Operational Strategies for
Attached Sunspaces
in Canada

A Thesis Submitted to the
College of Graduate Studies and Research
in Partial Fulfilment of the Requirements
for the Degree of Master of Science
in the Department of Mechanical Engineering
University of Saskatchewan

by
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Abstract

Sunspaces are gaining considerable consumer appeal and acceptance, however, very little quantitative information exists in terms of their thermal performance in occupied houses. A major concern in the year round use of sunspaces is the control of the air temperature. This problem is usually dealt with in the design stage through proper selection of window areas and envelope thermal properties. However, even a well designed sunspace can have temperatures that fluctuate outside the thermal comfort zone for a significant portion of the year. During this time, auxiliary energy for both heating and cooling must be provided if the sunspace temperature is to remain in the comfort zone. A mathematical model that can accurately predict the thermal performance of a sunspace is required if the auxiliary energy requirements are to be examined over a range of operating strategies and under typical meteorological conditions.

The sunspace model developed consists of finite difference approximations of all the major surfaces such as walls and ceilings. Heat transfer through the doors and windows and infiltration are included in the model as paths directly between the outside or house and the sunspace. Auxiliary energy, in the form of heating and air conditioning, and natural cooling, has also been included in the model. Four sunspaces located in Saskatoon, Saskatchewan are examined to verify the model.
Yearly simulations using Typical Meteorological Year weather data are performed on all the sunspaces to determine the auxiliary energy requirements under different strategies. These yearly simulations are extended to three other cities representative of the major climatic regions of Canada. From these simulations, operational strategies on the use of auxiliary energy for attached sunspaces are developed.

Of the four sunspaces investigated only one has the potential to become a net producer of energy. However, reductions in the yearly auxiliary energy requirements of the sunspace of up to 80% are possible when proper operating strategies are implemented. Effective operating strategies should include,

- the shutting down of the sunspace from December to February to reduce the heating load of the sunspace,
- venting any useful energy produced by the sunspace during the winter to the house for space heating, and,
- using a exhaust fan to the outside to reduce the air-conditioning requirements of the sunspace.
Acknowledgements

I would like to thank my supervisor, Dr. G. J. Schoenau for his support and guidance throughout the course of this research and during the writing of this thesis. The many helpful comments and suggestions provided by Prof. R. W. Besant are gratefully acknowledged. The technical assistance of Mr. D. Deutscher throughout the various stages of this work is appreciated. I would also like to thank my parents for their support and encouragement throughout the preparation of this thesis.

My sincere thanks to the Schoenau, Besant, Coxworth and Katz families for allowing me to intrude upon them.
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Nomenclature

$a^x$    House Shielding Coefficient \( (m^3/s\cdot Pa^n)^x \)

$a_{Ai}$  Sum of all Neighbouring Thermal Conductance-Areas, including the Time Neighbour, for the Exterior Siding of Surface \( i \) \( (W/K) \)

$a_{Ai}^o$  Internal Energy Rate per degree Kelvin of the Exterior Siding of Surface \( i \) \( (W/K) \)

$a_{ABi}$  Thermal Conductance-Area between the Exterior Siding and the Insulation of Surface \( i \) \( (W/K) \)

$a_b$  Thermal Conductance-Area between nodes \( b \) and \( p \) \( (W/K) \)

$a_{Bi}$  Sum of all Neighbouring Thermal Conductance-Areas, including the Time Neighbour, for the Insulation of Surface \( i \) \( (W/K) \)

$a_{Bi}^o$  Internal Energy Rate per degree Kelvin of the Insulation of Surface \( i \) \( (W/K) \)

$a_{BCi}$  Thermal Conductance-Area between the Insulation and the Interior Siding of Surface \( i \) \( (W/K) \)

$a_C$  Sum of all Thermal Conductance-Areas between the Crawlspace and Sunspace Nodes \( (W/K) \)

$a_{Ci}$  Sum of all Neighbouring Thermal Conductance-Areas, including the Time Neighbour, for the Interior Siding of Surface \( i \) \( (W/K) \)
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
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<tbody>
<tr>
<td>$a_{C_i}^o$</td>
<td>Internal Energy Rate per degree Kelvin of the Interior Siding of Surface $i$ (W/K)</td>
</tr>
<tr>
<td>$a_{C_iS}^o$</td>
<td>Thermal Conductance-Area between the Interior Siding of Surface $i$ and the Sunspace Node (W/K)</td>
</tr>
<tr>
<td>$a_e^o$</td>
<td>Thermal Conductance-Area between nodes $e$ and $p$ (W/K)</td>
</tr>
<tr>
<td>$a_{FAi}^o$</td>
<td>Thermal Conductance-Area between the Forcing Temperature and the Exterior Siding of Surface $i$ (W/K)</td>
</tr>
<tr>
<td>$a_{FBi}^o$</td>
<td>Thermal Conductance-Area between the Forcing Temperature and the Insulation of Surface $i$ (W/K)</td>
</tr>
<tr>
<td>$a_H$</td>
<td>Sum of all Thermal Conductance-Areas between the House and Sunspace Nodes (W/K)</td>
</tr>
<tr>
<td>$a_{p,n}^o$</td>
<td>Thermal Conductance-Area between nodes $p$ and $n$ (W/K)</td>
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<tr>
<td>$a_O^o$</td>
<td>Sum of all Thermal Conductance-Areas between the Sunspace and Outside Nodes (W/K)</td>
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<tr>
<td>$a_p^o$</td>
<td>Internal Energy Rate per degree Kelvin of Node $p$ (W/K)</td>
</tr>
<tr>
<td>$a_P$</td>
<td>Sum of all Neighbouring Thermal Conductances-Areas, including the Time Neighbour, for Node $p$ (W/K)</td>
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<td>$a_s$</td>
<td>Thermal Conductance-Area between nodes $s$ and $p$ (W/K)</td>
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<tr>
<td>$a_s^o$</td>
<td>Internal Energy Rate per degree Kelvin of Sunspace Node (W/K)</td>
</tr>
<tr>
<td>$a_t$</td>
<td>Thermal Conductance-Area between nodes $p$ and $t$ (W/K)</td>
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<td>$a_w$</td>
<td>Thermal Conductance-Area between nodes $p$ and $w$ (W/K)</td>
</tr>
<tr>
<td>$A$</td>
<td>Area (m$^2$)</td>
</tr>
<tr>
<td>$A_B$</td>
<td>Surface Area of Sunspace Envelope (m$^2$)</td>
</tr>
<tr>
<td>$A_d$</td>
<td>Surface Area of Sunspace Door (m$^2$)</td>
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A_{i,j} \quad \text{Cross Sectional Area of Layer } j \text{ for Surface } i \ (\text{m}^2)

A_w \quad \text{Window Area} \ (\text{m}^2)

b \quad \text{Power Sources and/or Sinks for Node } p \ (\text{W})

b^x \quad \text{House Shielding Exponent}

b_{Ai} \quad \text{Power Sources and/or Sinks in the Exterior Siding of Surface } i \ (\text{W})

b_{Aux} \quad \text{Auxiliary Energy Rate} \ (\text{W})

b_{Bi} \quad \text{Power Sources and/or Sinks in the Insulation of Surface } i \ (\text{W})

b_{Ci} \quad \text{Power Sources and/or Sinks in the Interior Siding of Surface } i \ (\text{W})

b_S \quad \text{Power Sources and/or Sinks of the Sunspace Node} \ (\text{W})

b_{Solar} \quad \text{Transmitted Solar Radiation Rate} \ (\text{W})

c \quad \text{Concentration of Tracer Gas in Structure at time } t \ (\text{ppm})

c_o \quad \text{Concentration of Tracer Gas in Structure at start of monitoring period} \ (\text{ppm})

c_p \quad \text{Specific Heat} \ (\text{J/kg·K})

c_{pH} \quad \text{Specific Heat of House Air} \ (\text{J/kg·K})

c_{pO} \quad \text{Specific Heat of Outside Air} \ (\text{J/kg·K})

c_{pS} \quad \text{Specific Heat of Sunspace Air} \ (\text{J/kg·K})

C \quad \text{Thermal Capacitance of Sunspace Surface} \ (\text{kJ/K})

C^x \quad \text{Flow Coefficient} \ (\text{m}^3/\text{s·Pa}^{n^x})

f \quad \text{Discretization Weighting Factor}

f_b \quad \text{Ratio of Sunlit Window Area to Total Window Area}
<table>
<thead>
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<tr>
<td>$F_{rg}$</td>
<td>Viewfactor Surface has to the Ground</td>
</tr>
<tr>
<td>$F_{rs}$</td>
<td>Viewfactor Surface has to the Sky</td>
</tr>
<tr>
<td>$G$</td>
<td>Net Rate of Generation of Tracer Gas in Structure (ppm/s)</td>
</tr>
<tr>
<td>$h_{i,j}$</td>
<td>Surface Conductance of Layer $j$ for Surface $i$ (W/m²·K)</td>
</tr>
<tr>
<td>$I$</td>
<td>Total Irradiance on Closed Blinds (W/m²)</td>
</tr>
<tr>
<td>$I_r$</td>
<td>Infiltration Rate of Sunspace (Air Changes per Hour (ACH) or m³/s)</td>
</tr>
<tr>
<td>$I_b$</td>
<td>Beam Irradiance on a Tilted Surface (W/m²)</td>
</tr>
<tr>
<td>$I_{bH}$</td>
<td>Beam Irradiance on a Horizontal Surface (W/m²)</td>
</tr>
<tr>
<td>$I_d$</td>
<td>Diffuse Irradiance on a Tilted Surface (W/m²)</td>
</tr>
<tr>
<td>$I_{dH}$</td>
<td>Diffuse Irradiance on a Horizontal Surface (W/m²)</td>
</tr>
<tr>
<td>$I_T$</td>
<td>Total Irradiance on Tilted Surface (W/m²)</td>
</tr>
<tr>
<td>$I_{TH}$</td>
<td>Total Irradiance on a Horizontal Surface (W/m²)</td>
</tr>
<tr>
<td>$I_{Tr}$</td>
<td>Total Irradiance Transmitted through Glazing Surface (W/m²)</td>
</tr>
<tr>
<td>$k$</td>
<td>Thermal Conductivity (W/m·K)</td>
</tr>
<tr>
<td>$k_b$</td>
<td>Thermal Conductivity between Nodes $b$ and $p$ (W/m·K)</td>
</tr>
<tr>
<td>$k_e$</td>
<td>Thermal Conductivity between Nodes $e$ and $p$ (W/m·K)</td>
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<tr>
<td>$k_t$</td>
<td>Thermal Conductivity between Nodes $p$ and $t$ (W/m·K)</td>
</tr>
<tr>
<td>$k_w$</td>
<td>Thermal Conductivity between Nodes $p$ and $w$ (W/m·K)</td>
</tr>
</tbody>
</table>
\( l \) Width of Homogeneous Wall (m)

\( l_{i,j} \) Width of Layer \( j \) for Surface \( i \) (m)

\( m \) Mass Infiltration/Exfiltration Rate of Sunspace (kg/s)

\( n^x \) Flow Exponent

\( \Delta P \) Inside/Outside Pressure Differential (Pa)

\( q_B \) Energy Flow into the Sunspace through Closed Blinds (W)

\( Q \) Volumetric Flow Rate of Air Leaving or Entering Structure (m\(^3\)/s)

\( Q_{aux} \) Energy furnished by Auxiliary Heating System (kW·hr)

\( Q_{net} \) Building Load (kW·hr)

\( r_\parallel \) Parallel Reflectance of Window

\( r_\perp \) Perpendicular Reflectance of Window

\( R_b \) Geometric Factor, Ratio of Beam Radiation on a Tilted Surface to that on a Horizontal Surface

\( R_{i56} \) Equivalent Resistance of Layers 5 and 6 for Surface \( i \) (K/W)

\( \overline{\Sigma} \) Volumetric Rate of Thermal Energy Generation (W/m\(^3\))

\( \overline{\Sigma}_{Ai} \) Power Sources and/or Sinks in the Exterior Siding of Surface \( i \) (W)

\( \overline{\Sigma}_{Bi} \) Power Sources and/or Sinks in the Insulation of Surface \( i \) (W)

\( \overline{\Sigma}_{Gi} \) Power Sources and/or Sinks in the Interior Siding of Surface \( i \) (W)

\( \overline{\Sigma}_S \) Power Sources and/or Sinks in the Sunspace Node (W)

SSF Solar Saving Fraction
\( t \)  \hspace{1cm} \text{Time (sec.)} \\
\( T \)  \hspace{1cm} \text{Temperature (C)} \\
\( T_{Ai} \)  \hspace{1cm} \text{Exterior Siding Temperature of Surface } i \text{ (C)} \\
\( T_{Bi} \)  \hspace{1cm} \text{Insulation Temperature of Surface } i \text{ (C)} \\
\( T_{Bl} \)  \hspace{1cm} \text{Blind Temperature (C)} \\
\( T_C \)  \hspace{1cm} \text{Crawlspace Temperature (C)} \\
\( T_{Ci} \)  \hspace{1cm} \text{Interior Siding Temperature of Surface } i \text{ (C)} \\
\( T_F \)  \hspace{1cm} \text{Forcing Temperature (C)} \\
\( T_H \)  \hspace{1cm} \text{House Temperature (C)} \\
\( T_o \)  \hspace{1cm} \text{Initial Temperature of a Homogeneous Wall (C)} \\
\( T_O \)  \hspace{1cm} \text{Outside Temperature (C)} \\
\( T_S \)  \hspace{1cm} \text{Sunspace Temperature (C)} \\
\( T(z,t) \)  \hspace{1cm} \text{Theoretical Temperature of a Homogeneous Wall (C)} \\
\( \Delta t \)  \hspace{1cm} \text{Time Step (sec.)} \\
\( \Delta T \)  \hspace{1cm} \text{Inside/Outside Temperature Differential (C)} \\
\( U_{bo} \)  \hspace{1cm} \text{Thermal Conductance of Outside Portion of Window with Blinds Closed (W/m}^2\cdot\text{K}) \\
\( U_d \)  \hspace{1cm} \text{Thermal Conductance of Sunspace Door (W/m}^2\cdot\text{K}) \\
\( U_{iw} \)  \hspace{1cm} \text{Thermal Conductance of Sunspace Window } i \text{ (W/m}^2\cdot\text{K}) \\
\( U_{sb} \)  \hspace{1cm} \text{Thermal Conductance of Inside Portion of Window with Blinds Closed (W/m}^2\cdot\text{K}) \\
\( U_{so} \)  \hspace{1cm} \text{Thermal Conductance of Window with Blinds Closed (W/m}^2\cdot\text{K})
\( \dot{v} \)  Volumetric Rate at which Air Leaves Structure (m\(^3\)/s)

\( Vol \)  Volume (m\(^3\))

\( Vol_s \)  Volume of Sunspace (m\(^3\))

\( \delta x \)  Distance between Nodes in X Dimension (m)

\( \Delta x \)  Control Volume Thickness in X Dimension (m)

\( \delta y \)  Distance between Nodes in Y Dimension (m)

\( \Delta y \)  Control Volume Thickness in Y Dimension (m)

\( \delta z \)  Distance between Nodes in Z Dimension (m)

\( \Delta z \)  Control Volume Thickness in Z Dimension (m)

\( \alpha \)  Thermal Diffusivity (m\(^2\)/s), or Absorbtivity of Surface

\( \alpha_b \)  Absorbtivity of Closed Blinds

\( \beta \)  Slope of Surface from Horizontal (°)

\( \phi_1 \)  Angle of Incidence (°)

\( \phi_2 \)  Angle of Refraction (°)

\( \pi \)  Pi

\( \rho \)  Mass Density (kg/m\(^3\))

\( \sigma \)  Ground Reflectance

\( \tau_b \)  Optical Transmittance of Window for Beam Radiation

\( \tau_g \)  Optical Transmittance of Window for Ground Reflected Radiation

\( \tau_N \)  Optical Transmittance of Window consisting of N Glazing Layers for Total Radiation

\( \tau_s \)  Optical Transmittance of Window for Sky Diffuse Radiation
Subscripts

\[ b \]  Node in the Negative Z Direction

\[ e \]  Node in the Positive X Direction

\[ n \]  Node in the Positive Y Direction

\[ p \]  Current Node being Examined

\[ s \]  Node in the Negative Y Direction

\[ t \]  Node in the Positive Z Direction

\[ w \]  Node in the Negative X Direction

Superscripts

\[ T \]  New or *unknown* Temperatures at time \( t + \Delta t \)

\[ T^o \]  Old or *given* Temperatures at time \( t \)

Counter

\[ i \]  Surface Counter

\[ j \]  Layer Counter of Surface \( i \)

\[ n \]  counter

\[ N \]  Number of Glazing Layers in Window Assembly
Chapter 1
Introduction

Canada enjoys an abundance of energy sources both non-renewable and renewable. This is fortunate in light of the fact that Canadians consume more energy on a per capita and per dollar of GNP basis, than citizens of most other industrialized countries, who, in turn, are the largest consumers of energy in the world. Climate and geography are major reasons for this high consumption rate [1].

Conservation measures in the residential sector emphasize the construction of super insulated dwellings. These structures are designed to have an annual space heating load of less than 20 GJ. Common features of this type of dwelling are airtight air-vapour barriers, air-to-air heat exchangers, very high insulation levels and extra window glazing layers on windows which mostly face south [2]. But other conservation measures which can be taken to reduce energy consumption include the use of high efficiency gas furnaces, night setback thermostats [3].

A feature that is becoming more common with homeowners is the sunspace. Many view it as an energy efficient option, however this depends upon how it is utilized as well as its design characteristics. A sunspace is a room located on the south side of a building and separated from other building spaces by a common wall. It often has much of its exterior walls and roof glazed to permit the entry of solar radiation. The temperature of the sunspace is not regulated closely and therefore requires little, if any, auxiliary heat. The sunspace receives solar energy all year long and therefore in warm periods shading must be provided and the sunspace vented to the outside to eliminate excess heat [4].
A sunspace may have several different functions depending upon owner lifestyle and preference. The two most common uses of sunspaces are as greenhouses or living spaces. The users of the former are interested in plant production, solar energy or the overall lifestyle benefits that an attached greenhouse can provide. This type of sunspace can vary quite widely according to the configuration of the structure, the materials chosen, the quality of workmanship and the overall investment.

The later type of sunspace is viewed by the home owner as a luxury item. The user is interested in the daylight space as an addition to the quality of his home environment. The sunspace may be a sitting room, a breakfast nook or any other type of living space. There is very little incentive for energy efficiency in this type of sunspace at present simply because low cost and energy consumption are not priorities of these users. They want the space and are willing to pay for it, and do not expect a return on their investment in the form of heat generated by solar energy [5].

1.1. Sunspace Design

The level of effort required to design a sunspace ranges from the use of simple rules of thumb and/or design charts to detailed simulations capable of accurately predicting the performance of sunspaces. Both types have their place in the design process. It would be a waste of time and money to implement in-depth simulations of a sunspace at the beginning of the design stage and equally so, the use of rules of thumb and design charts in the final stages of design.

The Passive Solar Heating Analysis developed at the Los Alamos National Laboratory is a methodology that allows the designer to choose from 28 different reference sunspaces. Estimates of annual and monthly consumption of energy required to maintain comfort during the heating season can then be determined. It is expected that this analysis will give results that are within 10 to 15% of the actual levels of energy consumption.
The effect on performance of a difference in one or more of the design parameters can be estimated using sensitivity curves [4].

The Tennessee Valley Authority (TVA) has also developed design guidelines that can be used to design attached sunspaces. These guidelines however are restricted to the climatic conditions encountered for that portion of the United States only. The types of sunspaces examined were heat producing, plant producing and a combination of the two defined as living space. The design guidelines that were developed cover [6],

- sizing (floor area and glazing),
- insulation levels,
- optimum slope of glazing surfaces,
- sizing of thermal storage mass, and
- sizing of interior and exhaust fans.

The computer has made it possible for detailed simulations to be performed on sunspaces with relative ease. The speed at which these simulations can be performed allows the detailed performance of the sunspace to be investigated much earlier in the design of the sunspace thereby reducing the need for rules of thumb or design charts. The chief advantages of computer simulations are [7],

- effects of simultaneous interaction of several inputs and component parameters on the system behaviour may be studied, and
- range of systems and their properties may be studied in less time and cost than if one were to build those systems.
1.2. Research Objectives and Outline

Attached sunspaces are gaining considerable consumer appeal and acceptance. However, very little quantitative information exists in terms of their thermal performance in actual installations. This information is required as a sound basis for the promotion of these structures and to avoid any exaggerated claims regarding their efficiency. The main objectives of the research work is to assess the thermal performance of several different sunspace designs with regards to the following,

- a determination of the heating energy efficiency of sunspaces,
- an assessment of the thermal comfort of sunspaces, and
- recommendations regarding the operation of sunspaces.

Since the emphasis is on occupied structures, as opposed to test-cells, four sunspaces were chosen for the investigation. The sunspaces cover the typical range of construction and orientations. Two of the sunspaces represent energy efficient building construction and were built at the same time as the adjoining houses. The other two sunspaces were owner built additions with lower levels of insulation and air tightness. In each of the above categories, one of the sunspaces has predominantly south facing glazing and the other a primary non-south glazed area.

Various simulation programs exist which allow the thermal behaviour of sunspaces to be investigated. Some programs originally developed for residential dwellings have been modified to allow sunspace modelling to be performed while others have been specifically designed for the modelling of these structures [8, 14].
An evaluation of software for the thermal design of passive solar residences was done which identified five programs which meet the following criteria:

- U.S. or Canadian in origin,
- commercially available,
- not research oriented, and
- designed primarily for single family residential construction.

The programs were ENERPASS, CALPAS3, SUNCODE, MICROPAS and SERI-PAS. Of these, ENERPASS, was available at the University of Saskatchewan. This program however does not allow on-site measurements to be used in the simulation process [15]. This limits its usefulness because the accuracy of the program can not be verified directly. It was decided therefore that a model capable of accurately predicting the thermal performance of the sunspaces being investigated should be developed.

An experimental investigation was performed on each of the chosen sunspaces to check the validity of the model developed. This investigation examines the sunspaces under several different conditions to determine whether the model is accurate and flexible enough to simulate a variety of operating conditions.

Yearly simulations of each of the sunspaces were initiated to determine the performance of the different sunspaces. From these simulations several sunspace operating strategies were developed and examined to determine their effectiveness in reducing the auxiliary energy demands of the sunspace. This study did not consider the capital and operating costs of the strategies.

A brief discussion of possible directions future work in this area can follow is presented.
Chapter 2
Experimental Investigation

2.1. Introduction

Any model developed to explore the auxiliary energy requirements of a sunspace must be a responsible representation of the structure if the model is to be a useful tool in determining the effect of different operational strategies on the auxiliary requirements of a sunspace. The simplest and probably the most logical method to check the model is to compare the predicted temperatures with measured sunspace temperatures.

2.2. Sunspace Descriptions

Four sunspaces of varying construction and style were selected for this investigation.

2.2.1. Sunspace A

Construction on house A was completed in 1985. The house was built in one of the newer subdivisions of Saskatoon. This two story super-insulated house has approximately 300 m² of floor area. The sunspace was built at the same time as the house.

The sunspace has a floor area of 26.8 m² and a volume of 67.5 m³. The floor plan of the sunspace is shown in Figure 2-1. The orientation of the sunspace is 18° NE but is shown as North in Figure 2-1.

As shown in the vertical north-south cross section, Figure 2-2, of the
sunspace it was constructed over an unheated crawlspace. The sunspace is a light structure with wood frame walls covered with gypsum board on the interior and stucco on the exterior. The floor is covered in ceramic tile and carpet. The sunspace is connected to the main part of the house by double french doors.

The sunspace has double glazed surfaces on the west, south and east exterior walls as well as on the interior wall connecting the house and the sunspace. The exterior windows have a low emissivity venetian type blind mounted between the glazings.

Table 2-1 presents the thermal characteristics of the sunspace. These thermal characteristics were calculated using standard ASHRAE
Figure 2-2: North-South Cross-sectional View of Sunspace A

techniques [16]. Appendix A provides detailed drawings of the sunspace construction.

<table>
<thead>
<tr>
<th>Surface Description</th>
<th>U</th>
<th>A</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Int. 1st and 2nd Floor Walls</td>
<td>.37</td>
<td>12.0</td>
<td>142.6</td>
</tr>
<tr>
<td>Int. Ceiling</td>
<td>.22</td>
<td>6.0</td>
<td>142.6</td>
</tr>
<tr>
<td>Carpeted Floor</td>
<td>.22</td>
<td>17.0</td>
<td>328.2</td>
</tr>
<tr>
<td>Tiled Floor</td>
<td>.22</td>
<td>9.8</td>
<td>167.5</td>
</tr>
<tr>
<td>Exterior Walls</td>
<td>.37</td>
<td>32.9</td>
<td>447.0</td>
</tr>
<tr>
<td>Ceiling</td>
<td>.25</td>
<td>22.2</td>
<td>299.2</td>
</tr>
<tr>
<td>Interior Windows</td>
<td>2.8</td>
<td>4.8</td>
<td>--</td>
</tr>
<tr>
<td>Interior Door</td>
<td>1.9</td>
<td>2.3</td>
<td>--</td>
</tr>
<tr>
<td>West Exterior Window</td>
<td>2.5</td>
<td>0.7</td>
<td>--</td>
</tr>
<tr>
<td>South Exterior Window</td>
<td>2.5</td>
<td>6.6</td>
<td>--</td>
</tr>
<tr>
<td>East Exterior Window</td>
<td>2.5</td>
<td>1.1</td>
<td>--</td>
</tr>
<tr>
<td>Exterior Door</td>
<td>2.3</td>
<td>1.6</td>
<td>--</td>
</tr>
</tbody>
</table>

Table 2-1: Thermal Characteristics of Sunspace A
2.2.2. Sunspace B

Constructed in 1983 House B is located on an acreage south of Saskatoon. This split-level super-insulated house has a floor area of 170 m². The sunspace was built at the same time as the house.

The sunspace has a floor area of 21.3 m² and a volume of 53.3 m³. The orientation and floor plan of the sunspace are shown in Figure 2-3.

![Floor Plan of Sunspace B](image)

**Figure 2-3: Floor Plan of Sunspace B**

Like sunspace A this one was also constructed over an unheated crawlspace. The sunspace is a light structure made of wood frame walls covered with gypsum board on the interior and cedar siding on the exterior. The north wall has cedar siding in addition to the gypsum board on the
Figure 2-4: North-South Cross-sectional View of Sunspace B

interior and the exterior cedar siding has been replaced with field stone. The floor is covered in ceramic tile. Sliding patio doors connect the house and sunspace. Figure 2-4 shows the east-west cross section of the sunspace.

The sunspace has outer facing glazed surfaces on the south and west walls as shown in Figure 2-3. These windows are double glazed factory sealed units. Vertical and horizontal venetian blinds were installed on the inside of the windows.

Table 2-2 presents the thermal characteristics of the sunspace. These thermal characteristics were calculated using standard ASHRAE techniques. Appendix A provides detailed drawings of the sunspace construction.
<table>
<thead>
<tr>
<th>Surface Description</th>
<th>U (\text{W/m}^2\text{K})</th>
<th>A (\text{m}^2)</th>
<th>C (\text{kJ/K})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interior Wall</td>
<td>.15</td>
<td>12.3</td>
<td>169.2</td>
</tr>
<tr>
<td>Tiled Floor</td>
<td>.33</td>
<td>21.3</td>
<td>233.3</td>
</tr>
<tr>
<td>North Exterior Wall</td>
<td>.57</td>
<td>4.6</td>
<td>246.9</td>
</tr>
<tr>
<td>Other Exterior Walls</td>
<td>.59</td>
<td>11.4</td>
<td>125.3</td>
</tr>
<tr>
<td>Ceiling</td>
<td>.18</td>
<td>21.6</td>
<td>380.8</td>
</tr>
<tr>
<td>Interior Patio Door</td>
<td>3.57</td>
<td>3.7</td>
<td>--</td>
</tr>
<tr>
<td>West Exterior Windows</td>
<td>2.52</td>
<td>6.3</td>
<td>--</td>
</tr>
<tr>
<td>South Exterior Windows</td>
<td>2.52</td>
<td>5.3</td>
<td>--</td>
</tr>
<tr>
<td>Exterior Door</td>
<td>1.72</td>
<td>3.6</td>
<td>--</td>
</tr>
</tbody>
</table>

Table 2-2: Thermal Characteristics of Sunspace B

2.2.3. Sunspace C

House C was constructed in the early 1960’s and is located in an older area of Saskatoon. This two story house has approximately 230 \(\text{m}^2\) of floor area. The sunspace was built in 1980 with the intention of using it as a greenhouse during the summer months.

The sunspace has a floor area of 13.3 \(\text{m}^2\) and a volume of 40.0 \(\text{m}^3\). The orientation and floor plan of the sunspace are shown in Figure 2-5.

The sunspace is constructed over an unheated crawlspace. With the exception of the two inch interlocking bricks that cover the floor the sunspace is a very light structure. The outside sunspace surfaces are either wood frame or plywood sandwich walls. The sunspace has doors to the outside and house. The sunspace is equipped with a thermostatically controlled fan to provide some degree of cooling when needed.

The sunspace has double glazed windows on the west, south and east walls as well as the ceiling as shown in Figures 2-5 and 2-6.

Table 2-3 presents the thermal characteristics of the sunspace. These thermal characteristics were calculated using standard ASHRAE techniques. Appendix A provides detailed drawings of the sunspace construction.
Figure 2-5: Floor Plan of Sunspace C
### Table 2-3: Thermal Characteristics of Sunspace C

<table>
<thead>
<tr>
<th>Surface Description</th>
<th>U</th>
<th>A</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interior Wall</td>
<td>.50</td>
<td>9.1</td>
<td>92.8</td>
</tr>
<tr>
<td>Tiled Floor</td>
<td>.29</td>
<td>13.3</td>
<td>488.5</td>
</tr>
<tr>
<td>Exterior Walls</td>
<td>1.11</td>
<td>12.0</td>
<td>105.9</td>
</tr>
<tr>
<td>Ceiling</td>
<td>.09</td>
<td>6.6</td>
<td>129.2</td>
</tr>
<tr>
<td>Interior Windows</td>
<td>3.52</td>
<td>3.1</td>
<td>--</td>
</tr>
<tr>
<td>Interior Door</td>
<td>2.25</td>
<td>2.0</td>
<td>--</td>
</tr>
<tr>
<td>West Exterior Windows</td>
<td>3.00</td>
<td>2.6</td>
<td>--</td>
</tr>
<tr>
<td>South Exterior Windows</td>
<td>3.00</td>
<td>5.2</td>
<td>--</td>
</tr>
<tr>
<td>East Exterior Windows</td>
<td>3.00</td>
<td>2.6</td>
<td>--</td>
</tr>
<tr>
<td>Skylights</td>
<td>3.61</td>
<td>6.9</td>
<td>--</td>
</tr>
<tr>
<td>Exterior Door</td>
<td>2.75</td>
<td>2.0</td>
<td>--</td>
</tr>
</tbody>
</table>
2.2.4. Sunspace D

House D was constructed in 1980 and was built in a northern subdivision of Saskatoon. This one story house has approximately 125 m\(^2\) of floor area. The sunspace was constructed six years after the house. The homeowners use the sunspace as a greenhouse throughout the year.

The sunspace has a floor area of 10.8 m\(^2\) and a volume of 30.8 m\(^3\). The floor plan of the sunspace is shown in Figure 2-7. The orientation of the sunspace is 14° NE but is shown as North in Figure 2-7.

![Figure 2-7: Floor Plan of Sunspace D](image)

The sunspace was constructed on a two inch concrete slab. It is a light structure with plywood sandwich exterior walls and doors connect it to
the house and outside. A heater and fan which are thermostatically controlled were installed to provide the sunspace with the necessary heating and cooling when needed.

The sunspace has exterior glazed surfaces on the south and east walls and on the roof as shown in Figures 2-7 and 2-8. These windows consist of a single sheet of plexiglas combined with a plastic film on the inside to form a dead air space between them.

Table 2-4 presents the thermal characteristics of the sunspace. These thermal characteristics were calculated using standard ASHRAE techniques. Appendix A provides detailed drawings of the sunspace construction.

![West-East Cross-sectional View of Sunspace D](image)

**Figure 2-8**: West-East Cross-sectional View of Sunspace D
<table>
<thead>
<tr>
<th>Surface Description</th>
<th>U</th>
<th>A</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>W/m²K</td>
<td>m²</td>
<td>kJ/K</td>
</tr>
<tr>
<td>Interior House Wall</td>
<td>.29</td>
<td>13.0</td>
<td>218.7</td>
</tr>
<tr>
<td>Interior House Basement Wall</td>
<td>.85</td>
<td>2.6</td>
<td>292.7</td>
</tr>
<tr>
<td>Floor</td>
<td>2.94</td>
<td>10.8</td>
<td>307.3</td>
</tr>
<tr>
<td>Exterior Walls</td>
<td>.64</td>
<td>8.9</td>
<td>133.7</td>
</tr>
<tr>
<td>House Overhang</td>
<td>.31</td>
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<td>70.2</td>
</tr>
<tr>
<td>Interior Windows</td>
<td>2.56</td>
<td>4.3</td>
<td>--</td>
</tr>
<tr>
<td>Interior Door</td>
<td>1.90</td>
<td>2.0</td>
<td>--</td>
</tr>
<tr>
<td>South Exterior Windows</td>
<td>3.33</td>
<td>1.8</td>
<td>--</td>
</tr>
<tr>
<td>East Exterior Windows</td>
<td>3.33</td>
<td>5.3</td>
<td>--</td>
</tr>
<tr>
<td>Skylights</td>
<td>3.33</td>
<td>6.9</td>
<td>--</td>
</tr>
<tr>
<td>Exterior Door</td>
<td>1.35</td>
<td>1.7</td>
<td>--</td>
</tr>
</tbody>
</table>

Table 2-4: Thermal Characteristics of Sunspace D

2.3. Instrumentation

2.3.1. Introduction

Various methodologies have been developed which identify the variables that need to be monitored when investigating passive solar residential dwellings [17, 23]. The variables identified as being important are,

- solar radiation on one or more planes,
- climate variables, with a minimum of ambient temperature and wind speed,
- structure temperature at several locations, and
- system status (i.e. movable insulation, blind, fan and/or heater operation).

The monitoring of the variables identified should allow for an accurate estimate of the building thermal performance to be made and provide detailed data regarding climate, temperature and energy needs of the structure.
2.3.2. Temperature Measurements

All temperature measurements were taken using Type 'T' thermocouples. With the exception of the crawlspace or slab thermocouples every thermocouple was fitted with a radiation shield of shiny aluminium to prevent any erroneous measurements due to radiation.

The number of thermocouples that were installed for each of the sunspaces is described in Table 2-5. To measure any stratification that may occur within the sunspace three thermocouples were mounted in a vertical string at prescribed distances from the ceiling and floor within each of the sunspaces as shown in Figure 2-9.

<table>
<thead>
<tr>
<th>Sunspace</th>
<th>Location</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>House</td>
<td></td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Sunspace</td>
<td></td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Crawlspace/Slab</td>
<td></td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Outside</td>
<td></td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 2-5: Placement of Thermocouples for the Four Sunspaces being Investigated

2.3.3. Radiation Measurements

Each sunspace was equipped with two pyranometers to allow the monitoring of solar insolation. Eppley Precision Model PSP Pyranometers, Eppley Black and White Model 8-48 Pyranometers and Hollis Model MR-5 Pyranometers were used for these measurements. Every pyranometer was mounted in the plane of a major glazing surface to allow for the direct determination of the solar radiation incident on the glazing surfaces. This is presented in Figure 2-9. Table 2-6 describes the pyranometers and their placement at each of the sunspaces.
Table 2-6: Placement of Pyranometers for the Four Sunspaces being Investigated

<table>
<thead>
<tr>
<th>Sunspace</th>
<th>Type</th>
<th>Orient.</th>
<th>Slope</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>PSP</td>
<td>South</td>
<td>Vert (90°)</td>
</tr>
<tr>
<td></td>
<td>MR-5</td>
<td>East</td>
<td>Vert (90°)</td>
</tr>
<tr>
<td>B</td>
<td>PSP</td>
<td>South</td>
<td>Vert (90°)</td>
</tr>
<tr>
<td></td>
<td>B+W</td>
<td>West</td>
<td>Vert (90°)</td>
</tr>
<tr>
<td>C</td>
<td>PSP</td>
<td>South</td>
<td>Vert (90°)</td>
</tr>
<tr>
<td></td>
<td>B+W</td>
<td>South</td>
<td>44°</td>
</tr>
<tr>
<td>D</td>
<td>MR-5</td>
<td>East</td>
<td>Vert (90°)</td>
</tr>
<tr>
<td></td>
<td>MR-5</td>
<td>East</td>
<td>12°</td>
</tr>
</tbody>
</table>

2.3.4. Wind Measurements

Due to the lack of proper equipment, on-site monitoring of the wind speed and direction was not performed. However hourly wind speeds and directions were taken from Monthly Meteorological Summaries of Saskatoon produced by Environment Canada [24].

2.3.5. Auxiliary Energy Measurements

Auxiliary energy was introduced into the sunspaces using exhaust fans and 1500 Watt electrical heaters. Auxiliary heating for all sunspaces was controlled by the computers. Due to system constraints however, only sunspaces A and B were provided with computer controlled fans, the homeowners controlling and monitoring the fan operation at the other two sunspaces.

For sunspace A and B, the fan velocity was monitored using an anemometer manufactured by Airflow Developments and mounted directly in the air stream as shown in Figure 2-9. Measurements were done using this same type of anemometer to determine the velocity of the fan at the other two sunspaces.
2.4. Measurement Instrumentation

The data acquisition systems used to monitor the four sunspaces were two M8082A Electronic Measurement Systems and two Labmates both manufactured by Sciemetric Instruments. The M8082A allows up to 64 analog and 16 digital inputs. The Labmate is limited to 16 analog and 8 digital inputs. The M8082A's and the Labmate's were controlled by three Commodore PC-10 computers and one Commodore Pet computer. The Pet was replaced by a Sanyo MBC-880 early in the monitoring process to ease future data analysis requirements. With the exception of the Pet all the micro-computers used were IBM compatible. One of the Commodore PC-10's was replaced when the power pole outside the house of one of the sunspaces was hit by lightning ruining the computer's power supply.

The analog to digital, (A/D), converters of both systems were controlled by software provided with the instruments. The data acquisition
software consisted of calling subroutines which then performed the A/D conversion for a particular channel. The various channels were monitored every fifteen seconds and then averaged every hour. These averages were stored on floppy disks at the end of each hour. Periodically the stored data was retrieved from the floppy disk. It was formatted using the Super-Calc 4 [25] spreadsheet program with the KERMIT communications program being used for data transfer to a Digital VAX 8600 computer for future analysis.
Chapter 3
Sunspace Modelling

3.1. Introduction

The development of a thermal model can be approached from two distinctly different points of view. The first, would be to assume that the thermal performance of the structure is dependent upon a large number of variables, all of which must be included to ensure the model achieves the desired accuracy. A problem with this approach is that the interactions between many of these variables may not be known. More importantly though, many of these variables may not even play a significant role in determining the thermal performance of the structure and therefore should be neglected.

A more practical approach would be to develop a model which includes only the most elementary variables. Once this model has been developed other variables may be considered if the accuracy of the model is in question.

Any model which will accurately predict the thermal performance of a sunspace must include at least the following;

1. A modelling technique which can accurately predict energy transfer and storage within the sunspace structure.

2. A model which will accurately represent the major surfaces of the sunspace. This model must connect the sunspace with the three driving temperatures, namely the house, crawlspace and the outside temperatures. Each node in the model must have the proper resistance and capacitance associated with it to ensure
accurate energy storage within that node and energy transfer between it and the other nodes in the model.

3. The accurate determination of solar radiation incident on the outside surfaces of the sunspace as well as any solar radiation that is transmitted through the glazing surfaces to inside surfaces.

4. An accurate representation of the infiltration rates which occurs within the sunspace. This must include both air transfer between the house and the sunspace as well as between the sunspace and the outside.

5. The inclusion of auxiliary energy. This energy can take the form of either heating or cooling of the sunspace air.

3.2. Modelling Techniques

3.2.1. Introduction

From a thermal standpoint any building can be viewed as a network of temperatures linked by conductive, convective and radiative processes. The manner in which this network is handled, where some nodes and/or processes are neglected or fixed values assigned will determine the type of model selected.

The simplest type of model which can be employed is the steady state model. This type has no mechanisms for dealing with the effects of solar or casual gains, and operational strategies, etc. and so addresses only the energy transfer within the structure and is not concerned with energy storage or time effects. Models of this type omit any consideration of the dynamic responses of the building and therefore lack the ability to realistically deal with any storage of energy occurring within the structure.

Finite difference models when constructed properly can be applied equally to conventional problems and to problems that are not otherwise solvable, such as, non-linear effects and system properties which are temperature, moisture or time dependent. Non-linearities and variable system properties can be handled through a simple iterative process [11].
3.2.2. Modelling

The governing equation for heat conduction can be written as,

\[
\frac{\partial}{\partial x} (k \frac{\partial T}{\partial x}) + \frac{\partial}{\partial y} (k \frac{\partial T}{\partial y}) + \frac{\partial}{\partial z} (k \frac{\partial T}{\partial z}) + \dot{S} = \rho_c \frac{\partial T}{\partial t} \tag{3.1}
\]

This equation states that at any point in a medium the net conduction heat rate into a unit volume plus the volumetric rate of thermal energy generation must equal the rate of change of thermal energy stored within the volume. In most cases the analytical solution of Equation (3.1) is very complex and must be solved using numerical methods. A numerical solution of such an equation consists of a set of temperatures at a finite number of locations, or nodal points, from which the distribution of the temperature can be constructed. The continuous distribution of temperatures is replaced with a discrete set of values.

Some restrictions however must be placed on the numerical solution chosen to ensure that the results have a physically realistic behaviour and overall balance. These restrictions are easy to explain. A realistic temperature variation should have the same qualitative trend as the exact variation has. In heat conduction without sources for example, no temperature can lie outside the range of temperatures imposed by the boundary conditions. The requirement of overall balance suggests that conservation be ensured over the entire domain. This implies that heat fluxes and mass flow rates must correctly give an overall balance with appropriate sources and sinks.

3.2.3. Discretization Schemes

One dimensional unsteady heat conduction is described by,

\[
\frac{\partial}{\partial x} (k \frac{\partial T}{\partial x}) = \rho_c \frac{\partial T}{\partial t} \tag{3.2}
\]

For convenience \(\rho_c p\) and \(k\) will be assumed to be constant and the
source term, $\mathbf{S}$ is temporarily dropped. Since time is a one-way coordinate, that is the conditions at a given location are influenced by changes in conditions on only one side of the location, the solution is obtained by marching in time from a given set of initial conditions. Thus in a typical time step one must find the values of $T$ at some time $t+\Delta t$ given the nodal values of $T$ at time $t$. If the node $p$ is considered, which has the nodes $e$ and $w$ as its neighbours then the old \textit{(given)} values of $T$ at time $t$ will be denoted as $T_p^0$, $T_e^0$ and $T_w^0$ and the new \textit{(unknown)} values at time $t$ by $T_p$, $T_e$ and $T_w$ ($e$ denotes the east side, or the positive $x$ direction, while $w$ stands for the west or the negative $x$ direction). The discretization equation is derived by integrating the equation over the $x$ dimension from $w$ to $e$ and over the time interval from $t$ to $t+\Delta t$. For the representation of the term $\partial T/\partial t$, the assumption shall be made that the $T_p$ node prevails throughout the time interval. Integrating Equation(3.2) with respect to $x$ and $t$ gives,

$$\int_t^{t+\Delta t} \left[ \frac{k_e(T_e-T_p)}{\delta x_e} - \frac{k_w(T_p-T_w)}{\delta x_w} \right] dt = \rho c_p \Delta x \left( T_p - T_p^0 \right) \tag{3.3}$$

An assumption must be made about how the temperatures vary with time from $t$ to $t+\Delta t$. Many are possible and some can be generalized by proposing,

$$\int_t^{t+\Delta t} T_p dt = [fT_p + (1-f)T_p^0] \Delta t \tag{3.4}$$

where $f$ is a weighting factor between 0 and 1. Using similar equations for the integrals of $T_e$ and $T_w$, Equation(3.3) can be expanded to

$$\rho c_p \frac{\Delta x}{\Delta t} (T_p - T_p^0) = f\left[ \frac{k_e(T_e-T_p)}{\delta x_e} - \frac{k_w(T_p-T_w)}{\delta x_w} \right] + (1-f)\left[ \frac{k_e(T_e-T_e^0)}{\delta x_e} - \frac{k_w(T_e^0-T_p^0)}{\delta x_w} \right] \tag{3.5}$$

Introducing $a_p$, $a_e$ and $a_w$ into Equation(3.5),
\[ a_p T_p = a_e [f T_e + (1-f) T^0_e] + a_w [f T_w + (1-f) T^0_w] \]
\[ + [a^0_p - (1-f) a_e - (1-f) a_w] T^0_p \]  

where \( a_e = k_e / \delta x_e \)
\( a_w = k_w / \delta x_w \)
\( a^0_p = \rho c_p \Delta x / \Delta t \)
\( a_p = f a_e + f a_w + a^0_p \)

For certain specific values of the weighting factor \( f \), the discretization equation reduces to one of the well known schemes for differential equations. In particular, \( f = 0 \) leads to the explicit scheme, \( f = 1/2 \) to the Crank-Nicolson scheme and \( f = 1 \) to the fully implicit scheme.

The different values of \( f \) can be interpreted in terms of the \( T_p \) versus time variations as shown in Figure 3-1. The explicit scheme assumes that the old value of \( T^0_p \) prevails over the entire time step except at time \( t + \Delta t \). The fully implicit scheme proposes, that at time \( t \), \( T_p \) suddenly drops from \( T^0_p \) to \( T_p \) and remains there for the entire time step. The Crank-Nicolson scheme assumes a linear variation of \( T_p \) over the entire time step.

For the explicit scheme \( (f = 0) \) the discretization equation becomes

\[ a_p T_p = a_e T^0_e + a_w T^0_w + (a^0_p - a_e - a_w) T^0_p \]  

This equation shows that \( T_p \) is not related to other unknowns such as \( T_e \) or \( T_w \), but is explicitly obtained in terms of known temperatures \( T^0_e \), \( T^0_w \) and \( T^0_p \). A scheme with the weighting factor not equal to zero would be implicit, that is \( T_p \) would be linked to the unknowns \( T_e \) and \( T_w \) and the solution of a set of simultaneous equations would be necessary.

With the explicit scheme the selection of \( \Delta x \) and \( \Delta t \) are restricted due
Figure 3-1: Variation of Temperature with Time for the Three Different Discretization Schemes

to stability problems. This scheme can become unstable if the coefficient of $T_p^0$ is allowed to become negative. To ensure that this does not happen the time step $\Delta t$ must be such that $a_p^0$ exceeds $a_c + a_w$. This condition can be derived mathematically, assuming uniform conductivities and

$$\delta z_c = \delta z_w = \Delta z,$$

$$\Delta t < \frac{\rho c_p \Delta z^2}{2k} \quad (3.8)$$

The problem that occurs most often with this type of scheme is that when $\Delta z$ is reduced to improve the spatial accuracy, $\Delta t$ is forced to take on a much smaller value to retain system stability which then results in an excessive amount of iterations being required to obtain the solution. The implicit scheme on the other hand ensures that the coefficient of $T_p^0$ remains positive and therefore is not restricted in the selection of $\Delta z$ and $\Delta t$.

The Crank-Nicolson is described as conditionally stable because though there may be oscillations present in the solution these will eventually die out.
The linear profile of the Crank-Nicolson scheme is a good approximation of the temperature-time relationship only for small intervals of time. Over a larger time interval however the natural exponential decay of temperature with time is approximated better by the fully implicit scheme.

The implicit discretization scheme therefore was chosen because it does not suffer from stability problems as does the explicit scheme and provides more physically realistic behaviour than does the Crank-Nicolson. The complexity of the solution was not considered an issue in choosing the implicit scheme over the other two schemes.

The one dimensional numerical approximation can be extended to three dimensions. For the node $P$, points $E$ and $W$ are its $x$-direction neighbours, while $N$ and $S$, are the $y$-direction neighbours, and finally $T$ and $B$ are the $z$-direction neighbours. The 3-D discretization equation becomes

$$a_p T_p = a_e T_e + a_w T_w + a_n T_n + a_s T_s + a_t T_t + a_b T_b + b \quad (3.9)$$

where

$$a_e = k_e/(\Delta y \Delta z)$$
$$a_w = k_w/(\Delta y \Delta z)$$
$$a_n = k_n/(\Delta z \Delta z)$$
$$a_s = k_s/(\Delta z \Delta z)$$
$$a_t = k_t/(\Delta z \Delta y)$$
$$a_b = k_b/(\Delta z \Delta y)$$

$$a_p^o = \rho c_p \Delta x \Delta y \Delta z / \Delta t$$

$$b = \Delta x \Delta y \Delta z a_p^o T_p^o$$

$$a_p = a_e + a_w + a_n + a_s + a_t + a_b + a_p^o$$

The neighbouring coefficients $a_e, a_w, a_n, \ldots, a_b$ represent the conductances between the point $P$ and its corresponding neighbours. The term, $a_p^o T_p^o$, is the internal energy contained in the control volume at time, $t$. The constant term $b$ consists of this internal energy and the rate of heat generation in the control volume. The center-point coefficient, $a_p$, is the sum of all the neighbouring coefficients including the time neighbour, $a_p^o T_p^o$ [26].
3.3. Model Development

3.3.1. Introduction

As stated in the introduction to this chapter, a model which accurately represents the major surfaces of the sunspace is needed if the model is to accurately predict the thermal performance of the sunspace. In the development of this model two questions must be asked. How many unique capacitive paths exist in the sunspace structure and secondly, how many nodes need to be used to accurately represent the temperature distribution and energy flows through these paths?

3.3.2. Preliminary Modelling

Modelling one of the sunspaces involved in this investigation has been previously attempted [27]. The model developed for sunspace A used an explicit finite difference scheme and treated the entire mass of the sunspace structure as one single node which was connected to the house, crawlspace and outside temperatures as described by Equation (3.10).

\[ a_S T_S = a_H T_H^0 + a_C T_C^0 + a_O T_O^0 + a_S^o T_S^0 + b_{Aux} + b_{Solar} \]  \hspace{1cm} (3.10)

where

\[ a_H = \sum \text{House/Sunspace UA's} \]
\[ a_C = \sum \text{Crawlspace/Sunspace UA's} \]
\[ a_O = \sum \text{Outside/Sunspace UA's} \]
\[ a_S^o = \sum \rho C_p V Vol/\Delta t \]
\[ a_S = a_H + a_C + a_O + a_S^o \]
\[ b_{Aux} = \text{Auxiliary Energy} \]
\[ b_{Solar} = \text{Transmitted Solar Radiation} \]

Some representative simulation results are shown in Figures 3-2 and
3-3. Figure 3-2 shows the thermal charging of the sunspace over a two day period with a 1500 watt heater. Figure 3-3 shows the sunspace free-wheeling over 2 days. Both simulations were compared to monitored data recorded during the month of December 1986.

Considering the assumptions made about the distribution of mass the model developed is a reasonable representation. This suggests that to achieve a higher level of accuracy the nodal model must be increased to a more detailed shape but that a high level of model complexity is not warranted for this investigation.

![Figure 3-2: Transient Behaviour of Sunspace A to a 1500 Watt Thermal Step Input](image)

### 3.3.3. Energy Paths

If the sunspaces being investigated are broken down into capacitive energy paths, sunspace A is the most complex, as described in Table 3-1. Any model describing sunspace A must have at least 10 unique capacitive paths to accurately represent it. The other sunspaces can be set up using simpler models of sunspace A, as described in Tables 3-2 to 3-4.
Figure 3-3: FreeWheeling Behaviour of Sunspace A  
During a 2 day Period of Large Daily Solar Gains [27]

<table>
<thead>
<tr>
<th>Surface</th>
<th>Description</th>
<th>Path</th>
</tr>
</thead>
<tbody>
<tr>
<td>House/Sunspace</td>
<td>Interior Ceiling</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Interior Wall</td>
<td>2</td>
</tr>
<tr>
<td>Crawlspace/Sunspace</td>
<td>Carpeted Floor</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Tiled Floor</td>
<td>4</td>
</tr>
<tr>
<td>Sunspace/Outside</td>
<td>North Exterior Wall</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>West Exterior Wall</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>South Exterior Wall</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>East Exterior Wall</td>
<td>8</td>
</tr>
<tr>
<td>Sunspace/Outside</td>
<td>North Exterior Ceiling</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>South Exterior Ceiling</td>
<td>10</td>
</tr>
</tbody>
</table>

Table 3-1: Capacitive Paths for Sunspace A
<table>
<thead>
<tr>
<th>Surface</th>
<th>Description</th>
<th>Path</th>
</tr>
</thead>
<tbody>
<tr>
<td>House/Sunspace</td>
<td>Interior Wall</td>
<td>1</td>
</tr>
<tr>
<td>Crawlspace/Sunspace</td>
<td>Tiled Floor</td>
<td>2</td>
</tr>
<tr>
<td>Sunspace/Outside</td>
<td>North Exterior Wall</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>West Exterior Wall</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>South Exterior Wall</td>
<td>5</td>
</tr>
<tr>
<td>Sunspace/Outside</td>
<td>North Exterior Ceiling</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>South Exterior Ceiling</td>
<td>7</td>
</tr>
</tbody>
</table>

**Table 3-2: Capacitive Paths for Sunspace B**

<table>
<thead>
<tr>
<th>Surface</th>
<th>Description</th>
<th>Path</th>
</tr>
</thead>
<tbody>
<tr>
<td>House/Sunspace</td>
<td>Interior Wall</td>
<td>1</td>
</tr>
<tr>
<td>Crawlspace/Sunspace</td>
<td>Tiled Floor</td>
<td>2</td>
</tr>
<tr>
<td>Sunspace/Outside</td>
<td>West Exterior Wall 1</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>West Exterior Wall 2</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>South Exterior Wall</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>East Exterior Wall 1</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>East Exterior Wall 2</td>
<td>7</td>
</tr>
<tr>
<td>Sunspace/Outside</td>
<td>Exterior Ceiling</td>
<td>8</td>
</tr>
</tbody>
</table>

**Table 3-3: Capacitive Paths for Sunspace C**

<table>
<thead>
<tr>
<th>Surface</th>
<th>Description</th>
<th>Path</th>
</tr>
</thead>
<tbody>
<tr>
<td>House/Sunspace</td>
<td>Interior Wall 1</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Interior Wall 2</td>
<td>2</td>
</tr>
<tr>
<td>Slab/Sunspace</td>
<td>Concrete Slab</td>
<td>3</td>
</tr>
<tr>
<td>Sunspace/Outside</td>
<td>South Exterior Wall</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>East Exterior Wall</td>
<td>5</td>
</tr>
<tr>
<td>Sunspace/Outside</td>
<td>South House Overhang</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>East House Overhang</td>
<td>7</td>
</tr>
</tbody>
</table>

**Table 3-4: Capacitive Paths for Sunspace D**
This model layout makes the assumptions that energy transfer through the paths is one-dimensional and that energy transfer between capacitive paths occurs only at nodes common to more than one path.

### 3.3.4. Surface Nodal Density

The next step to take in refining the model is to define each sunspace surface as a group of nodes which will then allow more detailed energy calculations to be performed. The number of nodes that could be selected to represent a surface, or more correctly a wall, ceiling or floor, is quite arbitrary, but there will be a point where the addition of extra nodes will not increase the accuracy of the temperature profile through the surface enough to justify the addition. The theoretical solution for the temperature \( T(x,t) \) through a uniform homogeneous wall of width \( l \) assuming,

\[
T(0,t) = 0, \quad t \geq 0 \\
T(l,t) = T_o, \quad t \geq 0 \\
T(x,0) = T_o, \quad 0 \leq x \leq l
\]

is,

\[
T(x,t) = \frac{T_o x}{l} + \frac{2}{\pi} \sum_{n=1}^{\infty} \frac{T_o}{n} e^{-\left(n\pi/l\right)^2 \alpha t} \sin \left(\frac{n\pi x}{l}\right)
\]

where \( \alpha^2 = \frac{k}{\rho c_p} \)

To determine the optimum nodal density required, a wall representing studs 38 mm by 89 mm, 406 mm on center filled with fiber glass insulation and covered with 12.7 mm gypsum board on both sides was used. The first situation to be studied was for the wall to be at an initial temperature of 20 C when at time zero the temperature at \( x=0 \) is dropped to 0 C while the temperature at \( x=l \) remains at 20 C.
Three different nodal densities were considered. These are 1, 3, and 5 nodes per wall. The most significant improvement that occurs in the accuracy of the temperature distribution is from one node to three nodes. For 5 nodes the numerical distribution approximates the theoretical temperature profile as shown in Figure 3-4.

The second situation that was considered was that of changing the temperature at \( x=0 \) from a constant to the sinusoidal function \( T(0,t)=20\sin\left(\frac{\pi t}{12}\right) \) to investigate the sinusoidal behaviour of the nodal densities. Again the most significant improvement occurs from one to three nodes and after that there is almost no change, as shown in Figure 3-5.

To ensure that the one hour time step used was not affecting the accuracy, calculations were performed with varying time steps. Figure 3-6 shows that an improvement in the accuracy of the temperature distribution occurs when the time step is reduced. However the number of calculations that are needed to calculate the temperature distribution increases tenfold for every reduction in the time step.

The most economical nodal density in terms of both accuracy and computing time was judged to be the three node wall.

\[\text{Figures 3-4: Transient Centerline Temperature Distribution of a Wall Subject to a Step Input (UA=4.96 W/K, } \alpha=3.15\times10^{-6} \text{ m}^2/\text{s)}\]
Figure 3-5: Transient Centerline Temperature Distribution of a Wall Subject to a Sinusoidal Input (UA=4.96 W/K, $\alpha=3.15\times10^{-6}$ m$^2$/s)

Figure 3-6: Error in the Centerline Temperature for a Three Node Wall Subject to a Step Input (UA=4.96 W/K, $\alpha=3.15\times10^{-6}$ m$^2$/s)
3.3.5. Selection of Control Volumes

One problem that remains is the placement of the control volumes in each of the capacitive surfaces. Since the previous section used control volumes which had homogeneous conductances and capacitances the logical choice would be to divide the wall into three equal volumes representing a series network even though the actual wall consists of a series-parallel-series network.

A better method would be to select boundaries which would divide the wall into an exterior siding, an insulation, and an interior siding volume. This method is favoured because even though the conductances and capacitances are biased towards one volume or another, the control volumes selected are based on similar materials. This will allow for easier computation of the conductances and capacitances of each volume.

Therefore each capacitive surface is assumed to be made up of ten layers which are grouped into three volumes. Layers 2 to 4 will make up the exterior node, layers 5 and 6 the middle node and layers 7 to 9 the interior node. Layers 1 and 10 are part of either the house, crawlspace, or outside and the sunspace nodes, respectively.

3.4. Mathematical Description of Sunspace

3.4.1. Definition of Nodal Temperatures

As explained previously ten unique paths, each having three temperatures associated with it, will be needed to describe the thermal structure of the sunspace adequately. The temperatures associated with the floor can be reduced by one because no exterior volume exists for these paths. Table 3-5 describes the nodal temperatures required.

The temperature distribution through sunspace surface $i$ is represented by the temperatures $T_{Ai}$, $T_{Bi}$, and $T_{Ci}$. These temperatures are coupled
together and to the sunspace temperature, $T_S$, and a forcing temperature, $T_F$, which is either the house, $T_H$, crawlspace, $T_C$, or outside, $T_O$, temperature as shown in Figure 3-7.

For node $A_i$ the governing equation is,

$$a_{Ai}T_{Ai} = a_{FAi}T_F + a_{ABi}T_{Bi} + b_{Ai}$$  \hspace{1cm} (3.12)$$

Similarly for nodes $B_i$ and $C_i$,

$$a_{Bi}T_{Bi} = a_{ABi}T_{Ai} + a_{BCi}T_{Ci} + b_{Bi}$$  \hspace{1cm} (3.13)$$

$$a_{Ci}T_{Ci} = a_{BCi}T_{Bi} + a_{CiS}T_S + b_{Ci}$$  \hspace{1cm} (3.14)$$

where

$$a_{FAi} = 1/\left( \frac{1}{h_{i,1}A_{i,1}} + \frac{1}{2} \sum_{j=2}^{4} \frac{l_{ij}}{k_{ij}A_{i,j}} \right)$$

$$a_{ABi} = 1/\left( \frac{1}{2} \sum_{j=2}^{4} \frac{l_{ij}}{k_{ij}A_{i,j}} + \frac{1}{2} R_{i56} \right)$$

$$a_{BCi} = 1/\left( \frac{1}{2} R_{i56} + \frac{1}{2} \sum_{j=7}^{9} \frac{l_{ij}}{k_{ij}A_{i,j}} \right)$$

$$a_{CiS} = 1/\left( \frac{1}{2} \sum_{j=7}^{9} \frac{l_{ij}}{k_{ij}A_{i,j}} + \frac{1}{h_{i,10}A_{i,10}} \right)$$

$$R_{i56} = 1/\left( \frac{k_{i,5}A_{i,5}}{l_{i,5}} + \frac{k_{i,6}A_{i,6}}{l_{i,6}} \right)$$

$$a_{Ai}^o = \sum_{j=2}^{4} \frac{(\rho c_p)_{ij} l_{ij} A_{i,j}}{\Delta t}$$
<table>
<thead>
<tr>
<th>Node</th>
<th>Description</th>
<th>Surface</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_1$</td>
<td>Exterior Siding</td>
<td>House/Sunspace Wall 1</td>
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<tr>
<td>$T_2$</td>
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<td></td>
</tr>
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<td>$T_3$</td>
<td>Interior Siding</td>
<td></td>
</tr>
<tr>
<td>$T_4$</td>
<td>Exterior Siding</td>
<td>House/Sunspace Wall 2</td>
</tr>
<tr>
<td>$T_5$</td>
<td>Insulation</td>
<td></td>
</tr>
<tr>
<td>$T_6$</td>
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<td></td>
</tr>
<tr>
<td>$T_7$</td>
<td>Insulation</td>
<td>Crawlspace/Sunspace Floor 1</td>
</tr>
<tr>
<td>$T_8$</td>
<td>Interior Siding</td>
<td></td>
</tr>
<tr>
<td>$T_9$</td>
<td>Insulation</td>
<td>Crawlspace/Sunspace Floor 2</td>
</tr>
<tr>
<td>$T_{10}$</td>
<td>Interior Siding</td>
<td></td>
</tr>
<tr>
<td>$T_{11}$</td>
<td>Sunspace/Outside North Wall</td>
<td></td>
</tr>
<tr>
<td>$T_{12}$</td>
<td>Insulation</td>
<td></td>
</tr>
<tr>
<td>$T_{13}$</td>
<td>Exterior Siding</td>
<td></td>
</tr>
<tr>
<td>$T_{14}$</td>
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<td>Sunspace/Outside West Wall</td>
</tr>
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<td>$T_{15}$</td>
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</tr>
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<td>$T_{16}$</td>
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</tr>
<tr>
<td>$T_{17}$</td>
<td>Interior Siding</td>
<td>Sunspace/Outside South Wall</td>
</tr>
<tr>
<td>$T_{18}$</td>
<td>Insulation</td>
<td></td>
</tr>
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<td>$T_{19}$</td>
<td>Exterior Siding</td>
<td></td>
</tr>
<tr>
<td>$T_{20}$</td>
<td>Interior Siding</td>
<td>Sunspace/Outside East Wall</td>
</tr>
<tr>
<td>$T_{21}$</td>
<td>Insulation</td>
<td></td>
</tr>
<tr>
<td>$T_{22}$</td>
<td>Exterior Siding</td>
<td></td>
</tr>
<tr>
<td>$T_{23}$</td>
<td>Interior Siding</td>
<td>Sunspace/Outside North Ceiling</td>
</tr>
<tr>
<td>$T_{24}$</td>
<td>Insulation</td>
<td></td>
</tr>
<tr>
<td>$T_{25}$</td>
<td>Exterior Siding</td>
<td></td>
</tr>
<tr>
<td>$T_{26}$</td>
<td>Interior Siding</td>
<td>Sunspace/Outside North Ceiling</td>
</tr>
<tr>
<td>$T_{27}$</td>
<td>Insulation</td>
<td></td>
</tr>
<tr>
<td>$T_{28}$</td>
<td>Exterior Siding</td>
<td></td>
</tr>
<tr>
<td>$T_{29}$ or $T_S$</td>
<td>Sunspace</td>
<td></td>
</tr>
<tr>
<td>$T_{30}$ or $T_H$</td>
<td>House</td>
<td></td>
</tr>
<tr>
<td>$T_{31}$ or $T_C$</td>
<td>Crawlspace</td>
<td></td>
</tr>
<tr>
<td>$T_{32}$ or $T_O$</td>
<td>Outside</td>
<td></td>
</tr>
</tbody>
</table>

**Table 3-5:** Nodal Temperatures of Sunspace A
Figure 3-7: Schematic of Sunspace Capacitive Surface

\[
a_{Bi}^o = \sum_{j=5}^{6} \frac{(pc_{p})_{ij}l_{ij}A_{ij}}{\Delta t}
\]

\[
a_{Ci}^o = \sum_{j=7}^{9} \frac{(pc_{p})_{ij}l_{ij}A_{ij}}{\Delta t}
\]

\[
b_{Ai} = S_{Ai} + a_{Ai}^o T_{Ai}^o
\]

\[
b_{Bi} = S_{Bi} + a_{Bi}^o T_{Bi}^o
\]

\[
b_{Ci} = S_{Ci} + a_{Ci}^o T_{Ci}^o
\]

\[
a_{Ai} = a_{FAi} + a_{ABi} + a_{Ai}^o
\]

\[
a_{Bi} = a_{ABi} + a_{BCi} + a_{Bi}^o
\]

\[
a_{Ci} = a_{BCi} + a_{Ci}S + a_{Ci}^o
\]
This set of equations remains valid for every capacitive path except the floor paths. These paths will have only two nodes instead of three and therefore the equation set can be reduced to,

\[
a_{Bi} T_{Bi} = a_{FBi} T_F + a_{BCi} T_C + b_{Bi}
\]

(3.15)

and,

\[
a_{Ci} T_{Ci} = a_{BCi} T_{Bi} + a_{CiS} T_S + b_{Ci}
\]

(3.16)

where \( a_{FBi} = \frac{1}{h_{i1} A_{i1} + \frac{1}{2} R_{i56}} \)

\( a_{BCi} = \frac{1}{\frac{1}{2} R_{i56} + \frac{1}{2} \sum_{j=7}^{9} \frac{l_{ij}}{k_{ij} A_{ij}}} \)

\( a_{CiS} = \frac{1}{\frac{1}{2} \sum_{j=7}^{9} \frac{l_{ij}}{k_{ij} A_{ij}} + \frac{1}{h_{i10} A_{i10}}} \)

\( a_{Bi}^o = \sum_{j=5}^{6} \frac{(\rho c_p)_{ij} l_{ij} A_{ij}}{\Delta t} \)

\( a_{Ci}^o = \sum_{j=7}^{9} \frac{(\rho c_p)_{ij} l_{ij} A_{ij}}{\Delta t} \)

\( b_{Bi} = \bar{S}_{Bi} + a_{Bi}^o T_{Bi}^o \)

\( b_{Ci} = \bar{S}_{Ci} + a_{Ci}^o T_{Ci}^o \)

\( a_{Bi} = a_{FBi} + a_{BCi} + a_{Bi}^o \)

\( a_{Ci} = a_{BCi} + a_{CiS} + a_{Ci}^o \)

The equation set; (3.12), (3.13) and (3.14) is used for eight of the capacitive paths and the equation set; (3.15) and (3.16) is used for the remaining two floor paths.
For the solution of the sunspace node the problem is more complex because the sunspace is coupled to each wall via the interior nodes. As well the sunspace is coupled directly to the outside and house temperatures through energy paths due to infiltration and, if it is assumed that no energy is stored in them, the various windows and doors of the sunspace. The layout for the sunspace node is presented in Figure 3-8.

The governing equation for the sunspace node is,

\[ a_s T_S = \sum_{i=1}^{10} a_{CiS} T_{Ci} + b_s \quad (3.17) \]

where \( a_{CiS} = 1 / \left( \frac{1}{2} \sum_{j=7}^{9} \frac{l_{ij}}{k_{ij} A_{ij}} + \frac{1}{h_{i,10} A_{i,10}} \right) \)

\[ a_s^o = \frac{(\rho c_p)_S Vol_s}{\Delta t} \]

\[ b_s = \dot{m} (c_{pH} T_H^o - c_{pS} T_S^o) + U_w A_w (T_H^o - T_S^o) + U_d A_d (T_H^o - T_S^o) + \sum_{i=1}^{4} U_{iw} A_{iw} (T_O^o - T_S^o) + \sum_{i=1}^{4} U_{iw} A_{iw} (T_O^o - T_S^o) + S_s + a_s^o T_S^o \]

\[ a_s = \sum_{i=1}^{10} a_{CiS} + a_s^o T_S^o \]

Combining Equation (3.17) for the sunspace node and the ten sunspace surfaces which are described by the equation sets (3.12) to (3.14) and (3.15) to (3.16) gives 29 equations that must be solved simultaneously to determine the thermal performance of the sunspace.
3.5. Solar Radiation

3.5.1. Introduction

The most important parameter effecting the sunspace temperature during the summer months is the solar radiation that is transmitted through the glazing surfaces of the sunspace. If a model is to be a good representation of the real structure it must be able to predict this radiation accurately.

The radiation coming directly from the sun, $I_b$, called beam or direct radiation, and the radiation coming from other sources, $I_d$, diffuse radiation, must be determined for each outside surface. The portion of each component which is transmitted through any glazing surfaces present must then be determined.
3.5.2. Radiation Components

The only information known about the solar climate is the total radiation incident on a horizontal surface. Several correlations have been developed [28, 30] which allow for the breakdown of the total radiation into beam and diffuse components. The correlation which was chosen was developed by Orgill and Hollands [30]. This method was chosen because it was developed using data from Canadian stations and thus is probably more accurate than others developed with data not representative of Canadian locations. More importantly though, it requires only the total horizontal radiation in determining the beam and diffuse components.

3.5.3. Radiation on a Tilted Surface

Once the beam radiation is known for a horizontal surface it can be determined for a tilted surface. The geometric factor, $R_b$, can be calculated which gives the ratio of beam radiation on a tilted surface to that on a horizontal surface at any time.

The diffuse component of the solar radiation incident on any surface consists of two types, diffuse radiation coming from the sky and the radiation reflected from the ground. A surface tilted at slope, $\beta$, from the horizontal has a viewfactor to the sky, $F_{rs}$, given by $(1+\cos \beta)/2$, and a viewfactor to the ground, $F_{rg}$, given by $(1-\cos \beta)/2$. If the ground has a reflectance of $\sigma$, the total solar radiation incident on a surface is,

$$ I_T = f_b \times R_b I_b H + F_{rs} \times I_d H + \sigma F_{fg} I_{TH} $$

(3.18)

Where $f_b$ is the ratio of sunlit window area to total window area calculated using a computer program developed by Sun [31]. If the surface has overhangs or wingwalls attached to it, $F_{rs}$ must be reduced to take this into account [32].
3.5.4. Transmitted Radiation

The amount of radiation that is transmitted through a glazing surface is a function of the incoming radiation, and the properties of the material. For a system of \( N \) covers, all of the same material, the transmittance is,

\[
\tau_N = \frac{1}{2} \left[ \frac{1 - r}{1 + (2N - 1)r_-} + \frac{1 - r_-}{1 + (2N - 1)r_-} \right]
\]  
(3.19)

\( r_- \) and \( r_\perp \) are the perpendicular and parallel components of the reflected radiation and are related to the angles of incidence, \( \phi_I \), and refraction, \( \phi_R \), by,

\[
\begin{align*}
    r_\perp &= \frac{\sin^2(\phi_2 - \phi_1)}{\sin^2(\phi_2 + \phi_1)} \\
    r_- &= \frac{\tan^2(\phi_2 - \phi_1)}{\tan^2(\phi_2 + \phi_1)}
\end{align*}
\]

Since Equation (3.19) considers only reflection losses it must be modified to take into account absorption losses as well before it is applied to the beam component of the solar radiation. Similar equations are applied to the diffuse and ground reflected radiation.

Equation (3.18) can now be modified to account for the loss of radiation through the glazing surfaces as

\[
I_{TR} = \tau_b f_b \times R_b I_{bH} + \tau_s F_{rs} \times I_{dH} + \tau_g \sigma \ F_{rg} \times I_{TH}
\]  
(3.20)

3.5.5. Effect of Shading Devices

Two different types of shading devices are used in the sunspaces being investigated. Sunspace A has horizontal venetian blinds mounted between the glazing surfaces whereas sunspace B has venetian blinds which are mounted on the inside of the windows. Both types are controlled manually.

The effect of the latter type of blinds is to reduce the amount of solar
radiation transmitted through the glazing surfaces. They do not increase the thermal resistance of the windows as the between-glazing venetian blinds do.

The reduction in solar radiation caused by between-glazing blinds can be determined by performing an energy balance on the blinds assuming that no energy storage occurs within the window components. As shown in Figure 3-9 the energy balance for the venetian blinds is,

\[
0 = q_{B_{in}} + q_{B_{out}} - q_{solar}
\]

\[
0 = U_{sb} A_w (T_{Bl} - T_S) + U_{bo} A_w (T_{Bl} - T_O) - \alpha_b A_w I
\]  

(3.21)

where

- \( U_{sb} \) = Thermal Conductance of Inside Portion of Window with Blinds Closed
- \( U_{bo} \) = Thermal Conductance of Outside Portion of Window with Blinds Closed
- \( A_w \) = Window Area
- \( T_S \) = Sunspace Temperature
- \( T_{Bl} \) = Blind Temperature
- \( T_O \) = Outside Temperature
- \( \alpha_b \) = Absorptivity of the Blinds
- \( I \) = Incident Radiation

Assuming that \( U_{sb} \) and \( U_{bo} \) are both equal to \( 2U_{so} \), where \( U_{so} \) is the conductance of the window when the blinds are closed, the energy flow into the sunspace is given by,

\[
q_{B_{in}} = \frac{\alpha_b A_w I}{2} + U_{so} A_w (T_O - T_S)
\]

(3.22)

The solar radiation absorbed by the venetian blinds goes directly into warming the sunspace air. If the blinds had been left open or removed the
solar radiation would be absorbed by the interior surfaces of the sunspace which in turn would warm the sunspace air.  

The effect on the conductance of the windows when the venetian blinds are closed can be taken from manufacturer's data or more accurately determined through experimental tests.

3.5.6. Absorbed Radiation

For the exterior siding equation of each outside surface the source term will be the absorbed radiation,

$$
\overline{S}_{Ai} = \alpha (f_b \times R_b I_{bH} + F_{rs} \times I_{dH} + \sigma F_{rg} \times I_{TH})
$$

The radiation transmitted through the glazing surfaces must strike the interior surfaces of the sunspace. It is assumed that all of the radiation strikes the floor. This is a common assumption made by energy programs [33]. In reality, however, most of the incident energy may be deposited on only a portion of the floor, making that region much warmer.
than the rest of the floor. The average floor temperature though should remain approximately the same. The source term of the interior siding equation of the sunspace floor surfaces will be,

\[ S_{Ci} = \alpha \left( r_b I_b \times R_b I_{bH} + r_s F_{rs} \times I_{dH} + r_g F_{rg} \times I_{TH} \right) \]  

(3.24)

3.6. Infiltration

Infiltration is the leakage of air through unintentional openings in the building envelope driven by pressure differences across the envelope. These pressure differentials are caused by either temperature differences or wind forces or a combination of the two.

Several techniques exist for estimating the amount of infiltration occurring in a structure. The air change method is perhaps the simplest available. It is based on past experience and applies to average houses under average weather conditions. A more detailed method is the crack method. This method calculates the flow produced by a pressure difference across each leakage path or building component. The limitations of this method are that the leakage areas must be known and the ability to predict the pressure difference across the leakage areas is in doubt [34].

The model selected was developed by Shaw [35]. This empirical model uses three equations to calculate the infiltration rate depending upon the relative strengths of the two weather parameters, the inside-outside temperature difference and the wind speed.

When the wind speed is less than 3.5 m/s, the infiltration rate depends upon the inside-outside temperature difference only,

\[ \dot{I} = 0.32 \left( \frac{A_B C^x \Delta T^{0.71}}{Vol_S} \right) \]  

(3.25)

where \( Vol_S \) = Volume of Sunspace
\( A_B \) = Surface Area of Building Envelope
\( C^x \) = Flow Coefficient
When the temperature difference is less than 20 $^\circ C$ and the wind speed is greater than 3.5 m/s, the wind becomes the dominant driving potential for causing air infiltration,

$$I = a^x \left( \frac{A_B C^x V^{b^x} n^x}{Vol_S} \right)$$

(3.26)

where $V =$ Wind speed
$n^x =$ flow exponent
$a^x = 0.42$, $b^x = 2$ (House Exposed)
$a^x = 0.76$, $b^x = 1$ (House Shielded)

When the wind speed is greater than 3.5 m/s and the temperature difference is greater than 20 $^\circ C$, the effect of the two weather parameters on the infiltration rate is the same and

$$I = 4.53 \left( \frac{A_B C}{Vol_S} \right)$$

(3.27)

The flow coefficient, $C^x$, and exponent, $n^x$, can be determined for a specific sunspace by conducting fan pressurization tests. These tests are presented in Chapter 4.

3.7. Simulation Program

The simulation program is written in DEC VMS FORTRAN and is entitled MAIN.FOR. A flowchart describing the main features of MAIN.FOR is given in Figure 3-10. The program allows the user to choose among the following options,

- Auxiliary Heating and Cooling of the Sunspace
- Use of an Air-to-Air Heat Exchanger
- Operation of Venetian Blinds
• Elimination of Solar Radiation
• Force House Temperature to track the Sunspace Temperature
• Force Sunspace Temperature to track the Outside Temperature

Outputs for the program are the monthly house, sunspace, crawlspace and outside temperatures, the percentage of the time the sunspace spends below, inside and above the comfort zone each month, and the monthly energy flows for the sunspace.

MAIN.FOR makes use of several subroutines to perform the simulation presented in this chapter.

The simulation starts by calling GEOMETRY.FOR where the geometry of the outside surfaces of the sunspace are located. These variables are used by SHADOW.FOR, to determine the shading of the outside surfaces, and VIEWFACTOR.FOR, to determine the viewfactors of each surface.

THERMAL.FOR and SURFCOND.FOR are called next. THERMAL.FOR has stored in it the thermal properties of the capacitive surfaces of the sunspace as well as the conductances and areas of the sunspace doors and windows. SURFCOND.FOR consists of equations that relate the surface conductance of the sunspace surfaces to the adjacent air velocity. Since the wind velocity changes with time SURFCOND.FOR must be called every time step.

Initialization of the nodal temperatures is performed next. The nodal matrix which stores the 29 equations governing the temperature distribution of the sunspace is setup for this and the actual time steps by calling SOLVE.FOR. This subroutine in turn passes the nodal matrix to SOLUTION.FOR which solves for the nodal temperatures.

Once the initialization is complete MAIN.FOR determines the nodal temperatures for each time step of the simulation. For every time step
MAIN.FOR calls SURFCOND.FOR to update the surface conductances. The solar radiation incident on the outside surfaces as well as what is transmitted through the glazing surfaces of the sunspace are calculated by calling SOLAR.FOR. This subroutine makes use of several other subroutines which perform such functions as the calculation of incidence angles (INCIDENCE.FOR), transmittances (OPTICS.FOR) and the amount of shading occurring on the exterior surfaces (SHADOW.FOR). The viewfactors do not have to be recalculated after the beginning of the simulation because they do not change with time.

If it has been requested, MAIN.FOR can determine the amount of auxiliary energy in the form of heating or air conditioning that is required to keep the sunspace within the comfort zone. This procedure begins with no auxiliary energy being used and simply increases the auxiliary energy, until the sunspace temperature is within the comfort zone.

Once the sunspace temperature distribution has been determined for the time step, QCALC.FOR is called which calculates the energy flows within the sunspace structure. These values and the temperatures mentioned earlier are then stored for later analysis.

Typical run times on a DIGITAL VAX 8600 are from 10 to 15 minutes of CPU time for a yearly freewheeling simulation to approximately one hour of CPU time for a yearly simulation to determine the auxiliary energy requirements.

The FORTRAN listings for MAIN.FOR and the subroutines that it utilizes can be found in Appendix B.
Figure 3-10: Flow Chart of MAIN.FOR
Chapter 4
Simulation and Measured Results

4.1. Introduction

Any operational strategies based on the four sunspaces investigated are dependent upon the accuracy of the model that was developed in Chapter 3. The validity of this model must be checked by comparing the measured results with values predicted by the model. This check will help ensure that the model and therefore the operational strategies are accurate.

Before a comparison of predicted and measured sunspace temperatures should be made, two components of the model that are dependent upon on-site tests should be presented. The first component is the infiltration rates of the sunspace and the second is the transmissivity of the sunspace windows.

4.2. Infiltration

The infiltration of a structure can be measured either by tracer gas or fan pressurization tests, though the latter are more correctly termed air tightness tests because they indicate how airtight the building is.

4.2.1. Tracer Gas Testing

Tracer gas tests consist of releasing a chemically stable gas which has a density comparable to air into the structure that is being studied. The decay of the gas over time is measured and from this the infiltration rate of the structure can be determined. Care must be taken to ensure that the tracer gas selected will not be absorbed by the walls and furnishings and that it is
not normally present in the air nor is there a source of this type of gas within the building.

The rate of change over time of the amount of tracer in the structure may be expressed by,

\[ Vol \frac{dc}{dt} = c_o \dot{v} + G - cv \]  \hspace{1cm} (4.1)

where \( Vol \) is the volume of the structure, \( c \) is the concentration of tracer gas in the structure at some time \( t \), \( c_o \) is the concentration at time \( t=0 \), \( \dot{v} \) is the rate at which air leaves the structure in volume per unit time, and \( G \) is the net rate of generation of tracer gas in the structure.

If the concentration of tracer gas in the incoming air is negligible and there is no tracer gas being generated or absorbed within the space, Equation (4.1) can be solved to give,

\[ c = c_o e^{-\frac{\dot{v}t}{Vol}} = c_o e^{-\dot{lt}} \]  \hspace{1cm} (4.2)

The solution of Equation (4.1) assumes perfect mixing of the tracer gas with the air in the space, both initially and throughout the measurement process. This mixing is not achieved in practice but it is usually approached closely enough to give good approximations of the air change rates.

For each of the sunspaces, Nitrous Oxide (\( N_2O \)) was used as a tracer gas in these tests. Monitoring of the tracer gas was done using a Foxboro Model 1B Ambient Air Analyzer which allowed continuous on-site measurements and a Beckman Nitrous Oxide Gas Analyzer which required that air samples be taken and analyzed in the laboratory.

Using linear regression techniques, best fit curves were found for each of the tests. Sunspace A has the lowest infiltration rate at .111 Air Changes per Hour (ACH). Sunspace B was next with an infiltration rate of .150 ACH followed by .212 ACH for Sunspace D and .395 ACH for Sunspace C.
Figure 4-1 gives a comparison between the measured concentration of tracer gas and the best fit curve for a test performed on sunspace C.

Figure 4-1: Decay of Tracer Gas over Time from Test performed at Sunspace C, measured using a Foxboro Model 1B Ambient Air Analyzer

4.2.2. Fan Pressurization Testing

The previous method provides a measure of the air leakage of a structure under more or less natural conditions. Where building tightness is required fan pressurization or evacuation tests are required. The method involves sealing a fan into an exterior door or window and then air is moved into or out of the building at a measured rate. The inside-outside pressure difference is measured as a function of flow rate.

Fan pressurization or evacuation data may be expressed by,

\[ Q = C^x \Delta P^n^x \]  
(4.3)
where \( Q \) = Flow Rate in Volume per Unit Time
\( C^x \) = Flow Coefficient
\( \Delta P \) = Inside/Outside Pressure Difference
\( n^x \) = Flow Exponent, \( 0.5 \leq n \leq 1.0 \)

Equation (4.3) has the form of a straight line on a log-log plot where \( n^x \) is the slope. Dividing both sides by the volume of the pressurized space converts the flow rate into air changes per unit time.

The flow coefficient and exponent can be found using linear regression techniques. Table 4.2 presents \( C^x \) and \( n^x \) for each of the sunspaces and for comparison purposes \( C^x \) and \( n^x \) for four different types of houses [36].

<table>
<thead>
<tr>
<th>Sunspace</th>
<th>( C^x ) ( \text{m}^3/\text{s} \cdot \text{Pa}^{n^x} )</th>
<th>( n^x )</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.0019</td>
<td>0.747</td>
</tr>
<tr>
<td>B</td>
<td>0.0049</td>
<td>0.674</td>
</tr>
<tr>
<td>C &amp; D</td>
<td>0.0171</td>
<td>0.703</td>
</tr>
<tr>
<td>Pre 1945 House</td>
<td>0.0520</td>
<td>0.725</td>
</tr>
<tr>
<td>1945-1960 House</td>
<td>0.0364</td>
<td>0.698</td>
</tr>
<tr>
<td>1960-1980 House</td>
<td>0.0305</td>
<td>0.718</td>
</tr>
<tr>
<td>Airtight House</td>
<td>0.0169</td>
<td>0.703</td>
</tr>
</tbody>
</table>

Table 4-1: Flow Coefficient and Exponent for the Four Sunspaces being Investigated

Once the flow coefficient and exponent are found from pressurization tests for each sunspace the infiltration rates calculated using Shaw's model [35] can be adjusted to those measured using the tracer gas technique.

Because the sunspace is connected to the house, the effect of the house must be determined. If tests are performed with the house/sunspace door open then the two can be considered as a single structure and the tightness
of the house and sunspace combined can be measured. If this test is then repeated with the house/sunspace door closed any change in the air exchange rate will be due to the house/sunspace wall alone. From such tests the sunspace air exchange rates can be broken down into house/sunspace and sunspace/outside air exchange rates. These ratios are presented in Figure 4-2.

![Figure 4-2: Breakdown of Pressurized Sunspace Air Exchange Rates](image)

4.2.3. Transmissivity Measurements

Solar radiation transmitted through a glazing surface is effected by the type of material, as well as the type of solar radiation that is incident on the surface. It is assumed that the transmissivity of normal glazing surfaces can be accurately predicted using the approach described in Chapter 3. Sunspace A has venetian blinds which are mounted between the double panes of glass and therefore field measurements are required to determine if this feature effects the transmissivity of the sunspace windows.
To determine the transmissivity of the glazing surfaces of the sunspace pyranometers were mounted on the inside and outside of the windows in the plane of the glazing surfaces and were then monitored over several days. Dividing the radiation monitored on the inside of the window by the outside radiation will give the transmissivity of the glazing surface. The monitored and corresponding theoretical transmissivities are shown in Figure 4-3 and 4-4 for Sunspace A.

As can be seen the theoretical values are higher than the measured values. For sunspace A the beam and diffuse transmissivities will be adjusted by a factor of 0.90 and 0.80, respectively. This decrease is due to the obstructions caused by the between-glazings venetian blinds which results in an effective window area lower than the actual window area.

4.3. Model Verification

4.3.1. Introduction

To ensure that the model is an accurate representation of the sunspace structure simulation results must be compared to the monitored temperatures. Every attempt was made to keep the sunspace environment isolated during the monitoring periods but inevitably some disturbances do occur. Sunspace A and B were for the most part isolated during the test periods but for the other two, particularly Sunspace D, this was not practical because of their use by the homeowners as greenhouses. Complete isolation of these two sunspaces was never achieved, though every attempt was made to identify and minimize, if possible, any disturbances that did occur during the monitoring periods.

As discussed in Chapter 2 the monitored variables at each of the sunspaces were the house, sunspace, crawlspace and outside temperatures as well as solar radiation incident on two glazing surfaces. Based on the monitored solar data, solar radiation was calculated for every exterior surface
Figure 4-3: Comparison of Theoretical and Monitored Beam Transmissivities of the East Window of Sunspace A

Figure 4-4: Comparison of Theoretical and Monitored Diffuse Transmissivities of the East Window of Sunspace A
with the exception of the two which were monitored. Excluding the sunspace temperature, the monitored temperatures for each time step were used as the forcing temperatures to predict the sunspace temperature. The predicted sunspace temperature was then compared to the monitored value.

4.3.2. Sunspace A

As mentioned previously this sunspace has the most complex model of the four and therefore required a more detailed investigation than the others. It was fortunate that the environment of this sunspace was the easiest to control. The tests that were performed on this sunspace attempted to investigate the ability of the thermal model to predict the monitored results. They would also confirm how accurate the solar and infiltration models were. Modelling the introduction of auxiliary energy, whether it is in the form of heating or cooling through the use of an air conditioner or a fan would also be checked. Finally the assumptions regarding the effectiveness of the venetian blinds would be tested.

4.3.2.1. Thermal Model

The first area that was investigated was the 'freewheeling' behaviour of the sunspace. This is achieved by closing all the doors and/or windows and eliminating any auxiliary energy sources within the sunspace.

Freewheeling tests were performed during both the winter and summer to see if there were any seasonal dependences in the model. Figure 4-5 presents predicted and monitored sunspace temperatures for a three day period during the month of December 1986. The range in measured temperatures is the difference between the upper and lower thermocouples on the string in the sunspace. This range indicates the degree of stratification that occurs within the sunspace.

For the most part the model agrees with the measured values, the higher predicted values during the second day being the exception. Since this
does not occur in either the day preceding or following, it suggests that the difference could be due to some extraneous information that was not accounted for during the test.

A week of summer freewheeling behaviour is presented in Figure 4-6 in which the model consistently over predicts the measured values. These differences are due primarily to the modelling of the venetian blinds. The effect of the venetian blinds was assumed to be constant throughout the year. The seasonal change in solar altitude angle affects the overall transmittance of the windows because of the degree of blockage caused by the horizontally positioned venetian blinds. Removal of the venetian blinds shows that the model approximates the measured values, as shown in Figure 4-7.

4.3.2.2. Effect of Venetian Blinds

The limitation of the model with regards to the venetian blinds when they are open has been previously noted. The increase in the window conductance due to the closure of the blinds though needs to be presented. When the blinds are closed at night the window conductance was found from insitu tests to decrease by 38 percent, compared to 53 percent as claimed by the manufacturer. This decrease is based on the assumption that the blinds have a low temperature emissivity of 50 percent [37].

Figure 4-9 shows two test periods during the month of March 1987 when the venetian blinds were closed. Figure 4-10 presents a similar test but during the later part of June of the same year. Both figures show agreement between the model and the measured values.

4.3.2.3. Auxiliary Energy

The next area which was investigated was the ability of the model to predict the effect of the different types of auxiliary energy that were used.

An auxiliary heater was introduced for a two day period of low
insolation during the month of December 1986. The heater was turned on during the day and then turned off for the night to generate sudden transients in energy input. Figure 4-8 shows that the model predicts the sunspace behaviour.

Cooling of the sunspace was achieved by introducing a fan which ventilated the sunspace air to the outside. One limitation that exists with this type of cooling is that the sunspace air can never be driven below the outside temperature. Figure 4-11 presents a week during the month of June 1987 when a fan was operating, as can be seen the model is in agreement with the measured values.

4.3.3. Sunspace B

Monitoring of this sunspace was not as extensive as the previous sunspace because it was assumed that sunspace A would justify the modelling techniques used. Monitoring of the remaining sunspaces would still be required to verify the setup of the site dependent parts of the model such as the thermal properties of the various components of the sunspace.

4.3.3.1. Thermal Model

A seven day monitoring period during the month of December 1986 is shown in Figure 4-12. Figure 4-13 compares the predicted temperatures to the monitored values for a six day period during the month of June the following year. As can be seen the model agrees with the measured values in both cases.

4.3.3.2. Effect of Venetian Blinds

The effect of the blinds that are installed in Sunspace B is to simply reduce the incoming solar radiation. This reduction is dependent upon the low temperature emissivity of the blinds, which was assumed to be 50 percent for this type of blind. Figure 4-14 shows a three day period during the summer of 1987, with the predicted temperatures agreeing with the measured values.
Figure 4-5: Winter FreeWheeling Behaviour of Sunspace A

Figure 4-6: Summer FreeWheeling Behaviour of Sunspace A
Figure 4-7: Summer FreeWheeling Behaviour of Sunspace A with the Venetian Blinds Removed

Figure 4-8: Thermal Charging of Sunspace A during the Winter
Figure 4-9: Nighttime Winter FreeWheeling Behaviour of Sunspace A with the Venetian Blinds closed

Figure 4-10: Summer FreeWheeling Behaviour of Sunspace A with the Venetian Blinds closed
4.3.4. Sunspace C

Because of its use by the homeowners, monitoring of this sunspace was limited during the summer months. Figure 4-15 presents six days during the month of February 1987 that were monitored. The model predicts the overall trends of the sunspace temperature but it over-predicts the actual values by several degrees.

A six day period during the month of August of the same year is presented in Figure 4-16. Though the model follows the trends quite well once again the predicted temperatures are in error. This is due in part to venting of the sunspace by the homeowner throughout the test period. This venting consisted of opening outside doors and windows of the sunspace as well as the operation of a thermostatically controlled fan to the outside.
Figure 4-12: Winter Free Wheeling Behaviour of Sunspace B

Figure 4-13: Summer Free Wheeling Behaviour of Sunspace B
4.3.5. Sunspace D

The problems that exist for sunspace C also exist for the last sunspace but to a lesser degree. Venting of the sunspace was performed by the homeowner, but was done with a fan for which the flow rate could be easily measured. Figure 4-17 shows a three day period when the sunspace was allowed to freewheel. The predicted temperatures agree with the measured values. Prediction of summer temperatures is shown in Figure 4-18. This shows agreement between the model and measured values as well.
Figure 4-15: Winter FreeWheeling Behaviour of Sunspace C

Figure 4-16: Summer FreeWheeling Behaviour of Sunspace C
Figure 4-17: Winter FreeWheeling Behaviour of Sunspace D

Figure 4-18: Summer Behaviour of Sunspace D with Auxiliary Cooling
4.3.6. Summary

The comparison of predicted and monitored sunspace temperatures show the simulation program developed is a good representation of the sunspaces being investigated [38, 40, 12, 13]. The model allows yearly simulations to be performed with a good degree of confidence in the results.

The poorest correlation between predicted and measured results was for sunspace C during the summer. This was in part a consequence of uncontrolled use of the sunspace by the owner during this period. A large degree of inaccuracy in the model also occurred when the blinds used in Sunspace A were open during the summer. This inaccuracy was due to greater blockage of solar energy than was assumed at the higher sun angles during this time of the year.
Chapter 5

Yearly Sunspace Performance

5.1. Introduction

The modelling techniques that were presented and verified in the previous chapters allow the behaviour of the four occupied sunspaces to be examined. Of greater interest though is not sunspace performance in the very short term but operating characteristics over a typical or average meteorological year. This long term behaviour can be broken down into three areas of interest,

- thermal comfort,
- cooling and heating energy, both supplied and produced, and
- operating strategies for efficient use of the sunspace.

Monthly temperatures of the sunspaces and the degree to which the four sunspaces stay within a defined comfort zone will be determined using the model developed. The ability of the blinds to change the sunspace temperature and decrease underheating and overheating will be determined as well. The production of useful energy by the four sunspaces will be examined. Various operating strategies will be investigated to determine whether or not reductions in the auxiliary energy loads are possible. Geographical locations of the sunspace will also be examined to determine what effect this has on the thermal behaviour of the sunspace.
5.2. Selection of Weather Data

Four Canadian cities were selected to study the effect of climatic variables on sunspace performance. The selection of the cities was somewhat arbitrary, but it can be argued that they do represent the major climatic regions of the most populated regions of Canada. The Canadian cities chosen were,

- Vancouver, British Columbia (West Coast Climate)
- Saskatoon, Saskatchewan (Prairie Climate)
- Toronto, Ontario (Central Canadian Climate)
- Fredericton, New Brunswick (East Coast Climate)

The selection of weather data must be made on the basis of how well it typifies the long term meteorological behaviour of the sites in question. Five different weather standards have been examined by WATSUN [41] to determine which one produces the most representative data. The weather standards that were examined are,

- synthesized data techniques
- the Design Year
- the Hedstrom Year
- Weather Year for Energy Calculations (WYEC)
- Typical Meteorological Year (TMY)

WATSUN selected the Typical Meteorological Year weather standard for two reasons. The first was that it provided reasonably accurate meteorological data and the second was that records of weather data do not go back far enough to allow the implementation of the WYEC standard, the only other standard seriously considered. Another argument favouring the use of the TMY standard is that it is widely used in the United States and therefore provides for a common standard between the two countries.
Table 5-1 presents the winter and summer design temperatures, the yearly horizontal radiation and the yearly heating and cooling degree days for the four cities. These variables were determined from the TMY datafiles for each of the sites in question. The yearly heating and cooling degree days are for a base of 18 C and 24 C, respectively. The meteorological variables are in good agreement with other data sources [42]. Figures 5-1 and 5-2 present the monthly ambient temperatures and horizontal radiation, respectively, for the four cities selected.

<table>
<thead>
<tr>
<th>Meteorological Variable</th>
<th>Vanc</th>
<th>Sask</th>
<th>Toro</th>
<th>Fred</th>
</tr>
</thead>
<tbody>
<tr>
<td>Latitude (degrees)</td>
<td>49.18</td>
<td>52.17</td>
<td>43.68</td>
<td>45.87</td>
</tr>
<tr>
<td>Longitude (degrees)</td>
<td>123.17</td>
<td>106.68</td>
<td>79.63</td>
<td>66.53</td>
</tr>
<tr>
<td>2.5% Winter Design Temp. C</td>
<td>-7.4</td>
<td>-34.2</td>
<td>-18.6</td>
<td>-27.3</td>
</tr>
<tr>
<td>97.5% Summer Design Temp. C</td>
<td>22.3</td>
<td>28.0</td>
<td>28.2</td>
<td>28.1</td>
</tr>
<tr>
<td>Yearly Horz. Rad. (W/m²)</td>
<td>3380</td>
<td>3782</td>
<td>3574</td>
<td>3363</td>
</tr>
<tr>
<td>Yearly Heating Degree Days</td>
<td>3263</td>
<td>6343</td>
<td>4505</td>
<td>5004</td>
</tr>
<tr>
<td>Yearly Cooling Degree Days</td>
<td>1</td>
<td>37</td>
<td>61</td>
<td>41</td>
</tr>
</tbody>
</table>

Table 5-1: Meteorological Data for the Selected Canadian Cities
Figure 5-1: Monthly Ambient Temperatures for the Selected Canadian Cities

Figure 5-2: Monthly Horizontal Radiation for the Selected Canadian Cities
5.3. Yearly Sunspace Performance

5.3.1. Introduction

Three different aspects of sunspace performance are examined. The first being the seasonal freewheeling behaviour of the sunspace. If the sunspace temperature never leaves the comfort zone, defined as 22 C to 27 C [43], then obviously there is no need to provide any auxiliary energy to condition the structure. However this is usually never the case.

The simplest way to change the environment of the sunspace is to make use of night-time insulation and/or blinds during the day. Sunspace A has venetian blinds which provide an increased window resistance when they are closed. Sunspace B has blinds which provide no adjustment to the window resistance when they are closed. The other two sunspaces have no shading devices installed but for the purposes of this investigation it is assumed that they are equipped with blinds similar to sunspace B. The use of the blinds is governed by the following conditions,

- if the sunspace temperature is greater than or equal to 27 C then the blinds will be closed, and,
- if the horizontal solar radiation is equal to zero then the blinds will be closed.

The first condition tries to limit the amount of solar radiation coming into the sunspace when it is overheating. The second condition simply implements night-time insulation however this is only effective with sunspace A.

Another aspect that will be investigated using yearly simulations is to determine how much auxiliary energy is required to keep the four sunspaces conditioned. The auxiliary energy can take the form of either heating to warm the sunspace or, air-conditioning of the sunspace to prevent overheating. The effectiveness of the blinds in reducing the auxiliary energy requirements will also be investigated.
The last area that will be examined is the production of energy within the sunspace. Two different methods of producing energy will be investigated. The first method is to simply vent any excess energy that is produced by the sunspace into the house. This energy has the potential of reducing the space heating requirements of the house. Another use of the sunspace is to use it as a pre-heater for a household heat recovery ventilator (HRV) or air-to-air heat exchanger. This option would increase the temperature of the ventilation air entering the HRV unit thereby reducing the energy required to bring this air to the house temperature.

5.3.2. FreeWheeling Behaviour of the Sunspaces

The monthly average freewheeling temperatures for each of the sunspaces at the four Canadian cities is presented in Figure 5-3. The cities which give the coldest and warmest winter temperatures are Saskatoon and Vancouver, respectively. These observations are reflected in the heating degree days of the two cities. These two cities have the highest and lowest heating degree days, respectively.

The thermal behaviour of the sunspaces during the summer are not reflected in the cooling degree days because the sunspace behaviour during the summer depends more on the amount of transmitted solar radiation than the ambient temperature at the site. The site which gives the highest sunspace freewheeling temperature varies with the sunspace. For the first two sunspaces Vancouver is the warmest, whereas for sunspace C and D, Saskatoon and Toronto, respectively, have the highest summer temperatures.

For sunspaces A and B, the transmitted radiation during the summer is higher for Vancouver than the other Canadian cities. This explains why a sunspace located in Vancouver has the highest summer freewheeling temperatures even though the summer ambient temperature of the city is the lowest of the four Canadian cities. Sunspace C has the same orientation as does sunspace A but in addition has glazing surfaces on the roof of the
sunspace. With the addition of glazing surfaces on the roof of sunspace C Saskatoon has the highest transmitted radiation. With this configuration Saskatoon is the warmest sunspace followed by Toronto. The total amount of transmitted radiation for sunspace C is 16 percent higher in Saskatoon than in Toronto. The order of Saskatoon and Toronto are reversed for sunspace D, even though the overall transmitted radiation is higher for Saskatoon by approximately 12 percent. With this slight decrease in the transmitted solar radiation the higher ambient temperatures for Toronto must influence the sunspace temperature enough to favour this city over Saskatoon.

In general, except for Vancouver, the sunspace temperatures tend to exhibit similar monthly trends at each location for the various types of sunspaces. The reverse in trends between sunspace B and D at Vancouver, suggest that an east facing sunspace is preferred over one that faces west in terms of both winter heating and summer cooling loads.

5.3.3. Effect of Shading Devices

As mentioned previously the venetian blinds in sunspace A increase the window resistance when they are closed and therefore should be better in controlling the sunspace temperature, especially during the winter, than the type of blinds in the other sunspaces.

Figure 5-4 presents the amount of time sunspace A spends within the comfort zone defined as 22 C to 27 C. The shaded zones in the figure describe the time spent in this comfort zone as a percentage of the month with and without the use of blinds. For every locale the use of the insulating blinds is effective in increasing the percentage of the month that is spent within the comfort zone when compared to the case without the use of the blinds. This is even more evident in the summer months.

The effect of the venetian blinds on the three remaining sunspaces is
Figure 5-3: Monthly FreeWheeling Behaviour of the Four Sunspaces Being Investigated at Four Different Canadian Cities
presented in Figures 5-5 to 5-7. The venetian blinds are effective in reducing
the amount of overheating that occurs in the sunspace but at the expense of
increasing the amount of time when auxiliary heating is required. This is
reflected by the increase in the amount of time the sunspace spends below
22 C when the venetian blinds are used. There is only a slight increase in
the time spent in the comfort zone for sunspaces B and D but sunspace C
experiences a three fold increase. This is due to the large amounts of south
facing window that this sunspace has.

5.3.4. Monthly Auxiliary Energy Requirements

The auxiliary heating and cooling loads that are required to keep the
sunspaces within the comfort zone at each of the four cities is presented in
Figures 5-8 and 5-9, respectively. The loads presented in these two figures
are minimum levels. The amount of heating energy calculated each hour was
that which would bring the sunspace temperature to between 22 C and
23 C. For the cooling energy requirements, the set point temperatures were
between 26 C and 27 C. Using these ranges gave a consistent method for
determining how much auxiliary energy was required for conditioning of the
sunspaces.

The monthly loads shown in Figure 5-8 present no great surprises. For
each of the sunspaces, as indicated by its heating degree days, Saskatoon has
the highest heating energy requirements of the four cities. Toronto and
Fredericton have similar monthly load profiles and with the exception of
December and January Saskatoon matches these two cities as well.
Vancouver’s mild winter is reflected in the monthly heating loads.

Sunspace A has the lowest heating requirements due to the low UA of
the sunspace. Sunspace B has heating loads which are roughly one third
greater than sunspace A. This increase is due in part to the very high
insulation levels between the house and the sunspace resulting in very little
transfer of energy between the two. The higher UA values of the sunspace
Figure 5-4: Time Spent Within the Comfort Zone each Month for Sunspace A at Four Different Canadian Cities
Figure 5-5: Time Spent Within the Comfort Zone each Month for Sunspace B at Four Different Canadian Cities
Figure 5-6: Time Spent Within the Comfort Zone each Month for Sunspace C at Four Different Canadian Cities
Figure 5-7: Time Spent Within the Comfort Zone each Month for Sunspace D at Four Different Canadian Cities
coupled with the significant amount of window area facing west also increase the heating requirements of this sunspace.

Sunspaces C and D have heating requirements which are approximately double that of the first two sunspaces. The way in which the outside walls of the sunspaces were constructed is the main reason for this large increase. The large amount of south facing window area helps offset the heating requirements of sunspace C but this will result in a large UA value. The poor glazing orientation of sunspace D results in larger heating loads than the other three sunspaces.

The solar radiation transmitted through the glazing surfaces has a significant effect on the heating loads of the sunspaces. One way to express this influence is through the use of the Solar Savings Fraction (SSF). This quantity is the ratio of the solar savings to the net auxiliary heating requirements of the structure where $Q_{net}$ is the building load including any losses through the glazing surfaces and $Q_{aux}$ is the amount of energy furnished by an auxiliary heating system to keep the building warm [44].

$$SSF = \frac{Q_{net} - Q_{aux}}{Q_{net}}$$

The Solar Savings Fraction for each of the sunspaces does not differ significantly between cities. The effectiveness of the sunspaces as solar collectors and therefore their ability to reduce the heating requirements of the sunspace can be seen quite clearly in Table 5-2.

Sunspaces A and C apparently perform well but due to different reasons. Sunspace A has a well insulated thermal envelope and modest window area whereas sunspace C has a poorly insulated thermal envelope but has large amounts of south facing window area. Although sunspace C has a very high proportion of its heating energy requirements supplied by the sun, it is still not very energy efficient when compared to sunspace A as indicated in Figure 5-8. Since the levels of insulation are comparable for
Figure 5-8: Monthly Heating Loads for Each of the Sunspaces at Four Different Canadian Cities
Table 5-2: Yearly Solar Savings Fraction for the Sunspaces Being Investigated

sunspaces C and D the low SSF of the latter can be attributed to the poor orientation of the principal glazing surfaces. This same argument can be made for sunspace B when compared to sunspace A but to a lesser degree because of the higher insulation levels of sunspace B.

Figure 5-9 presents the monthly cooling loads for all the sunspaces at each of the four Canadian cities. For sunspaces A and C the monthly cooling loads for each of the cities are roughly the same, if a distinction is to be made, Saskatoon and Vancouver are slightly higher than Toronto and Frederiction. For sunspace B Vancouver has the highest cooling load. The complete opposite occurs for sunspace D where Vancouver now has the lowest cooling load with the other three sites having approximately equal cooling loads. This apparent contradiction can be explained by comparing the solar radiation transmitted into sunspace D over the year for each of the cities. The yearly transmitted solar radiation for sunspace D is 46 percent lower for Vancouver than the other cities, indicating as previously discussed, that summer solar gains are much greater at this location for a west facing surface than one facing east.
Figure 5-9: Monthly Cooling Loads for Each of the Sunspaces at Four Different Canadian Cities
5.3.5. Production of Energy

As Figures 5-4 to 5-7 indicate the time spent within the comfort zone during the winter months is minimal and therefore occupant use of the sunspace will be very low if auxiliary heating is not implemented. This should not suggest however that the sunspace cannot be put to use in some fashion. Two approaches can be taken to utilize the sunspace during the winter months.

The amount of time spent above the comfort zone is also shown in Figures 5-4 to 5-7 and during these periods the excess energy that the sunspace generates can be used by the house for space heating. Not all this energy would be useful for the house however as the house may not require space heating at that time. Whether the house requires space heating or not depends on a number of factors such as the outside temperature, levels of insulation and air tightness, and internal and solar gains. An outside temperature, sometimes referred to as the balance point temperature [4], can be calculated. This is the outside temperature at which the heat loss from the house just balances or is equal to the gains from electrical energy and people and from solar energy. For a poorly insulated house under conditions of no solar gain and little internal gains; the balance point temperature would approach the house temperature of 22 C. On the other hand, under opposite conditions, this temperature would be lower than 0 C. A compromise balance point temperature of 14 C was selected. At outside temperatures less than 14 C it was further assumed that all excess energy could be used by the house while above 14 C, none of this energy could be utilized. In practice, energy would have to be transferred to the house by a thermostatically controlled fan interconnected to the auxiliary heating thermostat of the house.

From November to March more than 95 percent of the excess energy that the sunspaces produce can be vented to the house. This percentage is approximately the same for each of the cities studied. During some of the
winter months though the sunspaces did not produce any useful energy, this is particular true for sunspace D.

<table>
<thead>
<tr>
<th>Sunspace</th>
<th>City</th>
<th>Useful Energy (Winter) (kW·hr)</th>
<th>%-Yearly Cooling Load</th>
<th>Useful Energy (Yearly) (kW·hr)</th>
<th>%-Yearly Cooling Load</th>
</tr>
</thead>
<tbody>
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<td>A</td>
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<td>13</td>
<td>649</td>
<td>27</td>
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<td></td>
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<td></td>
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<td>19</td>
<td>694</td>
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<td>Fred.</td>
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<td></td>
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<td>Fred.</td>
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<td>Fred.</td>
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<td>Fred.</td>
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<td>4</td>
<td>508</td>
<td>21</td>
</tr>
</tbody>
</table>

Table 5-3: Comparison of the Useful Energy Produced by Each of the Sunspaces

The amount of energy that can be utilized both in terms of the magnitude and percentage of the yearly cooling load, changes very little between sunspace A, B and C as shown in Table 5-3. The useful energy that is produced by sunspace D however is negligible during the winter months and approximately two thirds of the yearly levels when compared with the other three sunspaces.

The second approach which can be considered is closing off the sunspace and drawing the ventilation inlet air for the HRV for the house through the sunspace. The sunspace would then serve as a pre-heater for the HRV. An air flow of 70.8 l/s (150 cfm), typical for the average HRV, was
used in this investigation. A comparison of the monthly sunspace temperature with and without the HRV operating is shown in Figure 5-10 for each of the sunspaces at Saskatoon. The sunspace temperature is reduced throughout the year. This would be identical to operating the HRV without a pre-heater. However the sunspace temperature also approaches the freewheeling temperature indicating that the sunspace does work in warming the fresh ventilation air.

The sunspace is effective as a pre-heater during the winter months of December to February reducing the HRV requirements by 25 percent for sunspace A and C and 16 percent for the other two sunspaces. However in the summer months, particularly July and August, the sunspace provides over 100 percent of the heat exchanger requirements. For these two months then a better option would be to use outside air directly. Table 5-4 presents the effectiveness of using the sunspaces as pre-heaters to an air-to-air heat exchanger.

The use of the sunspace as a pre-heater is not a completely economic issue however. One serious problem that exists with residential HRV’s is ice buildup on the inside surfaces of the unit. This buildup can be serious enough that the air flow through the exhaust side is restricted or even stopped. As shown in Figure 5-10 the range of sunspace temperatures that occur during the winter with the HRV in operation is significantly higher than the ambient temperature. This increase in temperature would serve to greatly reduce the frosting and may eliminate the problem completely.
Figure 5-10: The Effect of Using the Sunspace as a Pre-heater to a Heat Recovery Ventilator for Saskatoon
<table>
<thead>
<tr>
<th>Sunspace</th>
<th>City</th>
<th>Energy Produced (Winter) (kW·hr)</th>
<th>% of Required Winter Energy</th>
<th>Energy Produced (Yearly) (kW·hr)</th>
<th>% of Required Yearly Energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Vanc.</td>
<td>803</td>
<td>25</td>
<td>2872</td>
<td>39</td>
</tr>
<tr>
<td></td>
<td>Sask.</td>
<td>1817</td>
<td>26</td>
<td>4383</td>
<td>35</td>
</tr>
<tr>
<td></td>
<td>Toro.</td>
<td>1356</td>
<td>28</td>
<td>3328</td>
<td>37</td>
</tr>
<tr>
<td></td>
<td>Fred.</td>
<td>1545</td>
<td>28</td>
<td>3497</td>
<td>35</td>
</tr>
<tr>
<td>B</td>
<td>Vanc.</td>
<td>540</td>
<td>17</td>
<td>2243</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>Sask.</td>
<td>1095</td>
<td>16</td>
<td>3386</td>
<td>27</td>
</tr>
<tr>
<td></td>
<td>Toro.</td>
<td>863</td>
<td>18</td>
<td>2394</td>
<td>26</td>
</tr>
<tr>
<td></td>
<td>Fred.</td>
<td>981</td>
<td>18</td>
<td>2439</td>
<td>24</td>
</tr>
<tr>
<td>C</td>
<td>Vanc.</td>
<td>749</td>
<td>23</td>
<td>2333</td>
<td>31</td>
</tr>
<tr>
<td></td>
<td>Sask.</td>
<td>1476</td>
<td>21</td>
<td>4408</td>
<td>35</td>
</tr>
<tr>
<td></td>
<td>Toro.</td>
<td>1160</td>
<td>24</td>
<td>3042</td>
<td>34</td>
</tr>
<tr>
<td></td>
<td>Fred.</td>
<td>1289</td>
<td>23</td>
<td>3533</td>
<td>35</td>
</tr>
<tr>
<td>D</td>
<td>Vanc.</td>
<td>440</td>
<td>14</td>
<td>1798</td>
<td>31</td>
</tr>
<tr>
<td></td>
<td>Sask.</td>
<td>1007</td>
<td>15</td>
<td>3021</td>
<td>40</td>
</tr>
<tr>
<td></td>
<td>Toro.</td>
<td>762</td>
<td>15</td>
<td>2072</td>
<td>23</td>
</tr>
<tr>
<td></td>
<td>Fred.</td>
<td>875</td>
<td>16</td>
<td>2369</td>
<td>23</td>
</tr>
</tbody>
</table>

**Table 5-4:** Effectiveness of the four Sunspaces as a Pre-heater to a Heat Recovery Ventilator
5.4. Sunspace Operating Strategies

5.4.1. Introduction

The previous section presented the performance of the four sunspaces at the various Canadian cities with an emphasis towards presenting the thermal behaviour of the sunspaces on a monthly basis. In this section, the thermal performance is examined on an annual basis. Presentation on an annual basis enables condensed comparisons between sunspaces and locations under several different operating strategies to be made.

Seven different operating strategies were developed, some of which have already been described, to examine their effect on the thermal performance of the four sunspaces for each of the cities. Unless noted otherwise, for each of the strategies, the doors and windows of the sunspace will be assumed to be closed throughout the year, thereby eliminating any exchange of energy between the sunspace and house or between the sunspace and outside.

5.4.2. Definition of Operating Strategies

1. Base Condition - The first operating strategy defines how much auxiliary energy is required to keep the sunspace temperature within the comfort zone throughout a typical year. This auxiliary energy takes the form of either heating or air-conditioning of the sunspace. The blinds will be left open continuously.

2. Yearly Operation of Blinds - The ability of the blinds to increase the time spent within the comfort zone has been shown previously, however their effect on the heating and cooling loads has not been considered. The conditions for the operation of the blinds are repeated below,

1. If the sunspace temperature is greater than or equal to 27 C then the blinds will be closed, and,
2. If the horizontal solar radiation is equal to zero then the blinds will be closed.

This operating strategy determines how much auxiliary energy is required to keep the sunspace temperature within the comfort zone throughout a typical year when the blinds are operated as described above.

3. Useful Energy Transfer - Throughout the year any useful energy that is produced by the sunspace can be utilized by the house for space heating. For the energy transferred to the house to be deemed useful however the ambient temperature must be less than the balance point of 14 C. As explained before this energy is only potentially useful since the internal gains of the house and direct solar gains may produce the energy the house requires for heating when the sunspace is overheating.

The amount of useful energy produced by the sunspace depends upon whether the blinds are being used or not. By not closing the blinds, thereby allowing more solar radiation to enter the sunspace, the useful energy can be increased. This option however is only realistic from November to March when the increased levels of energy can be put to use.

This operating strategy uses the auxiliary energy loads of the second strategy but the useful energy produced from November to March is subtracted from both the yearly heating and cooling requirements. Heating requirements of the house are reduced using this strategy and this is reflected by reducing the heating load of the sunspace. The cooling load is reduced because air-conditioning is not required during the five winter months.

4. Forced Ventilation - This strategy uses ventilation cooling to achieve the desired reduction in sunspace temperature during the overheating season. A 20 Air Change per Hour (ACH) exhaust fan was selected, representing the upper limit in fan size, as shown in Figure 5-11. This fan to the outside provides sufficient circulation of the sunspace air to eliminate
overheating of the sunspace most of the time. This form of cooling can only lower the sunspace temperature to the ambient condition however and if the sunspace temperature is still above the comfort zone additional air-conditioning is required. Thus when the inside/outside temperature differential is low or negative an air-conditioner is required to condition the sunspace air completely.

The heating load of this strategy remains unchanged from that of the previous strategy. The cooling load of the previous strategy is reduced to the amount of air-conditioning that cannot be substituted with the introduction of ventilation cooling of the sunspace. Electrical costs of operating a fan were not considered in this strategy.

Figure 5-11: Percentage of the Time Forced Ventilation can replace Air Conditioning for Sunspace A in Saskatoon

5. Winter Shutdown - Allowing the sunspace to freewheel during the months of December, January and February would eliminate the major portion of the heating load. When the house and sunspace are at the same temperature no energy transfer between the two exists. When the sunspace is
allowed to freewheel the house heating requirements must increase to account for the energy transfer into the sunspace.

Transfer of energy to the house from the sunspace by air circulation during these three months was not performed. For the shutdown to be effective, the reduced heating requirements of the sunspace must be greater than the increase in the heating requirements of the house and the useful energy that was produced during this period.

The cooling load of this strategy remains unchanged from that of the previous strategy. The heating requirements for the months of December, January and February are subtracted from the heating load of the previous strategy.

6. Heat Exchanger Operation - Instead of shutting down the sunspace from December to February the sunspace can be used as a pre-heater for a heat recovery ventilator.

The heating load of the previous strategy will be reduced by the amount of energy the heat exchanger saves as a result of the sunspace. However because the sunspace is being operated at lower temperatures than when it is freewheeling the energy transfer from the house will increase. The cooling load of this strategy remains unchanged from that of the two previous strategies.

7. No Sunspace - This strategy examines the case when the sunspace is eliminated and the house is no longer buffered by the sunspace. When the ambient temperature is between 14 C and 20 C energy transfer through the house/sunspace surfaces was neglected. Energy transfer for this range of ambient temperatures was assumed to have no effect on either the heating or cooling loads of the house.

It is assumed that the heating load of the house will be reduced by the
solar radiation that is transmitted when the outside temperature is less than 14 °C. The cooling load of the house is increased by the solar radiation that is transmitted when the outside temperature is above 20 °C.

Because the model was not established to determine the transmitted solar radiation through the house/sunspace windows directly, the radiation transmitted through the sunspace/outside windows was adjusted. This adjustment assumes the transmittance of the interior windows is equal to the outside windows. For the house attached to sunspace D this will result in slightly lower radiation levels than expected. Another assumption is that the shading of the interior windows is equal to that occurring on the outside windows. The radiation levels for this house therefore will be slightly higher than expected tending to cancel the increase in transmittance. In the other three houses the radiation transmitted through the interior windows will be the same as for the the sunspaces.

5.4.3. Comparison of Heating Strategies

The yearly heating strategies for each of the sunspaces is presented in Figure 5-12. These procedures have been standardized by dividing the heating load by the floor area of the sunspace.

Of the four sunspaces sunspace A has the lowest base case energy requirement. For sunspace A the average base strategy for the four cities is 135 kWh/m², for sunspaces B C and D the average is 235, 332 and 986 kWh/m², respectively.

The use of blinds is beneficial for sunspace A only, reducing the yearly heating load by 8 percent. The other sunspaces require approximately 7, 47 and 2 % more auxiliary heating, respectively, when the blinds are in operation. This increase is because the blinds used in the last three sunspaces provide no increase in the window resistance well at the same time restricting the flow of solar energy into the sunspace. This condition results
in more heating energy being required to keep the sunspace conditioned properly.

Venting the excess energy produced by the sunspace into the house for space heating is an effective option for every sunspace. Sunspace A reduces its heating requirements by 28 percent when compared to the base strategy. The effectiveness of the other three sunspaces varies from 35 percent for sunspace C to 3 percent for sunspace D. Sunspace B compares with sunspace A with a 24 percent decrease in its heating requirements.

The next heating strategy is the shutdown of the sunspace during the winter months of December to February. This saves an average of 63 percent for the four sunspaces when compared to the respective base heating strategies. Sunspace C reduces its heating load by 86 percent whereas sunspace D reduces its load by only 41 percent.

When using the sunspace as a pre-heater to a HRV only sunspace A is effective in reducing the heating requirements when compared to operating strategy five. The remaining sunspaces do not provide significant savings and in some cases increase the heating requirements when the sunspace is operated in this fashion.

The last heating strategy to consider is the removal of the sunspace. For sunspace A this results in higher requirements than if an attached sunspace was operating at either heating strategy 5 or 6. Sunspace C has no clear pattern either way. The house/sunspace wall of sunspace B is so well insulated that the sunspace can never achieve comparable results. In fact for Vancouver this heating strategy is a net producer of 1 kWhr/m², but is shown as zero in Figure 5-12. The house/sunspace wall of sunspace D is insulated to the same level as sunspace A but requires so much heating that regardless of the operating procedure it can not approach operating strategy 7.
Figure 5-14 compares the yearly auxiliary heating requirements of the four sunspaces when located in the same city.

5.4.4. Comparison of Cooling Strategies

Figure 5-13 presents the different operating strategies for the four sunspaces normalized by dividing the cooling load by the floor area of the sunspace.

Sunspace A has the lowest cooling requirements at 80 kWhr/m², followed by sunspace D at 209 kWhr/m², and then sunspace B and C at 651 and 209 kWhr/m², respectively. As mentioned previously Vancouver has the highest sunspace temperatures for sunspace A and B. However as Figure 5-13 shows the cooling load of sunspace A is higher in Saskatoon than it is in Vancouver. As Figure 5-9 shows sunspace A has higher cooling loads during the swing seasons in Saskatoon than in Vancouver.

The use of blinds to reduce the yearly cooling loads is quite effective. The base yearly cooling loads of sunspace A and B are reduced by approximately 60 percent and for the other two the reduction is 30 percent. Because the overall thermal resistance of these sunspaces are higher than the other two, they are more sensitive to a reduction in the transmitted radiation.

Yearly cooling loads can be further reduced by transferring any useful energy to the house for space heating. For sunspace A and B this strategy further reduces the cooling load to 80 percent from the base condition. The total reduction for the other two sunspaces is only 50 percent.

With the inclusion of forced ventilation of sunspace A, the yearly base condition cooling load is reduced by 99 percent. With the other sunspaces, forced ventilation is nearly as effective. The reduction in the base condition is 92, 81 and 83 percent for the remaining sunspaces, respectively.
Figure 5-12: Yearly Auxiliary Heating Requirements of Four Sunspaces for Seven Different Operating Strategies
Figure 5-13: Yearly Auxiliary Cooling Requirements of Four Sunspaces for Seven Different Operating Strategies
Figure 5-14: Comparison of Yearly Auxiliary Heating Requirements for Seven Different Operating Strategies
Figure 5-15: Comparison of Yearly Auxiliary Cooling Requirements for Seven Different Operating Strategies
The cooling load for the house/sunspace wall is the last cooling strategy to be considered. For sunspace A and B the elimination of the sunspace results in higher cooling loads than strategy 6. This suggests that these two sunspaces are effective in reducing the cooling requirements of the house/sunspace structure. However the last two sunspaces do not achieve the same results. The sunspace increases the cooling requirements for these two structures.

Figure 5-15 compares the yearly auxiliary cooling requirements of the four sunspaces when located in the same city.

5.5. Summary

The work presented in this chapter shows that of the four sunspaces investigated only sunspace A has the potential to become a net producer of energy. This can be achieved by implementing the following operating strategy,

- use the sunspace as a pre-heater for an air-to-air heat exchanger during the months of December to February,

- vent any useful excess energy to the house for space heating during the months of November and March, and

- use an exhaust fan to provide cooling of the sunspace when required during the months of April to October.

The remaining sunspaces are net consumers of energy but all have the potential of significantly reducing their auxiliary energy requirements. The strategy described for sunspace A is also the most effective strategy for sunspace D as well. The remaining two sunspaces are better operated by shutting down the sunspace for the months of December to February instead of operating it as a pre-heater.
Chapter 6

Conclusions and Recommendations

6.1. Summary of Work Completed

The objectives outlined in Chapter 1 have been met. A model capable of predicting the thermal behaviour of a sunspace was developed. An experimental investigation of four sunspaces was performed to study the validity of the modelling techniques used. Experimental measurements of the four sunspaces showed that the temperatures predicted by the model agree reasonably well with measured values. The modelling of the in-between glazing horizontal venetian blinds installed at sunspace A result in sunspace temperatures during the summer which are higher than expected, however.

Yearly simulations were performed using Typical Meteorological Year weather data for four Canadian cities, namely Vancouver, Saskatoon, Toronto and Fredericton. For each of the sunspaces yearly simulations determined the sunspace temperatures under freewheeling conditions, the effect of venetian blinds on the sunspace temperature, the production of useful energy throughout the year by the sunspace and the auxiliary heating and cooling loads of the sunspaces.

From these simulations yearly heating and cooling operating strategies were developed for each of the sunspaces at the four Canadian cities.
6.2. Conclusions

TMY simulations show, as expected, that during the winter Vancouver and Saskatoon give the warmest and coldest sunspace temperatures, respectively, regardless of the type of sunspace. The summer freewheeling temperatures, however, are strongly influenced by the type of sunspace, specifically the amount and orientation of the glazing surfaces. For sunspaces with vertical glazing surfaces primarily orientated south, Vancouver will give the warmest summer temperature. When glazing surfaces are added to the roof of the sunspace Saskatoon give higher summer temperatures.

The use of venetian blinds, especially during the summer, are an effective way to increase the time spent within the comfort zone for each of the sunspaces investigated.

Sunspace A and B have the lowest heating requirements of the four sunspaces due to the low UA of the sunspace structures. Sunspace C and D have heating requirements which are double that of the first two sunspaces. The way in which the outside walls of the sunspaces were constructed is the main reason for this large increase. The large amounts of south facing window area helps offset the heating requirements of sunspace C but result in a large UA values. The poor glazing orientation of sunspace D results in larger heating loads than the other three sunspaces.

Two different methods of producing energy are possible. The first method, simply vents any useful energy produced by the sunspace into the house. With this method Sunspace D can produce only one-half the amount of energy that the other three can. Using the sunspace as a pre-heater to a HRV is the second option available. From December to February the HRV requirements can be reduced by 25 percent for sunspaces A and C, and 16 percent for the other two sunspaces.

Based on TMY simulations, only sunspace A has the potential to
become a net producer of energy. The remaining sunspaces are net consumers of energy but all have the potential of significantly reducing their auxiliary energy requirements. This can be achieved by using the sunspace as a preheater for a HRV during the months of December to February and venting any useful energy to the house for space heating during the months of November and March, and, using a 20 ACH fan to reduce the air-conditioning load of the sunspace during the months of April to October.

6.3. Recommendations for Future Work

Several areas of this thesis have the potential for further investigation.

The techniques used to model the sunspace are for the most part quite adequate however investigation of the following could be considered,

1. The increase in window resistance when in-between glazing venetian blinds are closed.
2. Reduction in transmitted solar radiation when in-between glazing venetian blinds are used.
3. The occurrence of extreme overheating of the sunspace during the simulation.
4. Radiative energy transfer between interior surfaces of the sunspace.
5. Prediction of incident radiation on exterior sunspace surfaces.
6. Deposition of transmitted radiation onto interior surfaces of the sunspace.
7. Infiltration/exfiltration of the sunspace

The yearly operating costs of the sunspaces investigated varied with the overall thermal resistance and capacitance of the sunspace, orientation and area of the glazing surfaces of the sunspace, and the locale of the sunspace. The effect on the operating costs when these parameters are varied could be examined. Three parameters in particular warrant further investigation,
1. Use of an effective night-time insulation, or the,

2. Use of super windows to reduce the auxiliary heating requirements, and

3. The effect of locale on the auxiliary energy requirements of the sunspaces.

Finally the calculation of capital and operating costs as well as determining the pay back period, if any, of the sunspace would allow a purely economic decision to be made about sunspace usage in Canada.
References


Appendix A
Sunspace Construction Details

A.1. Introduction

The four sunspaces that were investigated are presented in detail in this appendix. The cross-sectional views and floor plans of the four sunspaces are repeated from Chapter 2 where they were originally shown. Construction details of the four sunspaces are presented as well in this appendix.
A.2. Sunspace A

The floor plan and north-south cross-sectional view of sunspace A are shown in Figures A-2 and A-1, respectively.

Figure A-3 shows the construction details of the interior walls of the sunspace. The exterior walls of the sunspace are of similar construction as shown in Figure A-4.

The sunspace floor is shown in Figure A-5. Figure A-6 presents the construction details of the ceiling for sunspace A.

Figure A-1: North-South Cross-Sectional View of Sunspace A
Figure A-2: Floor Plan of Sunspace A
Figure A-3: Construction Details of the Interior Wall of Sunspace A

Figure A-4: Construction Details of the Exterior Wall of Sunspace A
**Figure A-5:** Construction Details of the Floor of Sunspace A

**Figure A-6:** Construction Details of the Ceiling of Sunspace A
A.3. Sunspace B

Figures A-8 and A-7 present the floor plan and east-west cross-sectional view of sunspace B, respectively.

The interior wall of sunspace B is presented in Figure A-9. The exterior walls of this sunspace are of two types. The construction details of both the west and south exterior walls are presented in Figure A-10 and Figure A-11 presents the details of the northern exterior wall of the sunspace.

The floor of sunspace B is shown in Figure A-12. Figure A-13 shows the ceiling of sunspace B.

Figure A-7: East-West Cross-Sectional View of Sunspace B
Figure A-8: Floor Plan of Sunspace B
Figure A-9: Construction Details of the Interior Wall of Sunspace B

Figure A-10: Construction Details of the South and West Exterior Walls of Sunspace B
Figure A-11: Construction Details of the Northern Exterior Wall of Sunspace B

Figure A-12: Construction Details of the Floor of Sunspace B
Figure A-13: Construction Details of the Ceiling of Sunspace B
A.4. Sunspace C

The floor plan and north-south cross-sectional view of sunspace C are presented in Figures A-15 and A-14, respectively.

The interior wall of sunspace C is described in Figure A-16. Figure A-17 describes the construction details for all the exterior walls of the sunspace below the glazing surfaces. The east and west walls have sections above the glazing surfaces which are of different construction than the sections below the glazing surfaces. These sections are presented in Figure A-18.

The floor of sunspace C is presented in Figure A-19. The ceiling of sunspace C is presented in Figure A-20. As shown in the cross-sectional view of sunspace C the thickness of the ceiling varies, however this is not shown in Figure A-20.

Figure A-14: North-South Cross-Sectional View of Sunspace C
Figure A-15: Floor Plan of Sunspace C
Figure A-16: Construction Details of the Interior
Wall of Sunspace C

Figure A-17: Construction Details of the Exterior
Wall (#1) of Sunspace C - Typical of Wall Below the Exterior Glazing Surfaces
Figure A-18: Construction Details of the Exterior Wall (#2) of Sunspace C - Typical of Wall Above the Exterior Glazing Surfaces on the East and West End Walls

Figure A-19: Construction Details of the Floor of Sunspace C
Figure A-20: Construction Details of the Ceiling of Sunspace C
A.5. Sunspace D

Figures A-22 and A-21 show the floor plan and west-east cross-sectional view of sunspace D, respectively.

The interior wall of sunspace D is shown in Figure A-23. Because Sunspace D is the only sunspace that is not on the same level as the house the basement walls make up part of the interior wall for this sunspace. The basement wall of the house is shown in Figure A-24. Figure A-25 presents the construction details of the exterior walls of the sunspace.

The floor of sunspace D is an insulated 2 inch concrete slab as shown in Figure A-26.

Glazing surfaces make up most of the ceiling area however the house overhangs are presented in Figure A-27.
Figure A-22: Floor Plan of Sunspace D
Figure A-23: Construction Details of the Interior Wall of Sunspace D

Figure A-24: Construction Details of the House Foundation of Sunspace D
Figure A-25: Construction Details of the Exterior Wall of Sunspace D

Figure A-26: Construction Details of the Floor of Sunspace D
Figure A-27: Construction Details of the Ceiling of Sunspace D
Appendix B
Simulation Program

B.1. Introduction

This appendix briefly discusses and then presents the programs that were used in the TMY simulations. Due to differences in the models for each of the sunspaces the set of programs that were used to determine the thermal behaviour of the sunspace are not identical. The modelling of Sunspace A was completed first and this model was then modified to predict the thermal behaviour of the other three sunspaces. For this reason the only programs that are presented in this Appendix are those that were used for the modelling of Sunspace A.

B.2. MAIN.FOR

This routine manages the interaction of the subroutines and determines the auxiliary energy requirements for each time step of the simulation. It allows the user to select between either monitored or TMY simulations. The user has the ability to vary the TMY simulations by providing auxiliary energy, controlling venetian blind operation, treating the house-sunspace surfaces as adiabatic surfaces as well as ignoring solar radiation to determine the cooling and heating loads in the absence of solar energy.

For the monitored simulations the routine saves only the predicted sunspace temperatures. In the TMY simulation the routine stores the following,

- Average monthly house, sunspace, crawlspace, outside
temperatures, and the standard deviation of the monthly sunspace temperature,

- Amount of time each month the sunspace temperature spends below, inside and above the comfort zone and,

- Monthly energy flows within the sunspace

Called by: -----

Calls: DATAREAD.FOR
GEOMETRY.FOR
THERMAL.FOR
SURFCOND.FOR
SOLVE.FOR
SOLARCALC.FOR
QCALC.FOR

B.3. SOLVE.FOR

This subroutine sets up the matrix for the 29 equations that define the thermal environment of the sunspace for each time step. This matrix is redefined every time step, due to changing internal energy levels, infiltration rates, auxiliary energy requirements and absorbed solar radiation.

Called by: MAIN.FOR

Calls: SOLUTION.FOR

B.4. SOLUTION.FOR

This subroutine finds the solution to a set of simultaneous linear algebraic equations using the Gauss-Jordan method. Pivoting is performed on the augmented matrix by selecting the pivot element which has the greatest magnitude. Pivoting ensures that the greatest overall computational accuracy is achieved by the Gauss-Jordan method. The process that is used
in this subroutine is known as partial pivoting because the the row which has the largest pivot element is switched with the original pivot element. Full pivoting would be performed by switching the matrix columns as well as the rows [1].

Called by: SOLVE.FOR

Calls: ------

B.5. QCALC.FOR

This subroutine calculates the hourly energy flows within the sunspace for the TMY simulations. These energy flows are based on temperatures calculated from the subroutine SOLVE.FOR.

Called by: MAIN.FOR

Calls: ------

B.6. SOLARCALC.FOR

This subroutine calculates the beam, diffuse sky and diffuse ground reflected radiation components incident on each exterior surface of the sunspace. The amount of radiation that is transmitted through any glazing surfaces present is also calculated [2].

Called by: MAIN.FOR

Calls: INCIDENCE.FOR

SHADOW.FOR

OPTICS.FOR
B.7. INCIDENCE.FOR

This subroutine calculates the incidence and zenith angles for each exterior surface at any particular time.

Called by: SOLARCALC.FOR

Calls: ------

B.8. SHADOW.FOR

This subroutine calculates the shading effect of overhangs and wingwalls for each time step. The treatment of shadow overlapping cast by various shading devices is included in the subroutine. The program was developed by Sun [3].

Called by: SOLARCALC.FOR

Calls: ------

B.9. OPTICS.FOR

This subroutine determines the beam, diffuse ground and diffuse sky transmittances for an exterior glazing surface.

Called by: SOLARCALC.FOR

Calls: ------

B.10. VIEWFACTOR.FOR

This subroutine calculates the surface to sky and surface to ground viewfactors for an exterior sunspace surface.

Called by: GEOMETRY.FOR

Calls: VIEWCALC.FOR
B.11. VIEWCALC.FOR

This subroutine determines the view factor of two surfaces in radiative contact. The shading device does not have to be at right angles to the receiver. Limiting angles between the two surfaces are ninety degrees plus or minus seventy degrees. These limits were imposed because the program did not give realistic values when the angle approached zero degrees on one side and one hundred and eighty degrees on the other. The number of nodes needed to accurately produce the results as taken from Utzinger and Klein [4] are quite low. The number of nodes defining the surface is therefore quite arbitrary [5].

Called by: GEOMETRY.FOR

Calls: ------

B.12. DATAREAD.FOR

This subroutine reads either the monitored or TMY datafiles as selected by the uses. The subroutine transfers a daily weather matrix to MAIN.FOR which includes hourly values for the TMY simulation or quarter hourly values for the monitored simulations of the following,

- Day,
- Time,
- House Temperature,
- Monitored Sunspace Temperature,
- Crawlspace Temperature,
- Outside Temperature,
- Monitored NonSouth Radiation or TMY ground reflectance,
- Monitored South Radiation or TMY Horizontal Radiation,
- Wind Speed,
• Monitored Heater Energy,
• Monitored Fan Speed

Called by: MAIN.FOR

Calls: -------

B.13. GEOMETRY.FOR

This subroutine stores the geometries of each outside surface of the sunspace including the glazing surfaces to determine the viewfactors and hourly shading that occurs on each surface. The areas of the internal windows and doors are stored in this subroutine as well.

Called by: MAIN.FOR

Calls: VIEWFACTOR.FOR

B.14. THERMAL.FOR

This subroutine stores the conductivities, lengths, densities, specific heats and areas of the different components of each sunspace surface. The conductivities of all the windows and doors are stored in this subroutine as well. These values were taken from the various references [6-10].

Called by: MAIN.FOR

Calls: -------

B.15. SURFCOND.FOR

This subroutine calculates the surface conductances of the exterior surfaces. Because of changing wind speeds this is performed for every time step. The equations were developed from Figure 1, Chapter 23, ASHRAE 1981 Fundamentals [11].

Called by: MAIN.FOR

Calls: -------
Figure B-1: Surface Conductance for Different 12 inch Square Surfaces as Affected by Air Movement [11]

For smooth plaster the surface conductance is,

\[ h = 1.395 \times V + 10.221 \]

For carpet the surface conductance of brick or rough plaster was used and is given by,

\[ h = 2.009 \times V + 11.357 \]

For plywood the surface conductance of clear pine was used and is given by,

\[ h = 1.609 \times V + 8.517 \]

For ceramic tile the surface conductance of concrete was used and is given by,

\[ h = 1.835 \times V + 11.357 \]
For stucco the surface conductance is,

\[ h = 2.650 \times V + 11.357 \]

For shingles whether they are cedar or asphalt the surface conductance of brick or rough plaster was used and is given by,

\[ h = 2.009 \times V + 11.357 \]
B.16. Program Listings of MAIN.FOR

* INTEGER TMPCNT(110) !TEMPERATURE DISTRIBUTION VECTOR
* INTEGER*4 STARTUP !TIMING VALUE
INTEGER FLAG1 !DATA FLAG
INTEGER AIRFLG !AIR COND. OPERATION FLAG
INTEGER FANFLG !FAN OPERATION FLAG
INTEGER HTRFLG !HEATER OPERATION FLAG
INTEGER VENFLG !VENETIAN BLIND OPERATION FLAG
INTEGER SUNFLG !SUN CONTROL FLAG
INTEGER HSEPLG !HOUSE TRACKING FLAG
INTEGER OUTFLG !OUTSIDE TRACKING FLAG
INTEGER MONCNT !NUMBER OF MONTH
INTEGER IDT !INTEGER TIME STEP
INTEGER ENDFLAG !END OF FILE FLAG
* REAL WINDGEOM(10,18) !WINDOW GEOMETRY MATRIX
REAL WALLGEOM(10,1?) !OUTSIDE WALL GEOMETRY MATRIX
REAL REFMI$C(9,2,21) !MISC. UA MATRIX
REAL MISCUA(9,2) !MISC. UA MATRIX
REAL WEATHER(96,11) !DAILY WEATHER STORAGE MATRIX
REAL COND(10,10) !CONDUCTIVITY MATRIX FOR WALLS
REAL LEN(10,10) !LENGTH MATRIX FOR WALLS
REAL DSSPT(10,10) !DENSITY*SPECIFIC HEAT MATRIX FOR WALLS
REAL AREA(10,10) !AREA MATRIX FOR WALLS
REAL RAD(15) !NET RADIATION VECTOR
REAL NODAL(10) !STORAGE MATRIX
REAL TEMP(32) !TEMPERATURE STORAGE VECTOR
REAL OLDTEMP(32) !TEMPERATURE STORAGE VECTOR
REAL AVGTM(5) !AVERAGE MONTHLY DAILY TEMP. VECTOR
REAL MONAVG(5,12) !AVERAGE MONTHLY TEMPERATURE MATRIX
REAL CZ(111,12) !COMFORT ZONE MATRIX
REAL QSUM(33) !HEAT FLOW STORAGE MATRIX
REAL QMONTH(33,12) !YEARLY HEAT FLOW MATRIX
* REAL CNT !STORAGE ITEMS FOR MEASURED TESTS
REAL HTRSET !MAX. TEMP FOR HEATER OPERATION
REAL CFM !FLOW RATE OF FAN IN CFM
REAL AIRSET !MIN. TEMP FOR AIR COND. OPERATION
REAL UAADJST !ADJUSTMENT FOR CLOSED VENETIAN BLINDS
REAL START !STARTING POINT FOR SIMULATION
REAL END !ENDING POINT FOR SIMULATION
REAL LAT !LATITUDE OF CITY
REAL LON !LONGITUDE TIME ADJUSTMENT
REAL ALT !ALTITUDE OF LOCATION IN KILOMETERS
REAL STEP !TIME COUNTER FOR SIMULATION
REAL VEXT !EXTERIOR WIND VELOCITY
REAL AIR !AUXILIARY AIR COND. ENERGY
REAL FAN !FLOW RATE OF FAN IN M••3/S
REAL HTR !AUXILIARY HEATER ENERGY
REAL FANLMT !LIMITING FAN SPEED
REAL TOTNEW !THERMAL CHARGING CHECK
REAL TOTOLD !OLD THERMAL CHARGING CHECK
REAL TMCNT !NUMBER OF HOURS IN MONTH
REAL DAY !DAY OF THE YEAR
REAL RTIME !REAL TIME
REAL DT !TIME STEP IN MINUTES
REAL G1 !SOUTH VERT. OR TVY HORIZ. RADIATION
REAL G2 !NONSOUTH VERTICAL RADIATION
REAL HTRSTP !INCREMENTAL HEATER ENERGY
REAL AIRSTP !INCREMENTAL AIR COND. ENERGY
REAL ETIME !ELAPSED TIME
REAL SUNTMP !MEASURED SUNSPACE TEMPERATURE
REAL EMON !ELAPSED MONTHS
REAL MONTH !END OF MONTH FLAG
REAL TOTRAD !TOTAL RADIATION ON OUTSIDE SURFACES

CHARACTER*4 CITY !LOCATION OF TEST
CHARACTER*10 DATAPLLE !RESULTS STORAGE FILE
CHARACTER*10 HOUSE !HOUSE CODE
CHARACTER*10 RESULT !TIMING STRING
CHARACTER*50 DATAPILL !RESULTS STORAGE FILE

- PRINT HEADER
ISTAT = LIB$INIT TIMER(STARTUP) !START TIMING
ISTAT = LIB$ERASE_PAGE(1,1) !CLEAR SCREEN
TYPE 100
100 FORMAT (',/,'SIMULATION OF SUNSPACES',/')

- SELECT SUNSPACE
TYPE 102
102 FORMAT (',/,'ENTER HOUSE CODE (A, B, C, OR D) : ','$
ACCEPT 103, HOUSE
103 FORMAT (6A)

- SELECT WEIGHTING FACTORS FOR MONITORED DATA
IF (FLAG1.EQ.0) THEN
VENFLG=0
ELSE
HEATER CONTROLLER
TYPE 108

108 FORMAT (' ',/,' DO YOU WANT AUXILIARY HEATING
1(0/1): ',$,')
ACCEPT 105,HTRFLG

HTRSET=22 !DEGREES CELCIUS

TYPE 109

109 FORMAT (' ',/,' DO YOU WANT A AIR-TO-AIR HEAT EXCHANGER
1(0/1): ',$,')
ACCEPT 105,FANFLG

CPM=150 !CUBIC FEET PER MINUTE

AIR CONDITIONING CONTROLLER

TYPE 111

111 FORMAT (' ',/,' DO YOU WANT AIR CONDITIONING
1(0/1): ',$,')
ACCEPT 105,AIRFLG

AIRSET=27 !DEGREES CELCIUS

VENETIAN BLINDS CONTROLLER

TYPE 112

112 FORMAT (' ',/,' DO YOU WANT VENETIAN BLIND CONTROL
1(0/1): ',$,')
ACCEPT 105,VENFLG

SOLAR RADIATION CONTROLLER

TYPE 115

115 FORMAT (' ',/,' DO YOU WANT TO TURN THE SUN ON
1(0/1): ',$,')
ACCEPT 105,SUNFLG

SUNSPACE TRACKING CONTROLLER

TYPE 116

116 FORMAT (' ',/,' HOUSE TRACKING THE SUNSPACE
1(0/1): ',$,')
ACCEPT 105,HSEFLG

TYPE 117

117 FORMAT (' ',/,' SUNSPACE TRACKING OUTSIDE
1(0/1): ',$,')
ACCEPT 105,OUTFLG

ENDIF

INPUT DAILY WEATHER DATA

CALL DATAREAD(FLAG1,WEATHER,START,END,CITY,LAT,LON,ALT)

ENTER DATA FILE

TYPE 118

118 FORMAT (' ',/,' ENTER STORAGE FILE NAME (10 LETTERS MAX)
1: ',$,')
ACCEPT 119,DATAFILE

OPEN DATA STORAGE DATAFILE

IF (FLAG1.EQ.0) THEN
DATAFILE1='WORK:[MEE.LUMGIS.'//HOUSE//'DATA.TEST]'//DATAFILE
OPEN (UNIT=02,FILE=DATAFILE1,STATUS='NEW')
CNT=7
WRITE (02,*) CNT
ELSE
DATAFILE1='WORK:[MEE.LUMGIS.'//HOUSE//'DATA.'//CITY//'']
DATAFILE1=DATAFILE1//DATAFILE
OPEN (UNIT=02,FILE=DATAFILE1,STATUS='NEW')
ENDIF

ISTAT=LIB$ERASE_PAGE(1,1) !CLEAR SCREEN
SETUP GEOMETRY OF SUNSPACE BASED ON WEIGHTING FACTORS
CALL GEOMETRY(WINDGEOM, WALLGEOM, REFMISC)

STEADY STATE THERMAL CHARGING OF THE SUNSPACE

TYPE 120
120 FORMAT (' ',//, ' SUNSPACE THERMAL CHARGING ',*)

SETUP THERMAL CHARACTERISTICS OF SUNSPACE
CALL THERMAL(COND, LEN, DSSPT, AREA, REFMISC)

DETERMINE SURFACE CONDUCTANCES OF SURFACES
VEXT = WEATHER(START, 9)
CALL SURFCOND(VEXT, COND)
DO 11 I = 1, 9
MISCUA(I, 1) = REFMISC(I, 1)
MISCUA(I, 2) = REFMISC(I, 2)
11 CONTINUE

ADJUST RESISTENCE OF WINDOWS IF VENETIAN CONTROL IS ON
RAD(15) = 0
UAADJST = .30/.49

MEASURED DATA
IF (FLAG1.EQ.0.AND. VENFLG.EQ.1) THEN
RAD(15) = 1
MISCUA(5, 1) = REFMISC(5, 1) * UAADJST
MISCUA(6, 1) = REFMISC(6, 1) * UAADJST
MISCUA(7, 1) = REFMISC(7, 1) * UAADJST
ENDIF

TMY DATA
IF (FLAG1.EQ.1.AND. VENFLG.EQ.1) THEN

END IF

SET SUNSPACE STARTING TEMPERATURES
IF (FLAG1.EQ.0) THEN
TEMP(29) = WEATHER(START, 4)
ELSE
IF (HTRFLG.EQ.1) TEMP(29) = HTRSET
IF (AIRFLG.EQ.1) TEMP(29) = AIRSET
IF (HTRFLG.EQ.1.AND. AIRFLG.EQ.1) THEN
TEMP(29) = (HTRSET + AIRSET) / 2
ENDIF
IF (HTRFLG.EQ.0.AND. AIRFLG.EQ.0.AND. OUTFLG.NE.1) THEN
DT = 3600
ENDIF

SET OTHER STARTING TEMPERATURES
TEMP(30) = WEATHER(START, 3)
IF (HSEFLG.EQ.1) TEMP(30) = TEMP(29)
TEMP(31) = WEATHER(START, 5)
TEMP(32)=WEATHER(STEP,6)
IF (OUTFLG.EQ.1) TEMP(29)=TEMP(32)

**CALCULATE NODAL TEMPERATURES**

CALL SOLVE(DT,TEWP,COND,LEN,DSSPT,AREA,MISCUA,AIR,FAN,HTR
1,VEXT,RAD,NODAL,FANLMT)

**DETERMINE TEMPERATURE VECTOR ACCURACY**

TOTNEW=0
DO 13 I=1,29
   TOTNEW=TOTNEW+TEMP(I)
13 CONTINUE

IF (ABS(TOTNEW-TOTOLD).GE.1E-3) THEN
   IDT=IDT+3600
   TOTOLD=TOTNEW
   GOTO 40
ENDIF

IDT=IDT/3600
TYPE 121,IDT
121 FORMAT ('COMPLETE AFTER ',13,' HOURS',/
**BEGIN CALCULATION OF SUNSPACE PERFORMANCE**

**INITIALIZE VARIABLES**

MONCNT=0
TMPCNT=0

DO 15 J=1,5
   AVGTMP(J)=0
15 CONTINUE

DO 16 I=1,110
   TMPCNT(I)=0
16 CONTINUE

**PERFORM DAILY THERMAL SIMULATION**

**TIME VARIABLES**

IF (FLAG1.EQ.0.AND.STEP.LT.96.0R.FLAG1.EQ.1.AND.STEP.LT.24) THEN
   DT=(WEATHER(STEP+1,2)-WEATHER(STEP,2))*3600
ELSE
   DT=DT
ENDIF

RTIME=WEATHER(STEP,2)
DAY=WEATHER(STEP,1)

**TEMPERATURE VARIABLES**

TEMP(30)=WEATHER(STEP,3)
IF (OUTFLG.EQ.1) TEMP(30)=TEMP(29)
TEMP(31)=WEATHER(STEP,5)
TEMP(32)=WEATHER(STEP,6)

IF (OUTFLG.EQ.1) THEN
   TEMP(29)=TEMP(32)
   DT=0
ENDIF

**DETERMINE SURFACE CONDUCTANCES OF SURFACES**

VEXT=WEATHER(STEP,9)
CALL SURFCOND(VEXT,COND)

DO 18 I=1,9
   MISCUA(I,1)=REFMISC(I,1)
   MISCUA(I,2)=REFMISC(I,2)
18 CONTINUE

**DETERMINE WHETHER SOLAR SUBROUTINE SHOULD BE CALLED**

**RADIATION VARIABLES**

C2=WEATHER(STEP,7)
C1=WEATHER(STEP,8)
* INITIALIZE SOLAR RADIATION VECTOR
  * DO 19 I=1,14
  * RAD(I)=0
  19 CONTINUE
  * IF (FLAG1.EQ.0.AND.GL.EQ.0.AND.G2.EQ.0) GOTO 51
  * IF (FLAG1.EQ.1.AND.GL.EQ.0) GOTO 51
  * IF (FLAG1.EQ.1.AND.SUNFLG.EQ.0) GOTO 51
  * CALCULATE RADIATION ON EXTERIOR SURFACES AND
  * TRANSMITTED THROUGH WINDOWS
  * CALL SOLARCALC(WINDGEOM,WALLGEOM,DT,RTIME,DAY,ALT,LANGL,ALT,GL,G2
  * RADIATION ON OUTSIDE SURFACES
  * DO 20 I=5,10
  * RAD(I)=RAD(I)*AREA(I,1)
  20 CONTINUE
  * TRANSMITTED RADIATION
  * RAD(11)=RAD(11)*MISCUA(5,2)
  * RAD(12)=RAD(12)*MISCUA(6,2)
  * RAD(13)=RAD(13)*MISCUA(7,2)
  * ADJUST RESISTENCE OF WINDOWS IF VENETIAN CONTROL IS ON
  * RAD(15)=0
  * UAADJST=.30/.49
  * MEASURED DATA
  * IF (FLAG1.EQ.0.AND.VENFLG.EQ.1) THEN
  * RAD(15)=1
  * MISCUA(5,1)=REFMISC(5,1)*UAADJST
  * MISCUA(6,1)=REFMISC(6,1)*UAADJST
  * MISCUA(7,1)=REFMISC(7,1)*UAADJST
  * ENDIF
  * TMY DATA
  * IF (FLAG1.EQ.1.AND.VENFLG.EQ.1) THEN
  * VENETIAN BLINDS CLOSED DURING THE NIGHT
  * IF (GL.EQ.0) THEN
  * RAD(15)=1
  * MISCUA(5,1)=REFMISC(5,1)*UAADJST
  * MISCUA(6,1)=REFMISC(6,1)*UAADJST
  * MISCUA(7,1)=REFMISC(7,1)*UAADJST
  * GOTO 52
  * ENDIF
  * SUNSPACE TEMPERATURE IS GREATER THAN OR EQUAL TO AIRSET
  * DO 21 I=1,32
  * OLDTEMP(I)=TEMP(I)
  21 CONTINUE
  * AIR=0
  * FAN=0
  * HTR=0
  * CALL SOLVE(DT,TEMP,COND,LEN,DSSPT,AREA,MISCUA,AIR,FAN
  * ,HTR,VEXT,RAD,NODAL,FANLMT)
  * IF (TEMP(29).GE.AIRSET) THEN
  * RAD(15)=1
  * MISCUA(5,1)=REFMISC(5,1)*UAADJST
  * MISCUA(6,1)=REFMISC(6,1)*UAADJST
  * MISCUA(7,1)=REFMISC(7,1)*UAADJST
  * ENDIF
  * DO 22 I=1,32
  * TEMP(I)=OLDTEMP(I)
  22 CONTINUE
  * ENDIF
  * CALCULATE AUXILIARY ENERGY
  * FOR MONITORED DATA
  * IF (FLAG1.EQ.0) THEN
  * AIR=0
  * FAN=0
  * HTR=0
  * IF (FANFLG.EQ.0) THEN
  * FAN=WEATHER(STEP,11) !DEFAULT
  * ELSE IF (FANFLG.EQ.1) THEN
  * FAN=WEATHER(STEP,9)/3.6*.1324*1.5*.49 !NATURAL
  * ELSE IF (FANFLG.EQ.2) THEN
  * FAN=WEATHER(STEP,11) + .615903*(4*.0254/2) = 2 !FORCED
  * ELSE IF (FANFLG.EQ.3) THEN
  * FAN=WEATHER(STEP,11) * .615903*(4*.0254/2) !FORCED
```plaintext
ELSE

FOR TM DATA

AIR=O
FAN=O
HTR=O

IF (AIRFLG.EQ.1.OR.FANFLG.EQ.1.OR.HTRFLG.EQ.1) THEN
AIRSTP=1000
HTRSTP=1000
DO 23 I=1,32
   OLDTEMP(I)=TEMP(I)
23 CONTINUE

DETERMINE AUXILIARY HEATING ENERGY

IF (HTRFLG.EQ.1) THEN
   CALL SOLVE(DT,TEMP,COND,LEN,DSSPT,AREA,MISCUA,AIR,FAN,HTR,VEXT,RAD,NODAL,FANLMT)
1      HTR=WEATHER(STEP,10)*15
   IF (HTR.EQ.0) THEN
      IF (TEMP(29).GE.HTRSET.AND.TEMP(29).LE.AIRSET) GOTO 56
      IF (TEMP(29).GT.AIRSET) THEN
         DO 24 I=1,32
            TEMP(I)=OLDTEMP(I)
         CONTINUE
         GOTO 57
      END IF
      IF (TEMP(29).GE.HTRSET.AND.TEMP(29).LE.(HTRSET+1)) THEN
         GOTO 56
      END IF
      IF (TEMP(29).LT.(HTRSET+1)) THEN
         HTR=HTR-HTRSTP
         HTRSTP=HTRSTP/10
      END IF
      HTR=HTR-HTRSTP
      DO 25 I=1,32
         TEMP(I)=OLDTEMP(I)
25 CONTINUE
   ENDIF
   GOTO 54
54 ENDIF

DETERMINE AUXILIARY AIR CONDITIONING ENERGY

IF (AIRFLG.EQ.1) THEN
   CALL SOLVE(DT,TEMP,COND,LEN,DSSPT,AREA,MISCUA,AIR,FAN
   HTR,VEXT,RAD,NODAL,FANLMT)
1      IF (AIR.EQ.0) THEN
         IF (TEMP(29).GE.HTRSET.AND.TEMP(29).LE.AIRSET) GOTO 56
         IF (TEMP(29).LT.HTRSET) THEN
            DO 26 I=1,32
               TEMP(I)=OLDTEMP(I)
            CONTINUE
            GOTO 58
         END IF
         IF (TEMP(29).LT.(AIRSET-1)) THEN
            AIR=AIR-AIRSTP
            AIRSTP=AIRSTP/10
         END IF
         AIR=AIR+AIRSTP
         DO 27 I=1,32
            TEMP(I)=OLDTEMP(I)
27 CONTINUE
      ENDIF
      GOTO 54
54 ENDIF

DETERMINE HEAT EXCHANGER EFFECT ON SUNSPACE TEMPERATURE

IF (FANFLG.EQ.1) THEN
   FAN=.02832/60*CFM
   !W**3/SEC
   CALL SOLVE(DT,TEMP,COND,LEN,DSSPT,AREA,MISCUA,AIR,FAN,HTR
1      ,VEXT,RAD,NODAL,FANLMT)
   HTR=HTR-HTRSTP
   HTRSTP=HTRSTP/10
   ENDIF
   GOTO 54
54 ENDIF

DETERMINE BEAT EXCHANGER EFFECT ON SUNSPACE TEMPERATURE

IF (FANFLG.EQ.1) THEN
   FAN=.02832/60*CFM
   !W**3/SEC
   CALL SOLVE(DT,TEMP,COND,LEN,DSSPT,AREA,MISCUA,AIR,FAN,HTR
1      ,VEXT,RAD,NODAL,FANLMT)
   HTR=HTR-HTRSTP
   HTRSTP=HTRSTP/10
   ENDIF
   GOTO 54
54 ENDIF

CALCULATE NODAL TEMPERATURES IF AUX. ENERGY IS NOT REQUIRED

CALL SOLVE(DT,TEMP,COND,LEN,DSSPT,AREA,MISCUA,AIR,FAN,HTR
1      ,VEXT,RAD,NODAL,FANLMT)
   GOTO 56
56 ENDIF

RECORD DATA IN PROPER DATA FILES

END IF
```

IF (FLAG1.EQ.0) THEN
  SUNTMP = WEATHER(STEP, 4)
  ETIME = DAY + RTIME/24
  WRITE (02, 130) ETIME, TEMP(30), TEMP(31), TEMP(32),
                 SUNTMP, G1
  FORMAT (' ', F8.2, 6(' ,', F7.2))
ELSE
  DO 30 J=1, 5
      AVGTEMP(J) = TEMP(J)/AVGNUM
  CONTINUE
ENDIF

END IF

FOR TMY DATA

TMCNT = TMCNT + 1
AVGTEMP(1) = AVGTEMP(1) + TEMP(30)
AVGTEMP(2) = AVGTEMP(2) + TEMP(29)
AVGTEMP(3) = AVGTEMP(3) + TEMP(31)
AVGTEMP(4) = AVGTEMP(4) + TEMP(32)
AVGTEMP(5) = AVGTEMP(5) + TEMP(29) + TEMP(29)

IF (OUTFLG.NE.1) THEN
  TMPCNT(INT(TEMP(29)) + 40) = TMPCNT(INT(TEMP(29)) + 40) + 1
ENDIF

CALL QCALC (TEMP, MISCUA, AIR, FAN, HTR, RAD, PANLMT, NODAL, 1, QSUM)

END IF

END IF

CONTINUE

DETERMINE THE MONTH OF THE YEAR

IF (FLAG1.EQ.1) THEN
  MONTH = 0
  IF (DAY .EQ. 31 .OR. DAY .EQ. 59 .OR. DAY .EQ. 90 .OR. DAY .EQ. 120) THEN
    MONTH = 1
  ENDIF
  IF (DAY .EQ. 151 .OR. DAY .EQ. 181 .OR. DAY .EQ. 212 .OR. DAY .EQ. 243) THEN
    MONTH = 1
  ENDIF
  IF (DAY .EQ. 273 .OR. DAY .EQ. 304 .OR. DAY .EQ. 334 .OR. DAY .EQ. 365) THEN
    MONTH = 1
  ENDIF
  IF (MONTH .EQ. 1) THEN

MNUMTH = MNUMTH + 1
ENDIF
TYPE 131, MNUMTH
FORMAT (' MONTH ', '12', ' SIMULATION COMPLETE')

DETERMINE AVERAGE MONTHLY TEMPERATURES

DO 30 J=1, 5
      MONAVG(J, MNUMTH) = AVGTEMP(J)/TMPCNT
      AVGTEMP(J) = 0
  CONTINUE

DETERMINE COMFORT ZONE HOURS

DO 35 I=1, 110
      CZ(I, MNUMTH) = TMPCNT(I)
      TMPCNT(I) = 0
  CONTINUE

RECORD MONTHLY HEAT FLOWS

DO 36 I=1, 33
      QMONTH(I, MNUMTH) = QSUM(I)
      QSUM(I) = 0
  CONTINUE

END IF
END IF

CONTINUE

DETERMINE THE MONTH OF THE YEAR

IF (FLAG1.EQ.1) THEN
  MONTH = 0
  IF (DAY .EQ. 31 .OR. DAY .EQ. 59 .OR. DAY .EQ. 90 .OR. DAY .EQ. 120) THEN
    MONTH = 1
  ENDIF
  IF (DAY .EQ. 151 .OR. DAY .EQ. 181 .OR. DAY .EQ. 212 .OR. DAY .EQ. 243) THEN
    MONTH = 1
  ENDIF
  IF (DAY .EQ. 273 .OR. DAY .EQ. 304 .OR. DAY .EQ. 334 .OR. DAY .EQ. 365) THEN
    MONTH = 1
  ENDIF
  IF (MONTH .EQ. 1) THEN

MNUMTH = MNUMTH + 1
ENDIF
TYPE 131, MNUMTH
FORMAT (' MONTH ', '12', ' SIMULATION COMPLETE')

DETERMINE AVERAGE MONTHLY TEMPERATURES

DO 30 J=1, 5
      MONAVG(J, MNUMTH) = AVGTEMP(J)/TMPCNT
      AVGTEMP(J) = 0
  CONTINUE

DETERMINE COMFORT ZONE HOURS

DO 35 I=1, 110
      CZ(I, MNUMTH) = TMPCNT(I)
      TMPCNT(I) = 0
  CONTINUE

RECORD MONTHLY HEAT FLOWS

DO 36 I=1, 33
      QMONTH(I, MNUMTH) = QSUM(I)
      QSUM(I) = 0
  CONTINUE

END IF
END IF

CONTINUE

DETERMINE THE MONTH OF THE YEAR

IF (FLAG1.EQ.1) THEN
  MONTH = 0
  IF (DAY .EQ. 31 .OR. DAY .EQ. 59 .OR. DAY .EQ. 90 .OR. DAY .EQ. 120) THEN
    MONTH = 1
  ENDIF
  IF (DAY .EQ. 151 .OR. DAY .EQ. 181 .OR. DAY .EQ. 212 .OR. DAY .EQ. 243) THEN
    MONTH = 1
  ENDIF
  IF (DAY .EQ. 273 .OR. DAY .EQ. 304 .OR. DAY .EQ. 334 .OR. DAY .EQ. 365) THEN
    MONTH = 1
  ENDIF
  IF (MONTH .EQ. 1) THEN

MNUMTH = MNUMTH + 1
ENDIF
TYPE 131, MNUMTH
FORMAT (' MONTH ', '12', ' SIMULATION COMPLETE')

DETERMINE AVERAGE MONTHLY TEMPERATURES

DO 30 J=1, 5
      MONAVG(J, MNUMTH) = AVGTEMP(J)/TMPCNT
      AVGTEMP(J) = 0
  CONTINUE

DETERMINE COMFORT ZONE HOURS

DO 35 I=1, 110
      CZ(I, MNUMTH) = TMPCNT(I)
      TMPCNT(I) = 0
  CONTINUE

RECORD MONTHLY HEAT FLOWS

DO 36 I=1, 33
      QMONTH(I, MNUMTH) = QSUM(I)
      QSUM(I) = 0
  CONTINUE

END IF
END IF

CONTINUE

INPUT NEXT DAILY WEATHER DATAFILE

ENDFLAG = FLAG1
CALL DATAREAD (FLAG1, WEATHER, START, END, CITY, LAT, LON, ALT)

IF (ENDFLAG.EQ.0.AND.FLAG1.EQ.2) GOTO 61
IF (ENDFLAG.EQ.1.AND.FLAG1.EQ.2) GOTO 60
GOTO 50

STORE AVERAGE MONTHLY TEMPERATURES

WRITE (02, * ) ' AVERAGE MONTHLY TEMPERATURES'
DO 70 I=1, 12

END
FORMAT (',I2,5(',','F7.2'))
CONTINUE

STORE COMFORT ZONE VALUES
WRITE (02,'*') 'COMFORT ZONE VALUES'
DO 71 I=1,111
   WRITE (02,134) I-40,(CZ(I,J),J=1,12)
CONTINUE

STORE HEAT FLOWS
WRITE (02,'*') 'HEAT FLOWS'
DO 72 I=1,12
   WRITE (02,135) I,(QMONTH(J,I),J=1,10)
CONTINUE

STORE AIR CONDITIONING CHECKS
WRITE (02,'*') 'AIR CONDITIONING CHECKS'
DO 73 I=1,12
   WRITE (02,136) I,CZ(I,111),(QMONTH(J,I),J=11,16)
CONTINUE

STORE AIR CONDITIONING LOADS
WRITE (02,'*') 'AIR CONDITIONING LOADS'
DO 74 I=1,12
   WRITE (02,137) I,(QMONTH(J,I),J=17,23)
CONTINUE

AIR-TO-AIR HEAT EXCHANGER LOADS
WRITE (02,'*') 'AIR-TO-AIR HEAT EXCHANGER LOADS'
DO 75 I=1,12
   WRITE (02,138) I,(QMONTH(J,I),J=24,33)
CONTINUE

WRITE INPUT INFORMATION TO DATAFILE

WRITE (02,200) HOUSE
   FORMAT ("","HOUSE CODE: ',6A,'")

   TYPE 201,HTRFLG
   WRITE (02,201) HTRFLG
   FORMAT ("","AUXILIARY HEATING: ',I1")

   TYPE 202,FANFLG
   WRITE (02,202) FANFLG
   FORMAT ("","AIR-TO-AIR HEAT EXCHANGER: ',I1")

   TYPE 204,AIRFLG
   WRITE (02,204) AIRFLG
   FORMAT ("","AIR CONDITIONING: ',I1")

   TYPE 205,VENFLG
   WRITE (02,205) VENFLG
   FORMAT ("","VENETIAN BLIND CONTROL: ',I1")

   TYPE 208,SUNFLG
   WRITE (02,208) SUNFLG
   FORMAT ("","SUN ON: ',I1")

   TYPE 209,HSEFLG
   WRITE (02,209) HSEFLG
   FORMAT ("","HOUSE TRACKING THE SUNSPACE: ',I1")

   TYPE 210,OUTFLG
   WRITE (02,210) OUTFLG
   FORMAT ("","SUNSPACE TRACKING OUTSIDE: ',I1")

   CLOSE DATA FILE
   CLOSE (UNIT=02)

DISPLAY RUN TIME OF THE COMPUTER PROGRAM
ISTAT = LIB$SHOW_TIMER(STARTUP,1)
ISTAT = LIB$SHOW_TIMER(STARTUP,2)

END
B.17. Program Listings of SOLVE.FOR

************************************************************************
*  SUBROUTINE SOLVE(DT, TEMP, COND, LEN, DSSPT, AREA, MISCUA, AIR, FAN, HTR
1, VEXT, RAD, NODAL, FANLMT)
*
************************************************************************
*
REAL TEMP(32)       ! TEMPERATURE STORAGE VECTOR
REAL COND(10,10)    ! CONDUCTIVITY MATRIX FOR WALLS
REAL LEN(10,10)     ! LENGTH MATRIX FOR WALLS
REAL DSSPT(10,10)   ! DENSITY-SPECIFIC HEAT MATRIX FOR WALLS
REAL AREA(10,10)    ! AREA MATRIX FOR WALLS
REAL MISCUA(9,2)    ! MISCELLANEOUS UA VALUES
REAL MATRIX(29,30)  ! DATA STORAGE MATRIX
REAL RAD(15)        ! NET RADIATION VECTOR
REAL OLDTEMP(32)    ! TEMPERATURE STORAGE VECTOR
REAL NODAL(10)      ! STORAGE UA VECTOR
*
REAL DT             ! TIME INCREMENT
REAL AIR            ! AUXILIARY AIR CONDITIONER ENERGY
REAL FAN            ! AUXILIARY FAN ENERGY
REAL HTR            ! AUXILIARY HEATER ENERGY
REAL VEXT           ! EXTERIOR WIND VELOCITY
REAL VENFLG         ! BLINDS CLOSED FLAG
REAL EXTREST        ! EXTERIOR RESISTANCE OF THE WALL
REAL EXTCP          ! EXTERIOR CAPACITANCE OF THE WALL
REAL RSTUD          ! RESISTANCE OF THE STUDDING
REAL RINS           ! RESISTANCE OF THE INSULATION
REAL PARREST        ! CAPACITANCE OF THE PARALLEL CIRCUIT
REAL CSTUD          ! CAPACITANCE OF THE STUDDING
REAL CINS           ! CAPACITANCE OF THE INSULATION
REAL PARCP          ! CAPACITANCE OF THE PARALLEL CIRCUIT
REAL INTREST        ! INTERIOR RESISTANCE OF THE WALL
REAL INTTCP         ! INTERIOR CAPACITANCE OF THE WALL
REAL EXTSURFREST    ! EXTERIOR WALL SURFACE RESISTANCE
REAL INTSURFREST    ! INTERIOR WALL SURFACE RESISTANCE
REAL EXTCOND        ! EXTERIOR CONDUCTANCE OF THE WALL
REAL PARCOND        ! PARALLEL CONDUCTANCE OF THE WALL
REAL EXTPARCOND     ! EXTERIOR-PARALLEL WALL CONDUCTANCE
REAL INTPARCOND     ! INTERIOR-PARALLEL WALL CONDUCTANCE
REAL INTCOND        ! INTERIOR CONDUCTANCE OF THE WALL
REAL ABSR           ! ABSORPTION OF BUILDING MATERIALS
REAL RATIO          ! RATIO OF SPECIFIC TO TOTAL FLOOR AREAS
REAL TOTRAD         ! TOTAL TRANSMITTED RADIATION
REAL C,N,PTR        ! INFILTRATION CONSTANTS
REAL TACH           ! TOTAL SUNSPACE INFILTRATION
REAL OAC  !SUNSPACE-OUTSIDE INFILTRATION
REAL CF0  !CAPACITANCE OF OUTSIDE AIR
REAL CPS  !CAPACITANCE OF SUNSPACE AIR
REAL AIRDENS  !DENSITY OF AIR
REAL SPHT  !SPECIFIC HEAT OF AIR
REAL VOL  !VOLUME OF SUNSPACE AIR
REAL FANCOEF  !SUMMATION OF 29 ROW
REAL FANLMT  !LIMITING FAN SPEED
REAL BDABSP  !ABSORPTANCE OF VENETIAN BLINDS

* SETTING OF VENETIAN BLIND FLAG
VENFLG=RAD(15)

* INITIALIZATION OF SUNSPACE NODES
INITIAL=0
IF (DT.EQ.0) THEN
  INITIAL=1
  DT=3600
ENDIF

* ABSORPTANCE OF BUILDING MATERIALS
ABS=.90

* ABSORPTANCE OF BLINDS
BDABSP=.50

* MATRIX INITIALIZATION
DO 10 I=1,29
  DO 20 J=1,30
    MATRIX(I,J)=0.0
  CONTINUE
10 CONTINUE

* STORE TEMPERATURE VECTOR
IF (FAN.NE.0) THEN
  DO 11 I=1,32
    OLDTEMP(I)=TEMP(I)
11 CONTINUE

* CALCULATION OF THE EXTERNAL RESISTANCE AND CAPACITANCE OF THE WALL
EXTREST=0.0
EXTCP=0.0
DO 40 J=2,4
  IF (COND(I,J).EQ.0.0) GOTO 40
  EXTREST=EXTREST+LEN(I,J)/COND(I,J)
  EXTCP=EXTCP+LEN(I,J)*AREA(I,J)*DSSPT(I,J)
  EXTCP=EXTCP*1000/DT
40 CONTINUE
  EXTREST=EXTREST/2

* CALCULATION OF THE EQUIVALENT RESISTANCE AND CAPACITANCE OF THE PARALLEL CIRCUIT
RSTUD=LEN(I,5)/COND(I,5)/AREA(I,5)
RINS =LEN(I,6)/COND(I,6)/AREA(I,6)
PARRST=AREA(I,1)/(1/RSTUD+1/RINS)/2
CSTUD=LEN(I,5)*AREA(I,5)*DSSPT(I,5)*1000/DT
CINS=LEN(I,6)*AREA(I,6)*DSSPT(I,6)*1000/DT
PARCP=CSTUD+CINS

* CALCULATION OF THE INTERNAL RESISTANCE AND CAPACITANCE OF THE WALL
INTREST=0.0
INTCP=0.0
DO 50 J=7,9
  IF (COND(I,J).EQ.0.0) GOTO 50
  INTREST=INTREST+LEN(I,J)/COND(I,J)
  INTCP=INTCP+LEN(I,J)*AREA(I,J)*DSSPT(I,J)
  INTREST=INTREST*1000/DT
50 CONTINUE
  INTREST=INTREST/2

* CALCULATION OF THE RESISTANCE OF THE WALL SURFACE
INTSURF REST=LEN(I,10)/COND(I,10)
EXTSURF REST=LEN(I,1)/COND(I,1)
IF (I.EQ.3 .OR. I.EQ.4) THEN
  EXTCOND=AREA(I,1)/(EXTSURFREST+2*EXTREST+PARREST)
  PARCOND=AREA(I,1)/(PARREST+INTREST)
  INTCOND=AREA(I,1)/(INTREST+INTSURFREST)

* STORE WALL RESISTENCE VALUES *
  NODAL(I)=1/(1/EXTCOND+1/PARCOND+1/INTCOND)
ELSE
  EXTCOND=AREA(I,1)/(EXTSURFREST+EXTREST)
  EXTPARCOND=AREA(I,1)/(EXTREST+PARREST)
  INTPARCOND=AREA(I,1)/(PARREST+INTREST)
  INTCOND=AREA(I,1)/(INTREST+INTSURFREST)

* STORE WALL RESISTENCE VALUES *
  NODAL(I)=1/(1/EXTPARCOND+1/INTPARCOND+1/INTCOND)
ENDIF

* SET UP OF THE STEADY STATE MATRIX *

IF (I.EQ.1) THEN
  MATRIX(1,1)=EXTCOND+EXTPARCOND+EXTCP
  MATRIX(1,2)=1+EXTPARCOND
  MATRIX(1,30)=EXTCP*TEMP(1)+EXTCOND*TEMP(30)
  MATRIX(2,1)=1+EXTPARCOND
  MATRIX(2,2)=EXTPARCOND+INTPARCOND+PARCP
  MATRIX(2,3)=1+INTPARCOND
  MATRIX(2,30)=PARCP*TEMP(2)
  MATRIX(3,2)=1+INTPARCOND
  MATRIX(3,3)=INTCOND+INTPARCOND+INTCP
  MATRIX(3,29)=1+INTCOND
  MATRIX(3,30)=INTCP*TEMP(3)
  MATRIX(29,3)=1+INTCOND
ELSE IF (I.EQ.2) THEN
  MATRIX(4,4)=EXTCOND+EXTPARCOND+EXTCP
  MATRIX(4,5)=1+EXTPARCOND
  MATRIX(4,30)=EXTCP*TEMP(4)+EXTCOND*TEMP(30)
  MATRIX(5,4)=1+EXTPARCOND
  MATRIX(5,5)=EXTPARCOND+INTPARCOND+PARCP
  MATRIX(5,6)=1+INTPARCOND
ELSE IF (I.EQ.3) THEN
  MATRIX(6,5)=-1*INTPARCOND
  MATRIX(6,6)=INTPARCOND+INTCOND+INTCP
  MATRIX(6,29)=-1*INTCOND
  MATRIX(6,30)=INTCP+TEMP(6)
  MATRIX(29,6)=-1*INTCOND
ELSE IF (I.EQ.4) THEN
  RATIO=AREA(3,1)/(AREA(3,1)+AREA(4,1))
  TOTRAD=RAD(11)+RAD(12)+RAD(13)
  MATRIX(7,7)=EXTCOND+PARCOND+PARCP
  MATRIX(7,8)=-1+PARCOND
  MATRIX(7,30)=PARCP*TEMP(7)+EXTCOND+TEMP(31)
  MATRIX(8,7)=-1+PARCOND
  MATRIX(8,8)=PARCOND+INTCOND+INTCP
  MATRIX(8,29)=-1*INTCOND
  MATRIX(8,30)=INTCP*TEMP(8)+(1-VENFLG)*RATIO+TOTRAD
  MATRIX(29,8)=-1*INTCOND
ELSE IF (I.EQ.5) THEN
  MATRIX(11,11)=INTCOND+INTPARCOND+INTCP
  MATRIX(11,12)=-1+INTPARCOND
  MATRIX(11,29)=-1*INTCOND
  MATRIX(11,30)=INTCP+TEMP(11)
  MATRIX(12,11)=-1*INTPARCOND
  MATRIX(12,12)=EXTPARCOND+INTPARCOND+PARCP
  MATRIX(12,13)=-1*EXTPARCOND
  MATRIX(12,30)=PARCP+TEMP(12)
ELSE IF (I.EQ.6) THEN
MATRIX(14,14)=INTCOND+INTPARCOND+INTCP
MATRIX(14,15)=-1+INTPARCOND
MATRIX(14,29)=-1*INTCOND
MATRIX(14,30)=INTCP+TEMP(14)

MATRIX(15,14)=-1+INTPARCOND
MATRIX(15,15)=EXTPARCOND+INTPARCOND+PARCP
MATRIX(15,16)=-1*EXTPARCOND
MATRIX(15,29)=-1*INTCOND
MATRIX(15,30)=PARCP*TEMP(15)

MATRIX(16,15)=-1*EXTPARCOND
MATRIX(16,16)=EXTCOND+EXTPARCOND+EXTP
MATRIX(16,30)=MATRIX(16,30)+ABSP+RAD(16)

MATRIX(29,14)=-1*INTCOND

ELSE IF (I.EQ.7) THEN
MATRIX(17,17)=INTCOND+INTPARCOND+INTCP
MATRIX(17,18)=-1*INTPARCOND
MATRIX(17,29)=-1+INTCOND
MATRIX(17,30)=INTCP+TEUP(17)

MATRIX(18,17)=-1+INTPARCOND
MATRIX(18,18)=EXTPARCOND+INTPARCOND+PARCP
MATRIX(18,19)=-1*EXTPARCOND
MATRIX(18,30)=PARCP*TEUP(18)

MATRIX(19,18)=-1*EXTPARCOND
MATRIX(19,19)=EXTCOND+EXTPARCOND+EXTCP
MATRIX(19,29)=-1*INTCOND
MATRIX(19,30)=MATRIX(19,30)+ABSP+RAD(7)

MATRIX(29,17)=-1*INTCOND

ELSE IF (I.EQ.8) THEN
MATRIX(20,20)=INTCOND+INTPARCOND+INTCP
MATRIX(20,21)=-1*INTPARCOND
MATRIX(20,29)=-1*INTCOND
MATRIX(20,30)=INTCP+TEMP(20)

MATRIX(21,20)=-1*INTPARCOND
MATRIX(21,21)=EXTPARCOND+INTPARCOND+PARCP
MATRIX(21,22)=-1*EXTPARCOND
MATRIX(21,30)=PARCP+TEMP(21)

MATRIX(22,21)=-1*EXTPARCOND
MATRIX(22,22)=EXTCOND+EXTPARCOND+EXTCP
MATRIX(22,30)=MATRIX(22,30)+ABSP+RAD(8)

MATRIX(29,20)=-1*INTCOND

ELSE IF (I.EQ.9) THEN
MATRIX(23,23)=INTCOND+INTPARCOND+INTCP
MATRIX(23,24)=-1*INTPARCOND
MATRIX(23,29)=-1*INTCOND
MATRIX(23,30)=INTCP+TEUP(23)

MATRIX(24,23)=INTCOND+INTPARCOND+INTCP
MATRIX(24,24)=EXTPARCOND+INTPARCOND+PARCP
MATRIX(24,25)=-1*EXTPARCOND
MATRIX(24,30)=PARCP*TEMP(24)

MATRIX(25,24)=INTCOND+INTPARCOND+INTCP
MATRIX(25,25)=EXTPARCOND+INTPARCOND+PARCP
MATRIX(25,30)=MATRIX(25,30)+ABSP+RAD(9)

MATRIX(29,23)=-1*INTCOND

ELSE IF (I.EQ.10) THEN
MATRIX(26,26)=INTCOND+INTPARCOND+INTCP
MATRIX(26,27)=-1*INTPARCOND
MATRIX(26,29)=-1*INTCOND
MATRIX(26,30)=INTCP+TEMP(26)

MATRIX(27,26)=INTCOND+INTPARCOND+INTCP
MATRIX(27,27)=EXTPARCOND+INTPARCOND+PARCP
MATRIX(27,28)=-1*EXTPARCOND
MATRIX(27,30)=PARCP*TEMP(27)

MATRIX(28,27)=-1*EXTPARCOND
MATRIX(28,28)=EXTCOND+EXTPARCOND+EXTCP
MATRIX(28,30)=MATRIX(28,30)+ABSP+RAD(10)

MATRIX(29,26)=-1*INTCOND

MATRIX(29,20)=-1*INTCOND

MATRIX(29,23)=-1*INTCOND

MATRIX(29,26)=-1*INTCOND
ENDIF

30 CONTINUE

SET UP FOR MATRIX FOR INITIALIZATION

IF (INITIAL.EQ.1) THEN
  DO 55 I=1,28
    MATRIX(29,I)=0
  CONTINUE
  MATRIX(29,29)=1
  MATRIX(29,30)=TEWP(29)
  CALL SOLUTION(MATRIX,TEWP)
  GOTo 250
ENDIF

INFILTRATION OF SUNSPACE

C=.0019
N=.747
FTR=.605

TYPE I (TEMPERATURE DEPENDENT)

IF (VEXT.LT.12.6) THEN
  TACH=FTR*.32*C*(ABS(TEMP(29)-TEMP(32)))**N
ELSE IF (VEXT.GE.12.6.AND.ABS(TEMP(29)-TEMP(32)).LT.20) THEN
  TACH=FTR*.76*C*(VEXT.3.6)**N
ENDIF

TYPE II (VELOCITY DEPENDENT)

TYPE III (BOTH)

ELSE
  TACH=FTR*4.53*C
ENDIF

BREAKDOWN OF THE INFILTRATION INTO COMPONENTS

HACH=.578*TACH
OACH=.432*TACH

CAPACITANCE OF HOUSE AIR

AIRDENS=1.218585-.003832*TEMP(30)
SPHT=(.103409E+1
1-.284870E-03*(TEMP(30)+273)
2+.781681E-06*(TEMP(30)+273)**2
3-.4970786E-09*(TEMP(30)+273)**3
4+.1077024E-12*(TEMP(30)+273)**4)*1000
CPH=AIRDENS*SPHT

CAPACITANCE OF SUNSPACE AIR

AIRDENS=1.218585-.003832*TEMP(29)
SPHT=(.103409E+1
1-.284870E-03*(TEMP(29)+273)
2+.781681E-06*(TEMP(29)+273)**2
3-.4970786E-09*(TEMP(29)+273)**3
4+.1077024E-12*(TEMP(29)+273)**4)*1000
CPS=AIRDENS*SPHT

CAPACITANCE OF OUTSIDE AIR

AIRDENS=1.218585-.003832*TEMP(32)
SPHT=(.103409E+1
1-.284870E-03*(TEMP(32)+273)
2+.781681E-06*(TEMP(32)+273)**2
3-.4970786E-09*(TEMP(32)+273)**3
4+.1077024E-12*(TEMP(32)+273)**4)*1000
CPO=AIRDENS*SPHT

MISCUA(3,1)=CPH
MISCUA(3,2)=CPS
MISCUA(8,1)=CPO
MISCUA(8,2)=TACH

VOL=67.451
AOSUN=VOL*CPS/DT
MATRIX(29,29)=AOSUN

FANCOEF=0
DO 70 I=1,28
  MATRIX(29,29)=MATRIX(29,29)-MATRIX(29,I)
  FANCOEF=FANCOEF+MATRIX(29,I)*TEUP(I)
70 CONTINUE

CAPACITANCE OF OUTSIDE AIR
DO 80 I=1,8
  IF (I.LT.3) THEN
    QFLOW=MISCUA(I,1)*MISCUA(I,2)*(TEMP(30)-TEMP(29))
  ELSE IF (I.EQ.3) THEN
    QFLOW=BACH*(TEMP(30)+MISCUA(I,1)-TEMP(29)+MISCUA(I,2))
  ELSE IF (I.EQ.4) THEN
    QFLOW=MISCUA(I,1)*MISCUA(I,2)*(TEMP(32)-TEMP(29))
  ELSE IF (I.GT.4.AND.I.LT.8) THEN
    TB=VENFLG*DBABSP/RAD(6+I)/4/MISCUA(I,1)/MISCUA(I,2)
    TB=TB+(TEMP(32)+TEMP(29))/2
    QFLOW=OACH*(TEMP(32)+MISCUA(I,1)+MISCUA(I,2)+(TB-TEMP(29))
  ELSE IF (I.EQ.8) THEN
    QFLOW=OACH*(TEMP(32)+MISCUA(I,1)+MISCUA(I,2)+(TB-TEMP(29))
  ENDIF
YATRIX(29,30)=YATRIX(29,30)+QFLOW
80 CONTINUE

*******************************************************************************

ADDITION OF AUXILIARY ENERGY

MATRIX(29,30)=MATRIX(29,30)+HTR-AIR

FIND MAXIMUM AIR COND. ENERGY THAT CAN BE REMOVED AND STILL KEEP THE SUNSPACE WITHIN THE COMFORT ZONE

FANLMT=FANCOEF-MATRIX(29,29)+22-MATRIX(29,30)

DETERMINE EFFECT OF HEAT EXCHANGER

FANEN=FAN*(CPO*TEMP(32)-CPS*TEMP(29))

MATRIX(29,30)=MATRIX(29,30)+FANEN

SOLVE FOR THE TEMPERATURE VECTOR

CALL SOLUTION(MATRIX,TEMP)

CHECK TO SEE IF FAN COOLING IS UNREALISTIC

IF (FAN.NE.0) THEN
  IF (TEMP(29).LT.TEMP(32)) THEN
    DO 90 I=1,32
      TEMP(I)=OLDTEMP(I)
    90 CONTINUE
    DO 91 I=1,28
      MATRIX(29,I)=0
    91 CONTINUE
    MATRIX(29,29)=1
    MATRIX(29,30)=TEMP(32)
    CALL SOLUTION(MATRIX,TEMP)
    GOTO 250
  ELSEIF (TBI.TEMP(32)) THEN
    DO 92 I=1,32
      TEMP(I)=OLDTEMP(I)
    92 CONTINUE
    IF (SUN2.GE.SUN1) THEN
      DO 94 I=1,28
        MATRIX(29,I)=0
      94 CONTINUE
      MATRIX(29,29)=1
      MATRIX(29,30)=TEMP(32)
      CALL SOLUTION(MATRIX,TEMP)
      GOTO 250
    ELSE
      MATRIX(29,30)=MATRIX(29,30)-SUN2
      CALL SOLUTION(MATRIX,TEMP)
      ENDIF
    ENDIF
  ENDIF
250 RETURN
END
**B.18. Program Listings of SOLUTION.FOR**

```
*************************************************************************
** SUBROUTINE SOLUTION(MATRIX, TEMP)                                 **
*************************************************************************
* REAL MATRIX(29,30) ! THE ORIGINAL AUGMENTED MATRIX                  **
* REAL A(29,30) ! THE ORIGINAL AUGMENTED MATRIX                       **
* REAL B(29,30) ! WORKING MATRIX OF SIZE SIMILAR TO A                  **
* REAL TEMP(29) ! TEMPERATURE VECTOR                                  **
* REAL PIVOT ! PIVOT ELEMENT                                          **
* INTEGER NROW ! THE NUMBER OF ROWS IN THE MATRICES                   **
* INTEGER NCOL ! THE NUMBER OF COLUMNS IN THE MATRICES                 **
* INTEGER ROWFLAG ! COUNTERS                                         **
* INTEGER I, J, K, L ! COUNTERS                                       **
*************************************************************************
NROW=29
NCOL=30
*************************************************************************
DO 1 I=1, 29
   DO 2 J=I, 30
      A(I, J)=MATRIX(I, J)
   2 CONTINUE
1 CONTINUE
*************************************************************************
DO 10 K=1, NROW
 FINDING THE LARGEST PIVOT

PIVOT=A(K, K)
ROWFLAG=K
DO 15 L=K+1, NROW
   IF (ABS(A(L, K)).LT.ABS(PIVOT)) GOTO 15
   ELSE
      PIVOT=A(L, K)
      ROWFLAG=L
      ENDIF
15 CONTINUE
```
* TRADE ROWS TO GET LARGEST PIVOT
* DO 20 L=1,NCOL
   SCRATCH=A(K,L)
   A(K,L)=A(ROWFLAG,L)
   A(ROWFLAG,L)=SCRATCH
20 CONTINUE
* NORMALIZING THE PIVOT ROW
* DO 25 J=1,NCOL
   B(K,J)=A(K,J)/PIVOT
25 CONTINUE
* PERFORM GAUSS-JORDAN ELIMINATION
* DO 30 I=1,NROW
   IF (I.EQ.K) GOTO 30
   DO 40 J=1,NCOL
      B(I,J)=A(I,J)-A(I,K)*B(K,J)
40 CONTINUE
30 CONTINUE
* UPDATE MATRIX A WITH MATRIX B
* DO 50 I=1,NROW
   DO 60 J=1,NCOL
      A(I,J)=B(I,J)
60 CONTINUE
50 CONTINUE
* 10 CONTINUE
*
*************************************************************************
* STORE NODAL TEMPERATURES IN VECTOR
* DO 70 J=1,NROW
   TEMP(J)=A(J,NCOL)
70 CONTINUE
*
*************************************************************************
* RETURN
END
*
*************************************************************************
B.19. Program Listing of QCALC.FOR

******************************************************************************
* SUBROUTINE QCALC(TEMP,MISCUA,AIR,FAN,HTR,RAD,FANLMT,NODAL,QSUM) *
******************************************************************************
* REAL TEMP(32) ! NODAL TEMPERATURE VECTOR *
* REAL MISCUA(9,2) ! MISCELLANEOUS UA VALUES *
* REAL RAD(15) ! RADIATION VECTOR *
* REAL NODAL(10) ! UA STORAGE VECTOR *
* REAL QNODE(18) ! HOURLY HEAT FLOW STORAGE VECTOR *
* REAL QSUM(33) ! MONTHLY HEAT FLOW STORAGE VECTOR *
* REAL BDABSP ! ABSORPTION OF BLINDS *
* REAL BACH ! HOUSE/SUNSPACE INFILTRATION *
* REAL OACH ! OUTSIDE/SUNSPACE INFILTRATION *
* REAL AIR ! AIR CONDITIONING ENERGY *
* REAL FAN ! FAN ENERGY *
* REAL HTR ! AUXILIARY HEATING ENERGY *
* REAL FANLMT ! LIMITING FAN SPEED *
* REAL TB ! VENETIAN BLIND TEMPERATURE *
* REAL TOTRAD ! TOTAL TRANSMITTED SOLAR RADIATION *
* REAL AIRENG ! ENERGY TRANSFER DUE TO FAN *
* REAL HSEENG ! ENERGY TO HOUSE DUE TO HEAT EX. *
* REAL OUTENG ! ENERGY FROM OUTSIDE DUE TO HEAT EX. *
* REAL HSEFLOW ! ENERGY TRANSFER FROM HOUSE TO SUNSPACE *
******************************************************************************
* BDABSP=.5 *
******************************************************************************
* BREAKDOWN OF THE INFILTRATION INTO COMPONENTS *
* HACH=.578*MISCUA(8,2) *
* OACH=.432*MISCUA(8,2) *
* CALCULATION OF HOURLY PATH HEAT FLOWS *
* QNODE(1)=NODAL(1)*(TEMP(1)-TEMP(29)) *
* QNODE(2)=NODAL(2)*(TEMP(4)-TEMP(29)) *
* QNODE(3)=NODAL(3)*(TEMP(7)-TEMP(29)) *
* QNODE(4)=NODAL(4)*(TEMP(9)-TEMP(29)) *
* QNODE(5)=NODAL(5)*(TEMP(13)-TEMP(29)) *
* QNODE(6)=NODAL(6)*(TEMP(16)-TEMP(29)) *
QNODE(7) = NODAL(7) * (TEMP(19) - TEMP(29))
QNODE(8) = NODAL(8) * (TEMP(22) - TEMP(29))
QNODE(9) = NODAL(9) * (TEMP(25) - TEMP(29))
QNODE(10) = NODAL(10) * (TEMP(28) - TEMP(29))

* CALCULATE MISC. HOURLY HEAT FLOWS *

QNODE(11) = MISCUA(1,1) * MISCUA(1,2) * (TEMP(30) - TEMP(29))
QNODE(12) = MISCUA(2,1) * MISCUA(2,2) * (TEMP(30) - TEMP(29))
QNODE(13) = OACH * (TEMP(30) * MISCUA(3,1) - TEMP(29) * MISCUA(3,2))
QNODE(14) = MISCUA(4,1) * MISCUA(4,2) * (TEMP(32) - TEMP(29))

TB = RAD(15) * BDABSP * RAD(11) / 4 / MISCUA(5,1) / MISCUA(5,2)
TB = TB + (TEMP(32) + TEMP(29)) / 2
QNODE(15) = 2 * MISCUA(5,1) * MISCUA(5,2) * (TB - TEMP(29))
TB = RAD(15) * BDABSP * RAD(12) / 4 / MISCUA(6,1) / MISCUA(6,2)
TB = TB + (TEMP(32) + TEMP(29)) / 2
QNODE(16) = 2 * MISCUA(6,1) * MISCUA(6,2) * (TB - TEMP(29))
TB = RAD(15) * BDABSP * RAD(13) / 4 / MISCUA(7,1) / MISCUA(7,2)
TB = TB + (TEMP(32) + TEMP(29)) / 2
QNODE(17) = 2 * MISCUA(7,1) * MISCUA(7,2) * (TB - TEMP(29))
QNODE(18) = OACH * (TEMP(32) * MISCUA(8,1) - TEMP(29) * MISCUA(3,2))

*********************************************************************************************

* MONTHLY HEAT FLOWS THROUGH WALLS *

QSUM(1) = QSUM(1) + QNODE(1) + QNODE(2) ! HSE/SUN WALLS
QSUM(2) = QSUM(2) + QNODE(3) + QNODE(4) ! CRL/SUN FLOORS
QSUM(3) = QSUM(3) + QNODE(5) + QNODE(6) ! OUT/SUN WALLS
QSUM(3) = QSUM(3) + QNODE(7) + QNODE(8) ! OUT/SUN WALLS
QSUM(3) = QSUM(3) + QNODE(9) + QNODE(10) ! OUT/SUN CEILING

* MONTHLY MISC. HEAT FLOWS *

QSUM(4) = QSUM(4) + QNODE(11) + QNODE(12) ! HSE/SUN WIND AND DOORS
QSUM(5) = QSUM(5) + QNODE(13) ! HSE/SUN INFILT
QSUM(6) = QSUM(6) + QNODE(14) + QNODE(15) ! OUT/SUN WIND AND DOORS
QSUM(6) = QSUM(6) + QNODE(16) + QNODE(17) ! OUT/SUN WIND AND DOORS
QSUM(7) = QSUM(7) + QNODE(18) ! OUT/SUN INFILT

* AUXILIARY ENERGY *

QSUM(8) = QSUM(8) + AIR ! AUXILIARY AIR COND
QSUM(9) = QSUM(9) + HTR ! AUXILIARY HEATING

* MONTHLY TRANSMITTED SOLAR RADIATION *

TOTRAD = RAD(11) + RAD(12) + RAD(13)
IF (RAD(15).EQ.1) TOTRAD=BDABSP*TOTRAD/2
QSUM(10)=QSUM(10)+TOTRAD !TRANSMITTED SOLAR RADIATION

* CAN FAN HANDLE AIR COND. LOAD

* VOL=67.451
AIRENG=(TEMP(32)+MISCUA(8,1)-TEMP(29)+MISCUA(3,2))
FAN1=-2*VOL*AIRENG/3600 !2 ACH FAN
FAN2=-5*VOL*AIRENG/3600 !5 ACH FAN
FAN3=-10*VOL*AIRENG/3600 !10 ACH FAN
FAN4=-20*VOL*AIRENG/3600 !20 ACH FAN
IF (AIR.NE.0) THEN ! COOLING WAS DONE
FANLMT=AIR-FANLMT
QSUM(11)=QSUM(11)+1
IF (TEMP(29).GT.TEMP(32)) THEN ! COOLING BY FAN

* KEEP TRACK NUMBER OF TIMES FAN CAN PROVIDE ENERGY WITHOUT
* LOWERING THE SUNSPACE TEMPERATURE BELOW THE COMFORT ZONE

* IF (FANLMT.LT.FAN1) THEN
  QSUM(12)=QSUM(12)+1
ELSE IF (AIR.LE.FAN1.AND.FAN1.LT.FANLMT) THEN
  QSUM(13)=QSUM(13)+1
ELSE IF (AIR.LE.FAN2.AND.FAN2.LT.FANLMT) THEN
  QSUM(14)=QSUM(14)+1
ELSE IF (AIR.LE.FAN3.AND.FAN3.LT.FANLMT) THEN
  QSUM(15)=QSUM(15)+1
ELSE IF (AIR.LE.FAN4.AND.FAN4.LT.FANLMT) THEN
  QSUM(16)=QSUM(16)+1
ENDIF

* KEEP TRACK COOLING LOAD REQUIRED BY SUNSPACE WITH FAN RUNNING

* IF (FAN1.LE.AIR) QSUM(18)=QSUM(18)+AIR-FAN1
IF (FAN2.LE.AIR) QSUM(19)=QSUM(19)+AIR-FAN2
IF (FAN3.LE.AIR) QSUM(20)=QSUM(20)+AIR-FAN3
IF (FAN4.LE.AIR) QSUM(21)=QSUM(21)+AIR-FAN4
IF (AIR.GT.FAN4) QSUM(22)=QSUM(22)+AIR
ELSE
  QSUM(17)=QSUM(17)+1
ENDIF

* AIR COND ENERGY COULD BE USED FOR HEATING HOUSE

* IF (TEMP(32).LT.14) THEN
  QSUM(23)=QSUM(23)+AIR
ENDIF
ENDIF

* ENERGY BOOST IF AIR-TO-AIR HEAT EXCHANGER WAS OPERATING

IF (FAN.NE.0) THEN
  HSEENG=(22*MISCUA(3,1)-TEMP(29)*MISCUA(3,2))
  QSUM(24)=QSUM(24)+FAN*HSEENG ! HOUSE/SUNSPACE ENERGY
  OUTENG=(TEMP(29)*MISCUA(3,2)-TEMP(32)*MISCUA(8,1))
  QSUM(25)=QSUM(25)+FAN*OUTENG ! SUNSPACE/OUTSIDE ENERGY
ENDIF

* KEEP TRACK OF HSE/SUN ENERGY FLOWS

HSEFLOW=QNODE(1)+QNODE(2)+QNODE(11)+QNODE(12)+QNODE(13)
IF (TEMP(32).GE.20) QSUM(26)=QSUM(26)+HSEFLOW ! COOLING LOAD
IF (TEMP(32).LE.14) QSUM(27)=QSUM(27)+HSEFLOW ! HEATING LOAD

* KEEP TRACK WHETHER SOLAR RADIATION IS COOLING OR HEATING LOAD

IF (TEMP(32).GE.20) THEN
  QSUM(28)=QSUM(28)+RAD(11) ! COOLING LOAD
  QSUM(29)=QSUM(29)+RAD(12) ! COOLING LOAD
  QSUM(30)=QSUM(30)+RAD(13) ! COOLING LOAD
ENDIF
IF (TEMP(32).LE.14) THEN
  QSUM(31)=QSUM(31)+RAD(11) ! HEATING LOAD
  QSUM(32)=QSUM(32)+RAD(12) ! HEATING LOAD
  QSUM(33)=QSUM(33)+RAD(13) ! HEATING LOAD
ENDIF

************************************************************************

RETURN
END

************************************************************************
B.20. Program Listing of SOLARCALC.FOR

************************************************************************
* SUBROUTINE SOLARCALC(WINDGEOM, WALLGEOM, DT, RTIME, DAY, LAT, LON
  1, ALT, G1, G2, RAD)
*************************************************************************

REAL WINDGEOM(10,18) ! WINDOW GEOMETRY MATRIX
REAL WALLGEOM(10,18) ! SURFACE GEOMETRY MATRIX
REAL RAD(15) ! NET RADIATION VECTOR

REAL DT ! TIME INCREMENT (SECONDS)
REAL RTIME, TIME ! REAL AND SOLAR TIME OF DAY (HOURS)
REAL DAY ! DAY OF YEAR
REAL G1 ! IRRADIANCE ON SOUTH SURFACE
REAL G2 ! IRRADIANCE ON NONSOUTH SURFACE
REAL PI
REAL ZLIMIT ! ZENITH ANGLE LIMIT FOR RB CALCULATIONS
REAL LAT ! LATITUDE
REAL LON ! LONGITUDIONAL TIME ADJUSTMENT
REAL ALT ! ALTITUDE IN KILOMETERS (NOT USED IN SUBROUTINE)
REAL RFCT ! GROUND REFLECTANCE
REAL SSURF ! SOUTH SURFACE FLAG
REAL NSURF ! NONSOUTH SURFACE FLAG
REAL BOTSURF ! BOTTOM SURFACE
REAL TOTSURF ! TOTAL-surfaces
REAL SWIND ! SOUTH WINDOW
REAL NWIND ! NONSOUTH WINDOW
REAL BOTWIND ! BOTTOM WINDOW
REAL TOTWIND ! TOTAL WINDOWS
REAL COVERS ! NUMBER OF GLAZINGS
REAL B ! EQUATION OF TIME CORRECTION
REAL E ! CORRECTION DUE TO LONGITUDINAL ERROR
REAL DEC ! DECLINATION OF SUN
REAL HR ! HOUR ANGLE
REAL ZSLP ! SLOPE OF HORIZONTAL SURFACE
REAL ZAZ ! AZIMUTH ANGLE OF HORIZONTAL SURFACE
REAL ZANGLE ! INCIDENCE ANGLE OF HORIZONTAL SURFACE AT HR
REAL GSC ! SOLAR CONSTANT
REAL IO ! EXTRATERRESTIAL IRRADIATION
REAL KI ! CLEARNESS INDEX
REAL DG ! DIFFUSE TO GLOBAL HORIZONTAL RADIATION RATIO
REAL ID ! HORIZONTAL DIFFUSE RADIATION
REAL IB ! HORIZONTAL DREAM RADIATION
REAL SAZ ! AZIMUTH ANGLE OF SOUTH SURFACE
REAL SSLP ! SLOPE OF SOUTH SURFACE
PI=3.141593

ZLIMIT=80

GROUND REFLECTANCE

IF (INT(G2).EQ.9999) THEN
RFCT=G2-INT(G2)
ELSE
RFCT=.6
END IF

IF (DAY.GT.90.AND.DAY.LT.304) RFCT=.2

ADJUSTMENT FOR SOLAR TIME

B=360.\(\times\)(DAY-81)/364
E=9.87*SIND(2.B)-7.53*COSD(B)-1.5*SIND(B)
TIME=RTIME+LON+E/60

CALCULATION OF DECLINATION AND HOUR ANGLE

DEC=23.45*SIND(360*(284+DAY)/365)
HR=(TIME-12)\(\times\)15

CALCULATION OF ZENITH ANGLE

ZSLP=0.0
ZAZ=0.0
CALL INCIDENCE(HR,DEC,LAT,ZSLP,ZAZ,ZANGLE)

CALCULATION OF SOLAR AZIMUTH ANGLE

SOLAZ=\(\cosD(ZANGLE)\times\sinD(LAT)\times\sinD(DEC))\times\sinD(ZANGLE)\times\cosD(LAT)
SOLAZ=ACOSD(SOLAZ)

CALCULATION OF SUNSET HOUR

SUNSET=ABS(ACOSD(-1.*TAND(LAT)\times TAND(DEC)))/15-1

SELECTION OF METHODS

IF (INT(G2).EQ.9999) THEN
DETERMINATION OF RADIATION COMPONENTS USING TMY DATA

IDENTIFICATION OF HOUSE DEPENDENT VARIABLES

SSURF=7 \(\Rightarrow\) SOUTH SURFACE
NSURF=8 \(\Rightarrow\) NONSOUTH SURFACE
BOTSURF=5 \(\Rightarrow\) FIRST OUTSIDE SURFACE
TOTSURF=10 \(\Rightarrow\) LAST OUTSIDE SURFACE
SWIND=2 \(\Rightarrow\) SOUTH WINDOW
NWND=3 \(\Rightarrow\) NONSOUTH WINDOW
BOTWIND=1 \(\Rightarrow\) FIRST OUTSIDE WINDOW
TOTWIND=3 \(\Rightarrow\) LAST OUTSIDE WINDOW
COVERS=2
IF (RAD(15).EQ.1) COVERS=1
DETERMINE EXTRATERRESTRIAL NORMAL RADIATION

\[ GSC = 1353 \times (1 + 0.033 \times \cos(360 \times \text{DAY}/365)) \]

\[ IO = GSC \times (\cos(\text{LAT}) \times \cos(\text{DEC}) \times \cos(\text{HR})) \]

\[ IO = IO + \sin(\text{LAT}) \times \sin(\text{DEC}) \]

DETERMINE CLEARNESS INDEX

\[
\text{IF (IO} \leq 0 \text{. OR ZANGLE} \geq 90 \text{deg. OR ZANGLE} > \text{ZLIMIT) THEN} \]

\[ KT = 0 \]

\[
\text{ELSE} \]

\[ KT = G1/(IO \times \cos(\text{ZANGLE})) \]

\[ \text{ENDIF} \]

DETERMINE DIFFUSE TO GLOBAL HORIZONTAL RADIATION RATIO

\[
\text{IF (KT} < 35 \text{ THEN} \]

\[ DG = 1.0 - 0.249 \times KT \]

\[
\text{ELSE IF (KT} \geq 75 \text{ THEN} \]

\[ DG = 0.177 \]

\[
\text{ELSE} \]

\[ DG = (1.557 - 1.84 \times KT) \]

\[ \text{ENDIF} \]

DETERMINE HORIZONTAL RADIATION COMPONENTS

\[ IT = G1 \]

\[
\text{IF (ABS(TIME-12)} < \text{SUNSET OR ZANGLE} \leq \text{ZLIMIT) THEN} \]

\[ ID = G1 \times DG \]

\[ IB = G1 - ID \text{ ! SUN IS IN THE SKY} \]

\[
\text{ELSE} \]

\[ IB = 0 \]

\[ ID = G1 \text{ ! SUN IS NOT IN THE SKY} \]

\[ \text{ENDIF} \]

CALCULATION OF HORIZ. INCIDENT RADIATION BASED ON MEASURED DATA

SOUTH SURFACE GEOMETRIC PROPERTIES

\[
\text{ELSE} \]

\[ \text{SAZ} = \text{WALLGEOM(SSURF,15)} \]

\[ \text{SSLP} = \text{WALLGEOM(SSURF,16)} \]

\[ \text{SFRG} = \text{WALLGEOM(SSURF,17)} \]

\[ \text{SFRS} = \text{WALLGEOM(SSURF,18)} \]

CALCULATION OF INCIDENCE ANGLE ON SOUTH SURFACE

\[ \text{IF (COSD(SANGLE)} < 0 \text{ THEN SANGLE} = 90 \text{ deg.} \]

CALL INCIDENCE(HR,DEC,LAT,SSLP,SAZ,ANGLE)

\[ \text{IF (COSD(ANGLE)} < 0 \text{ THEN ANGLE} = 90 \text{ deg.} \]

DETERMINE NONSOUTH GEOMETRIC FACTOR

\[
\text{IF (ABS(TIME-12)} < \text{SUNSET OR ZANGLE} \leq \text{ZLIMIT) THEN} \]

\[ NR=\text{COSD(ANGLE)} \times \text{COSD(ZANGLE)} \]

\[ \text{ELSE} \]

\[ NR = 0 \]

\[ \text{ENDIF} \]

DETERMINE EXTRATERRESTRIAL NORMAL RADIATION

\[ GSC = 1353 \times (1 + 0.033 \times \cos(360 \times \text{DAY}/365)) \]

\[ IO = GSC \times (\cos(\text{LAT}) \times \cos(\text{DEC}) \times \cos(\text{HR})) \]

\[ IO = IO + \sin(\text{LAT}) \times \sin(\text{DEC}) \]

DETERMINE CLEARNESS INDEX

\[
\text{IF (IO} \leq 0 \text{. OR SANGLE} \neq 90 \text{. OR ZANGLE} \geq 90 \text{ deg. OR ZANGLE} > \text{ZLIMIT) THEN} \]

\[ KT = 0 \]

\[
\text{ELSE} \]

\[ KT = G1/(IO \times \cos(\text{SANGLE})) \]

\[ \text{ENDIF} \]

DETERMINE DIFFUSE TO GLOBAL HORIZONTAL RADIATION RATIO

\[
\text{IF (KT} < 35 \text{ THEN} \]

IF (ABS(TIME-12) < SUNSET OR ZANGLE < ZLIMIT) THEN

\[ SR=\text{COSD(SANGLE)} \times \text{COSD(ZANGLE)} \]

ELSE

\[ SR = 0 \]

ENDIF

NONSOUTH SURFACE GEOMETRIC PROPERTIES

\[
\text{NAZ} = \text{WALLGEOM(NSURF,15)} \]

\[ \text{NSLP} = \text{WALLGEOM(NSURF,16)} \]

\[ \text{NFRG} = \text{WALLGEOM(NSURF,17)} \]

\[ \text{NFRS} = \text{WALLGEOM(NSURF,18)} \]

CALCULATION OF INCIDENCE ANGLE ON NONSOUTH SURFACE

\[ \text{CALL INCIDENCE(HR,DEC,LAT,NSLP,NAZ,ANGLE)} \]

\[ \text{IF (COSD(ANGLE)} < 0 \text{ THEN ANGLE} = 90 \text{ deg.} \]

DETERMINE NONSOUTH GEOMETRIC FACTOR

\[
\text{IF (ABS(TIME-12)} < \text{SUNSET OR ZANGLE} \leq \text{ZLIMIT) THEN} \]

\[ NR=\text{COSD(ANGLE)} \times \text{COSD(ZANGLE)} \]

\[ \text{ELSE} \]

\[ NR = 0 \]

\[ \text{ENDIF} \]
ELSE IF (KT.GE.75) THEN
DG=.177
ELSE
DG=(1.557-1.84*KT)
ENDIF

DETERMINE TOTAL GEOMETRIC FACTOR FOR SURFACES
SR=(1-DG)*SRB+DG*SFRS+RFCT*SFRG
NR=(1-DG)*NRB+DG*NFRS+RFCT*NFRG

DETERMINE TOTAL HORIZONTAL RADIATION
IS=G2/SR
IN=G2/NR
IT=MIN(IS,IN)
IF (IT.EQ.0.AND.IT.EQ.IS) IT=IS
IF (IT.EQ.0.AND.IT.EQ.IN) IT=IN

DETERMINE COMPONENTS OF HORIZONTAL RADIATION
ID=IT*DG
IB=IT-ID

BEGIN

CALCULATE INCIDENT RADIATION ON OUTSIDE SURFACES
DO 50 I=BOTSURF,TOTSURF
SRFCT=I
AZ=WALLGEOM(SRFCT,15)
SLP=WALLGEOM(SRFCT,16)
FRG=WALLGEOM(SRFCT,17)
FRS=WALLGEOM(SRFCT,18)

CALCULATE THE SURFACE INCIDENCE ANGLE
CALL INCIDENCE(HR,DEC,LAT,SLP,AZ,ANGLE)
IF (COSD(ANGLE).LT.0) ANGLE=90

CALCULATION OF SURFACE GEOMETRIC FACTOR
IF (ABS(TIME-12).LT.SUNSET.OR.ZANGLE.LE.ZLIMIT) THEN
RB=COSD(ANGLE)/COSD(ZANGLE)
ELSE

BEGIN

CALCULATE THE EFFECT OF THE ROOF OVERHANG
IF (I.NE.5.OR.I.NE.9) THEN
CALL SHADOW(SRFCT,WALLGEOM,SOLAZ,ZANGLE,SHRAT)
IF (SHRAT.LE.0.0) SHRAT=0.0
IF (SHRAT.GE.1.0) SHRAT=1.0
ELSE
SHRAT=0.0
ENDIF

CALCULATE THE INCIDENT RADIATION COMPONENTS ON THE OUTSIDE SURFACES
GBT=0
GDT=0
GRT=0
IF (INT(G2).NE.9999) THEN
IF (SRFCT.EQ.SSURF) THEN
GBT=G2*SHRAT
ELSE IF (SRFCT.EQ.NSURF) THEN
GBT=G2*SHRAT
ELSE
GBT=IB*SHRAT+RB
GDT=ID+FRS
GRT=IT+RFCT+FRG
ENDIF
ELSE
GBT=IB*SHRAT+RB
GDT=ID+FRS
GRT=IT+RFCT+FRG
ENDIF
ELSE
GBT=IB*SHRAT+RB
GDT=ID+FRS
GRT=IT+RFCT+FRG
ENDIF

SUM THE RADIATION COMPONENTS ON THE OUTSIDE SURFACES
RAD(SRFCT)=GBT+GDT+GRT
IF (RAD(SRFCT).LE.0) RAD(SRFCT)=0.0
50 CONTINUE

CALCULATE NET RADIATION THROUGH WINDOWS
DO 100 I=BOTWIND,TOTWIND
WDWCT=I
AZ=WINDGEOM(WDWCT,15)
SLP=WINDGEOM(WDWCT,16)
FRG=WINDGEOM(WDWCT,17)
FRS=WINDGEOM(WDWCT,18)

* CALCULATE THE WINDOW INCIDENCE ANGLE
* CALL INCIDENCE(HR,DEC,LAT,SLP,AZ,ANGLE)
  IF (COSD(ANGLE).LT.0) ANGLE=90

* CALCULATION OF SURFACE GEOMETRIC FACTOR
* IF (ABS(TIME-12).LT.SUNSET.OR.ZANGLE.LE.ZLIMIT) THEN
  RB=COSD(ANGLE)/COSD(ZANGLE)
ELSE
  RB=0
ENDIF

* CALCULATE THE EFFECT OF THE ROOF OVERHANG
* CALL SHADOW(WDWCT,WINDGEOM,SOLAZ,ZANGLE,SHRAT)
  IF (SHRAT.LE.0.0) SHRAT=0.0
  IF (SHRAT.GE.1.0) SHRAT=1.0

* CALCULATE THE INCIDENT RADIATION COMPONENTS ON THE WINDOWS
* GBT=0
  GDT=0
  GRT=0
  IF (INT(G2).NE.9999) THEN
    IF (WDWCT.EQ.SWIND) THEN
      GBT=G1*SHRAT
    ELSE IF (WDWCT.EQ.NWIND) THEN
      GBT=G2*SHRAT
    ELSE
      GBT=IB*SHRAT*RB
      GDT=ID*FRS
      GRT=IT*RFCT*FRG
    ENDIF
  ELSE
    GBT=IB*SHRAT*RB
    GDT=ID*FRS
    GRT=IT*RFCT*FRG
  ENDIF

* CALCULATE THE RADIATION TRANSMISSIVITY
* CALL OPTICS(ANGLE,SLP,COVERS,TRB,TRD,TRR)
  IF (TRB.LE.0) TRB=0.0
  IF (TRD.LE.0) TRD=0.0
  IF (TRR.LE.0) TRR=0.0

* CALCULATE THE TRANSMITTED RADIATION
* GBT=TRB*GBT
  GDT=TRD*GDT
  GRT=TRR*GRT
  IF (GBT.LE.0) GBT=0
  IF (GDT.LE.0) GDT=0
  IF (GRT.LE.0) GRT=0

* SUM THE RADIATION COMPONENTS
* RAD(WDWCT+10)=GBT+GDT+GRT
  IF (RAD(WDWCT+10).LE.0) RAD(WDWCT+10)=0.0
100 CONTINUE
*
* RETURN
* END
B.21. Program Listing of INCIDENCE.FOR

************************************************************************
* SUBROUTINE INCIDENCE(HR, DEC, LAT, SLP, AZ, ANGLE)
************************************************************************
* REAL DEC !DECLINATION
REAL LAT !LATITUDE
REAL SLP !SLOPE
REAL AZ !AZIMUTH
REAL HR !HOUR ANGLE
REAL ANGLE !INCIDENCE ANGLE
*
ANGLE=SIND(DEC)*SIND(LAT)*COSD(SLP)
ANGLE=ANGLE-SIND(DEC)*COSD(LAT)*SIND(SLP)*COSD(AZ)
ANGLE=ANGLE+COSD(DEC)*COSD(LAT)*COSD(SLP)*COSD(HR)
ANGLE=ANGLE+COSD(DEC)*SIND(LAT)*SIND(SLP)*COSD(AZ)*COSD(HR)
ANGLE=ANGLE+COSD(DEC)*SIND(SLP)*SIND(AZ)*SIND(HR)
ANGLE=ACOSD(ANGLE)
*
************************************************************************
* RETURN
END
*
************************************************************************
B.22. Program Listing of SHADOW.FOR

************************************************************************
* SUBROUTINE SHADOW(SURF,SHDX,PHI,COSZ,SHRAT)
*************************************************************************
*
REAL SHDX(10,18) ! STORAGE VECTOR
REAL SURF ! SURFACE FLAG
REAL PHI ! SOLAR AZIMUTH ANGLE
REAL COSZ ! SOLAR ZENITH ANGLE
REAL SHRAT ! SUNLed AREA TO THE TOTAL WINDOW AREA RATIO
REAL HT ! WINDOW HEIGHT
REAL FL ! WINDOW WIDTH
REAL FP ! DEPTH OF OVERHANG
REAL AW ! DIST. FROM TOP OF WINDOW TO THE OVERHANG
REAL B WL ! DIST. OF LEFT OVERHANG BEYOND WINDOW
REAL BWR ! DIST. OF RIGHT OVERHANG BEYOND WINDOW
REAL D ! DEPTH OF VERT. PROJ. AT END OF THE OVERHANG
REAL FP1 ! DEPTH OF THE LEFT FIN
REAL A1 ! DIST. OF THE LEFT FIN ABOVE THE WINDOW TOP
REAL B1 ! DIST. FROM THE LEFT EDGE OF FIN TO WINDOW
REAL C1 ! DIST. OF LEFT FIN BOTTOM FROM WINDOW BOTTOM
REAL FP2 ! DEPTH OF THE RIGHT FIN
REAL A2 ! DIST. OF THE RIGHT FIN ABOVE THE WINDOW TOP
REAL B2 ! DIST. FROM THE RIGHT EDGE OF FIN TO WINDOW
REAL C2 ! DIST. OF RIGHT FIN BOTTOM FROM WINDOW BOTTOM
REAL WAZI ! WINDOW AZIMUTH ANGLE
*
************************************************************************
*
FL=SHDX(SURF,1)
HT=SHDX(SURF,2)
FP=SHDX(SURF,3)
AW=SHDX(SURF,4)
BWL=SHDX(SURF,5)
BWR=SHDX(SURF,6)
FP1=SHDX(SURF,7)
A1=SHDX(SURF,8)
B1=SHDX(SURF,9)
C1=SHDX(SURF,10)
FP2=SHDX(SURF,11)
A2=SHDX(SURF,12)
B2=SHDX(SURF,13)
C2=SHDX(SURF,14)
WAZI=SHDX(SURF,15)
*
\[ v = U \cdot U \]

\[ \text{SHRAT} = 0.0 \]

\[ \text{IF } (T - A) < 27,27,2 \]

\[ \text{IF } (A - AB) < 14,14,3 \]

\[ \text{IF } (DE - B) < 12,12,4 \]

\[ \text{IF } (FM - B) < 11,11,5 \]

\[ \text{IF } (DE - (FL + B)) < 8,8,6 \]

\[ \text{IF } (FM - (FL - B)) < 9,7,7 \]

\[ \text{HORIZONTAL 9} \]

\[ \text{AREAO} = \text{FL} \cdot (0.5 \cdot (AB + UG) - A) \]

\[ \text{GOTO 37} \]

\[ \text{IF } (T - (H + A)) < 9,10,10 \]

\[ \text{HORIZONTAL 7} \]

\[ \text{AREAO} = (T - A) \cdot FL - ((FM - B) \cdot 2) \cdot T \cdot C \cdot T \cdot E \cdot A \cdot 0.5 \]

\[ L = 2 \]

\[ \text{GOTO 21} \]

\[ \text{HORIZONTAL 8} \]

\[ \text{AREAO} = H \cdot FL - (DE - B) \cdot 2 \cdot T \cdot C \cdot T \cdot E \cdot A \cdot 0.5 \]

\[ \text{GOTO 37} \]

\[ \text{SUN ON RIGHT} \]

\[ \text{AREAO} = 0.0 \]

\[ \text{ARSIF} = 0.0 \]

\[ \text{L} = 2 \]

\[ \text{GOTO 24} \]

\[ \text{AREAO} = H \cdot FL \]

\[ \text{GOTO 68} \]

\[ \text{FL} = \text{FL} \]

\[ K = 1 \]

\[ L = 1 \]

\[ \text{T} = \text{T1} \]

\[ \text{FM} = \text{FM1} \]

\[ \text{AB} = B + T \cdot C \cdot T \cdot E \]

\[ \text{UG} = (FL + B) \cdot T \cdot C \cdot T \cdot E \]

\[ \text{DE} = (H + A) / T \cdot C \cdot T \cdot E \]

\[ \text{HORIZONTAL OVERHANG *AREAO*} \]

\[ \text{HORIZONTAL 6} \]

\[ \text{AREAO} = (UG - A) / 2 / T \cdot C \cdot T \cdot E \cdot A \cdot 0.5 \]

\[ \text{GOTO 37} \]

\[ \text{IF } (T - (H + A)) < 20,19,19 \]

\[ \text{HORIZONTAL 5} \]
19  AREA=H*(FL-(A+0.5*B)/TCETA+B)
    GOTO 37

20  AREA=(T-A)*(FL+B-FM*(1.0-A/T)*0.5)
    L=2

21  FL3=FL+B-FM
    IF (T-D-(B+A)) 22,22,23

22  H3=D
    GOTO 3700

23  H3=H+A-T
    GOTO 3700

24  FL3=FL
    IF (T-D-(B+A)) 26,26,25

25  H3=H+A-T
    AREAV=H3+FL3
    GOTO 68

26  H3=D
    GOTO 3700

27  IF (T-D-A) 37,37,28
28  IF (FM-B) 34,34,29
29  IF (FM-(FL-B)) 31,37,37
31  FL3=FL-B-FM
    IF (T-D-(B+A)) 33,33,32

32  H3=H
    GOTO 3700

33  H3=T+D-A
    GOTO 3700

34  IF (T-D-(H+A)) 36,35,35

35  AREAV=H*FL
    GOTO 68

36  H3=T+D-A
    FL3=FL
    IF (FL3.LT.0.0) FL3=0.0
    IF (H3.LT.0.0) H3=0.0
    GOTO 3700

37  IF (GAMMA) 66,68,74

38  AREAV=H3*FL3
    GOTO 68

39  IF (FPF) 68,68,67

40  T=FPF.VERT
    FU=FPF.80RIZ=0
    AFl=AFGOTO 3700

41  IF (AREA) 73,73,88

42  IF (T+D-A) 37,37,28
43  IF (FM-B) 34,34,29
44  IF (FM-(FL-B)) 31,37,37
45  FL3=FL-B-FM
    IF (T-D-(B+A)) 33,33,32

46  H3=H
    GOTO 3700

47  VERTICAL 4

48  VERTICAL 5

49  VERTICAL 6

50  VERTICAL 7

51  VERTICAL 8

52  VERTICAL 9

53  SIDE FIN AND SHORT SIDE FIN

54  SIDE FIN "AREA1" "ARSIF"

55  IF (T+D-(H+A)) 36,35,35

56  TEST FOR OVERLAP OF FIN AND OVERHANG SHADOW

57  AT=A+(BF-B).*TCETA
    IF (AT-AF) 711,73,73

58  OVERLAP EXISTS .. L=2 IF OVERHANG SHADOW HAS HORIZ EDGE IN WINDOW

59  TEST FOR TYPE OF OVERLAP
IF ((FM-BF)-(FWI-B)) 621,622,622

SET L=1, SHADOW INTERSECTS ON INCLINED EDGE OF OVERHANG SHADOW

FIN SHADOW IS BELOW INCLINED EDGE OF OVERHANG SHADOW

AF=AT
L=1
GOTO 73

L=2, HORZ EDGE OF OVERHANG SHADOW, PORTION ABOVE HORZ EDGE

FIN SHADOW IS NOT IN OVERHANG SHADOW

AREA1=FL-(T1-A)-AREA0

RESET TO CALC FIN SHADOW BELOW HORZ EDGE OF OVERHANG SHADOW

AF=T1-A+AF1
H=H+AF1-AF

SHADOW OF FIN (K=1 ON GLASS, K=2 ON VERT PROJ SHADOW)

AB=BF+TCETA
UG=(FL+BF)+TCETA
DE=(H+AF)/TCETA
DJ=MX/TCETA
IF (FM-BF) 69,69,38
IF (AB-AF) 39,50,50
IF (UG-AF) 48,48,40
IF (T-AF) 47,47,41
IF (UG-(H+AF)) 44,44,42
IF (T-(H+AF)) 91,80,80

FIN 9

AREA1=H*(AF+H/0.5)/TCETA-BF)+AREA1
GOTO 58

IF (FM-(FL+BF)) 91,89,89

AREA1=(FM-BF)H-(T-AF)**2/TCETA*0.5+AREA1
GOTO 58

SHORT SIDE FINARSH1, ARSH1

SHORT 3

ARSH1=-(CX-AB)**2/TCETA*0.5
GOTO 69

SHORT 4

ARSH1=-(CX-AB)**2/TCETA*0.5
GOTO 69

ARSH1=FL*(CX-(BF+FL/2))*TCETA
GOTO 69

FIN 8

AREA1=H+FL-(UG-AF)**2/TCETA*0.5+AREA1
GOTO 58

FIN 7

AREA1=(FM-BF)H-(T-AF)**2/TCETA*0.5+AREA1

GOTO 63

IF (FM-(FL+BF)) 47,47,40

FIN 3

AREA1=H*(FM-BF)+AREA1
GOTO 63

FIN 2

AREA1=H+FL+AREA1
GOTO 58

IF (DE-BF) 69,69,51
IF (UG-(H+AF)) 55,55,52
IF (T-(H+AF)) 93,94,94

FIN 6

AREA1=(DE-BF)**2*TCETA*0.5+AREA1
GOTO 58

FIN 4

AREA1=(FM-BF)*(H+AF-(T+AB)*0.5)+AREA1
GOTO 63

FIN 5

AREA1=FL*(H-BF+FL*0.5)*TCETA+AF+AREA1

SHORT SIDE FIN "ARSH1", "ARSHF"

IF (DJ-BF) 69,69,59
IF (DJ-(FL+BF)) 61,61,60

SHORT 3

ARSH1=-(CX-AB)**2/TCETA*0.5
GOTO 69

SHORT 4

ARSH1=-(CX-AB)**2/TCETA*0.5
GOTO 69

IF (DJ-BF) 69,69,64
IF (DJ-(DJ-FM)) 61,61,65
SHORT 5

ARSH1 = -(FM-BF) * (CX-(T+AB)*0.5)

GOTO (77, 76), K

ARSH1 = -ARSH1
AREA1 = -AREA1

ARSHF = ARSHF + ARSH1
ARSIF = ARSIF + AREA1

GOTO (78, 68), K

IF (AREAV) 68, 68, 72

• RESET PARAMETERS TO DEDUCT FIN SHADOW OVERLAP
• ON VERT PROJ SHADOW

K=2
AREA1 = 0.0
ARSH1 = 0.0

BBF = BF
BF = FM1-B+BF

IF (BF) 186, 185, 185

BF = BBF

IF (HT+A-TI-D) 87, 87, 188

CX = AX-(HT+A-TI-D)
IF (CX) 85, 87, 87

CX = 0.0

AF = T1-A+AF
H = H3
FL = FL3

GOTO 73

SHARED AREA "ARSHA"

CONTINUE

ARSHA = AREAO + AREAV + ARSHF + ARSIF

SHRAT = (FL1*H1-ARSHA)/(FL1*H1)

FL = FL1

CONTINUE

RETURN

END

********************************************************************
Figure B-2: Explanation of Variables used in SHADOW.FOR
B.23. Program Listing of OPTICS.FOR

************************************************************************
*       SUBROUTINE OPTICS(ANGLE1,SLP,COVERS,TRB,TRD,TRR)
*  **************************************************************************
*  REAL ANGLE1 !ANGLE OF INCIDENCE
REAL SLP !SLOPE OF SURFACE
REAL COVERS !NUMBER OF COVERS OF GLASS IN WINDOW
REAL LEN !LENGTH OF GLASS
REAL EXTCOE = !EXTINCTION COEFFICIENT
REAL ARI !AVERAGE REFRACTIVE INDEX
REAL ANGLE2 !ANGLE OF REFRACTION
REAL TRB !BEAM TRANSMISSIVITY
REAL TRBADJ !ADJUSTMENT OF BEAM TRANSMISSIVITY
REAL ANGLED !ANGLE OF INCIDENCE FOR DIFFUSE TRANS.
REAL TRD !DIFFUSE TRANSMISSIVITY
REAL TRDADJ !ADJUSTMENT OF DIFFUSE TRANSMISSIVITY
REAL ANGLER !ANGLE OF INCIDENCE FOR REFLECTED TRANS.
REAL TRR !REFLECTED TRANSMISSIVITY
REAL TA !BEAM TRANSMISSIVITY (ABSORPTION ONLY)
************************************************************************
*  EXTCOEF=8 !1/METERS
LEN=.006 !METERS (1/4 INCHES)
ARI=1.526
************************************************************************
*  NORMALIZATION OF TRANSMISSIVITY BASED ON EXPERIMENTAL TESTS
*  TRBADJ=.90
TRDADJ=.80
************************************************************************
*  CALCULATION OF EFFECT OF ABSORPTION OF RADIATION
*  ANGLE2=ASIND(SIND(ANGLE1)/ARI)
TA=EXP(-1*EXTCOEF*LEN*COVERS/ANGLE2)
************************************************************************
*  CALCULATION OF TRANSMITTANCE FOR BEAM RADIATION
*  RPERP=(SIND(ANGLE2-ANGLE1))**2/(SIND(ANGLE2+ANGLE1))**2
RPAR=(TAND(ANGLE2-ANGLE1))**2/(TAND(ANGLE2+ANGLE1))**2
TRB=(1-RPERP)/(1+(2*COVERS-1)*RPERP)
TRB=(TRB+(1-RPAR)/(1+(2*COVERS-1)*RPAR))/2
TRB = TA + TRB + TRBADJ

* CALCULATION OF TRANSMITTANCE FOR DIFFUSE RADIATION

ANGLED = 59.68 - 1388 * SLP + 0.01497 * SLP ** 2
ANGLE2 = ASIND(SIND(ANGLE1)/ARI)
TA = EXP(-1 * EXTCOEF * LEN * COVERS / ANGLE2)
RPERP = (SIND(ANGLE2 - ANGLED)) ** 2 / (SIND(ANGLE2 + ANGLED)) ** 2
RPAR = (TAND(ANGLE2 - ANGLED)) ** 2 / (TAND(ANGLE2 + ANGLED)) ** 2
TRD = (1 - RPERP) / (1 + (2 * COVERS - 1) * RPERP)
TRD = (TRD + (1 - RPAR) / (1 + (2 * COVERS - 1) * RPAR)) / 2
TRD = TA * TRD * TRDADJ

* CALCULATION OF TRANSMITTANCE FOR REFLECTED RADIATION

ANGLER = 90 - 5788 * SLP + 0.02693 * SLP ** 2
ANGLE2 = ASIND(SIND(ANGLE1)/ARI)
TA = EXP(-1 * EXTCOEF * LEN * COVERS / ANGLE2)
RPERP = (SIND(ANGLE2 - ANGLER)) ** 2 / (SIND(ANGLE2 + ANGLER)) ** 2
RPAR = (TAND(ANGLE2 - ANGLER)) ** 2 / (TAND(ANGLE2 + ANGLER)) ** 2
TRR = (1 - RPERP) / (1 + (2 * COVERS - 1) * RPERP)
TRR = (TRR + (1 - RPAR) / (1 + (2 * COVERS - 1) * RPAR)) / 2
TRR = TA * TRR * TRDADJ

************************************************************************
* RETURN
END
************************************************************************
B.24. Program Listing of VIEWFACTOR.FOR

************************************************************************
* SUBROUTINE VIEWFACTOR(SURF,SURFGEOM)
************************************************************************
*
REAL SURFGEOM(10,18) !DIMENSION MATRIX FOR SHADED DEVICE
*
REAL SURF !SURFACE FLAG
REAL W !WIDTH OF THE WINDOW
REAL H !HEIGHT OF THE WINDOW
REAL P !LENGTH OF THE OVERHANG
REAL G !LENGTH OF GAP BETWEEN THE WINDOW AND OVERHANG
REAL EL !LENGTH OF THE LEFT SIDE OF THE OVERHANG
REAL ER !LENGTH OF THE RIGHT SIDE OF THE OVERHANG
REAL SLOPE !SLOPE OF THE RECEIVER
REAL FRO !VIEW FACTOR OF RECEIVER TO OVERHANG
REAL FRG !VIEW FACTOR OF RECEIVER TO GROUND
REAL FRF !VIEW FACTOR OF RECEIVER TO FIN
REAL FRS !VIEW FACTOR OF RECEIVER TO SKY
*
************************************************************************
*
CALCULATE RECIEVER-OVERHANG VIEWFACTOR
*

W=SURFGEOM(SURF,1)
H=SURFGEOM(SURF,2)
P=SURFGEOM(SURF,3)
G=SURFGEOM(SURF,4)
EL=SURFGEOM(SURF,5)
ER=SURFGEOM(SURF,6)
SLOPE=SURFGEOM(SURF,16)
*
CALL VIEWCALC(W,H,P,G,EL,ER,SLOPE,FRO)
*
CALCULATE RECIEVER-GROUND VIEWFACTOR
*
FRG=(1-COSD(SLOPE))/2
*
CALCULATE RECEIVER-FIN VIEWFACTOR
*
FRF=0
*
EAST WINDOW
*
IF (SURF.EQ.3) THEN
B.25. Program Listing of VIEWCALC.FOR

*********************************************************
* SUBROUTINE VIEWCALC(W,H,P,G,EL,ER,SLOPE,FCTR)
*********************************************************

REAL X1(10) !X DISTANCE VECTOR FOR RECIEVER
REAL X2(10) !X DISTANCE VECTOR FOR SHADING DEVICE
REAL Y(10) !Y DISTANCE VECTOR FOR RECIEVER
REAL Z(10) !Y DISTANCE VECTOR FOR SHADING DEVICE

REAL SURF !SURFACE FLAG
REAL PI
REAL W !WIDTH OF THE WINDOW
REAL H !HEIGHT OF THE WINDOW
REAL P !LENGTH OF THE OVERHANG
REAL G !GAP LENGTH BETWEEN THE WINDOW AND OVERHANG
REAL EL !LENGTH OF THE LEFT SIDE OF THE OVERHANG
REAL ER !LENGTH OF THE RIGHT SIDE OF THE OVERHANG
REAL ANGLE !ANGLE SEPERATING THE RECEIVER AND THE OVERHANG
REAL SLOPE !SLOPE OF THE RECEIVER
REAL NODES !NUMBER OF NODES USED IN THE CALCULATIONS
REAL DX1 !INCREMENTAL DISTANCE OF FOR RECIEVER
REAL DX2 !INCREMENTAL DISTANCE OF FOR OVERHANG
REAL DY !INCREMENTAL DISTANCE OF FOR RECIEVER
REAL EFFY !EFFECTIVE Y DISTANCE OF RECEIVER
REAL DZ !INCREMENTAL DISTANCE OF FOR OVERHANG
REAL EFFZ !EFFECTIVE Z DISTANCE OF OVERHANG
REAL DA1 !INCREMENTAL AREA FOR RECIEVER
REAL DA2 !INCREMENTAL AREA FOR OVERHANG
REAL DA !INCREMENTAL AREA FOR RECIEVER*OVERHANG
REAL FCTR !VIEW FACTOR

*********************************************************
* NODES=10
PI=3.141593
*********************************************************

*********************************************************
* CALCULATION OF VIEW FACTORS FOR OVERHANG AND FINS
*********************************************************

IF (SLOPE.EQ.90) THEN
    ANGLE=SLOPE
B.26. Program Listing of DATAREAD.FOR

************************************************************************
* SUBROUTINE DATAREAD(FLAG1,WEATHER,START,END,CITYNAME,LAT,LON
1,ALT)
************************************************************************

* THIS SUBROUTINE READS EITHER THE MONITORED DATA OR THE TMY DATA
* WEATHER(X, 1)= ** DAY **
* WEATHER(X, 2)= ** TIME **
* WEATHER(X, 3)= ** HOUSE TEMP **
* WEATHER(X, 4)= ** SUNSPACE TEMP **
* WEATHER(X, 5)= ** CRAWLSPACE TEMP **
* WEATHER(X, 6)= ** OUTSIDE TEMP **
* WEATHER(X, 7)= ** NONSOUTH RADIATION **
* WEATHER(X, 8)= ** SOUTH RADIATION **
* WEATHER(X, 9)= ** WIND SPEED **
* WEATHER(X,10)= ** HEATER **
* WEATHER(X,11)= ** FAN **
************************************************************************

REAL WEATHER (96,11) !WEATHER DATA MATRIX
REAL LAT !LATITUDE OF LOCATION
REAL LON !LONGITUDINAL TIME ADJUSTMENT
REAL ALT !ALTITUDE OF LOCATION IN KILOMETERS
REAL DAY !DAY OF YEAR
REAL REFLECT !GROUND REFLECTENCE

INTEGER FLAG1 !MONITORED (0) OR TMY (1) DATA
INTEGER FLAG2 !DATAFILE STATUS FLAG
INTEGER LEAP !LEAP YEAR FLAG

INTEGER YEAR !TMY YEAR INDICATOR (0000=TMY)
CHARACTER*4 CITYNAME !LOCATION OF DATA
CHARACTER*16 CITY !LOCATION OF DATA
CHARACTER*24 DIR !NAME OF SUBDIRECTORY
CHARACTER*40 DATAFILE !NAME OF MONITORED DATA

************************************************************************
* INITIALIZE DAILY WEATHER MATRICE
* DO 5 I=1,96
DO 6 J=1,11
    WEATHER(I,J)=0.0
CONTINUE

CONTINUE

**************************************************************************

* OPEN TEST DATA FILE

* IF (FLAG1.EQ.0.AND.FLAG2.EQ.0) THEN
    DIR='WORK: [MEE.LUMBIS.AHOUSE]'
    FLAG2=1
    TYPE 10
    FORMAT (' ',//,23X,' ENTER THE DATA FILE NAME: ',S)
    ACCEPT 11, DATAFILE
    10 FORMAT (A40)
    DATAFILE=DIR//DATAFILE
    OPEN(UNIT=01, FILE=DATAFILE, STATUS='OLD')
ENDIF

* READ TEST DATA FILE

* IF (FLAG1.EQ.0.AND.FLAG2.EQ.1) THEN
* DETERMINE TIME ADJUSTMENT DUE TO LONGITUDINAL ERROR
* LON=4*(120-106.68)/60
* LAT=52.167
ALT=.502
*
START=1
END=96
READ (01,*,END=50) DAY
DO 15 I=1,96 
    READ (01,*,END=50) (WEATHER(I,J), J=2,11)
    WEATHER(I,1)=DAY
    WEATHER(I,9)=WEATHER(I,9)
    WEATHER(I,10)=WEATHER(I,10)
    WEATHER(I,11)=WEATHER(I,11)
    IF (WEATHER(I-1,2).EQ.0.AND.WEATHER(I,2).NE.0) START=I
    IF (WEATHER(I,2).NE.0.AND.WEATHER(I+1,2).EQ.0) END=I
    15 CONTINUE
ENDIF
*
* OPEN TMY DATA FILE
*
IF (FLAG1.EQ.1.AND.FLAG2.EQ.0) THEN
DIR='WORK: [MEE.LUMBIS.TMY]' 
FLAG2=1 
TYPE 20 

20 FORMAT (' ', 'ENTER THE WEATHER FILE: ', $) 
ACCEPT 12, CITYNAME 

12 FORMAT (A4) 
DATAFILE=DIR//'CITYNAME' 
OPEN(UNIT=01, FILE=DATAFILE, STATUS='OLD') 
READ (01, 21, END=50) YEAR, LEAP, CITY, LAT, LON, ALT 

21 FORMAT (A4, x, I1, x, A16, F6.2, F7.2, F5.3) 

* DETERMINE TIME ADJUSTMENT DUE TO LONGITUDINAL ERROR 
* 
IF (LON.LT.75) LON=4*(75-LON)/60 
IF (LON.GE.75.AND.LON.LT.90) LON=4*(90-LON)/60 
IF (LON.GE.90.AND.LON.LT.105) LON=4*(105-LON)/60 
IF (LON.GE.105.AND.LON.LT.120) LON=4*(120-LON)/60 
ENDIF 

* READ TMY DATA FILE 
* 
IF (FLAG1.EQ.1.AND.FLAG2.EQ.1) THEN 
READ (01, 22, END=50) DAY, REFLECT, (WEATHER(I, 6), I=1, 24) 
22 FORMAT (F3.0, x, F3.1, 17x, 24F3.0) 
READ (01, 23, END=50) (WEATHER(I, 8), I=1, 24) 
READ (01, 23, END=50) (WEATHER(I, 9), I=1, 24) 
READ (01, 23, END=50) (WEATHER(I, 2), I=1, 24) 
23 FORMAT (24(F4.0)) 

* START=1 
END=24 
DO 30 I=1, 24 

WEATHER(I, 1)=DAY 
WEATHER(I, 2)=I 
WEATHER(I, 3)=22.00 !AVG HOUSE TEMP. 
WEATHER(I, 5)=12.50 !AVG CRAWLSPACE TEMP. 
WEATHER(I, 7)=9999+REFLECT 
30 CONTINUE 

ENDIF 
GOTO 60 

************************************************************************ 
* CLOSING DATA FILE 
* 
50 CLOSE (UNIT=01) 
FLAG1=2 
FLAG2=0
*  
*  
*  
60 RETURN
END

*
**B.27. Program Listing of GEOMETRY.FOR**

************************************************************************
* SUBROUTINE GEOMETRY(WDGM,WLGM,MISCUA)
************************************************************************
* THIS SUBROUTINE CONTAINS THE GEOMETRIES OF THE OUTSIDE SURFACES AND WINDOWS
************************************************************************
* REAL WDGM(10,18) !WINDOW GEOMETRY MATRIX
REAL WLGM(10,18) !WALL GEOMETRY MATRIX
REAL MISCUA(9,2) !MISC. CONDUCTIVITY AND AREA MATRIX
************************************************************************
* DOOR AND WINDOW AREAS
* UNITS ARE METER SQUARED
************************************************************************
*MISCUA(1,2)=2.331 !HOUSE/SUNSPACE DOOR
MISCUA(2,2)=5.690 !HOUSE/SUNSPACE WINDOW
MISCUA(3,2)=1.0 !HOUSE/SUNSPACE INFILTRATION
MISCUA(4,2)=1.583 !SUNSPACE/OUTSIDE DOOR
MISCUA(5,2)=1.50*0.49 !SUNSPACE/OUTSIDE WEST WINDOW
MISCUA(6,2)=9*1.50*0.49 !SUNSPACE/OUTSIDE SOUTH WINDOW
MISCUA(7,2)=(1.50*0.49+.410) !SUNSPACE/OUTSIDE EAST WINDOW
MISCUA(8,2)=1.0 !SUNSPACE/OUTSIDE INFILTRATION
MISCUA(9,2)=0.000 !SUNSPACE/OUTSIDE SKYLIGHTS
************************************************************************
* GEOMETRY OF WINDOW SURFACES
* UNITS ARE METERS AND DEGREES
* WINDOW 1 (WEST WINDOW)
* WDGM(1,1)=MISCUA(5,2)/1.50 !WIDTH
WDGM(1,2)=1.50 !HEIGHT
WDGM(1,3)=.400 !OVERHANG
WDGM(1,4)=.900 !WINDOW GAP
WDGM(1,5)=2.18-WDGM(1,1)/2 !LEFT OVERHANG EXT.
**WINDOW 1 (NORTH WINDOW)**

- \(WDGM(1,1) = 1.50\)
- \(WDGM(1,2) = .05\)
- \(WDGM(1,3) = .30\)
- \(WDGM(1,4) = 180.0\)
- \(WDGM(1,5) = 0.00\)
- \(WDGM(1,6) = 0.00\)
- \(WDGM(1,7) = 0.00\)
- \(WDGM(1,8) = 0.00\)
- \(WDGM(1,9) = 0.00\)
- \(WDGM(1,10) = 0.00\)
- \(WDGM(1,11) = 0.00\)
- \(WDGM(1,12) = 0.00\)
- \(WDGM(1,13) = 0.00\)
- \(WDGM(1,14) = 0.00\)
- \(WDGM(1,15) = 1.80\)
- \(WDGM(1,16) = 90.0\)

**WINDOW 2 (SOUTH WINDOW)**

- \(WDGM(2,1) = 1.50\)
- \(WDGM(2,2) = .60\)
- \(WDGM(2,3) = .03\)
- \(WDGM(2,4) = 0.00\)
- \(WDGM(2,5) = 0.00\)
- \(WDGM(2,6) = 0.00\)
- \(WDGM(2,7) = 0.00\)
- \(WDGM(2,8) = 0.00\)
- \(WDGM(2,9) = 0.00\)
- \(WDGM(2,10) = 0.00\)
- \(WDGM(2,11) = 0.00\)
- \(WDGM(2,12) = 0.00\)
- \(WDGM(2,13) = 0.00\)
- \(WDGM(2,14) = 0.00\)
- \(WDGM(2,15) = 180.0\)
- \(WDGM(2,16) = 90.0\)

**WINDOW 3 (EAST WINDOW)**

- \(WDGM(3,1) = 1.50\)
- \(WDGM(3,2) = .05\)
- \(WDGM(3,3) = .30\)
- \(WDGM(3,4) = 180.0\)
- \(WDGM(3,5) = 0.00\)
- \(WDGM(3,6) = 0.00\)
- \(WDGM(3,7) = 0.00\)
- \(WDGM(3,8) = 0.00\)
- \(WDGM(3,9) = 0.00\)
- \(WDGM(3,10) = 0.00\)
- \(WDGM(3,11) = 0.00\)
- \(WDGM(3,12) = 0.00\)
- \(WDGM(3,13) = 0.00\)
- \(WDGM(3,14) = 180.0\)
- \(WDGM(3,15) = 90.0\)

**WINDOW 4 (SKYLIGHTS)**

- \(WDGM(4,1) = 1.50\)
- \(WDGM(4,2) = .60\)
- \(WDGM(4,3) = .03\)
- \(WDGM(4,4) = 0.00\)
- \(WDGM(4,5) = 0.00\)
- \(WDGM(4,6) = 0.00\)
- \(WDGM(4,7) = 0.00\)
- \(WDGM(4,8) = 0.00\)
- \(WDGM(4,9) = 0.00\)
- \(WDGM(4,10) = 0.00\)
- \(WDGM(4,11) = 0.00\)
- \(WDGM(4,12) = 0.00\)
- \(WDGM(4,13) = 0.00\)
- \(WDGM(4,14) = 0.00\)
- \(WDGM(4,15) = 0.00\)
- \(WDGM(4,16) = 0.00\)

**WINDOW 5 (SKYLIGHTS)**

- \(WDGM(5,1) = 1.50\)
- \(WDGM(5,2) = .60\)
- \(WDGM(5,3) = .03\)
- \(WDGM(5,4) = 0.00\)
- \(WDGM(5,5) = 0.00\)
- \(WDGM(5,6) = 0.00\)
- \(WDGM(5,7) = 0.00\)
- \(WDGM(5,8) = 0.00\)
- \(WDGM(5,9) = 0.00\)
- \(WDGM(5,10) = 0.00\)
- \(WDGM(5,11) = 0.00\)
- \(WDGM(5,12) = 0.00\)
- \(WDGM(5,13) = 0.00\)
- \(WDGM(5,14) = 0.00\)
- \(WDGM(5,15) = 0.00\)
- \(WDGM(5,16) = 0.00\)
<table>
<thead>
<tr>
<th>WALL 6 (WEST OUTSIDE WALL)</th>
<th>WALL 7 (SOUTH OUTSIDE WALL)</th>
<th>WALL 8 (EAST OUTSIDE WALL)</th>
<th>WALL 9 (NORTH CEILING)</th>
<th>WALL 10 (SOUTH CEILING)</th>
</tr>
</thead>
<tbody>
<tr>
<td>WLGM(6,1)=3.63</td>
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<td>WLGM(10,1)=7.35</td>
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<td>WLGM(7,7)=0.00</td>
<td>WLGM(8,7)=0.00</td>
<td>WLGM(9,7)=4.00</td>
<td>WLGM(10,7)=9.86</td>
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<td>WLGM(7,8)=0.00</td>
<td>WLGM(8,8)=0.00</td>
<td>WLGM(9,8)=0.00</td>
<td>WLGM(10,8)=9.86</td>
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<tr>
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<td>WLGM(7,9)=0.00</td>
<td>WLGM(8,9)=0.00</td>
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<td>WLGM(10,11)=9.86</td>
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<td>WLGM(7,12)=0.00</td>
<td>WLGM(8,12)=0.00</td>
<td>WLGM(9,12)=0.00</td>
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<tr>
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<td>WLGM(8,13)=0.00</td>
<td>WLGM(9,13)=0.00</td>
<td>WLGM(10,13)=9.86</td>
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<td>WLGM(8,14)=0.00</td>
<td>WLGM(9,14)=0.00</td>
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<td>WLGM(6,16)=90.0</td>
<td>WLGM(7,16)=90.0</td>
<td>WLGM(8,16)=90.0</td>
<td>WLGM(9,16)=198.0</td>
<td>WLGM(10,16)=90.0</td>
</tr>
</tbody>
</table>

* WALL 8 (EAST OUTSIDE WALL)
* WALL 9 (NORTH CEILING)
* WALL 10 (SOUTH CEILING)
Determine outside surface view factors

DO 20 I=5,10
   SURF=I
   CALL VIEWFACTOR(SURF,WLGM)
20 CONTINUE

RETURN
END
B.28. Program Listing of THERMAL.FOR

***********************************************************************
*                                                             *
*  SUBROUTINE THERMAL(COND,LEN,DSSPT,AREA,MISCUA)             *
*                                                             *
***********************************************************************
*   THIS SUBROUTINE CONTAINS THE VARIOUS PARAMETERS           *
*   NEEDED FOR THE THERMAL SIMULATION OF THE SUNSPACE          *
*   THESE PARAMETERS INCLUDE:                                  *
*       CONDUCTIVITY                                          *
*       LENGTH                                               *
*       DENSITY                                              *
*       SPECIFIC HEAT                                        *
*       AREA                                                 *
***********************************************************************
*   THE SUBROUTINE IS BROKEN INTO THE FOLLOWING SECTIONS       *
*   1 - CONDUCTIVITIES OF THE INDIVIDUAL DOORS AND WINDOWS    *
*   2 - CONDUCTIVITIES OF ALL ELEMENTS IN THE WALLS           *
*   3 - LENGTHS OF ALL ELEMENTS IN THE WALLS                 *
*   4 - DENSITIES-SPECIFIC HEAT PRODUCT                       *
*       OF ALL ELEMENTS IN THE WALLS                         *
*   5 - CROSS-SECTIONAL AREAS OF ALL ELEMENTS IN THE WALLS    *
***********************************************************************
*   THE RESISTANCE-CAPACITANCE PATH DEVELOPED                 *
*   ASSUMES THAT THERE ARE FOUR RESISTANCES IN                 *
*   SERIES FOLLOWED BY TWO PARALLEL RESISTANCES               *
*   FOLLOWED IN TURN BY FOUR MORE RESISTANCES                 *
*   SEQUENCE OF ELEMENTS IN ALL WALLS IS THE SAME             *
*   (X,1) = EXTERIOR SURFACE CONDUCTANCE                      *
*   (X,2) = FIRST ELEMENT IN SERIES                           *
*   (X,3) = SECOND ELEMENT IN SERIES                          *
*   (X,4) = THIRD ELEMENT IN SERIES                           *
*   (X,5) = FIRST PARALLEL ELEMENT                            *
*   (X,6) = SECOND PARALLEL ELEMENT                           *
*   (X,7) = FOURTH ELEMENT IN SERIES                          *
(X,8) = FIFTH ELEMENT IN SERIES
(X,9) = SIXTH ELEMENT IN SERIES
(X,10) = SUNSPACE SURFACE CONDUCTANCE

<table>
<thead>
<tr>
<th>REAL COND(10,10)</th>
<th>CONDUCTIVITY MATRIX</th>
</tr>
</thead>
<tbody>
<tr>
<td>REAL LEN(10,10)</td>
<td>LENGTH MATRIX</td>
</tr>
<tr>
<td>REAL DSSPT(10,10)</td>
<td>DENSITY-SPECIFIC HT. MATRIX</td>
</tr>
<tr>
<td>REAL AREA(10,10)</td>
<td>AREA MATRIX</td>
</tr>
<tr>
<td>REAL MISCUA(9,2)</td>
<td>MISC. CONDUCTIVITY AND AREA MATRIX</td>
</tr>
<tr>
<td>REAL CF</td>
<td>CONVERSION FACTOR (ENGLISH TO SI)</td>
</tr>
<tr>
<td>REAL TOTAREA</td>
<td>TOTAL AREA OF WALL</td>
</tr>
<tr>
<td>REAL NETAREA</td>
<td>AREA OF WALL MINUS ANY WINDOWS/DOORS</td>
</tr>
</tbody>
</table>

| DOOR AND WINDOW CONDUCTIVITIES |

| UNITS ARE WATTS PER DEGREE KELVIN PER METER SQUARED |

| VISCUA(1,1)=1.891  | HOUSE/SUNSPACE DOOR |
| VISCUA(2,1)=2.328  | HOUSE/SUNSPACE WINDOW |
| VISCUA(3,1)=0.0  | HOUSE/SUNSPACE INfiltrATION |
| VISCUA(4,1)=2.271  | SUNSPACE/OUTSIDE DOOR |
| VISCUA(5,1)=2.504  | SUNSPACE/OUTSIDE WEST WINDOW |
| VISCUA(6,1)=2.504  | SUNSPACE/OUTSIDE SOUTH WINDOW |
| VISCUA(7,1)=2.504  | SUNSPACE/OUTSIDE EAST WINDOW |
| VISCUA(8,1)=0.0  | SUNSPACE/OUTSIDE INFILTRATION |
| VISCUA(9,1)=0.0  | SUNSPACE/OUTSIDE SKYLIGHTS |

| CONDUCTIVITIES OF WALL ELEMENTS |

| UNITS ARE WATTS PER METER PER DEGREE KELVIN |

| CF=.1442279  | FROM: BTU/IN/HR/FT**2/F |
| CF=.1442279  | TO: W/M/K |

| WALL 1 (INTERIOR WALL) |

| WALL 2 (BULKHEAD) |

| WALL 3 (CARPET FLOOR) |

| WALL 4 (TILED FLOOR) |

| WALL 5 (NORTH OUTSIDE WALL) |

| CF=.1442279  | FROM: BTU/IN/HR/FT**2/F |
| CF=.1442279  | TO: W/M/K |

<table>
<thead>
<tr>
<th>WALL 1 (INTERIOR WALL)</th>
<th>1/2 INCH GYPSUM BOARD</th>
</tr>
</thead>
<tbody>
<tr>
<td>COND(1,2)=2.22* .5*CF</td>
<td>1/2 INCH GYPSUM BOARD</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>WALL 2 (BULKHEAD)</th>
<th>CARPET</th>
</tr>
</thead>
<tbody>
<tr>
<td>COND(2,2)= .81<em>1.0</em>CF</td>
<td>5/8 INCH SUBFLOOR</td>
</tr>
<tr>
<td>COND(2,3)=1.22*.625*CF</td>
<td>1/2 INCH PLYWOOD</td>
</tr>
<tr>
<td>COND(2,4)= .80*CF</td>
<td>2&quot; BY 10&quot; JOISTS</td>
</tr>
<tr>
<td>COND(2,5)=.80*CF</td>
<td>2&quot; BY 10&quot; JOISTS</td>
</tr>
<tr>
<td>COND(2,6)=.316*CF</td>
<td>FIBRE GLASS INSULATION</td>
</tr>
<tr>
<td>COND(2,7)=2.22*.5*CF</td>
<td>1/2 INCH GYPSUM BOARD</td>
</tr>
<tr>
<td>COND(2,8)=0.0</td>
<td>DUMMY CONDUCTIVITY</td>
</tr>
<tr>
<td>COND(2,9)=0.0</td>
<td>DUMMY CONDUCTIVITY</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>WALL 3 (CARPET FLOOR)</th>
<th>1/2 INCH PLYWOOD</th>
</tr>
</thead>
<tbody>
<tr>
<td>COND(3,2)= .80*CF</td>
<td>1/2 INCH PLYWOOD</td>
</tr>
<tr>
<td>COND(3,3)=0.0</td>
<td>DUMMY CONDUCTIVITY</td>
</tr>
<tr>
<td>COND(3,4)=0.0</td>
<td>DUMMY CONDUCTIVITY</td>
</tr>
<tr>
<td>COND(3,5)=.80*CF</td>
<td>2&quot; BY 10&quot; JOISTS</td>
</tr>
<tr>
<td>COND(3,6)=.316*CF</td>
<td>FIBRE GLASS INSULATION</td>
</tr>
<tr>
<td>COND(3,7)=.80*CF</td>
<td>1/2 INCH PLYWOOD</td>
</tr>
<tr>
<td>COND(3,8)=1.22*.625*CF</td>
<td>5/8 INCH SUBFLOOR</td>
</tr>
<tr>
<td>COND(3,9)= .810<em>1.0</em>CF</td>
<td>CARPET</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>WALL 4 (TILED FLOOR)</th>
<th>15/16 INCH TILE</th>
</tr>
</thead>
<tbody>
<tr>
<td>COND(4,2)=.80*CF</td>
<td>3/8 INCH PLYWOOD</td>
</tr>
<tr>
<td>COND(4,3)=0.0</td>
<td>DUMMY CONDUCTIVITY</td>
</tr>
<tr>
<td>COND(4,4)=0.0</td>
<td>DUMMY CONDUCTIVITY</td>
</tr>
<tr>
<td>COND(4,5)=.80*CF</td>
<td>2&quot; BY 10&quot; JOISTS</td>
</tr>
<tr>
<td>COND(4,6)=.316*CF</td>
<td>FIBRE GLASS INSULATION</td>
</tr>
<tr>
<td>COND(4,7)=.80*CF</td>
<td>1/2 INCH PLYWOOD</td>
</tr>
<tr>
<td>COND(4,8)=1.22*.625*CF</td>
<td>5/8 INCH SUBFLOOR</td>
</tr>
<tr>
<td>COND(4,9)=12.50<em>5/16</em>CF</td>
<td>15/16 INCH TILE</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>WALL 5 (NORTH OUTSIDE WALL)</th>
<th>1/4 INCH STUCCO</th>
</tr>
</thead>
<tbody>
<tr>
<td>COND(5,2)=5.0*CF</td>
<td>1/4 INCH STUCCO</td>
</tr>
<tr>
<td>COND(5,3)=.80*CF</td>
<td>1/3 INCH PLYWOOD</td>
</tr>
<tr>
<td>COND(5,4)=0.0</td>
<td>DUMMY CONDUCTIVITY</td>
</tr>
<tr>
<td>COND(5,5)=.80*CF</td>
<td>2&quot; BY 6&quot; STUDDING</td>
</tr>
<tr>
<td>COND(5,6)=.316*CF</td>
<td>FIBRE GLASS INSULATION</td>
</tr>
</tbody>
</table>
WALL 6 (WEST OUTSIDE WALL)

COND(6, 2) = 5.0 * CF
COND(6, 3) = 0.80 * CF
COND(6, 4) = 0.0
COND(6, 5) = 0.80 * CF
COND(6, 6) = 0.316 * CF
COND(6, 7) = 2.22 * .5 * CF
COND(6, 8) = 0.0
COND(6, 9) = 0.0

1/2 INCH GYPSUM BOARD
! DUMMY CONDUCTIVITY

1/4 INCH STUCCO
!3/8 INCH PLYWOOD
! DUMMY CONDUCTIVITY
! 2" BY 6" STUDDING
! FIBRE GLASS INSULATION
! 1/2 INCH GYPSUM BOARD
! DUMMY CONDUCTIVITY

WALL 7 (SOUTH OUTSIDE WALL)

COND(7, 2) = 5.0 * CF
COND(7, 3) = 0.80 * CF
COND(7, 4) = 0.0
COND(7, 5) = 0.80 * CF
COND(7, 6) = 0.316 * CF
COND(7, 7) = 2.22 * .5 * CF
COND(7, 8) = 0.0
COND(7, 9) = 0.0

1/4 INCH STUCCO
!3/8 INCH PLYWOOD
! DUMMY CONDUCTIVITY
! 2" BY 6" STUDDING
! FIBRE GLASS INSULATION
! 1/2 INCH GYPSUM BOARD
! DUMMY CONDUCTIVITY

WALL 8 (EAST OUTSIDE WALL)

COND(8, 2) = 5.0 * CF
COND(8, 3) = 0.80 * CF
COND(8, 4) = 0.0
COND(8, 5) = 0.80 * CF
COND(8, 6) = 0.316 * CF
COND(8, 7) = 2.22 * .5 * CF
COND(8, 8) = 0.0
COND(8, 9) = 0.0

1/4 INCH STUCCO
!3/8 INCH PLYWOOD
! DUMMY CONDUCTIVITY
! 2" BY 6" STUDDING
! FIBRE GLASS INSULATION
! 1/2 INCH GYPSUM BOARD
! DUMMY CONDUCTIVITY

WALL 9 (NORTH CEILING)

COND(9, 2) = 1.06 * 1.0 * CF
COND(9, 3) = 0.80 * CF
COND(9, 4) = 0.0
COND(9, 5) = 0.80 * CF
COND(9, 6) = 0.316 * CF
COND(9, 7) = 2.22 * .5 * CF
COND(9, 8) = 0.0
COND(9, 9) = 0.0

1/2 INCH CEDAR SHAKES
!3/8 INCH PLYWOOD
! DUMMY CONDUCTIVITY
! 2" BY 8" JOISTS
! FIBRE GLASS INSULATION
! 1/2 INCH GYPSUM BOARD
! DUMMY CONDUCTIVITY

WALL 10 (SOUTH CEILING)

COND(10, 2) = 1.06 * 1.0 * CF
COND(10, 3) = 0.80 * CF
COND(10, 4) = 0.0
COND(10, 5) = 0.80 * CF
COND(10, 6) = 0.316 * CF
COND(10, 7) = 2.22 * .5 * CF
COND(10, 8) = 0.0
COND(10, 9) = 0.0

1/2 INCH CEDAR SHAKES
!3/8 INCH PLYWOOD
! DUMMY CONDUCTIVITY
! 12" BY 8" JOISTS
! FIBRE GLASS INSULATION
! 1/2 INCH GYPSUM BOARD
! DUMMY CONDUCTIVITY

LENGTH OF WALL ELEMENTS

UNITS ARE METERS

CF = .0254
! FROM: INCHES
! TO: METERS
WALL 3 (CARPET FLOOR)

LEN(3,1)=1.0
LEN(3,2)=0.375*CF
LEN(3,3)=0.0
LEN(3,4)=0.0
LEN(3,5)=9.25*CF
LEN(3,6)=9.25*CF
LEN(3,7)=5.5*CF
LEN(3,8)=625*CF
LEN(3,9)=1.0*CF
LEN(3,10)=1.0

WALL 4 (TILED FLOOR)

LEN(4,1)=1.0
LEN(4,2)=0.375*CF
LEN(4,3)=0.0
LEN(4,4)=0.0
LEN(4,5)=9.25*CF
LEN(4,6)=9.25*CF
LEN(4,7)=5.5*CF
LEN(4,8)=625*CF
LEN(4,9)=5/16*CF
LEN(4,10)=1.0

WALL 5 (NORTH OUTSIDE WALL)

LEN(5,1)=1.0
LEN(5,2)=.25*CF
LEN(5,3)=.375*CF
LEN(5,4)=0.0
LEN(5,5)=5.5*CF
LEN(5,6)=5.5*CF
LEN(5,7)=5.5*CF
LEN(5,8)=0.0
LEN(5,9)=0.0
LEN(5,10)=1.0

WALL 6 (WEST OUTSIDE WALL)

LEN(6,1)=1.0
LEN(6,2)=.25*CF
LEN(6,3)=.375*CF
LEN(6,4)=0.0
LEN(6,5)=5.5*CF
LEN(6,6)=5.5*CF

WALL 7 (SOUTH OUTSIDE WALL)

LEN(7,1)=1.0
LEN(7,2)=.25*CF
LEN(7,3)=.375*CF
LEN(7,4)=0.0
LEN(7,5)=5.5*CF
LEN(7,6)=5.5*CF
LEN(7,7)=.5*CF
LEN(7,8)=0.0
LEN(7,9)=0.0
LEN(7,10)=1.0

WALL 8 (EAST OUTSIDE WALL)

LEN(8,1)=1.0
LEN(8,2)=.25*CF
LEN(8,3)=.375*CF
LEN(8,4)=0.0
LEN(8,5)=5.5*CF
LEN(8,6)=5.5*CF
LEN(8,7)=.5*CF
LEN(8,8)=0.0
LEN(8,9)=0.0
LEN(8,10)=1.0

WALL 9 (NORTH CEILING)

LEN(9,1)=1.0
LEN(9,2)=1.0*CF
LEN(9,3)=.375*CF
LEN(9,4)=0.0
LEN(9,5)=7.25*CF
LEN(9,6)=7.25*CF
LEN(9,7)=.5*CF
LEN(9,8)=0.0
LEN(9,9)=0.0
LEN(9,10)=1.0

WALL 10 (SOUTH CEILING)

LEN(10,1)=1.0
LEN(10,2)=1.0*CF
LEN(10,3)=.375*CF
LEN(10,4)=0.0
LEN(10,5)=5.5*CF
LEN(10,6)=5.5*CF
LEN(10,7)=5.5*CF
LEN(10,8)=0.0
LEN(10,9)=0.0
LEN(10,10)=1.0

LEN(6,7)=.5*CF
LEN(6,8)=0.0
LEN(6,9)=0.0
LEN(6,10)=1.0

LEN(7,7)=.5*CF
LEN(7,8)=0.0
LEN(7,9)=0.0
LEN(7,10)=1.0

LEN(8,7)=.5*CF
LEN(8,8)=0.0
LEN(8,9)=0.0
LEN(8,10)=1.0

LEN(9,7)=.5*CF
LEN(9,8)=0.0
LEN(9,9)=0.0
LEN(9,10)=1.0

LEN(10,7)=.5*CF
LEN(10,8)=0.0
LEN(10,9)=0.0
LEN(10,10)=1.0

LEN(6,6)=5.5*CF
LEN(6,7)=.5*CF
LEN(6,8)=5.5*CF
LEN(6,9)=0.0
LEN(6,10)=0.0

LEN(7,6)=5.5*CF
LEN(7,7)=.5*CF
LEN(7,8)=0.0
LEN(7,9)=0.0
LEN(7,10)=1.0

LEN(8,6)=5.5*CF
LEN(8,7)=.5*CF
LEN(8,8)=0.0
LEN(8,9)=0.0
LEN(8,10)=1.0

LEN(9,6)=5.5*CF
LEN(9,7)=.5*CF
LEN(9,8)=0.0
LEN(9,9)=0.0
LEN(9,10)=1.0

LEN(10,6)=5.5*CF
LEN(10,7)=.5*CF
LEN(10,8)=0.0
LEN(10,9)=0.0
LEN(10,10)=1.0

LEN(6,5)=5.5*CF
LEN(6,6)=5.5*CF
LEN(6,7)=5.5*CF
LEN(6,8)=0.0
LEN(6,9)=0.0
LEN(6,10)=0.0

LEN(7,5)=5.5*CF
LEN(7,6)=5.5*CF
LEN(7,7)=5.5*CF
LEN(7,8)=0.0
LEN(7,9)=0.0
LEN(7,10)=0.0

LEN(8,5)=5.5*CF
LEN(8,6)=5.5*CF
LEN(8,7)=5.5*CF
LEN(8,8)=0.0
LEN(8,9)=0.0
LEN(8,10)=0.0

LEN(9,5)=5.5*CF
LEN(9,6)=5.5*CF
LEN(9,7)=5.5*CF
LEN(9,8)=0.0
LEN(9,9)=0.0
LEN(9,10)=0.0

LEN(10,5)=5.5*CF
LEN(10,6)=5.5*CF
LEN(10,7)=5.5*CF
LEN(10,8)=0.0
LEN(10,9)=0.0
LEN(10,10)=0.0
LEN(10,3)=.375*CF  
LEN(10,4)=.0    
LEN(10,5)=7.25*CF  
LEN(10,6)=7.25*CF  
LEN(10,7)=.5*CF    
LEN(10,8)=.0     
LEN(10,9)=.0     
LEN(10,10)=1.0

LEN(10,3)=.375*CF  
LEN(10,4)=.0    
LEN(10,5)=7.25*CF  
LEN(10,6)=7.25*CF  
LEN(10,7)=.5*CF    
LEN(10,8)=.0     
LEN(10,9)=.0     
LEN(10,10)=1.0

PENDENT-SPECIFIC HEAT PRODUCT OF WALL ELEMENTS
UNITS ARE KILOJOULES PER METER CUBED PER DEGREE CELCIUS
CF=1/.062428/2.3886*10000/1000
FROM: BTU/FT**3/F  
TO: KJ/M**3/C

WALL 1 (INTERIOR WALL)
DSSPT(1,1)=0.0
DSSPT(1,2)=50*.26*CF  
DSSPT(1,3)=0.0     
DSSPT(1,4)=0.0     
DSSPT(1,5)=32*.33*CF  
DSSPT(1,6)=.5*.23*CF  
DSSPT(1,7)=50*.26*CF  
DSSPT(1,8)=.0     
DSSPT(1,9)=.0     
DSSPT(1,10)=.0

WALL 2 (BULKHEAD)
DSSPT(2,1)=0.0
DSSPT(2,2)=300     
DSSPT(2,3)=40*.29*CF  
DSSPT(2,4)=34*.29*CF  
DSSPT(2,5)=32*.33*CF  
DSSPT(2,6)=.5*.23*CF  
DSSPT(2,7)=50*.26*CF  
DSSPT(2,8)=.0     
DSSPT(2,9)=.0     
DSSPT(2,10)=.0

WALL 3 (CARPET FLOOR)
DSSPT(3,1)=0.0
DSSPT(3,2)=34*.29*CF  
DSSPT(3,3)=0.0     
DSSPT(3,4)=0.0     
DSSPT(3,5)=32*.33*CF  
DSSPT(3,6)=.5*.23*CF  
DSSPT(3,7)=34*.29*CF  
DSSPT(3,8)=40*.29*CF  
DSSPT(3,9)=300     
DSSPT(3,10)=0.0

WALL 4 (TILED FLOOR)
DSSPT(4,1)=0.0
DSSPT(4,2)=34*.29*CF  
DSSPT(4,3)=0.0     
DSSPT(4,4)=0.0     
DSSPT(4,5)=32*.33*CF  
DSSPT(4,6)=.5*.23*CF  
DSSPT(4,7)=34*.29*CF  
DSSPT(4,8)=40*.29*CF  
DSSPT(4,9)=91*.19*CF
DSSPT(4,10)=0.0

WALL 5 (NORTH OUTSIDE WALL)
DSSPT(5,1)=0.0
DSSPT(5,2)=116*.22*CF  
DSSPT(5,3)=34*.29*CF  
DSSPT(5,4)=0.0     
DSSPT(5,5)=32*.33*CF  
DSSPT(5,6)=.5*.23*CF  
DSSPT(5,7)=50*.26*CF  
DSSPT(5,8)=.0     
DSSPT(5,9)=.0     
DSSPT(5,10)=.0

WALL 6 (WEST OUTSIDE WALL)
DSSPT(6,1)=0.0
DSSPT(6,2)=116*.22*CF  
DSSPT(6,3)=34*.29*CF  
DSSPT(6,4)=0.0     
DSSPT(6,5)=32*.33*CF  
DSSPT(6,6)=.5*.23*CF  
DSSPT(6,7)=50*.26*CF  
DSSPT(6,8)=.0     
DSSPT(6,9)=.0     
DSSPT(6,10)=.0

DSSPT(3,1)=0.0
DSSPT(3,2)=34*.29*CF  
DSSPT(3,3)=0.0     
DSSPT(3,4)=0.0     
DSSPT(3,5)=32*.33*CF  
DSSPT(3,6)=.5*.23*CF  
DSSPT(3,7)=34*.29*CF  
DSSPT(3,8)=40*.29*CF  
DSSPT(3,9)=300     
DSSPT(3,10)=0.0
DSSPT(6,9)=0.0 !DUMMY DENSITY-SPEC. HT
DSSPT(6,10)=0.0 !DUMMY DENSITY-SPEC. HT

WALL 7 (SOUTH OUTSIDE WALL)
DSSPT(7,1)=0.0 !DUMMY DENSITY-SPEC. HT
DSSPT(7,2)=116+.22*CF !DENSITY-SPEC. HT OF STUCCO
DSSPT(7,3)=34+.29*CF !DENSITY-SPEC. HT OF PLYWOOD
DSSPT(7,4)=0.0 !DUMMY DENSITY-SPEC. HT
DSSPT(7,5)=32+.33*CF !DENSITY-SPEC. HT OF STUDDING
DSSPT(7,6)=.5+.23*CF !DENSITY-SPEC. HT OF INSULATION
DSSPT(7,7)=50+.26*CF !DENSITY-SPEC. HT OF GYPSUM BOARD
DSSPT(7,8)=0.0 !DUMMY DENSITY-SPEC. HT
DSSPT(7,9)=0.0 !DUMMY DENSITY-SPEC. HT
DSSPT(7,10)=0.0 !DUMMY DENSITY-SPEC. HT

WALL 8 (EAST OUTSIDE WALL)
DSSPT(8,1)=0.0 !DUMMY DENSITY-SPEC. HT
DSSPT(8,2)=116+.22*CF !DENSITY-SPEC. HT OF STUCCO
DSSPT(8,3)=34+.29*CF !DENSITY-SPEC. HT OF PLYWOOD
DSSPT(8,4)=0.0 !DUMMY DENSITY-SPEC. HT
DSSPT(8,5)=32+.33*CF !DENSITY-SPEC. HT OF STUDDING
DSSPT(8,6)=.5+.23*CF !DENSITY-SPEC. HT OF INSULATION
DSSPT(8,7)=50+.26*CF !DENSITY-SPEC. HT OF GYPSUM BOARD
DSSPT(8,8)=0.0 !DUMMY DENSITY-SPEC. HT
DSSPT(8,9)=0.0 !DUMMY DENSITY-SPEC. HT
DSSPT(8,10)=0.0 !DUMMY DENSITY-SPEC. HT

WALL 9 (NORTH CEILING)
DSSPT(9,1)=0.0 !DUMMY DENSITY-SPEC. HT
DSSPT(9,2)=32+.31*CF !DENSITY-SPEC. HT OF CEDAR SHAKES
DSSPT(9,3)=34+.29*CF !DENSITY-SPEC. HT OF PLYWOOD
DSSPT(9,4)=0.0 !DUMMY DENSITY-SPEC. HT
DSSPT(9,5)=32+.33*CF !DENSITY-SPEC. HT OF STUDDING
DSSPT(9,6)=.5+.23*CF !DENSITY-SPEC. HT OF INSULATION
DSSPT(9,7)=50+.26*CF !DENSITY-SPEC. HT OF GYPSUM BOARD
DSSPT(9,8)=0.0 !DUMMY DENSITY-SPEC. HT
DSSPT(9,9)=0.0 !DUMMY DENSITY-SPEC. HT
DSSPT(9,10)=0.0 !DUMMY DENSITY-SPEC. HT

WALL 10 (SOUTH CEILING)
DSSPT(10,1)=0.0 !DUMMY DENSITY-SPEC. HT
DSSPT(10,2)=32+.31*CF !DENSITY-SPEC. HT OF CEDAR SHAKES
DSSPT(10,3)=34+.29*CF !DENSITY-SPEC. HT OF PLYWOOD
DSSPT(10,4)=0.0 !DUMMY DENSITY-SPEC. HT
DSSPT(10,5)=32+.33*CF !DENSITY-SPEC. HT OF STUDDING
DSSPT(10,6)=.5+.23*CF !DENSITY-SPEC. HT OF INSULATION
DSSPT(10,7)=50+.26*CF !DENSITY-SPEC. HT OF GYPSUM BOARD
DSSPT(10,8)=0.0 !DUMMY DENSITY-SPEC. HT
DSSPT(10,9)=0.0 !DUMMY DENSITY-SPEC. HT
DSSPT(10,10)=0.0 !DENSITY-SPEC. HT

* * *
AREA OF WALL ELEMENTS
* * *
UNITS ARE METERS SQUARED
* * *

WALL 1 (INTERIOR WALL)

TOTA=20.016
NETAREA=TOTA-MISCUA(1,2)-MISCUA(2,2)

DO 100 I=1,10
   AREA(1,I)=NETAREA
   IF (I.EQ.5) AREA(1,I)=NETAREA*.20
   IF (I.EQ.6) AREA(1,I)=NETAREA*.80
100 CONTINUE

WALL 2 (BULKHEAD)

NETAREA=6.012

DO 110 I=1,10
   AREA(2,I)=NETAREA
   IF (I.EQ.5) AREA(2,I)=NETAREA*.20
   IF (I.EQ.6) AREA(2,I)=NETAREA*.80
110 CONTINUE

WALL 3 (CARPET FLOOR)

NETAREA=17.027

DO 120 I=1,10
   AREA(3,I)=NETAREA
   IF (I.EQ.5) AREA(3,I)=NETAREA*.20
   IF (I.EQ.6) AREA(3,I)=NETAREA*.80
120 CONTINUE

WALL 4 (TILED FLOOR)

NETAREA=9.763

DO 130 I=1,10
   AREA(4,I)=NETAREA
IF (I.EQ.5) AREA(4,I)=NETAREA*.20
IF (I.EQ.5) AREA(4,I)=NETAREA*.80
CONTINUE

WALL 5 (NORTH OUTSIDE WALL)

NETAREA=6.148
DO 140 I=1,10
    AREA(5,I)=NETAREA
    IF (I.EQ.5) AREA(5,I)=NETAREA*.20
    IF (I.EQ.6) AREA(5,I)=NETAREA*.80
CONTINUE

WALL 6 (WEST OUTSIDE WALL)

TOTAREA=10.6611
NETAREA=TOTAREA-MISCUA(5,2)
DO 150 I=1,10
    AREA(6,I)=NETAREA
    IF (I.EQ.5) AREA(6,I)=NETAREA*.20
    IF (I.EQ.6) AREA(6,I)=NETAREA*.80
CONTINUE

WALL 7 (SOUTH OUTSIDE WALL)

TOTAREA=18.0075
NETAREA=TOTAREA-MISCUA(6,2)
DO 160 I=1,10
    AREA(7,I)=NETAREA
    IF (I.EQ.5) AREA(7,I)=NETAREA*.20
    IF (I.EQ.6) AREA(7,I)=NETAREA*.80
CONTINUE

WALL 8 (EAST OUTSIDE WALL)

TOTAREA=8.176
NETAREA=TOTAREA-MISCUA(4,2)-MISCUA(7,2)
DO 170 I=1,10
    AREA(8,I)=NETAREA
    IF (I.EQ.5) AREA(8,I)=NETAREA*.20
    IF (I.EQ.6) AREA(8,I)=NETAREA*.80
CONTINUE

WALL 9 (NORTH CEILING)

NETAREA=2.434
DO 180 I=1,10
    AREA(9,I)=NETAREA

CONTINUE

WALL 10 (SOUTH CEILING)

TOTAREA=19.735
NETAREA=TOTAREA-MISCUA(9,2)
DO 190 I=1,10
    AREA(10,I)=NETAREA
    IF (I.EQ.5) AREA(10,I)=NETAREA*.10
    IF (I.EQ.6) AREA(10,I)=NETAREA*.90
CONTINUE

RETURN
END
B.29. Program Listing of SURFCOND.FOR

*************************************************************************
* THIS SUBROUTINE DETERMINES THE SURFACE CONDUCTANCES OF THE        *
* VARIOUS SURFACES IN THE SUNSPACE MODEL. THE EQUATIONS FOR THE       *
* SURFACE CONDUCTANCES WERE DEVELOPED FROM FIGURE 1, PG 23.2 IN       *
* 1981 FUNDAMENTALS HDBK                                            *
*************************************************************************

REAL COND(10,10) !CONDUCTIVITY MATRIX

REAL VINT  !AIR VELOCITY OF INTERIOR SURFACES
REAL VSUN  !AIR VELOCITY OF SUNSPACE SURFACES
REAL VEXT  !AIR VELOCITY OF EXTERIOR SURFACES

ASSUMED AIR VELOCITIES !UNITS ARE MILES PER HOUR

VINT=0.0
VSUN=0.0
VEXT=VEXT/1.60934

*************************************************************************
* WALL 1 (INTERIOR WALL)                                               *
COND(1,1)=1.395*VINT+10.221 !SMOOTH PLASTER
COND(1,10)=1.395*VSUN+10.221 !SMOOTH PLASTER

*************************************************************************
* WALL 2 (BULKHEAD)                                                    *
COND(2,1)=2.009*VINT+11.357 !CARPET (BRK & RGH PLASTER)
COND(2,10)=1.395*VSUN+10.221 !SMOOTH PLASTER

*************************************************************************
* WALL 3 (CARPET FLOOR)                                                 *
COND(3,1)=1.609*VINT+8.517 !PLYWOOD (CLEAR PINE)
COND(3,10)=2.009*VSUN+11.357 !CARPET (BRK & RGH PLASTER)

*************************************************************************
* WALL 4 (TILED FLOOR)                                                  *
COND(4,1)=1.609*VINT+8.517 !PLYWOOD (CLEAR PINE)
COND(4,10)=1.835*VSUN+11.357 !TILE (CONCRETE)
* WALL 5 (NORTH OUTSIDE WALL)
* COND(5,1)=2.650*VEXT+11.357 !STUCCO
COND(5,10)=1.395*VSUN+10.221 !SMOOTH PLASTER
* WALL 6 (WEST OUTSIDE WALL)
* COND(6,1)=2.650*VEXT+11.357 !STUCCO
COND(6,10)=1.395*VSUN+10.221 !SMOOTH PLASTER
* WALL 7 (SOUTH OUTSIDE WALL)
* COND(7,1)=2.650*VEXT+11.357 !STUCCO
COND(7,10)=1.395*VSUN+10.221 !SMOOTH PLASTER
* WALL 8 (EAST OUTSIDE WALL)
* COND(8,1)=2.650*VEXT+11.357 !STUCCO
COND(8,10)=1.395*VSUN+10.221 !SMOOTH PLASTER
* WALL 9 (NORTH CEILING)
* COND(9,1)=2.009*VEXT+11.357 !SHINGLES (BRK & RGH PLASTER)
COND(9,10)=1.395*VSUN+10.221 !SMOOTH PLASTER
* WALL 10 (SOUTH CEILING)
* COND(10,1)=2.009*VEXT+11.357 !SHINGLES (BRK & RGH PLASTER)
COND(10,10)=1.395*VSUN+10.221 !SMOOTH PLASTER

************************************************************************
* RETURN
END
************************************************************************
REFERENCES


