ENVIRONMENTAL INFLUENCES IN THE SIMULATION OF A SOLAR SPACE HEAT-ETC

D M BROOKS

1980

AFIT-CI-80-20T

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Environmental Influences in the Simulation of a Solar Space Heating System.

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ABSTRACT (Continue on reverse side if necessary and identify by block number)
The objective of this thesis was to determine whether hourly departures in building heat loss given by a simplified degree day approach has a significant effect on the selection of an optimum collector size for the solar system. A numerical model was to do simulation studies. Using the results from this simulation an optimum collector size was determined from the energy requirements given by each model and a comparison made between the simulations and the degree day approaches.
THE UNIVERSITY OF OKLAHOMA

GRADUATE COLLEGE

ENVIRONMENTAL INFLUENCES IN THE SIMULATION

OF A SOLAR SPACE HEATING SYSTEM

A THESIS

SUBMITTED TO THE GRADUATE FACULTY

in partial fulfillment of the requirements for the

degree of

MASTER OF SCIENCE

by

DOUGLAS M. BROOKS

NORMAN, OKLAHOMA

1980
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ACKNOWLEDGEMENTS

I would like to express my gratitude to Professor Claude E. Duchon, who suggested the topic for this research, for his guidance, assistance, and encouragement throughout the course of this study.

I also wish to thank Professor Amos Eddy and Professor D. Barton Turkington for serving on my graduate committee and for their many helpful suggestions and comments, and to Dr. James S. Goerss, whose help with programming problems was invaluable.

Finally, I wish to sincerely thank my wife, Michela, and daughters, Barbara and Patricia, for their patience and understanding during the period I have worked on this thesis.
# Table of Contents

**LIST OF TABLES** .......................................................... v

**LIST OF FIGURES** .......................................................... vi

Chapter

I. INTRODUCTION ................................................................. 1

II. SOLAR RADIATION AND METEOROLOGICAL DATA. ......................... 4

III. HOUSE MODELS ............................................................... 7

IV. BUILDING HEAT LOSS MODELS. ........................................... 10

V. SOLAR COLLECTOR AND STORAGE MODELS ................................. 25

VI. COST OPTIMIZATION OF COLLECTOR AREA. ............................... 34

VII. RESULTS, CONCLUSIONS, AND RECOMMENDATIONS. ...................... 42

REFERENCES ................................................................. 59

APPENDIX A, HOUSE DESIGN AND INSULATION CHARACTERISTICS......... 62

APPENDIX B, SUMMARY OF SIMULATION RESULTS. ............................ 66

APPENDIX C, COMPUTER PROGRAM LISTING .................................. 94
LIST OF TABLES

<table>
<thead>
<tr>
<th>TABLE</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Capital Cost of Insulation.</td>
<td>38</td>
</tr>
<tr>
<td>2. Example of Simulation Results</td>
<td>43</td>
</tr>
<tr>
<td>B-1 to B-27. Summary of Simulation Results</td>
<td>67-93</td>
</tr>
</tbody>
</table>
## LIST OF FIGURES

<table>
<thead>
<tr>
<th>FIGURE</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Illustration of House Model</td>
<td>8</td>
</tr>
<tr>
<td>2. Transmissivity of 1, 2, and 3 Glazings.</td>
<td>20</td>
</tr>
<tr>
<td>3. Solar Collector Cross Section</td>
<td>26</td>
</tr>
<tr>
<td>4. Solar System Schematic.</td>
<td>31</td>
</tr>
<tr>
<td>5. Contributions to Annual Energy Cost</td>
<td>40</td>
</tr>
<tr>
<td>6. House Size I Annual Energy Cost</td>
<td>46</td>
</tr>
<tr>
<td>7. House Size II Annual Energy Cost</td>
<td>47</td>
</tr>
<tr>
<td>8. House Size III Annual Energy Cost</td>
<td>48</td>
</tr>
<tr>
<td>9. Daily Average Temperature, Wind Speed, and Cloud Cover.</td>
<td>49</td>
</tr>
<tr>
<td>10. Daily Average Heat Loss and Required Auxiliary Energy</td>
<td>50</td>
</tr>
<tr>
<td>11. Daily Average Storage Temperature</td>
<td>51</td>
</tr>
<tr>
<td>12. Hourly Temperature, Wind Speed, Cloud Cover</td>
<td>53</td>
</tr>
<tr>
<td>13. Hourly Heat Loss and Auxiliary Energy</td>
<td>54</td>
</tr>
<tr>
<td>14. Hourly Storage Temperature.</td>
<td>55</td>
</tr>
<tr>
<td>15. Hourly Collector Performance.</td>
<td>56</td>
</tr>
</tbody>
</table>
ENVIRONMENTAL INFLUENCES IN THE SIMULATION
OF A SOLAR SPACE HEATING SYSTEM

CHAPTER I

INTRODUCTION

Background

After about 35 years of limited development, solar energy has recently become a viable and economically attractive energy supplement, capable of reducing our reliance on increasingly scarce fossil fuel. Complete systems are now being sold and installed that have a storage medium with the capability to provide from one to three days space heating requirements.

Such systems involve a mix of both solar and conventional heating systems, since a solar system which provides all of the building heat demands is normally neither economically nor architecturally attractive. Given the short term storage and the unpredictable nature of the solar input, the size of the conventional system in this combination must be sufficient to provide all of the energy demands of the building under the most adverse conditions expected. The size of the solar system, on the other hand, is determined primarily by the marginal cost of the collector/storage system in comparison with the cost of the conventional fuel saved.
The amount of fuel saved is, in turn, a function of the performance characteristics of the solar system and the heat loss characteristics of the building. In many studies published in recent years, the optimum collector size, in an economic sense, has been determined from numerical simulation of hourly collector performance and building heat demand over a representative period. The usual method of modeling building heat loss in these studies has taken into account temperature effects only. A value for the building heat loss per hour per unit temperature difference is determined using the procedures outlined in the ASHRAE Handbook of Fundamentals [2] for the building construction characteristics and climatological design parameters at the location under study. It is this value and the hourly values of air temperature which then determine the building heat loss in the simulation. In actuality, these hourly values of building heat loss will vary not only with changes in air temperature, but with the wind through its effects on convective losses and air infiltration into the structure, and with solar radiation effects on the exterior of the structure.

**Objective**

Modeling building heat loss as a function of temperature only, in effect the degree day method, has been shown [20] to be reasonably accurate over a long period of time, but does not necessarily accurately simulate the short term nature of building heat loss. The objective of this study is to determine whether these hourly departures in building heat loss from the values given by a simplified
degree day approach have a significant effect on the selection of an optimum collector size for the solar system. In order to pursue the objective, a numerical model was developed which simultaneously simulates the hourly interactions between the solar system, the house, and the surrounding environment, using both the simplified model and an expanded parameter model which includes the effects of air movement over the structure and the influence of radiation on the structure itself. Using the results from this simulation an optimum collector size was determined from the energy requirements given by each model and a comparison made between the two approaches.
CHAPTER II

SOLAR RADIATION AND METEOROLOGICAL DATA

The model developed for this study is designed to use a SOLMET [24] data tape for the input values of solar radiation and meteorological parameters. These data tapes, obtained from the National Climatic Center, contain hourly solar radiation data and meteorological observations.

The radiation values on these tapes are of two types. At stations with solar observation facilities, they are the observed values corrected for known instrumentation errors [24]. For those stations without solar observations, radiation values were modeled through a regression procedure based on local meteorological conditions and radiation values at the nearest station with observed values [24]. These regression modeled values were originally reported to be accurate within a standard error of +/- 1.7% per month when compared with observed values [24]. However, these values have recently been questioned by Hoyt [11] who reports the monthly errors may be as large as 7% at some stations. The SOLMET values are still apparently the most accurate estimate of hourly solar radiation, particularly when compared with the frequently used ASHRAE clear sky values which Felske [7] reports give large overestimates of available solar energy.
The SOLMET tapes with regression modeled solar data have values only for global radiation on a horizontal surface. These values must be separated into direct and diffuse components for solar system performance calculations and this separation was accomplished using the method developed by Liu and Jordan [14] and modified by Hunn [12] for computer analysis. In this method, Liu and Jordan's attenuation index, KT, is taken to be

\[ KT = A \times (1 - 0.1 \times CC) \]

where A is the transmissivity and CC the total opaque cloud cover in tenths. The diffuse component is separated from the global horizontal value through a correlation of Liu and Jordan's value for the ratio of diffuse to horizontal radiation, D/H, with the attenuation index, KT, by assuming this ratio can be applied to the hourly SOLMET values:

\[ \frac{(D/H)}{=1-1.3575 \times KT} \]

\[ RHDU = (D/H) \times RHT \]

where RHDU is the diffuse component and RHT the global horizontal radiation. The horizontal direct value is then obtained by subtracting the diffuse from the global and a direct normal value calculated from this value and the solar altitude:

\[ RD = RHT - RHDU \]

\[ RDN = RD \div \sin(\alpha) \]

where RD is the horizontal direct value, RDN the direct normal value, and alpha the solar altitude.

Those SOLMET stations which have corrected observed values also have values of direct normal radiation on the tape [24]. The
computer model developed for this study is designed to take either
type tape as input, and, depending upon an input flag, use either the
given direct normal value or one calculated as indicated above. The
other parameters from the SOLMET tapes used in this study are the
year, month, day, solar time, temperature, wind speed and direction,
and total opaque cloud cover.

The SOLMET data tape for Oklahoma City, with 13 years (1952-
1964) of hourly radiation and hourly meteorological data was used for
this study. To reduce the computer time necessary for the simulation,
the 13 year data set was used to produce an average year which consist-
ed of the 13 year average hourly value for each parameter for each of
the 8760 hours in a 365 day year. The average year values were trans-
ferred to disk storage for more ready accessibility and served as the
data set for all computer simulations. Beckman, et al. [3] have shown
that the use of an average year in the simulation of solar system
operation closely approximates the results obtained by using the full
data set and averaging the results, thus providing an accurate esti-
mate of long term performance.
CHAPTER III

HOUSE MODELS

Construction Characteristics

The houses considered in this study were modeled as single story residences with an unventilated attic beneath a peaked roof, and a full basement, as illustrated in Figure 1, in which the solar system storage vessel and conventional heating system were placed. The floor space for the three different house sizes considered, denoted as size I, II, and III, is 93 square meters, 135 square meters, and 180 square meters. Each house faces south and is taken to be a rectangular structure with width to length ratio of about 1:1.5 as suggested by Olgay [21] for optimum winter thermal performance in temperate to cool climates. The solar collector array is taken as an integral part of the south facing roof and has a slope from the horizontal of latitude plus 15 degrees, the value reported by Liu and Jordan [14] to be optimum for solar space heating. Since the model is designed to run for different locations and many collector areas, the remaining dimensions of the roof, such as the slope and area of the north roof, the area of the attic walls, and the height of the peak, are calculated in the program when the collector tilt and area of collector to be integrated into the roof are specified. Each house
Figure 1. Illustration of house model.
has a total window area of approximately 10% of the house wall area, and following Olgay [21], the distribution is weighted in favor of southern exposure for maximum solar gain in winter. The window area distribution is set at 60% of total window area on the south wall, 10% on the east and west walls, and 20% on the north wall. Each house has two entrances, one on the north side and one on the south side of the structure. The dimensions for each house size are given in Table A-1 of Appendix A.

**Insulation**

For each house size in the model, three different insulation and weatherstripping levels were considered, corresponding to poorly insulated, moderately insulated, and well insulated houses, and denoted as types I, II, and III. Type I consists of minimum wall and ceiling insulation, single pane windows with aluminum sash, no storm windows or doors, and minimum weatherstripping. Type II has moderate wall and ceiling insulation, double pane windows with wood sash, storm doors, and moderate weatherstripping. Type III has heavy wall and ceiling insulation, double pane windows with wood storm sash, insulated doors and storm doors, and is tightly weatherstripped. The construction characteristics and heat transmission coefficients (U-values) for each component of the three insulation levels are given for each type in Tables A-2 and A-3 of Appendix A.
CHAPTER IV

BUILDING HEAT LOSS MODELS

Introduction

Calculation of the energy requirements for the heating of a building may be carried out at a very simple level to provide approximate results or at increasingly more complex levels for more refined determination of system performance.

At the lower end of the scale is the heat loss per unit temperature difference method, as outlined in the ASHRAE Handbook of Fundamentals [2]. This method is based upon the assumption of steady state heat transfer through the building fabric as a function of inside to outside temperature difference. In this simplified model, denoted in this study as Model I, an overall building heat loss coefficient calculated using the methods outlined in the ASHRAE Handbook provides the basis for determination of energy requirements for space heating. This simplified method is the one most frequently used in engineering calculations and has served as the model for building heat loss in many studies of solar energy for space heating, for example the widely quoted study by Løf and Tybout [15].

At the upper end of the scale is the numerical simulation of building heat loss by the rigorous method of simultaneous solution
of the non-steady state balance equations for each hour for each component of the structure. This approach is presented in reference 20, which outlines the National Bureau of Standards' computer program for heating and cooling loads, a sophisticated model primarily used to perform design studies of heating and cooling systems for large structures. The degree of complexity of this approach is, however, very time consuming and a model at an intermediate level was developed for this study. Denoted here as Model II, it takes into account wind and solar radiation effects on the building, as well as temperature differences, and will be used to determine if these influences are important considerations in the simulation of a solar space heating system.

**Model I**

The heat loss from a house consists of the energy lost by transmission through the walls, basement, ceiling, and other exposed surfaces and by energy carried away by exfiltrating air. The determination of an overall building heat transmission coefficient, the heating load imposed by infiltrating air, and the combination of the two effects into an overall coefficient of heat loss per unit temperature difference are presented below.

**Transmission Heat Loss**

Transmission heat loss through a given building surface, under the assumption of steady state conditions, may be determined using the procedures outlined in the ASHRAE Handbook of Fundamentals [2]. Using a heat transmission coefficient (U-value) for the construction characteristics of the surface, the total heat transmission
through the surface is

\[ Q = U A (t_i - t_o) \]  \hspace{1cm} (1)

- \( Q \) = heat transfer rate, kJ/h
- \( t_i, t_o \) = temperature at inside/outside surface, C
- \( A \) = total area of the surface, sq m
- \( U \) = heat transmission coefficient, kJ/(sq m-h-K)

The heat transmission coefficient can be expressed as

\[ U = \frac{1}{R} \]

- \( R \) = thermal resistance of the \( i \)th element in the composite structure, given by
  \[ R = x/k \]
  - \( x \) = thickness of the element, m
  - \( k \) = thermal conductivity of the element, kJ/(sq m-h-C)
- \( R = 1/C \)
  - \( C \) = thermal conductance
  - \( R = 1/h_i, 1/h_o \)
  - \( h_i, h_o \) = at the inside and outside surfaces, and
  - \( h \) = the surface film conductance.

The surface film conductance, which accounts for convective and radiative losses at the surface, is determined experimentally for a given surface and can be expressed as

\[ h = h_c + h_r \]

The term \( h_c \) is an experimentally determined convective heat transfer coefficient and \( h_r \) is a radiative transfer coefficient between the surface and its surroundings, given by

\[ h_r = \sigma F_a F_b (T_1^4 - T_2^4)/(T_1 - T_2) \]

- \( \sigma \) = Stefan Boltzman constant
- \( F_a \) = dimensionless factor to account for the shape and orientation of the surface to its surroundings
Fb = dimensionless factor which accounts for the emission and absorption characteristics of the surface and its surroundings.

T1, T2 = temperature of surface and surroundings, K

The radiation coefficient, hr, is about 1/5 the magnitude of the convective component of the surface film conductance and varies little [6] over the range of temperatures of interest, having only a 2% change with a 10 degree C change in temperature. A constant value of 14 kJ per sq m per hr per degree C [2] was used for this parameter in this study.

For a surface of given construction and thickness, the heat transmission coefficient, U, may be calculated for steady state conditions if the thermal conductivities, thicknesses, and surface resistances are known. The ASHRAE Handbook contains extensive tables of resistances, conductivities, and transmission coefficients for most building construction materials, determined from a vast amount of experimental and theoretical work. These tables were used to determine the U-values for the building components considered in this study.

Using the U-values determined from the ASHRAE tables, the total transmission heat loss through the building fabric per unit time may be expressed as

\[ Q_t = (t_i - t_o)\left( U_g A_g + U_d A_d + U_w A_w + U_c A_c \right) + (t_i - t_g)U_b P \]  \hspace{1cm} (2)

where U and A refer to the heat transmission coefficients and surface areas, P is the perimeter of the house, and the subscripts g, d, w, c, b refer to window glass, exterior doors, exterior walls, ceiling, and basement, respectively. U_b is an effective heat transmission coefficient per unit length for the basement walls and floor, determined as
outlined in the ASHRAE Handbook for below grade basements, and the value for $U_c$ is an overall coefficient of heat transfer for the combined ceiling and roof. The temperatures $t_i$, $t_o$, and $t_g$ are the inside temperature, outside air temperature, and the ground temperature at basement depth. If the expression is divided by ($t_i-t_o$), a value for the transmission loss per hour per unit temperature difference can be expressed as

$$\frac{Q_t}{t_i-t_o} = UgAg + UwAw + UdAd + UcAc + \frac{t_i-t_g}{t_i-t_o} UbP \quad (3)$$

As suggested in reference 5, the ratio ($t_i-t_g$)/($t_i-t_o$) is denoted by $K_b$ and assumed constant, so that (3) becomes

$$\frac{Q_t}{t_i-t_o} = UgAg + UwAw + UdAd + UcAc + K_b UbP \quad (4)$$

### Infiltration Heat Loss

The heat load due to infiltrating air can be determined using the air change method outlined in the ASHRAE Handbook as

$$Q_i = \rho*C_{pa}*Vol*I*(T_i-T_o) \quad (5)$$

$\rho$ = density of infiltrating air

$C_{pa}$ = specific heat of air, kJ/(kg-C)

$Vol$ = building volume, meters cubed

$I$ = number of building air changes per hour

$t_i$, $t_o$ = inside and outside air temperatures, C

The air change rate is a function of the density difference between the inside and outside air due to temperature effects (stack effect) and the static pressure effect of wind velocity on the structure. At present there is no analytical procedure for calculating the exact air infiltration into a building, though numerous studies have been
directed at this problem. Peterson [23] has reviewed the results of 20 years of research and produced an expression for the number of air changes per hour in residential structures from wind and stack effects for different levels of weatherstripping and building construction. The expression is

\[ I = A + B \times (t_i - t_o) + C \times V \]  

(6)

where \( I \) is the number of air changes per hour, \( (t_i - t_o) \) the temperature difference, \( V \) the wind velocity, and \( A \), \( B \), and \( C \) are empirically determined constants for the level of weatherstripping and building tightness. Peterson's expression was used here for determining the air change rate and values of the constants for each of the three house types are given in Table A-4 in Appendix A. A value for the number of air changes per hour for Model I is calculated in the computer program for the building type specified from the design wind velocity from the ASHRAE Handbook and the average daily winter temperature, both of which are input parameters. The air change rate varies from about 0.4 for a tightly constructed house (Type III) to 1 for a loosely constructed house (Type I). With the air change rate thus specified, the infiltration heat loss can be expressed as a loss per unit temperature difference as

\[ \frac{Q_i}{(t_i - t_o)} = \rho C_p a V_0 l I \]  

(7)

Building Heat Loss Coefficient

The heat losses through transmission and infiltration can be combined to give an overall building heat loss per hour per unit temperature difference as
The hourly building heat loss is then

$$HL = (Qt + Qi)/(ti-to)$$

where $QLOAD$ is the total heat loss in kilojoules. Following the usual practice [26], a reference temperature (18°C) less than the inside air temperature is used to account for the existence of heat sources not included in the model, such as solar heat gain through the windows.

This simplified model provides an approximation to the hourly heat loss for the building. The difficulty with this representation is that it incorrectly predicts the time distribution of the heating load. Gutierrez, et al. [9] found that changes in the time distribution of load produced variations of as much as 17% in required auxiliary energy in a study of the use of solar energy for hot water. The study considered only hot water requirements, and only for a one month period, and so did not address the long term effects or space heating.

The degree of departure of the Model I approximation from the heat loss given by a more complex model of space heating requirements will depend primarily upon the magnitude of the hourly differences in infiltration load from the constant rate assumed above, the effects of solar radiation on the building, and the variation of the surface film resistance with wind. These effects are considered in the second model of building heat loss used in this study.

**Model II**

In expanding the number of parameters in the building heat loss model the intent was to include, in addition to temperature, two
other major effects, wind and solar radiation, which act on the building. Steady state conditions for each hour of the simulation are still assumed, so that heat capacity effects are not included. The degree to which the inclusion of heat capacity effects would change the results is uncertain, though McQuiston and Parker [18] suggest they are significant only in structures of large thermal mass, which is not the case in this study.

Radiation Effects

The effects of radiation on the building were simulated by the replacement of outside air temperature with the sol-air temperature in computations of transmission heat loss. The sol-air temperature, first introduced by Mackey and Wright [17], is a fictitious temperature that in the absence of all radiative exchanges would produce the same rate of heat transfer at the exterior surface as actually occurs with solar radiation acting on the surface. It can be expressed as

\[ T_e = T_o + \frac{\alpha I}{\h_0} - \frac{\epsilon \Delta R}{\h_0} \]

where

\[ T_e = \text{sol-air temperature, K} \]
\[ T_o = \text{outside air temperature, K} \]
\[ I = \text{total radiation incident upon the surface, kJ/(sq m-h)} \]
\[ \alpha = \text{absorptivity of the surface, dimensionless} \]
\[ \epsilon = \text{emissivity of the surface, dimensionless} \]
\[ \h_0 = \text{surface film conductance, kJ/(sq m-h-K)} \]
\[ \Delta R = \text{difference between long wave radiation incident on the surface and radiation from a black body at } T_o, \text{ kJ/(sq m-h).} \]
The last term has been shown by McQuiston and Parker [18] to be negligible in comparison to the first two and in practice the expression is simplified to

\[ T_e = T_0 + \alpha I/h_0. \]

The solar temperature is thus dependent upon the absorptivity of the surface and its orientation relative to the sun, as well as the outside air temperature. A value of 0.7 was taken as representative of the absorptivity for the exterior building materials used in this study. The values for outside surface film conductance were those used in the computation of the overall heat transmission coefficient (U-value) for the surface under consideration. The solar radiation, I, incident upon the surface can be calculated [14] from

\[ I = RDN*\cos\theta + 0.5*RDU*(1+\cos\beta) + 0.5*RHT*\rho*(1-\cos\beta) \quad (8), \]

\[ \begin{align*} RDN &= \text{direct normal radiation,} \quad \text{kJ/sq m} \\ RDU &= \text{diffuse radiation,} \quad \text{kJ/sq m} \\ RHT &= \text{global horizontal radiation,} \quad \text{kJ/sq m} \\ \beta &= \text{tilt of the surface from the horizontal, deg} \\ \rho &= \text{surface reflectivity, dimensionless} \\ \theta &= \text{angle of incidence of direct radiation, deg.} \end{align*} \]

The angle of incidence on the surface is given by [3]

\[ \cos\theta = \sin\delta \sin\phi \cos\beta - \sin\delta \cos\phi \sin\beta \cos\gamma \]
\[ + \cos\delta \cos\phi \cos\beta \cos\omega + \cos\delta \sin\phi \sin\beta \cos\gamma \cos\omega \]
\[ + \cos\delta \sin\beta \sin\gamma \sin\omega \quad (9) \]

\[ \begin{align*} \delta &= 23.45*\sin[360*(284 + n)/360], \quad \text{deg} \\ n &= \text{day of the year} \\ \phi &= \text{latitude of the station, deg} \end{align*} \]
\[ \beta = \text{tilt angle from the horizontal, deg} \]
\[ \gamma = \text{surface azimuth angle, south = 0, east +, west - , deg} \]
\[ \omega = 2\pi*(\tau - 12)/24, \quad \text{the hour angle, deg} \]
\[ \tau = \text{solar time, h} \]

Using (9), (8), and (7) the angle of incidence, incident radiation, and sol-air temperature are calculated in the simulation each hour the sun is above the horizon. The transmission losses are then taken as a function of these sol-air temperatures instead of the outside air temperature.

Solar radiation also influences the hourly building heat balance by the solar heat gain through the windows. If a simplified model of solar heat gain, with the absorptivity of the glass assumed negligible, is used, the rate of heat entry from solar radiation through the window glass may be expressed [21] as

\[ \text{SHG} = \text{RDN} \times \text{TAUW} \times \cos(\theta) + 0.5 \times \text{RDU} \times \text{TAUD} \quad (10) \]

where \( \text{RDN} \), \( \text{RDU} \), and \( \theta \) are as described previously, and \( \text{TAUW} \) and \( \text{TAUD} \) are the transmissivities of the glass for direct and diffuse radiation. As suggested by Parmelee, et al. [22] for vertical windows, the transmissivity for diffuse radiation is taken as a constant value of 0.70 for single pane and 0.62 for double pane windows. The transmissivity for direct radiation was approximated here by a constant value for incidence angles less than 60 degrees and as a linearly decreasing function of incidence angle for angles greater than 60 degrees. Figure 2 depicts the transmissivity of one, two, and three glazings for direct radiation as given by Duffie and Beckman [6] (solid lines) and the approximations used in this study (dashed lines). For this model,
Figure 2. Transmissivity of 1, 2, and 3 glazings as given by Duffie and Beckman (solid lines) and approximations used (dashed lines).
the windows are assumed to have no setback from the building surface, and any effect from drapes or curtains on either the solar gain or transmission loss through the windows is neglected. In addition, the model assumes that window awnings which completely shade the windows are installed on June 1 and remain in place until September 1, so that only the diffuse component is considered during this period.

Wind Effects

The effect of variations in wind velocity on building heat loss is considered in Model II by including its influence on surface film conductance and on the infiltration rate. The convective component of the outside surface film conductance is calculated for each hour for each exposed surface as a function of wind speed and direction using an expression developed by Kimura and reported in reference 20. In this method, the air velocity close to the surface is

\[ VC = 0.25 \times V \] for \( V > 2 \) mps

\[ VC = 0.5 \] for \( V < 2 \) mps

for a relative wind direction less than 90 degrees, and

\[ VC = 0.3 + 0.05 \times V \]

for a relative wind direction greater than or equal to 90 degrees, where

\( V \) is the reported wind velocity, mps.

The relative wind is calculated from the azimuth angle of the building surface and the reported wind direction as

\[ RWD = \text{ABS}(WAZ - \text{DIR}) \] for \( RWD < 180 \) degrees

\[ RWD = 360 - RWD \] for \( RWD > 180 \) degrees,
where ABS indicates the absolute value, RWD is the relative wind direction, WAZ is the surface azimuth angle of the building surface (facing north = 0), and DIR is the reported wind direction in degrees. The convective component of the outside surface film conductance, $h_c$, is then calculated from

$$h_c = 67.049(VC^{0.605})$$

(12)

For each hour of the simulation, the surface film conductance is calculated from a convective component computed as outlined above and a constant value of 14 kJ/(sq m-h-K) for the radiation component [2]. The heat transmission coefficient ($U$-value) for each building surface exposed to the wind is calculated from this value of surface film conductance and the same values of thermal resistance for the interior construction used in Model I. The transmission heat losses for Model II for each exposed surface are then calculated as a function of these $U$-values and the sol-air temperature. Finally, infiltration losses for Model II differed from Model I in that an air change rate was calculated hourly as a function of wind and temperature from equation 6 and the infiltration heat loss calculated from equation 7.

Basement and Ceiling Transmission Losses

The transmission losses for the ceiling and basement for Model II also differ from Model I. The transmission loss through the ceiling was calculated as a function of attic temperature, calculated from the following expression given in the ASHRAE Handbook [2];

$$T_{attic} = \frac{(Ac*Uc*Tc+Ta*Ar*Tr+Ta*Aw*Uw)}{(Ac*Uc+Ar*Ur+Aw*Uw)}$$

(13)

where $A$ and $U$ refer to the areas and $U$-values and the subscripts $c$, $r$, $w$.
w refer to the ceiling, roof, and attic walls respectively. Tattic, Tc, and Ta are the attic, ceiling and outside air temperatures. As suggested in reference 2, the ceiling temperature was taken as 1 degree C higher than the reference room temperature (20 degrees C for Model II). The outside air temperature was replaced by the applicable roof or siding sol-air value. Basement transmission losses were calculated for Model II by the method outlined for Model I, except that a value of the ground temperature was calculated for each day by assuming it was a sinusoidal function of the day of the year. Values of 283 K for winter and 294 K for summer from reference 20 for average values at Lake Hefner, Oklahoma were used to determine the amplitude.

Domestic Hot Water Energy Requirements

Energy requirements for hot water for both models were calculated by assuming a requirement of 75 kg of hot water per occupant per day, evenly distributed between the hours of 6 a.m. and 9 p.m. The number of occupants was assumed to be 4, 5, and 6 for house sizes I, II, and III respectively. The required hot water temperature was set at 60 degrees C (140 degrees F) and the temperature of the feed water from the main assumed to be equal to the ground temperature. The energy required for hot water is then

\[
Q_{SHW} = \begin{cases} 
M_w \times C_{pw} (T_{hw} - T_g), & 6 < t < 21 \\
0, & \text{otherwise}
\end{cases} \tag{14}
\]

\(Q_{SHW}\) = hot water energy requirement, kJ/h

\(M_w\) = mass of water, kg/h

\(C_{pw}\) = specific heat of water, 4.189 kJ/(kg-K)
THW = hot water temperature, K
Tg = feed water temperature, K

Summary

This chapter has presented the models used for determining the building energy requirements for space and hot water heating. With Model I the hourly building heat requirements will vary only with temperature. With Model II the hourly heat requirements will vary with radiation and wind influences as well as temperature. The solar collector and storage models used in the hourly simulation of system performance will be discussed in Chapter V.
CHAPTER V

SOLAR COLLECTOR AND STORAGE MODELS

Collector Model

The solar collector modeled is a flat plate solar collector with basic components as illustrated in Figure 3. An absorbing plate is covered by one or more transparent cover plates to reduce convective heat losses and insulated to reduce transmission losses through the back. The absorbing plate, coated with a material having high absorptivity in the solar spectrum, heats up and in turn heats a fluid flowing through the tubes in the plate. The amount of energy collected is a function of the incident radiation, collector construction, the fluid temperature, and the surrounding environmental conditions.

In this study, the collector is a water heating flat plate collector with the following characteristics, taken from Duffie and Beckman's book on solar energy thermal processes [6]:

1. The absorbing plate is a copper tube-in-sheet plate with 10 cm spacing between tubes and a non-selective coating which has a constant absorptivity, independent of angle of incidence, of 0.95.

2. The glass covers (1, 2, and 3 covers are considered) are water white glass with a thickness of 0.3125 cm and an extinction coefficient of 0.04 per cm.

25
Figure 3. Solar collector cross section.
3. The absorbing plate has a plate-to-fluid heat transfer coefficient of 300 watts per sq meter per K.

Collector performance was modeled by the generalized flat plate performance equation proposed by Hottel and Whillier [10]. Duffie and Beckman [6] present a complete derivation of this expression, which relates the useful energy collected to the collector and environmental parameters as follows

\[ QU = AC \times FR \times (S - UL \times (TCI - TA)) \]  \hspace{1cm} (15)

- \( AC \) = collector area, sq m
- \( FR \) = heat removal factor, dimensionless
- \( S \) = radiation absorbed by the plate, kJ/(sq m-h)
- \( UL \) = collector loss coefficient, kJ/(sq m-h)
- \( TCI \) = inlet temperature of fluid, K
- \( TA \) = ambient air temperature, K.

The useful energy, \( QU \), is the energy collected by the heat transfer fluid in passing through the tubes in the collector plate. The radiation absorbed by the plate is a function of the incident radiation, the transmissivity of the glass covers, and the absorptivity of the plate. The incident radiation and the transmissivity were calculated as described in Chapter IV. The quantities \( FR \) and \( UL \) depend upon the construction characteristics of the collector, the heat transfer characteristics of the plate, the mass flow rate through the collector, and the number of collector covers. Values of \( UL \), the collector heat loss coefficient, for the collector characteristic previously listed, were taken from graphs in Duffie and Beckman's book [6] as

\[ UL = 7.2 \text{ kJ/(sq m-K)} \] for 3 covers
UL = 14.4 kJ/(sq m-K) for 2 covers
UL = 28.8 kJ/(sq m-K) for 1 cover

The effect of the heat removal factor, FR, in equation 15 is to reduce the calculated energy gain from the value given by assuming the fluid temperature throughout the collector to be at the inlet temperature to its actual value, given by a fluid temperature which increases as the fluid flows through the plate. It can be expressed [6] as

\[ FR = \left( FLO \times CP \times UL \right) \times \left( 1 - \exp\left( -UL \times F' \right) \right) \]

\[ F' = \text{collector efficiency factor, dimensionless} \]

As demonstrated by Duffie and Beckman [6], F' is primarily a function of the physical characteristics of the absorber plate and can be considered a constant. Values were taken from Duffie and Beckman's book for the collector characteristics considered here as

\[ F' = 0.96 \text{ for 1 cover} \]
\[ F' = 0.98 \text{ for 2 covers} \]
\[ F' = 0.99 \text{ for 3 covers} \]

Winn [24] reports that an optimum value for the mass flow rate per unit area of collector can be determined from

\[ FLO = \frac{F' \times F'' \times UL}{2 \times CP \times (F' - FR)} \]

Equations 16 and 17, with UL, CP, and F' are specified, form a set of equations in the two unknowns, FLO and FR, which is solved in the program using an iterative procedure for the optimal mass flow rate, FLO, and the heat removal factor, FR. With these parameters specified,
equation 15 can be used to determine the useful energy collected for each hour the solar system is operated.

The collectors modeled in this simulation were "operated" when the temperature of the absorbing plate was heated to a temperature ten degrees higher than the storage tank temperature (discussed below). As derived in reference 6, the temperature of the plate for any given hour can be expressed as

$$TP = TA + S/UL = [S/UL - (TPP - TA)] \cdot \exp(-UL/MCE)$$

where TP is the plate temperature for the current hour, TPP the plate temperature for the previous hour, S, UL, TA as previously indicated, and MCE is the effective heat capacity of the collector, calculated as outlined by Duffie and Beckman [6] for the 1, 2, and 3 cover collectors to be 6.6, 10.7, and 15.2 kJ/(sq m-K).

**Storage Model**

In this study water with a specific heat of 4.189 kJ/(kg-K) is used as both the heat transfer fluid and the storage medium. As shown in Løf and Tybout's [16] study on solar space heating, the optimum mass of storage is in the range of 50 to 75 kg per square meter of collector, with variations in this range having a relatively small effect on the cost of delivered energy or the fraction of heat load carried by the solar system. The mass of storage here is fixed at 61 kg of water per square meter of collector as suggested by Butz, et al. [4]. Beckman, et al. [3] show that modeling stratification effects in water storage produces results only 1 to 3% different from modeling an unstratified system, so the system modeled here uses an unstratified model for storage.
The storage vessel is a cylindrical water tank taken to have a height to diameter ratio of 3:1 and insulation with a heat transmission coefficient of 1.44 kJ/(sq m-hr-K) [6]. The size and surface area are determined in the program from the mass of storage water and the assumptions of a constant density of 1000 kg per cubic meter and the height to diameter ratio of 3:1. Thermal losses from storage are then determined from the area U-value product, the storage temperature, and the room temperature.

A schematic of the solar collector and storage system illustrating the mode of operation is presented in Figure 4. Energy is transferred from storage to incoming water from the main for hot water use by means of a heating coil located within the solar system storage tank, and from storage to the house by means of a water to air heat exchanger. The size and heat transfer characteristics of the heat exchanger are not specifically modeled, but it is assumed as suggested in reference 3, that the water and air flow rates are modulated so that the average rate of energy transfer across the load heat exchanger is equal to the average rate of energy required by the heating load. Thus the heat exchanger effects may be neglected.

For the system described above, an energy balance on the fully mixed storage tank is given by:

$$M \cdot C_{ps} \cdot \frac{dT_s}{dT} = QU - QL - Q_{SHW} - Q_{TL}$$

(18)

$M, C_{ps}$ = mass, specific heat of storage, kg, kJ/(kg-K)

$T_s$ = storage temperature, K

$t$ = time, h

$QU$ = rate of transfer of energy to storage, kJ/h
Figure 4. Solar system schematic.
QL = rate of transfer of energy to space heat load, kJ/h

QSHW = rate of transfer of energy to hot water load, kJ/h

QTL = rate of heat loss from storage, kJ/hr, given by

QTL = Us*As*(Ts-Tr)

Us, As = heat transfer coefficient and area of storage tank

Ts, Tr = storage tank and room temperatures, K

As indicated by Duffie and Beckman [6], equation 18 may be integrated in one hour time steps by Euler integration to determine the storage tank temperature at the end of the hour from the temperature at the beginning of the hour and the known energy inputs and outputs. The expression is solved hourly in the simulation for the storage temperature, which has an upper limit of 90 degrees C. When the useful energy collected raises the storage temperature above this maximum, the storage temperature is set equal to the maximum value and the amount of excess energy, which is assumed dumped to the atmosphere, tabulated.

The simulation thus assumes a controller which senses the storage temperature and halts the collector pump when the maximum temperature is reached. As indicated in reference 3, the minimum storage temperature at which the water to air heat exchanger is effective is on the order of 26-30 degrees C. A temperature of 29 degrees C was used here as the storage temperature below which delivery of energy from storage to the loads is halted and auxiliary energy used for both space and hot water. Thus, for space heating, either all or none of the energy requirements are met from storage in any given hour, based upon the calculated storage temperature for that hour. The solar system storage acts as a preheater for water from the mains when the storage
temperature is below the required hot water value of 60 degrees C. If the storage temperature is above 60 degrees, a control system and a mixing valve, not specifically modeled, are assumed to operate to mix water from the mains with water heated by the storage system to deliver 60 degree C water to the domestic hot water tank. Thus, for domestic hot water, auxiliary energy is used exclusively if the storage temperature is below the minimum storage temperature, is used to increase the domestic hot water temperature to the required value of 60 degrees if the storage temperature is above minimum but below 60 degrees, and is not required if the storage temperature is above 60 degrees.

With the known requirements for space heat and hot water, the solar energy input, and the simulation of the collector and storage system as outlined above, the annual requirements for auxiliary energy can be determined and used to find the most economic mix of conventional and solar energy. This economic optimization of the solar system size is discussed in the next chapter.
CHAPTER VI

COST OPTIMIZATION OF COLLECTOR AREA

Introduction

The preceding chapters have outlined the methods of modeling the thermal performance of the components used in the solar system simulation and have not dealt with questions of cost. However, the decision to incorporate solar energy for the heating of a residence and the selection of the size of the system, assuming the individual thinks rationally, is an economic one. This chapter will present the methodology used to determine the optimum size of the solar system from the results of the thermal performance simulation of the house and solar system.

As previously indicated in Chapter I, studies by Löf and Tybout [15, 16] have clearly shown that designing a solar system to provide 100% of the heating requirements for a conventionally constructed residence is not feasible. The size of the collector array and storage system required raise the cost far above the cost of conventional energy sources and produce architecturally undesirable consequences [1], such as the inability to incorporate the solar system into the construction of the residence. Consequently, a conventional system capable of meeting the worst case heating requirements of the
building must be part of the residence and its costs are required whether or not a solar system is included. The only savings then offered by solar energy, where it is of low enough cost, is in the reduction of the cost required for fuel for the conventional heating system. Thus, as demonstrated by Duffie, Beckman, and Klein in reference 3, the conventional system cost can be considered as a base cost common to both systems and the cost analysis carried out as a comparison of the costs above base.

In a similar manner, the cost of insulation was included in this study as a cost above base by assuming that a decision regarding the level of insulation is made concurrently with the decision regarding the solar system. Type II insulation, representing a moderately insulated house, is taken as the base level. The cost of increasing the insulation to Type III, or the savings from deciding to insulate only to the level of Type I are calculated and included in the cost analysis. In addition, it is assumed here that the solar system is well designed and has negligible maintenance and pumping costs.

Annual Energy Cost

The annual cost of energy with the mix of solar and conventional systems, under the assumptions listed above, may be expressed as:

\[ EUAC = (SOLCS + CSTI)I + CSTA \]  

\( EUAC \) = uniform annual cost of energy for space and hot water, dollars per year

\( SOLCS \) = total capital cost of solar system, dollars

\( CSTI \) = total capital cost of insulation, above or below base, dollars
I = capital recovery factor for assumed interest rate and time period, fraction per year

CSTA = uniform annual cost of auxiliary energy, where auxiliary energy refers to the energy provided by the conventional heating system.

Solar System Cost

The total capital cost of the solar system is the sum of the costs for the collector, piping, pumps, controls, and storage minus the tax incentive provided under current law for installation of a solar system. A cost of $100 per square meter for a two cover collector was taken as a base collector cost [18], with an additional cost or savings of $8.60 for a three cover and one cover collector, respectively. As indicated in the study by Butz, et al. [4], the cost of storage can be considered a linear function of collector area and their figure of $8/sq m for the cost of the storage vessel, water, and insulation was used here. The additional solar system costs for piping, pumps, and controls, as suggested in reference 3, were set at $375, independent of collector area. Current tax policy [25] provides that of the total cost of a solar installation, 30% of the first $2000 and 20% of the remaining cost, up to a maximum of $10000, are rebated to the purchaser as tax credit. Under these assumptions, the initial capital cost of the solar system is

\[
CCOST = (100 + 8.6*(N-2) + 8)*AC + 375
\]

where \(N\) is the number of collector covers and \(AC\) is the collector area. The tax savings is then
\[
\text{TAXSV} = \begin{cases} 
0.3 \times \text{CCOST} , & \text{CCOST} < 2000 \\
600 + 0.2 \times (\text{CCOST} - 2000) , & 2000 < \text{CCOST} < 10000 \\
2200 , & \text{CCOST} > 10000 
\end{cases}
\]

The final capital cost of the solar system is then

\[
\text{SOLCS} = \text{CCOST} - \text{TAXSV}
\]

Insulation Cost

As indicated previously, the cost of insulation, CSTI, was treated as a cost above or below the base cost of insulating the residence to insulation Type II. The cost of fibrous insulation used for the wall and ceiling insulation in the residences considered here was taken from the February 1980 ASHRAE Journal [13] as $0.08 per sq ft (0.0929 sq m) for the first inch (2.54 cm) and $0.05 per sq ft for each additional inch of insulation. These costs, the total wall and ceiling area, and the difference in insulation thickness from Type II insulation were then used to calculate the total cost or savings above or below base for each insulation type for each house size considered. Table 1 summarizes the results obtained. The capital recovery factor, I, used to convert the total capital costs to a uniform annual cost was 0.11746 [8] for the assumed 20 year amortization period at an interest rate of 10%.

Auxiliary Energy Cost

The cost of auxiliary energy is determined from the amount of auxiliary energy required and the unit cost of the fuel used. An initial cost of $6 per million kJ, at the upper range of values considered by Butz, et al. in their 1974 study, was used. It was not,
Table 1. Capital cost of insulation above or below insulation Type II. Negative values are savings, positive values increased cost.
however, held constant over the 20 year period considered in each simulation. A Westinghouse study prepared for the Department of Energy [28] indicates that conventional energy costs will increase at about 8% per year through the year 2000, and this factor was taken into account in order to make an equitable comparison between the uniform annual cost of the solar system and the annual cost of auxiliary energy over the 20 year period. This was accomplished by assuming the value of required auxiliary energy obtained from the simulation using the average year represents the average annual value over the 20 year period. Using the figure of $6 per million kJ as an initial cost, the total cost of auxiliary energy for the 20 year period was calculated and converted to an equivalent uniform annual cost by the use of a capital recovery factor (0.10185) at 8% for 20 years.

Summary

Under the assumptions listed above, equation 19 can be seen to represent the total annual cost above base for delivered energy for space and hot water heating from the solar and conventional systems as a function of collector area. Figure 5 illustrates the relative contributions of the two terms in the equation with increasing collector area. As the collector area increases, collector costs (for a fixed insulation cost) increase linearly. However, as annual solar system efficiency decreases with increasing collector size, less and less auxiliary energy is replaced by a unit increase in collector area because the solar system does not operate at full capacity on a year round basis. The result is a minimum on the curve depicting the total
Figure 5. Relative contributions of collector and insulation and auxiliary energy to cost of delivered energy for space and hot water heating.
annual cost of energy which occurs at the optimum collector size. Optimum in this case refers to the collector size which produces the lowest annual energy cost for space and hot water heating from the mix of solar and conventional energy sources.

This method of economic analysis, coupled with the thermal analyses of solar system performance and building heat loss as outlined in previous chapters, forms the basis for comparison of the effect of the two methods of modeling heat loss on the selection of optimum collector size. The results are presented in the next chapter.
CHAPTER VII

RESULTS, CONCLUSIONS, AND RECOMMENDATIONS

Results

The procedures outlined in previous chapters were used to develop a numerical model for the simulation of building heat loss and solar system performance. The program, listed in Appendix C, uses the Oklahoma City average year discussed in Chapter I for hourly simulation of the building heat loss and solar system performance using Model I and Model II methods. It determines the amount of auxiliary energy required, the percentage of the heating requirements provided by the solar system, and the annual cost of energy for space and hot water heating. A total of 172 simulation runs for various combinations of house size, insulation type, and number of collector covers and collector area were accomplished and are summarized in Tables B-1 to B-27 in Appendix B.

Each table in Appendix B presents a comparison of the simulation results for collector areas up to 100 square meters for a given house size, insulation type, and number of collector covers. Table 2 is an example of the information contained in each table in Appendix B. The first column, labeled AC, gives the collector size in square meters for which the comparison between Model I and Model II results
<table>
<thead>
<tr>
<th>AC (sq m)</th>
<th>HEAT LOSS MODEL</th>
<th>ANNUAL ENERGY COST</th>
<th>% SOLAR SPACE HEAT</th>
<th>% SOLAR HOT WATER</th>
<th>SOLAR SYSTEM ANNUAL EFF.</th>
<th>ANNUAL SAVINGS</th>
<th>SOLAR SYSTEM COST</th>
<th>AUXILIARY ENERGY (million kilojoules)</th>
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Table 2. Example of tables contained in Appendix B. This table summarizes the simulation results for house size III, insulation type II, 2 cover collector.
is made. The next column lists the uniform annual cost of energy for space and hot water requirements (EUAC, equation 19) obtained using each model for that collector size. In the next two columns, the percentage of the total annual energy requirement for space heat and hot water provided by the solar system are listed for each model. Next is the annual efficiency of the solar system, defined as the total amount of useful energy provided by the solar system divided by the annual amount of energy incident upon the collector array. The column labeled Annual Savings gives the dollar value of the annual energy saved by the solar system for the given collector area above that given by the use of conventional fuel alone for space and hot water heating. Under the heading Solar System Cost, the figures represent the initial capital cost of the solar system, minus the tax credit provided, and the resulting figure for the final capital cost of the solar system (SOLCS, equation 19). Finally, the last column presents the annual amount of auxiliary energy which the simulation produces for each heat loss model in millions of kilojoules.

It is apparent, upon reviewing the results given in these tables, that the same optimum collector area (as defined in Chapter VI) would be selected for each building heat loss model with a given house size, insulation level, and number of collector covers. The results from Model II indicate a slightly lower annual energy cost and amount of auxiliary energy and a slightly higher annual savings than the Model I results, though the difference is generally less than 5%. Model II results also show a slightly greater percentage of the space and hot water heating loads carried by the solar system.
than indicated by Model I results, but the annual system efficiency for Model II is lower than with Model I, a point which will be discussed in more detail later. It is also clear that regardless of the heat loss model used or the size of the house and solar system, a two cover collector is always significantly more cost effective than one cover and slightly more cost effective than three covers, a result which Løf and Tybout found to be true in their study of solar space heating [15]. Finally, recalling that the figure given for the annual cost of energy includes the cost of insulation above or below base, the results show that both models predict that the highest insulation level provides the least cost of energy for space and hot water heating.

These results are summarized in Figures 6, 7, and 8, which present plots of the annual cost of energy for space and hot water heating as a function of collector area for house sizes I, II, and III, respectively. The label on the cost curves in each plot indicate the insulation level, I, II, or III and the number of collector covers, 1 or 2. Since the values for both heat loss models resulted in nearly identical plot curves, for clarity the curves for Model II only are presented. Similarly, the values for a 3 cover collector were nearly coincident with the two cover values in each case and were not plotted. These figures clearly demonstrate the cost effectiveness of increased insulation for each house size, and the superiority of the two cover collector over the one cover collector.

Figures 9, 10, and 11 are presented as an example of the daily performance of the two models of heat loss and the influence by
Figure 6. Annual cost of delivered energy for space and hot water heating for house size I for 3 insulation levels and 1 or 2 collector covers.
Figure 7. Annual cost of delivered energy for space and hot water heating for house size II for 3 insulation levels and 1 or 2 collector covers.
Figure 8. Annual cost of delivered energy for space and hot water heating for house size III for 3 insulation levels and 1 or 2 collector covers.
Figure 9. Daily average value of temperature in degrees C, wind speed in meters per second, and cloud cover in tenths, for Oklahoma City, Oklahoma.
Figure 10. Daily average values of building heat requirements and auxiliary energy for Model I and Model II heat loss models.
Figure 11. Daily average solar system storage temperature.
each on the solar system performance. They were obtained with house size II, insulation type II, a two cover collector, and 36 square meters of collector. Figure 9 shows the daily average value of temperature in degrees C, the daily average wind speed in meters per second, and the daily average cloud cover in tenths. In Figure 10, the upper two plots are the daily average values of building heat requirements for space and hot water and the lower two plots are the daily average values of auxiliary energy, labeled for I for Model I and II for Model II. The values of building heat required and auxiliary energy are nearly coincident for both models, with the greatest departures in the spring and fall when the building space heat demand is at a low level. Figure 11 shows the daily average storage temperatures for both models. It indicates that the storage temperature with Model II is generally higher than with Model I. The lower annual solar system efficiency referred to earlier is a direct consequence of this higher storage temperature, since the collector losses are greater and the useful energy collected lower with a higher fluid inlet temperature to the collector.

A more detailed picture is given in Figures 12, 13, 14, and 15 where a 48 hour period of the hourly simulation for each model is shown for the same house and solar system. Figure 12 is an hourly plot of the same weather parameters as given in Figure 9. In Figure 13, the hourly heat requirements using Model I and Model II are presented, along with the auxiliary energy required for both models and the solar gain through the building windows for Model II. The Model II values of heat loss are greater than Model I at night and in the
Figure 12. Hourly values of temperature in degrees C, wind speed in meters per second, and cloud cover in tenths.
Figure 13. Hourly values of building heat requirements and auxiliary energy for heat loss models I and II and useful solar gain for model II.
Figure 14. Hourly solar system storage temperature with heat loss models I and II.
Figure 15. Solar collector performance with heat loss models I and II.
early morning, but are significantly reduced below the Model I values by the solar gain during the day. The effect on the storage temperature and efficiency of the solar system is apparent in Figures 14 and 15. As seen in Figure 14, the storage temperature with Model II falls below the value given by Model I at night and rises above the value given by Model I during the day when solar energy collection and input to storage takes place. The effect of the solar system efficiency can be seen in Figure 15 where the total energy incident on the collector, the useful energy collected, and the collector losses are plotted for each heat loss model. With the same value of incident energy on both collectors, the collector losses with Model II exceed those with Model I because of the higher fluid inlet temperature. Consequently, less useful energy is collected and the system efficiency is lower.

Conclusions
These results show that the time distribution of heating demand as simulated by heat loss Model II does result in a significant difference in solar system performance on a short term basis from the results given by Model I. However, in contrast to the results found by Gutierrez, et al. [9] for domestic hot water only, these short term differences between the two models do not result in significantly different long term fractions of the load carried by the solar system. Indeed, it is the departure in the time distribution of the heat load given by Model II from that of Model I which produces a lower annual efficiency and results in the selection of
the same optimum collector size for both approaches even though the Model II approach gives lower annual auxiliary requirements. Thus, the Model II approach, though more complex and requiring much more computer time, does not produce different results in the selection of the solar system size at Oklahoma City. This indicates that where the purpose is the simulation of long term average results for the selection of the size of the solar system, the increased complexity and cost of the Model II approach are not worthwhile. On the other hand, if the purpose is the simulation of the short term performance characteristics of a solar system, these results indicate that a higher level approach than that of Model I is necessary.

**Recommendations for Further Research**

1. This analysis was accomplished at a single station. SOLMET data tapes are available for locations with significantly different climate regimes and could be used to determine whether different climates would produce different results.

2. The building models used were of conventional construction characteristics. An extension of the analysis to houses designed to be solar residences could be accomplished. This could include an analysis of the effect of varying the size and location of the building windows in a conventionally constructed residence.

3. Each house considered here was a south facing structure with the collector optimally tilted for space heating. The program is written to accept off-south orientations and any collector tilt angle and could be used to study the differences between the optimum south facing system and other orientations.
REFERENCES


APPENDIX A

HOUSE DESIGN AND INSULATION CHARACTERISTICS
Table A-1. House Design Data

<table>
<thead>
<tr>
<th></th>
<th>House Size</th>
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<tr>
<td></td>
<td>I</td>
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<td>Area</td>
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<tr>
<td>Configuration</td>
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<td>Foundation Length</td>
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<td>Window Area</td>
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Table A-2. House Construction Data

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<th>I</th>
<th>II</th>
<th>III</th>
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<td>tile shingles</td>
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<tr>
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<td>building paper</td>
<td>on wood sheathing</td>
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<td><strong>Attic-Walls</strong></td>
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<td>brick veneer</td>
<td>brick veneer on wood sheathing</td>
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<tr>
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<td>wood sheathing</td>
<td>wood sheathing</td>
<td>1 in insulation board</td>
</tr>
<tr>
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<td>3/8 in gypsum</td>
<td>3/8 in gypsum</td>
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<tr>
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<td>1/2 in plaster</td>
<td>1/2 in plaster</td>
<td>1/2 in plaster</td>
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<tr>
<td></td>
<td>1 in fibrous insul</td>
<td>3 in fibrous insul</td>
<td>12 in fibrous insul</td>
</tr>
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<td>gypsum lath</td>
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<td></td>
<td>building paper</td>
<td>1 in fibrous insul</td>
<td>3 in fibrous insul</td>
</tr>
<tr>
<td></td>
<td>wood sheathing</td>
<td>building paper</td>
<td>building paper</td>
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<td>lapped wood siding</td>
<td>wood sheathing</td>
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<td></td>
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<td>double pane</td>
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<tr>
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<td>aluminum sash</td>
<td>wood sash</td>
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<td>below grade concrete</td>
<td>below grade concrete</td>
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<td>1 in wall insul</td>
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Table A-3. Heat Transmission Coefficients, kJ/(sq m-h-C)

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<th>Insulation Type</th>
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Table A-4. Coefficients for Peterson's Infiltration Equation

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<tr>
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APPENDIX B

SUMMARY OF SIMULATION RESULTS
<table>
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<th>AC (sq m)</th>
<th>HEAT LOSS MODEL</th>
<th>ANNUAL ENERGY COST</th>
<th>% SOLAR SPACE HEAT</th>
<th>% SOLAR HOT WATER</th>
<th>SOLAR SYSTEM ANNUAL EFF.</th>
<th>ANNUAL SAVINGS</th>
<th>SOLAR SYSTEM COST</th>
<th>AUXILIARY ENERGY (million kilojoules)</th>
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Table B-1. Summary of simulation results for house size I, insulation type I, 1 cover collector.
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<th>HEAT LOSS MODEL</th>
<th>ANNUAL ENERGY COST</th>
<th>% SOLAR SPACE HEAT</th>
<th>% SOLAR HOT WATER</th>
<th>SOLAR SYSTEM ANNUAL EFF.</th>
<th>ANNUAL SAVINGS</th>
<th>SOLAR SYSTEM COST</th>
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Table B-2. Summary of simulation results for house size I, insulation type I, 2 cover collector.
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<th>AC (sq m)</th>
<th>HEAT LOSS MODEL</th>
<th>ANNUAL ENERGY COST</th>
<th>% SOLAR SPACE HEAT</th>
<th>% SOLAR HOT WATER</th>
<th>SOLAR SYSTEM ANNUAL EFF.</th>
<th>ANNUAL SAVINGS</th>
<th>SOLAR SYSTEM COST (million kilojoules)</th>
<th>AUXILIARY ENERGY</th>
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Table B-3. Summary of simulation results for house size I, insulation type I, 3 cover collector.
<table>
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<th>AC (sq m)</th>
<th>HEAT LOSS MODEL</th>
<th>ANNUAL ENERGY COST</th>
<th>% SOLAR SPACE HEAT</th>
<th>% SOLAR HOT WATER</th>
<th>SOLAR SYSTEM ANNUAL EFF.</th>
<th>ANNUAL SAVINGS</th>
<th>SOLAR SYSTEM COST</th>
<th>AUXILIARY ENERGY (million kilojoules)</th>
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Table B-4. Summary of simulation results for house size I, insulation type II, 1 cover collector.
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<th>% SOLAR HOT WATER</th>
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<th>ANNUAL SAVINGS</th>
<th>SOLAR SYSTEM COST</th>
<th>AUXILIARY ENERGY (million kilojoules)</th>
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Table B-5. Summary of simulation results for house size I, insulation type II, 2 cover collector.
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<th>% solar hot water</th>
<th>Solar system annual eff.</th>
<th>Annual savings</th>
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<th>Auxiliary energy (million KJ)</th>
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Table B-6. Summary of simulation results for house size I, insulation type II, 3 cover collector.
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<th>% SOLAR HOT WATER</th>
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<th>ANNUAL SAVINGS</th>
<th>SOLAR SYSTEM COST</th>
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Table B-7. Summary of simulation results for house size I, insulation type III, 1 cover collector.
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<th>% SOLAR HOT WATER</th>
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Table B-8. Summary of simulation results for house size I, insulation type III, 2 cover collector.
Table 3-9. Summary of simulation results for house size I, insulation type III, 3 cover collector.

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<td>% SOLAR HOT WATER</td>
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Table B-10. Summary of simulation results for house size II, insulation type I, 1 cover collector.
Table 3-11. Summary of simulation results for house size II, insulation type I, 2 cover collector.
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<th>% SOLAR HOT WATER</th>
<th>SOLAR SYSTEM ANNUAL EFF</th>
<th>ANNUAL SAVINGS</th>
<th>SOLAR SYSTEM COST</th>
<th>AUXILIARY ENERGY (Million Kilojoules)</th>
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Table B-12. Summary of simulation results for house size II, insulation type I, 3 cover collector.
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<th>% SOLAR HOT WATER</th>
<th>SOLAR SYSTEM EFF.</th>
<th>ANNUAL SAVINGS</th>
<th>SOLAR SYSTEM COST</th>
<th>AUXILIARY ENERGY (TEN THOUSAND KILOCALOLES)</th>
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Table B-13. Summary of simulation results for house size II, insulation type II, 1 cover collector.
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Table B-14. Summary of simulation results for house size II, insulation type II, 2 cover collector.
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<th>% SOLAR SPACE HEAT</th>
<th>% SOLAR HOT WATER</th>
<th>SOLAR SYSTEM ANNUAL EFF.</th>
<th>ANNUAL SAVINGS</th>
<th>SOLAR SYSTEM COST</th>
<th>AUXILIARY ENERGY (million kilo)calorie</th>
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Table B-15. Summary of simulation results for house size II, insulation type II, 3 cover collector.
Table B-16. Summary of simulation results for house size II, insulation type III, 1 cover collector.

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<th>ANNUAL ENERGY COST</th>
<th>% SOLAR SPACE HEAT</th>
<th>% SOLAR HOT WATER</th>
<th>SOLAR SYSTEM ANNUAL EFF.</th>
<th>ANNUAL SAVINGS</th>
<th>SOLAR SYSTEM COST</th>
<th>AUXILIARY ENERGY (million kilocalories)</th>
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<td>68.4</td>
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<th>% SOLAR HOT WATER</th>
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<th>ANNUAL SAVINGS</th>
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Table B-13. Summary of simulation results for house size II, insulation type III, 3 cover collector.
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<th>% SOLAR HOT WATER</th>
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Table 3-20. Summary of simulation results for house size III, insulation type I, 2 cover collector.
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Table B-21. Summary of simulation results for house size III, insulation type I, 3 cover collector.
ENVIRONMENTAL INFLUENCES IN THE SIMULATION OF A SOLAR SPACE HEATING-ETC(U)

AFIT-CI-80-20T
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<th>% SOLAR HOT WATER</th>
<th>SOLAR SYSTEM ANNUAL EFF.</th>
<th>ANNUAL SAVINGS</th>
<th>SOLAR SYSTEM COST</th>
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Table B-22. Summary of simulation results for house size III, insulation type II, 1 cover collector.
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<th>% SOLAR HOT WATER</th>
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<th>ANNUAL SAVINGS</th>
<th>SOLAR SYSTEM COST</th>
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<td>$5284</td>
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<td>92.2</td>
<td>.223</td>
<td>$71</td>
<td>$8975</td>
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</table>

Table B-23. Summary of simulation results for house size III, insulation type II, 2 cover collector.
Table B-24. Summary of simulation results for house size III, insulation type II, 3 cover collector.
Table B-25. Summary of simulation results for house size III, insulation type III, 1 cover collector.
<table>
<thead>
<tr>
<th>AC (sq m)</th>
<th>HEAT LOSS MODEL</th>
<th>ANNUAL ENERGY COST</th>
<th>% SOLAR SPACE HEAT</th>
<th>% SOLAR HOT WATER</th>
<th>SOLAR SYSTEM ANNUAL EFF.</th>
<th>ANNUAL SAVINGS</th>
<th>SOLAR SYSTEM COST</th>
<th>AUXILIARY ENERGY SAVINGS (million kilojoules)</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>I</td>
<td>$811</td>
<td>31.7</td>
<td>63.1</td>
<td>.403</td>
<td>$101</td>
<td>$1995</td>
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<td>II</td>
<td>$800</td>
<td>33.1</td>
<td>66.5</td>
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<td>$115</td>
<td>$1396</td>
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<td>30</td>
<td>I</td>
<td>$753</td>
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<td>75.4</td>
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<td>$3615</td>
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<td>78.6</td>
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<td>I</td>
<td>$770</td>
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<td>91.0</td>
<td>.231</td>
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<td>$5284</td>
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<td>$8475</td>
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<td>94.7</td>
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<td>98.3</td>
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<td>$0</td>
<td>$8975</td>
<td>0.5</td>
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</table>

Table B-26. Summary of simulation results for house size III, insulation type III, 2 cover collector.
<table>
<thead>
<tr>
<th>AC (sq m)</th>
<th>HEAT LOSS MODEL</th>
<th>ANNUAL ENERGY COST</th>
<th>% SOLAR SPACE HEAT</th>
<th>% SOLAR HOT WATER</th>
<th>SOLAR SYSTEM ANNUAL EFF.</th>
<th>ANNUAL SAVINGS</th>
<th>SOLAR SYSTEM COST</th>
<th>AUXILIARY ENERGY (million kilojoules)</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
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<td>77.0</td>
<td>.407</td>
<td>$151</td>
<td>$3873</td>
<td>$2898</td>
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<td>80.5</td>
<td>.358</td>
<td>$164</td>
<td>$3873</td>
<td>20.5</td>
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<td>$4298</td>
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<td>87.4</td>
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<td>$125</td>
<td>$5622</td>
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<td>$862</td>
<td>95.5</td>
<td>91.0</td>
<td>.369</td>
<td>$33</td>
<td>$7371</td>
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<tr>
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<td>93.5</td>
<td>.320</td>
<td>$32</td>
<td>$7371</td>
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<td>$0</td>
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<td>0.09</td>
</tr>
</tbody>
</table>

Table B-27. Summary of simulation results for house size III, insulation type III, 3 cover collector.
APPENDIX C

COMPUTER PROGRAM LISTING
c enter data values for latitude, collector tilt, collector azimuth - all in degrees.

c p=35.50
beta=50.5
sama=0.0

c enter values for max collector size, acmx, no. of glass covers, n,
c design room temperature, and upper limit for service hot water temperature.

c acmx=125.
n=2
tr=293.16
tr2=291.48
thw=333.16

c enter values for collector cost, storage cost, piping and equipment costs, equivalent uniform annual cost factor, present worth factor, and fuel costs/million kJ.

c nm2=n-2
ccost=100.0+8.6*float(nm2)
stcst=8.0
c=375.
euacf=.11746
euac3=.10185
Pwf=8.932
cf=.00006

c enter flag for type radiation values on this data tape

c itype=0 no direct normal values on tape.
ctype=ne.0 direct normal values are available.

itype=0

c enter size(isize), design air temp (tdesn), design wind speed(vdesn), max and min ground temperatures (t(gmax), t(gmin)).
insul=2
isize=2
tdesn=279.2
vdesn=11.5
tsmx=294.4
tsmi=286.46
tmn=(tsmx+tsmi)/2.
tmxi=(tsmx-tsmi)/2.
write(6,162) tdesn,vdesn,tsmi,tsmx
write(6,162) tdesn,vdesn,tsmi,tsmx

do 900 nac=1,4
ac=0.2*acmx*float(nac)
cfuel=cf*ac*euc3*20.
c call subroutine initial to calculate initial one time constants
c for the station, house, and collector used.
c call init1(ph,beta,siga,sinph,cosp,tsmax,sinb,cosb,
sinb,cosb)
write(6,162) tdesn,vdesn,tsmi,tsmx,

print 5
print 5
print 5
print 5

print 4
print 4
print 4
print 4

write(6,162) tdesn,vdesn,tsmi,tsmx
write(6,162) tdesn,vdesn,tsmi,tsmx

print 44
print 44
print 44
print 44

print 158
write(6,40) ms,flo,exnsulfr

c call subroutine design to compute station specific house
c parameters, areas of house surfaces, area-
for exposed surfaces, design heat loss/deg c, and infiltration
c loss.
c call design(acibeta,±size,ansujl tdesnvachiapbrcpdp-e,
larunrareasubsxjsfopgexsopg,psoixerpvdesn,
larunrareasubsxjsfopgexsopg,psoixerpvdesn,

print all house parameters.
print 44
print 44
print 44
print 44

print 5
print 5
print 5
print 5

print 4
print 4
print 4
print 4

write(6,162) tdesn,vdesn,tsmi,tsmx
write(6,162) tdesn,vdesn,tsmi,tsmx

print 7
print 7
print 7
print 7

print 88
print 88
print 88
print 88

print 9
print 9
print 9
print 9

print 21
print 21
print 21
print 21

print 21
print 21
print 21
print 21
PRINT 11
PRINT 21, ODES, OINF, ACS, AC
PRINT 44
H1 = ODES
IDAY = 0
C
C run the model for the design year
C
DO 64 J = 1, 18
64 SUM(J) = 0.
DO 1 J = 1, 365
IDAY = IDAY + 1
DAY = FLOAT(IDAY)
C compute declination, cos and sin of declination,
ARG = (360. * (284. + DAY) / 365.) * 0.1745329
DELT = (23.45 * SIN(ARG)) * 0.1745329
SD = SIN(DELT)
CD = COS(DELT)
ARG2 = ARG - 516.426
C compute ground temperature for this day
TS = TSMN + TSMN * SIN(ARG2)
C compute basement losses/hr for this day.
BLS = AUB * (TR - TS)
IF (BLS .LT. 0) BLS = 0.
IF (DAY .GT. 150. AND. DAY .LT. 255) BLS = 0.
DO 1 I = 1, 24
C read weather and solar radiation parameters for each hour.
READ (4, 4) (KDATA(NV), NV = 1, 8)
4 FORMAT (8A2)
IRHT = KDATA(4)
MODA = KDATA(1)
TIME = FLOAT(ITIME)
ITEMP = KDATA(5)
TS = FLOAT(ITEMP) / 10.
TA = TA + 273.16
IDN = KDATA(3)
RD = FLOAT(IDN)
DN = FLOAT(IDN)
RHT = FLOAT(IRHT)
IC = KDATA(9)
CC = FLOAT(IC)
IWIND = KDATA(6)
WIND = FLOAT(IWIND)
ISPED = KDATA(7)
SPEED = (FLOAT(ISPED)) / 10.
C set initial solar temperatures to dry-bulb temperature.
TERN = TA
TERS = TA
TREW = TA
TSEW = TA
TENW = TA
ALPHA = 0.
THETA = 1.570716
if radiation values are greater than 0, compute the incidence angle on the collector and all building surfaces. If the angle of incidence on any surface exceeds 90 deg, set it = 90.

if(idn.le.0.or.idn.gt.9998) rdn=0.
if(irht.le.0.or.irht.gt.9998) rht=0.
if(irht.le.0.or.irht.gt.9998) go to 8

call angle(sin,cos,tan,sinb,cosb,sin,cos,1day,time,theta,salp,answ,answe,answw,ansnr,lsamin,ansnw,ph,sina,costh,cdelt,sdelt)

8 continue

call subroutine collector to compute the solar radiation incident on each collector and the useful energy collected, if any, by each.

call coll(ac,vfr,ul,tsold,ta,trp,flo,cpc,tco,rdn,rht,cc,ltype,alph,theta,alp,tau,ra,ac,rd,rdus,irht,speed,n,uls,a2,1c,bsina,costh,mce,exp,tm,absor,wind,fcc,tsol2,ult,fp)

sum(1)=sum(1)+ac

if the sun is up, calculate the solar temperature of each exposed building surface.

sol0n=0.
if(alpha.le.0.2) go to 102
call solair(answ,answe,answw,ansnr,theta,tern,ters,teew,lteew,tesw,tenw,rdn,rdw,ansnw,speed)

call shg(answe,rdn,rdw,insul,shgn,moda)
sol0n=sol0n+shgn*awine

call shg(answw,rdn,rdw,insul,shgn,moda)
sol0n=sol0n+awins*shgn

call shg(ansnr,rdw,rdw,insul,shgn,moda)
sol0n=sol0n+shgn*awinn

call shg(ansnw,rdn,rdw,insul,shgn,moda)
sol0n=sol0n+shgn*awinn

102 continue

set energy requirements for service hot water for this hour.

ashw=0.
ashw2=0.
if(itime.gt.5.and.itime.lt.21) ashw=vahw*(thw-ts)
ashw2=ashw
sum(4)=sum(4)+ashw/ac

compute building heat demand using design heat transmission coefficient (computed in subroutine design).

hls=0.
if(ta.lt.tr2) hls=hl*(tr2-ta)
aload=hls-strls
if(aload.lt.0.) aload=0.
compute storage temperature and storage losses for this hour.
call strge(ac,flor,au,load,tsold,tsnew,adum,f,aux,strls, 
ishw,axw,vuhw,ms,mcps,us) 
sum(12)=sum(12)+aux/ac 
sum(13)=sum(13)+axw/ac 

compute building heat demand as a function of temperature, 
wind, and radiation influences.

heat=0. 
call demand(speed,wind,fc,awen,awine,araw,aw,us,teew,aws,awins, 
lad,rd,tesw,ars,rf,ters,teew,awn,awinn,arn,tenw,tern,auc2,ac, 
ltp,aclu,ach,vol,bis,aub,heat1,wins,hi,ta) 

sum(7)=sum(7)+heat1/ac 
sum(8)=sum(8)+str12/ac 
q1=heat1-str12 
if(q1.lt.0.) q1=0. 
if(solgn.ge.q1) solgn=q1 
sum(10)=sum(10)+solgn/ac 
sum(11)=sum(11)+hi/ac 
q1=solgn 
if(q1.lt.0.) q1=0. 
sum(18)=sum(18)+q1/ac 

compute storage temperature and storage losses for the expanded 
parameter model. 
call strge(ac,flor,au,q1,tsol2,tsnw2,admp2,f,aux2,strl2, 
ishw2,axw2,vuhw2,ms,mcps,us) 
sum(14)=sum(14)+aux2/ac 
sum(15)=sum(15)+axw2/ac 
sum(16)=sum(16)+w1s/ac 
sum(17)=sum(17)+bls/ac 
sum(2)=sum(2)+q2/ac 
sum(3)=sum(3)+q2/ac 

continue 

compute annual efficiency, equivalent uniform annual costs, 
percentage solar, annual savings for each system.

anef1=sum(2)/sum(1) 
anef2=sum(3)/sum(1) 
colcs=(ccost+stcst)*ac+ce 
if(colcs.gt.2000.) taxsv=600.+0.2*(colcs-2000.) 
if(colcs.le.2000.) taxsv=0.3*colcs 
if(colcs.ge.10000.) taxsv=2200. 
ccf=colcs-ta-sv 
euac1=ccfn*euacf+(sum(12)+sum(13))*cfuel+csti(isize,insul) 
euac2=ccfn*euacf+(sum(14)+sum(15))*cfuel+csti(isize,insul) 

phw1=(1.-sum(13)/sum(4))*100.
\[ \text{Psht1} = (1 - \frac{\text{sum}(12)}{\text{sum}(9)}) \times 100, \]
\[ \text{Psht2} = (1 - \frac{\text{sum}(14)}{\text{sum}(18)}) \times 100. \]

\[ \text{fcst1} = \text{cfuel} \times (\text{sum}(9) + \text{sum}(4)) \]
\[ \text{fcst2} = \text{cfuel} \times (\text{sum}(18) + \text{sum}(4)) \]

\[ \text{if}(\text{fcst1} \leq \text{euac1}) \quad \text{ansv1} = 0, \]
\[ \text{if}(\text{fcst2} \leq \text{euac2}) \quad \text{ansv1} = \text{fcst1} - \text{euac1} \]
\[ \text{if}(\text{fcst2} \leq \text{euac2}) \quad \text{ansv2} = \text{fcst2} - \text{euac2} \]
\[ \text{lfsv1} = \text{ansv1} \times \text{pf} \]
\[ \text{lfsv2} = \text{ansv2} \times \text{pf} \]

\[ \text{Print results} \]
\[ \text{do 333} \quad \text{jk} = 1, 18 \]
\[ \text{333} \quad \text{sum}(\text{jk}) = \text{sum}(\text{jk}) \times \text{ac} \]
\[ \text{print 300} \]
\[ \text{print 100} \]
\[ \text{write}(6,99) (\text{sum}(\text{kk}), \text{kk} = 1, 9) \]
\[ \text{print 200} \]
\[ \text{write}(6,99) (\text{sum}(\text{kk}), \text{kk} = 10, 18) \]
\[ \text{print 44} \]
\[ \text{cful} = \text{cfuel} / \text{ac} \]
\[ \text{print 400}, \text{ccost}, \text{cful} \]
\[ \text{print 151}, \text{euac1}, \text{anef1} \]
\[ \text{print 153}, \text{phw1}, \text{Psht1} \]
\[ \text{print 152}, \text{euac2}, \text{anef2} \]
\[ \text{print 153}, \text{phw2}, \text{Psht2} \]
\[ \text{print 163}, \text{csti}(\text{isize, insul}) \]
\[ \text{print 44} \]
\[ \text{print 155}, \text{colcs}, \text{taxsv, ccfn} \]
\[ \text{print 156}, \text{ansv1}, \text{lfsv1} \]
\[ \text{print 157}, \text{ansv2}, \text{lfsv2} \]
\[ \text{print 44} \]

\[ \text{REWIND 4} \]
\[ \text{900} \quad \text{continue} \]

\[ \text{21 format}(10(1x, f12.2)) \]
\[ \text{44 format}(1x, /, 1x, 120(’*’), /) \]
\[ \text{5 format}(1x, ’house size ’, i2, ’5x, ’insulation level ’, i2, /) \]
\[ \text{6 format}(10(1x, f11.2)) \]
\[ \text{9 format}(1x, /, 6x, ’house surface areas’/, \]
\[ 16x, ’north roof’ south roof-ac house area attic walls’, \]
\[ 1’ s windows south walls n windows north walls’, \]
\[ 1’ end windows end walls ’) \]
\[ 88 format(1x, /, 5x, ’area roof ht b n-roof’ ln c, dis to pk’, \]
\[ 1’ drs-roof ln e hwd-c slope n-roof’) \]
\[ 7 format(1x, /, 6x, ’xhl doors xhl windows xhl basement xhl ceil’ \]
\[ 1’ n’ xhl walls xhl infilt total %’) \]
\[ 10 format(1x, /, 6x, ’area u-value products’, /, \]
\[ 16x ’ doors north roof south roof-ac attic walls’, 2x, \]
\[ 1’ windows walls floors ceiling sum’) \]
\[ 11 format(1x, /, 1x, ’design loss(deg c) design infil/c ach/hr’, \]
\[ 1’ area collector’) \]
\[ 99 format(1x, 9(e11.4, 1x), /) \]
100 format(1x,/1x,'incid. rad.',1x,'ou coll 1',3x,'ou coll2',3x, 
1'hot water',3x,'Heat loss 1',1x,'strae lss 1',1x,'heat loss 2',1x, 
1'strae lss 2',1x,'heat load 1'/) 
200 format(1x,/1x,'solar gain',1x,'infiltration',1x,'auxiliary 1', 
11x,'aux hw 1',1x,'auxiliary 2',1x,'aux hw 2',4x,'window loss',2x, 
1'smt loss',3x,'heat load 2'/) 
151 format(1x,/1x,'the standard system has equivalent annual costs', 
1' of ',f10.2,'$', with annual efficiency of ',f8.4'/) 
152 format(1x,/1x,'the expanded parameter system has equivalent', 
1' annual costs of ',f10.2,'$', with annual efficiency of', 
f8.4'/) 
300 format(1x,/1x,'annual energy totals'/) 
400 format(1x,'annual cost and efficiency analyses for collector',/1x, 
11x,'costs of ',f8.2,'$', per sq m and fuel costs of ',f10.8, 
1'dollars per kiloJoule'/) 
153 format(1x,'it provides ',f8.3,'% of hot water and', 
1f8.3,'% of space heat'/) 
155 format(1x,'the system cost above base is ',f10.2, 
1'dollars '/,1x,'a tax break of ',f10.2,'$', dollars', 
1'reduces this to a final cost of ',f10.2,'$', dollars'/) 
156 format(1x,'the annual energy savings for system 1 are', 
1f10.2,'$, and the present worth of the lifetime'/,1x, 
1'savings', with money valued at 8% is ',f10.2,'$', dollars'/) 
157 format(1x,'the annual energy savings for system 2 are', 
1f10.2,'$, and the present worth of the lifetime'/,1x, 
1'savings', with money valued at 8% is ',f10.2,'$', dollars'/) 
158 format(1x,'collector and storage parameters',/1x, 
11x,'mass of storage',1x,'mass flow rate/sq m of col.',1x, 
1'heat exchanger coef.',1x,'no. of glass covers',1x, 
1'col. u loss',1x,'heat removal factor'/) 
40 format(1x,f15.1,f6.5,f15.2,f6.5,f15.4,f6.4,i8.8,f11.2,f3x,f15.4/) 
159 format(1x,'design weather parameters',/1x, 
11x,'design air temp',1x,'design wind sp',1x, 
1'winter ground temp',1x,'summer ground temp'/) 
161 format(1x,'oklahoma city'/) 
162 format(1x,f15.2,f1x,f14.2,f3x,f15.2,f3x,f15.2/) 
163 format(1x,'the equivalent uniform annual cost of insulation is', 
1f8.2,'$', dollars'/) 
STOP 
end
This subroutine calculates the design heat loss for the structure under consideration as a function of the collector size, the tilt of the collector, the size and degree of insulation of the various components of the structure, and the design temperature and number of air changes per hour for the structure. The three house sizes (isize = 1, 2, or 3) are 92.9 sq m, 134.8 sq m, and 180 sq m. The three levels of insulation (insul = 1, 2, or 3) are poor, moderate, and heavy - relative terms. The subroutine has a table of values for \( u \) for all the components for each level of insulation, as well as the dimensions of each of the basic house sizes. The roof dimensions vary with location, since the collector is taken as an integral part of the roof. These dimensions are calculated in this subroutine.

The outputs are the areas of the surfaces of the structure, the dimensions of the roof structure (calculated here so that the collector is an integral part of the roof at a tilt beta), the design area-\( u \)-value products for all of the house components, and the design infiltration and overall heat transmission coefficient for the house.

dimension acw(3), acs(3)
dimension uct(3), uwt(3), uflt(3), ust(3), uawt(3), ufl(3), udl(3)
dimension array for house component sizes.
dimension ah(3),hlen(3),hwd(3),ht(3),fl(3),awin(3),ad(3)

c enter design u-values and air-change values in table:

data uct(1),uct(2),uct(3)/3.883,1.627,0.850/
data uwt(1),uwt(2),uwt(3)/5.870,2.730,1.463/
data ufl(1),ufl(2),ufl(3)/7.162,2.773,2.168/
data uct(1),uct(2),uct(3)/25.409,10.681,9.751/
data uwt(1),uwt(2),uwt(3)/8.856,8.856,5.928/
data ufl(1),ufl(2),ufl(3)/12.388,12.388,9.975/
data udt(1),udt(2),udt(3)/7.563,9.541,5.724/
data acw(1),acw(2),acw(3)/.030,.0225,.015/
data acs(1),acs(2),acs(3)/.0216,.0162,.0108/

c enter dimension of each house type in table:

data ah(1),hlen(1),hwd(1),ht(1),fl(1),awin(1),ad(1)/192.9,12.2,7.62,2.44,39.6,9.67,3.0/
data ah(2),hlen(2),hwd(2),ht(2),fl(2),awin(2),ad(2)/114.8,14.25,9.5,2.74,47.5,13.5,6.7/
data ah(3),hlen(3),hwd(3),ht(3),fl(3),awin(3),ad(3)/1180.0,15.0,12.0,3.0,54.0,17.6,7.31/

c cpa=1.20719
radcon=.01732945
args=beta*radcon
args2=(90.-beta)*radcon
snb=sin(args)
snb2=sin(args2)

c i=isize
in=insul
d=ac/(hlen(i)*0.8)
a=snb*xk
c=snb2*xk
e=hwd(i)-c
tars=a/e
samim=atan(tars)
b=(a*a+e*e)**0.5

c compute area of north and south facing roof surfaces.
arn=b*hlen(i)
ars=d*hlen(i)-ac

c compute area of attic walls.
ahr=ah(i)
aw=0.5*a*hwd(i)
c compute area of south facing windows.
awin=awin(i)*0.6

c compute area of south facing wall surface.
aws=hlen(i)*ht(i)-ad(i)/2.-awins

c compute area of north facing windows and walls.
awinn=awin(i)*.2
awin=hlen(i)*ht(i)-ad(i)/2.-awinn

c compute area of window glass and walls on ends of house.
awine=awin(i)*.1
awen = hwd(i) * ht(i) - awine
adr = ad(i) / 2.

c compute effective volume-density of inside of house for infiltration.
vol = ahs * ht(i) * cpa

c set design infiltration load due to wind and stack effects.
achw = acw(in)
achs = acs(in)
achs = 1.10 + achs * (291.5 - tdesn) + achw * vdesn
adin = vol * achs

c set design u-values for each surface for this house.
uc = uct(in)
uw = uwt(in)
ud = ust(in)
uaw = uawt(in)
urf = urft(in)
ud = udt(in)
ulf = uflt(in)

c compute design area-u value products for this house.
aud = adr * ud
arun = arn * urf
arus = ars * urf
aruaw = arau * uaw
auc = ahs * uc
auwin = awin(i) * ugs
auwn = awn * uw
auws = aws * uw
auwen = awen * uw
auw = auwn + auws + 2. * auwen
aub = ufl * f1(i)
aufl = aub * (291.5 - tmin) / (291.5 - tdesn)
auc2 = auc * 295.16
ausum = auc + arun + arus + 2. * aruaw + ac * urf

c calculate design attic temperature
desnat = tatic(auc2, tdesn, arun, tdesn, arus, ac, urf, tdesn, tdesn, tdesn, aruaw, aruaw, ausum)

c calculate design heat transmission coefficient.
odesn = auw + auwin + aufl + auc + 2. * aud + adinf
uw = 1. / uw - fc
uw = 1. / uaw - fc
ud = 1. / ud - fc
us = 1. / us - fc
urf = 1. / urf - fc

c set hourly energy requirements for hot water based on

c house size.
c 75kg/person-day
c 4 persons for size 1
c 5 persons for size 2
c 6 persons for size 3
kv = isize - 1
vahw = ((300. + float(kv) * 75.) * 4.19) / 15.
return
end
function tatic(auc2,tern,arun,ters,arus,ac,urf,tep,teew,teeww, laruae,aruaw,ausum)

C this subroutine calculates the temperature of attic
C using the procedure given in ASHRAE ch 25.6440.
tatic = (auc2 + tern * arun + ters * arus + ac * urf * ters + teew * aruae 
1 + teeww * aruaw) / ausum
return
end
This subroutine takes station latitude, collector tilt, beta, and the collector azimuth and angle, gamma and computes the trigonometric one time calculations needed for subroutine stagger and initializes values for subroutine storage collector, and design.

Input values for all angles are in degrees.

**REAL** 

<table>
<thead>
<tr>
<th><strong>DIMENSION</strong></th>
<th><strong>f(3),ult(3),tmce(3),ftr(3)</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>DATA</strong></td>
<td><em>(f(1),f(2),f(3)/.95,.98,.99/)</em>*</td>
</tr>
<tr>
<td><strong>DATA</strong></td>
<td><em>(frt(1),frt(2),frt(3)/.786,.824,.901/)</em>*</td>
</tr>
<tr>
<td><strong>DATA</strong></td>
<td><em>(ult(1),ult(2),ult(3)/28.8,14.4,7.2/</em>*</td>
</tr>
<tr>
<td><strong>DATA</strong></td>
<td><em>(tmce(1),tmce(2),tmce(3)/6.6,10.66,15.22/</em>*</td>
</tr>
</tbody>
</table>

**radcv=0.01745329**

**eps=1.111**

**p=ph*radcv**

**b=beta*radcv**

**s=gama*radcv**

**sinp=Sin(p)**

**cosh=cos(p)**

**tanp=tan(p)**

**sinb=sin(b)**

**cosd=cos(d)**

**cosb=cos(b)**

**sind=sin(d)**

**C** set storage mass

**ms=61.1**

**C** set heat capacity of storage mass, deg c/kj.

**mcp=1./(ms**4.19)**

**C** compute area of cylindrical storage vessel for this storage mass.

**area=9.4247779**(ms/9424.7)**0.66667**

**C** compute heat transmission coefficient for storage vessel.

**us=1.44**

**C** initialize storage temp,storage loss,plate temp,rho.

**tsold=333.16**

**tsol2=333.16**

**strls=0.**

**strl2=0.**

**tpp=273.16**

**rho=0.2**

**C** specific heat of water - kj/(ks - deg c).

**cpc=4.19**

**C** set collector heat loss coefficient for n covers, kj/deg c.

**ul=ult(n)**

**C** set effective collector heat capacity - deg c/(kj - sq m).

**mce=tmce(n)**

**C** compute exponential term for plate temperature calculations.
arg = -(ul/mce)
expterm = exp(arg)
c compute fr, heat removal factor for this collector.
fp = f(n)
fro = fnt(n)
eps = .001
ict = 0
13 continue
  etrm = -2.*((fp-fro)/fp)
  ict = ict + 1
  fnr = (fp*fp/(2.*((fp-fro)))*(1.-exp(etrm)))
  test = fnr - fro
  fro = fnr
  test = abs(test)
  if(ict.ge.100) go to 14
  if(test .lt. eps) go to 13
14 continue
  fr = fnr

c set mass flow rate
  fmp = fp**f*xu/(2.*cpc*(fp-fr))
  flow = fmp*ac
c calculate design outside film coefficient
  vc = 0.25*vdesn*4344881
  fc = 67.049*(vc**.605) + 14.0
  fc = 1./fc

c set absorbtivity of collector plate (copper, tube-in-sheet,black
  c non-selective coating).
  absor = 0.95
  return
  end
subroutine angle(sinph,cosphtanph,sinb,cosb,sing,coss, 
1day, time, theta, alpha, answe, answw, ansnr, 
1smin, ansnw, phrsinph, costh, cdelt, sde1t)

************************************************************************************
This subroutine computes angles used in solar calculations.

It requires that the subroutine compute the following:

- sinph, cosphtanph - the sin, cos, tan of the latitude.
- sing and coss - the sin and cos of the azimuth angle of the surface for which the incident solar angle is desired. Angles east of south are positive and west of south are negative.
- sinb and cosb - the sin and cos of the tilt from horizontal of the surface for which the angle of incidence is desired.
- day and time - day is the number of the day of the year, and time is the time of day on a 24 hour clock basis.

It returns the following:

- Theta - the angle of incidence on the surface.
- Alpha - the altitude of the sun.
- answe - angle of incidence on the south wall of the structure.
- answw, answe - the angles of incidence on the east and west walls of the structure.
- anstw, ansnr - the angle of incidence on the north wall and roof.

These angles used in later calculations of radiation and solar temperature and are set equal to pi/2 if >pi/2. This is done so that calculations taking the cosine of the angle of incidence will be 0 if the angle is >pi/2.

radcon=.01745329

c compute hour angle.

h=-6.28319*(time-12.)/24.

cosh=cos(h)
sinh=sin(h)

c compute cos of incidence angle on collector and sin of solar altitude.

costh=cdelt*sinph*cosb-sdelt*cosph*sinb*coss

costh=costh+cdelt*cosph*cosb*cosh+cdelt*sinh*sinb*coss*cosha
\begin{align*}
\text{costh} &= \text{costh} + \text{cde} \times \sin b \times \sin g \times \sin ha \\
\sin a &= \sin p \times \text{sinha} \times \cos p \times \text{delt} \times \cos ha \\
\alpha &= \arcsin (\sin a) \\
\text{if} (\alpha \lt \text{.1e} .0.) \text{ go to 6}
\end{align*}

C compute incidence angle on all house surfaces.

\begin{align*}
\theta &= \arccos (\text{costh}) \\
\text{an2} &= \text{h} \times \text{radcon} + 1.5707963 \\
\text{an} &= \text{p} \times \text{radcon} + \text{samin} \\
\text{can} &= \cos (\text{an}) \\
\text{san} &= \sin (\text{an}) \\
\text{can2} &= \cos (\text{an2}) \\
\text{san2} &= \sin (\text{an2}) \\
\text{cosnr} &= \text{can} \times \text{cde} \times \cos ha + \text{san} \times \text{sdel} \\
\text{cosnw} &= \text{can2} \times \text{cde} \times \cos ha + \text{san2} \times \text{sdel} \\
\text{cosws} &= -\text{delt} \times \cos p \times \text{cde} \times \sin p \times \cos ha \\
\text{coswe} &= \text{cde} \times \sin ha \\
\cosww &= -\text{cde} \times \sin ha \\
\text{angww} &= \arccos (\cosww) \\
\text{anwe} &= \arccos (\coswe) \\
\text{angws} &= \arccos (\cosws) \\
\text{angnr} &= \arccos (\cosnr) \\
\text{angnw} &= \arccos (\cosnw) \\
\text{test2} &= \abs (\cosww) \\
\text{test2} &= \abs (\coswe) \\
\text{test2} &= \abs (\cosws) \\
\text{test2} &= \abs (\cosnr) \\
\text{test2} &= \abs (\cosnw) \\
\text{if} (\text{testw}, \lt 1.0.) \text{ go to 1} \\
\text{angww} &= \arccos (\cosww) \\
1 \text{ continue} \\
\text{if} (\text{test2}, \lt 1.0.) \text{ go to 2} \\
\text{angwe} &= \arccos (\coswe) \\
2 \text{ continue} \\
\text{if} (\text{test2}, \lt 1.0.) \text{ go to 3} \\
\text{angws} &= \arccos (\cosws) \\
3 \text{ continue} \\
\text{if} (\text{test2}, \lt 1.0.) \text{ go to 4} \\
\text{angnr} &= \arccos (\cosnr) \\
4 \text{ continue} \\
\text{if} (\text{test2}, \lt 1.0.) \text{ go to 5} \\
\text{angnw} &= \arccos (\cosnw) \\
5 \text{ continue} \\
\text{if} (\cosww, \lt 0.0.) \text{ angww} &= 1.570716 \\
\text{if} (\coswe, \lt 0.0.) \text{ angwe} &= 1.570716 \\
\text{if} (\cosws, \lt 0.0.) \text{ angws} &= 1.570716 \\
\text{if} (\cosnr, \lt 0.0.) \text{ angnr} &= 1.570716 \\
\text{if} (\cosnw, \lt 0.0.) \text{ angnw} &= 1.570716 \\
\text{go to 7} \\
6 \text{ continue} \\
\theta &= 1.570716 \\
\text{ang2} &= 1.570716 \\
\text{angwe} &= 1.570716 \\
\text{angws} &= 1.570716 \\
\text{angnr} &= 1.570716 \\
\alpha &= 0..
continue
return
end
subroutine coll(ac,fr,ul,tsold,ta,tpp,flo,cpc,tco,rdr',rht,cc, 
lumpy,alp,theta,beta,rho,aq,rd,rdu,irhr,peed,ns,uls,au2, 
lcosb,sinb,costh,mce,exp,tm,absor,wind,fcc,tsul2,ult,fr)
real mce

dimension taul(3),b(3),slp(3)
data taul(1),tau1(2),tau1(3)/.92,.86,.75/
data b(1),b(2),b(3)/2.3567,2.2143,1.7257/
data slp(1),slp(2),slp(3)/.02,928,.02457,.021428/
c This subroutine computes the useful energy collected by a 
c water heating collector. The plate temperature must rise, based 
c on its heat capacity, heat loss characteristics, and the incident 
c radiation, at least 10 deg.c above the temperature of the 
c storage fluid before useful energy is collected.
c
the input arguments are:
c 1. ac - the collector area in meters.
c 2. fr - the heat removal factor for the collector.
c 3. ul - the heat loss coefficient for the collector in 
kJ/sa m-c.
c 4. tsold - the previous hour's storage temperature.
c 5. ta - the current hour's ambient air temperature.
c 6. tpp - the previous hour's mean plate temperature.
c 7. flo - the fluid mass flow rate (kg/hr).
c 8. rdrn - the current value of the direct normal component 
of radiation (kJ/sa m).
c 9. rht - the current value of the global horizontal 
radiation (kJ/sa m).
c 10. cc - the cloud cover in tenths of sky coverage.
c 11. itype - a flag denoting whether or not direct normal 
 radiation values are available;
   itype=0 - no direct normal values available.
   direct component calculated from
   global horizontal and cloud cover.
   itype.ne.0 - direct normal values are available 
on tape and are not calculated.
c 12. theta - the angle of incidence of direct component of 
radiation, from subroutine angle. (radians)
c 13. alpha - the solar altitude in radians.
c 14. beta - the tilt of the collector from the horizontal (rad.).
c 15. rho - the reflectivity of the surface. (dimensionless)
c
the output arguments are:
c 1. au,au2 - the useful energy collected (kJ/sa m).
c 2. uls,ult - the collector losses
3. tpp the collector plate temperature.

radcon=0.01745329
if(irht.gt.0.and.irht.lt.9999) go to 8
rd=0,
rd=0,
rd=0,
rh=0,
so to 6
8 continue
if(itype.ne.0) go to 1
7 continue
ckt=0.7*(1-0.1*cc)
ddbh=1.-1.3575*ckt
rdw=dhhb*rht
if(alpha.le.0.2) go to 2
rdn=(rht-rdu)/sina
rd=costh*rdn
so to 2
rd=rdn*cosinh

test2=rdn*sina
if(test2.ge.rht) go to 7
rd=rht-rdn*sina
2 continue
if(alpha.gt.0.2) go to 6
rd=0.
rdn=0.
rd=rht
6
ac=rd+rdu*0.5*(1.+cosb)+rht*0.5*(1.-cosb)*rho
tplate=ta+(ac/ul)-(ac/ul-(tpp-ta))*expfrm
tpp=tplate
if(ac.le.0.) go to 3
ttest=tplate-10.-tsold
if(ttest) 3,4,4
3 au=0.
au2=0.
ult=0.
uls=0.
so to 5
4 continue
ang=theta/radcon
if(ang.le.60.) tau=tau1(n)
if(ang.gt.60. and ang.lt.90) tau=beta(n)-slp(n)*ang
if(ang.ge.90) tau=0.
ult=ul*(tsold-ta)
au=ac*fr*(ac*tau*absor-ult)
if(au.le.0) au=0.
uls=ul*(tsol2-ta)
au2=ac*fr*(ac*tau*absor-uls)
if(au2.lt.0.) au2=0.
5 continue
return
end
subroutine strse(acl,flu,ou,uload,tsold,tsnew,adump,aux,  
istrls,ashw,vahw,va,nw,ms,mcps,us)
    real ns,mcps
    ! This subroutine computes the temperature of the storage fluid for a solar space heating system based on the useful energy collected by a flat plate collector, the heat loss characteristics of the storage vessel, the mass of the storage fluid, and a control strategy. Based on the system characteristics and control strategy, it also computes the uncontrolled heat losses from storage to the heated structure, the amount of energy which the collector must "dump" if the maximum storage temperature is reached, and the amount of auxiliary energy required if the heat load cannot be met from the solar system.
    ! data tmax,tmin/373.16,302.16/
    ! data strtrp,thw/298.16,333.16/
    tsnew=tsold+mcps*(au-us*(tsold-strtrp)-uload-ashw)
    if(tsnew.le.tmax) tdump=0.
    if(tsnew.gt.tmax) tdump=tsnew-tmax
    if(tsnew.le.tmax) tsnew=tmax
    if(tsnew.le.tmin) auxx=uload
    if(tsnew.le.tmin) auxw=ashw
    if(tsnew.gt.tmin) auxx=0.
    if(tsnew.gt.tmin) auxw=0.
    if(tsnew.le.thw.and.tsnew.gt.tmin) auxw=vahw*(thw-tsnew)
    if(auxw.le.0.) auxx=0.
    if(auxw.gt.0.) tsnew=tsnew+mcps*auxx
    strls=us*(tsold-strtrp)
    if(tsnew.le.tmin) tsnew=tsold-mcps*strls+mcps*au
    adump=tdump/mcps
    au=au-adump
    tsold=tsnew
    return
end
subroutine solair(angs, anwe, angw, ansr, theta, term, 
1ter, teew, teew, tesw, tenw, rdn, rdu, anaw, v)
c this subroutine calculates the solair temperature for 
c all of the exposed surfaces of the house from the hourly 
c radiation values, the angle of incidence on each surface 
c (calculated in subroutine), the absorptivity for solar 
c radiation for direct and diffuse radiation, and the 
c current value of ambient air temperature. If no solar 
c radiation is present, the solair temperature is the 
c ambient air temperature.
c
c set combined radiation - convection heat transfer coe?,
c see ASHRAE guide, chapter 23.
fcr=42.+15.6*v
c determine product of fcr and direct normal radiation.
c a value of 0.7 is used for absorbitivity.
adrdn=0.7*rdn/fcr
c determine product of fcr and diffuse radiation.
rhdu=rdu*0.7/fcr
c determine solair temperatures for each surface.
tern=tern+rhdu+adrdn*cos(ansnr)
ters=ters+adrdn*cos(theta)+rhdu
teew=teew+adrdn*cos(answe)+rhdu
tesw=tesw+adrdn*cos(answs)+rhdu
tenw=tenw+rhdu*cos(ansnw)*adrdn
return
end
subroutine demand(v,dir,fc,awen,awine,draw,uw,ug,teew,raws,awins,
  lad,ud,tesw,ars,surf,ters,teew,rawn,arn tenw,term,auc2,ac,
  tpr,aach,ach,svolbls,sub,heat1,winls,hlista)
tr=293.16

  c This subroutine calculates the building heat loss for
  c the house and insulation level specified as a function
  c of temperature, wind, and radiation influences.
  c
  c east side
  call fco(vvdir,90.,foc)
  fcoi=1./foc
  uwve=1./(uw+fcoi)
  uawve=1./(uaw+fcoi)
  ugv=1./(ug+fcoi)
  hle=uwve*awen*(tr-teew)
  if(teew.ge.tr) hle=0,
  c south side
  call fco(vvdir,180.,foc)
  fcoi=1./foc
  uwvs=1./(uw+fcoi)
  uawvs=1./(uaw+fcoi)
  ugdvs=1./(ug+fcoi)
  hls0=(uwvs*aavn*adr)*(tr-tesw)
  if(tesw.ge.tr) hls0=0.
  c west side
  call fco(vvdir,270.,foc)
  fcoi=1./foc
  uwvw=1./(uw+fcoi)
  uawvw=1./(uaw+fcoi)
  uavw=1./(ug+fcoi)
  hlwuwvw*aewer*(tr-teww)
  if(teww.ge.tr) hlw=0.
  c north side
  call fco(vvdir,360.,foc)
  fcoi=1./foc
  uwvn=1./(uw+fcoi)
  uawvn=1./(uaw+fcoi)
  uadvn=1./(ud+fcoi)
  urfvn=1./(urf+fcoi)
  hln=(uwvn*aavn*adr)*(tr-tenw)
  if(tenw.ge.tr) hln=0.
  c ceilings-attic losses
  auawe=uawve*aaraw
  auaww=uawvw*aaraw
  au2c=auc2/295.16
  aurn=arn*urfvn
  aurs=ars*urfvs
  avsum=au2c+aurn+aurst+auawe+auaww+ac*urfvs
  attmp=tatic(auc2,term,aurn,ters,aurst,ac,urfvs,ters,teew,teww,
  lauawe,auaww,avsum)
  hlc=au2c*(294.16-attmp)
  if(attmp.ge.294.16) hlc=0.
  c infiltration losses
  v2=v*2.30156
  hli=0.
if (ta.lt.tr) hli = (.10 + achw*v2 + achs*(tr-ta))*vol
  hli = hli*(tr-ta)

  c window losses
  wls = ugv*_awins
  if (ta.gt.tr) wls = 0.
  wln = ugv*_awinn
  if (ta.gt.tr) wln = 0.
  wle = ugv*_awine
  if (ta.gt.tr) wle = 0.
  wlw = ugv*_awine
  if (ta.ge.tr) wlw = 0.
  wlns = (wls+wln+wle+wlw)*(tr-ta)

  c total loss
  heatl = hle+hlso+hlw+hln+hlc+uls+hli+winls
  return
end
subroutine shg(ansi, rdn, rdu, insul, shan, moda)
  c This subroutine calculates the solar heat gain through
  c a window as a function of the angle of incidence of
  c direct radiation, the direct and diffuse components of
  c radiation, and the transmissivity of the window.
  c
dimension tau2(2), tau(2)
dimension slp2(2)
dimension b2(2)
data tau2(1), tau2(2)/0.92, 0.86/
data tau(1), tau(2)/.70, .62/
data b2(1), b2(2)/2.3657, 2.21143/
data slp2(1), slp2(2)/0.02628, 0.02457/
np=insul
apfc=.80
if(np.eq.3) np=2
np2=np-1
if(moda.ge.60. and moda.le.90) go to 1
  ang=arag*57.2957
if(ang.le.60.) tauw=tau2(np)
  if(ans.gt.60. and ans.lt.90.) tauw=b2(np)-slp2(np)*ang
  cani=cos(ansi)
  shan=((ansi*tauw*rdn+.5*rdu*tau(np))*1.-float(np2)*.10)*apfc
  go to 2
  shan=.5*rdu*tau(np)
1 continue
  return
end
subroutine fco(v, dir, waz, foc)
  c This subroutine calculates the surface film coefficient
  c according to the algorithm given by Kimura as a
  c function of wind direction and speed relative to the
  c building surface.
  c
  rwd = waz - dir
  rwd = abs(rwd)
  if(rwd .ge. 180) rwd = 360 - rwd
  if(rwd .ge. 90) go to 1
  if(v .le. 2.) vc = 0.5
  if(v .gt. 2) vc = 0.25 * v
     go to 2
  1 continue
  vc = 0.3 + 0.05 * v
  2 continue
  foc = 67.049 * (vc**.605) + 14.0
  return
end