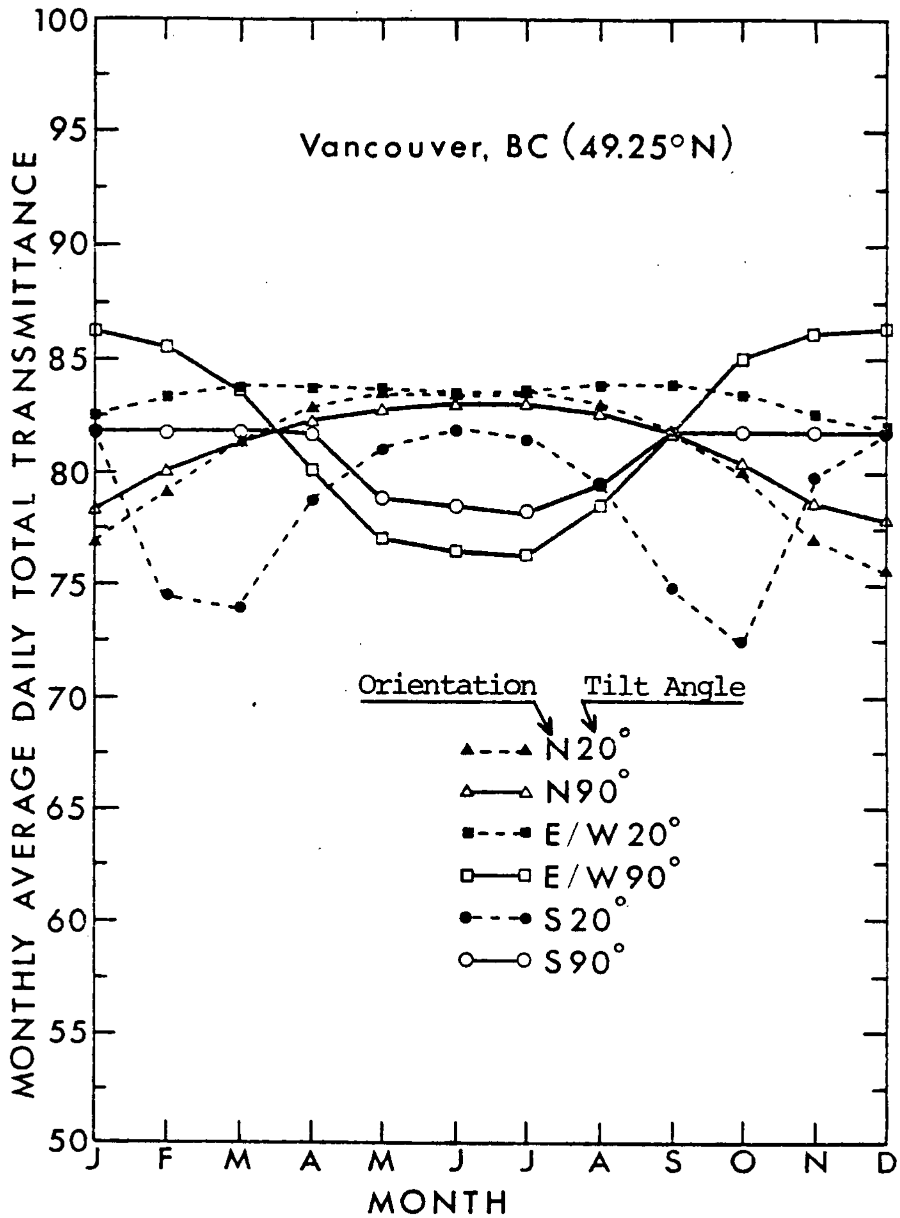


FIGURE 1.2: MONTHLY AVERAGE DAILY TOTAL TRANSMITTANCE ($\bar{\tau}$) FOR VARIOUS SURFACES OF A GREENHOUSE WITH SINGLE GLASS COVER.

VANCOUVER
DECEMBER

S	Area M**2	Solar Energy Transmitted (KJ/day) Beam	Diffuse	Total	Contribution To Total Beam	Diffuse	Total
1	100.	242904.	82072.	324976.	0.402	0.094	0.219
2	263.	342971.	333855.	676826.	0.568	0.380	0.457
3	263.	0.	333855.	333855.	0.0	0.380	0.225
4	28.	8962.	22958.	31919.	0.015	0.026	0.022
5	28.	8962.	22958.	31919.	0.015	0.026	0.022
6	100.	0.	81910.	81910.	0.0	0.093	0.055

Total Transmitted Beam	Diffuse	Total	BTF	DTF	TTF
603799.	877607.	1481404.	1.519	1.104	1.242

Table 1.2 **Sample Computer Output for an E-W single glass cover greenhouse (50m x 10m x 2m) and 18° Roof Slope**

S1: south wall   S4: east wall
S2: south roof   S5: west wall
S3: north roof   S6: north wall

BTF: defined Eq. 1
DTF: defined Eq. 2
TTF: defined Eq. 3

VANCOUVER
JULY

S	Area M**2	Solar Energy Transmitted (KJ/day) Beam	Diffuse	Total	Contribution To Total Beam	Diffuse	Total
1	100.	348908.	489930.	838838.	0.053	0.098	0.072
2	263	3233063.	1862202.	5095265.	0.489	0.374	0.439
3	263.	2613476.	1862202.	4475678.	0.395	0.374	0.386
4	28.	165209.	137180.	302389.	0.025	0.028	0.026
5	28.	165209.	137180.	302389.	0.025	0.028	0.026
6	100.	89404.	489930.	573349.	0.014	0.098	0.050

Total Transmitted Beam	Diffuse	Total	BTF	DTF	TTF
6615268.	4978622.	11593892.	0.927	1.118	1.000

Table 1.3 **Sample Computer Output for an E-W single glass cover greenhouse (50m x 10m x 2m) and 18° Roof Slope**

S1: south wall   S4: east wall
S2: south roof   S5: west wall
S3: north roof   S6: north wall

BTF: defined Eq. 1
DTF: defined Eq. 2
TTF: defined Eq. 3

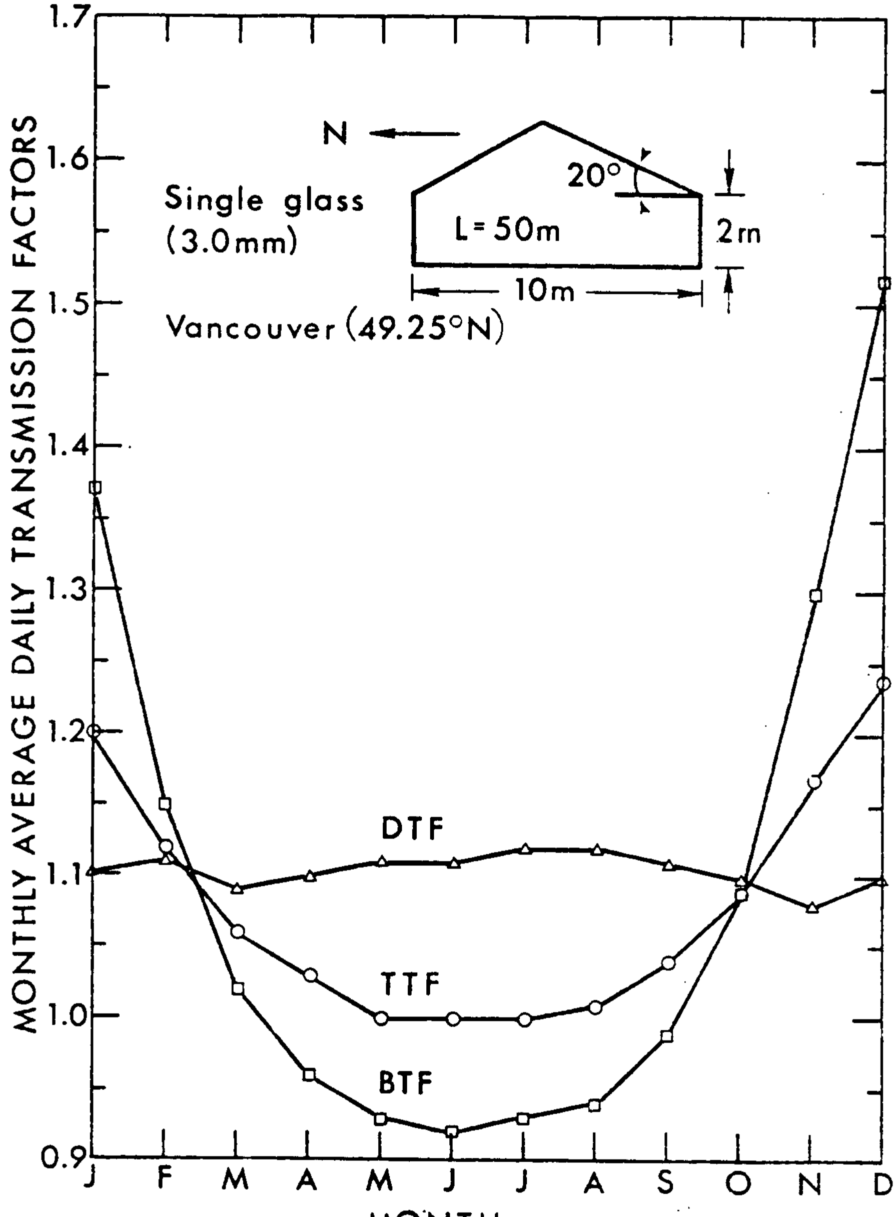


FIGURE 1.3: MONTHLY AVERAGE DAILY BEAM (BTF), DIFFUSE (DTF) AND TOTAL (TTF) SOLAR TRANSMISSION FACTORS FOR A GABLE GREENHOUSE.

year, since the glass transmittance to diffuse radiation is independent of the incidence angle. However, the greenhouse beam transmission factor (BTF) is high during the winter months (November, December, January and February), but low during the summer months. The high (BTF) during winter months for an east-west oriented greenhouse is due to high beam transmittance of the south roof and south wall (Fig.1.1) and high solar radiation incident on the south surfaces

Table 1.2 shows that for December the contribution of the two south surfaces to the total beam radiation input is 97%. For the summer months the daily beam transmittance of the south wall decreases (Fig. 1.1) and the beam radiation incident on the south surfaces also decreases (Table 1.3) which explains the lower (BTF) for the summer months. For the month of July the contribution of the two south surfaces to the total beam solar radiation input is only 54.2% as compared to 97% for December. Therefore, the high greenhouse total transmission factor (TTF) during the winter period for an east-west oriented greenhouse is due to the high contribution of the south surfaces to the beam component of solar radiation.

SECTION C

USE OF THE TOTAL TRANSMISSION FACTOR TO COMPARE GREENHOUSES FOR THEIR SOLAR RADIATION INPUT EFFICIENCY

USE OF THE TOTAL TRANSMISSION FACTOR

The percent loss or gain in solar radiation input to a greenhouse "y" as compared to a greenhouse "x" may be calculated from their greenhouse total solar radiation transmission factors (TTF) as follows:

$$\% \text{ LOSS/GAIN} = \frac{(TTF)_x - (TTF)_y}{(TTF)_x} \text{ X } 100.$$

EFFECT OF ORIENTATION ON THE GREENHOUSE TTF

Figure 1.4 shows the effect of north-south and east-west orientation on the total transmission factor. The total solar energy input is higher in the winter months and lower in the summer for the E-W orientation than for the N-S orientation. During January, the solar radiation input to the E-W greenhouse is (1.02-1.21/1.02)x100 = 18.6% higher than for the N-S greenhouse, but it is 6.6% lower in June and July. Therefore, an E-W oriented greenhouse requires less supplemental heat during the heating season and less ventilation in the summer if the heat loss from the greenhouse is assumed to be independent of orientation.

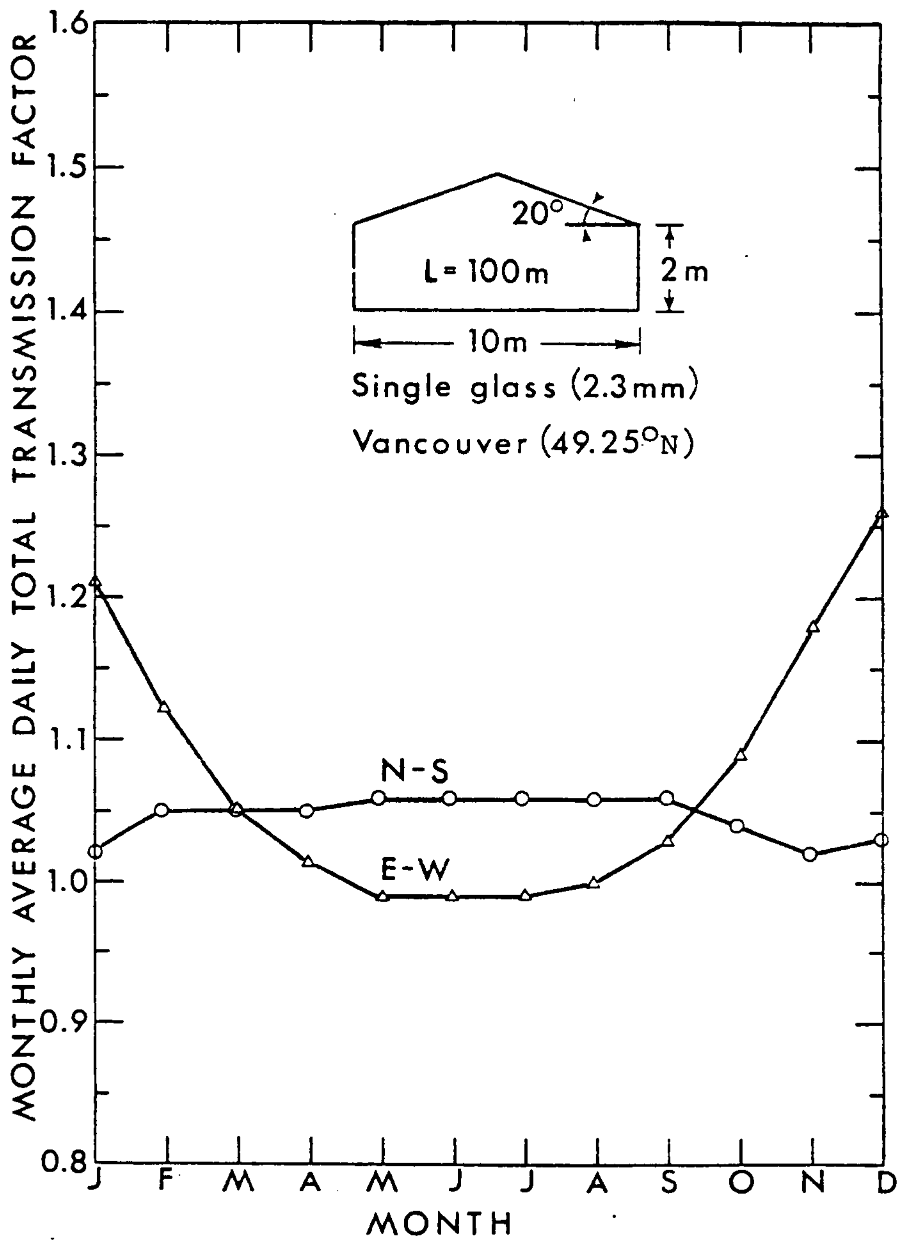


FIGURE 1.4: EFFECT OF E-W AND N-S ORIENTATION ON THE TOTAL TRANSMISSION FACTOR (TTF) FOR A GABLE GREENHOUSE.

EFFECT OF DOUBLE GLAZING ON THE GREENHOUSE TTF

The effect of double glazing on solar radiation input to the greenhouse is shown in Figure 1.5. The loss of solar energy input due to double glazing is only 13%. However, economics must be considered such that the savings in the cost of energy will offset the increase in capital cost for double glazing. Also, loss of productivity due to light reduction in the double glazed greenhouse must be considered.

EFFECT OF OPAQUE NORTH WALL ON THE TTF OF AN EAST-WEST GLASSHOUSE

The effect of covering the north wall of a greenhouse with opaque insulation on the heating load was investigated theoretically by Chandra et al.(1976) and experimentally by Wilson et al.(1977). The percent reduction in heating requirements is proportional to the relative surface area of the north wall to the total exposed surface area of the greenhouse. Wilson et al.(1977) found no change in light levels in the greenhouse with an opaque north wall. The Transmission Factors method (Figure 1.6) predicts a 5.6% loss of total solar radiation input due to the opaque insulation of the north wall of an East-West oriented greenhouse. Virtually all this loss is diffuse radiation. Therefore, its effect is restricted to a narrow band near the north wall.

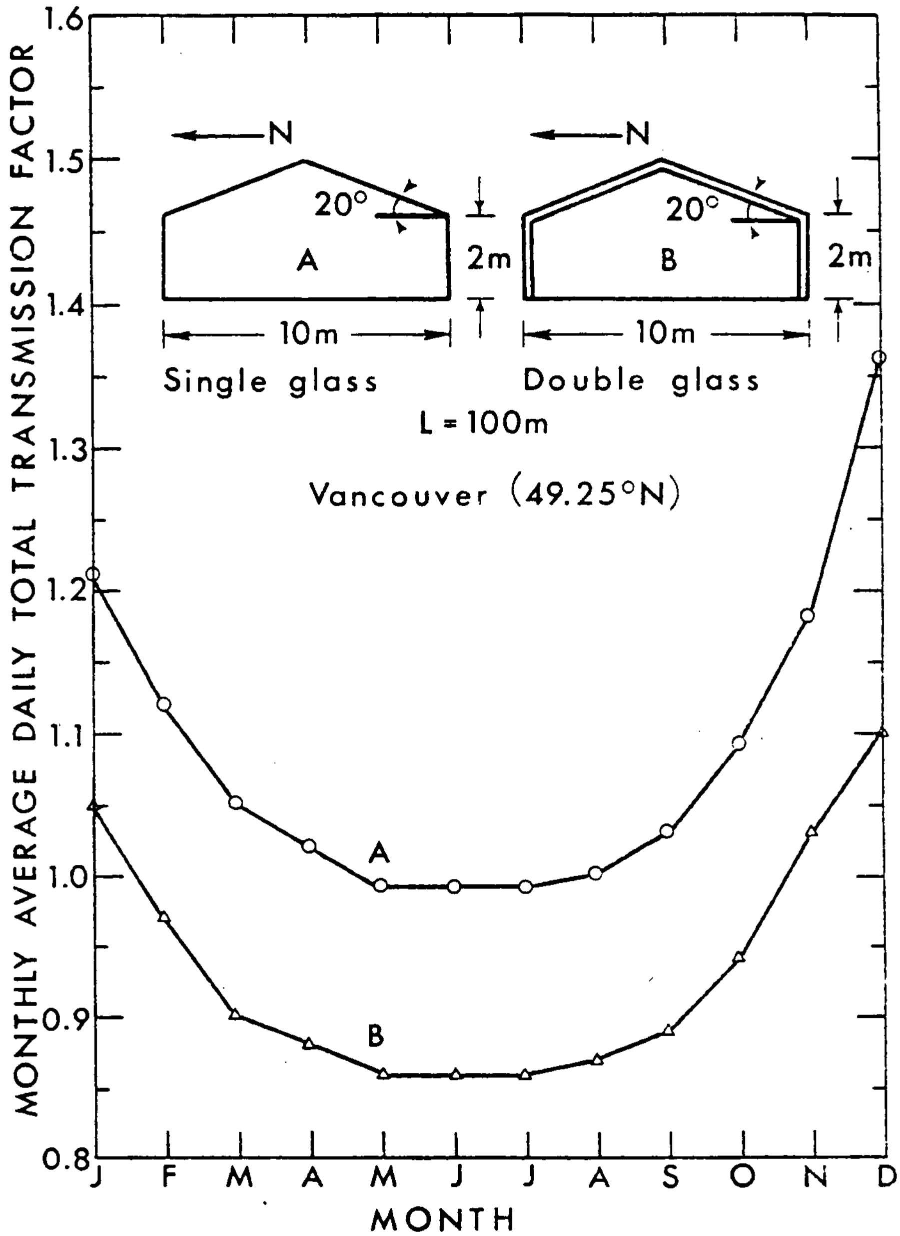


FIGURE 1.5: EFFECT OF DOUBLE GLAZING OF AN E-W ORIENTED GLASSHOUSE ON THE TOTAL TRANSMISSION FACTOR (TTF).

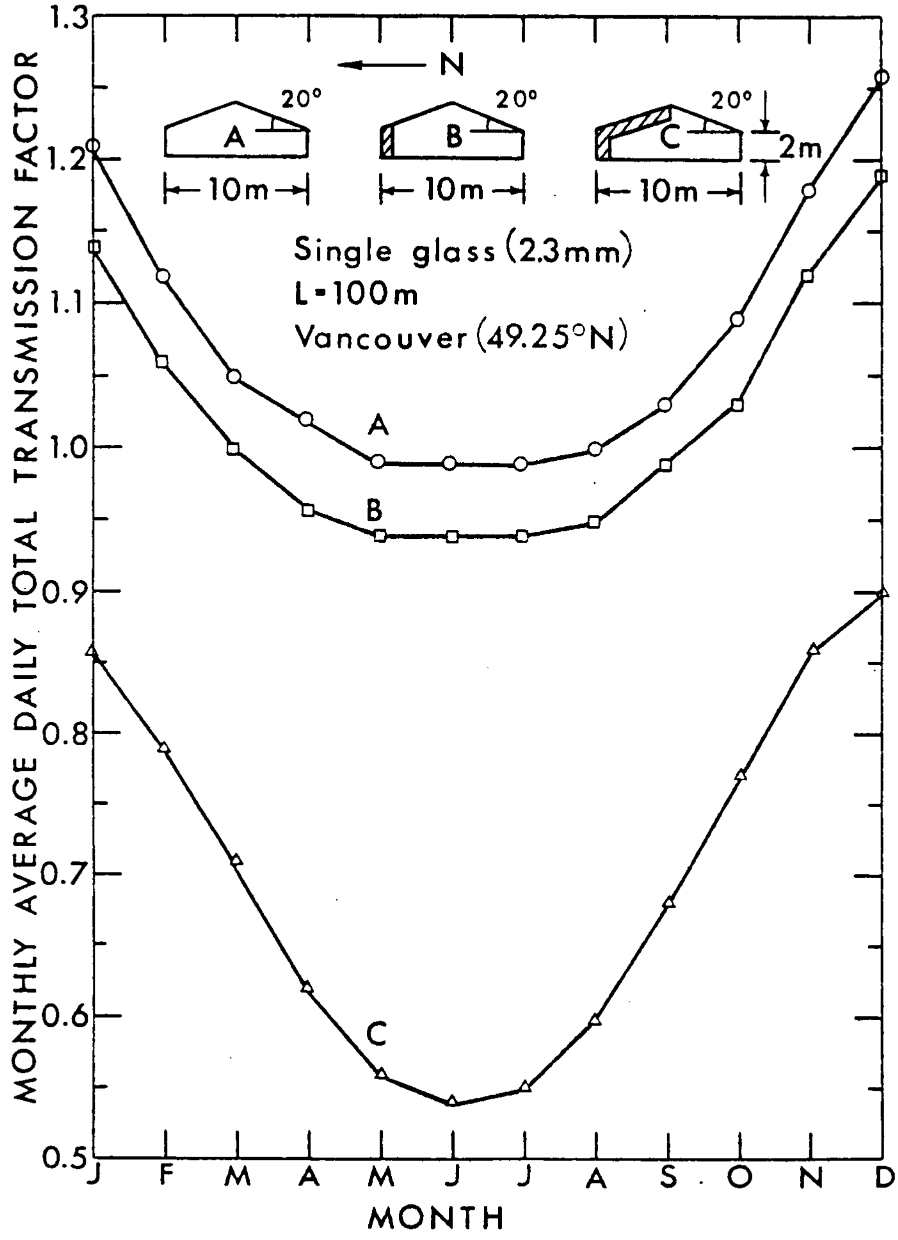


FIGURE 1.6: EFFECT OF INSULATING THE NORTH WALL OR NORTH WALL AND ROOF OF AN E-W ORIENTED GLASSHOUSE ON THE TOTAL TRANSMISSION FACTOR (TTF).

EFFECT OF OPAQUE NORTH WALL AND NORTH ROOF ON THE TTF OF AN EAST-WEST GLASSHOUSE

Insulating the north wall and the north roof totally or partially with an opaque material was proposed by Wilson et al.(1977). Figure 1.6 shows that a considerable loss in solar energy input may be experienced with this system of insulation. From Figure 1.6, the average losses may be calculated to be in the order of 25% for January and increasing to about 50% in June for a greenhouse located at Vancouver, B.C. (49.25°N) with all the north wall and roof being intransparent.

In addition, one expects a shading problem during most times of the year, depending on the latitude of the greenhouse. A movable or adjustable opaque insulation system might alleviate the shading problem.

EFFECT OF LOCATION ON THE GREENHOUSE TTF

An east-west oriented greenhouse (100m x 10m x 2m) was analyzed for four different locations in Canada, to determine the effect of latitude and solar radiation availability on the solar energy input to a greenhouse. The results expressed in terms of daily total transmission factors are included in Figure 1.7. The monthly average daily total solar radiation on a horizontal surface and the ground albedo used as input variables to the computer model are included in Table 1.1. The values for the ground albedo for Montreal

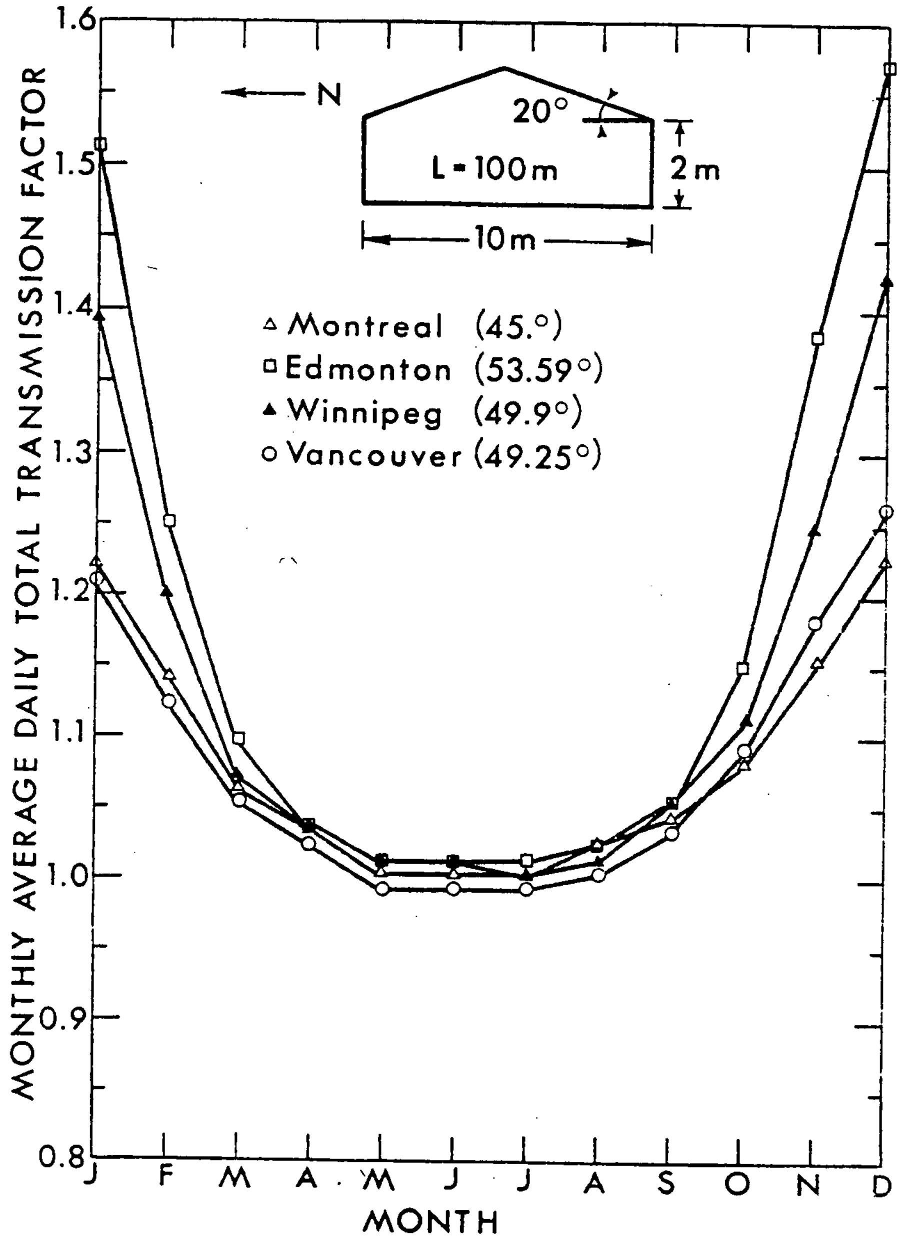


FIGURE 1.7: EFFECT OF LOCATION OF AN E-W ORIENTED GLASSHOUSE ON THE TOTAL TRANSMISSION FACTOR (TTF).

were taken from Hay (1976) and those of Winnipeg and Edmonton were were assumed to be the same as those of Montreal while those of Vancouver were from Hare & Hay (1974). The effects of errors in the estimation of the ground albedo on the solar energy input to a greenhouse is expected to be small since the contribution of the reflected component to total solar radiation incident on the various surfaces of the greenhouse is small, especially on the roof where the configuration factor between the roof and ground is only 0.03 for a 20° slope. Figure 1.7 shows that the same greenhouse located at a different location will have different solar radiation transmission factors, especially during the winter period. Among the four locations studied, the greenhouse located at Edmonton has the highest (TTF), while Montreal and Vancouver the lowest (TTF). For example, for the month of January, the transmission factor for the greenhouse used in this analysis is 1% higher for Montreal than for Vancouver, 16% for Winnipeg and 25% for Edmonton. The greenhouse total transmission factor is not only affected by the latitude of its location as shown by the difference in (TTF) between Winnipeg and Vancouver which are located at approximately the same latitude, but also by weather factors (i.e. cloud, smog etc.). The effect of weather factors on solar radiation may be estimated by the ratio of diffuse to total insolation $\bar{H}_d/\bar{H}$. The calculated values of these ratios are included in Table 1.1. These values suggest a correlation between total solar radiation transmission and capture and $\bar{H}_d/\bar{H}$ with lower ratios favouring the transmission factor.

SHED VS. GABLE GREENHOUSE

Changing the shape of a greenhouse from a conventional gable to a shed type construction increases the south facing surface area, thus improving the solar radiation input to the greenhouse during the winter months, as shown in Figure 1.8 for Montreal. However, during the summer months, the solar radiation input to the shed greenhouse is in the same order of magnitude as that for the gable greenhouse. The expected average increase in solar energy input to the shed greenhouse during the winter months over the gable greenhouse is about 20% (Figure 1.8).

Another advantage of the shed design is the facility by which a solar collector may be integrated within the greenhouse at the upper portion of the opaque north wall.

SHED VS. BRACE GREENHOUSE

The Brace greenhouse was developed by T.A. Lawand et al. (1975) at the Brace Research Institute. The design was specifically conceived for cold climate regions. A diagram of the Brace greenhouse is shown in Figure 1.8 (Shape B). The greenhouse must be east-west oriented with the north wall insulated and sloped at an angle equal to the sun's zenith.

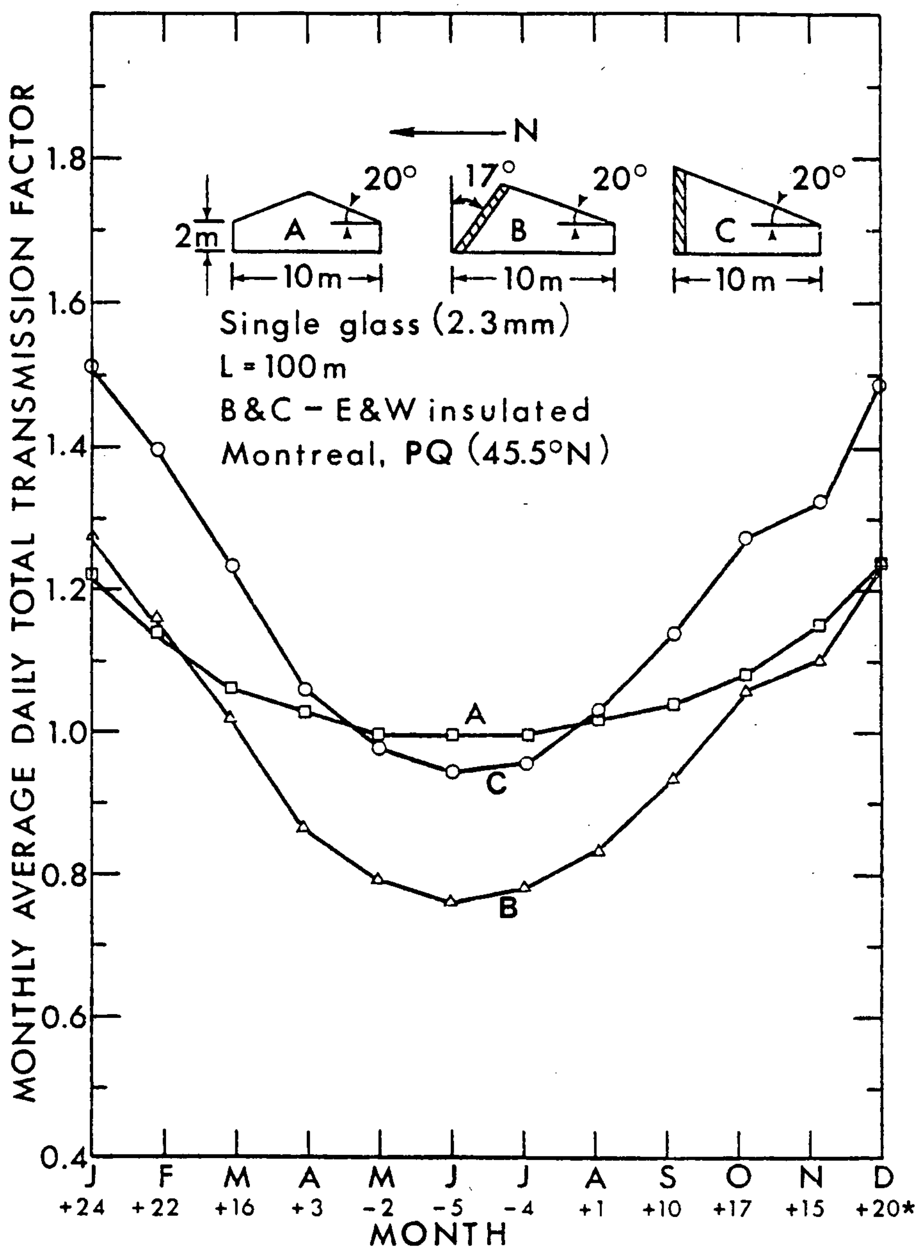


FIGURE 1.8: COMPARISON OF THE TOTAL TRANSMISSION FACTORS (TTF) FOR GABLE, BRACE AND SHED-TYPE GREENHOUSES.

* % Solar Radiation Input Gain/Loss for Shed vs Gable

angle during the summer solstice. The inner surface of the north wall is covered with a solar radiation reflection material (i.e. aluminum foil) to direct radiation on to the plant canopy.

The transmission factor method is used here to compare the Brace and the shed greenhouse for their solar radiation input efficiency as a function of the time of the year. The results for Montreal are shown in Figure 1.8. When the total transmission factors for Brace and shed are compared to that of a conventional gable greenhouse, it can be seen from Figure 1.8 that during the cold months (October to March inclusive), the Brace is equivalent to the gable greenhouse while the shed admits more solar radiation during that same period of the year. During the warm months (May to August inclusive), the shed becomes equivalent to the gable greenhouse while the Brace captures less solar radiation. Thus, the Brace greenhouse is more efficient than the gable or shed greenhouse due to its lower energy requirement for ventilation.

EFFECT OF LOCATION ON SHED GREENHOUSE TTF

The monthly average total transmission factors (TTF) were calculated for five locations having latitudes ranging from 32.5°N (Tuscon, AZ.) to 53.5°N (Edmonton, Alta.). The results for a shed greenhouse having a roof slope of 20 degrees and only the north wall insulated are shown in Figure 1.9. These results are based on data for $\overline{H}$ and α as given in Table 1.1. The ground albedo for Tuscon was assumed to be

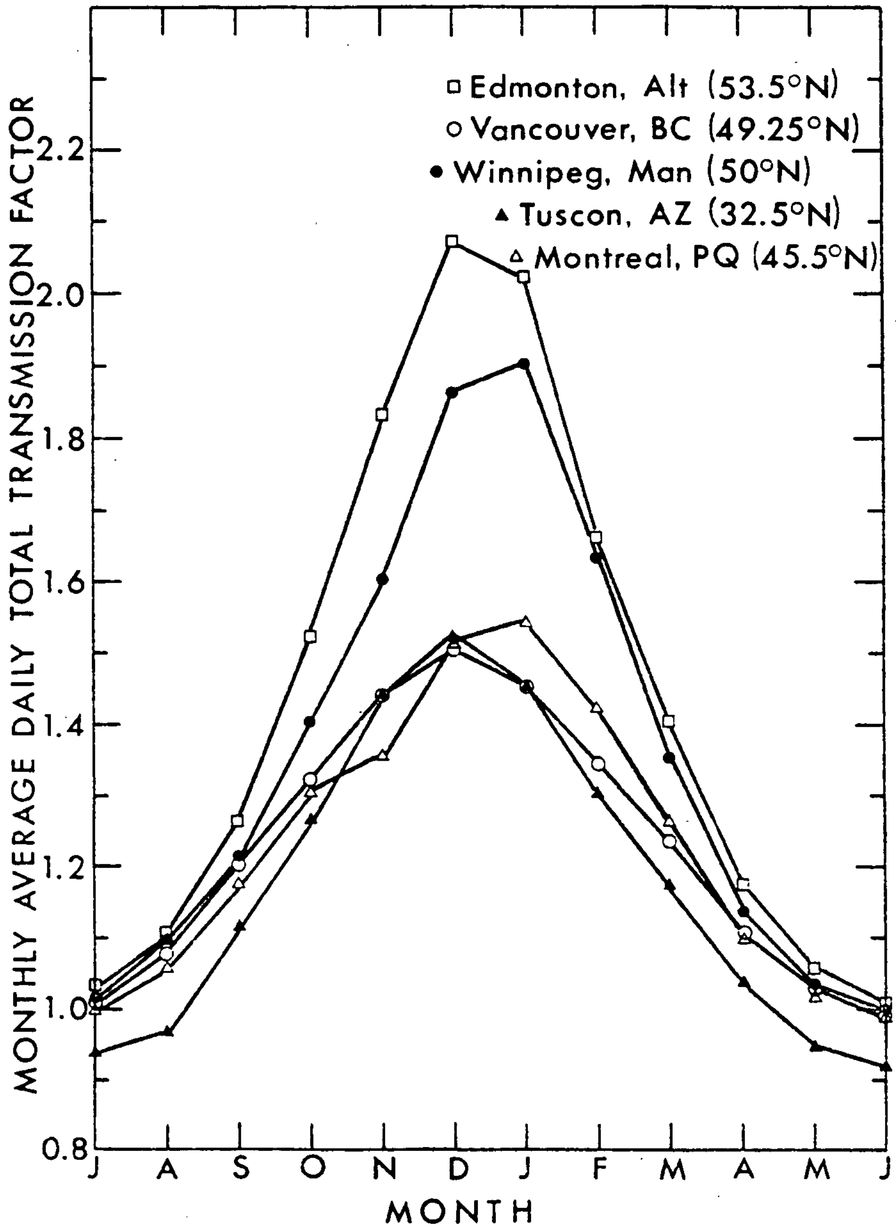


FIGURE 1.9: EFFECT OF LOCATION ON THE TOTAL TRANSMISSION FACTOR (TTF) FOR A SHED-TYPE GREENHOUSE.

constant over the year and equal to 0.20.

A simultaneous examination of Table 1.1 and Figure 1.9 indicates clearly the effect of latitude and cloudiness index $\bar{K}_T$ on the total transmission factor. As expected, the effect of latitude and $\bar{K}_T$ on (TTF) is small in the summer, giving a total transmission factor close to unity for all the five locations studied. However, during the winter months, the influence of $\bar{K}_T$ and latitude on (TTF) becomes more pronounced. It is interesting to notice the low (TTF) for Montreal for the month of November which can be explained by the relatively high cloudiness index ($\bar{K}_T = 0.64$) for that month. The effect of the cloudiness index on (TTF) can also be seen by comparing the results for Vancouver with those of Winnipeg. Even though these two cities are located at approximately the same latitude, the total transmission factors for Winnipeg during the winter months are significantly higher than those for Vancouver. Examination of Table 1.1 indicates that Winnipeg has lower cloudiness indices during the corresponding months.

The influence of latitude (TTF) can easily be seen if the results of Tuscon, Winnipeg and Edmonton are examined simultaneously (Figure 1.9 and Table 1.1). For the month of December, the average total transmission factor for the shed greenhouse is practically the same for Montreal, Vancouver and Tuscon (Figure 1.9). However (TTF) for Winnipeg and Edmonton, when compared to that of Montreal, are 23% and 37% higher respectively.

EFFECT OF LENGTH, WIDTH AND OPAQUE EAST AND WEST WALLS ON THE TTF OF A SHED GREENHOUSE

The contribution of the south wall, east and west walls and the south roof of a shed-type greenhouse to the beam, diffuse and total solar radiation input into the structure as it varies with time of the year is depicted in Figure 1.10. The shed greenhouse used in this example is 100 metres long by 10 metres wide with a south roof slope of 20 degrees from the horizontal. The height of the transparent section of the south wall is assumed to be 2 metres.

Figure 1.10 shows that the contribution of the south wall to the direct component of solar radiation input into the greenhouse is in the order of 20 percent during the winter months and decreased to a low value of only 3 percent during the summer period. This decrease in the beam radiation contribution can be attributed to the high incidence angle causing a reduction in the beam transmittance of the south cover.

On the other hand, the contribution of the same wall to the diffuse component of solar radiation input remained fairly constant throughout the year at an approximate value of 12 percent. This is a direct result of the assumed constant diffuse transmittance of the covering material.

The contribution of the east and west walls combined to beam solar radiation input to the shed greenhouse is

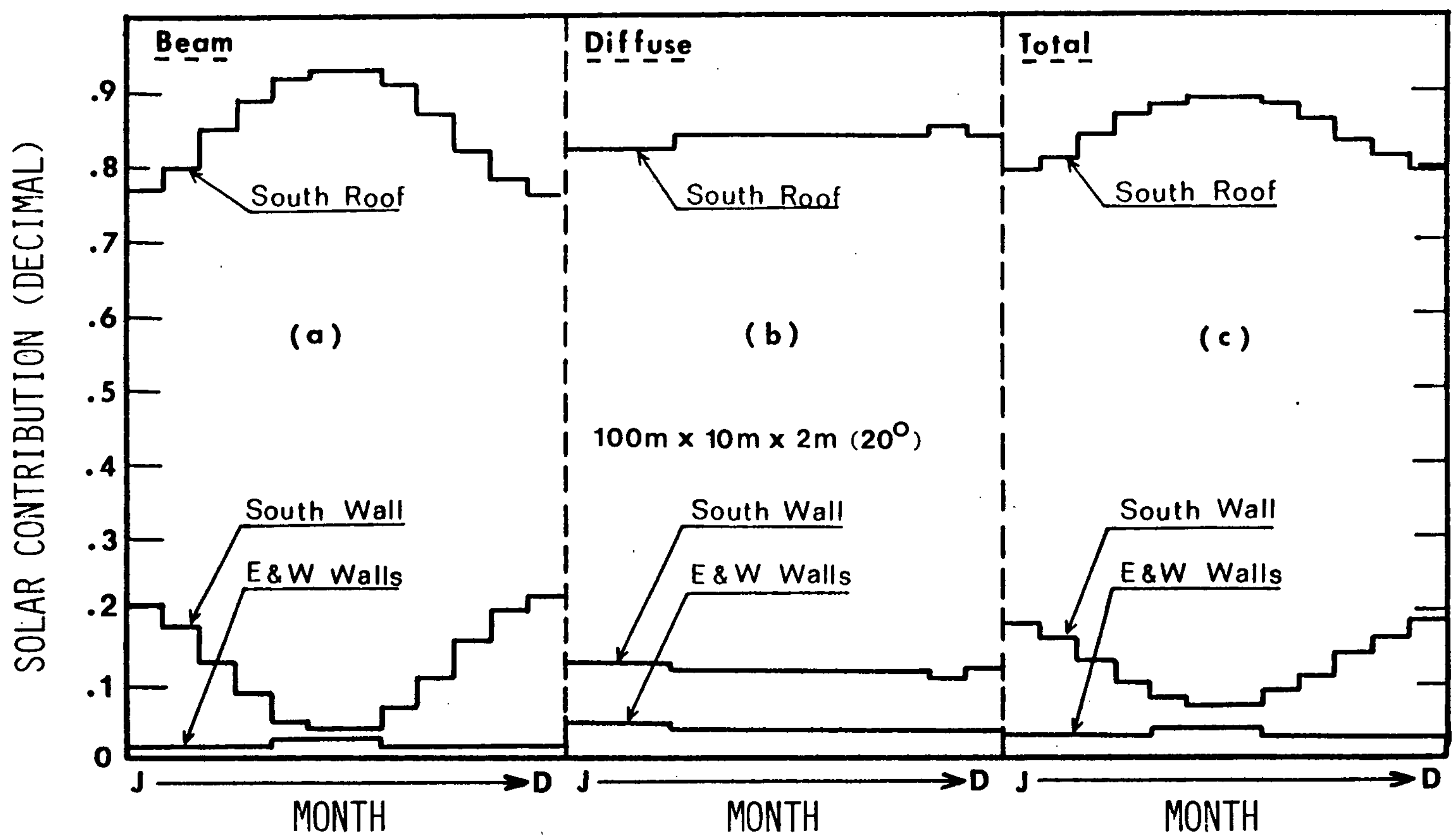


FIGURE 1.10: CONTRIBUTION BY THE DIFFERENT SURFACES OF A SHED-TYPE GREENHOUSE FOR THE BEAM (a), DIFFUSE (b) AND TOTAL (c) SOLAR RADIATION BY MONTH. (Location: Montréal, Québec).

very small throughout the year as is clearly indicated by Figure 1.10(a). The contribution of these walls to the diffuse component is slightly higher than that for the direct component, but still relatively low as can be depicted in Figure 1.10(b). Therefore, for this size of greenhouse, the east and west walls could be made opaque without a significant loss of total solar radiation input, as can be seen from Figure 1.10(c).

The effect of length on the total solar radiation transmission factor (TTF) of a 10 metre wide and 20 degree roof slope shed-type greenhouse is shown in Figure 1.11. The results indicated in the above mentioned figure are for a greenhouse located in the Montreal region. It is clear from Figure 1.11 that increasing the length of the shed greenhouse with transparent east and west wall decreases the total transmission factor significantly. The decrease in the daily TTF is more pronounced for the relatively shorter greenhouses. This is due to the large contribution of diffuse solar radiation transmitted through the east and west walls when compared to the total radiation input to the greenhouse. If the east and west walls of the shed greenhouse were insulated with an opaque material, then the monthly daily average total transmission factors become the same for any greenhouse length. Obviously, this implies that insulating the east and west walls of a short shed greenhouse results in a significant decrease in solar

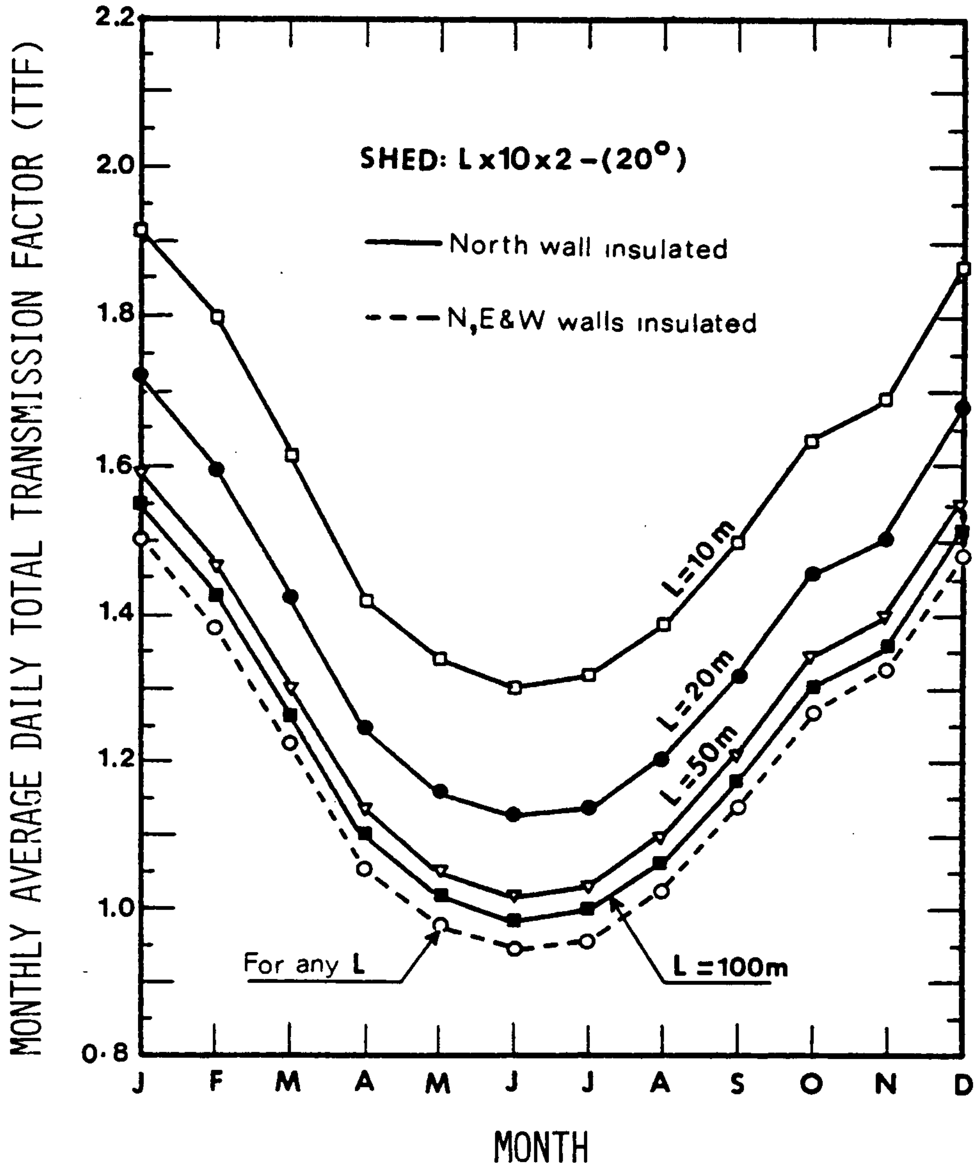


Figure 1.11: EFFECT OF LENGTH AND INSULATING THE EAST AND WEST WALLS OF A SHED-TYPE GREENHOUSE ON ITS TOTAL TRANSMISSION FACTOR. (Location: Montréal, Québec).

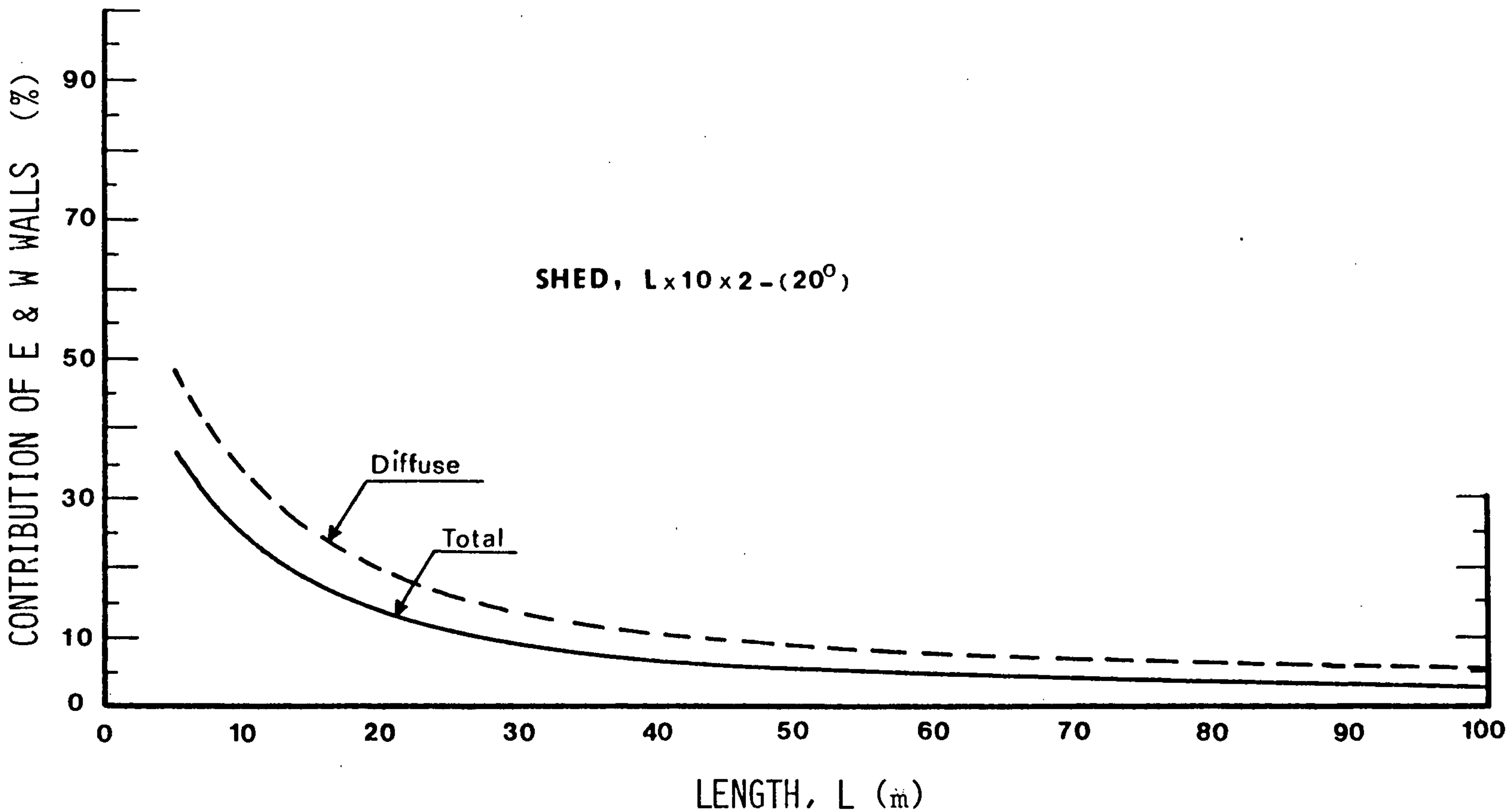


FIGURE 1.12: CONTRIBUTION OF THE EAST AND WEST WALLS OF A SHED-TYPE GREENHOUSE TO THE DIFFUSE AND TOTAL SOLAR RADIATION INPUT AS A FUNCTION OF GREENHOUSE LENGTH. (Location: Montréal, Québec).

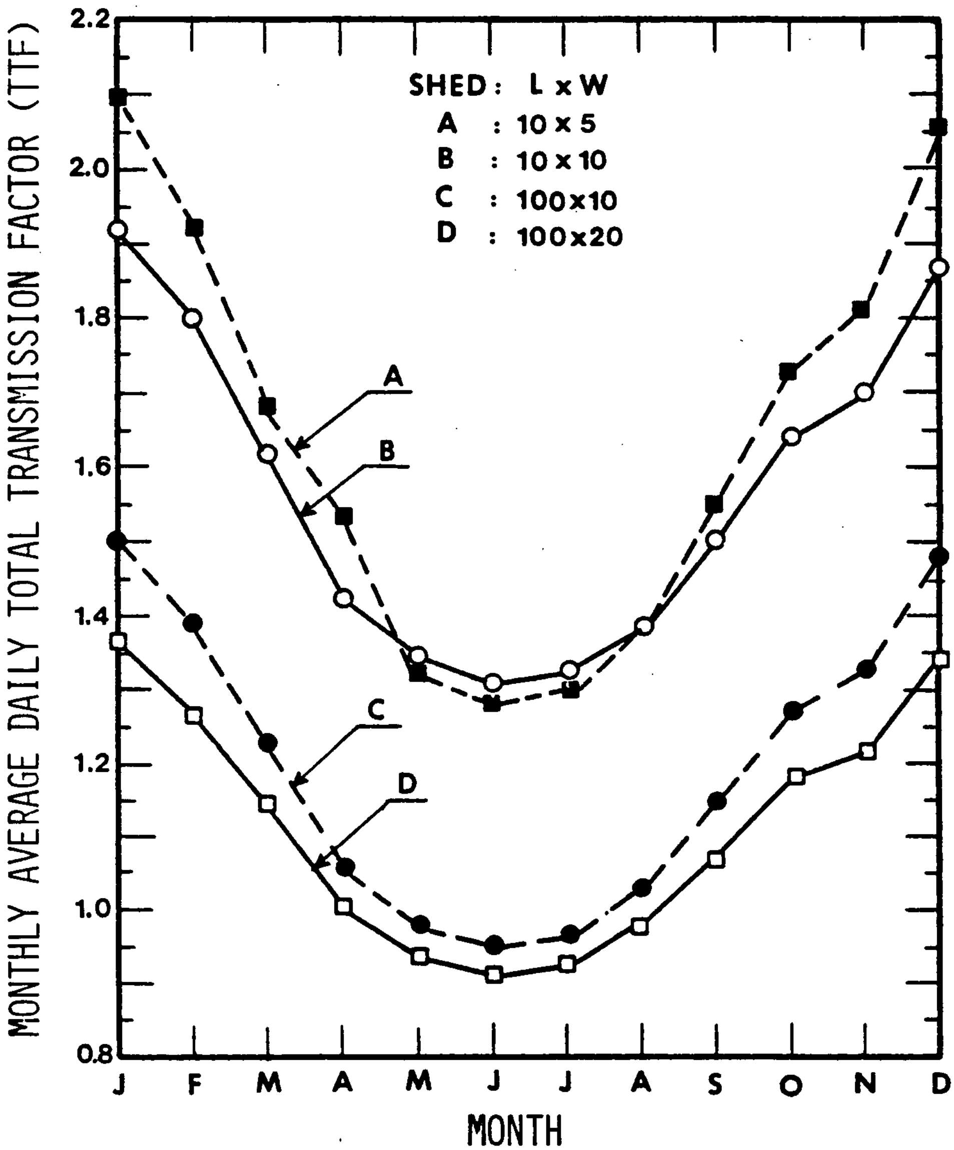


FIGURE 1.13: EFFECT OF LENGTH, WIDTH AND INSULATING EAST AND WEST WALLS OF AN E-W SHED GREENHOUSE ON ITS MONTHLY AVERAGE DAILY TOTAL TRANSMISSION FACTOR (TTF).

Curves A & B North Wall Insulated
Curves C & D N, E & W Walls Insulated

Other Construction Parameters:
Roof Slope: 20°
South Wall Height: 2 m
Covering Material: Single Layer Glass

Location: Montréal, Québec.

energy input to it (Fig. 1.11).

The above fact can better be seen by examination of Figure 1.12, which indicates the effect of the length on the percent contribution of the east and west walls of the shed greenhouse to the diffuse and total solar radiation input. According to the above figure, insulating the east and west walls of a shed greenhouse having a length of 50 metres or more results in only a small loss (less than 5 percent) in solar radiation input.

The effect of the width of a shed-type greenhouse on the total solar radiation transmission factor is shown in Figure 1.13. Doubling the width from 10 metres to 20 metres has resulted in a maximum decrease of the greenhouse TTF of only 9 percent. This decrease is due to the lower percent contribution of solar radiation input through the south wall relative to the south roof for the case of the wider greenhouse.

CONCLUSIONS

Using the total transmission factor as a criterion, the following conclusions were drawn for single span glasshouses as far as their solar radiation input efficiency was concerned.

1. An east-west oriented greenhouse captures more solar radiation during the winter than a north-south oriented greenhouse.

2. Double glazing (glass) results in 13% loss of solar energy input to an east-west oriented greenhouse as compared to single glass cover.

3. Opaque insulation of the north wall of an east-west oriented gable greenhouse causes less than 6% loss in the total solar radiation input. Virtually all this loss is diffuse radiation, and its effect is restricted to a narrow region near the north wall.

4. Opaque insulation of the north wall and roof of an east-west oriented gable greenhouse results in a considerable loss in solar energy input. For the greenhouse studied, the loss was from 29% in January to 50% in June.

5. On a per unit floor area basis, the solar energy input to a shed type greenhouse is higher during the heating season period than that to a gable greenhouse.

6. In general, an increase in the length of a shed-type greenhouse results in a decrease in the total solar radiation transmission factor (TTF). This rate of decrease in TTF is found to be in the order of 1%, 0.25% and 0.05% per metre for the greenhouse length ranges of 10 to 20m, 20 to 50m and 50 to 100m, respectively (Figure 1.11).

7. Doubling the width from 10 to 20m of a 100m long shed-type greenhouse has decreased the TTF by less than 9%.

8. Opaque insulation of the east and west walls of a shed-type greenhouse results in only a slight decrease in total solar radiation input (<5%) provided its length is kept above 50 metres.

9. The greenhouse total transmission factor was found to be a function of latitude and the ratio of diffuse to total solar radiation on a horizontal surface.

NOMENCLATURE

Symbol	Definition	Units
A_f	- area of greenhouse floor	m^2
A_i	- area of a specific surface "i" of the greenhouse enclosure	m^2
$\bar{H}_b$, $\bar{H}_d$, $\bar{H}$	- monthly average daily beam, diffuse and total radiation incident on a horizontal surface outside the greenhouse, respectively	$kJ \cdot m^{-2}$
$\bar{H}_{b,i}$, $\bar{H}_{d,i}$, $\bar{H}_i$	- monthly average beam, diffuse and total radiation incident on a specific surface "i" of the greenhouse enclosure, respectively	$kJ \cdot m^{-2}$
$\bar{H}_o$	- monthly average daily extraterrestrial solar radiation on a horizontal surface	kJ
I_b	- instantaneous beam radiation incident on a specific surface	
$I_{b,t}$	- instantaneous beam radiation transmitted through the specific surface	
$\dot{I}_b$	- hourly beam radiation incident on a surface	
$\bar{I}_{b,i}$	- monthly average hourly beam radiation incident on a specific surface "i" of the greenhouse enclosure	k
$\bar{I}_d$	- monthly average hourly diffuse radiation incident on a horizontal surface outside the greenhouse	k
$\bar{I}$	- monthly average hourly total radiation incident on a horizontal surface outside the greenhouse	k
$\bar{K}_T$	- cloudiness index ($\bar{K}_T = \bar{H}/\bar{H}_o$)	
$\bar{R}_{b,i}$	- ratio of beam radiation on a tilted surface "i" to that on a horizontal surface, respectively	
τ_b, $\dot{\tau}_b$, $\tau_{b,day}$	- instantaneous, average hourly and average daily transmittance of a transparent surface to beam solar radiation respectively	

$\bar{\tau}_{b,i}$, $\bar{\tau}_{d,i}$, $\bar{\tau}_i$	- monthly average daily transmittance of a specific surface "i" to beam, diffuse and total solar radiation respectively	
θ_h	- solar radiation incidence angle for a horizontal surface	radians
θ_i	- solar radiation incidence angle with respect to a specific surface "i" of the greenhouse enclosure	radians
ϕ	- latitude angle (location of the greenhouse)	radians
δ	- sun's declination angle	radians
ω	- hour angle	radians
β_i	- tilt angle of a specific surface "i" of the greenhouse enclosure (vertical, $\beta = 90°$)	radians
γ_i	- orientation angle of a specific surface "i" of the greenhouse enclosure (south, $\gamma = 0°$)	radians
ω_{sr}, ω_{ss}	- sunrise and sunset hour angles respectively	radians
α	- ground albedo near the greenhouse	

CHAPTER 2

TOTAL SOLAR RADIATION CAPTURE FACTORS
OF
GREENHOUSES

INTRODUCTION

This chapter discusses the diffuse solar radiation losses from greenhouses. The first section of the chapter is devoted to the special case of a gable greenhouse where two sources of diffuse losses are identified: direct loss from the gable roof and indirect loss of diffuse radiation due to the effective albedo of the plant canopy and the uncovered greenhouse floor. Taking these two losses into account, the total solar radiation transmission factor previously defined in chapter 1 is modified to give what the author calls "a greenhouse total capture factor". A mathematical expression for the solar radiation total capture factor is also given for the case of a gable greenhouse.

The second section of this chapter introduces a method of calculating the radiation configuration factors for greenhouse applications. Numerical values of the configuration factors are required for the estimation of the greenhouse capture factors.

SECTION A

TOTAL CAPTURE FACTORS
FOR
GABLE GREENHOUSES

TOTAL CAPTURE FACTORS FOR GABLE GREENHOUSES

The greenhouse total transmission factor as defined previously does not take into account the diffuse radiation losses through the roof and the reflection losses from the plant canopy. These two sources of solar radiation loss will be considered in the following chapter for the case of a gable greenhouse.

ASSUMPTIONS

With respect to the derivation of the greenhouse solar radiation capture factor, the following assumptions are made:

i) Only the absorption and reflection losses of the glass cover are accounted for.

ii) No condensation or dust accumulation on the glass cover.

iii) The effect of the structural frame is neglected.

iv) All the beam radiation transmitted through the glass cover is incident on plant canopy (i.e.tall plants and low roof slope).

v) Plant reflection for solar radiation is perfectly diffused.

vii) Multiple reflections between the plant canopy and the greenhouse cover are neglected (only the first reflection is considered).

THEORETICAL FORMULATION*

Assumption (iv) states that all the beam radiation transmitted through any greenhouse surface i reaches the plants. Then the beam radiation from surface i that is incident on the plant canopy is simply,

$$A_i \bar{\tau}_{b,i} \bar{H}_{b,i}. \tag{1}$$

But, only a fraction of the diffuse radiation transmitted through the surface i is reaching the plants. Therefore, the diffuse radiation from surface i which is incident on the plant canopy may be represented by

$$A_i \bar{\tau}_{d,i} \bar{H}_{d,i} (1 - \bar{\tau}_{d,i} F). \tag{2}$$

The above expression is valid only if the two roof slopes are made of the same material such that the diffuse transmittance can be considered equal for both slopes. Furthermore, in the case of tall plant canopies, such as tomatoes and roses, the factor F is close to zero for the vertical surfaces of the greenhouse, which implies that all the diffuse radiation transmitted through the vertical walls of the greenhouse reaches the plant canopy. However, in the case of the greenhouse roof, a fraction of the diffuse radiation coming from one side of the roof is transmitted and lost to the outside through the other side of the roof. The diffuse radiation loss through the greenhouse roof is represented in

* The definition of symbols used in this section can be found on Page 113.

equation (2) by the term which is proportional to $\bar{\tau}_{d,i}F$, where F is the radiation configuration factor between the two slopes of the greenhouse roof. The factor F may be calculated using the method described by Feingold (1966). A summary of the method and its application to greenhouse configuration factors is discussed in a later section of this chapter.

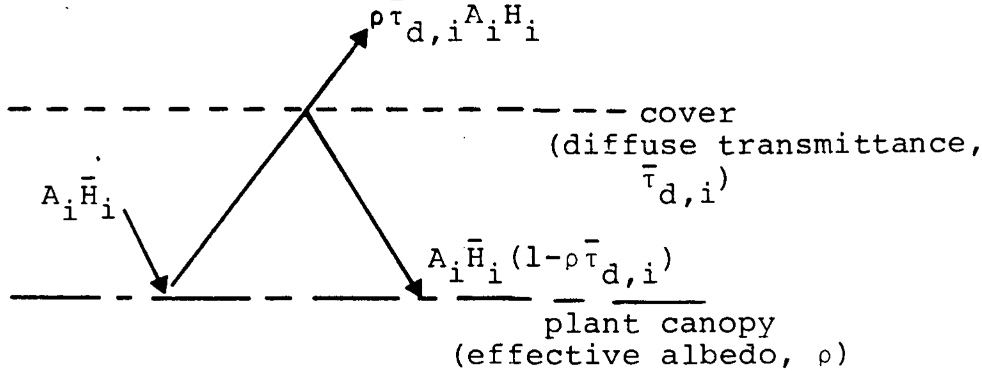
The total solar radiation from any surface i of the greenhouse which is incident on the plant canopy is then calculated using equations 1 and 2 as follows:

$$A_i \bar{H}_i = A_i [\bar{\tau}_{b,i} \bar{H}_{b,i} + \bar{\tau}_{d,i} \bar{H}_{d,i} (1 - \bar{\tau}_{d,i} F)]. \qquad (3)$$

The total solar radiation coming from any surface i of the greenhouse that is absorbed by the plant can be calculated by multiplying equation 3 by a correction factor for reflection losses due to the plant albedo, to give,

$$A_i \bar{H}_i (1 - \rho \bar{\tau}_{d,i}) \quad . \qquad (4)$$

In equation 4 only the first reflection is considered as shown in the sketch below. Also, the reflected radiation by the plant canopy is assumed to be diffused regardless of the original incident radiation.



Now, a "total solar radiation capture factor" for the greenhouse may be defined as the ratio of the solar energy captured by the plant canopy to that incident on a horizontal outside surface whose area is equal to the greenhouse ground area. The greenhouse total capture factor (TCF) may be calculated as follows:

$$TCF = \frac{\sum_{i=1}^{n} A_i[\bar{\tau}_{b,i}\bar{H}_{b,i} + \bar{\tau}_{d,i}\bar{H}_{d,i}(1-\bar{\tau}_{d,i}F)](1-\rho\bar{\tau}_{d,i})}{A_f\bar{H}} \quad . \quad (5)$$

The total solar radiation capture factor for a greenhouse is useful for comparing greenhouses at different locations and with various greenhouse construction parameters (i.e. insulation, roof slope, etc.) for their effectiveness as passive solar energy collectors.

RESULTS AND DISCUSSION

The effect of solar radiation loss through the greenhouse roof and the radiation loss due to the effective albedo of the plant canopy are shown in Figure 2.1. The curves represented in the figure are for a gable greenhouse located in the Vancouver, B.C. area and having the construction parameters as indicated on the diagram in Figure 2.1. The direct loss of solar radiation through the roof can be seen from Figure 2.1 by comparing the total transmission factor (TTF) curve to the curve for an effective plant canopy albedo of zero. The word direct loss is used here to distinguish it from that due to the

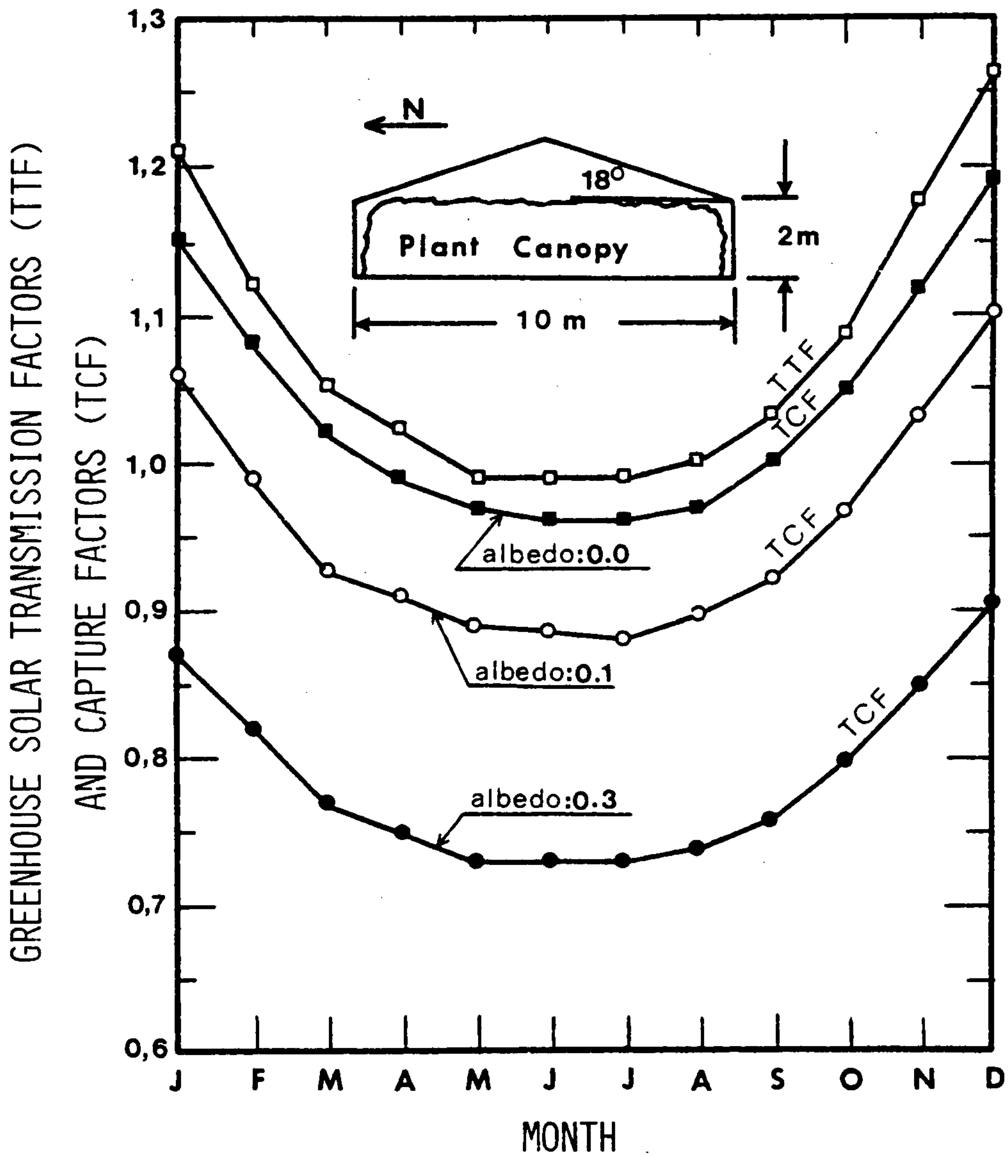


FIGURE 2.1: EFFECT OF PLANT ALBEDO ON THE SOLAR RADIATION CAPTURE FACTOR FOR A GABLE GREENHOUSE.

Dimensions: 100 m x 10 m
Orientation: E-W long-axis
Cover: Single Layer 3 mm Glass
Location: Vancouver, B.C. (49.25°N)

reflection of solar radiation by the plant canopy. The direct loss constitutes the solar radiation transmitted through the roof but has never reached the plants or any other object inside the greenhouse. As can be seen from Figure 2.1, this loss is small provided the roof slope is kept low. For the example cited here, this loss was found to be in the order of five percent of the total solar radiation entering the greenhouse.

On the other hand, the solar radiation loss due to reflection by the plant canopy and objects inside the greenhouse are found to be relatively more significant than the direct loss through the roof. Obviously , reflection losses are directly dependent on the effective albedo of the plant canopy including floor and other objects. Experimental values of the effective albedo within greenhouses are not readily available; however, two hypothetical values of 0.1 and 0.3 were used for illustration purposes. The solar radiation losses due to plant canopy reflection as expressed in terms of the greenhouse total capture factor are shown in Figure 2.1. These losses were found to be 8 and 24 percent for effective albedos of 0.1 and 0.3 respectively when compared to an albedo of zero.

In this analysis, the effective albedo is taken as a constant throughout the year. In reality, its value is closely related to the type of crop grown and its stage of development. The effective albedo could also be artifically modified to improve the greenhouse solar radiation capture factor. This indeed has been done with the use of Q-mats* for solar energy collection and storage. One effect of the Q-mats is a reduction in the effective greenhouse albedo.

---

* Q -mats is a trade name for a solar collector developed in France specifically for greenhouse applications. It consists of black plastic mats which are layed flat on the greenhouse floor and/or under the plants, then filled with water to transport the energy collected to a thermal storage tank. Q-mats are also used as a heat distribution system in waste energy recovery applications to greenhouses.

SECTION B

CALCULATION OF CONFIGURATION FACTORS
FOR
DIFFUSE RADIATION
IN
GREENHOUSES

CALCULATION OF CONFIGURATION FACTORS

In the first section of this chapter, it was found that the solar radiation capture factor for gable greenhouses is dependent on the diffuse radiation configuration factors between the two slopes of the roof. This section concentrates on an analytical method to calculate these configuration factors to be used with respect to gable greenhouses.

ASSUMPTIONS

The following assumptions are made with respect to the derivation of the radiant-interchange configuration factors for greenhouse applications:

i) The radiation from any surface i is perfectly diffuse.

ii) The surface is isothermal.

THEORY*

The radiation configuration factor F_{1-2} is defined as the fraction of the radiation leaving an isothermal wall of surface area A_1 that is incident upon another wall of area A_2.

A geometric shape commonly present with respect to

* The definition of symbols used in this section can be found on Page 113.

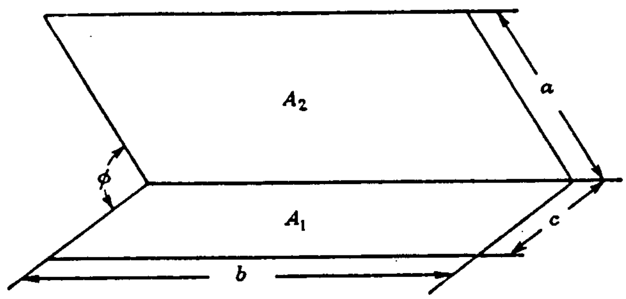
greenhouses can be treated as two rectangles having a common edge. The special case of such rectangles forming a right angle leads to a simple formula found in most heat transfer textbooks. The general case of two rectangles forming an arbitrary angle has been first treated by Hamilton and Morgan (1952) who obtained the expression shown in Figure 2.2. Numerical values of the configuration factors as calculated using Hamilton and Morgan's equation are given by Feingold (1966) for certain angles and dimensions. Unfortunately, the tabulated values do not cover the range of dimensions useful for greenhouse applications. It is the object of this section to obtain values for configuration factors to be used for diffuse radiation analysis in gable greenhouses. For a detailed analysis and more comprehensive results of configuration factors for triangular and circular roof greenhouses, the reader is referred to McAdam et al.(1971).

RESULTS AND DISCUSSION

The expression shown in Figure 2.2 is used to determine the configuration factor F between the two roof slopes of a gable greenhouse, and the configuration factor from one roof slope to the plant canopy, F'. Then, the radiation configuration factor from one roof slope to the two gable ends F" is calculated as follows:

$$F'' = 1 - F - F' \qquad (6)$$

The radiation configuration factors are determined for greenhouse lengths from 10 to 100 metres and having a width from 5 to 15 metres with roof slopes chosen to cover the



$L = c/b;\ N = a/b.$

$$F_{1-2} =$$

$$\frac{1}{\pi L}\Bigg[\!\!\Bigg[-\tfrac{1}{4}\sin 2\Phi \left[NL\sin\Phi + \left(\tfrac{1}{2}\pi - \Phi\right)(N^2+L^2) + L^2\tan^{-1}\left(\frac{N-L\cos\Phi}{L\sin\Phi}\right) + N^2\tan^{-1}\left(\frac{L-N\cos\Phi}{N\sin\Phi}\right)\right]$$

$$+ \tfrac{1}{4}\sin^2\Phi \ln\left\{\left[\frac{(1+N^2)(1+L^2)}{1+N^2+L^2-2NL\cos\Phi}\right]^{\operatorname{cosec}^2\Phi+\cot^2\Phi}\left[\frac{L^2(1+N^2+L^2-2NL\cos\Phi)}{(1+L^2)(N^2+L^2-2NL\cos\Phi)}\right]^{L^2}\right\}$$

$$+ \tfrac{1}{4}N^2\sin^2\Phi \ln\left[\left(\frac{N^2}{N^2+L^2-2NL\cos\Phi}\right)\left(\frac{1+N^2}{1+N^2+L^2-2NL\cos\Phi}\right)^{\cos^2\Phi}\right] + L\tan^{-1}\frac{1}{L}$$

$$+ N\tan^{-1}\left(\frac{1}{N}\right) - \sqrt{(N^2+L^2-2NL\cos\Phi)}\cot^{-1}\sqrt{(N^2+L^2-2NL\cos\Phi)}$$

$$+ \tfrac{1}{2}N\sin\Phi\sin 2\Phi\sqrt{(1+N^2\sin^2\Phi)}\left[\tan^{-1}\left(\frac{N\cos\Phi}{\sqrt{(1+N^2\sin^2\Phi)}}\right) + \tan^{-1}\left(\frac{L-N\cos\Phi}{\sqrt{(1+N^2\sin^2\Phi)}}\right)\right]$$

$$+ \cos\Phi\int_0^L \sqrt{(1+z^2\sin^2\Phi)}\left[\tan^{-1}\left(\frac{N-z\cos\Phi}{\sqrt{(1+z^2\sin^2\Phi)}}\right) + \tan^{-1}\left(\frac{z\cos\Phi}{\sqrt{(1+z^2\sin^2\Phi)}}\right)\right] dz \Bigg]\!\!\Bigg].$$

FIGURE 2.2: RADIATION CONFIGURATION FACTOR BETWEEN TWO RECTANGLES FORMING AN ARBITRARY ANGLE.*

* Source: Feingold, A. (1966)

range commonly used by the greenhouse industry. Three roof slopes were selected, namely 15°, 20° and 25° for which the results are shown in Figures 2.3, 2.4 and 2.5, respectively. For each roof slope, the values of F and F" are plotted as a function of greenhouse length and width. The effect of roof slope on the radiation configuration factors can be seen in Table 2.1.

EFFECT OF GREENHOUSE WIDTH

For any roof slope, increasing the width decreases the configuration factor. This effect is significant only for relatively short greenhouse. For example, for a roof slope of 20° (Figure 2.4) and a greenhouse length of 20 metres, an increase in the greenhouse width from 5 to 10 metres results in a decrease for the value of the factor F from 0.05657 to 0.05298. However, for the same roof slope but for a greenhouse length of 70 metres, the values of F become 0.0592 and 0.0582 for a 5 and 10 metres greenhouse width respectively.

EFFECT OF GREENHOUSE LENGTH

For roof slopes and widths investigated, the configuration factor F is found to increase with increasing greenhouse length. The rate of increase of F with length is larger for shorter greenhouses. For long greenhouses, the effect of length on the value of F becomes small. This is due to the effect of the gable ends which becomes very small for the long

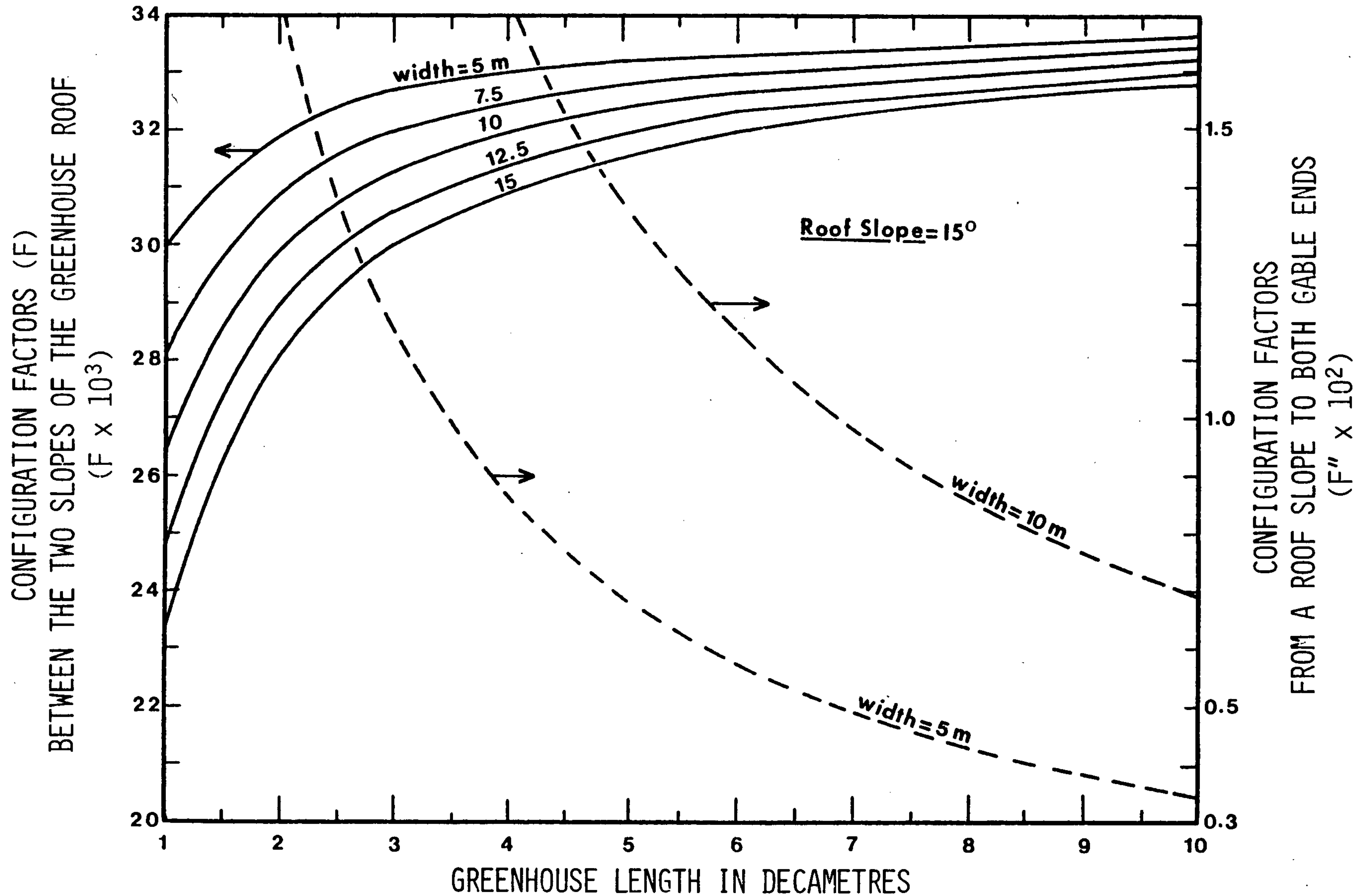


FIGURE 2.3: EFFECT OF LENGTH AND WIDTH ON THE RADIATION CONFIGURATION FACTORS FOR GABLE GREENHOUSES HAVING A ROOF SLOPE OF 15 DEGREES.

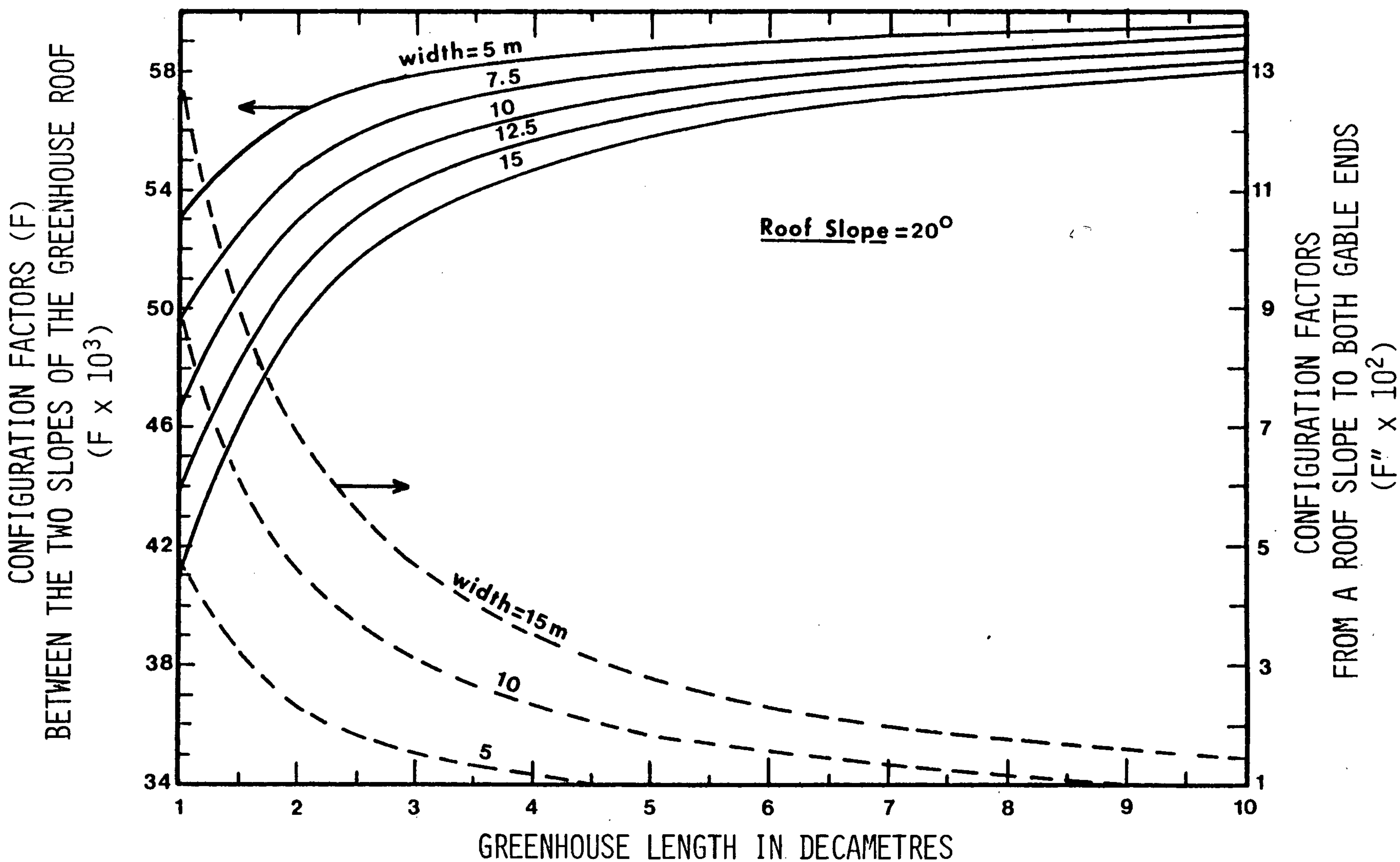


FIGURE 2.4: EFFECT OF LENGTH AND WIDTH ON THE RADIATION CONFIGURATION FACTORS FOR GABLE GREENHOUSES HAVING A ROOF SLOPE OF 20 DEGREES.

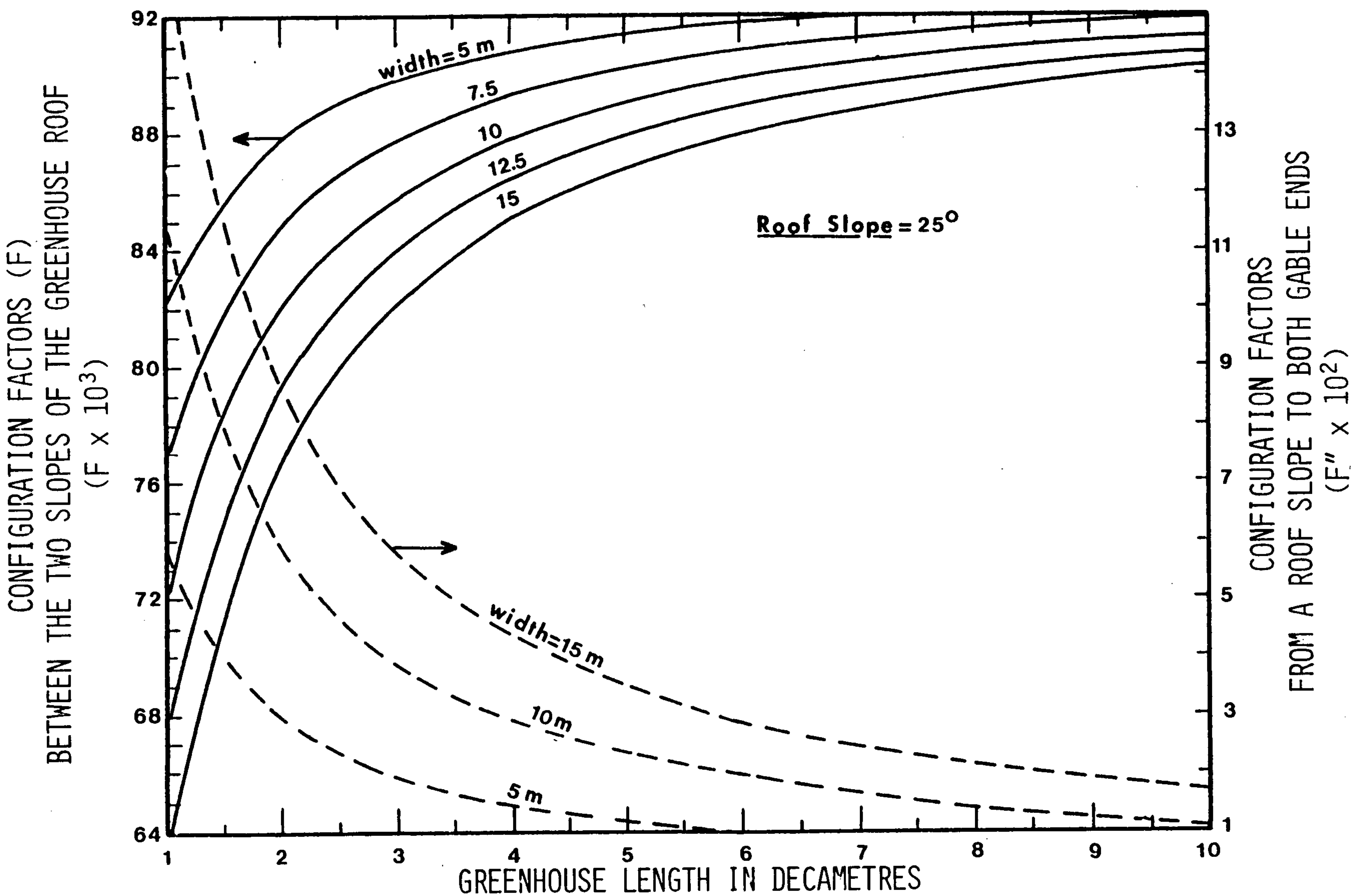


FIGURE 2.5: EFFECT OF LENGTH AND WIDTH ON THE RADIATION CONFIGURATION FACTORS FOR GABLE GREENHOUSES HAVING A ROOF SLOPE OF 25 DEGREES.

greenhouses as depicted in Figures 2.3 to 2.5 by the small values of the configuration factors between the roof slope and the gable ends F". For the purpose of illustration, take for example a greenhouse having a roof slope of 20 degrees and a width of 10 metres; then by Figure 2.4 it can be seen that the value of F increases from 0.0466 to 0.0573 for an increase in length from 10 to 50 metres. However, if the greenhouse length is increased from 60 to 100 metres, the values of F has increased only from 0.0578 to 0.0588.

EFFECT OF ROOF SLOPE

The greenhouse roof slope has more effect on the value of the configuration factor F than the length and width of the greenhouse. Table 2.1 gives the values of F and F" as a function of greenhouse length for three roof slopes and a constant width of 10 metres.

It is important to notice that the values of F" are much higher than those of F for short greenhouse regardless of the roof slope. This implies that the radiation loss from the gable ends must be considered when dealing with short greenhouses during the calculation of the total capture factors (TCF) defined in the previous section. In long greenhouses (say > 50 metres) the end effects may be neglected since the fraction of radiation transmitted through one roof slope that is lost through the gable ends is expected to be less than 2%. Therefore, equation 5 for the calculation of

TABLE 2.1

RADIATION CONFIGURATION FACTORS BETWEEN THE TWO SLOPES OF ROOF (F) AND FROM ONE ROOF SLOPE TO GABLE ENDS (F") FOR A GABLE GREENHOUSE HAVING A WIDTH OF 10 METRES

Length (m)	Greenhouse Roof Slope 15°		20°		25°	
	F	F"	F	F"	F	F"
10	0.0264	0.0674	0.0466	0.0902	0.0722	0.1130
20	0.0300	0.0342	0.0530	0.0461	0.0822	0.0581
30	0.0313	0.0229	0.0553	0.0309	0.0859	0.0390
40	0.0320	0.0172	0.0566	0.0232	0.0878	0.0293
50	0.0324	0.0138	0.0573	0.0181	0.0890	0.0235
60	0.0327	0.0115	0.0578	0.0155	0.0898	0.0196
70	0.0329	0.0098	0.0582	0.0133	0.0903	0.0168
80	0.0330	0.0086	0.0584	0.0116	0.0907	0.0147
90	0.0331	0.0077	0.0586	0.0103	0.0911	0.0130
100	0.0332	0.0069	0.0588	0.0093	0.0913	0.0117

the greenhouse total capture factor (TCF) as derived in section A of this chapter is valid for long greenhouses only, since during the derivation, the radiation loss by the gable ends has been neglected.

For the case of the greenhouse shown in Figure 2.1, having the dimensions of 100 m x 10 m with 18° roof slope, the factor F has a value of 0.0477 while that of F" is only 0.008. Therefore, the effect of F" on the radiation loss from the greenhouse was not considered during the analysis, thus the results given in Figure 2.1.

CONCLUSIONS

Based upon the calculated greenhouse configuration factors the following conclusions may be made with respect to diffuse radiation loss:

1. For a given roof slope, increasing the width results in a decreased direct diffuse radiation loss through the greenhouse roof. This effect is more significant for relatively short greenhouses.
2. For roof slopes and widths commonly used by the greenhouse construction industry, increasing the length tends to increase the direct diffuse radiation loss through the greenhouse roof. This effect is found to be more significant for relatively short greenhouses.
3. The extent of direct diffuse radiation loss through the greenhouse roof is more dependent on its roof slope than its length or width.

4. For relatively long greenhouses (> 50 m) the effect of length and width on the direct loss of diffuse radiation be neglected.
5. During the calculation of the total solar radiation capture factors of greenhouses, the gable ends effect may be neglected when dealing with long greenhouses (> 50 m) having low roof slopes (< 20°).
6. The total solar radiation capture factors (TCF) of greenhouses are highly dependent on the effective albedo of the plant canopy within the greenhouse. A high albedo results in large diffuse radiation loss, thus a low total solar radiation capture factor.

NOMENCLATURE

Symbol	Definition	Units
A_f	floor area of a greenhouse	m^2
A_i	area of a specific surface "i" of the greenhouse enclosure	m^2
F	radiation configuration factor between the two roof slopes of the greenhouse	
F'	radiation configuration factor from one roof slope to the plant canopy	
F"	radiation configuration factor from one roof slope to the two gable ends	
$\bar{H}$	monthly average daily insolation	$kJ.m^{-2}$
$\bar{H}_{b,i}$, $\bar{H}_{d,i}$	monthly average daily beam and diffuse radiation incident on a specific surface "i" of the greenhouse enclosure, respectively	$kJ.m^{-2}$
$\bar{H}_i$	as defined by equation (3)	$kJ.m^{-2}$
$\bar{\tau}_{b,i}$, $\bar{\tau}_{d,i}$	monthly average daily transmittance of a specific surface "i" to beam and diffuse solar radiation, respectively	
ρ	effective plant canopy albedo	

PART II

ANALYSIS OF GREENHOUSE-LIVESTOCK COMBINATION FOR POSSIBLE ENERGY CONSERVATION

CHAPTER 3

COMPUTER SIMULATION MODEL OF ENERGY REQUIREMENTS FOR LIVESTOCK BUILDINGS

INTRODUCTION

The first chapter of this study is mainly intended to examine the energy requirements of conventional livestock buildings. It is divided into two sections.

The first section deals primarily with the development of the mathematical model for the livestock building. The purpose of the model is to predict the thermal and electrical energy required to provide a controlled atmospheric environment within the livestock facility. Factors considered in the computer model development are ventilation, animal sensible and latent heat production, heat transmission through the building envelope, and solar radiation effects on heat loss or gain from the structure.

The computer model in its present form is designed to perform energy analyses on livestock buildings. It is not intended to predict the environmental conditions within the building. However, with simple modifications to some of the subroutines, the computer model could predict the inside temperature and relative humidity of a livestock facility.

The model could be used to examine the effect of varying the orientation and the level of insulation of the building, and the effect of varying the minimum winter and the maximum summer ventilation rates on the total energy consumption by the livestock building.

The second section gives a detailed discussion of the sol-air methods available for calculating the transmission heat transfer from buildings. A comparison between the results obtained by two sol-air methods to those resulting from a detailed heat balance about the building walls is included.

The last section of this chapter describes the application of the computer model through a case study. The model was used to determine the heating and ventilation requirements of a conventional swine finishing barn. Also, the results are analyzed to examine if excess heat is available for the purpose of supplying partially the heating load of an adjacent greenhouse.

SECTION A

MATHEMATICAL MODEL DEVELOPMENT
FOR THE
LIVESTOCK BUILDING

MODEL DEVELOPMENT

ASSUMPTIONS

In developing the model, several assumptions were made:

i) Effect of heat storage in the walls and the floor is neglected.

ii) Heat transfer through the floor is accounted for during the heat transfer calculations through the perimeter of the building.

iii) Complete mixing of the air in the building.

iv) Constant heat and moisture production by the animals housed within the building.

HEAT BALANCE ABOUT THE LIVESTOCK BUILDING

When the above assumptions are taken into consideration, the general heat balance about the building can be represented as:

ANIMAL SENSIBLE HEAT PRODUCTION + SUPPLEMENTAL HEAT = HEAT FOR VENTILATION + HEAT TRANSMISSION ;

or in equation form:

$$Q_{SENS} + Q_{SUP} = Q_{VENT} + Q_{TRAN} \qquad (1)$$

Details of each of the terms of the energy balance equation are represented in this chapter.

TRANSMISSION HEAT TRANSFER

The transmission heat transfer includes the conductive, convective and radiative heat exchange between the building and its environment. The effect of solar radiation on the transmission heat transfer also needs to be considered. Two methods are available to estimate the effect of the solar energy absorbed by the walls of the building on the transmission heat transfer. The sol-air temperature method is widely used and is well described by Threlkeld (1970) and O'Callaghan (1978) and the ASHRAE Handbook of Fundamentals (1977).

The solar radiation absorbed by a wall has the same effect as a rise in the outside temperature. The rise in the outside temperature is directly proportional to the absorptivity of a surface to solar radiation and to the solar radiation incident on that surface, and inversely proportional to the convective heat transfer coefficient due to wind. The outside temperature corrected for solar radiation effect is termed sol-air temperature and may be defined in its simplest form (Threlkeld, 1970) by the following expression:

$$T_{sa,i} = T_0 + \alpha_i I_{s,i}/\bar{h}_{w,i} \qquad (2)$$

O'Callaghan (1978) modified the above expression to take into account the effect of the emission of long-wave radiation by the surface. His modified expression for sol-air temperature is:

$$T_{sa,i} = T_0 + (\alpha_i I_{s,i} - \varepsilon_i I_\ell)/\bar{h}_{w,i} \qquad (3)$$

where I_ℓ is the intensity of long-wave radiation from a black body at the temperature of the ambient air. I_ℓ is taken as zero for a vertical wall because it is assumed that thermal radiation from the ground balances radiation lost to the sky. Sol-air methods are discussed further in Section B.

A second method based on a detailed heat balance about the outer surface of each of the walls making up the envelope of the building can be used to determine the effect of solar and thermal radiation on the transmission heat transfer. This method is suitable for digital computer calculations.

For the purpose of this analysis, the second method is used in order to take into consideration the effect of sky and ground radiant heat exchange to the exterior surfaces of the building.

The following general heat balance equation about each of the outer surfaces of the building envelope is used to calculate the surface temperatures:

$$\varepsilon_i \sigma \, [T_{s,i}^4 - 0.5\,(1 + \cos\beta_i)\, T_{sky}^4 - 0.5\,(1 - \cos\beta_i)\, T_g^4] + \bar{h}_{w,i}\,(T_{s,i} - T_0) - U_i\,(T_b - T_{s,i}) - \alpha_i\, I_{s,i} = 0 \quad (4)$$

where $\bar{h}_w$, the wind heat transfer coefficient is estimated using McAdams (1954) relationship

$$\bar{h}_w = 20.52 + 13.68\, W\,. \quad (5)$$

In equation (4) the ground temperature is assumed to be equal to the ambient air temperature. The total solar radiation incident on a surface of any tilt and orientation $I_{s,i}$ is calculated in Appendix C. The effective sky temperature is a function of many meteorological variables such as water vapour content and air temperature. Several correlation equations between the effective sky temperature and the meteorological variables have bcen proposed (Brunt (1932), Bliss (1961), Swinbank (1963), Whillier (1967), Morse and Read (1968)). In this analysis, Swinbank's correlation

$$T_{sky} = 0.0552\ T_0^{1.5} \qquad (6)$$

relating the sky temperature to the local environmental temperature is employed.

Solution of equation (4) is required for each exposed surface "i" of the building to determine its outer surface temperature, $T_{s,i}$.

For a building with an unventilated attic space, the attic temperature can be estimated whence the outer surface temperature of the roof surfaces are known using the following relationship:

$$T_a = (U_c A_c T_b + \sum_{j=1}^{m} U_j A_j T_{s,j})/(U_c A_c + \sum_{j=1}^{m} U_j A_j) \quad . \qquad (7)$$

where $U_j A_j$ are for the exposed surfaces of the attic space. The overall heat transfer coefficients U_j's exclude the outside film coefficients.

The total heat transmission between the building and its environment may then be calculated using the following equation:

$$Q_{TRAN} = U_f A_f \ (T_b - T_0) + U_p P (T_b - T_0)$$

$$+ U_c A_c (T_b - T_a) + \sum_{i=1}^{n} U_i A_i \ (T_b - T_{s,i}) \ , \qquad (8)$$

where U_i's are the overall heat transfer coefficients for the walls excluding the outside film coefficients. The terms on the right hand side of the above equation represent the heat loss or gain by the foundation, the perimeter, the ceiling and the walls of the building, respectively.

VENTILATION HEAT TRANSFER

Ventilation system design for livestock housing involves determining the optimum air flow rate and providing an even air distribution within the building. In this study, only the ventilation rate is determined and it is assumed that the ventilation system is properly designed for good air distribution.

Ventilation of a livestock building consists of three stages depending on the outside climatic conditions. For low outside temperature, ventilation is used for moisture control within the building. At intermediate outside temperatures, the inside temperature is maintained at its optimum level by increasing the ventilation rate. When the outside temperature approaches or exceeds the optimum inside temperature, animal comfort determines the required ventilation rate (Christianson and Hellickson, 1977). The MWPS * handbook (1980) and the Canadian Farm Building Code (1977) recommend typical ventilation rates for animal comfort based on animal type and size.

VENTILATION SYSTEM CONTROL

Ideally, the ventilation system should keep the inside temperature and relative humidity at their optimum levels for any outside climatic conditions. This is obviously not possible without the installation of a cooling system.

Several control systems have been used for livestock building ventilation control. The most commonly used control system is a constant low flow rate for winter ventilation and a constant high flow rate for summer ventilation. This type of system control can be achieved by either a two-speed fan and a thermostat or two-single speed fans with the low speed fan operating continuously. The Midwest Plan Service (1980) describes some ventilation control systems and gives their wiring diagrams.

For the purpose of this simulation, two sets of variable speed fans are selected. The variable low speed fans are used for moisture control during cold periods. These fans are controlled by a humidistat. For summer ventilation,

* MWPS: Midwest Plan Service

thermostatically controlled variable high-speed fans are used to control the inside temperature near an optimum level.

The low air flow rate is determined according to the mass balance equation when the humidistat is set at the maximum relative humidity allowable. For that relative humidity an air flow rate is determined using a moisture balance defined below; then, the supplemental heat required to keep the inside temperature at an optimum level is calculated from the energy balance equation. This procedure is continued until the heat balance predicts cooling requirements then the high flow rate fans are activated and the air flow rate increased to maintain the inside temperature at the desired level, resulting in a lower relative humidity within the building. The air flow rate will increase with increasing outside air temperature to a maximum rate recommended by local building codes for animal comfort. At this point, the resulting inside temperature is dictated by the outside climatic conditions.

VENTILATION RATE FOR HUMIDITY CONTROL

The ventilation rate for humidity control is determined by performing a moisture balance about the livestock building. Under normal operating conditions, there are two sources of water vapour production within the livestock building:

a) The water vapour released by the animals through respiration for non-sweating farm animals.

b) The water vapour evaporated from wetted surfaces within the building, including feces and urine.

The two sources of water vapour production are usually combined and referred to as the total building latent heat. If we let m_w be the total moisture produced, then the total building latent heat may be calculated using the latent heat of vaporization of water as follows:

$$Q_e = m_w \, h_{fg} \tag{9}$$

where the formula for h_{fg} is given by Cooper (1969) as

$$h_{fg} = 2504.44 - 2.4\ (T_b - 273.16). \tag{10}$$

When the rate of moisture production within the building is known, the mass balance about the open system will take the form

$$m_a \, W_b = m_a \, W_0 + m_w \quad . \tag{11}$$

Therefore, the air mass flow rate required to remove the moisture produced is

$$m_a = m_w / (W_b - W_0) \quad . \tag{12}$$

Then, the sensible heat lost due to the introduction of fresh air into the building can be calculated from the mass flow rate of ventilating air and the enthalpy change of the air as follows:

$$Q_{VENT} = m_a \ (h_b' - h_0) \tag{13}$$

where the enthalpy of the air in the building, h_b' is taken at the barn dry-bulb temperature and at the dew-point temperature of the outside air.

The ventilation rate, for an exhaust fan system, may then be calculated using the specific volume of the air at the inside condition, thus:

$$V = v\, m_a/3600 \quad . \tag{14}$$

Whence, the ventilation rate required to remove the moisture produced is known, the supplemental heat necessary to maintain the desired inside temperature may be estimated from the following heat balance equation about the building

$$Q_{SUP} = Q_{SENS} - Q_{TRAN} - Q_{VENT} \quad . \tag{15}$$

VENTILATION RATE FOR TEMPERATURE CONTROL

The ventilation rate required for temperature control is determined by performing a heat balance about the building. In this case, no supplemental heat is needed, but the ventilation rate must be increased to keep the inside temperature at its optimum level.

The heat balance for the inside temperature control can be written as

$$Q_{VENT} = Q_{SENS} - Q_{TRAN} \quad . \tag{16}$$

Then, the air mass flow rate required for temperature control can be calculated from Q_{VENT} and the enthalpy change of the incoming fresh air as follows:

$$m_a = Q_{VENT}/(h_b'-h_0) \quad . \tag{17}$$

The resulting relative humidity inside the building is then determined from the solution of the mass balance equation.

Details of the method used here for the calculation of the psychrometric properties of moist air are included in Appendix D.

VENTILATION RATE FOR ANIMAL COMFORT

The ventilation rate required for animal comfort during periods of hot weather is dictated by the type and age of the animal, location and construction parameters of the building and the air distribution system.

For this simulation model the maximum ventilation rate is left as a parameter to be selected by the user depending on the particular application of the model.

HEAT AND MOISTURE PRODUCTION BY LIVESTOCK

The use of the mathematical model requires accurate information on the heat and moisture released within the livestock confinement structure for the type of animals housed. The heat and moisture production rate is dependent upon the breed and size of the animals housed, the temperature and the relative humidity within the building and upon the management practices used in operating the livestock facility.

Extensive data are available for predicting the amounts of heat and water vapour generated by various types of livestock. The basal heat production of many types of animals is readily available in many publications related to farm animal environmental physiology. The basal heat production for most homeothermes may also be calculated using the equation developed by Brody (1945).

Data on the sensible and latent heat production by individual animals are also widely available for most domestic animals (Bond et al.(1952, 1959, 1963, 1965), Hazen and Mangold (1960), Kelly et al.(1948), Longhouse et al.(1960), Ota et al. (1953), Restrepo et al.(1977) and Riskowski et al.(1977)). However, data obtained through tests on single animals is not suitable for the design of heating, ventilating and air conditioning systems for livestock housing since this type of data does not represent the actual operating conditions of livestock facilities.

Care must be taken when using published research data on heat and moisture production rate of domestic animals since the conditions under which the experiments were conducted and the methods of measurements used influence the results obtained, thus, their range of applicability. For example, when estimating the moisture produced, it is necessary to distinguish between animal moisture production and room moisture production. The latter includes both water vapour released by the animals and the moisture evaporated from the wetted surfaces within the building and from waste products (feces and urine). The room moisture production is more useful for heating and ventilating systems design than animal moisture generation alone provided the management techniques to be adopted in the actual building are similar to those used to obtain the experimental data.

ENERGY CONSUMPTION BY VARIABLE SPEED FANS

Fan power requirements for variable air volume systems using variable speed fans as a means of volume control can be estimated from the ratio of the air flow delivered to the design air capacity for the fan. Hittle (1979) gives the following regression equation to calculate the fraction of full-load power:

$$P_f = 0.00153 + 0.005208\, L_f + 1.1086\, L_f^2 - 0.11635563\, L_f^3\ . \quad (18)$$

In the above equation, L_f is the part-load ratio defined as the delivered air flow in any period of one hour divided by the design air flow rate for the fan. It is recommended that L_f be kept above 0.4.

SECTION B

COMPARISON BETWEEN SOL-AIR AND HEAT BALANCE METHODS FOR TRANSMISSION LOSS CALCULATION

BUILDING TRANSMISSION LOSS: SOL-AIR TEMPERATURE METHODS VS HEAT BALANCE METHOD

In Section A of this chapter, it has been stated that two sol-air temperature methods are available for estimating the transmission heat transfer from buildings: Threlkeld's equation and O'Callaghan's equation.

This section is devoted to a discussion of the two sol-air temperature equations including a comparison of results obtained by the two equations to those calculated using a detailed heat balance about the walls of a typical farm building.

SOL-AIR TEMPERATURE METHODS

1. Threlkeld's Equation:

Threlkeld's sol-air temperature method as represented by equation 2 of this chapter does not take into account the thermal radiation losses from the building outer surfaces to the ground and sky. Therefore, the transmission heat as determined through the use of equation 2 is expected to be under-estimated. The under-estimation of the heat loss will be more pronounced if the building material making up the outer surface of walls has a high emissivity for infra-red radiation.

2. O'Callaghan's Equation:

Equation 3 of this chapter estimates the sol-air temperature as given by O'Callaghan (1978). When compared with Threlkeld's equation, O'Callaghan's expression includes the thermal radiation heat loss from the outer surface of the walls to the surroundings. This loss is represented in equation 3 by the inclusion of the term εI_ℓ.

During the application of O'Callaghan's equation the following two assumptions are made:

1. For vertical surfaces, I_ℓ becomes zero. This is based upon the argument that the thermal radiation loss from the wall to the sky is offset by the radiative gain from the ground.
2. For non-vertical walls, regardless of tilt angles, the net radiative loss by the surface is proportional to the absolute temperature of the ambient air raised to the fourth power, or in equation form,

$$I_\ell = \alpha T_o^4 \qquad (19)$$

The net radiative energy loss from a vertical wall to the ground and the sky is illustrated in Figure 3.1(a). The net radiative loss in this case is proportional to:

$$T_s^4 - 0.5\, T_{sky}^4 - 0.5\, T_g^4 \quad . \qquad (20)$$

In order for the first assumption to hold, the above expression must be identical to zero. In a similar manner, an examination of Figure 3.1(b) for a non-vertical wall

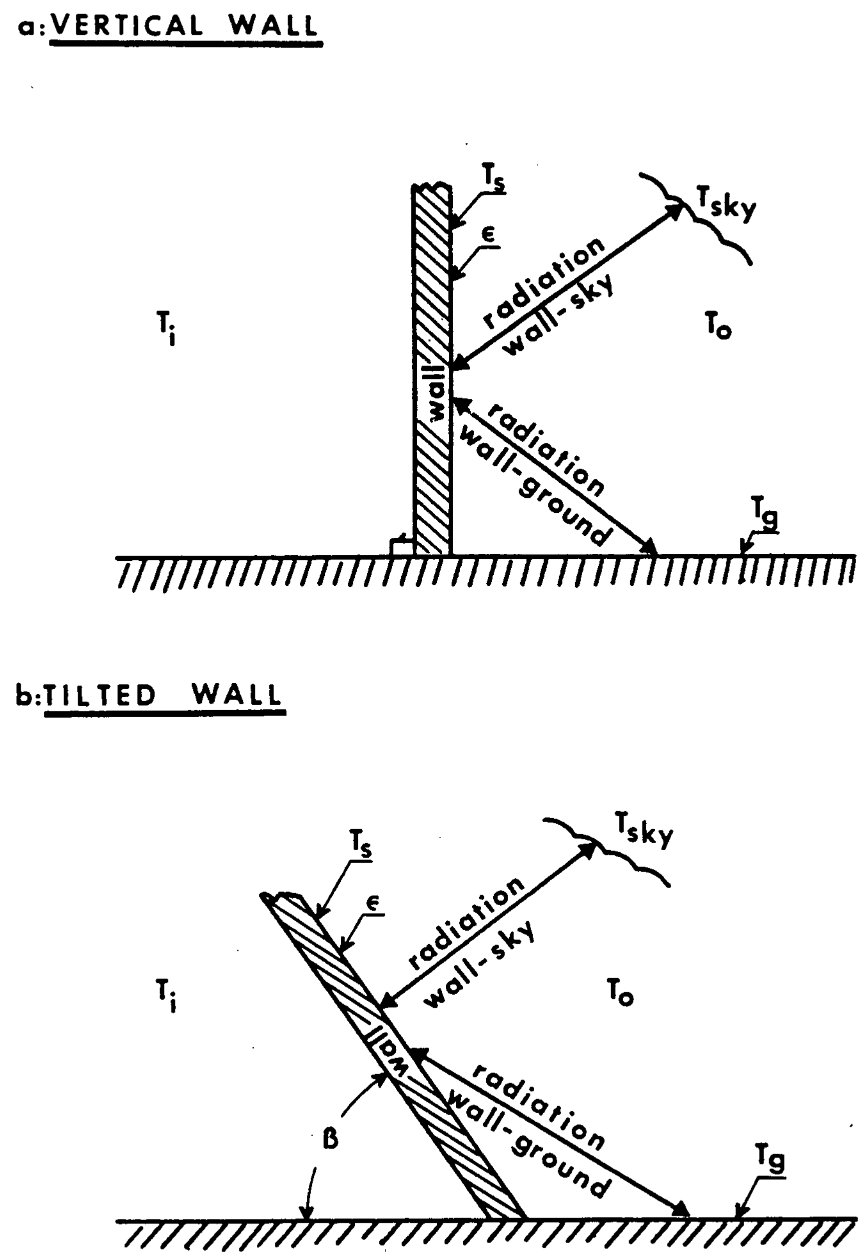


FIGURE 3.1: THERMAL RADIATION EXCHANGE BETWEEN A WALL AND ITS ENVIRONMENT.

reveals that the net radiative loss from the surface to the sky and ground is proportional to:

$$T_s^4 - 0.5\ (1 + \cos\beta)T_{sky}^4 - 0.5\ (1 - \cos\beta)T_g^4 \quad . \quad (21)$$

Therefore the second assumption is valid only if the above expression is equal to T_o^4.

It is interesting to note that for the special case of a horizontal surface, the second assumption becomes valid when,

$$T_s^4 - T_{sky}^4 = T_o^4 \quad . \qquad (22)$$

HEAT BALANCE METHOD

From the above discussion of the sol-air temperature methods for estimating transmission heat loss from buildings, it is clear that the assumptions underlying these methods are not always applicable. Therefore, a detailed heat balance about the outer surface of the walls is preferred if a digital computer is used. Details of the heat balance method is included in Section A of this chapter, equation 4 to equation 8. This method eliminates the two assumptions associated with O'Callaghan's equation. However, in equation 4 for calculating the surface temperature of the wall the ground temperature (T_g) appears as an unknown. Since, this temperature is seldom measured, it must be calculated or assumed. With the exception of special cases (i.e. asphalt surface exposed to sunlight), the ground temperature may be considered equal to the air temperature. This assumption is not expected to significantly affect the results considering the applications of the analyses are primarily intended for rural grass covered areas.

COMPARISON OF THE RESULTS BY THE THREE METHODS

The transmission heat loss from a typical swine building is calculated using Threlkeld's equation, O'Callaghan's equation and by a heat balance about the outer surfaces of building walls. The hourly heat loss from the selected building is calculated for the environmental temperature and solar radiation shown in Figure 3.2. The values in this figure represent an average day for the month of December in the Halifax area. The corresponding hourly heat transmission losses are given in Figures 3.3 and 3.4 for a constant indoor temperature of 18°C. Two types of surface coating are investigated, because of the effect of radiation properties of the surface on the radiative exchange.

In Figure 3.3, the absorptivity for solar radiation of the surface of the walls is taken as 20 percent while its emissivity to infra-red radiation is 90 percent. This surface condition is representative of white painted walls. Figure 3.4 is for the case where both the absorptivity and the emissivity are equal to 20 percent. This surface condition usually represents a building with aluminum siding finish.

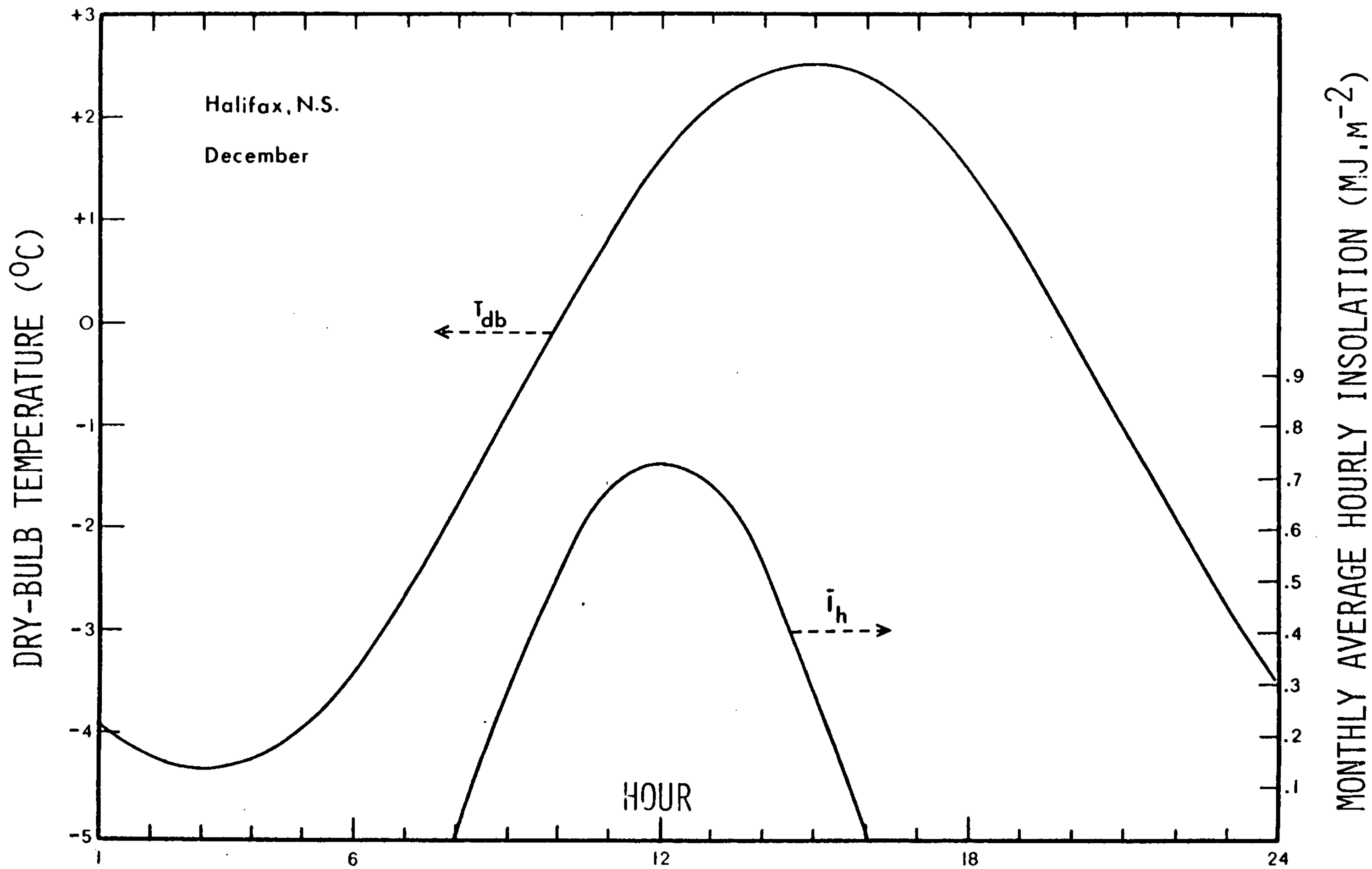


FIGURE 3.2: HOURLY TEMPERATURE AND SOLAR RADIATION ON A HORIZONTAL SURFACE USED FOR THE CALCULATION OF TRANSMISSION HEAT LOSS BY THE SOL-AIR TEMPERATURE AND HEAT BALANCE METHODS.

An examination of Figure 3.3 indicates that Threlkeld's equation, as expected, under-estimates the transmission heat loss because it does not consider the thermal radiation heat loss from the surface. On the other hand, O'Callaghan's sol-air temperature equation gives heat transmission values higher than those predicted by the detailed heat balance method. This indicates that the roof radiative heat loss is over-estimated, since the radiative loss from the vertical walls is taken as zero with this method of transmission heat loss calculation.

It is interesting to note when the surface emissivity is reduced from 0.9 (Fig. 3.3) to 0.2 (Fig. 3.4), the discrepancies between the results for transmission heat loss by the three methods become small. This further indicates that the difference between the three methods is due to the manner by which the radiative loss is treated. Therefore, it can be concluded that for walls with an outside surface having a low emissivity for long-wave radiation, the radiative heat loss becomes less significant; thus, the simpler sol-air temperature methods could be used to calculate transmission loss from buildings instead of the more complex heat balance method without introducing significant errors in the final results.

The sol-air temperature methods have also been compared to the heat balance method for the month of June. A similar trend in the comparative results to those obtained for

December was found indicating that the above conclusions could be applied to other months of the year as well.

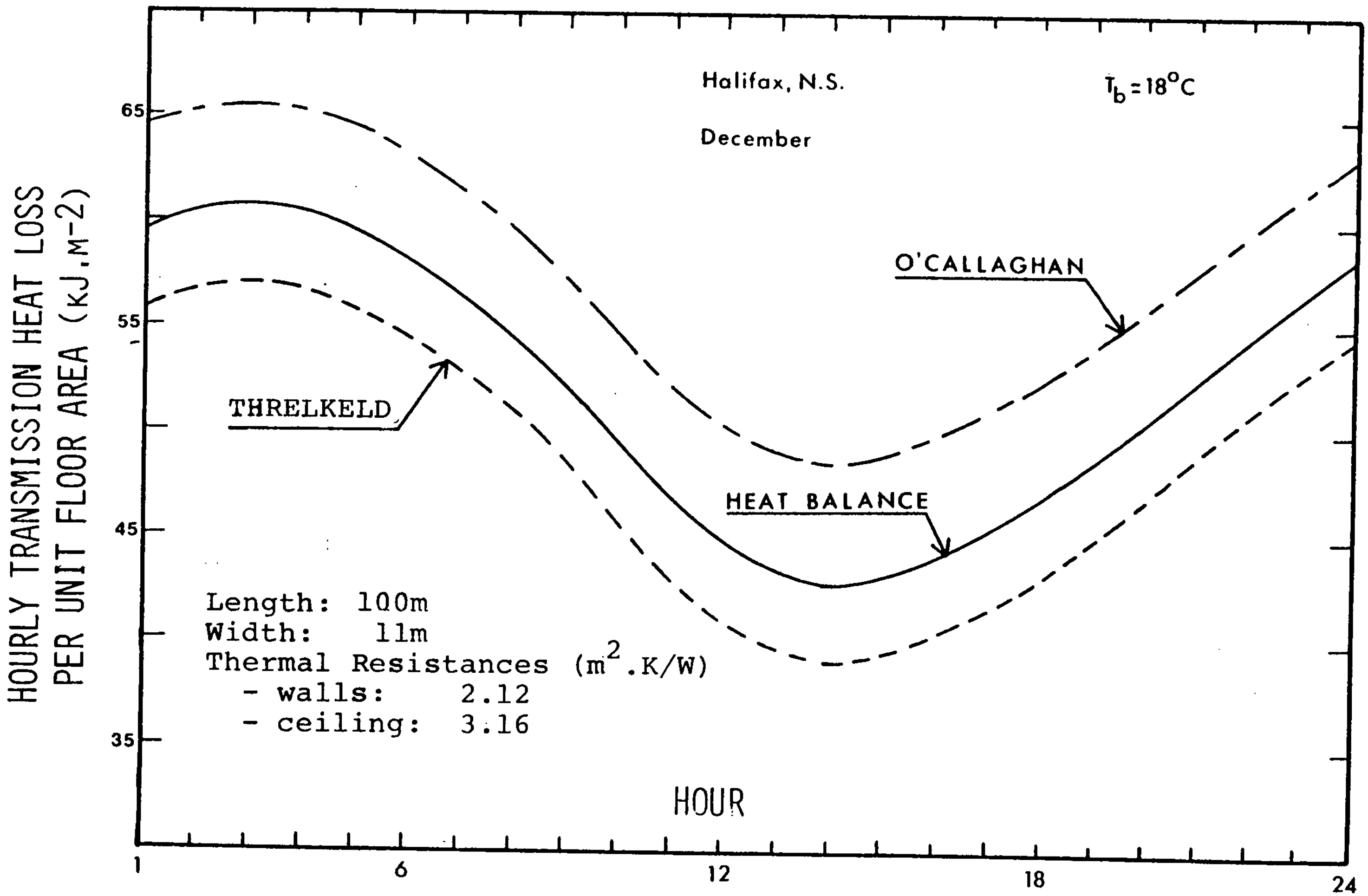


FIGURE 3.3: COMPARISON OF HOURLY TRANSMISSION HEAT LOSS AS ESTIMATED USING SOL-AIR TEMPERATURE EQUATIONS (THRELKELD, O'CALLAGHAN) AND CALCULATED BY HEAT BALANCE ABOUT THE WALLS OF A TYPICAL FARM BUILDING. $\{\alpha_s = 0.2; \quad \varepsilon_\ell = 0.9\}$

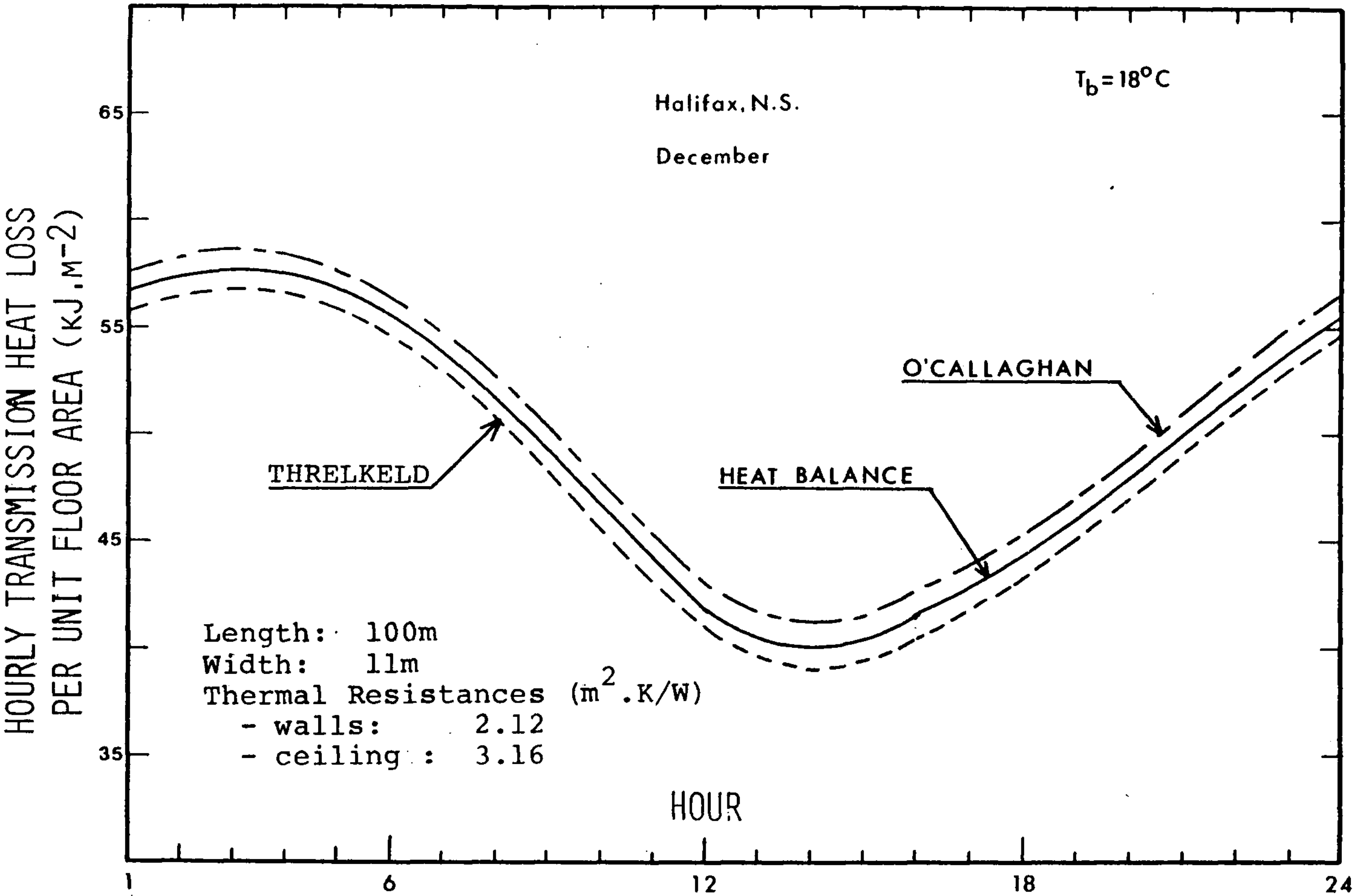


FIGURE 3.4: COMPARISON OF HOURLY TRANSMISSION HEAT LOSS AS ESTIMATED USING SOL-AIR TEMPERATURE EQUATIONS (THRELKELD, O'CALLAGHAN) AND CALCULATED BY HEAT BALANCE ABOUT THE WALLS OF A TYPICAL FARM BUILDING.

$\{\alpha_s = 0.2; \quad \varepsilon_\ell = 0.2\}$

SECTION C

CASE STUDY I

HEATING AND VENTILATION REQUIREMENTS OF A CONVENTIONAL SWINE FINISHING BARN

SWINE FINISHING BARN - A CASE STUDY

DESCRIPTION AND ASSUMPTIONS

The computer simulation model developed in Section A of this chapter was used to predict the supplemental heat requirement as well as the necessary ventilation rate for a swine finishing barn. For the purpose of the case study, the following assumptions are made:

i) The pigs enter the building at an average weight of 50 kg to be finished to a market weight of 90 kg.

ii) The size distribution of the animals in the barn is uniformly distributed between start and finish weight such that the average hog weight may be taken as 70 kg.

iii) The optimum dry-bulb temperature for maximum daily weight gain and maximum feed conversion efficiency is taken as 20°C (Turnbull and Bird, 1979).

iv) The maximum allowable relative humidity in the barn during cold weather periods is taken as 85 percent.

v) The maximum summer ventilation rate for animal comfort is chosen as 0.05 m^3/s per pig (MWSP-1, 1980).

vi) A net floor space requirement of 0.6 m^2 per pig is used.

Figures 3.5 and 3.6 show the floor plan and the cross-sectional view of the finishing hog barn, respectively. The building used in the case study is 100 m long by 11 m wide. A storage

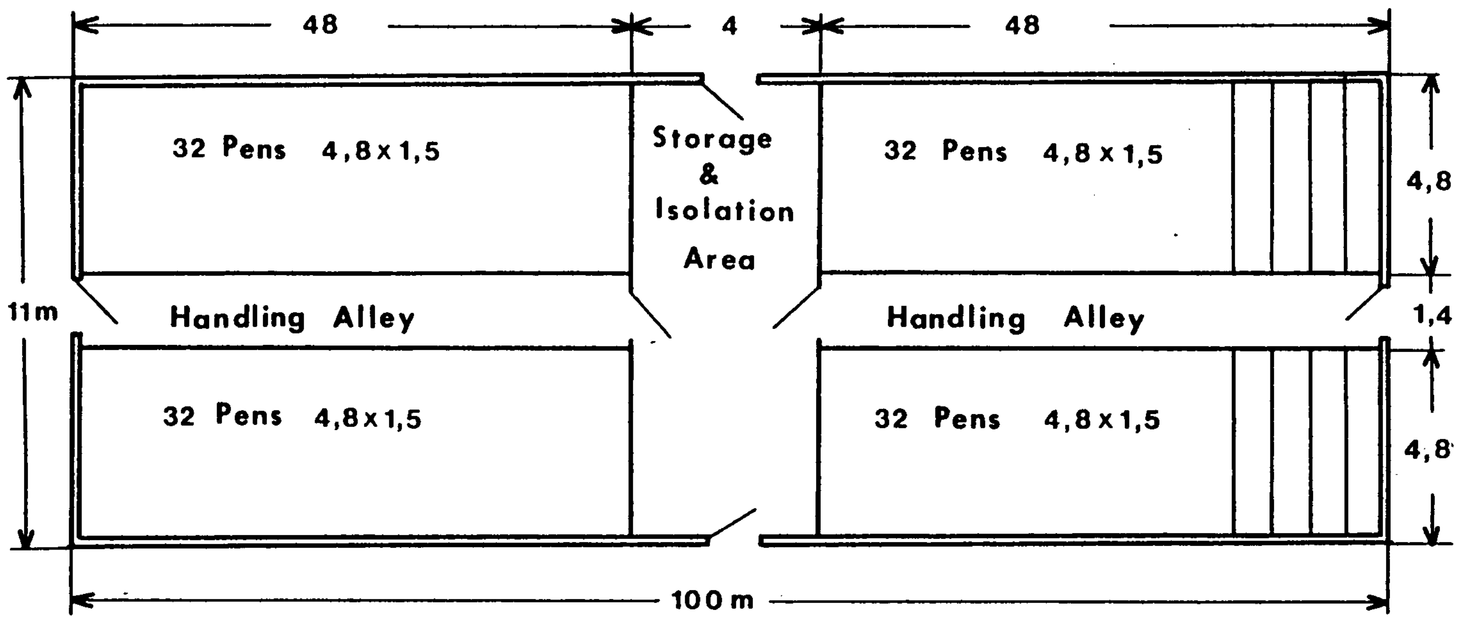


FIGURE 3.5: FLOOR PLAN OF THE SWINE FINISHING BARN USED IN CASE STUDY I.

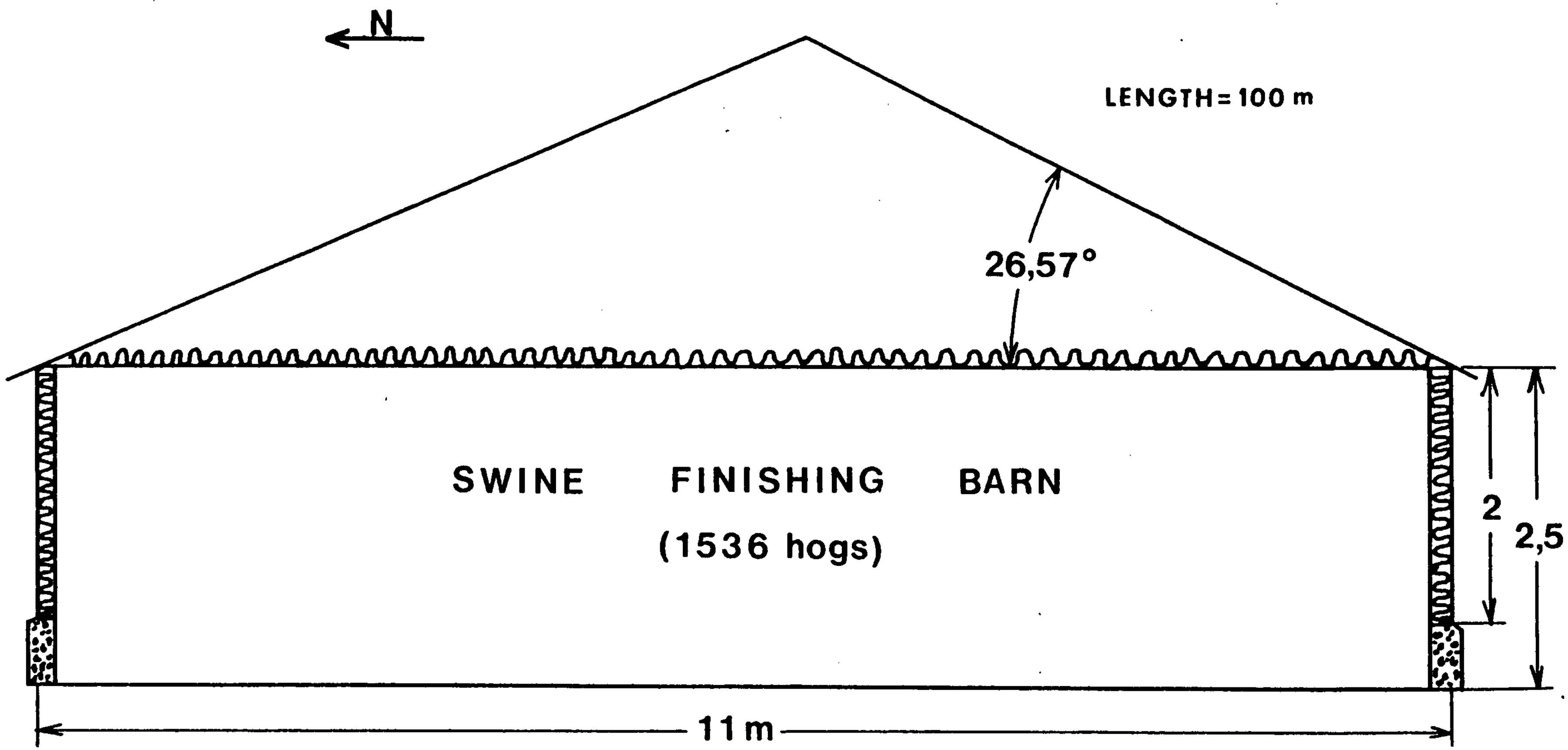


FIGURE 3.6: CROSS-SECTION OF THE SWINE FINISHING BARN USED IN CASE STUDY I.

and isolation area having a width of 4 m divides the barn into two equal sections of 64 pens each. All the pens are of equal size and have the dimensions of 4.8 m x 1.5 m. Each pen houses on the average 12 pigs; therefore, the total number of animals in the building at any instant would be around 1536 hogs if the barn is fully occupied. Assuming an average of ten weeks per finishing period, then the expected annual production would be 7980 hogs.

The total confinement swine building chosen for the case study has a solid concrete floor and is well insulated. The resistances to heat conduction are 5.88 and 4.0 m^2 K/W for the ceiling and for the walls, respectively. More information concerning the construction parameters of the building as well as the management practices used are included in Table 3.1.

The total heat and room latent heat produced by the hogs is estimated using the work done by Bond et al (1959) and Carson (1972). Detailed calculations for heat and moisture production within the hog barn are included in Appendix E.

RESULTS AND DISCUSSION

Hourly computer simulation results for a typical day of each month of the year are included in Appendix F. Tables F.1 to F.12 show the hourly and daily heat losses due to transmission through the building envelope and those due to ventilation for the outside dry-bulb and dew-point temperatures are indicated in the tables. The hourly supplemental heat and

TABLE 3.1

VARIABLES USED TO CALCULATE HEATING VENTILATION REQUIREMENTS OF A CONVENTIONAL SWINE FINISHING BARN

Construction Parameters

Length:	100 m
Width:	11 m
Height:	2.5 m
Roof Slope:	26.57°
Orientation:	East-West Long Axis

Construction Materials Properties

Building Component	Area (m^2)	RSI (m^2 K/W)	U (kJ $m^{-2}h^{-1}K^{-1}$)	α_s	ε_ℓ
South Roof	615	0.19	18.61	0.2	0.22
North Roof	615	0.19	18.61	0.2	0.22
South Wall	200	4.00	0.90	0.2	0.22
North Wall	200	4.00	0.90	0.2	0.22
East Wall	22	4.00	0.90	0.2	0.22
West Wall	22	4.00	0.90	0.2	0.22
Gable East End Wall	15	0.24	15.19	0.2	0.22
Gable West End Wall	15	0.24	15.19	0.2	0.22
Ceiling	1100	5.88	0.61	-	-
Foundation (Insulated)	111	1.49	2.41	-	-
Perimeter (Insulated)	222 (m)	1.45 (m.K/W)	2.48 (kJ.$m^{-1}h^{-1}K^{-1}$)	-	-

Management Parameters

Location:	Vancouver, B.C. Montreal, Quebec Halifax, N.S.
Number of hogs:	1536
Average weight:	70 kg
Minimum inside temperature:	20°C
Maximum inside relative humidity:	85%
Maximum ventilation rate:	50 litres per second per hog
Ventilation system type:	Variable speed fans (12 kW peak load)

ventilation rate requirements as well as the electrical energy consumed by the fans are included in the Tables of Appendix F.

As expected, the simulation results indicate that supplemental heat is not needed for the swine finishing barn with the construction parameters and the inside environmental conditions previously described in Table 3.1. The hogs produced enough sensible heat to compensate for the transmission heat loss and the energy needed to heat the amount of ventilation air that is required to keep the inside relative humidity below 85 percent.

It is interesting to note that the recommended ventilation rate for animal comfort of 50 litres per second per hog is adequate, since the inside temperature remained at the design level of 20°C until the outside temperature has risen above 18°C. The increase of the inside temperature above the optimum level occurred in the day time during the warm months of June, July, August and September.

Winter and summer hourly ventilation rates as predicted by the simulation model are shown in Figures 3.7 and 3.8, respectively. The curve for hourly ventilation rates for a typical day during the month of January (Fig. 3.7) follows very closely the outside dry-bulb temperature curve which indicates that the ventilation air is used for temperature control. Figure 3.8 shows the hourly ventilation rates for a typical day in August. It can be seen that the ventilation

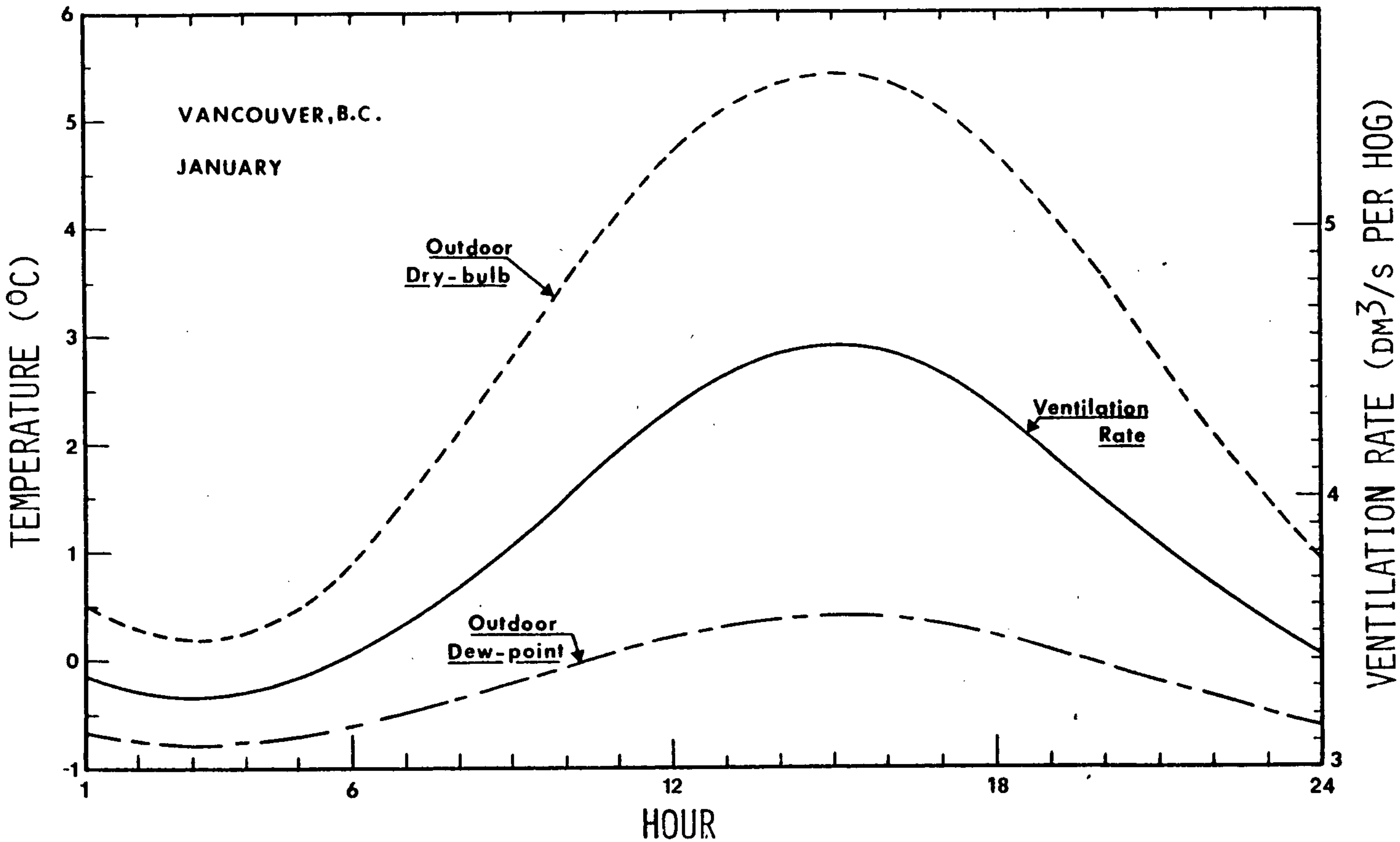


FIGURE 3.7: VENTILATION RATE REQUIREMENT OF THE SWINE FINISHING BARN FOR A MINIMUM INSIDE TEMPERATURE OF 20°C AND A MAXIMUM INSIDE RELATIVE HUMIDITY OF 85% FOR THE OUTSIDE DRY-BULB AND DEW-POINT TEMPERATURES INDICATED IN THE GRAPH.

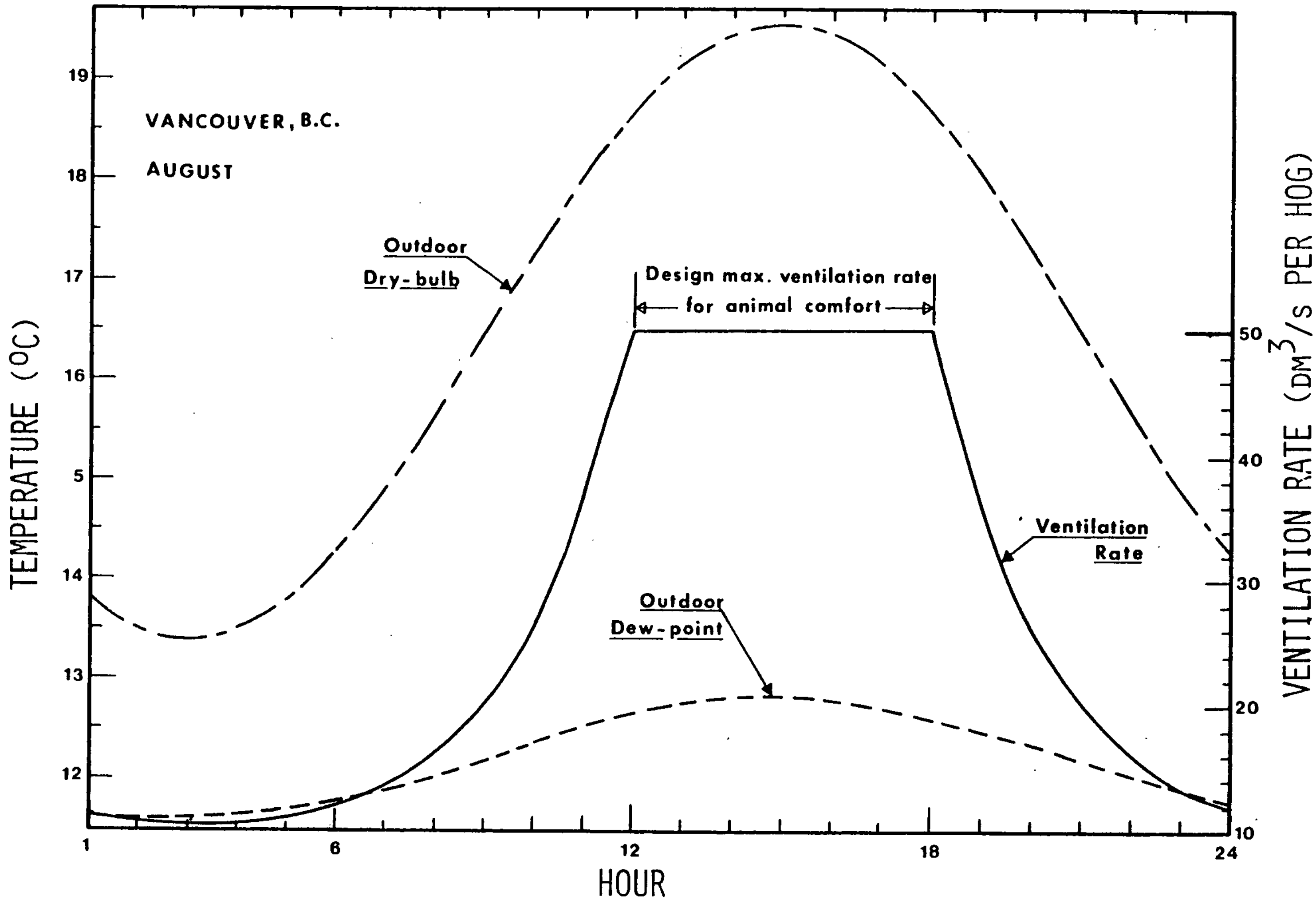


FIGURE 3.8: VENTILATION RATE REQUIREMENT OF THE SWINE FINISHING BARN FOR A MINIMUM INSIDE TEMPERATURE OF 20°C AND A MAXIMUM INSIDE RELATIVE HUMIDITY OF 85% FOR THE OUTSIDE DRY-BULB AND DEW-POINT TEMPERATURES INDICATED IN THE GRAPH.

rate is at its maximum value for most of the day time hours indicating that the inside temperature is above the set point of 20°C.

Appendix F also gives the electrical power input to the fans from which the monthly, then the yearly electrical energy consumption by the ventilation system may be estimated. By Tables F.1 to F.12, it can be calculated that a total annual electrical energy of 16869 kWh was used to ventilate the typical swine finishing barn. The expected annual hog production for the barn under study is in the order of 7980 hogs which results in a ventilation energy requirement per hog produced of about 2.11 kWh.

Figure 3.9 is a nomograph which can be used to determine the relative cost of energy to the market value of the product as a function of the unit cost of electricity and the market value of the finished hog. By Figure 3.9, it can be seen that at the present cost of electricity at six cents per kWh and for sales value of $100 per hog, the cost of electrical energy used for ventilation represents only 0.1 percent of the market value. Therefore, for a hog finishing enterprise, an increase in the cost of energy is not expected to affect significantly the operating cost in a direct manner; but, indirectly through the influence of the cost of energy on feed prices. Due to the small fraction of the operating cost of a hog finishing enterprise that can

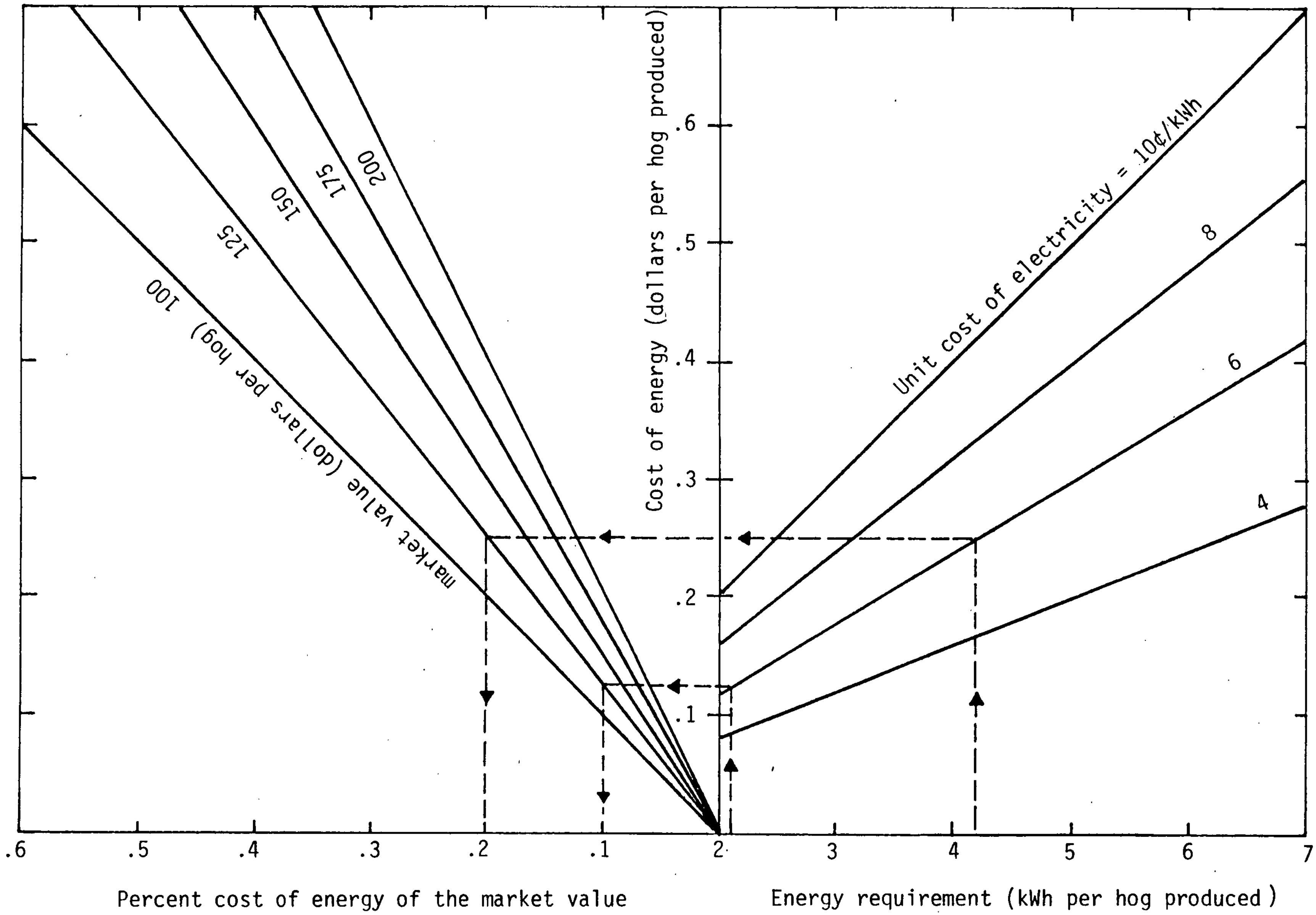


FIGURE 3.9: NOMOGRAPH FOR DETERMINING THE COST OF ENERGY USED FOR VENTILATION OF SWINE FINISHING BARNS.

be attributed to energy cost, it is unlikely that a combined greenhouse-livestock building, designed strictly for the purpose of energy conservation, will be beneficial to the hog producer.

The amount of sensible heat available in the ventilation air for potential use in greenhouse heating may be estimated using the total ventilation rate from Tables F.1 to F.12 of Appendix F as follows:

$$\frac{Q}{\Delta T} = 3600\ \rho V\ C_p \quad . \qquad (23)$$

The ventilation rate V varied from a winter low of 3.66 m^3/s to a maximum of 76.80 m^3/s during the summer months. As a first approximation, assume that the exhaust air from the swine building is at 20°C and standard atmospheric pressure, then the density "ρ" may be taken as 1.204 kg/m^3 and the specific heat "C_p" at constant pressure at 1.012 kJ/kg. °C. Therefore, the amount of heat available in the exhaust air "$q/\Delta T$" is in the range of 16 MJ/°C to 337 MJ/°C with the actual value depending on the outside temperature. The potential available energy in the upper scale of the range will not be useful since it corresponds to periods of high outside temperature when the greenhouse does not require heat. It is expected that most of the energy gain from the livestock building will be for moderate outside temperatures during the spring and fall periods. Note that direct waste heat recovery from the swine building ventilation system is useful only when the greenhouse temperature is below 20°C.

CONCLUSIONS

The following conclusions can be drawn from the results of the simulation of heating and ventilation requirements of the hog finishing barn described in this section:

1. For a well insulated building, no supplemental heat is required for an inside temperature of 20°C and a relative humidity below 85 percent.
2. For a variable speed fan system, it is found that about 2.1 kWh of electrical energy is required to finish a hog from 50 kg to market weight.
3. The cost of energy for ventilation is a small fraction of the operating cost and represents only 0.1 percent of the hog market value. The above estimated value is based upon $0.06/kWh for electrical power and $100 hog market value.
4. The amount of sensible heat available in the exhaust air from the swine barn is found to be between 16 and 337 MJ/°C. The actual value depends on the outside temperature.
5. A greenhouse-swine building combination is not beneficial to the hog producer if only energy is considered.

NOMENCLATURE

Symbol	Definition	Units
A_c	Surface area of the ceiling	m^2
A_f	Surface area of the foundation	m^2
A_i	Surface area of any wall "i"	m^2
A_j	Surface area of any exposed surface "j" of the attic space	m^2
C_p	Specific heat of air at constant pressure	$kJ.kg_a^{-1}.K^{-1}$
h'_b	Specific enthalpy of moist air at the inside dry-bulb temperature and at the dew-point temperature of the outside air	$kJ.kg_a^{-1}$
h_0	Specific enthalpy of moist air at the outside conditions	$kJ.kg_a^{-1}$
$\bar{h}_{w,i}$	Average convective heat transfer coefficient due to the wind for the outside surface of any wall "i"	$kJ.h^{-1}.m^{-2}.K^{-1}$
h_{fg}	Latent heat of vaporization of water	$kJ.kg_w^{-1}$
I_ℓ	Black body radiation at the outside dry-bulb temperature ($I_\ell = \sigma T_0^4$)	$kJ.h^{-1}.m^{-2}$
$I_{s,i}$	Total solar radiation incident on any wall "i"	$kJ.h^{-1}.m^{-2}$
L_f	Part-load ratio of the fan defined as the delivered air flow in any one hour divided by the design air flow rate for the fan	dimensionless

m_a	Mass flow rate of the ventilation air	$kg_a.h^{-1}$
m_w	Total moisture produced within the livestock building	$kg_w.h^{-1}$
P	Building parameter	m
P_f	Fraction of full-load power for a variable speed fan	dimensionless
Q	Sensible heat available in ventilation air	$kJ.h^{-1}$
Q_e	Total building latent heat	$kJ.h^{-1}$
Q_{SENS}	Total sensible heat production within the building	$kJ.h^{-1}$
Q_{SUP}	Supplemental heat requirement for the livestock building	$kJ.h^{-1}$
Q_{TRAN}	Heat loss or gain through the building envelope	$kJ.h^{-1}$
Q_{VENT}	Heat loss or gain due to ventilation	$kJ.h^{-1}$
T_a	Attic temperature	K
T_b	Inside dry-bulb temperature	K
T_0	Outside dry-bulb temperature	K
T_{sky}	Effective temperature of the sky	K
$T_{sa,i}$	Sol-air temperature for surface "i"	K
$T_{s,i}$	Outside surface temperature of any wall "i"	K
$T_{s,j}$	Outside surface temperature of any exposed surface "j" of the attic space	K
T_g	Temperature of the ground at the surface	K

U_c	Overall heat transfer coefficient of the ceiling	$kJ.h^{-1}.m^{-2}.K^{-1}$
U_f	Overall heat transfer coefficient of the foundation	$kJ.h^{-1}.m^{-2}.K^{-1}$
U_i	Heat transfer coefficient of any wall "i" excluding the outside film coefficient	$kJ.h^{-1}.m^{-2}.K^{-1}$
U_j	Heat transfer coefficient of any exposed surface "j" of the attice space excluding the outside film coefficient	$kJ.h^{-1}.m^{-2}.K^{-1}$
U_p	Effective heat transfer coefficient for the perimeter	$kJ.h^{-1}.m^{-1}.K^{-1}$
V	Ventilation rate	$m^3.s^{-1}$
v	Specific volume of inside air (exhaust ventilation system)	$m^3.kg_a^{-1}$
W	Wind speed	$m.s^{-1}$
W_b	Humidity ratio of inside air	$kg_w.kg_a^{-1}$
W_0	Humidity ratio of outside air	$kg_w.kg_a^{-1}$
β_i	Slope of surface "i" from the horizontal	radians
α_i	Absorptivity of surface "i" to solar radiation	
ϵ_i	Emissivity of surface "i" to long-wave radiation	

σ	Stefan-Boltzmann constant ($\sigma = 20.411 \times 10^{-8}$)	$kJ.h^{-1}.m^{-2}.K^{-4}$
ρ	Density of air	$kg.m^{-3}$
ΔT	Operating temperature difference between the livestock building and the greenhouse	K

CHAPTER 4

COMPUTER SIMULATION
MODEL
OF
HEATING REQUIREMENTS
FOR A
CONVENTIONAL GABLE GREENHOUSE

INTRODUCTION

This chapter is devoted to an analysis of energy flows with respect to a conventional greenhouse. It consists of two separate sections.

The first section deals with the development of a mathematical model using energy balances about the different components of the greenhouse. Also stated in this section, are the assumptions made during the greenhouse mathematical model development.

In the second section, simulation results of a case study are given for a conventional gable glasshouse. The computer simulation analyses concentrate on the effects of inside greenhouse temperature and infiltration on the heating loads. Also, the passive solar contributions to the greenhouse heating requirements for different minimum indoor temperatures are investigated in detail.

SECTION A

MATHEMATICAL MODEL
DEVELOPMENT
FOR THE
GABLE GREENHOUSE

MODEL DEVELOPMENT

ASSUMPTIONS

In developing the model, the following assumptions were made:

i) Effect of heat storage in the greenhouse floor is neglected.

ii) Effect of shading by the structural frame is neglected.

iii) No condensation or dust accumulation on the greenhouse covering such that the transmittance for solar radiation is for the covering material only.

iv) The greenhouse covering material is assumed to be opaque to long wave radiation.

v) The transmittance of the greenhouse covering material to diffuse radiation is assumed to be constant and equal to that of the beam transmittance for an angle of incidence of 1.0123 radians.

vi) The plant canopy reflects diffusely regardless of whether the original incident radiation is beam or diffuse in nature.

vii) Multiple reflection between the plant canopy and the greenhouse cover is neglected.

viii) Energy consumption by photosynthesis and evapotranspiration is assumed to be negligible.

The first assumption implies that the heat storage capacity of the soil is negligible relative to the daily energy input to the greenhouse. This assumption is adequate if the purpose of the simulation model is to compute heating requirements rather than inside environmental conditions, response times or time constants of different heating elements (Kindelan, 1980).

The second assumption may be justified for steel and aluminum greenhouse structures, since the percentage surface occupied by structural members is very small compared to the total area of the transparent cover. For wood construction this percentage usually does not exceed 5 percent.

The third assumption implies that the greenhouse cover must be clean from dust which is usually the case since greenhouse operators periodically wash the glass. As far as condensation is concerned, it usually does not occur in a significant amount to affect solar radiation input. Its effect is mainly on the night heat loss from plastic covered greenhouses. Its effect on heat loss from glasshouses was found to be negligible due to the low transmissivity of glass to long wave radiation compared to that of some plastics (Walker and Walton, 1971).

The fourth assumption is valid for greenhouse covered with glass and probably polycarbonate and fiber glass. The transmissivity of the above greenhouse covering materials to long wave radiation as measured by Godbey et al.(1977) are

0.03. 0.06 and for glass, polycarbonate and corrugated fiberglass, respectively. For polyethylene covered greenhouses, the theory formulated in this study should be modified accordingly to take into account the transmissivity of the plastic film to long wave radiation.

The fifth assumption was used by Duffie and Beckman (1974) for glass covered solar collector analyses. It is assumed to equally hold for glasshouse analyses.

Assumption (vi) of perfect diffuse reflection may not be in serious error provided the whole plant canopy is considered.

The seventh assumption implies that only the first reflection is considered. That is , solar radiation exchange associated with multiple reflections compared to the first reflection is negligible, because of the high absorption of the plant canopy and the high transmittance of the cover to solar radiation.

It has been proven by many researchers (Froehlich et al. (1979), Walker (1965)) that solar radiation used by plants for photosynthesis, and energy released during the respiration process are negligible relative to other energy inputs to the greenhouse. This justifies the first part of the eighth assumption. On the other hand, evapotranspiration may be significant during periods, the greenhouse usually does not require supplemental heating. Therefore, the effect of evapotranspiration on estimating daily heating loads is negligible.

HEAT BALANCE ABOUT THE GREENHOUSE

When all the above assumptions are taken into consideration, the heat balance about the greenhouse may be stated as follows:

SUPPLEMENTAL HEAT + SOLAR RADIATION INPUT

- INFILTRATION - HEAT TRANSMISSION = 0 .

or in equation form:

$$Q_{SOL} + Q_{SUP} - Q_{INF} - Q_{TRAN} = 0 \quad . \qquad (1)$$

TRANSMISSION HEAT TRANSFER

Basically the same method employed with respect to the livestock building is used to estimate the heat transfer by conduction, convection and radiation between the greenhouse and its environment. This method is valid since the greenhouse glass cover is assumed to be opaque to thermal radiation. The outside surface temperature of the glass cover for each of the walls of the greenhouse is calculated using equation (4) of Chapter 3. Then, the transmission heat transfer between the greenhouse and its environment is calculated as follows:

$$Q_{TRAN} = U_f A_f \; (T_g - T_o) + U_p P \; (T_g - T_o) + \sum_{i=1}^{n} U_i A_i \; (T_g - T_{s,i}) \qquad (2)$$

The heat transfer coefficient U_i includes the inside film coefficient and the resistance of the covering material of any surface i of the greenhouse.

Or

$$U_i = \frac{1}{R_i} \qquad (3)$$

where $$R_i = \frac{1}{\bar{h}_{i,i}} + R_{c,i} \qquad (4)$$

The first term on the right hand side of equation (2) represents the heat loss or gain through the foundation, the second term represents that of the greenhouse perimeter, and the third term represents the heat loss or gain through the walls and the roof of the greenhouse.

<u>INFILTRATION HEAT LOSS</u>

The sensible heat loss or gain due to air infiltration/exfiltration from the greenhouse is calculated using the air-exchange method.

$$Q_{INF} = \rho C_p V_g N_a \, (T_g - T_o) \qquad (5)$$

If the air is assumed at standard pressure and temperature of 20°C, then

$$C_p = 1.012 \text{ kJ.kg}^{-1}.\text{K}^{-1}$$

and

$$\rho = 1.204 \text{ kg.m}^{-3} \quad ,$$

and equation (5) becomes,

$$Q_{INF} = 1.218 \, V_g N_a \, (T_g - T_o) \qquad (6)$$

The number of air changes for any greenhouse will depend on the structure, covering material, maintenance, the extent of wind protection and the indoor-outdoor temperature differential. Representative values of air infiltration rates that can be expected in various types of greenhouse are given in a publication by the Ontario Ministry of Agriculture and Food*. For newly constructed glasshouses the estimated air infiltration rate is between 0.75 and 1.5 air changes per hour. For old glasshouses, the infiltration rate ranges between 1.0 and 2.0 air changes per hour, depending on the quality of the maintenance to the greenhouse glazing. For plastic-covered greenhouses, the infiltration and exfiltration rates range from 0.2 to 1.0 air changes per hour.

SOLAR ENERGY CAPTURED BY THE GREENHOUSE

The total solar radiation entering the greenhouse is the sum of the solar energy transmitted through each of the transparent surfaces making up the greenhouse envelope. Since the transmission of the covering material to solar radiation is dependent on the form of the original radiation incident on the surface, the solar radiation transmitted through each surface is treated separately for the beam and diffuse components of the total insolation.

For the vertical walls of the greenhouse, the direct radiation transmitted through any surface "i" is

$$B_{w,i} = B_{v,\gamma} \, \tau_{b,i} A_i \quad . \tag{7}$$

---

* Energy Conservation in Ontario Greenhouses. Publication 65. Ministry of Agriculture and Food, Ontario.

And, for the diffuse component, the diffuse solar radiation transmitted through surface "i" may be written as:

$$D_{w,i} = D_{v,\gamma} \tau_{d,i} A_i \quad , \qquad (8)$$

where "γ" is the orientation of the vertical wall.

If the plants in the greenhouse are tall, then all the solar radiation transmitted through the vertical walls of the greenhouse is intercepted by the plant canopy.

The solar radiation transmitted through surface "i" of the greenhouse that is captured by the plant canopy can be estimated by

$$I_{w,i} = (B_{w,i} + D_{w,i}) (1-\zeta) [1 + \zeta(1-\tau_{d,i}-\alpha_i)] \qquad (9)*$$

where "ζ" is the albedo of the plant canopy and "α_i" is the absorptivity of the covering material to solar radiation.

Two assumptions are made with respect to the above equation. First, the radiation reflected by the plant canopy is diffuse regardless of the form of the original radiation incident on the plants. The second assumption is that the transmissivity of the covering material to diffuse solar radiation is high and that the albedo of the plants is low such that the contribution of multiple reflections is negligible. Equation (9) takes into account only the first reflection.

The total solar radiation transmitted through the vertical walls of the greenhouse and captured by the plant canopy is simply

* Derivation of equation (9) is given in Appendix K.

$$I_w = (1-\zeta) \sum_{i=1}^{n} (B_{w,i} + D_{w,i}) \ [1+\zeta(1-\tau_{d,i}-\alpha_i)] \ . \qquad (10)$$

The contribution of the gable roof to the solar energy input to the greenhouse may be estimated in a similar manner. First the solar radiation incident on each slope of the roof is divided into its direct and diffuse components. Then, the solar radiation transmitted through slope "j" of the roof and intercepted by the plant canopy is calculated as follows:

$$I_{r,j} = B_{r,j} \ \tau_{b,j} \ A_{r,j} + D_{r,j} \ \tau_{d,j} \ A_{r,j}$$
$$[(1-F_{r\to r}) + F_{r\to r} \ (1-\tau_{d,j^*}-\alpha_{j^*}) \ F_{r\to p}] \qquad (11)^*$$

Equation (11) assumes that all the beam radiation transmitted through the roof of the greenhouse is intercepted by the plant canopy. This assumption is valid for relatively low roof slopes. Also, only the first reflection is considered in the above analysis. The "j*" in equation (11) indicates that the radiation properties of the opposite slope are used if the two slopes of the gable roof are not of the same material. The total solar radiation originating from the gable roof of the greenhouse and intercepted by the plant canopy is calculated from equation (11) through a simple summation to give,

$$I_r' = \sum_{j=1}^{2} B_{r,j} \ \tau_{b,j} \ A_{r,j} + D_{r,j} \ \tau_{d,j} \ A_{r,j} \ [(1-F_{r\to r})$$
$$+ F_{r\to r} \ (1-\tau_{d,j^*}-\alpha_{j^*}) \ F_{r\to p}] \qquad (12)$$

* Derivation of the diffuse component of equation (11) is given in Appendix K.

The radiation configuration factors $F_{r \rightarrow r}$ and $F_{r \rightarrow p}$ in equations (11) and (12) can be calculated using the method described in Section B of Chapter 2.

The calculation of the transmittance of the greenhouse covering materials for beam and diffuse solar radiation is described in detail in Appendix A.

The amount of total solar radiation originating from the roof slopes and captured by the greenhouse is dependent on the albedo of the plant canopy and the radiation properties of the roof-covering material. Again, if only the first reflection is considered then the solar energy captured by the top of the plant canopy may be estimated by

$$I_r = I_r' (1-\zeta) [1 + \zeta(1-\tau_{d,r}-\alpha_r)] \quad (13)$$

Equation (13) is valid when the two slopes of the gable roof have approximately the same values for the transmittance and absorptance to solar radiation.

The total solar energy captured by the greenhouse is the sum of the solar radiation from the vertical walls and roof of the greenhouse. Thus,

$$Q_{SOL} = I_w + I_r \quad . \quad (14)$$

SECTION B

CASE STUDY II

HEATING REQUIREMENTS OF A CONVENTIONAL GABLE GLASSHOUSE

CONVENTIONAL GABLE GREENHOUSE - A CASE STUDY

DESCRIPTION AND ASSUMPTIONS

The computer simulation model developed in Section A of this chapter was used to predict hourly values of the transmission heat loss from the greenhouse envelope, the heat loss due to infiltration, and the solar energy captured by the greenhouse. Then, the supplemental heat requirement as well as the fraction of the total heat load supplied through natural solar radiation capture by the greenhouse were calculated using the predicted hourly heat loss and solar energy inputs.

The following additional assumptions are made with respect to the conventional greenhouse case study.

i) Only the minimum greenhouse temperature is specified and assumed constant throughout the time of the simulation (This assumption is adequate if the main objective is the determination of heating loads).

ii) Infiltration rate is assumed to be constant.

iii) The albedo of the plant canopy within the greenhouse is constant and assumed equal to ten percent.

The gable greenhouse used in the case study has a length of 100m and a width of 10m. The long axis of the greenhouse is east-west oriented. The footing and the perimeter of the greenhouse are insulated to minimize heat loss to the ground. The greenhouse is covered with a single layer of glass. Other pertinent construction parameters, the properties of the construction materials as well as the greenhouse management parameters are given in Table 4.1. To complete the description of the facility a cross-sectional view of the greenhouse is shown in Figure 4.1.

RESULTS AND DISCUSSION

A sample computer simulation output for a conventional gable greenhouse located in Vancouver, B.C. is included in Appendix G (Tables G.1 to G.12). These tables give the hourly and daily results for a typical day of each month of the year. The results apply to the greenhouse described in Table 4.1 and operated at a minimum temperature (i.e.night temperature) of 15°C. The information in the tables include the solar radiation passively captured by the greenhouse, transmission and infiltration heat losses as well as the predicted supplemental heat requirement and the fraction of the total heat loss that is supplied by solar due to natural solar energy collection by the greenhouse. A summary of the results of Appendix G is shown, on a monthly basis, in Table 4.2.

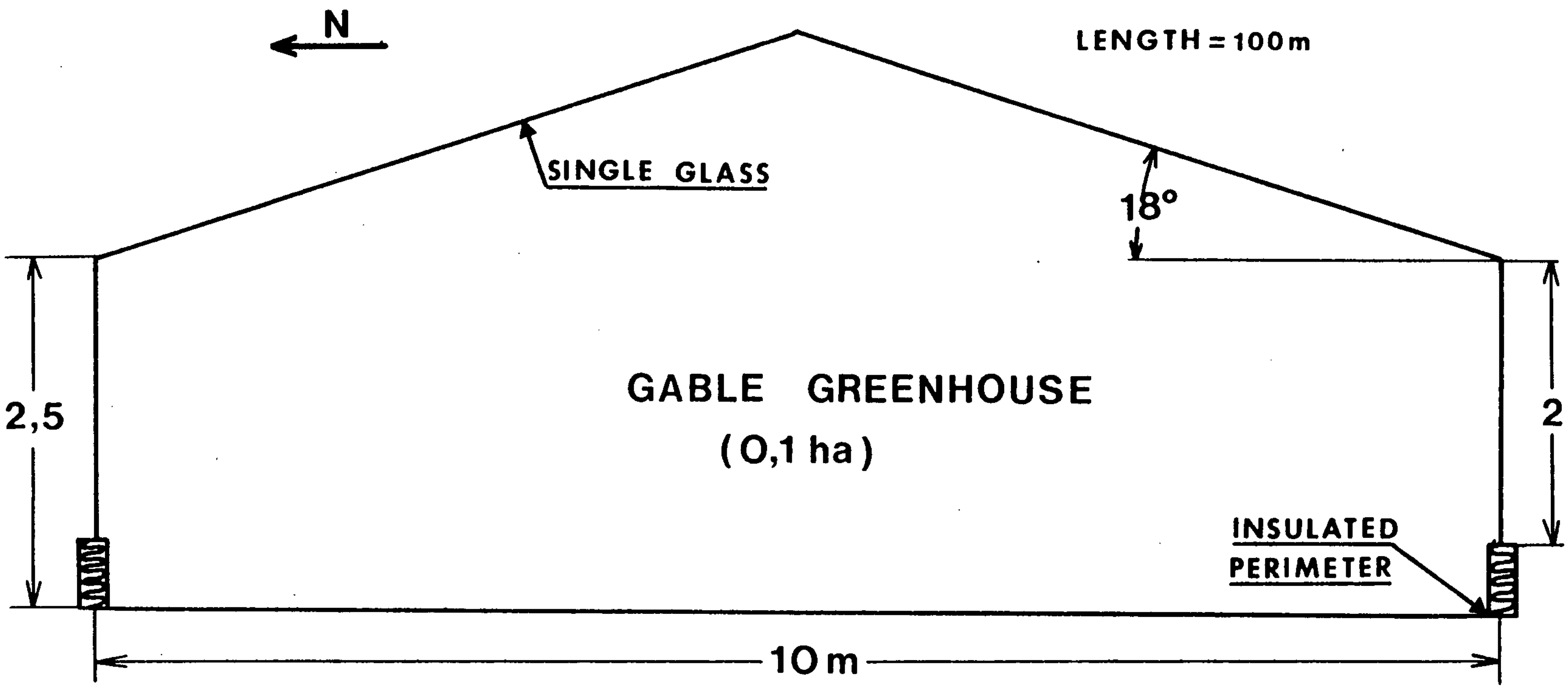


FIGURE 4.1: CROSS-SECTION OF THE CONVENTIONAL GABLE GREENHOUSE USED IN CASE STUDY II.

TABLE 4.1

VARIABLES USED TO CALCULATE HEATING DEMANDS OF A CONVENTIONAL GABLE GREENHOUSE

Construction Parameters

Length:	100 m
Width:	10 m
Height:	2 m
Roof Slope:	18°
Orientation:	East-West Long Axis

Construction Materials Properties

Surface	Material	Area (m^2)	U ($Wm^{-2}K^{-1}$)	α_s	ε_ℓ
South Roof	Single Glass	526	8.83	0.08	0.94
North Roof	Single Glass	526	8.83	0.08	0.94
South Wall	Single Glass	200	8.03	0.08	0.94
North Wall	Single Glass	200	8.03	0.08	0.94
East Wall	Single Glass	28	8.03	0.08	0.94
West Wall	Single Glass	28	8.03	0.08	0.94
Footing	Insulated Concrete	110	0.67	-	-
Perimeter	Insulated	220 (m)	0.67 ($Wm^{-1}K^{-1}$)	-	-

Glass Properties

Thickness:	0.3 cm
Extinction Coefficient:	0.252 cm^{-1}
Refraction Index:	1.526
Absorptivity to Solar Radiation:	0.08
Emissivity for Thermal Radiation:	0.94

Management Parameters

Location:	Vancouver, B.C. Montreal, Quebec Halifax, N.S.
Minimum Greenhouse Temperature:	10°C, 15°C, or 20°C
Infiltration Rate:	1.5 Air changes per hour
Plant Canopy Albedo:	0.1

A close examination of Table 4.2 reveals the following points with respect to a single glazed gable greenhouse operation at a minimum inside temperature of 15^{o}C and located in the Vancouver, B.C. area.

i) The heating season extends over the twelve months of the year. This is due to cool summer nights which are characteristic of the region.

ii) The natural contribution of solar radiation to the greenhouse heating load can be as low as 15 percent in the summer months and increasing to 37 percent in the spring period. The annual average is found to be only 28 percent even though the annual solar energy captured by the greenhouse well exceeds the annual heating load requirement. For this typical case, the ratio of annual solar energy input to annual heat loss is in the order of 1.5. Therefore, if an adequate seasonal thermal storage is incorporated; theoretically, the greenhouse could be heated solely by the natural solar energy capture of the greenhouse.

Further computer analyses were performed on an identical greenhouse to that used in the Vancouver case. The purpose of the additional analyses is to investigate the effect of climatic conditions on the greenhouse performance.

TABLE 4.2

MONTHLY AVERAGE HEATING LOAD, SOLAR ENERGY INPUT, SOLAR CONTRIBUTION AND SUPPLEMENTAL HEAT REQUIREMENTS IN MJ PER m^2 OF GREENHOUSE FLOOR AREA AND PERCENT OF THE HEATING LOAD SUPPLIED BY SOLAR FOR THE CONVENTIONAL GABLE GREENHOUSE OF CASE STUDY II (MINIMUM INSIDE TEMPERATURE = 15°C)

VANCOUVER, B.C.

Month	Heat Loss	Solar Input	Solar Contribution	Supplemental Heat	Percent Solar
January	462	187	112	350	24
February	365	225	106	259	29
March	383	360	130	253	34
April	262	394	97	165	37
May	153	465	53	100	35
June	77	528	24	53	31
July	43	512	10	33	21
August	32	487	6	26	17
September	80	372	13	67	15
October	232	276	66	166	28
November	340	160	84	256	25
December	449	138	101	348	22
Year	2878	4104	802	2076	28

Summaries of the results for the two additional locations in Canada are included in Tables 4.3 and 4.4 for Montreal, P.Q. and Halifax, N.S. respectively.

When the values in Tables 4.3 and 4.4 are compared to those in Table 4.2 for Vancouver, it can be seen that the extent of the greenhouse heating season in Halifax is similar to that for Vancouver; however, the heating season for Montreal is three months shorter. This may be attributed to the warmer summer nights in the Montreal region as compared to the Vancouver or Halifax regions. It is also interesting to notice that the annual solar energy contribution to the heating load is slightly lower for Halifax and Montreal than the value of 28 percent previously found for Vancouver even though the solar radiation input to the greenhouse is higher in the former cities than in the later. Obviously, the effect of the increased solar input was cancelled by the higher greenhouse heating loads for Halifax and Montreal when compared to Vancouver. The annual supplemental heat requirements in megajoules per square metre of floor area were found to be 2076, 2718 and 3262 for a greenhouse operated at a minimum temperature of 15°C and located in Vancouver, Halifax and Montreal respectively. Thus, a greenhouse located in the Vancouver area will require 31

TABLE 4.3

MONTHLY AVERAGE HEATING LOAD, SOLAR ENERGY INPUT, SOLAR CONTRIBUTION AND SUPPLEMENTAL HEAT REQUIREMENTS IN MJ PER m^2 OF GREENHOUSE FLOOR AREA AND PERCENT OF THE HEATING LOAD SUPPLIED BY SOLAR FOR THE CONVENTIONAL GABLE GREENHOUSE OF CASE STUDY II (MINIMUM INSIDE TEMPERATURE = 15°C)

MONTREAL, QUEBEC

Month	Heat Loss	Solar Input	Solar Contribution	Supplemental Heat	Percent Solar
January	908	170	170	738	19
February	750	218	191	559	26
March	609	367	200	409	33
April	340	392	125	215	37
May	85	465	17	68	20
June	4	525	0	4	0
July	0	510	0	0	0
August	0	485	0	0	0
September	47	370	5	42	11
October	257	270	67	190	26
November	465	150	115	350	25
December	810	123	123	687	15
Year	4275	4045	1013	3262	24

TABLE 4.4

MONTHLY AVERAGE HEATING LOAD, SOLAR ENERGY INPUT, SOLAR CONTRIBUTION AND SUPPLEMENTAL HEAT REQUIREMENTS IN MJ PER m^2 OF GREENHOUSE FLOOR AREA AND PERCENT OF THE HEATING LOAD SUPPLIED BY SOLAR FOR THE CONVENTIONAL GABLE GREENHOUSE OF CASE STUDY II (MINIMUM INSIDE TEMPERATURE = 15°C)

HALIFAX, N.S.

Month	Heat Loss	Solar Input	Solar Contribution	Supplemental Heat	Percent Solar
January	640	167	143	497	22
February	586	217	158	428	27
March	533	356	176	357	33
April	366	392	134	232	37
May	216	464	75	141	35
June	93	525	24	69	26
July	31	509	4	27	13
August	25	485	4	21	13
September	70	370	9	61	13
October	209	269	49	160	23
November	357	149	85	272	24
December	567	121	114	453	20
Year	3693	4024	975	2718	26

percent and 57 percent less energy when compared to greenhouses located in Halifax and Montreal respectively.

Furthermore, when the ratios of annual solar radiation captured by the greenhouse to the annual heat losses are compared, again, it is found that Vancouver area holds the advantage. These ratios are 0.95, 1.09 and 1.42 for Montreal, Halifax and Vancouver respectively. Therefore, long term thermal storages are likely to be more adaptable to the Vancouver area than the Halifax or Montreal areas.

A new area of research for energy conservation in greenhouse production is the development of low temperature hybrids of greenhouse crops. Therefore, the computer simulation model was used here, to investigate the effect of minimum greenhouse temperature on supplemental heat requirement and fraction of the heating load supplied by passive solar. The typical greenhouse with the construction parameters as specified in Table 4.1is again used in this analysis. For the purpose of this study, the greenhouse is assumed to be located in the Halifax area. Analyses were performed for minimum greenhouse temperatures of 10°C, 15°C and 20°. Summaries of these analyses are shown in Tables 4.4 to 4.6.

TABLE 4.5

MONTHLY AVERAGE HEATING LOAD, SOLAR ENERGY INPUT, SOLAR CONTRIBUTION AND SUPPLEMENTAL HEAT REQUIREMENTS IN MJ PER m^2 OF GREENHOUSE FLOOR AREA AND PERCENT OF THE HEATING LOAD SUPPLIED BY SOLAR FOR THE CONVENTIONAL GABLE GREENHOUSE OF CASE STUDY II (MINIMUM INSIDE TEMPERATURE = 10°C)

HALIFAX, N.S.

Month	Heat Loss	Solar Input	Solar Contribution	Supplemental Heat	Percent Solar
January	482	167	112	370	23
February	444	217	123	321	28
March	377	356	123	254	33
April	215	392	69	146	32
May	87	464	18	69	21
June	19	525	2	17	14
July	-	509	-	-	-
August	-	485	-	-	-
September	-	370	-	-	-
October	75	269	7	68	9
November	206	149	44	162	21
December	409	121	87	322	21
Year	2321	4024	585	1736	25

TABLE 4.6

MONTHLY AVERAGE HEATING LOAD, SOLAR ENERGY INPUT, SOLAR CONTRIBUTION AND SUPPLEMENTAL HEAT REQUIREMENTS IN MJ PER m^2 OF GREENHOUSE FLOOR AREA AND PERCENT OF THE HEATING LOAD SUPPLIED BY SOLAR FOR THE CONVENTIONAL GABLE GREENHOUSE OF CASE STUDY II (MINIMUM INSIDE TEMPERATURE = 20°C)

HALIFAX, N.S.

Month	Heat Loss	Solar Input	Solar Contribution	Supplemental Heat	Percent Solar
January	796	167	164	632	20
February	729	217	189	540	26
March	689	356	225	464	33
April	518	392	193	325	37
May	370	464	148	222	40
June	220	525	85	135	39
July	115	509	28	87	25
August	107	485	23	84	21
September	192	370	52	140	27
October	363	269	102	261	28
November	507	149	120	387	24
December	725	121	121	603	17
Year	5331	4024	1451	3880	27

Table 4.7 gives the predicted monthly supplemental heat requirements for the selected three minimum greenhouse temperatures as well as the expected potential energy savings due to reducing the minimum greenhouse temperature from 20°C to 15°C and to 10°C respectively. The annual potential energy saving due to reducing the minimum greenhouse temperature from 20°C to 15°C is about 30 percent. An additional 25 percent can be expected if the minimum temperature is further decreased to 10°C or around 5 percent saving per degree reduction in temperature. Obviously, the above approximation is only valid for all year around greenhouse operation as can clearly be seen in Table 4.7.

The contribution of solar radiation to the annual heating load is not significantly affected by lowering the greenhouse temperature as can be depicted in Tables 4.4 to 4.6. Reducing the greenhouse indoor temperature tends to increase the monthly fraction of the heating load supplied by solar during the winter months but it has an opposite effect during the other months of the year, thus resulting in a negligible overall effect when the entire year is considered (Tables 4.4 to 4.6).

As expected, lowering of the minimum inside temperature of the greenhouse increased significantly the ratio of solar radiation capture to heat loss. From Tables 4.4 to 4.6, this ratio on an annual basis, can be calcuated as 0.75, 1.09

TABLE 4.7

EFFECT OF MINIMUM INSIDE GREENHOUSE TEMPERATURE ON SUPPLEMENTAL HEAT REQUIREMENT AND EXPECTED ENERGY SAVINGS DUE TO REDUCING THE MINIMUM TEMPERATURE FROM 20°C

HALIFAX, N.S.

Month	Supple. Heat* T_g=20°C	Supple. Heat* T_g=15°C	Percent Savings	Supple. Heat* T_g=10°C	Percent Savings
January	632	497	21	370	41
February	540	428	21	321	41
March	464	357	23	254	45
April	325	232	29	146	55
May	222	141	36	69	69
June	135	69	49	17	87
July	87	27	69	-	100
August	84	21	75	-	100
September	140	61	56	7	95
October	261	160	39	68	74
November	387	272	30	162	58
December	603	453	25	322	47
Year	3880	2718	30	1736	55

* In MJ per m^2 greenhouse floor area per month

and 1.73 for minimum inside temperatures of 20^{o}C, 15^{o}C and 10^{o}C respectively.

Another method of conserving energy in greenhouses is reducing infiltration/exfiltration losses (i.e. plastic cover over a glasshouse). However, the economics of any retrofit to minimize infiltration heat loss depends on the net energy savings.

The mathematical model developed in Section A of this chapter is utilized here to predict the potential annual savings due to elimination of air infiltration into the greenhouse. A summary of the simulation results is included in Table 4.8. The results are for an east-west gable greenhouse with single glass cover and operated at a minimum inside temperature of 20^{o}C, other specification for the greenhouse are included in Table 4.1. The weather data used here are typical of the Halifax region.

Table 4.8 shows that the monthly average heat loss due to infiltration ranged between 7 to 13 percent resulting in an annual average of 12 percent. The energy savings as calculated from Table 4.8 are gross values; therefore, net savings are expected to be relatively smaller. Thus, it can be concluded that with the exception of old and badly maintained glasshouses, reducing infiltration is not considered to be a significant factor in energy conservation for greenhouse.

TABLE 4.8

EFFECT OF INFILTRATION RATE ON SUPPLEMENTAL HEAT REQUIREMENT FOR A CONVENTIONAL GABLE GLASSHOUSE KEPT AT A MINIMUM INSIDE TEMPERATURE OF 20°C

HALIFAX, N.S.

Month	Supplemental Heat (MJ/m^2 Floor Area per Month)		Percent Due to Infiltration
	1.5 Air Changes Per Hour	Zero Infiltration	
January	632	552	13
February	540	473	12
March	464	407	12
April	325	286	12
May	222	197	11
June	135	121	10
July	87	79	9
August	84	78	7
September	140	127	9
October	261	233	11
November	387	343	11
December	603	524	13
Year	3880	3420	12

Conventional greenhouses are basically passive solar heating systems. Their efficiencies when expressed as a fraction of the greenhouse heating load that is supplied by the sun were previously found to be in the order of 25 percent. The efficiency can be improved by making the greenhouse as an active system and providing for solar energy storage. The potential of active solar energy collection and storage can be determined using the solar energy utilization factor (S.E.U.) concept (Ben Abdallah, 1978 and 1979). This factor is defined as the ratio of the solar energy contribution (to the heating load) to the solar radiation captured by the greenhouse. By definition, a solar energy utilization factor of unity implies that all solar radiation captured by the greenhouse is utilized, therefore, no excess energy is available for storage. The monthly average solar energy utilization factor for an east-west gable greenhouse covered with single layer of glass are plotted in Figure 4.2. For the sake of comparison the monthly average fractions of the greenhouse heating load that is supplied by solar are also shown. The results are for two identical greenhouses one located in Vancouver and the other in Montreal.

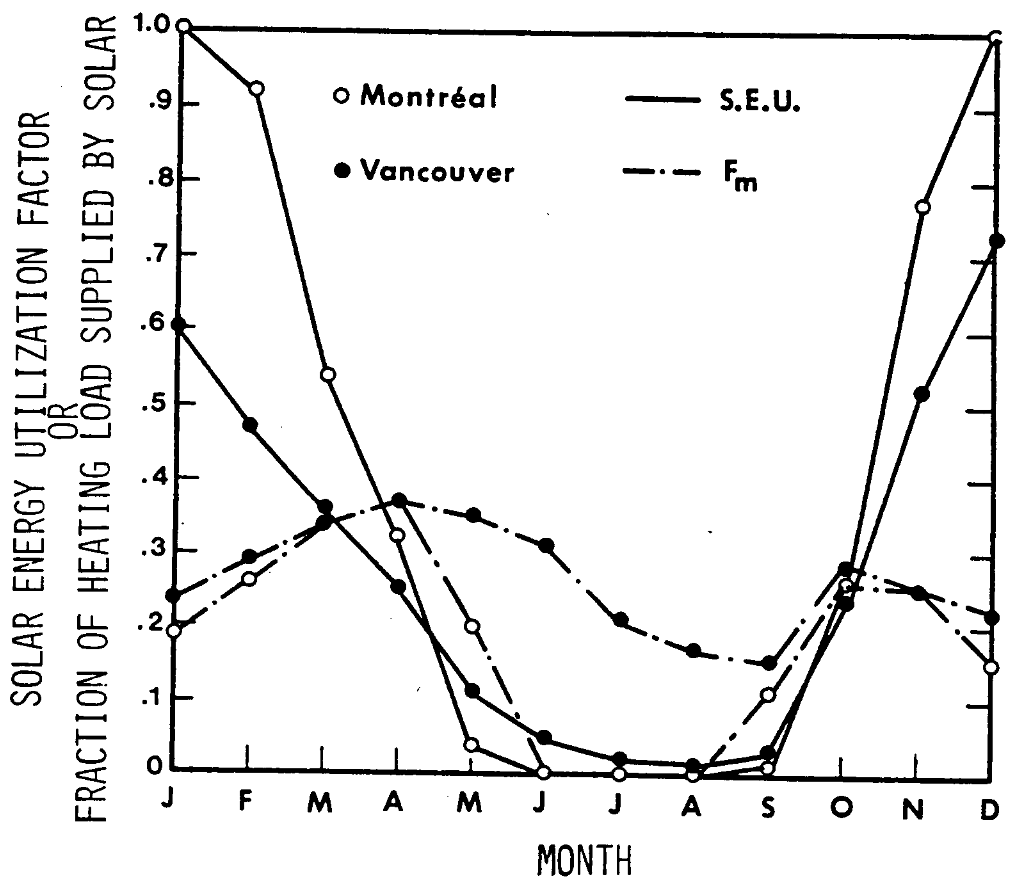


FIGURE 4.2: MONTHLY AVERAGE SOLAR ENERGY UTILIZATION FACTOR AND FRACTION OF HEATING LOAD SUPPLIED BY PASSIVE SOLAR FOR AN E-W GABLE GREENHOUSE (SINGLE GLASS COVER, MINIMUM INSIDE TEMPERATURE 15°C).

The information presented in the graph of Figure 4.2 can be interpreted as follows: for example, the month of January, it is seen that, for Vancouver, 60 percent of the solar radiation captured by the greenhouse is passively utilized to supply 24 percent of the heating load while in the case of Montreal, all the solar energy is utilized to supply only 19 percent of the greenhouse heating load.

For the summer months,the greenhouse heating load in Montreal is zero, thus, the solar energy utilization factor is zero for that period, while for Vancouver 1 to 5 percent of solar energy captured is utilized to supply 17 to 31 percent of the heating load.

Solar energy storage may contribute significantly to energy savings during the spring and fall. As can be seen from Figure 4.2 for example, in April, 25 percent for Vancouver, and 32 percent for Montreal of the solar energy captured by the greenhouse are utilized to supply 37 percent of the heating load.

The solar energy utilization factor is closely related to the environmental temperature and to the availability of solar radiation. Therefore, it is expected to be location dependent. The effect of location on the

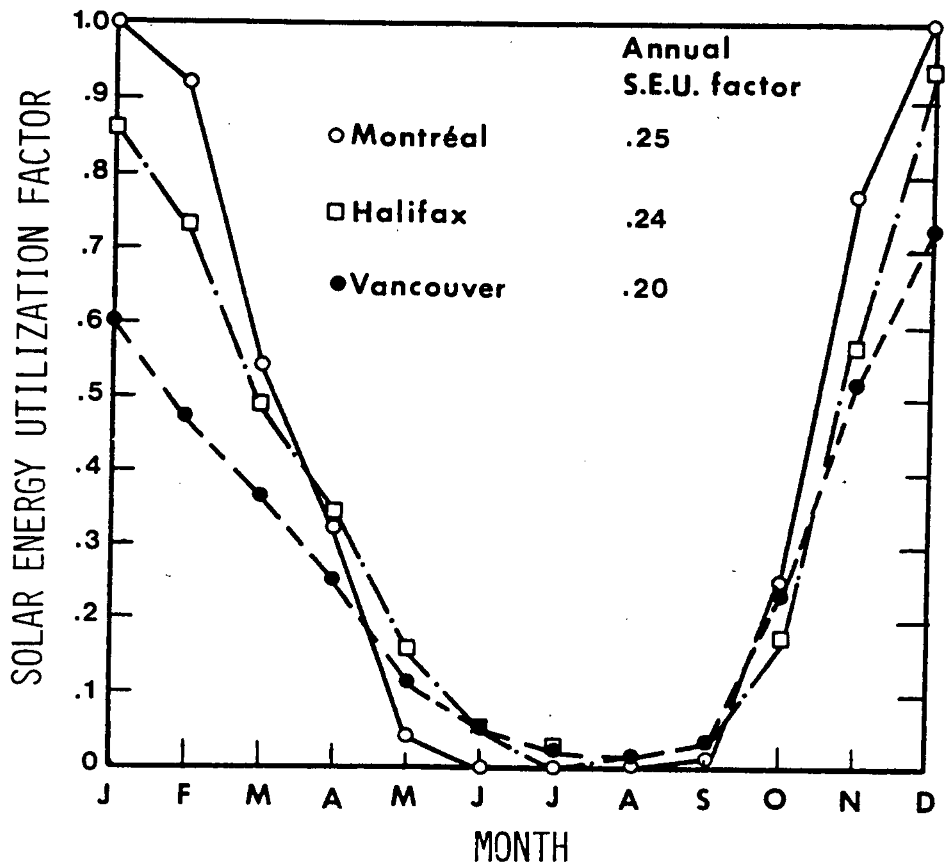


FIGURE 4.3: EFFECT OF LOCATION ON THE SOLAR ENERGY UTILIZATION FACTOR (S.E.U.) BY MONTH FOR AN E-W GABLE GREENHOUSE (SINGLE GLASS COVER, MINIMUM INSIDE TEMPERATURE OF 15°C).

solar energy utilization factor is depicted in Figure 4.3. The figure indicates that among the three locations analysed, Vancouver is more suitable for improvement to the solar energy utilization by the incorporation of a thermal storage. Also shown on Figure 4.3, the annual solar energy utilization factors for the three locations which have the values of 0.20, 0.24 and 0.25 for Vancouver, Halifax and Montreal respectively. The corresponding annual fractions of the heating loads which are supplied by solar are 0.28, 0.26 and 0.24 for Vancouver, Halifax and Montreal respectively. Obviously, the annual solar energy utilization factors are of value only when long-term thermal storages are anticipated.

CONCLUSIONS

The following conclusions can be drawn from the results of the simulation of heating requirements and solar energy utilization of the conventional gable greenhouse described in this section:

1. The annual solar energy contribution to the greenhouse heating load was found to be about 25 percent. This percentage is found to be only slightly affected

by location and minimum greenhouse temperature setting.

2. The ratio of solar radiation capture by the greenhouse to the annual heating load was found to be in the range of 0.75 to 1.75 depending on the location of the greenhouse and its minimum temperature setting. Therefore, theoretically a greenhouse with a seasonal thermal storage could be made self sufficient in energy for most cases.
3. Lowering of the greenhouse minimum temperature results in significant energy savings. A five percent energy saving for each degree Kelvin reduction in temperature could be expected.
4. For a well constructed and maintained greenhouse, minimizing infiltration was found to be an insignificant factor in energy conservation. Net savings of less than ten percent could be expected.
5. The solar energy utilization factor could be improved significantly during the spring and fall periods by storing daytime excess heat for nighttime use. This would increase the annual solar energy utilization factor from its low value of about 0.20 for conventional greenhouses.

NOMENCLATURE

Symbol	Definition	Units
A_f	Surface area of the foundation	m^2
A_i	Surface area of any vertical wall "i"	m^2
$A_{r,j}$	Surface area sloped roof "j"	m^2
$B_{r,j}$	Beam solar radiation incident on sloped roof "j"	$kJ.h^{-1}.m^{-2}$
$B_{v,\gamma}$	Beam solar radiation incident on a vertical wall of orientation γ	$kJ.h^{-1}.m^{-2}$
$B_{w,i}$	Beam solar radiation transmitted through any vertical wall "i"	$kJ.h^{-1}$
C_p	Specific heat of air at constant pressure	$kJ.kg_a^{-1}.K^{-1}$
$D_{r,j}$	Diffuse solar radiation incident on sloped roof "j"	$kJ.h^{-1}.m^2$
$D_{v,\gamma}$	Diffuse solar radiation incident on a vertical wall of orientation γ	$kJ.h^{-1}.m^{-2}$
$D_{w,i}$	Diffuse solar radiation transmitted through any vertical wall "i"	$kJ.h^{-1}$
$F_{r \to p}$	Radiation configuration factor between the roof and the plant canopy	
$F_{r \to r}$	Radiation configuration factor between the two slopes of the greenhouse roof	
F_m	Monthly average fraction of the greenhouse heating load supplied by passive solar	
$\bar{h}_{i,i}$	Average convective heat transfer coefficient for the inside surface of the greenhouse cover	$kJ.h^{-1}.m^{-2}.K^{-1}$

I_r	Total solar radiation transmitted through the roof that is captured by the plant canopy	$kJ.h^{-1}$
I'_r	Total solar radiation transmitted through the greenhouse roof and intercepted by the plant canopy	$kJ.h^{-1}$
$I_{r,j}$	Total solar radiation transmitted through roof slope "j" that is intercepted by the plant canopy	$kJ.h^{-1}$
I_w	Total solar radiation transmitted through the vertical walls of the greenhouse that is captured by the plant canopy	$kJ.h^{-1}$
$I_{w,i}$	Total solar radiation transmitted through wall "i" of the greenhouse that is captured by the plant canopy	$kJ.h^{-1}$
N_a	Greenhouse infiltration rate (air changes)	h^{-1}
P	Greenhouse perimeter	m
Q_{INF}	Heat loss due to infiltration	$kJ.h^{-1}$
Q_{SOL}	Solar energy input to the greenhouse	$kJ.h^{-1}$
Q_{SUP}	Supplemental heat requirement for the greenhouse	$kJ.h^{-1}$
Q_{TRAN}	Heat loss or gain through the greenhouse envelope	$kJ.h^{-1}$
R_i	Thermal resitance of the greenhouse cover for any surface "i" excluding the outside surface wind coefficient	$h.m^2.K.kJ^{-1}$

$R_{c,i}$	Thermal resistance of the greenhouse cover material of any surface "i"	$h.m^2.K.kJ^{-1}$
S.E.U.	Monthly average solar energy utilization factor	
T_g	Inside greenhouse temperature	K
T_0	Outside environmental temperature	K
$T_{s,i}$	Outside surface temperature of any wall "i"	K
U_f	Overall heat transfer coefficient of the foundation	$kJ.h^{-1}.m^{-2}K^{-1}$
U_i	Heat transfer coefficient of any surface "i" excluding the outside film coefficient	$kJ.h^{-1}.m^{-2}.K^{-1}$
U_p	Effective heat transfer coefficient for the perimeter	$kJ.h^{-1}.m^{-1}.K^{-1}$
V_g	Volume of the greenhouse	m^3
W	Wind speed	$km.h^{-1}$
$\tau_{b,i}$	Transmittance of wall "i" to beam solar radiation	
$\tau_{b,j}$	Transmittance of roof slope "j" to beam solar radiation	
$\tau_{d,i}$	Transmittance of wall "i" to diffuse solar radiation	
$\tau_{d,j}$	Transmittance of roof slope "j" to diffuse solar radiation	
α_i	Absorptance of wall "i" to solar radiation	
α_r	Absorptance of the greenhouse roof to solar radiation	

γ	Orientation of the surface from due south	radians
ρ	Density of air	$kg.m^{-3}$
ζ	Albedo of the plant canopy	

CHAPTER 5

COMPUTER SIMULATION
MODEL
OF
ENERGY REQUIREMENTS
FOR A
COMBINED GREENHOUSE-LIVESTOCK
BUILDING

INTRODUCTION

The mathematical model developed in Chapter 3 for the analysis of ventilation requirements of animal shelters, and that developed in Chapter 4 to predict the heating loads of conventional greenhouses are combined in this chapter to determine the potential energy savings which could be realized by a combined greenhouse-livestock building operation.

The chapter consists of two sections. In the first section, the combined model is described; also a brief discussion on the effects of pollutants present in the exhaust air from the animal shelter on plant growth is presented.

The second section is devoted to a computer simulation analysis of a typical retrofit case of a gable glasshouse-hog barn combination. In this case study, emphasis was on the contribution of animal waste heat recovery to the greenhouse heating requirements. Finally, a comparison of heat demands by a free-standing and an attached greenhouse is also given.

SECTION A

MATHEMATICAL MODEL DEVELOPMENT OF GREENHOUSE-LIVESTOCK COMBINATION

MODEL DEVELOPMENT

ASSUMPTIONS

All the assumptions stated with respect to the livestock model development in Chapter 3 and those made during the development of the conventional greenhouse mathematical model in Chapter 4 apply to the combined greenhouse-livestock case. In addition, the following assumptions were considered:

i) The ventilation air for temperature or moisture control of the livestock building is taken as 100 percent outside air.

ii) The ventilation air from the livestock building is exhausted directly into the greenhouse to be ultimately lost by exfiltration through the greenhouse vents.

iii) The wall separating the livestock space from that of the greenhouse is assumed to be adiabatic since conduction heat transfer between the two buildings is relatively small compared to the total heat exchange between the buildings and their environments.

iv) Only the sensible portion of the waste heat from the livestock building is recovered, thus the predicted energy savings by this model are conservative.

HEAT BALANCE ABOUT THE BUILDING

For the purpose of heating load calculations, the greenhouse-livestock combination system can be taken as a single structure composed of the following three zones:

i) The attic zone

ii) The livestock zone

iii) The greenhouse zone

ZONE I: ATTIC SPACE

The temperature in the attic space is estimated as indicated with respect to the conventional livestock unit in Chapter 3: equations (7), (2) and (3). The attic temperature is assumed to be a function of the barn temperature, the outside air temperature, the solar radiation absorbed by the roof, and the respective thermal resistances of the roof and the ceiling of the livestock building.

ZONE II: LIVESTOCK BUILDING

The supplemental heat required by the livestock building may be calculated whence the attic temperature is determined. The general heat balance equation about the livestock zone may be written as follows:

$$Q_{SUP,L} = Q_{SENS} - Q_{VENT}^{+} - Q_{TRAN}^{+}, \qquad (1)$$

where the plus sign (+) indicates that only the positive values are considered.

The sensible heat released by the animal, the ventilation rate and ventilation heat loss and transmission heat loss are calculated using the method presented in Chapter 3 with respect to the conventional livestock building.

ZONE III: GREENHOUSE

The general heat balance equation about the attached greenhouse may be stated as follows:

SUPPLEMENTAL HEAT + SOLAR ENERGY INPUT

+ HEAT RECOVERED FROM LIVESTOCK BUILDING - HEAT

TRANSMISSION = 0,

or in equation form:

$$Q_{SUP,G} = Q_{SOL} + Q_{HRL} - Q_{TRAN}^{+}, \qquad (2)$$

where the plus sign (+) indicates that only the positive values are considered.

The above equation is similar to equation (1) of Chapter 4 with the exception that the infiltration heat loss term is replaced by the heat recovery from ventilation air of the livestock zone.

The transmission heat loss through the greenhouse envelope is calculated using the same method which was developed earlier in Chapter 4 with respect to the conventional gable greenhouse.

The solar energy input to the greenhouse is estimated using the same methodology developed in Chapter 4, to determine the solar radiation captured by conventional gable greenhouse.

The only additional subroutine required for the case of a combined livestock-greenhouse system is an algorithm to determine the heat input from the livestock building that is used to partially supply the heating load of the greenhouse. Since, it is assumed that only the sensible portion of the livestock building heat is to be recovered, then the sensible heat available may be calculated as follows:

$$Q_{HRL} = \dot{m}\, C_p\, (T_b - T_g)\,. \tag{3}$$

The above equation clearly shows that the availability of sensible heat is directly proportional to the livestock ventilation rate in unit mass of air per unit time and to the temperature difference between that of the livestock building and of the greenhouse.

In calculating the contribution of the heat recovered to the greenhouse heating load, the sensible heat available from the livestock building is considered only during time periods when the attached greenhouse required supplemental heat. Thus, in most cases, the contribution of waste heat to the greenhouse heating load is zero around noon hours, because passive solar energy alone can supply the total greenhouse heat demand.

ADVANTAGES AND DISADVANTAGES OF DIRECT USE OF EXHAUST AIR

The introduction of exhaust air from the livestock building directly into the greenhouse has many advantages as well as disadvantages. An obvious advantage of the direct exchange system is its low cost. The existing exhaust fans used with conventional barns could easily be adapted for the combined greenhouse-livestock system without the addition of extra equipment, such as heat exchangers. Another advantage of the direct use of the exhaust air is its beneficial effect of increasing the air pressure within the greenhouse, thus reducing infiltration of outside air to a minimum level. A third advantage is the natural carbon dioxide enrichment of the greenhouse environment which could result in an increase in the yield of the crop.

Some of the disadvantages of the direct air exchange system between the livestock building and the greenhouse are related to dust and ammonia accumulation. Dust in the exhaust air from the livestock building may accumulate on the greenhouse covering material and on the leaves of the plants thus possibly causing a reduction in the solar radiation availability for photosynthesis as well as for passive solar energy collection. This problem of dust accumulation could be alleviated by installing air filters at the entrances of the exhaust fans.

Ammonia when present in high concentrations might be a serious problem with respect to undesirable odor and possibly damage to the plants. A very limited amount of research work has been done on the effects of ammonia on plants. Only a few species has been tested for acute injury by this gas but too little is known on plant responses to low-level, long-term exposure to consider chronic effects.

It has been reported in a U.S. Environmental Protection Agency (EPA) report (1978) and in the experimental work on tomato plants by Thornton and Setterstrom (1940) that internal pH increases in the leaf tissue and changes in pigmentation of the leaf could be considered chronic responses to NH_3. The EPA report states that concentrations of 55 ppm require one hour to injure tomato plants.

The other gas which may be present in the exhaust air from livestock buildings is hydrogen sulfide. Thornton and

Setterstrom (1940) found that H_2S was only mildly toxic to plant tissue as compared with other gases. With respect to tomato plants, they gave the following order of toxicity of the gases:

$$Cl_2 > SO_2 > NH_3 > HCH > H_2S .$$

Ammonia and hydrogen sulfide concentrations in livestock buildings depend on many factors including type and density of confined animals, type of manure handling system and the rate of ventilation.

van Dalfsen and Bulley (1982) measured NH_3 and H_2S concentrations within four dairy barns having subfloor manure storages. Their results indicated a range of ammonia concentrations in the buildings between 2.5 to 6.5 ppm during normal conditions, while H_2S was found in measurable quantities only during the agitation of manure. Even then hydrogen sulfide concentrations were less than 3 ppm. Consequently, H_2S is not expected to be a limiting factor for livestock-greenhouse combination systems because of its low concentration and its relatively low level of toxicity to plants.

Certainly acute injury to plants will not occur at the low level of ammonia concentrations reported by van Dalfsen and Bulley (1982) in animal buildings. However, research work is needed to determine the chronic effect of low-level concentrations of ammonia on the productivity of greenhouse plants. Also, one must consider the fact that species of plants have shown different levels of tolerance to gaseous pollution. There also may be considerable variation in pollutant sensitivity between cultivars within a species (Howe and Woltz, 1982).

Environmental factors such as temperature, humidity, light intensity, CO_2 concentration, water supply and nutrient availability may be significant in ascerning the plant susceptibility to gaseous pollutants (Ormrod and Blom, 1978).

SECTION B

CASE STUDY III

ENERGY REQUIREMENTS OF A GABLE GLASSHOUSE-SWINE FINISHING BARN COMBINATION

SWINE FINISHING BARN-GREENHOUSE COMBINATION - A CASE STUDY

DESCRIPTION AND ASSUMPTIONS

A schematic of the attached greenhouse to a hog finishing barn is shown in Figure 5.1. As can be seen in the figure, the two buildings have a common wall; obviously, this configuration will be impractical in regions where snow accumulation is a factor without provision for snow removal from the south roof of the livestock building or some other means of protecting the north roof of the greenhouse from snow loads. Otherwise, a space between the two structures should be left clear where snow sliding from the south roof of the livestock building can accumulate without damage to the greenhouse. The north wall of the greenhouse should still be insulated.

With the exception of the common wall, other construction parameters such as level of insulation, dimensions, and optical properties of the greenhouse glass cover; and management practices such as number of hogs, sizes, minimum and maximum ventilation rates etc...are identical to those used with respect to case studies I and II. Therefore, the reader is referred to section B of each of Chapters 3 and 4 for detailed information on building

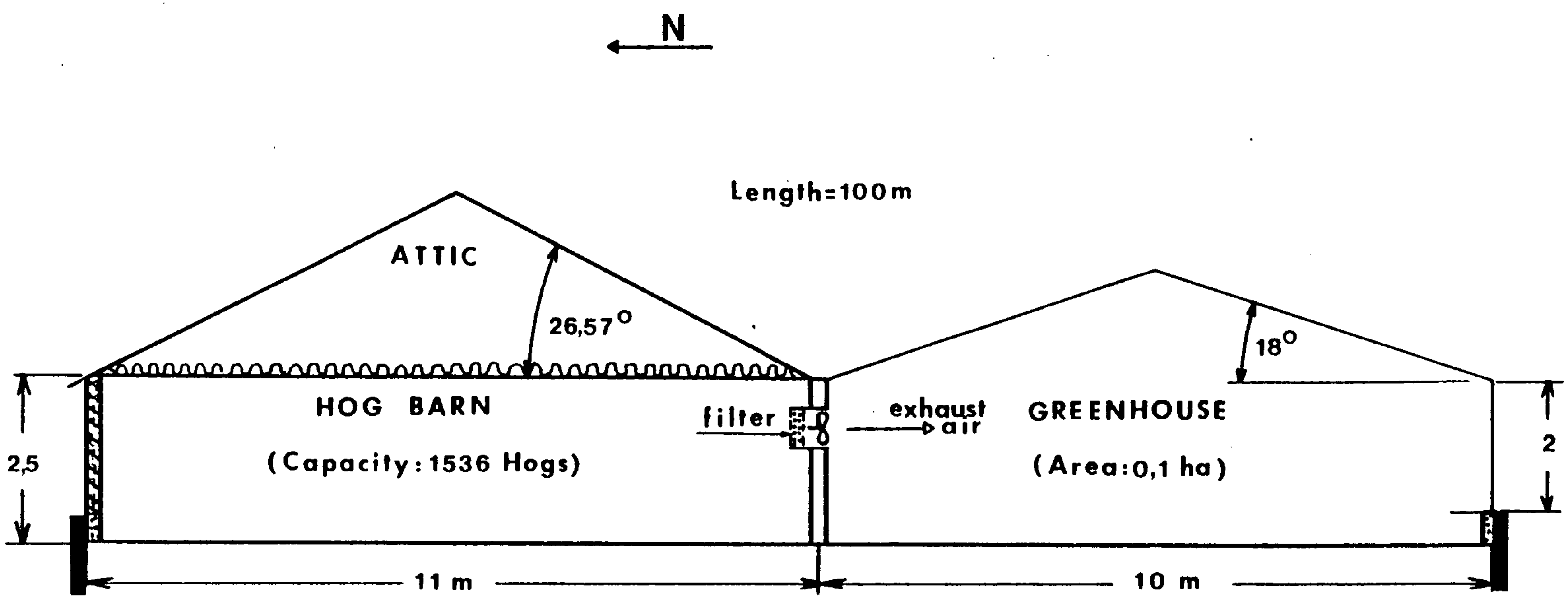


FIGURE 5.1: CROSS-SECTIONAL VIEW OF THE GABLE GREENHOUSE-HOG BARN COMBINATION (CASE STUDY III).

specifications, operating parameters and assumptions underlying case study III. Additional assumptions which apply specifically to this case study are as follows:

i) The ventilation air from the hog barn is drawn directly into the greenhouse following a dust removal process.

ii) No attempt is made in this study for barn latent heat recovery; therefore only the sensible portion is assumed recoverable. This implies that the predicted energy savings are rather conservative estimates of the potential savings.

iii) The ratio of number of animals to unit area of greenhouse is assumed constant throughout this analysis; actually, it is dependent on the number of hogs in the barn at any time to the design value.

RESULTS AND DISCUSSION

A sample output of the computer simulation model for an attached greenhouse to a finishing hog barn is included in Appendix H. Tables H.1 to H.12 show the hourly energy flows between the attached greenhouse, the livestock building and the outdoor environment for a typical day of each month of the year. Among the values shown in the tables are the hourly energy inputs to the greenhouse which include the solar radiation captured by the plant canopy and the sensible heat contained in the ventilation air from the livestock building that is potentially available for recovery and use by the attached greenhouse. The tables in Appendix H, also show the hourly heat losses from the greenhouse from which the hourly heating load when the energy input from ventilation air is neglected as well as the actual hourly heating load when the livestock sensible heat is recovered are calculated. The last two columns in Tables H.1 to H.12 are respectively, the hourly fraction of the greenhouse heat loss that is supplied by passive solar and the hourly fraction of the heating load (after the passive contribution of solar radiation) that is supplied by sensible heat recovery from the swine building ventilation air.

For the purpose of discussion, the information contained in Appendix H is summarized in Tables 5.1 and 5.2. Table 5.1 concentrates on the passive solar contribution to the attached greenhouse heating load while Table 5.2 gives the contribution of sensible heat recovery from the hog building ventilation air to the greenhouse heating load.

TABLE 5.1

MONTHLY AVERAGE HEAT LOSS, SOLAR ENERGY INPUT AND SOLAR ENERGY UTILIZED BY THE GREENHOUSE IN MJ PER m^2 OF FLOOR AREA FOR THE ATTACHED GREENHOUSE-SWINE FINISHING BARN OF CASE STUDY III (MINIMUM GREENHOUSE TEMPERATURE = 15°C)

HALIFAX, N.S.

Month	Heat Loss MJ/m^2	Solar Energy			Percent Supplied by Solar
		Captured (MJ/m^2)	Used (MJ/m^2)	Utili. Factor	
January	481	156	116	0.74	24
February	441	202	128	0.63	29
March	405	335	144	0.43	36
April	280	369	111	0.30	40
May	166	436	65	0.15	39
June	69	493	18	0.04	25
July	24	479	3	<0.01	13
August	18	458	3	<0.01	16
September	50	350	10	0.03	19
October	159	255	44	0.17	28
November	265	140	69	0.49	26
December	424	114	93	0.82	22
Year	2782	3787	804	0.21	29

TABLE 5.2

MONTHLY AVERAGE HEATING LOAD, WASTE HEAT CONTRIBUTION TO THE GREENHOUSE HEATING LOAD FROM THE LIVESTOCK BUILDING AND SUPPLEMENTAL HEAT REQUIREMENT IN MJ PER m^2 OF GREENHOUSE FLOOR AREA FOR THE ATTACHED GREENHOUSE-SWINE FINISHING BARN OF CASE STUDY III

(MINIMUM GREENHOUSE TEMPERATURE = 15°C)

HALIFAX, N.S.

Month	Heating Load (MJ/m^2)	Waste Heat Contribution (MJ/m^2)	Supplemental Heat Requirement (MJ/m^2)	Percent Supplied by Waste Heat
January	365	54	311	15
February	313	46	267	15
March	261	52	209	20
April	169	55	114	32
May	101	61	40	61
June	51	51	0	100
July	21	21	0	100
August	15	15	0	100
September	40	40	0	100
October	115	82	33	71
November	196	75	121	39
December	331	64	267	19
Year	1978	616	1362	31

The construction parameters and management practices of the greenhouse analyzed here are identical to the conventional gable greenhouse described in Chapter 4 , with the exception of the presence of a common wall with the livestock building. Therefore, the results of Table 5.1 of this chapter are directly comparable to results obtained in Chapter 4 and summarized in Table 4.4 of that chapter. Comparison of the results indicate that the annual heat loss from the attached greenhouse is 2782 megajoules per square meter of floor area (MJ/m^2) as compared to 3693 MJ/m^2 for the free standing greenhouse. This represents a reduction of 25 percent which is due to insulation of the north wall of the greenhouse and the elimination of infiltration heat loss. On the other hand, the solar radiation captured by the attached greenhouse is lower than that captured by the free standing greenhouse. The corresponding values are 3787 and 4024 megajoules per square metre of floor area annually. The six percent reduction in energy capture is attributed to the insulated north wall of the attached greenhouse. Even though, the solar contribution to the greenhouse heat loss was reduced from 975 to 804 megajoules per square meter of floor area; the net reduction in greenhouse heating load is 740 MJ/m^2 or 27 percent in favor of the attached greenhouse. The annual solar energy utilization factor was reduced from 0.24 for the free standing greenhouse (Fig. 4.3, Chapter 4) to 0.21 for the attached greenhouse (Table 5.1, Chapter 5). The lowering of the solar energy utilization factor is due to the reduced heat loss from the attached greenhouse. Table 5.2 gives the predicted monthly and annual contribution to the greenhouse heating load of sensible waste heat recovery from ventilation air of the livestock building. The monthly percentage of greenhouse heating load supplied by waste heat from the hog barn ranged from 15 percent in January to 100 percent during the summer months giving an annual predicted average in the order of 30 percent. In this case study, the expected annual savings in energy from waste heat are about 600 megajoules per square metre of greenhouse area. The predicted annual supplemental heat requirement for the attached greenhouse to the hog barn is 1362 MJ/m^2 as compared to 2718 MJ/m^2 for a free standing conventional greenhouse. In Chapter 4, it was concluded from the analysis of a conventional greenhouse that lowering the greenhouse minimum inside temperature by one degree Kelvin has resulted in a five percent reduction in the annual supplemental heat requirement. Tables 5.3 and 5.4 of this chapter give a summary of the results of an analysis which is performed primarily to determine the effect of lowering the greenhouse minimum

TABLE 5.3

MONTHLY AVERAGE HEAT LOSS, SOLAR ENERGY INPUT AND SOLAR ENERGY UTILIZED BY THE GREENHOUSE IN MJ PER m^2 OF FLOOR AREA FOR THE ATTACHED GREENHOUSE-SWINE FINISHING BARN OF CASE STUDY III

(MINIMUM GREENHOUSE TEMPERATURE = 10°C)

HALIFAX, N.S.

Month	Heat Loss MJ/m^2	Solar Energy			Percent Supplied by Solar
		Captured (MJ/m^2)	Used (MJ/m^2)	Utili. Factor	
January	364	156	88	0.56	24
February	334	202	100	0.50	30
March	289	335	103	0.31	36
April	166	369	61	0.17	37
May	62	436	14	0.03	23
June	14	493	2	<0.01	14
July	-	479	-	0.00	-
August	-	458	-	0.00	-
September	-	350	-	0.00	-
October	52	255	6	0.02	12
November	153	140	37	0.26	24
December	306	114	69	0.61	23
Year	1740	3787	480	0.13	28

TABLE 5.4

MONTHLY AVERAGE HEATING LOAD, WASTE HEAT CONTRIBUTION TO THE GREENHOUSE HEATING LOAD FROM THE LIVESTOCK BUILDING AND SUPPLEMENTAL HEAT REQUIREMENT IN MJ PER m^2 OF GREENHOUSE FLOOR AREA FOR THE ATTACHED GREENHOUSE-SWINE FINISHING BARN OF CASE STUDY III

(MINIMUM GREENHOUSE TEMPERATURE = 10°C)

HALIFAX, N.S.

Month	Heating Load (MJ/m^2)	Waste Heat Contribution (MJ/m^2)	Supplemental Heat Requirement (MJ/m^2)	Percent Supplied by Waste Heat
January	276	102	174	37
February	234	83	151	36
March	186	94	92	50
April	105	87	18	83
May	48	48	0	100
June	12	12	0	100
July	-	-	-	-
August	-	-	-	-
September	-	-	-	-
October	46	46	0	100
November	116	108	8	93
December	237	115	122	49
Year	1260	695	565	55

temperature on the supplemental heat requirement of an attached greenhouse to a swine finishing barn. For this analysis the greenhouse minimum temperature was reduced from 15°C to 10°C.

A comparison of Table 5.1 to Table 5.3 indicates that the annual heat loss from the greenhouse was reduced from 2782 to 1740 megajoules per square metre of floor area when the minimum temperature setting was dropped from 15°C to 10°C. Obviously the solar radiation captured by the greenhouse remained the same, but, as expected the solar energy utilization factor has been reduced significantly. The decrease in the solar energy utilization factor from a value of 0.21 to 0.13 is due to the lower greenhouse operating temperature.

The monthly and yearly contribution of sensible waste heat recovery from the hog barn to the attached greenhouse heating load is shown in Table 5.4 for a minimum greenhouse temperature setting of 10°C. Comparing the values in Table 5.2 (15°C) to those in Table 5.4 (10°C) indicate firstly that the heating season was reduced from 12 months to 9 months and the annual heating load, neglecting the contribution of waste heat, was reduced from 1978 to 1260 megajoules per square metre of floor area. Secondly, the waste heat contribution to the greenhouse heating load was increased during the winter months. The annual contribution of waste heat recovery from the hog barn to the greenhouse heating load has increased from 31 percent for a minimum greenhouse temperature of 15°C to 55 percent for a minimum temperature of 10°C. Thirdly, the annual supplemental heat requirement based upon greenhouse unit floor area has decreased from 1362 MJ/m^2 to 565 MJ/m^2 for minimum temperatures of 15°C and 10°C respectively. This represents about 60 percent in energy savings which indicates that greenhouse operating temperature is a significant factor for a greenhouse-livestock combination. The significance of lowering the minimum greenhouse operating temperature on energy savings for an attached greenhouse-swine finishing barn is evident from Table 5.5. The greenhouse minimum operating temperatures used in the analyses represented in Table 5.5 are 20°C, 15°C and 10°C respectively. The percent energy savings shown in the table are based upon the 20°C case. The predicted annual energy savings due to lowering the greenhouse minimum temperature from 20°C to 15°C and 10°C are 52 and 80 percent respectively.

As previously stated, the main purpose of Part II of this study is to determine the potential energy savings by recovering the waste heat from a livestock operation and using it to partially supply the heating demand of an

TABLE 5.5

EFFECT OF LOWERING THE MINIMUM GREENHOUSE TEMPERATURE ON ENERGY SAVINGS FOR THE ATTACHED GREENHOUSE-SWINE FINISHING BARN OF CASE STUDY III

HALIFAX, N.S.

Month	Supplemental Heat (MJ per m^2 Greenhouse Floor Area)			Percent Savings	
	T_g=20°C	T_g=15°C	T_g=10°C	T_g=15°C	T_g=10°C
January	462	311	174	33	62
February	395	267	151	32	62
March	339	209	92	38	73
April	235	114	18	51	92
May	159	40	0	75	100
June	100	0	0	100	100
July	64	0	0	100	100
August	59	0	0	100	100
September	99	0	0	100	100
October	189	33	0	82	100
November	280	121	8	57	97
December	433	267	122	38	72
Year	2814	1362	565	52	80

adjacent greenhouse. The promising case of a swine finishing barn is used as an example to demonstrate if significant energy savings could be achieved through the operation of a greenhouse-livestock combination. The results of a combination system operated in the Halifax area are given in Table 5.6. The potential energy savings are highly dependent on the minimum greenhouse temperature setting as can clearly be seen in the table. For this case study, the predicted annual energy savings were in the order of 27, 50 and 67 percent for minimum greenhouse temperatures of 20°C, 15°C and 10°C respectively. The above percentage energy savings are calculated using a conventional free standing gable greenhouse as a base for comparison.

In many instances, the greenhouse operators choose to grow low temperature crops during the winter season and a relatively higher temperature crop during the other seasons of the year. For such a case, the expected annual energy savings would be somewhat different from the values given above. Let us take for example, a greenhouse operated at a low temperature of 10°C during the months of November through February and at 15°C during the other months of the year; then from Table 5.6 , the predicted annual supplemental heating requirements can be calculated as 2243 megajoules per square metre of floor area for the conventional greenhouse and 851 MJ/m^2 for the attached greenhouse resulting in an expected annual energy savings in the order of 62 percent.

TABLE 5.6

MONTHLY AVERAGE SUPPLEMENTAL HEAT REQUIREMENTS
FOR A CONVENTIONAL AND AN ATTACHED GREENHOUSE*
(MJ PER m^2 GREENHOUSE FLOOR AREA)
ALSO EXPECTED PERCENT SAVINGS AS A FUNCTION
OF THE MINIMUM GREENHOUSE TEMPERATURE

Month	$T_g = 20°C$			$T_g = 15°C$			$T_g = 10°C$		
	Supplemental Heat		Percent Savings	Supplemental Heat		Percent Savings	Supplemental Heat		Percent Savings
	Con.	Att.		Con.	Att.		Con.	Att.	
January	632	462	27	497	311	37	370	174	53
February	540	395	27	428	267	38	321	151	53
March	464	339	27	357	209	41	254	92	64
April	325	235	28	232	114	51	146	18	88
May	222	159	28	141	40	72	69	0	100
June	135	100	26	69	0	100	17	0	100
July	87	64	26	27	0	100	-	-	-
August	84	59	30	21	0	100	-	-	-
September	140	99	29	61	0	100	7	0	100
October	261	189	28	160	33	79	68	0	100
November	387	280	28	272	121	56	162	8	95
December	603	433	28	453	267	41	322	122	62
Year	3880	2814	27	2718	1362	50	1736	565	67

* Location: Halifax, N.S.

The above savings in energy can be attributed to the elimination of the heat loss from the north wall of the greenhouse, the minimization of outside air infiltration into the greenhouse and the utilization of a fraction of the sensible heat produced by the animals. These savings could be further improved if an efficient latent heat recovery system could be designed and utilized to recover some of the latent heat produced by the animals.

CONCLUSIONS

From the information available on levels of ammonia and hydrogen sulfide concentrations encountered in the exhaust air from animal shelters under normal operating conditions, and on the tolerance of plants to these gases, it may be concluded that:

Introducing the air from the animal shelter directly into the attached greenhouse is not expected to have detrimental effects on the growth of at least some greenhouse crops.

Computer simulation analyses of a 1000 m^2 gable greenhouse attached to a conventional swine finishing barn housing 1536 hogs, and located in the Halifax, N.S. area, revealed the following results:

1. The yearly percentage of the heating requirements that could be supplied by animal waste heat recovery is in the order of 30 percent, while the greenhouse minimum operating temperature was set at 15°C. When this

temperature was reduced to $10^{o}C$, the above percentage increased to 55 percent.

2. The minimum greenhouse operating temperature is a significant factor in accessing the realizable energy savings from greenhouse-livestock combination systems.
3. The predicted annual energy savings of the attached greenhouse to the hog barn compared to a free-standing gable greenhouse having the same construction and management parameters are: 27, 50 and 67 percent for minimum greenhouse temperatures of $20^{o}C$, $15^{o}C$ and $10^{o}C$, respectively.

NOMENCLATURE

Symbol	Definition	Units
C_p	Specific heat of barn exhaust air	$kJ.kg^{-1}.K^{-1}$
$\dot{m}$	Mass flow rate of barn exhaust air	$kg.h^{-1}$
Q_{HRL}	Sensible heat recovered from livestock building	$kJ.h^{-1}$
Q_{SENS}	Sensible heat produced by the animals	$kJ.h^{-1}$
Q_{SOL}	Solar energy captured by the greenhouse	$kJ.h^{-1}$
$Q_{SUP,G}$	Supplemental heat requirement of the greenhouse	$kJ.h^{-1}$
$Q_{SUP,L}$	Supplemental heat requirement of the livestock building	$kJ.h^{-1}$
Q_{TRAN}	Transmission heat loss from - livestock building (equation 1) - greenhouse (equation 2)	$kJ.h^{-1}$
Q_{VENT}	Ventilation heat loss from livestock building	$kJ.h^{-1}$
T_b	Dry-bulb temperature of the barn	K
T_g	Dry-bulb temperature of the greenhouse	K

PART III

ANALYSIS OF A SOLAR-SHED GREENHOUSE-LIVESTOCK COMBINATION

CHAPTER 6

COMPUTER SIMULATION
MODEL
OF
HEATING REQUIREMENTS
OF
SOLAR-SHED GREENHOUSE

INTRODUCTION

This chapter gives a detailed analysis of a new solar greenhouse specifically designed for high latitude regions. The greenhouse has a shed shape from which the name "Solar-Shed" was adopted by the author. The long-axis of the solar-shed greenhouse must be east-west oriented. The north wall is insulated and a solar collector is installed at the upper part of its inner surface. The solar energy collected could be stored either in a rock storage under the benches or in wet earth underneath the greenhouse floor.

The chapter is divided into three sections. The first gives the energy balance equations used with the computer simulation model to determine the heat loss from the greenhouse. The second section goes into a detailed theoretical analysis of solar radiation capture by the plant canopy, as well as, an analytical technique of estimating the useful heat gain by the integral solar collector.

The theory developed in the first two sections is then applied to a case study in order to investigate the performance of the solar-shed greenhouse. The case study is the subject of the final section of this chapter where the effect of location, mean plate temperature and type of absorber plate on the monthly and yearly average solar fractions is studied. The energy savings realized by the solar-shed over a conventional gable greenhouse are estimated for three locations in Canada.

SECTION A

HEAT BALANCE

ABOUT THE

SOLAR-SHED GREENHOUSE

HEAT BALANCE ABOUT THE SOLAR-SHED GREENHOUSE

The physical model of the solar-shed greenhouse chosen for this study is shown schematically in Figure 6.1.

ASSUMPTIONS

The following assumptions were made in determining the heat balance of the greenhouse:

i) Thermal storage in the greenhouse structure, ground bed, benches and plant canopy is neglected to allow steady state heat transfer calculations.

ii) Evaporation from the soil surface in the greenhouse is negligible.

iii) Plants transpiration, photosynthesis and respiration are neglected.

iv) There is no internal energy generation inside the greenhouse.

v) There is no condensation on the inside surface of the glass cover, or dust accumulation, therefore the transmittance of the covering is taken as that of the glass layer only.

ENERGY BALANCE

When all the above assumptions were taken into account, the steady state heat balance equation for the physical model of Figure 6.1 is given by

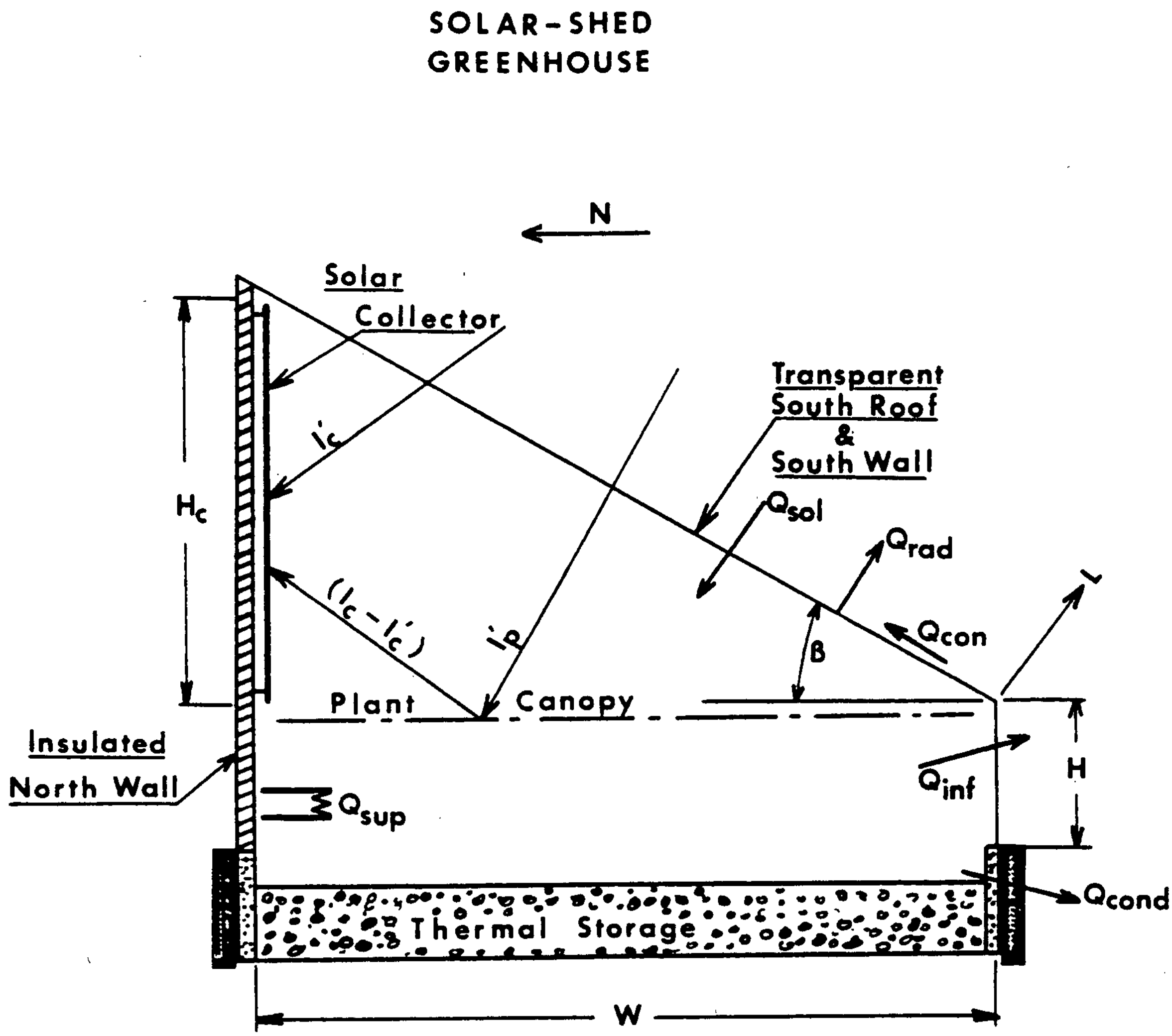


FIGURE 6.1: SCHEMATIC OF A SOLAR-SHED GREENHOUSE SHOWING ENERGY FLOWS AND SOLAR RADIATION INCIDENT ON THE INTEGRAL COLLECTOR.

$$Q_{sup} = Q_{sol} - Q_{rad} - Q_{con} - Q_{inf} - Q_{cond} \quad . \qquad (1)$$

From Figure 6.1 and equation (1) it can be seen that the energy input to the greenhouse includes the solar radiation absorbed by the plant canopy and objects in the greenhouse plus that absorbed by the covering material. For a completely closed system the heat is lost by convection and by radiation from the greenhouse cover. Since infiltration and exfiltration always occur in greenhouses, an additional term is included in equation (1) to account for the heat loss due to infiltration. If the right hand side of equation (1) is negative, supplemental heat is required. The supplemental heat can be provided by the solar heating system and/or by the furnace.

THERMAL RADIATION HEAT LOSS FROM GREENHOUSE COVER

Thermal radiation loss from the greenhouse is a function of the greenhouse walls temperature, sky temperature and ground temperature. The thermal radiation loss from the roof of the greenhouse can be written as

$$Q_{rad,roof} = A_r F_{r \to sky} \; \varepsilon_r \; \sigma (T_r^4 - T_{sky}^4) + A_r F_{r \to g} \; \varepsilon_r \; \sigma (T_r^4 - T_g^4) \quad . \qquad (2)$$

In general, the thermal radiation loss from any of the greenhouse walls may be calculated using the following equation:

$$Q_{rad,i} = A_i \; \varepsilon_i \; \sigma [F_{i \to sky} \; (T_i^4 - T_{sky}^4) + F_{i \to g} \; (T_i^4 - T_g^4)] \quad . \qquad (3)$$

For vertical walls, we have

$$F_{i \to sky} = F_{i \to g} = 0.5 \quad , \tag{4}$$

Therefore equation (3) reduces to:

$$Q_{rad,i} = [A_i \ \varepsilon_i \sigma/2] \ [2T_i^4 - T_{sky}^4 - T_g^4] \quad . \tag{5}$$

For the greenhouse roof, we have

$$F_{r \to sky} = \frac{1 + \cos \beta}{2} \tag{6}$$

and,

$$F_{r \to g} = \frac{1 - \cos \beta}{2} \quad . \tag{7}$$

Inserting equations (6) and (7) into (2) and simplifying we obtain,

$$Q_{rad,roof} = A_r \ \varepsilon_r \sigma \ [T_r^4 - \left(\frac{1 + \cos \beta}{2}\right) T_{sky}^4 - \left(\frac{1 - \cos \beta}{2}\right) T_g^4] \quad . \tag{8}$$

Evaluation of equations (5) and (8) requires the knowledge of the sky and ground temperatures.

The effective sky temperature is a function of many meterological variables such as water vapour content and air temperature. Several correlation equations between the effective sky temperature and the meteorological variables have been proposed (Brunt (1932), Bliss (1961), Swinbank (1963), Whillier (1967), Morse and Read (1968)).

In this analysis Swinbank's correlation relating the sky temperature to the local environmental temperature is used,

$$T_{sky} = 0.0552\ T_a^{1.5} \quad . \qquad (9)$$

The ground surface temperature may be different from the local air temperature especially during low wind speed periods. Due to the complexity of predicting the local ground surface temperature accurately, it is assumed to be equal to the local air temperature in this study.

CONVECTION HEAT LOSS FROM THE GREENHOUSE COVER

The convective heat exchange between any surface i of the greenhouse and the surroundings is given by

$$Q_{con,i} = \bar{h}_{w,i} A_i \ (T_i - T_a) \quad , \qquad (10)$$

where the average convective heat transfer coefficient, $\bar{h}_w$ is related to the wind speed.

McAdams (1954) suggests the following relationship for the convective heat transfer coefficient:

$$\bar{h}_w = 20.52 + 13.68\ V \quad . \qquad (11)$$

CALCULATION OF THE OUTSIDE SURFACE TEMPERATURE OF THE ROOF AND THE WALLS OF THE GREENHOUSE

The outside surface temperature of the greenhouse covering material is dependent upon the outside ambient temperature, the inside operating temperature of the greenhouse and resistance to heat flow of the cover itself. Therefore, to determine the outside surface temperature of any wall, a heat balance about the wall is required.

If the net radiant heat exchange between the greenhouse walls and the plant canopy is neglected and the absorptivity of the transparent cover to solar radiation is assumed to be constant and equal to α, then the solar energy absorbed by any surface i is:

$$Q_{sa,i} = \alpha_i \, I_{s,i} \quad . \qquad (12)$$

Then, using equations (8), (10) and (12), the heat balance equation for the roof becomes,

$$(A_r/R_r)(T_g-T_r) = A_r \, \varepsilon_r \sigma \, [T_r^4 - 0.5 \, (1 + \cos \beta) \, T_{sky}^4 - 0.5 \, (1 - \cos \beta) \, T_g^4] + \bar{h}_{w,r} \, A_r \, (T_r-T_a) - A_r \, \alpha_r \, I_{s,r} \qquad (13)$$

and for the walls, from equations (5), (10) and (12) we get

$$(A_i/R_i)(T_g-T_i) = 0.5 \, A_i \, \varepsilon_i \sigma \, (2T_i^4 - T_{sky}^4 - T_g^4) + \bar{h}_{w,i} \, A_i (T_i-T_a) - A_i \, \alpha_i \, I_{s,i} \qquad (14)$$

Equations (13) and (14) may be written in terms of the known meteorological variables, namely local air temperature and wind speed. Furthermore, the outside convective heat transfer coefficients for the roof and all the other greenhouse walls are assumed to be the same. In reality, they depend on the wind direction with respect to the surface. Equation (11) assumes the flow is parallel to the flat surface. In actual situations the wind may approach a surface at any angle. Iqbal and Khatry (1977) studied the effect of non-uniform flow on the external heat transfer coefficient using model greenhouses in the wind tunnel; their results indicate wind coefficient values higher than those obtained by assuming flow parallel to the flat surface. Since wind directions are seldom known, equation (11) for the wind coefficient is used for the purpose of developing the present greenhouse model.

Inserting equations (9) and (11) into (13) and (14) to obtain:

$$\frac{1}{R_r}(T_g - T_r) = \varepsilon_r \sigma \, [T_r^4 - 0.5\,(1 + \cos\beta)(0.0552\,T_a^{1.5})^4 - 0.5\,(1 - \cos\beta)\,T_a^4] - \alpha_r\, I_{s,r} + (20.52 + 13.68\,V)(T_r - T_a) \quad (15)$$

and

$$\frac{1}{R_i}(T_g - T_i) = \frac{\varepsilon_i \sigma}{2}\,[2T_i^4 - (0.0552\,T_a^{1.5})^4 - T_a^4] - \alpha_i\, I_{s,i} + (20.52 + 13.68\,V)\,(T_i - T_a) \quad (16)$$

In equations (15) and (16) the ground surface temperature is taken to be equal to the local air temperature. The overall resistances to heat flow R_r and R_i may be estimated using the following standard equations:

$$R_r = (1/f_{i,r}) + R_c \qquad (17)$$

and

$$R_i = (1/f_{i,i}) + R_c \qquad (18)$$

The inside surface film coefficients, f_i, for non-reflective surfaces are given in ASHRAE Handbook (1977). The cover resistance R_c depends whether the cover is single or double glazed.

Equation (15) with equation (17) and equation (16) with equation (18) may now be solved for the external surface temperatures for the greenhouse roof and walls. Then the total heat loss from the roof is:

$$Q_r = (A_r/R_r)\ (T_g - T_r) \quad , \qquad (19)$$

and the total heat loss from any wall i, is

$$Q_i = (A_i/R_i)\ (T_g - T_r) \quad . \qquad (20)$$

The total (convective plus radiative) heat loss from the greenhouse can then be calculated as follows:

$$Q = \sum_{r=1}^{m} (A_r/R_r)\ (T_g - T_r) + \sum_{i=1}^{n} (A_i/R_i)\ (T_g - T_i) \quad , \qquad (21)$$

where m is the number of roof slopes making up the greenhouse roof and n the number of vertical walls for the greenhouse under consideration.

CONDUCTION HEAT LOSS FROM THE GREENHOUSE

The conduction heat loss includes heat transfer through the greenhouse perimeter and through the foundation. Here it is assumed that the heat loss to the greenhouse floor is included in the perimeter heat loss.

The conductive heat transmission is then calculated as follows:

$$Q_{cond} = U_f A_f (T_g - T_a) + U_p P (T_g - T_a) \quad . \qquad (22)$$

INFILTRATION HEAT LOSS FROM THE GREENHOUSE

The air-exchange method used with respect to the gable greenhouse is employed here. Therefore the sensible heat loss due to infiltration/exfiltration may be estimated using the following equation:

$$Q_{inf} = (1/v) C_p V_g N_a (T_g - T_a) \quad . \qquad (23)$$

SUPPLEMENTAL HEAT REQUIREMENT

The supplemental heat requirement for the greenhouse may be calculated by the use of equation (1)

$$Q_{sup} = Q_{sol} - Q - Q_{inf} - Q_{cond} \quad , \qquad (24)$$

where

$$Q = Q_{rad} + Q_{con} \quad , \qquad (25)$$

as defined by equation (21).

Finally, the daily heating load for the greenhouse is simply:

$$Q_{sup,\ day} = \sum_{hour=1}^{24} Q_{sup}^{-} \qquad (26)$$

The minus sign indicates that only negative values are considered during the summation process.

The solar radiation input to the greenhouse represented by Q_{sol} in equation (24) is treated in the next section of this chapter where an expression for estimating the total solar energy captured by the plant canopy inside the greenhouse is derived. This expression in its simplest form may be written as,

$$Q_{sol} = I_g = I_p + I_w \quad . \qquad (27)$$

In equation (27), the term I_g represents the total amount of solar radiation absorbed by the plant canopy. The terms I_p and I_w indicate that the radiation is originating from the roof and the vertical walls of the greenhouse respectively. Detailed expressions for I_p and I_w are given by equations (49) and (47) respectively.

SECTION B

CALCULATION
OF
SOLAR RADIATION CAPTURE
BY A
SHED-GREENHOUSE
AND
SOLAR RADIATION INCIDENT
ON THE
COLLECTOR

CALCULATION OF SOLAR RADIATION CAPTURE BY A SHED-GREENHOUSE AND SOLAR RADIATION INCIDENT ON THE COLLECTOR

ASSUMPTIONS

For this analysis the following assumptions were made:

i. The plant canopy reflects diffusely regardless of whether the original incident radiation is beam or diffuse in nature.

ii. Multiple reflection between the plant canopy and the greenhouse cover is neglected.

iii. The reflectance of the collector to the solar radiation is small.

iv. The contribution of the east and west end walls of the greenhouse is neglected. (L >> W)

ESTIMATION OF THE TOTAL SOLAR RADIATION INCIDENT ON THE FLAT PLATE SOLAR COLLECTOR INSIDE A SHED-TYPE GREENHOUSE

The total solar radiation incident on the collector is the sum of the total solar radiation from the roof of the greenhouse, a fraction of the diffuse radiation reflected by the top of the plant canopy and a fraction of the diffuse radiation from the plants that is reflected by the inner surface of the roof.

Or mathematically,

$$I_c = I_{b,c} + I_{d,c} + I_{r,p} + I_{r,r} \quad (28)$$

where the first term in the summation represents the beam solar radiation transmitted through the greenhouse roof that is incident on the solar collector. This beam radiation may be estimated by:

$$I_{b,c} = I_{b,v} \quad \tau_{b,r} \, A_c \; . \qquad (29)$$

The second term is the diffuse solar radiation transmitted through the greenhouse roof that is incident on the collector. This diffuse radiation can be estimated from the diffuse solar radiation transmitted through the roof and the configuration factor between the roof and the collector, or in equation form,

$$I_{d,c} = I_{d,r} \quad \tau_{d,r} \, A_r \, F_{r \to c} \qquad (30)$$

Then the total solar radiation incident on the collector neglecting the reflected components is:

$$I'_c = I_{b,v} \, \tau_{b,r} \, A_c + I_{d,r} \, \tau_{d,r} \, A_r \, F_{r \to c} \quad . \qquad (31)$$

The last two terms in equation (28) represent the fraction of the reflected solar radiation from the top of the plant canopy that is reaching the vertical solar collector. The third term in the equation is the diffuse radiation reflected by the top of the plant canopy that is directly incident on the collector. This portion of the diffuse radiation may be expressed as:

$$I_{r,p} = \varrho \, I'_p \, F_{p \to c} = \varrho \, I'_{p,1} \, A_p \, F_{p \to c} \qquad (32)$$

Finally, the fourth term in equation (28) represents the diffuse solar radiation reflected by the top of the plant canopy and reaching the solar collector indirectly via the process of reflection of the inner surface of the greenhouse roof. In equation form, this portion of the diffuse radiation may be written as:

$$I_{r,r} = \rho \, I'_p \, F_{p \to r} \, (1 - \tau_{d,r} - \alpha_r) \, F_{r \to c} \quad . \tag{33}$$

Therefore, the total solar radiation incident on the collector with the reflected components included may be estimated by:

$$I_c = I'_c + \rho \, I'_p \, F_{p \to c} + \rho \, I'_p \, F_{p \to r} \, (1 - \tau_{d,r} - \alpha_r) \, F_{r \to c} \quad . \tag{34}$$

But,

$$F_{p \to r} = (A_r/A_p) \, F_{r \to p} \; , \tag{35}$$

therefore equation (34) becomes:

$$I_c = I'_c + \rho \, I'_p \, [F_{p \to c} + (A_r/A_p)(1 - \tau_{d,r} - \alpha_r) \, F_{r \to p} \, F_{r \to c}] \tag{36}$$

where the second term on the right hand side of equation (36) represents the total reflected radiation by the top of the plant canopy that is reaching the solar collector.

The solution of equation (36) requires the knowledge of the total solar radiation incident on the top of the plant canopy. This amount of radiation may be estimated from the beam and diffuse components of solar radiation transmitted through the roof of the greenhouse as follows:

i. Beam radiation incident on the top of the plant canopy:

$$I_{b,p} = I_{b,h}\ \tau_{b,r}\ A_p \quad . \tag{37}$$

ii. Diffuse radiation incident on the top of the plant canopy:

$$I_{d,p} = I_{d,r}\ \tau_{d,r}\ A_r\ F_{r\to p} \quad . \tag{38}$$

Then the total solar radiation incident on the top of the plant canopy is:

$$I'_p = I_{b,h}\ \tau_{b,r}\ A_p + I_{d,r}\ \tau_{d,r}\ A_r\ F_{r\to p} \quad . \tag{39}$$

Combining equations (31), (36) and (39) to get the total solar radiation reaching the collector

$$I_c = I_{b,v}\ \tau_{b,r}\ A_c + I_{d,r}\ \tau_{d,r}\ A_r\ F_{r\to c} + \rho\,[I_{b,h}\ \tau_{b,r}\ A_p + I_{d,r}\ \tau_{d,r}\ A_r\ F_{r\to p}]\ [F_{p\to c} + (A_r/A_p)(1 - \tau_{d,r} - \alpha_r)\ F_{r\to p}\ F_{r\to c}] \quad . \tag{40}$$

For comparing greenhouses of different roof slopes and locations, the solar radiation incident on a unit collector area is needed. Therefore, equation (40) may be rewritten as a function of the roof slope as follows:

$$I_{c,1} = I_{b,v}\ \tau_{b,r} + I_{d,r}\ \tau_{d,r}\ F_{r\to c}\ \text{cosec}\ \beta + \rho\,[I_{b,h}\ \tau_{b,r}\ \cot\beta + I_{d,r}\ \tau_{d,r}\ F_{r\to p}\ \text{cosec}\ \beta]\ [F_{p\to c} + (1 - \tau_{d,r} - \alpha_r)\ F_{r\to p}\ F_{r\to c}\ \sec\beta] \quad . \tag{41}$$

ESTIMATION OF THE TOTAL SOLAR RADIATION CAPTURED BY THE PLANT CANOPY

For a long east-west oriented shed-type greenhouse, the contribution of the east and west wall to solar radiation input may be neglected. Therefore, the total solar energy input to the greenhouse is through the transparent surfaces of the south roof and the vertical south facing wall.

The solar energy capture of the greenhouse depends upon the plant albedo and the type of the greenhouse covering material.

The total solar radiation captured by the top of the plant canopy may be estimated from equation (39) as follows:

$$I_p = I'_p (1 - \rho) + \rho I'_p F_{p \to r} (1 - \tau_{d,r} - \alpha_r) F_{r \to p} (1 - \rho) . \quad (42)$$

Then using equation (35) for $F_{p \to r}$ into equation (42) we get:

$$I_p = I'_p (1 - \rho) [1 + \rho(1 - \tau_{d,r} - \alpha_r) (A_r/A_p) F^2_{r \to p}] \quad . \quad (43)$$

The contribution of the vertical transparent south wall to the total solar energy capture of the greenhouse may be calculated from the beam and diffuse solar radiation incident on the wall as follows:

For the beam component of radiation we have:

$$I_{b,w} = I_{b,v} \tau_{b,w} A_w \quad , \quad (44)$$

and for the diffuse component, we have:

$$I_{d,w} = I_{d,v} \tau_{d,w} A_w \quad . \quad (45)$$

Therefore, the total solar radiation transmitted through the south wall that is captured by the plant canopy is:

$$I_w = (I_{b,w} + I_{d,w}) \ (1 - \rho) \ [1 + \rho(1 - \tau_{d,w} - \alpha_w)] \ . \tag{46}$$

or,

$$I_w = (I_{b,v} \ \tau_{b,w} + I_{d,v} \ \tau_{d,w}) \ A_w(1 - \rho) \ [1 + \rho(1 - \tau_{d,w} - \alpha_w)] \ . \tag{47}$$

Therefore, the total solar energy captured by the plant canopy inside the greenhouse may be estimated from equations (43) and (47).

$$I_g = I_p + I_w \tag{48}$$

Due to the albedo of the plant canopy, a portion of the incident radiation is reflected, then lost through the greenhouse roof. Equations (39) and (43) may be combined to give the total solar energy captured by the top of a plant canopy having a surface area A_p and an albedo ρ.

$$I_p = (I_{b,h} \ \tau_{d,r} \ A_p + I_{d,r} \ \tau_{d,r} \ A_r \ F_{r\rightarrow p}) \ (1 - \rho)$$
$$[1 + \rho(1 - \tau_{d,r} - \alpha_r) \ (A_r/A_p) \ F^2_{r\rightarrow p}] \ . \tag{49}$$

When expressed per unit plant floor area, we get:

$$I_{p,1} = (I_{b,h} \ \tau_{b,r} + I_{d,r} \ \tau_{d,r} \ F_{r\rightarrow p} \sec \beta) \ (1 - \rho)$$
$$[1 + \rho(1 - \tau_{d,r} - \alpha_r) \ F^2_{r\rightarrow p} \sec \beta] \ . \tag{50}$$

Equation (39) gives the total solar radiation incident on the top of the whole plant canopy. Likewise, this incident solar energy may be expressed in terms of unit greenhouse floor area, as:

$$I'_{p,l} = I_{b,h}\,\tau_{b,r} + I_{d,r}\,\tau_{d,r}\,F_{r\to p}\sec\beta\ . \tag{51}$$

The contribution of the south wall may also be expressed in terms of unit area of plant canopy by substituting (H/W) for A_w in equation (47). Thus,

$$I_{w,l} = (I_{b,v}\,\tau_{b,w} + I_{d,v}\,\tau_{d,w})(H/W)(1-\rho)$$
$$[1 + \rho(1 - \tau_{d,w} - \alpha_w)]\ . \tag{52}$$

EFFICIENCY OF SOLAR CAPTURE BY THE GREENHOUSE PLANT CANOPY

The plant canopy within a greenhouse may be treated as a passive solar collection system. The efficiency of solar collection is the ratio of the total solar energy captured to the total solar radiation incident on a horizontal surface outside the greenhouse. This efficiency can be estimated from equations (50) and (52) as:

$$E = (I_{p,l} + I_{w,l})/(I_{b,h} + I_{d,h}) \tag{53}$$

or

$$E = (1/I_h)\ [(I_{b,h}\,\tau_{b,r} + I_{d,r}\,\tau_{d,r}\,F_{r\to p}\sec\beta)\ (1-\rho)$$
$$\{1 + \rho(1 - \tau_{d,r} - \alpha_r)\ F^2_{r\to p}\sec\beta\} + (I_{b,v}\,\tau_{b,w}$$
$$+ I_{d,v}\,\tau_{d,w})\ (H/W)\ (1-\rho)\ \{1 + \rho(1 - \tau_{d,w} - \alpha_w)\}] \tag{54}$$

where

$\tau_{b,r}$, $\tau_{d,r}$, $\tau_{b,w}$, $\tau_{d,w}$, α_r and α_w are optical properties of the transparent covering material.

ρ is an optical property of the plant canopy,

and

H, W, $F_{r \to p}$ and β are greenhouse construction parameters.

The length of the greenhouse does not appear explicitly in the equations but its effect is included in the determination of the configuration factors as shown in Appendix D.

USEFUL ENERGY GAIN OF THE SOLAR COLLECTOR

The effects of the type and efficiency of the solar collector and the thermal energy storage upon the overall greenhouse system is outside the scope of this study, since the present work is intended only as a feasibility study to investigate the effect of changing the shape of the greenhouse on its heat loss and its solar energy input. Only the solar radiation incident on the integral collector and the estimated portion that is available for immediate use or storage is predicted.

The total solar radiation incident on a flat plate collector located at the upper portion of the inner side of the north wall of the shed-type greenhouse is derived previously, and the final result of the derivation is given by equation (40).

The remainder of this section will be devoted to finding an approximate method for determining the amount of solar energy available from the integral collector.

The maximum solar energy collectable may be approximated by the following expression:

$$Q_{col} = Q_{abs} - Q_{loss} \tag{55}$$

Since the solar collector is located inside the greenhouse and air is forced on both sides of the absorber plate, the heat loss from the collector is therefore considered mainly by thermal radiation to the greenhouse cover. Thus, equation (55) may be written as:

$$Q_{col} = A_c\ \alpha_c\ I_c - \{\sigma\ (\bar{T}_c^4 - T_r^4)/[(1 - \varepsilon_c)/\varepsilon_c\ A_c + (1/A_r\ F_{r \to c}) + (1 - \varepsilon_r)/\varepsilon_r\ A_r]\ \}\ . \tag{56}$$

where the two expressions on the right hand side of equation (56) represent the solar radiation absorbed by the collector and the thermal radiation heat loss. The roof temperature of the greenhouse, T_r, can be determined by the use of equations (15) and (17). The solar radiation incident on the collector, I_c, can be calculated using equation (41). The constants α_c and ε_c are the absorptivity for solar radiation and the emissivity for infra-red radiation of the absorber plate, respectively; and, ε_r is the emissivity of the greenhouse roof material to thermal radiation.

The solution of equation (56) requires the knowledge of the average plate temperature, $\bar{T}_c$. As a first approximation, it may be taken as a constant. Thus, let

$$\bar{T}_c = T_{g,min} + \Delta T \quad , \qquad (57)$$

where $T_{g,min}$ is a selected minimum greenhouse temperature, usually taken as the desired night time inside air temperature and ΔT is some selected temperature difference between the operating collector plate temperature and the desired minimum allowable greenhouse temperature.

In order to minimize the heat loss from the collector ΔT should be kept as small as possible, since as can be seen in equation (56) the thermal radiation heat exchange between the collector plate and the greenhouse roof is a function of the average plate temperature raised to the fourth power. The selection of ΔT is dependent upon the minimum useful temperature of the energy stored, and upon the energy consumed by the fans for solar energy collection and storage.

A constant absorber plate temperature implies a variable mass flow rate of the transport fluid in the collector. For the case of a constant mass flow rate system, a complete energy balance about the collector is required to determine the plate temperature.* Therefore, equation (56) is valid only for the case of constant plate temperature. If it is desired to determine the effect of the type of the collector and/or the type and size of the thermal energy storage; then mathematical models of these specific components must be incorporated within the system as needed. In most applications, daily values of energy

* The reader is referred to Appendix L for the detailed analysis of this case.

flows are desired, then the daily maximum solar energy collectable is simply:

$$Q_{col,day} = \sum_{\omega_{sr}}^{\omega_{ss}} Q^{+}_{col} \quad . \tag{58}$$

The plus sign in the above equation indicates that only positive values of Q_{col} are considered during the summation process.

CALCULATION OF DIFFUSE RADIATION CONFIGURATION FACTORS

Configuration factors for diffuse radiation between the roof and solar collector, the plant canopy and the collector and the roof and plant canopy are required for estimating the total solar radiation incident on the integral collector of a solar-shed greenhouse as indicated by equation (40). Furthermore, the above configuration factors are also needed for determining the total solar radiation incident on the plant canopy within the greenhouse as represented by equation (49), as well as, for calculating the radiative heat loss by the integral solar collector as given by equation (56).

These factors were calculated using Feingold's equation given in Figure 2.2. The results are represented in graphical form, in Figure 6.2 to Figure 6.4 for a solar-shed greenhouse with a range of lengths from 10 to 100 metres and for widths 5, 7.5 and 10 metres.

The required three configuration factors as a function of length and width of a solar-shed greenhouse having a roof slope of 20 degrees are shown in Figure 6.2. The roof slope is the angle measured from the horizontal at the south vertical wall of the greenhouse as indicated in Figure 6.1.

Configuration factors for solar-shed greenhouses having roof slopes of 30° and 45° are shown in Figures 6.3 and 6.4, respectively.

It is clearly seen from the curves for configuration factors versus length that for long solar-shed greenhouses (> 70 m), the effects of both length and width on the radiation configuration factors become negligible. This is due to the fact that at large greenhouse lengths, the edge effects (end walls) become small relative to total radiation exchange among other surfaces of the greenhouse. Thus, in such a case, the configuration factors may be taken as constants without significant sacrifice in the accuracy of the analyses final results.

Examination of Figures 6.2, 6.3 and 6.4 reveals the importance of the roof slope on the diffuse radiation exchange between plant canopy, integral collector and greenhouse roof. An increase in the roof slope of a solar-shed greenhouse decreases the amount of diffuse radiation originating from the roof that would be intercepted by the plant canopy. For example, the value of F_{r-p} is 0.79 for a greenhouse having dimensions of 100 m by 7.5 m and 20° roof slope. This value is reduced to 0.675 and 0.49 when the roof slope is increased to 30^{o} and 45^{o}, respectively.

On the other hand, the amount of diffuse radiation incident on the integral collector is increased for steeper roof slopes; so does, the radiative heat loss by the collector to the roof, since this loss is directly proportional to the value of F_{c-r} while in turn this value is related to that of F_{r-c} by the following relation,

$$A_r F_{r-c} = A_c F_{c-r} \quad . \qquad (59)$$

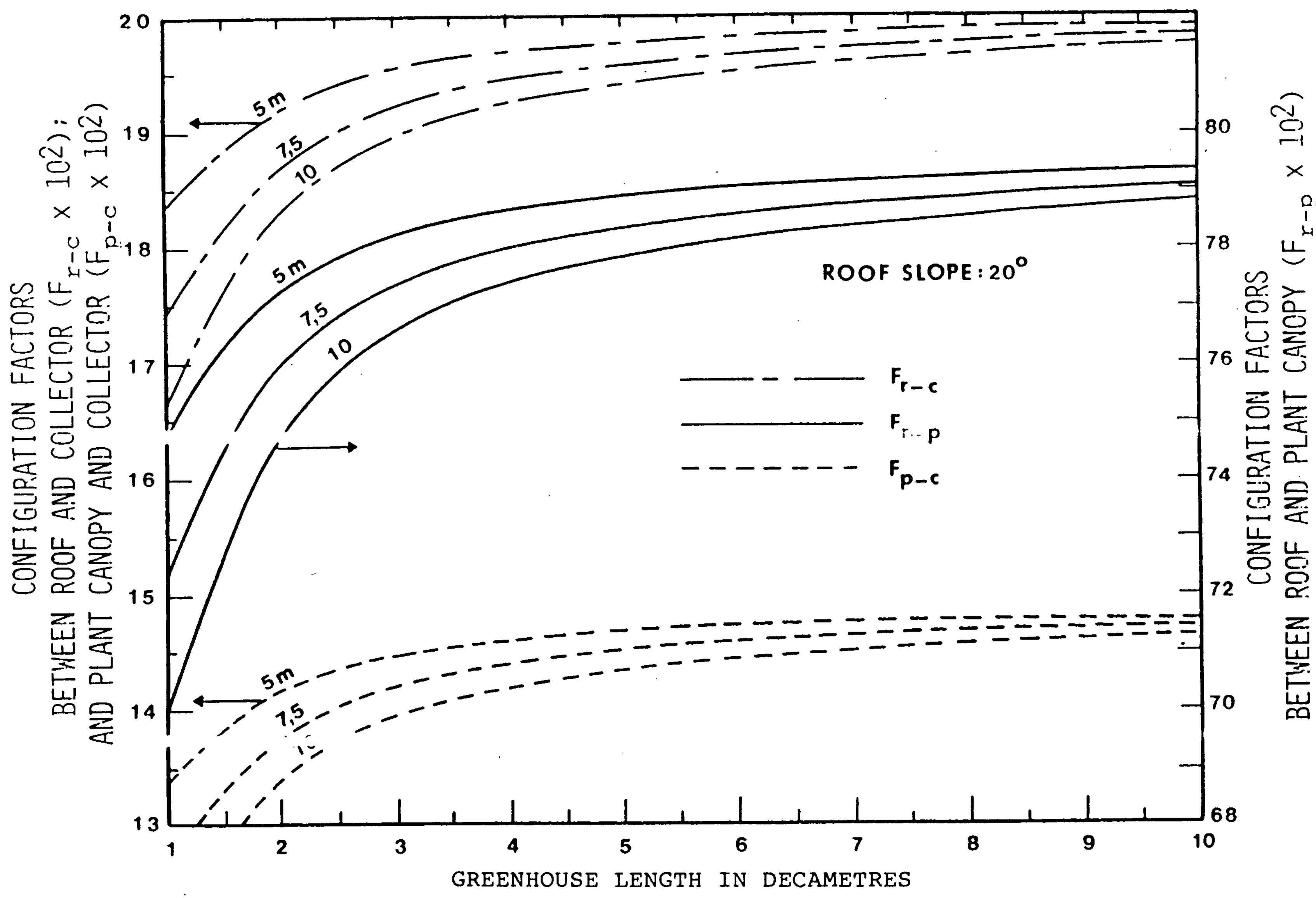


FIGURE 6.2: EFFECT OF LENGTH AND WIDTH ON THE RADIATION CONFIGURATION FACTORS FOR SOLAR-SHED GREENHOUSES HAVING A ROOF SLOPE OF 20 DEGREES.

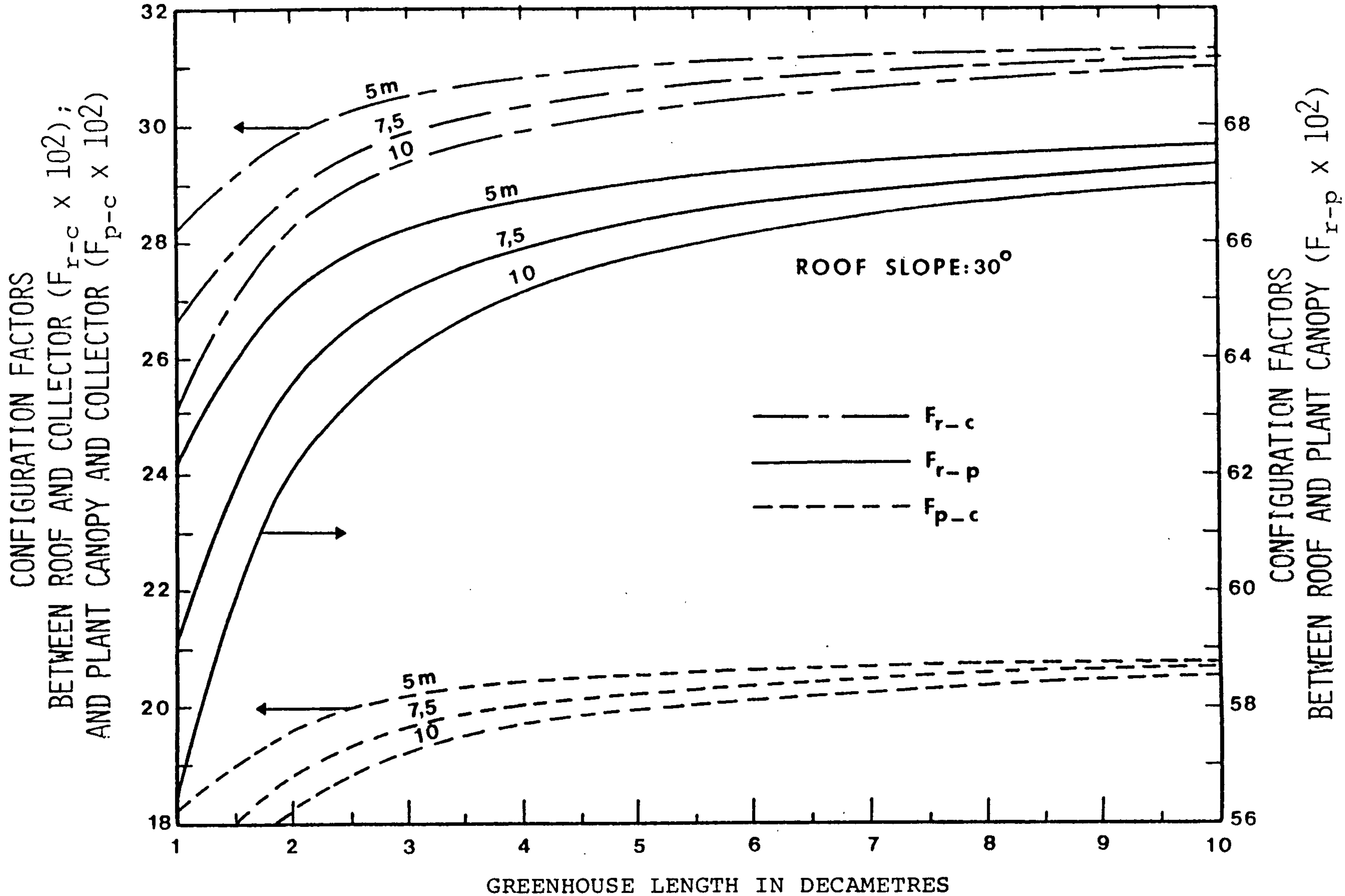


FIGURE 6.3: EFFECT OF LENGTH AND WIDTH ON THE RADIATION CONFIGURATION FACTORS FOR SOLAR-SHED GREENHOUSES HAVING A ROOF SLOPE OF 30 DEGREES.

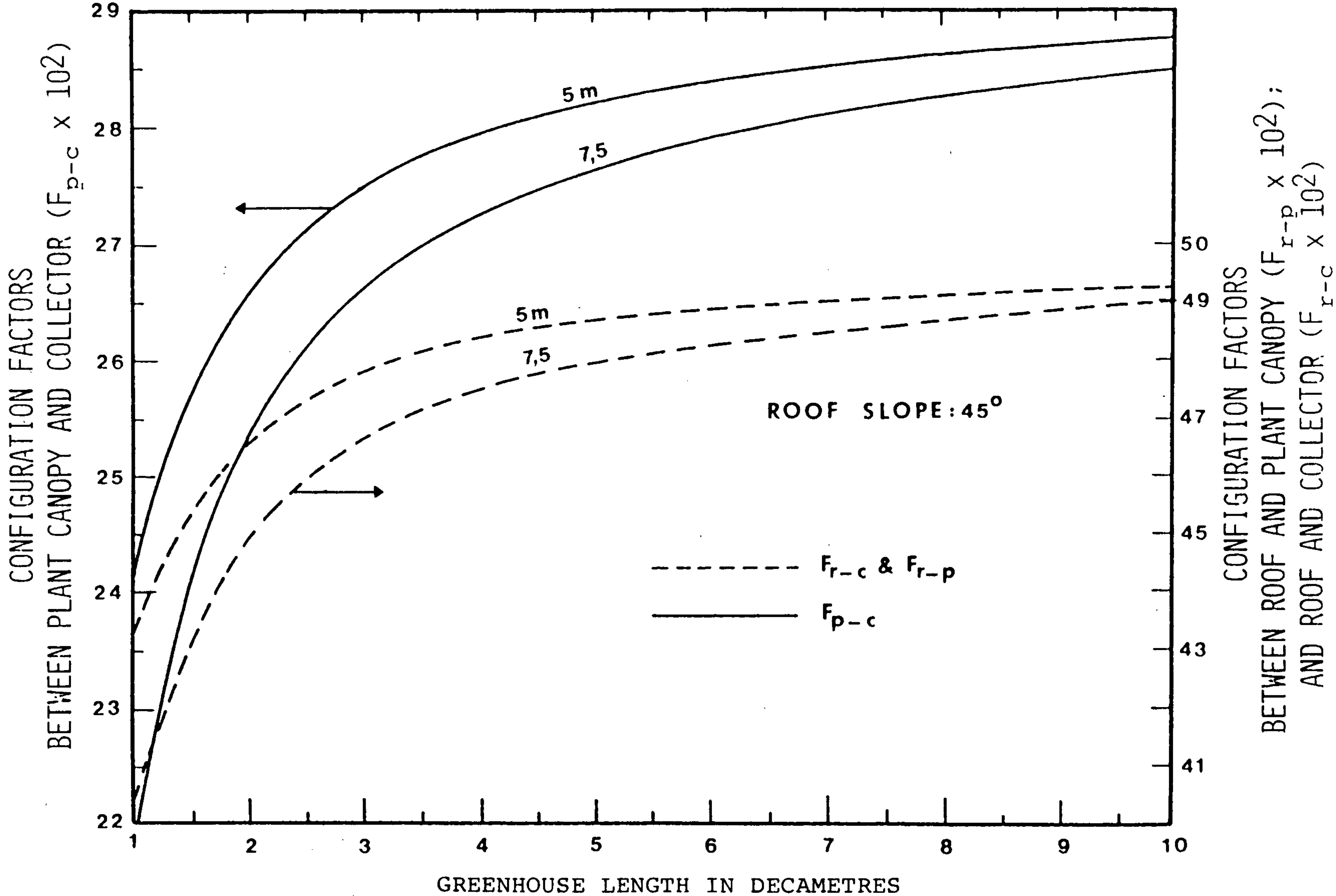


FIGURE 6.4: EFFECT ON LENGTH AND WIDTH ON THE RADIATION CONFIGURATION FACTORS FOR SOLAR-SHED GREENHOUSES HAVING A ROOF SLOPE OF 45 DEGREES.

SECTION C

CASE STUDY IV

SUPPLEMENTAL HEATING
REQUIREMENTS
OF A
SOLAR-SHED GREENHOUSE

CASE STUDY IV: SUPPLEMENTAL HEATING REQUIREMENTS OF A SOLAR-SHED GREENHOUSE

DESCRIPTION AND ASSUMPTIONS

The mathematical model developed in sections A and B of this chapter was solved using a digital computer to determine the hourly transmission loss, infiltration loss and the passive solar energy capture by the shed-type greenhouse. Then, the hourly supplemental heat requirement as well as the hourly and daily solar energy collectable by a solar collector placed on the north wall inside the greenhouse were calculated. Finally the monthly average daily fractions of the supplemental heat requirement of the greenhouse that could be supplied by the integral solar collector were estimated.

Throughout the time of the simulation the following are assumed to remain constant:

i) the minimum greenhouse temperature,

ii) the infiltration/exfiltration rate, and

iii) the albedo of the plant canopy within the greenhouse.

The solar-shed greenhouse used in this case study has a length of 100 metres and a width of 10 metres. The long axis of the greenhouse is east-west oriented. The roof is facing south and tilted at an angle of 30 degrees from the horizontal. An integral solar collector, having a surface area of 577 square metres, is installed on the inner surface of the vertical north wall of the shed greenhouse. The north wall, the footing and the perimeter of the greenhouse are insulated. The greenhouse is covered with a single layer of glass having a thickness of 3 millimetres. Other properties of the construction materials as well as the other pertinent construction and management parameters are detailed in Table 6.1.

RESULTS AND DISCUSSION

A sample computer simulation output for the solar-shed greenhouse described above and located in the Vancouver, B.C. area is included in Appendix I (Tables I.1 to I.12). The hourly and daily values shown in these tables are for a typical day of each month of the year. The information in the tables includes the passive solar radiation capture by the plant canopy, the infiltration heat loss, the transmission (convection, conduction and radiation) heat loss, the supplemental heat requirement (excluding the active solar energy contribution) and the solar energy collectable by the integral collector. A summary of the results of Appendix I is shown, on a monthly basis, in Table 6.2. It is important to notice that the solar input and solar contribution as indicated in this table are due to passive solar radiation collection only; that is, the solar energy captured by the plant canopy. Therefore, the values in Table 6.2 for the shed-type greenhouse are directly comparable to those in Table 4.2 for the gable greenhouse (Case Study II). By comparison between the results in these tables, it can be

TABLE 6.1

VARIABLES USED TO CALCULATE HEATING DEMANDS OF A SOLAR-SHED GREENHOUSE

Construction Parameters

Length:	100 m
Width:	10 m
Height:	2 m
Roof Slope:	30°
Orientation:	East-West Long Axis

Construction Materials Properties

Surface	Material	Area (m^2)	U ($Wm^{-2}K^{-1}$)	α_s	ε_ℓ
South Roof	Single Glass	1155	8.83	0.08	0.94
South Wall	Single Glass	200	8.03	0.08	0.94
North Wall	Insulated	777	0.25	0.20	0.94
East Wall	Single Glass	49	8.03	0.08	0.94
West Wall	Single Glass	49	8.03	0.08	0.94
Footing	Insulated	110	0.67	-	-
Perimeter	Insulated	220 (m)	0.67 ($Wm^{-1}K^{-1}$)	-	-

Glass Properties

Thickness:	0.3 cm
Extraction Coefficient:	0.252 cm^{-1}
Refraction Index:	1.526
Absorptivity to Solar Radiation:	0.08
Emissivity for Thermal Radiation:	0.94

Management Parameters

Location:	Vancouver, B.C. Montreal, P.Q. Halifax, N. S.
Minimum Greenhouse Temperature:	15°C
Infiltration Rate:	1.5 Air changes per hour
Plant Canopy Albedo:	0.1

TABLE 6.2

MONTHLY AVERAGE HEAT LOSS, SOLAR ENERGY INPUT, SOLAR CONTRIBUTION AND HEATING LOAD IN MJ PER m^2 OF GREENHOUSE FLOOR AREA AND PERCENT OF THE HEAT LOSS SUPPLIED BY SOLAR FOR THE SHED GREENHOUSE OF CASE STUDY IV (MINIMUM INSIDE TEMPERATURE = 15°C)

VANCOUVER, B.C.

Month	Heat Loss	Solar Input*	Solar Contribution**	Heating Load	Percent Solar**
January	492	172	116	376	24
February	387	210	108	279	28
March	407	334	134	273	33
April	277	345	97	180	35
May	161	393	52	109	32
June	81	442	23	58	28
July	44	432	8	36	18
August	33	429	5	28	15
September	83	340	11	72	13
October	244	261	66	178	27
November	361	146	85	276	24
December	477	122	99	378	21
YEAR	3047	3626	804	2243	26

* Solar input is the solar radiation captured by the plant canopy only and does not include solar radiation incident on the integral collector.

** Due to natural collection only.

seen that the monthly average heat loss from the shed greenhouse is higher than that from the gable greenhouse, due to the larger overall heat transfer coefficient of the shed structure as compared to the gable type. On an annual basis, the heat loss from the gable greenhouse is 2818 megajoules per square metre of floor area while for the shed-type the annual heat loss is estimated at 3047 megajoules per square metre; or, an increase in annual heat loss of six percent. Coupled with the increase in the heat loss, the solar radiation captured by the plant canopy in the shed-type greenhouse is also reduced from an annual value of 4104 megajoules per square metre to 3626 megajoules per square metre, representing a reduction in the order of twelve percent. However, the solar contribution or the solar energy passively utilized to compensate for the heat loss remained virtually the same at about 800 megajoules per square metre per year. The reason that the solar contribution remained unchanged is that more solar radiation is incident upon and captured by the plant canopy in the gable greenhouse than in the shed-type during the warm periods of the year while it is not needed for heating purposes. Therefore, it can be concluded that the shed-type requires less ventilation than the gable-type greenhouse provided the solar collector is covered or replaced by a reflective material during the summer months to allow some of the solar radiation incident upon the inner surface of the north wall to escape through the south roof of the greenhouse.

Since, the passive solar contribution has not been improved in the shed-type greenhouse while its heat loss has increased, then its heating load requirement is increased over the gable greenhouse. From Tables 6.2 and 4.2, this increase can be calculated as 167 megajoules per square metre annually or about eight percent. Therefore, it remains to be seen if the integral solar collector within the shed greenhouse can provide enough heat to offset the increased heat loss and result in a significant net energy saving. The contribution of the integral solar collector will be investigated later in this section.

The effect of climatic conditions on the heating load of the shed-type greenhouse is examined by performing analyses on an identical greenhouse using Montreal then Halifax weather data. Summaries of the results for the two additional locations in Canada are shown in Tables 6.3 and 6.4 for Montreal and Halifax, respectively. Again, these tables are directly comparable to those obtained for the gable greenhouse case (Tables 4.3 and 4.4).

Comparison of Table 6.3 to Table 4.3 for Montreal reveals the following points:

i) The annual average heat loss for the shed-type is found to be 4550 megajoules per square metre as compared to 4275 megajoules per square metre for the gable-type greenhouse or approximately six percent increase.

TABLE 6.3

MONTHLY AVERAGE HEAT LOSS, SOLAR ENERGY INPUT, SOLAR CONTRIBUTION AND HEATING LOAD IN MJ PER m^2 OF GREENHOUSE FLOOR AREA AND PERCENT OF THE HEAT LOSS SUPPLIED BY SOLAR FOR THE SHED GREENHOUSE OF CASE STUDY IV (MINIMUM INSIDE TEMPERATURE = 15°C)

MONTREAL, P.Q.

Month	Heat Loss	Solar Input*	Solar Contribution**	Heating Load	Percent Solar**
January	968	153	153	815	16
February	799	198	189	610	24
March	648	323	204	444	32
April	361	339	126	235	35
May	89	391	16	73	18
June	5	440	1	4	20
July	0	429	0	0	0
August	0	424	0	0	0
September	49	332	5	44	10
October	272	247	67	205	25
November	495	134	114	381	23
December	864	108	108	756	13
YEAR	4550	3518	983	3567	22

* Solar input is the solar radiation captured by the plant canopy only and does not include solar radiation incident on the integral collector.

** Due to natural collection only.

ii) The plant canopy in the shed-type greenhouse has captured 3518 megajoules per square metre per year on the average compared to 4045 megajoules per square metre for the plant canopy in the gable-type. This represents an annual reduction in solar radiation capture by the plant canopy in the order of thirteen percent.

iii) The passive solar contribution to the heat loss is three percent lower for the shed-type when compared to the gable-type greenhouse.

iv) When the energy contribution from the integral solar collector is neglected, the shed-type greenhouse requires nine percent more heat than the gable-type on an annual basis.

Comparison of Halifax results for the shed-type greenhouse (Table 6.4) and the gable-type greenhouse (Table 4.4) leads to similar conclusions as those obtained with Montreal and Vancouver weather data when the values are expressed on a percentage basis.

The performance of the integral solar collector expressed as the monthly average fraction of the greenhouse heating load supplied by solar is shown in Table 6.5 for the three locations under study.

The construction as well as the management parameters of the solar-shed greenhouse are identical for the three locations. The integral solar collector, having a surface

TABLE 6.4

MONTHLY AVERAGE HEAT LOSS, SOLAR ENERGY INPUT, SOLAR CONTRIBUTION AND HEATING LOAD IN MJ PER m^2 OF GREENHOUSE FLOOR AREA AND PERCENT OF THE HEAT LOSS SUPPLIED BY SOLAR FOR THE SHED GREENHOUSE OF CASE STUDY IV (MINIMUM INSIDE TEMPERATURE = 15°C)

HALIFAX, N.S.

Month	Heat Loss	Solar Input*	Solar Contribution**	Heating Load	Percent Solar**
January	684	150	140	544	21
February	627	195	159	468	25
March	572	321	181	391	32
April	390	338	135	255	35
May	228	390	71	157	31
June	97	439	21	76	22
July	32	428	4	28	13
August	25	423	3	22	11
September	72	330	8	64	11
October	218	245	48	170	22
November	379	132	85	294	22
December	606	106	106	500	17
YEAR	3930	3497	961	2969	25

* Solar input is the solar radiation captured by the plant canopy only and does not include solar radiation incident on the integral collector.

** Due to natural collection only.

area of 577 square metres, is installed on the inner surface of the vertical north wall of a solar shed greenhouse having 1000 square metres of floor area. Air is forced over both sides of the absorber plate at a flow rate to keep its average temperature at 35°C. The optical properties of the absorber plate are assumed to have equal absorptivity to solar radiation and emissivity for infra-red radiation of 0.9.

Examination of the results in Table 6.5 indicates that during the winter months the solar collector contribution is significantly higher for Vancouver than for Montreal or Halifax. For example, in January for Vancouver, the solar collector contribution is 97 megajoules per square metre of greenhouse floor area while for Montreal and Halifax, it is only 50 megajoules per square metre. The high contribution for Vancouver could be attributed to the fact that vertical collectors receive more radiation at higher latitudes during the winter period.

The low solar energy collection by the integral collector for Montreal and Halifax, coupled with relatively high greenhouse heating loads during the cold period of the year, resulted in a very small solar fraction for the months from November to February inclusive. These fractions ranged from as low as 4 percent in Montreal for December to 14 percent in Halifax for November compared to Vancouver which shows a low of 17 percent for December to 32 percent in

TABLE 6.5

MONTHLY AVERAGE HEATING LOAD AND SOLAR ENERGY SUPPLIED BY THE INTEGRAL COLLECTOR IN MJ PER m^2 FLOOR AREA AS WELL AS THE SOLAR FRACTIONS FOR THE SOLAR-SHED GREENHOUSE OF CASE STUDY IV

Location	Vancouver, B.C.			Montréal, Québec			Halifax, N.S.		
Month	Heating Load	Solar Contr.	Solar Fraction	Heating Load	Solar Contr.	Solar Fraction	Heating Load	Solar Contr.	Solar Fraction
January	376	97	0.26	815	50	0.06	544	51	0.09
February	279	89	0.32	610	54	0.09	468	55	0.12
March	273	108	0.39	444	82	0.19	391	82	0.21
April	180	72	0.40	235	62	0.26	255	59	0.23
May	109	64	0.59	74	64	0.87	157	55	0.35
June	58	58	1.00	4	4	1.00	76	61	0.80
July	36	36	1.00	0	-	-	28	28	1.00
August	28	28	1.00	0	-	-	22	22	1.00
September	72	72	1.00	44	44	1.00	64	64	1.00
October	178	112	0.63	205	88	0.43	170	85	0.50
November	276	69	0.25	381	42	0.11	294	42	0.14
December	378	65	0.17	756	27	0.04	500	29	0.06
Year	2243	870	0.39	3567	517	0.14	2969	633	0.21

Notes:
minimum greenhouse temperature 15°C.
average collector temperature 35°C.
absorptivity of collector 0.9
emissivity of collector 0.9

February. The relatively high solar fractions for Vancouver are due to a combination of high solar energy collection by the vertical collector and the relatively low greenhouse heat requirements during the winter months when compared to Halifax and Montreal.

The expected annual average fraction of the greenhouse heating load supplied by the integral solar collector is 0.39 for Vancouver, 0.14 for Montreal and 0.21 for Halifax. The low annual solar fraction for Montreal may be attributed firstly to the small amount of solar energy collected during the winter months when large quantities of supplemental heat are required; and, secondly to the absence of the heating requirement during the months of June, July and August when the availability of solar energy is not a limiting factor. A comparison of the monthly and annual average supplemental heat requirements between the conventional gable glasshouse and the solar-shed greenhouse for the three locations investigated is shown in Table 6.6.

At this point, one should recall from an earlier discussion, that the annual average heating load of the shed-type greenhouse is between eight and nine percent higher than that for the gable-type independently of the location of the greenhouse. Therefore, the contribution of the integral solar collector to the heating load must be much higher than the additional heat loss of the shed-type in order to make the use of the solar-shed greenhouse feasible.

TABLE 6.6

MONTHLY AVERAGE SUPPLEMENTAL HEAT REQUIREMENTS FOR THE CONVENTIONAL GABLE AND THE SOLAR-SHED GREENHOUSES IN MJ PER m^2 OF GREENHOUSE FLOOR AREA AND PERCENTAGE ENERGY SAVINGS AS AFFECTED BY LOCATION

Location	Vancouver, B.C.			Montréal, Québec			Halifax, N.S.		
Month	Conv.	Shed	% Savings	Conv.	Shed	% Savings	Conv.	Shed	% Savings
January	350	279	20	738	765	-4	494	493	<1
February	259	190	27	559	556	<1	428	413	4
March	253	165	35	409	362	11	357	309	13
April	165	108	35	215	173	20	232	196	16
May	100	45	55	68	10	85	141	102	28
June	53	0	100	4	0	100	69	15	78
July	33	0	100	0	0	0	27	0	100
August	26	0	100	0	0	0	21	0	100
September	67	0	100	42	0	100	61	0	100
October	166	66	60	190	117	38	160	85	47
November	256	207	19	350	339	3	272	252	7
December	348	313	10	687	729	-6	453	471	-4
Year	2076	1373	34	3262	3050	6	2718	2336	14

Notes: minimum greenhouse temperature 15°C.
average collector temperature 35°C.
absorptivity of collector 0.9
emissivity of collector 0.9

As can easily be seen from Table 6.6, the performance of the solar-shed greenhouse is highly dependent on its location. The annual average energy savings for the solar-shed as compared to the gable greenhouse are 34, 14 and 6 percent for Vancouver, Halifax and Montreal, respectively. Among the three Canadian locations tested, it is clear that the solar-shed greenhouse is suitable for Vancouver only. The good performance of the solar-shed greenhouse in the Vancouver region can be attributed to its high latitude (49.25°N) and to its characteristic weather with cool summer nights. The weather in the Halifax area is characterized by cool summer nights but its location is further south (44.65°N). Thus, the performance of the solar-shed is reduced to represent only 14 percent savings over the conventional gable greenhouse. Finally, for Montreal which is at a latitude of only one degree north of Halifax, has a climate which is characterized by warm summer nights; thus resulting in a further reduction to the performance of the solar-shed greenhouse.

EFFECT OF SELECTIVE COATING AND AVERAGE TEMPERATURE OF THE ABSORBER PLATE

The results discussed so far are for a non-selective absorber plate operating at an average temperature of 35°C. The effect of average plate temperature and the utilization of a selective coating on the monthly and yearly fraction of the greenhouse heating load supplied by the integral solar collector is shown in Table 6.7. The information contained in the table is for a solar-shed greenhouse located in the Halifax, N.S. region. The construction and management parameters are the same as those described in Table 6.1 and Figure 6.2 with the exception that the lower 2 metres of the east and west walls are insulated in order to decrease the overall heat transfer coefficient of the building.

Analyses were performed for a collector with a non-selective absorber plate having an absorptivity to solar radiation of 0.9 and an emissivity to infra-red radiation of 0.9, as well as, a collector with an absorber plate coated with a selective material having an absorptivity for solar radiation of 0.9 and an emissivity to thermal radiation of 0.2. Three average surface temperatures, namely 25°C, 30°C and 35°C, were used with each of the two absorber plates. Also, an analysis was conducted for the special case of an ideal absorber plate having an absorptivity to solar radiation of unity and an emissivity to infra-red radiation of zero.

An examination of the results in Table 6.7 indicates clearly that the effect of absorber plate temperature on the solar fraction is small for the selective absorber; however, a slight increase in the yearly fraction is observed with decrease in plate temperature for the non-selective absorber. The yearly fraction increased from 0.23 when the average plate temperature is kept at 35°C to 0.28 when the temperature is reduced to 25°C.

TABLE 6.7

MONTHLY AND YEARLY FRACTION OF HEATING LOAD SUPPLIED BY THE INTEGRAL SOLAR COLLECTOR AS A FUNCTION OF THE AVERAGE ABSORBER PLATE TEMPERATURE AND ITS OPTICAL PROPERTIES FOR THE SOLAR-SHED GREENHOUSE OF CASE STUDY IV (MINIMUM GREENHOUSE TEMPERATURE = 15°C)*

	$\alpha_c = 1.0$	$\alpha_c = 0.9$, $\varepsilon_c = 0.9$			$\alpha_c = 0.9$, $\varepsilon_c = 0.2$		
	$Q_{LOSS} = 0$	25°C	30°C	35°C	25°C	30°C	35°C
January	.23	0.13	0.12	0.10	0.18	0.18	0.17
February	.28	0.17	0.15	0.13	0.22	0.22	0.21
March	.45	0.28	0.26	0.23	0.36	0.35	0.34
April	.55	0.34	0.29	0.25	0.44	0.43	0.41
May	.86	0.53	0.45	0.38	0.68	0.65	0.62
June	1.00	1.00	1.00	0.84	1.00	1.00	1.00
July	1.00	1.00	1.00	1.00	1.00	1.00	1.00
August	1.00	1.00	1.00	1.00	1.00	1.00	1.00
September	1.00	1.00	1.00	1.00	1.00	1.00	1.00
October	0.91	0.65	0.60	0.54	0.76	0.74	0.72
November	0.34	0.20	0.18	0.15	0.27	0.26	0.25
December	0.18	0.09	0.08	0.06	0.13	0.13	0.12
Year	0.42	0.28	0.26	0.23	0.35	0.34	0.33

* Location: Halifax, N.S.

The effect of the selective coating on the solar fraction is more pronounced than that of the absorber temperature especially at high operating temperatures. At an average plate temperature of 35°C (Table 6.7), the yearly fraction for a non-selective surface is 0.23 as compared to 0.33 for the selective absorber. This increase in the yearly fraction of the greenhouse heating load supplied by solar represents about 43 percent. At the lower temperature of 25°C the increase in the yearly fraction is reduced to only 25 percent. Therefore, for a solar collector with non-selective absorber the plate temperature should be kept reasonably low to minimize the radiative heat loss from the collector to the greenhouse roof. This is especially true for steep roof slopes when the radiant-exchange configuration factors between the collector and the roof are relatively larger than those for low roof slopes.

The solar fractions for the ideal selective absorber case is also shown in Table 6.7 and from which it can be concluded that the maximum annual contribution by the solar collector to the heating load for the solar-shed greenhouse under study is about 42 percent.

CONCLUSIONS

The following conclusions can be drawn from the results obtained by computer simulation of heating requirements and solar energy contribution of the solar-shed greenhouse described in this section:

1. In general, a shed-type greenhouse has a higher heat loss than a conventional gable greenhouse of the same size due to an increase in the exposed surface area.

2. There is no significant difference in the solar energy capture by the plant canopy in a shed-type greenhouse when compared to that in a gable greenhouse.

3. The performance of a solar-shed greenhouse is highly dependent on its location. It is best adapted to regions with a high latitude (north or south), having climatic conditions characterized by cool summer nights and mild winters.

4. For the three Canadian locations investigated, the yearly average fraction of the greenhouse heating load supplied by the integral collector having a non-selective absorber plate and operated at 35°C, were found to be 0.39, 0.21 and 0.14 for Vancouver, Halifax and Montreal, respectively.

5. When the solar collector is operated at an average plate temperature of 35°C, the use of a selective coating has increased the yearly solar fraction by 43 percent over the use of the non-selective surface.

6. At lower average plate temperatures, the benefit of selective coating over non-selective surfaces becomes

less pronounced due to the reduced radiative heat loss from the collector to the greenhouse roof.

7. When non-selective absorbers are used the operating plate temperature should be kept as low as possible to minimize the radiative heat loss by the collector.
8. The expected average annual energy savings by the solar-shed greenhouse over a conventional gable glasshouse are 34%, 14% and 6% for Vancouver, Halifax and Montreal, respectively. These savings are for a collector having a non-selective absorber plate and operated at 35°C.

NOMENCLATURE

Symbol	Definition	Units
A_c	Surface area of the solar collector	m^2
A_f	Surface area of the insulated lower section of the vertical walls	m^2
A_r	Surface area of the roof	m^2
A_p	Surface area of the plant canopy	m^2
A_w	Surface area of the south wall of the shed-greenhouse	m^2
A_i	Surface area of any greenhouse wall i	m^2
C_p	Specific heat of air at constant pressure	$kJ.kg^{-1}.K^{-1}$
E	Efficiency of solar radiation capture by the greenhouse	dimensionless
$F_{r \to c}$, $F_{c \to r}$	Radiation configuration factors between the roof and the collector	dimensionless
$F_{p \to c}$	Radiation configuration factor between the plant canopy and the collector	dimensionless
$F_{p \to r}$, $F_{r \to p}$	Radiation configuration factors between the plant canopy and the roof of the greenhouse	dimensionless
$F_{r \to sky}$	Radiation configuration factor between the roof and the sky	dimensionless
$F_{r \to g}$	Radiation configuration factor between the roof and the surrounding ground	dimensionless

$f_{i,i}$	Inside convective heat transfer coefficient for any vertical wall i of the greenhouse	$kJ.h^{-1}.m^{-2}.K^{-1}$
$f_{i,r}$	Inside convective heat transfer coefficient for the roof of the greenhouse	$kJ.h^{-1}.m^{-2}.K^{-1}$
H	Height of the south vertical wall of the greenhouse	m
$\bar{h}_{kl,i}$	Average convective heat transfer coefficient due to wind for any surface i	$kJ.h^{-1}.m^{-2}.K^{-1}$
I_c	Total solar radiation incident on the collector	$kJ.h^{-1}$
I'_c	Total solar radiation incident on the collector neglecting the reflected component originating from the plant canopy	$kJ.h^{-1}$
I'_p	Total solar radiation incident on the top of the plant canopy	$kJ.h^{-1}$
I_p	Total solar radiation captured by the top of the plant canopy	$kJ.h^{-1}$
I_w	Total solar radiation transmitted through the south wall that is captured by the plant canopy	$kJ.h^{-1}$
I_g	Total solar radiation captured by the plant canopy ($I_g = I_p+I_w$)	$kJ.h^{-1}$

I_h	Total solar radiation incident on a horizontal surface outside the greenhouse	$kJ.h^{-1}$
$I_{c,l}$	Total solar radiation incident on a unit area of the collector	$kJ.h^{-1}.m^{-2}$
$I_{p,l}$	Total solar radiation captured by the top of the plant canopy expressed in terms of unit area of the floor of the greenhouse	$kJ.h^{-1}.m^{-2}$
$I'_{p,l}$	Total solar radiation incident on a unit area of the plant canopy	$kJ.h^{-1}.m^{-2}$
$I_{w,l}$	Total solar radiation transmitted through the south vertical wall of the greenhouse that is captured by the plant canopy expressed in terms of unit area of the floor of the greenhouse	$kJ.h^{-1}.m^{-2}$
$I_{b,c}$	Beam solar radiation incident on the collector	$kJ.h^{-1}$
$I_{b,h}$	Beam solar radiation incident on a horizontal surface outside the greenhouse	$kJ.h^{-1}.m^{-2}$
$I_{b,p}$	Beam solar radiation incident on top of the plant canopy	kJ.h

$I_{b,v}$	Beam solar radiation incident on a vertical south facing wall outside the greenhouse	$kJ.h^{-1}.m^{-2}$
$I_{b,w}$	Beam solar radiation transmitted through the south vertical wall of the greenhouse	$kJ.h^{-1}$
$I_{d,c}$	Non-reflected diffuse solar radiation incident on the collector	$kJ.h^{-1}$
$I_{d,p}$	Diffuse solar radiation incident on the top of the plant canopy	$kJ.h^{-1}$
$I_{d,r}$	Diffuse solar radiation incident on the roof of the greenhouse	$kJ.h^{-1}.m^{-2}$
$I_{d,v}$	Diffuse solar radiation incident on a vertical south facing surface	$kJ.h^{-1}.m^{-2}$
$I_{d,w}$	Diffuse solar radiation transmitted through the south vertical wall of the greenhouse	$kJ.h^{-1}$
$I_{r,p}$	Reflected diffuse solar radiation by the plant canopy that is directly incident on the collector	$kJ.h^{-1}$
$I_{r,r}$	Reflected diffuse solar radiation by the plant canopy that is incident on the collector via the roof	$kJ.h^{-1}$
$I_{s,i}$	Total solar radiation incident on any vertical surface i of the greenhouse	$kJ.h^{-1}.m^{-2}$

$I_{s,r}$	Total solar radiation incident on the roof of the greenhouse	$kJ.h^{-1}.m^{-2}$
L	Length of the greenhouse	m
N_a	Number of air exchanges per hour	h^{-1}
P	Greenhouse perimeter	m
Q_{abs}	Solar energy absorbed by the collector	$kJ.h^{-1}$
Q_{col}	Solar energy collected	$kJ.h^{-1}$
$Q_{col,day}$	Daily solar energy collected	kJ
Q_{con}	Convective heat loss from the greenhouse	$kJ.h^{-1}$
Q_{inf}	Infiltration heat loss from the greenhouse	$kJ.h^{-1}$
Q_{rad}	Thermal radiation heat loss from the greenhouse cover	$kJ.h^{-1}$
Q_{sol}	Solar radiation input to the greenhouse	$kJ.h^{-1}$
Q_{sup}	Supplemental heat requirement	$kJ.h^{-1}$
$Q_{sup,day}$	Daily heating load of the greenhouse	kJ
Q_{loss}	Heat loss from the collector	$kJ.h^{-1}$
$Q_{rad,i}$	Thermal radiation heat loss from any vertical wall i of the greenhouse	$kJ.h^{-1}$
$Q_{rad,roof}$	Thermal radiation heat loss from the roof of the greenhouse	$kJ.h^{-1}$
Q_r	Total heat loss through the roof of the greenhouse	$kJ.h^{-1}$

Q_i	Total heat loss through any vertical wall i of the greenhouse	$kJ.h^{-1}$
$Q_{sa,i}$	Solar radiation absorbed by any surface i of the greenhouse	$kJ.h^{-1}.m^{-2}$
R_c	Thermal resistance of the greenhouse	$h.m^2.K.kJ^{-1}$
R_i	Thermal resistance of any vertical wall i of the greenhouse excluding the outside film coefficient	$h.m^2.K.kJ^{-1}$
R_r	Thermal resistance of the roof of the greenhouse excluding the outside film coefficient	$h.m^2.K.kJ^{-1}$
T_a	Outside dry-bulb temperature	K
$\bar{T}_c$	Average temperature of the absorber plate of the collector	K
T_g	Dry-bulb temperature inside the greenhouse'	K
$T_{g,min}$	Minimum dry-bulb temperature inside the greenhouse	K
T_i	Surface temperature of any vertical wall i of the greenhouse	K
T_r	Surface temperature of the roof of the greenhouse	K
T_{sky}	Effective temperature of the sky	K
U_f	Conductive heat transfer coefficient of the insulated lower section of the vertical walls	$kJ.h^{-1}.m^{-2}.K^{-1}$
U_p	Effective conductive heat transfer coefficient for the greenhouse perimeter	$kJ.h^{-1}.m^{-1}.K^{-1}$

V	Wind speed	$m.s^{-1}$
V_g	Volume of the greenhouse	m^3
v	Specific volume of air	$m^3.kg^{-1}$
w	Width of the greenhouse	m
α_c	Absorptivity of the absorber plate of the collector to solar radiation	
α_i	Absorptivity of any surface i to solar radiation	
α_r	Absorptivity of the roof of the greenhouse to solar radiation	
α_w	Absorptivity of the south facing vertical wall of the greenhouse to solar radiation	
β	Tilt angle of the roof from the horizontal	radians
ε_c	Emissivity of the absorber plate of the collector for infra-red radiation	
ε_i	Emissivity of any vertical wall i of the greenhouse for infra-red radiation	
ε_r	Emissivity of the roof of the greenhouse for infra-red radiation	
ρ	Albedo of the plant canopy	
$\tau_{b,r}$	Transmissivity of the roof of the greenhouse to beam solar radiation	

$\tau_{b,w}$	Transmissity of the south facing vertical wall of the greenhouse to beam solar radiation	
$\tau_{d,r}$	Transmissivity of the roof of the greenhouse to diffuse solar radiation	
$\tau_{d,w}$	Transmissivity of the south facing vertical wall of the greenhouse to diffuse solar radiation	
σ	Stefan-Boltzmann constant ($\sigma = 20.411 \times 10^{-8}$)	$kJ.h^{-1}.m^{-2}.K^{-4}$
ω_{sr}	Sunrise angle	radians
ω_{ss}	Sunset angle	radians

CHAPTER 7

COMPUTER SIMULATION MODEL OF HEATING REQUIREMENTS OF A SOLAR-SHED GREENHOUSE-LIVESTOCK BUILDING COMBINATION

INTRODUCTION

In this chapter, the feasibility of attaching a livestock building to the vertical north wall of a solar-shed greenhouse is investigated with regard to potential energy conservation. Obviously, this type of combination, if proven energy efficient, could only be used with new farm buildings specifically constructed for the purpose. On the other hand, the conventional gable greenhouse-livestock building combination covered in Chapter 5 could easily be implemented in existing livestock operations. The retrofit of a conventional type building would normally require only minor modifications to the ventilation system.

The only advantage of the shed-type design is the possibility of incorporating an internal solar collector to the overall system.

This chapter is divided into two sections. The first section describes the design and operation of the combined solar-shed greenhouse-livestock building. The second section gives the computer simulation results for the performance of a typical solar-shed greenhouse-hog barn combination for two Canadian locations (Case Study V). Finally, the effect of the greenhouse size on the performance and potential energy savings of the combination is investigated in case study VI.

SECTION A

DESCRIPTION OF THE COMPUTER MODEL FOR THE SOLAR-SHED GREENHOUSE-LIVESTOCK BUILDING COMBINATION

SOLAR-SHED GREENHOUSE-LIVESTOCK BUILDING COMBINATION SIMULATION MODEL

ASSUMPTIONS

The assumptions stated with regard to the livestock computer model developed in Chapter 3 and those made during the development of the solar-shed greenhouse mathematical model in Chapter 6 apply to the combined solar-shed greenhouse-livestock building case. This system is similar to the conventional livestock-gable greenhouse combination case except for the addition of the integral solar collector and thermal storage within the shed-type greenhouse; consequently, the three general assumptions underlying the conventional case, as stated in Chapter 5, also apply to the present system.

DESCRIPTION OF THE COMPUTER MODEL

A schematic cross-section of the building showing the different thermal zones is included in Figure 7.2.

The heat balances about the three main thermal zones: Attic space, livestock building and greenhouse are identical to those used with the conventional gable greenhouse-livestock combination case described in Chapter 5.

The mathematical model developed in Chapter 3 for the livestock building is used here as the subprogram for energy balance calculations about the livestock building including the attic space. This subprogram is used simultaneously with the solar-shed greenhouse subprogram for the energy balance about the greenhouse including the solar energy collected by the integral solar collector. The mathematical model development for the shed greenhouse is described in detail in Chapter 6.

The greenhouse solar heating system has three modes of operation as shown in Figure 7.1.

MODE 1: This mode of operation is used when the greenhouse requires heat, and solar energy is available. In this case, the air is simply circulated from the greenhouse (GH) over the solar collector (SC) and back to the greenhouse as indicated in Figures 7.1(a) and 7.2. Supplemental heat (Q_{sup}) to keep the greenhouse at the desired temperature may be required as shown in Figure 7.2.

MODE 2: In this case, passive solar to the greenhouse and waste heat from the livestock building are sufficient to supply the greenhouse heating load while solar energy is available for collection.

During such periods the air from the greenhouse (GH) passes through the solar collector (SC) then forced, using blower (B), through a rock bed or wet ground thermal storage (ST) located underneath the greenhouse floor as shown in Figures 7.1(b) and 7.3. The air is then returned from the thermal storage to the greenhouse to complete the closed circuit.

MODE 3: This mode of operation is used at night and during periods of low solar radiation intensity when the waste heat from the livestock building does not supply an adequate amount of energy to keep the greenhouse at a minimum preset temperature.

In this case, the greenhouse air is circulated through the thermal storage (ST) in an opposite direction to that of MODE 2 operation, as indicated in Figures 7.1(c) and 7.4. Obviously, the furnace used to supply the supplemental heat must be sized to accommodate the greenhouse demand for heat when the thermal storage is empty.

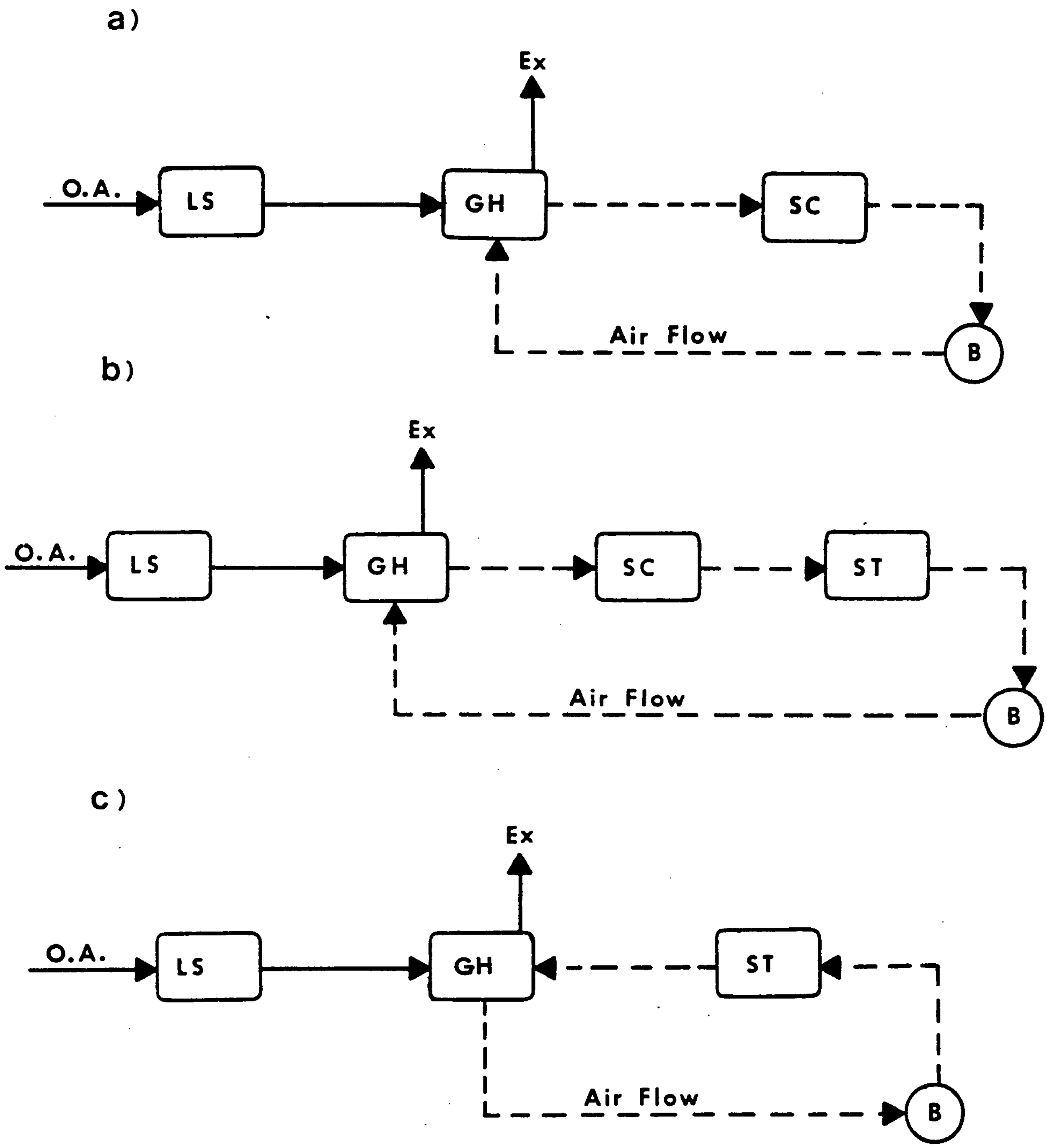


FIGURE 7.1: MODES OF OPERATION OF THE SOLAR HEATING SYSTEM OF A SOLAR-SHED GREENHOUSE-LIVESTOCK BUILDING COMBINATION.

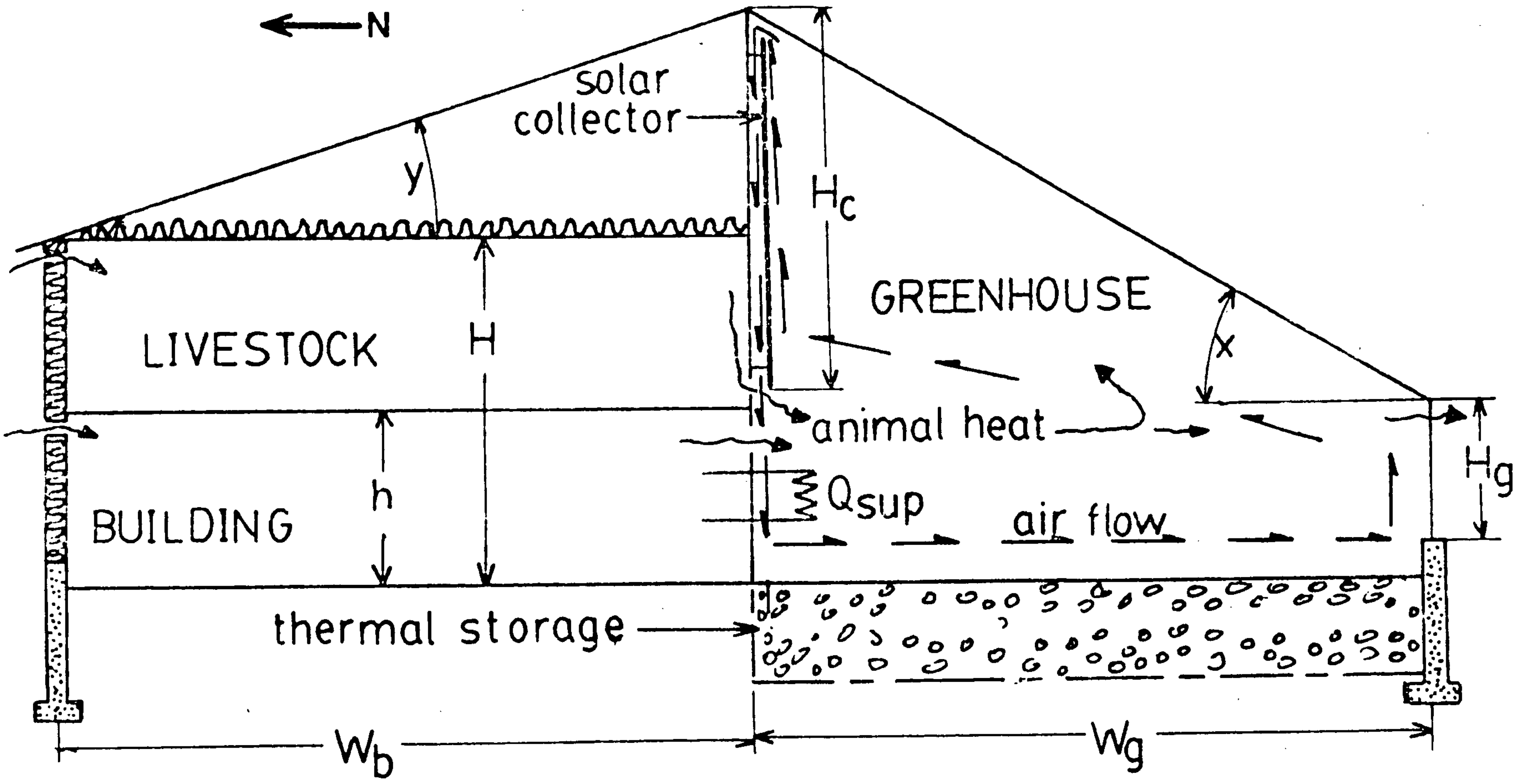


FIGURE 7.2: DIRECT HEATING OF A SOLAR-SHED GREENHOUSE-LIVESTOCK BUILDING COMBINATION BY THE INTEGRAL SOLAR HEATING SYSTEM (MODE 1 OPERATION).

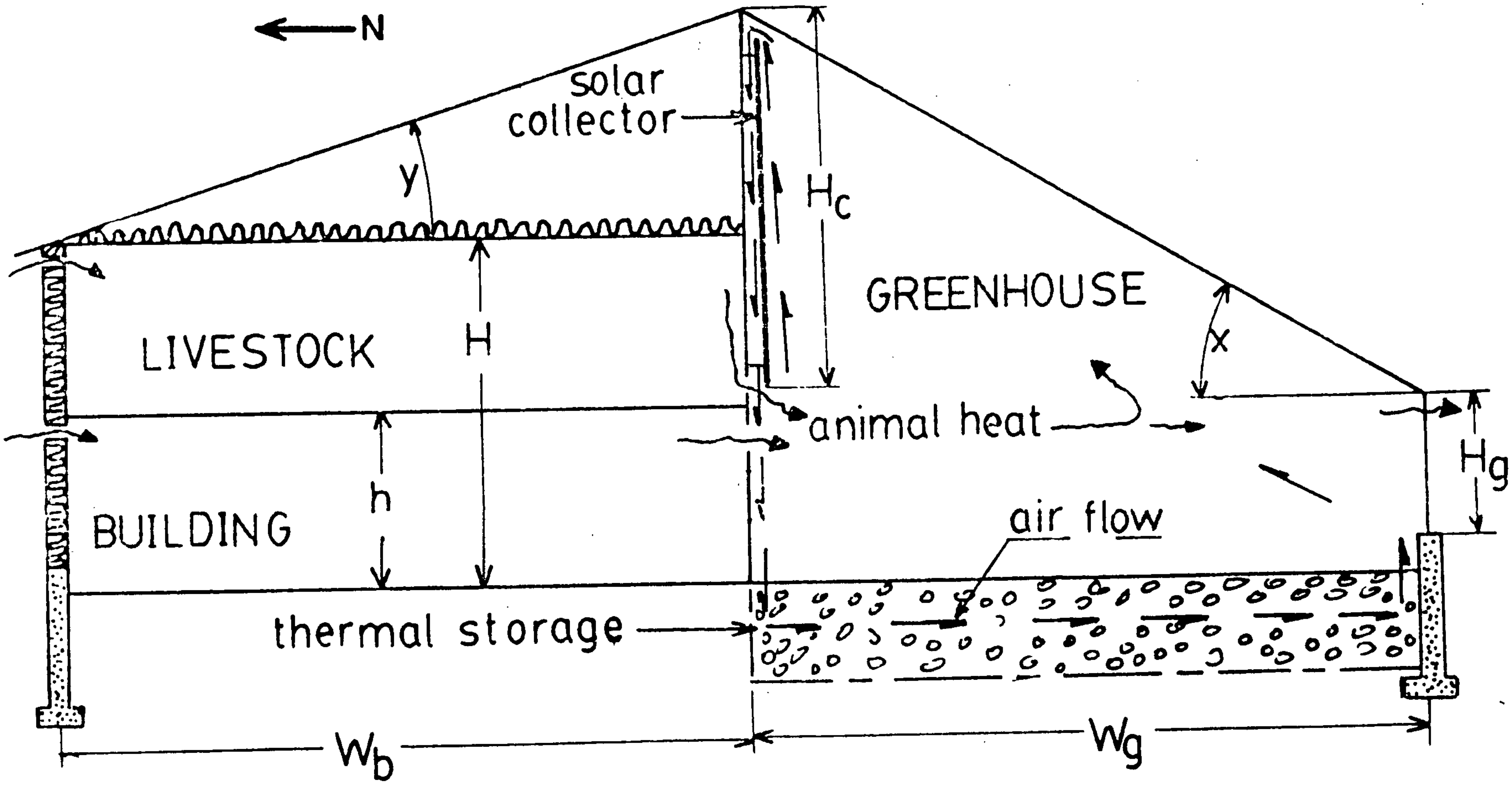


FIGURE 7.3: SOLAR ENERGY COLLECTION AND STORAGE IN A SOLAR-SHED GREENHOUSE-LIVESTOCK BUILDING COMBINATION (MODE 2 OPERATION).

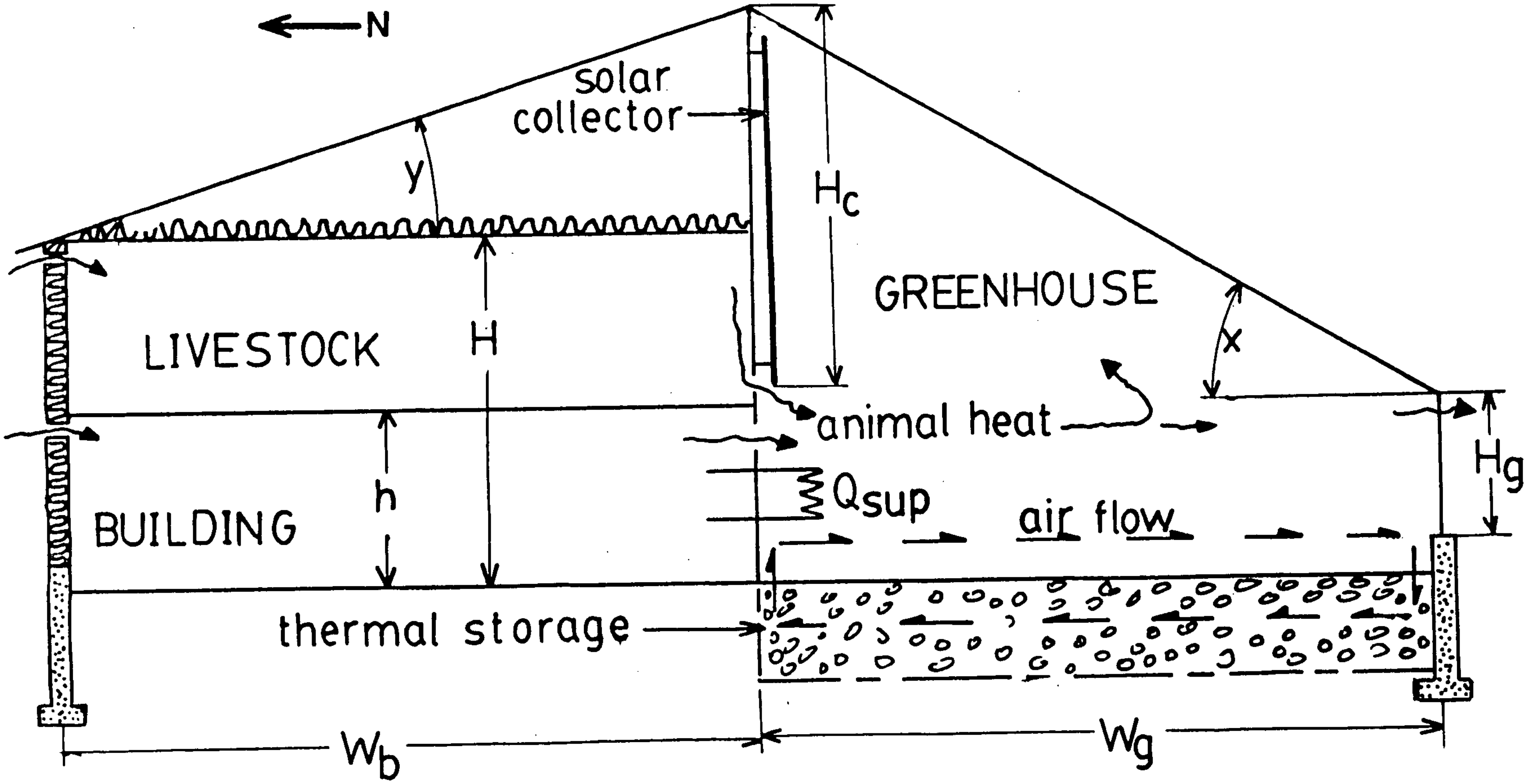


FIGURE 7.4: HEATING OF A SOLAR-SHED GREENHOUSE-LIVESTOCK BUILDING COMBINATION FROM THE THERMAL STORAGE (MODE 3 OPERATION).

SECTION B

CASE STUDIES V AND VI

HEATING REQUIREMENTS
OF A
SOLAR-SHED GREENHOUSE-SWINE FINISHING BARN
COMBINATION

SOLAR-SHED GREENHOUSE-HOG BARN COMBINATION

CASE STUDY V

DESCRIPTION AND ASSUMPTIONS

A schematic of the attached solar-shed greenhouse to a hog barn used in this case study is given in Figure 7.5.

The solar-shed greenhouse is identical to that used with respect to case study IV in Chapter 6. The construction and management parameters for the greenhouse are given in Table 7.1. A two-level hog barn having a shed roof is attached to the vertical north wall of the greenhouse (Fig. 7.5). The barn has a ground surface area equal to that used in case studies I and III, in Chapter 3 and Chapter 5, respectively, while the number of hogs at full capacity is doubled. The ratio hog density to greenhouse floor area can be calculated as 3.07 at full capacity. Other pertinent construction and management parameters for the two-level swine finishing building are given in Table 7.2.

RESULTS AND DISCUSSION

A sample computer simulation output for an attached solar-shed greenhouse-hog barn is included in Appendix J (Tables J.1 to J.12). These tables give the simulated hourly results and their daily totals for a typical day of each month of the year. The results apply to the greenhouse-swine finishing barn combination described in Tables 7.1 and 7.2.

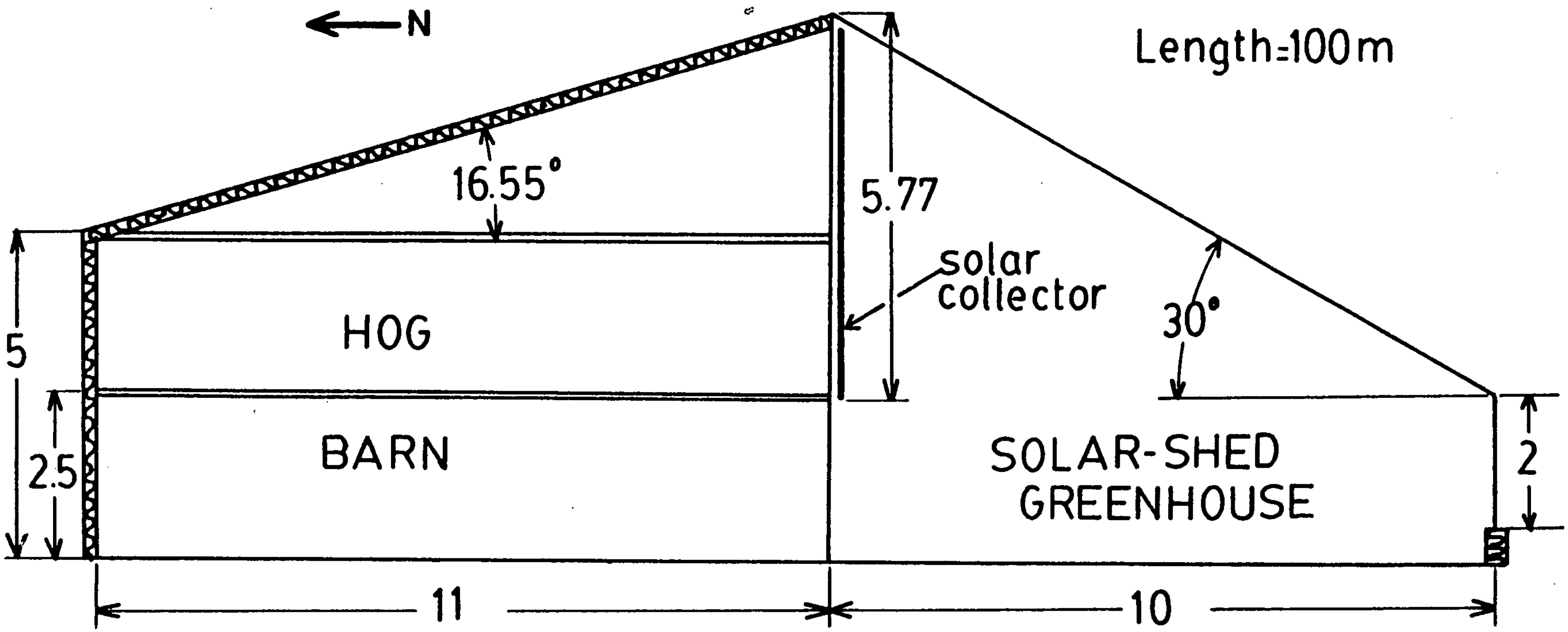


FIGURE 7.5: SCHEMATIC OF THE CROSS-SECTION OF A SOLAR-SHED GREENHOUSE-HOG BARN COMBINATION USED IN CASE STUDY V.

TABLE 7.1

VARIABLES USED TO CALCULATE HEATING DEMANDS OF A SOLAR-SHED GREENHOUSE

Construction Parameters

Length:	100 m
Width:	10 m
Height:	2 m
Roof Slope:	30°
Orientation:	East-West Long Axis

Construction Materials Properties

Surface	Material	Area (m^2)	U ($Wm^{-2}K^{-1}$)	α_s	ε_ℓ
South Roof	Single Glass	1155	8.83	0.08	0.94
South Wall	Single Glass	200	8.03	0.08	0.94
East Wall	Single Glass	49	8.03	0.08	0.94
West Wall	Single Glass	49	8.03	0.08	0.94
Footing	Insulated	60	0.67	-	-
Perimeter	Insulated	110 (m)	0.67 ($Wm^{-1}K^{-1}$)	-	-

Glass Properties

Thickness:	0.3 cm
Extraction Coefficient:	0.252 cm^{-1}
Refraction Index:	1.526
Absorptivity to Solar Radiation:	0.08
Emissivity for Thermal Radiation:	0.94

Management Parameters

Location:	Halifax, N.S. Vancouver, B.C.
Minimum Greenhouse Temperature:	15°C
Plant Canopy Albedo:	0.1

TABLE 7.2

VARIABLES USED TO CALCULATE VENTILATION

REQUIREMENTS OF A TWO-LEVEL SHED

SWINE FINISHING BARN

Construction Parameters

Length:	100 m
Width:	11 m
Height:	5 m (2 levels)
Roof Slope:	16.55°
Orientation:	East-West Long Axis

Construction Materials Properties

Building Component	Area (m^2)	RSI ($m^2.K/W$)	U ($kJ.m^{-2}.h^{-1}.K^{-1}$)	α_s	ε_ℓ
North Roof	1148	5.88	0.61	0.2	0.22
North Wall	450	4.00	0.90	0.2	0.22
East Wall	67.5	4.00	0.90	0.2	0.22
West Wall	67.5	4.00	0.90	0.2	0.22
Foundation	61	1.49	2.41	-	-
Perimeter	122 (m)	1.49 (m.K/W)	2.41 ($kJ.h^{-1}.m^{-1}.K^{-1}$)	-	-

Management Parameters

Location:	Halifax, N.S. Vancouver, B.C.
Number of Hogs:	3072
Average Weight:	70 kg
Minimum Inside Temperature:	20°C
Maximum Inside Relative Humidity:	85%
Maximum Ventilation Rate:	50 litres per second per hog
Ventilation System Type:	Variable speed fans (24 kW peak load)

The building is located in the Halifax region. The greenhouse is assumed to be operated at a minimum temperature of 15°C.

The information in Tables J.1 to J.12 include the solar radiation passively captured by the shed greenhouse, the waste heat available from the hog barn ventilation air, the greenhouse transmission heat loss and its predicted heating load and supplemental heat requirement. The table also gives the hourly fractions of the greenhouse transmission loss supplied by passive solar as well as by waste heat from the hog barn. The tables in Appendix J also include the estimated hourly and daily solar energy captured by the integral collector and the predicted monthly average daily fraction of the greenhouse heating load supplied by the solar collector.

A summary of the results of Appendix J is given on a monthly basis in Table 7.3. From the table, it is seen that the annual average heat loss from the shed greenhouse, expressed in terms of unit floor area, is 3191 megajoules per square metre (MJ/m^2) of which 826 MJ/m^2 or 26 percent are passively supplied by solar. The contribution of the sensible waste heat recovery from the hog barn ventilation air is estimated at 34 percent of the greenhouse heat loss or a contribution of 1097 MJ/m^2. The predicted annual contribution by the active solar collector is relatively small, accounting for only 11 percent of the total greenhouse heat loss or a contribution of 341 MJ/m^2.

TABLE 7.3

SUMMARY OF RESULTS OF THE SOLAR-SHED GREENHOUSE-HOG BARN COMBINATION LOCATED IN HALIFAX.

(MINIMUM GREENHOUSE TEMPERATURE 15°C)

Month	Heat Loss (MJ/m^2)	Passive Solar Contribution (MJ/m^2)	Fraction Supplied by Passive Solar	Heating Load (MJ/m^2)	Waste Heat Contribution (MJ/m^2)	Fraction Supplied by Waste Heat	Supplemental Heat Requirement (MJ/m^2)	Active Solar Contribution (MJ/m^2)	Fraction Supplied by Active Solar	Furnace Heat Requirement (MJ/m^2)
January	547	122	0.22	425	110	0.20	315	51	0.09	264
February	502	135	0.27	367	92	0.18	275	55	0.11	220
March	459	150	0.33	309	103	0.22	206	81	0.18	125
April	315	112	0.36	203	108	0.34	95	59	0.19	36
May	190	64	0.34	126	107	0.56	19	19	0.10	0
June	84	19	0.23	65	65	0.77	0	-	-	0
July	30	4	0.13	26	26	0.87	0	-	-	0
August	24	3	0.13	21	21	0.87	0	-	-	0
September	64	8	0.13	56	56	0.87	0	-	-	0
October	182	42	0.23	140	133	0.73	7	7	0.04	0
November	308	71	0.23	237	147	0.48	90	41	0.13	49
December	486	96	0.20	390	129	0.27	261	28	0.06	233
Year	3191	826	0.26	2365	1097	0.34	1268	341	0.11	927

An identical solar-shed greenhouse-hog barn combination was also simulated using Vancouver weather data. A summary of the computer simulation results is shown in Table 7.4. As indicated in the table, the estimated annual average heat loss by the shed greenhouse located in Vancouver is significantly lower than that predicted for Halifax. The 22 percent decrease in greenhouse heat loss is due to the mild climate experienced in the Vancouver region.

It is interesting to note that the predicted annual passive solar contribution in absolute terms is lower for a greenhouse located in Vancouver than in Halifax (826 MJ/m^2 compared to 684 MJ/m^2). However, the percent passive contribution is practically the same for both locations. The low passive solar contribution in Vancouver is due to the relatively warm climate of the region, which results in some of the available solar energy not being utilized.

From Table 7.4, the annual contribution of waste heat from the hog barn is estimated at 1204 MJ/m^2 or 48 percent of the greenhouse heat loss. These values are significantly higher than those predicted for Halifax. This difference is due to the larger fraction of the animal sensible heat not utilized to offset the heat loss from a barn located in Vancouver when compared to an identical barn located in Halifax.

The predicted annual average contribution of the active solar collector is 448 MJ/m^2 of floor area representing 18

TABLE 7.4

SUMMARY OF RESULTS OF THE SOLAR-SHED GREENHOUSE-HOG BARN COMBINATION LOCATED IN VANCOUVER.

(MINIMUM GREENHOUSE TEMPERATURE 15°C)

Month	Heat Loss (MJ/m^2)	Passive Solar Contribution (MJ/m^2)	Fraction Supplied by Passive Solar	Heating Load (MJ/m^2)	Waste Heat Contribution (MJ/m^2)	Fraction Supplied by Waste Heat	Supplemental Heat Requirement (MJ/m^2)	Active Solar Contribution (MJ/m^2)	Fraction Supplied by Active Solar	Furnace Heat Requirement (MJ/m^2)
January	400	96	0.24	304	141	0.35	163	96	0.24	67
February	316	92	0.29	224	123	0.39	101	89	0.28	12
March	331	112	0.34	219	125	0.38	94	94	0.28	0
April	227	82	0.36	145	115	0.51	30	30	0.13	0
May	134	44	0.33	90	90	0.67	0	0	-	0
June	69	21	0.30	48	48	0.70	0	0	-	0
July	39	8	0.21	31	31	0.79	0	0	-	0
August	30	5	0.17	25	25	0.83	0	0	-	0
September	71	10	0.14	61	61	0.86	0	0	-	0
October	202	56	0.28	146	140	0.69	6	6	0.03	0
November	296	72	0.24	224	156	0.53	68	68	0.23	0
December	388	86	0.22	302	149	0.38	153	65	0.17	88
Year	2503	684	0.27	1819	1204	0.48	615	448	0.18	167

percent of the greenhouse heat loss (Table 7.4). These values are slightly higher than those obtained with Halifax weather data. This is simply due to the fact that the solar-shed greenhouse has a higher efficiency in Vancouver than in Halifax as the results in Chapter 6 have indicated.

The above discussion was primarily concerned with annual values, the monthly performance of the solar-shed greenhouse-hog barn combination is clearly seen in Figure 7.6. In this figure, the monthly average fractions of the greenhouse heat loss supplied by passive solar, active solar and waste heat recovery from the hog barn ventilation air are plotted for two locations in Canada: Halifax and Vancouver.

It is clearly indicated in Figure 7.6 that barn waste heat recovery contributes more energy to the greenhouse heating than active solar collection.

For Halifax, the contribution of the integral solar collector is very low all year around. The same conclusion applies to Vancouver perhaps with the exception of the months of November, February and March when the solar fractions are reasonable.

The low contribution of the integral solar collector in both cities during the winter months is simply due to low solar radiation availability compared to the high heating requirement of the greenhouse.

At both locations, the solar fraction of the active system is practically zero from four to five months of the

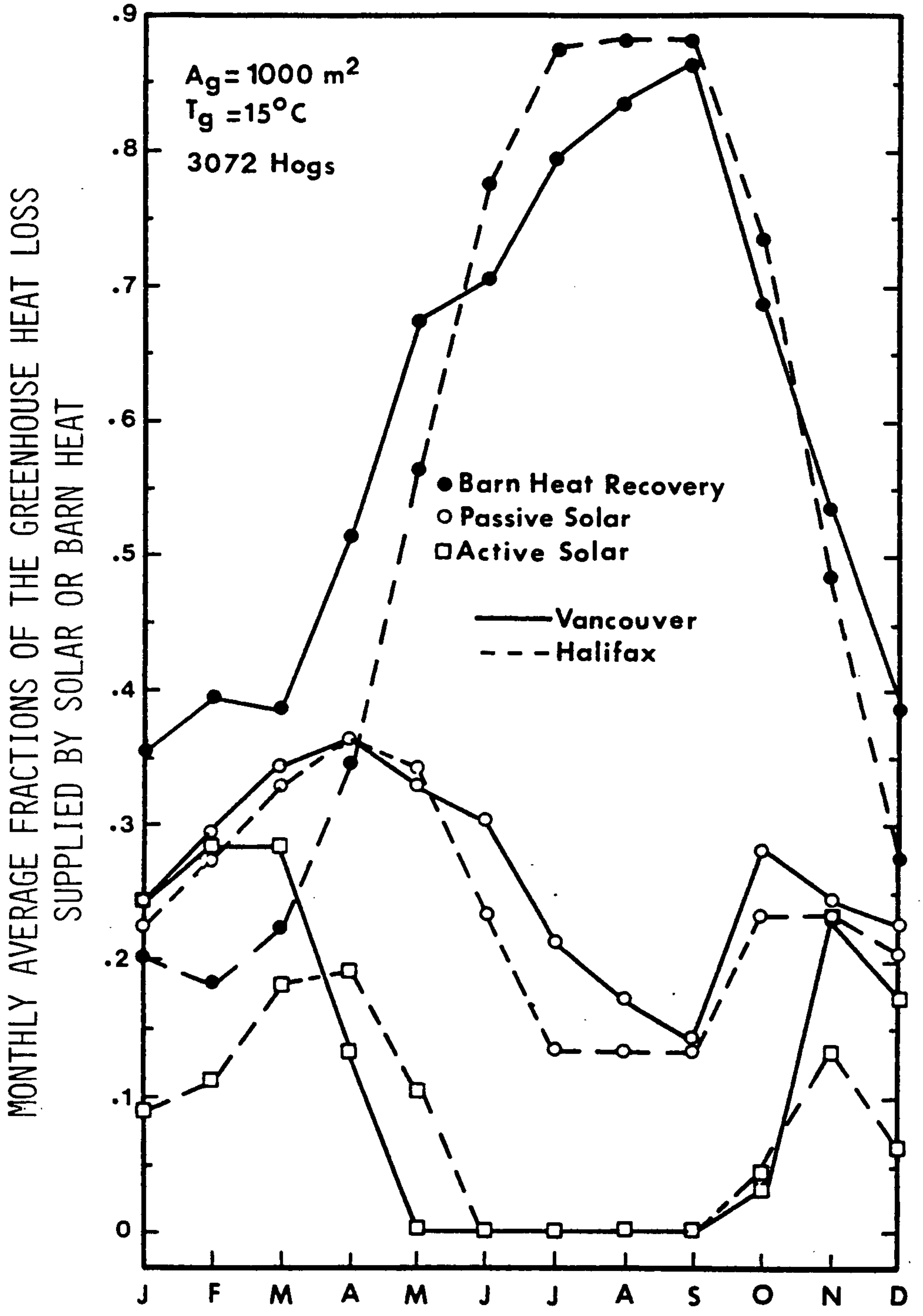


FIGURE 7.6: MONTHLY PERFORMANCE OF THE SOLAR-SHED GREENHOUSE-HOG BARN COMBINATION (CASE STUDY V).

summer season, because all the heat requirement by the greenhouse during those months is satisfied by passive solar collection and barn waste heat recovery. Therefore, it may be concluded that the economics of installing the solar heating system may not be favorable, unless part of the collectable solar energy during the summer could be utilized for other applications, for example, manure drying.

COMPARISON OF RESULTS WITH PREVIOUS CASE STUDIES

The monthly average performances of the gable greenhouse-hog barn (Case Study III), the detached solar-shed greenhouse (Case Study IV) and the attached solar-shed greenhouse-hog barn combination (Case Study V) as expressed in percent energy savings compared to the supplemental energy requirement of a conventional gable greenhouse (Case Study II) are given in Table 7.5. The values in the table apply to greenhouse located in the Halifax region.

From Table 7.5, the estimated annual realizable energy savings over a conventional gable greenhouse are: 14 percent for the free-standing solar-shed greenhouse, 50 percent for the gable greenhouse-hog barn combination and 66 percent for solar-shed greenhouse-hog barn combination.

The monthly average performances, for the case where the greenhouses are located in the Vancouver region are given in Table 7.6. As indicated in the table, the annual potential energy savings over the conventional gable greenhouse range

TABLE 7.5

COMPARISON OF MONTHLY SUPPLEMENTAL HEAT REQUIREMENT AND ENERGY SAVINGS BY THE DIFFERENT GREENHOUSE STUDIED. (ALL GREENHOUSES ARE LOCATED IN HALIFAX)

Month	Conventional Gable Glasshouse (Case Study II)	Gable Greenhouse-Swine Combination (Case Study III)		Solar-Shed Greenhouse (Case Study IV)		Solar-Shed-Swine Combination (Case Study V)	
	Q_{sup} (MJ/m^2)	Q_{sup} (MJ/m^2)	% Savings	Q_{sup} (MJ/m^2)	% Savings	Q_{sup} (MJ/m^2)	% Savings
January	494	311	37	493	<1	264	47
February	428	267	38	413	4	220	49
March	357	209	41	309	13	125	65
April	232	114	51	196	16	36	84
May	141	40	72	102	28	0	100
June	69	0	100	15	78	0	100
July	27	0	100	0	100	0	100
August	21	0	100	0	100	0	100
September	61	0	100	0	100	0	100
October	160	33	79	85	47	0	100
November	272	121	56	252	7	49	82
December	453	267	41	471	-4	233	49
Year	2718	1362	50	2336	14	927	66

TABLE 7.6

COMPARISON OF MONTHLY SUPPLEMENTAL HEAT REQUIREMENT AND ENERGY SAVINGS BY THE DIFFERENT GREENHOUSE STUDIED. (ALL GREENHOUSES ARE LOCATED IN VANCOUVER)

Month	Conventional Gable Glasshouse (Case Study II)	Solar-Shed Greenhouse (Case Study IV)		Solar-Shed-Swine Combination (Case Study V)	
	Q_{sup} (MJ/m^2)	Q_{sup} (MJ/m^2)	% Savings	Q_{sup} (MJ/m^2)	% Savings
January	350	279	20	67	81
February	259	190	27	12	95
March	253	165	35	0	100
April	165	108	35	0	100
May	100	45	55	0	100
June	53	0	100	0	100
July	33	0	100	0	100
August	26	0	100	0	100
September	67	0	100	0	100
October	166	66	60	0	100
November	256	207	19	0	100
December	348	313	10	88	75
Year	2076	1373	34	167	92

from 34 percent for the free-standing solar-shed greenhouse to as high as 92 percent for the solar-shed greenhouse hog barn combination.

The gable greenhouse-swine finishing barn combination was not analyzed for Vancouver; however, the energy savings are expected to be in the range of 50 to 55 percent.

From the results given above, it may be concluded that the performance of a solar-shed greenhouse-livestock building combination is location dependent as was the case of the free-standing solar-shed greenhouse investigated in Chapter 6. Therefore, it is important that performance and economical analyses be performed prior to the adaptation of the solar-shed-livestock building combination for a specific region.

CASE STUDY VI

DESCRIPTION AND ASSUMPTIONS

The objective of this case study is to investigate the effect of increasing the greenhouse floor area on the performance of a solar-shed-hog barn combination. In the present case, the floor area of the greenhouse is doubled by attaching a conventional gable greenhouse on the south side of the shed greenhouse as shown in Figure 7.7. All other construction and management parameters are identical to those used with respect to case study V. The operation of the solar heating and the hog barn waste heat recovery systems are also the same as for case study V. It is to be

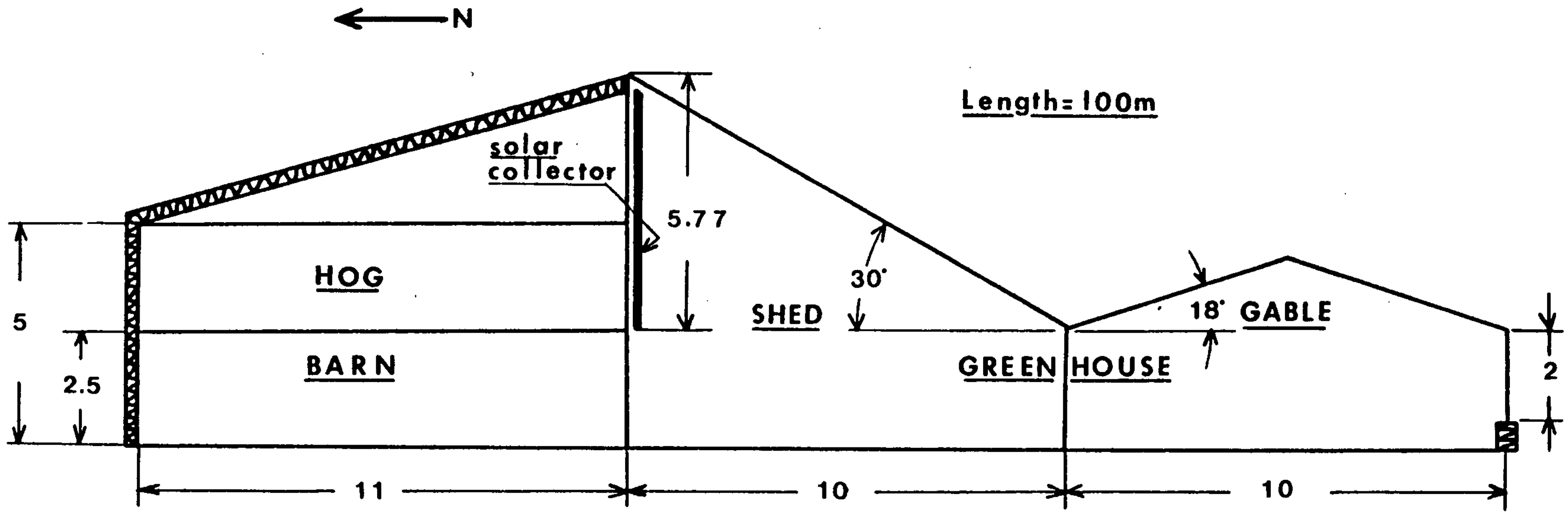


FIGURE 7.7: SCHEMATIC OF THE CROSS-SECTION OF A SOLAR-SHED GREENHOUSE-HOG BARN COMBINATION USED IN CASE STUDY VI.

noticed that the ratio of hog numbers to greenhouse floor area is halved or equal to 1.5 hogs per square metre of greenhouse floor area.

RESULTS AND DISCUSSION

The effect of doubling the floor area from 1000 m^2 (Case Study V) to 2000 m^2 (Case Study VI) may be seen in Table 7.7 for greenhouses located in the Halifax region.

The monthly and yearly heating loads shown in the table are after the passive solar contribution is accounted for (heating load = greenhouse heat loss - passive solar contribution). The percent contribution, as indicated in Table 7.7, is by the barn waste heat recovery and the active solar heating systems combined. This percentage is based upon the greenhouse heating load shown in the table.

On an annual basis, the percent contributions of the combined barn waste heat recovery and active solar collection to the greenhouse heating load are 61 percent and 40 percent for 1000 m^2 and 2000 m^2 greenhouse floor area, respectively. However, doubling the greenhouse area has increased the absolute value of the energy savings from 1438 MJ/m^2 to 1749 MJ/m^2 or about 22 percent.

The monthly average fractions of the greenhouse heating load supplied by combined barn waste heat recovery and active solar collection are shown in Figure 7.8. From this figure, it may be determined if further increase of the greenhouse

TABLE 7.7

EFFECT OF GREENHOUSE SIZE ON THE PERFORMANCE OF A SOLAR-SHED GREENHOUSE-HOG BARN COMBINATION LOCATED IN HALIFAX.

(MINIMUM GREENHOUSE TEMPERATURE 15°C, NUMBER OF HOGS: 3072)

Month	Greenhouse Floor Area					
	1000 m^2 (Case Study V)			2000 m^2 (Case Study VI)		
	Q_1 (MJ/m^2)	Q_2 (MJ/m^2)	Percent Contribution	Q_1 (MJ/m^2)	Q_2 (MJ/m^2)	Percent Contribution
January	425	161	38	791	163	21
February	367	147	40	680	149	22
March	309	184	60	571	187	33
April	203	167	82	372	171	46
May	126	126	100	227	180	79
June	64	64	100	116	116	100
July	26	26	100	46	46	100
August	21	21	100	36	36	100
September	56	56	100	97	97	100
October	141	141	100	255	251	98
November	237	188	79	433	195	45
December	390	157	40	721	158	22
Year	2365	1438	61	4345	1749	40

Notes: Q_1 = Monthly average greenhouse heating load

Q_2 = Monthly average contribution by the solar heating system and barn waste heat recovery combined

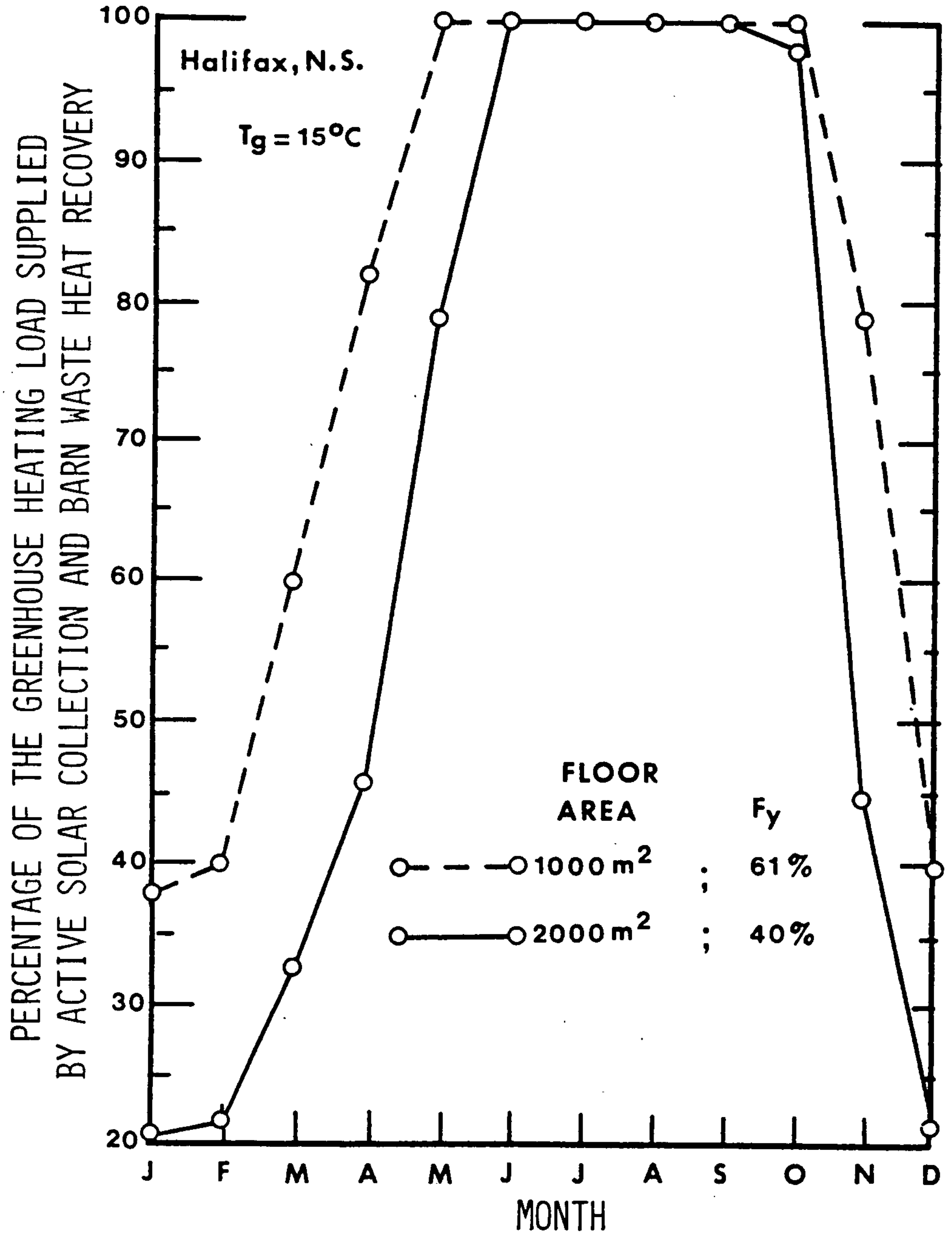


FIGURE 7.8: EFFECT OF GREENHOUSE FLOOR AREA ON THE MONTHLY AVERAGE FRACTION OF THE HEATING LOAD SUPPLIED BY ACTIVE SOLAR COLLECTION AND BARN WASTE HEAT RECOVERY FOR SOLAR-SHED GREENHOUSE-HOG BARN COMBINATION OF CASE STUDY VI.

area would result in a significant absolute savings in its supplemental heating. Firstly, it is noticed, when the area is doubled, all the solar energy collected and barn waste heat recovered are utilized for the additional two months of May and October. Therefore, excess heat is still available only for the period from June to September inclusive. But, the greenhouse supplemental heat requirement for that period is only about 6 percent of the annual requirement. Thus it may be concluded that further increase in the greenhouse floor area would result in only a small increase in energy savings per unit area.

CONCLUSIONS

From the results obtained by computer simulation analyses of the greenhouse-livestock combination of case studies V and VI, the following conclusions can be made:

1. The performance of a solar-shed greenhouse-hog barn combination is dependent on its location. This is mainly due to the dependence of the efficiency of the integral solar collector of the shed greenhouse on location.
2. For a solar-shed greenhouse-hog barn combination having a ratio of solar collector to floor area of 0.57, a hog density equivalent to about 3 hogs per square metre of greenhouse area and, a minimum greenhouse temperature of 15°C; the annual energy savings over a conventional

gable greenhouse are 92 percent and 66 percent for Vancouver and Halifax, respectively.

3. When the combined system is operated in the Halifax region, doubling the greenhouse size and keeping the number of hogs and the collector size unchanged resulted in a net increase in energy savings of about 22 percent. However, further increase in greenhouse area will result in a negligible increase in net energy savings.

SUMMARY

CONCLUSIONS

Specific conclusions related to the individual case studies for which analyses were performed during the present investigation are presented at the end of each corresponding chapter. The conclusions listed below represent the main findings related to the feasibility of the concept of greenhouse-animal shelter combination for both the retrofit and new construction cases. These general conclusions may be stated as follows:

1. The utilization of animal waste energy to heat an attached greenhouse was found to be a very attractive method of energy conservation for greenhouse heating.
2. The technical constraints associated with greenhouse-animal shelter systems are not expected to be limiting factors; but, acceptance of this new concept by the farmers may cause a delay in its implementation.
3. The use of the solar-shed greenhouse concept for active internal solar energy collection to improve the performance of a greenhouse-animal shelter combination, is highly dependent on the solar-shed greenhouse efficiency for the particular location.
4. The site specific factors affecting the performance of a solar-shed greenhouse are: latitude, bright sunshine periods during the winter season and monthly average day and night degree days for greenhouse heating.

RECOMMENDATIONS

1. The solar-shed greenhouse is not recommended for locations having low latitudes. Since, it was demonstrated that other factors than latitude also affect its performance, it is advised that a detailed theoretical analysis should be performed before its adaptation to new geographical regions.
2. The possibility of social and management problems associated with combined greenhouse animal shelter operations should be investigated.
3. Experimental work should be carried out on a prototype greenhouse-livestock building combination to
   a) demonstrate the feasibility of the combined system,
   b) calibrate and validate the mathematical model developed during the present study, and
   c) solve unforeseen practical engineering and operational problems.
4. Research and development are needed to design and test low cost systems for latent heat recovery from livestock buildings. Advances in this area should result in a significant improvement in the overall performance of greenhouse-animal shelter combinations.
5. Under favorable climatic conditions, a combined solar-shed greenhouse-animal shelter would be more efficient than a conventional combination. Thus for new constructions to be located in high latitude regions, it is recommended that a detailed study be performed to

determine the performance and the economic viability of a solar-shed greenhouse-animal shelter system.

CONTRIBUTIONS

The contributions of this thesis to the advancement in energy conservation and alternate sources of energy utilization for greenhouse heating can be summarized as follows:

1. An analytical procedure for determining the effectiveness of greenhouses as solar collectors was developed.
2. A new greenhouse design, suitable for regions of high latitudes, was proposed. Also, a general mathematical model to predict its performance, under different climatic conditions, was developed.
3. The feasibility of the concept of using animal waste heat as a supplemental energy source for greenhouse heating in cold climates was investigated for the case of greenhouse-hog barn combination. Also, a general mathematical model to predict potential energy savings from other types of combinations was developed.
4. A new concept in greenhouse-animal shelter combination design incorporationg an internal solar collection system was proposed. The case where hogs were used as animal type was analysed. Also, a general model was developed to predict the effectiveness of solar heating of greenhouse-animal shelter combinations. The model is suitable to study the effect of location, construction parameters, animal type and size of operation on the overall performance of the combined system.

REFERENCES

CITED REFERENCES

Albright, L.D., I. Seginer, R.W. Langhans and A. Donohoe. 1979. Q-mats as passive solar collectors. Proceedings of the fourth annual conference on Solar Energy for Heating Greenhouse and Greenhouse-Residence Combination. D.R. Mears, Editor. pp. 61-72.

ASHRAE Handbook of Fundamentals. 1977. Published by American Society of Heating, Refrigerating and Air-Conditioning Engineers, New York, N.Y.

Baird, C.D., W.E. Waters and D.R. Mears. 1977. Greenhouse solar heating system utilizing underbench rock storage. ASAE Paper No. 77-4012, ASAE, St. Joseph, MI 49085.

Ben Abdallah, N. 1978. An investigation of the effect of several greenhouse construction parameters on the efficiency of energy utilization. Bio-Resource Engineering Department, University of British Columbia, Vancouver, B.C.

Ben Abdallah, N. and L.M. Staley. 1978. Theoretical analyses of solar and thermal energy transfer in greenhouses. ASAE Paper No. 78-304, ASAE, St. Joseph, MI 49085.

Ben Abdallah, N. and L.M. Staley. 1979. Analysis of beam and diffuse solar radiation capture of greenhouses. ASAE Paper No. 79-4021, ASAE, St. Joseph, MI 49085.

Bliss, R.W. 1961. Atmospheric radiation near the surface of the ground. Solar energy, Vol. 5, pp. 103.

Bon, T.A., L.F. Backer, R.L. Witz. 1981. Operation and performance evaluation of two types of heat exchangers used in confinement livestock facilities. ASAE National Energy Symposium. Agricultural Energy, Vol. I. Livestock Production,pp. 202-207.

Bond, T.E., C.F. Kelly and H. Heitman. 1952. Heat and moisture loss from swine. Agricultural Engineering, Vol. 33, pp. 148-153.

Bond, T.E., C.F. Kelly and H. Heitman. 1959. Hog house air conditioning and ventilation data. Transactions of the ASAE, Vol. 2, pp. 1-4.

Bond, T.E., C.F. Kelly and H. Heitman. 1963. Effect of diurnal temperature on heat loss and well being of swine. Transactions of the ASAE, Vol. 6, pp. 132-135.

Bond, T.E., H. Heitman and C.F. Kelly. 1965. Effects of increased air velocities on heat and moisture loss and growth of swine. Transactions of the ASAE, Vol. 8, pp. 167-174.

Brody, S. 1945. Bioenergetics and Growth: with special reference to the efficiency complex in domestic animals. Reinhold, N.Y.

Brooker, D.B. 1967. Mathematical model of the psychrometric chart. Transactions of the ASAE, Vol. 10, pp. 558-560.

Brundrett, E. and A. Turkewitsch. 1979. Energy balances for solar storage greenhouses. ASAE Paper No. 79-4024.

Brundrett, E. and S. Abbot. 1981. An improved model for heat loss calculations in greenhouses. ASAE Paper No. 81-233, ASAE, St. Joseph, MI 49085.

Brunt, D. 1932. Notes on radiation in the atmosphere. Quart. J. Roy. Meteorol. Soc., Vol. 58, pp. 389-420.

Canadian Farm Building Code. 1977. Published by National Research Council of Canada, Ottawa. NRCC No. 15564.

Carson, W.M. 1972. A digital model for swine environments. Canadian Agricultural Engineering, Vol. 14, pp. 47-51.

Chandra, P., L.D. Albright and N.R. Scott. 1981. A time dependent analysis of greenhouse thermal environment. Transactions of the ASAE, Vol. 24, pp. 442-449.

Chandra, P. and M.G. Britton. 1976. Predicting the effects of orientation and insulation on greenhouse environment. ASAE Paper No. 76-4008, ASAE, St. Joseph, MI 49085.

Chandra, P. and D.H. Willits. 1980. An analysis to predict thermal behavior of a greenhouse collection/storage system. ASAE Paper No. 80-4025.

Christianson, L.L. and M.A. Hellickson. 1977. Simulation and optimization of energy requirements for livestock housing. Transactions of the ASAE, Vol. 20, pp. 327-335.

Click, L.S. and R.S. Pile. 1980. Performance of a greenhouse with an integral flat plate solar collector. ASAE Paper No. 80-4026, ASAE, St. Joseph, MI 49085.

Collares-Pereira, M. and A. Rabl. 1979. The average distribution of solar radiation correlations between diffuse and hemispherical and between daily and hourly insolation values. Solar Energy, Vol. 22, pp. 155-164.

Cooper, P.I. 1969. Digital simulation of transient solar still processes. Solar Energy, Vol. 12, pp. 313-331.

Deminet, C. 1976. Glass solar collectors for greenhouses and integrated greenhouse-residential systems. Proceedings of the Solar Energy-Fuel and Food Workshop. M.H. Jensen, Editor. Tuscon, Arizona. pp. 160-172.

Duffie, J.A. and W.A. Beckman. 1974. Solar Energy Thermal Processes. John Wiley and Sons, New York, N.Y.

Duncan, G.A., O.J. Loewer Jr. and D.G. Colliver. 1976. Simulation of solar energy availability, utilization, and storage in greenhouses. ASAE Paper No. 76-4010. ASAE, St. Joseph, MI 49085.

Feingold, A. 1966. Radiant-interchange configuration factors between various selected plane surfaces. Proceedings of the Royal Society of London. Series A. Mathematical and Physical Sciences, Vol. 292, pp. 51-60.

Froehlich, D.P. 1976. Steady-periodic analysis of the greenhouse thermal environment. Unpublished Ph.D. Thesis. Cornell University, Ithaca, N.Y.

Froehlich, D.P., L.D. Albright, N.R. Scott and P. Chandra. 1979. Steady-periodic analysis of glasshouse thermal environment. Transactions of the ASAE, Vol. 22, pp. 387-399.

Godbey, L.C., T.E. Bond and H.F. Zornig. 1977. Solar and long wavelength energy transmission of materials. ASAE Paper No. 77-4013, ASAE, St. Joseph, MI 49085.

Hamilton, D C. and W.R. Morgan. 1952. Radiant interchange configuration factors. NACA. TN 2836.

Hay, J.E. 1976. A revised method for determining the direct and diffuse components of the total short-wave radiation. Atmosphere, Vol. 14, pp. 278-287.

Hare, K. and J.E. Hay. 1974. Summary of Climate of Canada and Alaska, in "World Survey of Climatology, Vol. II. Elsevier Scientific Publication Co.

Hazen, T.E. and D.W. Mangold. 1960. Functional and basic requirements of swine housing. Agricultural Engineering, Vol. 41, pp. 585-590.

Hittle, D.C. 1979. The Building Loads Analysis System Thermodynamics (BLAST) Program. Version 2.0: Users Manual. Volume I. U.S. Army Construction Engineering Research Laboratory. Report NO. AD-A072-272.

Holman, J.P. 1976. Heat Transfer. McGraw-Hill, Inc.

Howe, T.K. and S.S. Woltz. 1982. Sensitivity of tomato cultivators to sulfur dioxide. HortScience, Vol. 17, pp. 249-250.

Husseini, I. T.H. Short and P.C. Badger. 1979. Radiation on a solar pond with greenhouse covers and reflectors. Transactions of the ASAE, Vol. 22, pp. 1385-1388.

Iqbal, M. 1978. Estimation of the monthly average of the diffuse component of total insolation on a horizontal surface. Solar Energy, Vol. 20, pp. 101-105.

Iqbal, M. 1979. A study of Canadian diffuse and total solar radiation data I. Monthly average daily horizontal radiation. Solar Energy, Vol. 22, pp. 81-86.

Iqbal, M. and A.K. Khatry. 1977. Wind-induced heat transfer coefficients from greenhouses. Transactions of the ASAE, Vol. 20, pp. 157-160.

Kelly, C.F., T.E. Bond and C. Lorenzen. 1948. Effect of environment on heat loss from swine. Agricultural Engineering, Vol. 29, pp. 525-529.

Kindelán, M. 1980. Dynamic modeling of greenhouse environment. Transactions of the ASAE, Vol. 23, pp. 1232-1239.

Klein, S.A. 1977. Calculation of monthly average insolation on tilted surfaces. Solar Energy, Vol. 19, pp. 325-329.

Klein, S.A., W.A. Beckman and J.A. Duffie. 1976. A design procedure for solar heating systems. Solar Energy, Vol. 18, pp. 113-127.

Lawand, T.A., R. Alward, J. Maghsood and M.A.S. Malik. 1973. Le rôle de l'énergie solaire dans le chauffage de serres au Québec. Proceedings of the International Congress "The Sun in the Service of Mankind" Paris, / Palais de l"UNESCO. pp. 312-321.

Lawand, T.A., R. Alward, B. Saulnier and E. Brunet. 1975. The development and testing of an environmentally designed greenhouse for colder regions. Solar Energy, Vol. 17, pp. 307-312.

Liu, B.Y.H. and R.C. Jordan. 1960. The interrelationship and characteristic distribution of direct, diffuse and total solar radiation. Solar Energy, Vol. 4, pp. 1-19.

Liu, B.Y.H. and R.C. Jordan. 1962. Daily insolation on surfaces tilted toward the equator. Transactions of the ASHRAE, Vol. 67, pp. 526-541.

Liu, R.C. and G.E. Carlson. 1976. Proposed solar greenhouse design. Proceedings of the Solar Energy-Fuel and Food Workshop. M.H. Jensen, Editor. pp. 129-141.

Longhouse, A.D., H. Ota and A. Wallace. 1960. Heat and moisture design data for poultry housing. Agricultural Engineering, Vol. 41, pp. 567-576.

McAdam, D.W., A.K. Khatry and M. Iqbal. 1971. Configuration factors for greenhouses. Trans. of the ASAE, Vol. 14, pp. 1068-1072.

McAdams, W.C. 1954. Heat Transmission. 3rd Edition. McGraw-Hill, New York, N.Y.

McCormick, P.O. 1976. Performance of non-integral solar collector greenhouses. Proceeding of the Solar Energy-Fuel and Food Workshop. M.N. Jensen, Ed. pp. 51-60.

McQuitty, J.B. and J.J.R. Feddes. 1982. Manure gases and the animal environment. Presented at the 1982 annual meeting of the CSAE, Univ. of British Columbia, Vancouver, B.C.

Mears, D.R. and C.D. Baird. 1976. Development of a low-cost solar heating system for greenhouses. Proceedings of the Solar Energy-Fuel and Food Workshop. pp. 88-109.

Mears, D.R., W.J. Roberts and P.W. Kendall. 1978. Development of a greenhouse solar heating demonstration. ASAE Paper No. 78-4512, ASAE, St. Joseph, MI 49085.

Mears, D.R., W.J. Roberts, P.W. Kendall and J.P. Cipolletti. 1979. Performance of the Kube Pak solar heated greenhouse. Proceedings of the 4th annual converence on Solar Energy for Heating Greenhouses and Greenhouse-Residence combinations. D.R. Mears, Editor. pp. 185-194.

Mears, D.R., W.J. Roberts, J.C. Simpkins and P.W. Kendall. 1977. The Rutgers solar heating system for greenhouses. ASAE Paper No. 77-4009, ASAE, St. Joseph, MI 49085.

Midwest Plan Service. 1980. Structures and Environment handbook. MWPS-1. Iowa State University, Ames, Iowa.

Milburn, W.F., and R.A. Aldrich. 1979. Optimization of excess internal heat collection and thermal storage in greenhouses. ASAE Paper No. 79-4026.

Milburn, W.F., R.A. Aldrich and J.W. White. 1977. Internal/external solar collectors for greenhouse heating. ASAE Paper No. 77-4008, ASAE, St. Joseph, MI 49085.

Morse, R.H. and W.R. Read. 1968. A rational basis for the engineering development of a solar still. Solar Energy, Vol. 12, pp. 5-12.

O'Callaghan, P.W. 1978. Building for Energy Conservation. Pergamon Press.

Ormrod, D.P. and T.J. Blom. 1978. Air pollution problems in greenhouses. Ontario Ministry of Agriculture and Food Report No. 78-009.

Ota, H., H.L. Garver and A. Wallace. 1953. Heat and moisture production of laying hens. Agricultural Engineering, Vol. 34, pp. 163-167.

Page, J.K. 1961. The estimation of monthly mean values of daily total short-wave radiation on vertical and inclined surfaces from sunshine records for latitudes 40°N - 40°S. Proceedings of U.N. Conference on New Sources of Energy. Paper No. 35/5/98.

Price, D.R., G.E. Wilson, D.P. Froehlich and R.W. Crump. 1976. Solar heating of greenhouses in the Northwest. Proceedings of the Solar Energy-Fuel and Food Workshop. M.H. Jensen, Editor. Environmental Research Laboratory. The University of Arizona, Tuscon. pp. 173-190.

Restropo. G., M.D. Shanklin and L. Hahn. 1977. Heat dissipation from growing pigs as a function of floor and ambient temperature. Transactions of the ASAE, Vol. 20, pp. 145-147.

Riskowski, G.L., J.A. DeShaza and F.B. Mather. 1977. Heat losses of white leghorn laying hens as affected by intermittent lighting schedules. Transactions of the ASAE, Vol. 20, pp. 727-731.

Roberts, W.J., J.C. Simpkins and P.W. Kendall. 1976. Using solar energy to heat plastic film greenhouses. Proceedings of the Solar Energy-Fuel and Food Workshop. M.H. Jensen, Editor. pp. 142-159.

Rotz, C.A. and R.A. Aldrich. 1978. Thermal insulation and solar heat for commercial greenhouses across the United States. ASAE Paper No. 78-4515.

Ruth, D.W. and R.E. Chant. 1976. The relationship of diffuse radiation to total radiation in Canada. Solar Energy, Vol. 18, pp. 153-154.

Selcuk, M.K. 1970. Use of digital computers for the heat and mass transfer analyses of controlled environment greenhouses. Environmental Research Laboratory. The University of Arizona, Tucson, Arizona.

Shah, S.A., T.H. Short and R.P. Fynn. 1981. A solar pond-assisted heat pump for greenhouses. Solar Energy, Vol. 26, pp. 491-496.

Short, T.H., W.L. Roller and P.C. Badger. 1976. A solar pond for heating greenhouses and rural residences - a preliminary report. Proceedings of the Solar Energy-Fuel and Food Workshop. M.H. Jensen, Editor. Environmental Research Laboratory. The University of Arizona, Tucson. pp. 41-50.

Simpkins, J.C., D.R. Mears and W.J. Roberts. 1979. Performance of the Rutgers solar heated greenhouse research units. Proceedings of the 4th annual conference on Solar Energy for Heating Greenhouses and Greenhouse-Residence Combinations. pp. 118-127.

Sokhansanj, S., K.A. Jordan and E.P. Moysey. 1981. Application of heat exchangers to livestock buildings. ASAE National Energy Symposium. Agricultural Energy, Vol. I. Livestock Production, pp. 253-256.

Spillman, C.K., J.K. Greig, G.A. Johnson, J.R. Hartford, B.A. Koch and R.H. Hines. 1980. Solar energy utilization in a greenhouse/animal shelter combination. ASAE National Energy Symposium. Agricultural Energy, Vol II. Crop Production. pp. 573-577.

Staley, L.M., J.M. Molnar and G.J. Monk. 1981. Design, construction and operating experience with two commercial solar heated greenhouses. CSAE. Paper No. 81-232.

Stauffer, L.A. and D.H. Vaughan. 1981. Ventilation heat recovery with a heat pipe heat exchanger. ASAE National Energy Symposium. Agricultural Energy, Vol. I. Livestock Production. pp. 247-252.

Swinbank, W.C. 1963. Long-wave radiation from clear skies. Quart. J. Roy. Meteorol. Soc., Vol. 89, p. 339.

Takakura, T., K.A. Jordan and L.L. Boyd. 1971. Dynamic simulation of plant growth and environment in the greenhouse. Transactions of the ASAE, Vol. 14, pp. 964-971.

Thornton, N.C. and C. Setterstrom. 1940. Toxicity of ammonia, chlorine, hydrogen cyanide, hydrogen sulphide, and sulphur dioxide gases. III. Green plants. Contribution to Boyce Thompson Inst. for Plant Research, Inc. Vol. 11, pp. 343-356.

Threlkeld, J.L. 1970. Thermal Environmental Engineering. Prentice-Hall, Inc., New Jersey.

Tuller, S.E. 1976. The relationship between diffuse, total and extraterrestrial solar radiation. Solar Energy, Vol. 18, pp. 259-263.

Turkewitsch, A. and E. Brundrett. 1979. Light levels in insulated greenhouses. ASAE Paper No. 79-4023.

Turnbull, J.E. and N.A. Bird. 1979. Confinement Swine Housing. Agriculture Canada. Publication 1451.

U.S. Environmental Protection Agency. 1978. Diagnosing Vegetation Injury Caused by Air Pollution by Applied Science Associates, Inc., Valencia, PA. Report No. EPA-450/3-78-005.

van Bavel, C.H.M. 1978. Projecting crop growth in a fluid-roof solar greenhouse. Acta horticulturae, Vol. 87, pp. 301-310.

van Bavel, C.H.M. and J. Damagnex. 1978. A simulation model for energy storage and savings of a fluid-roof solar greenhouse. Acta Horticulturae, Vol. 76, pp. 229-235.

van Bavel, C.H.M. and C.J. Sadler. 1979. Experimental tests of a fluid-roof greenhouse concept. Proceedings of the 4th annual conference on Solar Energy for Heating Greenhouses and Greenhouse-Residence Combinations. pp. 128-136.

van Bavel, C.H.M., E.J. Sadler and G.C. Heathman. 1980. Infra-red filters as greenhouse covers: Preliminary test of a model for evaluating their potential. ASAE National Energy Symposium. Agricultural Energy, Vol. II. Crop Production. pp. 552-557.

van Dalfsen, K.B. and N.R. Bulley. 1982. Ammonia and hydrogen sulfide concentrations in buildings with subfloor manure storage. CSAE, Paper No. 82-206.

Walker, J.N. 1965. Predicting temperatures in ventilated greenhouses. Transactions of the ASAE, Vol. 8, pp. 445-448.

Walker, J.N. and L.R. Walton. 1971. Effect of condensation on greenhouse heat requirement. Trnasactions of ASAE. Vol. 14, pp. 282-284.

Whillier, A. 1967. Design factors influencing solar collectors. In Low Temperature Engineering Applications of Solar Energy. ASHRAE, New York, N.Y.

Wiegand, J.B. 1976. Greenhouse solar heating: techniques and economics. Proceedings of the Solar Energy-Fuel and Food Workshop. M.H. Jensen, Editor. Tuscon, Arizona, pp. 28-40.

Wilhelm, L.R. 1976. Numerical calculations of psychrometric properties in S.I. units. Trans. of ASAE, Vol. 19, pp. 318-321, 325.

Willits, D.H., P. Chandra and C.H. Miller. 1979. Performance of a collection/storage system for greenhouses. Proceedings of the 4th annual conference on Solar Energy for Heating Greenhouses-Residence Combinations, pp. 73-82.

Willits, D.H. and M.M. Peet. 1981. CO_2 enrichment in a solar solar energy collection/storage greenhouse. ASAE Paper No. 81-4525, ASAE, St. Joseph, MI 49085.

Wilson, G.E., D.R. Price and R.W. Langhans. 1977. Increasing the effectiveness of the greenhouse as a solar collector. ASAE Paper No. 77-4527, ASAE, St. Joseph, MI 49085.

APPENDICES

APPENDIX A

CALCULATION OF BEAM TRANSMITTANCE

OF GREENHOUSE COVERS

TRANSMITTANCE OF GREENHOUSE COVERS

This appendix describes the procedure used to calculate the beam transmittance of greenhouse covers to solar radiation as given by Duffie and Beckman (1974).

TRANSMISSION DUE TO REFLECTION

a) Beam radiation, normal incidence:

At normal incidence there is no polarization effect, and the surface reflectivity, ρ, is dependent only on the refractive index, n as follows:

$$\rho = [(n - 1)/(n + 1)]^2 \quad . \tag{A.1}$$

For a system of N covers, all of the same material, then, it can be shown that the transmittance is,

$$\tau_r = (1 - \rho)/[1 + (2N - 1)\rho] \quad , \tag{A.2}$$

provided the radiation absorption in the covers is neglected.

b) Beam radiation, oblique incidence:

Polarization phenomena necessitate treating the reflection of radiation at air-cover interfaces separately for the two planes of polarization. The fractions of the polarized portions of an incident beam that are reflected at an interface are:

i) in the plane perpendicular to the plane of incidence,

$$\rho_1 = [\sin(i - i')/\sin(i + i')]^2 \quad , \tag{A.3}$$

and

ii) in the plane parallel to the plane of incidence,

$$\rho_2 = [\tan(i - i')/\tan(i + i')]^2 \quad . \tag{A.4}$$

Then, the transmission of the cover system, neglecting radiation absorption may be calculated as,

$$\tau_r = \frac{1}{2}\left[\frac{1 - \rho_1}{1 + (2N - 1)\rho_1} + \frac{1 - \rho_2}{1 + (2N - 1)\rho_2}\right] \quad . \tag{A.5}$$

The angle of incidence (i) and the angle of refraction (i') are related by the refractive index n through Snell's law:

$$n = \sin i/\sin i' \quad . \tag{A.6}$$

TRANSMISSION DUE TO ABSORPTION

The transmission due to absorption of N covers, all of the same material, is related to the extinction coefficient and thickness of the partially transparent medium by,

$$\tau_a = e^{-NKL} \quad . \tag{A.7}$$

where $L = t/\cos i'$. (A.8)

BEAM TRANSMITTANCE

The beam transmittance, allowing for both reflection and absorption, is obtained simply by multiplying the two transmittances together.

$$\tau = \tau_r \, \tau_a \quad . \tag{A.9}$$

Equation (A.9) is an approximate expression but sufficiently accurate for practical applications.

NOMENCLATURE

Symbol	Definition	Units
i	Angle of incidence	radians
i'	Angle of refraction	radians
K	Extinction coefficient	cm^{-1}
L	Length of the path of radiation within the partially transparent medium	cm
N	Number of covers	
n	Index of refraction	
t	Thickness of the cover	cm
ρ	Surface reflectivity	
ρ_1	Reflectivity in the plane perpendicular to the plane of incidence	
ρ_2	Reflectivity in the plane parallel to the plane of incidence	
τ_r	Transmissivity of the cover neglecting absorption by the material	
τ_a	Transmissivity of the cover due to absorption	
τ	Beam transmittance of the cover allowing for both reflection and absorption	

APPENDIX B

SAMPLE COMPUTER
OUTPUT
FOR GREENHOUSE TRANSMISSION FACTORS

.05 HECTARE

SINGLE GLASS COVER

GABLE GREENHOUSE

E-W ORIENTATION

LENGTH=50 M
WIDTH = 10M
HEIGHT=2 M
SLOPE =18DEG

GLASS CHARACTERISTICS:

THICKNESS=0.30 CM

K = 0.161 CM-1 ; IR=1.526

S1 = SOUTH WALL
S2= SOUTH ROOF
S3 = NORTH ROOF
S4 = WEST WALL
S5 = EAST WALL
S6 = NORTH WALL

Vancouver, B.C.

BTF: Beam Transmission Factor

DTF: Diffuse Transmission Factor

TTF: Total Transmission Factor

JANUARY

S	AREA M**2	SOLAR ENERGY TRANSMITTED (KJ/DAY) BEAM	DIFFUSE	TOTAL	CONTRIBUTION TO TOTAL BEAM	DIF.	TOTAL
1	100.	274169.	99422.	373592.	0.383	0.094	0.210
2	263.	418871.	402621.	821493.	0.585	0.380	0.463
3	263.	847.	402621.	403468.	0.001	0.380	0.227
4	28.	11018.	27838.	38856.	0.015	0.026	0.022
5	28.	11018.	27838.	38856.	0.015	0.026	0.022
6	100.	0.	99422.	99422.	0.0	0.094	0.056

TOTAL TRANSMITTED

BEAM	DIFFUSE	TOTAL	TBGH	TTGH	BTF	DTF	TTF
715924.	1059763.	1775685.	0.819	0.812	1.374	1.099	1.196

FEBRUARY

S	AREA M**2	SOLAR ENERGY TRANSMITTED (KJ/DAY) BEAM	DIFFUSE	TOTAL	CONTRIBUTION TO TOTAL BEAM	DIF.	TOTAL
1	100.	400279.	171649.	571928.	0.308	0.094	0.183
2	263.	782351.	689995.	1472346.	0.602	0.379	0.472
3	263.	65822.	689995.	755817.	0.051	0.379	0.242
4	28.	25584.	48039.	73623.	0.020	0.026	0.024
5	28.	25584.	48039.	73623.	0.020	0.026	0.024
6	100.	0.	171568.	171568.	0.0	0.094	0.055

TOTAL TRANSMITTED

BEAM	DIFFUSE	TOTAL	TBGH	TTGH	BTF	DTF	TTF
1299617.	1819285.	3118901.	0.782	0.796	1.145	1.105	1.121

MARCH

S	AREA M**2	SOLAR ENERGY TRANSMITTED (KJ/DAY) BEAM	DIFFUSE	TOTAL	CONTRIBUTION TO TOTAL BEAM	DIF.	TOTAL
1	100.	558113.	263889.	822001.	0.209	0.092	0.148
2	263.	1542392.	1100893.	2643285.	0.576	0.383	0.476
3	263.	457117.	1100893.	1558009.	0.171	0.383	0.281
4	28.	59561.	73889.	133450.	0.022	0.026	0.024
5	28.	59561.	73889.	133450.	0.022	0.026	0.024
6	100.	0.	263889.	263889.	0.0	0.092	0.048

TOTAL TRANSMITTED BEAM	DIFFUSE	TOTAL	TBGH	TTGH	BTF	DTF	TTF
2676742.	2877338.	5554083.	0.786	0.796	1.024	1.091	1.058

APRIL

S	AREA M**2	SOLAR ENERGY TRANSMITTED (KJ/DAY) BEAM	DIFFUSE	TOTAL	CONTRIBUTION TO TOTAL BEAM	DIF.	TOTAL
1	100.	442915.	381550.	824465.	0.118	0.094	0.106
2	263.	2023381.	1530681.	3554062.	0.539	0.379	0.456
3	263.	1114467.	1530681.	2645148.	0.297	0.379	0.339
4	28.	86594.	106834.	193428.	0.023	0.026	0.025
5	28.	86594.	106834.	193428.	0.023	0.026	0.025
6	100.	25.	381550.	381575.	0.000	0.094	0.049

TOTAL TRANSMITTED BEAM	DIFFUSE	TOTAL	TBGH	TTGH	BTF	DTF	TTF
3753973.	4038126.	7792102.	0.804	0.805	0.956	1.101	1.026

MAY

S	AREA M**2	SOLAR ENERGY TRANSMITTED (KJ/DAY) BEAM	DIFFUSE	TOTAL	CONTRIBUTION TO TOTAL BEAM	DIF.	TOTAL
1	100.	347001.	470804.	817804.	0.064	0.096	0.079
2	263.	2717831.	1839917.	4557748.	0.502	0.377	0.443
3	263.	2041721.	1839917.	3881638.	0.377	0.377	0.377
4	28.	131691.	131825.	263516.	0.024	0.027	0.026
5	28.	131691.	131825.	263516.	0.024	0.027	0.026
6	100.	40054.	470804.	510857.	0.007	0.096	0.050

TOTAL TRANSMITTED BEAM	DIFFUSE	TOTAL	TBGH	TTGH	BTF	DTF	TTF
5409985.	4885088.	10295077.	0.810	0.809	0.927	1.106	1.004

JUNE

S	AREA M**2	SOLAR ENERGY TRANSMITTED (KJ/DAY) BEAM	DIFFUSE	TOTAL	CONTRIBUTION TO TOTAL BEAM	DIF.	TOTAL
1	100.	278890.	509943.	788833.	0.045	0.097	0.069
2	263.	2979913.	1974053.	4953966.	0.481	0.376	0.433
3	263.	2529264.	1974053.	4503317.	0.408	0.376	0.393
4	28.	152272.	142784.	295056.	0.025	0.027	0.026
5	28.	152272.	142784.	295056.	0.025	0.027	0.026
6	100.	100168.	509943.	610111.	0.016	0.097	0.053

TOTAL TRANSMITTED BEAM	DIFFUSE	TOTAL	TBGH	TTGH	BTF	DTF	TTF
6192778.	5253558.	11446338.	0.814	0.811	0.924	1.113	1.002

JULY

S	AREA M**2	SOLAR ENERGY TRANSMITTED (KJ/DAY) BEAM	DIFFUSE	TOTAL	CONTRIBUTION TO TOTAL BEAM	DIF.	TOTAL
1	100.	348908.	489930.	838838.	0.053	0.098	0.072
2	263.	3233063.	1862202.	5095265.	0.489	0.374	0.439
3	263.	2613476.	1862202.	4475678.	0.395	0.374	0.386
4	28.	165209.	137180.	302389.	0.025	0.028	0.026
5	28.	165209.	137180.	302389.	0.025	0.028	0.026
6	100.	89404.	489930.	579334.	0.014	0.098	0.050

TOTAL TRANSMITTED BEAM	DIFFUSE	TOTAL	TBGH	TTGH	BTF	DTF	TTF
6615268.	4978622.	11593892.	0.811	0.809	0.927	1.118	1.000

AUGUST

S	AREA M**2	SOLAR ENERGY TRANSMITTED (KJ/DAY) BEAM	DIFFUSE	TOTAL	CONTRIBUTION TO TOTAL BEAM	DIF.	TOTAL
1	100.	492917.	421496.	914412.	0.092	0.097	0.094
2	263.	2793090.	1624704.	4417794.	0.522	0.375	0.456
3	263.	1786255.	1624704.	3410959.	0.334	0.375	0.352
4	28.	132019.	118019.	250038.	0.025	0.027	0.026
5	28.	132019.	118019.	250038.	0.025	0.027	0.026
6	100.	13492.	421496.	434987.	0.003	0.097	0.045

TOTAL TRANSMITTED BEAM	DIFFUSE	TOTAL	TBGH	TTGH	BTF	DTF	TTF
5349790.	4328434.	9678226.	0.805	0.806	0.942	1.115	1.012

SEPTEMBER

S	AREA M**2	SOLAR ENERGY TRANSMITTED (KJ/DAY) BEAM	DIFFUSE	TOTAL	CONTRIBUTION TO TOTAL BEAM	DIF.	TOTAL
1	100.	647908.	318523.	966431.	0.169	0.096	0.135
2	263.	2145094.	1249462.	3394556.	0.560	0.377	0.475
3	263.	851410.	1249462.	2100871.	0.222	0.377	0.294
4	28.	91945.	89186.	181131.	0.024	0.027	0.025
5	28.	91945.	89186.	181131.	0.024	0.027	0.025
6	100.	0.	318523.	318523.	0.0	0.096	0.045

TOTAL TRANSMITTED BEAM	DIFFUSE	TOTAL	TBGH	TTGH	BTF	DTF	TTF
3828298.	3314340.	7142641.	0.790	0.798	0.994	1.109	1.044

OCTOBER

S	AREA M**2	SOLAR ENERGY TRANSMITTED (KJ/DAY) BEAM	DIFFUSE	TOTAL	CONTRIBUTION TO TOTAL BEAM	DIF.	TOTAL
1	100.	501457.	200217.	701674.	0.275	0.093	0.176
2	263.	1085316.	822434.	1907749.	0.596	0.381	0.479
3	263.	157524.	822434.	979958.	0.086	0.381	0.246
4	28.	38496.	56061.	94556.	0.021	0.026	0.024
5	28.	38496.	56061.	94556.	0.021	0.026	0.024
6	100.	0.	200217.	200217.	0.0	0.093	0.050

TOTAL TRANSMITTED BEAM	DIFFUSE	TOTAL	TBGH	TTGH	BTF	DTF	TTF
1821286.	2157420.	3978708.	0.779	0.794	1.091	1.095	1.093

NOVEMBER

S	AREA M**2	SOLAR ENERGY TRANSMITTED (KJ/DAY) BEAM	DIFFUSE	TOTAL	CONTRIBUTION TO TOTAL BEAM	DIF.	TOTAL
1	100.	348100.	114997.	463098.	0.366	0.092	0.211
2	263.	562058.	476905.	1038964.	0.591	0.382	0.473
3	263.	6495.	476905.	483400.	0.007	0.382	0.220
4	28.	16803.	32199.	49002.	0.018	0.026	0.022
5	28.	16803.	32199.	49002.	0.018	0.026	0.022
6	100.	0.	114997.	114997.	0.0	0.092	0.052

TOTAL TRANSMITTED BEAM	DIFFUSE	TOTAL	TBGH	TTGH	BTF	DTF	TTF
950259.	1248203.	2198460.	0.805	0.806	1.303	1.082	1.158

DECEMBER

S	AREA M**2	SOLAR ENERGY TRANSMITTED (KJ/DAY) BEAM	DIFFUSE	TOTAL	CONTRIBUTION TO TOTAL BEAM	DIF.	TOTAL
1	100.	242904.	82072.	324976.	0.402	0.094	0.219
2	263.	342971.	333855.	676826.	0.568	0.380	0.457
3	263.	0.	333855.	333855.	0.0	0.380	0.225
4	28.	8962.	22958.	31919.	0.015	0.026	0.022
5	28.	8962.	22958.	31919.	0.015	0.026	0.022
6	100.	0.	81910.	81910.	0.0	0.093	0.055

TOTAL TRANSMITTED BEAM	DIFFUSE	TOTAL	TBGH	TTGH	BTF	DTF	TTF
603799.	877607.	1481404.	0.824	0.814	1.519	1.104	1.242

APPENDIX C

ESTIMATION OF HOURLY DIRECT, DIFFUSE AND TOTAL SOLAR RADIATION ON TILTED SURFACES OF ANY ORIENTATION

ESTIMATION OF MONTHLY AVERAGE HOURLY DIFFUSE AND TOTAL INSOLATION ON A HORIZONTAL SURFACE FROM MONTHLY AVERAGE DAILY DIFFUSE AND TOTAL INSOLATION

For locations where both monthly average daily diffuse and total insolation on a horizontal surface are measured, the monthly average hourly diffuse and total insolation on a horizontal surface may be estimated using the Liu and Jordan method (1960).

For the monthly average hourly diffuse solar radiation on a horizontal surface, we have

$$\bar{I}_d = \bar{H}_d \, \bar{r}_d \quad , \tag{C.1}$$

where

$$\bar{r}_d = (\pi/24) \, [(\cos \omega - \cos \omega_s)/(\sin \omega_s - \omega_s \cos \omega_s)] \ . \tag{C.2}$$

Similarly, for the monthly average hourly total solar radiation incident on a horizontal surface, we have

$$\bar{I} = \bar{H} \, \bar{r} \, . \tag{C.3}$$

The correlation of $\bar{r}$ with ω and ω_s is given by Collares-Pereira and Rabl (1979) as

$$\bar{r} = (\pi/24)(a + b \cos\omega)[(\cos\omega - \cos\omega_s)/(\sin\omega_s - \omega_s\cos\omega_s)], \tag{C.4}$$

where

$$a = 0.409 + 0.5016 \sin(\omega_s - 1.047) \text{ and}$$
$$b = 0.6609 - 0.4767 \sin(\omega_s - 1.047), \tag{C.5}$$

where ω_s is calculated using the following relation:

$$\omega_s = \arcos\ (-\tan \phi \tan \delta)\ . \qquad (C.6)$$

For locations where only the monthly average daily total insolation on a horizontal surface is known, then correlation equations must be used to separate the monthly average daily total solar radiation into its two components. Many semi-empirical equations have been proposed for such a purpose, for example, Liu and Jordan (1962), Page (1961), Tuller (1976) and Iqbal (1979).

LIU AND JORDAN'S CORRELATION

A least square fit to the data in Figure 8 of Liu and Jordan (1962) yields the following relationship between the ratio $\bar{H}_d/\bar{H}$ and $\bar{K}_T$, as given by Klein et al (1976):

$$\frac{\bar{H}_d}{\bar{H}} = 1.3903 - 4.0273\ \bar{K}_T + 5.5315\ \bar{K}_T^2 - 3.108\ \bar{K}_T^3\ . \qquad (C.7)$$

$\bar{K}_T$ in the above equation represents the ratio of the monthly average daily total insolation on a horizontal surface to the mean daily extraterrestrial solar radiation, $\bar{H}_0$, for the calendar month under consideration, therefore

$$\bar{K}_T = \bar{H}/\bar{H}_0 \quad . \qquad (C.8)$$

The mean daily extraterrestrial radiation on a horizontal surface may be calculated using

$$\bar{H}_0 = \frac{1}{(n_2-n_1)} \int_{n_1}^{n_2} H_0 \, dn \;, \qquad \text{(C.9)}$$

where n_1 and n_2 are the days of the year at the start and end of each calendar month, respectively, and H_0 is the daily extraterrestrial radiation on a horizontal surface for day n.

The daily solar radiation incident on a horizontal surface outside the atmosphere for any location may be calculated using the following equation as given by Duffie and Beckman (1974):

$$H_0 = \frac{24}{\pi} I_{sc} \; E \; (\cos \phi \cos \delta \sin \omega_s + \omega_s \sin \phi \sin \delta) \qquad \text{(C.10)}$$

where the solar constant I_{sc} = 4871 kJ/m^{2}h.

The eccentricity correction factor for the solar constant is calculated using:

$$E = 1 + 0.033 \cos (2\pi n/365) \qquad \text{(C.11)}$$

where the argument of the cosine is measured in radians.

The declination angle for any day n of the year may be calculated using the following relationship:

$$\delta = 23.45 \sin \{2\pi \; [(284+n)/365]\} \qquad \text{(C.12)}$$

where the argument of the sine is measured in radians. The mean daily extraterrestrial solar radiation on a horizontal surface can be calculated more conveniently from equation (C.10) above, by selecting for each month, the day of the year for which the daily extraterrestrial solar radiation is nearly the same as the monthly mean value. Recommended days for each month are given in Table C.1.

PAGE'S CORRELATION

The relationship reported by Page (1961) can be expressed as:

$$\frac{\bar{H}_d}{\bar{H}} = 1.00 - 1.13\ \bar{K}_T \quad . \qquad (C.13)$$

The above relationship is derived from experimental measurements at a limited number of ten stations.

For a comparison of the relationships reported by Liu and Jordan, and Page and for a detailed discussion on the accuracy of the two methods, the reader is referred to the publication by Klein (1977).

TULLER'S CORRELATION

Tuller (1976) developed the following linear regression equation:

$$\frac{\bar{H}_d}{\bar{H}} = 0.84 - 0.62\ \bar{K}_T \quad . \qquad (C.14)$$

The above equation is based on monthly average daily total and diffuse solar radiation data for the following four Canadian locations: Toronto, Montreal, Goose Bay and Resolute.

IQBAL'S CORRELATION

Ruth and Chant (1976), Hay (1976) and Tuller (1976) have found that data for Resolute gave anamalous results. Iqbal (1979) excluded the Resolute data from the regression analysis and obtained the following linear equation:

$$\frac{\bar{H}_d}{\bar{H}} = 0.914 - 0.847\ \bar{K}_T \quad . \tag{C.15}$$

when only Montreal and Toronto data are included in the linear regression analysis, Iqbal (1979) obtained the following relationship:

$$\frac{\bar{H}_d}{\bar{H}} = 0.958 - 0.982\ \bar{K}_T \quad . \tag{C.16}$$

Iqbal (1979) also performed a comparative study of all the correlations of the diffuse to the total radiation which are briefly discussed here. The reader is referred to the original publication by Iqbal for the detailed results and a more comprehensive discussion.

ESTIMATION OF MONTHLY AVERAGE HOURLY DIFFUSE AND TOTAL SOLAR RADIATION INCIDENT OF A TILTED SURFACE OF ANY ORIENTATION

If the sky diffuse radiation is assumed isotropic, then the total diffuse radiation and the ground reflected radiation incident on a tilted surface is independent of its azimuth angle and can simply be written as:

$$\bar{I}_{d\beta\gamma} = \bar{I}_d \frac{1 + \cos\beta}{2} + \rho\bar{I} \frac{1 - \cos\beta}{2} \quad . \qquad (C.17)$$

The two terms on the right hand side of equation (C.17) represent the sky diffuse radiation and the radiation reflected by the ground, respectively.

The beam radiation incident on a tilted surface can be written as:

$$\bar{I}_{b\beta\gamma} = (\bar{I} - \bar{I}_d) \frac{\cos\theta}{\cos\theta_h} \quad , \qquad (C.18)$$

where θ is the incidence angle for a surface having a tilt angle β from the horizontal and an orientation angle γ from due south while θ_h is the incidence angle for a horizontal surface.

The incidence angle for a horizontal surface is given by

$$\cos\theta_h = \sin\delta \sin\phi + \cos\delta \cos\phi \cos\omega \quad , \qquad (C.19)$$

For the tilted surface, the incidence angle can be calculated from the relation given by Duffie and Beckman (1974) as:

$$\cos\theta = \sin\delta\sin\phi\cos\beta - \sin\delta\cos\phi\sin\beta\cos\gamma$$
$$+ \cos\delta\cos\phi\cos\beta\cos\omega$$
$$+ \cos\delta\sin\phi\sin\beta\cos\gamma\cos\omega$$
$$+ \cos\delta\sin\beta\sin\gamma\sin\omega \quad . \qquad (C.20)$$

The monthly average hourly diffuse and total radiation on a horizontal surface are calculated using equations (C.1) and (C.3), respectively.

Iqbal's correlation, equation (C.16), is assumed to be valid for estimating the monthly average daily diffuse radiation on a horizontal surface as needed in equation (C.1).

TABLE C.1

RECOMMENDED AVERAGE DAY FOR EACH MONTH*

Month	Day of the Year	Date
January	17	January 17
February	47	February 16
March	75	March 16
April	105	April 15
May	135	May 15
June	162	June 11
July	198	July 17
August	228	August 14
September	258	September 15
October	288	October 15
November	318	November 14
December	344	December 10

* From S. A. Klein (1977)

NOMENCLATURE

Symbol	Definition	Units
E	Eccentricity correction factor	dimensionless
$\bar{H}$	Monthly average daily total solar radiation on a horizontal surface	$kJ.m^{-2}$
H_0	Daily extraterrestrial solar radiation on a horizontal surface for day n	$kJ.m^{-2}$
$\bar{H}_0$	Monthly average daily extraterrestrial solar radiation on a horizontal surface	$kJ.m^{-2}$
$\bar{H}_d$	Monthly average daily diffuse solar radiation on a horizontal surface	$kJ.m^{-2}$
$\bar{I}$	Monthly average hourly total solar radiation on a horizontal surface	$kJ.m^{-2}$
$\bar{I}_d$	Monthly average hourly diffuse solar radiation on a horizontal surface	$kJ.m^{-2}$
$\bar{I}_{b\beta\gamma}$	Monthly average hourly beam solar radiation on a tilted surface	$kJ.m^{-2}$
$I_{d\beta\gamma}$	Monthly average hourly diffuse solar radiation on a tilted surface	$kJ.m^{-2}$
I_{sc}	Solar constant	$kJ.m^{-2}.h^{-1}$
$\bar{K}_T$	Ratio of the monthly average daily total solar radiation on a horizontal surface to the daily extraterrestrial solar radiation, $\bar{K}_T = \bar{H}/\bar{H}_0$	dimensionless

n	Day of the year (January 1 → n = 1)	dimensionless
$\bar{r}$	Ratio of the monthly average hourly total to the monthly average daily total solar radiation on a horizontal surface $\bar{r} = \bar{I}/\bar{H}$	dimensionless
$\bar{r}_d$	Ratio of the monthly average hourly diffuse to the monthly average daily diffuse solar radiation on a horizontal surface $\bar{r}_d = \bar{I}_d/\bar{H}_d$	dimensionless
ϕ	Latitude angle (north positive)	radians
δ	Declination angle	radians
β	Tilt angle from the horizontal	radians
γ	Surface azimuth angle South → $\gamma = 0$ East → γ → positive West → γ → negative	radians
θ	Incidence angle for a tilted surface	radians
θ_h	Incidence angle for a horizontal surface	radians
ω	Hour angle Solar noon → $\omega = 0$ Mornings → ω → positive Afternoon → ω → negative	radians
ω_s	Sunrise or sunset from angle for a horizontal surface	radians
ρ	Ground albedo	dimensionless

APPENDIX D

NUMERICAL CALCULATION OF PSYCHROMETRIC PROPERTIES OF MOIST AIR

COMPUTER SIMULATION OF PSYCHROMETRIC PROPERTIES

The determination of selected psychrometric properties of moist air is required for the estimation of livestock ventilation rate and supplemental heat requirements.

Three computer subroutines for the calculation of the psychrometric properties are discussed. Input parameters requirement to the subroutine besides the total atmospheric pressure are dew-point and dry-bulb temperatures, or humidity and dry-bulb temperature. The method used here is that described by Wilhelm (1976). The choice of Wilhelm's procedure over methods given by Brooker (1967) is that Wilhelm used SI units throughout his analysis.

CALCULATION OF THE WATER VAPOUR SATURATION PRESSURE

The saturation pressure can be calculated from the absolute dry-bulb temperature using one of the following two equations, depending on the range of the dry-bulb temperature.

For the range: $-40\ ^{o}C \leq t_{db} \leq 0\ ^{o}C$ we have

$$P_{W,S} = \exp\,(24.2779 - 6238.64/T - 0.344438\ \ln T) \qquad \text{(D.1a)}$$

and for the range: $0^{o}C < t_{db} \leq 120^{o}C$ we have,

$$P_{W,S} = \exp\,(89.63121 - 7511.52/T + 0.02399897\ T - 1.1654551 \times 10^{-5}\ T^2 - 1.2810336 \times 10^{-8}\ T^3 + 2.0998405 \times 10^{-11}\ T^4 - 12.150799\ \ln T) \qquad \text{(D.1b)}$$

where T = absolute temperature (K) = $t_{db} + 273.16$

SUBROUTINE I

INPUT: - Dry-bulb temperature, t_{db}.

- Relative humidity, RH.

- Atmospheric pressure, P_{atm}.

OUTPUT: - Actual water vapour pressure, P_W:

$$P_W = (RH)\ (P_{W,S}) \quad . \tag{D.2}$$

- Saturation humidity ratio, W_S:

$$W_S = 0.62198\ [P_{W,S}/(P_{atm} - P_{W,S})]\ . \tag{D.3}$$

- Actual humidity ratio, W:

$$W = 0.62198\ [P_W/(P_{atm} - P_W)]\ . \tag{D.4}$$

- Degree of saturation, μ:

$$\mu = W/W_S\ . \tag{D.5}$$

- Specific volume, v:

$$v = (R_a\ T/P_{atm})(1 + 1.6078\ W)\ . \tag{D.6}$$

- Specific enthalpy of moist air, h:

$$h = 1.006\ t_{db} + W\ (2501 + 1.775\ t_{db}), \tag{D.7}$$

for $-\ 50^oC \leq t_{db} \leq 110^oC$.

- Dew-Point temperature, t_{dp}:

$$t_{dp} = 5.994 + 12.41a + 0.4273\ a^2\ , \tag{D.8a}$$

for $-\ 50^oC \leq t_{db} \leq 0^oC$;

$$t_{dp} = 6.983 + 14.38a + 1.079\ a^2\ , \tag{D.8b}$$

for $0^oC < t_{db} \leq 50^oC$; and,

$$t_{dp} = 13.80 + 9.478a + 1.991\ a^2\ , \tag{D.8c}$$

for $50^oC < t_{db} \leq 110^oC$,

where $a = \ln\ (P_W)$. (D.9)

SUBROUTINE II

In some instances weather data for environmental humidity are reported in terms of dew-point temperature rather than relative humidity. Therefore, subroutine I must be slightly modified in order to be able to determine the other psychrometric properties of the moist air.

First, the actual water vapour pressure must be determined by solving either equation (D.1a) or (D.1b) using the dew-point rather than the dry-bulb temperature as input. Then, the actual humidity ratio can be calculated directly using equation (D.4). With the use of this calculated actual humidity ratio, the specific volume and specific enthalpy of the moist air can be easily determined from equations (D.6) and (D.7), respectively.

Determination of the environmental relative humidity requires the solution of either equation (D.1a) or (D.1b) with the dry-bulb temperature as the independent variable to obtain the saturation water vapour pressure; then, the corresponding relative humidity is simply:

$$RH = P_W/P_{W,S} \quad . \qquad (D.10)$$

SUBROUTINE III

For inside conditions, usually the dry-bulb temperature and the humidity ratio are known and it is needed to calculate the dew-point temperature, the specific enthalpy, the specific volume and the relative humidity of the indoor moist air.

The specific volume may be calculated directly using equation (D.6) for the given dry-bulb temperature, actual humidity ratio and atmospheric pressure.

The specific enthalpy can be found directly using equation (D.7) for the known dry-bulb temperature and humidity ratio. The calculation of the dew-point temperature requires the knowledge of the actual vapour pressure of the moist air as indicated by equation (D.9). This vapour pressure may be calculated using a transformed form of equation (D.4) as follows:

$$P_W = (W \cdot P_{atm})/(0.62198 + W) \; ; \qquad (D.11)$$

then, the dew-point temperature is determined by the solution of one of the following equations: (D.8a), (D.8b) or (D.8c).

If it is desired to determine the inside relative humidity, then the saturation water vapour pressure must be calculated using either equation (D.1a) or (D.1b); and the relative humidity can then be calculated using equation (D.10).

NOMENCLATURE

Symbol	Definition	Units
h	Specific enthalpy	$kJ.kg_a^{-1}$
P_{atm}	Atmospheric pressure	kPa
P_W	Actual water vapour pressure	kPa
$P_{W,S}$	Saturation water vapour pressure	kPa
Ra		
RH	Relative humidity	-
t_{db}	Dry-bulb temperature	^oC
t_{dp}	Dew-point temperature	^oC
T	Absolute temperature	K
v	Specific volume	$m^3.kg_a^{-1}$
W	Actual humidity ratio	$kg_W.kg_a^{-1}$
W_S	Saturation humidity ratio	$kg_W.kg_a^{-1}$
μ	Degree of saturation	dimensionless

APPENDIX E

HEAT AND MOISTURE PRODUCTION BY SWINE

HEAT AND MOISTURE PRODUCTION BY SWINE

Experimental results for the total and room latent heat production of swine are given by Bond et al (1959). Carson (1972) has developed regression equations for the total heat generated by the animals and the total moisture produced within the building as a function of animal weight and barn temperature from the experimental data of Bond et al (1959).

The total animal heat production is given by

$$TH = 4.186 \times 10^{X} \tag{E.1}$$

where $X = 1.761 + 0.035 \log W - 0.00414t + 0.148 (\log W)^2$

$$+ 0.00023t^2 - 0.00563t \cdot \log W \quad . \tag{E.2}$$

while, the moisture produced within the barn may be estimated by

$$M_W = 10^Y \tag{E.3}$$

where M_W is in kilograms of water produced per hour per pig, and

$$Y = 0.00539W - 1.4147 + 0.00171t - 0.0000579W.t$$

$$- 0.0000141W^2 + 0.000446t^2 \quad . \tag{E.4}$$

Then, the room latent heat is determined using the heat of vaporization of water, h_{fg}, evaluated at the inside barn dry bulb temperature. Therefore,

$$LH = M_W \; h_{fg} \tag{E.5}$$

where

$$h_{fg} = 2504.44 - 2.4t \quad . \tag{E.6}$$

The total room sensible heat which is available for heating of the outside ventilation air can be estimated by

$$Q_{SENS} = N \, . \, SH \tag{E.7}$$

where N is the number of animals in the building, and, the sensible heat per animal is given by

$$SH = TH - LH \quad . \tag{E.8}$$

The estimated water vapour production within the swine building as well as the total, sensible and latent heat production by hogs as a function of animal weight and environmental temperature are given in Tables C.1 to Tables C.5. Also shown in the tables is the fraction of the total heat produced which is in the latent form.

NOMENCLATURE

Symbol	Definition	Units
h_{fg}	Latent heat of vaporization of water	$kJ.Kg_W$
LH	Latent heat production	$kJ.h^{-1}$ per pig
M_W	Moisture production	$kg_W.h^{-1}$ per pig
N	Number of animals in a building	-
Q_{SENS}	Total sensible heat production	$kJ.h^{-1}$
SH	Animal senisble heat production	$kJ.h^{-1}$ per pig
TH	Total animal heat production	$kJ.h^{-1}$ per pig
t	Inside dry-bulb temperature	^oC
W	Animal weight	kg

APPENDIX F

HOURLY SIMULATION RESULTS

FOR A

TYPICAL SWINE FINISHING BARN

LOCATED IN

VANCOUVER, B.C.

(CASE STUDY I)

(A):	MONTH OF THE YEAR	-
(B):	HOUR FROM MIDNIGHT	-
(C):	OUTDOOR DRY-BULB TEMPERATURE FOR THE HOUR	^{o}C
(D):	OUTDOOR DEW-POINT TEMPERATURE FOR THE HOUR	^{o}C
(E):	TRANSMISSION HEAT LOSS FOR THE HOUR	KJ PER HOG
(F):	VENTILATION HEAT LOSS FOR THE HOUR	KJ PER HOG
(G):	SUPPLEMENTAL HEAT REQUIREMENT FOR THE HOUR	KJ PER HOG
(H):	VENTILATION RATE REQUIREMENT	$DM^{3}.S^{-1}$ PER HOG
(I):	TOTAL VENTILATION RATE	$M^{3}.S^{-1}$
(J):	POWER INPUT TO FANS	KWH

TABLE F.1

(A) MONTH	(B) HOUR	(C) <OUTDOOR DRY	(D) TEMP.> DEW	(E) TRANS. LOSSES	(F) VENTLTN. LOSSES	(G) SUPL HEAT	(H) <VENTLTN /ANIMAL	(I) RATE> TOTAL	(J) FAN POWER
1	1	.5	-.7	25.5	280.1	0.0	3.34	5.13	.08
1	2	.3	-.7	25.9	279.7	0.0	3.29	5.06	.08
1	3	.2	-.8	26.0	279.6	0.0	3.28	5.03	.08
1	4	.3	-.7	25.9	279.7	0.0	3.29	5.06	.08
1	5	.5	-.7	25.5	280.1	0.0	3.34	5.13	.08
1	6	.9	-.6	25.0	280.6	0.0	3.42	5.26	.08
1	7	1.5	-.5	24.3	281.3	0.0	3.53	5.42	.09
1	8	2.1	-.3	23.4	282.2	0.0	3.67	5.63	.09
1	9	2.8	-.2	22.5	283.1	0.0	3.82	5.87	.10
1	10	3.5	-.1	21.4	284.2	0.0	4.00	6.14	.11
1	11	4.1	.1	20.5	285.1	0.0	4.17	6.41	.12
1	12	4.7	.2	19.7	285.8	0.0	4.33	6.65	.12
1	13	5.1	.3	19.2	286.4	0.0	4.46	6.85	.13
1	14	5.3	.3	18.9	286.7	0.0	4.55	6.98	.13
1	15	5.4	.4	18.9	286.7	0.0	4.57	7.02	.13
1	16	5.3	.3	19.2	286.4	0.0	4.54	6.97	.13
1	17	5.1	.3	19.6	286.0	0.0	4.45	6.84	.13
1	18	4.7	.2	20.1	285.4	0.0	4.32	6.64	.12
1	19	4.1	.1	20.8	284.8	0.0	4.17	6.40	.12
1	20	3.5	-.1	21.7	283.9	0.0	3.99	6.13	.11
1	21	2.8	-.2	22.5	283.0	0.0	3.82	5.87	.10
1	22	2.1	-.3	23.4	282.2	0.0	3.67	5.63	.09
1	23	1.5	-.5	24.3	281.3	0.0	3.53	5.42	.09
1	24	.9	-.6	25.0	280.6	0.0	3.42	5.26	.08
TOTAL OF DAY				539.2	6794.6	0.0			2.48

TABLE F.2

(A) MONTH	(B) HOUR	(C) <OUTDOOR DRY	(D) TEMP.> DEW	(E) TRANS. LOSSES	(F) VENTLTN. LOSSES	(G) SUPL HEAT	(H) <VENTLTN /ANIMAL	(I) RATE> TOTAL	(J) FAN POWER
2	1	2.1	1.4	23.5	282.1	0.0	3.66	5.62	.09
2	2	1.8	1.3	23.8	281.8	0.0	3.60	5.53	.09
2	3	1.7	1.3	23.9	281.7	0.0	3.58	5.50	.09
2	4	1.8	1.3	23.8	281.8	0.0	3.60	5.53	.09
2	5	2.1	1.4	23.5	282.1	0.0	3.66	5.62	.09
2	6	2.5	1.6	22.9	282.7	0.0	3.76	5.77	.10
2	7	3.1	1.7	22.2	283.4	0.0	3.89	5.98	.10
2	8	3.7	1.9	21.3	284.3	0.0	4.06	6.24	.11
2	9	4.4	2.1	20.2	285.4	0.0	4.26	6.54	.12
2	10	5.1	2.3	19.1	286.5	0.0	4.47	6.87	.13
2	11	5.8	2.5	18.1	287.4	0.0	4.69	7.21	.14
2	12	6.3	2.7	17.3	288.2	0.0	4.90	7.53	.15
2	13	6.8	2.8	16.8	288.8	0.0	5.07	7.78	.16
2	14	7.0	2.9	16.5	289.1	0.0	5.18	7.95	.17
2	15	7.1	2.9	16.5	289.1	0.0	5.21	8.01	.17
2	16	7.0	2.9	16.8	288.7	0.0	5.17	7.94	.17
2	17	6.8	2.8	17.4	288.2	0.0	5.06	7.77	.16
2	18	6.3	2.7	17.9	287.6	0.0	4.89	7.51	.15
2	19	5.8	2.5	18.7	286.9	0.0	4.68	7.20	.14
2	20	5.1	2.3	19.5	286.1	0.0	4.47	6.86	.13
2	21	4.4	2.1	20.4	285.2	0.0	4.25	6.53	.12
2	22	3.7	1.9	21.3	284.3	0.0	4.06	6.23	.11
2	23	3.1	1.7	22.2	283.4	0.0	3.89	5.98	.10
2	24	2.5	1.6	22.9	282.7	0.0	3.76	5.77	.10
TOTAL OF DAY				486.6	6847.3	0.0			2.98

TABLE F.3

(A) MONTH	(B) HOUR	(C) <OUTDOOR DRY	(D) TEMP.> DEW	(E) TRANS. LOSSES	(F) VENTLTN. LOSSES	(G) SUPL HEAT	(H) <VENTLTN /ANIMAL	(I) RATE> TOTAL	(J) FAN POWER
3	1	2.5	1.2	22.9	282.6	0.0	3.75	5.76	.10
3	2	2.2	1.1	23.3	282.3	0.0	3.68	5.66	.09
3	3	2.1	1.1	23.4	282.2	0.0	3.66	5.63	.09
3	4	2.2	1.1	23.3	282.3	0.0	3.68	5.66	.09
3	5	2.5	1.2	22.9	282.6	0.0	3.75	5.76	.10
3	6	3.0	1.3	22.4	283.2	0.0	3.86	5.93	.10
3	7	3.6	1.4	21.5	284.1	0.0	4.01	6.16	.11
3	8	4.3	1.6	20.4	285.1	0.0	4.20	6.46	.12
3	9	5.0	1.8	19.2	286.3	0.0	4.43	6.81	.13
3	10	5.7	2.0	18.1	287.5	0.0	4.68	7.19	.14
3	11	6.4	2.1	17.0	288.6	0.0	4.94	7.59	.15
3	12	7.0	2.3	16.2	289.4	0.0	5.18	7.96	.17
3	13	7.5	2.4	15.6	290.0	0.0	5.39	8.27	.18
3	14	7.8	2.4	15.3	290.3	0.0	5.52	8.48	.19
3	15	7.9	2.5	15.3	290.3	0.0	5.56	8.54	.19
3	16	7.8	2.4	15.6	290.0	0.0	5.51	8.47	.19
3	17	7.5	2.4	16.2	289.3	0.0	5.37	8.25	.18
3	18	7.0	2.3	17.0	288.6	0.0	5.17	7.94	.17
3	19	6.4	2.1	17.8	287.8	0.0	4.93	7.57	.15
3	20	5.7	2.0	18.7	286.9	0.0	4.67	7.18	.14
3	21	5.0	1.8	19.7	285.9	0.0	4.42	6.80	.13
3	22	4.3	1.6	20.7	284.9	0.0	4.20	6.45	.12
3	23	3.6	1.4	21.6	284.0	0.0	4.01	6.16	.11
3	24	3.0	1.3	22.4	283.2	0.0	3.86	5.93	.10
TOTAL OF DAY				466.6	6867.3	0.0			3.22

TABLE F.4

(A) MONTH	(B) HOUR	(C) <OUTDOOR DRY	(D) TEMP.> DEW	(E) TRANS. LOSSES	(F) VENTLTN. LOSSES	(G) SUPL HEAT	(H) <VENTLTN /ANIMAL	(I) RATE> TOTAL	(J) FAN POWER
4	1	5.2	3.0	19.4	286.2	0.0	4.50	6.91	.13
4	2	4.9	2.9	19.9	285.7	0.0	4.39	6.75	.13
4	3	4.8	2.9	20.0	285.6	0.0	4.36	6.69	.12
4	4	4.9	2.9	19.9	285.7	0.0	4.39	6.75	.13
4	5	5.2	3.0	19.4	286.2	0.0	4.50	6.91	.13
4	6	5.8	3.1	18.7	286.9	0.0	4.68	7.19	.14
4	7	6.5	3.2	17.6	288.0	0.0	4.94	7.59	.15
4	8	7.3	3.4	16.3	289.3	0.0	5.28	8.11	.17
4	9	8.2	3.6	14.9	290.7	0.0	5.70	8.75	.20
4	10	9.0	3.7	13.5	292.0	0.0	6.18	9.49	.23
4	11	9.9	3.9	12.3	293.2	0.0	6.70	10.29	.26
4	12	10.5	4.0	11.4	294.2	0.0	7.22	11.09	.30
4	13	11.1	4.1	10.7	294.9	0.0	7.67	11.78	.34
4	14	11.4	4.2	10.3	295.3	0.0	7.98	12.26	.36
4	15	11.5	4.2	10.3	295.3	0.0	8.09	12.42	.37
4	16	11.4	4.2	10.6	294.9	0.0	7.97	12.24	.36
4	17	11.1	4.1	11.3	294.2	0.0	7.65	11.75	.33
4	18	10.5	4.0	12.3	293.3	0.0	7.19	11.05	.30
4	19	9.8	3.9	13.4	292.2	0.0	6.67	10.25	.26
4	20	9.0	3.7	14.5	291.1	0.0	6.16	9.46	.23
4	21	8.2	3.5	15.6	290.0	0.0	5.68	8.73	.20
4	22	7.3	3.4	16.8	288.8	0.0	5.27	8.10	.17
4	23	6.5	3.2	17.8	287.8	0.0	4.94	7.58	.15
4	24	5.8	3.1	18.7	286.9	0.0	4.68	7.19	.14
TOTAL OF DAY				365.4	6968.5	0.0			5.29

TABLE F.5

(A) MONTH	(B) HOUR	(C) <OUTDOR DRY	(D) TEMP.> DEW	(E) TRANS. LOSSES	(F) VENTLTN. LOSSES	(G) SUPL HEAT	(H) <VENTLTN /ANIMAL	(I) RATE> TOTAL	(J) FAN POWER
5	1	8.5	6.0	15.2	290.4	0.0	5.84	8.97	.21
5	2	8.1	5.9	15.7	289.9	0.0	5.66	8.70	.19
5	3	8.0	5.9	15.8	289.8	0.0	5.60	8.61	.19
5	4	8.1	5.9	15.7	289.9	0.0	5.66	8.70	.19
5	5	8.5	6.0	15.2	290.4	0.0	5.84	8.97	.21
5	6	9.0	6.1	14.3	291.3	0.0	6.16	9.45	.23
5	7	9.8	6.3	13.1	292.5	0.0	6.61	10.16	.26
5	8	10.6	6.5	11.7	293.9	0.0	7.24	11.12	.30
5	9	11.5	6.8	10.3	295.3	0.0	8.04	12.35	.37
5	10	12.4	7.0	8.9	296.7	0.0	9.03	13.88	.46
5	11	13.2	7.2	7.7	297.9	0.0	10.19	15.66	.57
5	12	14.0	7.4	6.7	298.9	0.0	11.44	17.58	.71
5	13	14.5	7.5	6.0	299.6	0.0	12.62	19.39	.86
5	14	14.9	7.6	5.6	300.0	0.0	13.49	20.72	.98
5	15	15.0	7.7	5.6	300.0	0.0	13.81	21.21	1.02
5	16	14.9	7.6	5.9	299.6	0.0	13.47	20.69	.97
5	17	14.5	7.5	6.6	298.9	0.0	12.59	19.34	.86
5	18	14.0	7.4	7.7	297.9	0.0	11.40	17.51	.71
5	19	13.2	7.2	8.8	296.7	0.0	10.15	15.59	.57
5	20	12.4	7.0	10.1	295.5	0.0	8.99	13.81	.45
5	21	11.5	6.8	11.3	294.3	0.0	8.01	12.30	.36
5	22	10.6	6.5	12.5	293.1	0.0	7.22	11.09	.30
5	23	9.8	6.3	13.5	292.1	0.0	6.60	10.14	.26
5	24	9.0	6.1	14.5	291.1	0.0	6.15	9.45	.22
TOTAL OF DAY				258.2	7075.7	0.0			11.44

TABLE F.6

(A)	(B)	(C)	(D)	(E)	(F)	(G)	(H)	(I)	(J)
MONTH	HOUR	<OUTDOOR	TEMP.>	TRANS.	VENTLTN.	SUPL	<VENTLTN	RATE>	FAN
		DRY	DEW	LOSSES	LOSSES	HEAT	/ANIMAL	TOTAL	POWER
6	1	11.1	9.0	11.8	293.8	0.0	7.62	11.71	.33
6	2	10.8	8.9	12.2	293.4	0.0	7.34	11.27	.31
6	3	10.7	8.9	12.4	293.1	0.0	7.24	11.13	.30
6	4	10.8	8.9	12.2	293.4	0.0	7.34	11.27	.31
6	5	11.1	9.0	11.7	293.9	0.0	7.63	11.72	.33
6	6	11.6	9.1	10.8	294.8	0.0	8.14	12.50	.37
6	7	12.3	9.2	9.7	295.9	0.0	8.91	13.68	.44
6	8	13.1	9.3	8.4	297.2	0.0	10.00	15.36	.55
6	9	14.0	9.5	6.9	298.6	0.0	11.50	17.66	.72
6	10	14.9	9.7	5.6	300.0	0.0	13.49	20.73	.98
6	11	15.7	9.8	4.5	301.1	0.0	16.08	24.69	1.37
6	12	16.4	9.9	3.5	302.1	0.0	19.21	29.50	1.93
6	13	16.9	10.0	2.8	302.8	0.0	22.56	34.65	2.63
6	14	17.2	10.1	2.4	303.2	0.0	25.31	38.88	3.28
6	15	17.3	10.1	2.4	303.2	0.0	26.40	40.55	3.55
6	16	17.2	10.1	2.8	302.8	0.0	25.28	38.83	3.27
6	17	16.9	10.0	3.5	302.1	0.0	22.50	34.56	2.61
6	18	16.4	9.9	4.4	301.2	0.0	19.14	29.40	1.91
6	19	15.7	9.8	5.5	300.0	0.0	16.01	24.59	1.36
6	20	14.9	9.7	6.8	298.8	0.0	13.44	20.64	.97
6	21	14.0	9.5	8.0	297.5	0.0	11.45	17.58	.71
6	22	13.1	9.3	9.2	296.4	0.0	9.97	15.31	.55
6	23	12.3	9.2	10.2	295.3	0.0	8.89	13.65	.44
6	24	11.6	9.1	11.1	294.4	0.0	8.13	12.48	.37
TOTAL OF DAY				178.9	7155.0	0.0			29.60

TABLE F.7

(A) MONTH	(B) HOUR	(C) <OUTDOOR DRY	(D) TEMP.> DEW	(E) TRANS. LOSSES	(F) VENTLTN. LOSSES	(G) SUPL HEAT	(H) <VENTLIN /ANIMAL	(I) RATE> TOTAL	(J) FAN POWER
7	1	12.8	11.0	9.6	296.0	0.0	9.51	14.61	.50
7	2	12.4	10.9	10.1	295.5	0.0	9.02	13.85	.45
7	3	12.3	10.9	10.2	295.3	0.0	8.86	13.61	.44
7	4	12.4	10.9	10.1	295.5	0.0	9.02	13.85	.45
7	5	12.8	11.0	9.5	296.1	0.0	9.51	14.61	.50
7	6	13.4	11.1	8.5	297.1	0.0	10.42	16.01	.60
7	7	14.2	11.2	7.2	298.4	0.0	11.89	18.26	.77
7	8	15.1	11.4	5.7	299.9	0.0	14.19	21.80	1.08
7	9	16.1	11.6	4.1	301.4	0.0	17.86	27.44	1.68
7	10	17.1	11.8	2.6	303.0	0.0	24.02	36.89	2.96
7	11	18.0	12.0	1.3	304.3	0.0	35.20	54.07	6.17
7	12	18.8	12.1	.2	305.4	0.0	50.00	76.80	11.99
7	13	19.4	12.2	0.0	306.2	0.0	50.00	76.80	11.99
7	14	19.8	12.3	0.0	306.6	0.0	50.00	76.80	11.99
7	15	19.9	12.3	0.0	306.6	0.0	50.00	76.80	11.99
7	16	19.8	12.3	0.0	306.2	0.0	50.00	76.80	11.99
7	17	19.4	12.2	.2	305.4	0.0	50.00	76.80	11.99
7	18	18.8	12.1	1.3	304.3	0.0	50.00	76.80	11.99
7	19	18.0	12.0	2.6	303.0	0.0	35.01	53.78	6.11
7	20	17.1	11.8	4.0	301.6	0.0	23.89	36.69	2.93
7	21	16.1	11.6	5.3	300.3	0.0	17.76	27.31	1.66
7	22	15.1	11.4	6.6	299.0	0.0	14.14	21.72	1.07
7	23	14.2	11.2	7.8	297.8	0.0	11.86	18.22	.76
7	24	13.4	11.1	8.8	296.8	0.0	10.41	15.99	.60
TOTAL OF DAY				115.6	7221.5	0.0			112.64

TABLE F.8

(A) MONTH	(B) HOUR	(C) <OUTDOOR DRY	(D) TEMP.> DEW	(E) TRANS. LOSSES	(F) VENTLTN. LOSSES	(G) SUPL HEAT	(H) <VENTLTN /ANIMAL	(I) RATE> TOTAL	(J) FAN POWER
8	1	13.8	11.6	8.4	297.2	0.0	11.01	16.91	.66
8	2	13.5	11.6	8.8	296.8	0.0	10.47	16.08	.60
8	3	13.4	11.6	8.9	296.7	0.0	10.30	15.82	.58
8	4	13.5	11.6	8.8	296.8	0.0	10.47	16.08	.60
8	5	13.8	11.7	8.4	297.2	0.0	11.01	16.92	.66
8	6	14.3	11.8	7.6	298.0	0.0	12.00	18.44	.78
8	7	14.9	11.9	6.4	299.1	0.0	13.60	20.88	.99
8	8	15.7	12.0	5.1	300.5	0.0	16.05	24.66	1.36
8	9	16.5	12.2	3.6	302.0	0.0	19.88	30.53	2.06
8	10	17.3	12.4	2.3	303.3	0.0	26.00	39.94	3.45
8	11	18.1	12.5	1.1	304.5	0.0	36.34	55.82	6.56
8	12	18.7	12.6	.2	305.4	0.0	50.00	76.80	11.99
8	13	19.2	12.8	0.0	306.0	0.0	50.00	76.80	11.99
8	14	19.5	12.8	0.0	306.4	0.0	50.00	76.80	11.99
8	15	19.6	12.8	0.0	306.3	0.0	50.00	76.80	11.99
8	16	19.5	12.8	0.0	305.9	0.0	50.00	76.80	11.99
8	17	19.2	12.7	.5	305.1	0.0	50.00	76.80	11.99
8	18	18.7	12.6	1.5	304.1	0.0	50.00	76.80	11.99
8	19	18.1	12.5	2.7	302.9	0.0	36.11	55.47	6.48
8	20	17.3	12.4	3.8	301.7	0.0	25.85	39.70	3.41
8	21	16.5	12.2	4.9	300.7	0.0	19.78	30.38	2.04
8	22	15.7	12.0	5.9	299.7	0.0	16.00	24.58	1.36
8	23	14.9	11.9	6.9	298.7	0.0	13.57	20.84	.99
8	24	14.3	11.8	7.7	297.8	0.0	12.00	18.42	.78
TOTAL OF DAY				103.5	7232.7	0.0			117.28

TABLE F.9

(A) MONTH	(B) HOUR	(C) <OUTDOOR DRY	(D) TEMP.> DEW	(E) TRANS. LOSSES	(F) VENTLTN. LOSSES	(G) SUPL HEAT	(H) <VENTLTN /ANIMAL	(I) RATE> TOTAL	(J) FAN POWER
9	1	11.1	9.4	11.9	293.7	0.0	7.58	11.65	.33
9	2	10.7	9.3	12.3	293.3	0.0	7.29	11.20	.31
9	3	10.6	9.3	12.5	293.1	0.0	7.20	11.06	.30
9	4	10.7	9.3	12.3	293.3	0.0	7.30	11.21	.31
9	5	11.1	9.4	11.9	293.7	0.0	7.58	11.65	.33
9	6	11.6	9.5	11.2	294.4	0.0	8.09	12.43	.37
9	7	12.3	9.6	10.1	295.4	0.0	8.86	13.61	.44
9	8	13.1	9.8	8.8	296.8	0.0	9.96	15.30	.55
9	9	14.0	10.0	7.3	298.3	0.0	11.48	17.63	.72
9	10	14.9	10.2	5.9	299.7	0.0	13.51	20.75	.98
9	11	15.7	10.4	4.6	301.0	0.0	16.15	24.81	1.38
9	12	16.4	10.5	3.6	302.0	0.0	19.38	29.76	1.96
9	13	16.9	10.6	2.9	302.7	0.0	22.85	35.10	2.69
9	14	17.3	10.7	2.6	303.0	0.0	25.74	39.53	3.39
9	15	17.4	10.7	2.6	303.0	0.0	26.88	41.29	3.68
9	16	17.3	10.7	3.0	302.5	0.0	25.69	39.46	3.37
9	17	16.9	10.6	3.8	301.8	0.0	22.78	34.98	2.68
9	18	16.4	10.5	4.8	300.8	0.0	19.29	29.63	1.94
9	19	15.7	10.4	5.8	299.7	0.0	16.08	24.70	1.37
9	20	14.9	10.2	7.0	298.6	0.0	13.46	20.67	.97
9	21	14.0	10.0	8.0	297.5	0.0	11.44	17.58	.71
9	22	13.1	9.8	9.2	296.4	0.0	9.94	15.27	.55
9	23	12.3	9.6	10.3	295.3	0.0	8.85	13.60	.44
9	24	11.6	9.5	11.2	294.4	0.0	8.09	12.42	.37
TOTAL OF DAY				183.6	7150.3	0.0			30.12

TABLE F.10

(A) MONTH	(B) HOUR	(C) <OUTDOOR DRY	(D) TEMP.> DEW	(E) TRANS. LOSSES	(F) VENTLTN. LOSSES	(G) SUPL HEAT	(H) <VENTLTN /ANIMAL	(I) RATE> TOTAL	(J) FAN POWER
10	1	6.9	6.1	17.2	288.4	0.0	5.12	7.86	.16
10	2	6.7	6.0	17.5	288.0	0.0	5.00	7.68	.16
10	3	6.6	6.0	17.7	287.9	0.0	4.96	7.62	.15
10	4	6.7	6.0	17.5	288.0	0.0	5.00	7.68	.16
10	5	6.9	6.1	17.2	288.4	0.0	5.12	7.86	.16
10	6	7.4	6.2	16.6	289.0	0.0	5.31	8.15	.17
10	7	8.0	6.4	15.8	289.7	0.0	5.58	8.57	.19
10	8	8.7	6.6	14.9	290.7	0.0	5.94	9.12	.21
10	9	9.4	6.8	13.7	291.9	0.0	6.37	9.79	.24
10	10	10.1	7.0	12.5	293.1	0.0	6.87	10.56	.27
10	11	10.8	7.2	11.4	294.2	0.0	7.41	11.38	.32
10	12	11.4	7.4	10.6	295.0	0.0	7.94	12.19	.36
10	13	11.9	7.5	10.0	295.6	0.0	8.39	12.89	.40
10	14	12.1	7.6	9.7	295.9	0.0	8.70	13.36	.42
10	15	12.2	7.6	9.8	295.8	0.0	8.80	13.52	.43
10	16	12.1	7.6	10.1	295.5	0.0	8.69	13.34	.42
10	17	11.9	7.5	10.7	294.8	0.0	8.37	12.85	.39
10	18	11.4	7.4	11.4	294.2	0.0	7.91	12.15	.36
10	19	10.8	7.2	12.2	293.4	0.0	7.39	11.35	.31
10	20	10.1	7.0	13.1	292.5	0.0	6.86	10.53	.27
10	21	9.4	6.8	14.0	291.6	0.0	6.36	9.78	.24
10	22	8.7	6.6	14.9	290.6	0.0	5.94	9.12	.21
10	23	8.0	6.4	15.8	289.7	0.0	5.58	8.57	.19
10	24	7.4	6.2	16.6	289.0	0.0	5.31	8.15	.17
TOTAL OF DAY				331.1	7002.7	0.0			6.38

TABLE F.11

(A) MONTH	(B) HOUR	(C) <OUTDOOR DRY	(D) TEMP.> DEW	(E) TRANS. LOSSES	(F) VENTLTN. LOSSES	(G) SUPL HEAT	(H) <VENTLTN /ANIMAL	(I) RATE> TOTAL	(J) FAN POWER
11	1	3.9	2.4	21.2	284.4	0.0	4.09	6.28	.11
11	2	3.6	2.3	21.5	284.0	0.0	4.02	6.18	.11
11	3	3.5	2.3	21.6	284.0	0.0	4.00	6.15	.11
11	4	3.6	2.3	21.5	284.0	0.0	4.02	6.18	.11
11	5	3.9	2.4	21.2	284.4	0.0	4.09	6.28	.11
11	6	4.2	2.5	20.7	284.9	0.0	4.20	6.45	.12
11	7	4.8	2.6	20.0	285.6	0.0	4.35	6.67	.12
11	8	5.3	2.8	19.2	286.3	0.0	4.53	6.96	.13
11	9	6.0	2.9	18.3	287.2	0.0	4.75	7.30	.14
11	10	6.6	3.1	17.3	288.3	0.0	4.99	7.67	.16
11	11	7.2	3.3	16.4	289.2	0.0	5.24	8.04	.17
11	12	7.7	3.4	15.7	289.9	0.0	5.46	8.39	.18
11	13	8.1	3.5	15.2	290.4	0.0	5.65	8.68	.19
11	14	8.3	3.6	14.9	290.6	0.0	5.77	8.87	.20
11	15	8.4	3.6	15.0	290.6	0.0	5.81	8.93	.20
11	16	8.3	3.6	15.3	290.3	0.0	5.77	8.86	.20
11	17	8.1	3.5	15.7	289.9	0.0	5.64	8.66	.19
11	18	7.7	3.4	16.2	289.3	0.0	5.45	8.38	.18
11	19	7.2	3.3	16.9	288.7	0.0	5.23	8.03	.17
11	20	6.6	3.1	17.7	287.9	0.0	4.98	7.66	.16
11	21	6.0	2.9	18.5	287.1	0.0	4.75	7.29	.14
11	22	5.3	2.8	19.2	286.3	0.0	4.53	6.96	.13
11	23	4.7	2.6	20.0	285.6	0.0	4.34	6.67	.12
11	24	4.2	2.5	20.7	284.9	0.0	4.20	6.45	.12
TOTAL OF DAY				440.1	6893.8	0.0			3.58

TABLE F.12

(A) MONTH	(B) HOUR	(C) <OUTDOOR DRY	(D) TEMP.> DEW	(E) TRANS. LOSSES	(F) VENTLTN. LOSSES	(G) SUPL HEAT	(H) <VENTLTN /ANIMAL	(I) RATE> TOTAL	(J) FAN POWER
12	1	1.3	.5	24.5	281.1	0.0	3.49	5.36	.09
12	2	1.1	.5	24.8	280.8	0.0	3.45	5.30	.09
12	3	1.0	.5	24.9	280.7	0.0	3.43	5.27	.08
12	4	1.1	.5	24.8	280.8	0.0	3.45	5.30	.09
12	5	1.3	.5	24.5	281.1	0.0	3.49	5.36	.09
12	6	1.7	.6	24.0	281.5	0.0	3.56	5.47	.09
12	7	2.1	.6	23.4	282.2	0.0	3.66	5.63	.09
12	8	2.6	.7	22.8	282.8	0.0	3.78	5.81	.10
12	9	3.2	.8	22.0	283.6	0.0	3.92	6.03	.10
12	10	3.8	.9	21.1	284.5	0.0	4.07	6.26	.11
12	11	4.3	1.0	20.3	285.3	0.0	4.22	6.49	.12
12	12	4.8	1.1	19.6	285.9	0.0	4.36	6.70	.12
12	13	5.1	1.2	19.2	286.4	0.0	4.47	6.87	.13
12	14	5.3	1.2	19.0	286.6	0.0	4.54	6.97	.13
12	15	5.4	1.2	19.0	286.6	0.0	4.56	7.01	.13
12	16	5.3	1.2	19.2	286.4	0.0	4.54	6.97	.13
12	17	5.1	1.2	19.5	286.1	0.0	4.46	6.86	.13
12	18	4.8	1.1	20.0	285.6	0.0	4.35	6.69	.12
12	19	4.3	1.0	20.6	285.0	0.0	4.22	6.48	.12
12	20	3.8	.9	21.3	284.3	0.0	4.07	6.25	.11
12	21	3.2	.8	22.0	283.6	0.0	3.92	6.02	.10
12	22	2.6	.7	22.8	282.8	0.0	3.78	5.81	.10
12	23	2.1	.6	23.4	282.2	0.0	3.66	5.63	.09
12	24	1.7	.6	24.0	281.5	0.0	3.56	5.47	.09
TOTAL OF DAY				526.7	6807.2	0.0			2.57

APPENDIX G

HOURLY SIMULATION RESULTS

FOR A

TYPICAL GABLE GLASS HOUSE

VANCOUVER, B.C.

(CASE STUDY II)

MINIMUM INSIDE TEMPERATURE: 15^{o}C.

(A):	MONTH OF THE YEAR	-
(B):	HOUR FROM MIDNIGHT	-
(C):	SOLAR RADIATION INPUT	KJ
(D):	INFILTRATION HEAT LOSS	KJ
(E):	TRANSMISSION HEAT LOSS	KJ
(F):	TOTAL HEAT LOSS	KJ
(G):	SUPPLEMENTAL HEAT REQUIREMENT	KJ
(H):	FRACTION OF THE TOTAL HEAT LOSS SUPPLIED BY SOLAR	

TABLE G.1

(A) MONTH	(B) HOUR	(C) SOLAR RADIATION	(D) INFILTRATION	(E) TRANSMISSION LOSSES	(F) TOTAL LOSSES	(G) SUPPLEMENTAL HEAT REQUIRD	(H) FRACTION OF LOAD
1	1	0.	74086.	654441.	728527.	-728527.	0.000
1	2	0.	75432.	668640.	744072.	-744072.	0.000
1	3	0.	75890.	672056.	747946.	-747946.	0.000
1	4	0.	75429.	668639.	744069.	-744069.	0.000
1	5	0.	74082.	654440.	728522.	-728522.	0.000
1	6	0.	71938.	640117.	712055.	-712055.	0.000
1	7	0.	69146.	616367.	685512.	-685512.	0.000
1	8	0.	65894.	587881.	653776.	-653776.	0.000
1	9	235281.	62405.	559359.	621765.	-386484.	.378
1	10	670699.	58917.	527928.	586844.	0.	1.000
1	11	988208.	55666.	499443.	555109.	0.	1.000
1	12	1125816.	52875.	475693.	528568.	0.	1.000
1	13	1125816.	50734.	456788.	507522.	0.	1.000
1	14	988208.	49389.	447171.	496560.	0.	1.000
1	15	670699.	48931.	446360.	495290.	0.	1.000
1	16	235281.	49391.	453426.	502818.	-267537.	.468
1	17	0.	50739.	467626.	518365.	-518365.	0.000
1	18	0.	52882.	481949.	534831.	-534831.	0.000
1	19	0.	55675.	505699.	561374.	-561374.	0.000
1	20	0.	58926.	534184.	593111.	-593111.	0.000
1	21	0.	62415.	559361.	621776.	-621776.	0.000
1	22	0.	65904.	587883.	653787.	-653787.	0.000
1	23	0.	69154.	616368.	685522.	-685522.	0.000
1	24	0.	71945.	640118.	712064.	-712064.	0.000
TOTAL OF MONTH		6040006.	1497848.	13421936.	14919784.	-11279329.	.244

TABLE G.2

(A) MONTH	(B) HOUR	(C) SOLAR RADIATION	(D) INFILTRATION	(E) TRANSMISSION LOSSES	(F) TOTAL LOSSES	(G) SUPPLEMENTAL HEAT REQUIRD	(H) FRACTION OF LOAD
2	1	0.	65985.	591241.	657226.	-657226.	0.000
2	2	0.	67364.	602100.	669463.	-669463.	0.000
2	3	0.	67833.	605518.	673351.	-673351.	0.000
2	4	0.	67361.	602099.	669460.	-669460.	0.000
2	5	0.	65980.	591240.	657220.	-657220.	0.000
2	6	0.	63784.	572246.	636029.	-636029.	0.000
2	7	0.	60922.	548484.	609407.	-609407.	0.000
2	8	105825.	57591.	521305.	578895.	-473070.	.183
2	9	487117.	54016.	487447.	541463.	-54346.	.900
2	10	902483.	50441.	456580.	507021.	0.	1.000
2	11	1195902.	47110.	424159.	471270.	0.	1.000
2	12	1329671.	44250.	399820.	444071.	0.	1.000
2	13	1329671.	42057.	383158.	425214.	0.	1.000
2	14	1195902.	40678.	371204.	411882.	0.	1.000
2	15	902483.	40209.	371050.	411259.	0.	1.000
2	16	487117.	40681.	378119.	418799.	0.	1.000
2	17	105825.	42062.	392982.	435044.	-329219.	.243
2	18	0.	44258.	411977.	456234.	-456234.	0.000
2	19	0.	47119.	434420.	481539.	-481539.	0.000
2	20	0.	50451.	462917.	513368.	-513368.	0.000
2	21	0.	54026.	491453.	545479.	-545479.	0.000
2	22	0.	57601.	521306.	578907.	-578907.	0.000
2	23	0.	60931.	548486.	609417.	-609417.	0.000
2	24	0.	63791.	572247.	636038.	-636038.	0.000
TOTAL OF MONTH		8041994.	1296498.	11741558.	13038059.	-9249772.	.291

TABLE G.3

(A) MONTH	(B) HOUR	(C) SOLAR RADIATION	(D) INFILTRATION	(E) TRANSMISSION LOSSES	(F) TOTAL LOSSES	(G) SUPPLEMENTAL HEAT REQUIRD	(H) FRACTION OF LOAD
3	1	0.	63962.	573591.	637553.	-637553.	0.000
3	2	0.	65438.	587810.	653248.	-653248.	0.000
3	3	0.	65940.	591234.	657174.	-657174.	0.000
3	4	0.	65435.	587810.	653245.	-653245.	0.000
3	5	0.	63957.	573590.	637547.	-637547.	0.000
3	6	0.	61606.	554572.	616178.	-616178.	0.000
3	7	61648.	58543.	529461.	588005.	-526356.	.105
3	8	377622.	54977.	496842.	551819.	-174198.	.684
3	9	841215.	51151.	457927.	509078.	0.	1.000
3	10	1272174.	47324.	424771.	472095.	0.	1.000
3	11	1558719.	43759.	391654.	435414.	0.	1.000
3	12	1689188.	40698.	365692.	406391.	0.	1.000
3	13	1689188.	38350.	346593.	384943.	0.	1.000
3	14	1558719.	36874.	334625.	371499.	0.	1.000
3	15	1272174.	36372.	333888.	370260.	0.	1.000
3	16	841215.	36877.	342553.	379430.	0.	1.000
3	17	377622.	38355.	359023.	397378.	-19757.	.950
3	18	61648.	40706.	382127.	422833.	-361184.	.146
3	19	0.	43769.	407237.	451006.	-451006.	0.000
3	20	0.	47335.	439117.	486452.	-486452.	0.000
3	21	0.	51161.	469009.	520171.	-520171.	0.000
3	22	0.	54988.	500929.	555917.	-555917.	0.000
3	23	0.	58553.	530781.	589334.	-589334.	0.000
3	24	0.	61614.	554573.	616187.	-616187.	0.000
TOTAL OF MONTH		11601133.	1227744.	11135410.	12363154.	-8155505.	.340

TABLE G.4

(A) MONTH	(B) HOUR	(C) SOLAR RADIATION	(D) INFILTRATION	(E) TRANSMISSION LOSSES	(F) TOTAL LOSSES	(G) SUPPLEMENTAL HEAT REQUIRD	(H) FRACTION OF LOAD
4	1	0.	49893.	458168.	508061.	-508061.	0.000
4	2	0.	51614.	472425.	524039.	-524039.	0.000
4	3	0.	52200.	477179.	529379.	-529379.	0.000
4	4	0.	51611.	472424.	524035.	-524035.	0.000
4	5	0.	49887.	458167.	508053.	-508053.	0.000
4	6	41112.	47146.	434424.	481570.	-440458.	.085
4	7	270473.	43574.	402382.	445956.	-175483.	.607
4	8	627093.	39416.	364348.	403764.	0.	1.000
4	9	1029297.	34954.	320752.	355706.	0.	1.000
4	10	1358493.	30492.	280502.	310994.	0.	1.000
4	11	1569254.	26335.	243370.	269705.	0.	1.000
4	12	1665666.	22765.	214258.	237023.	0.	1.000
4	13	1665666.	20027.	191175.	211201.	0.	1.000
4	14	1569254.	18306.	178509.	196815.	0.	1.000
4	15	1358493.	17720.	177597.	195317.	0.	1.000
4	16	1029297.	18310.	186275.	204585.	0.	1.000
4	17	627093.	20033.	205196.	225230.	0.	1.000
4	18	270473.	22774.	234616.	257390.	0.	1.000
4	19	41112.	26346.	266658.	293004.	-251892.	.140
4	20	0.	30504.	301265.	331769.	-331769.	0.000
4	21	0.	34966.	337947.	372914.	-372914.	0.000
4	22	0.	39428.	372602.	412030.	-412030.	0.000
4	23	0.	43585.	405891.	449476.	-449476.	0.000
4	24	0.	47155.	434425.	481580.	-481580.	0.000
TOTAL OF MONTH		13122775.	839040.	7890555.	8729595.	-5509168.	.369

TABLE G.5

(A) MONTH	(B) HOUR	(C) SOLAR RADIATION	(D) INFILTRATION	(E) TRANSMISSION LOSSES	(F) TOTAL LOSSES	(G) SUPPLEMENTAL HEAT REQUIRD	(H) FRACTION OF LOAD
5	1	0.	33303.	323699.	357002.	-357002.	0.000
5	2	0.	35077.	337964.	373042.	-373042.	0.000
5	3	0.	35681.	342722.	378403.	-378403.	0.000
5	4	0.	35074.	337964.	373038.	-373038.	0.000
5	5	7584.	33296.	323698.	356994.	-349410.	.021
5	6	210324.	30470.	295857.	326327.	-116003.	.645
5	7	488813.	26787.	261466.	288253.	0.	1.000
5	8	837325.	22499.	222398.	244897.	0.	1.000
5	9	1180971.	17898.	178122.	196020.	0.	1.000
5	10	1450646.	13297.	136258.	149555.	0.	1.000
5	11	1622235.	9011.	99106.	108117.	0.	1.000
5	12	1701381.	5330.	67645.	72974.	0.	1.000
5	13	1701381.	2506.	44548.	47054.	0.	1.000
5	14	1622235.	732.	31793.	32525.	0.	1.000
5	15	1450646.	128.	29865.	29993.	0.	1.000
5	16	1180971.	735.	40219.	40954.	0.	1.000
5	17	837325.	2513.	60081.	62594.	0.	1.000
5	18	488813.	5339.	87922.	93261.	0.	1.000
5	19	210324.	9022.	123904.	132926.	0.	1.000
5	20	7584.	13310.	162039.	175349.	-167765.	.043
5	21	0.	17911.	200061.	217972.	-217972.	0.000
5	22	0.	22512.	238082.	260594.	-260594.	0.000
5	23	0.	26799.	271391.	298190.	-298190.	0.000
5	24	0.	30479.	301261.	331741.	-331741.	0.000
TOTAL OF MONTH		14998557.	429710.	4518063.	4947774.	-3223159.	.349

TABLE G.6

(A) MONTH	(B) HOUR	(C) SOLAR RADIATION	(D) INFILTRATION	(E) TRANSMISSION LOSSES	(F) TOTAL LOSSES	(G) SUPPLEMENTAL HEAT REQUIRD	(H) FRACTION OF LOAD
6	1	0.	19960.	215687.	235647.	-235647.	0.000
6	2	0.	21671.	228625.	250295.	-250295.	0.000
6	3	0.	22253.	233379.	255631.	-255631.	0.000
6	4	0.	21667.	228624.	250292.	-250292.	0.000
6	5	105106.	19954.	214287.	234241.	-129135.	.449
6	6	341724.	17229.	188135.	205364.	0.	1.000
6	7	656925.	13679.	154504.	168183.	0.	1.000
6	8	1019642.	9545.	113788.	123333.	0.	1.000
6	9	1363152.	5109.	71869.	76978.	0.	1.000
6	10	1631645.	674.	32281.	32955.	0.	1.000
6	11	1803035.	0.	0.	0.	0.	0.000
6	12	1882325.	0.	0.	0.	0.	0.000
6	13	1882325.	0.	0.	0.	0.	0.000
6	14	1803035.	0.	0.	0.	0.	0.000
6	15	1631645.	0.	0.	0.	0.	0.000
6	16	1363152.	0.	0.	0.	0.	0.000
6	17	1019642.	0.	0.	0.	0.	0.000
6	18	656925.	0.	0.	0.	0.	0.000
6	19	341724.	0.	21706.	21706.	0.	1.000
6	20	105106.	686.	56826.	57512.	0.	1.000
6	21	0.	5122.	95480.	100602.	-100602.	0.000
6	22	0.	9557.	133476.	143033.	-143033.	0.000
6	23	0.	13690.	166761.	180451.	-180451.	0.000
6	24	0.	17238.	195293.	212531.	-212531.	0.000
TOTAL OF MONTH		17607109.	198034.	2350720.	2548754.	-1757617.	.310

TABLE G.7

(A) MONTH	(B) HOUR	(C) SOLAR RADIATION	(D) INFILTRATION	(E) TRANSMISSION LOSSES	(F) TOTAL LOSSES	(G) SUPPLEMENTAL HEAT REQUIRD	(H) FRACTION OF LOAD
7	1	0.	11138.	147712.	158850.	-158850.	0.000
7	2	0.	13076.	162003.	175078.	-175078.	0.000
7	3	0.	13735.	166769.	180504.	-180504.	0.000
7	4	0.	13072.	162002.	175074.	-175074.	0.000
7	5	53923.	11131.	146971.	158101.	-104178.	.341
7	6	280680.	8044.	116758.	124802.	0.	1.000
7	7	582041.	4022.	78309.	82332.	0.	1.000
7	8	942788.	0.	32845.	32845.	0.	1.000
7	9	1290579.	0.	0.	0.	0.	0.000
7	10	1562649.	0.	0.	0.	0.	0.000
7	11	1735929.	0.	0.	0.	0.	0.000
7	12	1815938.	0.	0.	0.	0.	0.000
7	13	1815938.	0.	0.	0.	0.	0.000
7	14	1735929.	0.	0.	0.	0.	0.000
7	15	1562649.	0.	0.	0.	0.	0.000
7	16	1290579.	0.	0.	0.	0.	0.000
7	17	942788.	0.	0.	0.	0.	0.000
7	18	582041.	0.	0.	0.	0.	0.000
7	19	280680.	0.	0.	0.	0.	0.000
7	20	53923.	0.	0.	0.	0.	0.000
7	21	0.	0.	13209.	13209.	-13209.	0.000
7	22	0.	0.	52614.	52614.	-52614.	0.000
7	23	0.	4035.	90648.	94683.	-94683.	0.000
7	24	0.	8054.	122598.	130652.	-130652.	0.000
TOTAL OF MONTH		16529051.	86308.	1292436.	1378743.	-1084842.	.213

TABLE G.8

(A) MONTH	(B) HOUR	(C) SOLAR RADIATION	(D) INFILTRATION	(E) TRANSMISSION LOSSES	(F) TOTAL LOSSES	(G) SUPPLEMENTAL HEAT REQUIRD	(H) FRACTION OF LOAD
8	1	0.	6241.	112989.	119230.	-119230.	0.000
8	2	0.	7844.	127228.	135072.	-135072.	0.000
8	3	0.	8390.	131976.	140366.	-140366.	0.000
8	4	0.	7841.	127228.	135069.	-135069.	0.000
8	5	0.	6235.	112988.	119223.	-119223.	0.000
8	6	118767.	3681.	93198.	96879.	0.	1.000
8	7	394304.	353.	59441.	59794.	0.	1.000
8	8	802934.	0.	21096.	21096.	0.	1.000
8	9	1237843.	0.	0.	C.	0.	0.000
8	10	1585299.	0.	0.	C.	0.	0.000
8	11	1806115.	0.	0.	C.	0.	0.000
8	12	1906968.	C.	0.	C.	0.	0.000
8	13	1906968.	0.	0.	C.	0.	0.0C0
8	14	1806115.	0.	0.	C.	0.	0.000
8	15	1585299.	0.	0.	C.	0.	0.000
8	16	1237843.	0.	0.	C.	C.	0.000
8	17	802934.	0.	0.	C.	C.	0.000
8	18	394304.	0.	0.	C.	0.	0.000
8	19	118767.	0.	0.	C.	0.	0.000
8	20	0.	0.	0.	C.	0.	0.000
8	21	0.	0.	3572.	3572.	-3572.	0.000
8	22	0.	0.	36861.	36861.	-36861.	0.000
8	23	0.	363.	68788.	69151.	-69151.	0.000
8	24	0.	3689.	93940.	97629.	-97629.	0.000
TOTAL OF MONTH		15704458.	44635.	989306.	1033941.	-856172.	.172

TABLE G.9

(A) MONTH	(B) HOUR	(C) SOLAR RADIATION	(D) INFILTRATION	(E) TRANSMISSION LOSSES	(F) TOTAL LOSSES	(G) SUPPLEMENTAL HEAT REQUIRD	(H) FRACTION OF LOAD
9	1	0.	20182.	219067.	239248.	-239248.	0.000
9	2	0.	21918.	233326.	255244.	-255244.	0.000
9	3	0.	22509.	238082.	260590.	-260590.	0.000
9	4	0.	21914.	233326.	255240.	-255240.	0.000
9	5	0.	20175.	219066.	239241.	-239241.	0.000
9	6	0.	17410.	198665.	216075.	-216075.	0.000
9	7	136991.	13807.	166699.	180505.	-43514.	.759
9	8	481779.	9611.	126328.	135939.	0.	1.000
9	9	937004.	5109.	84317.	89427.	0.	1.000
9	10	1335271.	608.	40796.	41404.	0.	1.000
9	11	1594727.	0.	3659.	3659.	0.	1.000
9	12	1712727.	0.	0.	0.	0.	0.000
9	13	1712727.	0.	0.	0.	0.	0.000
9	14	1594727.	0.	0.	0.	0.	0.000
9	15	1335271.	0.	0.	0.	0.	0.000
9	16	937004.	0.	0.	0.	0.	0.000
9	17	481779.	0.	0.	0.	0.	0.000
9	18	136991.	0.	0.	0.	0.	0.000
9	19	0.	0.	28842.	28842.	-28842.	0.000
9	20	0.	620.	65483.	66103.	-66103.	0.000
9	21	0.	5122.	98826.	103948.	-103948.	0.000
9	22	0.	9623.	136832.	146455.	-146455.	0.000
9	23	0.	13818.	170127.	183944.	-183944.	0.000
9	24	0.	17419.	198666.	216085.	-216085.	0.000
TOTAL OF MONTH		12397000.	199844.	2462105.	2661949.	-2254530.	.153

TABLE G.10

(A) MONTH	(B) HOUR	(C) SOLAR RADIATION	(D) INFILTRATION	(E) TRANSMISSION LOSSES	(F) TOTAL LOSSES	(G) SUPPLEMENTAL HEAT REQUIRD	(H) FRACTION OF LOAD
10	1	0.	41188.	386865.	428053.	-428053.	0.000
10	2	0.	42633.	399762.	442394.	-442394.	0.000
10	3	0.	43125.	404501.	447626.	-447626.	0.000
10	4	0.	42630.	399761.	442391.	-442391.	0.000
10	5	0.	41182.	386864.	428046.	-428046.	0.000
10	6	0.	38880.	371199.	410079.	-410079.	0.000
10	7	0.	35881.	344071.	379952.	-379952.	0.000
10	8	185938.	32389.	314889.	347278.	-161340.	.535
10	9	582070.	28642.	279332.	307974.	0.	1.000
10	10	994016.	24895.	243856.	268751.	0.	1.000
10	11	1279527.	21404.	211988.	233392.	0.	1.000
10	12	1409716.	18407.	187709.	206115.	0.	1.000
10	13	1409716.	16107.	168698.	184805.	0.	1.000
10	14	1279527.	14662.	158407.	173069.	0.	1.000
10	15	994016.	14170.	158250.	172420.	0.	1.000
10	16	582070.	14665.	166913.	181578.	0.	1.000
10	17	185938.	16112.	185710.	201823.	-15885.	.921
10	18	0.	18414.	204802.	223216.	-223216.	0.000
10	19	0.	21413.	228585.	249998.	-249998.	0.000
10	20	0.	24906.	257107.	282013.	-282013.	0.000
10	21	0.	28653.	285670.	314322.	-314322.	0.000
10	22	0.	32400.	318895.	351294.	-351294.	0.000
10	23	0.	35891.	344072.	379963.	-379963.	0.000
10	24	0.	38888.	371200.	410088.	-410088.	0.000
TOTAL OF MONTH		8902534.	687537.	6779105.	7466642.	-5366661.	.281

TABLE G.11

(A) MONTH	(B) HOUR	(C) SOLAR RADIATION	(D) INFILTRATION	(E) TRANSMISSION LOSSES	(F) TOTAL LOSSES	(G) SUPPLEMENTAL HEAT REQUIRD	(H) FRACTION OF LOAD
11	1	0.	57006.	515233.	572239.	-572239.	0.000
11	2	0.	58252.	524753.	583005.	-583005.	0.000
11	3	0.	58676.	529482.	588158.	-588158.	0.000
11	4	0.	58249.	524752.	583002.	-583002.	0.000
11	5	0.	57001.	515232.	572233.	-572233.	0.000
11	6	0.	55017.	500934.	555950.	-555950.	0.000
11	7	0.	52431.	477215.	529646.	-529646.	0.000
11	8	0.	49420.	453431.	502851.	-502851.	0.000
11	9	239509.	46189.	424949.	471138.	-231629.	.508
11	10	599317.	42959.	394794.	437753.	0.	1.000
11	11	856478.	39949.	368100.	408049.	0.	1.000
11	12	970889.	37364.	346795.	384159.	0.	1.000
11	13	970889.	35382.	330165.	365547.	0.	1.000
11	14	856478.	34136.	322237.	356372.	0.	1.000
11	15	599317.	33712.	322090.	355801.	0.	1.000
11	16	239509.	34138.	329151.	363289.	-123780.	.659
11	17	0.	35386.	339330.	374717.	-374717.	0.000
11	18	0.	37371.	356974.	394345.	-394345.	0.000
11	19	0.	39957.	377347.	417304.	-417304.	0.000
11	20	0.	42968.	401132.	444099.	-444099.	0.000
11	21	0.	46199.	429613.	475812.	-475812.	0.000
11	22	0.	49429.	453432.	502861.	-502861.	0.000
11	23	0.	52439.	477216.	529655.	-529655.	0.000
11	24	0.	55023.	500935.	555958.	-555958.	0.000
TOTAL OF MONTH		5332386.	1108653.	10215291.	11323944.	-8537243.	.246

TABLE G.12

(A) MONTH	(B) HOUR	(C) SOLAR RADIATION	(D) INFILTRATION	(E) TRANSMISSION LOSSES	(F) TOTAL LOSSES	(G) SUPPLEMENTAL HEAT REQUIRD	(H) FRACTION OF LOAD
12	1	0.	70084.	624521.	694605.	-694605.	0.000
12	2	0.	71210.	634023.	705232.	-705232.	0.000
12	3	0.	71593.	635400.	706993.	-706993.	0.000
12	4	0.	71207.	634022.	705230.	-705230.	0.000
12	5	0.	70080.	624520.	694600.	-694600.	0.000
12	6	0.	68286.	610252.	678538.	-678538.	0.000
12	7	0.	65949.	591235.	657185.	-657185.	0.000
12	8	0.	63228.	567496.	630724.	-630724.	0.000
12	9	105854.	60309.	543726.	604034.	-498180.	.175
12	10	478059.	57389.	515951.	573341.	-95282.	.834
12	11	760585.	54669.	489961.	544631.	0.	1.000
12	12	880842.	52334.	471026.	523360.	0.	1.000
12	13	880842.	50542.	456758.	507300.	0.	1.000
12	14	760585.	49416.	447175.	496591.	0.	1.000
12	15	478059.	49033.	448707.	497740.	-19681.	.960
12	16	105854.	49418.	453430.	502849.	-396995.	.211
12	17	0.	50546.	462932.	513479.	-513479.	0.000
12	18	0.	52340.	478519.	530859.	-530859.	0.000
12	19	0.	54677.	497535.	552212.	-552212.	0.000
12	20	0.	57398.	519957.	577354.	-577354.	0.000
12	21	0.	60317.	543727.	604044.	-604044.	0.000
12	22	0.	63236.	567497.	630734.	-630734.	0.000
12	23	0.	65956.	591236.	657193.	-657193.	0.000
12	24	0.	68292.	610253.	678545.	-678545.	0.000
TOTAL OF MONTH		4450679.	1447510.	13019861.	14467371.	-11227663.	.224

27.49.UCLP, AATUNZ , 0.829KLNS. ATVA123.

APPENDIX H

HOURLY SIMULATION RESULTS

FOR A

GREENHOUSE/SWINE FINISHING BARN

COMBINATION

LOCATED IN

HALIFAX, N.S.

(CASE STUDY III)

MINIMUM GREENHOUSE TEMPERATURE; 10°C.

(A):	MONTH OF THE YEAR	-
(B):	HOUR FROM MIDNIGHT	-
(C):	SOLAR RADIATION CAPTURED BY THE GREENHOUSE	KJ
(D):	HEAT GAIN FROM LIVESTOCK BUILDING VENTILATION AIR BY THE GREENHOUSE	KJ
(E):	TRANSMISSION HEAT LOSS FROM THE GREENHOUSE	KJ
(F):	HEATING LOAD WHEN SOLAR ENERGY CAPTURED BY THE GREENHOUSE IS CONSIDERED = (E)-(C)	KJ
(G):	ACTUAL SUPPLEMENTAL HEAT REQUIREMENT WHEN HEATING FROM LIVESTOCK VENTILATION IS CONSIDERED = (F) - (D)	KJ
(H):	FRACTION OF TRANSMISSION LOSS SUPPLIED BY SOLAR = (C)/(E)	
(I):	FRACTION OF HEATING LOAD SUPPLIED BY VENTILATION AIR = (D)/(F)	

TABLE H.1

(A)	(B)	(C)	(D)	(E)	(F)	(G)	(H)	(I)
1	1	0.	-168376.	598684.	598684.	430308.	0.000	.281
1	2	0.	-165745.	610916.	610916.	445171.	0.000	.271
1	3	0.	-164868.	614966.	614966.	450098.	0.000	.268
1	4	0.	-165745.	610916.	610916.	445171.	0.000	.271
1	5	0.	-168376.	598684.	598684.	430308.	0.000	.281
1	6	0.	-172323.	581562.	581562.	409239.	0.000	.296
1	7	0.	-178023.	554932.	554932.	376909.	0.000	.321
1	8	3327.	-185477.	526412.	523085.	337608.	.006	.355
1	9	235110.	-193808.	495385.	260275.	66467.	.475	.745
1	10	565967.	-203016.	459636.	0.	0.	1.000	0.000
1	11	804435.	-212663.	429197.	0.	0.	1.000	0.000
1	12	912165.	-220994.	396506.	0.	0.	1.000	0.000
1	13	912165.	-228010.	372818.	0.	0.	1.000	0.000
1	14	804435.	-232833.	354730.	0.	0.	1.000	0.000
1	15	565967.	-234148.	346660.	0.	0.	1.000	0.000
1	16	235110.	-232394.	358346.	123236.	0.	.656	1.000
1	17	3327.	-227571.	377708.	374381.	146810.	.009	.608
1	18	0.	-220555.	396964.	396964.	176409.	0.000	.556
1	19	0.	-211786.	429361.	429361.	217575.	0.000	.493
1	20	0.	-202578.	462754.	462754.	260176.	0.000	.438
1	21	0.	-193808.	495385.	495385.	301577.	0.000	.391
1	22	0.	-185477.	526412.	526412.	340935.	0.000	.352
1	23	0.	-178023.	556456.	556456.	378433.	0.000	.320
1	24	0.	-172323.	581562.	581562.	409239.	0.000	.296
		5042008.	-4718920.	11736952.	8900532.	5622433.	.242	.368

TABLE H.2

(A)	(B)	(C)	(D)	(E)	(F)	(G)	(H)	(I)
2	1	0.	-166184.	610158.	610158.	443974.	0.000	.272
2	2	0.	-163553.	622307.	622307.	458754.	0.000	.263
2	3	0.	-162676.	626440.	626440.	463764.	0.000	.260
2	4	0.	-163553.	622307.	622307.	458754.	0.000	.263
2	5	0.	-166184.	610158.	610158.	443974.	0.000	.272
2	6	0.	-170130.	591280.	591280.	421150.	0.000	.288
2	7	0.	-175830.	565286.	565286.	389456.	0.000	.311
2	8	118713.	-182846.	536766.	418053.	235207.	.221	.437
2	9	452001.	-191177.	505739.	53738.	0.	.894	1.000
2	10	807786.	-200385.	474865.	0.	0.	1.000	0.000
2	11	1057940.	-209593.	443951.	0.	0.	1.000	0.000
2	12	1172565.	-217925.	417962.	0.	0.	1.000	0.000
2	13	1172565.	-224502.	399167.	0.	0.	1.000	0.000
2	14	1057940.	-229325.	384697.	0.	0.	1.000	0.000
2	15	807786.	-230640.	370905.	0.	0.	1.000	0.000
2	16	452001.	-228887.	372362.	0.	0.	1.000	0.000
2	17	118713.	-224063.	386380.	267667.	43604.	.307	.837
2	18	0.	-217048.	402300.	402300.	185252.	0.000	.540
2	19	0.	-208716.	423179.	423179.	214463.	0.000	.493
2	20	0.	-199947.	445828.	445828.	245881.	0.000	.448
2	21	0.	-191177.	476830.	476830.	285653.	0.000	.401
2	22	0.	-182846.	517911.	517911.	335065.	0.000	.353
2	23	0.	-175830.	551956.	551956.	376126.	0.000	.319
2	24	0.	-170130.	580319.	580319.	410189.	0.000	.293
		7218010.	-4653147.	11939052.	8385716.	5411265.	.298	.355

TABLE H.3

(A)	(B)	(C)	(D)	(E)	(F)	(G)	(H)	(I)
3	1	0.	-194247.	488000.	488000.	293753.	0.000	.398
3	2	0.	-191177.	501973.	501973.	310796.	0.000	.381
3	3	0.	-189862.	506102.	506102.	316240.	0.000	.375
3	4	0.	-191177.	502057.	502057.	310880.	0.000	.381
3	5	0.	-194247.	491357.	491357.	297110.	0.000	.395
3	6	0.	-199508.	473448.	473448.	273940.	0.000	.421
3	7	61473.	-206524.	450520.	389047.	182523.	.136	.531
3	8	354717.	-215732.	422103.	67386.	0.	.840	1.000
3	9	784300.	-226256.	393499.	0.	0.	1.000	0.000
3	10	1183028.	-238095.	364339.	0.	0.	1.000	0.000
3	11	1447234.	-249934.	336478.	0.	0.	1.000	0.000
3	12	1567391.	-261334.	312025.	0.	0.	1.000	0.000
3	13	1567391.	-270104.	295085.	0.	0.	1.000	0.000
3	14	1447234.	-276242.	282866.	0.	0.	1.000	0.000
3	15	1183028.	-277996.	278820.	0.	0.	1.000	0.000
3	16	784300.	-275804.	282866.	0.	0.	1.000	0.000
3	17	354717.	-269227.	295004.	0.	0.	1.000	0.000
3	18	61473.	-260019.	311394.	249921.	0.	.197	1.000
3	19	0.	-249057.	323292.	323292.	74235.	0.000	.770
3	20	0.	-237218.	342708.	342708.	105490.	0.000	.692
3	21	0.	-225817.	366101.	366101.	140284.	0.000	.617
3	22	0.	-215294.	399690.	399690.	184396.	0.000	.539
3	23	0.	-206524.	431652.	431652.	225128.	0.000	.478
3	24	0.	-199508.	453780.	453780.	254272.	0.000	.440
		10796286.	-5520903.	9305162.	5986515.	2969048.	.357	.504

TABLE H.4

(A)	(B)	(C)	(D)	(E)	(F)	(G)	(H)	(I)
4	1	0.	-243795.	319477.	319477.	75682.	0.000	.763
4	2	0.	-238533.	324790.	324790.	86257.	0.000	.734
4	3	0.	-236779.	335817.	335817.	99038.	0.000	.705
4	4	0.	-238533.	342408.	342408.	103875.	0.000	.697
4	5	0.	-243795.	331377.	331377.	87582.	0.000	.736
4	6	21599.	-252564.	316694.	295095.	42531.	.068	.856
4	7	231813.	-265719.	299174.	67361.	0.	.775	1.000
4	8	570221.	-282381.	270633.	0.	0.	1.000	0.000
4	9	960725.	-302551.	237908.	0.	0.	1.000	0.000
4	10	1283703.	-325791.	204708.	0.	0.	1.000	0.000
4	11	1490698.	-350346.	174415.	0.	0.	1.000	0.000
4	12	1585223.	-374462.	147691.	0.	0.	1.000	0.000
4	13	1585223.	-395070.	127368.	0.	0.	1.000	0.000
4	14	1490698.	-409102.	115131.	0.	0.	1.000	0.000
4	15	1283703.	-414364.	110993.	0.	0.	1.000	0.000
4	16	960725.	-408663.	115131.	0.	0.	1.000	0.000
4	17	570221.	-394194.	127368.	0.	0.	1.000	0.000
4	18	231813.	-373146.	147691.	0.	0.	1.000	0.000
4	19	21599.	-348592.	174415.	152816.	0.	.124	1.000
4	20	0.	-324037.	204712.	204712.	0.	0.000	1.000
4	21	0.	-301674.	237908.	237908.	0.	0.000	1.000
4	22	0.	-281504.	268956.	268956.	0.	0.000	1.000
4	23	0.	-265280.	297573.	297573.	32293.	0.000	.891
4	24	0.	-252564.	311371.	311371.	58807.	0.000	.811
		12287964.	-7523439.	5543708.	3489662.	586065.	.371	.832

TABLE H.5

(A)	(B)	(C)	(D)	(E)	(F)	(G)	(H)	(I)
5	1	0.	-324475.	178021.	178021.	0.	0.000	1.000
5	2	0.	-313952.	185829.	185829.	0.	0.000	1.000
5	3	0.	-310444.	192812.	192812.	0.	0.000	1.000
5	4	0.	-313952.	196951.	196951.	0.	0.000	1.000
5	5	0.	-324475.	189403.	189403.	0.	0.000	1.000
5	6	143086.	-342891.	161047.	17961.	0.	.888	1.000
5	7	411785.	-370954.	123930.	0.	0.	1.000	0.000
5	8	764073.	-409102.	84141.	0.	0.	1.000	0.000
5	9	1111904.	-459089.	57844.	0.	0.	1.000	0.000
5	10	1388025.	-523545.	29558.	0.	0.	1.000	0.000
5	11	1564323.	-600718.	0.	0.	0.	0.000	0.000
5	12	1645540.	-686660.	0.	0.	0.	0.000	0.000
5	13	1645540.	-771725.	0.	0.	0.	0.000	0.000
5	14	1564323.	-835304.	0.	0.	0.	0.000	0.000
5	15	1388025.	-859859.	0.	0.	0.	0.000	0.000
5	16	1111904.	-834427.	0.	0.	0.	0.000	0.000
5	17	764073.	-769532.	0.	0.	0.	0.000	0.000
5	18	411785.	-684467.	0.	0.	0.	0.000	0.000
5	19	143086.	-597210.	8292.	0.	0.	1.000	0.000
5	20	0.	-520476.	43283.	43283.	0.	0.000	1.000
5	21	0.	-457773.	80794.	80794.	0.	0.000	1.000
5	22	0.	-407786.	119030.	119030.	0.	0.000	1.000
5	23	0.	-370077.	154102.	154102.	0.	0.000	1.000
5	24	0.	-342891.	183359.	183359.	0.	0.000	1.000
		14057472.	-12431784.	1988397.	1541546.	0.	.225	1.000

TABLE H.6

(A)	(B)	(C)	(D)	(E)	(F)	(G)	(H)	(I)
6	1	0.	-478382.	68527.	68527.	0.	0.000	1.000
6	2	0.	-456019.	80628.	80628.	0.	0.000	1.000
6	3	0.	-449004.	81570.	81570.	0.	0.000	1.000
6	4	0.	-456019.	74371.	74371.	0.	0.000	1.000
6	5	25652.	-478382.	55981.	30329.	0.	.458	1.000
6	6	233661.	-519599.	22997.	0.	0.	1.000	0.000
6	7	552649.	-584932.	0.	0.	0.	0.000	0.000
6	8	939184.	-683590.	0.	0.	0.	0.000	0.000
6	9	1295447.	-832674.	0.	0.	0.	0.000	0.000
6	10	1575790.	-1065506.	0.	0.	0.	0.000	0.000
6	11	1755640.	-1434707.	0.	0.	0.	0.000	0.000
6	12	1838858.	-2034986.	0.	0.	0.	0.000	0.000
6	13	1838858.	-2998765.	0.	0.	0.	0.000	0.000
6	14	1755640.	-3367526.	0.	0.	0.	0.000	0.000
6	15	1575790.	-3367526.	0.	0.	0.	0.000	0.000
6	16	1295447.	-3367526.	0.	0.	0.	0.000	0.000
6	17	939184.	-2990872.	0.	0.	0.	0.000	0.000
6	18	552649.	-2027093.	0.	0.	0.	0.000	0.000
6	19	233661.	-1423306.	0.	0.	0.	0.000	0.000
6	20	25652.	-1058052.	0.	0.	0.	0.000	0.000
6	21	0.	-829166.	0.	0.	0.	0.000	0.000
6	22	0.	-680082.	0.	0.	0.	0.000	0.000
6	23	0.	-582740.	16982.	16982.	0.	0.000	1.000
6	24	0.	-518722.	47272.	47272.	0.	0.000	1.000
		16433762.	-32685176.	448328.	399679.	0.	.109	1.000

TABLE H.7

(A)	(B)	(C)	(D)	(E)	(F)	(G)	(H)	(I)
7	1	0.	-831358.	0.	0.	0.	0.000	0.000
7	2	0.	-766025.	0.	0.	0.	0.000	0.000
7	3	0.	-746293.	0.	0.	0.	0.000	0.000
7	4	0.	-766025.	0.	0.	0.	0.000	0.000
7	5	95.	-831358.	0.	0.	0.	0.000	0.000
7	6	191332.	-962902.	0.	0.	0.	0.000	0.000
7	7	489919.	-1209328.	0.	0.	0.	0.000	0.000
7	8	865119.	-1724103.	0.	0.	0.	0.000	0.000
7	9	1221547.	-3126362.	0.	0.	0.	0.000	0.000
7	10	1503218.	-3367526.	0.	0.	0.	0.000	0.000
7	11	1683409.	-3367526.	0.	0.	0.	0.000	0.000
7	12	1766570.	-3367526.	0.	0.	0.	0.000	0.000
7	13	1766570.	-3367526.	0.	0.	0.	0.000	0.000
7	14	1683409.	-3367526.	0.	0.	0.	0.000	0.000
7	15	1503218.	-3367526.	0.	0.	0.	0.000	0.000
7	16	1221547.	-3367526.	0.	0.	0.	0.000	0.000
7	17	865119.	-3367526.	0.	0.	0.	0.000	0.000
7	18	489919.	-3367526.	0.	0.	0.	0.000	0.000
7	19	191332.	-3367526.	0.	0.	0.	0.000	0.000
7	20	95.	-3367526.	0.	0.	0.	0.000	0.000
7	21	0.	-3112770.	0.	0.	0.	0.000	0.000
7	22	0.	-1712703.	0.	0.	0.	0.000	0.000
7	23	0.	-1207135.	0.	0.	0.	0.000	0.000
7	24	0.	-962464.	0.	0.	0.	0.000	0.000
		15442418.	-55001612.	0.	0.	0.	0.000	0.000

TABLE H.8

(A)	(B)	(C)	(D)	(E)	(F)	(G)	(H)	(I)
8	1	0.	-932647.	0.	0.	0.	0.000	0.000
8	2	0.	-857667.	0.	0.	0.	0.000	0.000
8	3	0.	-833989.	0.	0.	0.	0.000	0.000
8	4	0.	-857667.	0.	0.	0.	0.000	0.000
8	5	0.	-932647.	0.	0.	0.	0.000	0.000
8	6	74358.	-1087430.	0.	0.	0.	0.000	0.000
8	7	336418.	-1381650.	0.	0.	0.	0.000	0.000
8	8	734416.	-2013939.	0.	0.	0.	0.000	0.000
8	9	1165316.	-3367526.	0.	0.	0.	0.000	0.000
8	10	1513772.	-3367526.	0.	0.	0.	0.000	0.000
8	11	1735815.	-3367526.	0.	0.	0.	0.000	0.000
8	12	1837138.	-3367526.	0.	0.	0.	0.000	0.000
8	13	1837138.	-3367526.	0.	0.	0.	0.000	0.000
8	14	1735815.	-3367526.	0.	0.	0.	0.000	0.000
8	15	1513772.	-3367526.	0.	0.	0.	0.000	0.000
8	16	1165316.	-3367526.	0.	0.	0.	0.000	0.000
8	17	734416.	-3367526.	0.	0.	0.	0.000	0.000
8	18	336418.	-3367526.	0.	0.	0.	0.000	0.000
8	19	74358.	-3367526.	0.	0.	0.	0.000	0.000
8	20	0.	-3367526.	0.	0.	0.	0.000	0.000
8	21	0.	-3367526.	0.	0.	0.	0.000	0.000
8	22	0.	-1999907.	0.	0.	0.	0.000	0.000
8	23	0.	-1375512.	0.	0.	0.	0.000	0.000
8	24	0.	-1084361.	0.	0.	0.	0.000	0.000
		14794466.	-57135254.	0.	0.	0.	0.000	0.000

TABLE H.9

(A)	(B)	(C)	(D)	(E)	(F)	(G)	(H)	(I)
9	1	0.	-574847.	1081.	1081.	0.	0.000	1.000
9	2	0.	-546346.	19046.	19046.	0.	0.000	1.000
9	3	0.	-537576.	32261.	32261.	0.	0.000	1.000
9	4	0.	-546346.	29685.	29685.	0.	0.000	1.000
9	5	0.	-574847.	22781.	22781.	0.	0.000	1.000
9	6	0.	-626149.	2365.	2365.	0.	0.000	1.000
9	7	124404.	-709022.	0.	0.	0.	0.000	0.000
9	8	447666.	-837935.	0.	0.	0.	0.000	0.000
9	9	879605.	-1038759.	0.	0.	0.	0.000	0.000
9	10	1259113.	-1363234.	0.	0.	0.	0.000	0.000
9	11	1506043.	-1919227.	0.	0.	0.	0.000	0.000
9	12	1618221.	-2945270.	0.	0.	0.	0.000	0.000
9	13	1618221.	-3367526.	0.	0.	0.	0.000	0.000
9	14	1506043.	-3367526.	0.	0.	0.	0.000	0.000
9	15	1259113.	-3367526.	0.	0.	0.	0.000	0.000
9	16	879605.	-3367526.	0.	0.	0.	0.000	0.000
9	17	447666.	-3367526.	0.	0.	0.	0.000	0.000
9	18	124404.	-2931677.	0.	0.	0.	0.000	0.000
9	19	0.	-1910457.	0.	0.	0.	0.000	0.000
9	20	0.	-1357973.	0.	0.	0.	0.000	0.000
9	21	0.	-1035690.	0.	0.	0.	0.000	0.000
9	22	0.	-836620.	0.	0.	0.	0.000	0.000
9	23	0.	-708584.	0.	0.	0.	0.000	0.000
9	24	0.	-626149.	0.	0.	0.	0.000	0.000
		11670104.	-38464338.	107219.	107219.	0.	0.000	1.000

TABLE H.10

(A)	(B)	(C)	(D)	(E)	(F)	(G)	(H)	(I)
10	1	0.	-350784.	137418.	137418.	0.	0.000	1.000
10	2	0.	-340699.	140699.	140699.	0.	0.000	1.000
10	3	0.	-337191.	156661.	156661.	0.	0.000	1.000
10	4	0.	-340699.	165589.	165589.	0.	0.000	1.000
10	5	0.	-350784.	151834.	151834.	0.	0.000	1.000
10	6	0.	-368762.	134682.	134682.	0.	0.000	1.000
10	7	0.	-395070.	120622.	120622.	0.	0.000	1.000
10	8	187712.	-431026.	97032.	0.	0.	1.000	0.000
10	9	547118.	-477505.	67674.	0.	0.	1.000	0.000
10	10	915919.	-534507.	35286.	0.	0.	1.000	0.000
10	11	1170170.	-601156.	5005.	0.	0.	1.000	0.000
10	12	1286299.	-672628.	0.	0.	0.	0.000	0.000
10	13	1286299.	-739277.	0.	0.	0.	0.000	0.000
10	14	1170170.	-788387.	0.	0.	0.	0.000	0.000
10	15	915919.	-805926.	0.	0.	0.	0.000	0.000
10	16	547118.	-787072.	0.	0.	0.	0.000	0.000
10	17	187712.	-737085.	0.	0.	0.	0.000	0.000
10	18	0.	-669997.	0.	0.	0.	0.000	0.000
10	19	0.	-598964.	5005.	5005.	0.	0.000	1.000
10	20	0.	-533192.	35286.	35286.	0.	0.000	1.000
10	21	0.	-476628.	67757.	67757.	0.	0.000	1.000
10	22	0.	-430587.	97119.	97119.	0.	0.000	1.000
10	23	0.	-395070.	126366.	126366.	0.	0.000	1.000
10	24	0.	-368762.	140153.	140153.	0.	0.000	1.000
		8214436.	-12531758.	1684189.	1479192.	0.	.122	1.000

TABLE H.11

(A)	(B)	(C)	(D)	(E)	(F)	(G)	(H)	(I)
11	1	0.	-257388.	292044.	292044.	34656.	0.000	.881
11	2	0.	-252564.	296693.	296693.	44129.	0.000	.851
11	3	0.	-250811.	297826.	297826.	47015.	0.000	.842
11	4	0.	-252564.	305327.	305327.	52763.	0.000	.827
11	5	0.	-257388.	301758.	301758.	44370.	0.000	.853
11	6	0.	-266157.	279229.	279229.	13072.	0.000	.953
11	7	0.	-278435.	250123.	250123.	0.	0.000	1.000
11	8	27142.	-293782.	219582.	192440.	0.	.124	1.000
11	9	238429.	-312198.	201239.	0.	0.	1.000	0.000
11	10	523213.	-333245.	181245.	0.	0.	1.000	0.000
11	11	727777.	-355607.	157150.	0.	0.	1.000	0.000
11	12	820894.	-376654.	142046.	0.	0.	1.000	0.000
11	13	820894.	-395070.	127355.	0.	0.	1.000	0.000
11	14	727777.	-406909.	118972.	0.	0.	1.000	0.000
11	15	523213.	-411294.	114927.	0.	0.	1.000	0.000
11	16	238429.	-406471.	118972.	0.	0.	1.000	0.000
11	17	27142.	-394194.	127355.	100213.	0.	.213	1.000
11	18	0.	-375777.	145959.	145959.	0.	0.000	1.000
11	19	0.	-354730.	168089.	168089.	0.	0.000	1.000
11	20	0.	-332806.	194966.	194966.	0.	0.000	1.000
11	21	0.	-311759.	221799.	221799.	0.	0.000	1.000
11	22	0.	-293782.	250305.	250305.	0.	0.000	1.000
11	23	0.	-277996.	277105.	277105.	0.	0.000	1.000
11	24	0.	-266157.	299868.	299868.	33711.	0.000	.888
		4674910.	-7713738.	5089932.	3873742.	269714.	.239	.930

TABLE H.12

(A)	(B)	(C)	(D)	(E)	(F)	(G)	(H)	(I)
12	1	0.	-188546.	515608.	515608.	327062.	0.000	.366
12	2	0.	-185916.	524626.	524626.	338710.	0.000	.354
12	3	0.	-184600.	528671.	528671.	344071.	0.000	.349
12	4	0.	-185916.	522944.	522944.	337028.	0.000	.356
12	5	0.	-188546.	510736.	510736.	322190.	0.000	.369
12	6	0.	-192931.	483665.	483665.	290734.	0.000	.399
12	7	0.	-199508.	453780.	453780.	254272.	0.000	.440
12	8	0.	-207401.	419835.	419835.	212434.	0.000	.494
12	9	131680.	-217048.	388899.	257219.	40171.	.339	.844
12	10	406353.	-227133.	370906.	0.	0.	1.000	0.000
12	11	604266.	-237656.	351937.	0.	0.	1.000	0.000
12	12	692433.	-247303.	324614.	0.	0.	1.000	0.000
12	13	692433.	-255195.	308189.	0.	0.	1.000	0.000
12	14	604266.	-260019.	298792.	0.	0.	1.000	0.000
12	15	406353.	-261773.	302858.	0.	0.	1.000	0.000
12	16	131680.	-260019.	311563.	179883.	0.	.423	1.000
12	17	0.	-254757.	323526.	323526.	68769.	0.000	.787
12	18	0.	-246864.	342141.	342141.	95277.	0.000	.722
12	19	0.	-237218.	364260.	364260.	127042.	0.000	.651
12	20	0.	-227133.	390984.	390984.	163851.	0.000	.581
12	21	0.	-217048.	419490.	419490.	202442.	0.000	.517
12	22	0.	-207401.	446477.	446477.	239076.	0.000	.465
12	23	0.	-199508.	474878.	474878.	275370.	0.000	.420
12	24	0.	-192931.	497640.	497640.	304709.	0.000	.388
		3669464.	-5282370.	9877018.	7656361.	3943207.	.225	.485

APPENDIX I

HOURLY SIMULATION RESULTS

FOR A

SOLAR-SHED GREENHOUSE

VANCOUVER, B.C.

(CASE STUDY IV)

MINIMUM INSIDE TEMPERATURE: 15°C.

(A):	MONTH OF THE YEAR	-
(B):	HOUR FROM MIDNIGHT	-
(C):	PASSIVE SOLAR RADIATION INPUT	kJ
(D):	INFILTRATION HEAT LOSS	kJ
(E):	TRANSMISSION HEAT LOSS	kJ
(F):	TOTAL HEAT LOSS	kJ
(G):	SUPPLEMENTAL HEAT REQUIREMENT	kJ
(H):	FRACTION OF THE TOTAL HEAT LOSS SUPPLIED BY PASSIVE SOLAR	-
(I):	SOLAR RADIATION CAPTURED BY THE INTEGRAL SOLAR COLLECTOR	kJ

TABLE I.1

(A) MONTH	(B) HOUR	(C) PASSIVE SOLAR	(D) INFILT -RATION	(E) TRANSMTN LOSSES	(F) TOTAL LOSSES	(G) SUPLMENTL HEAT REQD	(H) FRACTN LOAD	(I) SOLAR COLECTED
1	1	0.	129651.	648955.	778606.	-778606.	0.000	0.
1	2	0.	132006.	659303.	791309.	-791309.	0.000	0.
1	3	0.	132807.	663117.	795925.	-795925.	0.000	0.
1	4	0.	132001.	659303.	791304.	-791304.	0.000	0.
1	5	0.	129643.	648954.	778596.	-778596.	0.000	0.
1	6	0.	125892.	631065.	756957.	-756957.	0.000	0.
1	7	0.	121005.	607611.	728616.	-728616.	0.000	0.
1	8	0.	115315.	583083.	698398.	-698398.	0.000	0.
1	9	197576.	109209.	554846.	664056.	-466480.	.298	0.
1	10	607757.	103104.	517896.	621000.	-13243.	.979	323474.
1	11	918972.	97416.	489626.	587042.	0.	1.000	564784.
1	12	1050120.	92532.	466171.	558703.	0.	1.000	660893.
1	13	1050120.	88785.	447494.	536279.	0.	1.000	663205.
1	14	918972.	86430.	437935.	524365.	0.	1.000	571133.
1	15	607757.	85629.	437580.	523209.	0.	1.000	333255.
1	16	197576.	86435.	446788.	533223.	-335647.	.371	0.
1	17	0.	88793.	460810.	549604.	-549604.	0.000	0.
1	18	0.	92544.	478699.	571243.	-571243.	0.000	0.
1	19	0.	97431.	498481.	595912.	-595912.	0.000	0.
1	20	0.	103121.	526681.	629802.	-629802.	0.000	0.
1	21	0.	109227.	554848.	664075.	-664075.	0.000	0.
1	22	0.	115332.	583085.	698417.	-698417.	0.000	0.
1	23	0.	121020.	607612.	728632.	-728632.	0.000	0.
1	24	0.	125904.	631066.	756971.	-756971.	0.000	0.
TOTAL OF DAY		5548851.	2621233.	13241010.	15862243.	-12129736.	.235	3116745.

FRACTION SUPPLIED BY SOLAR .257

TABLE I.2

(A) MONTH	(B) HOUR	(C) PASSIVE SOLAR	(D) INFILT -RATION	(E) TRANSMTN LOSSES	(F) TOTAL LOSSES	(G) SUPLMENTL HEAT REQD	(H) FRACTN LOAD	(I) SOLAR COLECTED
2	1	0.	115474.	583098.	698571.	-698571.	0.000	0.
2	2	0.	117886.	593451.	711337.	-711337.	0.000	0.
2	3	0.	118707.	597267.	715975.	-715975.	0.000	0.
2	4	0.	117882.	593451.	711332.	-711332.	0.000	0.
2	5	0.	115465.	583097.	698561.	-698561.	0.000	0.
2	6	0.	111622.	564339.	675960.	-675960.	0.000	0.
2	7	0.	106614.	540873.	647487.	-647487.	0.000	0.
2	8	84568.	100784.	513522.	614306.	-529737.	.138	0.
2	9	447173.	94527.	479948.	574475.	-127302.	.778	91101.
2	10	853748.	88272.	447165.	535437.	0.	1.000	357124.
2	11	1127690.	82443.	414702.	497145.	0.	1.000	527658.
2	12	1243456.	77438.	391166.	468605.	0.	1.000	600732.
2	13	1243456.	73599.	372551.	446149.	0.	1.000	603085.
2	14	1127690.	71186.	362775.	433961.	0.	1.000	534117.
2	15	853748.	70365.	362560.	432925.	0.	1.000	367654.
2	16	447173.	71191.	371770.	442961.	0.	1.000	104491.
2	17	84568.	73608.	390190.	463797.	-379229.	.182	0.
2	18	0.	77451.	409017.	486468.	-486468.	0.000	0.
2	19	0.	82458.	431692.	514150.	-514150.	0.000	0.
2	20	0.	88289.	456161.	544450.	-544450.	0.000	0.
2	21	0.	94545.	488085.	582630.	-582630.	0.000	0.
2	22	0.	100801.	517196.	617997.	-617997.	0.000	0.
2	23	0.	106630.	540875.	647504.	-647504.	0.000	0.
2	24	0.	111634.	564340.	675974.	-675974.	0.000	0.
TOTAL OF DAY		7513270.	2268871.	11569289.	13838160.	-9964668.	.280	3185962.

FRACTION SUPPLIED BY SOLAR .320

TABLE I.3

(A) MONTH	(B) HOUR	(C) PASSIVE SOLAR	(D) INFILT -RATION	(E) TRANSMTN LOSSES	(F) TOTAL LOSSES	(G) SUPLMENTL HEAT REQD	(H) FRACTN LOAD	(I) SOLAR COLECTED
3	1	0.	111934.	568901.	680834.	-680834.	0.000	0.
3	2	0.	114516.	579270.	693786.	-693786.	0.000	0.
3	3	0.	115395.	583091.	698486.	-698486.	0.000	0.
3	4	0.	114511.	579269.	693780.	-693780.	0.000	0.
3	5	0.	111924.	568900.	680824.	-680824.	0.000	0.
3	6	0.	107811.	550048.	657859.	-657859.	0.000	0.
3	7	48375.	102451.	521947.	624398.	-576023.	.077	0.
3	8	346465.	96210.	489094.	585304.	-238839.	.592	0.
3	9	795621.	89513.	451738.	541251.	0.	1.000	185372.
3	10	1195055.	82818.	415313.	498130.	0.	1.000	397361.
3	11	1446002.	76579.	382602.	459180.	0.	1.000	534736.
3	12	1552154.	71222.	354926.	426148.	0.	1.000	598698.
3	13	1552154.	67112.	335933.	403045.	0.	1.000	601071.
3	14	1446002.	64530.	326142.	390672.	0.	1.000	541839.
3	15	1195055.	63651.	325344.	388995.	0.	1.000	408566.
3	16	795621.	64535.	334417.	398952.	0.	1.000	200036.
3	17	346465.	67122.	352780.	419902.	-73437.	.825	0.
3	18	48375.	71235.	379909.	451145.	-402770.	.107	0.
3	19	0.	76595.	404337.	480932.	-480932.	0.000	0.
3	20	0.	82836.	432586.	515422.	-515422.	0.000	0.
3	21	0.	89533.	465410.	554943.	-554943.	0.000	0.
3	22	0.	96228.	493770.	589998.	-589998.	0.000	0.
3	23	0.	102467.	522880.	625347.	-625347.	0.000	0.
3	24	0.	107824.	550119.	657943.	-657943.	0.000	0.
TOTAL OF DAY		10767346.	2148552.	10968725.	13117277.	-8821223.	.328	3467679.

FRACTION SUPPLIED BY SOLAR .393

TABLE I.4

(A) MONTH	(B) HOUR	(C) PASSIVE SOLAR	(D) INFILT -RATION	(E) TRANSMTN LOSSES	(F) TOTAL LOSSES	(G) SUPLMENTL HEAT REQD	(H) FRACTN LOAD	(I) SOLAR COLECTED
4	1	0.	87313.	451471.	538783.	-538783.	0.000	0.
4	2	0.	90324.	465620.	555944.	-555944.	0.000	0.
4	3	0.	91349.	470316.	561665.	-561665.	0.000	0.
4	4	0.	90318.	465620.	555938.	-555938.	0.000	0.
4	5	0.	87302.	451470.	538771.	-538771.	0.000	0.
4	6	29501.	82505.	431696.	514201.	-484700.	.057	0.
4	7	211866.	76255.	399420.	475675.	-263809.	.445	0.
4	8	543323.	68978.	358056.	427033.	0.	1.000	0.
4	9	913370.	61169.	316138.	377307.	0.	1.000	135722.
4	10	1204376.	53361.	274221.	327582.	0.	1.000	273138.
4	11	1381945.	46086.	237097.	283182.	0.	1.000	365311.
4	12	1458017.	39839.	205174.	245013.	0.	1.000	411107.
4	13	1458017.	35047.	181869.	216917.	0.	1.000	414178.
4	14	1381945.	32036.	171321.	203357.	0.	1.000	373885.
4	15	1204376.	31011.	170735.	201746.	0.	1.000	286554.
4	16	913370.	32042.	179821.	211863.	0.	1.000	153304.
4	17	543323.	35058.	202179.	237237.	0.	1.000	0.
4	18	211866.	39855.	230158.	270013.	-58147.	.785	0.
4	19	29501.	46105.	262364.	308469.	-278968.	.096	0.
4	20	0.	53382.	296170.	349553.	-349553.	0.000	0.
4	21	0.	61191.	332906.	394097.	-394097.	0.000	0.
4	22	0.	68999.	370502.	439502.	-439502.	0.000	0.
4	23	0.	76274.	403447.	479722.	-479722.	0.000	0.
4	24	0.	82521.	431697.	514218.	-514218.	0.000	0.
TOTAL OF DAY		11484797.	1468321.	7759467.	9227788.	-6013817.	.348	2413198.

FRACTION SUPPLIED BY SOLAR .401

TABLE I.5

(A) MONTH	(B) HOUR	(C) PASSIVE SOLAR	(D) INFILT -RATION	(E) TRANSMTN LOSSES	(F) TOTAL LOSSES	(G) SUPLMENTL HEAT REQD	(H) FRACTN LOAD	(I) SOLAR COLECTED
5	1	0.	58280.	318835.	377115.	-377115.	0.000	0.
5	2	0.	61385.	332993.	394378.	-394378.	0.000	0.
5	3	0.	62442.	337691.	400133.	-400133.	0.000	0.
5	4	0.	61379.	332992.	394372.	-394372.	0.000	0.
5	5	5436.	58269.	318834.	377102.	-371667.	.014	0.
5	6	132139.	53322.	295021.	348343.	-216204.	.379	0.
5	7	352422.	46878.	258405.	305282.	0.	1.000	0.
5	8	708120.	39374.	217162.	256536.	0.	1.000	0.
5	9	1021696.	31322.	175012.	206333.	0.	1.000	119901.
5	10	1256945.	23270.	129541.	152812.	0.	1.000	231258.
5	11	1399518.	15768.	92397.	108165.	0.	1.000	306943.
5	12	1461197.	9327.	59668.	68995.	0.	1.000	345762.
5	13	1461197.	4386.	40531.	44916.	0.	1.000	348298.
5	14	1399518.	1281.	26159.	27440.	0.	1.000	315801.
5	15	1256945.	224.	25782.	26006.	0.	1.000	245120.
5	16	1021696.	1287.	34801.	36088.	0.	1.000	138685.
5	17	708120.	4397.	56954.	61351.	0.	1.000	12927.
5	18	352422.	9344.	88761.	98104.	0.	1.000	0.
5	19	132139.	15788.	124657.	140445.	-8306.	.941	0.
5	20	5436.	23293.	162510.	185802.	-180367.	.029	0.
5	21	0.	31345.	196455.	227800.	-227800.	0.000	0.
5	22	0.	39396.	234073.	273469.	-273469.	0.000	0.
5	23	0.	46898.	267108.	314006.	-314006.	0.000	0.
5	24	0.	53339.	299909.	353248.	-353248.	0.000	0.
TOTAL OF DAY		12674944.	751993.	4426250.	5178243.	-3511064.	.322	2064695.

FRACTION SUPPLIED BY SOLAR .588

TABLE I.6

(A) MONTH	(B) HOUR	(C) PASSIVE SOLAR	(D) INFILT -RATION	(E) TRANSMTN LOSSES	(F) TOTAL LOSSES	(G) SUPLMENTL HEAT REQD	(H) FRACTN LOAD	(I) SOLAR COLECTED
6	1	0.	34930.	215190.	250120.	-250120.	0.000	0.
6	2	0.	37923.	228477.	266400.	-266400.	0.000	0.
6	3	0.	38943.	233172.	272114.	-272114.	0.000	0.
6	4	0.	37918.	228476.	266394.	-266394.	0.000	0.
6	5	56966.	34919.	214186.	249105.	-192139.	.229	0.
6	6	186035.	30151.	186716.	216867.	-30831.	.858	0.
6	7	454220.	23938.	154655.	178592.	0.	1.000	0.
6	8	869294.	16704.	113436.	130140.	0.	1.000	2008.
6	9	1187575.	8941.	71523.	80464.	0.	1.000	135896.
6	10	1423689.	1180.	30329.	31509.	0.	1.000	250949.
6	11	1566934.	0.	0.	0.	0.	0.000	329937.
6	12	1628982.	0.	0.	0.	0.	0.000	370707.
6	13	1628982.	0.	0.	0.	0.	0.000	373300.
6	14	1566934.	0.	0.	0.	0.	0.000	338991.
6	15	1423689.	0.	0.	0.	0.	0.000	265118.
6	16	1187575.	0.	0.	0.	0.	0.000	154466.
6	17	869294.	0.	0.	0.	0.	0.000	22987.
6	18	454220.	0.	0.	0.	0.	0.000	0.
6	19	186035.	0.	22007.	22007.	0.	1.000	0.
6	20	56966.	1201.	58905.	60106.	-3140.	.948	0.
6	21	0.	8963.	96639.	105602.	-105602.	0.000	0.
6	22	0.	16725.	130559.	147284.	-147284.	0.000	0.
6	23	0.	23957.	163500.	187457.	-187457.	0.000	0.
6	24	0.	30166.	191746.	221913.	-221913.	0.000	0.
TOTAL OF DAY		14747389.	346559.	2339516.	2686075.	-1943394.	.276	2244358.

FRACTION SUPPLIED BY SOLAR 1.155

TABLE I.7

(A) MONTH	(B) HOUR	(C) PASSIVE SOLAR	(D) INFILT -RATION	(E) TRANSMTN LOSSES	(F) TOTAL LOSSES	(G) SUPLMENTL HEAT REQD	(H) FRACTN LOAD	(I) SOLAR COLECTED
7	1	0.	19492.	144687.	164178.	-164178.	0.000	0.
7	2	0.	22883.	162473.	185356.	-185356.	0.000	0.
7	3	0.	24037.	167250.	191287.	-191287.	0.000	0.
7	4	0.	22876.	162473.	185349.	-185349.	0.000	0.
7	5	32644.	19479.	144332.	163811.	-131168.	.199	0.
7	6	162122.	14077.	116086.	130163.	0.	1.000	0.
7	7	410166.	7039.	79206.	86245.	0.	1.000	0.
7	8	802466.	0.	33298.	33298.	0.	1.000	15621.
7	9	1122946.	0.	0.	0.	0.	0.000	149784.
7	10	1361663.	0.	0.	0.	0.	0.000	264953.
7	11	1506306.	0.	0.	0.	0.	0.000	344131.
7	12	1568873.	0.	0.	0.	0.	0.000	384605.
7	13	1568873.	0.	0.	0.	0.	0.000	387918.
7	14	1506306.	0.	0.	0.	0.	0.000	354050.
7	15	1361663.	0.	0.	0.	0.	0.000	280750.
7	16	1122946.	0.	0.	0.	0.	0.000	170052.
7	17	802466.	0.	0.	0.	0.	0.000	39612.
7	18	410166.	0.	0.	0.	0.	0.000	0.
7	19	162122.	0.	0.	0.	0.	0.000	0.
7	20	32644.	0.	0.	0.	0.	0.000	0.
7	21	0.	0.	11947.	11947.	-11947.	0.000	0.
7	22	0.	0.	50492.	50492.	-50492.	0.000	0.
7	23	0.	7061.	88193.	95254.	-95254.	0.000	0.
7	24	0.	14095.	120185.	134281.	-134281.	0.000	0.
TOTAL OF DAY		13934370.	151038.	1280622.	1431660.	-1149310.	.197	2391476.

FRACTION SUPPLIED BY SOLAR 2.081

TABLE I.8

(A) MONTH	(B) HOUR	(C) PASSIVE SOLAR	(D) INFILT -RATION	(E) TRANSMTN LOSSES	(F) TOTAL LOSSES	(G) SUPLMENTL HEAT REQD	(H) FRACTN LOAD	(I) SOLAR COLECTED
8	1	0.	10921.	114368.	125289.	-125289.	0.000	0.
8	2	0.	13727.	124827.	138553.	-138553.	0.000	0.
8	3	0.	14682.	129516.	144197.	-144197.	0.000	0.
8	4	0.	13721.	124826.	138547.	-138547.	0.000	0.
8	5	0.	10911.	114367.	125278.	-125278.	0.000	0.
8	6	79536.	6441.	91527.	97969.	-18433.	.812	0.
8	7	302938.	618.	59218.	59835.	0.	1.000	0.
8	8	706691.	0.	18181.	18181.	0.	1.000	37568.
8	9	1112081.	0.	0.	0.	0.	0.000	206742.
8	10	1421975.	0.	0.	0.	0.	0.000	353626.
8	11	1609574.	0.	0.	0.	0.	0.000	453045.
8	12	1689680.	0.	0.	0.	0.	0.000	502415.
8	13	1689680.	0.	0.	0.	0.	0.000	505058.
8	14	1609574.	0.	0.	0.	0.	0.000	460960.
8	15	1421975.	0.	0.	0.	0.	0.000	366763.
8	16	1112081.	0.	0.	0.	0.	0.000	223714.
8	17	706691.	0.	0.	0.	0.	0.000	57011.
8	18	302938.	0.	0.	0.	0.	0.000	0.
8	19	79536.	0.	0.	0.	0.	0.000	0.
8	20	0.	0.	0.	0.	0.	0.000	0.
8	21	0.	0.	6031.	6031.	-6031.	0.000	0.
8	22	0.	0.	38976.	38976.	-38976.	0.000	0.
8	23	0.	636.	67343.	67979.	-67979.	0.000	0.
8	24	0.	6456.	95485.	101941.	-101941.	0.000	0.
TOTAL OF DAY		13844950.	78111.	984666.	1062777.	-905225.	.148	3166902.

FRACTION SUPPLIED BY SOLAR 3.498

TABLE I.9

(A) MONTH	(B) HOUR	(C) PASSIVE SOLAR	(D) INFILT -RATION	(E) TRANSMTN LOSSES	(F) TOTAL LOSSES	(G) SUPLMENTL HEAT REQD	(H) FRACTN LOAD	(I) SOLAR COLECTED
9	1	0.	35318.	218967.	254285.	-254285.	0.000	0.
9	2	0.	38356.	233119.	271475.	-271475.	0.000	0.
9	3	0.	39390.	237815.	277206.	-277206.	0.000	0.
9	4	0.	38350.	233119.	271469.	-271469.	0.000	0.
9	5	0.	35307.	218966.	254273.	-254273.	0.000	0.
9	6	0.	30467.	195516.	225983.	-225983.	0.000	0.
9	7	111377.	24161.	163446.	187608.	-76230.	.594	0.
9	8	439261.	16819.	124960.	141779.	0.	1.000	11801.
9	9	872401.	8941.	79152.	88093.	0.	1.000	220212.
9	10	1234843.	1064.	33627.	34691.	0.	1.000	405003.
9	11	1458776.	0.	0.	0.	0.	0.000	526185.
9	12	1553617.	0.	0.	0.	0.	0.000	584510.
9	13	1553617.	0.	0.	0.	0.	0.000	587099.
9	14	1458776.	0.	0.	0.	0.	0.000	535230.
9	15	1234843.	0.	0.	0.	0.	0.000	418506.
9	16	872401.	0.	0.	0.	0.	0.000	238744.
9	17	439261.	0.	0.	0.	0.	0.000	32714.
9	18	111377.	0.	0.	0.	0.	0.000	0.
9	19	0.	0.	30689.	30689.	-30689.	0.000	0.
9	20	0.	1085.	63640.	64726.	-64726.	0.000	0.
9	21	0.	8964.	96709.	105673.	-105673.	0.000	0.
9	22	0.	16841.	134312.	151153.	-151153.	0.000	0.
9	23	0.	24181.	167263.	191444.	-191444.	0.000	0.
9	24	0.	30483.	195517.	226000.	-226000.	0.000	0.
TOTAL OF DAY		11340550.	349727.	2426818.	2776545.	-2400605.	.135	3560004.

FRACTION SUPPLIED BY SOLAR 1.483

TABLE I.10

(A) MONTH	(B) HOUR	(C) PASSIVE SOLAR	(D) INFILT -RATION	(E) TRANSMTN LOSSES	(F) TOTAL LOSSES	(G) SUPLMENTL HEAT REQD	(H) FRACTN LOAD	(I) SOLAR COLECTED
10	1	0.	72078.	384658.	456737.	-456737.	0.000	0.
10	2	0.	74607.	394161.	468768.	-468768.	0.000	0.
10	3	0.	75468.	398842.	474310.	-474310.	0.000	0.
10	4	0.	74602.	394161.	468763.	-468763.	0.000	0.
10	5	0.	72069.	384657.	456726.	-456726.	0.000	0.
10	6	0.	68041.	365883.	433924.	-433924.	0.000	0.
10	7	0.	62792.	342326.	405118.	-405118.	0.000	0.
10	8	161096.	56681.	309626.	366307.	-205211.	.440	0.
10	9	552982.	50123.	272282.	322406.	0.	1.000	162913.
10	10	953555.	43567.	235080.	278647.	0.	1.000	411389.
10	11	1215111.	37457.	203100.	240557.	0.	1.000	570205.
10	12	1325150.	32212.	179107.	211319.	0.	1.000	640156.
10	13	1325150.	28187.	160263.	188451.	0.	1.000	642624.
10	14	1215111.	25659.	150547.	176206.	0.	1.000	576981.
10	15	953555.	24798.	150329.	175127.	0.	1.000	422436.
10	16	552982.	25664.	163074.	188737.	0.	1.000	176947.
10	17	161096.	28197.	182151.	210348.	-49252.	.766	0.
10	18	0.	32225.	201207.	233432.	-233432.	0.000	0.
10	19	0.	37474.	224694.	262168.	-262168.	0.000	0.
10	20	0.	43585.	252932.	296516.	-296516.	0.000	0.
10	21	0.	50142.	284952.	335094.	-335094.	0.000	0.
10	22	0.	56699.	314090.	370789.	-370789.	0.000	0.
10	23	0.	62809.	342328.	405136.	-405136.	0.000	0.
10	24	0.	68054.	365884.	433938.	-433938.	0.000	0.
TOTAL OF DAY		8415789.	1203189.	6656335.	7859524.	-5755883.	.268	3603652.

FRACTION SUPPLIED BY SOLAR .626

TABLE I.11

(A) MONTH	(B) HOUR	(C) PASSIVE SOLAR	(D) INFILT -RATION	(E) TRANSMTN LOSSES	(F) TOTAL LOSSES	(G) SUPLMENTL HEAT REQD	(H) FRACTN LOAD	(I) SOLAR COLECTED
11	1	0.	99760.	511639.	611399.	-611399.	0.000	0.
11	2	0.	101941.	521110.	623051.	-623051.	0.000	0.
11	3	0.	102683.	522038.	624721.	-624721.	0.000	0.
11	4	0.	101936.	521110.	623047.	-623047.	0.000	0.
11	5	0.	99752.	511638.	611390.	-611390.	0.000	0.
11	6	0.	96279.	493774.	590053.	-590053.	0.000	0.
11	7	0.	91754.	474024.	565778.	-565778.	0.000	0.
11	8	0.	86485.	450466.	536951.	-536951.	0.000	0.
11	9	199892.	80831.	422269.	503100.	-303208.	.397	0.
11	10	541968.	75178.	389751.	464929.	0.	1.000	233430.
11	11	791394.	69910.	361730.	431641.	0.	1.000	416715.
11	12	896506.	65388.	338591.	403979.	0.	1.000	491062.
11	13	896506.	61918.	320586.	382504.	0.	1.000	493443.
11	14	791394.	59738.	314715.	374453.	0.	1.000	422653.
11	15	541968.	58996.	314508.	373503.	0.	1.000	242901.
11	16	199892.	59742.	323710.	383453.	-183561.	.521	0.
11	17	0.	61926.	337575.	399501.	-399501.	0.000	0.
11	18	0.	65399.	351766.	417165.	-417165.	0.000	0.
11	19	0.	69924.	375189.	445113.	-445113.	0.000	0.
11	20	0.	75194.	398747.	473941.	-473941.	0.000	0.
11	21	0.	80847.	423201.	504049.	-504049.	0.000	0.
11	22	0.	86501.	450467.	536968.	-536968.	0.000	0.
11	23	0.	91768.	474026.	565794.	-565794.	0.000	0.
11	24	0.	96291.	493775.	590066.	-590066.	0.000	0.
TOTAL OF DAY		4859520.	1940143.	10096406.	12036549.	-9205756.	.235	2300204.

FRACTION SUPPLIED BY SOLAR .250

TABLE I.12

(A) MONTH	(B) HOUR	(C) PASSIVE SOLAR	(D) INFILT -RATION	(E) TRANSMTN LOSSES	(F) TOTAL LOSSES	(G) SUPLMENTL HEAT REQD	(H) FRACTN LOAD	(I) SOLAR COLECTED
12	1	0.	122646.	616034.	738680.	-738680.	0.000	0.
12	2	0.	124617.	625487.	750103.	-750103.	0.000	0.
12	3	0.	125287.	630080.	755368.	-755368.	0.000	0.
12	4	0.	124613.	625486.	750099.	-750099.	0.000	0.
12	5	0.	122639.	616033.	738672.	-738672.	0.000	0.
12	6	0.	119501.	601942.	721442.	-721442.	0.000	0.
12	7	0.	115411.	583092.	698503.	-698503.	0.000	0.
12	8	0.	110650.	559648.	670298.	-670298.	0.000	0.
12	9	81444.	105540.	536104.	641644.	-560200.	.127	0.
12	10	413640.	100432.	508097.	608529.	-194889.	.680	166724.
12	11	680678.	95671.	484006.	579677.	0.	1.000	390514.
12	12	793540.	91584.	461625.	553209.	0.	1.000	477614.
12	13	793540.	88449.	447464.	535913.	0.	1.000	479349.
12	14	680678.	86479.	441682.	528160.	0.	1.000	395709.
12	15	413640.	85808.	442059.	527866.	-114227.	.784	174783.
12	16	81444.	86482.	446793.	533275.	-451831.	.153	0.
12	17	0.	88456.	459849.	548305.	-548305.	0.000	0.
12	18	0.	91595.	474871.	566466.	-566466.	0.000	0.
12	19	0.	95684.	493651.	589335.	-589335.	0.000	0.
12	20	0.	100446.	512631.	613076.	-613076.	0.000	0.
12	21	0.	105555.	536105.	641660.	-641660.	0.000	0.
12	22	0.	110664.	559650.	670313.	-670313.	0.000	0.
12	23	0.	115424.	583093.	698517.	-698517.	0.000	0.
12	24	0.	119511.	601943.	721454.	-721454.	0.000	0.
TOTAL OF DAY		3938605.	2533143.	12847423.	15380566.	-12193439.	.207	2084692.

FRACTION SUPPLIED BY SOLAR .171

APPENDIX J

HOURLY SIMULATION MODELS

FOR A

SOLAR-SHED GREENHOUSE/HOG BARN COMBINATION

HALIFAX, N.S.

(CASE STUDY V)

MINIMUM GREENHOUSE TEMPERATURE: 15°C.

(A):	MONTH OF THE YEAR	-
(B):	HOUR FROM MIDNIGHT	-
(C):	SOLAR RADIATION CAPTURED BY PLANT CANOPY	kJ
(D):	ANIMAL HEAT RECOVERY FROM HOG BARN	kJ
(E):	TRANSMISSION HEAT LOSS BY GREENHOUSE	kJ
(F):	HEATING LOAD WHEN SOLAR ENERGY CAPTURED BY THE GREENHOUSE IS CONSIDRED = (E)-(C)	kJ
(G):	ACTUAL SUPPLEMENTAL HEAT REQUIREMENT WHEN HEATING FROM LIVESTOCK VENTILATION IS CONSIDERED = (F)-(D)	kJ
(H):	FRACTION OF TRANSMISSION LOSS SUPPLIED BY SOLAR = (C)/(E)	
(I):	SOLAR RADIATION CAPTURED BY INTEGRAL SOLAR COLLECTOR	kJ
(J):	FRACTION OF HEATING LOAD SUPPLIED BY VENTILATION AIR	-

TABLE J.1

(A) MONTH	(B) HOUR	(C) PASSIVE SOLAR	(D) BARN HEAT	(E) TRANSMTN LOSSES	(F) TOTAL LOSSES	(G) SUPLMENTL HEAT REQD	(H) FRACTN LOAD	(I) SOLAR COLECTED	(J) FRACTN BY VETLN
1	1	0.	167400.	862036.	862036.	694635.	0.000	0.	.194
1	2	0.	164919.	875805.	875805.	710886.	0.000	0.	.188
1	3	0.	164097.	880396.	880396.	716299.	0.000	0.	.186
1	4	0.	164924.	875804.	875804.	710881.	0.000	0.	.188
1	5	0.	167409.	862035.	862035.	694625.	0.000	0.	.194
1	6	0.	171507.	839099.	839099.	667592.	0.000	0.	.204
1	7	0.	177147.	811548.	811548.	634400.	0.000	0.	.218
1	8	2681.	184175.	778544.	775864.	591688.	.003	0.	.237
1	9	208777.	192426.	733054.	524277.	331851.	.285	0.	.367
1	10	541041.	201403.	686844.	145803.	0.	.788	145805.	1.000
1	11	780807.	210517.	641807.	0.	0.	1.000	303607.	0.000
1	12	883116.	218969.	610006.	0.	0.	1.000	367605.	0.000
1	13	883116.	225882.	590884.	0.	0.	1.000	369833.	0.000
1	14	780807.	230417.	581082.	0.	0.	1.000	310831.	0.000
1	15	541041.	231940.	584993.	43953.	0.	.925	157957.	1.000
1	16	208777.	230243.	603482.	394705.	164462.	.346	0.	.583
1	17	2681.	225576.	626178.	623497.	397921.	.004	0.	.362
1	18	0.	218666.	645441.	645441.	426775.	0.000	0.	.339
1	19	0.	210252.	676665.	676665.	466413.	0.000	0.	.311
1	20	0.	201220.	708807.	708807.	507587.	0.000	0.	.284
1	21	0.	192322.	741840.	741840.	549518.	0.000	0.	.259
1	22	0.	184154.	778546.	778546.	594392.	0.000	0.	.237
1	23	0.	177130.	811549.	811549.	634419.	0.000	0.	.218
1	24	0.	171493.	839099.	839099.	667606.	0.000	0.	.204
TOTAL OF DAY		4832842.	4684189.	17645543.	13716768.	10161951.	.223	1655637.	.265

FRACTION SUPPLIED BY SOLAR .163

TABLE J.2

(A) MONTH	(B) HOUR	(C) PASSIVE SOLAR	(D) BARN HEAT	(E) TRANSMTN LOSSES	(F) TOTAL LOSSES	(G) SUPLMENTL HEAT REQD	(H) FRACTN LOAD	(I) SOLAR COLECTED	(J) FRACTN BY VETLN
2	1	0.	165449.	875768.	875768.	710319.	0.000	0.	.189
2	2	0.	163022.	889537.	889537.	726516.	0.000	0.	.183
2	3	0.	162218.	894128.	894128.	731911.	0.000	0.	.181
2	4	0.	163026.	889537.	889537.	726511.	0.000	0.	.183
2	5	0.	165458.	875768.	875768.	710310.	0.000	0.	.189
2	6	0.	169463.	852831.	852831.	683368.	0.000	0.	.199
2	7	0.	174974.	825280.	825280.	650306.	0.000	0.	.212
2	8	100176.	181890.	788462.	688286.	506397.	.127	0.	.264
2	9	435040.	189966.	742111.	307071.	117105.	.586	6595.	.619
2	10	792171.	198741.	692369.	0.	0.	1.000	212460.	0.000
2	11	1030046.	207614.	651584.	0.	0.	1.000	342737.	0.000
2	12	1131846.	215834.	619924.	0.	0.	1.000	399681.	0.000
2	13	1131846.	222551.	596988.	0.	0.	1.000	402463.	0.000
2	14	1030046.	226955.	587186.	0.	0.	1.000	350503.	0.000
2	15	792171.	228416.	590519.	0.	0.	1.000	224599.	0.000
2	16	435040.	226753.	608146.	173106.	0.	.715	22464.	1.000
2	17	100176.	222192.	635376.	535200.	313008.	.158	0.	.415
2	18	0.	215432.	659174.	659174.	443742.	0.000	0.	.327
2	19	0.	207253.	686725.	686725.	479472.	0.000	0.	.302
2	20	0.	198448.	723401.	723401.	524953.	0.000	0.	.274
2	21	0.	189779.	755573.	755573.	565793.	0.000	0.	.251
2	22	0.	181828.	792278.	792278.	610451.	0.000	0.	.229
2	23	0.	174957.	825281.	825281.	650325.	0.000	0.	.212
2	24	0.	169450.	852832.	852832.	683382.	0.000	0.	.199
TOTAL OF DAY		6978559.	4621666.	17910779.	13101778.	9833869.	.268	1961503.	.258

FRACTION SUPPLIED BY SOLAR .199

TABLE J.3

(A) MONTH	(B) HOUR	(C) PASSIVE SOLAR	(D) BARN HEAT	(E) TRANSMIN LOSSES	(F) TOTAL LOSSES	(G) SUPLMENTL HEAT REOD	(H) FRACTN LOAD	(I) SOLAR COLECTED	(J) FRACTN BY VETLN
3	1	0.	192848.	741804.	741804.	548956.	0.000	0.	.260
3	2	0.	189811.	755562.	755562.	565752.	0.000	0.	.251
3	3	0.	188786.	760150.	760150.	571364.	0.000	0.	.248
3	4	0.	189816.	755562.	755562.	565746.	0.000	0.	.251
3	5	0.	192859.	741803.	741803.	548944.	0.000	0.	.260
3	6	0.	197907.	723418.	723418.	525512.	0.000	0.	.274
3	7	49716.	204915.	695890.	646174.	441259.	.071	0.	.317
3	8	338072.	213780.	650750.	312677.	98898.	.520	0.	.684
3	9	765482.	224175.	605145.	0.	0.	1.000	115248.	0.000
3	10	1145040.	235544.	560108.	0.	0.	1.000	296271.	0.000
3	11	1384483.	247127.	519632.	0.	0.	1.000	414108.	0.000
3	12	1486940.	257940.	488572.	0.	0.	1.000	469322.	0.000
3	13	1486940.	266857.	469468.	0.	0.	1.000	471617.	0.000
3	14	1384483.	272747.	459677.	0.	0.	1.000	421547.	0.000
3	15	1145040.	274698.	463014.	0.	0.	1.000	308223.	0.000
3	16	765482.	272474.	480637.	0.	0.	1.000	130498.	0.000
3	17	338072.	266363.	506995.	168923.	0.	.667	0.	1.000
3	18	49716.	257292.	538983.	489267.	231974.	.092	0.	.526
3	19	0.	246488.	566511.	566511.	320024.	0.000	0.	.435
3	20	0.	235030.	598627.	598627.	363597.	0.000	0.	.393
3	21	0.	223802.	631632.	631632.	407830.	0.000	0.	.354
3	22	0.	213593.	663775.	663775.	450182.	0.000	0.	.322
3	23	0.	204855.	695891.	695891.	491036.	0.000	0.	.294
3	24	0.	197890.	723419.	723419.	525529.	0.000	0.	.274
TOTAL OF DAY		10339468.	5467597.	14797026.	9975196.	6656600.	.326	2626835.	.370

FRACTION SUPPLIED BY SOLAR .395

TABLE J.4

(A) MONTH	(B) HOUR	(C) PASSIVE SOLAR	(D) BARN HEAT	(E) TRANSMTN LOSSES	(F) TOTAL LOSSES	(G) SUPLMENTL HEAT REQD	(H) FRACTN LOAD	(I) SOLAR COLECTED	(J) FRACTN BY VETLN
4	1	0.	241329.	575737.	575737.	334408.	0.000	0.	.419
4	2	0.	236128.	594047.	594047.	357919.	0.000	0.	.397
4	3	0.	234409.	598640.	598640.	364232.	0.000	0.	.392
4	4	0.	236138.	594047.	594047.	357909.	0.000	0.	.398
4	5	0.	241348.	575737.	575737.	334388.	0.000	0.	.419
4	6	17119.	250119.	552790.	535672.	285552.	.031	0.	.467
4	7	192634.	262658.	520408.	327774.	65116.	.370	0.	.801
4	8	519078.	278886.	471695.	0.	0.	1.000	0.	0.000
4	9	891887.	298564.	426046.	0.	0.	1.000	92302.	0.000
4	10	1189726.	321082.	377149.	0.	0.	1.000	220394.	0.000
4	11	1373100.	345152.	336206.	0.	0.	1.000	306830.	0.000
4	12	1452412.	368770.	304532.	0.	0.	1.000	349718.	0.000
4	13	1452412.	389129.	281586.	0.	0.	1.000	352714.	0.000
4	14	1373100.	403022.	271200.	0.	0.	1.000	315197.	0.000
4	15	1189726.	407858.	270716.	0.	0.	1.000	234074.	0.000
4	16	891887.	402658.	283953.	0.	0.	1.000	110604.	0.000
4	17	519078.	388419.	310329.	0.	0.	1.000	0.	0.000
4	18	192634.	367829.	346016.	153383.	0.	.557	0.	1.000
4	19	17119.	344105.	382071.	364953.	20848.	.045	0.	.943
4	20	0.	320179.	418763.	418763.	98584.	0.000	0.	.765
4	21	0.	297908.	455485.	455485.	157578.	0.000	0.	.654
4	22	0.	278457.	492208.	492208.	213751.	0.000	0.	.566
4	23	0.	262460.	525227.	525227.	262767.	0.000	0.	.500
4	24	0.	250090.	556464.	556464.	306374.	0.000	0.	.449
TOTAL OF DAY		11271912.	7426696.	10521053.	6768137.	3159426.	.357	1981833.	.706

FRACTION SUPPLIED BY SOLAR .627

TABLE J.5

(A) MONTH	(B) HOUR	(C) PASSIVE SOLAR	(D) BARN HEAT	(E) TRANSMTN LOSSES	(F) TOTAL LOSSES	(G) SUPLMENTL HEAT REQD	(H) FRACTN LOAD	(I) SOLAR COLECTED	(J) FRACTN BY VETLN
5	1	0.	320179.	414212.	414212.	94033.	0.000	0.	.773
5	2	0.	309781.	431689.	431689.	121908.	C.000	0.	.718
5	3	0.	306377.	437153.	437153.	130776.	0.000	0.	.701
5	4	0.	309800.	431689.	431689.	121889.	0.000	0.	.718
5	5	0.	320219.	414211.	414211.	93993.	C.000	0.	.773
5	6	108069.	338436.	386403.	278333.	0.	.280	0.	1.000
5	7	314707.	365488.	341363.	26656.	0.	.922	0.	1.000
5	8	680312.	402737.	291862.	0.	0.	1.000	0.	C.000
5	9	1012456.	451835.	237791.	0.	0.	1.000	87895.	C.000
5	10	1266034.	514093.	187818.	0.	0.	1.000	196345.	0.000
5	11	1421458.	589378.	143134.	0.	0.	1.000	271881.	0.000
5	12	1489342.	673751.	106149.	0.	0.	1.000	310838.	C.000
5	13	1489342.	756482.	79343.	0.	0.	1.000	3146C3.	C.000
5	14	1421458.	819552.	64536.	0.	0.	1.000	282520.	0.000
5	15	1266034.	843261.	63901.	0.	0.	1.000	213153.	C.000
5	16	1012456.	818748.	80820.	0.	0.	1.000	108895.	C.000
5	17	680312.	755090.	107366.	0.	0.	1.000	0.	C.000
5	18	314707.	671926.	143099.	0.	0.	1.000	0.	C.000
5	19	108069.	587402.	188138.	80069.	0.	.574	0.	1.000
5	20	0.	512263.	229716.	229716.	0.	C.000	0.	1.000
5	21	0.	450438.	271045.	271045.	0.	0.000	0.	1.000
5	22	0.	401780.	316909.	316909.	0.	0.000	0.	1.000
5	23	0.	364932.	354530.	354530.	0.	0.000	0.	1.000
5	24	0.	338208.	390360.	390360.	52152.	0.000	0.	.866
TOTAL OF DAY		12584757.	12222157.	6113236.	4076572.	614751.	.333	1786131.	1.999

FRACTION SUPPLIED BY SOLAR 2.905

TABLE J.6

(A) MONTH	(B) HOUR	(C) PASSIVE SOLAR	(D) BARN HEAT	(E) TRANSMTN LOSSES	(F) TOTAL LOSSES	(G) SUPLMENTL HEAT REQD	(H) FRACTN LOAD	(I) SOLAR COLECTED	(J) FRACTN BY VETLN
6	1	0.	470815.	257237.	257237.	0.	0.000	0.	1.000
6	2	0.	448849.	274714.	274714.	0.	C.000	0.	1.000
6	3	0.	441858.	280178.	280178.	0.	0.000	0.	1.000
6	4	0.	448889.	274714.	274714.	0.	0.000	0.	1.000
6	5	19681.	470947.	257095.	237414.	0.	.077	0.	1.000
6	6	158082.	511077.	224752.	66670.	0.	.703	0.	1.000
6	7	401863.	574540.	183963.	0.	0.	1.00C	0.	C.000
6	8	825874.	670881.	130789.	0.	0.	1.000	0.	0.000
6	9	1186475.	817098.	77001.	0.	0.	1.000	107531.	0.000
6	10	1446588.	1043097.	23355.	0.	0.	1.COC	222420.	0.000
6	11	1606333.	1403006.	0.	0.	0.	0.0C0	302568.	C.000
6	12	1676281.	1990516.	0.	0.	0.	0.000	344196.	C.000
6	13	1676281.	2928649.	0.	0.	0.	C.000	3481C4.	0.000
6	14	1606333.	3263719.	0.	0.	0.	0.000	312958.	0.000
6	15	1446588.	3263719.	0.	0.	0.	0.000	239218.	C.00C
6	16	1186475.	3263719.	0.	0.	0.	0.000	129967.	0.000
6	17	825874.	2920561.	C.	0.	0.	0.000	18159.	0.000
6	18	401863.	1983485.	0.	0.	0.	0.000	0.	C.000
6	19	158082.	1397154.	27207.	0.	0.	1.000	0.	C.000
6	20	19681.	1038353.	72741.	53C60.	0.	.271	0.	1.000
6	21	0.	813801.	118604.	118604.	0.	0.000	0.	1.000
6	22	0.	668754.	159934.	159934.	0.	C.C00	0.	1.000
6	23	C.	573254.	197555.	197555.	0.	0.000	0.	1.000
6	24	0.	510449.	233385.	233385.	0.	C.000	0.	1.C00
TOTAL OF DAY		14642352.	10899816.	2793224.	2153465.	0.	.229	2025120.	3.902

FRACTION SUPPLIED BY SOLAR C.000

TABLE J.7

(A) MONTH	(B) HOUR	(C) PASSIVE SOLAR	(D) BARN HEAT	(E) TRANSMTN LOSSES	(F) TOTAL LOSSES	(G) SUPLMENTL HEAT REQD	(H) FRACTN LOAD	(I) SOLAR COLECTED	(J) FRACTN BY VETLN
7	1	0.	816026.	122264.	122264.	0.	0.000	0.	1.000
7	2	0.	752115.	136931.	136931.	0.	0.000	0.	1.000
7	3	0.	732541.	141535.	141535.	0.	0.000	0.	1.000
7	4	0.	752228.	136931.	136931.	0.	0.000	0.	1.000
7	5	75.	816282.	122263.	122188.	0.	.001	0.	1.000
7	6	136105.	944543.	89917.	0.	0.	1.000	0.	0.000
7	7	364107.	1186290.	45450.	0.	0.	1.000	0.	0.000
7	8	770784.	1685942.	0.	0.	0.	0.000	5495.	0.000
7	9	1117441.	3062689.	0.	0.	0.	0.000	130144.	0.000
7	10	1377796.	3263719.	0.	0.	0.	0.000	243898.	0.000
7	11	1537442.	3263719.	0.	0.	0.	0.000	323064.	0.000
7	12	1607213.	3263719.	0.	0.	0.	0.000	364137.	0.000
7	13	1607213.	3263719.	0.	0.	0.	0.000	368168.	0.000
7	14	1537442.	3263719.	0.	0.	0.	0.000	334457.	0.000
7	15	1377796.	3263719.	0.	0.	0.	0.000	261224.	0.000
7	16	1117441.	3263719.	0.	0.	0.	0.000	153289.	0.000
7	17	770784.	3263719.	0.	0.	0.	0.000	31689.	0.000
7	18	364107.	3263719.	0.	0.	0.	0.000	0.	0.000
7	19	136105.	3263719.	0.	0.	0.	0.000	0.	0.000
7	20	75.	3263719.	0.	0.	0.	0.000	0.	0.000
7	21	0.	3045093.	0.	0.	0.	0.000	0.	0.000
7	22	0.	1679355.	21275.	21275.	0.	0.000	0.	1.000
7	23	0.	1183286.	62574.	62574.	0.	0.000	0.	1.000
7	24	0.	943266.	94735.	94735.	0.	0.000	0.	1.000
TOTAL OF DAY		13821926.	9805932.	973875.	838433.	0.	.139	2215565.	10.069

FRACTION SUPPLIED BY SOLAR C.000

TABLE J.8

(A) MONTH	(B) HOUR	(C) PASSIVE SOLAR	(D) BARN HEAT	(E) TRANSMTN LOSSES	(F) TOTAL LOSSES	(G) SUPLMENTL HEAT REQD	(H) FRACTN LOAD	(I) SOLAR COLECTED	(J) FRACTN BY VETLN
8	1	0.	915438.	99332.	99332.	0.	0.000	0.	1.000
8	2	0.	841272.	113984.	113984.	0.	0.000	0.	1.000
8	3	0.	818733.	118582.	118582.	0.	0.000	0.	1.000
8	4	0.	841402.	113983.	113983.	0.	0.000	0.	1.000
8	5	0.	915735.	99331.	99331.	0.	0.000	0.	1.000
8	6	58968.	1065218.	72545.	13578.	0.	.813	0.	1.000
8	7	271097.	1352820.	31642.	0.	0.	1.000	0.	0.000
8	8	674485.	1968532.	0.	0.	0.	0.000	23978.	0.000
8	9	1090225.	3263719.	0.	0.	0.	0.000	180917.	0.000
8	10	1413777.	3263719.	0.	0.	0.	0.000	320512.	0.000
8	11	1611663.	3263719.	0.	0.	0.	0.000	415979.	0.000
8	12	1697020.	3263719.	0.	0.	0.	0.000	464337.	0.000
8	13	1697020.	3263719.	0.	0.	0.	0.000	467702.	0.000
8	14	1611663.	3263719.	0.	0.	0.	0.000	426042.	0.000
8	15	1413777.	3263719.	0.	0.	0.	0.000	337198.	0.000
8	16	1090225.	3263719.	0.	0.	0.	0.000	202089.	0.000
8	17	674485.	3263719.	0.	0.	0.	0.000	48219.	0.000
8	18	271097.	3263719.	0.	0.	0.	0.000	0.	0.000
8	19	58968.	3263719.	0.	0.	0.	0.000	0.	0.000
8	20	0.	3263719.	0.	0.	0.	0.000	0.	0.000
8	21	0.	3263719.	0.	0.	0.	0.000	0.	0.000
8	22	0.	1961468.	7503.	7503.	0.	0.000	0.	1.000
8	23	0.	1350056.	44231.	44231.	0.	0.000	0.	1.000
8	24	0.	1064372.	76361.	76361.	0.	0.000	0.	1.000
TOTAL OF DAY		13634472.	11126515.	777494.	686884.	0.	.117	2886974.	14.311

FRACTION SUPPLIED BY SOLAR 0.000

TABLE J.9

(A) MONTH	(B) HOUR	(C) PASSIVE SOLAR	(D) BARN HEAT	(E) TRANSMTN LOSSES	(F) TOTAL LOSSES	(G) SUPLMENTL HEAT REQD	(H) FRACTN LOAD	(I) SOLAR COLECTED	(J) FRACTN BY VETLN
9	1	0.	564912.	202143.	202143.	0.	0.000	0.	1.000
9	2	0.	537222.	219596.	219596.	0.	0.000	0.	1.000
9	3	0.	528432.	224191.	224191.	0.	0.000	0.	1.000
9	4	0.	537273.	219596.	219596.	0.	0.000	0.	1.000
9	5	0.	565019.	202143.	202143.	0.	0.000	0.	1.000
9	6	0.	615394.	182862.	182862.	0.	0.000	0.	1.000
9	7	105927.	696345.	146220.	40294.	0.	.724	0.	1.000
9	8	422136.	822168.	100886.	0.	0.	1.000	0.	0.000
9	9	842658.	1018671.	47302.	0.	0.	1.000	182041.	0.000
9	10	1197383.	1336165.	0.	0.	0.	0.000	345971.	0.000
9	11	1418043.	1879167.	0.	0.	0.	0.000	453725.	0.000
9	12	1512526.	2880372.	0.	0.	0.	0.000	506301.	0.000
9	13	1512526.	3263719.	0.	0.	0.	0.000	509573.	0.000
9	14	1418043.	3263719.	0.	0.	0.	0.000	463511.	0.000
9	15	1197383.	3263719.	0.	0.	0.	0.000	360900.	0.000
9	16	842658.	3263719.	0.	0.	0.	0.000	201997.	0.000
9	17	422136.	3263719.	0.	0.	0.	0.000	20942.	0.000
9	18	105927.	2867813.	0.	0.	0.	0.000	0.	0.000
9	19	0.	1871097.	7557.	7557.	0.	0.000	0.	1.000
9	20	0.	1331229.	40586.	40586.	0.	0.000	0.	1.000
9	21	0.	1015778.	77320.	77320.	0.	0.000	0.	1.000
9	22	0.	820674.	117726.	117726.	0.	0.000	0.	1.000
9	23	0.	695634.	150756.	150756.	0.	0.000	0.	1.000
9	24	0.	615215.	182863.	182863.	0.	0.000	0.	1.000
TOTAL OF DAY		10997348.	12235264.	2121746.	1867632.	0.	.120	3044962.	5.767

FRACTION SUPPLIED BY SOLAR 0.000

TABLE J.10

(A) MONTH	(B) HOUR	(C) PASSIVE SOLAR	(D) BARN HEAT	(E) TRANSMTN LOSSES	(F) TOTAL LOSSES	(G) SUPLMENTL HEAT REQD	(H) FRACTN LOAD	(I) SOLAR COLECTED	(J) FRACTN BY VETLN
10	1	0.	346161.	377484.	377484.	31322.	0.000	0.	.917
10	2	0.	335954.	391255.	391255.	55301.	C.000	0.	.859
10	3	0.	332626.	395847.	395847.	63221.	0.000	0.	.840
10	4	0.	335973.	391255.	391255.	55282.	0.000	0.	.859
10	5	0.	346200.	377483.	377483.	31283.	0.000	0.	.917
10	6	0.	363766.	354543.	354543.	0.	C.00C	0.	1.000
10	7	0.	389468.	326988.	326988.	0.	0.000	0.	1.000
10	8	168019.	424485.	285772.	117753.	0.	.588	0.	1.C00
10	9	531298.	469699.	235600.	0.	0.	1.C00	111613.	0.000
10	10	892244.	525363.	185995.	0.	0.	1.000	311075.	C.000
10	11	1126967.	590170.	145204.	0.	0.	1.C00	437996.	C.000
10	12	1226981.	659751.	113681.	0.	0.	1.000	495046.	C.000
10	13	1226981.	725078.	90742.	0.	0.	1.000	498175.	C.C00
10	14	1126967.	772946.	80938.	0.	0.	1.000	446734.	0.000
10	15	892244.	790476.	84128.	0.	0.	1.00C	324734.	C.000
10	16	531298.	772051.	101756.	0.	0.	1.000	129477.	0.C00
10	17	168019.	723570.	132520.	0.	0.	1.000	0.	C.000
10	18	0.	658034.	160855.	160855.	0.	C.000	0.	1.C00
10	19	0.	588738.	188411.	188411.	0.	C.000	0.	1.000
10	20	0.	524285.	220558.	220558.	0.	0.000	0.	1.000
10	21	0.	469026.	257269.	257269.	0.	0.000	0.	1.000
10	22	0.	424187.	293980.	293980.	0.	0.000	0.	1.000
10	23	0.	389383.	326989.	326989.	0.	0.000	0.	1.000
10	24	0.	363706.	354544.	354544.	0.	0.C00	0.	1.000
TOTAL OF DAY		7891018.	12321096.	5873796.	4535212.	236408.	.228	2754851.	2.098

FRACTION SUPPLIED BY SOLAR 11.653

TABLE J.11

(A) MONTH	(B) HOUR	(C) PASSIVE SOLAR	(D) BARN HEAT	(E) TRANSMTN LOSSES	(F) TOTAL LOSSES	(G) SUPLMENTL HEAT REQD	(H) FRACTN LOAD	(I) SOLAR COLECTED	(J) FRACTN BY VETLN
11	1	0.	254865.	542713.	542713.	287848.	0.000	0.	.470
11	2	0.	249861.	552792.	552792.	302931.	0.000	0.	.452
11	3	0.	248208.	557377.	557377.	309169.	0.000	0.	.445
11	4	0.	249871.	552792.	552792.	302921.	0.000	0.	.452
11	5	0.	254884.	542713.	542713.	287829.	0.000	0.	.470
11	6	0.	263254.	520665.	520665.	257412.	0.000	0.	.506
11	7	0.	275001.	496823.	496823.	221822.	0.000	0.	.554
11	8	21540.	290053.	465584.	444044.	153991.	.046	0.	.653
11	9	209586.	308224.	428204.	218619.	0.	.489	0.	1.000
11	10	493211.	328729.	382900.	0.	0.	1.000	125384.	0.000
11	11	692712.	350344.	346549.	0.	0.	1.000	251811.	0.000
11	12	777863.	371205.	319317.	0.	0.	1.000	304112.	0.000
11	13	777863.	388880.	296551.	0.	0.	1.000	307095.	0.000
11	14	692712.	400816.	287191.	0.	0.	1.000	259552.	0.000
11	15	493211.	404924.	291108.	0.	0.	1.000	137236.	0.000
11	16	209586.	400505.	308729.	99144.	0.	.679	0.	1.000
11	17	21540.	388360.	327015.	305475.	0.	.066	0.	1.000
11	18	0.	370663.	349924.	349924.	0.	0.000	0.	1.000
11	19	0.	349879.	372905.	372905.	23026.	0.000	0.	.938
11	20	0.	328371.	405005.	405005.	76634.	0.000	0.	.811
11	21	0.	308011.	437132.	437132.	129120.	0.000	0.	.705
11	22	0.	290007.	469258.	469258.	179251.	0.000	0.	.618
11	23	0.	274964.	496824.	496824.	221861.	0.000	0.	.553
11	24	0.	263226.	520666.	520666.	257441.	0.000	0.	.506
TOTAL OF DAY		4389824.	7613105.	10270741.	7884873.	3011256.	.232	1385191.	.741

FRACTION SUPPLIED BY SOLAR .460

TABLE J.12

(A) MONTH	(B) HOUR	(C) PASSIVE SOLAR	(D) BARN HEAT	(E) TRANSMTN LOSSES	(F) TOTAL LOSSES	(G) SUPLMENTL HEAT REQD	(H) FRACTN LOAD	(I) SOLAR COLECTED	(J) FRACTN BY VETLN
12	1	0.	187324.	765627.	765627.	578302.	0.000	0.	.245
12	2	0.	184560.	779379.	779379.	594818.	0.000	0.	.237
12	3	0.	183636.	783102.	783102.	599466.	0.000	0.	.234
12	4	0.	184565.	779378.	779378.	594813.	0.000	0.	.237
12	5	0.	187335.	765626.	765626.	578291.	0.000	0.	.245
12	6	0.	191888.	746390.	746390.	554502.	0.000	0.	.257
12	7	0.	198163.	723409.	723409.	525247.	0.000	0.	.274
12	8	0.	205991.	691309.	691309.	485319.	0.000	0.	.298
12	9	108920.	215145.	654649.	545729.	330584.	.166	0.	.394
12	10	372158.	225110.	613159.	241001.	15891.	.607	39603.	.934
12	11	568982.	235251.	576806.	7826.	0.	.986	177787.	1.000
12	12	653085.	244634.	545184.	0.	0.	1.000	233141.	0.000
12	13	653085.	252332.	526668.	0.	0.	1.000	235404.	0.000
12	14	568982.	257384.	517167.	0.	0.	1.000	185122.	0.000
12	15	372158.	259088.	521084.	148926.	0.	.714	50832.	1.000
12	16	108920.	257217.	535174.	426254.	169037.	.204	0.	.603
12	17	0.	252067.	552740.	552740.	300673.	0.000	0.	.456
12	18	0.	244389.	571976.	571976.	327587.	0.000	0.	.427
12	19	0.	235012.	598630.	598630.	363618.	0.000	0.	.393
12	20	0.	224955.	627057.	627057.	402102.	0.000	0.	.359
12	21	0.	215059.	659184.	659184.	444125.	0.000	0.	.326
12	22	0.	205967.	691310.	691310.	485343.	0.000	0.	.298
12	23	0.	198143.	723410.	723410.	525267.	0.000	0.	.274
12	24	0.	191873.	746391.	746391.	554518.	0.000	0.	.257
TOTAL OF DAY		3406288.	5237088.	15694812.	12574656.	8429505.	.199	921890.	.334

FRACTION SUPPLIED BY SOLAR .109

APPENDIX K

DERIVATION OF EQUATIONS 9 & 11

OF

CHAPTER 4

DERIVATION OF EQUATION 9

(CHAPTER 4, PAGE 168)

Let $B_{v,\gamma}$ be the beam solar radiation incident on any vertical surface "i" of the greenhouse, having an azimuth angle "γ". Furthermore, let $D_{v,\gamma}$ be the diffuse component incident on that surface. Then, the beam and diffuse solar radiation transmitted through a unit area of greenhouse cover may respectively be written as:

$$B_{w,i} = B_{v,\gamma} \, \tau_{b,i} \quad , \qquad \text{(K.1)}$$

and

$$D_{w,i} = D_{v,\gamma} \, \tau_{d,i} \quad . \qquad \text{(K.2)}$$

The first absorption by a plant canopy having an effective albedo "ξ" to total solar radiation is given by

$$(B_{w,i} + D_{w,i})(1 - \xi) \quad , \qquad \text{(K.3)}$$

as shown in Figure K.1.

Now, assume that the radiation reflected by the plants and objects within the greenhouse is perfectly diffuse regardless of the form of the original incident radiation, then, the total solar radiation absorbed by the plant canopy after the first reflection by the cover may be calculated as:

$$(B_{w,i} + D_{w,i})(1 - \tau_{d,i} - \alpha_i)(1 - \xi)\xi \quad . \qquad \text{(K.4)}$$

The term $(1 - \tau_{d,i} - \alpha_i)$ in the above equation is simply the reflectance of the greenhouse cover to diffuse solar radiation.

If only the first reflection is taking into account, then the total solar radiation absorbed by the plants may be approximated by summing equations K.3 and K.4 to give,

$$I_{w,i} = (B_{w,i} + D_{w,i})(1 - \xi)[1 + \xi(1 - \tau_{d,i} - \alpha_i)] \ . \qquad (K.5)$$

The contribution of subsequent reflections to the solar radiation captured by the plants is negligible provided the transmittance of the covering material to diffuse solar radiation is high and the albedo of the plant canopy is low.

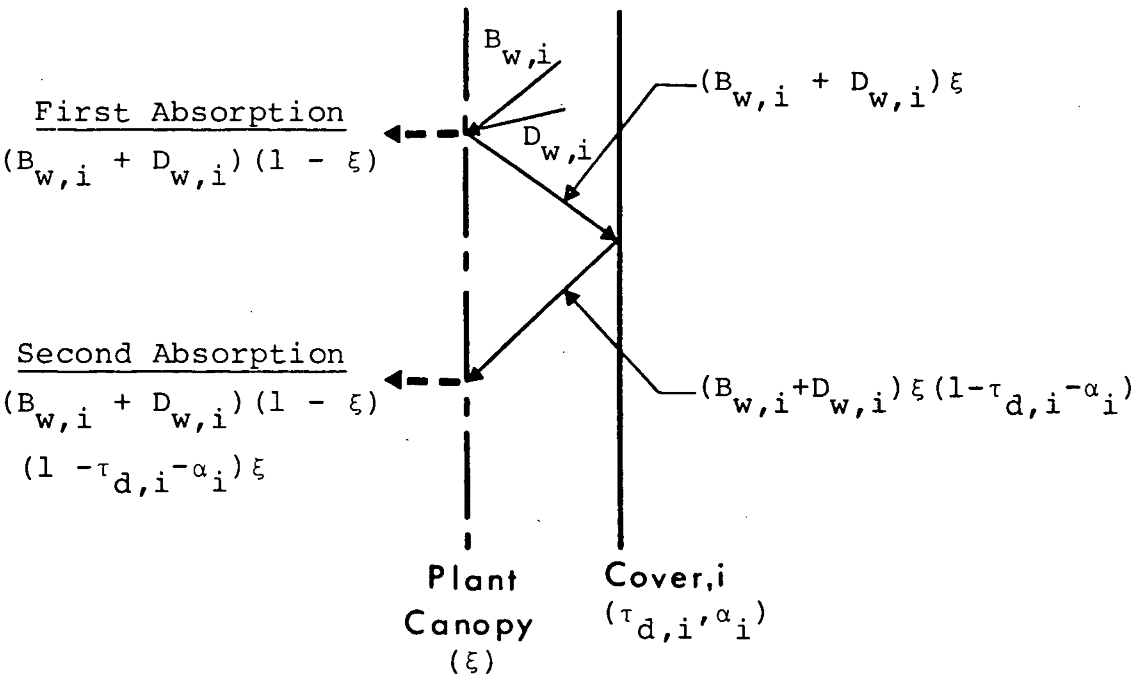


FIGURE K.1: BEAM AND DIFFUSE SOLAR RADIATION INPUT FROM A VERTICAL WALL OF A GREENHOUSE.

DERIVATION OF EQUATION 11

(CHAPTER 4, PAGE 169)

Let the diffuse component of solar radiation incident upon roof slope "j" of surface area $A_{r,j}$ be:

$$D_{r,j}\ A_{r,j} \quad ; \tag{K.6}$$

then, as shown in Figure K.2, the portion of the diffuse radiation originating from roof slope "j" that is directly incident on the plant canopy is given by,

$$A_{r,j}\ D_{r,j}\ \tau_{d,j}\ (1 - F_{r\rightarrow r}) \quad ; \tag{K.7}$$

and the portion incident on the opposite roof slope "j*" is,

$$A_{r,j}\ D_{r,j}\ \tau_{d,i}\ F_{r\rightarrow r} \quad . \tag{K.8}$$

It is clear, from the above two equations that their sum is equal to diffuse radiation transmitted through roof slope "j" or,

$$A_{r,j}\ D_{r,j}\ \tau_{d,j} \quad . \tag{K.9}$$

This, of course, implies that all the diffuse radiation transmitted by one roof slope is intercepted by the plants and by the opposite roof slope. Obviously, the above assumption is valid only if the fraction of diffuse radiation originating from the roof and intercepted by the gable end walls is small. Therefore, equations K.7 and K.8 are strictly applicable to long greenhouses.

Equation K.8 gives the diffuse radiation originating from one roof slope and incident on the other. However, not all that energy may be considered as loss, since a certain amount is reflected back on the plant canopy.

The amount of diffuse solar radiation transmitted through roof slope "j" and reflected by the opposite roof slope "j*" upon the plant canopy may be approximated by the following expression:

$$D_{r,j}\ \tau_{d,j}\ F_{r\rightarrow r}\ (1 - \tau_{d,j^*} - \alpha_{j^*})\ A_{r,j}\ F_{r\rightarrow p}\ . \qquad (K.10)$$

In the above equation, the symbols τ_{d,j^*} and α_{j^*} represents respectively the transmittance and absorptance of the opposite roof slope "j*" to diffuse solar radiation.

The total diffuse radiation originating from one roof slope and incident on the plant canopy is found by summing equations K.7 and K.10 to give,

$$A_{r,j}\ D_{r,j}\ \tau_{d,j}\ [(1 - F_{r\rightarrow r}) + F_{r\rightarrow r}(1 - \tau_{d,j^*} - \alpha_{j^*})\ F_{r\rightarrow p}]\ . \qquad (K.11)$$

Equation K.11 takes into account the first reflection only by the cover. The contribution of subsequent reflections to diffuse radiation incident on the plant canopy is considered negligible.

Furthermore, if all the beam radiation transmitted through the roof of the greenhouse is intercepted by the plants (i.e. low roof slope); then, the total solar radiation transmitted by roof slope "j" and incident on the plant canopy may be calculated as follows:

$$I_{r,j} = B_{r,j}\ \tau_{b,j}\ A_{r,j} + D_{r,j}\ \tau_{d,j}\ A_{r,j}$$
$$[(1 - F_{r\to r}) + F_{r\to r}\ (1 - \tau_{d,j*} - \alpha_{j*})F_{r\to p}]. \quad (K.12)$$

The same analysis applies for the radiation originating from the opposite roof slope.

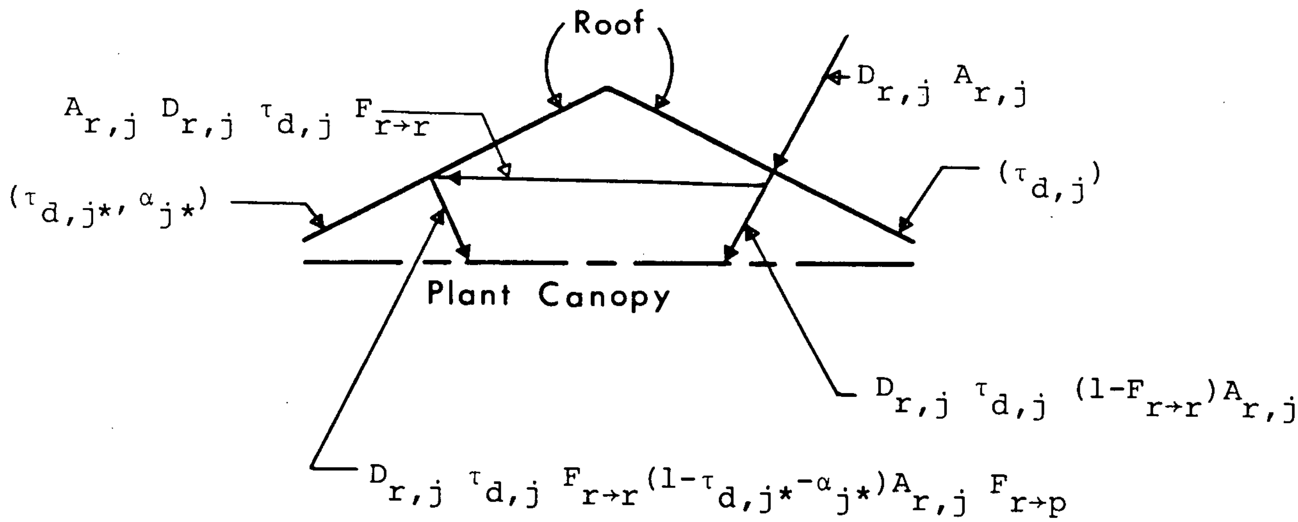


FIGURE K.2 DIFFUSE SOLAR RADIATION INPUT FROM A GABLE ROOF OF A GREENHOUSE.

NOMENCLATURE

Symbol	Definition	Units
$A_{r,j}$	Surface area of sloped roof "j"	m^2
$B_{r,j}$	Beam solar radiation incident on sloped roof "j"	$kJ \cdot h^{-1} \cdot m^{-2}$
$B_{v,\gamma}$	Beam solar radiation incident on a vertical wall of orientation γ	$kJ \cdot h^{-1} \cdot m^{-2}$
$B_{w,i}$	Beam solar radiation transmitted through any vertical wall "i"	$kJ \cdot h^{-1} \cdot m^{-2}$
$D_{r,j}$	Diffuse solar radiation incident on sloped roof "j"	$kJ \cdot h^{-1} \cdot m^{-2}$
$D_{v,\gamma}$	Diffuse solar radiation incident on a vertical surface of γ orientation	$kJ \cdot h^{-1} \cdot m^{-2}$
$D_{w,i}$	Diffuse solar radiation transmitted through any vertical wall i	$kJ \cdot h^{-1} \cdot m^{-2}$
$F_{r \rightarrow p}$	Radiation configuration factor between the roof and the plant canopy	
$F_{r \rightarrow r}$	Radiation configuration factor between the two slopes of the greenhouse roof	
$I_{r,j}$	Total solar radiation transmitted through roof slope "j" that is intercepted by the plant canopy	$kJ \cdot h^{-1}$

Symbol	Definition	Units
$I_{w,i}$	Total solar radiation transmitted through vertical wall "i" and absorbed by the plant canopy	$kJ \cdot h^{-1} \cdot m^{-2}$
$\tau_{b,i}$	Transmittance of wall "i" to beam solar radiation	
$\tau_{b,j}$	Transmittance of roof slope "j" to beam solar radiation	
$\tau_{d,i}$	Transmittance of wall "i" to diffuse solar radiation	
$\tau_{d,i}$	Transmittance of roof slope "j" to diffuse solar radiation	
α_i	Absorptance of wall "i" to solar radiation	
α_j	Absorptance of roof slope "j" to solar radiation	
γ	Orientation of the surface from due south	radians
ξ	Effective albedo of the plant canopy	

APPENDIX L

CALCULATION OF THE MEAN PLATE TEMPERATURE OF THE COLLECTOR FOR THE CONSTANT FLOW CASE

THEORY

A section of the air solar collector used in this study is shown schematically in Figure L.1. As indicated in the figure, the following heat flows are considered during the analysis:

i) Heat loss by thermal radiation from the top of the absorber plate to the greenhouse cover.

ii) Heat loss by natural convection from the top of the plate to the greenhouse air.

iii) Heat loss by forced convection from the back of the plate to the transport fluid.

iv) Radiative heat transfer between the back of the absorber plate and the insulated greenhouse north wall.

EVALUATION OF THE RADIATIVE HEAT TRANSFER COEFFICIENT BETWEEN COLLECTOR PLATE AND GREENHOUSE ROOF ($\bar{h}_{r,1}$):

The thermal radiation heat loss from the collector to the greenhouse roof may be calculated using equation 56 of Chapter 6 (page 251) as:

$$A_c\bar{h}_{r,1}\ (T_c-T_g) = A_r\ F_{r\to c}\ \sigma(T_c^{\ 4}-T_r^{\ 4})\ , \qquad \text{(L.1)}$$

$$= \sigma(T_c^{\ 4}-T_r^{\ 4})/[(1-\varepsilon_c)/\varepsilon_c A_c + (1/A_r F_{r\to c}) + (1-\varepsilon_r)/\varepsilon_r A_r], \qquad \text{(L.2)}$$

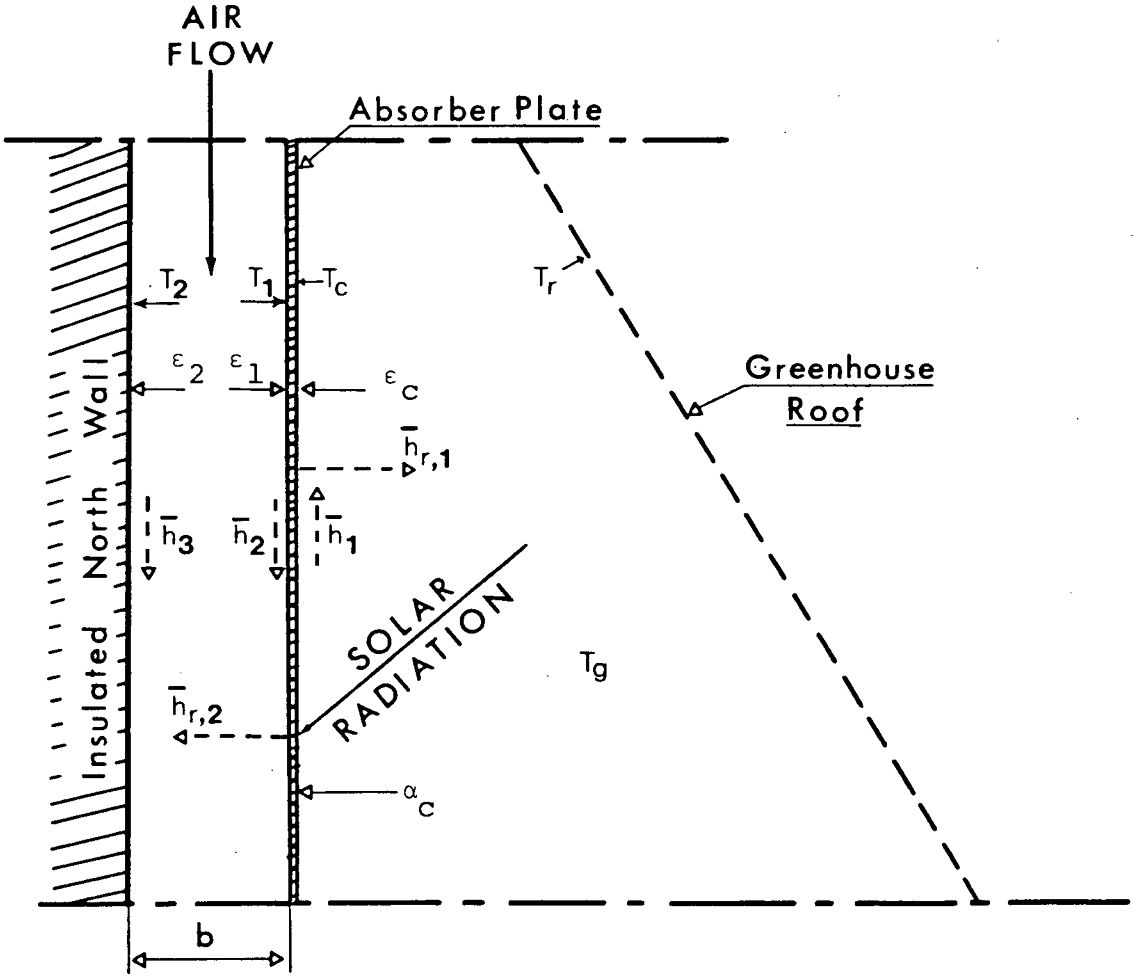


FIGURE L.1: SCHEMATIC OF A SECTION OF THE AIR SOLAR COLLECTOR LOCATED WITHIN A SOLAR-SHED GREENHOUSE (NOT TO SCALE).

where the radiative heat loss is linearized and expressed in terms of the temperature difference between the average plate and greenhouse temperature.

The radiative heat transfer coefficient can be determined by equations L.1 and L.2, as:

$$\bar{h}_{r,1} = A_r F_{r\to c}\ \sigma(T_c^{\,4}-T_r^{\,4})/A_c(T_c-T_g) \quad , \qquad (L.3)$$

where $$A_r F_{r\to c} = \left[\frac{1-\varepsilon_c}{\varepsilon_c A_c} + \frac{1}{A_r F_{r\to c}} + \frac{1-\varepsilon_r}{\varepsilon_r A_r}\right]^{-1}$$

EVALUATION OF THE AVERAGE NATURAL CONVECTION HEAT TRANSFER COEFFICIENT ($\bar{h}_1$):

The heat trnasfer from the top of the collector to the greenhouse air is essentially a case of natural convection from a vertical plate at a uniform heat flux. Holman (1976) gives the following emperical correlations:

For the laminar flow range,

$$h_x = (k/x)\ [0.60(Gr_x^* \ Pr)^{0.2}] \quad , \qquad (L.4)$$

for $10^5 < Gr_x^* < 10^{11}$ and q_w = constant,

where Gr_x^* is a modified Grashof number and defined as:

$$Gr_x^* = (g\beta q_w x^4)/(k\nu^2) .$$

where, q_w, in this case is taken as the solar radiation absorbed by the plate ($q_w = \alpha_c I_c$) .

For fully developed turbulent flow, the local heat transfer coefficients were correlated with,

$$h_x = (k/x)\ [0.17(Gr_x^* \ Pr)^{0.25}] \ , \qquad (L.5)$$

for $2 \times 10^{13} < Gr_x^* < 10^{16}$ and q_w = constant.

The average heat transfer coefficient for the laminar region may be evaluated by integrating the equation for h_x (L.4) from x = 0 to x = H, where H is the height of the collector. Thus,

$$\bar{h}_1 = (5/4)\ h_{x = H} \ . \qquad (L.6)$$

When turbulent natural convection is encountered, Holman (1976) has shown that the local heat transfer coefficient is essentially constant with height.

All the thermophysical properties of the air in the above equations are evaluated at the film temperature, $T_f = (T_c + T_g)/2$.

EVALUATION OF THE AVERAGE FORCED CONVECTION HEAT TRANSFER COEFFICIENT ($\bar{h}_2$ & $\bar{h}_3$):

For forced convection between two parallel flat plates, the following correlations can be derived from Kay's data (Duffie and Beckman (1974)) for air flowing between two plates with one surface insulated and the other at uniform wall heat flux.

For fully developed laminar flow,

$$\bar{h}_2 = 5.4\ k/D_e \quad , \qquad \text{(L.7)}$$

and for fully developed turbulent flow,

$$\bar{h}_2 = (k/D_e)(0.0158\ Re^{0.8}) \quad . \qquad \text{(L.8)}$$

The Reynolds number is based upon the hydraulic diameter

$$D_e = 4A/P \qquad \text{(L.9)}$$

where $A = a \cdot b$ and $P = 2a + 2b$.

Since $a >> b$, then $P \approx 2a$, therefore $D_e = 2b$ or twice the separation distance between the plates.

The suggested critical Reynolds number in this case is 2300; thus, if it is desirable to keep the flow between the two plates in the turbulent region, then the minimum required air velocity may be calculated as follows:

$$Re = 2b\ \bar{v}/\nu > 2300 \quad .$$

For air at 300 K,

$$\nu = 16.84 \times 10^{-6}\ m^2s^{-1} \quad ,$$

then

$$b\bar{v} > 0.02\ m^2s^{-1}$$, or for a spacing of 10 cm

$$\bar{v} > 0.2\ m \cdot s^{-1}.$$

EVALUATION OF THE RADIATIVE HEAT TRANSFER COEFFICIENT BETWEEN THE TWO PLATES ($\bar{h}_{r,2}$):

The heat transfer coefficient for radiative exchange between the absorber plate and the insulated back surface of an air solar collector is given by Duffie and Beckman (1974) as

$$\bar{h}_{r,2} = \sigma(T_1^2+T_2^2)(T_1+T_2)/(1/\varepsilon_1+1/\varepsilon_2-1) \quad . \qquad \text{(L.10)}$$

EVALUATION OF THE COLLECTOR EFFICIENCY FACTOR (F') AND HEAT REMOVAL FACTOR (F_R):

Duffie and Beckman (1974) give an expression to calculate the efficiency factor for an air solar collector when the fluid flow is underneath the absorber plate as

$$F' = \left\{1 + U_L/\{\bar{h}_2+1/[(\bar{h}_3)^{-1} + (\bar{h}_{r,2})^{-1}]\}\right\}^{-1} \qquad \text{(L.11)}$$

where, U_L is the collector overall heat loss coefficient.

The collector heat removal factor can be expressed in terms of the efficiency factor and the heat loss coefficient as

$$F_R = (GC_p/U_L)[1 - \exp(-\{U_1F'/GC_p\})] \quad . \qquad \text{(L.12)}$$

Finally, the total useful energy gain of the collector as a function of the inlet temperature can be estimated by the following equation:

$$Q_u = A_cF_R[S-U_L(T_{f,i} - T_a)] \quad . \qquad \text{(L.13)}$$

EVALUATION OF THE MEAN TEMPERATURE OF THE ABSORBER PLATE (T_c):

All the heat transfer coefficients discussed in this Appendix are a function of plate temperature and an iterative process becomes necessary. The iterative approach proposed by Duffie and Beckman (1974) is used during this study.

The mean plate temperature is related to the mean fluid temperature by

$$T_c = \bar{T}_f + Q_u/\bar{h}_2 \quad . \qquad \text{(L.14)}$$

The above equation is only an approximation since the temperature difference between the plate and the fluid varies along the flow direction due to changes in the heat loss from the collector.

The mean fluid temperature is calculated using the expression given by Duffie and Beckman as

$$\bar{T}_f = T_{f,i} + \{[Q_u/A_c]/U_L F_R\}\{1-F_R/F'\} \quad . \qquad \text{(L.15)}$$

EVALUATION OF THE THERMOPHYSICAL PROPERTIES OF AIR:

Estimation of the convective heat transfer coefficients require the knowledge of the thermophysical properties of air at the film temperature which is a function of plate temperature.

The following equations are derived from tabulated values given by Holman (1976) assuming a linear relationship between the properties and temperature within the range 300 K to 350 K.

1. Density ($kg \cdot m^{-3}$):

$$\rho = 1.1774 - 0.003588\ (T-300). \tag{L.16}$$

2. Specific heat ($kJ \cdot kg^{-1} \cdot K^{-1}$):

$$C_p = 1.0057 + 0.000066\ (T-300). \tag{L.17}$$

3. Thermal conductivity ($W \cdot m^{-1} \cdot K^{-1}$):

$$k = 0.02624 + 0.0000758\ (T-300). \tag{L.18}$$

4. Kinematic viscosity ($m^2 \cdot s^{-1}$):

$$\nu = [16.84 + 0.0784\ (T-300)] \times 10^{-6}. \tag{L.19}$$

5. Prandl number:

$$Pr = 0.708 - 0.0002\ (T-300). \tag{L.20}$$

CONSTANT PLATE TEMPERATURE VS CONSTANT FLOW RATE: A COMPARISON

The solar-shed greenhouse of case study IV was analysed for the case of constant flow rate of air through the collector using the theory developed in the previous section. The greenhouse size and construction parameters used with respect to this analysis are identical to those listed in Table 6.1, page 262. In addition, the following parameters were chosen for the integral solar collector:

i) Absorptivity of the collector absorber plate to solar radiation (α_c) = 0.9.

ii) Emissivity of absorber plate to thermal radiation on both sides (ε_c and ε_1) = 0.9.

iii) Emissivity of back insulated wall to thermal radiation (ε_2) = 0.1.

iv) Collector height (flow direction) = 5.77 m

v) Collector length = 100 m.

vi) Width of space between plate and back wall = 0.1 m.

Three flow rates of the transport fluid (i.e. air) were selected:

i) Low (0.007 kg s^{-1} m^{-2}).

ii) Medium (0.014 kg s^{-1} m^{-2}).

iii) High (0.028 kg s^{-1} m^{-2}).

Solution for the mean plate temperature was obtained by an iteration technique to the nearest 0.1°C for each hour from sunrise to sunset for the integral collector of a solar-shed greenhouse located in the Vancouver, B.C. region.

The computer simulation results are summarized in Table L.1 for the three selected air flow rates. The values indicated in the table are given as minimum and maximum for the day. Early morning and late afternoon hours were neglected since very small amounts of solar radiation are available for collection during these periods. Table L.1 also shows the corresponding air temperatures leaving the collector.

The predicted outlet temperatures from the collector range between 53°C to 36°C for the low flow rate, 41°C to 31°C for the medium flow rate and 34°C to 28°C for the high flow rate. For the above outlet temperature ranges, the corresponding mean plate temperatures were 63°C to 42°C, 59°C to 39°C and 53°C to 36°C for low, medium and high flow rates respectively.

The minimum acceptable outlet temperature is usually dictated by the type of application. For greenhouse heating the minimum useful temperature is related to the night time greenhouse temperature requirement for the specific crop grown. For example, the greenhouse nighttime

TABLE L.1

EFFECT OF AIR FLOW RATE THROUGH THE COLLECTOR ON THE ABSORBER AND THE OUTLET TEMPERATURE FOR THE SOLAR-SHED GREENHOUSE OF CASE STUDY IV (VANCOUVER, B.C.)

AIR FLOW*	0.007		0.014		0.028	
TEMP** (°C)	T_c	$T_{f,o}$	T_c	$T_{f,o}$	T_c	$T_{f,o}$
Jan	63-49	53-42	59-46	41-34	53-42	34-30
Feb	61-49	52-41	57-46	40-34	51-42	33-30
Mar	62-51	52-43	58-47	40-35	52-43	33-31
Apr	54-45	45-38	50-42	36-32	45-39	31-29
May	51-44	43-37	48-41	35-32	43-38	30-29
June	53-45	44-38	49-42	36-32	44-39	31-29
July	53-46	45-38	50-43	36-32	45-39	31-29
Aug	59-50	49-42	55-46	38-34	49-42	32-30
Sept	62-51	52-43	58-48	40-35	51-43	33-30
Oct	64-51	53-43	59-48	41-35	53-43	34-30
Nov	56-44	47-37	52-41	37-32	47-38	32-29
Dec	55-42	46-36	51-39	37-31	46-36	31-28

* Air mass flow rate in $kg \cdot s^{-1}$ per unit area (m^2) of collector

** Daily maximum and minimum average absorber plate temperature (T_c) and collector outlet air temperature ($T_{f,o}$). These temperatures are for the period ± 3 hours from solar noon.

temperature for tomatoes should be at least 13°C, while for lettuce, this temperature may be allowed to drop as low as 7°C. Thus for a lettuce crop, the collector may be operated at a lower temperature (i.e. high transport fluid flow rate) in order to improve the collector efficiency.

The effect of air flow rate on the monthly average daily solar energy collected and the fraction of the greenhouse heating load supplied by the solar collector can be seen in Table L.2. The monthly average solar percentage values shown in the table are valid for a minimum nightime greenhouse temperature of 15°C (e.g. cucumbers, melons, tomatoes ...).

Findings from this simulated case study has indicated that doubling the air flow rate resulted in a decrease in the monthly fractions in the order of 2 to 3 percentage points.

Simulated values for the constant absorber plate temperature case treated in Chapter 6 are also included in Table L.2 for comparison purposes. Examination of the results in the table indicates that the fractions of the greenhouse heating load supplied by the integral solar collector are higher when the collector is operated at a constant temperature of 35°C than at constant air flow rates.

TABLE L.2

EFFECT OF AIR FLOW RATE THROUGH THE COLLECTOR ON THE SOLAR ENERGY COLLECTED AND SOLAR FRACTION FOR THE SOLAR-SHED GREENHOUSE OF CASE STUDY IV (VANCOUVER, B.C.)

Air Flow*	Variable (T_c=35°C)		0.007		0.014		0.028	
	Q_c**	f_m***	Q_c	f_m	Q_c	f_m	Q_c	f_m
Jan	3218	27.0	2241	18.8	2476	20.8	2688	22.6
Feb	3114	31.9	2178	22.3	2406	24.6	2614	26.8
Mar	3363	38.8	2322	26.8	2565	29.6	2789	32.2
Apr	2401	40.4	1798	30.3	1931	32.5	2104	35.4
May	2120	61.1	1626	46.9	1739	50.2	1895	54.7
Jun	2335	100.0	1791	93.1	1925	100.0	2037	100.0
July	2466	100.0	1858	100.0	2052	100.0	2180	100.0
Aug	3177	100.0	2273	100.0	2512	100.0	2668	100.0
Sept	3500	100.0	2463	100.0	2727	100.0	2908	100.0
Oct	3499	62.1	2389	42.4	2644	46.9	2878	51.0
Nov	2284	25.2	1694	18.7	1867	20.6	2027	22.4
Dec	2038	17.1	1556	13.1	1665	14.0	1743	14.6

* Air mass flow rate in $kg \cdot s^{-1}$ per unit area (m^2) of collector
** Q_c = monthly average daily solar energy collected in MJ (A_c = 577 m^2)
*** f_m = monthly average percentages of the heating supplied by solar

NOMENCLATURE

Symbol	Definition	Units
A	Cross-sectional area of air flow space of the solar collector = a x b	m^2
A_c	Area of the absorber plate	m^2
A_r	Greenhouse roof area	m^2
a	Long side of the air flow space	m
b	Spacing between absorber plate and insulated back wall	m
C_p	Specific heat of air	$kJ \cdot kg^{-1} \cdot K^{-1}$
D_e	Hydraulic diameter of air flow space = 4 A/P	m
F'	Collector efficiency factor	
F_R	Collector heat-removal factor	
$F_{r \to c}$	Configuration factor between the solar collector and the greenhouse roof	
f_m	Monthly average percentage of the greenhouse heating load supplied by solar collector	
$\mathcal{F}_{r \to c}$	Thermal radiation exchange factor as defined in equation L.3	
G	Air flow rate per unit of collector area	$kg\ s^{-1}\ m^{-2}$
Gr_x^*	Local Grashof number	
g	Gravitational constant	

Symbol	Definition	Units
H	Height of the solar collector	m
$\bar{h}_1$	Average natural convection heat transfer coefficient at the top of plate	$W{\cdot}m^{-2}{\cdot}K^{-1}$
$\bar{h}_2$	Average forced convection heat transfer coefficient at back of plate	$W{\cdot}m^{-2}{\cdot}K^{-1}$
$\bar{h}_3$	Average forced convection heat transfer coefficient at insulated back wall	$W{\cdot}m^{-2}{\cdot}K^{-1}$
h_x	Local natural convection heat transfer coefficient at a distance x from leading edge of the absorber plate	$W{\cdot}m^{-2}{\cdot}K^{-1}$ m
$\bar{h}_{r,1}$	Radiative heat transfer coefficient between absorber plate and greenhouse roof	$W{\cdot}m^{-2}{\cdot}K^{-1}$
$\bar{h}_{r,2}$	Radiative heat transfer coefficient between absorber plate and insulated back wall	$W{\cdot}m^{-2}{\cdot}K^{-1}$
I_c	Solar radiation incident on the absorber plate	$W{\cdot}m^{-2}$
k	Thermal conductivity of air	$W{\cdot}m^{-1}{\cdot}K^{-1}$
P	Perimeter of the air flow space of the solar collector = 2(a+b)	m

Symbol	Definition	Units
Pr	Prandtl number for air	
Q_c	Monthly average daily solar energy collected	MJ
Q_u	Useful heat gain of the collector	W
q_w	Heat flux on the collector = $\alpha_c I_c$	$W \cdot m^{-2}$
Re	Reynolds number	
S	Solar radiation absorbed by the collector	$W \cdot m^{-2}$
T_a	Ambient temperature near the collector	K
T_c	Average absorber plate temperature of the collector	K
T_f	Film temperature for convection heat transfer	K
$\bar{T}_f$	Mean fluid temperature for the collector	K
$T_{f,o}$	Outlet fluid temperature from the collector	K
$T_{f,i}$	Inlet fluid temperature to the collector	K
T_g	Greenhouse temperature	K
T_r	Greenhouse roof temperature (inside surface)	K
T_1	Absorber plate temperature (back surface)	K
T_2	Insulated back wall temperature	K

Symbol	Definition	Units
U_L	Overall-heat loss coefficient for the collector	$W \cdot m^{-2} \cdot K^{-1}$
$\bar{v}$	Average air velocity in the collector	$m\ s^{-1}$
x	Distance from leading edge of the absorber plate	m
β	Volumetric coefficient of expansion of air	K^{-1}
ν	Kinematic viscosity of air	$m^2 \cdot s^{-1}$
ρ	Density of air	$kg \cdot m^{-3}$
σ	Stefan-Boltzmann Constant = 5.6697×10^{-8}	$W \cdot m^{-2} \cdot K^{-4}$
α_c	Absorptance of plate to solar radiation	
ε_c	Emmittance of plate for infra-red radiation	
ε_r	Emmittance of greenhouse roof for infra-red radiation	
ε_1	Emmittance of back of plate for infra-red radiation	
ε_2	Emmittance of insulated back wall for infra-red radiation	

APPENDIX M

FORTRAN COMPUTER PROGRAM

```
      PROGRAM GRLS ( TAPE5 , TAPE6 , OUTPUT )
C
C   DECLARE COMMON BLOCKS
C
      COMMON / THOUT / TDBO(288) , TSKY(288) , WIND(12) , TDPO(288)
      COMMON / HSOUT / TTILT(288,10)
      COMMON / STOUT / TI(288,10)
      COMMON / SPOUT / TB , SV , FLOW(288)
C
      DIMENSION QSOL(12,24) , COL(12,24)
C
      INTEGER ANSYS , RUN
C
C   READ TYPE OF ANALYSIS
C
      READ(5,*) ANSYS
      RUN = ANSYS
      IF ( ANSYS .EQ. 3 ) RUN = 1
    5 CONTINUE
C
C   CALCULATE HOURLY TEMPERATURES
C
      CALL WDATA
C
C   CALCULATE HOURLY RADIATION
C
      CALL HSRP
C
C   CALCULATE SURFACE TEMPERATURES OF EXTERNAL WALLS
C
      CALL SURTEMP
C
C   CALCULATE HEAT LOSSES OF A BUILDING WITHOUT ATTIC
C
      CALL QCONP1 ( ANSYS , RUN )
C
C   DO FURTHER ANALYSIS ACCORDING TO TYPE OF ANALYSIS.
C
      IF ( ANSYS .EQ. 0 ) CALL GRNHSO ( QSOL )
      IF ( RUN .EQ. 2 ) GO TO 10
      IF ( ANSYS .NE. 2 ) CALL SUP ( ANSYS )
      RUN = 2
      GO TO 5
   10 CONTINUE
C
C   CALCULATE HEAT LOSSES THROUGH GABLE
C
      CALL GRNHS1 ( QSOL , COL )
C
C   CALCULATE TOTAL LOAD , SUPPLY AND FRACTION OF LOADS
C
      CALL TOTAL1 ( QSOL , COL , ANSYS )
      STOP
      END
```

```
      SUBROUTINE WDATA
C
C--SUBROUTINE TO SIMULATE THE HOURLY OUTDOOR,DEWPOINT AND
C--SKY TEMPERATURES FROM MONTHLY MEAN AND RANGE OF
C--OUTDOOR AND DEWPOINT TEMPERATURES
C
C  DECLARE COMMON BLOCKS
C

      COMMON / THOUT / TDBO(288) , TSKY(288) , WINDM(12) , TDPO(288)
C
      DIMENSION TDBOM(12),TDBRM(12),TDPOM(12),TDPRM(12)
C


      INTEGER HTREP
C
      READ(5,*) HTREP
      READ(5,*)(TDBOM(J),TDBRM(J),TDPOM(J),TDPRM(J),WINDM(J),J=1,12)
      DO 40J=1,12

C--TO SIMULATE HOURLY OUTDOOR TEMPERATURES

      CALL HTP(TDBOM(J),TDBRM(J),TDBO,J)

C--TO SIMULATE HOURLY DEWPOINT TEMPERATURES

      CALL HTP(TDPOM(J),TDPRM(J),TDPO,J)

C--TO SIMULATE HOURLY SKY TEMPERATURES FROM HOURLY
C--OUTDOOR TEMPERATURES

      CALL TSKYP(TDBO,TSKY,J)

   40 CONTINUE
      IF ( HTREP .LE. 0 )  RETURN
      WRITE(6,80)
      DO 70 MM = 1 , 12
      DO 70 NN = 1 , 24
         I = ( ( MM - 1 ) * 24 ) + NN
         WRITE(6,75) MM , NN , TDBO(I) , TDPO(I) , TSKY(I) , WINDM(MM)
   70 CONTINUE
      RETURN
   75 FORMAT(I3,5X,I3,4(5X,F10.2))
   80 FORMAT(1H1,//,15X,*HOURLY OUTDOOR , DEWPOINT AND SKY *,
     1        *TEMPERATURES FROM SUBROUTINE -- WDATA-- * ,//)
      END
```

```
      SUBROUTINE HTP(TM,TR,T,J)
      DIMENSION T(288)
      PI=3.141593
      DO 20I=1,24
         MQ = ( ( J - 1 ) * 24 ) + I
      HE=(2.*I-1.)*30.
      T(MQ)=(TR/2.)*SIN(((2.*PI/(24.*60.))*HE)-PI/1.412)+TM
   20 CONTINUE
      RETURN
      END
```

```
      SUBROUTINE TSKYP(TA,TSKY,J)
      DIMENSION TA(24),TS(24),TSKY(288)
      DO 20I=1,24
         MQ = ( ( J - 1 ) * 24 ) + I
      TS(I)=.0552*(TA(MQ)+273.16)**1.5
      TSKY(MQ)=TS(I)-273.16
   20 CONTINUE
      RETURN
      END
```

```
      SUBROUTINE HSRP
C
C--SUBROUTINE TO EVALUATE THE HOURLY RADITATION FOR ANY ANGLE
C--AND ORIENTATION FROM DAILY TOTALS AND  ALBIDO
C--LAT: LATITUDE
C--DGAMA: ORIENTATION OF THE SURFACE
C--DS: TILT OF SURFACE
C--SC:SOLAR CONSTANT
C
C  DECLARE COMMON BLOCKS
C
      COMMON / HSOUT / TTILT(288,10)
C
      DIMENSION DGAMA(10),DS(10)
      REAL LAT,KT
      INTEGER HRREP
C
      READ(5,*) HRREP , DLAT , N
      PI=3.141593
      SC=4871.
      LAT=DLAT*PI/180.
      MQ = 0
      READ(5,*)(DGAMA(I),DS(I),I=1,N)
      DO 12 NCD = 1 , 12
      READ(5,*)DAY,HBAR,ALB
      CORFAC=1.+0.033*COS(PI*2.*DAY/365.)
      DEC=23.45*SIN(((284.+DAY)/365.)*6.2832)
      DEC=DEC*PI/180.
```

```
      WS=ACOS(-TAN(LAT)*TAN(DEC))
      DAYL=2./15.*WS*180./PI
      EXTRAD=24./PI*SC*CORFAC*(COS(LAT)*COS(DEC)*SIN(WS)
     1+WS*SIN(LAT)*SIN(DEC))
      KT=HBAR/EXTRAD
      RATIO=0.958-0.982*KT
      DBAR=RATIO*HBAR
      DW=172.5
30    W=DW*PI/180.
      MQ = MQ + 1
      DO 25I=1,N
      GAMA=DGAMA(I)*PI/180.
      S=DS(I)*PI/180.
      SKY=0.5*(1.+COS(S))
      GROUND=0.5*ALB*(1.-COS(S))
      HCIA=COS(LAT)*COS(DEC)*COS(W)+SIN(LAT)*SIN(DEC)
      IF(HCIA.LE.0.) GO TO 94
      RT1=0.409+0.5016*SIN(WS-1.047)
      RT2=0.6609-0.4767*SIN(WS-1.047)
      RT=(PI/24.)*(RT1+RT2*COS(W))*(COS(W)-COS(WS))/(SIN(WS)-WS*COS(WS))
      TIBAR=RT*HBAR
      RATH=PI/24.*((COS(W)-COS(WS))/(SIN(WS)-WS*COS(WS)))
      DIBAR=RATH*DBAR
      TCIA=COS(S)*SIN(DEC)*SIN(LAT)-SIN(DEC)*COS(LAT)*SIN(S)
     1*COS(GAMA)+COS(DEC)*COS(LAT)*COS(S)*COS(W)+COS(W)*COS(DEC)
     2*SIN(S)*COS(GAMA)*SIN(LAT)+COS(DEC)*SIN(S)*SIN(GAMA)
     3*SIN(W)
      IF(TCIA.GT.0.) GO TO 70
      BTILT=0.
      GO TO 80
70    RB=TCIA/HCIA
      IF(TIBAR.LT.DIBAR) TIBAR=DIBAR
      BTILT=(TIBAR-DIBAR)*RB
80    DTILT=SKY*DIBAR+GROUND*TIBAR
      TTILT(MQ,I)=BTILT+DTILT
      GO TO 91
94    BTILT=0.
      DTILT=0.
      TTILT(MQ,I)=0.
91    J=DS(I)
25    CONTINUE
      DW=DW-15.
      IF(DW.GT.-180.)GO TO 30
 12   CONTINUE
      IF ( HRREP .LE. 0 ) RETURN
      WRITE (6,21)
      DO 100 MQ = 1 , 288
         WRITE(6,31) (TTILT(MQ,I),I=1,N)
100   CONTINUE
21    FORMAT(1H1,//,10X,*HOURLY RADIATION FROM SUBROUTINE -- HSRP --*,
     1        //                                                      )
31    FORMAT(10F10.1)
      RETURN
      END
```

```
      SUBROUTINE SURTEMP
C
C--TO EVALUATE THE SURFACE TEMPERATURE OF THE EXTERNAL
C--WALLS TO BE USED IN THE EVALUATION OF TRANSMISSION
C--LOSSES FROM THE BUILDING
C--TTILT:RADIATION AVALIABLE ON THAT SURFACE HOURLY
C--RI:RESISTANCE OF THE WALL
C--TDBO:OUTDOOR TEMPERATURE
C--ABY:ABSORPTIVITY
C--EMY:EMISSIVITY
C--N:NUMBER OF SURFACES
C--TB:INDOOR TEMPERATURE OF THE HOUSE IN ABSOLUTE SCALE
C
C
C  DECLARE COMMON BLOCKS
C
      COMMON / THOUT / TDBO(288) , TSKY(288) , WIND(12)
      COMMON / HSOUT / TTILT(288,10)
      COMMON / STOUT / TI(288,10)
C
      DIMENSION DS(10),TI(10),RI(10)
C
C
      INTEGER STREP
C
      READ(5,*)  STREP , N , ABY , EMY , TB
      READ(5,*)((DS(K),K=1,N),(RI(K),K=1,N))
      SIGMA=2.04E-7
      IF ( STREP .LE. 0 ) GO TO 5
      WRITE(6,55)
    5 CONTINUE
      DO 50 MJ = 1 , 12
      DO 50 NJ = 1 , 24
      I = ( ( MJ - 1 ) * 24 ) + NJ
      TDBOK=TDBO(I)+273.16
      TSKYK=TSKY(I)+273.16
      WINDC = WIND(MJ)
      DO 40K=1,N
      TI(I,K)=333.16
 10   CALL SURFACE(SUT,EMY,SIGMA,DS,TSKYK,TDBOK,
     1WINDC,HW,TB,RI,ABY,I,K)
      IF(SUT.EQ.0.0) GO TO 34
      IF(SUT.LT.0.)GO TO 20
      TI(I,K)=TI(I,K)-10.
      GO TO 10
 20   TI(I,K)=TI(I,K)+10.
   24 TI(I,K)=TI(I,K)-1.
 25   CALL SURFACE(SUT,EMY,SIGMA,DS,TSKYK,TDBOK,
     1WINDC,HW,TB,RI,ABY,I,K)
      IF(SUT.EQ.0.0) GO TO 34
      IF(SUT.LT.0.)GO TO 30
      GO TO 24
 30   TI(I,K)=TI(I,K)+1.
  32  TI(I,K)=TI(I,K)-0.1
      CALL SURFACE(SUT,EMY,SIGMA,DS,TSKYK,TDBOK,
```

```
     1WINDC,HW,TB,RI,ABY,I,K)
      IF(SUT.LE.0.0)GO TO 34
      GO TO 32
   34 TI(I,K)=TI(I,K)-273.16
  40  CONTINUE
      IF ( STREP .LE. 0 ) GO TO 50
      WRITE(6,45)(MJ,NJ,(TI(I,K),K=1,N))
  50  CONTINUE
  45  FORMAT(I3,3X,I3,10F12.2)
  55  FORMAT(1H1,//,10X,*SURFACE TEMPERATURES OF EXTERNAL WALLS*,
     1        *FROM SUBROUTINE -- SURTEMP -- *,//                )
      RETURN
      END




      SUBROUTINE SURFACE(SUT,EMY,SIGMA,DS,TSKYK,TDBOK,WINDC,
     1HW,TB,RI,ABY,I,K)
C
C--THIS SUBROUTINE EVALUATES THE SURFACE TEMPERATURE
C
C  DECLARE COMMON BLOCKS
C

      COMMON / HSOUT / TTILT(288,10)
      COMMON / STOUT / TI(288,10)
C
      DIMENSION DS(10),RI(10)
C
      HW=20.52+13.68*WINDC
      SUT=EMY*SIGMA*(TI(I,K)**4-((1.+COSD(DS(K)))/2.)*TSKYK**4
     1-((1.-COSD(DS(K)))/2.)*TDBOK**4)+HW*(TI(I,K)-TDBOK)
     2-((TB-TI(I,K))/RI(K))-ABY*TTILT(I,K)
      RETURN
      END




      SUBROUTINE QCONP1 ( ANSYS , RUN )
C
C        TO EVALUATE THE TOTAL HEAT LOSSES FROM A BUILDING
C        WITHOUT AN ATTIC
C       TO EVALUATE THE TOTAL TRANSMISSION LOSS
C        TO EVALUATE THE INFILTRATION LOSSESAND THE
C        TOTAL HEAT LOSSES FROM THE BUILDING
C       UF=HEAT LOSS CONDUCTANCE FROM FOUNDATION
C       AF=AREA OF FOUNDATION
C       UP=HEAT LOSS CONDUCTANCE FROM PERIMETER IN KJ/HR.SCM.K.
C       P=PERIMETER
C       UV=HEAT LOSS CONDUCTANCE FROM THESIDE WALLS
C       AV=AREA OF THE SIDE WALLS
C        TB=INDOOR TEMPERATURE
C        ACH=NUMBER OF AIR EXCHANGES PER HOUR
```

```
C       VG=VOLUME OF THE HOUSE
C
C
C   DECLARE COMMON BLOCKS
C
      COMMON / THOUT / TDBO(288)
      COMMON / HSOUT / QINF(288) , QC(288) , QTOT(288)
      COMMON / STOUT / SAT(288,10)
      COMMON / SPOUT / TB , SV , FLOW(288)
C
      DIMENSION UV(10),AV(10)
C
      INTEGER INFREP , ANSYS , RUN

      READ(5,*) INFREP , N , UF , AF , TG , UP , P
      IF ( (ANSYS .EQ. 2) .OR. (ANSYS .EQ. 0) ) READ(5,*) ACH , VG
      IF ( RUN .EQ. 1 ) TB = TG
      CONF=UF*AF
      CONP=UP*P
C--TDBO:HOURLY OUTDOOR TEMPERATURE FROM PROGRAM WDATA
C--TO EVALUATE INFILTRATION LOSSES
C
      IF ( RUN .NE. 1 ) CALL QINFP(VG,ACH,TG,ANSYS)
C
      READ(5,*)(UV(K),K=1,N),(AV(K),K=1,N)
C
C--SAT:SURFACE TEMPERATURE FROM PROGRAM SURTEMP
C
      IF ( INFREP .LE. 0 ) GO TO 5
      WRITE(6,35)
    5 CONTINUE
      DO 20 MJ = 1 , 12
      DO 20 NJ = 1, 24
         I = ( ( MJ - 1 ) * 24 ) + NJ
      COND=0.0
      DO 10K=1,N
C--TO EVALUATE TRANSMISSION LOSSES
      COND=COND+UV(K)*AV(K)*(TG-SAT(I,K))
   10 CONTINUE
      QC(I)=CONF*(TG-TDBO(I))+CONP*(TG-TDBO(I))+COND
      IF ( INFREP .LE. 0 ) GO TO 20
      WRITE (6,16) MJ,NJ,TDBO(I),QC(I),QINF(I),QTOT(I)
   16 FORMAT(I3,3X,I3,5X,F7.2,5X,F12.2,5X,F12.2,5X,F20.2)
   20 CONTINUE
  30  CONTINUE
      RETURN
   35 FORMAT(1H1,//,10X,*INFILTRATION AND TRANSMISSION LOSSES FROM*,
     1        *SUBROUTINE -- QCONP1 -- * ,//                              )
      END
```

```
      SUBROUTINE QINFP(VG,ACH,TG,ANSYS)
C
C--THIS SUBROUTINE EVALUATES THE INFILTRATION LOSSES
C
C
C   DECLARE COMMON BLOCKS
C
      COMMON / THOUT / TDBO(288)
      COMMON / HSOUT / QINF(288)
      COMMON / SPOUT / TB , SV , FLOW(288)
C
      INTEGER ANSYS
C
C
      DO 10I=1,288
      IF ( ANSYS .NE. 3 ) QINF(I)=1.218*VG*ACH*(TG-TDBO(I))
      IF ( ANSYS .EQ. 3 ) QINF(I) = ( FLOW(I)/SV*3600. ) * ( TB-TG )
10    CONTINUE
20    CONTINUE
      RETURN
      END




      SUBROUTINE GRNHS1 ( GRE , COL )
C
C
C   DECLARE COMMON BLOCK
C
      COMMON / GABLE / GBLREP , FRP , FRC , FPR , FPC
C
C
      DIMENSION DGAMA(10),GAMA(10),DS(10),S(10),N(10),AREA(10),
     1A(10),B(10),TRAND(10),TAD(10),TTD(10),SKY(10),GROUND(10),
     2TCIA(10),BTILT(10),RB(10),DTILT(10),TT(10),TIA(10),AOFI(10),
     3AOFR(10),XX(10),YY(10),PERE(10),PARE(10),AA(10),BB(10),
     4TRANS(10),TA(10),
     5 IST(12) , GRE(12,24) , COL(12,24)
C
      INTEGER GBLREP
      REAL LAT,KT
C
C   INTIALIZE DAT
C
      DO 65 MQ = 1 , 12
         IST(MQ) = 0
         DO 60 NQ = 1 , 24
            GRE(MQ,NQ) = 0.0
            COL(MQ,NQ) = 0.0
   60    CONTINUE
   65 CONTINUE
C
C--CALCULATION OF TRANSMITTANCE THROUGH GLASS COVER
C
```

```
C--READ REQUIRED CONSTANTS AND DATA
C
      READ(5,*) GBLREP , DLAT , NW , AF , ALP , RINDEX , AK , AL
      READ(5,*) FRP , FRC , FPR , FPC
      READ(5,*) ( DGAMA(I) , DS(I) , N(I) , AREA(I) , I = 1 , NW )
C
      IF ( GBLREP .LE. 0 ) GO TO 1000
      WRITE(6,1)
      WRITE(6,108)
 1000 CONTINUE
      PI=3.141593
      SC=4871.
      LAT=DLAT*PI/180.
C
C--CHARACTERISTICS OF GLASS COVER
C
C--CALCULATION OF TRANSMITTANCE FOR DIFFUSE RADIATION
      AODI=1.0123
      AODR=ASIN(SIN(AODI)/RINDEX)
      X=AODR-AODI
      Y=AODI+AODR
      PEREF=(SIN(X)/SIN(Y))**2
      PAREF=(TAN(X)/TAN(Y))**2
      M=0
      DO 12 MCD = 1 , 12
      READ(5,*) DAY,HBAR,ALB
      M=M+1
      CORFAC=1.+0.033*COS(PI*2.*DAY/365.)
      DEC=23.45*SIN(((284.+DAY)/365.)*2.0*PI)
      DEC=DEC*PI/180.
      WS=ACOS(-TAN(LAT)*TAN(DEC))
      EXTRAD=24./PI*SC*CORFAC*(COS(LAT)*COS(DEC)*SIN(WS)
     1+WS*SIN(LAT)*SIN(DEC))
      KT=HBAR/EXTRAD
      RATIO=0.958-0.982*KT
      DBAR=RATIO*HBAR
      IF ( GBLREP .LE. 0 ) GO TO 1001
      IF(M.EQ.1) WRITE(6,110)
      IF(M.EQ.2) WRITE(6,111)
      IF(M.EQ.3) WRITE(6,112)
      IF(M.EQ.4) WRITE(6,113)
      IF(M.EQ.5) WRITE(6,114)
      IF(M.EQ.6) WRITE(6,115)
      IF(M.EQ.7) WRITE(6,116)
      IF(M.EQ.8) WRITE(6,117)
      IF(M.EQ.9) WRITE(6,118)
      IF(M.EQ.10) WRITE(6,119)
      IF(M.EQ.11) WRITE(6,120)
      IF(M.EQ.12) WRITE(6,121)
 1001 CONTINUE
      DO 20 I =1,NW
      A(I)=(2.*N(I)-1.)*PEREF
      B(I)=(2.*N(I)-1.)*PAREF
C****CALCULATION OF TRANSMITTANCE DUE TO REFLECTION ONLY
      TRAND(I)=0.5*((1.-PEREF)/(1.+A(I))+(1.-PAREF)/(1.+B(I)))
```

```
C****CALCULATION OF TRANSMITTANCE DUE TO ABSORPTION ONLY
      TAD(I)=EXP(-N(I)*AK*AL/COS(AODR))
C****CALCULATION OF TOTAL TRANSMITTANCE CONSIDERING ABSORPTION & REF
      TTD(I)=TRAND(I)*TAD(I)
      GAMA(I)=DGAMA(I)*PI/180.
      S(I)=DS(I)*PI/180.
      SKY(I)=0.5*(1.+COS(S(I)))
      GROUND(I)=0.5*ALB*(1.-COS(S(I)))
   20 CONTINUE
      DW=127.5
 30   W=DW*PI/180.
      HCIA=COS(LAT)*COS(DEC)*COS(W)+SIN(LAT)*SIN(DEC)
      IF(HCIA.LE.0.) GO TO 94
      RT1=0.409+0.5016*SIN(WS-1.047)
      RT2=0.6609-0.4767*SIN(WS-1.047)
      RT=(PI/24.)*(RT1+RT2*COS(W))*(COS(W)-COS(WS))/(SIN(WS)-WS*COS(WS))
      TIBAR=RT*HBAR
      RATH=PI/24.*((COS(W)-COS(WS))/(SIN(WS)-WS*COS(WS)))
      DIBAR=RATH*DBAR
      DO 40 I=1,NW
      TCIA(I)=COS(S(I))*SIN(DEC)*SIN(LAT)-SIN(DEC)*COS(LAT)*SIN(S(I))*
     1COS(GAMA(I))+COS(DEC)*COS(LAT)*COS(S(I))*COS(W)+COS(W)*COS(DEC)*
     2SIN(S(I))*COS(GAMA(I))*SIN(LAT)+COS(DEC)*SIN(S(I))*SIN(GAMA(I))*
     3SIN(W)
      IF(TCIA(I).GT.0.) GO TO 70
      BTILT(I)=0.
      RB(I)=0.
      GO TO 80
   70 RB(I)=TCIA(I)/HCIA
      IF(TIBAR.LT.DIBAR) TIBAR=DIBAR
      BTILT(I)=(TIBAR-DIBAR)*RB(I)
   80 DTILT(I)=SKY(I)*DIBAR+GROUND(I)*TIBAR
      IF(TCIA(I).GT.0.) GO TO 90
      TT(I)=0.
      GO TO 40
 90   TIA(I)=ACOS(TCIA(I))
C--CALCULATION OF TRANSMITTANCE FOR BEAM RADIATION
      AOFI(I)=TIA(I)
      AOFR(I)=ASIN(SIN(AOFI(I))/RINDEX)
      XX(I)=AOFR(I)-AOFI(I)
      YY(I)=AOFI(I)+AOFR(I)
      PERE(I)=(SIN(XX(I))/SIN(YY(I)))**2
      PARE(I)=(TAN(XX(I))/TAN(YY(I)))**2
      AA(I)=(2.*N(I)-1.)*PERE(I)
      BB(I)=(2.*N(I)-1.)*PARE(I)
C****CALCULATION OF TRANSMITTANCE DUE TO REFLECTION ONLY
      TRANS(I)=0.5*((1.-PERE(I))/(1.+AA(I))+(1.-PARE(I))/(1.+BB(I)))
C****CALCULATION OF TRANSMITTANCE DUE TO ABSORPTION ONLY
      TA(I)=EXP(-N(I)*AK*AL/COS(AOFR(I)))
C****CALCULATION OF TOTAL TRANSMITTANCE CONSIDERING ABSORPTION & REF
      TT(I)=TRANS(I)*TA(I)
   40 CONTINUE
      CALL CAPFAC1 (BTILT,DTILT,TT,TTD,AREA,TIBAR,DIBAR,NW,AF,ALP,DW,
     1  M ,
     2  GRE , COL , IST )
```

```
 94  DW=DW-15.
     IF(DW.GT.0.) GO TO 30
  12 CONTINUE
     IF ( GBLREP .LE. 0 )  GO TO 700
   6 WRITE(6,2)
     DO 600 MG = 1 , 12
        KG = IST(MG)
        DO 550 NG = 1 , KG
        WRITE(6,105) COL(MG,NG) , GRE(MG,NG) , MG
 550    CONTINUE
 600 CONTINUE
 700 CONTINUE
C
C  REARRANGE LOSSES
C
     CALL PRG1 ( COL , GRE , IST )
C
     RETURN
   2 FORMAT(1H1,//,10X,*VALUES OF -- COL -- AND -- GRE -- FROM *,
    1       *SUBROUTINE -- GRNHS1 -- *,//                            )
 100 FORMAT(2F6.1,I1,F6.0)
 105 FORMAT(5X,2F15.5,I5)
   1 FORMAT(*1*/////,29X,*.10 HECTARE*//,25X,*SINGLE GLASS ROOF *//,
    126X,* SHED GREENHOUSE*//,26X,*E-W ORIENTATION*//,29X,
    2*LENGTH=100M*/,29X,*WIDTH = 10M*/,29X,*HEIGHT=2 M*/,29X,
    3*SLOPE =30DEG*//,24X,*GLASS CHARACTERISTICS:*//,24X,
    4*THICKNESS=0.30 CM*//,24X,*K = 0.252 CM-1 ; IR=1.526*///)
 110 FORMAT(*1*///,35X,*JANUARY*//)
 111 FORMAT(*1*///,35X,*FEBRUARY*//)
 112 FORMAT(*1*///,35X,*MARCH*//)
 113 FORMAT(*1*///,35X,*APRIL*//)
 114 FORMAT(*1*///,35X,*MAY*//)
 115 FORMAT(*1*///,35X,*JUNE*//)
 116 FORMAT(*1*///,35X,*JULY*//)
 117 FORMAT(*1*///,35X,*AUGUST*//)
 118 FORMAT(*1*///,35X,*SEPTEMBER*//)
 119 FORMAT(*1*///,35X,*OCTOBER*//)
 120 FORMAT(*1*///,35X,*NOVEMBER*//)
 121 FORMAT(*1*///,35X,*DECEMBER*//)
 108 FORMAT(29X,*S1 = SOUTH WALL*/,29X,*S2= SOUTH ROOF*/,29X,
    1*S3 =  EAST WALL*/,29X,*S4 = WEST WALL*/,29X,*S5 = COLLECTOR*/)
     END
```

```
      SUBROUTINE CAPFAC1 (B,D,BTR,DTR,AREA,HBAR,DBAR,NW,AF,ALB,HR,M,
     1                     GRE , COL , IST                          )
C
C  DECLARE COMMON BLOCKS
C
      COMMON / GABLE / GBLREP , FRP , FRC , FPR , FPC
C
      DIMENSION B(10),D(10),T(10),TB(10),TD(10),TT(10),BTR(10),
     1DTR(10),AREA(10),RB(10),RD(10),RT(10) ,TBB(10),TDD(10),
     2 GRE(12,24) , COL(12,24) , IST(12)
C
       INTEGER GBLREP
C
C--CAPTURE FACTORS FOR SHED  GREENHOUSES,LCSS FROM ROOF INCLUDED.
C--ALSC REFLECTION LOSSES
C
      BBAR=HBAR-DBAR
      IF ( GBLREP .LE. 0 ) GO TO 100
      WRITE(6,105)  HR
  100 CONTINUE
      DO 10 I=1,NW
C--REFECTION LOSSES
      IF(I.EQ.2) GO TO 50
      IF(I.EQ.5) GO TO 60
C--FACTOR (TRANSO*F )VALID ONLY FOR GABLE WITH SLOPES OF SAME MATERI
      TB(I)=B(I)*BTR(I)*AREA(I) *(1.-ALB*DTR(I))
      TD(I)=D(I)*DTR(I)*AREA(I) *(1.-ALB*DTR(I))
      GO TO 40
 50   TBB(I)=B(I)*AREA(I)*BTR(I)-B(1)*AREA(5)*BTR(I)
      TB(I)=TBB(I)*(1.-ALB*(FPR*DTR(I)+FPC))
      TDD(I)=D(I)*AREA(I)*DTR(I)*FRP
      TD(I)=TDD(I)*(1.-ALB*(FPR*DTR(I)+FPC))
      GO TO 40
 60   TB(I)=B(1)*AREA(I)*BTR(2)
      TD(I)=D(2)*AREA(2)*DTR(2)*FRC+ALB*FPC*(TBB(2)+TDD(2))
   40 TT(I)=TB(I)+TD(I)
  10  CONTINUE
      BEAM=0.
      DIFF=0.
      TOTA=0.
      DO 20 J=1,NW
      BEAM=BEAM+TB(J)
      DIFF=DIFF+TD(J)
      TOTA=TOTA+TT(J)
  20  CONTINUE
      DO 30 K=1,NW
      IF(BEAM.EQ.0.) GO TO 17
      RB(K)=TB(K)/BEAM
      GO TO 18
  17  RB(K)=0.
  18  RD(K)=TD(K)/DIFF
      RT(K)=TT(K)/TOTA
      IF ( GBLREP .LE. 0 ) GO TO 30
      WRITE(6,101) K,AREA(K),TB(K),TD(K),TT(K),RB(K),RD(K),RT(K)
  30  CONTINUE
```

```
      HOR=AF*HBAR
      EFF=TOTA/HOR
      DHOR=AF*DBAR
      BHOR=AF*BBAR
      DEFF=DIFF/DHOR
      IF(BHOR.EQ.0.) GO TO 19
      BEFF=BEAM/BHOR
      GO TO 21
 19   BEFF=0.
  21  IF ( GBLREP .LE. 0 ) GO TO 500
      WRITE(6,106)
      WRITE(6,102) BEAM,DIFF,TOTA,BEFF,DEFF,EFF
 500  IST(M) = IST(M) + 1
      GRE ( M , IST(M) ) = TOTA
      COL ( M , IST(M) ) = TT(5)
      RETURN
 101  FORMAT(9X,I1,2X,F6.0,3F10.0,3X,3F7.3/)
 102  FORMAT(9X,3F10.0,3F7.3//)
 105  FORMAT(9X,*S*,4X,*AREA*,4X,*SOLAR ENERGY CAPTURED    *,F8.1,3X,
     1*CONTRIBUTION*/,14X,*M**2*,11X,*(KJ/HR )*,22X,*TO TOTAL*//,
     223X,*BEAM*,3X,*DIFFUSE*,5X,*TOTAL*,6X,*BEAM*,3X,*DIF.*,3X,
     3*TOTAL*/)
 106  FORMAT(15X,*TOTAL CAPTURED    */,13X,*BEAM*,4X,*DIFFUSE*,4X,
     1*TOTAL*,4X,*BCF *,3X,*DCF*,4X,*TCF*/)
      END



      SUBROUTINE PRG1 ( COL , GRE , IST )
C
C  DECLARE COMMON BLOCK
C
      COMMON / GABLE / GBLREP
C
C
      DIMENSION IST(12),COL(12,24),GRE(12,24)
C
C     INTEGER GBLREP
C
      DO 400 IB=1,12
      DO 500 JB=1,23
      IF(COL(IB,JB+1).NE.0.) GO TO 500
      KB=IST(IB)
      DO 600 K=1,KB
      L=13-K
      M=12+K
      N=KB-K+1
      COL(IB,L)=COL(IB,M)=COL(IB,N)
      GRE(IB,L)=GRE(IB,M)=GRE(IB,N)
 600  COL(IB,N)=GRE(IB,N)=0.
      GO TO 400
 500  CONTINUE
 400  CONTINUE
      IF ( GBLREP .LE. 0 ) GO TO 800
```

```
      WRITE(6,950)
      DO 700 IC=1,12
      DO 700 JC=1,24
      WRITE(6,900) IC,JC,COL(IC,JC),GRE(IC,JC)
 700  CONTINUE
 800  RETURN
  900 FORMAT(5X,2I5,2F15.6)
  950 FORMAT(1H1,10X,*VALUES OF -- QSOL -- FROM SUBROUTINE --PRG1--*,//)
      END




      SUBROUTINE TOTAL1 ( GRES , COLS , ANSYS )
C
C
C  DECLARE COMMON BLOCKS
C
C
      COMMON / HSOUT / QINF(288) , QTR(288) , QLOAD(288)
      COMMON / STOUT / TI(288,10)
      COMMON / OPTCS / ABC,AC,AR,E1,E2,EC,ER,FRC,H,L,S,TGD,TCC,UM
C
      DIMENSION COLS(12,24) , GRES(12,24)
C
      INTEGER ANSYS
C

      SIG=2.04E-7
C  READ IN CONSTANTS
      READ(5,*) AC , ABC , EC , ER , AR , FRC , TC
C  READ IN CONSTANTS FOR SUBROUTINE OPTTC
      READ(5,*) E1 , E2 , H , S , L , UM , TGD , TCC
      TC = TC + 273.16

      DO 20 I=1,12
      SINF=0.
      SQTR=0.
      SSOL=0.
      SSUP=0.
      SLOAD=0.
      SQCOL=0.
C
C  FOLLOWING STATEMENTS ARE FOR SUBROUTINE OPTTC -- MAR. 83
C
        WRITE(6,177) I
177     FORMAT(1H1,10X,"MONTH NO. = ",I3,/)
        MON = I
        CALL OPTTC(MON,SIG,COLS)
C
C  END OF NEW STATEMENTS ------ MAR. 83
      IF ( ANSYS .EQ. 2 ) WRITE(6,25)
      IF ( ANSYS .EQ. 3 ) WRITE(6,26)
      DO 30 J=1,24
```

```
        COL = COLS(I,J)
        GR  = GRES(I,J)
        MQ = ( ( I - 1 ) * 24 ) + J
        TR = TI(MQ,2)
      IF(COL.EQ.0.) GO TO 50
      TR=TR+273.16
      COLOSS=(SIG*(TC**4-TR**4))/(((1.-EC)/(EC*AC))
     1+(1/(AR*FRC))+((1-ER)/(ER*AR)))
      QCOL=ABC*COL-COLOSS
      IF(QCOL.LT.0.) QCOL=0.
      GO TO 51
 50   COLOSS=0.
      QCOL=0.
 51   QSOL=GR-COL
      IF ( QINF(MQ) .LE. 0.0 ) QINF(MQ) = 0.0
      IF ( QTR(MQ) .LE. 0.0 ) QTR(MQ) = 0.0
      F = 0.0
C
C  ANALYSIS TYPE 2
C
      IF ( ANSYS .EQ. 3 ) GO TO 100
      QLOAD(MQ) = QINF(MQ) + QTR(MQ)
      IF ( QLOAD(MQ) .LE. 0.0 ) QLOAD(MQ) = 0.0
      QSUP = QSOL - QINF(MQ) - QTR(MQ)
      IF ( QSUP .GT. 0.0 ) QSUP = 0.0
      IF ( QLOAD(MQ) .NE. 0.0 ) F = ( QLOAD(MQ) + QSUP ) / QLOAD(MQ)
      WRITE(6,40) I,J,QSOL,QINF(MQ),QTR(MQ),QLOAD(MQ),QSUP,F,QCOL
      GO TO 105
  100 CONTINUE
C
C  ANALYSIS TYPE 3
C
      QLOAD(MQ) = QTR(MQ) - QSOL
      IF ( QLOAD(MQ) .LE. 0.0 ) QLOAD(MQ) = 0.0
      QSUP = QLOAD(MQ) - QINF(MQ)
      IF( QSUP .LT. 0.0 ) QSUP = 0.0
      IF ( QTR(MQ) .NE. 0.0 ) F = ( QTR(MQ) - QLOAD(MQ) ) / QTR(MQ)
      QFCT = 0.0
      IF ( QLOAD(MQ).NE.0.0 ) QFCT = ( QLOAD(MQ) - QSUP ) / QLOAD(MQ)
      WRITE(6,42) I,J,QSOL,QINF(MQ),QTR(MQ),QLOAD(MQ),QSUP,F,QCOL,QFCT
      IF ( QTR(MQ) .EQ. 0.0 ) QINF(MQ) = 0.0
  105 CONTINUE
      SINF=SINF+QINF(MQ)
      SQTR=SQTR+QTR(MQ)
      SSOL=SSOL+QSOL
      SSUP=SSUP+QSUP
      SLOAD=SLOAD+QLOAD(MQ)
      SQCOL=SQCOL+QCOL
 30   CONTINUE
      DAYF = 0.0
      IF ( ( SLOAD .EQ. 0.0 ) .AND. ( ANSYS .EQ. 2 ) ) GO TO 115
      IF ( ( SQTR .EQ. 0.0 ) .AND. ( ANSYS .EQ. 3 ) ) GO TO 115
      IF ( ANSYS .EQ. 2 ) DAYF = ( SLOAD + SSUP ) / SLOAD
      IF ( ANSYS .EQ. 3 ) DAYF = ( SQTR - SLOAD ) / SQTR
  115 COLF = 0.0
```

```
      IF ( SSUP .NE. 0.0 ) COLF = SQCOL / SSUP
      SFCT = 0.0
      IF ( SQTR .NE. 0.0 ) SFCT = SINF / SQTR
      IF ( ANSYS .EQ. 2 )
     .WRITE(6,41) SSOL,SINF,SQTR,SLOAD,SSUP,DAYF,SQCOL,COLF
      IF ( ANSYS .EQ. 3 )
     .WRITE(6,43) SSOL,SINF,SQTR,SLOAD,SSUP,DAYF,SQCOL,SFCT,COLF
 20   CONTINUE
   25 FORMAT(5(/),15X,
     1       *MONTH HOUR   PASSIVE    INFILT  TRANSMTN       TOTAL  *,
     2       *SUPLMENTL  FRACTN    SOLAR                    *,/,15X,
     3       *                SOLAR    -RATION    LOSSES      LOSSES  *,
     4       *HEAT REQD    LOAD  COLECTED                   *,/15X,81(1H-),/)
   40 FORMAT(17X,I2,3X,I2,1X,2F10.0,3F11.0,F8.3,2F10.0)
   41 FORMAT(/,15X,81(1H=),/,17X,*TOTAL*,/,19X,*OF*,4X,2F10.0,3F11.0,
     1        F8.3,F10.0,/,17X,* DAY *,/,15X,81(1H=)                 ,
     2        //,62X,*FRACTION SUPPLIED BY SOLAR*,F8.3               )
   26 FORMAT(5(/),15X,
     1       *MONTH HOUR   PASSIVE    INFILT  TRANSMTN       TOTAL  *,
     2       *SUPLMENTL  FRACTN    SOLAR      FRACTN    *,/,15X,
     3       *                SOLAR    -RATION    LOSSES      LOSSES  *,
     4       *HEAT REQD    LOAD  COLECTED  BY VETLN    *,/15X,91(1H-),/)
   42 FORMAT(17X,I2,3X,I2,1X,2F10.0,3F11.0,F8.3,F10.0,F10.3)
   43 FORMAT(/,15X,91(1H=),/,17X,*TOTAL*,/,19X,*OF*,4X,,2F10.0,3F11.0,
     1        F8.3,F10.0,F10.3,/,17X,* DAY *,/,15X,91(1H=)          ,
     2        //,72X,*FRACTION SUPPLIED BY SOLAR*,F8.3               )
      END



      SUBROUTINE SUP ( ANSYS )
C
C  DECLARE COMMON BLOCKS
C
      COMMON / THOUT / TO(288) , TSKY(288) , WIND(12) , TOPO(288)
      COMMON / HSOUT / QVENT(288) , QTRANS(288) , QSUP(288) , KWH(288)
     1                 ,UFLOW(288) , UQVENT(288) , UQTR(288) , UWH(288)
     2                 ,UQSUP(288)
      COMMON / SPOUT / TB , ZZZZ , FLOW(288)
C
      REAL KWH
      INTEGER SUPREP , ANSYS
C
C
C  READ IN REQUIRED CONSTANTS
C
      READ(5,*) SUPREP , N , VER , VENT , WT , TB , RHB , PAT , PMAX
C
      FMAX = VENT * N
C
      CALL HMPRO ( WT , TB , WVP , HL , CSENS , TH )
      AMW = N * WVP
      SVP = VP(TB)
      CALL DBRH ( TB,RHB,PAT,SVP,AVP,SUR,WB,SV,SPH,DPT )
```

```
C
C   ASSIGN VALUE OF SV TO ZZZZ OF COMMON BLOCK.
C   THIS IS DONE TO VALUE OF SV IN SUBROUTINE 'QCONP1'.
C   VALUE OF ZZZZ IS TRANSFERED BY COMMON BLOCK 'SPOUT'.
C
        ZZZZ = SV
C
        DO 20 J = 1 , 12
        IF ( SUPREP .NE. 0 ) WRITE(6,30)
        DO 20 K = 1 , 24
           I = ( ( J - 1 ) * 24 ) + K
           SVPO = VP(TO(I))
           AVPO = VP(TDPO(I))
           CALL DBDP ( TO(I),RHU,PAT,SVPO,AVPO,SURO,WO,SVO,ENTO,TDPO(I))
           AMA = AMW / ( WB - WO )
           CALL DBDP ( TB,RHX,PAT,SVP,AVPO,SURX,WX,SVX,ENTB,TDPO(I))
           QVENT(I) = AMA * (ENTB - ENTO )
           QSUP(I) = N * QSENS - QTRANS(I) - QVENT(I)
           IF ( QSUP(I) .LE. 0.0 ) GO TO 10
           QVENT(I) = N * QSENS - QTRANS(I)
           AMA = QVENT(I) / ( ENTB - ENTO )
           QSUP(I) = 0.0
   10      FLOW(I) = ( AMA * SV ) / 3600.0
           IF ( ( FLOW(I) .LT. 0.0 ) .OR. ( FLOW(I) .GT. FMAX ) )
     .                                      FLOW(I) = FMAX
           KWH(I) = FLOW(I) / VER
           UWH(I) = ( KWH(I) * 1000.0 ) / N
           UFLOW(I) = FLOW(I) / N
           UQVENT(I) = QVENT(I) / N
           UQTR(I) = QTRANS(I) / N
           UQSUP(I) = QSUP(I) / N
           IF ( SUPREP .NE. 0 )
     1     WRITE(6,40) J,K,TO(I),TDPO(I),QTRANS(I),QVENT(I),CSUP(I),
     2     FLOW(I),KWH(I),UFLOW(I),UQVENT(I),UQTR(I),UQSUP(I),UWH(I)
   20 CONTINUE
C
C   IF TYPE OF ANALYSIS EQUAL TO THEN PRODUCE TABLE,
C   OTHERWISE RETURN TO CALLING SUBPROGRAM FOR FURTHER
C   ANALYSIS. STOP PROGRAM IF NO ANALYSIS NEEDED.
C
        IF ( ANSYS .EQ. 3 ) RETURN

C
        CALL NEWMON ( N , VENT , PMAX )
C
        STOP
C
   30 FORMAT(10(/),1H1,*MON*,3X,*HOR*,4X,*TO*,4X,*TDPO*,4X,*QTRANS*,8X,
     1  *QVENT*,6X,*QSUP*,8X,*FLOW*,3X,*KWH*,3X,*UFLOW*,3X,*UQVENT*,2X,
     2          *UQTR*,4X,*UQSUP*,4X,*UWH*,/                              )
   40 FORMAT ( I3,3X,I3,2F7.1,3F12.1,2F8.2,F7.5,3F8.2,3X,F6.3 )
C
        END
C
```

```
      SUBROUTINE HMPRO ( WT , TB , MW , LH , SH , TH )
C
C
      REAL LH , MW
C
      A = 0.00539*WT + 0.00171*TB - 0.0000579*WT*TB - 0.C000141*WT**2
     .  + 0.000446*TB**2 - 1.4147
      MW = 10.0 ** A
      B = 1.761 + 0.035*ALOG10(WT) - 0.00414*TB + 0.148*(ALOG10(WT))**2
     .  + 0.00023*TB**2 - 0.00563*TB*ALOG10(WT)
      TH = 4.186 * 10.0 ** B
      LH = MW * ( 2504.44 - 2.4*TB )
      SH = TH - LH
C
      RETURN
      END




      SUBROUTINE DBDP ( DBT,RHU,PAT,SVP,AVP,SUR,AUR,SPV,SPH,DPT )
C
C-----------------------------------------------------------------------
C
C  THIS SUBROUTINE CALCULATES MOIST AIR PROPERTIES
C  WHEN DB TEMPERATURE AND DB ARE KNOWN
C
C  INPUT:
C
C     DBT - DRY-BULB TEMP.(DEG.CELCIUS) FROM THHFX
C     DPT - DEW POINT TEMPERATURE FROM THHFX
C     PAT - ATMOSPHERIC PRESSURE(KPA)
C     SVP - SATURATION WATER VAPOUR PRESSURE (KPA) FROM FUNCT. VP
C     AVP - ACTUAL WATER VAPOUR PRESSURE (KPA) FROM FUNCTION VP
C
C
C  OUTPUT:
C
C     SUR - SATURATION HUMIDITY RATIO (KG.WATER/KG.DRY-AIR)
C     AUR - ACTUAL HUMIDITY RATIO (KG.WATER/KG.DRY-AIR)
C     SPV - SPECIFIC VOLUME (CU.METRE/KG.DRY-AIR)
C     SPH - SPECIFIC ENTHAPLY (KJ/KG,DRY-AIR)
C     RHU - RELATIVE HUMIDITY (DEG.CELCIUS)
C
C
C-----------------------------------------------------------------------
C

      PAT = 101.325
      RAR = 0.28705
C
C  CALCULATION OF RELATIVE HUMIDITY
C
      RHU = AVP / SVP
```

```
C
C   CALCULATION OF SATURATION HUMIDITY RATIO
C
       SUR = 0.62198 * SVP / ( PAT - SVP )
C
C   CALCULATION OF ACTUAL HUMIDITY RATIO
C
       AUR = 0.62198 * AVP / ( PAT - AVP )
C
C   CALCULATION OF DEGREE OF SATURATION
C
       DES = AUR / SUR
C
C   CALCULATION OF SPECIFIC VOLUME
C
       ADB = DBT + 273.16
       SPV = RAR * ADB / PAT * ( 1.0 + 1.6078 * AUR )
C
C   CALCULATION OF SPECIFIC ENTHAPLY
C
C    FOLOWING EQUATION IS VALID FOR DBT IN THE RANGE OF -50 TO 110 ONLY
C
       SPH = 1.006 * DBT + AUR * ( 2501 + 1.775 * DBT )
       RETURN
       END




       SUBROUTINE DBRH ( DBT,RHU,PAT,SVP,AVP,SUR,AUR,SPV,SPH,DPT )
C
C-----------------------------------------------------------------------
C
C
C   SUBROUTINE TO CALCULATE MOIST AIR PROPERTIES
C   WHEN DB TEMPERATURE AND RH ARE KNOWN
C
C   INPUT:
C
C     DBT - DRY-BULB TEMPERATURE ( DEG.CELCIUS ) FROM SUBROUTINE -SUP-
C     RHU - RELATIVE HIMUDITY (DECIMAL) FROM SUBROUTINE -SUP-
C     PAT - ATMOSPHERIC PRESSURE (KPA) FROM SUBROUTINE -SUP-
C     SVP - SATURATION WATER VAPOUR PRESSURE (KPA) FROM FUNCTION -VP-
C
C   OUTPUT
C
C     AVP - ACTUAL WATER VAPOUR PRESSURE (KPA)
C     SUR - SATURARTION HUMIDITY RATIO (KG.WATER/KG.DRY-AIR)
C     AUR - ACTUAL HUMIDITY RATIO (KG.WATER/KG.DRY-AIR)
C     SPV - SPECIFIC VOLUME (CU.METRE/KG.DRY-AIR)
C     SPH - SPECIFIC ENTHAPLY (KJ/KG.DRY-AIR)
C     DPT - DEW-POINT TEMPERATURE (DEG.CELCIUS)
C
C
C
C-----------------------------------------------------------------------
```

```
C
C
      RAR = 0.28705
C
C   CALCULATE ACTUAL WATER VAPOUR PRESSURE
C
      AVP = RHU *SVP
C
C   CALCULATE SATURATION HUMIDITY RATIO
C
      SUR =0.62198 * SVP / ( PAT - SVP )
C
C   CALCULATE ACTUAL HUMIDITY RATIO
C
      AUR = 0.62198 * AVP / ( PAT - AVP )
C
C   CALCULATE DEGREE OF SATURATION
C
      DES = AUR / SUR
C
C   CALCULATE SPECIFIC VOLUME
C
      ADB = DBT + 273.16
      SPV = RAR * ADB / PAT * ( 1.0 + 1.6078 * AUR )
C
C   CALCULATE SPECIFIC ENTHAPLY
C
C    FOLLOWING EQUATION IS VALID FOR DBT IN RANGE OF -50 TO 110 ONLY
C
      SPH = 1.006 * DBT + AUR * ( 2501 + 1.775 * DBT )
C
C   CALCULATE DEW POINT TEMPERATURE
C
      ALP = ALOG(AVP)
      IF ( ( DBT .GE. -50.0 ) .OR. ( DBT .LE. 0.0 ) )  GO TO 20
      IF ( ( DBT .GT. 0.0 ) .OR. ( DBT .LE. 50.0 ) ) GO TO 10
C
C   DRY BULB TEMPERATURE IN THE THE RANGE ( 50 TO 110 )
C
      DPT = 13.8 + 9.478*ALP + 1.991*ALP**2
      RETURN
C
C   DRY BULB TEMPERATURE IN THE RANGE ( 0 TO 50 )
C
   10 DPT = 6.983 + 14.38*ALP + 1.079*ALP**2
      RETURN
C
C   FOR DRY BULB TEMPERATURE IN THE RANGE ( -50 TO 0 )
C
   20 DPT = 5.994 + 12.41*ALP + 0.4273*ALP**2
C
      RETURN
      END
```

```
      FUNCTION VP(TC)
C
C   FUNCTION TO CALCULATE VAPOUR PRESSURE
C
C   SOURCE:-
C         L.R.WILHELM "NUMERICAL CALCULATION OF PSYCHROMETRIC
C                        PROPERT952 IN SI UNITS" ASAE TRANS. 1976
C
C     TK - TEMPERATURE IN DEGREE KELVIN
C     VP - VAPOUR PRESSURE ( KILO-PASCLE)
C     TC - DUMMY VARIABLE FOR TEMPERATURE IN DEGREE CELCIUS
C
C   IF (TC .EQ. DRY - BULB ) OUTPUT IS SATURATION VAPOUR PRESSURE
C
C   IF (TC .EQ. DEW POINT  ) OUTPUT IS ACTUAL VAPOUR PRESSURE
C
C
      TK = TC + 273.16
      IF ( TC .GT. 0.0 ) GO TO 10
      EXPO = 24.2779 - 6238.64/TK - 0.344438*ALOG(TK)
      GO TO 15
   10 EXPO = 89.63121 - 7511.52/TK + 0.02399897*TK - 1.165455E-05*TK**2
     .     - 1.281034E-08*TK**3 + 2.09984E-11*TK**4 - 12.1508*ALOG(TK)
   15 VP = EXP(EXPO)
C
      RETURN
      END



      SUBROUTINE NEWMON ( N , VENT , PMAX )
C
C   DECLARE COMMON BLOCKS
C
      COMMON / THOUT / TO(288) , TSKY(288) , WIND(12) , TDPO(288)
      COMMON / HSOUT / QVENT(288) , QTRANS(288) , QSUP(288) , KWH(288)
     1                 ,UFLOW(288) , UQVENT(288) , UQTR(288) , UWH(288)
     2                 ,UQSUP(288)
      COMMON / SPOUT / TB , ZZZZ , FLOW(288)
C
      REAL KWH
C
      FMAX=VENT*N
      DO 20 I=1,12
      WRITE(6,30)
      STRANS=0.
      SVENT=0.
      SSUP=0.
      SKWH=0.
      UST=0.
      UVT=0.
      USUP=0.
      UWAT=0.
      FKWH=0.
```

```
      DO 10 J=1,24
      MQ = ( ( I - 1 )* 24 ) + J
      IF(QTRANS(MQ).LT.0.) QTRANS(MQ)=0.
      IF(QVENT(MQ).LT.0.) QVENT(MQ)=0.
      IF(QSUP(MQ).LT.0.) QSUP(MQ)=0.
      IF(UQTR(MQ).LT.0.) UQTR(MQ)=0.
      IF(UQVENT(MQ).LT.0.) UQVENT(MQ)=0.
      IF(UQSUP(MQ).LT.0.) UQSUP(MQ)=0.
      UFLOW(MQ)=UFLOW(MQ)*1000.
      PLR=FLOW(MQ)/FMAX
      FFLP=0.00153+0.005208*PLR+1.1086*PLR**2-0.11635563*PLR**3
      FANE=PMAX*FFLP
      STRANS=STRANS+QTRANS(MQ)
      SVENT=SVENT+QVENT(MQ)
      SSUP=SSUP+QSUP(MQ)
      SKWH=SKWH+KWH(MQ)
      UST=UST+UQTR(MQ)
      UVT=UVT+UQVENT(MQ)
      USUP=USUP+UQSUP(MQ)
      UWAT=UWAT+UWH(MQ)
      FKWH=FKWH+FANE
      WRITE(6,40) I,J,TO(MQ),TDPO(MQ),UQTR(MQ),UQVENT(MQ),UQSUP(MQ),
     1            UFLOW(MQ),FLOW(MQ),FANE
   10 CONTINUE
      WRITE(6,50) UST,UVT,USUP,FKWH
   20 CONTINUE
C
      RETURN
C
   30 FORMAT(1H1,10(/),15X,
     1       *MONTH HOUR   <OUTDOOR TEMP.>   TRANS.   VENTLTN.    SUPL  *
     2       ,*  <VENTLTN RATE>      FAN*,/,15X,
     3       *                  DRY       DEW    LOSSES     LOSSES     HEAT  *
     4       ,*  /ANIMAL  TOTAL    POWER*,  /,15X,82(1H-),/       )
   40 FORMAT(17X,I2,3X,I2,2X,2F8.1,2X,F7.1,2X,F9.1,2X,F6.1,2X,3F8.2)
   50 FORMAT(/,15X,82(1H=),//,15X,*TOTAL OF DAY  *,15X,
     1       F7.1,2X,F9.1,F8.1,19X,F7.2,//,15X,82(1H=)     )
      END




      SUBROUTINE GRNHSO ( GRE )
C
C
      DIMENSION DGAMA(10),GAMA(10),DS(10),S(10),N(10),AREA(10),
     1A(10),B(10),TRAND(10),TAD(10),TTD(10),SKY(10),GROUND(10),
     2TCIA(10),BTILT(10),RB(10),DTILT(10),TT(10),TIA(10),AOFI(10),
     3AOFR(10),XX(10),YY(10),PERE(10),PARE(10),AA(10),BB(10),
     4TRANS(10),TA(10) , IST(12) , GRE(12,24)
C
C
      REAL LAT,KT
      INTEGER GBLREP
C--CALCULATION OF TRANSMITTANCE THROUGH GLASS COVER
```

```
C
      READ(5,*) GBLREP , DLAT , NW , AF , ALP , F , RINDEX , AK , AL
      READ(5,*) (DGAMA(I),DS(I),N(I),AREA(I),I=1,NW)
      IF ( GBLREP .LE. 0 ) GO TO 1000
      WRITE(6,1)
      WRITE(6,108)
 1000 CONTINUE
      PI=3.141593
      SC=4871.
      LAT=DLAT*PI/180.
C--CHARACTERISTICS OF GLASS COVER
C--CALCULATION OF TRANSMITTANCE FOR DIFFUSE RADIATION
      AODI=1.0123
      AODR=ASIN(SIN(AODI)/RINDEX)
      X=AODR-AODI
      Y=AODI+AODR
      PEREF=(SIN(X)/SIN(Y))**2
      PAREF=(TAN(X)/TAN(Y))**2
      M=0
      DO 65 MQ = 1 , 12
         IST(MQ) = 0
         DO 60 NQ = 1 , 24
            GRE(MQ,NQ) = 0.0
   60    CONTINUE
   65 CONTINUE
      DO 12 NCD = 1 ,12
      READ(5,*) DAY,HBAR,ALB
      M=M+1
      CORFAC=1.+0.033*COS(PI*2.*DAY/365.)
      DEC=23.45*SIN(((284.+DAY)/365.)*2.0*PI)
      DEC=DEC*PI/180.
      WS=ACOS(-TAN(LAT)*TAN(DEC))
      EXTRAD=24./PI*SC*CORFAC*(COS(LAT)*COS(DEC)*SIN(WS)
     1+WS*SIN(LAT)*SIN(DEC))
      KT=HBAR/EXTRAD
      RATIO=0.958-0.982*KT
      DBAR=RATIO*HBAR
      IF ( GBLREP .LE. 0 ) GO TO 1001
      IF(M.EQ.1) WRITE(6,110)
      IF(M.EQ.2) WRITE(6,111)
      IF(M.EQ.3) WRITE(6,112)
      IF(M.EQ.4) WRITE(6,113)
      IF(M.EQ.5) WRITE(6,114)
      IF(M.EQ.6) WRITE(6,115)
      IF(M.EQ.7) WRITE(6,116)
      IF(M.EQ.8) WRITE(6,117)
      IF(M.EQ.9) WRITE(6,118)
      IF(M.EQ.10) WRITE(6,119)
      IF(M.EQ.11) WRITE(6,120)
      IF(M.EQ.12) WRITE(6,121)
 1001 CONTINUE
      DO 20 I =1,NW
      A(I)=(2.*N(I)-1.)*PEREF
      B(I)=(2.*N(I)-1.)*PAREF
C****CALCULATION OF TRANSMITTANCE DUE TO REFLECTION ONLY
```

```
      TRAND(I)=0.5*((1.-PEREF)/(1.+A(I))+(1.-PAREF)/(1.+B(I)))
C****CALCULATION OF TRANSMITTANCE DUE TO ABSORPTION ONLY
      TAD(I)=EXP(-N(I)*AK*AL/COS(AODR))
C****CALCULATION OF TOTAL TRANSMITTANCE CONSIDERING ABSORPTION & REF
      TTD(I)=TRAND(I)*TAD(I)
      GAMA(I)=DGAMA(I)*PI/180.
      S(I)=DS(I)*PI/180.
      SKY(I)=0.5*(1.+COS(S(I)))
      GROUND(I)=0.5*ALB*(1.-COS(S(I)))
   20 CONTINUE
      DW=127.5
   30 W=DW*PI/180.
      HCIA=COS(LAT)*COS(DEC)*COS(W)+SIN(LAT)*SIN(DEC)
      IF(HCIA.LE.0.) GO TO 94
      RT1=0.409+0.5016*SIN(WS-1.047)
      RT2=0.6609-0.4767*SIN(WS-1.047)
      RT=(PI/24.)*(RT1+RT2*COS(W))*(COS(W)-COS(WS))/(SIN(WS)-WS*COS(WS))
      TIBAR=RT*HBAR
      RATH=PI/24.*((COS(W)-COS(WS))/(SIN(WS)-WS*COS(WS)))
      DIBAR=RATH*DBAR
      DO 40 I=1,NW
      TCIA(I)=COS(S(I))*SIN(DEC)*SIN(LAT)-SIN(DEC)*COS(LAT)*SIN(S(I))*
     1COS(GAMA(I))+COS(DEC)*COS(LAT)*COS(S(I))*COS(W)+COS(W)*COS(DEC)*
     2SIN(S(I))*COS(GAMA(I))*SIN(LAT)+COS(DEC)*SIN(S(I))*SIN(GAMA(I))*
     3SIN(W)
      IF(TCIA(I).GT.0.) GO TO 70
      BTILT(I)=0.
      RB(I)=0.
      GO TO 80
   70 RB(I)=TCIA(I)/HCIA
      IF(TIBAR.LT.DIBAR) TIBAR=DIBAR
      BTILT(I)=(TIBAR-DIBAR)*RB(I)
   80 DTILT(I)=SKY(I)*DIBAR+GROUND(I)*TIBAR
      IF(TCIA(I).GT.0.) GO TO 90
      TT(I)=0.
      GO TO 40
   90 TIA(I)=ACOS(TCIA(I))
C--CALCULATION OF TRANSMITTANCE FOR BEAM RADIATION
      AOFI(I)=TIA(I)
      AOFR(I)=ASIN(SIN(AOFI(I))/RINDEX)
      XX(I)=AOFR(I)-AOFI(I)
      YY(I)=AOFI(I)+AOFR(I)
      PERE(I)=(SIN(XX(I))/SIN(YY(I)))**2
      PARE(I)=(TAN(XX(I))/TAN(YY(I)))**2
      AA(I)=(2.*N(I)-1.)*PERE(I)
      BB(I)=(2.*N(I)-1.)*PARE(I)
C****CALCULATION OF TRANSMITTANCE DUE TO REFLECTION ONLY
      TRANS(I)=0.5*((1.-PERE(I))/(1.+AA(I))+(1.-PARE(I))/(1.+BB(I)))
C****CALCULATION OF TRANSMITTANCE DUE TO ABSORPTION ONLY
      TA(I)=EXP(-N(I)*AK*AL/COS(AOFR(I)))
C****CALCULATION OF TOTAL TRANSMITTANCE CONSIDERING ABSORPTION & REF
      TT(I)=TRANS(I)*TA(I)
   40 CONTINUE
      CALL CAPFACO (BTILT,DTILT,TT,TTD,AREA,TIBAR,DIBAR,NW,AF,ALP,DW,
     1M,F,    GRE , IST , GBLREP )
```

```
94   DW=DW-15.
     IF(DW.GT.0.) GO TO 30
  12 CONTINUE
     IF ( GBLREP .LE. 0 ) GO TO 700
     DO 600 MG = 1 , 12
        KG = IST(MG)
        DO 550 NG = 1 , KG
           WRITE(6,107) GRE(MG,NG) , MG
550     CONTINUE
600  CONTINUE
700  CALL PRGO ( IST , GRE , GBLREP )
     CALL TOTALO ( GRE )
  1  FORMAT(*1*/////,29X,*.10 HECTARE*//,25X,*SINGLE GLASS COVER *//,
    126X,* GABLE GREENHOUSE*//,26X,*E-W ORIENTATION*//,29X,
    2*LENGTH=100M*/,29X,*WIDTH = 10M*/,29X,*HEIGHT=2 M*/,29X,
    3*SLOPE =18DEG*//,24X,*GLASS CHARACTERISTICS:*//,24X,
    4*THICKNESS=0.30 CM*//,24X,*K = 0.252 CM-1 ; IR=1.526*///)
107  FORMAT(F10.0,I5)
110  FORMAT(*1*///,35X,*JANUARY*//)
111  FORMAT(*1*///,35X,*FEBRUARY*//)
112  FORMAT(*1*///,35X,*MARCH*//)
113  FORMAT(*1*///,35X,*APRIL*//)
114  FORMAT(*1*///,35X,*MAY*//)
115  FORMAT(*1*///,35X,*JUNE*//)
116  FORMAT(*1*///,35X,*JULY*//)
117  FORMAT(*1*///,35X,*AUGUST*//)
118  FORMAT(*1*///,35X,*SEPTEMBER*//)
119  FORMAT(*1*///,35X,*OCTOBER*//)
120  FORMAT(*1*///,35X,*NOVEMBER*//)
121  FORMAT(*1*///,35X,*DECEMBER*//)
108  FORMAT(29X,*S1 = SOUTH WALL*/,29X,*S2= SOUTH ROOF*/,29X,
    1*S3 =  NORTH ROOF*/,29X,*S4 = WEST WALL*/,29X,*S5 = EASTWALL*/,
    229X,*S6=NORTH WALL*)
     STOP
     END




     SUBROUTINE CAPFACO (B,D,BTR,DTR,AREA,HBAR,DBAR,NW,AF,ALB,HR,M,F,
    1    GRE , IST , GBLREP )
C
C
     DIMENSION B(10),D(10),T(10),TB(10),TD(10),TT(10),BTR(10),
    1DTR(10),AREA(10),RB(10),RD(10),RT(10) ,TBB(10),TDD(10) ,
    2     GRE(12,24) , IST(12)
C
C
     INTEGER GBLREP
C
C--CAPTURE FACTORS FOR GABLE  GREENHOUSES,LOSS FROM ROOF INCLUDED.
C
     BBAR=HBAR-DBAR
     IF ( GBLREP .LE. 0 ) GO TO 100
     WRITE(6,105)  HR
```

```
  100 CONTINUE
      DO 10 I=1,NW
      T(I)=(B(I)+D(I))*AREA(I)
C--REFECTION LOSSES
C--FACTOR (TRANSD*F )VALID ONLY FOR GABLE WITH SLOPES OF SAME MATERI
      TB(I)=B(I)*BTR(I)*AREA(I) *(1.-ALB*DTR(I))
      TD(I)=D(I)*DTR(I)*AREA(I) *(1.-ALB*DTR(I))
      IF(I.EQ.2)GO TO 50
      IF(I.EQ.3)GO TO 50
      GO TO 40
  50  TD(I)=TD(I)*(1.0-DTR(I)*F)
   40 TT(I)=TB(I)+TD(I)
  10  CONTINUE
      BEAM=0.
      DIFF=0.
      TOTA=0.
      BINC=0.
      DINC=0.
      TINC=0.
      DO 20 J=1,NW
      BEAM=BEAM+TB(J)
      DIFF=DIFF+TD(J)
      TOTA=TOTA+TT(J)
      BINC=BINC+B(J)*AREA(J)
      DINC=DINC+D(J)*AREA(J)
      TINC=TINC+T(J)
  20  CONTINUE
      IF(BINC.EQ.0.)GOTO 15
      BOF=BEAM/BINC
      GO TO 16
 15   BCF=0.
   16 DCF=DIFF/DINC
      TCF=TOTA/TINC
      DO 30 K=1,NW
      IF(BEAM.EQ.0.) GO TO 17
      RB(K)=TB(K)/BEAM
      GO TO 18
  17  RB(K)=0.
  18  RD(K)=TD(K)/DIFF
      RT(K)=TT(K)/TOTA
      IF ( GBLREP .LE. 0 )  GO TO 30
      WRITE(6,101) K,AREA(K),TB(K),TD(K),TT(K),RB(K),RD(K),RT(K)
  30  CONTINUE
      HOR=AF*HBAR
      EFF=TOTA/HOR
      DHOR=AF*DBAR
      BHOR=AF*BBAR
      DEFF=DIFF/DHOR
      IF(BHOR.EQ.0.) GO TO 19
      BEFF=BEAM/BHOR
      GO TO 21
  19  BEFF=0.
   21 IF ( GBLREP .LE. 0 ) GO TO 500
      WRITE(6,106)
      WRITE(6,102) BEAM,DIFF,TOTA,BEFF,DEFF,EFF
```

```
 500 IST(M) = IST(M) + 1
     GRE( M , IST(M) ) = TOTA
     RETURN
 101  FORMAT(9X,I1,2X,F6.0,3F10.0,3X,3F7.3/)
 102  FORMAT(9X,3F10.0,3F7.3//)
 105  FORMAT(9X,*S*,4X,*AREA*,4X,*SOLAR ENERGY CAPTURED    *,F8.1,3X,
     1*CONTRIBUTION*/,14X,*M**2*,11X,*(KJ/HR )*,22X,*TO TOTAL*//,
     223X,*BEAM*,3X,*DIFFUSE*,5X,*TOTAL*,6X,*BEAM*,3X,*DIF.*,3X,
     3*TOTAL*/)
 106  FORMAT(15X,*TOTAL CAPTURED    */,13X,*BEAM*,4X,*DIFFUSE*,4X,
     1*TOTAL*,4X,*BCF *,3X,*DCF*,4X,*TCF*/)
      END


      SUBROUTINE PRGO ( IST , GRE , GBLREP )
C
C
      DIMENSION IST(12),GRE(12,24)
C
      INTEGER GBLREP
C
      DO 400 IB = 1 , 12
      DO 500 JB = 1 , 23
      IF(GRE(IB,JB+1).NE.0.) GO TO 500
      KB=IST(IB)
      DO 600 K=1,KB
      L=13-K
      M=12+K
      N=KB-K+1
      GRE(IB,L)=GRE(IB,M)=GRE(IB,N)
 600  GRE(IB,N)=0.
      GO TO 400
 500  CONTINUE
 400  CONTINUE
      IF ( GBLREP .LE. 0 ) GO TO 800
      WRITE(6,950)
      DO 700 IC = 1 ,12
      DO 700 JC = 1 ,24
         WRITE(6,900) IC , JC , GRE(IC,JC)
 700 CONTINUE
 800 CONTINUE
     RETURN
 900 FORMAT(5X,2I5,F15.6)
 950 FORMAT(1H1,10X,* VALUES OF -QSOL- FROM SUBROUTINE -PRGO-*,//)
     END
```

```
      SUBROUTINE TOTALO ( GRE )
C
C   DECLARE COMMON BLOCKS
C
      COMMON / HSOUT / QINF(288) , QTR(288) , QLOAD(288)
      DIMENSION GRE(12,24)
C
      DO 25 I = 1 , 12
         SSOL = 0.0
         SINF = 0.0
         SQTR = 0.0
         SLOD = 0.0
         SSUP = 0.0
         WRITE(6,30)
         DO 20 J = 1 , 24
            MQ = ( ( I - 1 ) * 24 ) + J
            IF ( QINF(MQ) .LE. 0.0 ) QINF(MQ) = 0.0
            IF ( QTR(MQ) .LE. 0.0 ) QTR(MQ) = 0.0
            QLOAD(MQ) = QINF(MQ) + QTR(MQ)
            IF ( QLOAD(MQ) .LE. 0.0 ) QLOAD(MQ) = 0.0
            QSOL = GRE(I,J)
            QSUP = QSOL - QINF(MQ) - QTR(MQ)
            IF ( QSUP .GT. 0.0 ) QSUP = 0.0
            F = 0.0
            IF ( QLOAD(MQ) .EQ. 0.0 ) GO TO 10
            F = ( QLOAD(MQ) + QSUP ) / QLOAD(MQ)
   10       CONTINUE
            SINF = SINF + QINF(MQ)
            SQTR = SQTR + QTR(MQ)
            SSOL = SSOL + QSOL
            SSUP = SSUP + QSUP
            SLOD = SLOD + QLOAD(MQ)
            DAYF = 0.0
            IF ( SLOD .EQ. 0.0 ) GO TO 15
            DAYF = ( SLOD + SSUP ) / SLOD
   15       CONTINUE
            WRITE(6,35) I , J , QSOL , QINF(MQ) , QTR(MQ) ,
     1                  QLOAD(MQ) , QSUP , F
   20    CONTINUE
         WRITE(6,40) SSOL , SINF , SQTR , SLOD , SSUP , DAYF
   25 CONTINUE
      RETURN
C
   30 FORMAT(1H1,15(/),15X,
     1       *MONTH HOUR      SOLAR       INFILTRATION  TRANSMISSION*,
     2       *            TOTAL  SUPPLEMENTAL  FRACTION*,/,15X,
     3       *                  RADIATION                        LOSSES   *,
     4       *            LOSSES  HEAT REQUIRD   OF LOAD*,/,10X,100(1H-)
     5       ,/                                                      )
   35 FORMAT(17X,I2,3X,I2,1X,5F14.0,F10.3)
   40 FORMAT(/,10X,100(1H=),//,10X,*TOTAL OF MONTH *,5F14.0,F10.3,//,
     1        10X,100(1H=)                                           )
   45 FORMAT(I3,3X,I3,5X,F7.2,5X,F12.2,5X,F12.2,5X,F20.2)
      END
```

```
      SUBROUTINE OPTTC(II,SIG,COLS)
C
      COMMON / STOUT / TI(288,10)
      COMMON / OPTCS / ABC,AC,AR,E1,E2,EC,ER,FRC,H,L,S,TGDD,TCC,UM
C
      DIMENSION COLS(12,24)
C
C     E1=0.9
C     E2=0.1
C     H=5.77
C     S=0.1
C     L=100
C     UM=0.014
C     TGD=25.0

      TGD = TGDD
      WRITE(6,100) E1 , E2 , H , S , L , UM , TGD , TCC
100     FORMAT(6X,"E1         E2        H       S     L          UM     TGD     TCC"
     $        ,/,4F8.3,I4,3F8.3,///)
        WRITE(6,178)
178   FORMAT(2X,"HR",8X,"RED",9X,"GRL",4X,"HRA",5X,"H1",5X,"H2",
     14X,"HR",5X,"QU2",5X,"FP",5X,"FR",4X,"TFI",4X,"TFM",4X,"TFO",
     24X,"TPM",4X,"DELT",8X,"QCOL",4X,"EFF",/,2X,130(1H=),/)

      TGD=TGD+273.16
      DO 30 JJ = 1 , 24
         COL = COLS(II,JJ)
         IF ( COL .LE. 0.0 ) GO TO 30
         MQ = ( ( II-1 ) * 24 ) + JJ
         TR = TI(MQ,2)
         TC = TCC
         TR=TR+273.16
         TC=TC+273.16
         QW=ABC*COL/(AC*3.6)
         DE=2.*S
         AX=S*L
         STEP=10.
         ITER=0

5        ITER=ITER+1
         TFP=(TC+TGD)/2.
         DUM1=TFP-300.
         DEN=1.1774-0.003588*DUM1
         CK=0.02624+0.0000758*DUM1
         VIS=(16.84+0.0784*DUM1)*(1.0E-06)
         CP=1.0057+0.000066*DUM1
         PR=0.708-0.00022*DUM1
         COLOSS=((SIG*(TC**4-TR**4))/(((1.-EC)/(EC*AC))
     1   +(1/(AR*FRC))+((1-ER)/(ER*AR))))/3.6
         DUM3=TC-TGD
         IF(DUM3 .LE. 0.0 ) GO TO 30
         HRA=COLOSS/(AC*DUM3)
         BETA=1./TFP
         GRL=9.8*BETA*QW*(H**4)/(CK*(VIS**2))
         H1=(CK/H)*(0.17*((GRL*PR)**0.25))
```

```
      VFR=UM*AC/DEN
      VEL=VFR/AX
      RED=VEL*DE/VIS
      H2=(CK/DE)*(0.0158*(RED**0.8))
      DUM2=UM*CP*1000.
      TFI=TGD+(H1/DUM2)*DUM3
      UL=HRA+H1
      HR=(SIG*(TC**2+TFI**2)*(TC+TFI))/(1.0/E1+1.0/E2-1.0)
      HR = HR / 3.6
      FD=1.0/(1.0/H2+1.0/HR)
      FP=1.0/(1.0+UL/(H2+FD))
      FR=(DUM2/UL)*(1.-(EXP(-(UL*FP/DUM2))))
      QU2=FR*(QW-UL*(TFI-TGD))
      TFM=TFI+(QU2/UL*FR)*(1.0-FR/FP)
      TPM=TFM+QU2/H2
      DELT=TC-TPM
      IF(ITER.EQ.1)GO TO 10
      IF(((DELT*DELTOLD).LE.0.0).AND.(STEP.LE.0.1))GO TO 25
      IF((DELT*DELTOLD).LE.0.0)STEP=STEP/10.
 10   IF(DELT)15,25,20

 15   TC=TC+STEP
      DELTOLD=DELT
      GO TO 5
 20   TC=TC-STEP
      DELTOLD=DELT
      GO TO 5
 25   CONTINUE
      TFO=TFI+QU2/DUM2
      QCOL=DUM2*(TFO-TGD)*AC*3.6
      EFF=QCOL/COL*100.
      WRITE(6,200)JJ,RED,GRL,HRA,H1,H2,HR,QU2,FP,FR,TFI,TFM,TFO,TPM
     1          ,DELT,QCOL,EFF
 30   CONTINUE
200   FORMAT(1X,I3,2X,E10.4,2X,E10.4,3(2X,F5.2),2(F6.2,2X),2(F5.3,2X),
     14(F5.1,2X),F6.2,2X,F10.1,2X,F5.1)

      RETURN
      END
```