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Thermal Model of Attic Systems with Radiant Barriers

Kenneth E. Wilkes

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ORNL/CON-262

Energy Division

THERMAL MODEL OF ATTIC SYSTEMS WITH RADIANT BARRIERS

K. E. Wilkes

Date Published - July 1991

Existing Buildings Research Program

Prepared for the
Tennessee Valley Authority
and the
U.S. Department of Energy
Office of Buildings Energy Research

Prepared by the
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37831
managed by
MARTIN MARIETTA ENERGY SYSTEMS, INC.
for the
U.S. DEPARTMENT OF ENERGY
Under Contract No. DE-AC05-84OR21400

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CONTENTS

LIST OF FIGURES v

LIST OF TABLES vii

ABSTRACT ix

EXECUTIVE SUMMARY xi

1. INTRODUCTION 1

2. OBJECTIVE 3

3. THERMAL MODEL 5
   - 3.1 CONDUCTION 5
   - 3.2 CONVECTION 10
   - 3.3 RADIATION 13
   - 3.4 VENTILATION 15
   - 3.5 MOISTURE 18
   - 3.6 HEAT BALANCES 21
   - 3.7 COMPUTER PROGRAMS 27

4. COMPARISON OF MODEL WITH EXPERIMENTS 33
   - 4.1 OWENS-CORNING FIBERGLAS 33
   - 4.2 JOY 34
   - 4.3 FLORIDA SOLAR ENERGY CENTER 44
   - 4.4 TENNESSEE VALLEY AUTHORITY 52
   - 4.5 MINERAL INSULATION MANUFACTURERS ASSOCIATION . . . 57

5. SUMMARY AND CONCLUSIONS 73

REFERENCES 75

APPENDIX A, RBSOR1 COMPUTER PROGRAM 79

APPENDIX B, RBSOR2 COMPUTER PROGRAM 103

APPENDIX C, RBSOR3 COMPUTER PROGRAM 119

APPENDIX D, SAMPLE INPUT FOR RBSOR1 137

APPENDIX E, SAMPLE INPUT FOR RBSOR2 141

APPENDIX F, SAMPLE INPUT FOR RBSOR3 145

LIST OF FIGURES

3.1. Schematic of residential attic showing heat transfer phenomena. 6

3.2. Heat transfer phenomena for truss radiant barrier . . 24

3.3. Flow chart for attic models 28

4.1 Comparison of predicted and measured heat fluxes for FSEC test with R-19 insulation and no radiant barrier 48

4.2. Comparison of predicted and measured heat fluxes for FSEC test with R-19 insulation and truss radiant barrier using RBSOR2 and emittance of 0.05 for RB bottom 48

4.3. Comparison of predicted and measured heat fluxes for FSEC test with R-19 insulation and truss radiant barrier using RBSOR1 and emittance of 0.05 for RB bottom 54

4.4. Comparison of predicted and measured heat fluxes for TVA test with R-30 insulation and no radiant barrier 54

4.5. Comparison of predicted and measured heat fluxes for TVA test with R-30 insulation and horizontal radiant barrier 58

4.6. Comparison of predicted and measured heat fluxes for TVA test with R-19 insulation and horizontal radiant barrier 58

4.7. Comparison of predicted and measured heat fluxes for TVA test with R-19 insulation and rafter radiant barrier using RBSOR1. 59

4.8. Comparison of predicted and measured heat fluxes for TVA test with R-11 insulation and horizontal radiant barrier 59

4.9. Comparison of predicted and measured heat fluxes for MIMA test with R-19 insulation and no radiant barrier 69

4.10. Comparison of predicted and measured heat fluxes for MIMA test with R-19 insulation and draped truss radiant barrier using RBSOR3 and emittance of 0.10 for RB bottom 69

4.11. Comparison of predicted and measured heat fluxes for MIMA test with R-19 insulation and draped truss radiant barrier using RBSOR1 and emittance of 0.10 for RB bottom 72

LIST OF TABLES

3.1. Correlations for convection coefficients. 12

4.1. Results of Owens-Corning Fiberglas tests. 35

4.2. Material properties for Owens-Corning Fiberglas tests 36

4.3. Comparison of predicted and measured heat flows for Owens-Corning Fiberglas steady-state tests. 37

4.4. Material properties for Joy's tests 39

4.5. Comparison of predicted and measured heat flows for Joy's data with a gabled roof 41

4.6. Comparison of predicted and measured heat flows for Joy's data with a flat roof 42

4.7. Comparison of predicted and measured heat flows for Joy's data with a flat roof (assuming 17-inch dead air space below roof) 43

4.8. Material properties for FSEC tests. 46

4.9. Comparison of predicted and measured heat flows for FSEC test with no radiant barrier (Cell 2). 47

4.10. Comparison of predicted and measured heat flows for FSEC test with truss radiant barrier (Cell 1) using RBSOR2 50

4.11. Comparison of predicted and measured heat flows for FSEC test with truss radiant barrier (Cell 1) using RBSOR1 53

4.12. Material properties for TVA tests. 56

4.13. Comparison of predicted and measured heat flows for TVA tests with R-30 insulation and no radiant barrier. 60

4.14. Comparison of predicted and measured heat flows for TVA tests with R-30 insulation and horizontal radiant barrier. 61

4.15. Comparison of predicted and measured heat flows for TVA tests with R-19 insulation and horizontal radiant barrier. 62

4.16. Comparison of predicted and measured heat flows for TVA tests with R-19 insulation and truss radiant barrier. 63

4.17. Comparison of predicted and measured heat flows for TVA tests with R-11 insulation and horizontal radiant barrier. 64

4.18. Material properties for MIMA tests 66

4.19. Comparison of predicted and measured heat flows for MIMA test with no radiant barrier. 67

4.20. Comparison of predicted and measured heat flows for MIMA test with draped truss radiant barrier using RBSOR3 70

4.21. Comparison of predicted and measured heat flows for MIMA test with draped truss radiant barrier using RBSOR1 71

ABSTRACT

This report summarizes the first phase of a project to model the thermal performance of radiant barriers. The objective of this phase of the project was to develop a refined model for the thermal performance of residential house attics, with and without radiant barriers, and to verify the model by comparing its predictions against selected existing experimental thermal performance data. Models for the thermal performance of attics with and without radiant barriers have been developed and implemented on an IBM PC/AT computer. The validity of the models has been tested by comparing their predictions with ceiling heat fluxes measured in a number of laboratory and field experiments on attics with and without radiant barriers. Cumulative heat flows predicted by the models were usually within about 5 to 10 percent of measured values. In future phases of the project, the models for attic/radiant barrier performance will be coupled with a whole-house model and further comparisons with experimental data will be made. Following this, the models will be utilized to provide an initial assessment of the energy savings potential of radiant barriers in various configurations and under various climatic conditions.

EXECUTIVE SUMMARY

Experiments by a number of organizations have clearly demonstrated that radiant barriers (RBs) are effective in reducing ceiling heat flows, especially under cooling conditions. While the results from these experiments are generally in qualitative agreement in indicating heat flow reductions, there is a controversy regarding the magnitude of the thermal performance of these systems. The reasons for the differences among the various results are not completely understood at present, but the different conditions under which the experiments were run may contribute to these differences. Factors such as weather conditions, type and location of radiant barrier, attic ventilation method and rate, and size and geometry of attic space may contribute to the observed differences in results. There is clearly a need to understand the extent to which experimental results differ and the reasons for these differences.

Many of the experiments thus far have been limited to time periods of a few days or weeks at various times during the year, and have been performed in the warmer parts of the country. There is a need to assess the performance of radiant barriers on a seasonal and annual basis, as well as in a variety of climatic conditions.

Thermal models offer means for addressing both these issues. They will be useful in identifying reasons for differences among the various sets of data, and in extrapolating the experimental results to other conditions. This report summarizes the first phase of a project to model the thermal performance of radiant barriers. The objective of this phase of the project was to develop a refined model for the thermal performance of residential attics, with and without radiant barriers, and to verify the model by comparing its predictions against selected existing experimental thermal performance data.

In future phases of the project, the models for attic/radiant barrier performance will be coupled with a whole-house model and further comparisons with experimental data will be made. Following this, the models will be utilized to provide an initial assessment of the energy savings potential of radiant barriers in various configurations and under various climatic conditions.

Models for the thermal performance of attics with and without radiant barriers have been developed and implemented on an IBM PC/AT computer. The models consist of systems of heat balance equations at the interior and exterior surfaces of the ceiling, roof sections, and gables, as well as a heat balance on the air mass within the attic. The models discussed in this report are based on previously published models, but have several improvements and extensions. Improvements and extensions include more detailed convection heat transfer coefficients, inclusion of latent heat effects due to the sorption and desorption of moisture at the wood surfaces that face the attic space, an algorithm to estimate the rate of flow of ventilation air through the attic, and additional heat balances to handle the extra air spaces created by the truss radiant barrier system.

The validity of the models has been tested by comparing their predictions with the results of a number of laboratory and field experiments on attics with and without radiant barriers. Cumulative heat flows for attics without radiant barriers are generally predicted to within about 5 to 10 percent of the measured values. Cumulative heat flows for attics with radiant barriers are often also predicted with this accuracy. Model predictions for instantaneous heat flows are generally not as good as those for cumulative heat flows over periods of days; here, the agreement between predicted and measured values may be on the order of 25 percent.

The comparisons have raised several questions about the applicability of the models. For the small test cells used by the Tennessee Valley Authority (TVA), the models predicted high attic air

change rates, and as a consequence, the predicted heat flows were low. More reasonable air change rates and heat flows were predicted when the vent areas were arbitrarily reduced by a factor of 10. For the large scale tests by the Mineral Insulation Manufacturers Association (MIMA), the models predicted very reasonable air change rates and heat flows. Thus the ventilation algorithms may not be applicable for small test cells, but may be adequate for large scale tests. More research on attic ventilation with a range of attic sizes is needed to understand this better.

With a truss radiant barrier, radiation across the attic space is still an important heat transfer mechanism, as evidenced by the runs with the convection coefficient at the top of the insulation set to zero. Because of this, the choice of an effective emittance for the bottom of the roof presents a problem. For the FSEC tests, an emittance of 0.05 worked best, while for the MIMA tests, a higher emittance was needed. This may be due to the two different truss configurations. For the FSEC tests, the radiant barrier was placed 3.5 inches below the roof between 2 x 10 inch rafters. Consequently, the exposed surfaces of the rafters would have been cooler than the radiant barrier and an area averaged emittance would not have been appropriate. For the MIMA tests, the radiant barrier was draped between 2 x 4 inch rafters and hot sides of the rafters were exposed. With this configuration, an area averaged emittance would have been appropriate. The emittance values used here were based on simple engineering calculations; more detailed analyses would be needed to develop a more rigorous esimation of this parameter.

For some cases, the effects of moisture sorption/desorption could be included in the models. For these cases, the inclusion of moisture effects improved the model predictions for the nighttime heat flows, but did not consistently improve the predictions for the daytime heat flows.

The validity of the models has been demonstrated to the extent that they may form the basis for providing an initial assessment of the energy savings potential for radiant barriers. However, further refinements are needed to answer questions that remain about the differences among the various sets of experimental data. Further refinements would include more detailed algorithms for the air flow patterns within the attic space, especially in the presence of a truss radiant barrier. Experiments carried out under carefully controlled laboratory conditions, both steady-state and dynamic, would greatly assist in these refinements. Flow visualization experiments would also aid in developing flow pattern algorithms.

1. INTRODUCTION

Experiments by a number of organizations have clearly demonstrated that radiant barriers (RBs) are effective in reducing ceiling heat flows, especially under cooling conditions. While the results from these experiments are generally in qualitative agreement in indicating heat flow reductions, there is a lack of agreement regarding the magnitude of the thermal performance of these systems. The reasons for the differences among the various results are not completely understood at present, but the different conditions under which the experiments were run may contribute to these differences. Factors such as weather conditions, type and location of radiant barrier, attic ventilation method and rate, and size and geometry of attic space may contribute to the observed differences in results. There is clearly a need to understand the extent to which experimental results differ and the reasons for these differences.

Many of the experiments thus far have been limited to time periods of a few days or weeks at various times during the year. In addition, most of the experiments have been performed in the warmer parts of the country, such as Florida and Tennessee. There is a need to assess the performance of radiant barriers on a seasonal and annual basis, as well as in a variety of climatic conditions.

Thermal models offer means for addressing both of these issues. They will be useful in sorting out reasons for differences among the various sets of data, and in extrapolating the experimental results to other conditions. This report summarizes the first phase of a project to model the thermal performance of radiant barriers. It covers the development of the thermal models and comparisons of the model with selected available experimental data. In future phases of the project, the models for attic/radiant barrier performance will be coupled with a whole-house model and further comparisons with experimental data will be made. Following this, the models will be utilized to provide an initial assessment of the energy savings potential of radiant barriers in various configurations and under various climatic conditions.

2. OBJECTIVE

The objective of this phase of the project was to develop a refined model for the thermal performance of residential attics, with and without radiant barriers, and to verify the model by comparing its predictions against selected existing experimental thermal performance data.

3. THERMAL MODEL

A number of models for the thermal performance of attics have been developed. During a previous review of the models that were available in 1979,[1] it was concluded that the best model was the one that had been developed by B. Peavy of the National Bureau of Standards (NBS).[2] Several improvements were made to the model.[3] In this project, additional improvements and extensions have been made. These include more detailed convection heat transfer coefficients, inclusion of latent heat effects due to the sorption and desorption of moisture at the wood surfaces that face the attic space, an algorithm to estimate the rate of flow of ventilation air through the attic, and additional heat balances to handle the extra air spaces created by a radiant barrier system.

The sketch of an attic given in Figure 1 shows the various heat transfer mechanisms that occur within an attic. Although the sketch shows ventilation occurring at soffit-and-ridge vents, the location of the vents may be at other locations, such as at the gables. The model treats all of these phenomena through a system of heat balance equations at the interior and exterior surfaces of the ceiling, roof sections, and gables, as well as a heat balance on the air mass within the attic. To handle the case of raised trusses, short vertical walls at the eaves are also included. Each of the surfaces is assumed to be isothermal. Thus, for an attic consisting of a ceiling, two roof sections, two gables, two vertical eave sections, and one air space, a total of 15 heat balance equations are used. In this section, detailed descriptions of each of the phenomena are presented separately. Then the phenomena are combined into the heat balance equations. Finally, the structure of the computer programs is given.

3.1 CONDUCTION

As with most building simulation codes, the models developed here utilize the thermal response factor method to analyze conduction

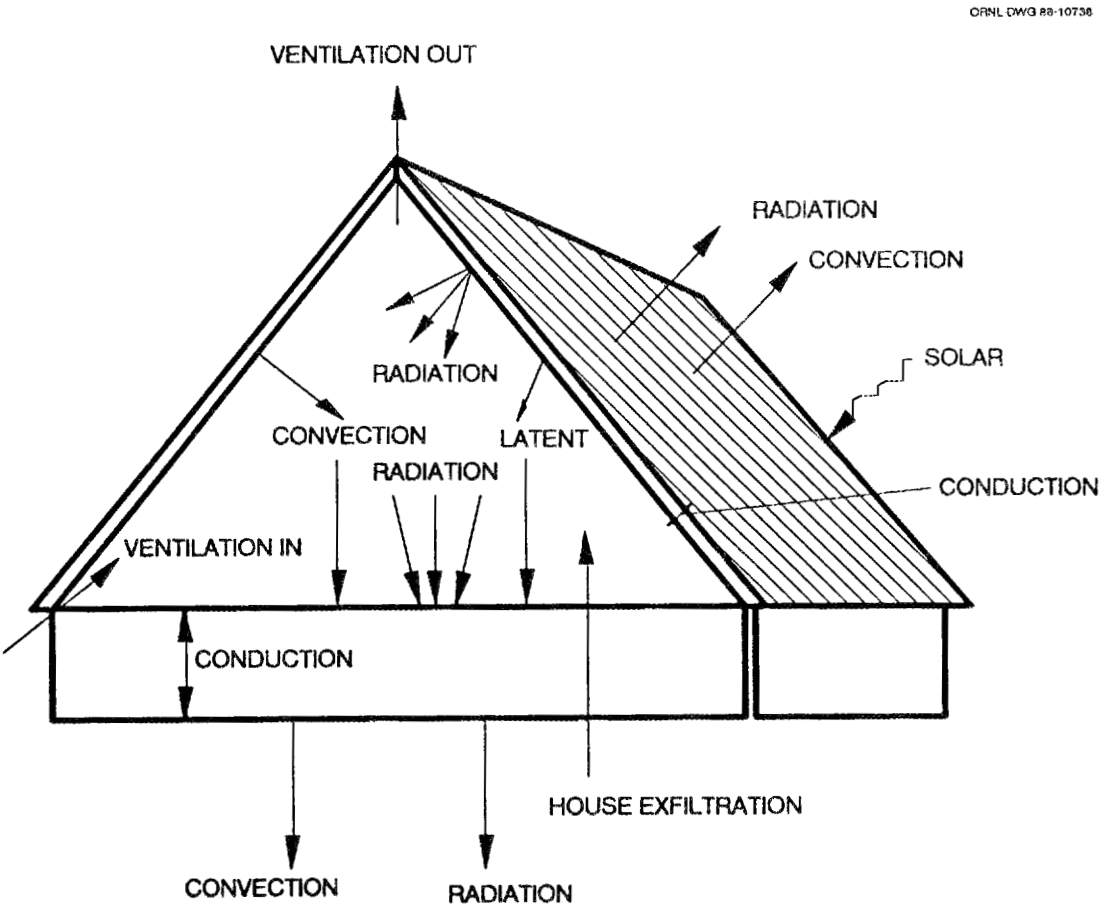

Fig. 3.1. Schematic of residential attic showing heat transfer phenomena.

through building envelope sections. The thermal response factor method was developed by Mitalas and Arseneault,[4] and was extended by Kusuda.[5] The method is based on an exact analytical solution of the heat conduction equation for one-dimensional heat flow through a multilayer slab having temperature-independent thermal properties. The only approximation is that the surface temperatures are taken to vary linearly with time between time steps. For analysis of buildings, the time step is normally taken to be one hour. The response factor equations relate the heat fluxes at the surfaces of the slab to the present and previous temperatures at the two surfaces. The equations are

$$QI = \sum_{j=0}^{\infty} Z'(j)\ (TIS(j) - TR) - \sum_{j=0}^{\infty} Y'(j)\ (TOS(j) - TR) \qquad (1)$$

$$QO = \sum_{j=0}^{\infty} Y'(j)\ (TIS(J) - TR) - \sum_{j=0}^{\infty} X'(j)\ (TOS(j) - TR) \qquad (2)$$

where

QI = heat flux at inside surface at present time (note, the positive heat flow direction is from the inside to the outside)

QO = heat flux at outside surface at present time

TIS(j) = temperature at inside surface j hours previous to present time

TOS(j) = temperature at outside surface j hours previous to present time

X'(j), Y'(j), Z'(j) = response factors

TR = reference temperature

The response factors are determined from a sequence of calculations that involve the thermal conductivity, specific heat, density, and thickness of each of the layers in the multilayer slab. An efficient computer program for calculating the response factors has been

developed by George Walton of the National Institute of Standards and Technology, and was made available for this project.[6]

The efficiency of the response factor calculations can be increased by making use of the fact that after a sufficient number of terms, the ratio of two consecutive response factors becomes constant. This is expressed by

$$\frac{X'(j+1)}{X'(j)} = \frac{Y'(j+1)}{Y'(j)} = \frac{Z'(j+1)}{Z'(j)} = CR \qquad j \geqslant N \tag{3}$$

where CR is the common ratio, and N is a sufficiently large number.

The common ratio is used to define a new set of functions, called the first order conduction transfer functions, X(j), Y(j), and Z(j), which are given by

$$X(0) = X'(0) \tag{4}$$

$$Y(0) = Y'(0) \tag{5}$$

$$Z(0) = Z'(0) \tag{6}$$

$$\left.\begin{aligned} X(j) &= X'(j) - CR\ X'(j-1) \quad (7)\\ Y(j) &= Y'(j) - CR\ Y'(j-1) \quad (8)\\ Z(j) &= Z'(j) - CR\ Z'(j-1) \quad (9)\end{aligned}\right\} \quad \text{for } j \leqslant N$$

$$\left.\begin{aligned} X(j) &= 0 \quad (10)\\ Y(j) &= 0 \quad (11)\\ Z(j) &= 0 \quad (12)\end{aligned}\right\} \quad \text{for } j > N$$

With the conduction transfer functions, the heat fluxes and surface temperatures are related by:

$$QI = \sum_{j=0}^{N} Z(j)\ (TIS(j) - TR) - \sum_{j=0}^{N} Y(j)\ (TOS(j) - TR) + CR\ QI' \tag{13}$$

$$QO = \sum_{j=0}^{N} Y(j)\ (TIS(j) - TR) - \sum_{j=0}^{N} X(j)\ (TOS(j) - TR) + CR\ QO' \tag{14}$$

where QI′ = heat flux at inside surface at previous time step

QO′ = heat flux at outside surface at previous time step

N = number of significant conduction transfer functions.

When parallel heat flow paths occur in an envelope component, separate response factors for each path may be needed. However, if the boundary temperatures of the two paths may be assumed to be equal, then the response factors may be added together as

$$X' = A_1 X'_1 + A_2 X'_2 \tag{15}$$

where

A_1, A_2 = area fractions for paths 1 and 2

X'_1, X'_2 = response factors for paths 1 and 2

and similarly for the Y′ and Z′ response factors. Parallel conduction transfer functions may be calculated from these parallel response factors, provided that the common ratio for the path with the largest number of significant terms is used.

The original derivation of the response factor technique relied upon the assumption of temperature-independent thermal properties. An approximate method has been developed to account for the temperature dependence of the thermal properties.[3] The thermal transmission coefficient of the component is taken to vary linearly with temperature as

$$U = U_{TR} \, [1 + b(T - TR)] \tag{16}$$

The conduction transfer function equations then become

$$QI = \sum_{j=0}^{N} Z(j) \, (TIS(j) - TR) - \sum_{j=0}^{N} Y(j) \, (TOS(j) - TR) + CR \, QI'$$

$$+ b/2 \sum_{j=0}^{N} Z(j) \, (TIS(j) - TR)^2 - b/2 \sum_{j=0}^{N} Y(j) \, (TOS(j) - TR)^2 \tag{17}$$

$$QO = \sum_{j=0}^{N} Y(j)\ (TIS(j) - TR) - \sum_{j=0}^{N} X(j)\ (TOS(j) - TR) + CR\ QO'$$

$$+ b/2 \sum_{j=0}^{N} Y(j)\ (TIS(j) - TR)^2 - b/2 \sum_{j=0}^{N} X(j)\ (TOS(j) - TR)^2 \quad (18)$$

These equations will be used in the system of heat balance equations.

3.2 CONVECTION

Convection heat transfer from the interior and exterior surfaces of the envelope components is calculated using correlations from the literature.[7] The coefficients are based on correlations that have been developed for isolated isothermal flat plates. The correlations are in the form of a Nusselt number, Nu, as a function of a Rayleigh number, Ra, a Grashof number, Gr, or a Reynolds number, Re, where

$$Nu = hL/k \quad (19)$$

$$Ra = g\beta\rho C_p \Delta T\ L^3/\nu k \quad (20)$$

$$Gr = Ra/Pr \quad (21)$$

$$Pr = \nu/\alpha \quad (22)$$

$$Re = V\ L/\nu \quad (23)$$

and

h = convection heat transfer coefficient
L = characteristic length of plate
k = thermal conductivity of air
g = acceleration of gravity
β = volume coefficient of expansion of air
ρ = density of air
C_p = specific heat of air
ΔT = temperature difference between surface and air
ν = kinematic viscosity of air
Pr = Prandtl number for air

α = thermal diffusivity of air

V = velocity of air stream

The model accounts for the temperature dependence of the properties of air by evaluating them at the film temperature, which is defined as the average of the temperatures of the surface and the air. Relationships for the temperature dependent properties were obtained from NBS Circular 564, which is a standard reference.[8]

The model utilizes correlations that have been developed for various orientations of the plate with respect to gravity, and for the direction of heat flow (up vs down). Correlations for both laminar and turbulent flow are used, with the choice depending upon the magnitude of the Rayleigh number for natural convection and of the Reynolds number for forced convection. Separate coefficients are calculated for natural and forced flow, and a mixed coefficient is calculated by taking the third root of the sum of the cubes of the two separate coefficients.[9]

The correlations used in the model are given in Table 3.1. They account for the effects of the following variables: surface-to-air temperature difference, heat flow direction, film temperature, surface size, and surface orientation. The correlations are contained in a subroutine called HCON. Values of surface temperature, air temperature, plate tilt angle, plate characteristic length, a flag to denote whether the plate faces up or down, and air speed past the plate are passed to the subroutine. The subroutine returns the mixed convection coefficient. For exterior surfaces, the air speed is taken to be the wind speed obtained from meteorological data. For interior surfaces, a crude estimate of air speed is obtained by dividing the attic ventilation volume flow rate by an average cross-sectional area for the attic. For the interior surfaces, a crude estimate for air speed should suffice, since natural convection should dominate over forced convection.

Table 3.1. Correlations for convection coefficients.

I. Natural Convection:

A. Horizontal surface, heat flow up

$Nu = 0.54\ Ra^{1/4}$ for $Ra < 8 \times 10^6$

$Nu = 0.15\ Ra^{1/3}$ for $Ra > 8 \times 10^6$

B. Horizontal surface, heat flow down

$Nu = 0.58\ Ra^{0.2}$

C. Vertical surface

$Nu = 0.59\ Ra^{1/4}$ for $Ra < 1 \times 10^9$

$Nu = 0.10\ Ra^{1/3}$ for $Ra > 1 \times 10^9$

D. Nearly horizontal surface (tilt angle less than 2 degrees), heat flow down

$Nu = 0.58\ Ra^{0.2}$

E. Tilted surfaces (greater than 2 degrees tilt), heat flow down

$Nu = 0.56\ (Ra \sin(\varphi))^{1/4}$ φ = tilt angle

F. Tilted surface, heat flow up

$Nu = 0.56\ (Ra \sin(\varphi))^{1/4}$ for $Ra/Pr < Gr_c$

$Nu = 0.14\ (Ra^{1/3} - (Gr_c\ Pr)^{1/3})$
$+ 0.56\ (Gr_c Pr \sin(\varphi))^{1/4}$ for $Ra/Pr > Gr_c$

$Gr_c = 1 \times 10^6$ for $\varphi < 15$ degrees

$Gr_c = 10**(\varphi/(1.1870 + 0.0870*\varphi))$
for 15 degrees $< \varphi < 75$ degrees

$Gr_c = 5 \times 10^9$ for $\varphi > 75$ degrees

II. Forced Convection

$Nu = 0.664\ Pr^{1/3}\ Re^{1/2}$ for $Re < 5 \times 10^5$

$Nu = Pr^{1/3}\ (0.037\ Re^{0.8} - 850)$ for $Re > 5 \times 10^5$

The applicability of correlations based on isolated isothermal plates exposed to an isothermal air mass has been questioned. A possible improvement is to use correlations for isolated isothermal plates exposed to an air mass that is stratified.[10,11] However, a better improvement would be to use correlations that account for coupling of the various surfaces rather than those for isolated plates. A number of studies have been reported for convection within a triangular enclosure.[12-18] These correlations have two deficiencies for attic modeling. The first is that they were obtained for systems that have isothermal surfaces, even at the intersections of the surfaces. This leads to a large contribution due to conduction in the "tip region." For the analytical studies, this arises from a mathematical singularity. For the experimental studies, this arises from the large lateral conduction through the surfaces, which are usually made of metal. In a real attic, the contacting surfaces will not have large lateral conduction, and the "tip region" will not contribute an overwhelmingly large amount to the total heat transfer. The other deficiency is that the correlations were obtained for enclosures that are sealed, and so would have limited applicability to attics that are ventilated.

3.3 RADIATION

Radiation interchanges within the attic space are handled using the enclosure method described by Sparrow and Cess.[19] With this method, each of the surfaces is assumed to be plane, opaque, gray, and isothermal, to be diffusely emitting and reflecting, and to have a uniform radiant flux over the surface. The assumption of diffuse emission and reflection for radiant barrier surfaces may be questioned. Very flat radiant barrier surfaces would be expected to exhibit specular properties. However, real radiant barrier surfaces are usually not flat and hence the diffuse assumption is probably more appropriate.

The net radiant heat flux away from surface i is given by

$$Q_{ri} = \sum_{j=1}^{M} G_{ij}\ \sigma(T_i^4 - T_j^4) \tag{24}$$

with the following relations

$$G_{ij} = \frac{\epsilon_i}{1 - \epsilon_i} \qquad \psi_{ij}$$

ψ_{ij} = inverse of the matrix χ_{ij}

$$\chi_{ij} = \frac{\delta_{ij} - (1 - \epsilon_i)F_{ij}}{\epsilon_i} \qquad \delta_{ij} = \begin{cases} 0 & i \neq j \\ 1 & i = j \end{cases}$$

F_{ij} = radiation view factor from surface i to surface j

ϵ_i = emittance of surface i

σ = Stefan-Boltzmann constant

M = number of surfaces in enclosure

The heat flux equation may be cast into a form that is linear in the temperatures by factoring as

$$Q_{ri} = \sum_{j=1}^{M} G_{ij}\ \sigma(T_i^2 + T_j^2)\ (T_i + T_j)\ (T_i - T_j)$$

$$= \sum_{j=1}^{M} HR_{ij}\ (T_i - T_j) \tag{25}$$

The quantities appearing in these equations are calculated in several subprograms: subroutine VIEW2, and functions FMN, FP, and HRAD. Function FMN calculates the view factor between two rectangular surfaces that meet at an angle and share a common edge, while function FP calculates the view factor between two parallel surfaces that have the same dimensions. Expressions for the two view factors are given by Sparrow and Cess. The functions themselves are based on those given by Peavy, with some necessary modifications. The functions have been verified by comparison with the calculations of Feingold.[20] Subroutine VIEW2 calculates the view factors among the surfaces that face the attic space, using view factor algebra and calls to functions FMN and

FP. The G_{ij} matrix is also calculated within VIEW2. The HR_{ij} matrix is calculated by function HRAD using G_{ij}, T_i, and T_j as inputs.

The algorithm for radiation interchanges allows each of the surfaces to have different emittances. The algorithm accounts for all inter-reflections within the enclosure and properly accounts for the T^4 (Stefan-Boltzmann) law for radiation exchange.

3.4 VENTILATION

Heat transfer to the ventilation air is treated by an extension of the method used by Peavy. With this method, the temperature of the air is assumed to increase (or decrease) as it moves along a fictitious flow path and picks up heat by convection from the surrounding surfaces. This is expressed by the following first order ordinary differential equation:

$$\dot{m}\, C_p\, dT/dx = \sum_{j=1}^{M} A(j)\, HC(j)\, (TIS(j) - T) \tag{26}$$

where

$\dot{m}$ = mass flow rate of ventilation air

C_p = specific heat of air

T = air temperature at position x

x = normalized position (0-1) along flow path

A(j) = area of surface j in contact with ventilation air

HC(j) = convection heat transfer coefficient at surface j

TIS(j) = temperature of surface j

M = number of surfaces in contact with ventilation air

In the absence of a detailed picture of the ventilation air flow pattern within the attic, the simplifying assumption has been made that equal proportions of area of each surface are contacted as the air flows along a differential length of its flow path.

Integrating this equation yields the following expression for the temperature as a function of flow path position:

$$T = T_o \exp(-ax) + b\,[1 - \exp(-ax)] \tag{27}$$

where

T_o = temperature at x = 0

$$a = \sum_{j=1}^{M} A(j)\ HC(j)/\dot{m}C_p$$

$$b = \sum_{j=1}^{M} A(j)\ HC(j)\ TIS(j) / \sum_{j=1}^{M} A(j)\ HC(j)$$

An average air temperature is defined by

$$TA = \int_0^1 T\ dx$$

$$= b\,[1 + (\exp(-a) - 1)/a] - T_o/a\,[\exp(-a) - 1] \tag{28}$$

and the temperature of the air exiting from the attic at x = 1 is

$$TE = b\,[1 - \exp(-a)] + T_o \exp(-a) \tag{29}$$

The flow rate of ventilation air is determined from a combination of stack and wind pressure effects. For the stack effect calculation, the air inside the attic space is assumed to be well-mixed, and relations from Chapter 22 of the 1985 ASHRAE Handbook of Fundamentals are used.[21] The volume flow rate due to the stack effect is given by

$$\dot{V}_S = C_D\ A\ [2gh\ (TA - T_o)/TA]^{1/2} \qquad \text{for } TA > T_o \tag{30}$$

$$\dot{V}_S = C_D\ A\ [2gh\ (T_o - TA)/T_o]^{1/2} \qquad \text{for } T_o > TA \tag{31}$$

where

$\dot{V}_S$ = volume flow rate due to stack effect

C_D = discharge coefficient, taken to be 0.65

A = net free area of the lesser of the vent inlet and outlet areas

h = height of the neutral pressure level from the lower opening

T_o = absolute temperature of inlet air

TA = average absolute temperature of air in attic

The height of the neutral pressure level is given by

$$h = H/(1 + (AI/AO)^2\ TA/T_o) \text{ for } TA > To \tag{32}$$

$$h = H/(1 + (AI/AO)^2\ T_o/TA) \text{ for } To > TA \tag{33}$$

where

H = difference in elevation between inlet and outlet vents

AI = net free area of inlet vents

AO = net free area of outlet vents

The volume flow rate due to wind pressure is given by

$$\dot{V}_W = C_F\ A\ WS \tag{34}$$

where

C_F = discharge coefficient

A = net free area of the lesser of the vent inlet and outlet areas

WS = wind speed

From data given by Burch and Treado[22], the discharge coefficients for the wind pressure effect are estimated to be 0.38 for soffit and ridge vents, and 0.54 for soffit and gable vents. For soffit vents only, C_F is estimated from

$$C_F = 0.089 + 0.132\ \sin^{2.5}D \tag{35}$$

where

D = wind direction, measured from a direction parallel to the ridge, radians

Mass flow rates for the stack and wind pressure effects are obtained by multiplying the volume flow rates by the density of the air. A total mass flow rate is given by

$$\dot{m} = (\dot{m}_S^2 + \dot{m}_W^2)^{1/2} \tag{36}$$

Finally, the adjustment recommended by ASHRAE is made to account for unequal inlet and outlet vent areas

$$\dot{m} = [1 + 0.4077\ (1 - (A_{min}/A_{max})^{1.5})]\ (\dot{m}_S^2 + \dot{m}_W^2)^{1/2} \tag{37}$$

where the quantity in parentheses is a fit to the graph in Fig. 3.2 on page 22.7 of the 1985 ASHRAE Handbook of Fundamentals. The air flow due to exfiltration of air from the house into the attic space is added to the flow due to the stack and wind pressure effects. The algorithm for estimating ventilation rates is embodied in a subroutine called VENT.

Although some other results in the literature are in qualitative agreement,[23,24] there appears to be a good deal of uncertainty in this ventilation algorithm. Burch[25] has suggested that the ventilation rates he and Treado measured may be in error because of problems of mixing tracer gases in an attic. Ober[26] has suggested that a better stack ventilation rate might be obtained by using the roof temperature rather than the average air temperature as the driving force during the daytime hours. Additional experimental data appear to be needed to develop better algorithms for ventilation.

3.5 MOISTURE

Approximations have been built into the models to account for the latent heat effects due to sorption and desorption of moisture at the wood surfaces that face the attic space. These generally follow the suggestions given by Burch, et. al.[27] and Cleary.[28] In this model, the wood surface is assumed to be in moisture equilibrium with a thin layer of air adjacent to the surface. The humidity ratio of this layer of air is given by[28]

$$\omega_s = (b + c\ u + d\ u^2 + e\ u^3)\ \ \exp(T/a) \tag{38}$$

where

ω_s = humidity ratio of air near wood surface

T = temperature of wood surface

u = moisture content of wood (dimensionless fraction)

a, b, c, d = constants from fit to equilibrium moisture content data.

The rate of transfer of moisture from the air in the attic space to the surface is given by

$$\dot{m}_w = h_w (\omega_a - \omega_s) \tag{39}$$

where

$\dot{m}_w$ = mass flow rate of moisture per unit area of exposed wood surface

ω_a = humidity ratio of air in attic space

h_w = mass transfer coefficient

The mass transfer coefficient is obtained from the analogy between heat and mass transfer as

$$h_c/(h_w C_p) = (\alpha/D)^{2/3} \approx 1 \tag{40}$$

where

h_c = convection heat transfer coefficient

C_p = specific heat of air

α = thermal diffusivity of air

D = coefficient for diffusion of water vapor through air

The humidity ratio of the attic air is obtained by performing a steady-state moisture balance on the attic space, including diffusion of moisture through the boundary surfaces, convection of moisture into the attic space from the outside air and from exfiltration from the house, convection of moisture out of the attic space by the ventilation air, and moisture transfer to or from the wood surfaces. The attic moisture balance is given by

$$\sum_{j=1}^{M} A(j)\ Perm(j)\ (P(j) - P_a) + \dot{m}_v\ (\omega_o - \omega_a) + \dot{m}_E\ (\omega_i - \omega_a)$$

$$+ \sum_{j=1}^{M} h_w(j)\ A'(j)\ (\omega_s(j) - \omega_a) = 0 \qquad (41)$$

where

Perm (j) = water vapor permeance of surface j

$\dot{m}_v$ = mass flow rate of ventilation air

$\dot{m}_E$ = mass flow rate of exfiltration air

$\omega_s(j)$ = humidity ratio at surface j

ω_a = humidity ratio of air in attic space

ω_o = humidity ratio of outside air

ω_i = humidity ratio of indoor air

P(j) = partial pressure of water vapor in air on outside of surface j

P_a = partial pressure of water vapor in attic air

$h_w(j)$ = water vapor mass transfer coefficient at surface j

A(j) = area of surface j

A'(j) = exposed wood area at surface j

When the humidity ratio of the attic air and the mass transfer rates have been calculated, the heat transferred to the surface by latent heat effects, Q_{lat}, is given by

$$Q_{lat} = \dot{m}_w\ h_v \qquad (42)$$

where h_v = latent heat of vaporization of water. For this model, h_v has been taken to have a constant value of 1060 Btu/lb.

The mass transfer to a surface is used to estimate a new surface moisture content, assuming that only a thin layer of wood participates in the moisture exchanges.

It should be noted that the intent of this treatment of moisture is only to estimate the effect of latent heats on the heat flow rates, and not to determine the accumulation of moisture itself. An estimation of moisture accumulation rates over long periods of time would require a more detailed treatment than is used here.

The algorithms for calculating moisture effects are embodied in several subprograms. The humidity ratio at the wood surface is calculated by function WDHUM. Subroutine PSY is used to calculate humidity ratios and partial pressures of water vapor from known values of air temperature and relative humidity. The mass transfer coefficients are calculated in subroutine HMASS, and the moisture balance is performed in subroutine MOIST.

3.6 HEAT BALANCES

The heat balance equations combine the heat flows by various mechanisms at the inside and outside surfaces of the components of the attic envelope, and on the attic air mass. The heat balance at an interior surface, i.e. one facing the attic space, is obtained by summing the contributions due to conduction through the component, radiation interchanges with each of the other surfaces that it sees, convection exchanges with the attic air mass, and latent heat loads due to moisture sorption/desorption. With the notations used above, the interior heat balances are

$$\sum_{j=0}^{N} Z(i,j)\ (TIS(i,j) - TR) - \sum_{j=0}^{N} Y(i,j)\ (TOS(i,j) - TR)$$

$$+b(i)/2 \sum_{j=0}^{N} Z(i,j)\ (TIS(i,j)-TR)^2 - b(i)/2 \sum_{j=0}^{N} Y(i,j)(TOS(i,j)-TR)^2$$

$$+ CR(i)\ QI'(i) + HC(i)\ (TIS(i,0) - TA)$$

$$+ \sum_{\substack{k=1 \\ k\neq i}}^{M} HR(i,k)\ (TIS(i,0) - TIS(k,0)) - \dot{m}_w(i)\ h_v = 0 \qquad (43)$$

In these equations, the index i refers to the surface for which the heat balance is being written. Index k refers to the other surfaces that face the attic space, and j is the index for the conduction transfer function time sequence, with j = 0 representing the current time. An equation of this form is obtained for each of the surfaces facing the attic space.

The heat balance at the exterior surface relates the heat conducted through the envelope surface to the heat convected to the outdoor air, the heat radiated by the surface to the surroundings, and the solar radiation absorbed by the surface. Since the exterior surface of the bottom of the attic is the ceiling of the house, the balance is modified to allow convection to the indoor air, radiation to the surfaces of the room below the attic, and no direct absorption of solar radiation. The exterior heat balances have the form:

$$\sum_{j=0}^{N} Y(i,j)\ (TIS(i,j) - TR) - \sum_{j=0}^{N} X(i,j)\ (TOS(i,j) - TR)$$

$$+b(i)/2 \sum_{j=0}^{N} Y(i,j)\ (TIS(i,j)-TR)^2 - b(i)/2 \sum_{j=0}^{N} X(i,j)(TOS(i,j)-TR)^2$$

$$+ CR(i)\ QO'(i) + HC(i)\ (T_o - TOS(i,0))$$

$$+ HR(i)\ (T_s - TOS(i,0)) + \alpha(i)\ Q_s(i) = 0 \qquad (44)$$

where

T_s = temperature of surroundings

$\alpha(i)$ = solar absorptance of surface i

$Q_s(i)$ = solar radiation incident on surface i

At this point in the development of the computer programs, several approximations have been made for the exterior surface heat balances. For roof surfaces, the solar radiation is taken to be equal to that on a horizontal surface, while no solar radiation is assumed to be incident on the other surfaces. Also, the temperature of the

surroundings has been taken to be equal to the ambient air temperature. Later versions of the program will contain more detailed algorithms for incident solar radiation and for effective sky temperatures.

The heat balance on the attic air mass accounts for the heat convected to the air from each of the surfaces facing the attic space, convection of outdoor air into the space, and convection of attic air out of the space. With the model given above for the temperature rise of the ventilation air, the attic air heat balance is given by

$$\sum_{i=1}^{M} A(i)\ HC(i)\ TIS(i,0) \quad - \quad C_1/(\ 1 + C_2C_3)\ \ TA$$

$$= \quad \dot{m}_v\ C_p\ T_o\ C_3/(\ 1 + C_2C_3) \tag{45}$$

where

$$C_1 = \sum_{i=1}^{M} A(i)\ HC(i)$$

$$C_2 = \dot{m}_v\ C_p/\ C_1$$

$$C_3 = \exp(-1/C_2) - 1$$

The treatment of the truss radiant barrier configuration requires additional heat balances, as shown in Fig. 3.2. These are similar in form to the heat balances given above. The surfaces for the model are taken to be: (1) the plane of the radiant barrier, and (2) the plane of the bottom surface of the roof. Both these surfaces are assumed to be isothermal. With these two boundary temperatures, one heat balance equation consists of conduction through the rafter (assumed to be one-dimensional), convection to the air within the space between the radiant barrier and the roof (using the average air temperature), and radiation across the air space (assuming the lateral surface of the rafter to have no net radiant flux). It should be noted that the emittance of both sides of the radiant barrier may be specified independently. The emittance of the bottom side of the radiant barrier surface may be replaced with an effective emittance that represents

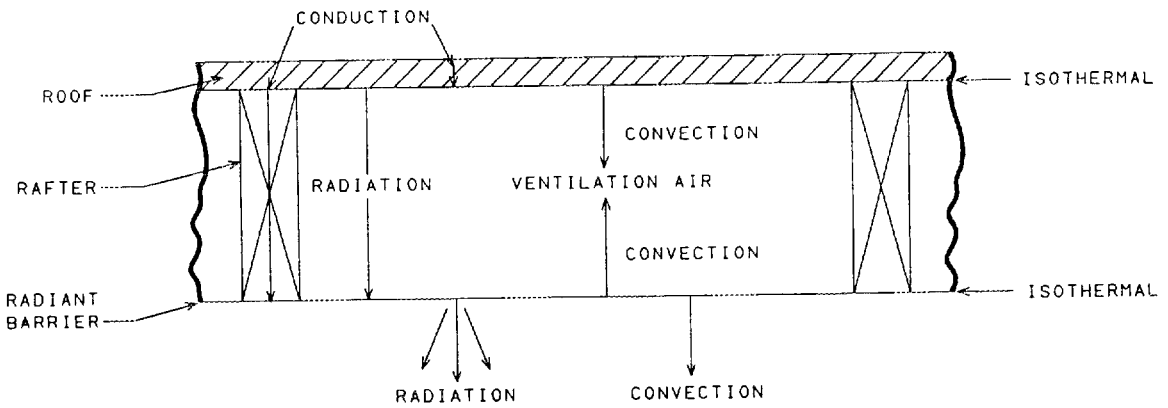

Fig. 3.2. Heat transfer phenomena for truss radiant barrier

both the emittance of the radiant barrier material itself as well as the emittance of exposed wood framing surfaces.

The other equation is a balance on the air within the space between the radiant barrier and the roof, using an equation that parallels the one given in the ventilation section. With a truss radiant barrier on only one roof section, two additional heat balance equations are introduced, while with truss barriers on both roof sections, four additional equations are required. The ventilation air flow through the radiant barrier air space may be calculated using the algorithms for stack and wind pressure effects. However, when both the RB space and the main attic space are ventilated, a problem arises in assigning the separate flows to the different spaces. For the model used here, the user allocates the total inlet and outlet vent areas to the different spaces. The estimation of separate flow rates for the main attic space and the spaces between the roof and the truss radiant barriers is a problem that is unresolved. Another unresolved problem is how the separate flows interact: do the flows remain separate, or do they mix with each other?

The system of heat balance equations is arranged in a matrix form, with the interior and exterior surface temperatures and the air temperatures at the current time step being the unknown quantities. Values for these temperatures at previous time steps are known. The matrix equation may be written as

$$(AA)\ (T) = (BB) \tag{46}$$

where (AA) is a square matrix of coefficients, (T) is a vector of unknown temperatures, and (BB) is a known vector. Detailed expressions for the elements of the matrices are lengthy. They may be found in the listings of the computer programs, and will not be repeated here.

This system of equations is solved by Gauss-Jordan elimination, using a subroutine named SOLVP, which was developed by Peavy.[29] Since

many of the coefficients in the square matrix and the constant vector depend upon the unknown temperatures, the system of equations is solved iteratively. When the temperatures have been determined, the heat flows are calculated using the conduction transfer function equations.

Only one numerical instability has been observed with the iterative solution technique. This involved the latent heat term in the heat balances on the interior surfaces, and arose because the mass flow rate of moisture depends strongly upon the surface temperature through the exponential relation between surface temperature and surface humidity ratio. The instability was removed by expanding the surface humidity ratio in a Taylor series such that

$$\begin{aligned}\dot{m}_w(i) &= h_w(i)\ A'(i)\ (\omega_a - \omega_s(i)) \\ &= h_w(i)\ A'(i)\ [(\omega_a - \omega_s'(i) - d\omega_s/dT\ (TIS(i) - TIS'(i))] \qquad (47)\end{aligned}$$

where $\omega_s'(i)$ is the surface humidity ratio evaluated at a previously estimated surface temperature TIS'(i). The coefficients of TIS(i) are included in the (AA) matrix, while the other terms are included in the (BB) vector. With this scheme, the solutions have been found to converge.

The system of equations is set up to allow the model to be driven by weather conditions, with all the surface and air temperatures being unknown. For comparison of the model with experiments, it is often helpful to use measured values of exterior roof and ceiling temperatures as boundary conditions. The model is set up to allow any of the surface temperatures to be forced to its measured value. This is accomplished using a method suggested by D. Ober[30] wherein the diagonal element of (AA) that corresponds to the forced temperature is multiplied by a very large number, and the corresponding element of (BB) is set to the product of the new element of (AA) and the known temperature.

3.7 COMPUTER PROGRAMS

The algorithms described above have been incorporated into three separate computer programs that have been implemented on an IBM PC/AT. The three programs are very similar; they differ only in their capability to handle the extra heat balances required for truss radiant barrier configurations. The program named RBSOR1 is used for attics with no truss radiant barrier. RBSOR2 is used for attics with a truss radiant barrier on one roof surface only, while RBSOR3 is used for attics with truss radiant barriers on both roof surfaces. Listings for the three programs are given in Appendices A, B, and C, while sample input files are given in Appendices D, E, and F. Since the three programs contain most of the same subprograms, for the sake of brevity, only Appendix A contains a complete listing of all subprograms.

A general flow chart that applies to any of the three programs is given in Fig. 3.3. The program starts by initializing all temperatures to 75°F and all heat fluxes to 0 through the use of DATA statements. DATA statements are also used to set various other quantities to 0, such as the elements of the (AA) matrix. Many of these elements will remain at 0, while others are recalculated later in the program.

Next, material property and geometrical input data are read in. This consists of conduction transfer functions, solar absorptances, infrared emittances, the length and width of the attic, roof pitches, height of eave walls, orientation of the house, vent inlet and outlet areas and type of vents, water vapor permeances, wood surface areas and participating masses, and wood moisture contents. The house exfiltration rate and the latent heat of vaporization are also read as inputs. By setting the latent heat to 0, moisture effects may be ignored. The input read in also includes a series of flags that specify whether surface temperatures are to be forced to known values, or are to be calculated from weather conditions.

ORNL-DWG 90-5955

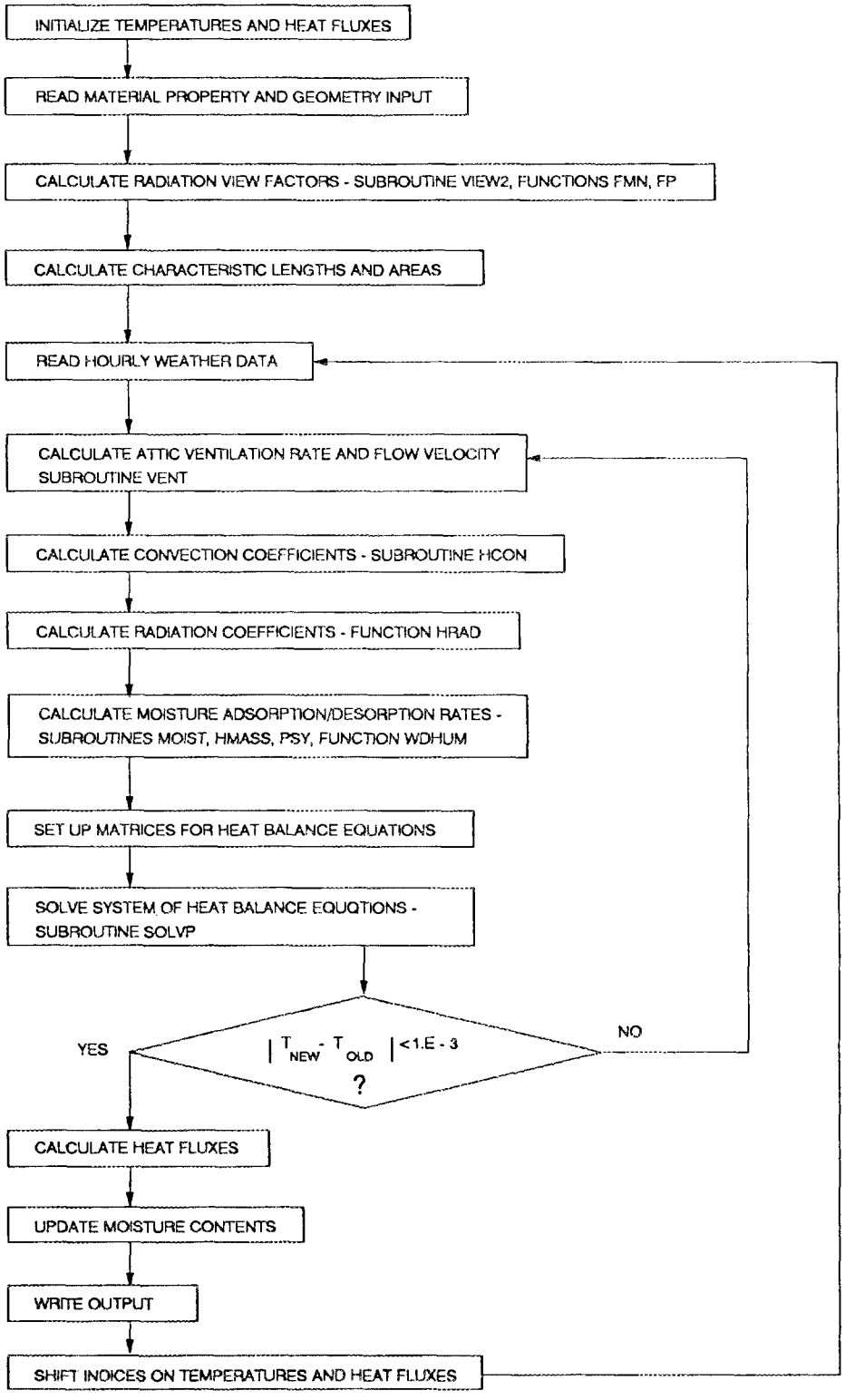

Fig. 3.3. Flow chart for attic models.

The program then calls subroutine VIEW2. The attic length, width, roof pitches, height of eave walls and emittances of the surfaces facing the attic space are passed into VIEW2. The subroutine utilizes function FMN to calculate view factors between two rectangular surfaces that share an edge, and function FP to calculate view factors between two equal parallel rectangles. The subroutine then uses view factor algebra to calculate the view factors among the surfaces that face the attic space and the overall view factor matrix G_{ij}, which is passed back out of the subroutine.

Next, the program calculates characteristic lengths and areas of surfaces. For the ceiling, the characteristic length is taken to be the average of the length and width of the attic. For a roof surface, it is taken to be the distance from the eave to the ridge. For gables, it is taken to be the average height, and for the eave walls, it is taken to be the height. These characteristic lengths are the ones normally chosen for use in correlations for convection heat transfer coefficients.

In the next step, the program reads a line of hourly weather data. This includes the outdoor temperature, incident solar radiation, wind speed, wind direction, outdoor relative humidity, indoor temperature, and indoor relative humidity. At this step, the program is also set up to read in measured values for surface temperatures, ventilation rate, average attic air temperature, exit air temperature, and ceiling heat flux. If the appropriate flags are set, the program will use the indicated measured surface temperatures or ventilation rate in the calculations. The other measured values are not used in the calculations but are read in and then written out in the output file for comparison purposes. When the program is to be used for predictions for hypothetical cases where no measured data are available, this read statement will need to be altered.

If the flag is set so that the measured ventilation rate is not to be used, then the program makes a call to subroutine VENT for each of

the air spaces (i.e., the main attic air space and the air spaces between the truss radiant barrier and the roof). Quantities passed into the subroutine are: outdoor air temperature, average air temperature within the air space, wind speed and direction, difference in elevation between inlet and outlet vents, inlet and outlet vent areas, and a flag to indicate the type of vent. The subroutine uses the algorithms described above for the stack and wind pressure effects to calculate ventilation volume and mass flow rates, and the product of the mass flow rate and the specific heat of air. These last three quantities are passed back out of the subroutine. If the flag is set to use the measured ventilation volume flow rate, VENT is bypassed and the measured volume flow rate is used to calculate the mass flow rate and the product of the mass flow rate and the specific heat. Next, a crude estimate for the flow velocity is calculated by dividing the volume flow rate by an average cross sectional area for the attic.

The program then makes several calls to subroutine HCON to calculate convection heat transfer coefficients for the interior and exterior surfaces. Quantities passed into HCON are: the previous estimates of the surface temperature and the adjacent average air temperature, surface tilt angle, characteristic length of surface, a flag to indicate whether the surface faces up or down, and the air speed past the surface. For interior surfaces, the crude estimate of ventilation flow velocity is used. For exterior surfaces, the wind speed is used (except for the exterior of the ceiling, where the air speed is set to 0). HCON utilizes the correlations described above to calculate natural, forced, and mixed convection heat transfer coefficients. The mixed coefficient is passed back out of HCON.

Radiation heat transfer coefficients are calculated using the HRAD function. The function uses the previous estimates of the two bounding temperatures and either the appropriate element of the G_{ij} matrix (for an interior surface), or the emittance (for an exterior surface).

If the latent heat is not set close to zero, the program makes calls to subroutines that calculate moisture sorption/desorption rates for the surfaces facing each of the air spaces. For program RBSOR1, subroutine MOIST is called. The quantities passed into MOIST are the previous estimates of the surface temperatures, the outdoor and indoor air temperatures, the previous estimate of the average air temperature within the space, the convection heat transfer coefficients, surface areas, wood surface areas and masses, wood moisture contents, indoor and outdoor relative humidities, water vapor permeances, attic ventilation mass flow rate, and house exfiltration mass flow rate. The subroutine calculates wood surface humidity ratios from the surface moisture content and temperature using function WDHUM. Subroutine PSY is used to calculate humidity ratios and water vapor partial pressures for the indoor and outdoor air using the given temperatures and relative humidities. Mass transfer coefficients are calculated using subroutine HMASS which uses the analogy between heat and mass transfer.

The humidity ratio of the air in the air space is then calculated from a moisture balance on the space. This calculation is done iteratively since the moisture balance involves both the humidity ratio and the partial pressure. With the humidity ratio of the air established, the moisture flow rate parameters that were described above are calculated and passed back out of the subroutine. When a truss radiant barrier is present, the moisture balances on the main air space and the RB air space are coupled, requiring a slight modification of the subroutine. For RBSOR2, subroutines MOIST1 and MOIST2 are used. For RBSOR3, subroutines MOIST2 and MOIST3 are used. If the latent heat is set close to zero, all of these calculations are bypassed.

At this point, all of the quantities for the matrices (AA) and (BB) are available. The matrices are set up in the main program and are solved using subroutine SOLVP. The result of this solution is a new set of estimates for the surface and air space temperatures. The new estimates are compared with the old estimates. If any differences are greater than 10^{-3}°F, then the program goes back to subroutine VENT

and new elements for the matrices of the heat balance equations are calculated using the newly estimated temperatures.

When all of the new estimates for surface and air temperatures agree with old estimates to within 10^{-3}°F, or when the limit of 15 iterations has been reached, heat fluxes are calculated using the conduction transfer function equations, moisture contents are updated, and results are written out for the current hour. The WRITE and FORMAT statements may need to be changed to suit the user's needs. In the present version, the output for RBSOR1 includes the outdoor temperature, the exterior roof surface temperatures, calculated ceiling heat flux, measured ceiling heat flux, calculated and measured average attic air temperatures, calculated and measured exit air temperatures, attic air change rate, moisture content of one roof surface, and number of iterations.

The time indices on the temperatures and heat fluxes are shifted, the program goes back to read another line of weather data and the calculations proceed as before for the next hour.

4. COMPARISON OF MODEL WITH EXPERIMENT

Since the models described above combine a number of heat transfer phenomena and make several simplifying assumptions, their validity must be established by comparing their predictions with experimental data. In this section, ceiling heat flows predicted by the models are compared with values measured in a number of experimental programs. Because of the additional uncertainties associated with solar absorptances of roofing materials and exterior convection and radiation coefficients, the best method to test the validity of the attic/radiant barrier models is to take measured exterior roof temperatures as the boundary condition.

Further work, in which the attic model will be coupled with a whole-house model, will make use of the coupling of the exterior surface of the roof with its environment. The most reliable data obtained by the Oak Ridge National Laboratory at the Karns research houses are in terms of heating and cooling loads on the entire house, and house energy consumptions. Comparisons with these data will be made in the next phase of the project when the attic model is coupled with a whole-house model.

4.1 OWENS-CORNING FIBERGLAS

The predecessor to the present models was developed at Owens-Corning Fiberglas as an extension of the model developed by Peavy. That model was compared with the results of experiments performed on an attic module under controlled laboratory conditions.[3,31] Although none of these tests involved radiant barriers, it is still useful to compare the present model with those results. The attic test module was a gabled attic built with trusses with a roof pitch of 5 in 12. The module was 14.58 feet long and 20.58 feet wide. The trusses were raised such that the height of the vertical eave walls varied from 1.125 feet with no attic insulation to 0.271 feet with nominal R-38 insulation. The attic was ventilated with a blower that drew air out

of a ridge vent, with the air being drawn into the attic along the eaves. The ventilation flow rate was measured. A number of tests were performed with various levels of attic insulation. For each insulation level, tests were conducted under simulated summer and winter conditions, for both steady-state and dynamic conditions. The steady-state tests are summarized in Table 4.1.[31]

These steady-state tests were simulated using the RBSOR1 model (i.e., the model with no truss radiant barriers). Measured roof temperatures and ventilation rates were used as inputs to the model. Material properties used as inputs are given in Table 4.2, and the temperature dependence of the thermal transmission coefficients was included as given in Ref. 30. Since the measured ceiling heat flow was obtained with a calorimetric measurement of the total heat flow over the ceiling, the edge corrections described in Ref. 30 were also applied to the results from the model. Ceiling heat flows and attic air temperatures predicted by the model are compared with the experimental values in Table 4.3. Note that the sign convention used in this report is that heat flows through the ceiling into the space below are taken to be positive, while heat flows out of the space below the ceiling are taken to be negative. With three exceptions, the predicted ceiling heat flows are within 10 percent of the measured values. The reasons for the three larger discrepancies are not known.

4.2 JOY

The earliest study of radiant barriers was performed by F. A. Joy at the Pennsylvania State University.[32] The results of this study form the basis for the table of "effective resistance of ventilated attics" in Chapter 23 of the ASHRAE Handbook of Fundamentals.[33] His measurements were performed under steady-state conditions in the laboratory. The test attic had ceiling dimensions of 12 feet by 13 feet. It was constructed so that tests could be run either with a flat roof, or with a gabled roof, having a pitch of about 5.5 in 12. The attic was insulated to about R-7.5 using high density fiberglass board

Table 4.1. Results of Owens-Corning Fiberglas Tests

	Test	Temperature Conditions, °F Attic	Roof	Outside	Inside	Ventilation Rate, CFM/ft^2	Measured Ceiling Heat Flow, Btu/hr**
R-0	1	36	19	0	75	0	-6526
	2	18	13	0	74	0.5	-9013
	3	94	114	81	75	0	3103
	4	93	113	90	75	0.5	2759
	5	97	106	101	75	1.5	2942
R-11 batts	1	7	3	-3	75	0	-1776
	2	1	1	-3	75	0.5	-1848
	3	132	156	79	77	0	1300
	4	110	148	89	77	0.5	1125
	5	115	151	101	77	1.5	1181
R-19 batts	1	9	6	1	75	0	-1156
	2	5	5	1	75	0.5	-1212
	3	132	155	80	74	0	1155
	4	116	155	91	74	0.5	960
	5	116	154	100	74	1.5	953
	2a*	8	5	1	75	0.5	-1111
	4a*	116	151	90	76	0.5	902
R-38 batts	1	4	2	0	76	0	-706
	2	0	0	-2	76	0.5	-731
	3	140	155	80	75	0	633
	4	115	153	91	76	0.5	483
	5	113	152	101	76	1.5	480

* Repeat tests performed after tests on R-38 insulation.

** Positive heat flows indicate heat is flowing into the space below the ceiling.

Note: Tests 1 and 2 represent winter conditions; tests 3-5 represent summer conditions.

Table 4.2. Material properties for Owens-Corning Fiberglas tests.

Material	Thickness (in.)	Thermal Conductivity Btu/(hr-ft-^{o}F)
Ceiling		
Drywall	0.63	0.09225
R-11 Insulation	3.5	0.02732
R-19 Insulation	5.5	0.02637
R-38 Insulation	10.25	0.02583
Joists	3.5	0.06533
Roof		
Plywood	0.475	0.07533
Rafters	5.5	0.06533
Gables		
Sheathing	0.51	0.03283
Studs	3.5	0.06533
Eave Walls		
Plywood	0.475	0.07533
Studs	3.5	0.06533

Note: All framing is 24 inches on center. All emittances taken to be 0.9.

Table 4.3. Comparison of predicted and measured heat flows for Owens-Corning Fiberglas steady-state tests.

	Test	Total Ceiling Heat Flow, Btu/hr* Measured	Predicted	Percent Difference**
R-0	1	-6526	-6321	-3.1
	2	-9013	-8476	-6.0
	3	+3103	3405	9.7
	4	+2759	3299	19.6
	5	+2942	3167	7.6
R-11	1	-1776	-1588	-10.6
	2	-1848	-1690	-8.5
	3	+1300	1707	31.3
	4	+1125	1229	9.2
	5	+1181	1283	8.6
R-19	1	-1156	-1147	-0.8
	2	-1212	-1198	-1.2
	3	+1155	1264	9.4
	4	+960	1038	8.1
	5	+953	993	4.2
	1a	-1111	-1198	7.8
	4a	+902	943	4.5
R-38	1	-706	-700	-0.8
	2	-731	-726	-0.7
	3	+633	650	2.7
	4	+483	516	6.8
	5	+480	514	7.1

*In this report, positive heat flows indicate heat is flowing into the space below the ceiling.

**Values are predicted minus measured, as percentage of measured value.

Note: Tests 1 and 2 represent winter conditions; tests 3-5 represent summer conditions.

insulation about 2 inches thick. (Note: In this report R-values have units of hr-ft^2-^{o}F/Btu.) The attic had vertical eave walls about 1.83 feet high. All vertical walls of the attic (including gables) were covered with aluminum foil faced insulating boards and were also guarded with heaters to minimize heat losses. The ceiling heat flow was measured with four specially constructed heat flow meters that covered about 9 percent of the ceiling area, and included the heat flow through the ceiling joists as well as that through the insulation.

Tests were performed both with and without radiant barriers. The radiant barrier consisted of kraft backed perforated aluminum foil laid on top of the insulation with the foil side up. For summer conditions, the top surface of the roof was maintained at 150°F and the room below the attic was maintained at 75°F. Tests were run with the attic sealed, and with the attic ventilated with air having inlet temperatures of 85, 95, or 105°F and flow rates of 0.2, 0.46, or 1.04 cfm per square foot of ceiling. The ventilation was imposed with a fan. For the gabled roof, the air entered through a louver on one gable near the peak and exited through a slot also near the peak. For the flat roof, the air entered and exited through slots at the level of the ceiling joists.

The RBSOR1 model was used to predict the ceiling heat flows. Measured values of the exterior roof, ceiling bottom, and inlet air temperatures and the ventilation rate were used as inputs to the model. Material properties and other system parameters used in the model are given in Table 4.4. The emittance of the inside surface of the roof was taken to be 0.9, and the emittances of the interior of all vertical walls were taken to be 0.05. While very clean aluminum foils may have emittances of about 0.03, a value of 0.05 was chosen as a practical value for use in this report. For the attic floor, the emittance was taken to be 0.9 for the case of no radiant barrier, and 0.096 for the case of a radiant barrier. A value higher than 0.05 was used for the emittance of the attic floor because the heat flux transducers measured the heat flow through the joists, which were not covered with foil, as

Table 4.4. Material properties for Joy's tests.

	Material	Thickness (in.)	Thermal Conductivity Btu/(hr-ft-^{o}F)
Ceiling			
	Drywall	0.75	0.0925
	Insulation	1.98	0.02206
	Joists	5.5	0.06667
Roof			
	Plywood	0.75	0.06667
	Rafters	5.5	0.06667
Walls			
	Active guarding simulated by R = 1000		

Note: Ceiling and roof have 2x6 framing, 16 inches on center.

well as that through the insulation. An average emittance for the attic floor may be obtained by area averaging the 0.05 emittance of the radiant barrier with the 0.9 emittance of the joists, giving an average value of 0.13. This value would be valid if the radiant barrier and joist surfaces were at the same temperature. Another estimate may be obtained by approximating the heat flow by parallel flows through a joist path and an insulation path, each of which consists of radiation across parallel plates in series with conduction through R-10 insulation. This approach yields an effective emittance of 0.061 for the attic floor. This value would be valid if the temperatures of the two surfaces were completely independent. Since the two surfaces are coupled by the attic air, the real situation should be intermediate between the two estimates and so an average of the two values was used for the emittance of the attic floor.

The heat flows predicted by the model are compared with values measured for the gabled roof in Table 4.5, and for the flat roof in Table 4.6. With the exception of two tests, summer heat flows for the gabled roof were predicted within 5 percent, and to within 15 percent for the other two tests. The agreement for the flat roof was not as good, with predicted heat flows being as much as 25 percent different from the measured values. The model was then modified to use a convection coefficient of 0.01 Btu/(hr-ft^2-^{o}F) between the roof and the attic air. This value corresponds to conduction through a 17-inch layer of still air, 17 inches being the distance between the roof and the ventilation slots. Table 4.7 shows the predictions with this modification. For the tests with a flat roof and a radiant barrier, the predicted heat flows are very close to the measured values. For the tests with a flat roof and no radiant barrier, the predicted heat flows are not changed significantly by the modification, as would be expected when radiation dominates the heat transfer across the air space.

It is speculated that the results observed for the flat roof with no radiant barrier are due to the special method of ventilation where

Table 4.5. Comparison of predicted and measured heat flows for Joy's data with a gabled roof.

Test	Inlet Air temperature (°F)	Ventilation rate (cfm/ft^2)	Heat Flows measured	Heat Flows predicted	Percent diff.*
No Foil:					
17	--	0	6.38	6.64	4.1
18	86.5	0.20	5.65	5.67	0.4
19	84.7	0.46	4.71	4.61	-2.1
20	84.5	1.04	3.83	3.73	-2.6
21	106.8	0.20	5.85	5.96	1.9
22	105.4	0.46	5.42	5.45	0.6
23	106.1	1.04	4.77	4.96	4.0
Foil, Summer:					
24	--	0	4.55	4.78	5.1
25	86.4	0.20	3.83	3.78	-1.3
26	84.2	0.46	3.47	3.01	-13.3
27	84.7	1.04	2.79	2.36	-15.4
28	106.3	0.20	4.20	4.25	1.2
29	105.9	1.04	3.43	3.58	4.4
30	105.8	1.04	3.44	3.60	4.7
Foil, Winter:					
33	--	0	5.27	5.60	6.3
34	-0.3	0.56	6.10	6.89	13.0

*Values are predicted minus measured, as percentage of measured value.

Table 4.6. Comparison of predicted and measured heat flows for Joy's data with a flat roof.

Test	Inlet Air temperature (°F)	Ventilation rate (cfm/ft^2)	Heat Flows measured	predicted	percent difference
No Foil:					
1	--	0	5.96	6.59	10.6
2	84.6	0.20	4.78	5.25	9.8
3	85.8	0.46	4.10	4.44	8.3
4	85.4	1.04	3.31	3.72	12.4
5	94.9	1.04	3.78	4.16	10.1
6	104.0	0.20	5.39	5.82	8.0
7	105.2	1.04	4.44	4.86	9.5
Foil, Summer:					
8	--	0	4.30	4.68	8.8
9	86.0	0.20	2.88	3.43	19.1
10	85.4	0.46	2.13	2.67	25.4
11	84.3	1.04	1.72	1.90	10.5
12	95.1	1.04	2.41	2.59	7.5
13	104.1	0.20	3.59	3.86	7.5
14	105.2	0.46	3.49	3.76	7.7
15	105.1	1.04	3.30	3.38	2.4
Foil, Winter:					
31	--	0	5.06	5.31	4.9
32	-2.0	0.56	6.44	6.99	8.5

*Values are predicted minus measured, as percentage of measured value.

Table 4.7. Comparison of predicted and measured heat flows for Joy's data with a flat roof.
(Assuming 17-inch dead air space below roof.)

Test	Heat Flows Measured	Predicted	Percent Difference
No Foil:			
1	5.96	6.58	10.4
2	4.78	5.16	7.9
3	4.10	4.42	7.8
4	3.31	3.80	14.8
5	3.78	4.23	11.9
6	5.39	5.76	6.9
7	4.44	4.92	10.8
Foil, Summer:			
8	4.30	4.37	1.6
9	2.88	2.83	-1.7
10	2.13	2.29	7.5
11	1.72	1.74	1.2
12	2.41	2.48	2.9
13	3.59	3.67	2.2
14	3.49	3.61	3.4
15	3.30	3.32	0.6

*Values are predicted minus measured, as percentage of measured value.

the cooler ventilation air is brought in just above the insulation and is not well coupled thermally to the roof. For the flat roof with no radiant barrier, the predicted heat flows being higher than the measured values may be partly due to the rafters forming a partial radiation shield between the roof and the attic floor. This effect would be more significant for the flat roof than for the gabled roof because of the close spacing between the roof and attic floor for the flat roof.

4.3 FLORIDA SOLAR ENERGY CENTER

A number of field experiments recently performed by P. Fairey at the Florida Solar Energy Center have generated considerable interest in radiant barriers.[34,35] The experimental setup consisted of three side-by-side sections of the attic space over a laboratory building at FSEC in Cape Canaveral, Florida. Each section was approximately 5.75 feet long and 9.25 feet wide. The roof consisted of one eastward facing section having a slope of about 6.5 in 12. The other surfaces were vertical, including a vertical eave wall with a height of about 3.17 feet. The vertical walls were made of rigid insulation sheets with aluminum foil facings. Partitions between adjacent cells consisted of two such sheets separated by a 1.5-inch air space which was ventilated with outside air. Ventilation of the attic space was provided by a blower which drew air in through soffit vents and discharged the air through a duct near the ridge. For the tests analyzed in this report, the ventilation rate was nearly constant at an air change rate of about 2.5 air changes per hour. An exception occurred for the first 13 hours of the tests in Cell 2, where the ventilation rate was about 6 air changes per hour. Ceiling heat flows were measured using 2-inch square heat flux transducers that were placed midway between the ceiling joists, thus measuring only the heat flow through the insulation and not that through the joists.

Detailed temperature, heat flow, ventilation, and weather data were provided by Fairey for tests conducted on September 25-27, 1987.

For these tests, all three cells had R-19 batt insulation. Cells 1 and 3 had a truss radiant barrier which consisted on a single-sided radiant barrier placed 3.5 inches below the roof deck between nominal 2 x 10 roof rafters, with the reflective surface facing down. Cell 2 had no radiant barrier. The RBSOR1 (no truss RB) and the RBSOR2 (one truss RB) models were used to predict heat flows. Measured values of exterior roof, ceiling bottom, and outdoor air temperatures and ventilation rates were used as inputs to the models. The heat balances at the exterior faces of the vertical walls included radiation and convection to the outdoor air temperature. All vertical surfaces were taken to be shaded. Material properties used in the models are given in Table 4.8. The emittances of nonreflective surfaces were taken to be 0.9, and the emittances of the vertical walls were taken to be 0.05. The emittance of the bottom of the radiant barrier was taken to be either 0.05 (to represent the RB material only), or 0.10 (to represent the effect of exposed framing). Since the test data included the outdoor relative humidity, some model runs included moisture sorption/desorption. For these, the fractional initial wood moisture content was taken to be 0.09, the ratio of exposed wood area to plane roof area was taken to be 1.8, and the thickness of wood exchanging moisture was taken to be 0.25 inches.

The RBSOR1 model was used to predict the heat flows for the cell with no radiant barrier. The results of five runs are given in Table 4.9, and the results of the first two of these runs are plotted in Fig. 4.1. Table 4.9 contains comparisons of the daily peak heat fluxes and the sums of the positive and negative heat flows over the three day period.

Run 1 was performed with moisture sorption/desorption neglected, while Run 2 included moisture. Either of these two runs predicts the peak heat fluxes within about 10 percent. Run 1 predicts the positive heat flow very well, while Run 2 is only slightly worse at 7.5 percent. For the negative heat flows (at night), the predictions of Run 2 are

Table 4.8. Material properties for FSEC tests.

Material	Thickness in.	Thermal conductivity (Btu/(hr-ft-^{o}F)	Specific Heat Btu/(lb-^{o}F)	Density lb/ft^{3}
Ceiling:				
Drywall	0.50	0.09250	0.26	50.0
R-19 Insulation	6.25	0.02741	0.19	0.6
Roof:				
Plywood	0.50	0.0667	0.29	34.0
Rafters	9.25	0.06833	0.39	28.0
Walls:				
Polyisocyanurate foam	0.75	0.01167	0.22	2.0

Table 4.9. Comparison of predicted and measured heat flows for FSEC test with no radiant barrier (Cell 2).

		Predicted, %**				
	Measured*	Run 1	Run 2	Run 3	Run 4	Run 5
Day 1 Peak	1.37	8.8	5.8	25.5	-0.7	9.5
Day 2 Peak	1.47	9.5	-3.4	27.2	-3.4	11.6
Day 3 Peak	1.55	0.6	-9.7	18.1	-11.6	2.6
Sum of Period Positive Flows	32.2	-0.6	-7.4	16.5	-12.4	0.9
Sum of Period Negative Flows	-3.4	75.7	-4.4	81.9	46.5	83.0

Run 1: No moisture sorption/desorption
Run 2: Moisture sorption/desorption
Run 3: No moisture; HC = 0 on top of insulation
Run 4: No moisture; emittance of vertical walls = 0.9
Run 5: No moisture; framing on roof ignored

*Peak values are Btu/(hr-ft^2), sums are Btu/ft^2.

**Values are predicted minus measured, as percentage of measured value.

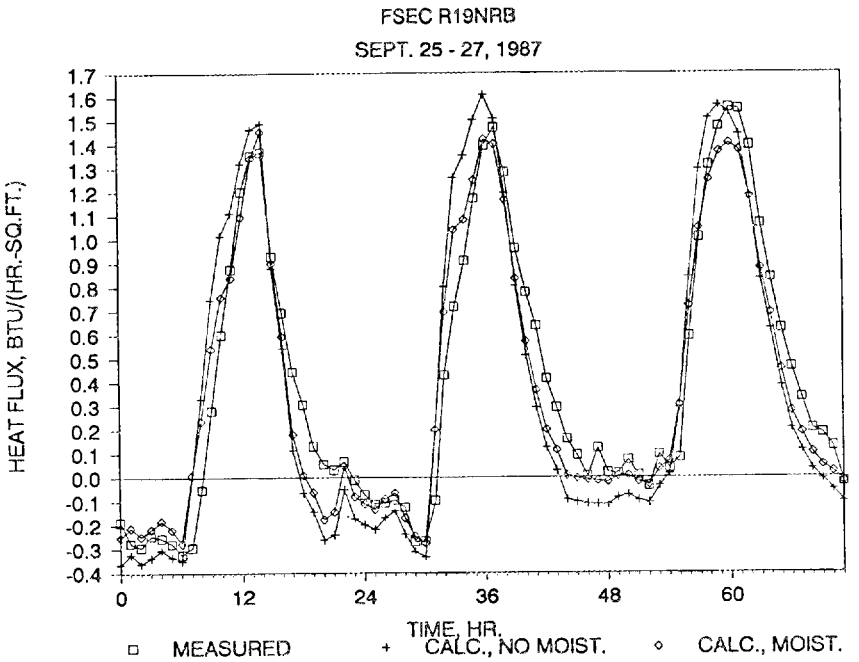

Fig. 4.1. Comparison of predicted and measured heat fluxes for FSEC test with R-19 insulation and no radiant barrier.

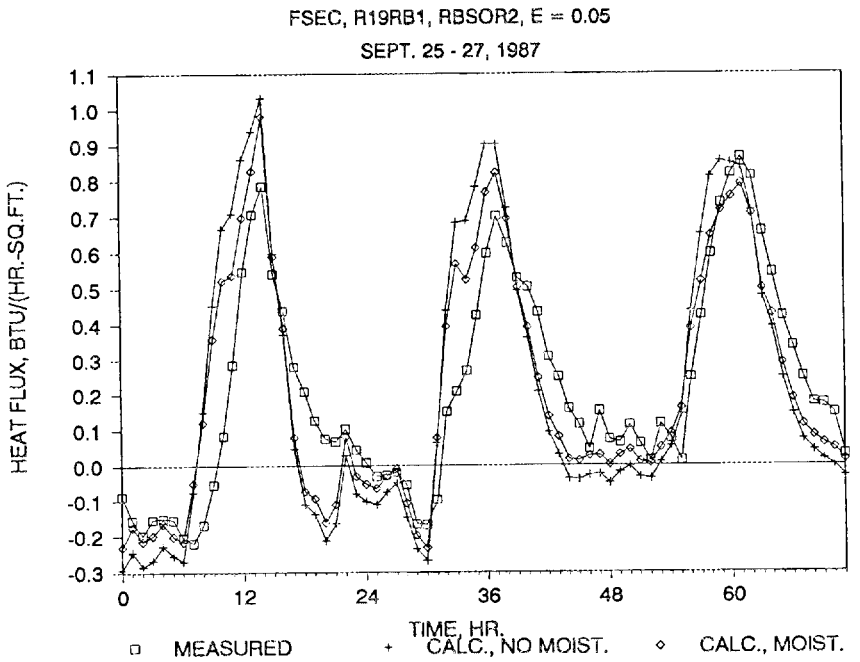

Fig. 4.2. Comparison of predicted and measured heat fluxes for FSEC test with R-19 insulation and truss radiant barrier using RBSOR2 and emittance of 0.05 for RB bottom.

much better than that for Run 1. However, it should be noted that the magnitude of the negative heat flow is much smaller than the positive one.

Run 3 was performed to study the sensitivity of the predictions to the convection coefficient on top of the insulation. Setting this coefficient to zero significantly increases the predicted heat flows, since convection to the attic air stream provides a mechanism for cooling the top of the insulation when no radiant barrier is present. Run 4 was inadvertently performed, with the emittances of the walls being 0.9 rather than 0.05. The results are interesting in that they show that the reflective walls produce higher heat fluxes than would be seen with nonreflective walls. The integrated positive heat flow for the reflective walls is about 12 percent higher than that for the nonreflective walls. Run 5 was performed to determine whether the results were sensitive to whether or not the roof rafters were included in the conduction transfer functions (CTFs) for the roof. The Run 5 results differ only slightly from those of Run 1, indicating that the results are not sensitive to inclusion of the rafters in the CTFs.

Considering Runs 1 and 2 as the most realistic, it is concluded that the model is capable of predicting the heat flows without a radiant barrier to within 10 percent for the daily peaks, and somewhat better for the sums over the period.

The RBSOR2 model was used to predict the heat flows for the cell with a truss radiant barrier. The results of 8 runs of this model are given in Table 4.10, and the results of the first two runs are shown in Fig. 4.2. Since only the total ventilation rate was known, the split between the flows through the main attic space and the space between the roof and the radiant barrier had to be estimated. Two cases were studied: 90 percent of the flow through the RB space, and 10 percent of the flow through the RB space.

Table 4.10. Comparison of predicted and measured heat flows for FSEC tests with truss radiant barrier (Cell 1) using RBSOR2.

		Predicted, %**							
	Measured*	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7	Run 8
Day 1 Peak	0.78	31.5	24.8	43.4	29.7	28.5	18.5	28.8	12.7
Day 2 Peak	0.70	28.5	17.1	48.8	25.8	23.8	3.7	18.3	-4.0
Day 3 Peak	0.86	-1.2	-8.6	15.5	-3.8	-5.4	-21.1	-9.5	-27.3
Sum of Period Positive Flows	17.5	8.2	1.1	23.9	6.0	4.2	-12.3	0.3	-18.8
Sum of Period Negative Flows	-2.1	86.2	24.2	100.9	75.7	64.8	34.0	40.0	31.4

	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7	Run 8
Moisture Included	No	Yes	No	No	No	No	No	No
Emittance of RB Bottom	0.05	0.05	0.10	0.05	0.05	0.05	0.10	0.05
Fraction of Vent Flow through RB Space	0.9	0.9	0.9	0.1	0.9	0.9	0.9	0.1
RB Temperature Known	No	No	No	No	No	Yes	Yes	Yes
HC = 0 on Top of Insulation	No	No	No	No	Yes	No	No	No

*Peak values are Btu/(hr-ft^2), sums are Btu/ft^2.

**Values are predicted minus measured, as percentage of measured value.

For the first five runs, the measured exterior roof temperature was taken as the boundary condition. The results given in Fig. 4.2 show that Runs 1 and 2 are in reasonably good agreement for Day 3, but overpredict the peaks for Days 1 and 2. The sums of positive heat flows for both these runs are within 8 percent of the measured value, while the results of Run 2 (with moisture) are in much better agreement for the sums of the negative heat flows (note, however, the small magnitude of the negative heat flows).

Increasing the emittance of the radiant barrier bottom to 0.10 in Run 3 gives results that differ significantly from the measured values. The 0.10 value represents an area averaging of the emittances of the radiant barrier and the exposed wood surfaces. It would apply if the bottom of the rafters were at the same temperature as the radiant barrier. Because of the large thermal resistance of the rafter compared with the resistance across the (nonreflective) radiant barrier space, the bottom of the rafters may be significantly cooler than the radiant barrier and thus may not contribute as much to the radiation heat transfer as the 0.10 emittance would assume.

Comparing Run 4 (10 percent of flow through RB space) with Run 1 (90 percent of flow through RB space) shows that, for this case, the assumption of the split of flow is not very significant. Comparing Run 5 with Run 1 shows that setting the convection coefficient on top of the insulation to zero does not produce major changes. This is to be contrasted with the results without a radiant barrier where the air stream provided a significant cooling mechanism. Since heat transfer between the air stream and the top of the insulation is completely eliminated by setting the convection coefficient to zero, the only source of heat at the top of the insulation is radiation from the roof and side walls. The small change between Runs 1 and 5 indicates that radiation is an important mechanism for heat transfer across the air space, even when a truss radiant barrier is present.

For Runs 6, 7 and 8, the measured radiant barrier temperature was taken to be the boundary condition rather than the exterior roof temperature. These runs both underpredict and overpredict the individual daily peak fluxes. One positive sum is predicted very well, while the other two differ by more than 10 percent. The results of these predictions are not entirely consistent with those using the exterior roof temperature. Part of the difference may be due to difficulties in measuring an average value for the temperature of the radiant barrier, while part may be due to the approximations in the models.

The RBSOR1 model was also used to predict the heat flows for the cell with a truss radiant barrier. In this case, the bottom of the roof was taken to have an emittance of either 0.05 or 0.10. The results given in Table 4.11 and Fig. 4.3 show that the predictions of RBSOR1 are not as good as those of RBSOR2 where the radiant barrier space is included. The period sums of positive heat flows predicted by RBSOR1 are 9 to 13 percent higher than those predicted by RBSOR2.

From the results given in Table 4.10 for Runs 1, 2, and 4, it is concluded that the RBSOR2 model predicts the period sums of positive heat flows for a truss radiant barrier to within about 10 percent, but that predicted daily peak heat fluxes differ significantly from the measured values.

4.4 TENNESSEE VALLEY AUTHORITY

Several field experiments have been conducted by J. A. Hall using five test cells at a site near Chattanooga, Tennessee.[36] The attics of the test cells are about 8.54 feet long and 6.02 feet wide. The roofs have a pitch of about 3.5 in 12. The attics are ventilated naturally, with various ventilation strategies being used. For the test data examined here, the vents consisted of soffit vents with a free area of about 0.16 square feet and gable vents with a free area of about 0.17 square feet. Ceiling heat flows are measured with small (2-1/4 inch

Table 4.11 Comparison of predicted and measured heat flows for FSEC tests with truss radiant barrier (Cell 1) using RBSOR1.

		Predicted, %**		
	Measured*	Run 1	Run 2	Run 3
Day 1 Peak	0.78	37.2	32.4	50.8
Day 2 Peak	0.70	41.6	29.8	65.6
Day 3 Peak	0.86	9.8	0.7	29.4
Sum of Period Positive Flows	17.5	18.3	10.3	37.2
Sum of Period Negative Flows	-2.1	92.8	37.1	117.1
		Run 1	Run 2	Run 3
Moisture Included		No	Yes	No
Emittance of RB Bottom		0.05	0.05	0.10

*Peak values are Btu/(hr-ft^2), sums are Btu/ft^2.

**Values are predicted minus measured, as percentage of measured value.

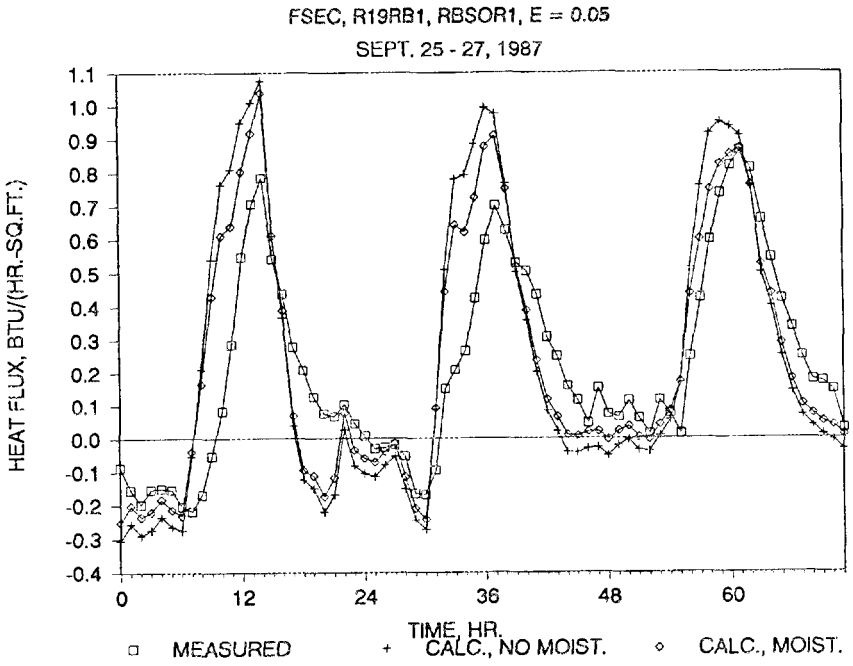

Fig. 4.3. Comparison of predicted and measured heat fluxes for FSEC test with R-19 insulation and truss radiant barrier using RBSOR1 and emittance of 0.05 for RB bottom.

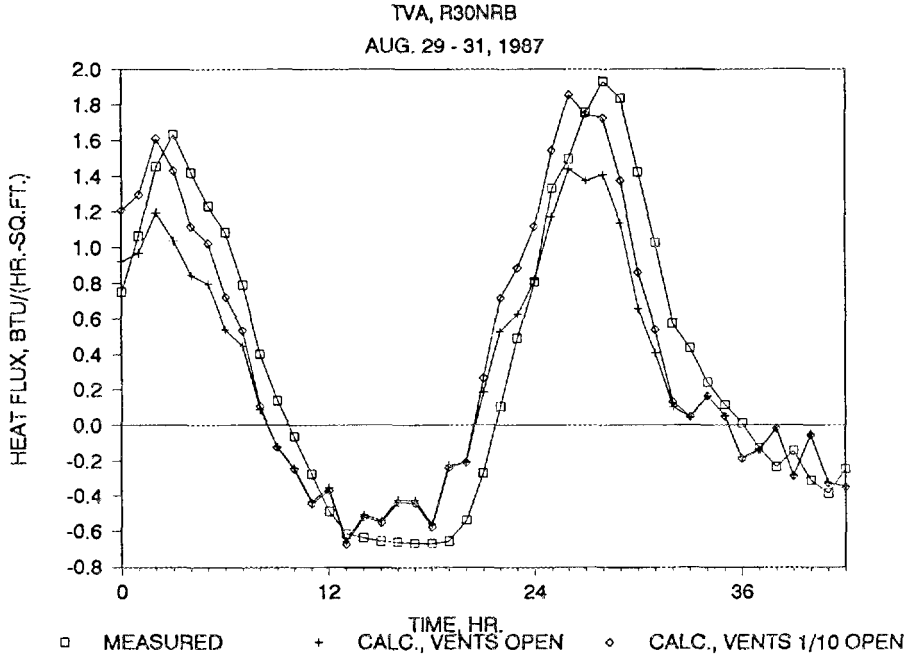

Fig. 4.4. Comparison of predicted and measured heat fluxes for TVA test with R-30 insulation and no radiant barrier.

square) heat flux transducers located between the ceiling joists, such that they measure the heat flow through the insulation and not through the joists.

Detailed temperature, heat flow, and weather data were provided by Hall for tests conducted between August 27 and September 8, 1987. A continuous set of data between noon on August 29 and 6 a.m. on August 31 was selected for analysis. The cells contained the following combinations of insulation and radiant barriers: (1) R-30 insulation with no radiant barrier (R30NRB), (2) R-30 insulation with a horizontal radiant barrier laid on top of the insulation (R30RBT), (3) R-19 insulation with a horizontal radiant barrier laid on top of the insulation (R19RBT), (4) R-19 insulation with a radiant barrier attached to the rafters (R19RBR), and (5) R-11 insulation with a horizontal radiant barrier laid over the ceiling joists (R11RBT). The radiant barrier material was reflective on both sides.

The RBSOR1 model was used to predict the heat flows for all cells. Measured values of exterior roof, ceiling bottom, and outdoor air temperatures were used as inputs to the model. Material properties used in the model are given in Table 4.12. For the R11RBT configuration, the radiant barrier was laid over the 2 x 6 inch ceiling joists, so that an extra air space was created between the radiant barrier and the insulation. From an analysis of the heat flow and temperature data, the resistance of this air space was estimated to be about 3.5, and was included in the model.

For each configuration, two runs of the model were made. The first run was made as normal. For several of the configurations, the heat flows were obviously too low. The problem appears to be with the ventilation algorithm which predicted attic air change rates of 10 to 85 air changes per hour, which are much higher than had been measured by Hall during a previous experiment. For the second run, the vent areas were reduced to 1/10 of their normal values. With these vent

Table 4.12. Material properties for TVA tests.

Material	Thickness in.	Thermal conductivity (Btu/hr-ft-^{o}F)	Specific heat (Btu/lb-^{o}F)	Density lb/ft^3
Ceiling (R-11)				
Plywood	0.25	0.0667	0.29	34.0
R-11 Insulation	3.5	0.02741	0.19	0.6
Air Space	--	R = 3.5*		
Ceiling (R-19)				
Plywood	0.25	0.0667	0.29	34.0
R-19 Insulation	6.25	0.02741	0.19	0.6
Ceiling (R-30)				
Plywood	0.25	0.0667	0.29	34.0
R-19 Insulation	6.25	0.02741	0.19	0.6
R-11 Insulation	3.5	0.02652	0.19	0.6
Roof				
Plywood	0.25	0.0667	0.29	34.0
Rafters	3.5	0.06833	0.39	28.0
Gables				
Plywood	0.25	0.0667	0.29	34.0
or Duct Tape	--	R = 0.05*		
Eaves				
Plywood	0.25	0.0667	0.29	34.0

*Units = hr-ft^2-^{o}F/Btu.

areas, the air change rates were about 1 to 9 per hour, which are more reasonable.

Predicted hourly heat fluxes are compared with measured values in Figs. 4.4 through 4.8. Peak daily heat fluxes and period positive and negative heat flow sums are given in Tables 4.13 through 4.17. With the smaller vent areas, the predictions for the R30NRB case are in good agreement with the measured values, except for the time shift of about one hour. Also, with this smaller vent area, the predicted positive heat flow sums are in reasonable agreement with the measured values for three other cells: 11 percent for R30RBT, 6 percent for R19RBR, and 1.5 percent for the R11RBT configurations. For the R19RBT cell, the positive heat flow sum is underpredicted with the normal vent area, and overpredicted with the smaller vent area.

These results call into question the applicability of the models for small test cells, with the ventilation algorithm being especially suspicious. The reasons for the ventilation rates being much larger than expected are not clear, but may be related to the small distance that is available for the stack effect, or to unaccounted flow obstructions.

4.5 MINERAL INSULATION MANUFACTURERS ASSOCIATION

The Mineral Insulation Manufacturers Association has recently conducted a field experiment on radiant barriers at a test site in Ocala, Florida.[37,38] The experimental setup consisted of a duplex house with the attic divided into two separate spaces. Each space was about 26.67 feet long and 30.0 feet wide. The roof had a pitch of 6 in 12. The two spaces were separated by insulation at about the R-30 level. Each space had soffit vents with an area of about 4.5 square feet and ridge vents with an area of about 3.25 square feet, and were ventilated naturally. Both spaces had well-characterized fiberglass batt insulation, with a nominal R-value of 19 and an installed R-value of about 20. All gable interior surfaces were painted black. The east

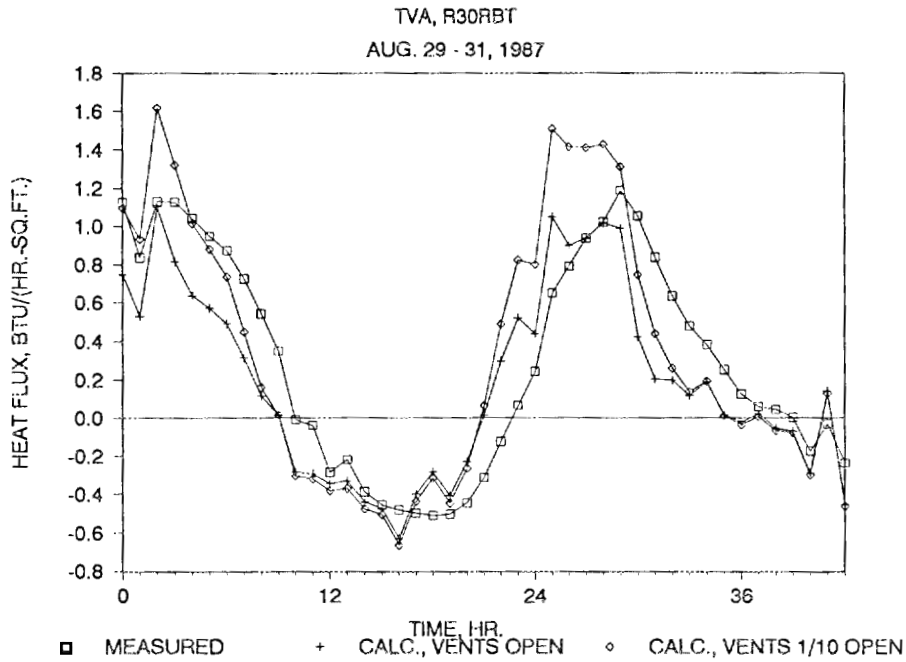

Fig. 4.5. Comparison of predicted and measured heat fluxes for TVA test with R-30 insulation and horizontal radiant barrier.

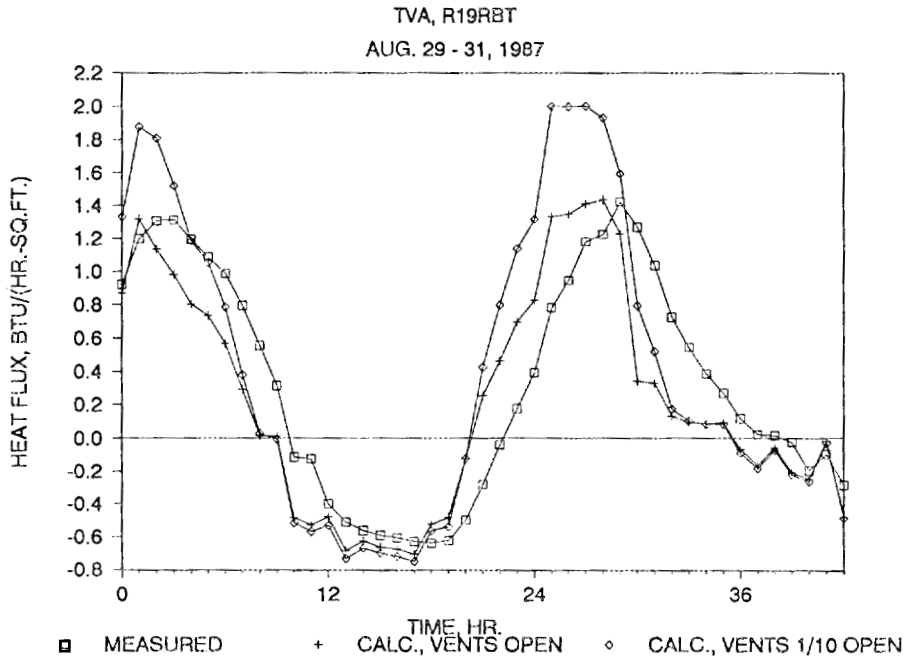

Fig. 4.6. Comparison of predicted and measured heat fluxes for TVA test with R-19 insulation and horizontal radiant barrier.

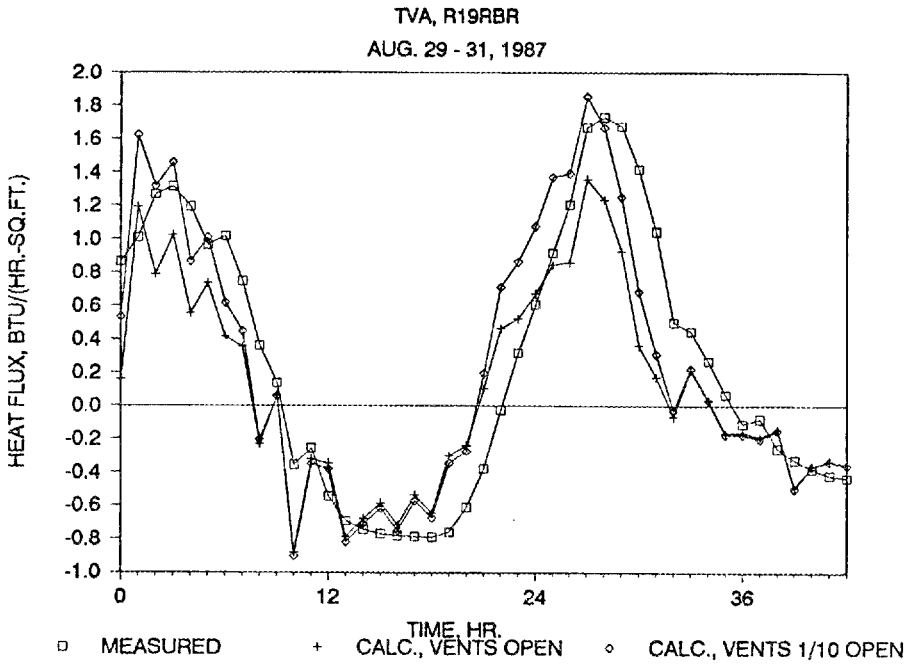

Fig. 4.7. Comparison of predicted and measured heat fluxes for TVA test with R-19 insulation and rafter radiant barrier using RBSOR1.

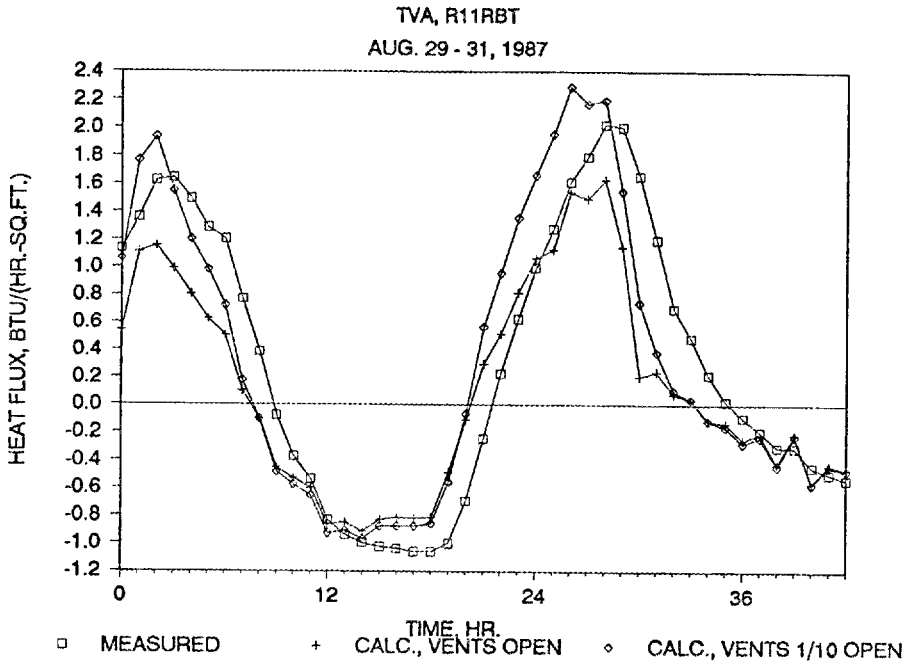

Fig. 4.8. Comparison of predicted and measured heat fluxes for TVA test with R-11 insulation and horizontal radiant barrier.

Table 4.13. Comparison of predicted and measured heat flows for TVA tests with R-30 insulation and no radiant barrier.

		Predicted, %**	
	Measured*	Run 1	Run 2
Day 1 Peak	1.63	-26.9	-1.3
Day 2 Peak	1.93	-25.4	-4.0
Sum of Period Positive Flows	23.5	-28.0	-6.3
Sum of Period Negative Flows	-7.6	-6.3	-18.8

Run 1: Vents open
Run 2: Vents 1/10 open

*Peak values are Btu/(hr-ft^2), sums are Btu/ft^2.

**Values are predicted minus measured, as percentage of measured value.

Table 4.14. Comparison of predicted and measured heat flows for TVA tests with R-30 insulation and horizontal radiant barrier.

		Predicted, %**	
	Measured*	Run 1	Run 2
Day 1 Peak	1.13	-2.6	43.3
Day 2 Peak	1.19	-11.6	27.2
Sum of Period Positive Flows	17.5	-26.7	11.0
Sum of Period Negative Flows	-4.7	5.9	15.3

Run 1: Vents open
Run 2: Vents 1/10 open

*Peak values are Btu/(hr-ft^2), sums are Btu/ft^2.

**Values are predicted minus measured, as percentage of measured value.

Table 4.15 Comparison of predicted and measured heat flows for TVA tests with R-19 insulation and horizontal radiant barrier.

		Predicted, %**	
	Measured*	Run 1	Run 2
Day 1 Peak	1.31	0.7	43.2
Day 2 Peak	1.42	1.0	40.6
Sum of Period Positive Flows	20.2	-16.7	23.5
Sum of Period Negative Flows	-6.2	15.6	24.8

Run 1: Vents open
Run 2: Vents 1/10 open

*Peak values are Btu/(hr-ft^2), sums are Btu/ft^2.

**Values are predicted minus measured, as percentage of measured value.

Table 4.16. Comparison of predicted and measured heat flows for TVA tests with R-19 insulation and truss radiant barrier.

		Predicted, %**	
	Measured*	Run 1	Run 2
Day 1 Peak	1.31	-9.1	23.5
Day 2 Peak	1.73	-21.6	7.2
Sum of Period Positive Flows	20.7	-37.1	-5.7
Sum of Period Negative Flows	-9.5	-10.1	-6.3

Run 1: Vents open
Run 2: Vents 1/10 open

*Peak values are Btu/(hr-ft^2), sums are Btu/ft^2.

**Values are predicted minus measured, as percentage of measured value.

Table 4.17. Comparison of predicted and measured heat flows for TVA tests with R-11 insulation and horizontal radiant barrier.

		Predicted, %**	
	Measured*	Run 1	Run 2
Day 1 Peak	1.64	-29.8	17.8
Day 2 Peak	2.02	-19.4	13.4
Sum of Period Positive Flows	25.7	-37.8	-1.4
Sum of Period Negative Flows	-12.3	-10.2	-4.4

Run 1: Vents open
Run 2: Vents 1/10 open

*Peak values are Btu/(hr-ft^2), sums are Btu/ft^2.

**Values are predicted minus measured, as percentage of measured value.

section had no radiant barrier. The west section had a radiant barrier that was draped between the rafters (top truss chords). The RB material was reflective on both sides. Ceiling heat flows were measured by 5 one square foot heat flux transducers in each attic space. The transducers were placed between the ceiling joists, and measured the heat flow through the insulation, and not that through the joists.

Detailed temperature, heat flow, and weather data were provided by Ober for the period of August 24-30, 1987. The RBSOR1 (no truss RB) and the RBSOR3 (two truss RBs) models were used to predict the heat flows for these periods. Measured values of exterior roof, ceiling bottom, and outdoor air temperatures were used as inputs to the models. The exterior surfaces of the gables were modeled as shaded surfaces exposed to the outdoor air. The material properties used in the models are given in Table 4.18. The emittances of the nonreflective surfaces were taken to be 0.9. Moisture effects were not included since ambient relative humidities were not available.

The predictions of RBSOR1 are compared with measured values for the section with no radiant barrier in Table 4.19. Measured gable interior temperatures were used in Run 2, while in Run 1, the gable temperatures were calculated with the model. The results of Run 1 are in better agreement with the measured data and are shown in Fig. 4.9. The peak heat fluxes and the sum of positive heat flows are in very good agreement. The slight underprediction of the sum appears to be caused by an underprediction at night. It is possible that inclusion of moisture effects in the model would improve the predictions during this time period. It should be noted that the ventilation rate was calculated using the ventilation algorithm described above. The calculated ventilation rates were all very reasonable, being in the range of one to eight air changes per hour.

The predictions of RBSOR3 are compared with measured values for the section with a draped radiant barrier in Table 4.20 and in Fig.

Table 4.18. Material properties for MIMA tests.

Material	Thickness in.	Thermal conductivity (Btu/hr-ft-^{o}F)	Specific heat (Btu/lb-^{o}F)	Density lb/ft^3
Ceiling:				
Drywall	0.5	0.09250	0.26	50.0
R-20 Insulation	7.2	0.02985	0.20	0.40
Roof				
Plywood	0.5	0.0667	0.29	34.0
Rafters	3.5	0.06833	0.39	28.0
Gables				
Polyisocyanurate foam	0.75	0.01167	0.22	2.0
Divider between Attics:				
Fiberglass	7.5	0.02083	0.20	8.0
Eave Walls				
Plywood	0.5	0.0667	0.29	34.0

Table 4.19. Comparison of predicted and measured heat flows for MIMA test with no radiant barrier.

	Measured*	Predicted, %**	
		Run 1	Run 2
Day 1 Peak	2.85	2.4	-0.4
Day 2 Peak	2.70	2.2	-0.4
Day 3 Peak	2.88	1.0	-1.4
Day 4 Peak	2.83	1.8	-0.7
Day 5 Peak	2.91	1.0	-1.4
Day 6 Peak	2.85	0.4	-2.5
Day 7 Peak	2.56	-2.7	-5.9
Sum of Period Positive Flows	188.1	-3.0	-9.9

Run 1: Gable temperatures not known
Run 2: Gable temperatures known

*Peak values are Btu/(hr-ft^2), sum is Btu/ft^2.

**Values are predicted minus measured, as a percentage of the measured value.

4.10. Runs were made with various values for the emittance of the bottom of the RB and with two assumptions about the split of the ventilation flow between the main attic space and the space between the roof and the radiant barrier. Two runs were also made using the measured gable interior temperatures. All of the runs that did not use measured gable temperatures underpredicted the heat flows by 20 to 50 percent. The two runs using measured gable temperatures were in much better agreement with the data. This indicates that radiation from warm nonreflective gables is an important contributor to the ceiling heat flow when a truss radiant barrier is present. It also indicates that modeling the gables as shaded exterior surfaces is not adequate when a truss radiant barrier is present. The calculations shown in Fig. 4.10 are from Run 6.

The RBSOR1 model (no truss RB) was also used to predict the heat flows for the section with the radiant barrier, with the results given in Table 4.21 and in Fig. 4.11. The first four runs were made without using the measured gable temperatures, while the fifth run used them. The results of the first four runs are seen to be in much better agreement with the measured values than were the corresponding RBSOR3 predictions. The daily peak heat fluxes using a roof bottom emittance of 0.10 are in best agreement with the data, while the sum heat flow predicted with an emittance of 0.13 is best. The reason for the runs with emittances higher than 0.05 being better may be due to the draped configuration of the radiant barrier where the hot sides of the rafters near the roof are exposed and radiate toward the attic floor. The higher emittances represent an area averaging of the emittances of the radiant barrier and the exposed wood surfaces. The results of Run 5 are also in good agreement with the measured values and are the calculated values shown in Fig. 4.11.

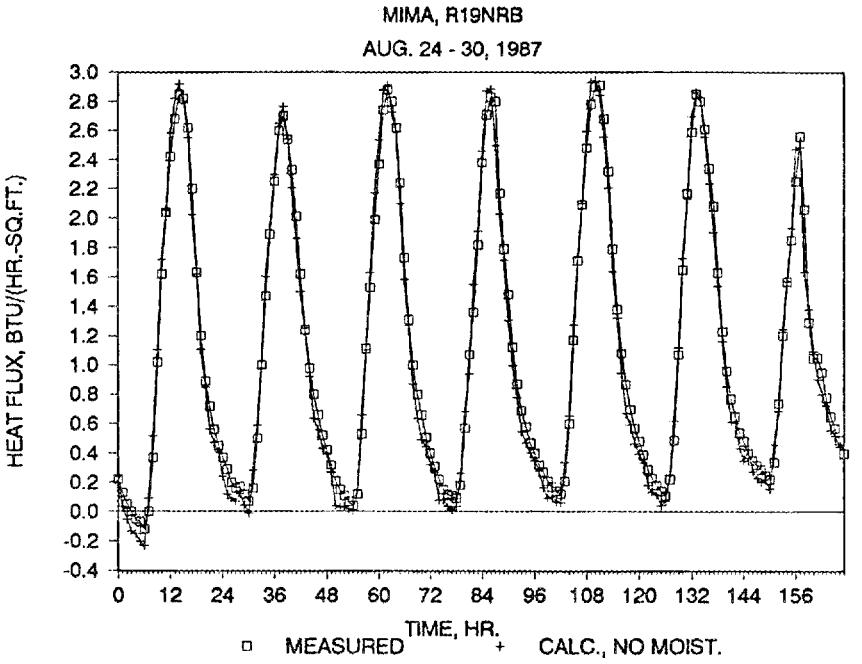

Fig. 4.9. Comparison of predicted and measured heat fluxes for MIMA test with R-19 insulation and no radiant barrier.

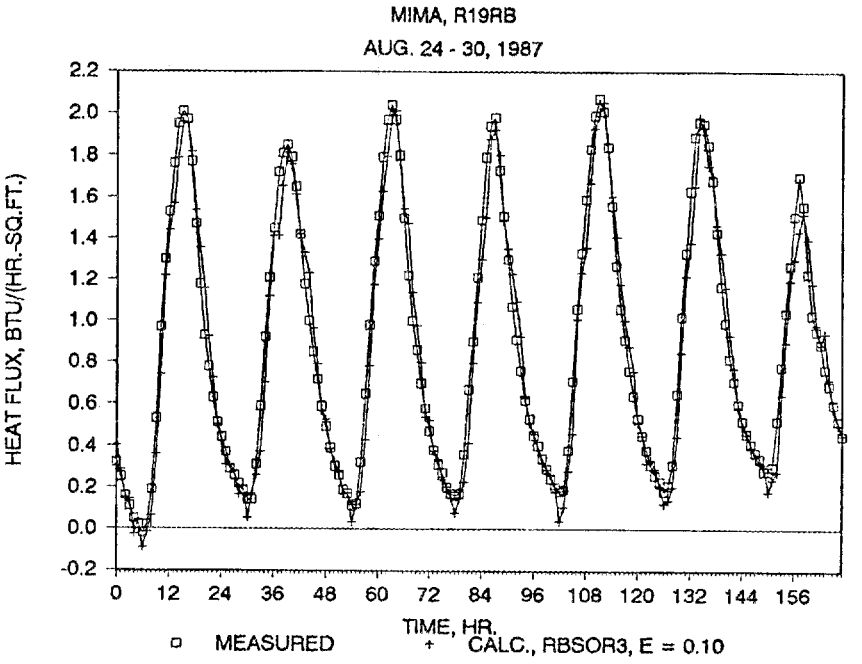

Fig. 4.10. Comparison of predicted and measured heat fluxes for MIMA test with R-19 insulation and draped truss radiant barrier using RBSOR3 and emittance of 0.10 for RB bottom.

Table 4.20. Comparison of predicted and measured heat fluxes for MIMA test with draped truss radiant barrier using RBSOR3.

		Predicted, %**						
	Measured*	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7
Day 1 Peak	2.01	-34.8	-29.4	-27.4	-29.4	-37.8	-2.5	-9.0
Day 2 Peak	1.85	-33.5	-28.6	-26.5	-28.6	-36.8	-1.6	-8.1
Day 3 Peak	2.04	-34.8	-29.4	-27.0	-29.4	-37.2	-1.5	-8.3
Day 4 Peak	1.98	-34.8	-31.8	-26.8	-29.3	-37.9	-3.0	-10.1
Day 5 Peak	2.07	-35.3	-30.4	-28.5	-30.4	-37.7	-1.0	-7.7
Day 6 Peak	1.96	-29.6	-24.0	-21.9	-24.0	-32.6	-1.0	-4.6
Day 7 Peak	1.70	-43.5	-39.4	-37.6	-39.4	-45.3	-10.6	-18.2
Sum of Period Positive Flows	148.9	-34.2	-29.8	-28.1	-28.7	-36.7	-3.1	-7.0

	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7
Emittance of RB Bottom	0.05	0.10	0.13	0.10	0.05	0.10	0.10
Fraction of Vent Flow through RB Space	0.9	0.9	0.9	0.1	0.9	0.9	0.1
HC = 0 on Top of Insulation	No	No	No	No	Yes	No	No
Gable Temperature Known	No	No	No	No	No	Yes	Yes

*Peak values are Btu/(hr-ft^2), sums are Btu/ft^2.

**Values are predicted minus measured, as percentage of measured value.

Table 4.21. Comparison of predicted and measured heat flows for MIMA test with draped truss radiant barrier using RBSOR1.

		Predicted, %**				
	Measured*	Run 1	Run 2	Run 3	Run 4	Run 5
Day 1 Peak	2.01	-9.0	2.0	6.5	-8.5	7.0
Day 2 Peak	1.85	-10.8	0	2.7	-10.3	5.9
Day 3 Peak	2.04	-9.8	1.0	4.9	-9.3	5.9
Day 4 Peak	1.98	-5.6	6.6	11.1	-4.5	8.1
Day 5 Peak	2.07	-8.2	3.4	8.2	-7.2	5.3
Day 6 Peak	1.96	-3.1	8.7	13.3	-2.0	11.7
Day 7 Peak	1.70	-14.7	-1.2	4.1	-14.7	-1.8
Sum of Period Positive Flows	148.9	-15.2	-6.0	-2.5	-15.6	3.1

	Run 1	Run 2	Run 3	Run 4	Run 5
Emittance of RB Bottom	0.05	0.10	0.13	0.05	0.10
HC = 0 on Top of Insulation	No	No	No	Yes	No
Gable Temperature Known	No	No	No	No	Yes

*Peak values are Btu/(hr-ft^2), sums are Btu/ft^2.

**Values are predicted minus measured, as percentage of measured value.

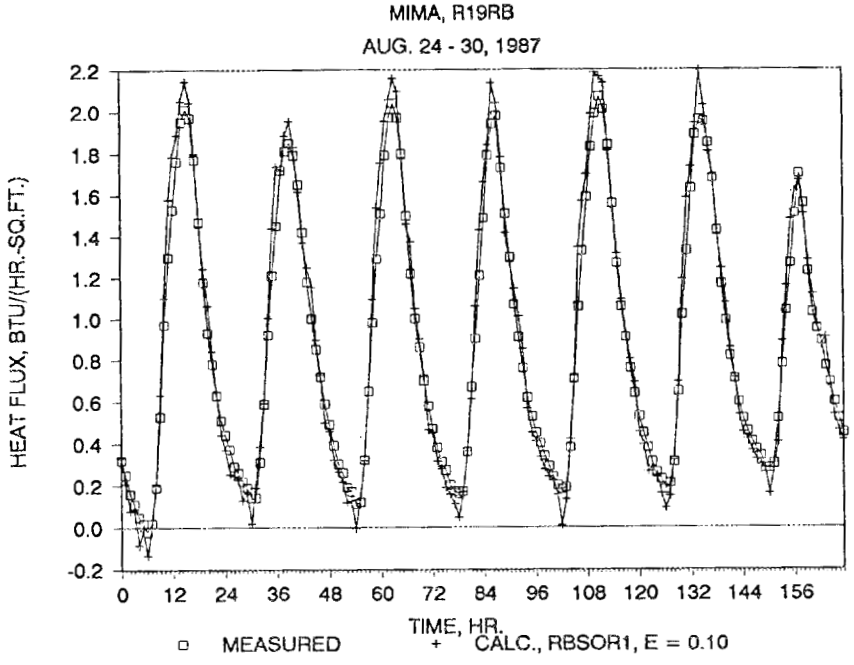

Fig. 4.11. Comparison of predicted and measured heat fluxes for MIMA test with R-19 insulation and draped truss radiant barrier using RBSOR1 and emittance of 0.10 for RB bottom.

5. SUMMARY AND CONCLUSIONS

Models for the thermal performance of attics with and without radiant barriers have been developed and implemented on an IBM PC/AT computer. The new models are based on existing ones, but have several improvements and extensions. These include more detailed convection heat transfer coefficients, inclusion of latent heat effects due to the sorption and desorption of moisture at the wood surfaces that face the attic space, an algorithm to estimate the rate of flow of ventilation air through the attic, and additional heat balances to handle the extra air spaces created by the truss radiant barrier system.

The validity of the models has been tested by comparing their predictions with the results of a number of laboratory and field experiments on attics with and without radiant barriers. Cumulative heat flows for attics without radiant barriers are generally predicted to within about 5 to 10 percent of the measured values. Cumulative heat flows for attics with radiant barriers are often also predicted with this accuracy. The model predictions for instantaneous heat flows are generally not as good as those for cumulative heat flows over periods of days.

The comparisons have raised several questions about the applicability of the models. For the small test cells used by TVA, the models predicted high attic air change rates, and as a consequence, the predicted heat flows were low. More reasonable air change rates and heat flows were predicted when the vent areas were arbitrarily reduced by a factor of 10. For the large scale tests by MIMA, the models predicted very reasonable air change rates and heat flows. Thus, the ventilation algorithms may not be applicable for small test cells, but may be adequate for large scale tests. More research on attic ventilation with a range of attic sizes is needed to understand this better.

With a truss radiant barrier, radiation across the attic space is still an important heat transfer mechanism, as evidenced by model runs with the convection coefficient at the top of the insulation set to zero. Because of this, the choice of an effective emittance for the bottom of the roof presents a problem. For the FSEC tests, an emittance of 0.05 worked best, while for the MIMA tests, a higher emittance was needed. This may be due to the two different truss configurations. For the FSEC tests, the radiant barrier was placed 3.5 inches below the roof between 2 x 10 inch rafters. Consequently, the exposed surfaces of the rafters would have been cooler than the radiant barrier and an area averaged emittance would not have been appropriate. For the MIMA tests, the radiant barrier was draped between 2 x 4 inch rafters and hot sides of the rafters were exposed. With this configuration, an area averaged emittance would have been appropriate. The emittances used here were based on simple engineering calculations; more detailed analyses would be needed to develop a more rigorous estimation of this parameter.

For some cases, the effects of moisture sorption/desorption could be included in the models. For these cases, the inclusion of moisture effects improved the model predictions for the nighttime heat flows, but did not consistently improve the predictions for the daytime heat flows.

The validity of the models has been demonstrated to the extent that they may form the basis for providing an initial assessment of the energy savings potential for radiant barriers. However, further refinements are needed to answer questions that remain about the differences among the various sets of experimental data. Further refinements would include more detailed algorithms for the air flow patterns within the attic space, especially in the presence of a truss radiant barrier. Experiments carried out under carefully controlled laboratory conditions, both steady-state and dynamic, would greatly assist in these refinements. Flow visualization experiments would also aid in developing flow pattern algorithms.

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APPENDIX A
RBSOR1 COMPUTER PROGRAM

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C*********************************************************************
C**                                                                 **
C**                        PROGRAM RBSOR1                           **
C**                                                                 **
C*********************************************************************
C  THIS PROGRAM CALCULATES THE HEAT TRANSFER THROUGH THE CEILING
C  BELOW A GABLED ATTIC HAVING A FIVE-SIDED CROSS SECTION
C  ASSUMES THE AIR WITHIN THE ATTIC IS NOT WELL-MIXED
C  INCLUDES APPROXIMATE CALCULATIONS FOR LATENT HEAT EFFECTS
C  DUE TO MOISTURE ADSORPTION AND DESORPTION
C  SURFACE TEMPERATURES ON INSIDE OR OUTSIDE, OR VENTILATION RATE
C  MAY BE SPECIFIED THROUGH KFLAG(I) = 1
C  NOMENCLATURE:
C   N(I) = NUMBER OF CONDUCTION TRANSER FUNCTIONS FOR SURFACE I
C   U(I) = SURFACE-TO-SURFACE U-VALUE FOR SURFACE I
C   CR(I) = COMMON RATIO OF RESPONSE FACTORS FOR SURFACE I
C   BETA(I) = TEMPERATURE DEPENDENT COEFFICIENT FOR CONDUCTION
C             TRANSFER FUNCTIONS FOR SURFACE I
C   X(I,J), Y(I,J), Z(I,J) = CONDUCTION TRANSFER FUNCTIONS FOR
C             SURFACE I
C   SURFACES ARE NUMBERED AS (FOR NORTH-SOUTH RIDGE):
C     1 = CEILING
C     2 = EAST ROOF
C     3 = WEST ROOF
C     4 = SOUTH GABLE
C     5 = NORTH GABLE
C     6 = EAST EAVE WALL
C     7 = WEST EAVE WALL
C   ALF(I) = SOLAR ABSORPTANCE FOR SURFACE I
C   EO(I) = INFRARED EMITTANCE FOR OUTSIDE OF SURFACE I
C   EI(I) = INFRARED EMITTANCE FOR INSIDE OF SURFACE I
C   TIS(I,J) = INSIDE SURFACE TEMPERATURE FOR SURFACE I
C   TOS(I,J) = OUTSIDE SURFACE TEMPERATURE FOR SURFACE I
C   TA = AVERAGE TEMPERATURE OF AIR IN ATTIC
C   QI(I,J) = INSIDE HEAT FLUX FOR SURFACE I
C   QO(I,J) = OUTSIDE HEAT FLUX FOR SURFACE I
C   HCI(I) = CONVECTION COEFFICIENT FOR INSIDE OF SURFACE I
C   HR(I,K) = RADIATION INTERCHANGE COEFFICIENT FROM SURFACE I
C             TO SURFACE K
C   AA(I,J) = MATRIX OF COEFFICIENTS FOR SIMULTANEOUS EQUATIONS
C   BB(I) = KNOWN VECTOR FOR SIMULTANEOUS EQUATIONS
C   XXX(I) = SOLUTION VECTOR FOR SIMULTANEOUS EQUATIONS
C   QSOL(I) = SOLAR RADIATION INCIDENT ON SURFACE I
C   A(I) = AREA OF SURFACE I
C   G(I,K) = OVERALL RADIATION VIEW FACTOR FROM SURFACE I TO
C            SURFACE K
C   HCO(I) = CONVECTION COEFFICIENT ON OUTSIDE OF SURFACE I
C   HRO(I) = RADIATION COEFFICIENT ON OUTSIDE OF SURFACE I
C   R(I) = SURFACE-TO-SURFACE RESISTANCE FOR SURFACE I
C   AMC(I) = MOISTURE CONTENT (WEIGHT FRACTION) FOR SURFACE I
C   PERM(I) = MOISTURE PERMEANCE OF SURFACE I
C   AWRAT(I) = RATIO OF EXPOSED SURFACE AREA TO PROJECTED SURFACE
```

```
C               AREA FOR SURFACE I
C   AMASS(I) = MASS PER UNIT AREA OF SURFACE I THAT PARTICIPATES IS
C               MOISTURE EXCHANGE
C   AMW(I) = MOISTURE FLUX TOWARD SURFACE I
C   BMW(I) = TERM IN TAYLOR SERIES EXPANSION FOR MOISTURE FLUX
C   TS(I) = TEMPERATURE OF INSIDE OF SURFACE I
C   KFLAG = FLAG FOR SPECIFIED SURFACE TEMPERATURES
C       0 = PARAMETER NOT SPECIFIED
C       1 = PARAMETER SPECIFIED
C       I = 1,7 FOR TIS(I,1)
C       I = 8,14 FOR TOS(I-7,1)
C       I = 15 FOR VENTILATION RATE
C   AL = LENGTH OF ATTIC, FEET
C   W  = WIDTH OF ATTIC, FEET
C   PITCH1 = PITCH OF EAST ROOF, DEGREES
C   PITCH2 = PITCH OF WEST ROOF, DEGREES
C   ORIENT = ORIENTATION OF HOUSE
C   H1 = HEIGHT OF VERTICAL WALLS AT EAVES, FEET
C   AI = AREA OF INLET VENT, SQUARE FEET
C   AO = AREA OF OUTLET VENT, SQUARE FEET
C   ITYPE = TYPE VENTS
C       1 = SOFFIT AND RIDGE VENTS
C       2 = SOFFIT AND GABLE VENTS
C       3 = SOFFIT VENTS ONLY
C   QLAT = HEAT OF VAPORIZATION OF WATER, BTU/LBM
C   EXFIL = RATE OF FLOW OF AIR FROM HOUSE TO ATTIC, LB/HR
C   AL1 ... AL7 = CHARACTERISTIC LENGTHS OF SURFACES 1 ... 7, FEET
C   TO = OUTDOOR TEMPERATURE, F
C   QSOLH = SOLAR RADIATION INCIDENT ON HORIZONTAL SURFACE
C           BTU/(HR.-SQ.FT.)
C   WS = WIND SPEED, MPH
C   DIR = WIND DIRECTION
C   HUM = OUTDOOR RELATIVE HUMIDITY, PERCENT
C   TI = INDOOR TEMPERATURE, F
C   HUMI = INDOOR RELATIVE HUMIDITY, PERCENT
C   VDOT = VENTILATION RATE, CUBIC FEET PER HOUR
C   IVFLAG = FLAG FOR CALCULATING FLOW VELOCITY
C        0 = FLOW THROUGH BOTH SIDE OF ATTIC
C        1 = FLOW THROUGH ONE SIDE OF ATTIC
C   FLUX = MEASURED CEILING HEAT FLUX, BTU/(HR.-SQ.FT.)
C   TAIR = MEASURED ATTIC AIR TEMPERATURE, F
C   TEXIT = MEASURED EXIT AIR TEMPERATURE, F
C   H = HEIGHT, FEET
C   AMDOT = VENTILATION RATE, POUNDS PER HOUR
C   AMCDOT = VENTILATION RATE TIMES SPECIFIC HEAT
C   V = CRUDE ESTIMATE OF AIR SPEED THROUGH ATTIC, FEET PER HOUR
C   ACH = AIR CHANGE RATE FOR ATTIC, AIR CHANGES PER HOUR
      DIMENSION N(7),U(7),CR(7),BETA(7),X(7,100),Y(7,100),Z(7,100)
      DIMENSION ALF(7),EO(7),EI(7),TIS(7,100),TOS(7,100),TA(2)
      DIMENSION QI(7,2),QO(7,2),HCI(7),HR(7,7),AA(15,15),BB(15)
      DIMENSION XXX(15),QSOL(7),A(7),G(7,7),HCO(7),HRO(7),R(7)
      DIMENSION AMC(7),PERM(7),AWRAT(7),AMASS(7),AMW(7),TS(7)
```

```
      DIMENSION BMW(7),KFLAG(15)
      DATA TIS/700*75.0/,TOS/700*75.0/,AA/225*0.0/,TR/75.0/
      DATA TA/2*75.0/,QI/14*0.0/,QO/14*0.0/,BMW/7*0.0/
C  READ IN KFLAG
      READ (5,*) (KFLAG(I),I=1,7)
      READ (5,*) (KFLAG(I),I=8,14)
      READ (5,*) KFLAG(15)
C  READ IN CONDUCTION TRANSFER FUNCTIONS
      DO 100 I = 1,7
      READ (5,*)  N(I),U(I),CR(I),BETA(I)
      M = N(I)
      DO 100 J = 1,M
      READ (5,*) X(I,J),Y(I,J),Z(I,J)
  100 CONTINUE
      DO 101 I = 1,7
  101 R(I) = 1./U(I)
C  CONVENTION FOR CTF'S IS SAME AS USED IN TARP
C  CONVENTION FOR ATTIC MODEL IS THAT INSIDE SURFACES
C  FACE THE ATTIC SPACE
C  CTF'S FOR THE CEILING ARE CALCULATED FOR USE IN A
C  WHOLE HOUSE MODEL, WHERE THE OUTSIDE SURFACE FACES
C  THE ATTIC;  THEREFORE, FOR USE INTERNAL TO THE ATTIC
C  MODEL, INTERCHANGE THE X'S AND THE Z'S
      M = N(1)
      DO 110 J = 1,M
      XX = X(1,J)
      X(1,J) = Z(1,J)
      Z(1,J) = XX
  110 CONTINUE
C  READ IN SOLAR ABSORPTANCES OF OUTSIDE SURFACES AND
C  EMITTANCES OF BOTH OUTSIDE AND INSIDE SURFACES
      READ(5,*)  (ALF(I), I = 1,7)
      READ(5,*)  (EO(I), I = 1,7)
      READ(5,*)  (EI(I), I = 1,7)
C  READ IN ATTIC GEOMETRY:  LENGTH, WIDTH, PITCHES OF ROOF
C  SURFACES(DEGREES), ORIENTATION ANGLE OF HOUSE
C  AND HEIGHT OF SIDE WALLS
      READ (5,*)  AL,W,PITCH1,PITCH2,ORIENT,H1
C  READ VENT INLET AND OUTLET AREAS, AND VENT TYPE
C  TYPE 1 = SOFFIT AND RIDGE VENTS
C  TYPE 2 = SOFFIT AND GABLE VENTS
C  TYPE 3 = SOFFIT VENTS ONLY
      READ(5,*) AI,AO,ITYPE
C  READ WATER VAPOR PERMEANCES OF ATTIC SURFACES
C  PERM = GRAINS PER (HR-FT2-INCH HG)
      READ (5,*) (PERM(I),I=1,7)
C CONVERT PERM VALUES TO POUNDS PER (HR-FT2-PSIA)
      DO 120 I = 1,7
  120 PERM(I) = PERM(I)*(29.921/14.696)/7000.
C  READ RATIO OF TOTAL AREA OF EXPOSED WOOD TO GEOMETRICAL
C  PROJECTION OF SURFACE AREAS
      READ (5,*) (AWRAT(I),I=1,7)
```

```
C  READ WEIGHT OF WOOD PER UNIT PROJECTED AREA FOR EACH SURFACE
      READ (5,*) (AMASS(I),I=1,7)
C  READ INITIAL MOISTURE CONTENTS OF WOOD, WEIGHT FRACTION
      READ (5,*) (AMC(I),I=1,7)
C  READ LATENT HEAT OF VAPORIZATION, BTU/LB
      READ (5,*) QLAT
C  READ RATE OF FLOW OF HOUSE AIR INTO ATTIC, POUNDS PER HOUR
      READ (5,*) EXFIL
      CALL VIEW2(AL,W,PITCH1,PITCH2,H1,EI,G,7)
C  CALCULATE CHARACTERISTIC LENGTHS AND AREAS OF SURFACES
C  CHAR. LENGTHS ARE TAKEN TO BE:
C  CEILING - AVERAGE OF LENGTH AND WIDTH
C  ROOF - DISTANCE FROM EAVE TO RIDGE
C  GABLE - AVERAGE HEIGHT
C  SIDE WALLS - HEIGHT
      AL1 = (AL+W)/2.
      P1 = PITCH1*3.14159265/180.
      P2 = PITCH2*3.14159265/180.
      P3 = 3.14159265 - P1 - P2
      IP1 = PITCH1
      IP2 = PITCH2
      IP3 = 180.0 - PITCH1 - PITCH2
      IF(IP3.EQ.180) GO TO 5
      AL2 = W*SIN(P2)/SIN(P3)
      AL3 = W*SIN(P1)/SIN(P3)
      AL4 = 0.5*(AL2*SIN(P1)) + H1
      GO TO 6
    5 AL2 = W/2.0
      AL3 = W/2.0
      AL4 = H1
    6 AL5 = AL4
      AL6 = H1
      AL7 = H1
      A(1) = AL*W
      A(2) = AL*AL2
      A(3) = AL*AL3
      A(4) = W*AL4
      A(5) = A(4)
      A(6) = AL*H1
      A(7) = AL*H1
C  READ LINE OF WEATHER DATA
C***********************************************************************
   10 READ(5,*,END = 999) TO,QSOLH,WS,DIR,HUM,TI,HUMI,(TIS(I,1),I=1,7),
     & (TOS(I,1),I=1,7),VDOT,IVFLAG,FLUX,TAIR,TEXIT
C  RESTORE ESTIMATES FOR TEMPERATURES NOT SPECIFIED
      DO 15 I = 1,7
      IF(KFLAG(I).EQ.0) TIS(I,1) = TIS(I,2)
   15 IF(KFLAG(I+7).EQ.0) TOS(I,1) = TOS(I,2)
C***********************************************************************
C  CALCULATE SOLAR LOAD ON EACH SURFACE
C  NEED TO INVOKE APPROPRIATE ALGORITHMS
C  THE FOLLOWING ARE TEMPORARY
```

```
      QSOL(1) = 0.0
      QSOL(2) = QSOLH
      QSOL(3) = QSOLH
      QSOL(4) = 0.0
      QSOL(5) = 0.0
      QSOL(6) = 0.0
      QSOL(7) = 0.0
      NIT = 1
C*********************************************************************
C  CALCULATE ATTIC VENTILATION RATE AND FLOW VELOCITY
      H = AL4 + AL2*SIN(P1)/2.0
   20 CONTINUE
      IF(KFLAG(15).EQ.0) THEN
        CALL VENT(TO,TA(1),WS,DIR,H,AI,AO,ITYPE,AMCDOT,AMDOT,VDOT)
      ELSE
C  ASSUME VENTILATION RATES ARE BASED ON OUTSIDE AIR TEMPERATURE
        AMDOT = VDOT*22.0493/((TO+459.67)/1.8)
        AMCDOT = AMDOT*(3.4763 + 1.066E-4*((TO+459.67)/1.8))*0.068559
      END IF
C  ESTIMATE CRUDE FLOW VELOCITY
      IF(IVFLAG.EQ.0) V = VDOT/(AL4*AL)
      IF(IVFLAG.EQ.1) V = VDOT*2.0/(AL4*AL)
      ACH = VDOT/A(4)/AL
C*********************************************************************
C  CALCULATE CONVECTION COEFFICIENTS AT INSIDE SURFACES
      CALL HCON(TIS(1,1),TA(1),0.0,AL1,1,V,HCI(1))
      CALL HCON(TIS(2,1),TA(1),PITCH1,AL2,2,V,HCI(2))
      CALL HCON(TIS(3,1),TA(1),PITCH2,AL3,2,V,HCI(3))
      CALL HCON(TIS(4,1),TA(1),90.0,AL4,1,V,HCI(4))
      CALL HCON(TIS(5,1),TA(1),90.0,AL5,1,V,HCI(5))
      CALL HCON(TIS(6,1),TA(1),90.0,AL6,1,V,HCI(6))
      CALL HCON(TIS(7,1),TA(1),90.0,AL7,1,V,HCI(7))
C  CALCULATE CONVECTION COEFFICIENTS AT OUTSIDE SURFACES
      WS1 = WS*5280.
      CALL HCON(TOS(1,1),TI,0.0,AL1,2,0.0,HCO(1))
      CALL HCON(TOS(2,1),TO,PITCH1,AL2,1,WS1,HCO(2))
      CALL HCON(TOS(3,1),TO,PITCH2,AL3,1,WS1,HCO(3))
      CALL HCON(TOS(4,1),TO,90.0,AL4,1,WS1,HCO(4))
      CALL HCON(TOS(5,1),TO,90.0,AL5,1,WS1,HCO(5))
      CALL HCON(TOS(6,1),TO,90.0,AL6,1,WS1,HCO(6))
      CALL HCON(TOS(7,1),TO,90.0,AL7,1,WS1,HCO(7))
C  CALCULATE RADIATION COEFFICIENTS AT INSIDE SURFACES
      DO 200 I = 1,7
      DO 200 J = 1,7
      HR(I,J) = HRAD(G(I,J),TIS(I,1),TIS(J,1))
  200 CONTINUE
C  CALCULATE RADIATION COEFFICIENTS AT OUTSIDE SURFACES
      HRO(1) = HRAD(EO(1),TOS(1,1),TI)
      DO 250 I = 2,7
      HRO(I) = HRAD(EO(I),TOS(I,1),TO)
  250 CONTINUE
C  CALCULATE MOISTURE BALANCES, LATENT HEATS
```

```
      IF(QLAT.LE.1.) THEN
         DO 259 I = 1,7
         AMW(I) = 0.0
         BMW(I) = 0.0
  259    CONTINUE
      ELSE
      DO 260 I = 1,7
  260 TS(I) = TIS(I,1)
      CALL MOIST(TS,TO,TI,TA(1),HCI,A,AWRAT,AMC,AMASS,HUM,HUMI,PERM,
     &   AMDOT,EXFIL,AMW,BMW,7)
      DO 270 I = 1,7
      IF(AMC(I).LE.1.E-6.AND.AMW(I).LT.0.0) THEN
         AMW(I) = 0.0
         BMW(I) = 0.0
      ELSE IF(AMW(I).LT.0.0.AND.ABS(AMW(I)).GT.(AMC(I)*AMASS(I))) THEN
         FACT = ABS(AMC(I)*AMASS(I)/AMW(I))
         AMW(I) = AMW(I)*FACT
         BMW(I) = BMW(I)*FACT
      ELSE
         CONTINUE
      END IF
  270 CONTINUE
      END IF
C*********************************************************************
C  SET UP MATRIX OF COEFFICIENTS IN HEAT BALANCE EQUATIONS
      DO 300 I = 1,7
      DO 300 J = 1,7
      AA(I,J) = -HR(I,J)
  300 CONTINUE
      DO 310 I = 1,7
      DO 305 J = 1,7
  305 AA(I,I) = AA(I,I) + HR(I,J)
  310 AA(I,I) = AA(I,I) + Z(I,1) + HCI(I)
C  ADD IN LATENT HEAT TERMS
      DO 315 I = 1,7
  315 AA(I,I) = AA(I,I) + BMW(I)*QLAT
C*********************************************************************
      DO 320 I = 1,7
      AA(I,I+7) = - Y(I,1)
      AA(I,15) = -HCI(I)
      AA(I+7,I) = -Y(I,1)
      AA(I+7,I+7) = X(I,1) + HCO(I) + HRO(I)
  320 AA(15,I) = A(I)*HCI(I)
C*********************************************************************
      C1 = 0.0
      DO 330 I = 1,7
  330 C1 = C1 + A(I)*HCI(I)
      C2I = (AMCDOT + EXFIL*0.24)/C1
      IF(C2I.GT.0.02)  C3 = EXP(-1./C2I) - 1.0
      IF(C2I.LE.0.02)  C3 = -1.0
      AA(15,15) = -C1/(1. + C2I*C3)
C*********************************************************************
```

```
C  SET UP VECTOR FOR RIGHT HAND SIDE OF HEAT BALANCE EQUATIONS
      DO 400 I = 1,7
      BB(I) = TR*(Z(I,1)-Y(I,1)) - CR(I)*QI(I,2)
      BB(I) = BB(I) -BETA(I)/2.*(Z(I,1)*(TIS(I,1)-TR)**2
     &   -Y(I,1)*(TOS(I,1)-TR)**2)
      DO 400 J = 2,N(I)
  400 BB(I)=BB(I)-Z(I,J)*(TIS(I,J)-TR)+Y(I,J)*(TOS(I,J)-TR)
     &  -BETA(I)/2.*(Z(I,J)*(TIS(I,J)-TR)**2
     &  -Y(I,J)*(TOS(I,J)-TR)**2)
C  ADD IN LATENT HEAT EFFECTS
      DO 405 I = 1,7
  405 BB(I) = BB(I) + AMW(I)*QLAT + BMW(I)*QLAT*TIS(I,1)
      DO 410 I = 1,7
      BB(I+7) = TR*(X(I,1)-Y(I,1)) + CR(I)*QO(I,2)
      BB(I+7) = BB(I+7) -BETA(I)/2.*(X(I,1)*(TOS(I,1)-TR)**2
     &    -Y(I,1)*(TIS(I,1)-TR)**2)
      DO 410 J = 2,N(I)
  410 BB(I+7) = BB(I+7)-X(I,J)*(TOS(I,J)-TR)+Y(I,J)*(TIS(I,J)-TR)
     &  -BETA(I)/2.*(X(I,J)*(TOS(I,J)-TR)**2
     &  -Y(I,J)*(TIS(I,J)-TR)**2)
      BB(8) = BB(8) + HCO(1)*TI + HRO(1)*TI
      DO 420 I = 2,7
C  IN NEXT EQUATION, SHOULD MULTIPY HRO(I) BY TS, I.E.,
C  THE TEMPERATURE OF THE SURROUNDING SURFACES
C  TEMPORARILY, USE TO IN PLACE OF TS
  420 BB(I+7) = BB(I+7) + HCO(I)*TO + HRO(I)*TO + ALF(I)*QSOL(I)
      BB(15) = (AMCDOT*TO + EXFIL*0.24*TI)*C3/(1.0 + C2I*C3)
C*********************************************************************
      SKBIG = 1.E20
      DO 450 I = 1,7
      IF(KFLAG(I).EQ.0)  GO TO 460
      AA(I,I) = AA(I,I)*SKBIG
      BB(I) = TIS(I,1)*AA(I,I)
  460 IF(KFLAG(I+7).EQ.0) GO TO 450
      AA(I+7,I+7) = AA(I+7,I+7)*SKBIG
      BB(I+7) = TOS(I,1)*AA(I+7,I+7)
  450 CONTINUE
C*********************************************************************
C  SOLVE SYSTEM OF EQUATIONS
      CALL SOLVP(15,AA,BB,XXX)
C*********************************************************************
C  TEST FOR CONVERGENCE OF SOLUTION
      EPS = 1.E-3
      IFLAG = 0
      DO 500 I = 1,7
  500 IF(ABS(XXX(I)-TIS(I,1)).GT.EPS)  GO TO 600
      DO 510 I = 1,7
  510 IF(ABS(XXX(I+7)-TOS(I,1)).GT.EPS)  GO TO 600
      IF(ABS(XXX(15)-TA(1)).GT.EPS)  GO TO 600
C*********************************************************************
      GO TO 700
  600 IFLAG = 1
```

```
  700 CONTINUE
C*********************************************************************
      DO 800  I = 1,7
      TIS(I,1) = XXX(I)
  800 TOS(I,1) = XXX(I+7)
      TA(1) = XXX(15)
C*********************************************************************
      S1 = 0.0
      DO 850 I = 1,7
  850 S1 = S1 + A(I)*HCI(I)*TIS(I,1)
C  NEXT TWO LINES CORRECTED 8-30-89
      TE = AMCDOT*TO + EXFIL*0.24*TI + (S1 - C1*TA(1))
      TE = TE/(AMCDOT + EXFIL*0.24)
      NIT = NIT + 1
      IF(IFLAG.EQ.1.AND.NIT.LE.15)  GO TO 20
C  CALCULATE HEAT FLUXES
      DO 900 I = 1,7
      QI(I,1) = CR(I)*QI(I,2)
  900 QO(I,1) = CR(I)*QO(I,2)
      DO 950 I = 1,7
      DO 950 J = 1,N(I)
      QI(I,1) = QI(I,1) + Z(I,J)*(TIS(I,J)-TR)-Y(I,J)*(TOS(I,J)-TR)
     & +BETA(I)/2.*(Z(I,J)*(TIS(I,J)-TR)**2-Y(I,J)*(TOS(I,J)-TR)**2)
  950 QO(I,1) = QO(I,1) + Y(I,J)*(TIS(I,J)-TR)-X(I,J)*(TOS(I,J)-TR)
     &  +BETA(I)/2.*(Y(I,J)*(TIS(I,J)-TR)**2-X(I,J)*(TOS(I,J)-TR)**2)
C  CALCULATE TOTAL CEILING HEAT FLOW
      QCEIL = QO(1,1)*A(1)
C  CALCULATE NEW MOISTURE CONTENTS
      DO 960 I = 1,7
      AMC(I) = AMC(I) + AMW(I)/AMASS(I)
  960 IF(AMC(I).LE.0.0) AMC(I) = 0.0
C  WRITE OUT RESULTS
      WRITE(6,1001) TO,TOS(2,1),TOS(3,1),QO(1,1),FLUX,TA(1),TAIR,
     &              TE,TEXIT,ACH,AMC(2),NIT
 1000 FORMAT(2X,2F15.4,I10)
 1001 FORMAT(1X,3F7.2,2F10.4,4F7.2,F15.4,F6.3,I5)
C  UPDATE TEMPERATURES AND HEAT FLUXES FOR NEXT HOUR
      DO 1100 I = 1,7
      QI(I,2) = QI(I,1)
      QO(I,2) = QI(I,1)
      DO 1100 J = 1,N(I)-1
      TIS(I,N(I)-J+1) = TIS(I,N(I)-J)
 1100 TOS(I,N(I)-J+1) = TOS(I,N(I)-J)
      TA(2) = TA(1)
      GO TO 10
  999 STOP
      END
C*********************************************************************
C**                                                                 **
C**                          FUNCTION FMN                           **
C**                                                                 **
C*********************************************************************
```

```
      FUNCTION FMN(A,B,C,PHI)
C  THIS FUNCTION CALCULATES THE VIEW FACTOR BETWEEN TWO FINITE
C  RECTANGULAR PLATES SHARING AN EDGE
C  SEE APPENDIX A OF SPARROW AND CESS, CONFIGURATION 2
C  SEE ALSO A. FEINGOLD, PROC. ROY. SOC., A, VOL. 292, PP. 51-60 (1965)
C  VIEW FACTOR FROM PLATE 1 TO PLATE 2
C  A = WIDTH OF PLATE 2, C = WIDTH OF PLATE 1
C  B = LENGTH OF BOTH PLATES
C  PHI = ANGLE BETWEEN PLATES (RADIANS)
C  NUMERICAL INTEGRATION PERFORMED BY SIMPSON'S RULE
      DIMENSION Q(65)
      X = A/B
      Y = C/B
      SP = SIN(PHI)
      S2P = SIN(2.*PHI)
      CP = COS(PHI)
      C2P = COS(2.*PHI)
      Z = X*X + Y*Y - 2.*X*Y*CP
      DXI = Y/64.
      DO 1 N = 1,65
      ANM1 = N - 1
      XI = DXI*ANM1
      E = SQRT(1. + XI*XI*SP*SP)
      F = ATAN((X-XI*CP)/E) + ATAN(XI*CP/E)
    1 Q(N) = E*F
      AINT = Q(1) + 4.*Q(64) + Q(65)
      DO 2  N = 1,31
      K = 2*N
    2 AINT = AINT + 4.*Q(K) + 2.*Q(K+1)
      FMN = CP*AINT*DXI/3.
      E = SQRT(1.+X*X*SP*SP)
      F = ATAN(X*CP/E) + ATAN((Y-X*CP)/E)
      FMN = FMN + SP*S2P/2.*X*E*F
      FMN = FMN + X*ATAN(1./X) + Y*ATAN(1./Y)
     &      - SQRT(Z)*ATAN(1./SQRT(Z))
      E = 1. + X*X
      F = 1. + Y*Y
      FMN = FMN + (0.5 - SP*SP/4.)*ALOG(E*F/(1.+Z))
      FMN = FMN + SP*SP/4.*(Y*Y*ALOG(Y*Y*(1.+Z)/F/Z)
     &      + X*X*(ALOG(X*X/Z) + C2P*ALOG(E/(1.+Z))))
      E = Y*Y*ATAN((X-Y*CP)/Y/SP) + X*X*ATAN((Y-X*CP)/X/SP)
      FMN = FMN - S2P/4.*(X*Y*SP + (3.14159265/2. - PHI)
     &      * (X*X + Y*Y) + E)
      FMN = FMN/3.14159265/Y
      RETURN
      END
C*********************************************************************
C**                                                                 **
C**                          FUNCTION FP                            **
C**                                                                 **
C*********************************************************************
      FUNCTION FP(A,B,C)
```

```
C  THIS FUNCTION CALCULATES THE VIEW FACTOR BETWEEN TWO FINITE EQUAL
C  PARALLEL PLATES
C  SEE APPENDIX A OF SPARROW AND CESS, CONFIGURATION 1
C  A AND B = DIMENSIONS OF PLATES, C = SEPARATION OF PLATES
      X = A/C
      Y = B/C
      D = SQRT(1.+X*X)
      E = SQRT(1.+Y*Y)
      F = SQRT(1.+X*X+Y*Y)
      FP = ALOG(D*E/F) + Y*D*ATAN(Y/D) + X*E*ATAN(X/E)
     &     - Y*ATAN(Y) - X*ATAN(X)
      FP = FP*2./(3.14159265*X*Y)
      RETURN
      END
C*********************************************************************
C**                                                                 **
C**                          SUBROUTINE HCON                        **
C**                                                                 **
C*********************************************************************
      SUBROUTINE HCON(TS,TA,PHI,AL,IFLAG,V,HC)
C  THIS SUBROUTINE CALCULATES NATURAL CONVECTION HEAT TRANSFER
C  COEFFICIENTS BASED ON ISOLATED ISOTHERMAL FLAT PLATES
C  CALCULATES FORCED CONVECTION COEFFICIENTS AND TOTAL
C  CONVECTION HEAT TRANSFER COEFFICIENTS
C  SEE HOLMAN, 5TH EDITION, PP. 272-286
C  TS = SURFACE TEMPERATURE, F
C  TA = AIR TEMPERATURE, F
C  PHI = TILT ANGLE, DEGREES, 0 FOR HORIZONTAL, 90 FOR VERTICAL
C  AL = CHARACTERISTIC LENGTH OF SURFACE
C  IFLAG = 1 FOR SURFACE FACING UPWARD
C  IFLAG = 2 FOR SURFACE FACING DOWNWARD
C  V = AIR SPEED, FEET PER HOUR
C  HCF = FORCED CONVECTION COEFFICIENT
C  HCN = NATURAL CONVECTION COEFFICIENT
C  HC = TOTAL CONVECTION COEFFICIENT
C
      REAL NUS,K,MU,NU
      DT = TS - TA
      IF (IFLAG.EQ.2)  DT = -DT
C  CALCULATE FILM TEMPERATURE
      TF = (TS+TA)/2.0
      TF1 = TF
      IF(ABS(PHI).GT.1.E-3.AND.ABS(PHI-90.).GT.1.E-3)
     &    TF = TS - 0.25*(TS-TA)
      IF(ABS(PHI).GT.1.E-3.AND.ABS(PHI-90.).GT.1.E-3)
     &    TF1 = TA + 0.25*(TS-TA)
      TK = (TF+459.67)/1.8
C  THERMAL CONDUCTIVITY OF AIR FROM EQUATION IN NBS CIRC. 564
C  THERMAL COND. IN BTU/(HR-FT-F)
      K = 0.6325E-5*SQRT(TK)/(1.+(245.4*10.**(-12./TK))/TK)*241.77
C  DYNAMIC VISCOSITY OF AIR FROM EQUATION IN NBS CIRC. 564
C  LB/(HR-FT)
```

```
      MU = (145.8*TK*SQRT(TK)/(TK+110.4))*241.90E-7
C  PRANDTL NUMBER, LINEAR REGRESSION FROM 220 K TO 360 K
C  FROM NBS CIRC. 564
      PR = 0.7880 - 2.631E-4*TK
C  VOLUME EXPANSION COEFFICIENT OF AIR, 1/TABS, PERFECT GAS
      BETA = 1./(TF1+459.67)
C  DENSITY OF AIR, PERFECT GAS, NBS CIRC. 564, LB/CF
      RHO = 22.0493/TK
C  KINEMATIC VISCOSITY, FT2/HR
      NU = MU/RHO
C  SPECIFIC HEAT OF AIR, LINEAR REGRESSION FROM 220 K TO 360 K
C  FROM NBS CIRC. 564, BTU/(LB-F)
      CP = (3.4763 + 1.066E-4*TK)*0.068559
C  RAYLEIGH NUMBER, LEADING COEFFICIENT IS
C  32.174*3600*3600, FT/HR2
      RA = (4.16975E8)*BETA*RHO*CP*ABS(DT)*(AL**3)/NU/K
C  BRANCH TO DIFFERENT CORRELATIONS DEPENDING UPON
C  SURFACE ORIENTATION
      IF(ABS(PHI).LE.1.E-3)  GO TO 100
      IF(ABS(PHI-90.).LE.1.E-3)  GO TO 200
      IF(ABS(PHI).GT.1.E-3.AND.ABS(PHI).LT.2.)  GO TO 300
      IF(ABS(PHI).GT.2.0.AND.ABS(PHI-90.).GT.1.E-3)  GO TO 400
C  FOR HORIZONTAL SURFACES
  100 IF(DT.LT.0.0)  GO TO 150
      NUS = 0.15*RA**(1./3.)
      IF(RA.LT.8.E6)  NUS = 0.54*RA**0.25
      GO TO 1000
  150 NUS = 0.58*RA**0.2
      GO TO 1000
C  FOR VERTICAL SURFACES
  200 NUS = 0.10*RA**(1./3.)
      IF(RA.LT.1.E9)  NUS = 0.59*RA**0.25
      GO TO 1000
C  FOR NEARLY HORIZONTAL(UP TO 2 DEGREES TILT) SURFACES
  300 IF(DT.GT.0.0)  GO TO 450
      NUS = 0.58*RA**0.2
      GO TO 1000
C  FOR TILTED SURFACES
  400 IF(DT.GT.0.0)  GO TO 450
      NUS = 0.56*(RA*COS((90.-PHI)*3.14159265/180.))**0.25
      GO TO 1000
  450 GRC = 10.0**(PHI/(1.1870+0.0870*PHI))
      IF(ABS(PHI).LT.15.)  GRC = 1.E6
      IF(ABS(PHI).GT.75.)  GRC = 5.E9
      GR = RA/PR
      IF(GR.LE.GRC)  NUS=0.56*(RA*COS((90.-PHI)*3.14159265/180.))**0.25
      IF(GR.GT.GRC)  NUS = 0.14*(RA**(1./3.) - (GRC*PR)**(1./3.))
     &   +0.56*(GRC*PR*COS((90.-PHI)*3.14159265/180.))**0.25
      GO TO 1000
 1000 HCN = NUS*K/AL
C  CALCULATE FORCED CONVECTION COEFFICIENT
C  SEE HOLMAN, 5TH EDITION, PG. 191, EQN. 5-44, 5-46
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```
C  AND PG. 202, EQN. 5-85
      RE = V*AL/NU
      IF(RE.LT.5.E5)  NUS = 0.664*(PR**(1./3.))*SQRT(RE)
      IF(RE.GT.5.E5)  NUS = (PR**(1./3.))*(0.037*(RE**0.8)-850.)
      HCF = NUS*K/AL
C  COMBINE NATURAL AND FORCED CONVECTION COEFFICIENTS
C  USING CHURCHILL'S CORRELATION
C  SEE J. HEAT TRANS., VOL. 108, PP. 835-840 (1986)
C  ASSUME ASSISTING FLOW IN ALL CASES
      HC = (HCF**3 + HCN**3)**(1./3.)
      RETURN
      END
C*********************************************************************
C**                                                                 **
C**                          SUBROUTINE HMASS                       **
C**                                                                 **
C*********************************************************************
      SUBROUTINE HMASS(TS,TA,HC,HM)
C  THIS SUBROUTINE CALCULATES THE MASS TRANSFER COEFFICIENT FOR
C  MOISTURE TRANSFER BETWEEN A SURFACE AND MOIST AIR
C  USING THE LEWIS RELATIONSHIP, AND EVALUATING ALL THERMOPHYSICAL
C  PROPERTIES AS THOSE OF DRY AIR
C  SEE HOLMAN, 5TH EDITION, PP. 494
C  TS = SURFACE TEMPERATURE, F
C  TA = AIR TEMPERATURE, F
C  HC = CONVECTION HEAT TRANSFER COEFFICIENT
C  HM = MASS TRANSFER COEFFICIENT, LB/(HR-FT2)
C
      REAL K
C  CALCULATE FILM TEMPERATURE
      TF = (TS+TA)/2.0
      TK = (TF+459.67)/1.8
C  THERMAL CONDUCTIVITY OF AIR FROM EQUATION IN NBS CIRC. 564
C  THERMAL COND. IN BTU/(HR-FT-F)
      K = 0.6325E-5*SQRT(TK)/(1.+(245.4*10.**(-12./TK))/TK)*241.77
C  DENSITY OF AIR, PERFECT GAS, NBS CIRC. 564, LB/CF
      RHO = 22.0493/TK
C  SPECIFIC HEAT OF AIR, LINEAR REGRESSION FROM 220 K TO 360 K
C  FROM NBS CIRC. 564, BTU/(LB-F)
      CP = (3.4763 + 1.066E-4*TK)*0.068559
C  CALCULATE THERMAL DIFFUSIVITY, FT2/HR
      ALF = K/CP/RHO
C  CALCULATE DIFFUSION COEFFICIENT FOR WATER VAPOR THROUGH AIR
C  D = FT2/HR, SEE 1985 ASHRAE HANDBOOK, PG. 5.2
      D = 0.035883/101.32*(TK**2.5)/(TK+245.0)
      HM = HC/CP/((ALF/D)**(2.0/3.0))
      RETURN
      END
C*********************************************************************
C**                                                                 **
C**                        FUNCTION HRAD                            **
C**                                                                 **
```

```
C*********************************************************************
      FUNCTION HRAD(G,T1,T2)
C  THIS FUNCTION CALCULATES RADIATIVE COEFFICIENTS FOR HEAT BALANCE
C  EQUATIONS
      T1R = (T1 + 459.67)/100.
      T2R = (T2 + 459.67)/100.
      HRAD = 1.714E-3*(T1R*T1R+T2R*T2R)*(T1R+T2R)*G
      RETURN
      END
C*********************************************************************
C**                                                                 **
C**                          SUBROUTINE MOIST                       **
C**                                                                 **
C*********************************************************************
      SUBROUTINE MOIST(TS,TO,TI,TA,HCI,A,AWRAT,AMC,AMASS,HUM,HUMI,PERM,
     1   AMDOT,EXFIL,AMW,BMW,K)
C  THIS SUBROUTINE PERFORMS A MOISTURE BALANCE ON THE ATTIC SPACE
C  TS = SURFACE TEMPERATURE, DEGREES F
C  TO = OUTSIDE AIR TEMPERATURE
C  TI = INSIDE AIR TEMPERATURE
C  TA = ATTIC AIR TEMPERATURE
C  HCI = CONVECTION HEAT TRANSFER COEFFICIENTS
C  A = PROJECTED SURFACE AREAS
C  AWRAT = RATIO OF EXPOSED WOOD SURFACE AREAS TO PROJECTED AREAS
C  AMC = WOOD MOISTURE CONTENTS, FRACTION OF DRY WEIGHT
C  HUM = RELATIVE HUMIDITY OF OUTSIDE AIR
C  HUMI = RELATIVE HUMIDITY OF INSIDE AIR
C  PERM = WATER VAPOR PERMEANCES
C  AMDOT = MASS FLOW OF VENTILATION AIR
C  EXFIL = MASS FLOW OF AIR FROM HOUSE INTO ATTIC
C  AMW = MOISTURE ADSORBED PER UNIT PROJECTED AREA
C  BMW = COEFFICIENT OF LINEAR TERM IN TAYLOR SERIES
C        EXPANSION OF WS(I)
C  K = NUMBER OF SURFACES
      DIMENSION TS(K),HCI(K),A(K),AWRAT(K),AMC(K),PERM(K),AMW(K)
      DIMENSION WS(10),P(10),HM(10),AMASS(K),BMW(K)
      EPS = 1.E-3
C  CALCULATE HUMIDITY RATIOS AT WOOD SURFACES
      DO 10 I = 1,K
   10 WS(I) = WDHUM(AMC(I),TS(I))
C  CALCULATE HUMIDITY RATIOS OF INSIDE AND  OUTSIDE AIR
      CALL PSY(TI,HUMI,PI,WI)
      CALL PSY(TO,HUM,PO,WO)
C  CALCULATE MASS TRANSFER COEFFICIENTS
      DO 20 I = 1,K
   20 CALL HMASS(TS(I),TA,HCI(I),HM(I))
C  SET UP WATER VAPOR PARTIAL PRESSURES
      P(1) = PI
      DO 30 I = 2,K
   30 P(I) = PO
C CALCULATE HUMIDITY RATIO OF ATTIC AIR FROM MOISTURE BALANCE
      PA = PO
```

```
      X = 0.0
      DO 40 I = 1,K
      X = X + A(I)*PERM(I)*P(I)
   40 X = X + A(I)*AWRAT(I)*HM(I)*WS(I)
      X = X + AMDOT*WO + EXFIL*WI
      NIT = 0
  100 Y = 0.0
      DO 50 I = 1,K
   50 Y = Y + A(I)*AWRAT(I)*HM(I)
      Y = Y + AMDOT + EXFIL
      DO 60 I = 1,K
   60 Y = Y + A(I)*PERM(I)*(14.696 - PA)/0.62198
      WA = X/Y
      XX = WA/0.62198
      PANEW = 14.696*XX/(1.0 + XX)
      NIT = NIT + 1
      IF (NIT.GT.10)  GO TO 200
      IF(ABS(1.-PANEW/PA).LT.EPS)  GO TO 200
      PA = PANEW
      GO TO 100
  200 CONTINUE
C  CALCULATE WATER ADSORBED BY EACH SURFACE
      DO 300 I = 1,K
  300 AMW(I) = HM(I)*AWRAT(I)*(WA-WS(I))
C  CALCULATE CORRECTION TERM FOR TAYLOR SERIES EXPANSION OF
C  ADSORBED WATER
      DO 310 I = 1,K
  310 BMW(I) = HM(I)*AWRAT(I)*WS(I)/28.6
      RETURN
      END
C*********************************************************************
C**                                                                 **
C**                          SUBROUTINE PSY                         **
C**                                                                 **
C*********************************************************************
      SUBROUTINE PSY(T,HUM,P,W)
C  THIS SUBROUTINE CALCULATES THE WATER VAPOR PARTIAL PRESSURE AND
C  THE HUMIDITY RATIO, GIVEN THE TEMPERATURE AND RELATIVE HUMIDITY
C  USING EQUATION FROM 1985 ASHRAE FUNDAMENTALS P.6.6
C  AND ERRATA FROM 1988 ASHRAE HANDBOOK
C  T = DRYBULB TEMPERATURE, DEGREES F
C  HUM = RELATIVE HUMIDITY, PERCENT
C  P = WATER VAPOR PARTIAL PRESSURE, PSIA
C  W = HUMIDITY RATIO, POUNDS OF WATER PER POUNDS OF DRY AIR
      C1 = -10214.16
      C2 = -4.8932631
      C3 = -0.53769056E-2
      C4 = 0.19202377E-6
      C5 = 0.35575832E-9
      C6 = 0.090344688E-12
      C7 = 4.1635019
      C8 = -10440.397
```

```
      C9 = -11.2946496
      C10 = -0.027022355
      C11 = 0.12890360E-4
      C12 = -0.2478068E-8
      C13 = 6.5459673
      TR = T + 459.67
      IF(T.GE.32.0)  GO TO 10
      X = C1/TR + C2 + C3*TR + C4*TR*TR +C5*TR**3+C6*TR**4+C7*ALOG(TR)
      GO TO 20
   10 X = C8/TR + C9 + C10*TR + C11*TR*TR + C12*TR**3 + C13*ALOG(TR)
   20 PSAT = EXP(X)
      P = (HUM/100.0)*PSAT
      W = 0.62198*P/(14.696-P)
      RETURN
      END
C*********************************************************************
C**                                                                 **
C**                          SUBROUTINE SOLVP                       **
C**                                                                 **
C*********************************************************************
      SUBROUTINE SOLVP (I,C,D,X)
C  SUBROUTINE TAKEN FROM NBSLD
C  THIS SUBROUTINE SOLVES A SET OF SIMULTANEOUS LINEAR EQUATIONS
C  USING GAUSSIAN ELIMINATION
C  I = NUMBER OF EQUATIONS TO BE SOLVED
C  C = MATRIX OF COEFFICIENTS OF SET OF EQUATIONS
C  D = VECTOR ON RIGHT HAND SIDE OF EQUATIONS
C  X = SOLUTION VECTOR, CX = D
      DIMENSION A(100,101),C(I,I),D(I),X(I)
      M = I
      N = M + 1
      DO 10 IX = 1,M
      DO 10 IY = 1,M
   10 A(IX,IY) = C(IX,IY)
      DO 20 IZ = 1,M
   20 A(IZ,N) = D(IZ)
      L = 1
   30 AA = A(L,L)
      DO 40 K = L,N
   40 A(L,K) = A(L,K)/AA
      DO 60 K = 1,M
      IF (K.EQ.L)  GO TO 60
      AA = -A(K,L)
      DO 50 IA = L,N
   50 A(K,IA) = A(K,IA) + AA*A(L,IA)
   60 CONTINUE
      L = L + 1
      IF (L.LE.M)  GO TO 30
      DO 70 IP = 1,M
   70 X(IP) = A(IP,N)
      RETURN
      END
```

```
C*********************************************************************
C**                                                                 **
C**                        SUBROUTINE VENT                          **
C**                                                                 **
C*********************************************************************
      SUBROUTINE VENT(TO,TA,WS,DIR,H,AI,AO,ITYPE,AMCDOT,AMDOT,V)
C  THIS SUBROUTINE CALCULATES THE VENTILATION RATE FOR A GABLED ATTIC
C  TO = OUTDOOR AIR TEMPERATURE, F
C  TA = AVERAGE ATTIC AIR TEMPERATURE, F
C  WS = WIND SPEED, MPH
C  DIR = WIND DIRECTION
C  H = HEIGHT OF ATTIC
C  AI = AREA OF VENT INLET, SQUARE FEET
C  AO = AREA OF VENT OUTLET, SQUARE FEET
C  ITYPE = 1, SOFFIT AND RIDGE VENTS
C  ITYPE = 2, SOFFIT AND GABLE VENTS
C  ITYPE = 3, SOFFIT VENTS
C  AMCDOT = AIR MASS FLOW RATE TIMES SPECIFIC HEAT, BTU/HR-F
C  V = VOLUME FLOW RATE, CUBIC FEET PER HOUR
C  CALCULATE ABSOLUTE TEMPERATURES, R
      TOR = TO + 459.67
      TAR = TA + 459.67
C CALCULATE DENSITIES AND SPECIFIC HEATS OF AIR
      RHOO = 22.0493/(TOR/1.8)
      RHOA = 22.0493/(TAR/1.8)
      CP = (3.4763 + 1.066E-4*(TAR/1.8))*0.068559
C  DETERMINE MINIMUM VENT AREA AND MAXIMUM VENT AREAS
      AMIN = AMIN1(AI,AO)
      AMAX = AMAX1(AI,AO)
C  CALCULATE HEIGHT OF NEUTRAL PRESSURE LEVEL FROM LOWER OPENING
C  SEE PG. 22.3 OF 1985 ASHRAE HANDBOOK OF FUNDAMENTALS
      HNPL = H/(1.+AI*AI/AO/AO*TAR/TOR)
      IF(TAR.LT.TOR)  HNPL = H/(1.+AI*AI/AO/AO*TOR/TAR)
C  CALCULATE FLOW DUE TO STACK EFFECT, SEE ASHRAE PG. 22.7
      IF(TAR.GE.TOR)  QSTACK = 0.65*AMIN*SQRT(2.0*32.174*3600.*3600.
     &                         *HNPL*(TAR-TOR)/TAR)
      IF(TAR.GE.TOR)  AMSTACK = QSTACK*RHOO
      IF(TAR.LT.TOR)  QSTACK = 0.65*AMIN*SQRT(2.0*32.174*3600.*3600.
     &                         *HNPL*(TOR-TAR)/TOR)
      IF(TAR.LT.TOR)  AMSTACK = QSTACK*RHOA
      IF(ITYPE.EQ.3)  QSTACK = 0.0
      IF(ITYPE.EQ.3)  AMSTACK = 0.0
C  CALCULATE FLOW DUE TO WIND PRESSURE, SEE ASHRAE PG. 22.6
      QWIND = 5280.0*0.6*AMIN*WS
C  MULTIPLY BY EFFECTIVENESS COEFFICIENT DERIVED FROM
C  BURCH AND TREADO'S DATA FOR ATTIC VENTILATION
C  TYPE 1 = SOFFIT AND RIDGE VENTS
C  TYPE 2 = SOFFIT AND ROOF VENTS, ASSUMED TO BE SAME AS SOFFIT AND
C           GABLE VENTS
C  TYPE 3 = SOFFIT VENTS ONLY
      IF(ITYPE.EQ.1) CF = 0.38
      IF(ITYPE.EQ.2) CF = 0.54
```

```
      IF(ITYPE.EQ.3) CF = 0.089 + 0.132*(SIN(DIR*3.14159265/180.))**2.5
      QWIND = QWIND/0.6*CF
      AMWIND = QWIND*RHOO
C  COMBINE STACK AND WIND FLOWS, SEE ASHRAE PG. 22.5
      AMDOT = SQRT(AMSTACK*AMSTACK + AMWIND*AMWIND)
C  CORRECT FOR UNEQUAL INLET AND OUTLET AREAS (ASHRAE PG. 22.7)
      ARAT = AMIN/AMAX
      AMDOT = AMDOT * (1.0 + 0.4077*(1.0-ARAT**1.5))
      AMCDOT = CP*AMDOT
C  CALCULATE VOLUME FLOW RATE, CUBIC FEET PER HOUR
      V = AMDOT/RHOA
      RETURN
      END
C***********************************************************************
C**                                                                   **
C**                          SUBROUTINE VIEW2                         **
C**                                                                   **
C***********************************************************************
      SUBROUTINE VIEW2(AL,W,PITCH1,PITCH2,H1,EI,G,K)
C  THIS SUBROUTINE CALCULATES THE VIEW FACTORS AMONG THE SURFACES
C  IN A GABLED ATTIC, HAVING A FIVE-SIDED CROSS-SECTION, AND
C  HAVING ARBITRARILY PITCHED ROOF SURFACES
C  AL = LENGTH OF ATTIC
C  W = WIDTH OF ATTIC
C  PITCH1 = PITCH OF SOUTH ROOF, DEGREES
C  PITCH2 = PITCH OF NORTH ROOF, DEGREES
C  H1 = HEIGHT OF SIDE WALL
C  SURFACE 1 = CEILING
C  SURFACE 2 = SOUTH ROOF (FOR E-W RIDGE)
C  SURFACE 3 = NORTH ROOF
C  SURFACE 4 = EAST GABLE
C  SURFACE 5 = WEST GABLE
C  SURFACE 6 = SOUTH SIDE WALL
C  SURFACE 7 = NORTH SIDE WALL
C  EI = EMITTANCE OF SURFACE FACING ATTIC SPACE
C  F(I,J) = RADIATION VIEW FACTOR FROM SURFACE I TO
C           SURFACE J
C  G(I,J) = RADIATION FACTOR
      DIMENSION F(7,7),CHI(7,7),PSI(7,7),E(7),B(7),EI(K),G(7,7)
      PI = 3.14159265
      PIO2 = PI/2.0
      P1 = PITCH1*PI/180.
      P2 = PITCH2*PI/180.
      F(1,1) = 0.0
      F(2,2) = 0.0
      F(3,3) = 0.0
      F(4,4) = 0.0
      F(5,5) = 0.0
      F(6,6) = 0.0
      F(7,7) = 0.0
      P3 = (180.-PITCH1-PITCH2)*PI/180.
      IP1 = PITCH1
```

```
      IP2 = PITCH2
      IP3 = 180.0 - PITCH1 - PITCH2
      IF(IP1.EQ.90.AND.IP2.EQ.90) STOP
      IF(IP1.EQ.0.AND.IP2.NE.0)  STOP
      IF(IP1.NE.0.AND.IP2.EQ.0)  STOP
      IF(IP1.EQ.0)  GO TO 20
      A2 = W*SIN(P2)/SIN(P3)
      A3 = W*SIN(P1)/SIN(P3)
      A2EXT = H1/SIN(P1)
      A3EXT = H1/SIN(P2)
      IF(IP1.NE.90)  W2EXT = H1/TAN(P1)
      IF(IP1.EQ.90)  W2EXT = 0.0
      IF(IP2.NE.90)  W3EXT = H1/TAN(P2)
      IF(IP2.EQ.90)  W3EXT = 0.0
      A2P = A2 + A2EXT
      A3P = A3 + A3EXT
      W2P = W + W2EXT
      W3P = W + W3EXT
      IF(IP1.NE.90)  F(1,2) = (W2P*FMN(A2P,AL,W2P,P1)
     &        +W2EXT*FMN(A2EXT,AL,W2EXT,P1)
     &        -W2P*FMN(A2EXT,AL,W2P,P1)-W2EXT*FMN(A2P,AL,W2EXT,P1))/W
      IF(IP1.EQ.90)  F(1,2) = FMN(A2P,AL,W,P1)-FMN(H1,AL,W,P1)
      IF(IP2.NE.90)  F(1,3) = (W3P*FMN(A3P,AL,W3P,P2)
     &        +W3EXT*FMN(A3EXT,AL,W3EXT,P2)
     &        -W3P*FMN(A3EXT,AL,W3P,P2)-W3EXT*FMN(A3P,AL,W3EXT,P2))/W
      IF(IP2.EQ.90)  F(1,3) = FMN(A3P,AL,W,P2)-FMN(H1,AL,W,P2)
      F(1,6) = FMN(H1,AL,W,PIO2)
      F(1,7) = FMN(H1,AL,W,PIO2)
      F(1,4) = (1.0 - F(1,2) - F(1,3) - F(1,6) - F(1,7))/2.0
      F(1,5) = F(1,4)
      F(2,1) = W*AL*F(1,2)/A2/AL
      F(2,3) = FMN(A3,AL,A2,P3)
      ANG = P1 + PIO2
      IF(IP1.NE.90)  F(2,6) = FMN(H1,AL,A2,ANG)
      IF(IP1.EQ.90)  F(2,6) = 0.0
      ANG = PIO2 - P1
      IF(IP1.EQ.90) GO TO 5
      A2P = W/SIN(ANG)
      A2EXT = A2P - A2
      H1EXT = W/TAN(ANG)
      H1P = H1 + H1EXT
C NEXT LINE ADDED 4-6-88
      IF(IP2.NE.90) THEN
      F(2,7) = (A2P*FMN(H1P,AL,A2P,ANG)+A2EXT*FMN(H1EXT,AL,A2EXT,ANG)
     &        -A2P*FMN(H1EXT,AL,A2P,ANG)-A2EXT*FMN(H1P,AL,A2EXT,ANG))/A2
C NEXT 3 LINES ADDED 4-6-88
      ELSE
      F(2,7) = FMN(H1P,AL,A2,ANG) - FMN(H1EXT,AL,A2,ANG)
      END IF
      GO TO 6
    5 F(2,7) = ((A2+H1)*FP((A2+H1),AL,W)-H1*FP(H1,AL,W)-A2*FP(A2,AL,W))/
     &          2.0/A2
```

```
    6 F(2,4) = (1.0 - F(2,1) - F(2,3) - F(2,6) - F(2,7))/2.0
      F(2,5) = F(2,4)
      F(3,1) = W*AL*F(1,3)/A3/AL
      F(3,2) = A2*AL*F(2,3)/A3/AL
      ANG = P2 + PIO2
      IF(IP2.NE.90)  F(3,7) = FMN(H1,AL,A3,ANG)
      IF(IP2.EQ.90)  F(3,7) = 0.0
      ANG = PIO2 - P2
      IF(IP2.EQ.90) GO TO 7
      A3P = W/SIN(ANG)
      A3EXT = A3P - A3
      H1EXT = W/TAN(ANG)
      H1P = H1 + H1EXT
C NEXT LINE ADDED 4-6-88
      IF(IP1.NE.90) THEN
      F(3,6) = (A3P*FMN(H1P,AL,A3P,ANG)+A3EXT*FMN(H1EXT,AL,A3EXT,ANG)
     &         -A3P*FMN(H1EXT,AL,A3P,ANG)-A3EXT*FMN(H1P,AL,A3EXT,ANG))/A3
C NEXT 3 LINES ADDED 4-6-88
      ELSE
      F(3,6) = FMN(H1P,AL,A3,ANG) - FMN(H1EXT,AL,A3,ANG)
      END IF
      GO TO 8
    7 F(3,6) = ((A3+H1)*FP((A3+H1),AL,W)-H1*FP(H1,AL,W)-A3*FP(A3,AL,W))/
     &           2.0/A3
    8 F(3,4) = (1.0 - F(3,1) - F(3,2) - F(3,6) - F(3,7))/2.0
      F(3,5) = F(3,4)
      F(6,1) = W*AL*F(1,6)/H1/AL
      F(6,2) = A2*AL*F(2,6)/H1/AL
      F(6,3) = A3*AL*F(3,6)/H1/AL
      F(6,7) = FP(H1,AL,W)
      F(6,4) = ( 1.0 - F(6,1) - F(6,2) - F(6,3) - F(6,7))/2.0
      F(6,5) = F(6,4)
      F(7,1) = W*AL*F(1,7)/H1/AL
      F(7,2) = A2*AL*F(2,7)/H1/AL
      F(7,3) = A3*AL*F(3,7)/H1/AL
      F(7,6) = F(6,7)
      F(7,4) = F(6,4)
      F(7,5) = F(7,4)
      F(4,1) = W*AL*F(1,4)/(0.5*A2*SIN(P1)*W + W*H1)
      F(4,2) = A2*AL*F(2,4)/(0.5*A2*SIN(P1)*W + W*H1)
      F(4,3) = A3*AL*F(3,4)/(0.5*A2*SIN(P1)*W + W*H1)
      F(4,6) = H1*AL*F(6,4)/(0.5*A2*SIN(P1)*W + W*H1)
      F(4,7) = H1*AL*F(7,4)/(0.5*A2*SIN(P1)*W + W*H1)
      F(4,5) = 1.0 - F(4,1) - F(4,2) - F(4,3) - F(4,6) - F(4,7)
      F(5,1) = F(4,1)
      F(5,2) = F(4,2)
      F(5,3) = F(4,3)
      F(5,4) = F(4,5)
      F(5,6) = F(4,6)
      F(5,7) = F(4,7)
      GO TO 50
   20 F(1,2) = 0.5*FP(W,AL,H1)
```

```
      F(1,3) = F(1,2)
      F(1,4) = FMN(H1,W,AL,PIO2)
      F(1,5) = F(1,4)
      F(1,6) = FMN(H1,AL,W,PIO2)
      F(1,7) = F(1,6)
      F(2,1) = 2.0*F(1,2)
      F(2,3) = 0.0
      X = W/2.0
      F(2,6) = FMN(H1,AL,X,PIO2)
      X = W/2.0
      F(2,7) = H1*(FMN(W,AL,H1,PIO2)-FMN(X,AL,H1,PIO2))/X
      F(2,4) = (1.0 - F(2,1) - F(2,3) - F(2,6) - F(2,7))/2.0
      F(2,5) = F(2,4)
      F(3,1) = F(2,1)
      F(3,2) = 0.0
      F(3,4) = F(2,4)
      F(3,5) = F(2,5)
      F(3,6) = F(2,7)
      F(3,7) = F(2,6)
      F(4,1) = AL*F(1,4)/H1
      F(4,2) = (AL*W/2.0)*F(2,4)/(H1*W)
      F(4,3) = F(4,2)
      F(4,5) = FP(H1,W,AL)
      F(4,6) = FMN(AL,H1,W,PIO2)
      F(4,7) = F(4,6)
      F(5,1) = F(4,1)
      F(5,2) = F(4,2)
      F(5,3) = F(4,3)
      F(5,4) = F(4,5)
      F(5,6) = F(4,6)
      F(5,7) = F(4,7)
      F(6,1) = W*F(1,6)/H1
      F(6,2) = (AL*W/2.0)*F(2,6)/(AL*H1)
      F(6,3) = (AL*W/2.0)*F(3,6)/(AL*H1)
      F(6,4) = W*F(4,6)/AL
      F(6,5) = F(6,4)
      F(6,7) = FP(H1,AL,W)
      F(7,1) = F(6,1)
      F(7,2) = F(6,3)
      F(7,3) = F(6,2)
      F(7,4) = F(6,4)
      F(7,5) = F(6,5)
      F(7,6) = F(6,7)
C
   50 CONTINUE
      DO 100 I = 1,7
      DO 100 J = 1,7
  100 CHI(I,J) = -(1. - EI(I))*F(I,J)/EI(I)
      DO 200 I = 1,7
  200 CHI(I,I) = CHI(I,I) + 1./EI(I)
C  INVERT CHI MATRIX TO OBTAIN PSI MATRIX
      DO 500  L = 1,7
```

```
      DO 300 I = 1,7
      E(I) = 0.0
  300 IF(I.EQ.L)  E(I) = 1.0
      CALL SOLVP(7,CHI,E,B)
      DO 400 I = 1,7
  400 PSI(I,L) = B(I)
  500 CONTINUE
      DO 600  I = 1,7
      DO 600  J = 1,7
  600 G(I,J) = PSI(I,J)*EI(I)/(1. - EI(I))
      RETURN
      END
C*********************************************************************
C**                                                                 **
C**                        FUNCTION WDHUM                           **
C**                                                                 **
C*********************************************************************
      FUNCTION WDHUM(AMC,T)
C  THIS FUNCTION CALCULATES THE HUMIDITY RATIO OF A WOOD SURFACE
C  USING THE EQUATION FROM P. G. CLEARY (1985).
C  WDHUM = HUMIDITY RATIO, POUNDS OF WATER PER POUND OF DRY AIR
C  AMC = WOOD MOISTURE CONTENT, FRACTION OF DRY WEIGHT OF WOOD
C  T = WOOD SURFACE TEMPERATURE, DEGREES F
      A = 28.6
      B = -0.00049
      C = 0.0172
      D = -0.060
      E = 0.076
      WDHUM = B + C*AMC + D*AMC*AMC + E*AMC**3
C NEXT LINE ADDED 11-2-88
      IF(WDHUM.LT.0.0) WDHUM = 0.0
      WDHUM = WDHUM * EXP(T/A)
      RETURN
      END
```

APPENDIX B
RBSOR2 COMPUTER PROGRAM

```
C*********************************************************************
C**                                                                 **
C**                        PROGRAM RBSOR2                           **
C**                                                                 **
C*********************************************************************
C  THIS PROGRAM CALCULATES THE HEAT TRANSFER THROUGH THE CEILING
C  BELOW A GABLED ATTIC HAVING A FIVE-SIDED CROSS SECTION
C  AND A TRUSS RADIANT BARRIER ON ONE ROOF SECTION
C  ASSUMES THE AIR WITHIN THE ATTIC IS NOT WELL-MIXED
C  INCLUDES APPROXIMATE CALCULATIONS FOR LATENT HEAT EFFECTS
C  DUE TO MOISTURE ADSORPTION AND DESORPTION
C  SURFACE TEMPERATURES ON INSIDE OR OUTSIDE, OR VENTILATION RATE
C  MAY BE SPECIFIED THROUGH KFLAG(I) = 1
C  NOMENCLATURE:
C   N(I) = NUMBER OF CONDUCTION TRANSER FUNCTIONS FOR SURFACE I
C   U(I) = SURFACE-TO-SURFACE U-VALUE FOR SURFACE I
C   CR(I) = COMMON RATIO OF RESPONSE FACTORS FOR SURFACE I
C   BETA(I) = TEMPERATURE DEPENDENT COEFFICIENT FOR CONDUCTION
C             TRANSFER FUNCTIONS FOR SURFACE I
C   X(I,J), Y(I,J), Z(I,J) = CONDUCTION TRANSFER FUNCTIONS FOR
C             SURFACE I
C   SURFACES ARE NUMBERED AS (FOR NORTH-SOUTH RIDGE):
C     1 = CEILING
C     2 = EAST ROOF RADIANT BARRIER
C     3 = WEST ROOF
C     4 = SOUTH GABLE
C     5 = NORTH GABLE
C     6 = EAST EAVE WALL
C     7 = WEST EAVE WALL
C     8 = EAST ROOF
C   ALF(I) = SOLAR ABSORPTANCE FOR SURFACE I
C   EO(I) = INFRARED EMITTANCE FOR OUTSIDE OF SURFACE I
C   EI(I) = INFRARED EMITTANCE FOR INSIDE OF SURFACE I
C   TIS(I,J) = INSIDE SURFACE TEMPERATURE FOR SURFACE I
C   TOS(I,J) = OUTSIDE SURFACE TEMPERATURE FOR SURFACE I
C   TA(1,J) = AVERAGE TEMPERATURE OF AIR IN MAIN ATTIC SPACE ATTIC
C   TA(2,J) = AVERAGE TEMPERATURE OF AIR IN VENT SPACE
C   QI(I,J) = INSIDE HEAT FLUX FOR SURFACE I
C   QO(I,J) = OUTSIDE HEAT FLUX FOR SURFACE I
C   HCI(I) = CONVECTION COEFFICIENT FOR INSIDE OF SURFACE I
C   HR(I,K) = RADIATION INTERCHANGE COEFFICIENT FROM SURFACE I
C             TO SURFACE K
C   AA(I,J) = MATRIX OF COEFFICIENTS FOR SIMULTANEOUS EQUATIONS
C   BB(I) = KNOWN VECTOR FOR SIMULTANEOUS EQUATIONS
C   XXX(I) = SOLUTION VECTOR FOR SIMULTANEOUS EQUATIONS
C   QSOL(I) = SOLAR RADIATION INCIDENT ON SURFACE I
C   A(I) = AREA OF SURFACE I
C   G(I,K) = OVERALL RADIATION VIEW FACTOR FROM SURFACE I TO
C            SURFACE K
C   HCO(I) = CONVECTION COEFFICIENT ON OUTSIDE OF SURFACE I
C   HRO(I) = RADIATION COEFFICIENT ON OUTSIDE OF SURFACE I
C   R(I) = SURFACE-TO-SURFACE RESISTANCE FOR SURFACE I
```

```
C   AMC(I) = MOISTURE CONTENT (WEIGHT FRACTION) FOR SURFACE I
C   PERM(I) = MOISTURE PERMEANCE OF SURFACE I
C   AWRAT(I) = RATIO OF EXPOSED SURFACE AREA TO PROJECTED SURFACE
C              AREA FOR SURFACE I
C   AMASS(I) = MASS PER UNIT AREA OF SURFACE I THAT PARTICIPATES IS
C              MOISTURE EXCHANGE
C   AMW(I) = MOISTURE FLUX TOWARD SURFACE I
C   BMW(I) = TERM IN TAYLOR SERIES EXPANSION FOR MOISTURE FLUX
C   TS(I) = TEMPERATURE OF INSIDE OF SURFACE I
C   KFLAG(I) = FLAG FOR SPECIFIED SURFACE TEMPERATURES
C       0 = PARAMETER NOT SPECIFIED
C       1 = PARAMETER SPECIFIED
C       I = 1,8 FOR TIS(I,1)
C       I = 9,15 FOR TOS(1,1), TOS(3,1)...TOS(8,1)
C       I = 16,17 FOR VENTILATION RATES IN MAIN AND VENT SPACES
C   AL = LENGTH OF ATTIC, FEET
C   W  = WIDTH OF ATTIC, FEET
C   PITCH1 = PITCH OF EAST ROOF, DEGREES
C   PITCH2 = PITCH OF WEST ROOF, DEGREES
C   ORIENT = ORIENTATION OF HOUSE
C   H1 = HEIGHT OF VERTICAL WALLS AT EAVES, FEET
C   AI = AREA OF INLET VENT, SQUARE FEET
C   AO = AREA OF OUTLET VENT, SQUARE FEET
C   ITYPE = TYPE VENTS
C       1 = SOFFIT AND RIDGE VENTS
C       2 = SOFFIT AND GABLE VENTS
C       3 = SOFFIT VENTS ONLY
C   QLAT = HEAT OF VAPORIZATION OF WATER, BTU/LBM
C   EXFIL = RATE OF FLOW OF AIR FROM HOUSE TO ATTIC, LB/HR
C   AL1 ... AL7 = CHARACTERISTIC LENGTHS OF SURFACES 1 ... 7, FEET
C   TO = OUTDOOR TEMPERATURE, F
C   QSOLH = SOLAR RADIATION INCIDENT ON HORIZONTAL SURFACE
C           BTU/(HR.-SQ.FT.)
C   WS = WIND SPEED, MPH
C   DIR = WIND DIRECTION
C   HUM = OUTDOOR RELATIVE HUMIDITY, PERCENT
C   TI = INDOOR TEMPERATURE, F
C   HUMI = INDOOR RELATIVE HUMIDITY, PERCENT
C   VDOT = VENTILATION RATE, CUBIC FEET PER HOUR
C   IVFLAG = FLAG FOR CALCULATING FLOW VELOCITY
C        0 = FLOW THROUGH BOTH SIDES OF ATTIC
C        1 = FLOW THROUGH ONE SIDE OF ATTIC
C   FLUX = MEASURED CEILING HEAT FLUX, BTU/(HR.-SQ.FT.)
C   TAIR = MEASURED ATTIC AIR TEMPERATURE, F
C   TEXIT = MEASURED EXIT AIR TEMPERATURE, F
C   H = HEIGHT, FEET
C   AMDOT = VENTILATION RATE, POUNDS PER HOUR
C   AMCDOT = VENTILATION RATE TIMES SPECIFIC HEAT
C   V = CRUDE ESTIMATE OF AIR SPEED THROUGH ATTIC, FEET PER HOUR
C   ACH = AIR CHANGE RATE FOR ATTIC, AIR CHANGES PER HOUR
      DIMENSION N(8),U(8),CR(8),BETA(8),X(8,100),Y(8,100),Z(8,100)
      DIMENSION ALF(8),EO(8),EI(8),TIS(8,100),TOS(8,100),TA(2,2)
```

```
      DIMENSION QI(8,2),QO(8,2),HCI(8),HR(7,7),AA(17,17),BB(17)
      DIMENSION XXX(17),QSOL(8),A(8),G(7,7),HCO(8),HRO(8),R(8)
      DIMENSION AMC1(7),PERM1(7),AWRAT1(7),AMASS1(7),AMW1(7),TS1(7)
      DIMENSION BMW1(7),KFLAG(17)
      DIMENSION AMC2(2),PERM2(2),AWRAT2(2),AMASS2(2),AMW2(2),TS2(2)
      DIMENSION BMW2(2)
      DATA TIS/800*75.0/,TOS/800*75.0/,AA/289*0.0/,TR/75.0/
      DATA TA/4*75.0/,QI/16*0.0/,QO/16*0.0/,BMW1/7*0.0/,BMW2/2*0.0/
      DATA WA1/0.0/,WA2/0.0/
C  READ IN KFLAG: 0 = PARAMETER NOT SPECIFIED
C                 1 = PARAMETER SPECIFIED
      READ (5,*) (KFLAG(I),I=1,8)
      READ (5,*) (KFLAG(I),I=9,15)
      READ (5,*) KFLAG(16),KFLAG(17)
C  READ IN CONDUCTION TRANSFER FUNCTIONS
      DO 100 I = 1,8
      READ (5,*)  N(I),U(I),CR(I),BETA(I)
      M = N(I)
      DO 100 J = 1,M
      READ (5,*) X(I,J),Y(I,J),Z(I,J)
  100 CONTINUE
      DO 101 I = 1,8
  101 R(I) = 1./U(I)
C  CONVENTION FOR CTF'S IS SAME AS USED IN TARP
C  CONVENTION FOR ATTIC MODEL IS THAT INSIDE SURFACES
C  FACE THE ATTIC SPACE
C  CTF'S FOR THE CEILING ARE CALCULATED FOR USE IN A
C  WHOLE HOUSE MODEL, WHERE THE OUTSIDE SURFACE FACES
C  THE ATTIC;  THEREFORE, FOR USE INTERNAL TO THE ATTIC
C  MODEL, INTERCHANGE THE X'S AND THE Z'S
      M = N(1)
      DO 110 J = 1,M
      XX = X(1,J)
      X(1,J) = Z(1,J)
      Z(1,J) = XX
  110 CONTINUE
C  READ IN SOLAR ABSORPTANCES OF OUTSIDE SURFACES AND
C  EMITTANCES OF BOTH OUTSIDE AND INSIDE SURFACES
      READ(5,*)  (ALF(I), I = 1,8)
      READ(5,*)  (EO(I), I = 1,8)
      READ(5,*)  (EI(I), I = 1,8)
C  READ IN ATTIC GEOMETRY:  LENGTH, WIDTH, PITCHES OF ROOF
C  SURFACES(DEGREES), ORIENTATION ANGLE OF HOUSE
C  AND HEIGHT OF SIDE WALLS
      READ (5,*)  AL,W,PITCH1,PITCH2,ORIENT,H1
C  READ VENT INLET AND OUTLET AREAS, AND VENT TYPE
C  TYPE 1 = SOFFIT AND RIDGE VENTS
C  TYPE 2 = SOFFIT AND GABLE VENTS
C  TYPE 3 = SOFFIT VENTS ONLY
      READ(5,*) AI1,AO1,AI2,AO2,ITYPE,FLOW1
C  READ RAFTER SPACING AND THICKNESS, INCHES
      READ(5,*) RAFTSP,RAFTTHK
```

```
C  READ WATER VAPOR PERMEANCES OF ATTIC SURFACES
C  PERM = GRAINS PER (HR-FT2-INCH HG)
      READ (5,*) (PERM1(I),I=1,7)
      READ (5,*) (PERM2(I),I=1,2)
C CONVERT PERM VALUES TO POUNDS PER (HR-FT2-PSIA)
      DO 120 I = 1,7
  120 PERM1(I) = PERM1(I)*(29.921/14.696)/7000.
      DO 121 I = 1,2
  121 PERM2(I) = PERM2(I)*(29.921/14.696)/7000.
C  READ RATIO OF TOTAL AREA OF EXPOSED WOOD TO GEOMETRICAL
C  PROJECTION OF SURFACE AREAS
      READ (5,*) (AWRAT1(I),I=1,7)
      READ (5,*) (AWRAT2(I),I=1,2)
C  READ WEIGHT OF WOOD PER UNIT PROJECTED AREA FOR EACH SURFACE
      READ (5,*) (AMASS1(I),I=1,7)
      READ (5,*) (AMASS2(I),I=1,2)
C  READ INITIAL MOISTURE CONTENTS OF WOOD, WEIGHT FRACTION
      READ (5,*) (AMC1(I),I=1,7)
      READ (5,*) (AMC2(I),I=1,2)
C  READ LATENT HEAT OF VAPORIZATION, BTU/LB
      READ (5,*) QLAT
C  READ RATE OF FLOW OF HOUSE AIR INTO ATTIC, POUNDS PER HOUR
      READ (5,*) EXFIL
C  CALCULATE CHARACTERISTIC LENGTHS AND AREAS OF SURFACES
C  CHAR. LENGTHS ARE TAKEN TO BE:
C  CEILING - AVERAGE OF LENGTH AND WIDTH
C  ROOF - DISTANCE FROM EAVE TO RIDGE
C  GABLE - AVERAGE HEIGHT
C  SIDE WALLS - HEIGHT
      AL1 = (AL+W)/2.
      P1 = PITCH1*3.14159265/180.
      P2 = PITCH2*3.14159265/180.
      P3 = 3.14159265 - P1 - P2
      IP1 = PITCH1
      IP2 = PITCH2
      IP3 = 180.0 - PITCH1 - PITCH2
      IF(IP3.EQ.180) GO TO 5
      AL2 = W*SIN(P2)/SIN(P3)
      AL3 = W*SIN(P1)/SIN(P3)
      AL4 = 0.5*(AL2*SIN(P1)) + H1
      GO TO 6
    5 AL2 = W/2.0
      AL3 = W/2.0
      AL4 = H1
    6 AL5 = AL4
      AL6 = H1
      AL7 = H1
      AL8 = AL2
      A(1) = AL*W
      A(2) = AL*AL2
      A(3) = AL*AL3
      A(4) = W*AL4
```

```
      A(5) = A(4)
      A(6) = AL*H1
      A(7) = AL*H1
      A(8) = A(2)
      ARAFT = 1.5/RAFTSP
C  CALCULATE RADIATION INTERCHANGE FACTORS WITHIN ATTIC SPACE
      CALL VIEW2(AL,W,PITCH1,PITCH2,H1,EI,G,8)
C  CALCULATE RADIATION INTERCHANGE BETWEEN FOIL AND ROOF, USING
C  HOTTEL'S STRING METHOD
      RAT = RAFTTHK/(RAFTSP - 1.5)
      F28 = SQRT(1.0 + RAT*RAT) - RAT
      G28 = 1./(2./(1.+F28) + 1./EO(2) + 1./EI(8) - 2.)
C  READ LINE OF WEATHER DATA
C***********************************************************************
   10 READ(5,*,END = 999) TO,QSOLH,WS,DIR,HUM,TI,HUMI,(TIS(I,1),I=1,8),
     &  TOS(1,1),(TOS(I,1),I=3,8),VDOT,IVFLAG,FLUX,TAIR,TEXIT
C  RESTORE ESTIMATES FOR TEMPERATURES NOT SPECIFIED
      DO 15 I = 1,8
   15 IF(KFLAG(I).EQ.0) TIS(I,1) = TIS(I,2)
      IF(KFLAG(9).EQ.0) TOS(1,1) = TOS(1,2)
      DO 16 I = 3,8
   16 IF(KFLAG(I+7).EQ.0) TOS(I,1) = TOS(I,2)
C  NEXT TWO LINES ARE FOR ESTIMATING FLOWS IN FSEC EXPERIMENT
      VDOT1 = VDOT*FLOW1
      VDOT2 = VDOT*(1.0 - FLOW1)
C***********************************************************************
C  CALCULATE SOLAR LOAD ON EACH SURFACE
C  NEED TO INVOKE APPROPRIATE ALGORITHMS
C  THE FOLLOWING ARE TEMPORARY
      QSOL(1) = 0.0
      QSOL(2) = 0.0
      QSOL(3) = QSOLH
      QSOL(4) = 0.0
      QSOL(5) = 0.0
      QSOL(6) = 0.0
      QSOL(7) = 0.0
      QSOL(8) = QSOLH
      NIT = 1
C***********************************************************************
C  CALCULATE ATTIC VENTILATION RATE AND FLOW VELOCITY
      H = AL4 + AL2*SIN(P1)/2.0
   20 CONTINUE
      IF(KFLAG(16).EQ.0) THEN
      CALL VENT(TO,TA(1,1),WS,DIR,H,AI1,AO1,ITYPE,AMCDOT1,AMDOT1,VDOT1)
      ELSE
C  ASSUME VENTILATION RATES ARE BASED ON OUTSIDE AIR TEMPERATURE
      AMDOT1 = VDOT1*22.0493/((TO+459.67)/1.8)
      AMCDOT1 = AMDOT1*(3.4763 + 1.066E-4*((TO+459.67)/1.8))*0.068559
      END IF
      IF(IVFLAG.EQ.0) V1 = VDOT1/(AL4*AL)
      IF(IVFLAG.EQ.1) V1 = VDOT1*2.0/(AL4*AL)
      IF(KFLAG(17).EQ.0) THEN
```

```
      CALL VENT(TO,TA(2,1),WS,DIR,H,AI2,AO2,ITYPE,AMCDOT2,AMDOT2,VDOT2)
      ELSE
      AMDOT2 = VDOT2*22.0493/((TO+459.67)/1.8)
      AMCDOT2 = AMDOT2*(3.4763 + 1.066E-4*((TO+459.67)/1.8))*0.068559
      END IF
      V2 = VDOT2/(AL*RAFTTHK/12.*(1.0-ARAFT))
      ACH1 = VDOT1/A(4)/AL
      ACH2 = VDOT2/(AL*AL2*RAFTTHK/12.*(1.0-ARAFT))
C*********************************************************************
C  CALCULATE CONVECTION COEFFICIENTS AT INSIDE SURFACES
      CALL HCON(TIS(1,1),TA(1,1),0.0,AL1,1,V1,HCI(1))
      CALL HCON(TIS(2,1),TA(1,1),PITCH1,AL2,2,V1,HCI(2))
      CALL HCON(TIS(3,1),TA(1,1),PITCH2,AL3,2,V1,HCI(3))
      CALL HCON(TIS(4,1),TA(1,1),90.0,AL4,1,V1,HCI(4))
      CALL HCON(TIS(5,1),TA(1,1),90.0,AL5,1,V1,HCI(5))
      CALL HCON(TIS(6,1),TA(1,1),90.0,AL6,1,V1,HCI(6))
      CALL HCON(TIS(7,1),TA(1,1),90.0,AL7,1,V1,HCI(7))
C  CALCULATE COEFFICIENTS AT SURFACES OF SPACES BETWEEN RB'S AND ROOFS
      CALL HCON(TIS(2,1),TA(2,1),PITCH1,AL2,1,V2,HCO(2))
      CALL HCON(TIS(8,1),TA(2,1),PITCH1,AL2,2,V2,HCI(8))
C  CALCULATE CONVECTION COEFFICIENTS AT OUTSIDE SURFACES
      WS1 = WS*5280.
      CALL HCON(TOS(1,1),TI,0.0,AL1,2,0.0,HCO(1))
C     CALL HCON(TOS(2,1),TO,PITCH1,AL2,1,WS1,HCO(2))
      CALL HCON(TOS(3,1),TO,PITCH2,AL3,1,WS1,HCO(3))
      CALL HCON(TOS(4,1),TO,90.0,AL4,1,WS1,HCO(4))
      CALL HCON(TOS(5,1),TO,90.0,AL5,1,WS1,HCO(5))
      CALL HCON(TOS(6,1),TO,90.0,AL6,1,WS1,HCO(6))
      CALL HCON(TOS(7,1),TO,90.0,AL7,1,WS1,HCO(7))
      CALL HCON(TOS(8,1),TO,PITCH1,AL2,1,WS1,HCO(8))
C  CALCULATE RADIATION COEFFICIENTS AT INSIDE SURFACES
      DO 200 I = 1,7
      DO 200 J = 1,7
      HR(I,J) = HRAD(G(I,J),TIS(I,1),TIS(J,1))
  200 CONTINUE
C  CALCULATE RADIATION COEFFICIENTS ACROSS RB SPACES
      HRO(2) = HRAD(G28,TIS(2,1),TOS(2,1))
C  CALCULATE RADIATION COEFFICIENTS AT OUTSIDE SURFACES
      HRO(1) = HRAD(EO(1),TOS(1,1),TI)
      DO 250 I = 3,8
      HRO(I) = HRAD(EO(I),TOS(I,1),TO)
  250 CONTINUE
C  CALCULATE MOISTURE BALANCES, LATENT HEATS
      IF(QLAT.LE.1.) THEN
           DO 255 I = 1,7
           AMW1(I) = 0.0
  255      BMW1(I) = 0.0
           DO 256 I = 1,2
           AMW2(I) = 0.0
  256      BMW2(I) = 0.0
      ELSE
      DO 260 I = 1,7
```

```
  260 TS1(I) = TIS(I,1)
      CALL MOIST1(TS1,TO,TI,TA(1,1),HCI,A,AWRAT1,AMC1,AMASS1,HUM,HUMI,
     &   PERM1,AMDOT1,EXFIL,AMW1,BMW1,8,WA1,WA2)
      TS2(1) = TIS(2,1)
      TS2(2) = TIS(8,1)
      HC1 = HCO(2)
      HC2 = HCI(8)
      A1 = A(2)
      A2 = A(8)
      CALL MOIST2(TS2,TO,TI,TA(2,1),HC1,HC2,A1,A2,AWRAT2,AMC2,AMASS2,
     &   HUM,HUMI,PERM2,AMDOT2,0.0,AMW2,BMW2,WA1,WA2)
      DO 270 I = 1,7
      IF(AMC1(I).LE.1.E-6.AND.AMW1(I).LT.0.0) THEN
         AMW1(I) = 0.0
         BMW1(I) = 0.0
      ELSE IF(AMW1(I).LT.0.0.AND.ABS(AMW1(I)).GT.(AMC1(I)*AMASS1(I)))
     &   THEN
         AMWOLD = AMW1(I)
         FACT = ABS(AMC1(I)*AMASS1(I)/AMWOLD)
         AMW1(I) = AMW1(I)*FACT
         BMW1(I) = BMW1(I)*AMW1(I)/AMWOLD
      ELSE
         CONTINUE
      END IF
  270 CONTINUE
      DO 271 I = 1,2
      IF(AMC2(I).LE.1.E-6.AND.AMW2(I).LT.0.0) THEN
         AMW2(I) = 0.0
         BMW2(I) = 0.0
      ELSE IF(AMW2(I).LT.0.0.AND.ABS(AMW2(I)).GT.(AMC2(I)*AMASS2(I)))
     &   THEN
         AMWOLD = AMW2(I)
         FACT = ABS(AMC2(I)*AMASS2(I)/AMWOLD)
         AMW2(I) = AMW2(I)*FACT
         BMW2(I) = BMW2(I)*AMW2(I)/AMWOLD
      ELSE
         CONTINUE
      END IF
  271 CONTINUE
      END IF
C***********************************************************************
C  SET UP MATRIX OF COEFFICIENTS IN HEAT BALANCE EQUATIONS
      DO 300 I = 1,7
      DO 300 J = 1,7
      AA(I,J) = -HR(I,J)
  300 CONTINUE
      DO 310 I = 1,7
      DO 305 J = 1,7
  305 AA(I,I) = AA(I,I) + HR(I,J)
  310 AA(I,I) = AA(I,I) + Z(I,1) + HCI(I)
C  ADD IN LATENT HEAT TERMS
      DO 315 I = 1,7
```

```
  315 AA(I,I) = AA(I,I) + BMW1(I)*QLAT
      AA(2,2) = AA(2,2) + BMW2(1)*QLAT
      AA(2,2) = AA(2,2) + (1.0 - ARAFT)*(HCO(2)+HRO(2)-Z(2,1))
      AA(1,9) = -Y(1,1)
      DO 316 I = 3,8
  316 AA(I,I+7) = -Y(I,1)
C*********************************************************************
      DO 320 I = 1,7
C     AA(I,I+7) = - Y(I,1)
      AA(I,16) = -HCI(I)
C     AA(I+7,I) = -Y(I,1)
C     AA(I+7,I+7) = X(I,1) + HCO(I) + HRO(I)
  320 AA(16,I) = A(I)*HCI(I)
      AA(2,8) = -ARAFT*Y(2,1) - (1.0 - ARAFT)*HRO(2)
      AA(2,17) = -HCO(2)*(1.0 - ARAFT)
      AA(8,2) = -ARAFT*Y(2,1) - (1.0 - ARAFT)*HRO(2)
      AA(8,8) = Z(8,1) + X(2,1)*ARAFT + (1.0 - ARAFT)*(HRO(2)+HCI(8))
      AA(8,8) = AA(8,8) + BMW2(2)*QLAT
      AA(8,17) = -(1.0 - ARAFT)*HCI(8)
      AA(9,1) = -Y(1,1)
      AA(9,9) = X(1,1) + HCO(1) + HRO(1)
      DO 325 I = 3,8
      AA(I+7,I) = -Y(I,1)
  325 AA(I+7,I+7) = X(I,1) + HCO(I) + HRO(I)
C*********************************************************************
      C11 = 0.0
      DO 330 I = 1,7
  330 C11 = C11 + A(I)*HCI(I)
      C12 = (1.0 - ARAFT)*(A(2)*HCO(2) + A(8)*HCI(8))
      C21I = (AMCDOT1 + EXFIL*0.24)/C11
      C22I = AMCDOT2/C12
      IF(C21I.GT.0.02) C31 = EXP(-1./C21I) - 1.0
      IF(C21I.LE.0.02) C31 = -1.0
      IF(C22I.GT.0.02) C32 = EXP(-1./C22I) - 1.0
      IF(C22I.LE.0.02) C32 = -1.0
C*********************************************************************
      AA(16,16) = -C11/(1. + C21I*C31)
      AA(17,17) = -C12/(1. + C22I*C32)
      AA(17,2) = (1.0 - ARAFT)*A(2)*HCO(2)
      AA(17,8) = (1.0 - ARAFT)*A(8)*HCI(8)
C*********************************************************************
C  SET UP VECTOR FOR RIGHT HAND SIDE OF HEAT BALANCE EQUATIONS
      DO 400 I = 1,8
      BB(I) = TR*(Z(I,1)-Y(I,1)) - CR(I)*QI(I,2)
      BB(I) = BB(I) -BETA(I)/2.*(Z(I,1)*(TIS(I,1)-TR)**2
     1   -Y(I,1)*(TOS(I,1)-TR)**2)
      DO 400 J = 2,N(I)
  400 BB(I)=BB(I)-Z(I,J)*(TIS(I,J)-TR)+Y(I,J)*(TOS(I,J)-TR)
     1  -BETA(I)/2.*(Z(I,J)*(TIS(I,J)-TR)**2
     1  -Y(I,J)*(TOS(I,J)-TR)**2)
      BB(2) = BB(2)*ARAFT
C  ADD IN LATENT HEAT EFFECTS
```

```
      DO 405 I = 1,7
  405 BB(I) = BB(I) + AMW1(I)*QLAT + BMW1(I)*QLAT*TIS(I,1)
      BB(2) = BB(2) + AMW2(1)*QLAT + BMW2(1)*QLAT*TIS(2,1)
      BB(8) = BB(8) + AMW2(2)*QLAT + BMW2(2)*QLAT*TIS(8,1)
      DO 410 I = 2,2
      BB(I+6) = BB(I+6) + ARAFT*(TR*(X(I,1)-Y(I,1)) + CR(I)*QO(I,2))
      BB(I+6) = BB(I+6) -ARAFT*BETA(I)/2.*(X(I,1)*(TOS(I,1)-TR)**2
     1    -Y(I,1)*(TIS(I,1)-TR)**2)
      DO 410 J = 2,N(I)
  410 BB(I+6) = BB(I+6)-ARAFT*(X(I,J)*(TOS(I,J)-TR)-Y(I,J)*(TIS(I,J)-TR)
     1  -BETA(I)/2.*(X(I,J)*(TOS(I,J)-TR)**2
     1  -Y(I,J)*(TIS(I,J)-TR)**2))
      BB(9) = TR*(X(1,1)-Y(1,1)) + CR(1)*QO(1,2)
      BB(9) = BB(9) - BETA(1)/2.*(X(1,1)*(TOS(1,1)-TR)**2
     &              -Y(1,1)*(TIS(1,1)-TR)**2)
      DO 415 J = 2,N(1)
  415 BB(9) = BB(9) - X(1,J)*(TOS(1,J)-TR) + Y(1,J)*(TIS(1,J)-TR)
     &    -BETA(1)/2.*(X(1,J)*(TOS(1,J)-TR)**2
     &    -Y(1,J)*(TIS(1,J)-TR)**2)
      BB(9) = BB(9) + HCO(1)*TI + HRO(1)*TI
      DO 420 I = 3,8
      BB(I+7) = TR*(X(I,1)-Y(I,1)) + CR(I)*QO(I,2)
      BB(I+7) = BB(I+7) - BETA(I)/2.*(X(I,1)*(TOS(I,1)-TR)**2
     &    -Y(I,1)*(TIS(I,1)-TR)**2)
      DO 420 J = 2,N(I)
  420 BB(I+7) = BB(I+7)-X(I,J)*(TOS(I,J)-TR)+Y(I,J)*(TIS(I,J)-TR)
     &  -BETA(I)/2.*(X(I,J)*(TOS(I,J)-TR)**2
     &   -Y(I,J)*(TIS(I,J)-TR)**2)
C  IN NEXT EQUATION, SHOULD MULTIPY HRO(I) BY TS, I.E.,
C  THE TEMPERATURE OF THE SURROUNDING SURFACES
C  TEMPORARILY, USE TO IN PLACE OF TS
      DO 430 I = 3,8
  430 BB(I+7) = BB(I+7) + HCO(I)*TO + HRO(I)*TO + ALF(I)*QSOL(I)
      BB(16) = (AMCDOT1*TO + EXFIL*0.24*TI)*C31/(1.0 + C21I*C31)
      BB(17) = (AMCDOT2*TO )*C32/(1.0 + C22I*C32)
C*********************************************************************
      SKBIG = 1.E20
      DO 450 I = 1,8
      IF(KFLAG(I).EQ.0)  GO TO 460
      AA(I,I) = AA(I,I)*SKBIG
      BB(I) = TIS(I,1)*AA(I,I)
  460 IF(I.LT.3) THEN
      IF(I.EQ.2) GO TO 450
      IF(KFLAG(I+8).EQ.0) GO TO 450
      AA(I+8,I+8) = AA(I+8,I+8)*SKBIG
      BB(I+8) = TOS(I,1)*AA(I+8,I+8)
      ELSE
      IF(KFLAG(I+7).EQ.0) GO TO 450
      AA(I+7,I+7) = AA(I+7,I+7)*SKBIG
      BB(I+7) = TOS(I,1)*AA(I+7,I+7)
      END IF
  450 CONTINUE
```

```
C*********************************************************************
C  SOLVE SYSTEM OF EQUATIONS
      CALL SOLVP(17,AA,BB,XXX)
C*********************************************************************
C  TEST FOR CONVERGENCE OF SOLUTION
      EPS = 1.E-3
      IFLAG = 0
      DO 500 I = 1,8
  500 IF(ABS(XXX(I)-TIS(I,1)).GT.EPS)  GO TO 600
      IF(ABS(XXX(9)-TOS(1,1)).GT.EPS)  GO TO 600
C*********************************************************************
      DO 510 I = 3,8
  510 IF(ABS(XXX(I+7)-TOS(I,1)).GT.EPS)  GO TO 600
      IF(ABS(XXX(16)-TA(1,1)).GT.EPS)  GO TO 600
      IF(ABS(XXX(17)-TA(2,1)).GT.EPS)  GO TO 600
C*********************************************************************
      GO TO 700
  600 IFLAG = 1
  700 CONTINUE
C*********************************************************************
      DO 800  I = 1,8
  800 TIS(I,1) = XXX(I)
      TOS(1,1) = XXX(9)
      TOS(2,1) = TIS(8,1)
      DO 810 I = 3,8
  810 TOS(I,1) = XXX(I+7)
      TA(1,1) = XXX(16)
      TA(2,1) = XXX(17)
C*********************************************************************
      S11 = 0.0
      S12 = 0.0
      DO 850 I = 1,7
  850 S11 = S11 + A(I)*HCI(I)*TIS(I,1)
      TE1 = AMCDOT1*TO + EXFIL*0.24*TI + (S11 - C11*TA(1,1))
      TE1 = TE1/(AMCDOT1 + EXFIL*0.24)
      S12 =S12 +(1.-ARAFT)*(A(2)*HCO(2)*TIS(2,1) + A(8)*HCI(8)*TIS(8,1))
      TE2 = TO + (S12 - C12*TA(2,1))/AMCDOT2
      TE = (AMDOT1*TE1 + AMDOT2*TE2)/(AMDOT1 + AMDOT2)
      NIT = NIT + 1
      IF(IFLAG.EQ.1.AND.NIT.LE.15)  GO TO 20
C  CALCULATE HEAT FLUXES
      DO 900 I = 1,8
      QI(I,1) = CR(I)*QI(I,2)
  900 QO(I,1) = CR(I)*QO(I,2)
      DO 950 I = 1,8
      DO 950 J = 1,N(I)
      QI(I,1) = QI(I,1) + Z(I,J)*(TIS(I,J)-TR)-Y(I,J)*(TOS(I,J)-TR)
     1 +BETA(I)/2.*(Z(I,J)*(TIS(I,J)-TR)**2-Y(I,J)*(TOS(I,J)-TR)**2)
  950 QO(I,1) = QO(I,1) + Y(I,J)*(TIS(I,J)-TR)-X(I,J)*(TOS(I,J)-TR)
     1  +BETA(I)/2.*(Y(I,J)*(TIS(I,J)-TR)**2-X(I,J)*(TOS(I,J)-TR)**2)
C  CALCULATE TOTAL CEILING HEAT FLOW
      QCEIL = QO(1,1)*A(1)
```

```
C  CALCULATE NEW MOISTURE CONTENTS
      DO 960 I = 1,7
      AMC1(I) = AMC1(I) + AMW1(I)/AMASS1(I)
  960 IF(AMC1(I).LE.0.0) AMC1(I) = 0.0
      DO 961 I = 1,2
      AMC2(I) = AMC2(I) + AMW2(I)/AMASS2(I)
  961 IF(AMC2(I).LE.0.0) AMC2(I) = 0.0
C  WRITE OUT RESULTS
      WRITE(6,1001) TO,TOS(8,1),TIS(2,1),TOS(3,1),QO(1,1),FLUX,TA(1,1),
     &              TA(2,1),TAIR,TE,TEXIT,ACH1,ACH2,AMC2(2),NIT
 1000 FORMAT(2X,2F15.4,I10)
 1001 FORMAT(1X,4F7.2,2F10.4,5F7.2,2F15.4,F6.3,I5)
C  UPDATE TEMPERATURES AND HEAT FLUXES FOR NEXT HOUR
      DO 1100 I = 1,8
      QI(I,2) = QI(I,1)
      QO(I,2) = QI(I,1)
      DO 1100 J = 1,N(I)-1
      TIS(I,N(I)-J+1) = TIS(I,N(I)-J)
 1100 TOS(I,N(I)-J+1) = TOS(I,N(I)-J)
      TA(1,2) = TA(1,1)
      TA(2,2) = TA(2,1)
      GO TO 10
  999 STOP
      END
C*********************************************************************
C**                                                                 **
C**                          SUBROUTINE MOIST1                      **
C**                                                                 **
C*********************************************************************
      SUBROUTINE MOIST1(TS,TO,TI,TA,HCI,A,AWRAT,AMC,AMASS,HUM,HUMI,PERM,
     &   AMDOT,EXFIL,AMW,BMW,K,WA,WA2)
C  THIS SUBROUTINE PERFORMS A MOISTURE BALANCE ON THE MAIN ATTIC SPACE
C  WITH ONE TRUSS RADIANT BARRIER OVER THE MAIN SPACE
C  TS = SURFACE TEMPERATURE, DEGREES F
C  TO = OUTSIDE AIR TEMPERATURE
C  TI = INSIDE AIR TEMPERATURE
C  TA = ATTIC AIR TEMPERATURE
C  HCI = CONVECTION HEAT TRANSFER COEFFICIENTS
C  A = PROJECTED SURFACE AREAS
C  AWRAT = RATIO OF EXPOSED WOOD SURFACE AREAS TO PROJECTED AREAS
C  AMC = WOOD MOISTURE CONTENTS, FRACTION OF DRY WEIGHT
C  HUM = RELATIVE HUMIDITY OF OUTSIDE AIR
C  HUMI = RELATIVE HUMIDITY OF INSIDE AIR
C  PERM = WATER VAPOR PERMEANCES
C  AMDOT = MASS FLOW OF VENTILATION AIR
C  EXFIL = MASS FLOW OF AIR FROM HOUSE INTO ATTIC
C  AMW = MOISTURE ADSORBED PER UNIT PROJECTED AREA
C  BMW = COEFFICIENT OF LINEAR TERM IN TAYLOR SERIES
C        EXPANSION OF WS(I)
C  K = NUMBER OF SURFACES
      DIMENSION TS(7),HCI(K),A(K),AWRAT(7),AMC(7),PERM(7),AMW(7)
      DIMENSION WS(10),P(10),HM(10),AMASS(7),BMW(7)
```

```
      EPS = 1.E-3
C  CALCULATE HUMIDITY RATIOS AT WOOD SURFACES
      DO 10 I = 1,7
   10 WS(I) = WDHUM(AMC(I),TS(I))
C  CALCULATE HUMIDITY RATIOS OF INSIDE AND  OUTSIDE AIR
      CALL PSY(TI,HUMI,PI,WI)
      CALL PSY(TO,HUM,PO,WO)
C  CALCULATE MASS TRANSFER COEFFICIENTS
      DO 20 I = 1,7
   20 CALL HMASS(TS(I),TA,HCI(I),HM(I))
C  SET UP WATER VAPOR PARTIAL PRESSURES
      P(1) = PI
      XX = WA2/0.62198
      P(2) = 14.696*XX/(1.0 + XX)
      DO 30 I = 3,7
   30 P(I) = PO
C CALCULATE HUMIDITY RATIO OF ATTIC AIR FROM MOISTURE BALANCE
      PA = PO
      X = 0.0
      DO 40 I = 1,7
      X = X + A(I)*PERM(I)*P(I)
   40 X = X + A(I)*AWRAT(I)*HM(I)*WS(I)
      X = X + AMDOT*WO + EXFIL*WI
      NIT = 0
  100 Y = 0.0
      DO 50 I = 1,7
   50 Y = Y + A(I)*AWRAT(I)*HM(I)
      Y = Y + AMDOT + EXFIL
      DO 60 I = 1,7
   60 Y = Y + A(I)*PERM(I)*(14.696 - PA)/0.62198
      WA = X/Y
      XX = WA/0.62198
      PANEW = 14.696*XX/(1.0 + XX)
      NIT = NIT + 1
      IF (NIT.GT.10)  GO TO 200
      IF(ABS(1.-PANEW/PA).LT.EPS)  GO TO 200
      PA = PANEW
      GO TO 100
  200 CONTINUE
C  CALCULATE WATER ADSORBED BY EACH SURFACE
      DO 300 I = 1,7
  300 AMW(I) = HM(I)*AWRAT(I)*(WA-WS(I))
C  CALCULATE CORRECTION TERM FOR TAYLOR SERIES EXPANSION OF
C  ADSORBED WATER
      DO 310 I = 1,7
  310 BMW(I) = HM(I)*AWRAT(I)*WS(I)/28.6
      RETURN
      END
C*********************************************************************
C**                                                                 **
C**                        SUBROUTINE MOIST2                        **
C**                                                                 **
```

```
C*********************************************************************
      SUBROUTINE MOIST2(TS,TO,TI,TA,HC1,HC2,A1,A2,AWRAT,AMC,AMASS,HUM,
     &   HUMI,PERM,AMDOT,EXFIL,AMW,BMW,WA1,WA)
C  THIS SUBROUTINE PERFORMS A MOISTURE BALANCE ON THE SPACEX
C  BETWEEN THE ROOF AND A TRUSS RADIANT BARRIER
C  TS = SURFACE TEMPERATURE, DEGREES F
C  TO = OUTSIDE AIR TEMPERATURE
C  TI = INSIDE AIR TEMPERATURE
C  TA = ATTIC AIR TEMPERATURE
C  HCI = CONVECTION HEAT TRANSFER COEFFICIENTS
C  A = PROJECTED SURFACE AREAS
C  AWRAT = RATIO OF EXPOSED WOOD SURFACE AREAS TO PROJECTED AREAS
C  AMC = WOOD MOISTURE CONTENTS, FRACTION OF DRY WEIGHT
C  HUM = RELATIVE HUMIDITY OF OUTSIDE AIR
C  HUMI = RELATIVE HUMIDITY OF INSIDE AIR
C  PERM = WATER VAPOR PERMEANCES
C  AMDOT = MASS FLOW OF VENTILATION AIR
C  EXFIL = MASS FLOW OF AIR FROM HOUSE INTO ATTIC
C  AMW = MOISTURE ADSORBED PER UNIT PROJECTED AREA
C  BMW = COEFFICIENT OF LINEAR TERM IN TAYLOR SERIES
C        EXPANSION OF WS(I)
C  K = NUMBER OF SURFACES
      DIMENSION TS(2),A(2),AWRAT(2),AMC(2),PERM(2),AMW(2)
      DIMENSION WS(10),P(10),HM(10),AMASS(2),BMW(2)
      EPS = 1.E-3
      A(1) = A1
      A(2) = A2
C  CALCULATE HUMIDITY RATIOS AT WOOD SURFACES
      DO 10 I = 1,2
   10 WS(I) = WDHUM(AMC(I),TS(I))
C  CALCULATE HUMIDITY RATIOS OF INSIDE AND  OUTSIDE AIR
      CALL PSY(TI,HUMI,PI,WI)
      CALL PSY(TO,HUM,PO,WO)
C  CALCULATE MASS TRANSFER COEFFICIENTS
      CALL HMASS(TS(1),TA,HC1,HM(1))
      CALL HMASS(TS(2),TA,HC2,HM(2))
C  SET UP WATER VAPOR PARTIAL PRESSURES
      XX = WA1/0.62198
      P(1) = 14.696*XX/(1.0 + XX)
      P(2) = PO
C CALCULATE HUMIDITY RATIO OF ATTIC AIR FROM MOISTURE BALANCE
      PA = PO
      X = 0.0
      DO 40 I = 1,2
      X = X + A(I)*PERM(I)*P(I)
   40 X = X + A(I)*AWRAT(I)*HM(I)*WS(I)
      X = X + AMDOT*WO + EXFIL*WI
      NIT = 0
  100 Y = 0.0
      DO 50 I = 1,2
   50 Y = Y + A(I)*AWRAT(I)*HM(I)
      Y = Y + AMDOT + EXFIL
```

```
      DO 60 I = 1,2
   60 Y = Y + A(I)*PERM(I)*(14.696 - PA)/0.62198
      WA = X/Y
      XX = WA/0.62198
      PANEW = 14.696*XX/(1.0 + XX)
      NIT = NIT + 1
      IF (NIT.GT.10)  GO TO 200
      IF(ABS(1.-PANEW/PA).LT.EPS)  GO TO 200
      PA = PANEW
      GO TO 100
  200 CONTINUE
C  CALCULATE WATER ADSORBED BY EACH SURFACE
      DO 300 I = 1,2
  300 AMW(I) = HM(I)*AWRAT(I)*(WA-WS(I))
C  CALCULATE CORRECTION TERM FOR TAYLOR SERIES EXPANSION OF
C  ADSORBED WATER
      DO 310 I = 1,2
  310 BMW(I) = HM(I)*AWRAT(I)*WS(I)/28.6
      RETURN
      END
```

Note: RBSOR2 also contains the following subprograms as given in Appendix A: FMN, FP, HCON, HMASS, HRAD, PSY, SOLVP, VENT, VIEW2, AND WDHUM.

APPENDIX C
RBSOR3 COMPUTER PROGRAM

```
C*********************************************************************
C**                                                                 **
C**                          PROGRAM RBSOR3                         **
C**                                                                 **
C*********************************************************************
C  THIS PROGRAM CALCULATES THE HEAT TRANSFER THROUGH THE CEILING
C  BELOW A GABLED ATTIC HAVING A FIVE-SIDED CROSS SECTION
C  AND A TRUSS RADIANT BARRIER ON BOTH ROOF SECTIONS
C  ASSUMES THE AIR WITHIN THE ATTIC IS NOT WELL-MIXED
C  INCLUDES APPROXIMATE CALCULATIONS FOR LATENT HEAT EFFECTS
C  DUE TO MOISTURE ADSORPTION AND DESORPTION
C  SURFACE TEMPERATURES ON INSIDE OR OUTSIDE, OR VENTILATION RATE
C  MAY BE SPECIFIED THROUGH KFLAG(I) = 1
C  NOMENCLATURE:
C   N(I) = NUMBER OF CONDUCTION TRANSER FUNCTIONS FOR SURFACE I
C   U(I) = SURFACE-TO-SURFACE U-VALUE FOR SURFACE I
C   CR(I) = COMMON RATIO OF RESPONSE FACTORS FOR SURFACE I
C   BETA(I) = TEMPERATURE DEPENDENT COEFFICIENT FOR CONDUCTION
C             TRANSFER FUNCTIONS FOR SURFACE I
C   X(I,J), Y(I,J), Z(I,J) = CONDUCTION TRANSFER FUNCTIONS FOR
C             SURFACE I
C   SURFACES ARE NUMBERED AS (FOR NORTH-SOUTH RIDGE):
C     1 = CEILING
C     2 = EAST ROOF RADIANT BARRIER
C     3 = WEST ROOF RADIANT BARRIER
C     4 = SOUTH GABLE
C     5 = NORTH GABLE
C     6 = EAST EAVE WALL
C     7 = WEST EAVE WALL
C     8 = EAST ROOF
C     9 = WEST ROOF
C   ALF(I) = SOLAR ABSORPTANCE FOR SURFACE I
C   EO(I) = INFRARED EMITTANCE FOR OUTSIDE OF SURFACE I
C   EI(I) = INFRARED EMITTANCE FOR INSIDE OF SURFACE I
C   TIS(I,J) = INSIDE SURFACE TEMPERATURE FOR SURFACE I
C   TOS(I,J) = OUTSIDE SURFACE TEMPERATURE FOR SURFACE I
C   TA(1,J) = AVERAGE TEMPERATURE OF AIR IN MAIN ATTIC SPACE ATTIC
C   TA(2,J) = AVERAGE TEMPERATURE OF AIR IN EAST VENT SPACE
C   TA(3,J) = AVERAGE TEMPERATURE OF AIR IN WEST VENT SPACE
C   QI(I,J) = INSIDE HEAT FLUX FOR SURFACE I
C   QO(I,J) = OUTSIDE HEAT FLUX FOR SURFACE I
C   HCI(I) = CONVECTION COEFFICIENT FOR INSIDE OF SURFACE I
C   HR(I,K) = RADIATION INTERCHANGE COEFFICIENT FROM SURFACE I
C             TO SURFACE K
C   AA(I,J) = MATRIX OF COEFFICIENTS FOR SIMULTANEOUS EQUATIONS
C   BB(I) = KNOWN VECTOR FOR SIMULTANEOUS EQUATIONS
C   XXX(I) = SOLUTION VECTOR FOR SIMULTANEOUS EQUATIONS
C   QSOL(I) = SOLAR RADIATION INCIDENT ON SURFACE I
C   A(I) = AREA OF SURFACE I
C   G(I,K) = OVERALL RADIATION VIEW FACTOR FROM SURFACE I TO
C            SURFACE K
C   HCO(I) = CONVECTION COEFFICIENT ON OUTSIDE OF SURFACE I
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C   HRO(I) = RADIATION COEFFICIENT ON OUTSIDE OF SURFACE I
C   R(I) = SURFACE-TO-SURFACE RESISTANCE FOR SURFACE I
C   AMC(I) = MOISTURE CONTENT (WEIGHT FRACTION) FOR SURFACE I
C   PERM(I) = MOISTURE PERMEANCE OF SURFACE I
C   AWRAT(I) = RATIO OF EXPOSED SURFACE AREA TO PROJECTED SURFACE
C              AREA FOR SURFACE I
C   AMASS(I) = MASS PER UNIT AREA OF SURFACE I THAT PARTICIPATES IS
C              MOISTURE EXCHANGE
C   AMW(I) = MOISTURE FLUX TOWARD SURFACE I
C   BMW(I) = TERM IN TAYLOR SERIES EXPANSION FOR MOISTURE FLUX
C   TS(I) = TEMPERATURE OF INSIDE OF SURFACE I
C   KFLAG(I) = FLAG FOR SPECIFIED SURFACE TEMPERATURES
C       0 = PARAMETER NOT SPECIFIED
C       1 = PARAMETER SPECIFIED
C       I = 1,9 FOR TIS(I,1)
C       I = 10,16 FOR TOS(1,1), TOS(4,1)...TOS(9,1)
C       I = 17,19 FOR VENTILATION RATES IN MAIN AND VENT SPACES
C   AL = LENGTH OF ATTIC, FEET
C   W  = WIDTH OF ATTIC, FEET
C   PITCH1 = PITCH OF EAST ROOF, DEGREES
C   PITCH2 = PITCH OF WEST ROOF, DEGREES
C   ORIENT = ORIENTATION OF HOUSE
C   H1 = HEIGHT OF VERTICAL WALLS AT EAVES, FEET
C   AI = AREA OF INLET VENT, SQUARE FEET
C   AO = AREA OF OUTLET VENT, SQUARE FEET
C   ITYPE = TYPE VENTS
C       1 = SOFFIT AND RIDGE VENTS
C       2 = SOFFIT AND GABLE VENTS
C       3 = SOFFIT VENTS ONLY
C   QLAT = HEAT OF VAPORIZATION OF WATER, BTU/LBM
C   EXFIL = RATE OF FLOW OF AIR FROM HOUSE TO ATTIC, LB/HR
C   AL1 ... AL7 = CHARACTERISTIC LENGTHS OF SURFACES 1 ... 7, FEET
C   TO = OUTDOOR TEMPERATURE, F
C   QSOLH = SOLAR RADIATION INCIDENT ON HORIZONTAL SURFACE
C           BTU/(HR.-SQ.FT.)
C   WS = WIND SPEED, MPH
C   DIR = WIND DIRECTION
C   HUM = OUTDOOR RELATIVE HUMIDITY, PERCENT
C   TI = INDOOR TEMPERATURE, F
C   HUMI = INDOOR RELATIVE HUMIDITY, PERCENT
C   VDOT = VENTILATION RATE, CUBIC FEET PER HOUR
C   IVFLAG = FLAG FOR CALCULATING FLOW VELOCITY
C        0 = FLOW THROUGH BOTH SIDES OF ATTIC
C        1 = FLOW THROUGH ONE SIDE OF ATTIC
C   FLUX = MEASURED CEILING HEAT FLUX, BTU/(HR.-SQ.FT.)
C   TAIR = MEASURED ATTIC AIR TEMPERATURE, F
C   TEXIT = MEASURED EXIT AIR TEMPERATURE, F
C   H = HEIGHT, FEET
C   AMDOT = VENTILATION RATE, POUNDS PER HOUR
C   AMCDOT = VENTILATION RATE TIMES SPECIFIC HEAT
C   V = CRUDE ESTIMATE OF AIR SPEED THROUGH ATTIC, FEET PER HOUR
C   ACH = AIR CHANGE RATE FOR ATTIC, AIR CHANGES PER HOUR
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      DIMENSION N(9),U(9),CR(9),BETA(9),X(9,100),Y(9,100),Z(9,100)
      DIMENSION ALF(9),EO(9),EI(9),TIS(9,100),TOS(9,100),TA(3,2)
      DIMENSION QI(9,2),QO(9,2),HCI(9),HR(7,7),AA(19,19),BB(19)
      DIMENSION XXX(19),QSOL(9),A(9),G(7,7),HCO(9),HRO(9),R(9)
      DIMENSION AMC1(7),PERM1(7),AWRAT1(7),AMASS1(7),AMW1(7),TS1(7)
      DIMENSION BMW1(7),KFLAG(19)
      DIMENSION AMC2(2),PERM2(2),AWRAT2(2),AMASS2(2),AMW2(2),TS2(2)
      DIMENSION BMW2(2)
      DIMENSION AMC3(2),PERM3(2),AWRAT3(2),AMASS3(2),AMW3(2),TS3(2)
      DIMENSION BMW3(2)
      DATA TIS/900*75.0/,TOS/900*75.0/,AA/361*0.0/,TR/75.0/
      DATA TA/6*75.0/,QI/18*0.0/,QO/18*0.0/,BMW1/7*0.0/,BMW2/2*0.0/
      DATA BMW3/2*0.0/
      DATA WA1/0.0/,WA2/0.0/,WA3/0.0/
C  READ IN KFLAG: 0 = PARAMETER NOT SPECIFIED
C                 1 = PARAMETER SPECIFIED
      READ (5,*) (KFLAG(I),I=1,9)
      READ (5,*) (KFLAG(I),I=10,16)
      READ (5,*) (KFLAG(I),I=17,19)
C  READ IN CONDUCTION TRANSFER FUNCTIONS
      DO 100 I = 1,9
      READ (5,*)  N(I),U(I),CR(I),BETA(I)
      M = N(I)
      DO 100 J = 1,M
      READ (5,*) X(I,J),Y(I,J),Z(I,J)
  100 CONTINUE
      DO 101 I = 1,9
  101 R(I) = 1./U(I)
C  CONVENTION FOR CTF'S IS SAME AS USED IN TARP
C  CONVENTION FOR ATTIC MODEL IS THAT INSIDE SURFACES
C  FACE THE ATTIC SPACE
C  CTF'S FOR THE CEILING ARE CALCULATED FOR USE IN A
C  WHOLE HOUSE MODEL, WHERE THE OUTSIDE SURFACE FACES
C  THE ATTIC;  THEREFORE, FOR USE INTERNAL TO THE ATTIC
C  MODEL, INTERCHANGE THE X'S AND THE Z'S
      M = N(1)
      DO 110 J = 1,M
      XX = X(1,J)
      X(1,J) = Z(1,J)
      Z(1,J) = XX
  110 CONTINUE
C  READ IN SOLAR ABSORPTANCES OF OUTSIDE SURFACES AND
C  EMITTANCES OF BOTH OUTSIDE AND INSIDE SURFACES
      READ(5,*)  (ALF(I), I = 1,9)
      READ(5,*)  (EO(I), I = 1,9)
      READ(5,*)  (EI(I), I = 1,9)
C  READ IN ATTIC GEOMETRY:  LENGTH, WIDTH, PITCHES OF ROOF
C  SURFACES(DEGREES), ORIENTATION ANGLE OF HOUSE
C  AND HEIGHT OF SIDE WALLS
      READ (5,*)  AL,W,PITCH1,PITCH2,ORIENT,H1
C  READ VENT INLET AND OUTLET AREAS, AND VENT TYPE
C  TYPE 1 = SOFFIT AND RIDGE VENTS
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C  TYPE 2 = SOFFIT AND GABLE VENTS
C  TYPE 3 = SOFFIT VENTS ONLY
      READ(5,*) AI1,AO1,AI2,AO2,AI3,AO3,ITYPE,FLOW1
C  READ RAFTER SPACING AND THICKNESS, INCHES
      READ(5,*) RAFTSP,RAFTTHK
C  READ WATER VAPOR PERMEANCES OF ATTIC SURFACES
C  PERM = GRAINS PER (HR-FT2-INCH HG)
      READ (5,*) (PERM1(I),I=1,7)
      READ (5,*) (PERM2(I),I=1,2)
      READ (5,*) (PERM3(I),I=1,2)
C CONVERT PERM VALUES TO POUNDS PER (HR-FT2-PSIA)
      DO 120 I = 1,7
  120 PERM1(I) = PERM1(I)*(29.921/14.696)/7000.
      DO 121 I = 1,2
      PERM3(I) = PERM3(I)*(29.921/14.696)/7000.
  121 PERM2(I) = PERM2(I)*(29.921/14.696)/7000.
C  READ RATIO OF TOTAL AREA OF EXPOSED WOOD TO GEOMETRICAL
C  PROJECTION OF SURFACE AREAS
      READ (5,*) (AWRAT1(I),I=1,7)
      READ (5,*) (AWRAT2(I),I=1,2)
      READ (5,*) (AWRAT3(I),I=1,2)
C  READ WEIGHT OF WOOD PER UNIT PROJECTED AREA FOR EACH SURFACE
      READ (5,*) (AMASS1(I),I=1,7)
      READ (5,*) (AMASS2(I),I=1,2)
      READ (5,*) (AMASS3(I),I=1,2)
C  READ INITIAL MOISTURE CONTENTS OF WOOD, WEIGHT FRACTION
      READ (5,*) (AMC1(I),I=1,7)
      READ (5,*) (AMC2(I),I=1,2)
      READ (5,*) (AMC3(I),I=1,2)
C  READ LATENT HEAT OF VAPORIZATION, BTU/LB
      READ (5,*) QLAT
C  READ RATE OF FLOW OF HOUSE AIR INTO ATTIC, POUNDS PER HOUR
      READ (5,*) EXFIL
C  CALCULATE CHARACTERISTIC LENGTHS AND AREAS OF SURFACES
C  CHAR. LENGTHS ARE TAKEN TO BE:
C  CEILING - AVERAGE OF LENGTH AND WIDTH
C  ROOF - DISTANCE FROM EAVE TO RIDGE
C  GABLE - AVERAGE HEIGHT
C  SIDE WALLS - HEIGHT
      AL1 = (AL+W)/2.
      P1 = PITCH1*3.14159265/180.
      P2 = PITCH2*3.14159265/180.
      P3 = 3.14159265 - P1 - P2
      IP1 = PITCH1
      IP2 = PITCH2
      IP3 = 180.0 - PITCH1 - PITCH2
      IF(IP3.EQ.180) GO TO 5
      AL2 = W*SIN(P2)/SIN(P3)
      AL3 = W*SIN(P1)/SIN(P3)
      AL4 = 0.5*(AL2*SIN(P1)) + H1
      GO TO 6
    5 AL2 = W/2.0
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      AL3 = W/2.0
      AL4 = H1
    6 AL5 = AL4
      AL6 = H1
      AL7 = H1
      AL8 = AL2
      AL9 = AL3
      A(1) = AL*W
      A(2) = AL*AL2
      A(3) = AL*AL3
      A(4) = W*AL4
      A(5) = A(4)
      A(6) = AL*H1
      A(7) = AL*H1
      A(8) = A(2)
      A(9) = A(3)
      ARAFT = 1.5/RAFTSP
C  CALCULATE RADIATION INTERCHANGE FACTORS WITHIN ATTIC SPACE
      CALL VIEW2(AL,W,PITCH1,PITCH2,H1,EI,G,9)
C  CALCULATE RADIATION INTERCHANGE BETWEEN FOIL AND ROOF, USING
C  HOTTEL'S STRING METHOD
      RAT = RAFTTHK/(RAFTSP - 1.5)
      F28 = SQRT(1.0 + RAT*RAT) - RAT
      G28 = 1./(2./(1.+F28) + 1./EO(2) + 1./EI(8) - 2.)
      G39 = 1./(2./(1.+F28) + 1./EO(3) + 1./EI(9) - 2.)
C  READ LINE OF WEATHER DATA
C*********************************************************************
   10 READ(5,*,END = 999) TO,QSOLH,WS,DIR,HUM,TI,HUMI,(TIS(I,1),I=1,9),
     &  TOS(1,1),(TOS(I,1),I=4,9),VDOT,IVFLAG,FLUX,TAIR,TEXIT
C  RESTORE ESTIMATES FOR TEMPERATURES NOT SPECIFIED
      DO 15 I = 1,9
   15 IF(KFLAG(I).EQ.0) TIS(I,1) = TIS(I,2)
      IF(KFLAG(10).EQ.0) TOS(1,1) = TOS(1,2)
      DO 16 I = 4,9
   16 IF(KFLAG(I+7).EQ.0) TOS(I,1) = TOS(I,2)
C  NEXT TWO LINES ARE FOR ESTIMATING FLOWS IN FSEC EXPERIMENT
      VDOT1 = VDOT*FLOW1
      VDOT2 = VDOT*(1.0 - FLOW1)/2.0
      VDOT3 = VDOT*(1.0 - FLOW1)/2.0
C*********************************************************************
C  CALCULATE SOLAR LOAD ON EACH SURFACE
C  NEED TO INVOKE APPROPRIATE ALGORITHMS
C  THE FOLLOWING ARE TEMPORARY
      QSOL(1) = 0.0
      QSOL(2) = 0.0
      QSOL(3) = 0.0
      QSOL(4) = 0.0
      QSOL(5) = 0.0
      QSOL(6) = 0.0
      QSOL(7) = 0.0
      QSOL(8) = QSOLH
      QSOL(9) = QSOLH
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      NIT = 1
C*********************************************************************
C  CALCULATE ATTIC VENTILATION RATE AND FLOW VELOCITY
      H = AL4 + AL2*SIN(P1)/2.0
   20 CONTINUE
      IF(KFLAG(17).EQ.0) THEN
      CALL VENT(TO,TA(1,1),WS,DIR,H,AI1,AO1,ITYPE,AMCDOT1,AMDOT1,VDOT1)
      ELSE
C  ASSUME VENTILATION RATES ARE BASED ON OUTSIDE AIR TEMPERATURE
      AMDOT1 = VDOT1*22.0493/((TO+459.67)/1.8)
      AMCDOT1 = AMDOT1*(3.4763 + 1.066E-4*((TO+459.67)/1.8))*0.068559
      END IF
      IF(IVFLAG.EQ.0) V1 = VDOT1/(AL4*AL)
      IF(IVFLAG.EQ.1) V1 = VDOT1*2.0/(AL4*AL)
      IF(KFLAG(18).EQ.0) THEN
      CALL VENT(TO,TA(2,1),WS,DIR,H,AI2,AO2,ITYPE,AMCDOT2,AMDOT2,VDOT2)
      ELSE
      AMDOT2 = VDOT2*22.0493/((TO+459.67)/1.8)
      AMCDOT2 = AMDOT2*(3.4763 + 1.066E-4*((TO+459.67)/1.8))*0.068559
      END IF
      V2 = VDOT2/(AL*RAFTTHK/12.*(1.0-ARAFT))
      IF(KFLAG(19).EQ.0) THEN
      CALL VENT(TO,TA(3,1),WS,DIR,H,AI3,AO3,ITYPE,AMCDOT3,AMDOT3,VDOT3)
      ELSE
      AMDOT3 = VDOT3*22.0493/((TO+459.67)/1.8)
      AMCDOT3 = AMDOT3*(3.4763 + 1.066E-4*((TO+459.67)/1.8))*0.068559
      END IF
      V3 = VDOT3/(AL*RAFTTHK/12.*(1.0-ARAFT))
      ACH1 = VDOT1/A(4)/AL
      ACH2 = VDOT2/(AL*AL2*RAFTTHK/12.*(1.0-ARAFT))
      ACH3 = VDOT3/(AL*AL3*RAFTTHK/12.*(1.0-ARAFT))
C*********************************************************************
C  CALCULATE CONVECTION COEFFICIENTS AT INSIDE SURFACES
      CALL HCON(TIS(1,1),TA(1,1),0.0,AL1,1,V1,HCI(1))
      CALL HCON(TIS(2,1),TA(1,1),PITCH1,AL2,2,V1,HCI(2))
      CALL HCON(TIS(3,1),TA(1,1),PITCH2,AL3,2,V1,HCI(3))
      CALL HCON(TIS(4,1),TA(1,1),90.0,AL4,1,V1,HCI(4))
      CALL HCON(TIS(5,1),TA(1,1),90.0,AL5,1,V1,HCI(5))
      CALL HCON(TIS(6,1),TA(1,1),90.0,AL6,1,V1,HCI(6))
      CALL HCON(TIS(7,1),TA(1,1),90.0,AL7,1,V1,HCI(7))
C  CALCULATE COEFFICIENTS AT SURFACES OF SPACES BETWEEN RB'S AND ROOFS
      CALL HCON(TIS(2,1),TA(2,1),PITCH1,AL2,1,V2,HCO(2))
      CALL HCON(TIS(8,1),TA(2,1),PITCH1,AL2,2,V2,HCI(8))
      CALL HCON(TIS(3,1),TA(3,1),PITCH2,AL3,1,V3,HCO(3))
      CALL HCON(TIS(9,1),TA(3,1),PITCH2,AL3,2,V3,HCI(9))
C  CALCULATE CONVECTION COEFFICIENTS AT OUTSIDE SURFACES
      WS1 = WS*5280.
      CALL HCON(TOS(1,1),TI,0.0,AL1,2,0.0,HCO(1))
C     CALL HCON(TOS(2,1),TO,PITCH1,AL2,1,WS1,HCO(2))
C     CALL HCON(TOS(3,1),TO,PITCH2,AL3,1,WS1,HCO(3))
      CALL HCON(TOS(4,1),TO,90.0,AL4,1,WS1,HCO(4))
      CALL HCON(TOS(5,1),TO,90.0,AL5,1,WS1,HCO(5))
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      CALL HCON(TOS(6,1),TO,90.0,AL6,1,WS1,HCO(6))
      CALL HCON(TOS(7,1),TO,90.0,AL7,1,WS1,HCO(7))
      CALL HCON(TOS(8,1),TO,PITCH1,AL2,1,WS1,HCO(8))
      CALL HCON(TOS(9,1),TO,PITCH2,AL3,1,WS1,HCO(9))
C  CALCULATE RADIATION COEFFICIENTS AT INSIDE SURFACES
      DO 200 I = 1,7
      DO 200 J = 1,7
      HR(I,J) = HRAD(G(I,J),TIS(I,1),TIS(J,1))
  200 CONTINUE
C  CALCULATE RADIATION COEFFICIENTS ACROSS RB SPACES
      HRO(2) = HRAD(G28,TIS(2,1),TOS(2,1))
      HRO(3) = HRAD(G39,TIS(3,1),TOS(3,1))
C  CALCULATE RADIATION COEFFICIENTS AT OUTSIDE SURFACES
      HRO(1) = HRAD(EO(1),TOS(1,1),TI)
      DO 250 I = 4,9
      HRO(I) = HRAD(EO(I),TOS(I,1),TO)
  250 CONTINUE
C  CALCULATE MOISTURE BALANCES, LATENT HEATS
      IF(QLAT.LT.1.) THEN
         DO 255 I = 1,7
         AMW1(I) = 0.0
  255    BMW1(I) = 0.0
         DO 256 I = 1,2
         AMW2(I) = 0.0
         BMW2(I) = 0.0
         AMW3(I) = 0.0
  256    BMW3(I) = 0.0
      ELSE
      DO 260 I = 1,7
  260 TS1(I) = TIS(I,1)
      CALL MOIST3(TS1,TO,TI,TA(1,1),HCI,A,AWRAT1,AMC1,AMASS1,HUM,HUMI,
     &   PERM1,AMDOT1,EXFIL,AMW1,BMW1,9,WA1,WA2,WA3)
      TS2(1) = TIS(2,1)
      TS2(2) = TIS(8,1)
      TS3(1) = TIS(3,1)
      TS3(2) = TIS(9,1)
      HC21 = HCO(2)
      HC22 = HCI(8)
      HC31 = HCO(3)
      HC32 = HCI(9)
      A21 = A(2)
      A22 = A(8)
      A31 = A(3)
      A32 = A(9)
      CALL MOIST2(TS2,TO,TI,TA(2,1),HC21,HC22,A21,A22,AWRAT2,AMC2,
     &   AMASS2,HUM,HUMI,PERM2,AMDOT2,0.0,AMW2,BMW2,WA1,WA2)
      CALL MOIST2(TS3,TO,TI,TA(3,1),HC31,HC32,A31,A32,AWRAT3,AMC3,
     &   AMASS3,HUM,HUMI,PERM3,AMDOT3,0.0,AMW3,BMW3,WA1,WA3)
      DO 270 I = 1,7
      IF(AMC1(I).LE.1.E-6.AND.AMW1(I).LT.0.0) THEN
         AMW1(I) = 0.0
         BMW1(I) = 0.0
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      ELSE IF(AMW1(I).LT.0.0.AND.ABS(AMW1(I)).GT.(AMC1(I)*AMASS1(I)))
     &   THEN
         AMWOLD = AMW1(I)
         FACT = ABS(AMC1(I)*AMASS1(I)/AMWOLD)
         AMW1(I) = AMW1(I)*FACT
         BMW1(I) = BMW1(I)*AMW1(I)/AMWOLD
      ELSE
         CONTINUE
      END IF
  270 CONTINUE
      DO 271 I = 1,2
      IF(AMC2(I).LE.1.E-6.AND.AMW2(I).LT.0.0) THEN
         AMW2(I) = 0.0
         BMW2(I) = 0.0
      ELSE IF(AMW2(I).LT.0.0.AND.ABS(AMW2(I)).GT.(AMC2(I)*AMASS2(I)))
     &   THEN
         AMWOLD = AMW2(I)
         FACT = ABS(AMC2(I)*AMASS2(I)/AMWOLD)
         AMW2(I) = AMW2(I)*FACT
         BMW2(I) = BMW2(I)*AMW2(I)/AMWOLD
      ELSE
         CONTINUE
      END IF
  271 CONTINUE
      DO 272 I = 1,2
      IF(AMC3(I).LE.1.E-6.AND.AMW3(I).LT.0.0) THEN
         AMW3(I) = 0.0
         BMW3(I) = 0.0
      ELSE IF(AMW3(I).LT.0.0.AND.(AMW3(I)).GT.(AMC3(I)*AMASS3(I)))
     &   THEN
         AMWOLD = AMW3(I)
         FACT = ABS(AMC3(I)*AMASS3(I)/AMWOLD)
         AMW3(I) = AMW3(I)*FACT
         BMW3(I) = BMW3(I)*AMW3(I)/AMWOLD
      ELSE
         CONTINUE
      END IF
  272 CONTINUE
      END IF
C*********************************************************************
C  SET UP MATRIX OF COEFFICIENTS IN HEAT BALANCE EQUATIONS
      DO 300 I = 1,7
      DO 300 J = 1,7
      AA(I,J) = -HR(I,J)
  300 CONTINUE
      DO 310 I = 1,7
      DO 305 J = 1,7
  305 AA(I,I) = AA(I,I) + HR(I,J)
  310 AA(I,I) = AA(I,I) + Z(I,1) + HCI(I)
C  ADD IN LATENT HEAT TERMS
      DO 315 I = 1,7
  315 AA(I,I) = AA(I,I) + BMW1(I)*QLAT
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      AA(2,2) = AA(2,2) + BMW2(1)*QLAT
      AA(2,2) = AA(2,2) + (1.0 - ARAFT)*(HCO(2)+HRO(2)-Z(2,1))
      AA(3,3) = AA(3,3) + BMW3(1)*QLAT
      AA(3,3) = AA(3,3) + (1.0 - ARAFT)*(HCO(3)+HRO(3)-Z(3,1))
      AA(1,10) = -Y(1,1)
      DO 316 I = 4,9
  316 AA(I,I+7) = -Y(I,1)
C*********************************************************************
      DO 320 I = 1,7
C     AA(I,I+7) = - Y(I,1)
      AA(I,17) = -HCI(I)
C     AA(I+7,I) = -Y(I,1)
C     AA(I+7,I+7) = X(I,1) + HCO(I) + HRO(I)
  320 AA(17,I) = A(I)*HCI(I)
      AA(2,8) = -ARAFT*Y(2,1) - (1.0 - ARAFT)*HRO(2)
      AA(2,18) = -HCO(2)*(1.0 - ARAFT)
      AA(3,9) = -ARAFT*Y(3,1) - (1.0 - ARAFT)*HRO(3)
      AA(3,19) = -HCO(3)*(1.0 - ARAFT)
      AA(8,2) = -ARAFT*Y(2,1) - (1.0 - ARAFT)*HRO(2)
      AA(8,8) = Z(8,1) + X(2,1)*ARAFT + (1.0 - ARAFT)*(HRO(2)+HCI(8))
      AA(8,8) = AA(8,8) + BMW2(2)*QLAT
      AA(8,18) = -(1.0 - ARAFT)*HCI(8)
      AA(9,3) = -ARAFT*Y(3,1) - (1.0 - ARAFT)*HRO(3)
      AA(9,9) = Z(9,1) + X(3,1)*ARAFT + (1.0 - ARAFT)*(HRO(3)+HCI(9))
      AA(9,9) = AA(9,9) + BMW3(2)*QLAT
      AA(9,19) = -(1.0 - ARAFT)*HCI(9)
      AA(10,1) = -Y(1,1)
      AA(10,10) = X(1,1) + HCO(1) + HRO(1)
      DO 325 I = 4,9
      AA(I+7,I) = -Y(I,1)
  325 AA(I+7,I+7) = X(I,1) + HCO(I) + HRO(I)
C*********************************************************************
      C11 = 0.0
      DO 330 I = 1,7
  330 C11 = C11 + A(I)*HCI(I)
      C12 = (1.0 - ARAFT)*(A(2)*HCO(2) + A(8)*HCI(8))
      C13 = (1.0 - ARAFT)*(A(3)*HCO(3) + A(9)*HCI(9))
      C21I = (AMCDOT1 + EXFIL*0.24)/C11
      C22I = AMCDOT2/C12
      C23I = AMCDOT3/C13
      IF(C21I.GT.0.02) C31 = EXP(-1./C21I) - 1.0
      IF(C21I.LE.0.02) C31 = -1.0
      IF(C22I.GT.0.02) C32 = EXP(-1./C22I) - 1.0
      IF(C22I.LE.0.02) C32 = -1.0
      IF(C23I.GT.0.02) C33 = EXP(-1./C23I) - 1.0
      IF(C23I.LE.0.02) C33 = -1.0
C*********************************************************************
      AA(17,17) = -C11/(1. + C21I*C31)
      AA(18,18) = -C12/(1. + C22I*C32)
      AA(19,19) = -C13/(1. + C23I*C33)
      AA(18,2) = (1.0 - ARAFT)*A(2)*HCO(2)
      AA(18,8) = (1.0 - ARAFT)*A(8)*HCI(8)
```

```
      AA(19,3) = (1.0 - ARAFT)*A(3)*HCO(3)
      AA(19,9) = (1.0 - ARAFT)*A(9)*HCI(9)
C*********************************************************************
C  SET UP VECTOR FOR RIGHT HAND SIDE OF HEAT BALANCE EQUATIONS
      DO 400 I = 1,9
      BB(I) = TR*(Z(I,1)-Y(I,1)) - CR(I)*QI(I,2)
      BB(I) = BB(I) -BETA(I)/2.*(Z(I,1)*(TIS(I,1)-TR)**2
     1   -Y(I,1)*(TOS(I,1)-TR)**2)
      DO 400 J = 2,N(I)
  400 BB(I)=BB(I)-Z(I,J)*(TIS(I,J)-TR)+Y(I,J)*(TOS(I,J)-TR)
     1  -BETA(I)/2.*(Z(I,J)*(TIS(I,J)-TR)**2
     1  -Y(I,J)*(TOS(I,J)-TR)**2)
      BB(2) = BB(2)*ARAFT
      BB(3) = BB(3)*ARAFT
C  ADD IN LATENT HEAT EFFECTS
      DO 405 I = 1,7
  405 BB(I) = BB(I) + AMW1(I)*QLAT + BMW1(I)*QLAT*TIS(I,1)
      BB(2) = BB(2) + AMW2(1)*QLAT + BMW2(1)*QLAT*TIS(2,1)
      BB(8) = BB(8) + AMW2(2)*QLAT + BMW2(2)*QLAT*TIS(8,1)
      BB(3) = BB(3) + AMW3(1)*QLAT + BMW3(1)*QLAT*TIS(3,1)
      BB(9) = BB(9) + AMW3(2)*QLAT + BMW3(2)*QLAT*TIS(9,1)
      DO 410 I = 2,3
      BB(I+6) = BB(I+6) + ARAFT*(TR*(X(I,1)-Y(I,1)) + CR(I)*QO(I,2))
      BB(I+6) = BB(I+6) -ARAFT*BETA(I)/2.*(X(I,1)*(TOS(I,1)-TR)**2
     1    -Y(I,1)*(TIS(I,1)-TR)**2)
      DO 410 J = 2,N(I)
  410 BB(I+6) = BB(I+6)-ARAFT*(X(I,J)*(TOS(I,J)-TR)-Y(I,J)*(TIS(I,J)-TR)
     1  -BETA(I)/2.*(X(I,J)*(TOS(I,J)-TR)**2
     1  -Y(I,J)*(TIS(I,J)-TR)**2))
      BB(10) = TR*(X(1,1)-Y(1,1)) + CR(1)*QO(1,2)
      BB(10) = BB(10) - BETA(1)/2.*(X(1,1)*(TOS(1,1)-TR)**2
     &               -Y(1,1)*(TIS(1,1)-TR)**2)
      DO 415 J = 2,N(1)
  415 BB(10) = BB(10) - X(1,J)*(TOS(1,J)-TR) + Y(1,J)*(TIS(1,J)-TR)
     &    -BETA(1)/2.*(X(1,J)*(TOS(1,J)-TR)**2
     &    -Y(1,J)*(TIS(1,J)-TR)**2)
      BB(10) = BB(10) + HCO(1)*TI + HRO(1)*TI
      DO 420 I = 4,9
      BB(I+7) = TR*(X(I,1)-Y(I,1)) + CR(I)*QO(I,2)
      BB(I+7) = BB(I+7) - BETA(I)/2.*(X(I,1)*(TOS(I,1)-TR)**2
     &    -Y(I,1)*(TIS(I,1)-TR)**2)
      DO 420 J = 2,N(I)
  420 BB(I+7) = BB(I+7)-X(I,J)*(TOS(I,J)-TR)+Y(I,J)*(TIS(I,J)-TR)
     &  -BETA(I)/2.*(X(I,J)*(TOS(I,J)-TR)**2
     &   -Y(I,J)*(TIS(I,J)-TR)**2)
C  IN NEXT EQUATION, SHOULD MULTIPY HRO(I) BY TS, I.E.,
C  THE TEMPERATURE OF THE SURROUNDING SURFACES
C  TEMPORARILY, USE TO IN PLACE OF TS
      DO 430 I = 4,9
  430 BB(I+7) = BB(I+7) + HCO(I)*TO + HRO(I)*TO + ALF(I)*QSOL(I)
      BB(17) = (AMCDOT1*TO + EXFIL*0.24*TI)*C31/(1.0 + C21I*C31)
      BB(18) = (AMCDOT2*TO )*C32/(1.0 + C22I*C32)
```

```
      BB(19) = (AMCDOT3*TO)*C33/(1.0 + C23I*C33)
C*********************************************************************
      SKBIG = 1.E20
      DO 450 I = 1,9
      IF(KFLAG(I).EQ.0)  GO TO 460
      AA(I,I) = AA(I,I)*SKBIG
      BB(I) = TIS(I,1)*AA(I,I)
  460 IF(I.LT.4) THEN
      IF(I.EQ.2) GO TO 450
      IF(I.EQ.3) GO TO 450
      IF(KFLAG(I+9).EQ.0) GO TO 450
      AA(I+9,I+9) = AA(I+9,I+9)*SKBIG
      BB(I+9) = TOS(I,1)*AA(I+9,I+9)
      ELSE
      IF(KFLAG(I+7).EQ.0) GO TO 450
      AA(I+7,I+7) = AA(I+7,I+7)*SKBIG
      BB(I+7) = TOS(I,1)*AA(I+7,I+7)
      END IF
  450 CONTINUE
C*********************************************************************
C  SOLVE SYSTEM OF EQUATIONS
      CALL SOLVP(19,AA,BB,XXX)
C*********************************************************************
C  TEST FOR CONVERGENCE OF SOLUTION
      EPS = 1.E-3
      IFLAG = 0
      DO 500 I = 1,9
  500 IF(ABS(XXX(I)-TIS(I,1)).GT.EPS)  GO TO 600
      IF(ABS(XXX(10)-TOS(1,1)).GT.EPS)  GO TO 600
C*********************************************************************
      DO 510 I = 4,9
  510 IF(ABS(XXX(I+7)-TOS(I,1)).GT.EPS)  GO TO 600
      IF(ABS(XXX(17)-TA(1,1)).GT.EPS)  GO TO 600
      IF(ABS(XXX(18)-TA(2,1)).GT.EPS)  GO TO 600
      IF(ABS(XXX(19)-TA(3,1)).GT.EPS)  GO TO 600
C*********************************************************************
      GO TO 700
  600 IFLAG = 1
  700 CONTINUE
C*********************************************************************
      DO 800  I = 1,9
  800 TIS(I,1) = XXX(I)
      TOS(1,1) = XXX(10)
      TOS(2,1) = TIS(8,1)
      TOS(3,1) = TIS(9,1)
      DO 810 I = 4,9
  810 TOS(I,1) = XXX(I+7)
      TA(1,1) = XXX(17)
      TA(2,1) = XXX(18)
      TA(3,1) = XXX(19)
C*********************************************************************
      S11 = 0.0
```

```
      S12 = 0.0
      S13 = 0.0
      DO 850 I = 1,7
  850 S11 = S11 + A(I)*HCI(I)*TIS(I,1)
      TE1 = AMCDOT1*TO + EXFIL*0.24*TI + (S11 - C11*TA(1,1))
      TE1 = TE1/(AMCDOT1 + EXFIL*0.24)
      S12 =S12 +(1.-ARAFT)*(A(2)*HCO(2)*TIS(2,1) + A(8)*HCI(8)*TIS(8,1))
      TE2 = TO + (S12 - C12*TA(2,1))/AMCDOT2
      S13 =S13 +(1.-ARAFT)*(A(3)*HCO(3)*TIS(3,1) + A(9)*HCI(9)*TIS(9,1))
      TE3 = TO + (S13 - C13*TA(3,1))/AMCDOT3
      TE = (AMDOT1*TE1 + AMDOT2*TE2 + AMDOT3*TE3)/(AMDOT1+AMDOT2+AMDOT3)
      NIT = NIT + 1
      IF(IFLAG.EQ.1.AND.NIT.LE.15)  GO TO 20
C  CALCULATE HEAT FLUXES
      DO 900 I = 1,9
      QI(I,1) = CR(I)*QI(I,2)
  900 QO(I,1) = CR(I)*QO(I,2)
      DO 950 I = 1,9
      DO 950 J = 1,N(I)
      QI(I,1) = QI(I,1) + Z(I,J)*(TIS(I,J)-TR)-Y(I,J)*(TOS(I,J)-TR)
     1 +BETA(I)/2.*(Z(I,J)*(TIS(I,J)-TR)**2-Y(I,J)*(TOS(I,J)-TR)**2)
  950 QO(I,1) = QO(I,1) + Y(I,J)*(TIS(I,J)-TR)-X(I,J)*(TOS(I,J)-TR)
     1  +BETA(I)/2.*(Y(I,J)*(TIS(I,J)-TR)**2-X(I,J)*(TOS(I,J)-TR)**2)
C  CALCULATE TOTAL CEILING HEAT FLOW
      QCEIL = QO(1,1)*A(1)
C  CALCULATE NEW MOISTURE CONTENTS
      DO 960 I = 1,7
      AMC1(I) = AMC1(I) + AMW1(I)/AMASS1(I)
  960 IF(AMC1(I).LE.0.0) AMC1(I) = 0.0
      DO 961 I = 1,2
      AMC3(I) = AMC3(I) + AMW3(I)/AMASS3(I)
      AMC2(I) = AMC2(I) + AMW2(I)/AMASS2(I)
      IF(AMC3(I).LE.0.0) AMC3(I) = 0.0
  961 IF(AMC2(I).LE.0.0) AMC2(I) = 0.0
C  WRITE OUT RESULTS
      WRITE(6,1001) TO,TOS(8,1),TIS(2,1),TOS(9,1),TIS(3,1),QO(1,1),FLUX,
     &              TA(1,1),TA(2,1),TA(3,1),TAIR,TE,TEXIT,ACH1,ACH2,
     &              ACH3,AMC2(2),NIT
 1000 FORMAT(2X,2F15.4,I10)
 1001 FORMAT(1X,5F7.2,2F10.4,6F7.2,3F15.4,F6.3,I5)
C  UPDATE TEMPERATURES AND HEAT FLUXES FOR NEXT HOUR
      DO 1100 I = 1,9
      QI(I,2) = QI(I,1)
      QO(I,2) = QI(I,1)
      DO 1100 J = 1,N(I)-1
      TIS(I,N(I)-J+1) = TIS(I,N(I)-J)
 1100 TOS(I,N(I)-J+1) = TOS(I,N(I)-J)
      TA(1,2) = TA(1,1)
      TA(2,2) = TA(2,1)
      TA(3,2) = TA(3,1)
      GO TO 10
  999 STOP
```

```
      END
C*********************************************************************
C**                                                                 **
C**                          SUBROUTINE MOIST2                      **
C**                                                                 **
C*********************************************************************
      SUBROUTINE MOIST2(TS,TO,TI,TA,HC1,HC2,A1,A2,AWRAT,AMC,AMASS,HUM,
     &   HUMI,PERM,AMDOT,EXFIL,AMW,BMW,WA1,WA)
C  THIS SUBROUTINE PERFORMS A MOISTURE BALANCE ON THE SPACEX
C  BETWEEN THE ROOF AND A TRUSS RADIANT BARRIER
C  TS = SURFACE TEMPERATURE, DEGREES F
C  TO = OUTSIDE AIR TEMPERATURE
C  TI = INSIDE AIR TEMPERATURE
C  TA = ATTIC AIR TEMPERATURE
C  HCI = CONVECTION HEAT TRANSFER COEFFICIENTS
C  A = PROJECTED SURFACE AREAS
C  AWRAT = RATIO OF EXPOSED WOOD SURFACE AREAS TO PROJECTED AREAS
C  AMC = WOOD MOISTURE CONTENTS, FRACTION OF DRY WEIGHT
C  HUM = RELATIVE HUMIDITY OF OUTSIDE AIR
C  HUMI = RELATIVE HUMIDITY OF INSIDE AIR
C  PERM = WATER VAPOR PERMEANCES
C  AMDOT = MASS FLOW OF VENTILATION AIR
C  EXFIL = MASS FLOW OF AIR FROM HOUSE INTO ATTIC
C  AMW = MOISTURE ADSORBED PER UNIT PROJECTED AREA
C  BMW = COEFFICIENT OF LINEAR TERM IN TAYLOR SERIES
C        EXPANSION OF WS(I)
C  K = NUMBER OF SURFACES
      DIMENSION TS(2),A(2),AWRAT(2),AMC(2),PERM(2),AMW(2)
      DIMENSION WS(10),P(10),HM(10),AMASS(2),BMW(2)
      EPS = 1.E-3
      A(1) = A1
      A(2) = A2
C  CALCULATE HUMIDITY RATIOS AT WOOD SURFACES
      DO 10 I = 1,2
   10 WS(I) = WDHUM(AMC(I),TS(I))
C  CALCULATE HUMIDITY RATIOS OF INSIDE AND  OUTSIDE AIR
      CALL PSY(TI,HUMI,PI,WI)
      CALL PSY(TO,HUM,PO,WO)
C  CALCULATE MASS TRANSFER COEFFICIENTS
      CALL HMASS(TS(1),TA,HC1,HM(1))
      CALL HMASS(TS(2),TA,HC2,HM(2))
C  SET UP WATER VAPOR PARTIAL PRESSURES
      XX = WA1/0.62198
      P(1) = 14.696*XX/(1.0 + XX)
      P(2) = PO
C CALCULATE HUMIDITY RATIO OF ATTIC AIR FROM MOISTURE BALANCE
      PA = PO
      X = 0.0
      DO 40 I = 1,2
      X = X + A(I)*PERM(I)*P(I)
   40 X = X + A(I)*AWRAT(I)*HM(I)*WS(I)
      X = X + AMDOT*WO + EXFIL*WI
```

```
      NIT = 0
  100 Y = 0.0
      DO 50 I = 1,2
   50 Y = Y + A(I)*AWRAT(I)*HM(I)
      Y = Y + AMDOT + EXFIL
      DO 60 I = 1,2
   60 Y = Y + A(I)*PERM(I)*(14.696 - PA)/0.62198
      WA = X/Y
      XX = WA/0.62198
      PANEW = 14.696*XX/(1.0 + XX)
      NIT = NIT + 1
      IF (NIT.GT.10)  GO TO 200
      IF(ABS(1.-PANEW/PA).LT.EPS)  GO TO 200
      PA = PANEW
      GO TO 100
  200 CONTINUE
C  CALCULATE WATER ADSORBED BY EACH SURFACE
      DO 300 I = 1,2
  300 AMW(I) = HM(I)*AWRAT(I)*(WA-WS(I))
C  CALCULATE CORRECTION TERM FOR TAYLOR SERIES EXPANSION OF
C  ADSORBED WATER
      DO 310 I = 1,2
  310 BMW(I) = HM(I)*AWRAT(I)*WS(I)/28.6
      RETURN
      END
C*********************************************************************
C**                                                                 **
C**                        SUBROUTINE MOIST3                        **
C**                                                                 **
C*********************************************************************
      SUBROUTINE MOIST3(TS,TO,TI,TA,HCI,A,AWRAT,AMC,AMASS,HUM,HUMI,PERM,
     &   AMDOT,EXFIL,AMW,BMW,K,WA,WA2,WA3)
C  THIS SUBROUTINE PERFORMS A MOISTURE BALANCE ON THE MAIN ATTIC SPACE
C  WITH TWO TRUSS RADIANT BARRIERS OVER THE MAIN SPACE
C  TS = SURFACE TEMPERATURE, DEGREES F
C  TO = OUTSIDE AIR TEMPERATURE
C  TI = INSIDE AIR TEMPERATURE
C  TA = ATTIC AIR TEMPERATURE
C  HCI = CONVECTION HEAT TRANSFER COEFFICIENTS
C  A = PROJECTED SURFACE AREAS
C  AWRAT = RATIO OF EXPOSED WOOD SURFACE AREAS TO PROJECTED AREAS
C  AMC = WOOD MOISTURE CONTENTS, FRACTION OF DRY WEIGHT
C  HUM = RELATIVE HUMIDITY OF OUTSIDE AIR
C  HUMI = RELATIVE HUMIDITY OF INSIDE AIR
C  PERM = WATER VAPOR PERMEANCES
C  AMDOT = MASS FLOW OF VENTILATION AIR
C  EXFIL = MASS FLOW OF AIR FROM HOUSE INTO ATTIC
C  AMW = MOISTURE ADSORBED PER UNIT PROJECTED AREA
C  BMW = COEFFICIENT OF LINEAR TERM IN TAYLOR SERIES
C        EXPANSION OF WS(I)
C  K = NUMBER OF SURFACES
      DIMENSION TS(7),HCI(K),A(K),AWRAT(7),AMC(7),PERM(7),AMW(7)
```

```
      DIMENSION WS(10),P(10),HM(10),AMASS(7),BMW(7)
      EPS = 1.E-3
C  CALCULATE HUMIDITY RATIOS AT WOOD SURFACES
      DO 10 I = 1,7
   10 WS(I) = WDHUM(AMC(I),TS(I))
C  CALCULATE HUMIDITY RATIOS OF INSIDE AND  OUTSIDE AIR
      CALL PSY(TI,HUMI,PI,WI)
      CALL PSY(TO,HUM,PO,WO)
C  CALCULATE MASS TRANSFER COEFFICIENTS
      DO 20 I = 1,7
   20 CALL HMASS(TS(I),TA,HCI(I),HM(I))
C  SET UP WATER VAPOR PARTIAL PRESSURES
      P(1) = PI
      XX = WA2/0.62198
      P(2) = 14.696*XX/(1.0 + XX)
      XX = WA3/0.62198
      P(3) = 14.696*XX/(1.0 + XX)
      DO 30 I = 4,7
   30 P(I) = PO
C CALCULATE HUMIDITY RATIO OF ATTIC AIR FROM MOISTURE BALANCE
      PA = PO
      X = 0.0
      DO 40 I = 1,7
      X = X + A(I)*PERM(I)*P(I)
   40 X = X + A(I)*AWRAT(I)*HM(I)*WS(I)
      X = X + AMDOT*WO + EXFIL*WI
      NIT = 0
  100 Y = 0.0
      DO 50 I = 1,7
   50 Y = Y + A(I)*AWRAT(I)*HM(I)
      Y = Y + AMDOT + EXFIL
      DO 60 I = 1,7
   60 Y = Y + A(I)*PERM(I)*(14.696 - PA)/0.62198
      WA = X/Y
      XX = WA/0.62198
      PANEW = 14.696*XX/(1.0 + XX)
      NIT = NIT + 1
      IF (NIT.GT.10)  GO TO 200
      IF(ABS(1.-PANEW/PA).LT.EPS)  GO TO 200
      PA = PANEW
      GO TO 100
  200 CONTINUE
C  CALCULATE WATER ADSORBED BY EACH SURFACE
      DO 300 I = 1,7
  300 AMW(I) = HM(I)*AWRAT(I)*(WA-WS(I))
C  CALCULATE CORRECTION TERM FOR TAYLOR SERIES EXPANSION OF
C  ADSORBED WATER
      DO 310 I = 1,7
  310 BMW(I) = HM(I)*AWRAT(I)*WS(I)/28.6
      RETURN
      END
```

Note: RBSOR3 also contains the following subprograms as given in Appendix A: FMN, FP, HCON, HMASS, HRAD, PSY, SOLVP, VENT, VIEW2, AND WDHUM.

APPENDIX D
SAMPLE INPUT FOR RBSOR1

```
   0     0     0     0     0     0     0
   1     1     1     0     0     0     0
   0
                    4  4.865945500000D-02  2.338271197053D-04  0.0
 6.510323269211D-02  3.465043546778D-02  5.938244857148D-01
-1.645759836361D-02  1.399176785434D-02 -5.452404525582D-01
 2.441690826560D-06  5.872669649739D-06  6.404266021864D-05
 5.148901056844D-12  3.269729469338D-11  2.076391709666D-10
                    9  1.513401462125D+00  5.751187041324D-01  0.0
 1.687484488308D+00  1.436559894257D+00  1.689944585440D+00
-1.132396395167D+00 -7.595037350060D-01 -1.135998987219D+00
 8.741888267615D-02 -3.452911674750D-02  8.852836964659D-02
 4.555761177217D-04  4.340832069045D-04  4.852020521034D-04
 4.763290255358D-05  4.888081025282D-05  5.064954399140D-05
 5.153136266877D-06  5.311984474480D-06  5.478947129581D-06
 5.586538871300D-07  5.760318802595D-07  5.939716176594D-07
 6.057160459862D-08  6.245683377326D-08  6.440087799661D-08
 6.567478669310D-09  6.771891599078D-09  6.982667691216D-09
                    9  1.513401462125D+00  5.751187041324D-01  0.0
 1.687484488308D+00  1.436559894257D+00  1.689944585440D+00
-1.132396395167D+00 -7.595037350060D-01 -1.135998987219D+00
 8.741888267615D-02 -3.452911674750D-02  8.852836964659D-02
 4.555761177217D-04  4.340832069045D-04  4.852020521034D-04
 4.763290255358D-05  4.888081025282D-05  5.064954399140D-05
 5.153136266877D-06  5.311984474480D-06  5.478947129581D-06
 5.586538871300D-07  5.760318802595D-07  5.939716176594D-07
 6.057160459862D-08  6.245683377326D-08  6.440087799661D-08
 6.567478669310D-09  6.771891599078D-09  6.982667691216D-09
                   12  3.332800050000D-02  7.196903971694D-01  0.0
 2.059971586652D-01  1.283894041631D-05  2.059971586652D-01
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 6.699344809749D-02  4.205776061770D-03  6.699344809749D-02
 4.033234030789D-03  2.629424994941D-03  4.033234030789D-03
 9.177810170431D-04  8.452279837720D-04  9.177810170431D-04
 2.383028485323D-04  2.345448037748D-04  2.383028485323D-04
 6.352398752458D-05  6.332932905890D-05  6.352398752458D-05
 1.702092947093D-05  1.701084659004D-05  1.702092947093D-05
 4.565226114113D-06  4.564703842471D-06  4.565226114113D-06
 1.224686916800D-06  1.224659864225D-06  1.224686916800D-06
 3.285519428962D-07  3.285505416746D-07  3.285519428962D-07
 8.814265421361D-08  8.814258151834D-08  8.814265421361D-08
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 1.958866650539D-01  1.821366643527D-01  1.958866650539D-01
-9.166667134107D-03  4.583333567053D-03 -9.166667134107D-03
 7.226266322164D-32 -3.613133161082D-32 -2.388335384659D-21
                    3  1.600672010000D+00  2.000649330112D-17  0.0
 1.737627380136D+00  1.532194284511D+00  1.737627380136D+00
-1.369553970832D-01  6.847769854162D-02 -1.369553970832D-01
 2.739997234297D-18 -1.369998617149D-18  2.271883498890D-18
                    3  1.600672010000D+00  2.000649330112D-17  0.0
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      0.9       0.9       0.9       0.9       0.9       0.9       0.9
      0.9       0.9       0.9       0.9       0.9       0.9       0.9
    26.67     30.00     26.60     26.60       0.0      0.67
   4.4983    3.2327         1
      0.0       0.0       0.0       0.0       0.0       0.0       0.0
      0.0       1.0       1.0       0.0       0.0       1.0       1.0
      0.0       1.9       1.9       0.0       0.0       1.9       1.9
    0.001     0.001     0.001     0.001     0.001     0.001     0.001
   0000.0
      0.0
  73.0000    0.0000    0.1000  165.7000    0.0000   68.4500    0.0000
  72.7600   70.1400   71.6700   74.7000   73.3000    0.0000    0.0000
  69.0600   66.0500   67.5000    0.0000    0.0000    0.0000    0.0000
  1107.51         0    0.2200   73.8700    0.0000
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APPENDIX E
SAMPLE INPUT FOR RBSOR2

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-2.038479788999D-02  1.622542533361D-02 -5.482540681362D-01
 5.894183448028D-06  1.397722527561D-05  1.887573337387D-04
 1.789389301028D-11  1.558770913386D-10  1.357874817201D-09
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 9.747026614829D-01  6.983799368443D-03  9.747026614829D-01
-1.042475084407D+00  7.093966676529D-02 -1.042475084407D+00
 1.850185618408D-01  3.942328184943D-02  1.850185618408D-01
 3.443077657355D-03  3.342615059467D-03  3.443077657355D-03
 1.861539438358D-04  1.860076880653D-04  1.861539438358D-04
 1.020624874677D-05  1.020603581890D-05  1.020624874677D-05
 5.597856474047D-07  5.597853375965D-07  5.597856474047D-07
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-9.166667134107D-03  4.583333567053D-03 -9.166667134107D-03
 7.226266322164D-32 -3.613133161082D-32 -2.388335384659D-21
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 1.958866650539D-01  1.821366643527D-01  1.958866650539D-01
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-9.166667134107D-03  4.583333567053D-03 -9.166667134107D-03
 7.226266322164D-32 -3.613133161082D-32 -2.388335384659D-21
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 1.958866650539D-01  1.821366643527D-01  1.958866650539D-01
-9.166667134107D-03  4.583333567053D-03 -9.166667134107D-03
 7.226266322164D-32 -3.613133161082D-32 -2.388335384659D-21
                   3  1.600672010000D+00  2.000649330112D-17  0.0
 1.737627380136D+00  1.532194284511D+00  1.737627380136D+00
-1.369553970832D-01  6.847769854162D-02 -1.369553970832D-01
 2.739997234297D-18 -1.369998617149D-18  2.271883498890D-18
     0.0      0.0      0.0      0.0      0.0      0.9      0.0      0.9
     0.9     0.90     0.05     0.05     0.05      0.9     0.05      0.9
     0.9     0.05     0.05     0.05     0.05     0.05     0.05      0.9
    5.75     9.25    28.50    90.00      0.0     3.17
  0.0885   0.0885   0.0885   0.0885        1      0.9
    24.0      3.5
     0.0      0.0      0.0      0.0      0.0      0.0      0.0
     0.0      0.0
     0.0   0.5417      0.0      0.0      0.0      0.0      0.0
   0.292   0.9375
   0.001    0.316    0.001    0.001    0.001    0.001    0.001
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0.09	0.09						
0000.0							
0.0							
74.5500	-0.3700	3.6400	33.5800	82.1310	79.0700	0.0000	
76.2800	74.0300	0.0000	0.0000	0.0000	0.0000	0.0000	71.9800
79.0700	0.0000	0.0000	0.0000	0.0000	0.0000	69.5200	
789.5607	1	-0.0870	75.6200	75.5200			

APPENDIX F
SAMPLE INPUT FOR RBSOR3

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-1.645759836361D-02  1.399176785434D-02 -5.452404525582D-01
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-1.042475084407D+00  7.093966676529D-02 -1.042475084407D+00
 1.850185618408D-01  3.942328184943D-02  1.850185618408D-01
 3.443077657355D-03  3.342615059467D-03  3.443077657355D-03
 1.861539438358D-04  1.860076880653D-04  1.861539438358D-04
 1.020624874677D-05  1.020603581890D-05  1.020624874677D-05
 5.597856474047D-07  5.597853375965D-07  5.597856474047D-07
 3.070305996285D-08  3.070305909714D-08  3.070305996285D-08
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 9.747026614829D-01  6.983799368443D-03  9.747026614829D-01
-1.042475084407D+00  7.093966676529D-02 -1.042475084407D+00
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 3.443077657355D-03  3.342615059467D-03  3.443077657355D-03
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 2.383028485323D-04  2.345448037748D-04  2.383028485323D-04
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 1.702092947093D-05  1.701084659004D-05  1.702092947093D-05
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 8.814265421361D-08  8.814258151834D-08  8.814265421361D-08
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 1.737627380136D+00  1.532194284511D+00  1.737627380136D+00
-1.369553970832D-01  6.847769854162D-02 -1.369553970832D-01
 2.739997234297D-18 -1.369998617149D-18  2.271883498890D-18
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739997234297D-18 -1.369998617149D-18  2.271883498890D-18
               3  1.600672010000D+00  2.000649330112D-17  0.0
737627380136D+00  1.532194284511D+00  1.737627380136D+00
369553970832D-01  6.847769854162D-02 -1.369553970832D-01
739997234297D-18 -1.369998617149D-18  2.271883498890D-18
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   0.9     0.05     0.05      0.9      0.9      0.9      0.9      0.9      0.9
   0.9     0.10     0.10      0.9      0.9      0.9      0.9      0.9      0.9
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0.4498   0.3233   2.0242   1.4547   2.0242   1.4547        1      0.1
  24.0      3.5
   0.0      0.0      0.0      0.0      0.0      0.0      0.0
   0.0      0.0
   0.0      0.0
   0.0      0.0      0.0      0.0      0.0      1.0      1.0
   0.0      1.0
   0.0      1.0
   0.0      0.0      0.0      0.0      0.0      1.9      1.9
   0.0      1.9
   0.0      1.0
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 0.001    0.001
 0.001    0.001
0000.0
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  0.00         0    1.5300  109.6700    0.0000
```

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