A SOLAR CLIMATE CONTROL SYSTEM USING A WATER FILM FLOW TO CONSERVE ENERGY IN GREENHOUSES

by

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ABSTRACT

One of the greatest problem encountered in greenhouses and buildings with large glazing is control of the internal atmosphere. The inherent characteristic of these buildings to act as solar collectors is to be used effectively for collecting and storing the excess solar energy. A new type of glazed roof, a Solar Climate Control roof system, was designed as a means to cool the interior environment of the greenhouses during the daytime and to heat during the nightime or on overcast days.

A heat exchanger-storage system, using water as a thermal mass is included in the design of the Solar Climate Control system. A film of water flows on the inner surface of the roof and absorbs the direct solar heat radiation, acting then as a cooling agent. The energy absorbed may be reused for nightime heating.

An efficient water dispersion pipe for the Solar Climate Control system was developed. The use of a soap solution rather than water alone for the Solar Climate Control water film system permitted a significant reduction in pumping rate and improved uniformity of the film.

A computer simulation model was run to determine the energy loads for both a conventional (double glazed roof) greenhouse and one equipped with the Solar Climate Control system. The Solar Climate Control system shows low operating cost and very good efficiency in heat removal.

RESUME

Un des grands problèmes rencontrés dans les serres et les immeubles ayant de grandes surfaces vitrées est le contrôle de l'atmosphère intérieure. Ces capteurs solaires naturels pourraient être utilisés plus efficacement pour capter, emmagasiner et réutiliser l'énergie solaire. Un nouveau type de toiture, le système de "Contrôle Solaire", a été mis au point pour permettre de maintenir la température intérieure des serres à un niveau optimum en captant les surplus d'énergie durant le jour et en réutilisant cette énergie pour chauffer durant la nuit ou les jours nuageux.

Un système d'échangeur de chaleur utilisant l'eau comme masse thermique est à la base du système de Contrôle Solaire. Un film d'eau coule sur la paroi interne de la toiture et absorbe les rayons solaires, agissant alors comme agent refroidissant. L'énergie emmagasinée dans l'eau peut être réutilisée comme agent chauffant la nuit.

Un système efficace de distribution de l'eau a été développé. Une solution savonneuse a été préférée à l'eau pure, permettant une répartition plus uniforme du film d'eau sur la paroi interne de la toiture et une réduction significative du taux de pompage.

Une simulation par ordinateur a été réalisée pour comparer les niveaux d'énergie consommée par une serre conventionnelle et une autre équipée du système de Contrôle Solaire.

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		UNITS
A_r	Roof glazing surface area	m^2
A_w	Wall surface area	m^2
C_p	Specific heat of fluid (a=air, w=water)	J/kg °C
CCP	Solar Climate Control coefficient of cooling performance	
CHP	Solar Climate Control coefficient of heating performance	
COP	Coefficient Of Performance	
d	Flow depth	m
d_f	Flow thickness	m
e	Efficiency of the pump	-
g	Gravitational acceleration	m/s^2
H	Head of water	m
I	Solar radiation flux on glazed surface	W/m^2
K_n	Thermal heat capacity of the fluid volume	J/°C
K_1	Thermal heat capacity of the inside air volume	J/°C
K_2	Thermal heat capacity of the thermal mass vol.	J/°C
$\hat{m}$	Mass flow rate of the thermal mass	kg/s
m	Mass of the thermal mass (a=air, w=water)	kg

n	Manning's roughness coefficient for open channel flow	-
q	Discharge per unit length	$m^3/s/m$
q_f	Discharge per unit length	L/s/m
Q_1	Net heat flow to interior air	W
$Q_{\alpha 1}$	Net heat flow absorbed to interior air	W
Q_2	Net heat flow to thermal mass water	W
Q_{abs}	Heat absorbed by the thermal mass	W
Q_{air}	Heat flow to the air	W
Q_{cond}	Heat conducted to the inside building	W
Q_f	Net heat flow through floor	W
Q_{loss}	Total heat loss by the thermal mass	W
Q_r	Net heat flow through roof (i=ceiling panel, o=roof panel)	W
Q_s	Heat flow through soil	W
Q_{acc}	Heat flow to water film	W
Q_{sr}	Heat flow from solar input	W
$Q_{\alpha sr}$	Heat flow absorbed from solar input	W
$Q_{\tau sr}$	Heat flow transmitted from solar input	W
Q_w	Heat flow through the walls	W
Q_{water}	Heat flow to the thermal mass	W
R	Hydraulic radius	m
Re	Reynolds number	-

S	Slope of energy grade line	m/m
t	Unit of time	s or h
T_1	Inside greenhouse temperature	°C
T_2	Temperature of the thermal mass	°C
T_2	Average water-film temperature	°C
T_{2i}	Inlet water temperature (thermal mass)	°C
T_{2o}	Outlet water temperature	°C
T_∞	Ambient temperature	°C
U_c	Heat transfer coefficient of ceiling/ condensation interface	W/m²°C
U_r	Heat transfer coefficient for water-film/roof interface	W/m²°C
U_w	Wall heat transfer coefficient	W/m²°C
V	Volume of fluid	m^3
V	Velocity	m/s
α	Absorbtivity	-
σ	Reflectivity	-
τ	Transmissivity	-
α_{sr}	Fraction of solar radiation flux absorbed directly by water-film	-
η_c	Absorption efficiency of the water-film	-
η_h	Heating efficiency of the water-film	-
ρ	Density of fluid	kg/m^3

$\alpha 1$	Fraction of solar radiation flux absorbed by the blackbody	
σ_{sr}	Fraction of solar radiation flux reflected by the Tedlar panels	
τ_{scc}	Fraction of solar radiation flux transmitted through water-film	-
ν	Kinematic viscosity	m^2/s

I. INTRODUCTION

"Protected cultivation" (Takakura, 1983) in greenhouses and tunnels is one way of extending the period in which fresh produce is available for regions with limited growing seasons. Until the early seventies, the greenhouse industry depended on relatively abundant and cheap fuels. This was reflected in the technology used to maintain optimum conditions for plant growth in the glass- and synthetic- covered structures. The philosophy was simple: heat when cold, vent when too hot and do both when too humid. Low energy costs at the time justified the philosophy.

In the 1970's, the realities of energy supplies, price trends associated with the "oil crisis" and predictions on the future availability of non-renewable fuels was followed by concerted efforts to harness solar, waste and recyclable energies in all sectors including the greenhouse industry. The trend in greenhouse research and development changed, albeit momentarily. The emphasis in research had shifted to energy-efficiency of the structure and covering materials and to the use of alternate energy sources to provide heat during cold periods. Although a 1990 tour of the nation's greenhouses and the statistics on greenhouse bankruptcies do not reflect the huge research and development effort in these directions, there have been a number of implemented improvements and research continues.

Today, it is evident that if the greenhouse industry is to survive in the present socio-economic system, the research dating back to the early 1960's must provide economically-viable solutions to the energy requirements for heating and photosynthesis. The concept of a solar greenhouse is not new, but continues to be appealing because solar energy performs two essential services: promotes plant growth and provides heat. It is understood that in certain regions, insolation alone is insufficient to provide all energy requirements; however, a well-conceived solar-based system should be at least economically-viable almost anywhere.

The main criterion involved in the design of any commercial greenhouse is that the internal environment be suitable for plant growth and comfortable for greenhouse workers. This is in conflict with the inherent characteristic of a glazed structure to act as a solar collector. A greenhouse left to itself will overheat during sunny periods and approach ambient temperatures in the absence of sunlight. The "Solar Climate Control" system developed by Thermactive Systems Corporation Ltd, is an attempt to resolve this conflict and the subject of this thesis is to evaluate its ability to do so.

The "Solar Climate Control" consists of a day time water film cooling system wherein excess energy is absorbed, stored and made available for night time heating. Preliminary investigations have demonstrated its potential, (Nelson, 1980); however, further research is needed to evaluate the performance of the system in terms of engineering design criteria. In particular, the thermal properties (overall heat transfer coefficient) of the water film and the water film flow distribution must be evaluated.

1.1 Objectives

The primary objective is to study and evaluate the Solar Climate Control system's ability to prevent overheating in a glazed structure. This is accomplished through theoretical analyses and empirical verification. The study also includes laboratory investigation of the water flow characteristics, determination of the overall heat transfer coefficient and monitoring of the Solar Climate Control system behavior in a prototype.

1.2 Scope

Solar Climate Control is an active process for controlling the intensity and quality of illumination provided by glazing materials, and to remove the "solar heat load" and other low grade heat in the building by means of a water film flow.

This system offers a solution to present problems encountered in passive solar buildings, which, while they may achieve a balanced climate during winter, suffer from a tendency to over-heat in summer. Excessively high temperatures cause discomfort to workers and can adversely affect plant growth and development. The most widely used solution to this problem is ventilation; however, this imposes added investment and operating costs which reduce the energy saved by passive heat gain in cooler periods. Mechanical ventilation with evaporative cooling is used widely in plant production despite its many disadvantages, but it has been found to be unsatisfactory for human comfort. The Solar Climate Control system may provide a truly "air-conditioned" environment at a lower cost than the conventional methods, and a completely effective active solar capture/storage/reuse mechanism for the cold seasons.

II. REVIEW OF LITERATURE

2.1 Introduction

Baird and Waters (1979) reviewed a number of solar greenhouse designs that were shown to be technically feasible but mentioned (as did others) that adoption by growers would be slow because of high initial investment costs and uncertainty about the effects of new designs on plant growth and management schemes. One should add that competition and price fluctuations in the produce markets underlie this reluctance to invest in new systems. At the engineering research level, the main problem in solar greenhouse design has therefore been to arrive at a compromise between energy efficiency, climate control and cost. The light, temperature and humidity requirements of plants and greenhouse workers constrain the design criteria pertaining to efficient heat collection and storage which are inherent in the greenhouse structure. The purpose of this review is to outline those aspects of recent research in greenhouse design and technology that were taken into consideration in the development of the Solar Climate Control system and in its evaluation.

2.2 Solar Energy in a Greenhouse

As previously mentioned, the appeal of solar energy in greenhouse applications is that it provides light as well as heat. The subjects that have received the most attention in solar greenhouse research and development have been the transmittance of photosynthetically active radiation (PAR) to the plant canopy and the capture, storage and recycling of solar heat.

Greenhouses that are to be operated during periods of low naturally available light should be designed to maximize the percentage of available sunlight reaching the crop and, in particular, to maximize transmission of photosynthetically active wavelengths (Aldrich et al., 1966). Aldrich and White (1969) concluded that a relationship exists between the structural form and covering material of a greenhouse and the resulting distribution of transmitted solar light. They showed that the orientation and location of the structure also affect the amount of solar light available to the plants within the greenhouse. Although optimization of these factors is important, it is understood that supplementary lighting is nevertheless necessary for the off-season productions in northern latitudes in order to compensate for low available light intensity and short day-length.

Robbins and Spillman (1980) presented a method to calculate the solar transmittance of solar collector cover systems that employ one or two covers. The accuracy of the calculated solar transmittance varies from material to material. For clear, homogeneous materials like glass and Dupont Tedlar, they have found the calculated transmittance to be within 2% of the measured values at angles of incidence up to 60°. The use of more than two layers of glazings has also been studied for heat capture applications but the added insulation becomes marginally effective due to an approximate 8% reduction in transmittance per layer due resulting from absorption by the glazing (Daniels, 1964).

Different systems were designed to use solar energy for heating a greenhouse. Ebeling and Krangler (1983) tested a solar system using an existing solar hop drying installation to supplement the heating requirements of an existing fiberglass greenhouse. The energy was stored in an underbench rock storage. They estimated that 37% of the annual heating load could be met by the solar system. Up to 75% of the heating load could be met based on a limited growing season (March through October). The study was performed in the state of Washington. Bernier (1987) developed a system for storing excess solar radiation in moist greenhouse soil. The system consisted of two layers of rows of corrugated non-perforated plastic drainage pipes buried at 450 and 750 mm depths. Greenhouse air was circulated through the pipes to remove excess daytime heat and the stored energy was reused during cold periods and at night. They reported an overall energy conservation of 33%. The prototype was in Quebec, Canada.

Van Bavel and Damagnez (1978) performed a numerical analysis of the energetics and water balance of a fluid-roof solar greenhouse which included external storage and continuous circulation. They predicted considerable savings in heating and ventilation requirements as well as more favourable plant growth conditions. Reduced heating and ventilation costs were later reported by Van Bavel and Sadler (1979) who tested a $CuCl_2$ solution film system in an arid climate. They also reported higher daytime humidity, lower temperature and increased plant growth.

Church and Baird (1983) evaluated a direct contact filacell heat exchanger for solar and low-temperature greenhouse heating using solar heated water and well water as the heating medium. The most interesting conclusion was that the system could be used for both heating and cooling making CO_2 enrichment more effective since venting requirements would be reduced. The one disadvantage noted was the increase in humidity and condensation.

Ventilation is an important feature in the management of greenhouses since it is used for cooling, dehumidification, enhancing CO_2 exchange and conditioning plants to be set in the field. Dehumidification is particularly important for disease control; however, dehumidification by venting tends to be expensive on cool, cloudy days, since heat is vented as well as moisture. Moreover, conventional exchangers for dehumidification require large surface areas. Albright and Behler (1984) therefore designed and tested a compact air-liquid-air heat exchanger for greenhouse dehumidification. They reported performance values comparable to those of counter-flow air-air heat exchangers.

The above developments are a mere sample of the research on solar applications to greenhouses. There have been numerous studies on the transmission and strength properties of glazing materials, on the viability of solar capture/storage systems, on greenhouse designs and on crop performance in a number of solar-design greenhouses. Although the energetic benefits of efficient use of solar energy are usually of the order of 25 to 40% many authors arrive at the conclusion that the payback period on the investment is too long.

2.3 Use of Liquid Films in Solar Greenhouses

2.3.1 Transmission and Absorption of Radiant Energy

The use of liquid films to collect and store excess solar energy for reuse has been investigated over the past few years. Water and copper chloride solutions ($CuCl_2$, to prevent growth of algae) have received the most attention. Dorsey (1940) describes the physical properties of water under various temperature and pressure influences. Water is almost completely transparent to wavelengths in the range of 0.17 to 1.0 μm which includes the PAR range (Van Bavel and Sadler, 1978) of 0.35 to 0.7 μm . Water is almost completely absorbent of wavelengths in the 1.0 μm to 1.0 m range, thus including infrared, and in the band from 0.00005 to 0.17 μm (Dorsey, 1940). A thin water film condensed on a window absorbs all solar radiation flux for which $\lambda > 0.13$ μm; a layer 1.0 cm thick absorbs 38% at $\lambda = 0.995$ μm and 95% at $\lambda = 1.4$ μm.

Van Bavel and Sadler claim that $CuCl_2$ solution absorbs all solar radiation beyond 0.7 μm and no PAR. However, Chiapale (1978) noted that some infrared is beneficial to plant growth and he later tried to reduce the absorption by using a $CuCl_2$ + $CoCl_2$ solution. Although infrared transmission increased, visible light was reduced by 48%. Weichman (1981) also noted that the transmission of visible light was greater through water in a channeled plastic roof than $CuCl_2$ in the same setup and that all liquids tested absorb heat energy much more than visible light. A water film absorbs 40% of non-visible radiation or 16% of total available radiation assuming a transmissivity of 80% of the glazing covering the water film and that 50% of total available is in the non-visible ranges.

The literature has demonstrated the efficacity of water and some aqueous solutions in absorbing a significant amount of incoming and outgoing radiant heat energy while transmitting nearly all PAR. Implementation of water or aqueous $CuCl_2$ solution films for controlling the greenhouse environment was therefore worth investigating. The conceived and confirmed advantages are outlined in the next section.

2.3.2 Benefits of Liquid Film Systems

Results from a simulation model by Van Bavel (1978) indicated that a fluid roof should result in increased dry matter accumulation due to better use of transmitted PAR. Lower leaf temperaures, reduced transpiration and reduced water stress were judged to be the factors most directly affected by the difference in solar energy transmission compared to a conventionally-roofed greenhouse. It was concluded that the reduction in ventilation requirements during the cool season should enhance the efficiency of CO_2 enrichment. It was also concluded from the simulation that warm season production at 30° latitude would not be practical without shading and additional artificial cooling as is the case for conventional greenhouses in the south.

Mannan and Cheema (1979), having studied natural heating and cooling of greenhouses in northern India, reported that a water film on the outside of single-glazed greenhouses maintained summer greenhouse temperatures 3 to 4°C above ambient air temperature (10 to 12°C cooler than greenhouses without the film). They suggested that evaporative cooling from the exposed water film augmented the direct absorption of infrared by the film.

In a simultaneous study of water, 1% $CuCl_2$ and 2% $CuCl_2$ solution films in a tomato cropped greenhouse, Chiapale (1978) reported good growing conditions, reduced evaporation and lower ventilation requirements compared to a conventional east-west oriented greenhouse. It was also concluded from row yield analyses, that the film filtered light was more evenly distributed to the crop canopy than would be the case in a conventional greenhouse. Biochemical analyses compared favourably with field tomatoes with respect to nutritional quality.

These studies indicate that water films have the potential to enhance crop performance in a greenhouse through modification of a number of interrelated factors. In northern climates, energy efficiency considerations tend to be emphasized to a greater extent because of night-time and cold season heating requirements.

2.4 Mathematical Models

Simulation and modelling studies have played an important role in solar greenhouse research, design and development, as they have permitted the study of factors involved in crop and energy performance. Abdallah and Staley (1983) defined a method to estimate the solar radiation captured by greenhouses. The method consists of calculating a "greenhouse total capture factor" (TCF) which is a function of the availability of the beam and diffuse radiation. It also takes into consideration construction parameters such as the greenhouse shape, orientation and the transmittance of the covering material as well as losses due to reflection by the plant canopy and diffused radiation losses through the roof. The authors concluded that the extent of direct diffuse radiation loss through the greenhouse roof is more dependent on the roof slope than on the length or width and that the TCF is highly dependent on the plant canopy's effective albedo.

Critten (1983) described the physical, mathematical and philosophical rationales for a model to study the effect of changes of geometry on internal light distribution and transmissivity. The model embraced the principal light transmitting and attenuating surface associated with a typical U.K. greenhouse. Transmissivity prediction and experimental measurements were successfully compared for one greenhouse.

Walker (1965) developed mathematical relationships to predict temperatures inside ventilated greenhouses. He used an energy-balance approach to develop his model which can also be used to predict the heat requirement during cold-weather periods. He concluded that during periods of high solar radiation when ventilation is required, the heat loss to the ground, the heat of respiration and heat utilized in photosynthesis can be neglected.

Takakura et al. (1971) simulated the effects of environmental conditions on the plant leaf within a greenhouse. The simulation model developed provided better analysis of the relationship between plant leaf temperature and the environment as the complexity of the model increased.

Chandra et al. (1981) developed an analysis procedure to predict heating or cooling loads, and moisture addition or removal required to maintain optimal conditions within the greenhouse.

Arinze et al. (1981) worked on a mathematical model for predicting temperature and moisture levels in an energy conserving tomato growing greenhouse. Comparison between the greenhouse measured data and the computer simulated results showed that the model adequately predicted the thermal performance of the greenhouse thermal storage system. An interesting conclusion was that computer model predictions depend greatly on the time steps used. Sufficient accuracy was obtained for time steps between 300 s and 600 s.

Many of the concepts and factors included in the above studies were considered in the development of the simulation performed in the present work.

2.5 Control Systems for Research and Operation

One of the major problems in research on solar heating or cooling is to design an effective control and monitoring system. Jones et al. (1983) presented the theoretical and practical basis for the design and development of a computer-based control system that can produce a wide range of constant or time-varying environments. Mitchell and Drury (1982) compared a solid-state analog computer circuit and a microcomputer-based system to control heat flow in various parts of a solar-heated poultry brooding facility. The digital approach is simple and widely used. Its accuracy is dependent on the analog-to-digital conversion components used to convert the original analog data into digital form and on the frequency with which data are scanned. A signal that changes slowly (outdoor temperature) requires much slower sampling rates than a signal that changes rapidly (such as solar radiation on a partly cloudy day).

Mitchell and Drury (1982) listed the following advantages of microcomputer systems over conventional solid-state controls: i) the microcomputer strategy was implemented in considerably less time than the solid-state system; ii) changes in control strategy and setpoints were easily made through software with the microcomputer; iii) errors were minimized; microcomputer controlled setpoints could be expected to be within ± 0,5°C of the programmed values, while the setpoint temperatures with the conventional controls were subject to errors of several degrees. Overall the microcomputer control system offered a greater flexibility at approximately the same price. The one disadvantage pointed out was the need to become familiar with microcomputer architecture, interfacing devices and programming.

The microcomputer approach was chosen for this study because of the advantages noted above. Moreover, since the time of the Mitchell and Drury (1982) study, microcomputers have become a standard component of major greenhouse installations (Takakura, 1983).

2.6 Summary

The uncertainty of continuous supplies and the rapid increase in fossil fuel costs in recent years are serious threats to the nation's greenhouse industry, especially in northern climates. The search for alternate energy sources has brought many researchers to believe in the economic feasibility of utilizing solar energy. If the required materials, structural changes and control systems for collecting, storing and reusing solar energy can be made economically feasible and operationally practical for the grower, the literature indicates that crop productivity will not suffer and may even benefit.

Few researchers have worked on the use of solution liquid films ($CuCl_2$) to collect, store and reuse solar energy. The main disadvantage noted was the reduction of the light transmittance to the crops. The transmittance characteristics of water appear to be more suitable for greenhouse climate applications; however, precise environmental control with this technology has not yet been achieved. Although most of the authors discussed the use of a liquid film on roof/glazing systems, none of the experimental set-ups or objectives duplicated those proposed for the Solar Climate Control system.

The ability to change the control strategy may be quite desirable in a solar heating system in order to maximize the efficiency of collection and distribution of heat energy. The measurements of many variables may be desirable to evaluate the performance of the system. This study concentrated its effort on the measurement and determination of heat flow in various parts of the system. The microcomputer system seems to be the best approach to use in the proposed study even though it involves the need to gain a reasonable degree of familiarity with microcomputer architecture, programming and interfacing devices.

III. THEORETICAL DEVELOPMENT

The unit built for this study is a modular roof canopy system (Figure 3.1) which may be utilized in various building structures, including greenhouses. Panels are employed to enclose the structure and to control the climate in the building. When mounted on the roof structure, the panels can be seen as rectangular in cross section (Figure 3.2). The panel used for this study is mounted on a 9,1 m long trailer and is 0,6 m high, 2,4 m wide and 5,15 m long. The test rig consists of a typical roof module on an enclosed triangular base. This base, whose interior simulates that of a building or greenhouse, is mounted by pivoting hinges on a trailer. The tilt angle of the roof is controlled by means of a hydraulic system. Thus the test rig affords complete flexibility in terms of orientation and slope, as shown in Figure 4.3, in order to facilitate the performance study of the Solar Climate Control system under any possible conditions.

3.1 The Solar Climate Control System

The unit operates with the Solar Climate Control system. It controls the gain in solar energy and the thermal loss from the glazed area. Solar Climate Control system makes use of a water film to absorb undesired solar energy and bring down the inside temperature.

Considering a closed Solar Climate Control system modeled on the basis of an infinitely long roof and floor area, any heat gain resulting in temperature increase of the inside environment and/or the thermal mass is due to the solar input and the temperature difference prevailing between the interior and exterior environments. The interior climate is controlled with water film flowing over the surface of the ceiling panel and draining back

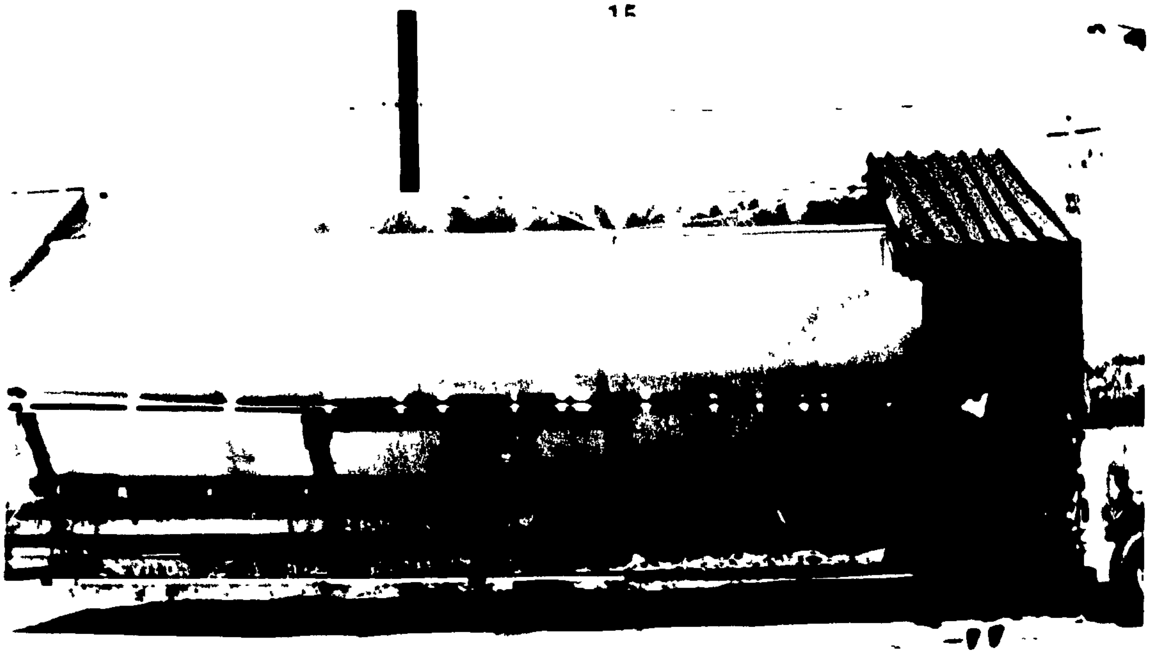


Figure 3.1

Modular roof canopy system

Figure 3.2

Side view of the prototype

to the thermal mass. The Solar Climate Control system controls the climate within a building by means of a novel system for heating and cooling. This system is an improvement upon the prior art of climate control characterized as "natural" or "passive" systems.

The Solar Climate Control system provides natural heating by storing the solar heat gains of the day for later use at night, and natural cooling is obtained by storing conductive, convective, evaporative and radiative heat losses of the night for later use during the day.

The stored heating or cooling capacity is obtained by subjecting a large thermal mass within the system to balancing thermal loads from natural sources. The day-time temperature gain of the thermal mass provides night-time heating capacity and the night-time temperature loss of the thermal mass provides day-time cooling capacity.

The building is characterized as a "passive solar" construction; meaning that at least a portion of the building envelope comprises a glazed area. This glazing area permits penetration of the solar radiation into the building, causing a direct temperature gain within the building enclosure. The term "glazing" means not only glass but any flexible or rigid sheet, membrane or film material that permits the transmission of solar energy.

More specifically, the Solar Climate Control system is a system for climate control of a building wherein the glazed area comprises a double glazing with a cavity between two glasses or other transparent glazings. Greenhouses are a good example of such buildings which require both heat and light from the sun inside the building.

Passive solar climate control methods have not provided adequate control at all times nor under all seasonal conditions and climate zones. Temperatures have been known to fluctuate well above and below set limits. The passive climate control methods have suffered from both inadequate thermal capacity of the thermal mass and inadequate heat exchange means from the building climate to the thermal mass. The first problem results in over-heating of the thermal mass and the second in over-heating of the building interior (Chiapale, 1978, Kurosaki and Viskana 1978, Van Bavel and Sadler, 1979).

The Solar Climate Control system overcomes these limitations since it defines a very large and relatively cool thermal mass which is constant and a very efficient heat exchanger. The preferred thermal mass capacity is the equivalent of 500 to 1000 kilograms of water per square meter of the building glazed area. The maximum daily heat gain permitted of this thermal mass is 5°C to avoid large inside temperature fluctuations. The base temperature of the thermal mass is maintained at 10°C. Therefore the maximum permitted temperature is 15°C. A high rate of heat exchange between the thermal mass and the building climate ensures that the maximum temperature attained by the building climate does not exceed the set limit for maximum plant growth. However because of the physical limitations of this study, only one rate of 140 kg of water per square meter was used.

3.2 Theoretical Analysis of the System

The following system of differential equations modelled on a lumped heat capacity analysis describes the rate of change of the structure's interior temperature (T_1) and that of the thermal mass temperature (T_2).

$$K_1 \frac{dT_1}{dt} = Q_{\tau sr} + Q_{cond} \tag{1}$$

$$= A_r\ \tau_{acc}\ I + A_r\ U_c\ (\overline{T_2} - T_1) + A_w\ U_w\ (T_\infty - T_1) \tag{2}$$

$$K_2 \frac{dT_2}{dt} = Q_{asr} + Q_{ri} + Q_{ro} \tag{3}$$

$$= A_r\ \alpha_{acc}\ I + A_r\ U_c\ (\overline{T_2} - T_1) + A_r\ U_r\ (T_\infty - \overline{T_2}) \tag{4}$$

$$K_n = (\rho V C_p) \tag{5}$$

$$\overline{T_2} = \frac{T_{2o} + T_{2i}}{2} \tag{6}$$

The building interior temperature is influenced by the fraction of solar radiation flux transmitted through the glazing (τ_{acc}), the overall heat transfer coefficient prevailing on the inside glazing surface (U_c), and the wall heat transfer coefficient (U_w). The thermal mass temperature is affected by the solar radiation flux absorbed by the water film (α_{acc}) and the overall heat transfer coefficient prevailing below (U_c) and above (U_r) the water film. Figure 3.3 shows a schematic of the Solar Climate Control system.

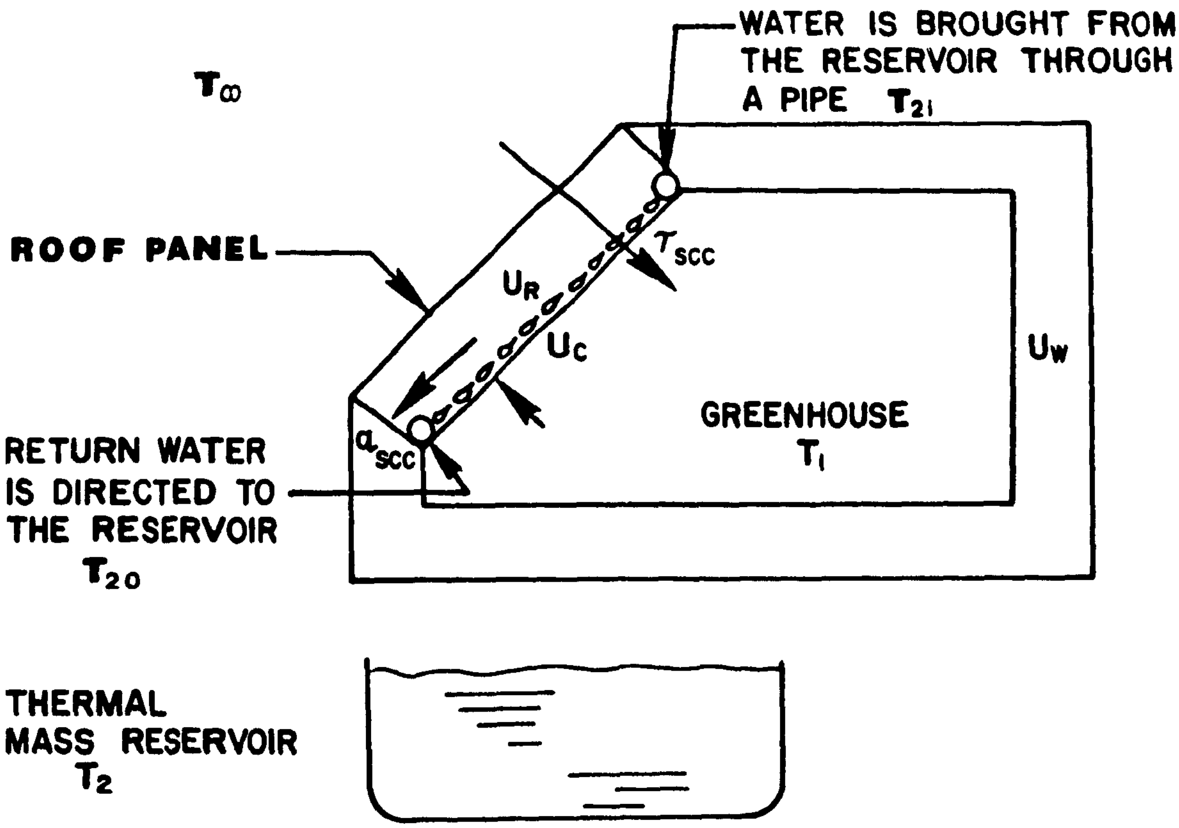


Figure 3.3 Schematic of the Solar Climate Control System

3.3 System Efficiency

The performance of the Climate Control system is evaluated differently depending on whether the control circumstance is heating or cooling. For cooling, the absorption efficiency of the water film component is defined as the ratio of the heat absorbed by the water film to the total incoming solar radiation and heat flowing inside through the glazing.

$$\eta_c = \frac{Q_{abs}}{Q_{sr} + Q_w} \tag{7}$$

$$= \frac{A_r\, \alpha_{sc}\, I + A_r\, U_c\, (\overline{T_2} - T_1) + A_r\, U_r\, (T_\infty - \overline{T_2})}{A_r\, I + A_w\, U_w\, (T_\infty - \overline{T_2})} \tag{8}$$

The heating efficiency of the water film component is defined as the ratio of heat conducted to the inside building from the water film to the total heat loss by the water film.

$$\eta_h = \frac{Q_{ct}}{Q_{loss}} \tag{9}$$

$$= \frac{A_r\, U_c\, (\overline{T_2} - T_1)}{[\dot{m}\, C_p\, (T_{2o} - T_{2i})]} \tag{10}$$

It would be interesting to evaluate the Solar Climate Control coefficients of cooling and heating performance (CCP and CHP, respectively). The CCP is defined as the ratio of heat absorbed by the water film to the input energy to perform the task (the pumping load). The CHP is defined as the ratio of heat supplied by the water film to the pumping load.

$$CCP = \frac{Q_{abs}}{\dot{m}gH / e} \quad (11)$$

$$CHP = \frac{Q_{rl}}{\dot{m}gH / e} \quad (12)$$

3.4 Water Film Flow Study

This experiment was conducted to assess film dispersion on an inclined surface which was essential for the design of the water distribution hose. A water film flow study was undertaken on a small roof panel to determine flow characteristics, flow depth and head loss encountered along the water film distribution pipe. The parameters studied are presented in Table 3.1.

Table 3.1 Parameters studied during the water film flow experiment held during the summer 1985

VARIABLES		RANGE OF STUDY
Panel inclination angle	:	20 - 70°
Flow rate	:	0,07 - 0,4 L/s/m of roof length
Soap concentration	:	0 and 0,5% by volume

Flow types were determined by computing the Reynold's number:

$$Re = \frac{VR}{\nu} \qquad (13)$$

Depth of flow was determined experimentally. It was expected from the scale tests that a simple relationship would be found to predict a reasonable value for film thickness. The average velocity of the liquid film was determined by means of the Manning formula, a relation widely used for open channel flow:

$$V = \frac{R^{2/3} S^{1/2}}{n} \qquad (14)$$

Results permit the verification of these equations for water film flow over plastic film. The water pipe distribution system consists of a hose in a hose as depicted in Figure 3.4. This permits a better pressure distribution and of lower magnitude in the outer pipe. To achieve a uniform film, the water must be dispersed evenly over a wetted surface.

These tests established the flow rates at varying tilt angles, and the required water film thickness. The results led to a simpler design for the dispersion hose, operating cost estimation and Solar Climate Control power requirements and finally the effect of solution viscosity (different soap concentration) on the distribution and dispersion.

A small scale test unit was constructed in the summer of 1985. The test surface was 4-mil Tedlar over 7 mm Lexan. The Lexan provided support. It was important to minimize sagging and variability. The Lexan also provided a much simpler design for ease of construction especially because of its strength. Essentially, compared to polyethylene, the

Figure 3.4 The water pipe distribution system consisting of a hose in a hose, as installed in the roof panel of the prototype

test roof unit was a wooden box with a plastic bottom. The 35 cm high sides give structural strength and rigidity. Further support for the surface was provided at key places by strips of 7 x 25 mm aluminum alloy running along the underside of the Lexan. These provide a solid immovable channel bottom. Depth readings were taken using a point gauge at three places along the length of the seven strips. The readability of the point gauge was 0,05 mm. At each of these 21 points two alternate readings were taken for both channel bottom and the water surface, giving a total of 84 readings or 42 differences. The point at which the depth was taken never varied by more than 1 cm in the y-direction and 0,3 cm in the x-direction.

3.4.1 Water Distribution System

The water distribution system consists of a hose within a hose. The inner hose was 38 mm I.D. black plastic corrugated sump pump hose. The outer hose was 64 mm clear 6 mil polyethylene. The outer hose had uniformly sized holes distributed at regular intervals along its length. The inner hose had uniformly sized holes distributed unequally along its length such that holes were placed farther apart towards the entrance end to compensate for pressure drop.

Both the inner and outer tubes were purchased intact. The holes were then melted in each of them with a pencil-type soldering iron. It is a result of the method. This method was chosen because it was easy although it resulted in holes with somewhat ragged edges.

The inside hose was operated under a fairly high pressure. But the outside hose was at a lower uniform pressure compared to that of inside hose. Therefore the holes were distributed equally along the length of the hose. The soft outer hose had holes with an approximate diameter of 2,6 mm. In a one meter length of hose there were close to 200 holes. The distance between the edges of consecutive holes was roughly equal to the diameter of the holes. The area of discharge per length of tube was approximately 0,0011 m^2/m.

The corrugated, rigid, inner tube had a hole diameter of approximately 3,7 mm. The location of the holes was as follows:

From 0 to 114,4 cm, there were 14 holes separated roughly by 9 cm.

From 114,4 cm to 169,5 cm, there were 7 holes separated roughly by 7 cm.

From 170 cm to 227 cm there were 9 holes separated roughly by 6,3 cm.

The hole distribution in the hoses was chosen by trial and error. Approximately 20 combinations of various hole distributions were rejected before the one described was selc ted. The hole pattern exhibits a trend. The hole spacing changes at one half of the remaining hose length.

The inner tube of the Solar Climate Control is of constant cross section. The streamlines expand at each hole as the discharge and velocity are reduced. Non uniform flow results. Along these expanding streamlines an increase in pressure head will result. On the other hand, there are losses between the outlets due to form resistance and boundary resistance, that will cause a decrease in pressure head.

These two conditions tend to conteract each other. The net change in piezometric head could be either positive or negative along the length of the tube. The Solar Climate Control tube had a net negative change.

Attemps were made to produce a theoretical relation to predict the area needed per length of pipe to provide an even distribution along its length.

The problem was found to be very complex due to, among other things, the complications of orifice flow into a region of intermediate pressure between the head in the inner hose and atmosphere pressure. Further the friction factor in the Solar Climate Control tube is a variable due to variable flow rates. This theoretical aspect was beyond the scope of this study. Furthermore, the system tested by trial and error gave satisfactory results.

The flow was rapid and laminar under the range of study. The film thickness was found to be fairly constant down the flow path. Furthermore the film thickness was also found to be fairly constant down the length of the distribution hose. The thickness of the film was about 1,1 mm for water at 0% soap concentration and varied from 0,4 to 1,0 mm for water at 0,5% soap concentration. The thickness was found to be constant with respect to the angle of inclination of the roof panel.

IV. MATERIALS AND METHODS

The Solar Climate Control system provides that the interior glazing material of the building is maintained at a low temperature relative to the building inside temperature by utilization of flow of cooling water over the top-surface of the interior glazing material. Therefore the under-surface of the panel will be sufficiently cooled caused by the heat transfer regime of the climate conditioning unit of the building. This will result in moisture condensation on the other side of the panel. The condensate formed on the underside of the panel flows in the direction of slope to fall into gutters provided for the purpose of disposal of this collected water. The cooling water inside the climatic conditioning unit is returned to the reservoir for recycling.

The excess solar heat is therefore transferred through the thin sheet material of the interior panel to the flowing water which returns to the thermal mass water reservoir; thereby transferring the excess heat to storage, and in turn cooling the interior of the building. This water, derived from the thermal mass is cooler relative to the interior temperature and we thus describe it during its flow path over the interior panel as the "cooling water".

The circulation of the cooling water to the glazed area of the roof permits rapid heat transfer to the thermal mass reservoir. Natural convection of the building atmosphere brings the solar heated air in contact with the interior panel of the building envelope for efficient climate control.

4.1 Operating Modes of the System

The system operates to produce a day to night building climate temperature variation in the range of 15 to 25°C. The temperature variations have been found to be beneficial not only for building occupants but also lead to better growth and productivity of plants (Van Bavel, 1978). Thus, the building's inside temperature is measured and automatically controlled by the cooling water flow (pumped from the thermal mass reservoir). Later when the building climate temperature falls below a certain set limit the cooling water flow ceases. The pumping of water to the roof envelope may be initiated again during the night to provide heat loss protection to the interior climate or alternatively to permit heat loss from the thermal mass i.e. to provide heat rejection. These operating modes are shown in Figures 4.1 and 4.2.

Where thermal loads are high, the system provides for reduction in the pumping and the volume of flow by means of heat rejection through evaporation of some of the cooling water as it flows over the interior panel. Since the quantity of heat loss in the vapor is small, it is not considered in equations 3 and 4. The device also reduces the thermal capacity required of the thermal mass and permits a definite control over the actual temperature gains of the system including the limitation of the peak interior climate temperature. The Solar Climate Control may be used during the night and/or during the day. It becomes operative at any time when the cooling water flow exceeds an upper limit temperature, or when the thermal mass upper temperature limit is exceeded.

This Solar Climate Control system calls for a plant leaf canopy situated under the interior panel, such that the controlled environment is largely shaded from the direct solar

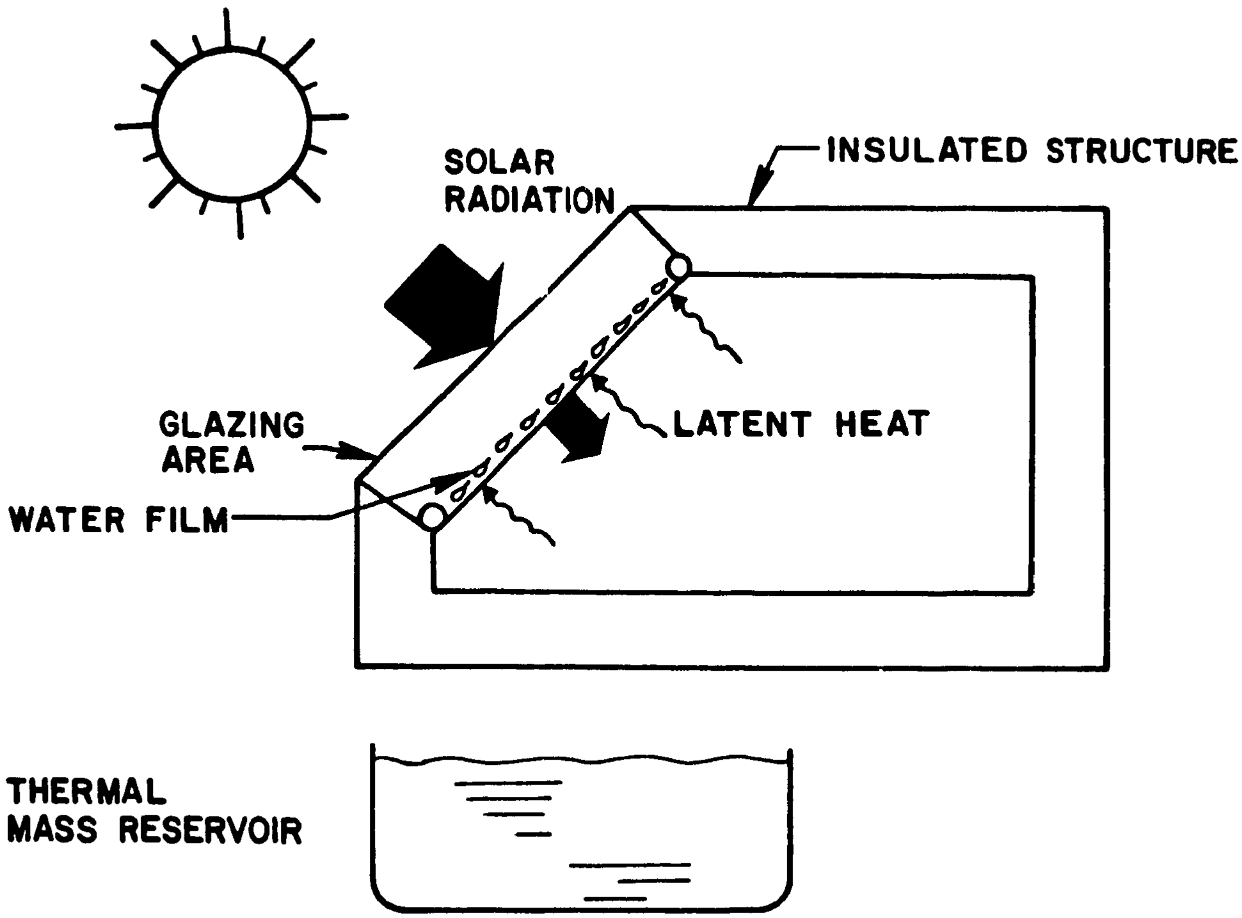


Figure 4.1 Day-time operating mode of the Solar Climate Control system. The water film removes and stores sensible and latent heat from building atmosphere. The water film also absorbs heat from direct solar radiation

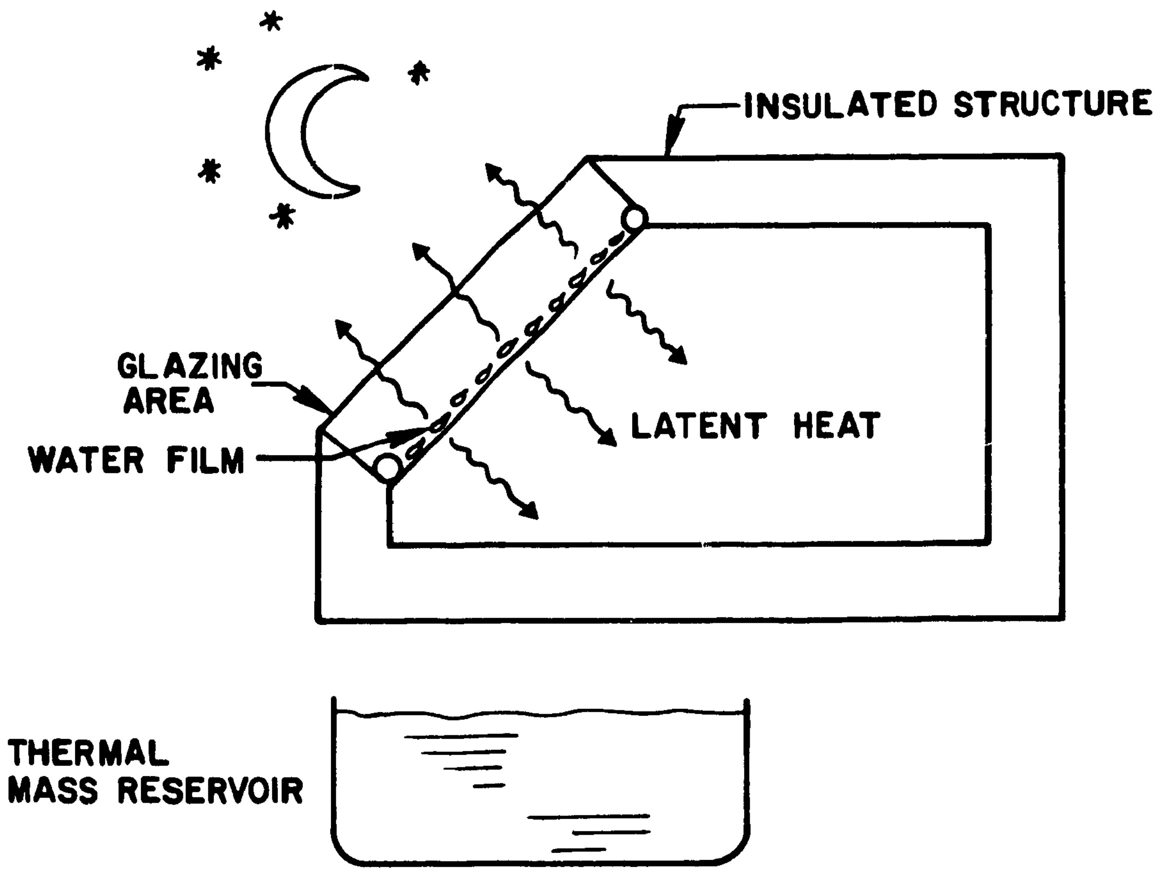


Figure 4.2 Night-time operating mode of the Solar Climate Control system. Night sky radiation cooling results in stored cooling capacity of the thermal mass for use on the following day

radiation by means of its interception by the said plant canopy. The purpose of the plant canopy is the conversion of the radiant heat energy to latent heat of moisture, due to the capacity of the plant leaves to transpire moisture proportional to the first approximation of the evaporative potential of the incident solar radiation. The solar heat load is therefore transferred as non-sensible latent heat which then becomes sensible heat of condensation at the condensation interface on the under surface of the interior panel. Since the condensation interface is continually chilled by the cooling water flow over the top surface of the interior panel, this transpiration/condensation cycle of energy transfer is continuously operative. Thus, plant production and controlled climate environments in a building are linked. Such installations therefore conserve available resources for food, water and energy.

4.2 Experimental Set-Up

The use of the prototype will permit optimization of the design of the Solar Climate Control system. The prototype allows complete flexibility in terms of orientation and slope in order to facilitate the performance study under various conditions. The instrumentation used reflects the intention to study varying parameters. The prototype, as it was constructed, is shown in Figure 4.3. It was located in Valleyfield, Quebec (appx. 46°N 74°W), and oriented north-south longitudinally. The tilt angle was chosen to be 22° because the flow was most uniform at that setting. The prototype comprises two roof panels installed side by side. Each roof panel covers a 7,4 m^2 area and they sit on a triangular base so as to permit experimentation at several tilt angles, orientations and site locations. The tilt angle of the roof is controlled by means of a hydraulic system. The triangular base (3/4" plywood) is well insulated with Thermax sheet (RSI 5.3) and is mounted over a pivot welded

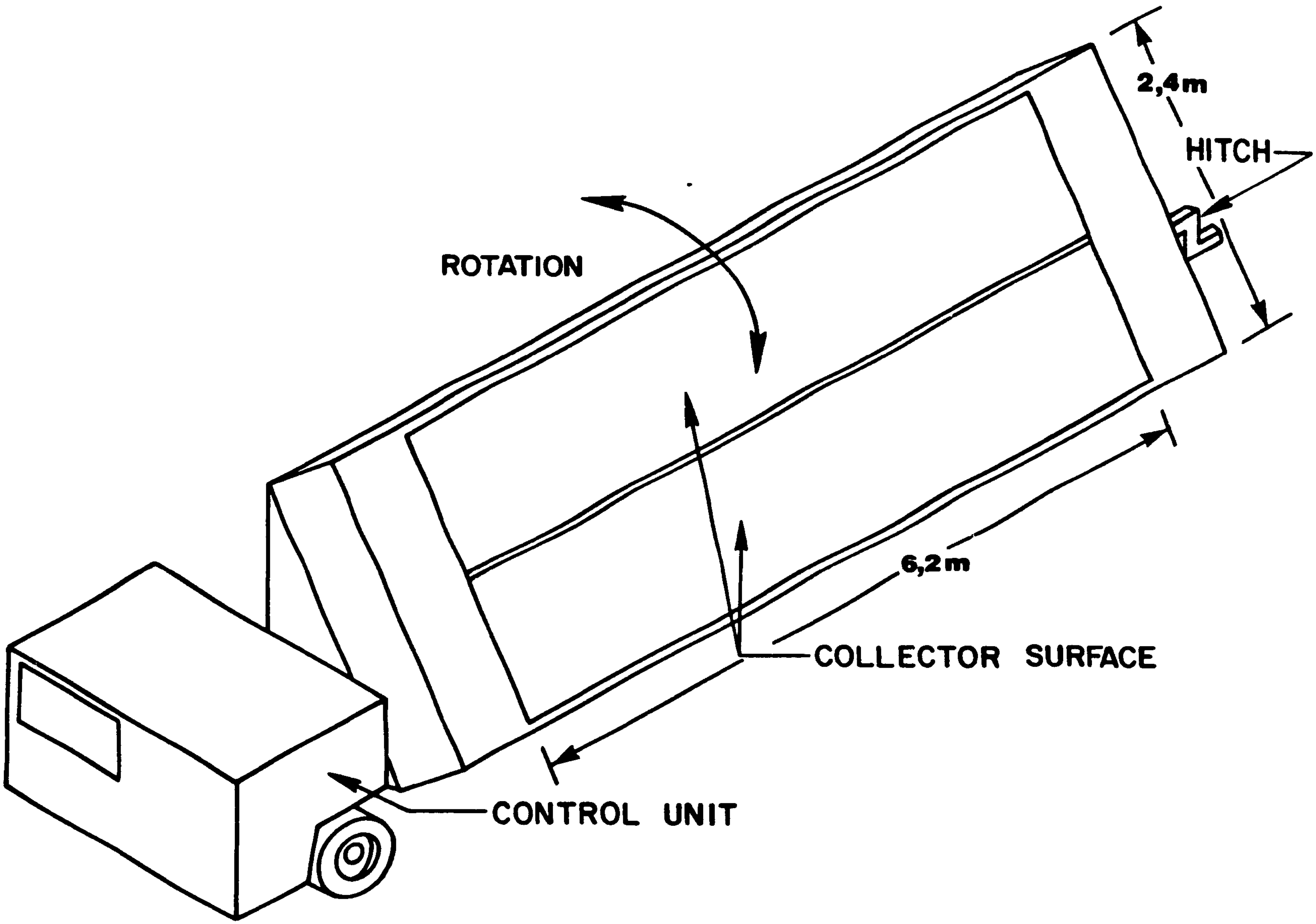


Figure 4.3 Three dimensional diagram of the prototype

to a 9,1 m long trailer. The interior of the base was painted black to give it blackbody characteristics to prevent reflection from the interior and thereby simplify the analysis.

The roof system has three components which include the trusses, Tedlar panels and manifolds. The design description of each of these components follows. The truss extrusion is made of aluminum. The slider fits and attaches to the chord, using 8 mm bolts. It is used to apply tension to the membrane. The truss is comprised of a top and bottom chord, using square tubing for diagonal webbing. Polypropylene plates are employed as thermal barriers between the chords and diagonals. The roof module is made of three trusses. Figure 4.4 depicts a cross-sectional view of the roof prototype. The Tedlar panel has two membrane thicknesses. The surface exposed to the atmosphere is 4/1000" thick (4 mil) (0,0001 m) and the surface exposed to the inside environment is 2/1000" thick (2 mil) (0,00005 m). The thinner layer allows greater heat transfer to the water film whereas the 4 mil layer provides greater strength for structural loads. The two layers were initially joined, forming a closed duct, by means of heat sealing. However, this method resulted in a distortion of the panels due to shrinkage and as a result, an adhesive was employed. The Tedlar panel is attached between two trusses by means of the gripper section of the chord. The trusses are spaced at every 1 200 cm and the chord spacing is done at 600 cm. The Tedlar duct envelopes a nylon chord at each corner. The chords are aligned with the gripper and slid the length of the truss. For installation, the tensioning members are slack and are subsequently tightened to form the ceiling and roof panels. The water film distribution pipe is attached to the upper corner of the ceiling panel. The pipe consists of a hose in a hose. This system results in a even distribution of water along the entire length of the pipe.

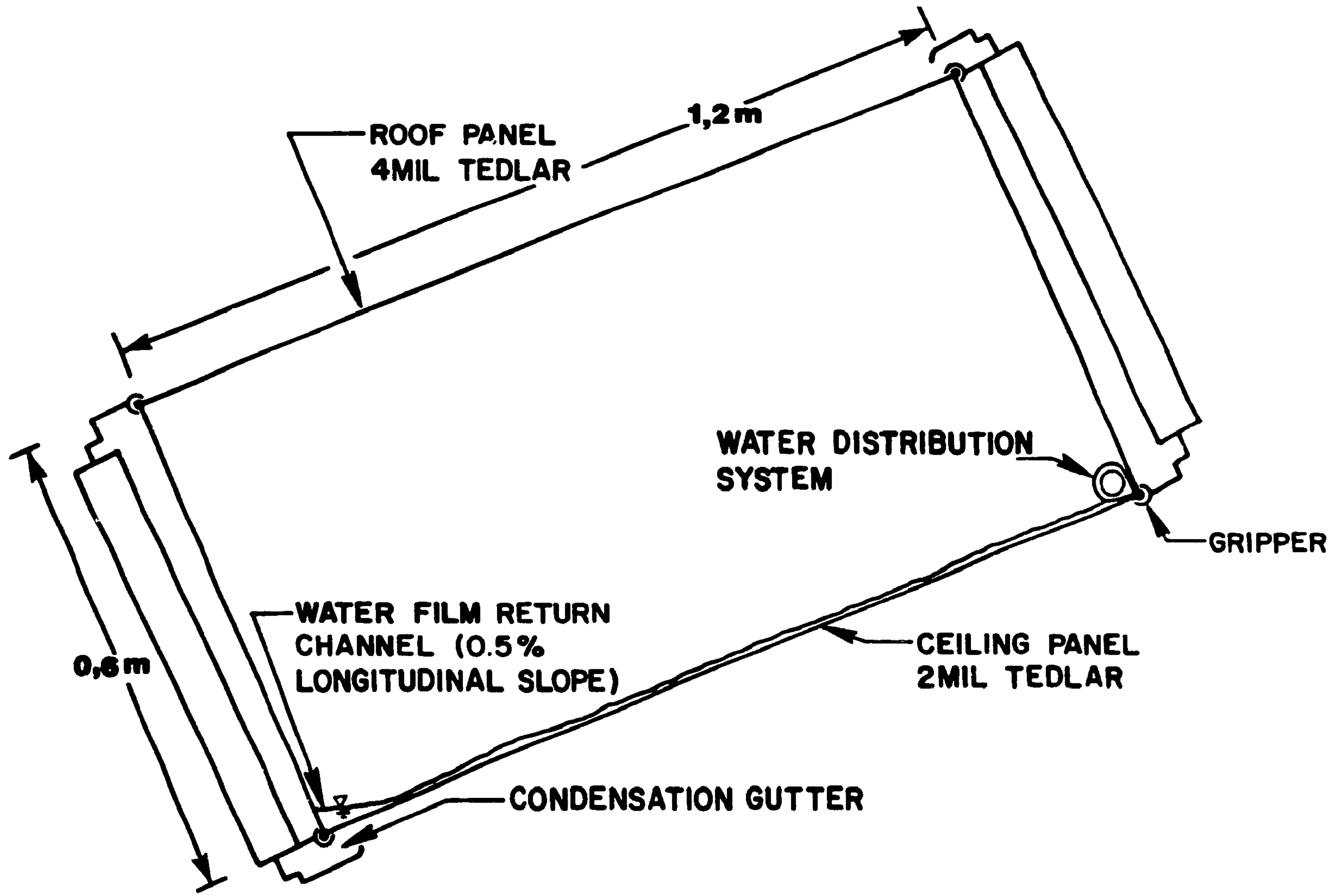


Figure 4.4 Prototype roof cross section

Manifolds are located at the extremes of a typical roof module. They are manufactured of fiberglass and their dimensions are arranged so as to accomodate the ends of a module section. The drainage system is built into these manifolds.

4.3 Data Acquisition and Control

The prototype was constructed so that some thermodynamic properties of the roof system could be assessed. An optimal roof management system would require a logic unit capable of selecting one of several roof operating modes. This decision would be based on monitored data of environmental conditions, past, present and predicted weather patterns as well as temperature and illumination restrictions imposed on the inside environment.

For the prototype, a less sophisticated approach was taken to control data acquisition and operating control, making the operation of the Solar Climate Control system continuous.

Location of the sensors is shown in Figure 4.5. Heat absorbed by the Solar Climate Control water film is assessed with type J thermocouples placed at the entrance and exit of the water flow path (positions 8 and 9). Interior (0,1), exterior (2,3), glazing (4,5) and water tank temperature (6,7) are also recorded with type J thermocouples.

Control and data acquisition are designated to an HP3421A control unit which is commanded by an HP41CV programmable hand-held calculator. The calculator is equipped with a ROM containing command subroutines for the operation of the control unit as well as a ROM for time modulation environmental monitoring. Signals are transmitted through an HPIL cable in bit form. The data acquisition unit monitors operations and sends the reading signals to a thermal printer and mass storage device. The new prototype status is then transmitted to the control box which activates the Solar Climate Control pump. The

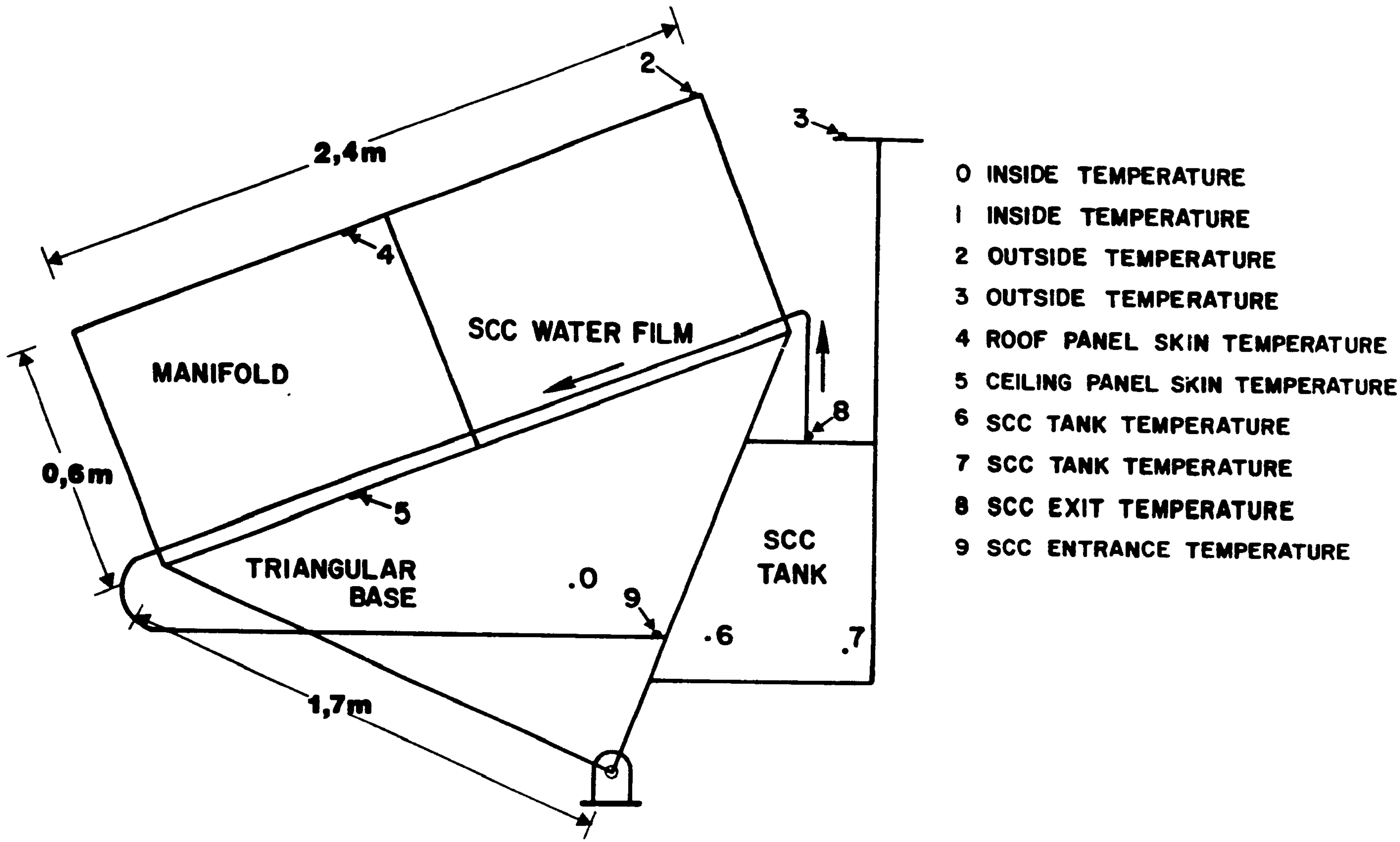


Figure 4.5 Schematic description of the location of the sensors on the prototype

logicial scheme of the data acquisition and control program is flowcharted in Figure 4.6. A schematic diagram of the control set-up is shown in Figure 4.7. Figures 4.8 and 4.9 depict the actual set-up.

4.4 Calculation Methods

The Solar Climate Control system can either extract or emit heat at different rates depending on the situation. The heat extraction rate (day time operation) is greater than the heat delivery rate (night time operation). This difference will affect the pumping time required to match the demand, depending on the situation considered. The general equations for the system are:

$$K_1 \frac{\Delta T_1}{\Delta t} = A_r \tau_{acc} I + A_r U_c (\overline{T_2} - T_1) + A_w U_w (T_\infty - T_1) \tag{15}$$

$$K_2 \frac{\Delta T_2}{\Delta t} = A_r \alpha_{acc} I + A_r U_c (\overline{T_2} - T_1) + A_r U_r (T_\infty - \overline{T_2}) \tag{16}$$

The time interval for the data collection is 15 minutes. The only unknown in the series of equations is the overall heat transfer coefficient of the roof when the system is operating. Rearranging the equations gives:

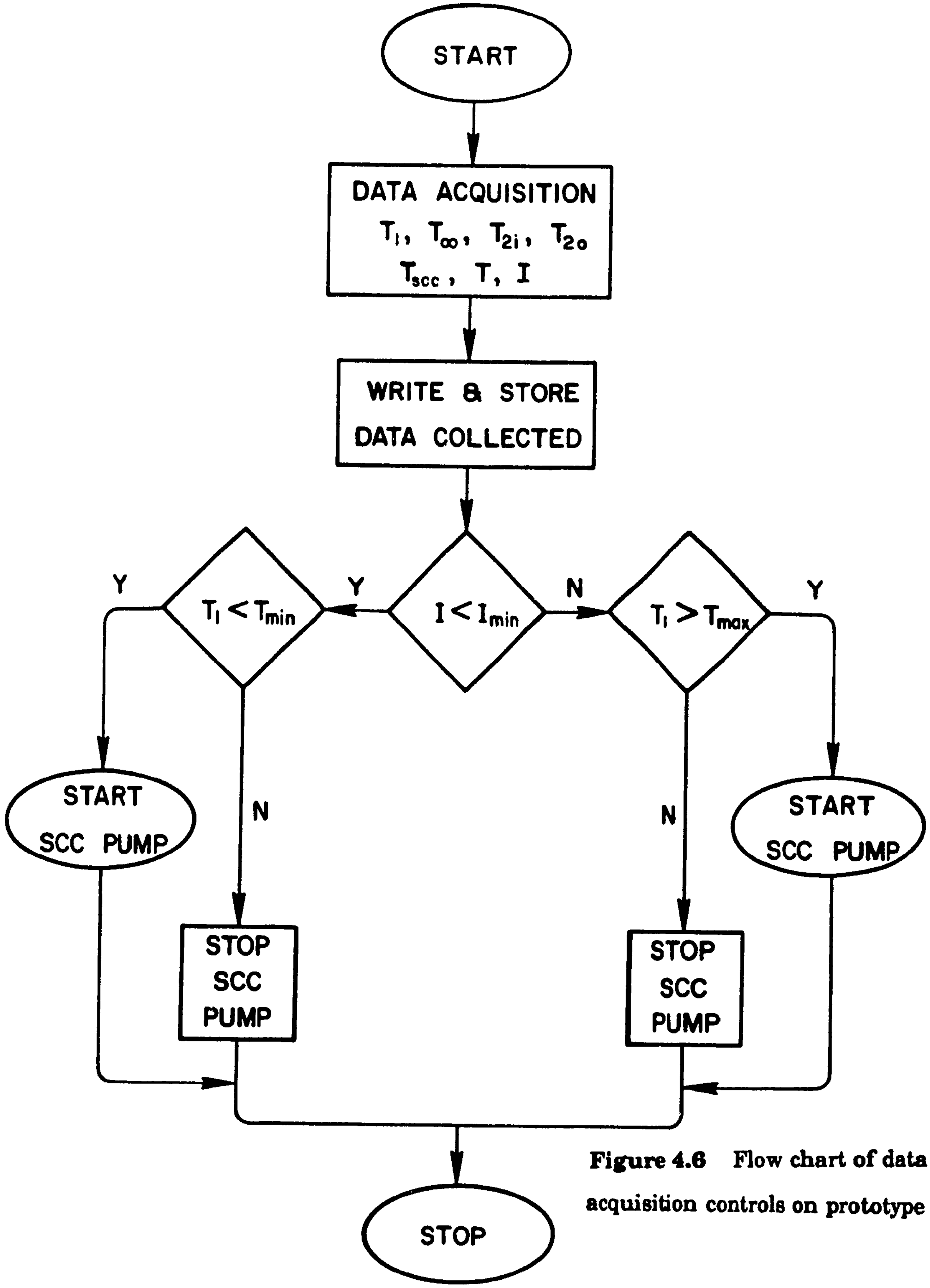


Figure 4.6 Flow chart of data acquisition controls on prototype

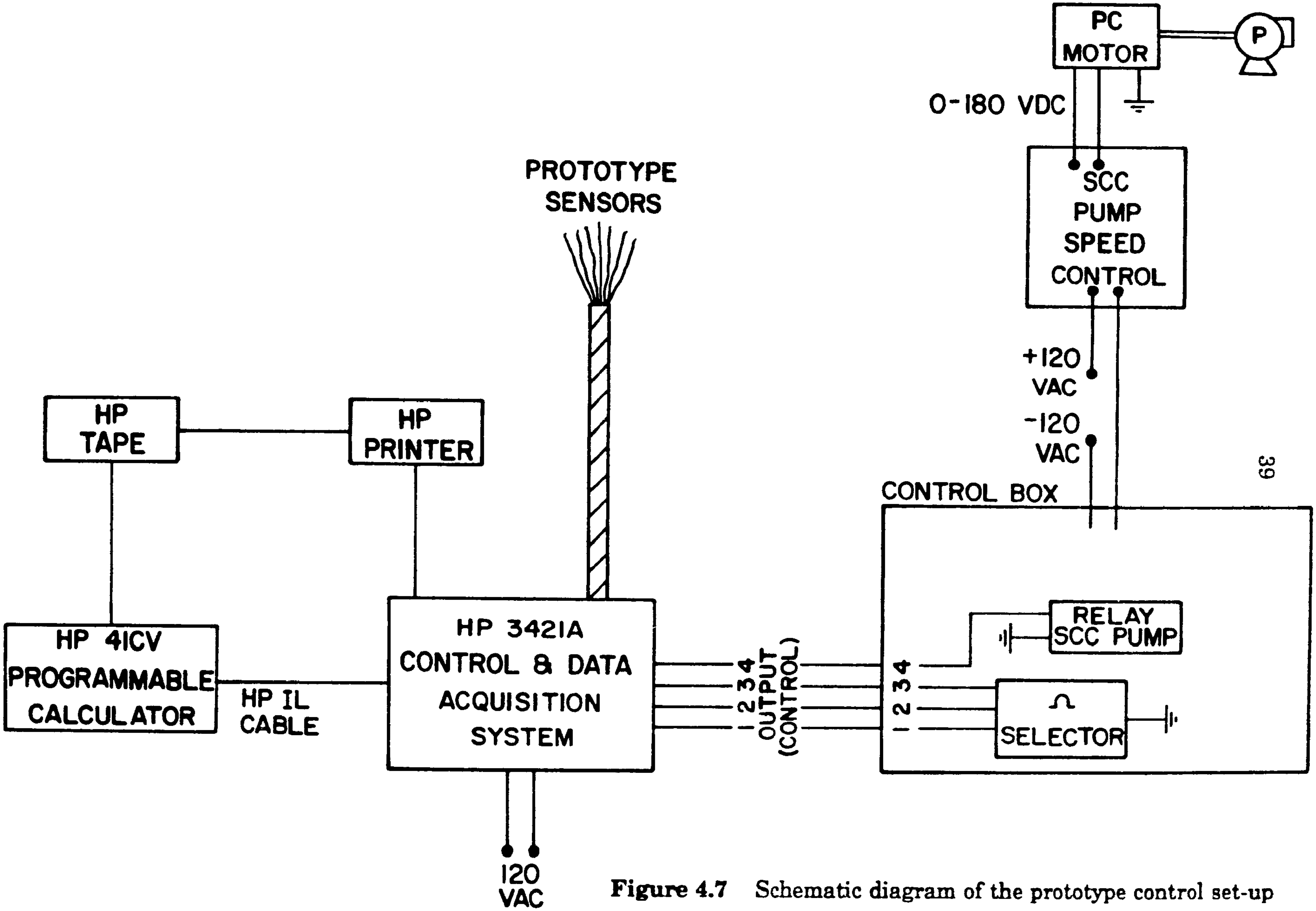


Figure 4.7 Schematic diagram of the prototype control set-up

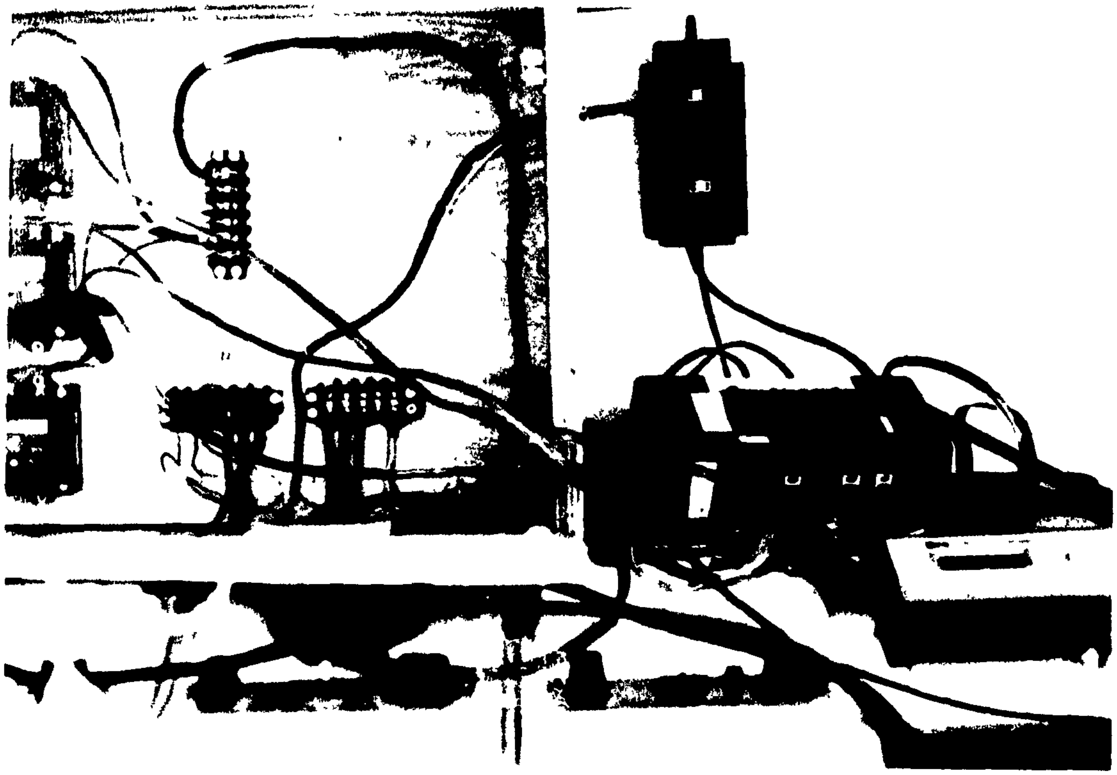
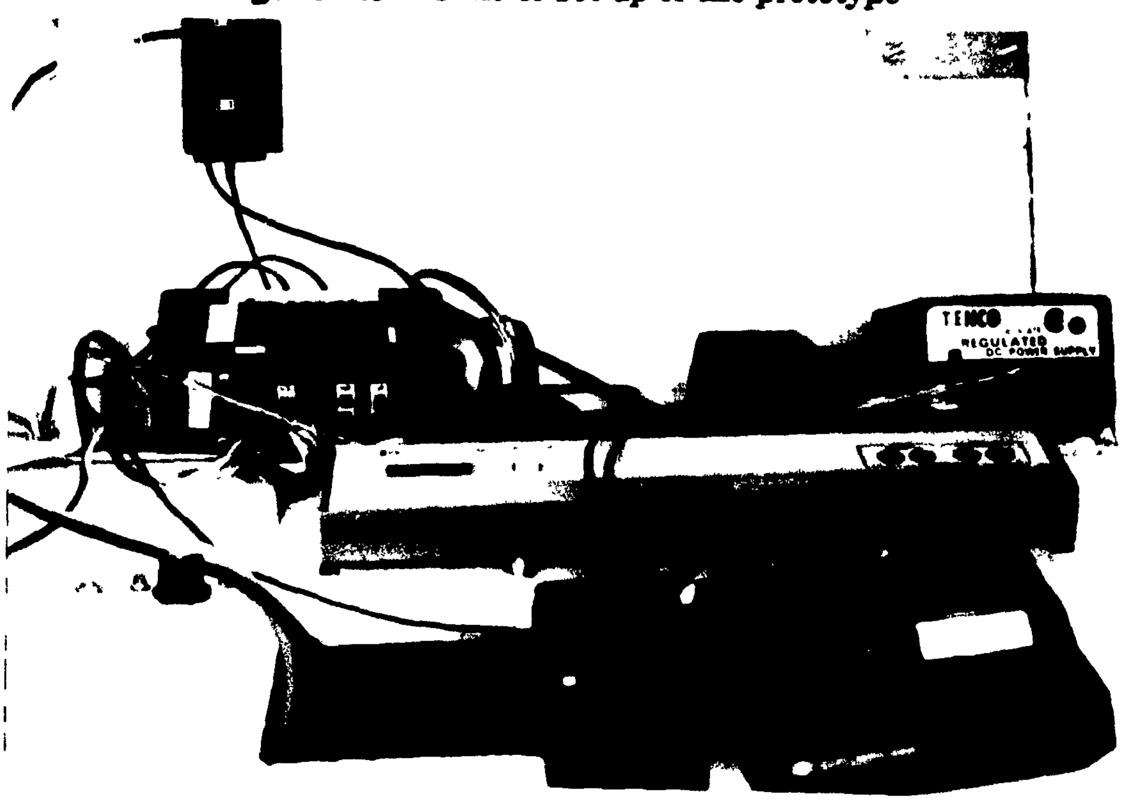


Figure 4.8 Electrical set-up of the prototype

Figure 4.9 Control set-up of the prototype



$$U_c = \frac{K_1 \, \Delta \, T_1 \, / \, \Delta \, t \, - \, A_r \, \tau_{scr} \, I \, - \, A_w \, U_w \, (T_\infty \, - \, T_1)}{A_r \, (\overline{T}_2 \, - \, T_1)} \tag{17}$$

$$U_r = \frac{K_2 \, \Delta \, T_2 \, / \, \Delta \, t \, - \, A_r \, \alpha_{scr} \, I \, - \, A_r \, U_c \, (T_1 \, - \, \overline{T}_2)}{A_r \, (T_\infty \, - \, \overline{T}_2)} \tag{18}$$

Analysis of the data can give an average value of the heat transfer coefficient for a given situation.

4.4.1 Computer simulation

A computer simulation program written in FORTRAN for the purpose of this study was utilized to evaluate the effect of thermal mass volume and temperature on the inside air temperature of a greenhouse. The flowchart of the program is given in Figure 4.10. The program is listed in Appendix A, and the results are discussed in Appendix C. A simulation considering the water film's absorbtivity rate of long wave radiation and the overall heat transfer coefficient of the fenestration will permit evaluation on their respective importance on the performance of the Solar Climate Control system. The program solves numerically the equations 1 to 4 and permits the computation of the system heat balance for different typical seasons.

This simulation program predicts the heating and cooling loads for a greenhouse equipped with the Solar Climate Control roof system. At first calculations were based on the dimensions and characteristics of a greenhouse of standard dimensions to evaluate the feasability of the system.

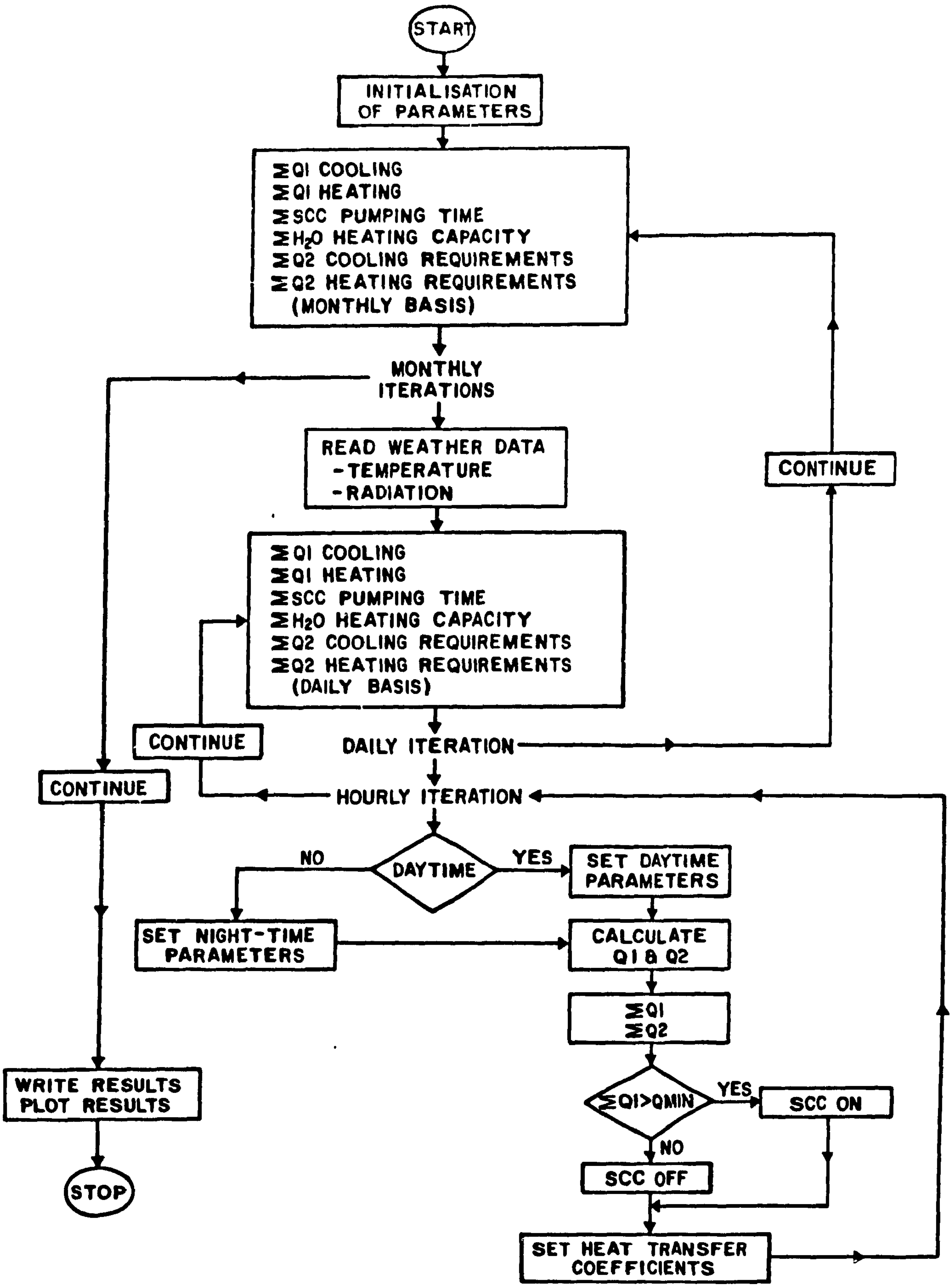


Figure 4.10 Flowchart of the simulation program

V. RESULTS AND DISCUSSION

The Solar Climate Control roof system has two benefits not present in a conventional double glazed greenhouse. It can act as a roof integrated solar collector which would heat water and as a climate control system. The concept being particularly new, several aspects needed to be investigated. This study first looked at the water flow distribution. A prototype equipped with the Solar Climate Control roof system was tested. A computer simulation was then used to evaluate the potential of the project over a longer period of time than the testing period of the prototype.

5.1 Experimental Investigations

Many efforts were made to develop a new concept for transparent roof canopies. One problem encountered in the design of the Solar Climate Control roof system was the water film dispersion on an inclined surface. The results of this study were used for design purposes in the construction of the prototype unit and later for larger greenhouse systems.

5.1.1 Laboratory Scale Experiment

There were 22 successful trials out of a total of 35 trials. A minimum discharge was required to give total coverage of the glazing by the liquid film. This was less for the soapy solution. Further, the steeper the slope of the panel, the greater was the minimum required flow. These results are shown in Table 5.1. Alternatively, there is a minimum sustainable thickness and the flow must be increased at increased slopes to achieve this thickness. The average temperature of the water was 25,9°C with a standard deviation of 2,31. The physical properties of the water were interpolated for both the 0% and 0,5% soap solution.

Table 5.1 Thickness, velocity, physical properties, Reynolds and Froude numbers of the water film flow

ANGLE degree	DISCHARGE L/s/m	THICKNESS mm	VELOCITY m/s	SPECIFIC WEIGHT N/m.cu.	KINEMATIC VISCOSITY m.sq /s (x 10E-07)	REYNOLDS NUMBER	FROUDE NUMBER
TAP WATER ONLY : 0% SOAP							
20	0.1862	1.12	0.166	9787	9.87	189	1.59
	0.3011	1.18	0.256	9777	8.78	343	2.38
35	0.3011	1.12	0.272	9783	9.41	320	2.61
	0.3244	1.16	0.279	9783	9.41	345	2.61
	0.4842	1.14	0.425	9778	8.93	542	4.02
	0.4941	1.14	0.433	9779	9.01	548	4.10
50	0.4552	1.03	0.441	9777	8.78	518	4.38
0.5% SOAP							
20	0.0030	0.56	0.144	9784	9.50	84	1.95
	0.1474	0.68	0.216	9776	8.74	169	2.65
	0.2044	0.85	0.240	9772	8.39	244	2.62
	0.2787	0.88	0.318	9771	8.30	336	3.43
35	0.0660	0.44	0.152	9783	9.45	70	2.32
	0.1527	0.63	0.242	9777	8.82	173	3.07
	0.2106	0.78	0.270	9774	8.61	245	3.08
	0.2787	0 91	0.306	9773	8.53	327	3.24
50	0.0730	0.47	0.156	9771	8.32	88	2.30
	0.1423	0.64	0.221	9767	8.03	177	2.79
	0.2106	0.73	0.290	9780	9.08	232	3.45
	0.2787	0.82	0.340	9774	8.61	324	3.77
70	0.1635	0.70	0.230	9772	8.31	195	2.76
	0.2170	0.90	0.242	9772	8.45	257	2.58
	0.2787	0.98	0.283	9774	8.61	324	2.89

The actual thickness of the flow is the average of 42 readings for each trial. The thickness of the film was about 1,1 mm for water at 0% soap concentration and varied from 0,4 to 1,0 mm for water at 0,5% soap concentration.

The velocity of flow down the panel was calculated with the continuity equation:

$$V = \frac{q}{d} \tag{19}$$

Typical values fall between 0,14 and 0,44 m/s. This velocity is a direct result of the discharge and film thickness combinations and consequently follows their behavior. The Reynolds number for the flow was calculated considering it to be in an infinitely wide channel. The flow may safely be assumed to be laminar as Re < 500 for most cases. For any given flow rate and discharge, the Reynolds number was higher for the soap solution since the film thickness is less. The water film with 0% soap concentration had greater discharge rates. This was so in order to ensure total coverage of the roof with no dry spots. Dry spots tended to be strips that widened towards the bottom of the panel as the fluid pulled itself together due to surface tension effects. In the case of very low flow the film disintegrated into a series of streams running down the face. The soap solution permitted a lower pumping rate and thus a greater efficiency. The Froude number indicated a rapid flow. Roll waves were present but jump did not occur in any of the test situations.

5.1.1.1 Depth prediction: In the design and operating of the Solar Climate Control system, it is critical to be able to predict a reasonable value for film thickness, at various angles and different soap concentrations. From the model tests, it was found that the ratio of velocity to thickness was fairly constant, with respect to different angles and soap concentrations, which led to the following simple relationship:

$$d_f = \sqrt{\frac{q_f}{320}} \tag{20}$$

5.1.2 Prototype Performance

Data from the prototype were collected from September 29 to October 15, 1986. Outside and inside temperature, roof and ceiling panel skin temperatures, and the thermal mass temperature were recorded on an hourly basis. The data are shown in Appendix B.

As shown in the Figure 4.5, the inside temperature was measured with two thermocouples and the mean was calculated. The outside temperature was also measured with two thermocouples and averaged; however, the data seem to indicate that their positions were not optimal or that they were not adequately shielded because the averaged daytime temperatures were about 5 to 8°C higher than reported local maxima on a number of occasions. The reasons for the anomalies cannot be found since the wind and radiation were not available. The inside temperature of the prototype varied as the outside temperature did. It was not possible to keep the inside temperature at an optimum level, since the prototype was not only well insulated but its interior was painted in black to absorb all radiation incident upon it. Therefore no solar radiation was reflected except from the Tedlar panels. Figure 5.13 illustrates this situation. A fraction of the solar radiation is reflected from the Tedlar panels, another is absorbed by the water film and the rest is transmitted to the inside and absorbed by the blackbody. Equations 21 and 22 express the situation:

$$Q_{w} = Q_{sw} + Q_{aw} + Q_{tw} \tag{21}$$

$$Q_{tw} = Q_{el} \tag{22}$$

Typical data collected for the 12th and 13th of October 1986 are presented in Figure 5.1. When the experiment started, the inside temperature was in the range of 80°C. Within few hours after the water film started to flow, the inside temperature significantly dropped to a more acceptable level. Figure 5.2 shows the difference between the inside and outside temperature as well as the original inside temperature for the first two days of the experiment. After 10 hours of the system running, the inside temperature was 25°C compared to 75°C when it started.

Figure 5.3 shows the roof panel skin and outside temperature profiles. A close relationship exists between the two. This was noted for the entire period of the experiment. The outside temperature was therefore used to determine the overall heat transfer coefficient of the roof. The inside temperature closely followed the ceiling skin temperature (Figure 5.4). The inside temperature was used in the calculations.

The temperature difference between the outside and inside temperatures was at its peak during mid-day (Figure 5.5). The temperature profile of the water followed the same path as the outside/inside temperature difference but with a lag of a few hours indicating the heat gain and loss by the water in order to keep the inside temperature as constant as possible. When the outside/inside temperature difference was high, the water film absorbed

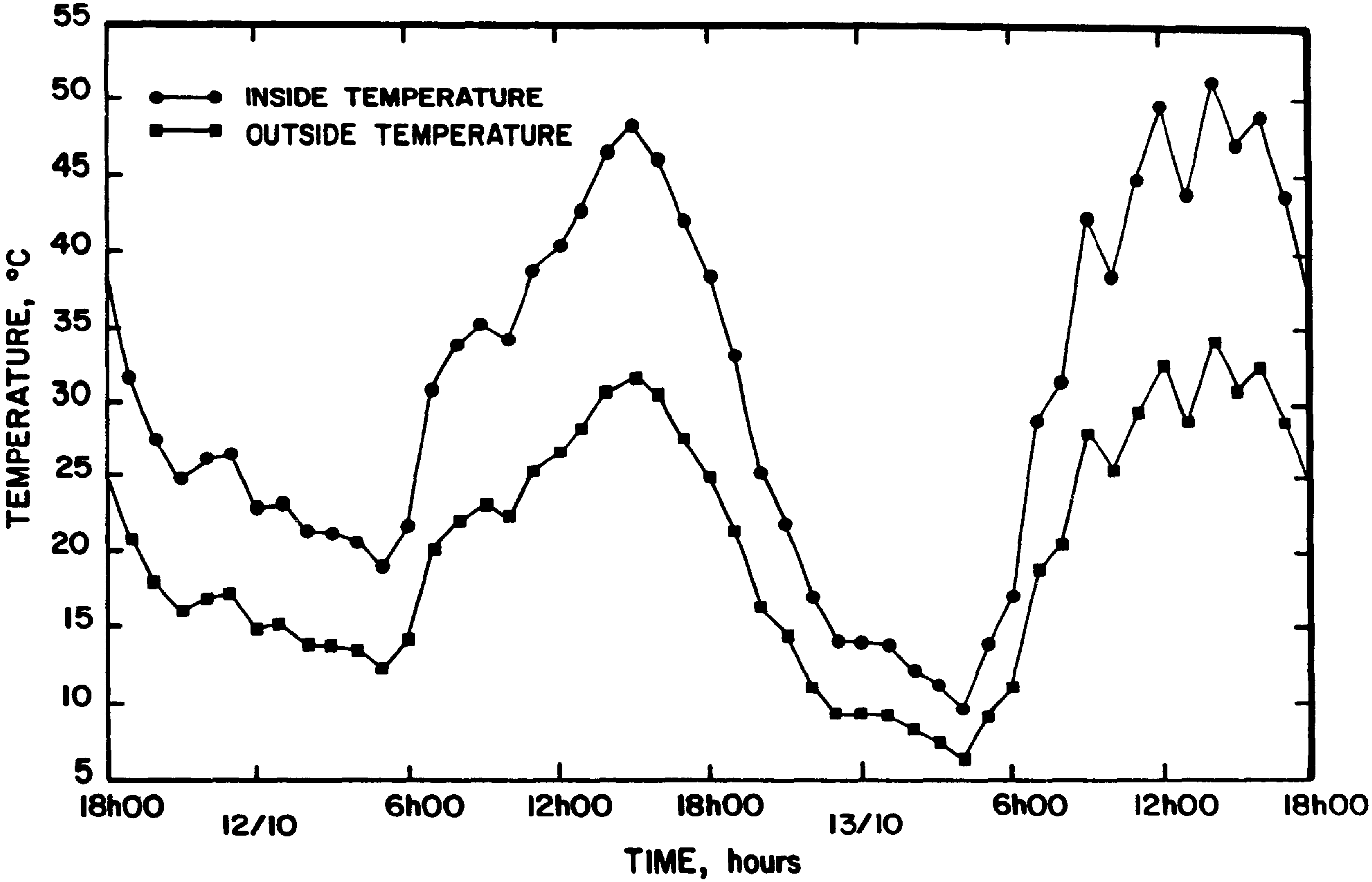


Figure 5.1 Temporal variation of inside and outside temperature

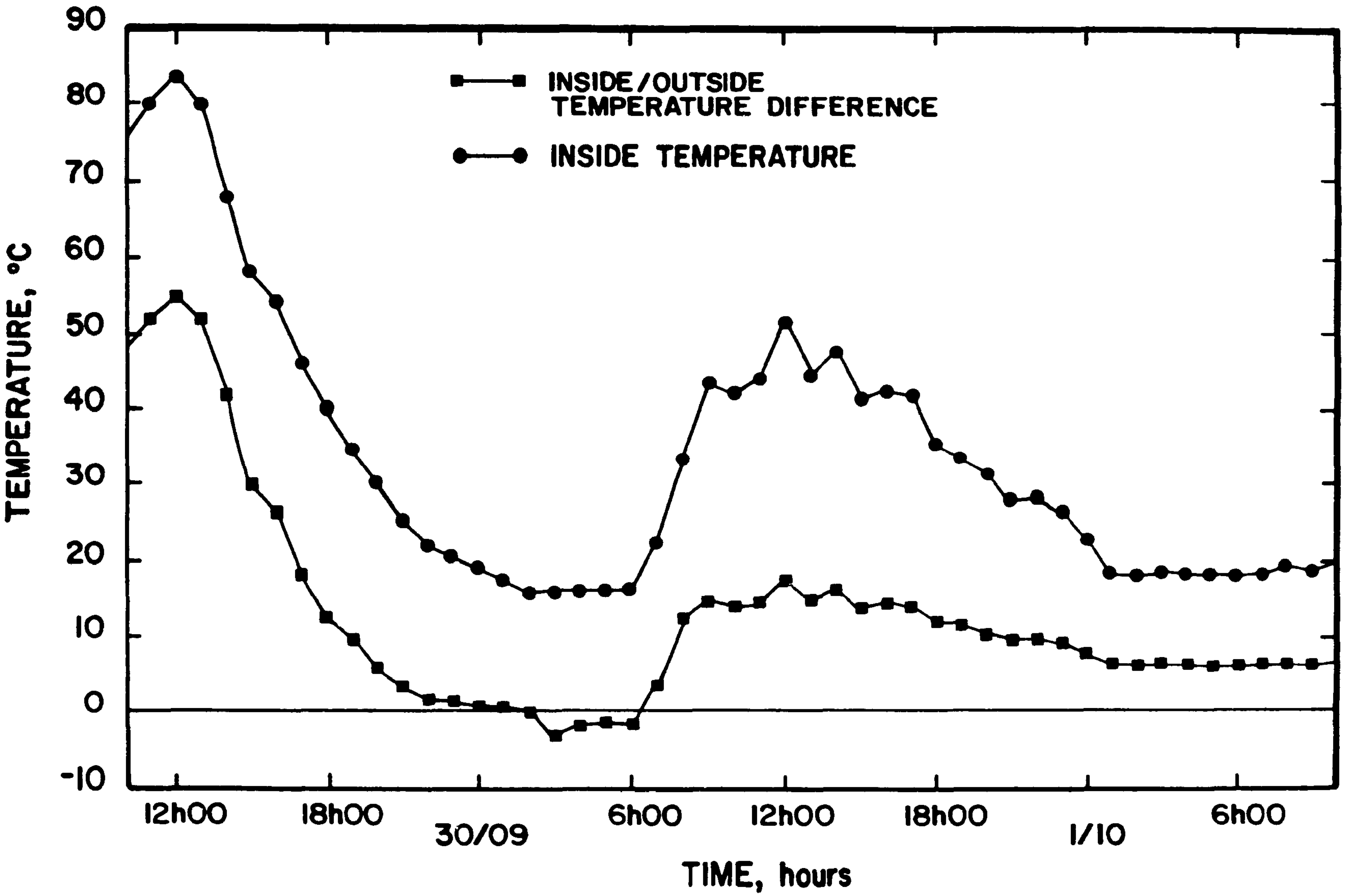


Figure 5.2 Temporal variation of inside/outside temperature difference compared to the inside temperature for the first two days of the experiment

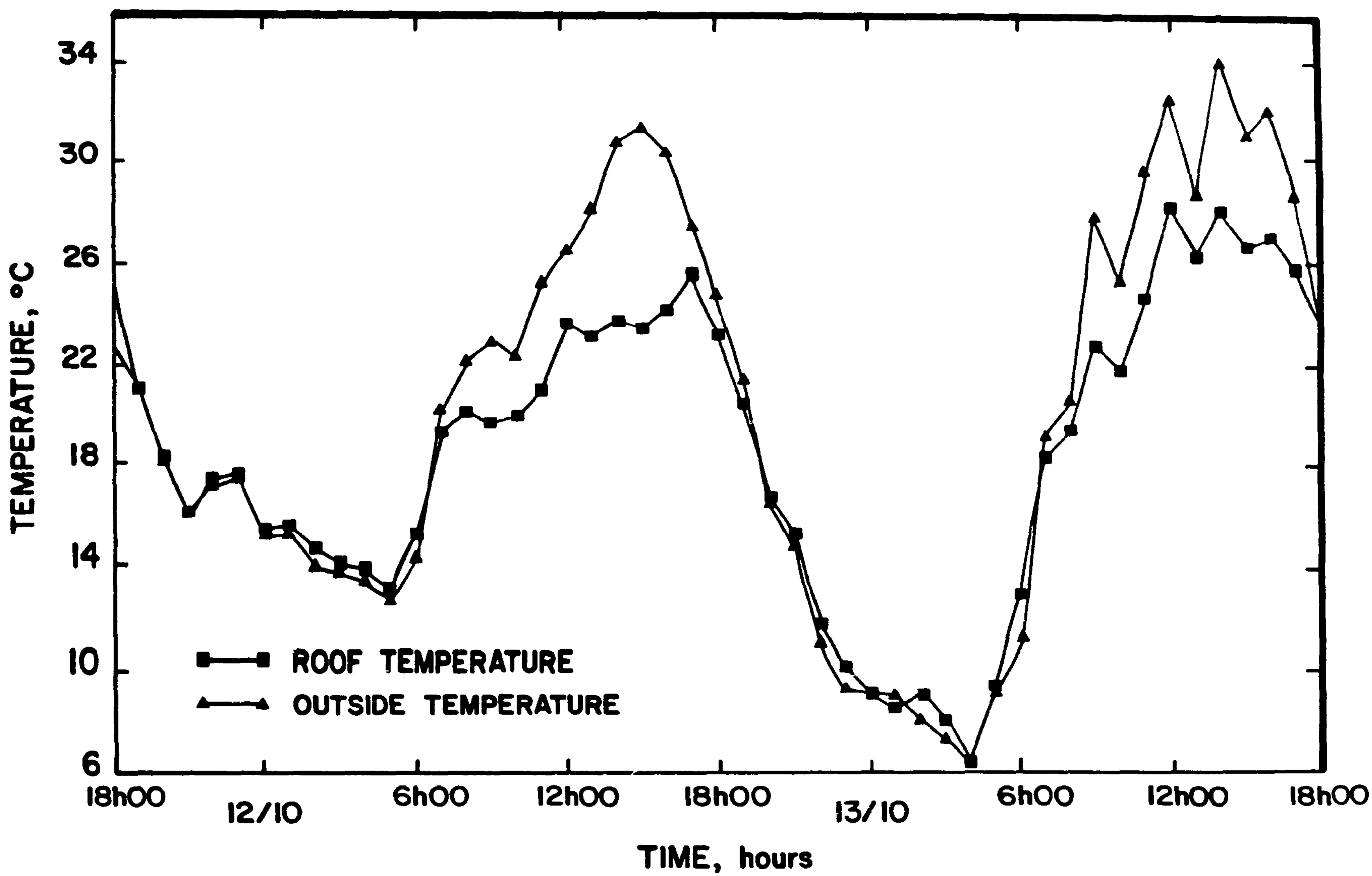


Figure 5.3 Temporal variation of the roof panel skin and outside temperature

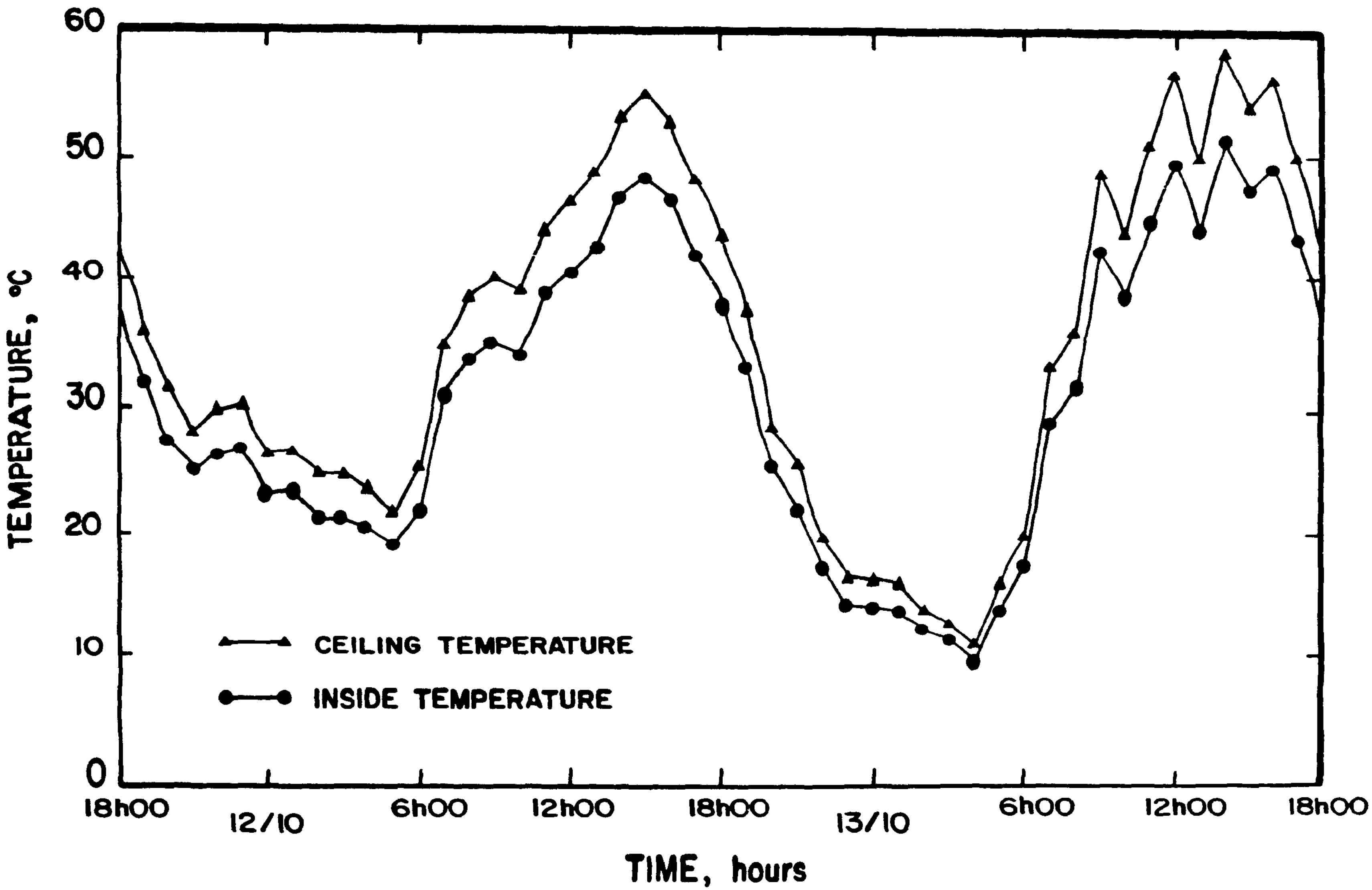


Figure 5.4 Temporal variation of the ceiling skin and inside temperature

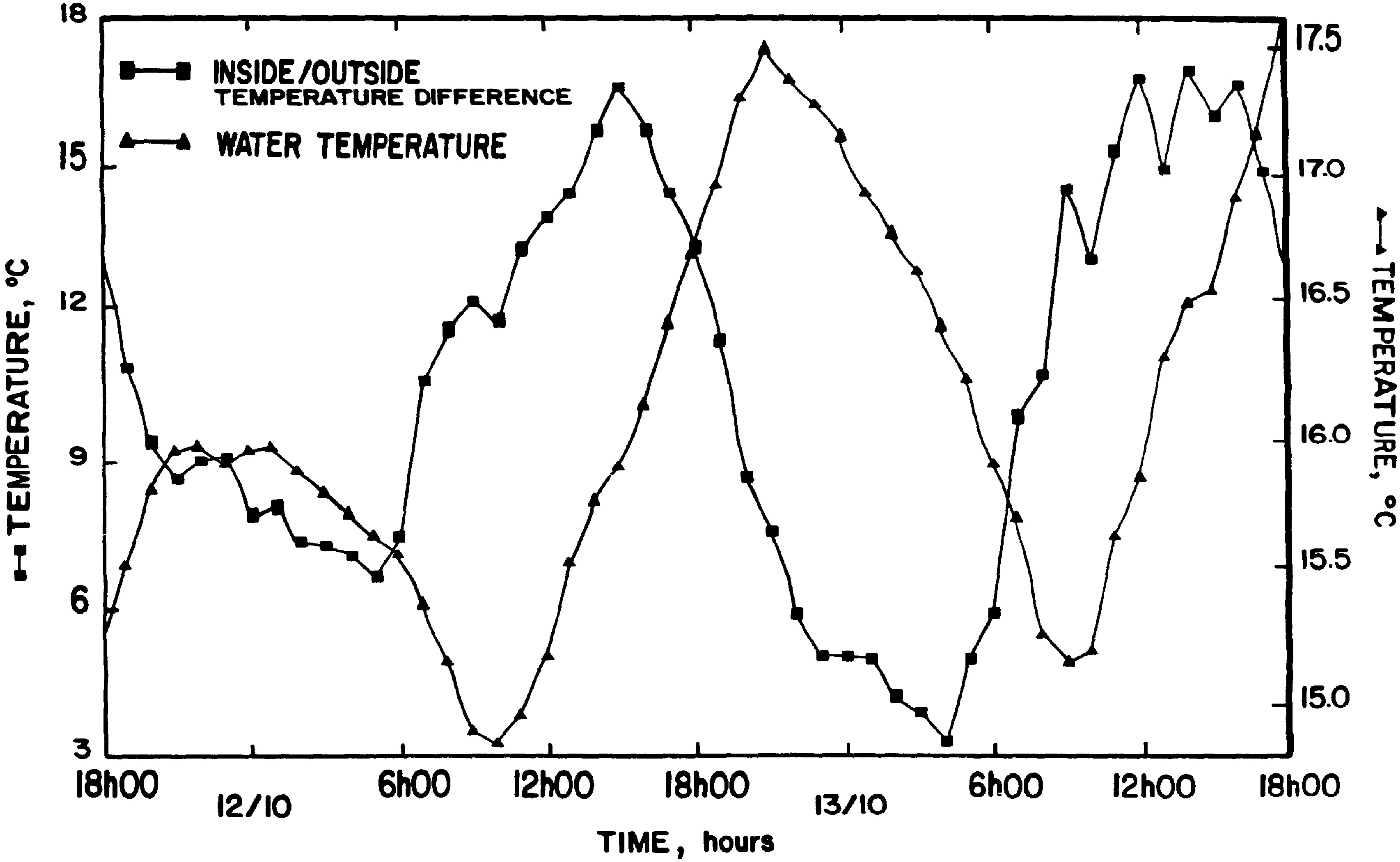


Figure 5.5 Comparison of the inside/outside temperature difference to the water film flow temperature

heat which was reflected in an increase of its temperature. When the outside/inside temperature difference was low, the water film rejected heat and its temperature decreased.

The heat gain or loss by the water was calculated based on the temperature difference of the water in the reservoir over a chosen time period, its mass (1 728 liters) and its specific heat (C_p). The time period was 60 minutes based on the fact that the parameters measured had a slow rate of change.

$$Q_{water} = m_w (C_p)_w \Delta T_2 \tag{23}$$

$$Q_{air} = m_a (C_p)_a \Delta T_1 \tag{24}$$

The results are shown in Figure 5.6 and are tabulated on a daily basis in Table 5.2. Based on equation 24 and taking into account the characteristics of air, the heat gain or loss by the inside environment of the prototype was also calculated. Results are shown in Figure 5.7 and are also tabulated in Table 5.2. No correlation can be clearly established between the heat transfer to or from either the thermal mass (water) or the inside environment because no data were collected on the transmitted radiation through the glazings. However, some calculations were made to compare the heat gain by the water to the heat loss of the inside environment and the heat loss by the water to the heat gain by the inside environment. Table 5.2 shows these comparaisons. Over the entire period of testing, the heat gain by the inside environment represented 0,53% of the total heat loss by the system, and the heat loss by the inside environment represented 0,55% of the total heat gain by the

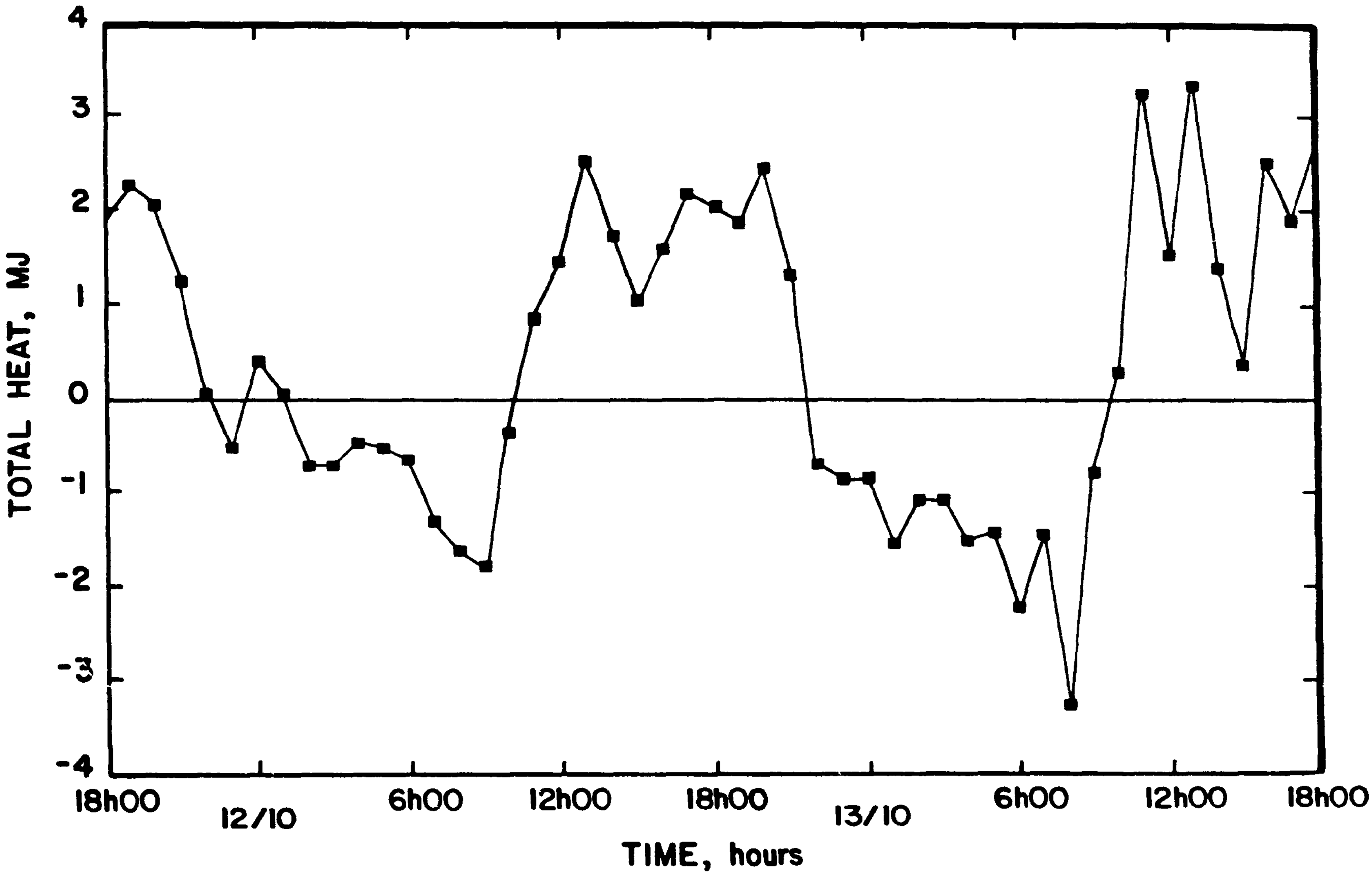


Figure 5.6 Temporal variation of the total heat gain or loss by the thermal mass

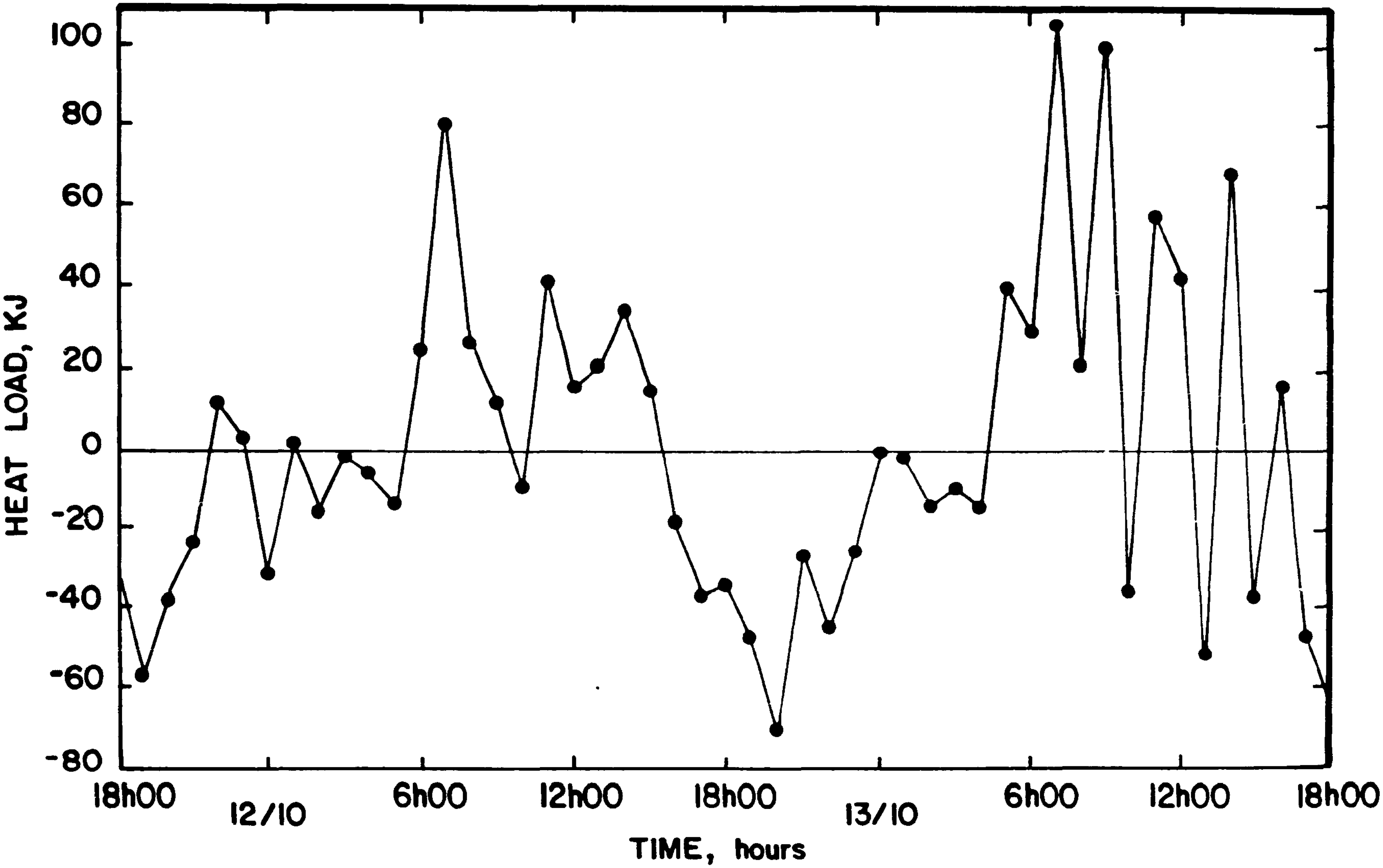


Figure 5.7 Temporal variation of the total heat gain or loss by the interior environment of the prototype

TABLE 5.2 Energy load of the thermal mass, and of the interior environment of the prototype, and heating and cooling efficiencies of the system

Date (1986)	Heat gain by SCC system (GJ)	Heat loss by SCC system (GJ)	Heat gain by interior environment (KJ)	Heat loss by interior environment (KJ)	%	%
29-9	0,0616	0,0795	366,3 (0,46%)*	399,3 (0,64%)	99,54	99,36
30-9	0,0315	0,0925	193,9 (0,21%)	243,7 (0,77%)	99,79	99,23
1-10	0,0610	0,0687	100,3 (0,15%)	227,4 (0,37%)	99,85	99,63
2-10	0,0282	0,0418	384,2 (0,92%)	215,0 (0,76%)	99,08	99,24
3-10	0,0187	0,0108	286,5 (2,59%)	247,0 (1,30%)	97,41	98,70
4-10	0,0377	0,0025	155,0 (5,84%)	227,9 (0,60%)	94,16	99,40
5-10	0,0894	0,1154	311,8 (0,27%)	236,7 (0,26%)	99,73	99,74
6-10	0,1341	0,0994	239,3 (0,24%)	317,3 (0,24%)	99,76	99,76
7-10	0,0688	0,0401	196,8 (0,49%)	118,5 (0,17%)	99,51	99,83
8-10	0,1029	0,1527	387,0 (0,25%)	244,3 (0,24%)	99,75	99,76
9-10	0,1021	0,0816	346,1 (0,42%)	404,5 (0,39%)	99,58	99,61
10-10	0,0053	0,0610	239,8 (0,39%)	221,7 (4,02%)	99,61	95,98

11-10	0,0269	0,0133	242,3 (1,79%)	182,8 (0,67%)	98,21	99,33
12-10	0,0184	0,0066	337,1 (4,86%)	281,1 (1,50%)	95,14	98,5
13-10	0,0190	0,0140	444,9 (3,08%)	436,2 (2,24%)	96,92	97,76
14-10	0,0212	0,0153	468,7 (2,97%)	436,1 (2,02%)	97,03	97,98
15-10	0,0264	0,0072	119,8 (1,64%)	250,1 (0,94%)	98,36	99,06
TOTAL	0,8532	0,9024	4820,0 (0,53)	4690,0 (0,55)	99,47	99,45

* Fraction of the heat loss or gain by the Solar Climate Control system.

system. The total heat gain by the thermal mass over the entire period is 0,8532 GJ and the heat loss is 0,9024 GJ. This shows that the system is at equilibrium. The heat gain during the day, maintaining the inside temperature of the prototype as stable and optimum as possible, was lost during the night accomplishing the same role (Figure 5.8). When using equation 11, ΔT_2 is evaluated to be 6,8°C. From the data collected a ΔT_2 of 5,9°C is noted, which correlate satisfactorily to the theoretical value. The small percentage of heat gain or loss over the total heat gain or loss by the inside environment also shows the positive effect of the water film. Whithout it, the interior temperature would have fluctuated between 85°C and 20°C. But, with the water film circulation, an average temperature of 27°C was maintained.

The values of the total heat gain or loss by the system were used to determine the overall heat transfer of the Solar Climate Control system. The values fluctuated from 5 to 570 $W/m^2{}^\circ C$ which corresponds to the values found in the literature (Nelson, 1980). The overall heat transfer coefficient prevailing between the ceiling membrane and the interior air temperature is the major restriction for heat flow, and the inside environmental conditions (whether it is dry still air or the air is humid and water is condensing) are responsible for this wide range of values.

However, it was not possible to accurately evaluate the efficiency of the Solar Climate Control system since no data on solar radiation and its reflected, absorbed and transmitted fractions were collected. But comparing the heat gain or loss by the inside environment (equation 23) to the total heat gain or loss by the system (equation 24), the efficiency of the system was determined. The cooling and heating efficiencies were determined to be

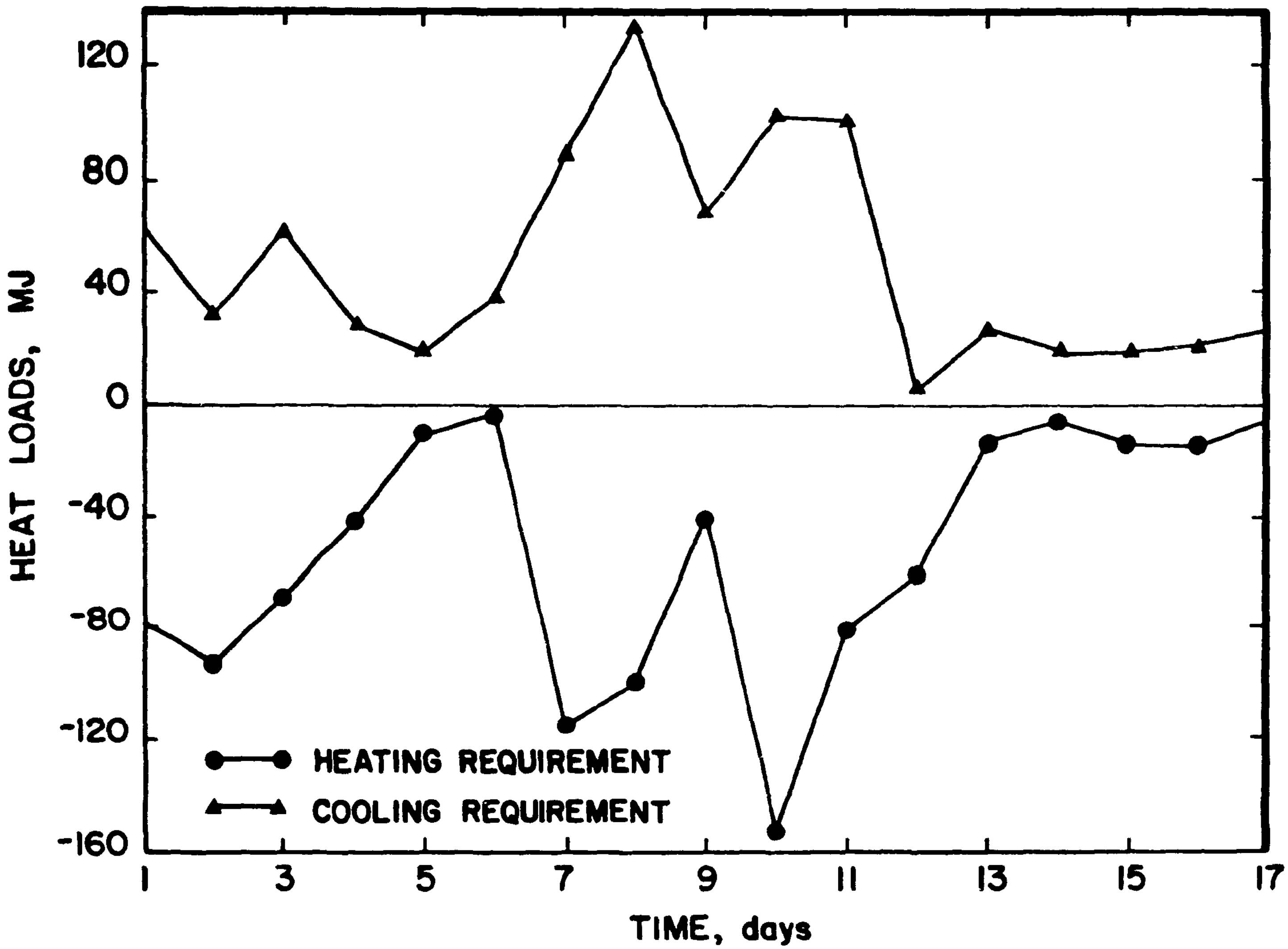


Figure 5.8 Temporal variation of the heating and cooling loads for the prototype

respectively 99,47 and 99,45%.

The coefficients of cooling and heating performance of the system is the ratio of the useful heat delivery whether the system rejected or absorbed heat from the inside environment, to maintain the interior temperature of the prototype as stable as possible to the input energy to perform the task. Table 5.3 shows the values of the coefficient of performance when the system is under the cooling mode, the heating mode and a combined value based on the operating time of each mode. The calculations were based on a mass flow rate of 1 728 L/hour, a head of water of 6,0 m and a pump efficiency of 0,5. The average combined value was 21,2 with a standard deviation of 15,9. There were no significant difference between the coefficient of performance under the cooling or heating mode although the first one varied over a larger range, 5,2 to 84,4, compared to 2,1 to 50,2 for the latter.

5.2 Operating Costs

The operating expenditure of a greenhouse system includes heating and cooling costs as well as the operational cost of auxiliary equipment. In this analysis, heating and cooling costs are determined for both the Solar Climate Control roof system and the conventional double glazed greenhouse and a comparison is presented in Table 5.4.

TABLE 5.3 **Coefficients of Cooling and Heating performance of the Solar Climate Control system as tested with the prototype.**

Date (1986)	Cooling mode Operating time (hours) t_1	CCP	Heating mode Operating time (hours) t_2	CHP	Combined $\frac{t_1CCP + t_2CHP}{t_1 + t_2}$
29-9	8	50,5	16	26,1	34,2
30-9	13	11,9	11	41,4	25,4
1-10	13	23,1	11	30,7	26,6
2-10	8	17,3	16	13,7	14,4
3-10	17	5,4	7	7,6	6,1
4-10	18	10,3	6	2,1	8,2
5-10	11	40,0	13	43,7	42,0
6-10	10	66,0	14	34,9	47,9
7-10	12	28,2	12	16,4	22,3
8-10	6	84,4	18	41,7	52,4
9-10	16	31,4	8	50,2	37,7
10-10	5	5,2	19	15,8	13,6
11-10	14	9,5	10	6,5	8,2
12-10	16	5,7	8	4,1	5,1
13-10	11	8,5	13	5,3	6,8
14-10	12	8,7	12	6,3	7,5
15-10	13	10,0	11	3,9	7,2
MEAN:	11,9	24,5	12,1	20,6	21,2
S. Dev.:	3,7	23,4	3,6	16,6	15,9

Table 5.4 Comparative operating costs of a conventional double glazed greenhouse and one equipped with the Solar Climate Control system

Energy used for	Conventional greenhouse $/year	SCC system $/year
Fuel heating	1 138,00	
Absorption chiller	2 451,00	
Pumping cost for:		
Heating		54,00
Cooling		73,00
TOTAL:	**3 589,00**	**127,00**

a reduction of 3 462,00$/year in energy cost for a 74,3 m^2 greenhouse.

5.2.1 Conventional greenhouse

For a conventional double glazed greenhouse, an oil furnace using No. 2 heating oil is considered to fulfill the heating requirements. By selecting an efficiency of 65% for the unit, heating costs were determined by considering the annual heating energy demand and the calorific conversion of the unit at an assumed fuel cost of $0,393/L.

With the conventional greenhouse, cooling is generally provided by means of an exhaust fan. However, ventilation does not permit maintenance of interior air at a fixed 24°C. Air exchange rates in the range of three-fourths and one per minute are most efficient during the summer. Most often, this system will maintain temperatures in the greenhouse 3 to 8°C above exterior dry bulb temperature (Walker, 1983). To maintain temperatures around 24°C, an absorption chiller (coefficient of performance = 1) is required.

5.2.2 Solar Climate Control roof system

As previously mentioned, the Solar Climate Control system can either extract or emit heat at different rates, depending on the requirement. The heat extraction rate is greater than the heat delivery rate. This difference will affect the pumping time required to match the demand. Experimental investigation has shown that practical water film flow rates would be around 32 $m^3/hr/m^2$ of duct (Kaplansky and Plasse, 1985).

VI. SUMMARY AND CONCLUSIONS

The Solar Climate Control system investigated in this study is a unique design which prevents overheating of a glazed structure. The main advantages of this system are: i) Preservation of moisture transpired by plants within the building; ii) Control of the atmosphere within the building; and iii) Conservation of all available solar heat for its use in cold climates.

An efficient water dispersion pipe for the Solar Climate Control system was developed. The use of a soap solution rather than water alone for the Solar Climate Control water film system permitted a significant reduction in pumping rate.

Monitoring of the prototype started in Fall 1986, for a 17 day period, permitting the study of the heating and cooling modes. Before the monitoring started, the inside temperature varied directly with the outside temperature reaching the 80°C during the day and dropping to 20°C during the night. The flowing of the water film maintained an average inside temperature of 27°C with a standard deviation of 10,1. No comparison between a conventional greenhouse and one equipped with the Solar Climate Control system could be made through this monitoring. Overall the system has a good potential. It needs refinement in order to adequatly manage the Solar Climate Control system.

VII. RECOMMENDATIONS

Further investigations are required in order to assess the full potential of the new technique:

i) Verification of the model parameters must be carried out through further experimentation, and a more dynamic simulation should be undertaken using the refined parameters;

ii) A comparative study between a control greenhouse and the one equipped with the Solar Climate Control system should be done, in order to evaluate the overall impacts on energy consumption and on crop yield for different production schemes.

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APPENDICES

APPENDIX A

Listing of the computer simulation program.

```
$debug
      PROGRAM SCCSIM
C-------------------------------------------------------------------------C
C     FILENAME  SCC SIM                                                   C
C     SUBJECT  SIMULATION OF A CONVENTIONAL GREENHOUSE AND ONE  WITH      C
C     THE SCC SYSTEM TO COMPARE BOTH SYSTEMS   THIS SIMULATION  PROGRAM C
C     PREDICTS THE HEATING AND COOLING LOADS EXPECTED.                    C
C                                                                         C
C                                                                         C
C     THE MODEL PARAMETERS ARE :                                          C
C                                                                         C
C     1  Greenhouse dimensions .                                          C
C        Exterior wall surface area              41.8 m.sq.               C
C        Interior wall surface area              69.7 m.sq.               C
C        Floor surface area                      69.7 m sq.               C
C        Roof surface area                       75.1 m.sq.               C
C        Roof angle                              21.8 deg.                C
C                                                                         C
C     2. Resistance to heat flow :                                        C
C        Exterior wall                           3.26 m.sq. C/W           C
C        Interior wall                           5.22 m.sq. C/W           C
C        Floor                                   0.1606 m.sq. C/W         C
C                                                                         C
C        Conventional double glazed roof         0.3522 m  sq. C/W        C
C                                                                         C
C        Roof equipped with the SCC system :                              C
C        Resistance of water film to inside air  0.0176 m.sq. C/W         C
C        Outside roof resistance                 0.3522 m.sq. C/W         C
C        Thermal mass to soil                    1.00 m.sq. C/W           C
C                                                                         C
C     3. Optical properties of roofs :                                    C
C                                                                         C
C        Roof       Transmissivity  Absorptivity    Reflectivity          C
C        type                                                             C
C       -----------------------------------------------------------       C
C        Conventional      0.80          0.05              0.15           C
C                                                                         C
C        SCC system        0.60          0.20              0.20           C
C       -----------------------------------------------------------       C
C                                                                         C
C     4. Design temperature :                                             C
C                                                                         C
C        Thermal mass                            18.3 C                   C
C        Inside air  - daytime                   29.5 C                   C
C                    - night time                12.8 C                   C
C                                                                         C
C     5. Pumping system parameters  :                                     C
C                                                                         C
C        Head of air                             0.07m                    C
C        Head of water                           6.0 m                    C
C        Specific weight of water             9800.0 N/m.cu.              C
C        Specific weight of air                 11.88 N/m.cu.             C
C        Water film flow rate                   32 m.cu./hr/m.sq.         C
C        Pumping system efficiency               0.5                      C
C        SCC system efficiency (assumed to be)   1.0                      C
C                                                                         C
C-------------------------------------------------------------------------C
```

```
C     DIMENSIONALISATION                                                          C
C-----------------------------------------------------------------------------------C
      DIMENSION TIME(150),SAL(20),SAZ(20),TOM(40),TOMI(40),TO(150),
     1Q2S(6,366),XIDN1(20),XID1(20),TIMEX(366),Q2ST(6),Q2STP(6),
     2Q1T(6),XP(366),XPMIN(6),XPMAX(6),YP(366),YPMIN(6),YPMAX(6),
     3JTITOT(6),JTOT(6),Q1PC(6,370),SCCTC(6),SCCTCP(6),Q1PH(6,370),
     4SCCTH(6),SCCTHP(6)
C-----------------------------------------------------------------------------------C
C     KNOWN AND UNCHANGEABLE PARAMETERS                                             C
C                                                                                   C
C     A  ROOF AREA                                                                  C
C     PAIR  DENSITY OF AIR                                                          C
C     PWATER  DENSITY OF WATER                                                      C
C     ABSWO  ABSORPTANCE OF FENESTRATION      SCC ON     ISIT    = 2               C
C     ABSOO                                   SCC OFF    ISIT    = 4               C
C                                                                                   C
C                                                                                   C
C     TRANWO  TRANSMITTANCE OF FENESTRATION    SCC ON    ISIT    = 2               C
C     TRANOO                                   SCC OFF   ISIT    = 4               C
C                                                                                   C
C                                                                                   C
C     UAVG  HEAT TRANSFER COEFFICIENT FROM INSIDE THE GREENHOUSE                   C
C           THROUGH THE WATER FILM                                                  C
C     UFEWO FENESTRATION HEAT TRANSFER COEFFICIENT FROM THE WATER FILM             C
C           TO OUTSIDE                                                              C
C                                                                                   C
C     QG  REFLECTANCE OF THE FOREGROUND                                             C
C     CP  SPECIFIC HEAT OF AIR                                                      C
C     CP40  SPECIFIC HEAT OF WATER AT  5 C                                          C
C     CP50                         AT 10 C                                          C
C     CP60                         AT 15 C                                          C
C     CP70                         AT 20 C                                          C
C     F  ABSORPTANCE FACTOR                                                         C
C     SAL  SOLAR ALTITUDE                                                           C
C     SAZ  SOLAR AZIMUTH                                                            C
C-----------------------------------------------------------------------------------C
      A=14.640
      PAIR=1.23480
      PWATER=999.2
      ABSWW=0.20
      ABSWO=0.20
      ABSOW=0.00
      ABSOO=0.00
      TRANWW=0.60
      TRANWO=0.60
      TRANOW=0.80
      TRANOO=0.80
      TRANDP=0.80
CEU   UAVG=10.0
CEU   UFEW=0.10
CEU   UFEWO=0.5
      QG=0.2
      CP=1.00570
      CP40=4.208
      CP50=4.195
      CP60=4.186
      CP70=4.179
```

```
      F=0 5
      PI=3.141592654
      N=1
      AF=69.713
      RF=0.1606
      T2=18.3
      T1=29.5
      AWI=69 713
      RWI=5.22
      TI=29 5
      AWO=41.828
      RWO=3.26
      AR=75.083
      RR1=0 3522
      RR2=1.7611
      RR3=0.1761
      RRO=0.3522
      RRO1=10.*0.1761
      RRD=RR1
      RRN=RR2
      A=75 083
      AS=116.1288
      RS=2.0
      TS=12.8
      JOQ=0
      IVROOF=1
C-----------------------------------------------------------------C
C     N--NEGATIVE                                                 C
C     P--POSITIVE                                                 C
C     S--STORAGE                                                  C
C     RR1-- DOUBLE POLYETHYLENE --  SCC OFF                       C
C     RR2-- SCC OFF                                               C
C     RR3-- SCC ON                                                C
C                                                                 C
C     RRO-- RESISTANCE FROM THE WATER FILM TO THE OUTSIDE WORLD   C
C                                                                 C
C-----------------------------------------------------------------C
C                                                                 C
C     MONTHLY ITERATIONS                                          C
C                                                                 C
C-----------------------------------------------------------------C
      DO 18 IMOIS=1,12
      READ(5,*)MOIS,M1,M2,XM3
      M3=M1+1
      M4=M2-1
      DO 10 I=M1,M2
      READ(5,*)SAL(I),SAZ(I),XIDN1(I),XID1(I)
CC    WRITE(6,119)I,SAL(I),SAZ(I)
      SAL(I)=SAL(I)*PI/180.0
      SAZ(I)=SAZ(I)*PI/180.0
      XIDN1(I)=XIDN1(I)*1000000.
      XID1(I)=XID1(I)*1000000.
   10 CONTINUE
      ARAD=387.0
      BRAD=0.149
      CRAD=0.063
      DTIME=1.0/6.0
```

```
C---------------------------------------------------------------------C
C   SIMULATING WITH DATA FROM OCTOBER 1983 TO SEPTEMBER 1984          C
C---------------------------------------------------------------------C
      MTEMP=MOIS+1
      DO 6 I=1,MTEMP
      READ(5,*)TOM(I),TOMI(I)
    6 CONTINUE
C---------------------------------------------------------------------C
C     COMPUTING THE TEMPERATURE FOR EVERY HOUR OF THE DAY ASSUMING A  C
C     MINIMUM TEMPERATURE AT 3:00 AND A MAXIMUM AT 12:00              C
C---------------------------------------------------------------------C
      TIME(1)=3.00
      DO 1 I=2,144
      TIME(I)=TIME(I-1)+DTIME
    1 CONTINUE
C---------------------------------------------------------------------C
C     SET INITIAL VALUE FOR THE TEMPERATURE                           C
C---------------------------------------------------------------------C
      TOMT=TOM(1)
      TOMIT=TOMI(1)
      ROA=21.8*PI/180 0
      WRITE(6,99)
C     WRITE(6,113)JO
C     WRITE(6,102)
      WRITE(6,108)XM3
C---------------------------------------------------------------------C
C     DAILY ITERATIONS                                                C
C---------------------------------------------------------------------C
      JOQCO=JOQ
      DO 9 JO=1,MOIS
      JOQ=JOQ+1
      TIMEX(JOQ)=JOQ
C     WRITE(6,103)TIMEX(JO),TOMT,TOMIT
      DO 2 I=1,55
      TT=FLOAT(I)
      TO(I)=TOMT-(1.-(TT-1.)/54.)*(TOMT-TOMIT)
    2 CONTINUE
      J=JO+1
      TOMIT=TOMI(J)
      DO 3 I=1,90
      TT=FLOAT(I)
      TO(I+55)=TOMT-(TT/90.)*(TOMT-TOMIT)
    3 CONTINUE
      TOMT=TOM(J)
C---------------------------------------------------------------------C
C     SIMULATING FOR DIFFERENT VALUES OF R ROOF IN ORDER TO FIND      C
C     THE OPTIMUM VALUE                                               C
C                                                                     C
C    IROOF=1  R=0.1761              H1                                C
C          2     0.2 * 0.1761       H5                                C
C          3     0.1 * 0.1761       H10                               C
C          4     0.0667 * 0.1761    H15                               C
C          5     0.05 * 0.1761      H20                               C
C       IVROOF  INFINI              H0                                C
C---------------------------------------------------------------------C
      DO 20 IROOF=3,3
      RR=(IROOF-1)*5.*5.9
```

```
      IF(IROOF EQ 1)RR=5 9
      IF(IROOF EQ 6)RR=0.0000000001
      RR=1 /RR
C-----------------------------------------------------------------------C
C     HOURLY ITERATIONS                                                 C
C-----------------------------------------------------------------------C
      DO 5 JJ=1,24
C-----------------------------------------------------------------------C
C     10-MINUTES ITERATIONS                                             C
C-----------------------------------------------------------------------C
C     Q1 --- HEAT TRANSFER FROM AND TO THE GREENHOUSE ENVIRONMENT       C
C     Q2 --- HEAT TRANSFER TO THE THERMAL MASS FROM OUTSIDE AND GREENH C
C                                                                       C
C      TESTING TO FIND OUT IF THE SOLAR INPUT IS GREATER THAN THE HEAT C
C      LOSS THROUGH THE ROOF AREA COMPARING THE 2 POSSIBLE DIFFERENT    C
C      SYSTEM, WITH AND WITHOUT SCC.                                    C
C-----------------------------------------------------------------------C
      DO 4 I=1,6
      IJ=(JJ-1)*6+I
      JJJ=(JJ+2)*100+I*10
      IF(JJ LT.M1)GOTO 200
      IF(JJ.GT.M2)GOTO 200
      T1=29.5
      TWI=29.5
      COSO=COS(SAL(JJ))*COS(SAZ(JJ))*SIN(ROA)+SIN(SAL(JJ))*COS(ROA)
      XIT=XIDN1(JJ)*COSO+XID1(JJ)
      IF(ISIT EQ.3)GOTO 236
      IF(ISIT.EQ 4)GOTO 236
      ISIT=2
      ABS1=ABSWO
      TRAN=TRANWO
      RRU=RR
      Q1=((AF/RF*(T2-T1))+(AWI/RWI*(TI-T1))+((AWO/RWO)*(TO(IJ)-T1))
     1+((AR/RRU)*(T2-T1))
     2+TRAN*XIT*A/3600.)*600.0
      Q2=((AF/RF*(T1-T2))+(AS/RS*(TS-T2))+ABS1*XIT*A/3600.
     1+((AR/RRU)*(T1-T2))+((AR/RRO)*(TO(IJ)-T2)))*600.
      GOTO 222
  236 ISIT=4
      ABS1=ABSOO
      TRAN=TRANOO
      Q1=((AF/RF*(T2-T1))+(AWI/RWI*(TWI-T1))+((AWO/RWO+AR/RRD)*(TO(IJ)-T
     11))+TRAN*XIT*A/3600.)*600.0
C-----------------------------------------------------------------------C
C     THE WATER IS NOT AFFECTED BY THE OUTSIDE TEMPERATURE              C
C     SINCE THE SCC SYSTEM IS NOT RUNNING.                              C
C-----------------------------------------------------------------------C
      Q2=((AF/RF*(T1-T2))+(AS/RS*(TS-T2)))*600.0
C-----------------------------------------------------------------------C
C      DETERMINE WETHER THERE IS A HEATING REQUIREMENT OR A COOLING     C
C      REQUIREMENT AND ADJUST THE SITUATION WITH RESPECT TO THE         C
C      THE REQUIREMENT, I.E. START OR STOP THE SCC SYSTEM.              C
C-----------------------------------------------------------------------C
  222 Q1T(IROOF)=Q1T(IROOF)+Q1/1000000000.
      Q2S(IROOF,JOQ)=Q2S(IROOF,JOQ)+Q2/1000000000.
      IF(Q1T(IROOF).GT.0.05)ISIT=2
      IF(Q1T(IROOF).LE.0.0)ISIT=4
```

```
      IF(ISIT.EQ 2)Q1PC(IROOF,JOQ)=Q1PC(IROOF,JOQ)+1/6
      GOTO 4
C-----------------------------------------------------------------------C
C     NO RADIATION DURING NIGHT-TIME                                    C
C-----------------------------------------------------------------------C
  200 XIT=0.0
      IF(TO(IJ).GE.12.8)GOTO 232
      T1=12.8
      TWI=12 8
      GOTO 233
  232 T1=TO(IJ)
      TWI=TO(IJ)
  233 IF(ISIT.EQ.2)GOTO 238
      IF(ISIT.EQ.1)GOTO 238
      ISIT=3
      ABS1=ABSOW
      TRAN=TRANOW
      Q1=((AF/RF*(T2-T1))+(AWI/RWI*(TWI-T1))+((AWO/RWO+AR/RRN)*(TO(IJ)-T
     11)))*600.0
C-----------------------------------------------------------------------C
C     THE WATER IS NOT AFFECTED BY THE OUTSIDE TEMPERATURE              C
C     SINCE THE SCC SYSTEM IS NOT RUNNING.                              C
C-----------------------------------------------------------------------C
      Q2=((AF/RF*(T1-T2))+(AS/RS*(TS-T2)))*600.0
      GOTO 239
  238 ISIT=1
      TRAN=TRANWW
      ABS1=ABSWW
      RRU=0.5*0.1761
      Q1=((AF/RF*(T2-T1))+(AWI/RWI*(TI-T1))+((AWO/RWO)*(TO(IJ)-T1))
     1+((AR/RRU)*(T2-T1))
     2+TRAN*XIT*A/3600.)*600.0
      Q2=((AF/RF*(T1-T2))+(AS/RS*(TS-T2))+ABS1*XIT*A/3600.
     1+((AR/RRU)*(T1-T2))+((AR/RRO1)*(TO(IJ)-T2)))*600.
  239 Q1T(IROOF)=Q1T(IROOF)+Q1/1000000000
      Q2S(IROOF,JOQ)=Q2S(IROOF,JOQ)+Q2/1000000000.
      IF(Q1T(IROOF).LT.-0 05)ISIT=1
      IF(Q1T(IROOF).GE.0.0)ISIT=3
      IF(ISIT.EQ.1)Q1PH(IROOF,JOQ)=Q1PH(IROOF,JOQ)+1/6.
    4 CONTINUE
C>    WRITE(6,130)JJ,ISIT,IROOF,Q1T(IROOF),Q1PC(IROOF,JOQ),
C>   1Q1PH(IROOF,JOQ)
C>130 FORMAT(2I6,3F12.7)
    5 CONTINUE
   20 CONTINUE
C~    IF(IRFI.EQ.1) GOTO 215
C~    IF(IRFI.EQ.2) GOTO 216
C~    IF(IRFI.EQ.3) GOTO 217
C~    WRITE(6,112)JJJ,TO(IJ),TI,TW,XIT
C~    GOTO 9
C~215 WRITE(6,109)JJJ,TO(IJ),TI,TW,XIT
C~    GOTO 9
C~216 WRITE(6,110)JOQ,JTITOT(1),(Q1N(IROOF,JOQ),Q1P(IROOF,JOQ),
C~   1IROOF=1,6)
C~    GOTO 9
C~217 WRITE(6,110)JOQ,JTITOT(1),(Q1N(IROOF,JOQ),Q1P(IROOF,JOQ),
C~   1IROOF=1,6)
```

```
C 202 WRITE(6,100)JJJ,I,TO(IJ),F,XIDN1,COSO,XID1,XIT,QRAD,QLOSS,QABS,TW
C 202 WRITE(6,104)JJJ,I,TO(IJ),TI,TW,XIT,IRFI,N,TIMEX(N),XP(N,1),XP(N,2)
C    1,XP(N,3)
    9 CONTINUE
      DO 23 IRO=3,3
      DO 27 IRRO=JOQCO,JOQ
      Q1PC(IRO,IRRO)=Q1PC(IRO,IRRO)*3600.*0.0152*9800.*6./500000000.
      Q1PH(IRO,IRRO)=Q1PH(IRO,IRRO)*3600 *0.0152*9800.*6./500000000.
      Q2ST(IRO)=Q2ST(IRO)+Q2S(IRO,IRRO)
      SCCTCP(IRO)=SCCTCP(IRO)+Q1PC(IRO,IRRO)
      SCCTHP(IRO)=SCCTHP(IRO)+Q1PH(IRO,IRRO)
      SCCTC(IRO)=SCCTC(IRO)+Q1PC(IRO,IRRO)
      SCCTH(IRO)=SCCTH(IRO)+Q1PH(IRO,IRRO)
      Q1PH(IRO,IRRO)=Q1PH(IRO,IRRO)*(-1.0)
   27 CONTINUE
      DO 25 IROOF=3,3
      Q2STP(IROOF)=Q2ST(IROOF)-Q2STP(IROOF)
   25 CONTINUE
      WRITE(6,122)IRO
  228 WRITE(6,120)Q2STP(IRO),SCCTHP(IRO),SCCTCP(IRO)
   23 CONTINUE
      DO 22 IROOF=3,3
      SCCTCP(IROOF)=0.0
      SCCTHP(IROOF)=0 0
      Q2STP(IROOF)=Q2ST(IROOF)
   22 CONTINUE
   18 CONTINUE
      DO 24 IRO=3,3
      WRITE(6,122)IRO
      WRITE(6,121)Q2ST(IRO),SCCTH(IRO),SCCTC(IRO)
   24 CONTINUE
      WRITE(6,123)(Q1T(IROOF),IROOF=3,3)
C-----------------------------------------------------------------------C
C     SUBROUTINE TO PLOT                                                C
C-----------------------------------------------------------------------C
      CALL PLOTM(IVROOF, JOQ,TIMEX,Q1PC,Q1PH,XPMIN,XPMAX,
     1YPMIN,YPMAX)
C-----------------------------------------------------------------------C
      WRITE(6,99)
C-----------------------------------------------------------------------C
C     FORMAT SECTION                                                    C
C-----------------------------------------------------------------------C
   99 FORMAT(1H1)
  100 FORMAT(4X,I4,2X,I2,7F10.2,2F12.2,F10.2)
c 101 FORMAT(' ',2F5.1)
  102 FORMAT(//,4X,'JJJ',3X,' I',6X,'TO',9X,'F',7X,'XIDN',6X,'COSO',7X,
     1'XID',7X,'XIT',6X,'QRAD',6X,'QLOSS',7X,'QABS',7X,'TW',//)
  103 FORMAT(//,' DAY : ',F5.1,/,'  TOMT = ',F15.5,10X,'TOMIT = ',
     1F15.5,/)
  104 FORMAT(4X,I4,2X,I2,4F10.2,6X,I3,8X,I3,4X,4F10.2)
  106 FORMAT(2F15.5)
  107 FORMAT('  ',F6.3,' ',F6.3,' ',F6.3,'  ',F6.3)
  108 FORMAT(//,' MONTH ',F7.4,//)
C 108 FORMAT(//,' MONTH ',F7.4,//,1X,'DAY',15X,'Q1N1',6X,'Q1P1',6X,
C    1'Q1N2',6X,'Q1P2',6X,'Q1N3',6X,'Q1P3',6X,'Q1N4',6X,'Q1P4',6X,'Q1N5'
C    2,6X,'Q1P5',6X,'Q1N6',6X,'Q1P6',///)
  109 FORMAT(4X,I4,4X,4F10.2,6X,'ON',7X,'ON')
```

```
  110 FORMAT(' ',I3,1X,I4,4X,12F10.5)
  111 FORMAT(' ',I3,1X,I4,4X,4F10 2,6X,'OFF',6X,'ON',7X,5F11 5)
  112 FORMAT(4X,I4,4X,4F10 2,6X,'OFF',6X,'OFF')
  113 FORMAT(//,' DAY : ',I4)
  117 FORMAT(4F15.5)
c 118 FORMAT(' ',3I2,' ',F7 4)
  119 FORMAT(' ',I2,' ',F6 3,' ',F6.3)
  120 FORMAT(/,' THE ABSORPTION CAPACITY OF THE WATER IS : ',F12 5,
     1' GEGAJOULES',/,' THE TOTAL TIME SCC IS RUNNING IS :',F6 3,
     2' GEGAJOULES FOR HEATING AND ',/,F6 3,' GEGAJOULES FOR COOLING')
  121 FORMAT(//,' THE TOTAL ABSORPTION CAPACITY OF THE WATER IS : ',
     1F12.5,' GEGAJOULES',/,' THE TOTAL TIME SCC IS RUNNING IS : ',F6 3,
     2' GEGAJOULES FOR HEATING AND ',/,F6.3,' GEGAJOULES FOR COOLING')
  122 FORMAT(//,' FOR CASE ',I2)
  123 FORMAT(/,' THE FINAL HEAT OR COOLING REQUIREMENT AT THE END OF ONE
     1 YEAR IS :',F12.6,/)
      STOP
      END
```

APPENDIX B

Raw and treated data.

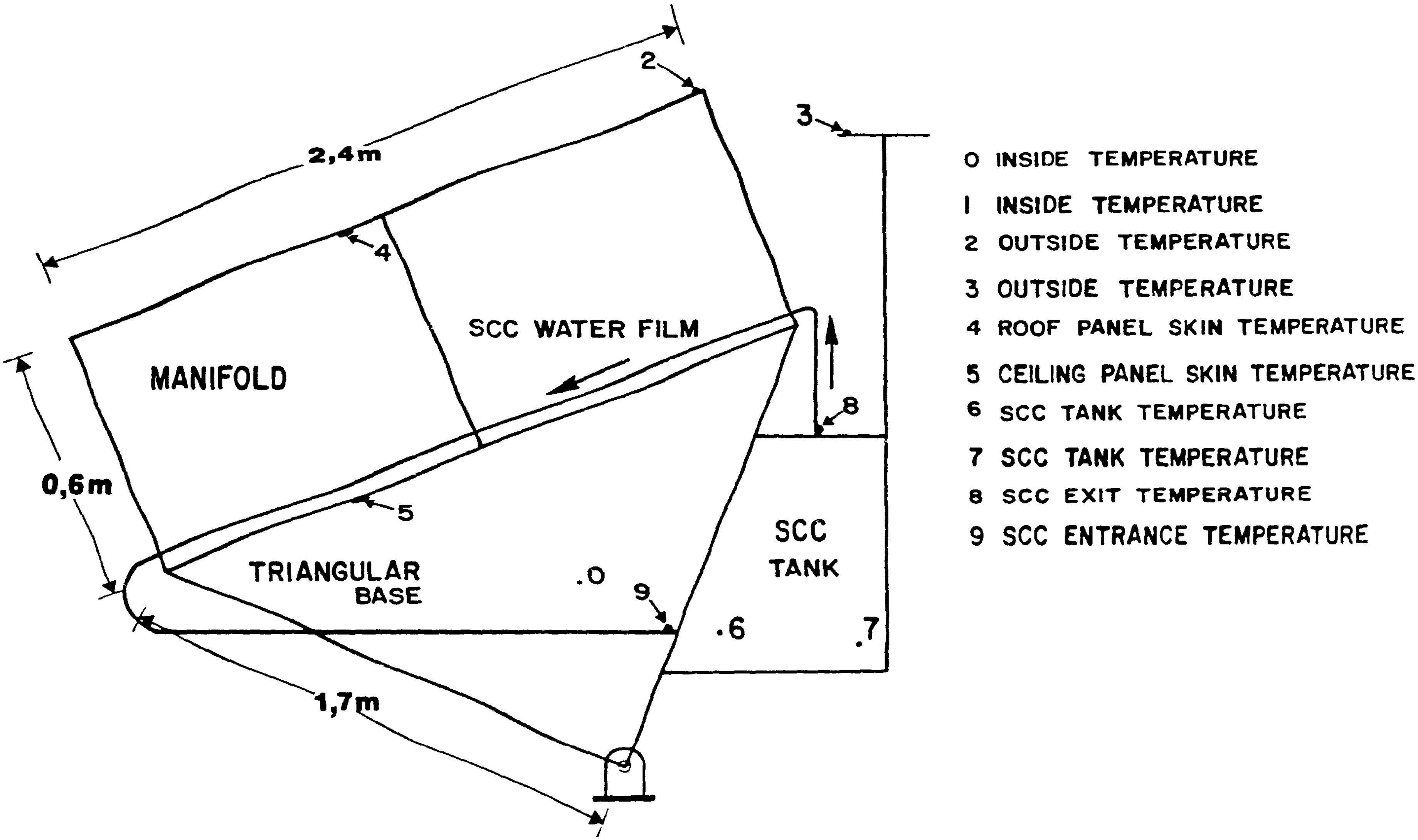

Figure B.1 Schematic description of the location of the sensors on the prototype

Time (day)	Inside temp C	C	Ti mean C	Qair KJ	Outside temp C	C	To. mean C
Sensor #	0	1			2	3	
Formula			(T0 + T1) / 2	m cp dT			(T2 + T3) / 2
0.17		77.39	75.18		29.38	25.46	27.42
0.21	70.16	89.95	80.05	43.70	30.54	25.50	28.02
0.25	73.58	94.33	83.96	35.00	31.45	27.13	29.29
0.29	69.93	89.66	79.79	-37.35	29.78	25.85	27.82
0.33	59.76	76.61	68.19	-104.13	27.58	25.05	26.32
0.38	50.83	65.16	58.00	-91.41	29.54	27.16	28.35
0.42	47.64	61.08	54.36	-32.62	28.75	27.00	27.88
0.46	40.11	51.43	45.77	-77.08	28.49	27.02	27.75
0.50	35.07	44.96	40.01	-51.62	27.46	27.39	27.43
0.54	30.61	39.24	34.93	-45.66	25.33	25.43	25.38
0.58	26.13	33.50	29.82	-45.85	23.92	24.00	23.96
0.62	22.25	28.53	25.39	-39.70	21.88	22.18	22.03
0.67	19.33	24.78	22.06	-29.92	20.34	21.00	20.67
0.71	17.95	23.01	20.48	-14.13	19.08	19.42	19.25
0.75	16.74	21.46	19.10	-12.38	18.52	18.85	18.69
0.79	15.36	19.69	17.53	-14.13	17.06	17.27	17.17
0.83	13.94	17.88	15.91	-14.51	15.81	16.81	16.31
0.87	14.14	18.12	16.13	2.01	19.20	19.84	19.52
0.92	14.42	18.49	16.45	2.90	18.39	18.83	18.61
0.96	14.17	18.17	16.17	-2.57	17.64	18.10	17.87
1.00	14.32	18.35	16.34	1.52	18.03	18.31	18.17
1.04	19.56	25.08	22.32	53.68	18.86	18.64	18.75
1.08	28.98	37.15	33.07	96.41	21.13	19.25	20.19
1.12	41.98	44.56	43.27	91.54	29.98	27.01	28.50
1.17	41.89	41.56	41.72	-13.88	29.92	25.19	27.55
1.21	45.63	42.36	44.00	20.42	32.60	25.68	29.14
1.25	53.51	50.63	52.07	72.41	38.22	30.68	34.45
1.29	45.41	43.28	44.34	-69.31	32.44	26.23	29.33
1.33	49.87	46.41	48.14	34.06	35.62	28.13	31.88
1.38	41.02	41.23	41.13	-62.93	29.30	24.99	27.15
1.42	41.75	43.13	42.44	11.78	29.82	26.14	27.98
1.46	39.79	43.43	41.61	-7.46	28.42	26.32	27.37
1.50	33.77	37.36	35.56	-54.24	24.12	22.64	23.38
1.54	31.07	35.99	33.53	-18.26	22.19	21.81	22.00
1.58	28.78	33.73	31.26	-20.38	20.56	20.44	20.50
1.63	25.33	30.69	28.01	-29.13	18.09	18.60	18.35
1.67	25.84	31.15	28.50	4.40	18.46	18.88	18.67
1.71	23.80	29.73	26.77	-15.53	17.00	18.02	17.51
1.75	20.80	25.00	22.90	-34.68	14.86	15.15	15.01
1.79	16.98	20.31	18.65	-38.16	12.13	12.31	12.22
1.83	16.24	19.78	18.01	-5.70	11.60	11.99	11.80
1.88	16.93	20.10	18.51	4.48	12.09	12.18	12.14
1.92	16.77	19.60	18.19	-2.91	11.98	11.88	11.93
1.96	16.88	19.90	18.39	1.83	12.06	12.06	12.06
2.00	16.74	19.68	18.21	-1.59	11.96	11.93	11.95

	Inside temp. C	C	Ti. mean C	Qair KJ	Outside temp. C	C	To. mean C
Sensor #	0	1			2	3	
Formula			$\frac{(T0 + T1)}{2}$	m cp dT			$\frac{(T2 + T3)}{2}$
Time (day)							
2.04	17.08	20.20	18.64	3.80	12.20	12.24	12.22
2.08	18.02	20.99	19 50	7.76	12.87	12.72	12.80
2.13	17.39	20.05	18.72	-7.04	12.42	12.15	12.29
2.17	18.56	21.19	19.88	10.38	13 26	12.84	13.05
2.21	21.21	25.82	23.52	32.67	15.15	15.65	15.40
2.25	27.93	26 20	27.07	31 85	19.95	15.88	17.92
2.29	30.46	29.60	30.03	26.61	21.76	17.94	19.85
2.33	35.07	30.84	32 95	26.21	25.05	18.69	21.87
2.38	37.98	34.82	36.40	30.90	27.13	21.10	24.12
2.42	33.68	32.69	33.19	-28.83	24.06	19.81	21.94
2.46	35.11	34.15	34.63	12 99	25.08	20.70	22.89
2.50	30.21	34.77	32.49	-19.24	21.58	21.07	21.33
2.54	24.84	31.10	27.97	-40.55	17.74	18.85	18.30
2.58	21.71	25.29	23.50	-40.06	15 51	15.33	15.42
2.62	17.84	21.58	19.71	-34.05	12.74	13.08	12.91
2.67	17.79	21.50	19.65	-0.56	12.71	13.03	12.87
2.71	15.68	19.30	17.49	-19.33	11.20	11.70	11.45
2.75	15.48	19.62	17.55	0.53	11.06	11.89	11.48
2.79	13.94	18.36	16.15	-12.53	9.96	11.13	10.55
2.83	15 44	18.43	16.94	7.02	11.03	11.17	11.10
2.87	16.07	19.16	17.61	6.08	11.48	11.61	11.55
2.92	14.22	17.19	15.71	-17.10	10 16	10.42	10.29
2.96	15.04	17.99	16.51	7.20	10.74	10.90	10.82
3.00	15.93	19.34	17.64	10.09	11.38	11.72	11.55
3.04	17.51	20.72	19.12	13.31	12.51	12.56	12.54
3.08	17.16	20.20	18.68	-3.94	12 26	12.24	12.25
3.12	16.28	19.24	17.76	-8.25	11.63	11.66	11.65
3.17	15.02	17.89	16.45	-11.72	10.73	10.84	10.79
3.21	18.03	21.30	19.67	28.82	12.88	12.91	12.90
3.25	15.48	31.25	23.37	33.20	11.06	18.94	15.00
3.29	16.90	20.49	18.70	-41.91	12.07	12.42	12.25
3.33	17.36	19.92	18.64	-0.52	12.40	12.07	12.24
3.37	14.11	16.52	15.31	-29.82	10.08	10.01	10.05
3.42	13.73	15.71	14.72	-5.32	9.81	9.52	9.67
3.46	12.74	15.02	13.88	-7.57	9.10	9.10	9.10
3.50	12.56	16.02	14.29	3.70	8.97	9.71	9.34
3.54	13.13	16.17	14.65	3.24	9.38	9.80	9.59
3.58	14.39	16.95	15.67	9.13	10.28	10.27	10.28
3.62	13.45	15.69	14.57	-9.83	9.61	9.51	9.56
3.67	20.71	20.86	20.78	55.70	14.79	12.64	13.72
3.71	25.10	25.34	25.22	39.85	17.93	15.36	16.65
3.75	21.84	22.24	22.04	-28.55	15.60	13.48	14.54
3.79	18.02	20.34	19.18	-25.66	12.87	12.33	12.60
3.83	17.01	22.03	19.52	3.03	12.15	13.35	12.75
3.87	15.29	20.01	17.65	-16.75	10.92	12.13	11.53

	Inside temp. C	C	Ti. mean C	Qair KJ	Outside temp C	C	To mean C
Sensor #	0	1			2	3	
Formula			(T0 + T1) / 2	m cp dT			(T2 + T3) / 2
Time (day)							
3.92	12.00	15.15	13.57	-36.59	8.57	9.18	8.88
3.96	10.14	13.51	11.82	-15.68	7.24	8.19	7.72
4.00	8.79	11.85	10.32	-13.50	6.28	7.18	6.73
4.04	5.19	6.75	5.97	-39.01	3.71	4.09	3.90
4.08	4.38	5.56	4.97	-8.97	3.13	3.37	3.25
4.12	3.71	4.16	3.93	-9.31	2.65	2.52	2.59
4.17	3.53	5.69	4.61	6.07	2.52	3.45	2.99
4.21	19.15	16.40	17.78	118.12	13.68	9.94	11.81
4.25	23.25	18.30	20.78	26.91	16.61	11.09	13.85
4.29	28.81	20.77	24.79	36.03	20.58	12.59	16.59
4.33	32.00	23.69	27.85	27.42	22.86	14.36	18.61
4.37	31.14	26.86	29.00	10.32	22.24	16.28	19.26
4.42	34.86	27.14	31.00	17.96	24.90	16.45	20.68
4.46	31.54	29.01	30.27	-6.52	22.53	17.58	20.06
4.50	30.52	28.99	29.76	-4.66	21.80	17.57	19.69
4.54	34.43	32.59	33.51	33.66	24.59	19.75	22.17
4.58	31.71	34.14	32.92	-5.23	22.65	20.69	21.67
4.62	29.08	33.23	31.15	-15.88	20.77	20.14	20.46
4.67	24.63	29.17	26.90	-38.18	17.59	17.68	17.64
4.71	22.93	26.86	24.90	-17.96	16.38	16.28	16.33
4.75	20.83	25.23	23.03	-16.75	14.88	15.29	15.09
4.79	16.80	21.30	19.05	-35.70	12.00	12.91	12.46
4.83	14.87	18.93	16.90	-19.32	10.62	11.47	11.05
4.88	13.08	16.69	14.88	-18.08	9.34	10.11	9.73
4.92	10.33	14.31	12.32	-22.99	7.38	8.67	8.03
4.96	9.74	13.15	11.45	-7.82	6.96	7.97	7.47
5.00	8.68	13.33	11.01	-3.96	6.20	8.08	7.14
5.04	8.22	12.11	10.16	-7.55	5.87	7.34	6.61
5.08	10.42	13.37	11.89	15.48	7.44	8.10	7.77
5.13	12.46	15.94	14.20	20.71	8.90	9.66	9.28
5.17	16.62	19.93	18.28	36.56	11.87	12.08	11.98
5.21	17.08	25.56	21.32	27.31	12.20	15.49	13.85
5.25	29.32	30.95	30.14	79.09	20.94	18.76	19.85
5.29	38.11	35.90	37.01	61.64	27.22	21.76	24.49
5.33	35.90	35.85	35.88	-10.14	25.64	21.73	23.69
5.38	36.43	35.33	35.88	0.02	26.02	21.41	23.72
5.42	41.75	40.29	41.02	46.14	29.82	24.42	27.12
5.46	40.32	40.54	40.43	-5.30	28.80	24.57	26.69
5.50	37.42	39.48	38.45	-17.74	26.73	23.93	25.33
5.54	36.40	39.52	37.96	-4.44	26.00	23.95	24.98
5.58	34.10	38.20	36.15	-16.22	24.36	23.15	23.76
5.63	31.28	35.41	33.34	-25.19	22.34	21.46	21.90
5.67	31.57	38.49	35.03	15.16	22.55	23.33	22.94
5.71	29.71	35.31	32.51	-22.64	21.22	21.40	21.31
5.75	30.14	35.99	33.06	4.98	21.53	21.81	21.67

	Inside temp		Ti mean	Qair	Outside temp		To. mean
	C	C	C	KJ	C	C	C
Sensor #	0	1			2	3	
Formula			(T0 + T1) / 2	m cp dT			(T2 + T3) / 2
Time (day)							
5.79	26.81	31.60	29.20	-34.63	19.15	19.15	19.15
5.83	25.12	29 70	27.41	-16 11	17.94	18.00	17.97
5.88	23.52	27.72	25.62	-16.04	16.80	16.80	16.80
5.92	21.71	25.51	23.61	-18.02	15.51	15.46	15 49
5.96	21.78	25.92	23.85	2.16	15.56	15.71	15.64
6.00	21.80	26.07	23.93	0.73	15.57	15.80	15.69
6.04	20.30	24.22	22.26	-15.01	14.50	14.68	14.59
6.08	19.88	23.73	21.80	-4.10	14.20	14.38	14.29
6.13	20.16	24 06	22.11	2.74	14.40	14.58	14.49
6.17	21.18	25.10	23.14	9.25	15.13	15.21	15.17
6.21	21.04	24.77	22.90	-2.11	15.03	15.01	15.02
6.25	20.61	24.01	22.31	-5.35	14.72	14.55	14.64
6.29	18.94	21.95	20.44	-16.72	13.53	13.30	13.42
6.33	19.74	23.07	21.40	8.61	14.10	13.98	14.04
6.38	19.24	22.94	21.09	-2.85	13.74	13.90	13.82
6.42	18.96	22.31	20.63	-4.07	13.54	13.52	13.53
6.46	25.38	28.83	27.10	58.06	18.13	17.47	17.80
6.50	32.94	33.15	33.05	53.30	23.53	20.09	21.81
6.54	29.04	30.62	29.83	-28.85	20.74	18.56	19.65
6.58	28.57	29.17	28.87	-8.59	20.41	17.68	19.05
6.63	27.08	29.30	28.19	-6.13	19.34	17.76	18.55
6.67	25.44	29.22	27.33	-7.72	18.17	17.71	17.94
6.71	21.31	25.46	23.38	-35.40	15.22	15.43	15.33
6 75	17.85	21.47	19.66	-33.42	12.75	13.01	12.88
6.79	15.45	20.06	17.76	-17.04	11.04	12.16	11.60
6.83	12 80	16.34	14 57	-28.65	9 14	9.90	9.52
6.88	13.13	16.85	14.99	3.80	9.38	10.21	9.80
6.92	9.38	13.98	11.68	-29.71	6.70	8.47	7.59
6.96	8.86	10.15	9.50	-19.49	6.33	6.15	6.24
7.00	11.00	13.12	12.06	22.93	7.86	7.95	7.91
7.04	8.43	11.76	10.10	-17.62	6.02	7.13	6.58
7.08	11.35	13.07	12.21	18.97	8.11	7.92	8.02
7.13	11.84	14.14	12.99	7.01	8.46	8.57	8.52
7.17	17.89	22.09	19.99	62.80	12.78	13.39	13.09
7.21	21.34	24.93	23.13	28.18	15.24	15.11	15.18
7.25	26.10	29.29	27.69	40.89	18.64	17.75	18.20
7.29	27.34	30.79	29.07	12.32	19.53	18.66	19.10
7.33	30.52	33.51	32.02	26.47	21.80	20.31	21.06
7.38	29.81	35.01	32.41	3.53	21.29	21.22	21.26
7.42	33.71	39.32	36.52	36.84	24.08	23.83	23.96
7.46	39.20	44.55	41.88	48.08	28.00	27.00	27.50
7.50	32.45	44.98	38.72	-28.35	23.18	27.26	25.22
7.54	34.10	42.31	38.21	-4.58	24.36	25.64	25.00
7.58	32.31	41.20	36.76	-13.00	23.08	24.97	24.03
7.63	28.50	37.36	32.93	-34.33	20.36	22.64	21.50

	Inside temp. C	C	Ti mean C	Qair KJ	Outside temp C	C	To mean C
Sensor #	0	1			2	3	
Formula			(T0 + T1) / 2	m cp dT			(T2 + T3) / 2
Time (day)							
7.67	24.18	29.01	26.59	-56.86	17.27	17.58	17.43
7.71	22.16	25.94	24.05	-22.81	15.83	15.72	15.78
7.75	20.83	24.39	22.61	-12.92	14.88	14.78	14.83
7.79	21.73	25.66	23.69	9.72	15.52	15.55	15.54
7.83	21.28	24.93	23.11	-5.27	15.20	15.11	15.16
7.88	21.32	25.34	23.33	2.05	15.23	15.36	15.30
7.92	21.36	25.20	23.28	-0.49	15.26	15.27	15.27
7.96	19.61	23.08	21.35	-17.32	14.01	13.99	14.00
8.00	18.28	21.37	19.83	-13.66	13.06	12.95	13.01
8.04	16.41	19.39	17.90	-17.30	11.72	11.75	11.74
8.08	16.45	19.68	18.07	1.52	11.75	11.93	11.84
8.13	21.21	26.19	23.70	50.51	15.15	15.87	15.51
8.17	24.86	29.63	27.25	31.86	17.76	17.96	17.86
8.21	28.38	33.94	31.16	35.08	20.27	20.57	20.42
8.25	36.40	39.60	38.00	61.37	26.00	24.00	25.00
8.29	40.50	44.63	42.57	40.97	28.93	27.05	27.99
8.33	40.11	43.85	41.98	-5.24	28.65	26.58	27.62
8.38	38.47	44.83	41.65	-2.98	27.48	27.17	27.33
8.42	35.35	40.84	38.09	-31.92	25.25	24.75	25.00
8.46	33.63	39.09	36.36	-15.57	24.02	23.69	23.86
8.50	26.53	31.12	28.82	-67.59	18.95	18.86	18.91
8.54	26.95	32.08	29.51	6.18	19.25	19.44	19.35
8.58	26.77	31.23	29.00	-4.59	19.12	18.93	19.03
8.63	26.01	30.46	28.24	-6.87	18.58	18.46	18.52
8.67	25.75	30.36	28.05	-1.64	18.39	18.40	18.40
8.71	25.55	30.01	27.78	-2.43	18.25	18.19	18.22
8.75	25.77	30.46	28.12	3.00	18.41	18.46	18.44
8.79	25.23	30.01	27.62	-4.45	18.02	18.19	18.11
8.83	25.44	30.53	27.98	3.24	18.17	18.50	18.34
8.88	27.99	33.45	30.72	24.53	19.99	20.27	20.13
8.92	28.95	34.63	31.79	9.66	20.68	20.99	20.84
8.96	29.15	34.95	32.05	2.29	20.82	21.18	21.00
9.00	29.72	35.03	32.38	2.94	21.23	21.23	21.23
9.04	28.56	33.59	31.08	-11.65	20.40	20.36	20.38
9.08	28.92	33.81	31.37	2.59	20.66	20.49	20.58
9.13	29.78	34.80	32.29	8.27	21.27	21.09	21.18
9.17	33.17	37.39	35.28	26.82	23.69	22.66	23.18
9.21	41.29	42.19	41.74	57.96	29.49	25.57	27.53
9.25	39.30	41.53	40.41	-11.88	28.07	25.17	26.62
9.29	45.95	45.05	45.50	45.59	32.82	27.30	30.06
9.33	43.65	46.28	44.97	-4.75	31.18	28.05	29.62
9.38	41.19	45.80	43.50	-13.20	29.42	27.76	28.59
9.42	36.64	46.02	41.33	-19.45	26.17	27.89	27.03
9.46	39.10	45.75	42.43	9.87	27.93	27.73	27.83
9.50	36.97	44.53	40.75	-15.02	26.41	26.99	26.70

	Inside temp		Ti. mean	Qair	Outside temp.		To. mean
	C	C	C	KJ	C	C	C
Sensor #	0	1			2	3	
Formula			(T0 + T1) / 2	m cp dT			(T2 + T3) / 2
Time (day)							
9.54	34.12	42.36	38.24	-22.58	24.37	25.67	25.02
9.58	31.25	37.62	34.43	-34.12	22.32	22.80	22.56
9.62	29.57	35.62	32.60	-16.49	21.12	21.59	21.36
9.67	27.65	33.26	30.46	-19.19	19.75	20.16	19.96
9.71	26.78	32.65	29.72	-6.63	19.13	19.79	19.46
9.75	21.48	25.94	23.71	-53.92	15.34	15.72	15.53
9.79	18.02	22.04	20.03	-32.98	12.87	13.36	13.12
9.83	15.65	19.19	17.42	-23.42	11.18	11.63	11.41
9.87	15.18	18.98	17.08	-3.10	10.84	11.50	11.17
9.92	13.99	17.13	15.56	-13.63	9.99	10.38	10.19
9.96	13.33	16.80	15.06	-4.43	9.52	10.18	9.85
10.00	14.31	17.51	15.91	7.58	10.22	10.61	10.42
10.04	19.21	22.09	20.65	42.56	13.72	13.39	13.56
10.08	23.14	24.52	23.83	28.53	16.53	14.86	15.70
10.12	28.39	29.01	28.70	43.68	20.28	17.58	18.93
10.17	33.01	31.81	32.41	33.31	23.58	19.28	21.43
10.21	33.91	33.17	33.54	10.09	24.22	20.10	22.16
10.25	35.35	34.58	34.97	12.83	25.25	20.96	23.11
10.29	34.27	34.98	34.63	-3.06	24.48	21.20	22.84
10.33	36.81	38.45	37.63	26.91	26.29	23.30	24.80
10.37	38.28	57.68	47.98	92.89	27.34	34.96	31.15
10.42	36.11	40.10	38.10	-88.63	25.79	24.30	25.05
10.46	33.56	39.65	36.60	-13.43	23.97	24.03	24.00
10.50	32.72	39.60	36.16	-3.99	23.37	24.00	23.69
10.54	30.17	38.59	34.38	-15.94	21.55	23.39	22.47
10.58	24.74	29.55	27.14	-64.93	17.67	17.91	17.79
10.62	42.64	48.44	45.54	165.07	30.46	29.36	29.91
10.67	40.60	46.71	43.66	-16.94	29.00	28.31	28.66
10.71	36.16	43.20	39.68	-35.67	25.83	26.18	26.01
10.75	26.10	30.86	28.48	-100.52	18.64	18.70	18.67
10.79	25.98	30.29	28.14	-3.02	18.56	18.36	18.46
10.83	26.26	31.42	28.84	6.29	18.76	19.04	18.90
10.87	27.03	32.21	29.62	7.01	19.31	19.52	19.42
10.92	20.30	24.06	22.18	-66.77	14.50	14.58	14.54
10.96	18.10	21.71	19.91	-20.37	12.93	13.16	13.05
11.00	15.60	19.11	17.35	-22.94	11.14	11.58	11.36
11.04	14.53	17.75	16.14	-10.84	10.38	10.76	10.57
11.08	12.66	15.61	14.13	-18.04	9.04	9.46	9.25
11.12	11.24	13.98	12.61	-13.66	8.03	8.47	8.25
11.17	12.42	15.16	13.79	10.59	8.87	9.19	9.03
11.21	11.30	13.76	12.53	-11.32	8.07	8.34	8.21
11.25	12.98	13.83	13.40	7.83	9.27	8.38	8.83
11.29	16.16	17.06	16.61	28.76	11.54	10.34	10.94
11.33	17.70	17.37	17.54	8.31	12.64	10.53	11.59
11.37	14.90	15.84	15.37	-19.44	10.64	9.60	10.12

	Inside temp		Ti mean	Qair	Outside temp		To mean
	C	C	C	KJ	C	C	C
Sensor #	0	1			2	3	
Formula			(T0 + T1) / 2	m cp dT			(T2 + T3) / 2
Time (day)							
11.42	20.82	20.53	20.67	47.58	14.87	12.44	13.66
11.46	23.55	23.63	23.59	26.16	16.82	14.32	15.57
11.50	25.28	23.66	24.47	7.94	18.06	14.34	16.20
11.54	27.94	27.80	27.87	30.51	19.96	16.85	18.41
11.58	23.35	24.85	24.10	-33.85	16.68	15.06	15.87
11.62	24.75	27.75	26.25	19.31	17.68	16.82	17.25
11.67	23.35	26.12	24.74	-13.61	16.68	15.83	16.26
11.71	24.04	28.97	26.51	15.88	17.17	17.56	17.37
11.75	21.01	25.33	23.17	-29.92	15.01	15.35	15.18
11.79	19.01	23.03	21.02	-19.27	13.58	13.96	13.77
11.83	16.91	20.84	18.88	-19.26	12.08	12.63	12.36
11.87	16.59	20.38	18.48	-3.52	11.85	12.35	12.10
11.92	16.81	20.16	18.49	0.04	12.01	12.22	12.12
11.96	15.60	19.01	17.30	-10.64	11.14	11.52	11.33
12.00	14.66	17.82	16.24	-9.54	10.47	10.80	10.64
12.04	13.33	16.40	14.86	-12.33	9.52	9.94	9.73
12.08	13.01	16.65	14.83	-0.33	9.29	10.09	9.69
12.12	12.00	15.66	13.83	-8.96	8.57	9.49	9.03
12.17	10.99	14.42	12.71	-10.07	7.85	8.74	8.30
12.21	11.73	14.65	13.19	4.36	8.38	8.88	8.63
12.25	13.22	16.10	14.66	13.17	9.44	9.76	9.60
12.29	21.92	23.23	22.58	71.04	15.66	14.08	14.87
12.33	27.06	24.65	25.86	29.41	19.33	14.94	17.14
12.37	31.02	29.16	30.09	37.98	22.16	17.67	19.92
12.42	32.45	29.42	30.94	7.59	23.18	17.83	20.51
12.46	27.52	29.65	28.59	-21.07	19.66	17.97	18.82
12.50	33.54	32.77	33.16	40.99	23.96	19.86	21.91
12.54	28.64	31.14	29.89	-29.31	20.46	18.87	19.67
12.58	30.45	33.51	31.98	18.76	21.75	20.31	21.03
12.62	34.31	36.40	35.36	30.29	24.51	22.06	23.29
12.67	32.12	36.07	34.09	-11.34	22.94	21.86	22.40
12.71	30.72	35.01	32.86	-11.02	21.94	21.22	21.58
12.75	27.45	35.24	31.35	-13.60	19.61	21.36	20.49
12.79	25.66	32.47	29.07	-20.47	18.33	19.68	19.01
12.83	20.73	25.48	23.11	-53.49	14.81	15.44	15.13
12.87	19.92	24.29	22.11	-8.97	14.23	14.72	14.48
12.92	19.94	24.11	22.02	-0.75	14.24	14.61	14.43
12.96	19.03	23.50	21.26	-6.82	13.59	14.24	13.92
13.00	18.62	22.59	20.60	-5.89	13.30	13.69	13.50
13.04	19.10	23.18	21.14	4.80	13.64	14.05	13.85
13.08	17.11	20.87	18.99	-19.28	12.22	12.65	12.44
13.12	17.36	21.96	19.66	6.02	12.40	13.31	12.86
13.17	15.37	19.42	17.40	-20.32	10.98	11.77	11.38
13.21	15.46	19.26	17.36	-0.36	11.04	11.67	11.36
13.25	17.04	20.64	18.84	13.31	12.17	12.51	12.34

	Inside temp		Ti. mean	Qair	Outside temp		To mean
	C	C	C	KJ	C	C	C
Sensor #	0	1			2	3	
Formula			(T0 + T1) / 2	m cp dT			(T2 + T3) / 2
Time (day)							
13 29	28.66	28.30	28.48	86.47	20.47	17.15	18.81
13 33	28 88	28.22	28.55	0.63	20 63	17.10	18 87
13.37	34.90	30.62	32 76	37.81	24.93	18.56	21.75
13.42	38.32	34.06	36.19	30.72	27 37	20.64	24.01
13.46	39.66	35.64	37.65	13.13	28.33	21.60	24.97
13.50	39 66	35.72	37.69	0.37	28 33	21.65	24.99
13.54	45.86	27.19	36.53	-10.44	32.76	16.48	24.62
13.58	47.47	46.30	46.89	92.93	33.91	28.06	30.99
13.62	41.01	41.27	41.14	-51.59	29.29	25.01	27.15
13 67	40.52	43.03	41.77	5.72	28.94	26.08	27.51
13.71	38.57	43.74	41.16	-5.55	27.55	26 51	27.03
13.75	34.41	41.55	37.98	-28.50	24.58	25.18	24.88
13.79	29.65	33.63	31.64	-56.88	21.18	20 38	20.78
13.83	25 56	29.29	27.43	-37.80	18.26	17.75	18.01
13.87	22.23	27.37	24.80	-23.53	15.88	16.59	16.24
13.92	23.60	28.64	26.12	11.85	16.86	17.36	17.11
13.96	23.88	29.09	26.49	3.25	17.06	17.63	17.35
14.00	21.01	24.98	23.00	-31.30	15.01	15.14	15.08
14.04	20.99	25.29	23.14	1.28	14.99	15.33	15.16
14.08	19.25	23.58	21.41	-15.48	13.75	14.29	14.02
14.12	19.26	23.25	21.26	-1.42	13.76	14.09	13.93
14.17	18.80	22.37	20.59	-6.00	13.43	13.56	13.50
14.21	17.18	21.02	19.10	-13.35	12.27	12.74	12.51
14.25	19.96	23.69	21.83	24.49	14.26	14.36	14.31
14.29	28.71	32.85	30.78	80.33	20.51	19.91	20.21
14.33	31.72	35.89	33.81	27.12	22.66	21.75	22.21
14.37	32.16	38.07	35.11	11.72	22.97	23.07	23.02
14.42	31.04	37.03	34.03	-9 69	22.17	22.44	22.31
14.46	35.84	41.58	38.71	41.97	25.60	25.20	25.40
14.50	38.54	42.44	40.49	15.97	27.53	25.72	26.63
14.54	44.60	40.94	42.77	20.46	31.86	24.81	28.34
14.58	49.53	43.61	46.57	34.10	35.38	26.43	30.91
14.62	42.87	53.56	48.21	14.74	30.62	32.46	31.54
14.67	46.21	46.04	46.12	-18.74	33.01	27.90	30.46
14.71	39.66	44.52	42.09	-36.20	28.33	26.98	27.66
14.75	32.37	44.15	38.26	-34.35	23.12	26.76	24.94
14.79	28.76	37.16	32.96	-47.58	20.54	22.52	21.53
14.83	22.36	27.77	25.06	-70.81	15.97	16.83	16.40
14.87	19.85	24.30	22.08	-26.78	14.18	14.73	14.46
14.92	13.47	20.71	17.09	-44.77	9.62	12.55	11.09
14.96	11.63	16.80	14.22	-25.77	8.31	10.18	9.25
15.00	10.81	17.49	14.15	-0.60	7.72	10.60	9.16
15.04	10.71	17.08	13.89	-2.29	7.65	10.35	9.00
15.08	10.75	13.76	12.26	-14.69	7.68	8.34	8.01
15.12	8.13	14.16	11.15	-9.97	5.81	8.58	7.20

	Inside temp		Ti. mean	Qair	Outside temp		To mean
	C	C	C	KJ	C	C	C
Sensor #	0	1			2	3	
Formula			(T0 + T1) / 2	m cp dT			(T2 + T3 / 2
Time (day)							
15.17	8.30	10.63	9.47	-15.07	5.93	6.44	6.19
15.21	10.43	17.44	13.94	40.10	7.45	10.57	9.01
15.25	14.24	20.18	17.21	29.37	10.17	12.23	11.20
15.29	27.30	30.64	28.97	105.52	19.50	18.57	19.04
15.33	30.69	32.01	31.35	21.34	21.92	19.40	20.66
15.37	40.63	44.35	42.49	99.95	29.02	26.88	27.95
15.42	37.69	39.15	38.42	-36.50	26.92	23.73	25.33
15.46	42.78	46.79	44.79	57.13	30.56	28.36	29.46
15.50	48.34	50.75	49.55	42.69	34.53	30.76	32.65
15.54	42.11	45.38	43.74	-52.07	30.08	27.50	28.79
15.58	56.80	45.82	51.31	67.88	40.57	27.77	34.17
15.62	48.51	45.77	47.14	-37.40	34.65	27.74	31.20
15.67	47.91	50.01	48.96	16.32	34.22	30.31	32.27
15.71	42.01	45.33	43.67	-47.46	30.01	27.47	28.74
15.75	33.28	39.63	36.46	-64.72	23.77	24.02	23.90
15.79	28.60	36.71	32.66	-34.08	20.43	22.25	21.34
15.83	22.23	27.82	25.03	-68.47	15.88	16.86	16.37
15.87	22.26	27.34	24.80	-2.02	15.90	16.57	16.24
15.92	17.44	22.72	20.08	-42.33	12.46	13.77	13.12
15.96	15.78	21.43	18.61	-13.25	11.27	12.99	12.13
16.00	17.44	21.63	19.54	8.36	12.46	13.11	12.79
16.04	16.91	20.13	18.52	-9.12	12.08	12.20	12.14
16.08	14.87	18.99	16.93	-14.28	10.62	11.51	11.07
16.12	16.13	19.59	17.86	8.32	11.52	11.87	11.70
16.17	13.99	18.45	16.22	-14.72	9.99	11.18	10.59
16.21	15.15	18.71	16.93	6.40	10.82	11.34	11.08
16.25	21.29	25.46	23.38	57.84	15.21	15.43	15.32
16.29	30.17	34.15	32.16	78.82	21.55	20.70	21.13
16.33	36.89	36.84	36.87	42.21	26.35	22.33	24.34
16.37	45.42	44.29	44.85	71.63	32.44	26.84	29.64
16.42	35.28	36.84	36.06	-78.85	25.20	22.33	23.77
16.46	40.70	41.63	41.16	45.77	29.07	25.23	27.15
16.50	47.94	48.91	48.42	65.11	34.24	29.64	31.94
16.54	47.36	47.39	47.38	-9.38	33.83	28.72	31.28
16.58	55.85	48.00	51.92	40.80	39.89	29.09	34.49
16.62	43.29	45.85	44.57	-65.95	30.92	27.79	29.36
16.67	45.35	49.20	47.27	24.26	32.39	29.82	31.11
16.71	40.70	46.55	43.62	-32.77	29.07	28.21	28.64
16.75	37.72	45.36	41.54	-18.71	26.94	27.49	27.22
16.79	34.57	40.21	37.39	-37.22	24.69	24.37	24.53
16.83	30.84	36.56	33.70	-33.06	22.03	22.16	22.10
16.87	28.06	35.08	31.57	-19.16	20.04	21.26	20.65
16.92	27.78	33.28	30.53	-9.32	19.84	20.17	20.01

Time (day)	Roof C	Ceiling C	T water C	Q water KJ	Q system KJ	T(in-out) C	U system W/m.sq C
Sensor #	4	5	6				
Formula				m cp dT	Qw + Qa		Q water / (Tin-Tout)
0.17	37.80	52.15	22.82			47.76	
0.21	42.93	77.94	23.14	2290.8	2334.5	52.03	5.95
0.25	43.58	82.04	24.58	10410.3	10445.3	54.67	25.73
0.29	42.62	77.25	24.17	-2939.7	-2977.0	51.98	7.64
0.33	36.93	66.04	24.01	-1145.0	-1249.2	41.87	3.70
0.38	39.72	61.29	24.93	6636.7	6545.2	29.95	30.25
0.42	36.14	51.95	25.31	2776.9	2744.3	26.48	14.17
0.46	32.19	43.83	25.86	3937.9	3860.8	18.02	29.54
0.50	31.09	38.96	25.60	-1837.3	-1888.9	12.59	19.72
0.54	26.71	33.96	24.76	-6092.0	-6137.6	9.55	86.24
0.58	24.41	29.37	23.81	-6871.7	-6917.6	5.86	158.60
0.62	20.42	24.96	22.42	-10054.4	-10094.1	3.36	404.38
0.67	18.49	22.18	21.17	-9041.8	-9071.7	1.38	892.21
0.71	17.55	20.95	19.75	-10271.4	-10285.6	1.23	1128.48
0.75	17.21	19.82	19.13	-4484.7	-4497.1	0.41	1460.34
0.79	15.48	18.12	18.03	-7956.8	-7970.9	0.36	2986.77
0.83	14.40	16.56	17.34	-4969.4	-4983.9	-0.40	1678.84
0.87	17.99	17.94	19.62	16492.2	16494.2	-3.39	657.16
0.92	17.83	18.28	18.74	-6394.3	-6391.4	-2.15	401.07
0.96	17.08	17.80	18.11	-4549.8	-4552.4	-1.70	361.67
1.00	17.72	18.20	18.09	-130.2	-128.7	-1.84	9.59
1.04	18.94	23.17	17.70	-2821.0	-2767.3	3.57	106.72
1.08	23.19	33.09	18.21	3660.1	3756.5	12.88	38.40
1.12	31.47	49.33	19.38	8507.9	8599.5	14.77	77.82
1.17	30.63	47.56	20.33	6841.4	6827.5	14.17	65.25
1.21	31.81	50.16	21.25	6683.7	6704.1	14.86	60.77
1.25	37.32	59.36	21.88	4535.3	4607.8	17.62	34.79
1.29	31.01	50.55	21.91	209.8	140.5	15.01	1.89
1.33	34.29	54.88	22.01	723.3	757.4	16.27	6.01
1.38	32.28	46.88	22.75	5352.7	5289.8	13.98	51.73
1.42	32.12	48.38	23.72	7016.4	7028.2	14.46	65.57
1.46	33.43	47.43	24.05	2387.0	2379.6	14.24	22.66
1.50	26.91	40.54	22.24	-13092.5	-13146.7	12.18	145.24
1.54	23.31	38.22	21.39	-6148.4	-6166.7	11.53	72.08
1.58	20.26	35.63	20.51	-6365.4	-6385.8	10.76	79.98
1.63	16.85	31.93	19.02	-10777.8	-10806.9	9.66	150.73
1.67	17.91	32.49	18.95	-506.3	-501.9	9.83	6.96
1.71	17.13	30.51	18.19	-5497.4	-5512.9	9.26	80.26
1.75	14.33	26.11	15.49	-19530.2	-19564.9	7.90	334.26
1.79	12.47	21.26	12.63	-20687.6	-20725.7	6.43	435.00
1.83	11.83	20.53	12.38	-1808.4	-1814.0	6.22	39.31
1.88	11.74	21.10	12.53	1085.0	1089.5	6.38	22.99
1.92	11.71	20.73	12.30	-1663.7	-1666.6	6.26	35.93
1.96	11.99	20.97	12.47	1229.7	1231.5	6.33	26.25
2.00	11.60	20.76	12.23	-1736.0	-1737.6	6.27	37.42

	Roof C	Ceiling C	T water C	Q water KJ	Q system KJ	T(in-out) C	U system W/m sq C
Sensor #	4	5	6				
Formula				m cp dT	Qw + Qa		Q water / (Tin-Tout)
Time (day)							
2.04	11.68	21.25	12.28	361.7	365.5	6.42	7.62
2.08	12.91	22.23	12.53	1808.4	1816.1	6.71	36.43
2.13	13.68	21.34	11.87	-4774.1	-4781.1	6.43	100.29
2.17	16.70	22.66	11.89	144.7	155.1	6.83	2.86
2.21	20.96	26.81	12.69	5786.7	5819.4	8.12	96.35
2.25	25.01	30.86	13.55	6220.7	6252.6	9.15	91.86
2.29	33.04	34.24	14.57	7378.1	7404.7	10.18	97.92
2.33	33.99	37.57	15.82	9041.8	9068.0	11.08	110.23
2.38	40.96	41.49	16.27	3255.0	3285.9	12.28	35.81
2.42	33.70	37.83	17.63	9837.4	9808.6	11.25	118.16
2.46	29.24	39.48	18.22	4267.7	4280.7	11.74	49.11
2.50	23.33	37.04	18.31	651.0	631.8	11.16	7.88
2.54	17.16	31.88	17.63	-4918.7	-4959.3	9.67	68.71
2.58	13.26	26.79	16.26	-9909.8	-9949.8	8.08	165.65
2.62	10.47	22.47	14.13	-15407.2	-15441.2	6.80	306.23
2.67	11.52	22.40	13.74	-2821.0	-2821.6	6.78	56.25
2.71	8.85	19.94	12.75	-7161.1	-7180.4	6.04	160.15
2.75	9.65	20.01	12.37	-2748.7	-2748.2	6.08	61.13
2.79	9.08	18.42	11.94	-3110.4	-3122.9	5.61	74.93
2.83	10.57	19.31	11.41	-3833.7	-3826.7	5.84	88.77
2.87	10.78	20.08	11.96	3978.4	3984.5	6.07	88.58
2.92	8.09	17.91	11.11	-6148.4	-6165.5	5.42	153.34
2.96	10.34	18.82	11.57	3327.4	3334.6	5.69	79.02
3.00	11.43	20.10	11.44	-940.3	-930.3	6.09	20.88
3.04	12.36	21.80	12.45	7305.7	7319.1	6.58	149.95
3.08	12.48	21.30	12.28	-1229.7	-1233.6	6.43	25.84
3.12	11.87	20.25	11.68	-4340.0	-4348.3	6.12	95.90
3.17	11.05	18.76	10.82	-6220.7	-6232.5	5.67	148.29
3.21	14.68	22.42	11.64	5931.4	5960.2	6.77	118.37
3.25	11.22	26.64	11.09	-3978.4	-3945.2	8.37	64.25
3.29	14.10	21.31	11.57	3472.0	3430.1	6.45	72.74
3.33	13.73	21.25	11.64	506.3	505.8	6.40	10.69
3.37	10.72	17.46	10.44	-8680.1	-8709.9	5.27	222.61
3.42	9.48	16.78	9.84	-4340.0	-4345.4	5.06	116.00
3.46	9.50	15.82	9.29	-3978.4	-3985.9	4.78	112.53
3.50	9.12	16.29	9.67	2748.7	2752.4	4.95	75.04
3.54	9.86	16.70	9.94	1953.0	1956.3	5.06	52.15
3.58	9.88	17.86	10.33	2821.0	2830.2	5.39	70.68
3.62	9.49	16.61	9.81	-3761.4	-3771.2	5.01	101.40
3.67	13.84	23.69	10.57	5497.4	5553.1	7.07	105.14
3.71	18.65	28.75	9.99	-4195.4	-4155.5	8.58	66.09
3.75	15.25	25.13	10.09	723.3	694.8	7.50	13.03
3.79	12.47	21.87	10.02	-506.3	-532.0	6.58	10.40
3.83	11.85	22.25	9.98	-289.3	-286.3	6.77	5.78
3.87	10.80	20.12	10.03	361.7	344.9	6.13	7.98

	Roof	Ceiling	T water	Q water	Q system	T(in-out)	U system
	C	C	C	KJ	KJ	C	W/m.sq.C
Sensor #	4	5	6				
Formula				m cp dT	Qw + Qa		Q water / (Tin-Tout)
Time (day)							
3.92	8.52	15.47	10.00	-217.0	-253.6	4.70	6.24
3.96	7.43	13.48	9.90	-723.3	-739.0	4.11	23.78
4.00	6.08	11.76	9.72	-1302.0	-1315.5	3.59	49.02
4.04	1.80	6.81	9.40	-2314.7	-2353.7	2.07	151.02
4.08	2.07	5.67	9.40	0.0	-9.0	1.72	0.00
4.12	1.02	4.48	9.32	-578.7	-588.0	1.35	57.97
4.17	1.70	5.26	8.36	-6944.1	-6938.0	1.63	577.38
4.21	11.72	20.27	8.94	4195.4	4313.5	5.97	95.02
4.25	13.60	23.68	7.96	-7088.7	-7061.8	6.93	138.31
4.29	17.48	28.26	7.82	-1012.7	-976.6	8.21	16.67
4.33	20.19	31.75	7.88	434.0	461.4	9.24	6.35
4.37	21.52	33.06	8.05	1229.7	1240.0	9.74	17.06
4.42	22.48	35.34	8.17	868.0	886.0	10.33	11.36
4.46	20.37	34.51	8.31	1012.7	1006.2	10.22	13.39
4.50	21.20	33.92	8.37	434.0	429.3	10.07	5.82
4.54	24.75	38.20	8.49	868.0	901.7	11.34	10.35
4.58	23.87	37.53	8.79	2170.0	2164.8	11.25	26.06
4.62	21.19	35.52	9.14	2531.7	2515.8	10.70	31.98
4.67	17.69	30.66	9.55	2965.7	2927.5	9.26	43.26
4.71	16.42	28.38	9.83	2025.4	2007.4	8.57	31.95
4.75	14.64	26.25	10.02	1374.3	1357.6	7.95	23.38
4.79	11.74	21.72	10.19	1229.7	1194.0	6.60	25.19
4.83	10.08	19.26	10.34	1085.0	1065.7	5.85	25.06
4.88	8.92	16.96	10.40	434.0	415.9	5.15	11.38
4.92	6.31	14.04	10.36	-289.3	-312.3	4.29	9.11
4.96	5.44	13.05	10.33	-217.0	-224.8	3.98	7.36
5.00	4.67	12.55	10.34	72.3	68.4	3.87	2.53
5.04	4.51	11.59	10.28	-434.0	-441.6	3.56	16.48
5.08	6.76	13.56	10.23	-361.7	-346.2	4.12	11.86
5.13	8.36	16.19	10.14	-651.0	-630.3	4.92	17.88
5.17	11.31	20.83	10.03	-795.7	-759.1	6.30	17.07
5.21	15.47	24.30	9.92	-795.7	-768.4	7.47	14.39
5.25	20.12	34.35	9.80	-868.0	-788.9	10.29	11.40
5.29	25.07	42.19	9.83	217.0	278.6	12.52	2.34
5.33	25.10	40.90	10.11	2025.4	2015.2	12.19	22.45
5.38	25.30	40.90	10.57	3327.4	3327.4	12.16	36.97
5.42	28.67	46.76	10.92	2531.7	2577.8	13.90	24.61
5.46	28.08	46.09	11.35	3110.4	3105.1	13.75	30.58
5.50	27.59	43.84	11.84	3544.4	3526.6	13.12	36.50
5.54	26.24	43.27	12.47	4571.5	4567.1	12.98	47.58
5.58	24.49	41.21	12.93	3312.9	3296.7	12.40	36.12
5.63	22.56	38.01	13.37	3182.7	3157.5	11.44	37.59
5.67	22.46	39.94	13.53	1157.3	1172.5	12.09	12.93
5.71	21.02	37.06	13.80	1953.0	1930.4	11.20	23.57
5.75	21.56	37.69	14.07	1953.0	1958.0	11.39	23.16

	Roof	Ceiling	T water	Q water	Q system	T(in-out)	U system
	C	C	C	KJ	KJ	C	W/m sq C
Sensor #	4	5	6				
Formula				m cp dT	Qw + Qa		Q water / (Tin-Tout)
Time (day)							
5.79	19.10	33.29	14.33	1880.7	1846.1	10.05	25.28
5.83	17.95	31.25	14.54	1519.0	1502.9	9.44	21.75
5.88	16.79	29.21	14.72	1302.0	1286.0	8.82	19.95
5.92	15.31	26.92	14.83	795.7	777.7	8.13	13.23
5.96	15.51	27.19	14.90	506.3	508.5	8.22	8.33
6.00	15.62	27.28	15.00	723.3	724.1	8.25	11.85
6.04	14.30	25.38	14.98	-144.7	-159.7	7.67	2.55
6.08	14.06	24.86	14.96	-144.7	-148.8	7.51	2.60
6.13	14.04	25.20	14.98	144.7	147.4	7.62	2.57
6.17	15.12	26.38	14.31	-506.3	-497.1	7.97	8.59
6.21	15.02	26.11	14.92	72.3	70.2	7.88	1.24
6.25	14.29	25.43	14.92	0.0	-5.4	7.67	0.00
6.29	13.69	23.31	14.92	0.0	-16.7	7.03	0.00
6.33	13.12	24.40	14.92	0.0	8.6	7.36	0.00
6.38	13.59	24.04	14.97	361.7	358.8	7.27	6.73
6.42	13.29	23.52	14.92	-361.7	-365.7	7.10	6.88
6.46	19.11	30.90	16.12	8680.1	8738.2	9.30	126.08
6.50	23.76	37.67	21.56	39349.8	39403.1	11.24	473.29
6.54	21.22	34.01	24.76	23146.9	23118.1	10.18	307.27
6.58	19.22	32.92	26.07	9475.8	9467.2	9.83	130.29
6.63	18.85	32.14	26.10	217.0	210.9	9.64	3.04
6.67	17.60	31.16	25.17	-6727.1	-6734.8	9.39	96.81
6.71	14.71	26.66	23.83	-9692.8	-9728.2	8.06	162.54
6.75	11.90	22.41	21.92	-13808.6	-13842.0	6.78	275.30
6.79	10.44	20.25	19.89	-14691.1	-14708.1	6.16	322.30
6.83	8.04	16.60	17.89	-14466.8	-14495.5	5.05	387.47
6.88	8.26	17.09	16.14	-12658.5	-12654.7	5.19	329.33
6.92	5.88	13.31	14.37	-12803.1	-12832.8	4.09	422.74
6.96	5.71	10.84	12.71	-12007.5	-12027.0	3.26	497.02
7.00	7.29	13.75	11.12	-11501.1	-11478.2	4.16	373.99
7.04	5.55	11.51	10.82	-2170.0	-2187.6	3.52	83.28
7.08	7.59	13.92	10.43	-2821.0	-2802.1	4.20	90.85
7.13	8.18	14.81	10.18	-1808.4	-1801.3	4.48	54.58
7.17	12.35	22.79	11.32	8246.1	8308.9	6.91	161.32
7.21	14.42	26.37	14.20	20832.2	20860.4	7.96	353.72
7.25	18.07	31.57	17.47	23653.3	23694.1	9.50	336.58
7.29	17.78	33.13	20.49	21844.9	21857.2	9.97	296.07
7.33	20.21	36.50	22.83	16926.2	16952.6	10.96	208.68
7.38	22.09	36.95	24.52	12224.5	12228.0	11.15	148.10
7.42	24.49	41.63	25.73	8752.4	8789.3	12.56	94.16
7.46	27.00	47.74	28.00	16419.8	16467.9	14.38	154.36
7.50	28.14	44.14	28.39	2821.0	2792.7	13.50	28.25
7.54	24.98	43.55	26.01	-17215.5	-17220.1	13.21	176.18
7.58	23.92	41.90	26.96	6871.7	6858.7	12.73	72.94
7.63	20.09	37.54	25.97	-7161.1	-7195.4	11.43	84.66

	Roof C	Ceiling C	T water C	Q water KJ	Q system KJ	T(in-out) C	U system W/m sq.C
Sensor #	4	5	6				
Formula				m cp dT	Qw + Qa		Q water / (Tin-Tout)
Time (day)							
7.67	16.87	30.32	24.67	-9403.4	-9460.3	9.17	138.61
7.71	15.57	27.42	23.26	-10199.1	-10221.9	8.28	166.56
7.75	14.86	25.77	21.06	-15913.5	-15926.4	7.78	276.43
7.79	15.50	27.01	20.37	-4991.1	-4981.3	8.16	82.68
7.83	15.02	26.34	19.07	-9403.4	-9408.7	7.95	159.83
7.88	15.33	26.60	18.93	-1012.7	-1010.6	8.04	17.02
7.92	15.25	26.54	18.44	-3544.4	-3544.9	8.01	59.76
7.96	13.87	24.34	17.59	-6148.4	-6165.7	7.35	113.06
8.00	13.02	22.60	17.38	-1519.0	-1532.7	6.82	30.10
8.04	11.29	20.40	16.60	-5642.1	-5659.4	6.16	123.72
8.08	11.52	20.60	16.00	-4340.0	-4338.5	6.23	94.18
8.13	15.06	27.02	15.58	-3038.0	-2987.5	8.19	50.14
8.17	17.36	31.06	16.12	3906.0	3937.9	9.39	56.22
8.21	20.30	35.52	17.22	7956.8	7991.8	10.74	100.12
8.25	26.00	43.32	20.00	20108.9	20170.3	13.00	209.03
8.29	29.21	48.53	22.37	17143.2	17184.2	14.58	158.92
8.33	30.07	47.86	24.53	15624.2	15618.9	14.37	146.94
8.38	28.00	47.48	26.07	11139.5	11136.5	14.33	105.08
8.42	25.31	43.43	27.04	7016.4	6984.5	13.09	72.41
8.46	24.28	41.45	26.58	-3327.4	-3342.9	12.50	35.96
8.50	18.99	32.86	26.44	-1012.7	-1080.3	9.92	13.80
8.54	18.86	33.64	25.14	-9403.4	-9397.3	10.17	124.97
8.58	18.47	33.06	24.16	-7088.7	-7093.3	9.98	96.02
8.63	18.69	32.19	23.21	-6871.7	-6878.6	9.72	95.58
8.67	18.40	31.98	22.85	-2604.0	-2605.7	9.66	36.44
8.71	18.31	31.67	22.58	-1953.0	-1955.5	9.56	27.60
8.75	18.47	32.05	22.52	-434.0	-431.0	9.68	6.06
8.79	17.96	31.49	21.91	-4412.4	-4416.8	9.52	62.66
8.83	18.00	31.90	21.72	-1374.3	-1371.1	9.65	19.25
8.88	19.75	35.02	22.18	3327.4	3351.9	10.59	42.48
8.92	20.49	36.24	22.68	3616.7	3626.4	10.96	44.60
8.96	20.88	36.53	22.69	72.3	74.6	11.05	0.88
9.00	21.19	36.91	22.90	1519.0	1522.0	11.15	18.42
9.04	20.41	35.43	23.18	2025.4	2013.7	10.70	25.59
9.08	20.62	35.76	22.98	-1446.7	-1444.1	10.79	18.12
9.13	21.03	36.81	22.95	-217.0	-208.7	11.11	2.64
9.17	21.91	40.22	23.98	7450.4	7477.2	12.10	83.19
9.21	27.80	47.58	26.58	18806.9	18864.8	14.21	178.87
9.25	27.26	46.07	28.34	12730.8	12718.9	13.79	124.72
9.29	32.48	51.87	31.14	20253.5	20299.1	15.44	177.30
9.33	31.28	51.26	32.95	13092.5	13087.7	15.35	115.24
9.38	30.12	49.59	32.21	-5352.7	-5365.9	14.91	48.53
9.42	29.11	47.11	31.23	-7088.7	-7108.2	14.30	67.00
9.46	28.98	48.37	28.98	-16275.2	-16265.3	14.60	150.66
9.50	27.79	46.46	27.12	-13454.1	-13469.2	14.05	129.37

	Roof	Ceiling	T water	Q water	Q system	T(in-out)	U system
	C	C	C	KJ	KJ	C	W/m.sq C
Sensor #	4	5	6				
Formula				m cp dT	Qw + Qa		Q water / (Tin-Tout)
Time (day)							
9.54	24.93	43.59	25.88	-8969 4	-8992.0	13.22	91.71
9.58	22.59	39.25	24.85	-7450.4	-7454 5	11.87	84.79
9.62	21.03	37.16	23.58	-9186.4	-9202 9	11.24	110.44
9.67	19.76	34.72	22 32	-9114.1	-9133 3	10.50	117 28
9.71	19.48	33.88	21.06	-9114.1	-9120 7	10.26	120 07
9.75	15.55	27.03	18.79	-16419.8	-16473 8	8.18	271.36
9.79	12.96	22.84	16.34	-17721.9	-17754.8	6.92	346.28
9.83	11 11	19.86	14.74	-11573 5	-11596.9	6.02	259.98
9.87	10.78	19.47	13.72	-7378 1	-7381 2	5.91	168.83
9 92	9.77	17.73	12.92	-5786 7	-5800 4	5.37	145.58
9.96	9.27	17.17	12 25	-4846.4	-4850 8	5.21	125 64
10.00	10.02	18.13	11.81	-3182.7	-3175 1	5 49	78 31
10.04	15.93	23 54	11.97	1157.3	1199 9	7.10	22 04
10.08	20.91	27.17	13.28	9446 8	9475 4	8.14	156 92
10.12	26.64	32.72	15 9	18980.5	19024.1	9.77	262.54
10.17	29.24	36.95	17.09	8607.8	8641.1	10.98	105.92
10.21	31.11	38.23	15.84	-9041.8	-9031 7	11.38	107 40
10.25	28.82	39.86	15.15	-4991.1	-4978 2	11.86	56 86
10.29	30.11	39.47	14.79	-2604.0	-2607.1	11.79	29 86
10.33	35 53	42.89	15.09	2170.0	2196 9	12.83	22 86
10.37	35.30	54.70	15.13	299 5	392 4	16.83	2.40
10.42	32.67	43.43	15.82	4980.9	4892.3	13.06	51.56
10.46	22.60	41.73	16.36	3906.0	3892.6	12.60	41.88
10.50	25.87	41.22	16.85	3544.4	3540.4	12 47	38 40
10.54	22.12	39.20	17.20	2531.7	2515.7	11.91	28.72
10.58	18.32	30.95	17.69	3544 4	3479 4	9.35	51.20
10.62	33.82	51.92	22.75	36601.1	36766.1	15.63	316.37
10.67	33.37	49.77	22.51	-1736 0	-1753.0	15.00	15.64
10.71	24.27	45.23	23.13	4484.7	4449.0	13.67	44.32
10.75	18.75	32.46	25.06	13960 5	13860 0	9.81	192.40
10.79	18.11	32.08	26.64	11428.8	11425.8	9.68	159.57
10.83	19.00	32.88	27.55	6582.4	6588 7	9.94	89.49
10.87	19.57	33.77	28.68	8173.8	8180.8	10.21	108.23
10.92	14.76	25.28	28.08	-4340.0	-4406.8	7.64	76.78
10.96	13.25	22.70	25.73	-16998.5	-17018.9	6.86	334.71
11.00	11.77	19.78	24.16	-11356.5	-11379 4	5 99	256.14
11.04	10.95	18.40	22.99	-8463.1	-8473.9	5.57	205.21
11.08	9.67	16.11	21.96	-7450.4	-7468.4	4.88	206.21
11.12	8.88	14.38	20.88	-7812.1	-7825.7	4.36	242.18
11.17	9.28	15.72	19.92	-6944.1	-6933.5	4.76	197.11
11.21	8.42	14.28	18.95	-7016.4	-7027.7	4.32	219.25
11.25	8.45	15.28	18.07	-6365.4	-6357.6	4.58	187 92
11.29	11.03	18.93	17.11	-6944.1	-6915.3	5.67	165.54
11.33	10.96	19.99	16.26	-6148.4	-6140.1	5.95	139.64
11.37	9.82	17.52	15.38	-6365.4	-6384.8	5.25	163.91

Time (day)	Roof C	Ceiling C	T water C	Q water KJ	Q system KJ	T(in-out) C	U system W/m.sq.C
Sensor #	4	5	6				
Formula				m cp dT	Qw + Qa		Q water / (Tin-Tout)
11.42	12 26	23.57	14 70	-4918.7	-4871.1	7.02	94.73
11 46	14 33	26.89	14 16	-3906 0	-3879 9	8.02	65.83
11.50	13 83	27.90	13.63	-3833.7	-3825.8	8.27	62.63
11.54	15.73	31.78	13.29	-2459.4	-2428.8	9.47	35.10
11.58	14.73	27.47	13.11	-1302.0	-1335.9	8.23	21.38
11.62	15 72	29.93	13 38	1953.0	1972 3	9.00	29.32
11.67	15.61	28.20	13.60	1591.4	1577.7	8.48	25.36
11.71	16 34	30.22	13 48	-868.0	-852 1	9.14	12.83
11.75	15 20	26.41	13.60	868.0	838.1	7.99	14.68
11.79	14.07	23.97	13.71	795.7	776.4	7.25	14.82
11.83	12.69	21.52	13.72	72 3	53.1	6.52	1.50
11.87	12.46	21.07	13.48	-1736.0	-1739.5	6.38	36.75
11.92	12.22	21.08	13.22	-1880.7	-1880.6	6.37	39.88
11.96	11 62	19.72	13.01	-1519 0	-1529.7	5.97	34.37
12.00	10.77	18.51	12.84	-1229.7	-1239.2	5.60	29.65
12.04	10.04	16.95	12.58	-1880.7	-1893.0	5.13	49.50
12.08	10.19	16.90	12.45	-940.3	-940.7	5.14	24.74
12.12	9.55	15.76	12.27	-1302.0	-1311.0	4.80	36.67
12.17	8.83	14.48	12.21	-434.0	-444.1	4.41	13.30
12.21	8.89	15.04	12.08	-940.3	-936 0	4.56	27.85
12.25	9.98	16.71	11.94	-1012.7	-999.5	5.06	27.05
12.29	16.18	25.74	11.78	-1157.3	-1086.3	7.71	20.29
12.33	15.24	29.48	11.56	-1591.4	-1561.9	8.72	24.66
12.37	18.42	34.30	11.46	-723.3	-685.4	10.17	9.61
12.42	18.51	35.27	11.60	1012.7	1020.3	10.43	13.12
12.46	17.84	32.59	11.66	434.0	412.9	9.77	6.00
12.50	19.82	37.80	11.82	1157.3	1198.3	11.25	13.91
12.54	18.96	34.07	12.10	2025.4	1996.0	10.22	26.77
12.58	19.63	36.46	12.43	2387.0	2405.8	10.95	29.46
12 62	21.69	40.31	12.62	1374.3	1404.6	12.07	15.39
12.67	20.98	38.87	13.01	2821.0	2809.7	11.69	32.60
12.71	20.64	37.47	13.41	2893.4	2882.3	11.28	34.65
12.75	19.98	35.74	13.80	2821.0	2807.4	10.86	35.09
12.79	18.83	33.14	14.02	1591.4	1570.9	10.06	21.37
12.83	15.70	26.34	14.21	1374.3	1320.9	7.98	23.27
12.87	14.78	25.20	14.26	361.7	352.7	7.63	6.41
12.92	14.80	25.10	14.28	144.7	143.9	7.60	2.57
12.96	14.38	24.24	14.73	3255.0	3248.2	7.35	59.88
13.00	13.85	23.49	14.29	-3182.7	-3188.6	7.11	60.50
13.04	14.22	24.10	14.27	-144.7	-139.9	7.29	2.68
13.08	12.96	21.65	14.72	3255.0	3235.8	6.56	67.10
13.12	13.45	22.41	14.18	-3906.0	-3900.0	6.81	77.56
13.17	11.85	19.83	14.09	-651.0	-671.3	6.02	14.61
13.21	11.68	19.79	14.04	-361.7	-362.0	6.00	8.14
13.25	12.50	21.48	13.90	-1012.7	-999.4	6.50	21.05

Time (day)	Roof	Ceiling	T water	Q water	Q system	T(in-out)	U system
	C	C	C	KJ	KJ	C	W/m.sq.C
Sensor #	4	5	6				
Formula				m cp dT	Qw + Qa		Q water / (Tin-Tout)
13.29	15.98	32.46	13.74	-1157.3	-1070.9	9.67	16.18
13.33	17.26	32.55	13.63	-795.7	-795.0	9.68	11.10
13.37	18.50	37.35	13.50	-940.3	-902.5	11.02	11.53
13.42	19.52	41.25	13.54	289.3	320.1	12.18	3.21
13.46	22.01	42.92	13.59	361.7	374.8	12.69	3.85
13.50	21.63	42.97	13.77	1302.0	1302.4	12.70	13.85
13.54	23.91	41.64	13.94	1229.7	1219.2	11.91	13.95
13.58	24.32	53.45	14.12	1302.0	1394.9	15.90	11.06
13.62	23.36	46.90	14.38	1880.7	1829.1	13.99	18.17
13.67	23.85	47.62	14.64	1880.7	1886.4	14.26	17.82
13.71	23.83	46.92	14.95	2242.4	2236.8	14.13	21.45
13.75	22.70	43.30	15.21	1880.7	1852.2	13.10	19.40
13.79	21.11	36.07	15.52	2242.4	2185.5	10.86	27.90
13.83	18.32	31.27	15.80	2025.4	1987.6	9.42	29.05
13.87	16.12	28.28	15.97	1229.7	1206.1	8.57	19.40
13.92	17.43	29.78	15.98	72.3	84.2	9.01	1.08
13.96	17.59	30.19	15.91	-506.3	-503.1	9.14	7.48
14.00	15.38	26.22	15.97	434.0	402.7	7.92	7.40
14.04	15.48	26.38	15.98	72.3	73.6	7.98	1.22
14.08	14.51	24.41	15.88	-723.3	-738.8	7.39	13.22
14.12	14.16	24.23	15.78	-723.3	-724.8	7.33	13.33
14.17	13.91	23.47	15.72	-434.0	-440.0	7.09	8.27
14.21	13.13	21.77	15.65	-506.3	-519.7	6.59	10.38
14.25	15.18	24.89	15.56	-651.0	-626.5	7.52	11.70
14.29	19.30	35.09	15.38	-1302.0	-1221.7	10.57	16.64
14.33	20.13	38.54	15.15	-1663.7	-1636.6	11.60	19.38
14.37	19.68	40.03	14.90	-1808.4	-1796.6	12.09	20.21
14.42	19.97	38.80	14.85	-361.7	-371.4	11.73	4.17
14.46	20.98	44.13	14.97	868.0	910.0	13.31	8.81
14.50	23.73	46.16	15.17	1446.7	1462.7	13.87	14.10
14.54	23.18	48.76	15.52	2531.7	2552.2	14.44	23.70
14.58	23.92	53.09	15.76	1736.0	1770.1	15.67	14.98
14.62	23.62	54.96	15.90	1012.7	1027.4	16.67	8.21
14.67	24.37	52.58	16.12	1591.4	1572.6	15.67	13.72
14.71	25.77	47.98	16.42	2170.0	2133.8	14.43	20.32
14.75	23.26	43.62	16.70	2025.4	1991.0	13.32	20.55
14.79	20.60	37.57	16.96	1880.7	1833.1	11.43	22.24
14.83	16.67	28.57	17.30	2459.4	2388.5	8.66	38.36
14.87	15.09	25.17	17.48	1302.0	1275.2	7.62	23.08
14.92	11.64	19.48	17.38	-723.3	-768.1	6.00	16.28
14.96	10.10	16.21	17.26	-868.0	-893.8	4.97	23.60
15.00	9.08	16.13	17.14	-868.0	-868.6	4.99	23.51
15.04	8.53	15.84	16.92	-1591.4	-1593.6	4.89	43.94
15.08	9.03	13.97	16.77	-1085.0	-1099.7	4.25	34.53
15.12	8.03	12.71	16.62	-1085.0	-1095.0	3.95	37.12

	Roof C	Ceiling C	T water C	Q water KJ	Q system KJ	T(in-out) C	U system W/m.sq.C
Sensor #	4	5	6				
Formula				m cp dT	Qw + Qa		Q water / (Tin-Tout)
Time (day)							
15.17	6.57	10.79	16.41	-1519.0	-1534.1	3.28	62.59
15 21	9.43	15.89	16.21	-1446.7	-1406.6	4.93	39.69
15.25	13.05	19.62	15.90	-2242.4	-2213.0	6.01	50.43
15.29	18 26	33 03	15.70	-1446.7	-1341.2	9.94	19.68
15.33	19.36	35.74	15.25	-3255.0	-3233.7	10.69	41.15
15.37	22.76	48.44	15.14	-795.7	-695.7	14.54	7.40
15.42	21.72	43.80	15.18	289.3	252.8	13.10	2.99
15.46	24.75	51.06	15.63	3255.0	3312.2	15.33	28.70
15.50	28.44	56.48	15.84	1519.0	1561.7	16.90	12.14
15.54	26.31	49.87	16.30	3327.4	3275.3	14.95	30.07
15.58	28.21	58.49	16.49	1374.3	1442.2	17.14	10.84
15.62	26.63	53.74	16.54	361.7	324.3	15.95	3.07
15.67	27.13	55.81	16.89	2531.7	2548.0	16.69	20.49
15.71	25.81	49.78	17.15	1880.7	1833.2	14.93	17.02
15.75	23.53	41.56	17.53	2748.7	2684.0	12.56	29.57
15.79	20.41	37.23	17.69	1157.3	1123.3	11.32	13.82
15.83	16.02	28.53	18.02	2387.0	2318.6	8.66	37.27
15.87	16.43	28.27	18.12	723.3	721.3	8.57	11.41
15.92	13.07	22.89	17.99	-940.3	-982.7	6.97	18.24
15.96	11.61	21.21	17.92	-506.3	-519.6	6.48	10.57
16.00	13.43	22.27	17.76	-1157.3	-1149.0	6.75	23.16
16.04	12.91	21.11	17.61	-1085.0	-1094.1	6.38	22.98
16.08	12.04	19.30	17.51	-723.3	-737.6	5.86	16.67
16.12	12.60	20.36	17.38	-940.3	-932.0	6.16	20.62
16.17	11.33	18.49	17.24	-1012.7	-1027.4	5.63	24.30
16.21	11.56	19.30	17.10	-1012.7	-1006.3	5.85	23.39
16.25	14.78	26.65	16.90	-1446.7	-1388.8	8.06	24.27
16.29	19 06	36.67	16.75	-1085.0	-1006.2	11.04	13.28
16.33	22.44	42.03	16.60	-1085.0	-1042.8	12.53	11.70
16.37	27.27	51.13	16.47	-940.3	-868.7	15.21	8.35
16.42	21.86	41.11	16.77	2170.0	2091.2	12.30	23.85
16.46	24.39	46.93	16.98	1519.0	1564.8	14.01	14.65
16.50	28.45	55.20	17.08	723.3	788.4	16.48	5.93
16.54	27.06	54.01	17.29	1519.0	1509.6	16.10	12.75
16.58	27.12	59.19	17.64	2531.7	2572.5	17.43	19.63
16.62	26.75	50.81	17.99	2531.7	2465.7	15.22	22.48
16.67	27.71	53.89	18.47	3472.0	3496.3	16.17	29.02
16.71	26.82	49.73	18.83	2604.0	2571.3	14.98	23.49
16.75	26.10	47.35	19.21	2748.7	2730.0	14.32	25.93
16.79	24.42	42.62	19.55	2459.4	2422.1	12.86	25.85
16.83	22.75	38.42	19.76	1519.0	1486.0	11.61	17.68
16.87	20.38	35.99	19.93	1229.7	1210.5	10.92	15.22
16.92	20.61	34.80	20.00	506.3	497.0	10.52	6.50

APPENDIX C

COMPUTER SIMULATION

C.1 Computer Simulation

To evaluate over a longer period of time the benefit of the Solar Climate Control system, a computer simulation, as previously described, was done. Weather data for the simulation were taken from Environment Canada norms for the Montreal area on a year-round basis. The exterior temperature (T_∞) varies throughout the day, as determined by linear interpolation between the minimum and maximum daily temperature data (Figures C.1 and C.2). The incoming solar radiation is determined from monthly averages as depicted in Figures C.3 and C.4. The simulation program calculates the energy flow between the greenhouse and the exterior on a ten minute interval with respect to the weather data provided. Heating and cooling loads are then predicted for the conventional greenhouse, and the benefit of incorporating the roof is determined. A schematic description of the heat flow for the day and night periods is shown in Figures C.5 and C.6. The general heat balance equations may be written as follows:

$$Q_1 = Q_{ter} + Q_R + Q_c + Q_v \qquad \text{(C.1)}$$

$$Q_2 = Q_{ser} + Q_R + Q_c + Q_s \qquad \text{(C.2)}$$

For the conventional greenhouse only the equation C.1 apply, but for a greenhouse equipped with a Solar Climate Control, both equations C.1 and C.2 are to be utilized. The component Q_{tar} will be greater for the conventional greenhouse.

During the day, the temperature of the greenhouse is kept constant at 29,5°C. During

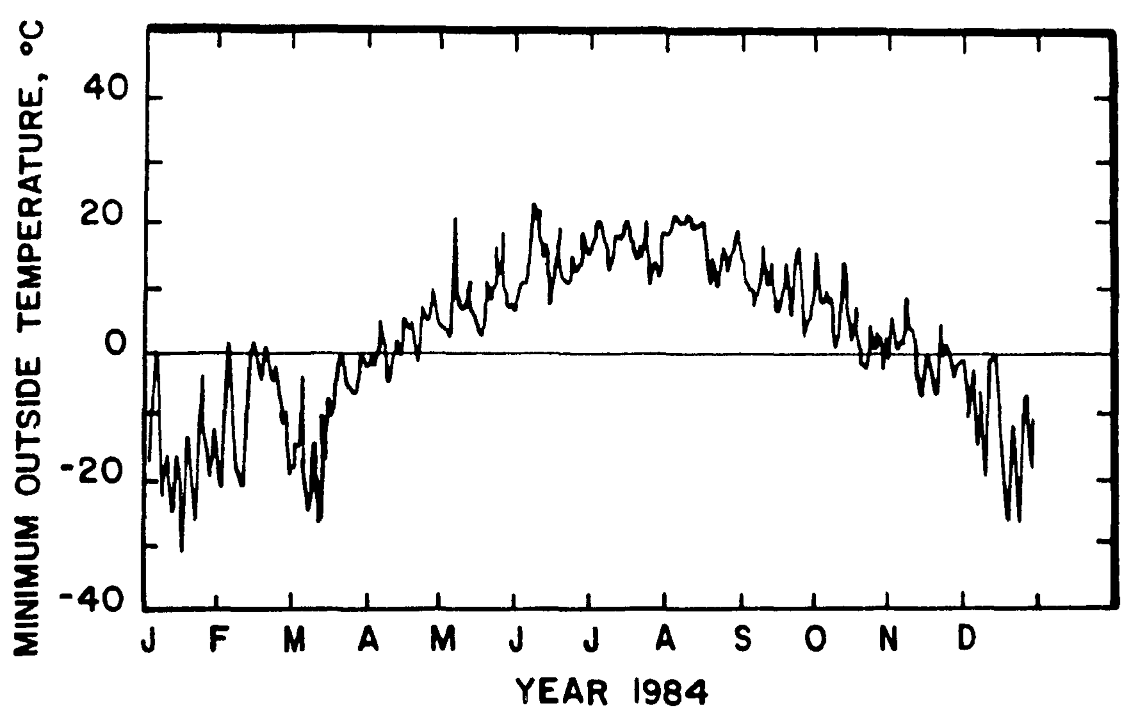

Figure C.1 Average minimum exterior temperature for Montreal region

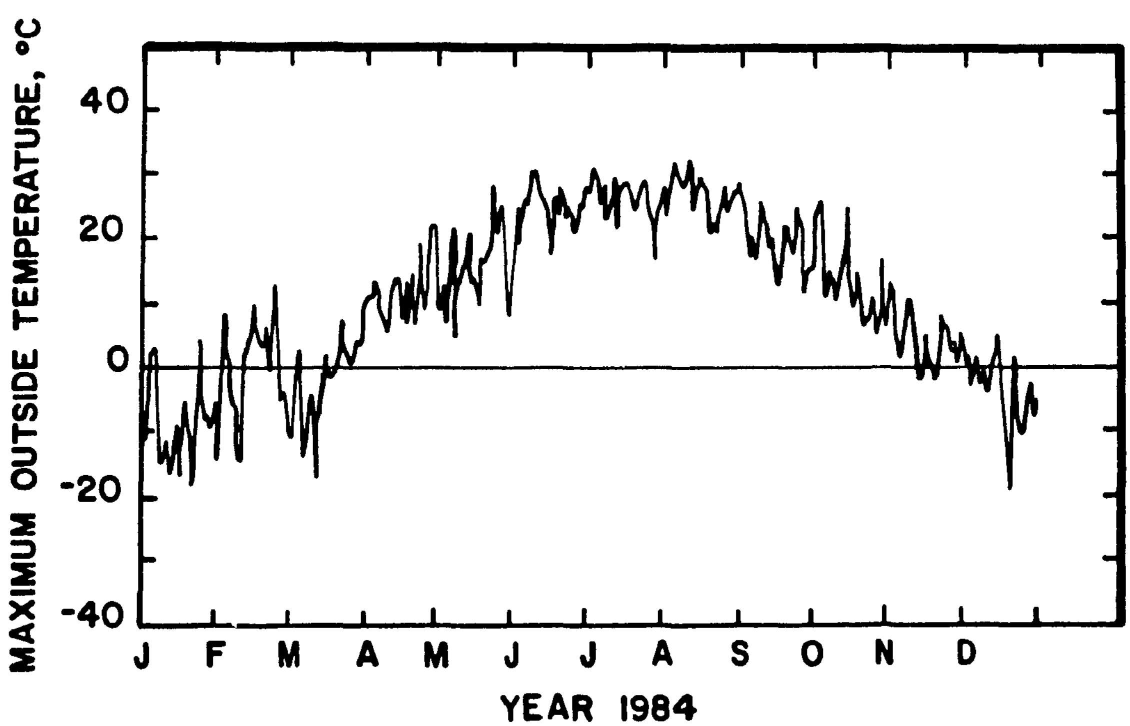

Figure C.2 Average maximum exterior temperature for Montreal region

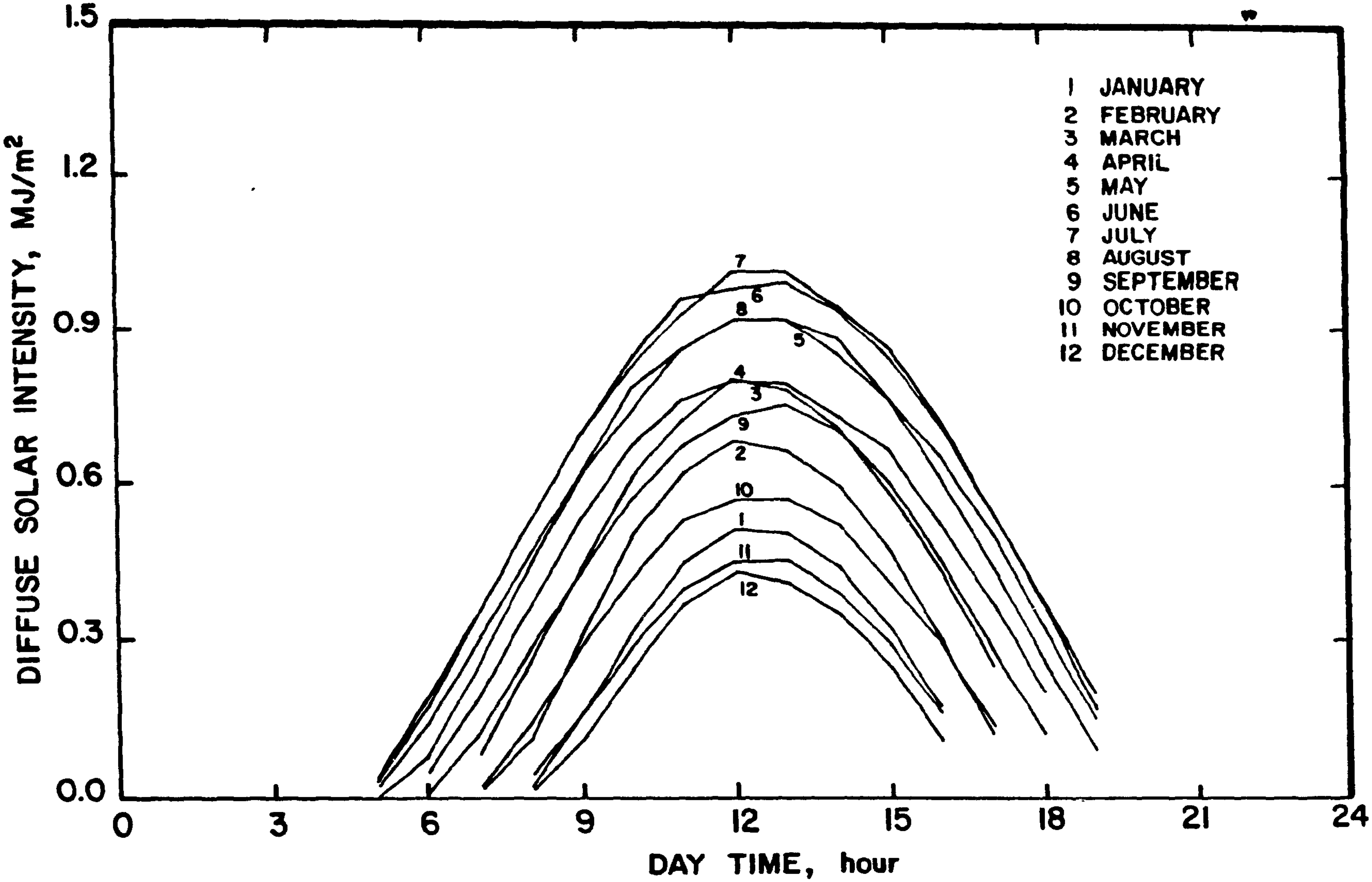

Figure C.3 Average hourly diffuse solar intensity for Montreal region

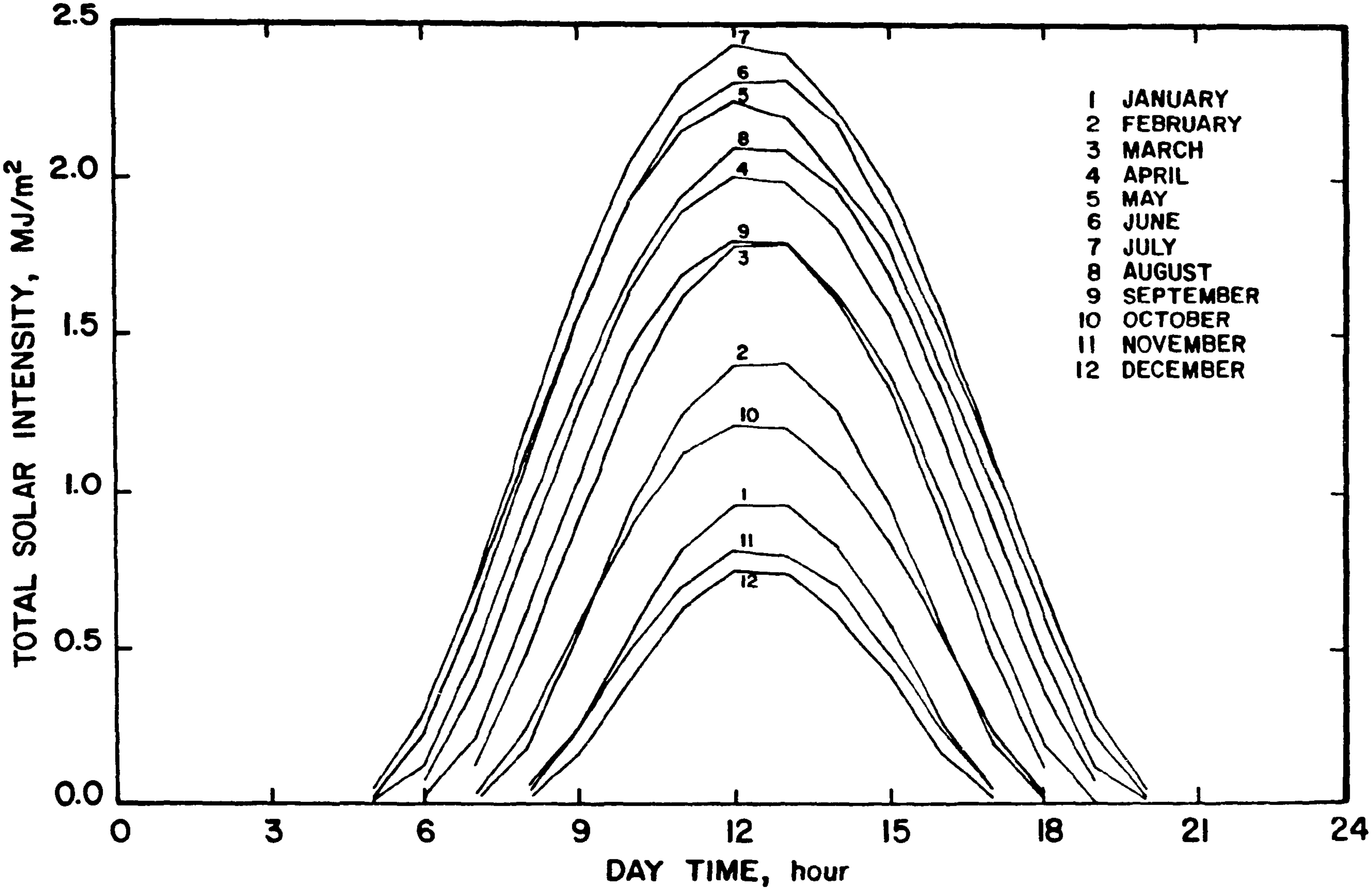

Figure C.4 Average hourly total solar intensity for Montreal region

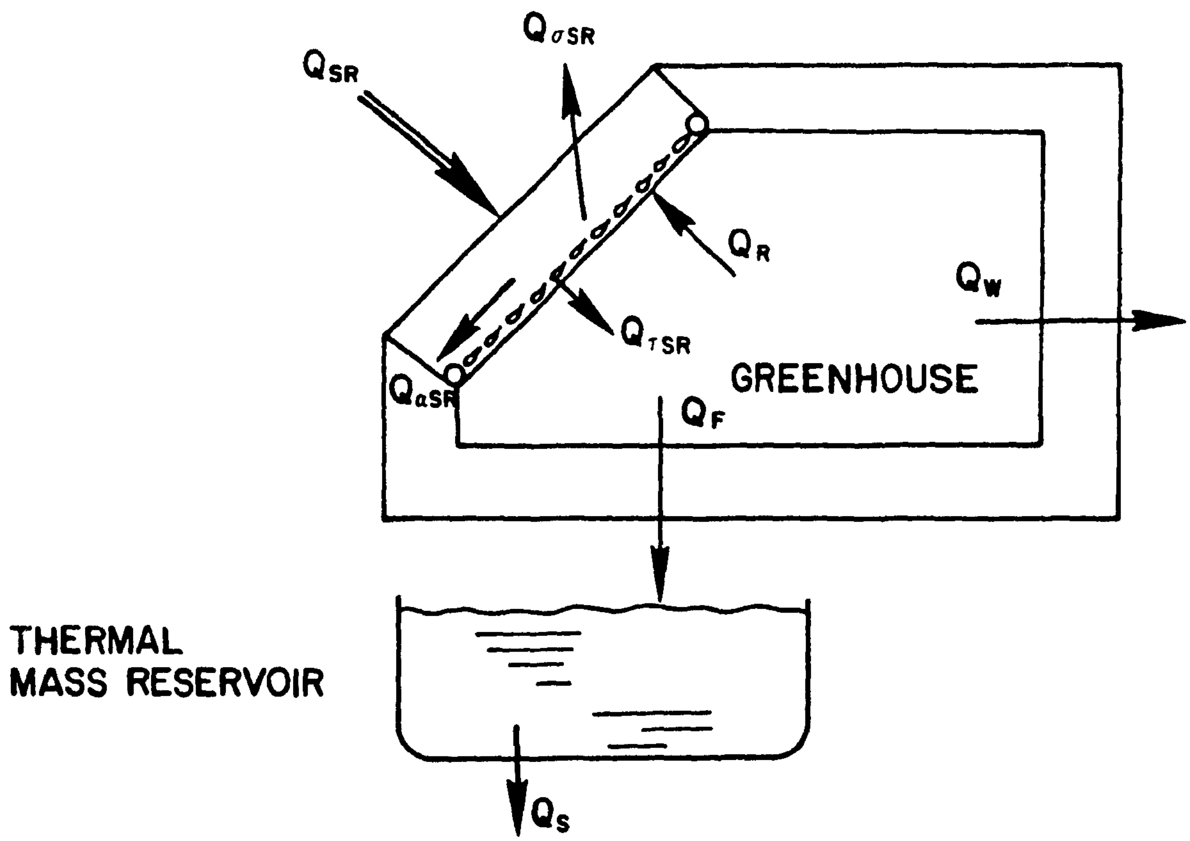

Figure C.5 Schematic description of the heat flows during the day

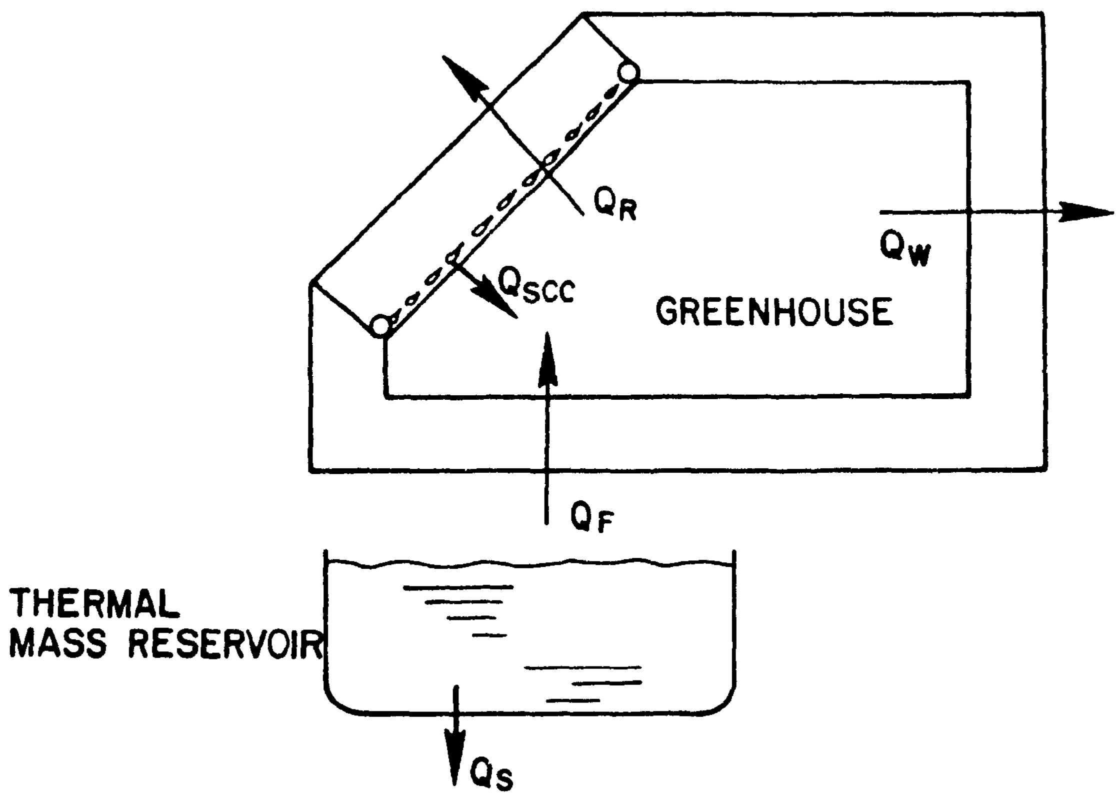

Figure C.6 Schematic description of the heat flows during the night the night, the set-back temperature is allowed to fall to 13°C, unless the exterior temperature is higher, in which case T_{-} is set equal to T_1. For the purpose of the computer simulation, the thermal mass temperature is considered to remain constant at 18,3°C.

The Solar Climate Control system is activated as soon as there exists a cooling or heating load to take care of. The Solar Climate Control reduces the cooling load in two ways: the first is due to its infrared filtering capability while the second is due to heat extraction by conduction through the ceiling panel. Night-time heating is achieved by running the water film continuously. The water transfers heat into the greenhouse at a rate depending on the temperature difference between the greenhouse interior (winter night T_1 = 13°C), and the outside temperature, considering that the water temperature is assumed constant. Nelson (1980) studied the heat extraction rate by a water film. It was shown that the overall heat transfer coefficient (U), prevailing between the ceiling membrane and the interior air is the major restriction for heat flow and could vary within the range of 5,7 W/m^2°C for dry still air and 455 W/m^2°C when the air is humid and water vapour is condensing.

The coefficients of cooling and heating performance of the Solar Climate Control system as a function of the temperature gradient prevailing for the heat flow, and the overall heat transfer coefficient are presented in Figure C.7. The rise in water film temperature (after one pass) as affected by the temperature gradient and the overall heat transfer coefficient, is shown in Figure C.8.

C.1.1 Cost performance

The heat accumulation in the thermal mass was determined by simulation. The water

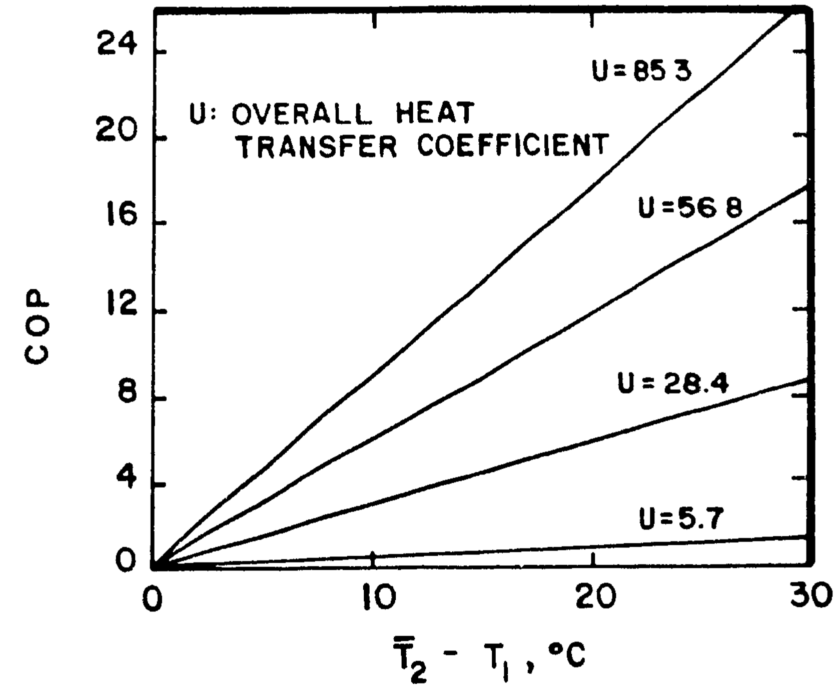

Figure C.7 Coefficient of performance of Solar Climate Control system as a funtion of difference in temperature prevailing between the water film and the interior air temperature

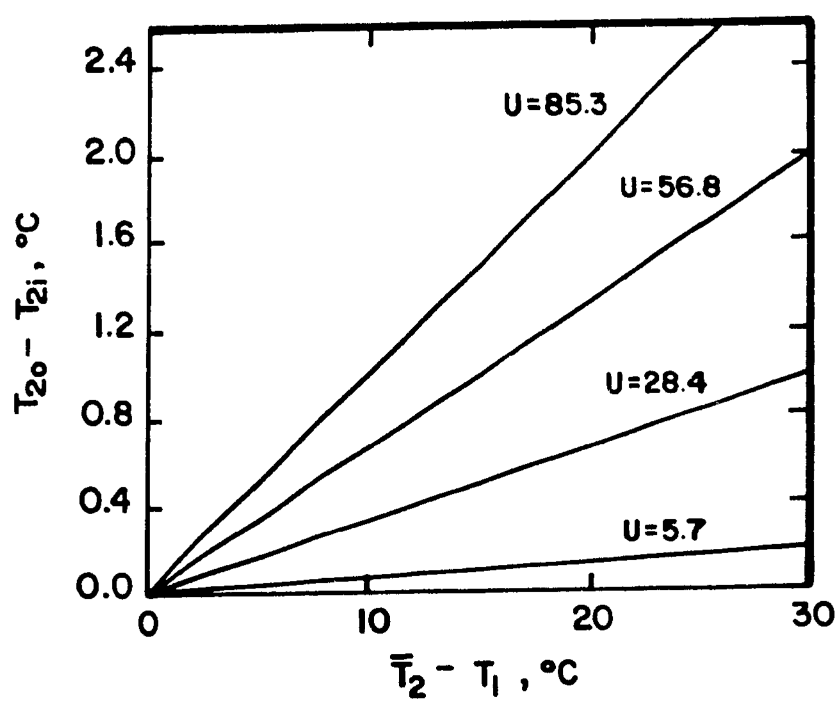

Figure C.8 Change in water film temperature after one pass as a function of temperature prevailing between the water film and the interior air temperature heating capacity is calculated by substracting the heat provided for night-time heating from the heat accumulated in the thermal mass. Figure C.9 shows the simulated year round energy loads for the conventional double-glazed greenhouse and a greenhouse equipped with the Solar Climate Control system. The pumping load necessary to control these loads by the Solar Climate Control system is determined for a heat transfer coefficient of 56,8 W/m$^{2\circ}$C for cooling and 11,36 W/m$^{2\circ}$C for heating. The difference between the two modes is primarily due to external environmental changes. The heat extraction rate (cooling, day time operation) is smaller than the heat delivery rate (heating, mostly night-time operation). This difference will affect the pumping time required to match the demand.

From Table C.1 the heating and cooling benefit, (in GJ), of the roof system, can be calculated as follows:

Heating benefits	=	Heating loads conventional	-	pumping load	**(C.3)**
Cooling benefits	=	Cooling loads conventional	-	pumping load	**(C.4)**

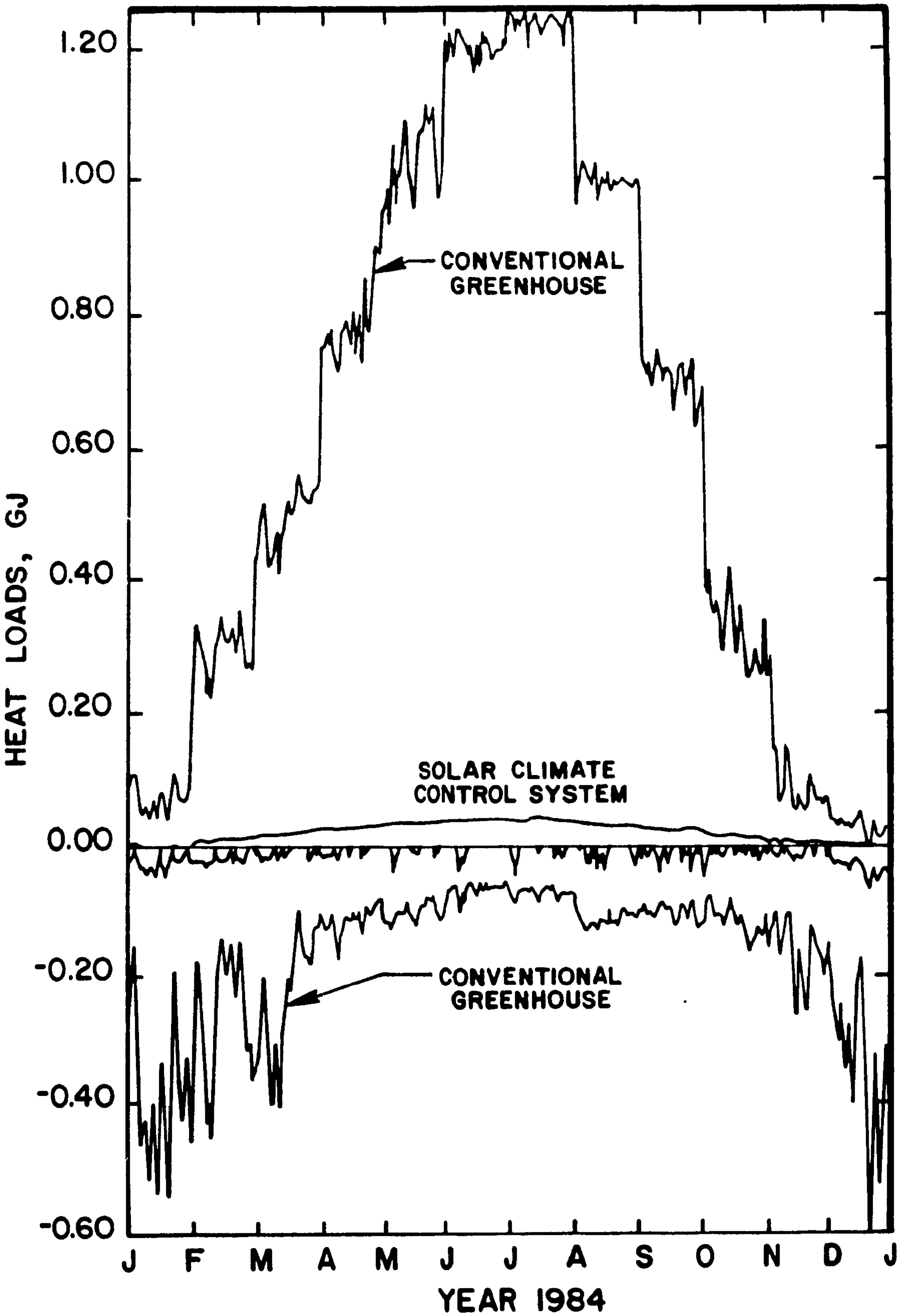

Figure C.9 Heating and cooling loads for a conventional greenhouse and pumping loads of one equipped with the Solar Climate Control system

Table C.1 **Energy load of a conventional double glazed greenhouse and one equipped with the Solar Climate Control system, as simulated with weather data of 1984.**

MONTH	CONVENTIONAL GREENHOUSE		SCC SYSTEM PUMPING LOADS		WATER HEATING CAPACITY
	Heating	Cooling	Heating	Cooling	
	GJ	GJ	GJ	GJ	GJ
Jan.	11,37	2,24	0,8	0,0	-2,06
Feb.	7,22	8,45	0,6	0,3	6,95
Mar.	6,88	15,27	0,3	0,5	15,58
Apr.	3,31	23,34	0,2	0,7	26,43
May	3,08	31,87	0,1	1,0	36,85
June	1,93	35,99	0,1	1,1	42,71
July	2,19	38,41	0,2	1,1	46,05
Aug.	3,42	30,93	0,3	0,8	37,32
Sep.	3,01	20,88	0,4	0,6	23,86
Oct.	3,58	9,86	0,3	0,3	10,86
Nov.	4,78	2,52	0,4	0,1	1,27
Dec.	10,37	0,85	1,2	0,0	-3,61
TOTAL:	61,14	220,61	4,9	6,5	242,24

The sum of the heating and cooling benefits represents the energy saved by the installation of the Solar Climate Control roof system when compared to a conventional double glazed roof. Part of the energy collected by the Solar Control Climate system during the day is used for night-time heating. The remaining energy is defined as the water heating capacity. This portion of useful energy could be added to the energy savings. However because no study has be done as to how to use this available energy, it will not be added to the energy savings to keep the ratio as realistic as possible.

The cost performance ratio is described as the cost of the roof including installation, to the energy performance value. The cost of the roof was estimated at $549/m^2$. The energy saved and collected by the Solar Climate Control system gives the following figures:

Heating benefits	=	56,24 GJ
Cooling benefits	=	214,11 GJ
TOTAL	=	270,35 GJ

$$\text{COST PERFORMANCE RATIO} = \frac{\$549/\text{m}^2}{270{,}35\ \text{GJ}/74{,}3\ \text{m}^2}$$

$$= \$150{,}88/\text{GJ}$$