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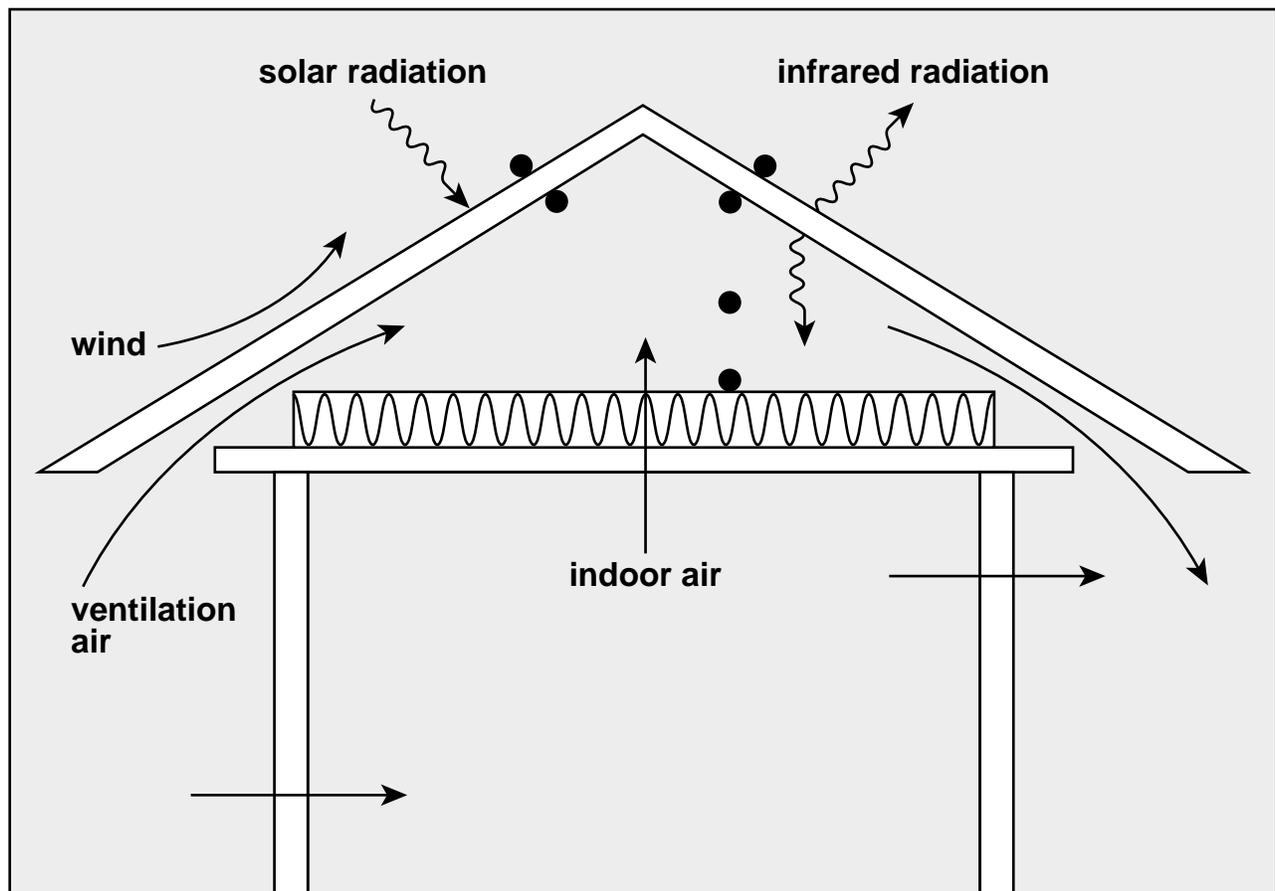
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FPL Roof Temperature and Moisture Model

Description and Verification

Anton TenWolde



Abstract

This paper describes a mathematical model developed by the Forest Products Laboratory to predict attic temperatures, relative humidities, and roof sheathing moisture content. Comparison of data from model simulation and measured data provided limited validation of the model and led to the following conclusions: (1) the model can provide reasonably accurate estimates for temperatures of roof sheathing and attic air, although heat storage effects often cause delay of 1 to 2 h in attic air temperatures; (2) the model can accurately predict the frequency of occurrence of high roof sheathing temperatures ($> 120^{\circ}\text{F}$ (49°C)) during summer, but accuracy is highly dependent on solar absorptance and emissivity values of the roof shingles; (3) the model consistently overpredicts the extent of night-time cooling from sky radiation losses, leading to predicted temperatures that are too low; (4) treatment of the effect of snow cover is too simplistic, but no better alternatives are apparent for simulating this very complex behavior; (5) the model apparently can predict average moisture conditions in the sheathing with reasonable accuracy, generally within 1% moisture content, when moisture content is not excessively high or low; and (6) hourly moisture behavior is not represented as well as is daily or seasonal behavior, especially for north-facing sheathing. The model would benefit from verification with data that include measured emissivity and solar absorptance of the shingles, addition of thermal mass in attic and roof, better algorithms to calculate direct and diffuse solar radiation, and verification for roof with east–west orientation.

Keywords: attic, fire retardant, humidity, moisture, plywood, roof, temperature, ventilation.

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FPL Roof Temperature and Moisture Model

Description and Verification

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Introduction

Attic ventilation has historically been considered an effective strategy for preventing moisture problems in attics. Ventilation usually relies on fixed openings in the end walls, eaves, and ridge, although an increasing number of attics are equipped with mechanical fans. Recommendations for minimum attic ventilation rates necessary to prevent condensation during winter are primarily based on the results from laboratory measurements of small test houses at the University of Minnesota (Rowley and others 1939) that were insulated well below current insulation standards.

Recently, concerns have been raised about the effectiveness of attic ventilation in reducing moisture levels in the attic or roof (TenWolde and Carll 1992). Depending on climate, ventilation air may occasionally carry moisture into the attic rather than remove it. During the night, the roof may be as much as 10°F to 15°F (5°C to 8°C) colder than the ambient air as a result of radiation to the sky. This can cause moisture from the ventilation air to be absorbed by, or condense on, the sheathing, increasing its moisture content. Ventilation also limits the opportunities to insulate the roof, especially a flat roof or cathedral ceiling. When converting an attic space into heated living space, the need for ventilation between the sheathing and insulation has been called into question.

The Forest Products Laboratory (FPL) roof temperature and moisture model was created to investigate the effect of construction, ventilation strategies, and indoor and outdoor climate on moisture conditions in the attic (Gorman 1987). Although the model was conceived to analyze winter conditions, it was soon used to predict temperatures and moisture content in fire-retardant-treated (FRT) plywood roof sheathing during the summer. This work was precipitated by the failure of several FRT plywood roof decks, presumably as a result, in part, of thermal degradation (LeVan and Collet 1989).

The purposes of the model were (1) to provide an estimate of temperature and moisture content of roof sheathing and

temperature and humidity of attic air at any geographical location for which hourly weather data are available and (2) to evaluate the effect of design and indoor climate. The intent was to achieve this goal in the simplest way possible with the greatest practical benefits. More detail in heat and moisture transfer equations does not necessarily provide better information because of uncertainties in input data and parameters, such as actual attic ventilation rates and other air flows.

Since the conception of the FPL attic model, Burch (1992) has adapted the MOIST computer model, originally developed for moisture analysis of walls, to examine moisture in roofs. The MOIST program contains much more detail on moisture transfer in building materials than does the FPL attic model, and it is capable of calculating liquid moisture flows. However, the MOIST program does not currently include interaction between different sheathing surfaces, and it contains less detailed convective heat transfer coefficient calculations for the exterior roof surface. Both models make many simplifying assumptions that may affect their accuracy.

Description of FPL Model

Origin

Burch and Luna (1980) developed the first mathematical model that simulates moisture transfer to and from the attic. Burch and others (1984) modified this model to account for moisture sorption in the sheathing. Cleary (1984) was able to predict daily variations in attic humidity by assuming moisture equilibrium between the attic air and the sheathing. This means that the moisture content and temperature of the sheathing determine the absolute humidity of the attic air. Cleary observed that the absolute humidity of the attic air peaks at mid-day because solar radiation drives moisture from the sheathing.

The FPL roof temperature and moisture model is based on the models developed by Burch and Luna (1980) and Cleary (1984). By adding three heat and moisture balance equations to Burch and Luna's model, we are able to differentiate

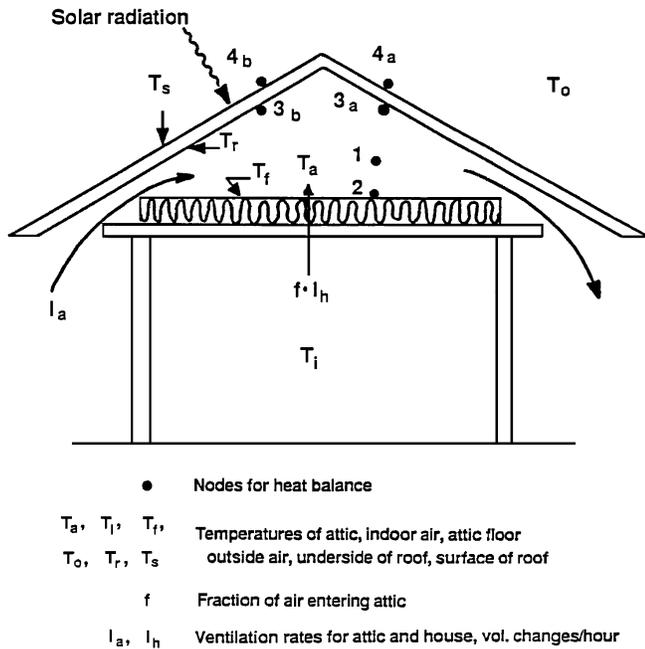


Figure 1—Schematic diagram of attic.

between two separate surfaces of a gable roof and account for differences in incident solar radiation (Fig. 1). Where Cleary treated the roof sheathing as one single element, we distinguish between moisture transfer between the attic air and a thin surface layer, and moisture transfer between this surface layer and the interior of the sheathing. The interior of the sheathing is subdivided into two layers. As in the previous models, we ignored moisture storage in other wood framing members and other hygroscopic materials in the attic.

An improved subroutine to calculate surface heat transfer coefficients was also added to the heat balance. We incorporated a subroutine developed by Wilkes (1989) in the existing model. The heat transfer coefficients are a function of temperature, wind speed, and direction of heat flow. The formulas used in this subroutine were taken from Holman (1981) (App. A). We also added the ability to evaluate the effect of mechanical attic ventilation, running continuously or controlled by timer, humidistat, or photosensor.

Capabilities

The data required for the FPL model are described in Table 1. The FPL model (App. B) runs on a personal computer, programmed in FORTRAN, and it calculates the following:

- Hourly temperatures in sheathing (two sides of gable roof)
- Hourly average moisture content of sheathing (two sides of gable roof)
- Hourly moisture content of inside sheathing surface (two sides of gable roof)
- Hourly attic air temperature
- Hourly attic air relative humidity
- Fraction of time attic fan is turned on

Table 1—Data required for FPL roof temperature and moisture model^a

Hourly weather data	Outdoor temperature (°F) Outdoor dew point (°F) Wind speed (knots) Solar radiation (Btu/h·ft ²) ^b Cloud cover (0–10) Snow cover (0 or 1)
Building data	Length of building (ft) Width of building (ft) Distance from floor of first floor to ceiling of top floor (ft) Roof overhang (ft) Thickness of roof sheathing (in.) Building orientation (input for SUNDAT, degrees from north) Pitch of roof (rise/run) R-value of attic floor (h·ft ² /Btu) Combined R-value of roof sheathing and roofing materials (h·ft ² /Btu) R-value of roof sheathing (h·ft ² /Btu) R-value of end walls and eaves (h·ft ² /Btu) Solar absorptance of roof shingles Fan capacity (ft ³ /min), type of attic fan control, ^c and control set points
Other data	Wind shading (0–1) Ventilation rate of living space (ach) ^d Fraction of living space ventilation air escaping to attic Natural attic ventilation rate (ach) Living space air temperature (°F) Living space air relative humidity (0–1) Initial moisture content of sheathing (two roof orientations, 0–1)

^a $T_F = T_C (1.8) + 32$; 1 J = 9.5×10^{-4} Btu; 1 m = 3.28 ft; 1 mm = 0.039 in.

^bSolar radiation on the two roof sides must first be calculated with a separate program (SUNDAT) from solar radiation weather data (in Langley units; 1 Langley = 1 cal/cm² = 3.687 Btu/ft²) and data on home location and roof orientation.

^cHumidistat, timer, or photo-sensor.

^dach = air change per hour.

Structure

The program sequentially solves a heat balance and moisture balance for the attic space (Fig. 1), which are calculated every 10 min, using interpolated hourly weather data (snow cover data are not interpolated) and interpolated solar radiation data. Temperatures and attic air relative humidity (RH) during the first 10-min period and moisture content results from the last 10-min period of the previous hour are reported as hourly results.

Figure 2 shows the interaction and function of the main program components. SUNDAT calculates hourly solar

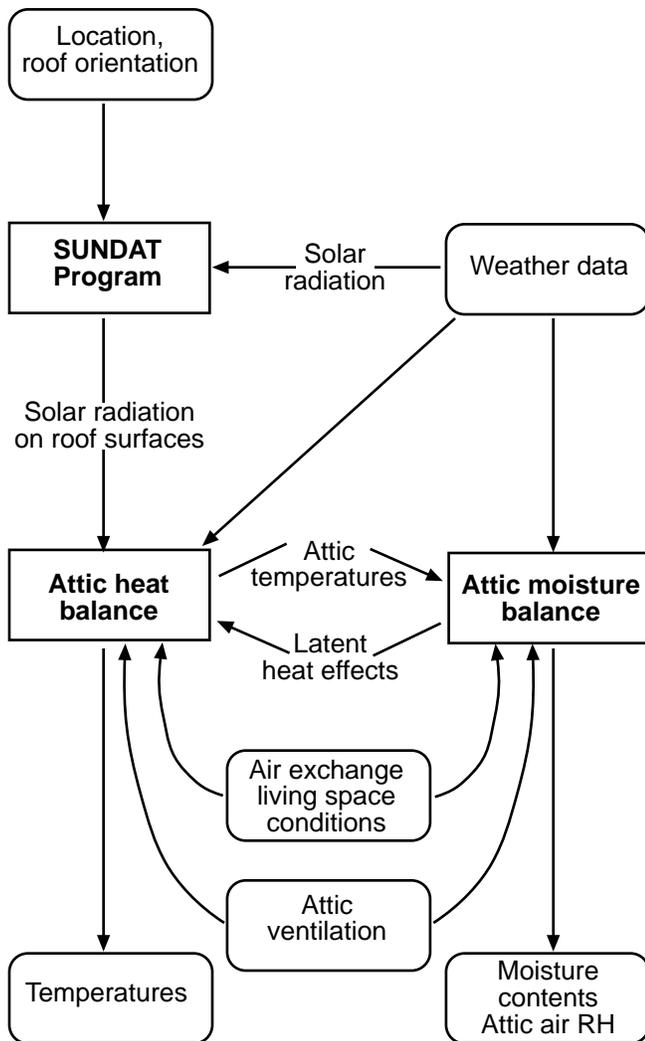


Figure 2—Structure of FPL roof temperature and moisture model.

radiation on each roof surface from measured solar radiation (on horizontal surface, in Langley units), geographical location, roof orientation, and roof pitch, and converts the results into British thermal units per hour per square foot (Btu/h ft²).¹ SUNDAT creates two input files for the main program, one for each roof surface. SUNDAT is described in detail in Appendix C. Figure 3 shows all programs, subroutines, and functions with their major purpose.

The main program uses hourly solar radiation and weather data in a steady-state heat balance to calculate temperatures in the attic and roof sheathing. Because the surface heat transfer coefficients depend on the temperatures, the heat balance is solved iteratively. The moisture balance is solved on the basis of these temperatures and previous moisture content. The heat balance is solved again, adjusting for calculated latent heat flows. This process is repeated until latent heat

¹ 1 Btu/h·ft² = 3.155 W/m².

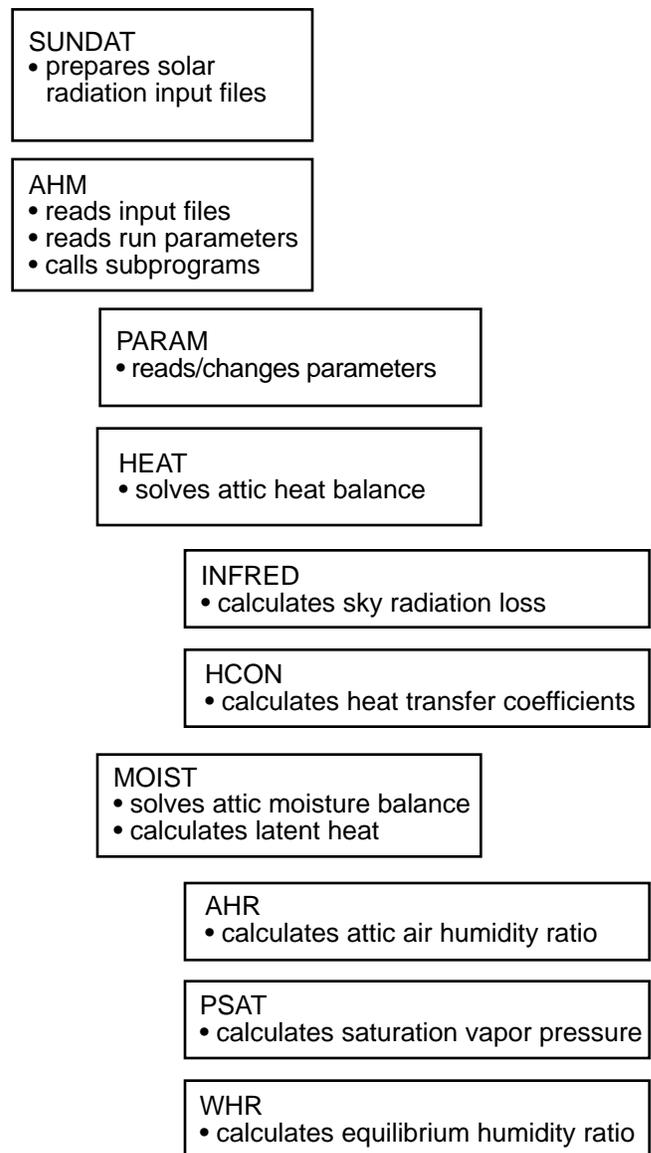


Figure 3—FORTRAN programs, subroutines, and functions in FPL model.

flows converge within 5%. This iterative procedure is repeated six times each hour, representing 10-min intervals, using interpolated weather and solar radiation data.

Home Configuration

Building

The building is assumed to be rectangular with a simple gable roof. Building length, width, and height (distance from floor of first floor to ceiling of top floor) are used to determine the approximate volume of the living space. This volume, in turn, is used to calculate air flow into the attic from below, using the air exchange rate and the fraction escaping through the ceiling to the attic.

Attic

The dimensions of the attic are calculated from building length, building width, roof overhang, and roof pitch. The model assumes a simple isosceles triangular shape (see Fig. 1). The R-values of the attic floor, roof (including all roofing materials), roof sheathing, and end walls are also required. Solar absorptance of the exterior roof surface is used in the heat balance to calculate the amount of solar radiation absorbed.

Ventilation

Attic Ventilation

Air enters the attic directly from the outside and from the living space below. The natural attic ventilation rate specified by the user sets the amount of outside air entering the attic. The net amount leaving the attic is the sum of the two air flows. Thus, even when attic ventilation is specified as zero, an equal amount of air escapes from the attic as enters from below. All flows are held constant throughout the simulation run.

When the user specifies an attic fan, the fan is assumed to provide all the outside air to the attic while the fan is running. When the fan is off, the specified natural attic ventilation rate is assumed. Air leakage through the ceiling is assumed to be unaffected by the fan. The fan can be controlled with a humidistat, a timer, or a photosensor. If the user specifies a timer control, the user is asked to specify the hours at which the fan is turned on and off. The fan can also be operated continuously by providing the appropriate timer control settings. With a humidistat, the user specifies the minimum attic RH setting and with a photosensor, the minimum solar radiation level. When snow is on the roof, the photosensor will not receive any solar radiation and the attic fan will remain off.

Living Space Ventilation

The user specifies the overall ventilation rate of the living space in air changes per hour and the fraction of the exhaust air escaping to the attic. The user needs to judge the relationship between air flow through the ceiling and total ventilation rate by choosing appropriate values. These air flows are used in the attic heat balance and moisture balance.

Attic Heat Balance

The attic heat balance is solved in the HEAT subroutine. Six simultaneous equations are used to calculate the temperature at the nodes shown in Figure 1. Heat balance equations for the attic air (node 1), attic floor (node 2), and underside of the sheathing (nodes 3a and 3b) are the same as those used by Burch and Luna (1980). We added heat balance equations for the exterior roof surface (nodes 4a and 4b) to allow for the effects of solar radiation and night radiant heat loss. The attic heat balance includes heat conduction through the roof, ceiling, end walls, and soffits; air flows from the living space and attic ventilation; radiation exchange between attic floor and roof sheathing; solar radiation; radiation loss to the sky; and latent heat effects.

Solar Radiation

Solar radiation on each roof surface is calculated with the SUNDAT program. The program calculates the ratio of radiation on a surface with a specified tilt and orientation and on a horizontal surface at a given location and hour. The calculation is performed for a cloudless sky, apportioning direct and diffuse radiation based on chapter 27 of the ASHRAE *Handbook of Fundamentals* (ASHRAE 1993). This ratio is then applied to measured solar radiation data (horizontal surface) to obtain solar radiation incident on the specified tilted surface. SUNDAT produces solar radiation input files for the main program. In the main program, total radiation absorbed by the roof surface is obtained by multiplying incident radiation by the roof's solar absorptance (see App. C).

Surface Heat Transfer Coefficients

Calculation of surface heat transfer coefficients takes place in the HCON subroutine (Fig. 3). The formulas for natural and forced convective heat transfer coefficients are shown in Appendix A. Natural convection is assumed for the floor surface and underside of the roof, and a combination of natural and forced convection applies to the exterior roof surface. The formulas used to calculate natural and forced convection (App. A) are taken from Holman (1981) and were also used by Wilkes (1989) in his roof thermal performance model. For the characteristic length of the plate, which is needed to calculate the Reynolds, Raleigh, and Nusselt numbers, we use the average of length and width of the surface (e.g., roof surface), primarily because the direction of the convective or forced air flow is unknown. We use wind speed directly for calculating the forced convective transfer coefficient. Wind direction is not considered. The user can specify a wind shading factor from 0 to 1 to modify the effect of wind, where 0 represents complete shelter and 1 no shelter.

Long-Wave Radiation

The heat balance includes long-wave radiation exchange between the underside of the sheathing and the attic floor, and between the top surface of the roof and the sky. The emissivity of all surfaces has been assumed at 0.9, a typical value for many nonmetallic building materials (ASHRAE 1993). To facilitate the calculation, the nonlinear formulas for radiation exchange were converted to linear equations in the following way:

$$\begin{aligned} Q_{x \rightarrow y, \text{ net}} &= \varepsilon \sigma (T_x^4 - T_y^4) \\ &= \varepsilon \sigma (T_x^2 + T_y^2)(T_x + T_y)(T_x - T_y) \approx F(T_x - T_y) \end{aligned} \quad (1)$$

where

$$\begin{aligned} Q_{x \rightarrow y, \text{ net}} &= \text{net radiation from surface } x \text{ to surface } y \\ T_x, T_y &= \text{temperatures of surfaces } x \text{ and } y, \\ &\quad \text{respectively } (^\circ\text{R}) \\ \varepsilon &= \text{surface emissivity} \\ \sigma &= \text{Stefan-Boltzman constant } (\text{Btu/h}\cdot\text{ft}^2\cdot^\circ\text{R}^4) \end{aligned}$$

The equation is linearized by treating the factor F as a constant and calculating F from initial values for T_x and T_y .

The error introduced by this linearization is relatively small if the absolute temperatures are relatively close.

Snow

Measurements in an attic in Madison, Wisconsin, suggest that the upper roof surface temperatures were held steady at approximately 32°F (0°C) with significant snow accumulation. Winandy and Beaumont (1995) also reported this phenomenon in tests on a series of small test chambers near Madison, Wisconsin. Therefore, we included an alternate heat balance for the sheathing that fixes the temperature of the exterior roof surface at 32°F (0°C) when snow is present, regardless of outdoor temperature or solar radiation.

Equations

Attic Air—The heat balance for the attic air (node 1) is given by

$$\begin{aligned} & A_c h_f (T_f - T_a) + f I_h V_h \rho C_p (T_i - T_a) \\ &= \frac{A_r}{2} h_{r,1} (T_a - T_{r,1}) + \frac{A_r}{2} h_{r,2} (T_a - T_{r,2}) + \frac{A_{es}}{R_{es}} (T_a - T_o) \\ &+ I_a \rho C_p V_a (T_a - T_o) \end{aligned} \quad (2)$$

where

- $A_c, A_r,$
 A_{es} = surface areas of ceiling, total roof area, and combined area of soffit and end walls (ft²)
- C_p = specific heat of air (Btu/lb·°F)
- f = fraction of house exfiltration that transfers into attic
- $h_f, h_{r,n}$ = convective heat transfer coefficients at attic floor and underside of roof (surface n), respectively (Btu/h·ft²·°F)
- I_h = house exfiltration rate (h⁻¹)
- I_a = attic ventilation rate, i.e., outdoor air entering attic (h⁻¹)
- $R_{e,s}$ = average thermal resistance of end walls and eaves (h·ft²·°F/Btu)
- T_a = attic air temperature (°R)
- T_f = temperature of attic floor surface (°R)
- T_i = indoor air temperature (°R)
- T_o = outdoor air temperature (°R)
- $T_{r,1}$ = temperature of roof sheathing underside a (°R)
- $T_{r,2}$ = temperature of roof sheathing underside b (°R)
- V_a = volume of attic space (ft³)
- V_h = volume of house (ft³)
- ρ = density of air (lb/ft³)

The convective heat transfer coefficients are calculated iteratively with the HCON subroutine. If the iterations do not converge, the value of 1 Btu/h·ft² is used and an error message is printed in the MESSAGE output file.

Attic Floor—The heat balance for the attic floor (node 2) is

$$\frac{T_i - T_f}{R_c} = h_f (T_f - T_a) + \frac{F_1}{2} (T_f - T_{r,1}) + \frac{F_2}{2} (T_f - T_{r,2}) \quad (3)$$

where

- R_c = thermal resistance of attic floor (ceiling) (h·ft²·°F/Btu)
- F_1, F_2 = radiative heat transfer coefficients between attic floor and undersides of roof (Btu/h·ft²·°F), with the following definition:

$$F_n = \frac{\sigma}{(1/\epsilon_f) + (1/\epsilon_r) - 1} (T_f^2 + T_{r,n}^2) (T_f + T_{r,n}) \quad n = 1, 2 \quad (4)$$

where

- ϵ_f = emissivity of attic floor surface (assumed to be 0.9)
- ϵ_r = emissivity of roof sheathing surface (underside, assumed to be 0.9)
- σ = Stefan–Boltzman constant (Btu/h·ft²·°R⁴)

To facilitate the calculation, radiation exchange between the floor and the sheathing is approximated in a linear equation and included in Equation (3). Radiation exchange between the two sheathing surfaces is neglected because the aspect ratio is usually low. Radiation exchange with end walls is also neglected.

Sheathing—The heat balance at the underside of sheathing (nodes 3a and 3b) is

$$\begin{aligned} \frac{T_{r,n} - T_{s,n}}{R_r} &= h_r (T_a - T_{r,n}) \\ &+ \frac{A_c}{A_r} F_n (T_f - T_{r,n}) + \frac{2}{A_r} L_h W_{r,n} \quad n = 1, 2 \end{aligned} \quad (5)$$

where

- L_h = latent heat of vaporization (1,050 Btu/lb)
- R_r = thermal resistance of roof (h·ft²·°F/Btu)
- $T_{s,n}$ = temperature of outside roof surface (°R)
- $W_{r,n}$ = rate of moisture adsorption into sheathing (lb/h)

The approximate latent heat of sorption/desorption or condensation/evaporation is calculated from the moisture deposition rate on the sheathing surface, using a value of 1,050 Btu/lb. The adjusted heat balance and associated moisture balance are solved iteratively until the latent heat adjustment is within 5% of the previous value. If convergence is not reached, the latent heat is ignored and an error message is printed in the MESSAGE file.

The heat balance at the top surface of sheathing (nodes 4a and 4b) is

$$\frac{T_{s,n} - T_{r,n}}{R_r} = \alpha I_n + (h_{o,n} + h_{IR})(T_o - T_{s,n}) - L_{IR} \quad n = 1, 2 \quad (6)$$

where

- h_{IR}, L_{IR} = adjustments for infrared radiation exchange with sky (see Eqs. (7), (8), and (9))
- $h_{o,n}$ = convective heat transfer coefficient at exterior roof surface n (Btu/h·ft²·°F)
- I_n = total solar radiation incident on roof surface (Btu/h·ft²)
- α = solar absorptance

The adjustments for infrared sky radiation were adapted from Martin and Berdahl (1984) and take the effect of outdoor temperature, dew point temperature, and cloud cover into account. The base of the clouds is assumed at 1.24 mi (2 km). The radiation exchange is approximated with corrections to the surface heat transfer coefficients and incident solar radiation. In Equation (5), the contribution of sky radiation was linearized to facilitate calculation. The terms L_{IR} and h_{IR} are computed in the INFRED subroutine:

$$h_{IR} = 4\epsilon_s \sigma T_o^3 \quad (7)$$

$$L_{IR} = \epsilon_s \sigma T_o^4 (1 - \epsilon_{IR}) \quad (8)$$

where

$$\begin{aligned} \epsilon_s &= \text{emissivity of roof shingles (assumed to be 0.9)} \\ \epsilon_{IR} &= \text{sky emissivity with clouds} \end{aligned}$$

The sky emissivity is calculated with equations from Martin and Berdahl (1984). The emissivity for a clear sky is

$$\epsilon_0 = 0.711 + 0.56 \frac{T_d}{100} + 0.73 \left(\frac{T_d}{100} \right)^2 + 0.013 \cos \left(\frac{2\pi t}{24} \right) \quad (9)$$

where

$$\begin{aligned} \epsilon_0 &= \text{emissivity of clear sky} \\ T_d &= \text{outdoor dew point temperature (}^\circ\text{C)} \\ t &= \text{time (h)} \end{aligned}$$

and the emissivity of the sky with clouds is

$$\epsilon_{IR} = \epsilon_0 + 0.784C(1 - \epsilon_0) \quad (10)$$

where C = total cloud cover as recorded by National Climatic Center (Asheville, NC). Values of C range from 0 to 10.

Attic Moisture Balance

The attic moisture balance requires that the water vapor transfer by convective air flow through the ceiling equal the combined net loss of moisture from the attic air by attic ventilation and transfer to the two sheathing surfaces:

$$fI_h V_h \rho (\omega_i - \omega_a) = I_a V_a \rho (\omega_a - \omega_o) + W_{r,1} + W_{r,2} \quad (11)$$

where

$$\begin{aligned} \omega_i, \omega_a, \omega_o &= \text{humidity ratios of indoor, attic, and} \\ &\quad \text{outside air, respectively (dry air basis)} \\ W_{r,n} &= \text{rate of moisture adsorption into sheathing} \\ &\quad \text{surfaces (lb/h)} \end{aligned}$$

Water vapor transfer by diffusion through the ceiling is ignored because it is generally much less than that by air leakage through the ceiling. Moisture exchange with the outside through the roof is also ignored because it is likely to be much smaller than losses through ventilation.

Moisture transfer from the attic air to the two sheathing surfaces is given by

$$W_{r,n} = \frac{A_r}{2} h_{D,r} (\omega_a - \omega_{r,n}) \quad (12)$$

where

$$\begin{aligned} h_{D,r} &= \text{air-surface moisture transfer coefficient} \\ &\quad \text{(set at 1.1 lb/h-ft}^2\text{)} \\ \omega_r &= \text{equilibrium humidity ratio of surface air in} \\ &\quad \text{equilibrium with wood sheathing surface} \\ &\quad \text{(dry air basis)} \end{aligned}$$

For the equilibrium humidity ratio ω_r at the sheathing surface, we used the correlation developed by Cleary (1984):

$$\omega_r = e^{T/A} (B + CM + DM^2 + EM^3) \quad (13)$$

where

$$\begin{aligned} T &= \text{wood surface temperature (}^\circ\text{F)} \\ M &= \text{moisture content of wood, expressed as a ratio} \\ A &= 28.6^\circ\text{F} \\ B &= -0.00049 \\ C &= 0.0172 \\ D &= -0.060 \\ E &= 0.076 \end{aligned}$$

Cleary based this correlation on isothermal sorption data for untreated clear wood. It is not adjusted for any fire-retardant or other treatment.

The sheathing is divided into three layers: a 1/16-in. (1.6-mm) surface layer facing the attic, an adjacent 1/16-in. (1.6-mm) layer, and a core layer representing the rest of the sheathing. With plywood sheathing, the first two layers combined represent the surface veneer layer that faces the attic. Moisture diffusion from layer m to layer $m + 1$ (surface layer is layer 1) is approximated with

$$w_{m,m+1} = \frac{K_w (\omega_m - \omega_{m+1})}{(d_m + d_{m+1})/2} \quad m = 1, 2 \quad (14)$$

where

$$\begin{aligned} w_{m,m+1} &= \text{moisture flux from layer } m \text{ to} \\ &\quad \text{next layer (lb/h-ft}^2\text{)} \\ K_w &= \text{diffusion coefficient (lb/h-ft)} \\ \omega_{m,m+1} &= \text{equilibrium humidity ratio, layer } m, \\ &\quad \text{layer } m + 1, \text{ respectively} \\ d_m, d_{m+1} &= \text{thickness of layer } m, \text{ layer } m + 1, \\ &\quad \text{respectively (ft)} \end{aligned}$$

The equilibrium humidity ratio is calculated with Equation (13). We obtained approximate values for K_w from data for isothermal moisture diffusion coefficients for clear wood published by Choong (1965). Choong's diffusion coefficient applies to moisture content (MC) gradients rather than humidity ratios. An approximate conversion yielded

$$\begin{aligned} K_w &= -11.48 - 0.000083 T^2 + 0.0222 T \\ &\quad + 168.27M^3 - 102.4M^2 + 37.9M \end{aligned} \quad (15)$$

where

T = average temperature of the two layers (°F)

M = average MC of the two layers, expressed as a ratio

Choong's diffusion coefficient applies to clear wood under isothermal conditions. The effect of glue lines, temperature gradients, and fire retardants on diffusion coefficients is unknown. In addition, the coefficients only apply below fiber saturation. We assumed that the coefficient remains constant at MC above 30%.

Model Validation

Introduction

To assess the accuracy of temperature and moisture predictions with the FPL roof temperature and moisture model, we obtained data collected by William Rose and Jeffrey Gordon in a test building at the Building Research Council (BRC), University of Illinois, Champaign–Urbana. Temperature and moisture were measured in locations similar to the nodes in the model, and most of the necessary input data were also available, such as weather and solar radiation. Missing were data for attic ventilation and absorptance of the shingles.

We compared predictions of sheathing temperatures, attic air temperature, attic air RH, and sheathing MC with measured data taken during the winter and summer of 1993.

Description of Test House

The test building was designed, configured, and instrumented to measure the performance of various roof/attic assemblies under natural conditions. The 80-ft- (24-m-) long, 20-ft- (6-m-) wide building had one story and a gable roof.

There were 10 separate roof bays, of which 8 were instrumented; the roof bays at the gable ends were not instrumented. Of the instrumented bays, only data from bay 2 were used for validation of the FPL roof. Bay 2 had black shingles, solid vinyl soffit panels, and no ridge vent. It had a flat ceiling and therefore represented traditional attic construction. There were no penetrations in the ceiling during the winter and summer of 1993.

All the flat ceiling bays (attics) were constructed with standard roof trusses at a 5:12 pitch, 24 in. (61 cm) on center (o.c.), with 2-ft (0.6-m) overhangs. The orientation of the ridge was east to west. The roof was covered with single thickness, triple-tab asphalt shingles over 15-lb felt underlayment. The roof sheathing material was 7/16-in. (11-mm) oriented strandboard (OSB). The ceiling was 5/8-in. (16-mm) gypsum drywall, overlaid with R-30 unfaced glass fiber batt insulation. There was no vapor retarder. The flat ceiling bays were thermally separated by 1-in. (25-mm) foil-faced polyisocyanurate foam panels; cracks were filled with urethane foam.

Data Collection

Temperature

Roof surface temperatures were taken with type-T thermocouples. A resistance temperature detector (RTD) was used as a reference junction. The temperatures were sampled every 10 min, averaged, and stored as hourly values.

In each bay, thermocouples were located at the following sites:

- at underside of sheathing and between sheathing and felt underlayment,
- on north- and south-facing slopes, and
- at low and high locations on the roof: 3 ft (0.9 m) away from wall plate and ridge, respectively.

Attic air temperature was measured with one platinum RTD in each bay.

Moisture Content and Humidity

Attic air humidity was measured with one polyamide humidity sensor in each bay. Although the error of measurement should not have been more than 4% RH, there is reason to believe that these sensors were not capable of handling the wide temperature swings in the attic bays and did not produce reliable data.

Humidity conditions in the sheathing were measured with small, wood electrical resistance sensors modified from the type described by Duff (1966). The modifications included the use of conductive epoxy and a polyethylene “sleeve” around part of the sensor. Sensors were inserted in the middle of the sheathing as well as installed on its surface. Although the accuracy of these sensors is not very high (TenWolde and Courville 1985), they are nevertheless the most practical available equipment for research on building moisture. The sensors were not individually calibrated, and the data were recorded as electrical resistance. We converted these data to MC, using generic calibration data for electrical resistance wood moisture meters. We used measured MC data for the north-facing sheathing of bay 2 only.

Other Instrumentation

On-site measurements were taken of wind speed and direction, air temperature, RH, total horizontal solar radiation, and total infrared radiation. Barometric pressure, snow cover, and rainfall were measured at a meteorology station 1/4 mi (0.4 km) from the site.

Model Runs

We ran the FPL roof temperature and moisture model from February 3 to March 28, 1993, and May 1 to June 30, 1993, using measured data for outdoor temperature and humidity. Solar radiation on the roof surfaces was determined by running the SUNDAT program with measured solar radiation (horizontal surface) and the location of the test house and roof slope and orientation.

We selected input parameters to match the conditions in bay 2 (black shingles and unvented). Because we did not know the solar absorptance of the shingles, we did several runs with varying values for absorptance. We then compared the temperatures at the top surface of the sheathing with the measured values to determine which value of absorptance produced the closest match.

Selection of Input Values

Because the model could not handle the exact configuration of the test house with separate attic/roof bays and shingles of different colors, we selected a configuration that would most closely approximate the actual situation, keeping in mind the assumptions and equations used in the model. The heat transfer coefficient at the exterior roof surface as calculated in the model depends on the building dimensions. We therefore used the full dimensions of the building as input, instead of the dimensions of the individual bays. Heat loss through the side walls separating each bay from its neighbors was assumed to be minimal because the bays are separated by 1-in. (25-mm) foil-faced foam insulation and the measured air temperature differences between bays were relatively small.² Because the model assumes outdoor air temperature on the exterior of the end walls, we specified a very high R-value (R-100, RSI-18) for the end walls to simulate minimal heat flow between bays. Table 2 lists the input parameters for bay 2, with the exception of solar absorptance.

Selection of Shingle Absorptance

We did several runs for bay 2 with varying absorptance values and compared the temperatures at the top surface of the sheathing with the measured values to determine which absorptance value produced the closest match. We used weather data for the first 15 days of May 1993. Reagan and Acklam (1979) recommend the following values for solar absorptance of shingles:

Shingle color	Absorptance
Very light	0.25
Light	0.35
Medium	0.55
Dark	0.75
Very dark	0.90

Since bay 2 had dark shingles, it would have an expected absorptance value of approximately 0.75.

Figure 4 compares the measured temperature on the top of the south- and north-facing sheathing surfaces, respectively, of bay 2 with the model results, using absorptance values of 0.6 and 0.65. Solar absorptance plays a role only during

²Measured temperature differences between bays 1 and 2 averaged less than 6°F (3°C) during May and June 1993, and even less during February and March 1993. Maximum temperature difference was around 27°F (15°C). Temperature differences between bays 2 and 3 were much less than that between bays 2 and 1.

Table 2—Input parameters used for model validation, bay 2

Building length	80 ft (24 m)
Building width	20 ft (6 m)
Ceiling height	8 ft (2.4 m)
Roof overhang	2 ft (0.6 m)
Roof pitch	0.42
Sheathing thickness	0.44 in. (11 mm)
R-value of ceiling	11 h·ft ² ·°F/Btu (1.94 m ² ·K/W)
R-value of roof, total	1.04 h·ft ² ·°F/Btu (0.183 m ² ·K/W)
R-value of roof sheathing	0.6 h·ft ² ·°F/Btu (0.1 m ² ·K/W)
R-value of end walls	100 h·ft ² ·°F/Btu (17.6 m ² ·K/W)
Wind shade factor	1
House ventilation rate	0.1 ach
Fraction of exhaust air to attic	0.01
Attic ventilation rate	0.01 ach
Indoor temperature, winter	70°F (21°C)
Indoor temperature, summer	75°F (24°C)
Indoor relative humidity	50%
Initial sheathing moisture content, February 1	9.3%
Initial sheathing moisture content, May 1	7.0%

daylight hours and the comparison should therefore be limited to that period. For the purpose of selecting solar absorptance values, we focused on the peak temperatures during mid-day.

Both absorptance values of 0.6 and 0.65 produced reasonably accurate temperature profiles during mid-day on most days and would be acceptable choices. Some differences between model results and measurements were likely the result of errors in the calculation of solar radiation on the south- and north-facing roof surfaces, because the amount of diffuse radiation was not measured, but estimated from the total amount of horizontal radiation. In addition, wind is likely to provide a discrepancy between model results and measurements. The 0.65 value produced slightly better results and was therefore selected for the “dark” shingles. This compares with the value of 0.75 recommended by Reagan and Acklam (1979) for dark shingles.

Results

Attic Air Temperature—Winter

Figure 5 compares measured attic air temperatures in bay 2 from February 3 to 16, 1993, and air temperatures from the FPL model. Most discrepancies were due to a time delay of about 1 to 2 h in the measured temperatures, most likely the result of heat storage in the building materials in the roof and attic. If the time delay is ignored, the model predictions were usually within 5°F (3°C), but greater discrepancies of approximately 10°F (6°C) occurred, especially during the night. As will be discussed later, the model consistently overpredicted the extent of night-time cooling from infrared

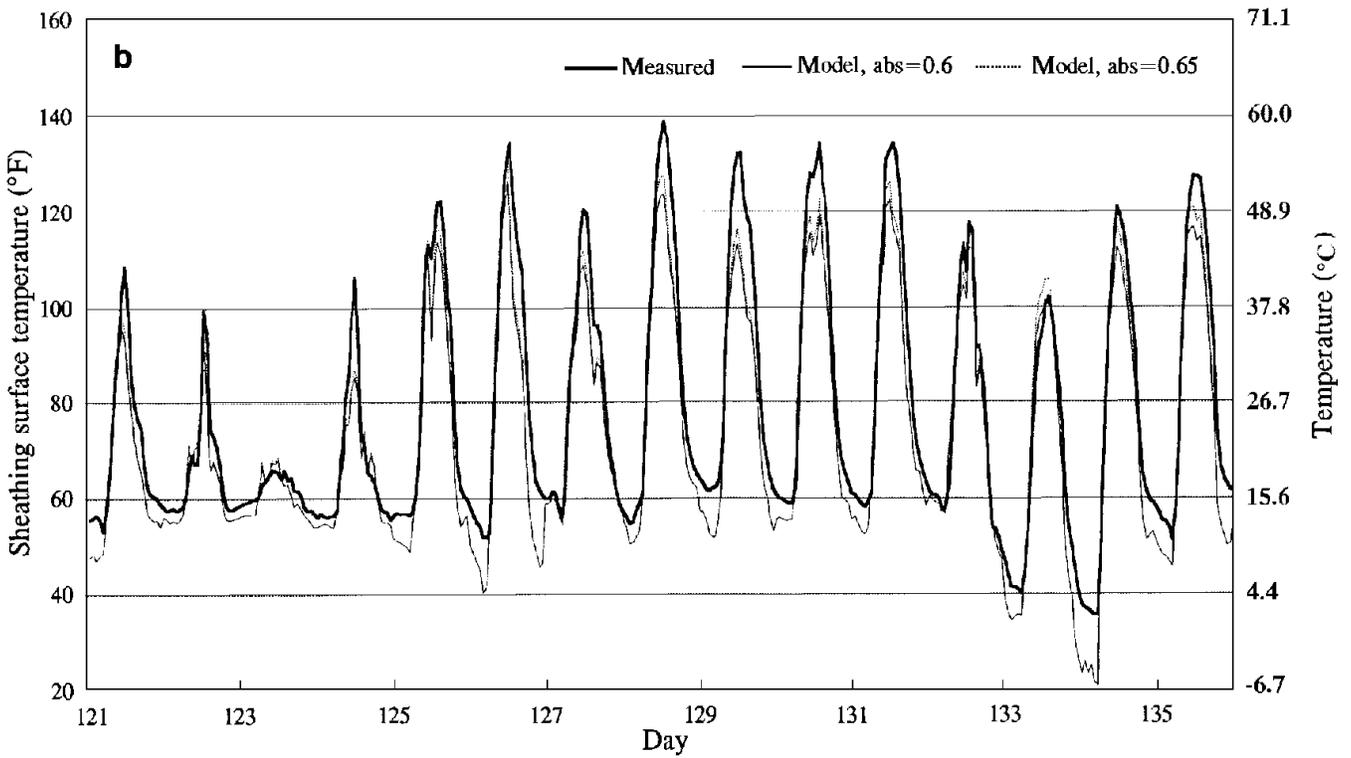
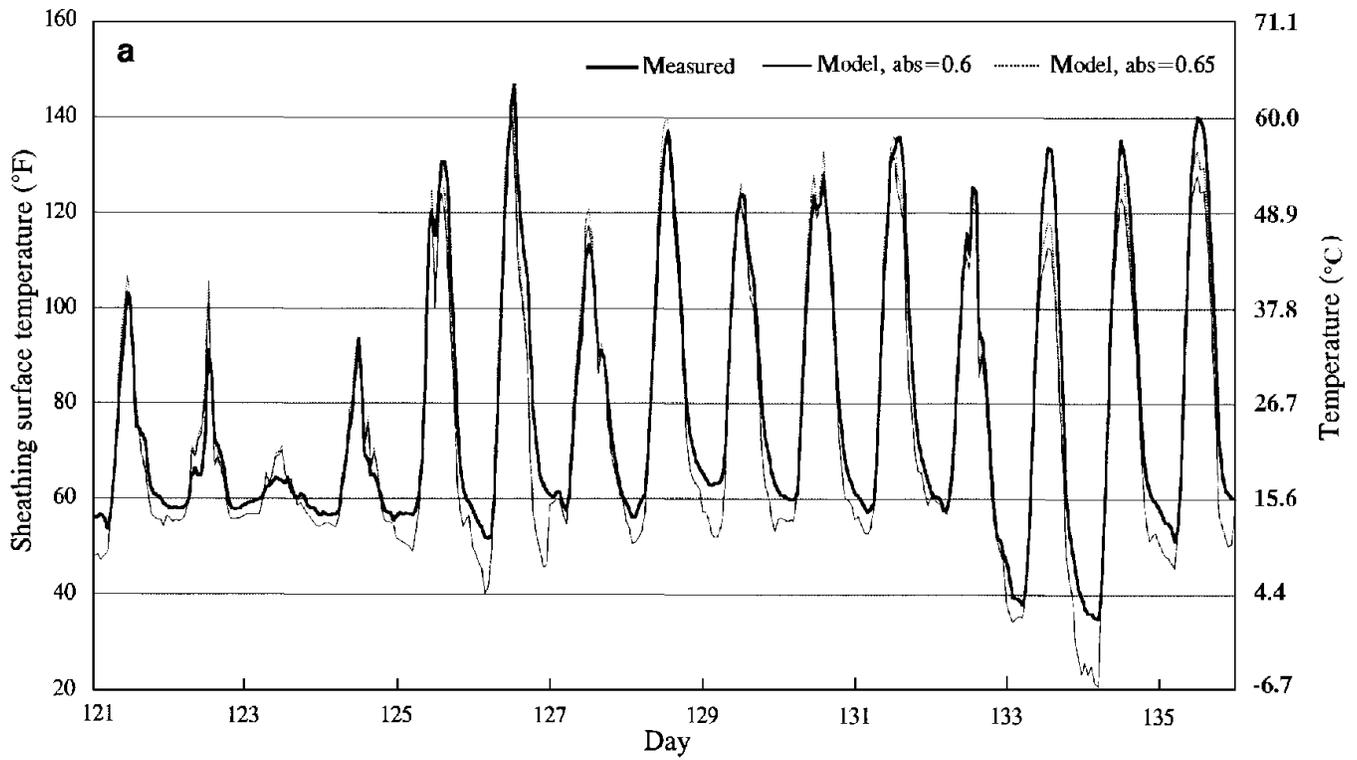


Figure 4—Exterior sheathing surface temperature, bay 2, May 1–15, 1993. (a) south facing; (b) north-facing.

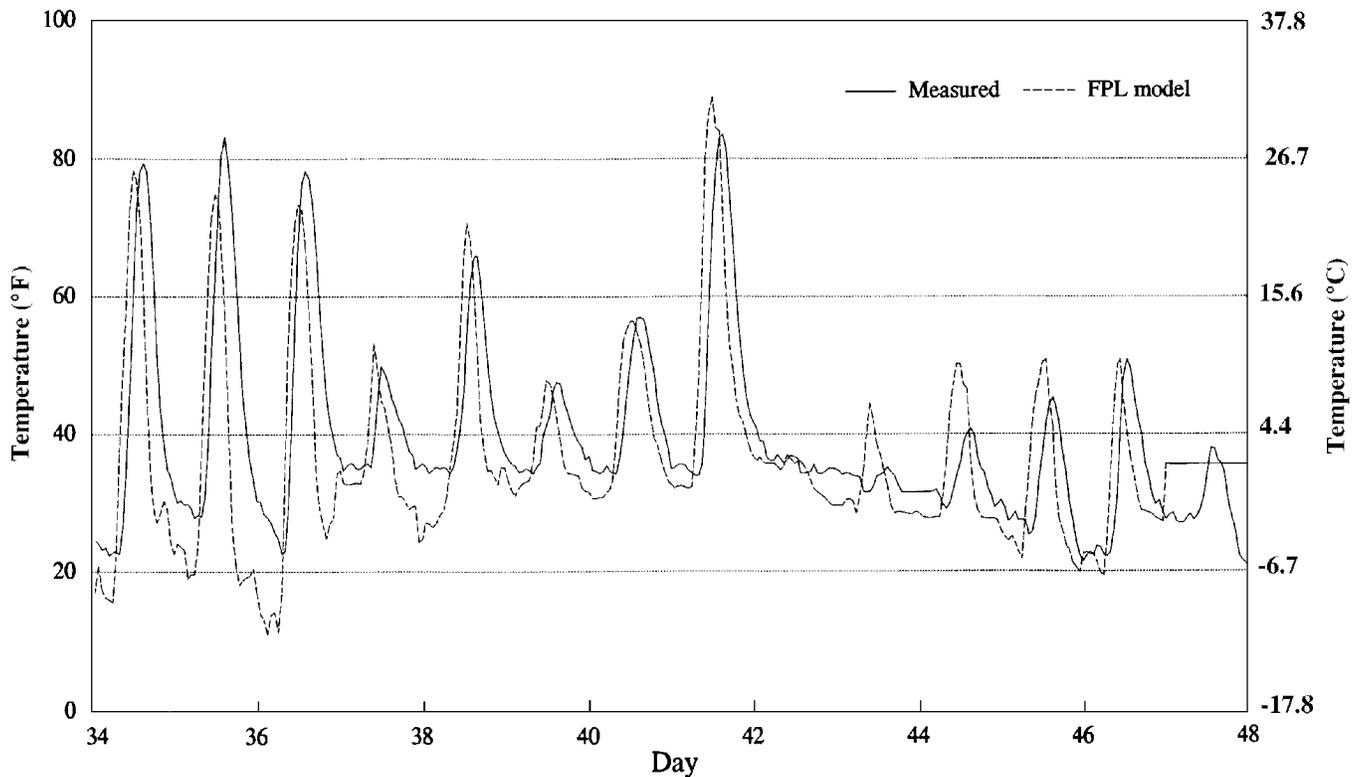


Figure 5—Attic air temperature, bay 2, February 3–16, 1993; absorptance = 0.65.

radiation to the sky. This, led to predicted attic air temperatures that were too low during the night, especially when there were no clouds.

The weather data indicate that day 42 (February 11) was very cloudy (little solar radiation) and windy, with temperatures dropping throughout the day. This explains the steady low attic temperatures during that day. Snow could have also been a contributing factor, although snow cover data do not indicate snow on the ground that day.

Snow cover on the ground on day 47 (February 16) caused the model to hold the exterior surface temperature of the roof at 32°F (0°C), which then held the attic air temperature steady at about 35°F (2°C). Although this is a crude approach to the effect of snow cover, the model did provide a fair approximation of measured temperatures. However, snow cover data did not necessarily match actual snow cover on the roof. The model was also unable to deal with partial snow cover on the roof, leading to additional errors.

Attic Air Relative Humidity—Winter

Figure 6 shows a consistently large discrepancy between predicted and measured RH of the attic air during the same period (February 3 to 16, 1993). The measured humidity data are inconsistent with the measured MC in the sheathing; in private conversations, William Rose of the University of Illinois expressed skepticism about the accuracy of the sensor when used in the highly variable attic environment. We

therefore defer judgment on the accuracy of the model’s RH predictions.

Sheathing Moisture Content—Winter

Figure 7 shows the measured MC on the underside of the north-facing sheathing near the eaves and the ridge compared with the results from the model. Both the MC at the under surface and the average MC are shown. The results prompt several observations:

- measured MC varies significantly with location,
- swings in measured MC suggest that values represent MC of sheathing surface, rather than average MC,
- measured MC maxima and minima coincide with model minima and maxima, respectively, and
- the difference between calculated average MC and measured MC is usually within 2%, fairly close when considering that estimated measurement error was 2% to 3% MC.

The discrepancy in maxima and minima of the calculated and measured MC of the north-facing sheathing is explored further in Figure 8. Although the variations in the average measured MC of the north-facing sheathing are different than the simulated surface MC of the north-facing sheathing, there is much better agreement between measured MC of the north-facing sheathing and the model results for the south-facing

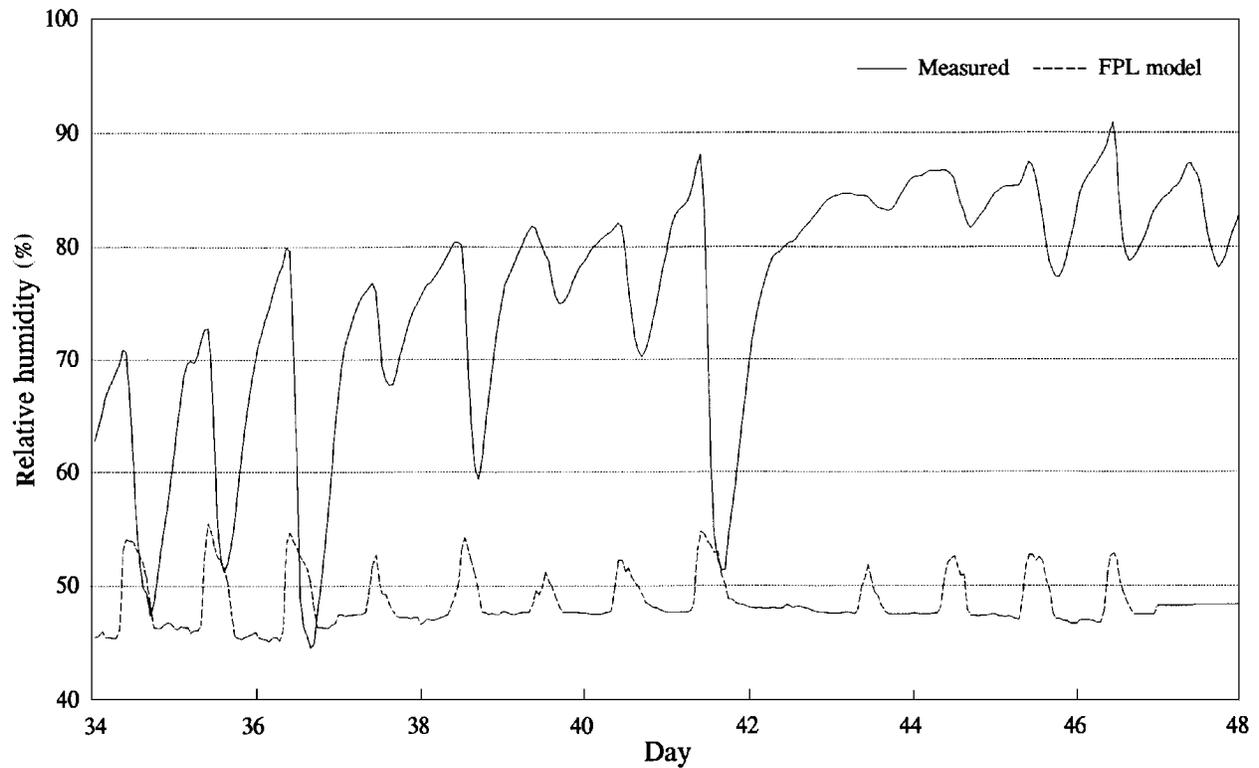


Figure 6—Attic air relative humidity, bay 2, February 3–16, 1993; absorptance = 0.65.

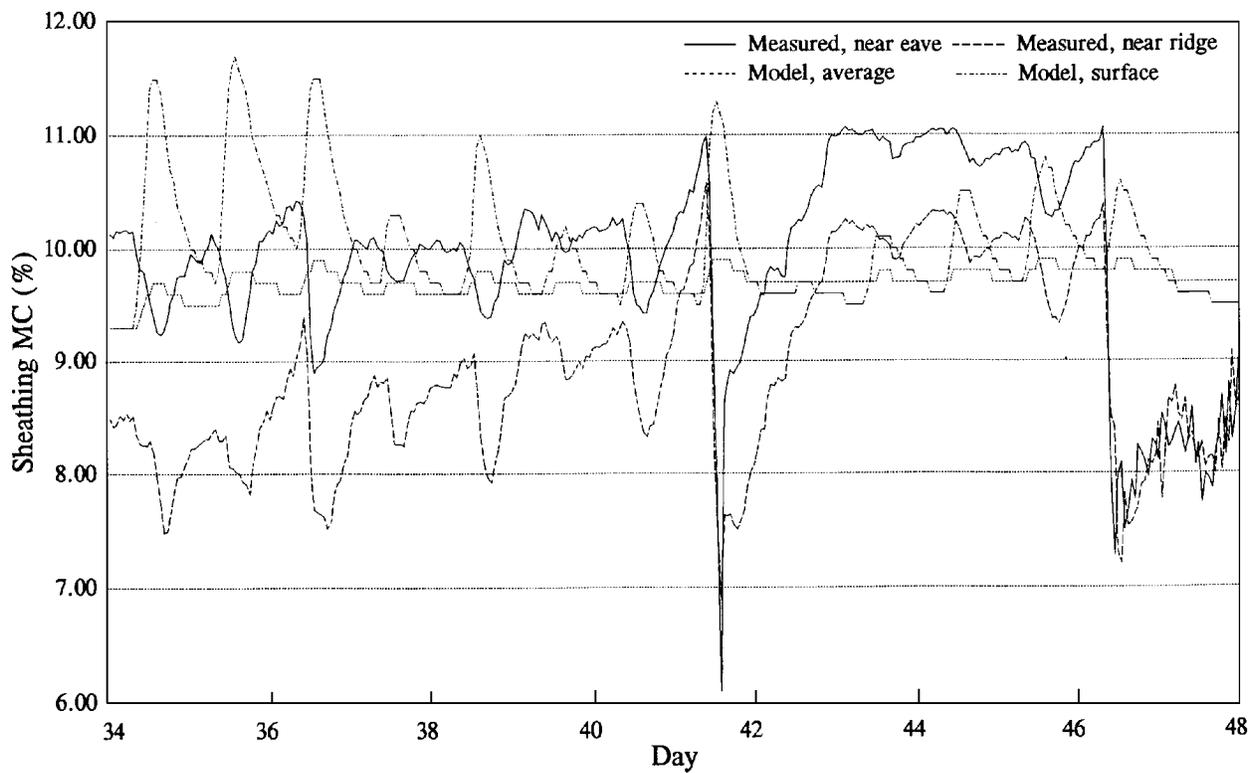


Figure 7—Sheathing moisture content, bay 2, north-facing, February 3–16, 1993; absorptance = 0.65.

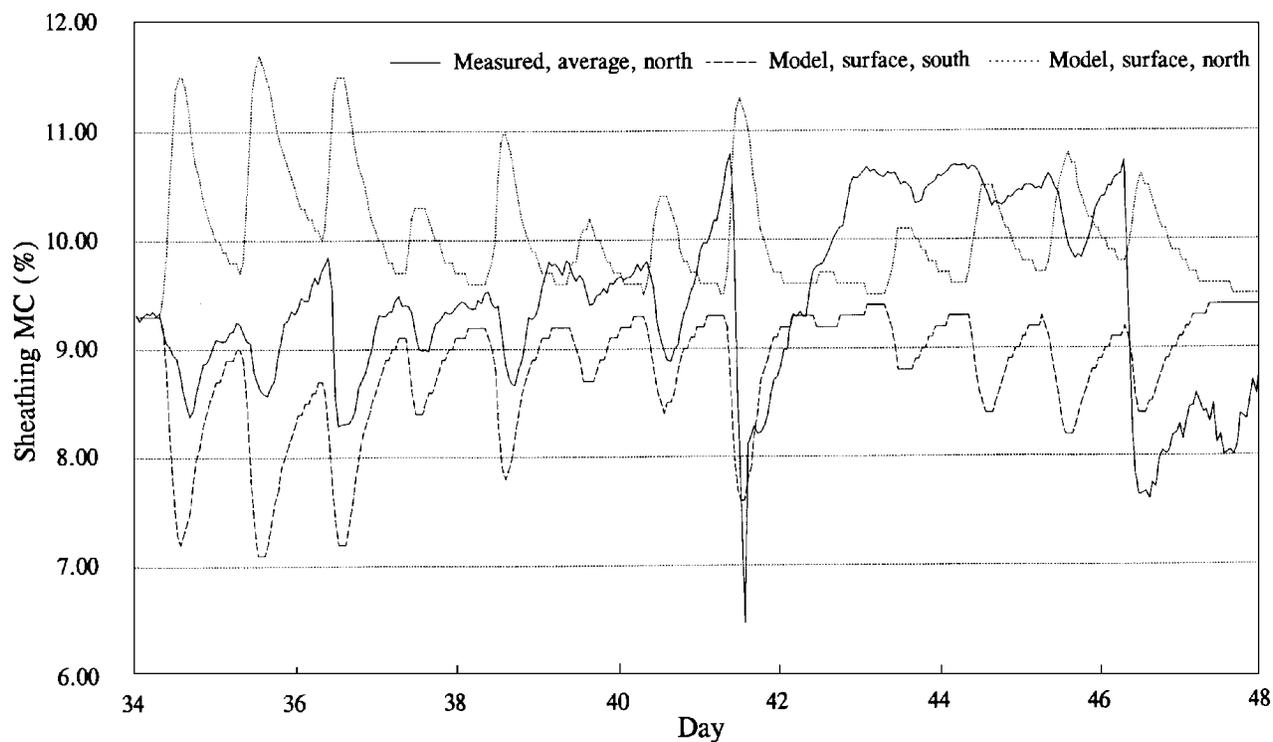


Figure 8—Sheathing moisture content, bay 2, north- and south-facing, February 3–16, 1993; absorptance = 0.65.

sheathing (i.e., the minima and maxima coincide). The model results for the north- and south-facing sheathing surfaces behave in this fashion because the model assumes that most or all of the moisture driven from the south-facing sheathing is deposited on the north-facing sheathing when sunlight hits the south-facing roof. The measurements show that the north-facing sheathing in fact behaves very similar to the south-facing sheathing. This means that when sunlight hits the roof, moisture is driven from both sides and is absorbed elsewhere in the attic (for example, rafters, floors, end walls, insulation). The model only accounts for moisture in the sheathing and does not provide for moisture storage elsewhere. Figure 8 demonstrates the importance and role of the temporary moisture storage in materials other than the sheathing. The lack of such a mechanism in the FPL model seriously hampers its ability to predict hourly changes in sheathing MC and tends to exaggerate the difference in MC between north- and south-facing sheathing.

Sheathing Temperature—Summer

Figure 9 compares measured temperatures on the top surface of the plywood sheathing (immediately under the roof felt) during May 1 to 15, 1993, with results from the model. In contrast to the attic air temperature, there is no discernible time shift between measured top surface temperatures and model results. This supports the view that the time delay in attic air temperatures was caused by heat storage in the sheathing and other materials in the attic, which the model does not take into account. On most days, measurements and simulation results were reasonably close (within 5°F (3°C)),

except during clear nights and during mid-day on some days, especially May 13 to 15.

The data show discrepancies during the night of up to 15°F (8°C). This error is primarily due to an overestimate of cooling by sky radiation. Research into alternative equations for sky radiation did not reveal substantial differences between results from these equations. We therefore surmise that the fault did not lie in the equations or calculations. Rather, radiation loss to the sky was perhaps partially compensated by radiation received from the surroundings, or the choice of emissivity (0.9) for the roof surface was too high.

The discrepancies during mid-day could be the result of errors in the estimated effect of wind cooling. Inspection of the measured temperature and wind data did show an effect of wind direction on roof surface temperatures, but wind direction is not considered in the model. The discrepancies could also be caused by errors in the calculated radiation input data for each roof surface. This calculation was prone to errors partly because of inaccurate cloud cover data, which influence the ratio of direct to diffuse radiation.

To determine the potential for thermal degradation of the sheathing, the model can be used to generate temperature–duration distributions. Figures 10 and 11 show temperature–time distributions from May 1 through June 30, 1993, for the top surface of north- and south-facing sheathing, as compiled from the measured data and the model results. For the north side, the model underpredicted the maximum

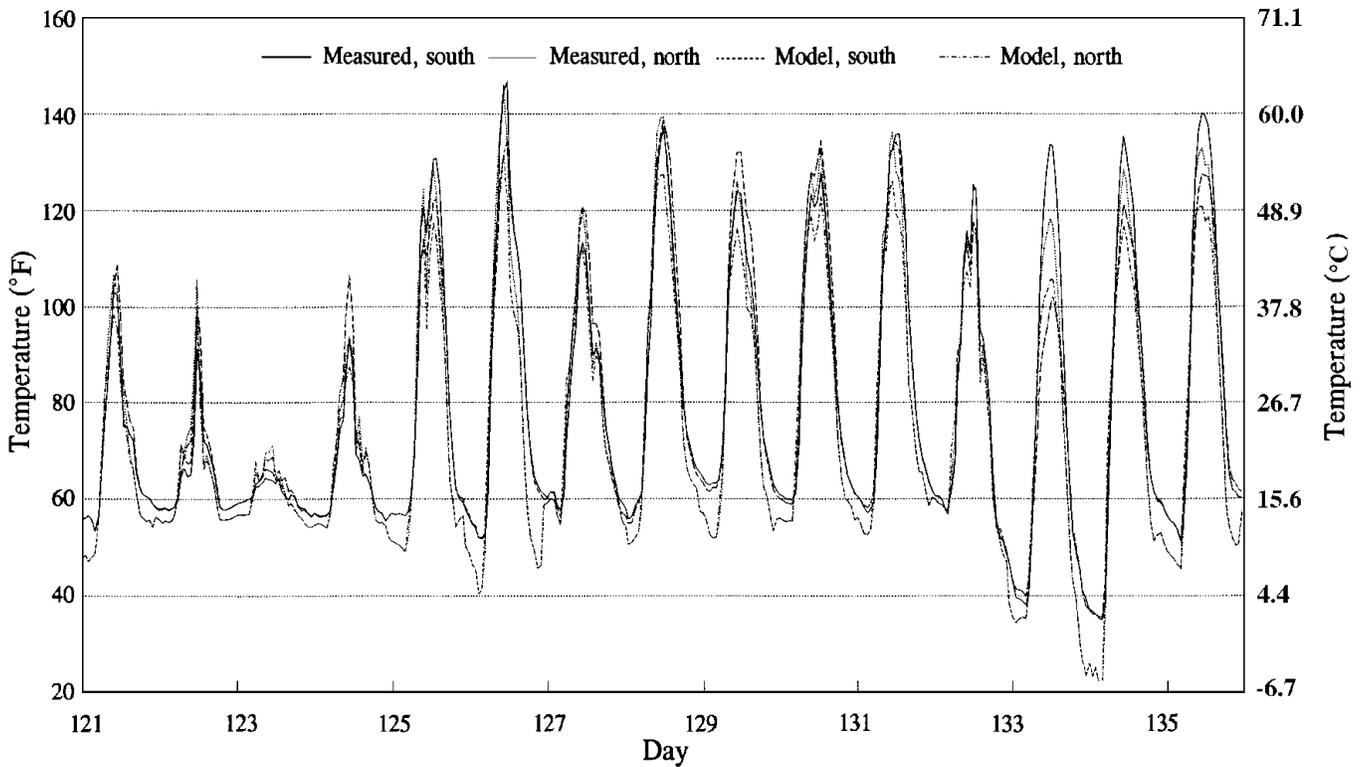


Figure 9—Sheathing temperatures, bay 2, top surface, May 1–15, 1993; absorptance = 0.65.

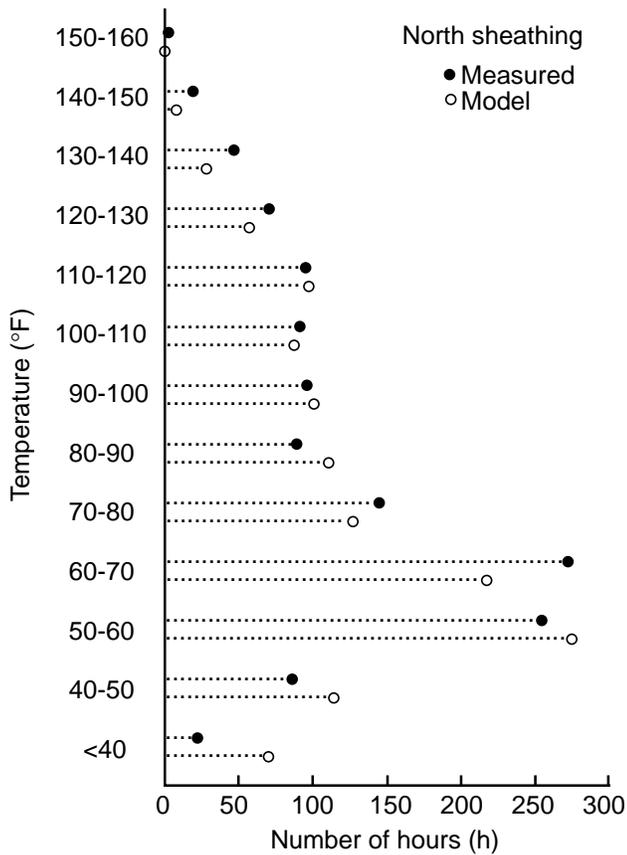


Figure 10—Temperature–time distribution, bay 2, top of north sheathing, May 1–15, 1993; absorptance = 0.65.
 $T_c = [T_F - 32]/1.8.$

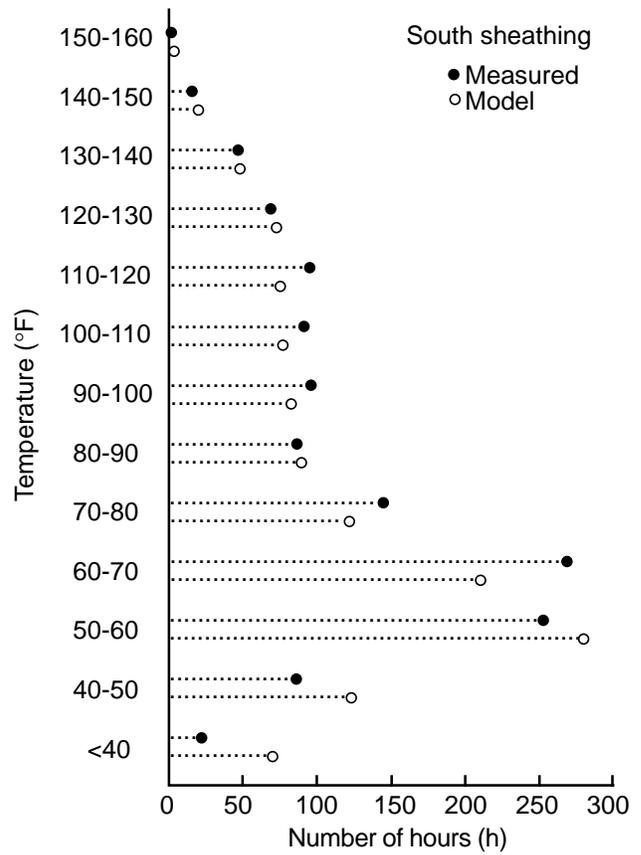


Figure 11—Temperature–time distribution, bay 2, top of south sheathing, May 1–15, 1993; absorptance = 0.65.
 $T_c = [T_F - 32]/1.8.$

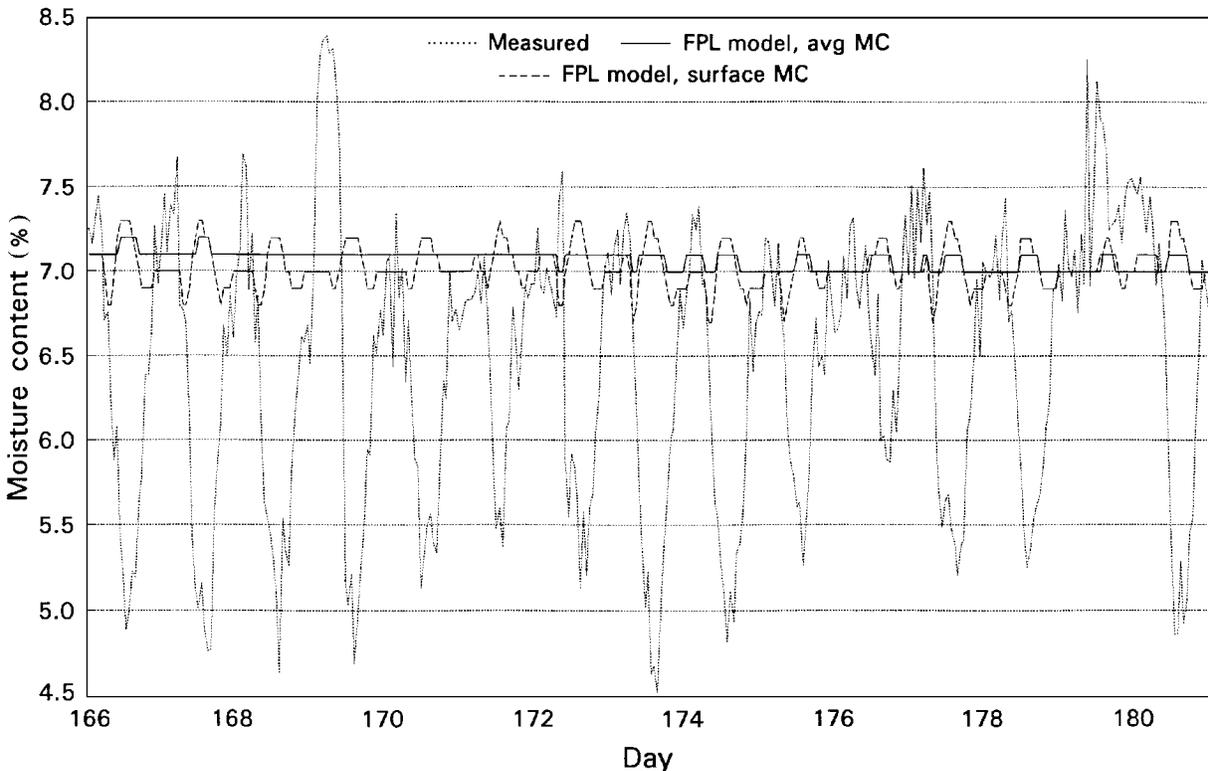


Figure 12—Sheathing moisture content, bay 2, north-facing, May 1–15, 1993; absorptance = 0.65.

temperature and frequency of temperatures above 120°F (49°C) (Fig. 10). The model overpredicted the number of hours below 60°F (16°C), primarily because of its overprediction of night sky cooling. On the south side (Fig. 11), the model appears quite accurate for temperatures above 120°F (49°C), generally underpredicted the frequency of mid-range temperatures between 60°F and 120°F (15°C and 49°C), and overpredicted the occurrence of temperatures below 60°F (49°C). Usually, for thermal degradation concerns, the frequency of occurrence of high temperatures is of the most interest, and for that purpose the model results appear to have acceptable accuracy.

Sheathing Moisture Content—Summer

Figure 12 compares the MC of the north-facing sheathing as calculated from the model (average and surface MC) with the measured MC (average of two locations) during the last 2 weeks of June 1993. The conclusions are similar to those made earlier. On average, the measured MC was close to the model results (about 1% lower), especially when considering an estimated error in the measured MC of at least 2%. However, the data show that moisture storage in the attic needs to be added to the model to accurately simulate the moisture behavior of the north-facing sheathing.

Conclusions

The model validation described in this report is not a complete test of the model's accuracy over the full range of conditions and can therefore provide only an indication of its performance. However, we feel that the results justify the following conclusions:

- Comparison of measured data and data from the FPL roof temperature and moisture model shows that the model is capable of providing reasonably accurate estimates for temperatures of the roof sheathing and attic air, with the difference usually within 5°F (3°C). However, heat storage effects, which are not accounted for in the model, often cause a time shift (delay) of 1 to 2 h in attic air temperatures.
- The model can accurately predict the frequency of occurrence of high roof sheathing temperatures (above 120°F (49°C)) during summer, but its accuracy is highly dependent on the values chosen for solar absorptance and emissivity of the roof shingles. However, data on emissivity and solar absorptance are usually not available for specific shingles.
- The model consistently overpredicts the extent of nighttime cooling from sky radiation losses, leading to

predicted temperatures that are too low. A possible explanation is that the roof surfaces may receive night-time radiation from the surrounding buildings, lights, and other objects, which may not be included in the measured radiation input data, or that the choice of 0.9 for the emissivity of the shingles is too high.

- The model's treatment of the effect of snow cover is too simplistic, but no better alternatives are apparent for simulating this very complex behavior.
- We were unable to determine the model's accuracy of attic air relative humidity predictions because of the suspect quality of measured relative humidity data.
- The model appears capable of predicting average moisture conditions in the sheathing with reasonable accuracy, generally within 1%, when moisture content is not excessively high or low. Moisture behavior at high and very low moisture content and humidity conditions was not tested.
- Hourly moisture behavior is not well represented by the model as daily or seasonal behavior, especially when considering the north-facing sheathing. To improve the model's performance, a mass with moisture storage needs to be added to the model to represent moisture sorption in the attic floor, insulation, structural members, and other hygroscopic materials.
- The model would further benefit from
 - verification with data that include measured emissivity and solar absorptance of the shingles,
 - addition of thermal mass in the attic and roof,
 - better algorithms to calculate direct and diffuse solar radiation, and
 - verification for roof with east–west orientation.

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Nomenclature

A_c	= surface areas of ceiling (ft ²)
A_{es}	= combined surface area of soffit and end walls (ft ²)
A_r	= total roof surface area (ft ²)
C	= total cloud cover (0 to 10)
C_p	= specific heat of air, Btu/lb·°F
d_m	= thickness of sheathing layer m (ft)
f	= fraction of house exfiltration that transfers into attic
F_1, F_2	= radiative heat transfer coefficients between attic floor and undersides of roof (Btu/h·ft ² ·°F)
$h_{D,r}$	= air-surface moisture transfer coefficient (set at 1.1 lb/h·ft ²)
h_f	= convective heat transfer coefficient at attic floor (Btu/h·ft ² ·°F)
h_{IR}	= adjustment in heat transfer coefficient for infrared radiation exchange with sky (Btu/h·ft ² ·°F)
$h_{o,n}$	= convective heat transfer coefficient at exterior roof surface n (Btu/h·ft ² ·°F)
$h_{r,n}$	= convective heat transfer coefficient at underside of roof (surface n) (Btu/h·ft ² ·°F)
I_a	= attic ventilation rate, i.e., outdoor air entering attic (h ⁻¹)
I_h	= house exfiltration rate (h ⁻¹)
I_n	= total solar radiation incident on roof surface (Btu/h·ft ²)
K_w	= diffusion coefficient (lb/h·ft)
L_{IR}	= partial adjustment for infrared radiation exchange with sky (Btu/h·ft ²)
L_h	= latent heat of vaporization (1,050 Btu/lb)
M	= moisture content of wood, unitless
R_c	= thermal resistance of attic floor (ceiling) (h·ft ² ·°F/Btu)
$R_{e,s}$	= average thermal resistance of end walls and eaves (h·ft ² ·°F/Btu)
R_r	= thermal resistance of roof (h·ft ² ·°F/Btu)
t	= time (h)
T	= temperature (°F)
T_a	= temperature of attic air (°R)
T_d	= temperature of outdoor dew point (°C)
T_f	= temperature of attic floor surface (°R)
T_i	= temperature of indoor air (°R)
T_o	= temperature of outdoor air (°R)
$T_{r,1}$	= temperature of underside of roof sheathing a (°R)
$T_{r,2}$	= temperature of underside of roof sheathing b (°R)
T_s	= temperature of outside roof surface (°R)
V_a	= volume of attic space (ft ³)
V_h	= volume of house (ft ³)
$w_{m,m+1}$	= moisture flux from layer m to next layer (lb/h·ft ²)
$\bar{W}_{r,n}$	= rate of moisture adsorption into sheathing surfaces (lb/h)
α	= solar absorptance
ϵ_f	= emissivity of attic floor surface
ϵ_{IR}	= emissivity of sky with clouds
ϵ_r	= emissivity of roof sheathing surface (underside)
ϵ_s	= emissivity of roof shingles (assumed to be 0.9)
ϵ_0	= emissivity of clear sky
ρ	= density of air (lb/ft ³)
σ	= Stefan–Boltzman constant (Btu/h·ft ² ·°R ⁴)
ω_a	= humidity ratio of attic air, dry air basis
ω_i	= humidity ratio of indoor air, dry air basis
ω_m	= equilibrium humidity ratio, sheathing layer m , dry air basis
ω_o	= humidity ratio of outside air, dry air basis
ω_r	= equilibrium humidity ratio of surface air in equilibrium with wood sheathing surface, dry air basis

Appendix A—Convective Heat Transfer Correlations

The following convective heat transfer correlations were adapted from Wilkes (1989).

A. Natural convection, horizontal or nearly horizontal surface (tilt angle $\phi < 2^\circ$):

a. Heat flow up:

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

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

b. Heat flow down:

$$\text{Nu} = 0.58 \text{Ra}^{1/5}$$

B. Natural convection, tilted surface (tilt angle $\phi > 2^\circ$):

a. Heat flow up:

$$\text{Nu} = 0.56 (\text{Ra} \cos(\phi))^{1/4} \quad \text{for } \text{Ra}/\text{Pr} < \text{Gr}_c$$

$$\text{Nu} = 0.14 (\text{Ra}^{1/3} - (\text{Gr}_c \text{Pr})^{1/3}) + 0.56 (\text{Ra} \cos(\phi))^{1/4} \quad \text{for } \text{Ra}/\text{Pr} > \text{Gr}_c$$

$$\text{with } \text{Gr}_c = 1 \times 10^6 \quad \text{for } \phi < 15^\circ$$

$$\text{Gr}_c = 10^{(\phi/(1.1870 + 0.0870\phi))} \quad \text{for } 15^\circ < \phi < 75^\circ$$

$$\text{Gr}_c = 5 \times 10^9 \quad \text{for } \phi > 75^\circ$$

b. Heat flow down:

$$\text{Nu} = 0.56 (\text{Ra} \cos(\phi))^{1/4}$$

C. Forced convection:

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

$$\text{Nu} = \text{Pr}^{1/3} (0.037 \text{Re}^{4/5} - 850) \quad \text{for } \text{Re} > 5 \times 10^5$$

Combined forced and natural convection:

$$h_{\text{combined}} = (h_{\text{forced}}^3 + h_{\text{natural}}^3)^{1/3}$$

Nu = Nusselt number = hL/k

Ra = Raleigh number = $g\beta\rho C_p \Delta T L^3 / \nu k$

Gr = Grasshof number = Ra/Pr

Pr = Prandtl number = ν/α

Re = Reynolds number = $\nu L/\nu$

h = convective heat transfer coefficient

L = characteristic length of “plate” (average of length and width)

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

α = thermal diffusivity of air

ν = velocity of air (wind speed)

Appendix B—Program Listing for FPL Model

```
PROGRAM AHM
$DEBUG
C VERSION 7A
C Date: April 15, 1992 revision of COMMON block
C Works with MOIST7A, PARAM7A, HEAT7A, HCON6
C Requires input of dewpoint temperatures and cloudcover data
C in range of 0-10
C New convective heat transfer and infrared sky radiation
C Added wind speeds from weather data (in knots)
C Added option to bypass latent heat calculations
C Changed output file format to single column (version 5C)
C Version 6: WEXTRA introduced
C Updated August 13, 1992: changed name of message file to MESSAGE.PRN
C Updated August 15, 1992: streamlining
C Major revision August 17, 1992: All hourly input parameters (except
C snow cover) are linearly interpolated between hours in 10-minute
C increments.
C Major revision February 28, 1993: change to 3-layer sheathing (from 5)
C Revision April 15, 1993: made sheathing thickness and R-value variable
C input parameters.
C
      DOUBLE PRECISION WMC(6),WEXTRA
      COMMON A,AC,AES,AF,AR,ALR,ALF,F,I1,I2,IA,IAF,IFLAG,IH,ITMOIST,
1JJ,KK,L,NFAN,RC,RES,RHMAX,RR,RS,VA,VH,RHA,RHI,PITCH,VENT,PHI,
2VLHA,VLHB,T(10),TARR(184,24),RAARR(184,24),WIND(184,24),WSHADE,
3RBARR(184,24),SKYCOV(184,24),SNOCOV(184,24),TATT(184,24),
4TRA(185,24),TRB(185,24),OUTDP(184,24),WMCA(185,24),
5WMCB(185,24),RHAT(184,24),FAN(184,24),TEMPA(184,24),TEMPB(184,24),
6TEMPOA(184,24),TEMPOB(184,24),AVEMC(1,24),D,IIILAT,SLOPE(6),JJJ
      REAL I1,I2,IA,IAF,IH,L
      CHARACTER*12 FLTEMP,FLSOLA,FLSOLB,FLCLD,FLSNOW,FLDEWP,FLWND
C      A      ROOF SURFACE ABSORPTANCE
C      AC      AREA OF CEILING, SQ. FT.
C      AES     COMBINED AREA OF ENDWALLS AND SOFFITS, SQ. FT.
C      AR      AREA OF ROOF. SQ. FT.
C      AF      ATTIC FAN VENTILATION RATE, CFM
C      ALF     CHARACTERISTIC LENGTH OF FLOOR (FOR HCON SUBROUTINE)
C      ALR     CHARACTERISTIC LENGTH OF ROOF (FOR HCON SUBROUTINE)
C      DC      DISTANCE FROM FLOOR TO CEILING, FT.
C      DL      LENGTH OF HOUSE, FT.
C      DOH     AMOUNT OF ROOF OVERHANG, FT.
C      DW      WIDTH OF HOUSE, FT.
C      D       THICKNESS OF ROOF SHEATHING (set at 0.47" in PARAM)
C      DWA     WOOD-TO-WOOD MOISTURE TRANSFER COEFFICIENT FOR SHEATHING
C              "A", LB/FT.*HR
C      DWB     WOOD-TO-WOOD MOISTURE TRANSFER COEFFICIENT FOR SHEATHING
C              "B", LB/FT.*HR
C      F       FRACTION OF HOUSE EXFILTRATION THAT TRANSFERS INTO ATTIC
C      HDR     AIR-TO-WOOD SURFACE MOISTURE TRANSFER COEFFICIENT,
C              LB/FT.SQ.*HR
C      HF      CONVECTIVE HEAT TRANSFER COEFFICIENT AT ATTIC FLOOR,
C              BTU/H*FT.SQ.*F.
C      HRA,
```

C HRB CONVECTIVE HEAT TRANSFER COEFFICIENT AT UNDERSIDE OF ROOF,
C BTU/H*FT.SQ.*F.
C HRI HUMIDITY RATIO OF INDOOR AIR, (UNITLESS)
C HRO HUMIDITY RATIO OF OUTSIDE AIR, (UNITLESS)
C HRR A HUMIDITY RATIO OF INTERIOR SURFACE OF SHEATHING "A"
C HRR B HUMIDITY RATIO OF INTERIOR SURFACE OF SHEATHING "B"
C HOA,
C HOB CONVECTIVE HEAT TRANSFER COEFFICIENT AT ROOF SURFACE,
C BTU/H*FT.SQ.*F.
C I1 SOLAR RADIATION ON ROOF SURFACE "A", BTU/H*FT.SQ.
C I2 SOLAR RADIATION ON ROOF SURFACE "B", BTU/H*FT.SQ.
C IA NATURAL ATTIC VENTILATION RATE, VOLUME CHANGES/H.
C IAF ATTIC FAN VENTILATION CAPACITY, VOLUME CHANGES/H.
C IH HOUSE EXFILTRATION RATE, VOLUME CHANGES.H.
C L RADIATION LOSS FROM ROOF SURFACE TO SKY, BTU/H*FT.SQ.
C NFAN VARIABLE USED TO INDICATE NUMBER OF QUARTER HOURS FAN IS
C TO BE RUN DURING AN HOUR'S CALCULATIONS (INTEGER)
C PITCH SLOPE OF ROOF, RISE/RUN
C PHI ROOF ANGLE, DEGREES
C RC THERMAL RESISTANCE OF ATTIC FLOOR, H*FT.SQ.*F./BTU
C RES AVERAGE THERMAL RESISTANCE OF ENDWALLS AND EAVES,
C H*FT.SQ.*F./BTU
C RS THERMAL RESISTANCE OF ROOF SHEATHING, H*FT.SQ.*F/BTU
C RHA RELATIVE HUMIDITY OF THE ATTIC
C RHI RELATIVE HUMIDITY OF THE INDOOR LIVING SPACE
C DPO DEWPOINT TEMPERATURE OF THE OUTSIDE AIR, R.
C RR THERMAL RESISTANCE OF ROOF, INCL. SHINGLES, H*FT.SQ.*F./BTU
C T(1) ATTIC AIR TEMPERATURE, R.
C T(2) ATTIC FLOOR TEMPERATURE, R.
C T(3) TEMPERATURE OF UNDERSIDE OF ROOF "A" SHEATHING, R.
C T(4) TEMPERATURE OF UNDERSIDE OF ROOF "B" SHEATHING, R.
C T(5) TEMPERATURE OF OUTSIDE SURFACE OF ROOF "A", R.
C T(6) TEMPERATURE OF OUTSIDE SURFACE OF ROOF "B", R.
C T(7) TEMPERATURE OF THE INDOOR LIVING SPACE, R.
C T(8) TEMPERATURE OF OUTSIDE AIR, R.
C VA VOLUME OF THE ATTIC SPACE, CU.FT.
C VENRAT RATIO OF ATTIC VENT AREA/CEILING AREA
C VENT TOTAL ATTIC VENTILATION RATE, VOLUME CHANGES/H.
C VH VOLUME OF HOUSE LIVING SPACE, CU.FT.
C WEXTRA SURPLUS MOISTURE, LB/HR
C WIND WINDSPEED (WEATHER DATA), KNOTS
C WMC(1) MOISTURE CONTENT OF UNDERSIDE SURFACE SHEATHING "A"
C WMC(2) MOISTURE CONTENT OF UNDERSIDE SURFACE SHEATHING "B"
C WMC(3) MOISTURE CONTENT OF SHEATHING "A" LAYER 2
C WMC(4) MOISTURE CONTENT OF SHEATHING "B" LAYER 2
C WMC(5) MOISTURE CONTENT OF SHEATHING "A" LAYER 3
C WMC(6) MOISTURE CONTENT OF SHEATHING "B" LAYER 3

C The first step in the program is to read in the house parameters:
C CALL PARAM(WMC)

C
C

C All sheathing layers are assigned a moisture content
C equal to that of the initial moisture contents:
C DO 20 K=3,5,2

```

        WMC(K)=WMC(1)
        WMC(K+1)=WMC(2)
20 CONTINUE
C
C   The capacity of the attic fan is translated into volume changes
C   per hour:
        IAF=AF*60./VA
        IRHMAX=0
C
        WRITE (*,99)
99 FORMAT (' ENTER NUMBER OF DAYS ')
        READ (*,*) IDAYS
C
C   The fan control variables are set to artificially high values so
C   as not to interfere with operation of the program.  If a humidity
C   or photoperiod fan control is desired, these variables will be
C   reassigned in the next step:
        RHMAX=10.0
        BTU=1000.0
C
C   Menu-driven selection of fan control devices is displayed on the
C   screen and control variables are assigned:
100 WRITE (*,101)
101 FORMAT (' HUMIDISTAT-CONTROLLED ATTIC FAN? (0=NO, 1=YES)')
        READ (*,*) HCONT
        IF (HCONT) 120,120,102
102 WRITE (*,103)
103 FORMAT (' ENTER MAXIMUM HUMIDITY DESIRED (DECIMAL)')
        READ (*,*) RHMAX
        PCONT=0
        TCONT=0
        GOTO 138
C
120 WRITE (*,121)
121 FORMAT (' PHOTOPERIOD-CONTROLLED ATTIC FAN? (0=NO, 1=YES)')
        READ (*,*) PCONT
        IF (PCONT) 130,130,122
122 WRITE (*,123)
123 FORMAT (' ', 'ON WHICH ROOF SURFACE IS PHOTOSENSOR LOCATED?')
        WRITE (*,124)
124 FORMAT (' ', '0) SURFACE "A" OR 1) SURFACE "B" (ENTER NUMBER)')
        READ (*,*) ISURF
        WRITE (*,125)
125 FORMAT (' ENTER MINIMUM BTU/SQFT/H NEEDED TO TRIGGER FAN')
        READ (*,*) BTU
        TCONT=0
        GOTO 138
C
130 WRITE (*,131)
131 FORMAT (' TIMER-CONTROLLED ATTIC FAN? (0=NO, 1=YES)')
        READ (*,*) TCONT
        IF (TCONT) 138,138,132
132 WRITE (*,133)
133 FORMAT (' ENTER HOUR TO BEGIN FAN (INTEGER)')
        READ (*,*) IHOURL

```

```

134 WRITE (*,135)
135 FORMAT (' ENTER LAST HOUR FAN IS TO RUN (INTEGER)')
    READ (*,*) IHOURL2
C
138 WRITE (*,136)
136 FORMAT (' INCLUDE LATENT HEAT EFFECTS? (0=NO, 1=YES)'/
A' Note: inclusion greatly increases run time!')
    READ (*,*) IILLAT
C
C    Specify input file names
    WRITE (*,400)
400  FORMAT (' ENTER 7 FILENAMES FOR',/, ' DRYBULB TEMP',/, ' SOLAR',
1' RADIATION, A AND B',/, ' CLOUDCOVER',/, ' SNOWCOVER',/,
2' DEWPOINT TEMP',/, ' WINDSPEED')
    READ (*,410) FLTEMP
410  FORMAT (A12)
    READ (*,410) FLSOLA
    READ (*,410) FLSOLB
    READ (*,410) FLCLD
    READ (*,410) FLSNOW
    READ (*,410) FLDEWP
    READ (*,410) FLWND
C
C    The data files are read from disk.  To facilitate operation of the
C    program in its present format, the names of the files are given
C    here rather than asked for as input:
C
C    Outdoor temperature:
    OPEN (4,FILE=FLTEMP)
    READ (4,*) ((TARR(IROW,ICOL), ICOL=1,24), IROW=1,IDAYS)
    CLOSE (4,STATUS='KEEP')
C
C    Solar radiation on roof surface "A":
    OPEN (4,FILE=FLSOLA)
    READ (4,*) ((RAARR(IROW,ICOL), ICOL=1,24), IROW=1,IDAYS)
    CLOSE (4,STATUS='KEEP')
C
C    Solar radiation roof surface "B":
    OPEN (4,FILE=FLSOLB)
    READ (4,*) ((RBARR(IROW,ICOL), ICOL=1,24), IROW=1,IDAYS)
    CLOSE (4,STATUS='KEEP')
C
C    Cloud cover data:
    OPEN (4,FILE=FLCLD)
    READ (4,*) ((SKYCOV(IROW,ICOL), ICOL=1,24), IROW=1,IDAYS)
    CLOSE (4,STATUS='KEEP')
C
C    Depth of snow on the roof:
    OPEN (4,FILE=FLSNOW)
    READ (4,*) ((SNOCOVIROW,ICOL), ICOL=1,24), IROW=1,IDAYS)
    CLOSE (4,STATUS='KEEP')
C
C    Outdoor dewpoint temperature:
    OPEN (4,FILE=FLDEWP)
    READ (4,*) ((OUTDPIROW,ICOL), ICOL=1,24), IROW=1,IDAYS)

```

```

CLOSE (4,STATUS='KEEP')
C
C Windspeed
OPEN (4,FILE=FLWND)
READ (4,*) ((WIND(IROW,ICOL), ICOL=1,24), IROW=1,IDAYS)
CLOSE (4,STATUS='KEEP')
C
C Open the message file
OPEN (6,FILE='MESSAGE.PRN',STATUS='UNKNOWN')
C
C Initialize surface and attic air temperatures
T(2)=TARR(1,1)+459.67
T(1)=T(2)
T(3)=T(2)
T(4)=T(2)
T(5)=T(2)
T(6)=T(2)
C
C Initialize surplus moisture
WEXTRA=0.0D0
C
C The beginning of the DO loop to perform each hour's calculations:
DO 210 JJ=1,IDAYS
WRITE (*,139) JJ
139 FORMAT (' ', 'DAY ', I3)
DO 200 KK=1,24
WRITE (6,140) JJ, KK
140 FORMAT (' ', 'DAY ', I3, '      HOUR ', I2)
C
C Calculate 10-minute increment for hourly inputs:
NXTDAY=JJ
NXTHR=KK+1
IF (KK.EQ.24) THEN
NXTDAY=JJ+1
NXTHR=1
IF (JJ.EQ.IDAYS) THEN
NXTDAY=JJ
NXTHR=24
ENDIF
ENDIF
SLOPE(1)=(TARR(NXTDAY,NXTHR)-TARR(JJ, KK))/6
SLOPE(2)=(RAARR(NXTDAY,NXTHR)-RAARR(JJ, KK))/6
SLOPE(3)=(RBARR(NXTDAY,NXTHR)-RBARR(JJ, KK))/6
SLOPE(4)=(SKYCOV(NXTDAY,NXTHR)-SKYCOV(JJ, KK))/6
SLOPE(5)=(OUTDP(NXTDAY,NXTHR)-OUTDP(JJ, KK))/6
SLOPE(6)=(WIND(NXTDAY,NXTHR)-WIND(JJ, KK))/6
C
C Initializing ventilation rates and flags:
IF (IRHMAX.EQ.1) THEN
NFAN=1
VENT=IAF
ELSE
NFAN=0
VENT=IA
ENDIF
C

```

```

C      The next section, to line 150, determines if an attic fan control
C      device was selected, and if so determines the attic ventilation
C      rate appropriate for the type of control and the attic condition.
C
      IF (PCONT) 144,144,141
141 IF (ISURF) 142,142,143
142 IF ((RAARR(JJ,KK) .GT. BTU) .AND. (SNOCOV(JJ,KK) .LT. 0.5)) GO TO
      A 147
143 IF ((RBARR(JJ,KK) .GT. BTU) .AND. (SNOCOV(JJ,KK) .LT. 0.5)) GO TO
      A 147
144 IF ((KK .GE. IHOURL) .AND. (KK .LE. IHOURL2)) GO TO 147
C
145 GO TO 148
147 NFAN=6
      VENT=IAF
C
148 CONTINUE
C
C      The beginning of the DO loop to perform the 6 iterations within
C      each hour:
      DO 180 JJJ=1,6
C
      Initialize latent heat:
      VLHA=0.0
      VLHB=0.0
C      The heat balance subroutine is called:
155 CALL HEAT
C
C      More initializing:
      IFLAG=0
      ITMOIST=0
C      The moisture balance subroutine is called:
160 CALL MOIST(WMC,WEXTRA)
C
      IF (NFAN.EQ.6) GO TO 180
C      Check if humidistat-controlled fan should be turned on next period
      IF (RHA.GT.RHMAX) THEN
          VENT=IAF
          IRHMAX=1
          IF (JJJ.LT.6) THEN
              NFAN=NFAN+1
              VLHA=0.0
              VLHB=0.0
              CALL HEAT
          ENDIF
      ELSE
          VENT=IA
          IF (IRHMAX.EQ.1.AND.JJJ.LT.6) THEN
              VLHA=0.0
              VLHB=0.0
              CALL HEAT
          ENDIF
          IRHMAX=0

```

```

        ENDIF
C
180 CONTINUE
C
C   The fraction of the hour that the fan was operated is calculated
C   and assigned to the output matrix:
190 FAN(JJ, KK)=NFAN/6
C
C
200 CONTINUE
210 CONTINUE
C
C   Close message file
CLOSE (6)
C
C   Output files are opened and written to disk:
OPEN (7, FILE='XTAXXXXXX.PRN', STATUS='UNKNOWN')
WRITE (7, 300) ((TEMPA(IROW, ICOL), ICOL=1, 24), IROW=1, IDAYS)
CLOSE (7, STATUS='KEEP')
OPEN (7, FILE='XTBXXXXXX.PRN', STATUS='UNKNOWN')
WRITE (7, 300) ((TEMPB(IROW, ICOL), ICOL=1, 24), IROW=1, IDAYS)
CLOSE (7, STATUS='KEEP')
OPEN (7, FILE='XTCXXXXXX.PRN', STATUS='UNKNOWN')
WRITE (7, 300) ((TEMPOA(IROW, ICOL), ICOL=1, 24), IROW=1, IDAYS)
CLOSE (7, STATUS='KEEP')
OPEN (7, FILE='XTDXXXXXX.PRN', STATUS='UNKNOWN')
WRITE (7, 300) ((TEMPOB(IROW, ICOL), ICOL=1, 24), IROW=1, IDAYS)
CLOSE (7, STATUS='KEEP')
OPEN (7, FILE='XTTXXXXXX.PRN', STATUS='UNKNOWN')
WRITE (7, 300) ((TATT(IROW, ICOL), ICOL=1, 24), IROW=1, IDAYS)
CLOSE (7, STATUS='KEEP')
OPEN (7, FILE='XRHXXXXXX.PRN', STATUS='UNKNOWN')
WRITE (7, 300) ((RHAT(IROW, ICOL), ICOL=1, 24), IROW=1, IDAYS)
CLOSE (7, STATUS='KEEP')
OPEN (7, FILE='WMCA.PRN', STATUS='UNKNOWN')
WRITE (7, 300) ((WMCA(IROW, ICOL), ICOL=1, 24), IROW=1, IDAYS)
CLOSE (7, STATUS='KEEP')
OPEN (7, FILE='XMAXXXXXX.PRN', STATUS='UNKNOWN')
WRITE (7, 300) ((TRA(IROW, ICOL), ICOL=1, 24), IROW=1, IDAYS)
CLOSE (7, STATUS='KEEP')
OPEN (7, FILE='WMCB.PRN', STATUS='UNKNOWN')
WRITE (7, 300) ((WMCB(IROW, ICOL), ICOL=1, 24), IROW=1, IDAYS)
CLOSE (7, STATUS='KEEP')
OPEN (7, FILE='XMBXXXXXX.PRN', STATUS='UNKNOWN')
WRITE (7, 300) ((TRB(IROW, ICOL), ICOL=1, 24), IROW=1, IDAYS)
CLOSE (7, STATUS='KEEP')
OPEN (7, FILE='FAN.PRN', STATUS='UNKNOWN')
WRITE (7, 300) ((FAN(IROW, ICOL), ICOL=1, 24), IROW=1, IDAYS)
CLOSE (7, STATUS='KEEP')
C
300 FORMAT (' ', 4416(F7.3, /, ' '))
C
STOP
END

```

```

SUBROUTINE PARAM(WMC)
$DEBUG
C VERSION 7B
C May 7, 1994, corrected June 3, 1994
C As 7A but with correction of error in reading of windshade factor WSHADE
C Revised April 16, 1993: made sheathing R and D variable, eliminated VENRAT
C Revised February 28, 1993, Anton TenWolde
C As version 6A but with 3-layered sheathing.
C WARNING: SHEATHING THICKNESS IS SET AT 0.47 INCH
C History:
C Added: windspeed, windshade factor, char. lengths (1/13/90)
C Deleted: heat transfer coefficients (1/13/90) [handled by HCON]
C Corrected attic volume calculations (8/21/91)
C Revised August 17, 1992
C
      DOUBLE PRECISION WMC(6)
      COMMON A,AC,AES,AF,AR,ALR,ALF,F,I1,I2,IA,IAF,IFLAG,IH,ITMOIST,
1JJ, KK,L,NFAN,RC,RES,RHMAX,RR,RS,VA,VH,RHA,RHI,PITCH,VENT,PHI,
2VLHA,VLHB,T(10),TARR(184,24),RAARR(184,24),WIND(184,24),WSHADE,
3RBARR(184,24),SKYCOV(184,24),SNOCOV(184,24),TATT(184,24),
4TRA(185,24),TRB(185,24),OUTDP(184,24),WMCA(185,24),
5WMCB(185,24),RHAT(184,24),FAN(184,24),TEMPA(184,24),TEMPB(184,24),
6TEMPOA(184,24),TEMPOB(184,24),AVEMC(1,24),D,IIILAT,SLOPE(6),JJJ
      REAL I1,I2,IA,IAF,IH,L
      CHARACTER*12 FNAME
C
C
      WRITE (*,20)
20 FORMAT (' ENTER NAME OF HOUSE PARAMETER FILE')
      READ (*,21) FNAME
21 FORMAT (A12)
      OPEN (4,FILE=FNAME)
      READ (4,*) DL,DW,DC,DOH,PITCH,D,F,WSHADE,A,IH,RC,RES,RR,RS,
1T(7),RHI,WMC(1),WMC(2),AF,IA
      CLOSE (4)
26 DOW=DW+2*DOH
      AC=DL*DW
      ALF=(DW+DL)/2
      EDGE=SQRT(DOW**2+(PITCH*DOW)**2)
      AR=DL*EDGE
      ALR=(DL+EDGE/2)/2
      AES=(2*DOH*DL)+2*PITCH*(DOW/2)**2
      VA=DL*PITCH*(DOW/2)**2
      VH=AC*DC
      PHI=ATAN(PITCH)*180/3.14159265
      TRA(1,1)=WMC(1)
      TRB(1,1)=WMC(2)
      WMCA(1,1)=WMC(1)
      WMCB(1,1)=WMC(2)
C
      WRITE (*,27)
27 FORMAT (' HOUSE PARAMETERS ARE AS FOLLOWS:')
      WRITE (*,28)

```

```

28 FORMAT ('0DIMENSIONS:')
   WRITE (*,31)
31 FORMAT (' ',15X,'CEILING',3X,'ROOF',5X,'ROOF',3X,'SHEATHING')
   WRITE (*,32)
32 FORMAT (' LENGTH WIDTH HEIGHT OVERHANG PITCH THICKNESS')
   WRITE (*,33) DL,DW,DC,DOH,PITCH,D
33 FORMAT (F6.2,1X,F6.2,2X,F6.2,4X,F6.2,2X,F6.2,3X,F6.2)
   WRITE (*,34)
34 FORMAT (' MATERIAL PROPERTIES:')
   WRITE (*,35)
35 FORMAT (1X,12X,'R-VALUES')
   WRITE (*,36)
36 FORMAT (' CEILING ROOF SHEATHING ENDWALLS/SOFFITS WINDSHADE FA
1CTOR SHINGLE ABSORPT. ')
   WRITE (*,37) RC,RR,RS,RES,WSHADE,A
37 FORMAT (' ',3(F6.2,' '),6X,F6.2,13X,F6.2,8X,F6.2)
   WRITE (*,38)
38 FORMAT (' VENTILATION DATA:')
   WRITE (*,39)
39 FORMAT (' HOUSE EXFILTRATION ATTIC VENTILATION')
   WRITE (*,40)
40 FORMAT (' VOL. CHG. FRACTION NATURAL FAN')
   WRITE (*,41)
41 FORMAT (' PER HOUR TO ATTIC (VOL./HR) (CFM)')
   WRITE (*,42) IH,F,IA,AF
42 FORMAT (' ',2(F6.2,' '),',', ' ',2(F6.2,' '))
   WRITE (*,43)
43 FORMAT (' ENVIRONMENT:')
   WRITE (*,44)
44 FORMAT (' INDOOR INDOOR MOISTURE CONTENT MOISTURE CON
1TENT')
   WRITE (*,45)
45 FORMAT (' TEMP. (F.) RH SHEATHING "A" SHEATHING "
1B"')
   WRITE (*,46) T(7)-459.67,RHI,WMC(1),WMC(2)
46 FORMAT (' ',2(' ',F6.2,' '),2(' ',F6.3,' '))
   WRITE (*,50)
50 FORMAT ('01 CHANGE DIMENSIONS')
   WRITE (*,51)
51 FORMAT (' 2 CHANGE MATERIAL PROPERTIES')
   WRITE (*,52)
52 FORMAT (' 3 CHANGE VENTILATION DATA')
   WRITE (*,53)
53 FORMAT (' 4 CHANGE ENVIRONMENT')
   WRITE (*,54)
54 FORMAT (' 5 PROCEED')
   WRITE (*,55)
55 FORMAT (' (ENTER CHOICE)')
   READ (*,*) K
   IF (K .NE. 1) GO TO 70

C
   WRITE (*,60) DL
60 FORMAT (' LENGTH OF HOUSE (' ,F6.2,')')
   READ (*,*) ADL
   DL=ADL

```

```

61 WRITE (*,62) DW
62 FORMAT (' WIDTH OF HOUSE (' ,F6.2,')')
   READ (*,*) ADW
   DW=ADW
   WRITE (*,63) DC
63 FORMAT (' HEIGHT OF CEILING (' ,F6.2,')')
   READ (*,*) ADC
   DC=ADC
   WRITE (*,64) DOH
64 FORMAT (' WIDTH OF ROOF OVERHANG (' ,F6.2,')')
   READ (*,*) ADOH
   DOH=ADOH
   WRITE (*,65) PITCH
65 FORMAT (' ROOF PITCH (RISE/RUN) (' ,F6.3,')')
   READ (*,*) APITCH
   PITCH=APITCH
   WRITE (*,66) D
66 FORMAT (' SHEATHING THICKNESS (' ,F6.3,')')
   READ (*,*) AD
   D=AD
   GO TO 26
70 IF (K .NE. 2) GO TO 80
   WRITE (*,71) RC
71 FORMAT (' R-VALUE OF CEILING INSULATION (' ,F6.2,')')
   READ (*,*) ARC
   RC=ARC
   WRITE (*,72) RR
72 FORMAT (' TOTAL R-VALUE OF ROOF (' ,F6.2,')')
   READ (*,*) ARR
   RR=ARR
   WRITE (*,75) RS
75 FORMAT (' R-VALUE OF WOOD SHEATHING (' ,F6.2,')')
   READ (*,*) ARS
   RS=ARS
   WRITE (*,73) RES
73 FORMAT (' R-VALUE OF ENDWALLS AND SOFFITS (' ,F6.2,')')
   READ (*,*) ARES
   RES=ARES
   WRITE (*,74) WSHADE
74 FORMAT (' WINDSHADE FACTOR: 1=NO SHADE, 0=FULL SHADING (' ,
1F6.2,')')
   READ (*,*) ASHADE
   WSHADE=ASHADE
   WRITE (*,76) A
76 FORMAT (' ABSORBTIVITY EXTERIOR ROOF SURFACE (' ,F6.2,')')
   READ (*,*) A
   GO TO 26
80 IF (K .NE. 3) GO TO 90
   WRITE (*,81) IH
81 FORMAT (' HOUSE AIR EXCHANGE RATE (VOLUME CHANGES/HR) (' ,F6.2,')')
   READ (*,*) AIH
   IH=AIH
   WRITE (*,82) F
82 FORMAT (' FRACTION OF HOUSE EXFILTRATION ENTERING ATTIC (' ,F6.2,')
1')

```

```

      READ (*,*) AFA
      F=AFA
85  WRITE (*,86) IA
86  FORMAT (' NATURAL ATTIC VENTILATION (AIR CHANGES/HR) (' ,F6.2,')')
      READ (*,*) AIA
      IA=AIA
      WRITE (*,87) AF
87  FORMAT (' ATTIC FAN CAPACITY (CFM) (' ,F6.2,')')
      READ (*,*) AAF
      AF=AAF
      GO TO 26
90  IF (K .NE. 4) GO TO 100
      WRITE (*,91) T(7)-459.67
91  FORMAT (' INDOOR TEMP., F. (' ,F6.2,')')
      READ (*,*) ATEM
      T(7)=ATEM+459.67
      WRITE (*,92) RHI
92  FORMAT (' INDOOR RELATIVE HUMIDITY (' ,F6.2,')')
      READ (*,*) ARHI
      RHI=ARHI
      WRITE (*,93) WMC(1)
93  FORMAT (' MOISTURE CONTENT OF SHEATHING "A" (' ,F6.3,')')
      READ (*,*) AWMCA
      WMC(1)=AWMCA
      WRITE (*,94) WMC(2)
94  FORMAT (' MOISTURE CONTENT OF SHEATHING "B" (' ,F6.3,')')
      READ (*,*) AWMCB
      WMC(2)=AWMCB
      GO TO 26
100 CONTINUE
C
      RETURN
      END

```

SUBROUTINE HEAT

\$DEBUG

C VERSION 7A

C Correction: 5/7/94. Corrected handling of windshade factor

C Date April 15, 1993: updated COMMON block

C Correction: March 2, 1993

C Cloud cover data in range 1 - 10

C Convective heat transfer routine for top and bottom of roof

C from Wilkes (1989). (for other sources see HCON subroutine)

C Infrared radiation routine on basis of Martin and Berdahl,

C Solar Energy vol 33, no 3/4, pp 321-336, 1984

C Revised August 4, 1992, Anton TenWolde

C Major revision August 17, 1992: incorporated SLOPE

```

      COMMON A,AC,AES,AF,AR,ALR,ALF,F,I1,I2,IA,IAF,IFLAG,IH,ITMOIST,
      1JJ,KK,L,NFAN,RC,RES,RHMAX,RR,RS,VA,VH,RHA,RHI,PITCH,VENT,PHI,
      2VLHA,VLHB,T(10),TARR(184,24),RAARR(184,24),WIND(184,24),WSHADE,
      3RBARR(184,24),SKYCOV(184,24),SNOCOV(184,24),TATT(184,24),
      4TRA(185,24),TRB(185,24),OUTDP(184,24),WMCA(185,24),
      5WMCB(185,24),RHAT(184,24),FAN(184,24),TEMPA(184,24),TEMPB(184,24),

```

```

6TEMPOA(184,24),TEMPOB(184,24),AVEMC(1,24),D,IIILAT,SLOPE(6),JJJ
REAL I1,I2,IA,IAF,IH,L
DOUBLE PRECISION AK(6,6),Q(6),X(6)
DIMENSION TOLD(6),TDEFLT(6)

C
C
C Initialize
T(8)=TARR(JJ,KK)+(JJJ-1)*SLOPE(1)+459.67

C
ITERAT=0

C
C If the depth of the snow layer is 1/2 inch or greater, determine
C the heat balance with nodes 4a and 4b set at 32 degrees F.
C Otherwise, go to line 1000 and perform the heat balance for
C all 6 nodes:
IF (SNOCOV(JJ,KK) .LT. 0.5) GO TO 1000
C XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
C Snow-covered roof:
C
C Start iterative loop
200 ITERAT=ITERAT+1
IF (ITERAT.GE.10) THEN
WRITE (6,10)
10 FORMAT(' ERROR: TEMPERATURE CALCULATION DID NOT CONVERGE')
C Assign default temperatures (temperatures at end of first iteration)
DO 201 MI=1,4
T(MI)=TDEFLT(MI)
201 CONTINUE
GO TO 2000

ENDIF
FA=0.15426E-8*(T(2)*T(2)+T(3)*T(3))*(T(2)+T(3))
FB=0.15426E-8*(T(2)*T(2)+T(4)*T(4))*(T(2)+T(4))
DO 210 MI=1,4
TOLD(MI)=T(MI)
210 CONTINUE

C
C For first calculation set all heat transfer coeff. at 1.
IF (ITERAT.EQ.1) THEN
HRA=1.
HRB=1.
HF=1.
ELSE
C Calculate heat transfer coefficients HRA, HRB, HF
TS=T(3)-459.67
TA=T(1)-459.67
PPHI=PHI
AL=ALR
CALL HCON(TS,TA,PPHI,AL,2,0.0,HRA)
TS=T(4)-459.67
CALL HCON(TS,TA,PPHI,AL,2,0.0,HRB)
TS=T(2)-459.67
AL=ALF
CALL HCON(TS,TA,0.,AL,1,0.0,HF)
ENDIF
C

```

```

      AK(1,1)=- (AC*HF)- (F*IH*VH*.018)- (AR/2)* (HRA+HRB)- (AES/RES)
A      - (VENT*.018*VA)
      AK(1,2)=AC*HF
      AK(1,3)=.5*AR*HRA
      AK(1,4)=.5*AR*HRB
      AK(2,1)=-HF
      AK(2,2)=HF+FA/2+FB/2+1/RC
      AK(2,3)=-FA/2
      AK(2,4)=-FB/2
      AK(3,1)=HRA
      AK(3,2)=(AC/AR)*FA
      AK(3,3)=-HRA-(AC/AR)*FA-1/RR
      AK(3,4)=0.0D0
      AK(4,1)=HRB
      AK(4,2)=(AC/AR)*FB
      AK(4,3)=0.0D0
      AK(4,4)=-HRB-(AC/AR)*FB-1/RR
C
      X(1)=-0.018*F*IH*VH*T(7)-(T(8)*AES/RES)-(0.018*VENT*VA*T(8))
      X(2)=T(7)/RC
      X(3)=-VLHA-491.67/RR
      X(4)=-VLHB-491.67/RR
C
      DO 300 I=1,4
300 Q(I)=X(I)
C      Solve the simultaneous equations using the Gauss-Jordan method:
500 DO 530 K=1,3
      DO 515 I=K+1,4
      IF (K .EQ. 1) GO TO 510
      DO 505 J=1,K-1
505 AK(I,K)=AK(I,K)-AK(I,J)*AK(J,K)
510 AK(I,K)=AK(I,K)/AK(K,K)
515 CONTINUE
      DO 525 I=K+1,4
      DO 520 J=1,K
520 AK(K+1,I)=AK(K+1,I)-AK(K+1,J)*AK(J,I)
525 CONTINUE
530 CONTINUE
      DO 540 I=2,4
      DO 535 K=1,I-1
535 Q(I)=Q(I)-AK(I,K)*Q(K)
540 CONTINUE
      DO 555 I=4,1,-1
      IF(I .EQ. 4) GO TO 550
      DO 545 K=I+1,4
545 Q(I)=Q(I)-AK(I,K)*Q(K)
550 Q(I)=Q(I)/AK(I,I)
555 CONTINUE
      DO 560 I=1,4
560 T(I)=Q(I)
C
C      Set temperatures at nodes 4a and 4b to 32 degrees F (491.67 R):
      T(5)=491.67
      T(6)=491.67
C

```

```

C      Set default temperatures
      IF (ITERAT.EQ.1) THEN
          DO 570 MI=1,4
570      TDEFLT(MI)=T(MI)
      ENDIF

C
C      Check for convergence in surface temperatures (change<0.1F)
      NCVNVRG=0
      DO 600 MI=2,4
      IF (ABS(TOLD(MI)-T(MI)).GT.0.1) NCVNVRG=1
600 CONTINUE
      IF (NCVNVRG.EQ.1) GOTO 200
      GO TO 2000

C XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
C      Without snow on the roof:
C
C      Calculate contribution of infrared radiation to sky
1000 TD=OUTDP(JJ, KK)+(JJJ-1)*SLOPE(5)
      CLDAMT=SKYCOV(JJ, KK)+(JJJ-1)*SLOPE(4)
      TO=T(8)
      CALL INFRED(TO, TD, KK, CLDAMT, QINFRD, HINFRD)

C
C      Convert windspeed from knots to feet per hour,
C      and correct for windshading
      V=6077.28*WSHADE*(WIND(JJ, KK)+(JJJ-1)*SLOPE(6))

C
C      Start iterative loop
1200 ITERAT=ITERAT+1
      IF (ITERAT.GE.10) THEN
C      Write error message
          WRITE (6,10)
C      Assign default temperatures (temperatures at end of first iteration)
          DO 1201 MI=1,6
          T(MI)=TDEFLT(MI)
1201 CONTINUE
          GO TO 2000
      ENDIF

C
      FA=0.15426E-8*(T(2)*T(2)+T(3)*T(3))*(T(2)+T(3))
      FB=0.15426E-8*(T(2)*T(2)+T(4)*T(4))*(T(2)+T(4))
      DO 1010 MI=1,6
      TOLD(MI)=T(MI)
1010 CONTINUE

C
C      For first calculation set all heat transfer coeff. at 1.
      IF (ITERAT.EQ.1) THEN
          HRA=1.
          HRB=1.
          HF=1.
          HOA=1.
          HOB=1.
      ELSE
C      Calculate heat transfer coefficients HRA, HRB, HF, HOA, HOB
          TS=T(3)-459.67
          TA=T(1)-459.67

```

```

PPHI=PHI
AL=ALR
CALL HCON(TS,TA,PPHI,AL,2,0.0,HRA)
TS=T(4)-459.67
CALL HCON(TS,TA,PPHI,AL,2,0.0,HRB)
TS=T(2)-459.67
AL=ALF
CALL HCON(TS,TA,0.,AL,1,0.0,HF)
TA=T(8)-459.67
TS=T(5)-459.67
AL=ALR
VV=V
CALL HCON(TS,TA,PPHI,AL,1,VV,HOA)
TS=T(6)-459.67
CALL HCON(TS,TA,PPHI,AL,1,VV,HOB)
ENDIF

```

C

```

AK(1,1)=- (AC*HF) - (F*IH*VH*0.018) - (AR/2.0D0) * (HRA+HRB) - (AES/RES)
A      - (VENT*0.018D0*VA)
AK(1,2)=AC*HF
AK(1,3)=0.5D0*AR*HRA
AK(1,4)=0.5D0*AR*HRB
AK(1,5)=0.0D0
AK(1,6)=0.0D0
AK(2,1)=-HF
AK(2,2)=HF+FA/2.0D0+FB/2.0D0+1.0D0/RC
AK(2,3)=-FA/2.0D0
AK(2,4)=-FB/2.0D0
AK(2,5)=0.0D0
AK(2,6)=0.0D0
AK(3,1)=HRA
AK(3,2)=(AC/AR)*FA
AK(3,3)=-HRA-(AC/AR)*FA-1.0D0/RR
AK(3,4)=0.0D0
AK(3,5)=1.0D0/RR
AK(3,6)=0.0D0
AK(4,1)=HRB
AK(4,2)=(AC/AR)*FB
AK(4,3)=0.0D0
AK(4,4)=-HRB-(AC/AR)*FB-1.0D0/RR
AK(4,5)=0.0D0
AK(4,6)=1.0D0/RR
AK(5,1)=0.0D0
AK(5,2)=0.0D0
AK(5,3)=1.0D0/RR
AK(5,4)=0.0D0
AK(5,5)=-1.0D0/RR-HOA-HINFRD
AK(5,6)=0.0D0
AK(6,1)=0.0D0
AK(6,2)=0.0D0
AK(6,3)=0.0D0
AK(6,4)=1.0D0/RR
AK(6,5)=0.0D0
AK(6,6)=-1.0D0/RR-HOB-HINFRD
X(1)=-0.018D0*F*IH*VH*T(7)-(T(8)*AES/RES)-(0.018D0*VENT*VA*T(8))

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```

X(2)=T(7)/RC
X(3)=-VLHA
X(4)=-VLHB
X(5)=-A*(RAARR(JJ, KK)+(JJJ-1)*SLOPE(2))+QINF RD-T(8)*(HOA+HINF RD)
X(6)=-A*(RBARR(JJ, KK)+(JJJ-1)*SLOPE(3))+QINF RD-T(8)*(HOB+HINF RD)
C
DO 1300 I=1,6
1300 Q(I)=X(I)
C
C Solve the simultaneous equations using the Gauss-Jordan method:
1500 DO 1530 K=1,5
DO 1515 I=K+1,6
IF (K .EQ. 1) GO TO 1510
DO 1505 J=1, K-1
1505 AK(I, K)=AK(I, K)-AK(I, J)*AK(J, K)
1510 AK(I, K)=AK(I, K)/AK(K, K)
1515 CONTINUE
DO 1525 I=K+1,6
DO 1520 J=1, K
1520 AK(K+1, I)=AK(K+1, I)-AK(K+1, J)*AK(J, I)
1525 CONTINUE
1530 CONTINUE
DO 1540 I=2,6
DO 1535 K=1, I-1
1535 Q(I)=Q(I)-AK(I, K)*Q(K)
1540 CONTINUE
DO 1555 I=6, 1, -1
IF (I .EQ. 6) GO TO 1550
DO 1545 K=I+1,6
1545 Q(I)=Q(I)-AK(I, K)*Q(K)
1550 Q(I)=Q(I)/AK(I, I)
1555 CONTINUE
DO 1560 I=1,6
1560 T(I)=Q(I)
C
C
C Set default temperatures
IF (ITERAT.EQ.1) THEN
DO 1570 MI=1,6
1570 TDEFLT(MI)=T(MI)
ENDIF
C
C Check for convergence in surface temperatures (change<0.1F)
NCNVRG=0
DO 1600 MI=2,6
IF (ABS(TOLD(MI)-T(MI)).GT.0.1) NCNVRG=1
1600 CONTINUE
IF (NCNVRG.EQ.1) GOTO 1200
GO TO 2000
C
C End of iterative loops
C XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
2000 TATT(JJ, KK)=T(1)-459.67
RETURN
END

```

```

C XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
C XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
  SUBROUTINE INFRED(TO,TD,IHR,CLDAMT,QINFRED,HINFRED)
C
C   Calculates infrared radiation to and from sky. Part (QINFRED) is
C   subtracted from solar radiation; the rest is handled with a
C   modification of heat transfer coefficient HO (HINFRED)
C   Base of clouds is assumed at 2 km.
C
  EPSRF=0.9
  TDD=(TD-32)/1.8
C   Clear sky emissivity
  EPS0=0.711+0.0056*TDD+0.000073*TDD*TDD+0.013*COS(3.14159*IHR/12)
C   With clouds:
  EPS=EPS0+0.784*(1-EPS0)*CLDAMT/10
  HINFRED=4*0.17117E-8*EPSRF*TO*TO*TO
  QINFRED=HINFRED*(1-EPS)*TO*0.25
  RETURN
  END

  SUBROUTINE HCON(TS,TA,PHI,AL,IFLAG,V,HC)
$DEBUG
C   Version 7
C   Corrected May 7, 1994, Anton TenWolde
C   Latest update August 7, 1992
C
C   Adapted from HCON routine in "Model for roof thermal performance",
C   K.E. Wilkes, ORNL/CON-274, Oak Ridge Nat.Lab., 1989.
C   Limited to flat surface and surfaces with tilt over 2 degrees
C   TS = surface temperature, F
C   TA = air temperature, F
C   PHI = tilt angle, degrees (horizontal=0)
C   AL = characteristic length ,(length + width)/2, ft
C   IFLAG = 1 for surface facing up
C   IFLAG = 2 for surface facing down
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
  NERROR=0
  DT=TS-TA
  ABSPHI=ABS(PHI)
  IF (IFLAG.EQ.2) DT=-DT
C   Calculate film temperature
  IF (ABSPHI.LT.0.001) THEN
    TF=(TS+TA)/2
    TF1=TF
  ELSE
    TF=TS-0.25*(TS-TA)
    TF1=TA+0.25*(TS-TA)
  ENDIF

```

```

TK=(TF+459.67)/1.8
C Check for negative temperatures
IF (TK.LE.0) NERROR=1
IF (TF1.LT.-459.) NERROR=2
IF (NERROR.NE.0) GOTO 100
C
PI=3.14159265
C Thermal conductivity of air, Btu/hr-ft-F
K=0.6325E-5*SQRT(TK)/(1+(245.4*10**(-12/TK))/TK)*241.77
C Dynamic viscosity of air, lb/hr-ft
MU=(145.8*TK*SQRT(TK)/(TK+110.4))*241.9E-7
C Prandtl number
PR=0.788-2.631E-4*TK
IF (PR.LE.0.) NERROR=3
C In case of errors:
IF (NERROR.NE.0) THEN
100 WRITE (6,10) NERROR
10 FORMAT(' ERROR ',I1,' IN CONVECTIVE HEAT TRANSFER COEFFICIENT')
HC=1.
RETURN
ENDIF
C
C Volume expansion coefficient of air, perfect gas
BETA=1/(TF1+459.67)
C Density of air, lbs/ft3
RHO=22.0493/TK
C Kinematic viscosity
NU=MU/RHO
C Specific heat of air, Btu/lb-ft
CP=(3.4763+1.066E-4*TK)*0.068559
C Raleigh number
RA=4.16975E8*BETA*RHO*CP*ABS(DT)*(AL**3)/(NU*K)
C
C Calculate convection coefficient (w/o forced convection)
C Branch to different correlations depending on surface orientation
C Roof is considered flat if tilt is less than 2 degrees
IF (ABSPHI.LT.2.0) THEN
C Horizontal surface (0-2 degrees)
IF (DT.GE.0.0) THEN
C Heat flow upwards
NUS=0.15*RA**0.33333
IF (RA.LT.8.0E6) NUS=0.54*RA**0.25
ELSE
C Heat flow down
NUS=0.85*RA**0.2
ENDIF
ELSE
C Tilted surface (over 2 degrees)
IF (DT.GT.0.0) THEN
C Heat flow upwards
C Calculate critical Grasshof number
GRC=10**((PHI/(1.1870+0.0870*PHI))
IF (ABSPHI.LT.15.) GRC=1.0E6
IF (ABSPHI.GT.75.) GRC=5.0E9
GR=RA/PR

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```

        NUS=0.56*(RA*COS((90.-PHI)*PI/180))**0.25
        IF (GR.GT.GRC) NUS=0.14*(RA**0.33333-(GRC*PR)**0.33333)
A          +NUS
        ELSE
C          Heat flow down
          NUS=0.56*(RA*COS((90.-PHI)*PI/180))**0.25
        ENDIF
      ENDIF
      HCN=NUS*K/AL
C      Set a minimum of 0.1 for HCN to avoid swings in
C      iterative calculations
      HCN=MAX(0.1,HCN)
      IF (V.LE.1.0E-12) THEN
        HC=HCN
        RETURN
      ENDIF
C
C      Calculate forced convection coefficient
      RE=V*AL/NU
      IF (RE.LT.5.0E5) THEN
        NUS=0.664*(PR**0.33333)*SQRT(RE)
      ELSE
        NUS=(PR**0.33333)*(0.037*(RE**0.8)-850)
      ENDIF
      HCF=NUS*K/AL
C      Combine natural and forced convection coefficients
      HC=(HCF**3+HCN**3)**0.3333333
      RETURN
      END

      SUBROUTINE MOIST(WMC,WEXTRA)
$DEBUG
C VERSION 7A
C April, 1993
C Works with outdoor dewpoint temperature and cloud cover data 0-10
C
C This version of the moisture balance subroutine utilizes a three-layer
C system to represent the plywood sheathing. The first and second layers
C make up the first ply (1/8") facing the interior of the attic.
C The third layer makes up the remaining thickness of the plywood.
C
C History:
C Revised August 4, 1992 by Anton TenWolde
C Revised August 8, 1992 by Anton TenWolde: introduced surplus moisture
C storage and carry over to next time iteration (WEXTRA).
C Revised August 11, 1992: simplified diffusion coefficient;
C [reintroduced liquid transfer (proportional to delta MC)](removed 8/18)
C Revised August 12, 1992: Limited moisture loss from sheathing to
C equilibrium MC with attic air when RH attic=100%;
C Adjusted definition of WEXTRA
C Revised August 13, 1992: added messages when equilibrium limits are
C invoked
C Revised August 14, 1992: added temperature protection for PSAT

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C      August 15, 1992: added MC protection for PSAT
C Major revision August 17, 1992: incorporated SLOPE, synchronized timing
C of output reports
C August 18, 1992: tightened latent heat convergance criterion to 5%;
C removed liquid transfer; fixed error in WEXTRA calculation
C
C February 28, 1993: Created version 7: 3-layered sheathing, set TLAYER(1)
C and TLAYER(3) at surface temperature, changed definition of MCAVG(5) and
C MCAVG(6)
C April 15, 1993: incorporated variable sheathing thickness and R-value
C
      DOUBLE PRECISION WMC(6),WRA,WRB,WW(4),ULAYER(6),WDA,WDB,SATMC,
      1WHR,WEXTRA,WRAVVL,WRBVVL,WRMIN
      COMMON A,AC,AES,AF,AR,ALR,ALF,F,I1,I2,IA,IAF,IFLAG,IH,ITMOIST,
      1JJ,KK,L,NFAN,RC,RES,RHMAX,RR,RS,VA,VH,RHA,RHI,PITCH,VENT,PHI,
      2VLHA,VLHB,T(10),TARR(184,24),RAARR(184,24),WIND(184,24),WSHADE,
      3RBARR(184,24),SKYCOV(184,24),SNOCOV(184,24),TATT(184,24),
      4TRA(185,24),TRB(185,24),OUTDP(184,24),WMCA(185,24),
      5WMCB(185,24),RHAT(184,24),FAN(184,24),TEMPA(184,24),TEMPB(184,24),
      6TEMPOA(184,24),TEMPOB(184,24),AVEMC(1,24),D,IIILAT,SLOPE(6),JJJ
      REAL I1,I2,IA,IAF,IH,L,MCAV(4)
      DIMENSION TLAYER(6),DW(4)
C
      LERROR=0
C      Set the surface diffusion coefficient:
      HDR=1.1
C
C      Read the outdoor dewpoint temperature (F) and convert to R:
      DPO=OUTDP(JJ,KK)+(JJJ-1)*SLOPE(5)+459.67
C
C      Calculate humidity ratios for indoor air, outdoor air, surface of
C      sheathing "A", and surface of sheathing "B", respectively:
      HRI=AHR(T(7),RHI)
      HRO=AHR(DPO,1.0)
10     WDA=WMC(1)
      WDB=WMC(2)
      HRRR=WHR(T(3),WDA)
      HRRB=WHR(T(4),WDB)
C
C
C      Determine the temperature of the interface between the 1/8" bottom ply
C      of the sheathing and the remaining mass of each sheathing:
C      NOTE: The R-value of the shingles = R roof - R sheathing
C      E.g.: R roof = 1.04, R sheathing = 0.6, then R shingles = 0.44
C
      TINTA=(0.125/D)*(RS/RR)*(T(5)-T(3))+T(3)
      TINTB=(0.125/D)*(RS/RR)*(T(6)-T(4))+T(4)
C
C      Determine temperature at each node: 1st layer is at surface temperature,
C      2nd and 3rd layers are at temperature in middle of layer
      TLAYER(1)=T(3)
      TLAYER(2)=T(4)
      TLAYER(3)=0.75*(TINTA-T(3))+T(3)
      TLAYER(4)=0.75*(TINTB-T(4))+T(4)
      TOUTA=T(3)+RS*(T(5)-T(3))/RR

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TOUTB=T(4)+RS*(T(6)-T(4))/RR
TLAYER(5)=(TOUTA+TINTA)/2
TLAYER(6)=(TOUTB+TINTB)/2
C
C
C Calculate the humidity ratio at dewpoint for sheathing surfaces:
DPTSA=PSAT(T(3))/48.1
DPTSB=PSAT(T(4))/48.1
C
C Set humidity ratios for each sheathing surface to the minimum of
C the humidity ratios based on current MC and humidity ratios based
C on dewpoint temperatures:
C
HRRAAIR=MIN(HRRA,DPTSA)
HRRBAIR=MIN(HRRB,DPTSB)
C
C
C Calculate the humidity ratio of the attic air (revised 8/7/92):
HRA=(WEXTRA+0.075*F*IH*VH*HRI+0.075*VENT*VA*HRO+AR*HDR*HRRAAIR*
a0.5+AR*HDR*HRRBAIR*0.5)/(0.075*F*IH*VH+0.075*VENT*VA+AR*HDR)
C
C Calculate the saturation humidity ratio of the attic air:
HRASAT=PSAT(T(1))/48.1
C Convert the humidity ratio to relative humidity:
RHA=HRA/HRASAT
C
C If attic RH is less than 100%:
IF (RHA .LE. 1.0) THEN
WRAVVL=HDR*(HRA-HRRAAIR)
WRBVVL=HDR*(HRA-HRRBAIR)
MRH100=0
ELSE
C Attic RH=100%:
HRA=HRASAT
RHA=1
MRH100=1
WRAVVL=HDR*(HRA-HRRAAIR)
WRBVVL=HDR*(HRA-HRRBAIR)
C The next section only applies if moisture is driven from sheathing
C surface A.
IF (WRAVVL.LT.0.0D0) THEN
C Calculate equilibrium MC at surface. This is minimum MC of
C surface and moisture loss is allowed down to this minimum MC
C Note: WRAVVL is negative: WRMIN is a maximum negative flow
Z=HRA/(PSAT(T(3))*15.8514)
WMCEQL=0.029+169.6*Z-269200*Z**2+2.2E08*Z**3
WRMIN=0.08125*6*(WMCEQL-WMC(1))
IF (WRMIN.GE.0.0D0) WRMIN=0.0D0
IF (WRAVVL.LT.WRMIN) THEN
WRAVVL=WRMIN
WRITE(6,28)
28 FORMAT(' WRAVVL has been limited')
ENDIF
ENDIF
C Same for B side:

```

```

IF (WRBVVL.LT.0.0D0) THEN
  Z=HRA/(PSAT(T(4))*15.8514)
  WMCEQL=0.029+169.6*Z-269200*Z**2+2.2E08*Z**3
  WRMIN=0.08125*6*(WMCEQL-WMC(1))
  IF (WRMIN.GE.0.0D0) WRMIN=0.0D0
  IF (WRBVVL.LT.WRMIN) THEN
    WRBVVL=WRMIN
    WRITE(6,29)
29    FORMAT(' WRBVVL has been limited')
  ENDIF
ENDIF
ENDIF
ENDIF
C
WRA=0.5*AR*WRAVVL/6
WRB=0.5*AR*WRBVVL/6
C
C Bypass latent heat section if IIIILAT=0 or LERROR=1
IF (IIIILAT.EQ.0.OR.LERROR.EQ.1) GOTO 53
C
C Calculate the heat flux attributed to the latent heat of
C vaporization for each sheathing surface:
VVLHA=WRAVVL*1050
VVLHB=WRBVVL*1050
C
C If this is the first iteration of the moisture subprogram,
C prepare for next iteration (latent heat).
IF (ITMOIST.EQ. 0) GO TO 200
C
C Compare the new latent heat values with the old. If the new value
C is very small or within 5% of the old or the difference is very small,
C set the flag and continue:
IF (ABS(VVLHA-VLHA).LT.1.0E-20.OR.ABS(VVLHA).LT.1.0E-20) GOTO 50
IF (ABS(VVLHA-VLHA).GT.ABS(VLHA*.05)) GOTO 200
50 IF (ABS(VVLHB-VLHB).LT.1.0E-20.OR.ABS(VVLHB).LT.1.0E-20) GOTO 53
IF (ABS(VVLHB-VLHB).GT.ABS(VLHB*.05)) GOTO 200
53 IFLAG=1
ITMOIST=0
C
C If RH attic =100%, calculate amount of "surplus" moisture, lbs/hr:
C Note: surplus is added to moisture balance in next time iteration.
WEXTRA=0.0D0
IF (MRH100.EQ.1) WEXTRA=0.075*(F*IH*VH*(HRI-HRASAT)-
a VENT*VA*(HRASAT-HRO))-6*WRA-6*WRB
C
IF (WEXTRA.GT.0.0D0) THEN
  WRITE (6,31) WEXTRA
ELSE
  WEXTRA=0.0D0
ENDIF
31 FORMAT (' ', 'EXCESS MOISTURE (LBS/HR): ',G9.2)
C
C
C These next steps determine wood humidity ratios for the sheathing
C layers, based on current MC and temps:
SATMC=.3

```

```

DO 100 J=1,5,2
C
C If the wood moisture content is above saturation, humidity ratio is
C the same as at saturation (liquid transfer ignored).
  IF (WMC(J)-SATMC) 55,55,60
55 WDA=WMC(J)
  U LAYER(J)=WHR(T LAYER(J),WDA)
  GO TO 62
60 U LAYER(J)=WHR(T LAYER(J),SATMC)
62 CONTINUE
  IF (WMC(J+1)-SATMC) 65,65,70
65 WDB=WMC(J+1)
  U LAYER(J+1)=WHR(T LAYER(J+1),WDB)
  GO TO 72
70 U LAYER(J+1)=WHR(T LAYER(J+1),SATMC)
72 CONTINUE
C
100 CONTINUE
C
C Determine diffusion coefficients for moisture transfer between
C layers, and calculate amount of moisture transferred:
DO 110 III=1,4
C
C First, calculate average MC between adjacent sheathing layers:
IF (WMC(III).LT.1000.0D0.AND.WMC(III+2).LT.1000.0D0) THEN
MCAV(III)=WMC(III)/2+WMC(III+2)/2
ELSE
MCAV(III)=SATMC
ENDIF
C
C If the average MC is above saturation, calculate the interior
C diffusion coefficient at saturation; also check for negative MC.
IF (MCAV(III).GT.SATMC) MCAV(III)=SATMC
IF (MCAV(III).LT.0) MCAV(III)=1.0E-10
C Calculate transport coefficients
DW(III)=EXP(-9.37455+19.97645*MCAV(III))
110 CONTINUE
C Calculate the amount of moisture transferred between first two
C sheathing layers (every 1/6 hour):
DO 130 III=1,2
WW(III)=(DW(III)*AR/12)*(U LAYER(III)-U LAYER(III+2))/((1.0/16)/12)
130 CONTINUE
C Same for layers 5 and 6
DO 170 III=3,4
WW(III)=(DW(III)*AR/12)*(U LAYER(III)-U LAYER(III+2))
a/(((D-.0625)/2)/12)
170 CONTINUE
C
C Given the following mass for sheathing surface and interior wood
C layers, calculate the new MC for each portion:
WMASS=(AR/2)*((.125/2)/12)*31.2
WMC(1)=WMC(1)+(WRA-WW(1))/WMASS
WMC(2)=WMC(2)+(WRB-WW(2))/WMASS
WMC(3)=WMC(3)+(WW(1)-WW(3))/WMASS
WMC(4)=WMC(4)+(WW(2)-WW(4))/WMASS

```

```

WMC(5)=WMC(5)+(WW(3))/((AR/2)*((D-.125)/12)*31.2)
WMC(6)=WMC(6)+(WW(4))/((AR/2)*((D-.125)/12)*31.2)
C
C Assign RH and temperatures at start of hour to output array:
  IF (JJJ.EQ.1) THEN
    RHAT(JJ, KK)=RHA
    TEMPA(JJ, KK)=T(3)-459.67
    TEMPB(JJ, KK)=T(4)-459.67
    TEMPOA(JJ, KK)=TOUTA-459.67
    TEMPOB(JJ, KK)=TOUTB-459.67
  ENDIF
C
C Calculate average MC for the sheathing and at end of hour.
C Assign MC values at end of hour to next hour out put array:
  IF (JJJ.EQ.6) THEN
    NXTHR=KK+1
    NXTDAY=JJ
    IF (KK.EQ.24) THEN
      NXTHR=1
      NXTDAY=JJ+1
    ENDIF
    TRA(NXTDAY, NXTHR)=((WMC(1)+WMC(3))/2)*(.125/D)
A  +WMC(5)*((D-.125)/D)
    TRB(NXTDAY, NXTHR)=((WMC(2)+WMC(4))/2)*(.125/D)
A  +WMC(6)*((D-.125)/D)
C Assign current calculated MC values to output arrays:
    WMCA(NXTDAY, NXTHR)=WMC(1)
    WMCB(NXTDAY, NXTHR)=WMC(2)
  ENDIF
C
  GO TO 210
C
C Preparation for next latent heat iteration:
200 ITMOIST=ITMOIST+1
  IF (ITMOIST.GE.10) THEN
    WRITE (6,202)
202   FORMAT (' ERROR: LATENT HEAT ITERATIONS DID NOT CONVERGE')
C   Substitute temperatures and mc's without latent heat
    LERROR=1
    VVLHA=0.
    VVLHB=0.
  ENDIF
  VLHA=VVLHA
  VLHB=VVLHB
  CALL HEAT
  GO TO 10
C
C
210 CONTINUE
C
  RETURN
  END
C
C
C THE FOLLOWING FUNCTION RETURNS AN AIR HUMIDITY RATIO WHEN GIVEN

```

```

C   AIR TEMP. AND RELATIVE HUMIDITY
C
C   FUNCTION AHR(TEM,RH)
C   AHR=RH*PSAT(TEM)/48.1
C   RETURN
C   END
C
C
C   THE FOLLOWING FUNCTION RETURNS THE SATURATED VAPOR PRESSURE WHEN
C   GIVEN AIR TEMP (vapor pressure in inch Hg., temperature in degree R)
C
C   FUNCTION PSAT(TEM)
C   Set limits to prevent overflow
C   IF (TEM.LT.70) THEN
C   EW=0.
C   ELSE IF (TEM.GT.671.69) THEN
C   EW=1013.246
C   Note: = saturation pressure at steam point, in mb
C   ELSE
C   RATIO=671.69/TEM
C   EWEXP=-7.90298*(RATIO-1)+5.02808*LOG10(RATIO)-
A   0.13816E-06*(10**(11.344*(1-1/RATIO))-1)+
B   .81328E-02*(10**(-3.49149*(RATIO-1))-1)+3.005715
C   Check to prevent overflow
C   IF (EWEXP.LT.-30) EWEXP=-30
C   IF (EWEXP.GT.30) EWEXP=30
C   EW=10**EWEXP
C   END IF
C   PSAT=EW*.02953
C   RETURN
C   END
C
C
C   THE FOLLOWING FUNCTION RETURNS A WOOD HUMIDITY RATIO WHEN GIVEN
C   WOOD TEMPERATURE (degree R) AND MOISTURE CONTENT (ratio)
C
C   FUNCTION WHR(TEM,XMC)
C   DOUBLE PRECISION WHR,XMC,YMC,OMEGA50
C   IF (XMC.GT.0.0D0) THEN
C   YMC=XMC
C   IF (YMC.GT.1.0D0) YMC=1.0D0
C   Calculate humidity ratio according to Cleary's formula at 50 F
C   Then adjust for temperature
C   (EXP(50F/28.6)=5.744551, saturation pressure @ 50F = 0.3624 in Hg)
C   OMEGA50=5.744551*(-.49E-03+.0172*YMC-.06*YMC**2+.076*YMC**3)
C   WHR=OMEGA50*PSAT(TEM)/0.3624
C   IF (WHR.LT.0.0D0) WHR=0.0D0
C   ELSE
C   WHR=0.0D0
C   ENDIF
C   RETURN
C   END

```

Appendix C—SUNDAT Program

The SUNDAT program can be used to calculate solar radiation on each roof surface. The program calculates the ratio of radiation on a surface with a specified tilt and orientation and on a horizontal surface at a given location and hour. The calculation is performed for a cloudless sky, apportioning direct and diffuse radiation based on chapter 27 of the *ASHRAE Handbook of Fundamentals* (1989). This ratio is then applied to measured solar radiation data (horizontal surface) to obtain solar radiation incident on the specified tilted surface. SUNDAT produces solar radiation input files for the main program. In the main program, radiation absorption is obtained by multiplying incident radiation by the roof's solar absorptance. Inputs to the program are measured solar radiation on horizontal surface (Langley units), latitude, longitude, time zone, roof tilt angle (degrees from horizontal), and roof orientation. To generate the solar data for one building, SUNDAT has to be run for each roof surface (two orientations), using the same solar radiation input data.

A listing of the SUNDAT program follows below:

```
C  Program SUNDAT
C  Version 2, Date May 12, 1994;
C  revised July 19, 1994: added zero divide protection if S(13)=0
C  revised July 15, 1994: added zeroing of output array (initialization)
C  revised June 7, 1994: fixed old mistake in program
C  revised June 6, 1994 (changed diffuse radiation on surface calculations)
C  Based on SUN4 program (does not use cloud cover data)
C  Calculates solar radiation on roof surface from solar radiation data
C  for horizontal surface (in Btu/h.ft2)
C  Use only for tilted roof surfaces
      REAL LATD, LONG, MERID, LOND
      INTEGER FDAY, LDAY, LCOUNT
      CHARACTER*12 FILENM
      CHARACTER*12 FNAME
      DIMENSION A0(5), A1(5), A2(5), A3(5), B1(5), B2(5), B3(5), SRAD(184, 24),
1RADDAT(184, 24)
      DOUBLE PRECISION S(35)
      DATA A0/0.302, -0.0002, 368.44, 0.1717, 0.0905/,
2 A1/-22.93, 0.4197, 24.52, -0.0344, -0.0410/,
3 A2/-0.229, -3.2265, -1.14, 0.0032, 0.0073/,
4 A3/-0.243, -0.0903, -1.09, 0.0024, 0.0015/,
5 B1/3.851, -7.351, 0.58, -0.0043, -0.0034/,
6 B2/0.002, -9.3912, -0.18, 0., 0.0004/,
7 B3/-0.055, -0.3361, 0.28, -0.0008, -0.0006/
C  S(1) = latitude, degrees (+ North, - South)
C  S(2) = longitude, degrees (+ West, - East)
C  S(3) = time zone number, standard time
C  Atlantic 4
C  Eastern 5
C  Central 6
C  Mountain 7
C  Pacific 8
C  S(4) = days (from start of year)
C  S(5) = hour, after midnight
C  S(6) = daylight saving time indicator (set at 0)
C  S(7) = ground reflectivity
C  S(8) = clearness number
C  S(9) = azimuth angle, degrees from south
C  S(10) = tilt angle, degrees from horizon
C  S(11) = sun rise time
C  S(12) = sunset time
C  S(13) = cosine of angle between ray and normal (horiz. surface)
```

```

C   S(14) = cosine of angle between ray and West
C   S(15) = cosine of angle between ray and South
C   S(16) = direction cosines normal to surface
C   S(17),S(18) = angles
C   S(19) = cosine of incidence angle
C   S(20) = solar altitude angle
C   S(21) = solar azimuth angle
C   S(22) = diffuse sky radiation on horizontal surface
C   S(23) = diffuse ground reflected radiation
C   S(24) = direct normal radiation
C   S(25) = total solar radiation intensity on surface
C   S(26) = diffuse sky radiation intensity, for roof tilts >45 degree
C   S(27) = ground reflected diffuse radiation intensity
C   S(28) = sun declination angle, degrees
C   S(29) = equation of time, hours
C   S(30),S(31),S(32) = solar factors
C   S(33) = cloud cover modifier
C   S(34) = intensity of direct solar radiation on surface
C   S(35) = hour angle, degrees
      S(6)=0
      S(7)=0.2
      S(8)=1.
      S(33)=1.
      PI=3.1415927
C
      WRITE (*,2)
      2 FORMAT (' ENTER DAYS OF YEAR TO BE INCLUDED IN FILE')
      WRITE (*,3)
      3 FORMAT (' FIRST DAY '\)
      READ (*,*) FDAY
      WRITE (*,4)
      4 FORMAT (' LAST DAY '\)
      READ (*,*) LDAY
      WRITE (*,15)
      15 FORMAT (' LATITUDE (DEGREES, NORTH = +, SOUTH = -)'\)
      READ (*,*) S(1)
      WRITE (*,16)
      16 FORMAT (' LONGITUDE (DEGREES, + = WEST, - = EAST)'\)
      READ (*,*) S(2)
      WRITE (*,17)
      17 FORMAT (' TIMEZONE (ATL=4, EAST=5, CENTR=6, MOUNT=7,PAC=7)'\)
      READ (*,*) S(3)
C
      IDAYS=LDAY-FDAY+1
C
C   Read in solar radiation data
      WRITE (*,8)
      8 FORMAT (' ENTER NAME OF FILE CONTAINING SOLAR RADIATION DATA '\)
      READ (*,7) FNAME
      OPEN (7,FILE=FNAME,STATUS='OLD')
      READ (7,*) ((RADDAT(IROW,ICOL), ICOL=1,24), IROW=1,IDAYS)
      CLOSE (7)
C
      1000 WRITE (*,1)
      1 FORMAT (' ENTER NAME OF FILE TO BE CREATED '\)

```

```

      READ (*,7) FILENM
C
      WRITE (*,5)
5  FORMAT (' ENTER ROOF TILT ANGLE (DEGREES FROM HORIZONTAL) '\)
      READ (*,*) S(10)
      WRITE (*,6)
6  FORMAT (' ENTER ROOF SURFACE AZIMUTH ANGLE (DEGREES FROM SOUTH '\
1'  + = WEST, - = EAST)'\)
      READ (*,*) S(9)
C
      7  FORMAT (A12)
C
C Initialize output array (added on 7/15/94)
      DO 100 MM=1,184
      DO 100 MMM=1,24
      SRAD(MM,MMM)=0.
100  CONTINUE
C
      LCOUNT=0
C
      DO 1300 JJ=FDAY,LDAY
      S(4)=JJ
      WRITE (*,200) JJ
200  FORMAT(' DAY: ',I3)
      LCOUNT=LCOUNT+1
      DO 1200 KK=1,24
      S(5)=KK-1.
C
      X=2*PI/366.*S(4)
      C1=COS(X)
      C2=COS(2*X)
      C3=COS(3*X)
      S1=SIN(X)
      S2=SIN(2*X)
      S3=SIN(3*X)
      DO 10 K=1,5
      KS=(K-1)+28
10  S(KS)=A0(K)+A1(K)*C1+A2(K)*C2+A3(K)*C3+B1(K)*S1+B2(K)*S2+B3(K)*S3
      S(29)=S(29)/60.
      LATD=S(1)
      LONG=S(2)
      MERID=15*S(3)
      LOND=LONG-MERID
      Y=S(28)*PI/180.
      YY=LATD*PI/180.
      HP=-TAN(Y)*TAN(YY)
      TR=12/PI*ACOS(HP)
      S(11)=(12-TR)-S(29)+LOND/15.
      S(12)=24.-S(11)
      H=15*(S(5)-12+S(3)+S(29)-S(6))-S(2)
      S(35)=H
      S13=SIN(YY)*SIN(Y)+COS(YY)*COS(Y)*COS(H*PI/180.)
      S(13)=S13
      HP1=180.*ACOS(HP)/PI
      X1=ABS(HP1)

```

```

X2=ABS(H)
IF (X1.LT.X2) THEN
  DO 140 J=14,27
140  S(J)=0.
    S(34)=0.
    GO TO 150
  ENDIF
C
20  S(14)=COS(Y)*SIN(H*PI/180.)
  COSSSQ=1.-S(13)*S(13)-S(14)*S(14)
  IF (COSSSQ.LE.0) THEN
    S(15)=0
  ELSE
    S(15)=SQRT(COSSSQ)
  ENDIF
  STEST=S(15)
  STEST1=COS(H*PI/180.)-TAN(Y)/TAN(YY)
  IF (STEEST1) 40,30,30
30  S(15)=STEEST
  GO TO 50
40  S(15)=-STEEST
50  IF (S(13).GE.1) THEN
    S(20)=PI/2
  ELSEIF (S(13).LE.-1) THEN
    S(20)=-PI/2
  ELSE
    S(20)=ASIN(S(13))
  ENDIF
C fixed error on 6/7/94
  RATIO=S(14)/COS(S(20))
  IF (S(15)) 70,60,60
60  IF (RATIO.GE.1) THEN
    S(21)=PI/2
  ELSEIF (RATIO.LE.-1) THEN
    S(21)=-PI/2
  ELSE
    S(21)=ASIN(RATIO)
  ENDIF
  GO TO 80
70  IF (RATIO.GE.1) THEN
    S(21)=PI/2
  ELSEIF (RATIO.LE.-1) THEN
    S(21)=3*PI/2
  ELSE
    S(21)=PI-ASIN(RATIO)
  ENDIF
80  S(20)=180.*S(20)/PI
    S(21)=180.*S(21)/PI
C
C Calculate direct normal, diffuse and ground reflected radiation
C (no clouds)
C Revision 7/19/94
  IF (S(13).LT.0.000001) THEN
    S(24)=0.
  ELSE

```

```

        S(24)=S(30)*S(8)*S(33)*EXP(-S(31)/S(13))
    ENDIF
C end of revision
    S(22)=S(32)*S(24)/S(8)/S(8)
    S(23)=S(7)*(S(22)+S(24)*S(13))
C   CALCULATE SOLAR RADIATION ON SURFACE (CLOUDLESS)
    WT=S(10)*PI/180.
    WA=S(9)*PI/180.
    S(16)=COS(WT)
    S(17)=SIN(WA)*SIN(WT)
    S(18)=COS(WA)*SIN(WT)
    S(19)=S(16)*S(13)+S(17)*S(14)+S(18)*S(15)
    S(34)=S(24)*S(19)
C If roof tilt <45, diffuse radiation same as on horizontal surface
C Tilt >45: use equations for vertical surface
    IF (S(10).LT.45.) THEN
        Y=1.
    ELSE
        Y=0.55+0.437*S(19)+0.313*S(19)**2
        IF (S(19).LE.-0.2) Y=0.45
    ENDIF
    IF (S(19)) 110,110,120
110 S(19)=0.
    S(34)=0.
120 CONTINUE
    S(26)=S(22)*Y
    S(27)=S(23)*(1-S(16))/2.
    S(25)=S(34)+S(26)+S(27)
    IF (S(25).LT.0.000001) S(25)=0.00
C
C Calculate radiation on horizontal surface
150 SHORIZ=S(24)*S(13)+S(22)
C
C Convert measured solar data from Langleys to Btu/h.ft2
    SDATA=RADDAT(LCOUNT, KK)
    IF (SDATA.GT.9000) SDATA=0.
    IF (SDATA.LT.0.) SDATA=0.
    SDATA=0.3687*SDATA
C
    IF (SHORIZ.LT.0.000001) THEN
C     If SDATA not zero, radiation is assumed to be diffuse:
        SRAD(LCOUNT, KK)=SDATA
    ELSE
C     Calculate adjustment factor from measured data (factor includes
C     effect of cloudcover)
        FACTOR=SDATA/SHORIZ
        SRAD(LCOUNT, KK)=FACTOR*S(25)
    ENDIF
C
1200 CONTINUE
1300 CONTINUE
    OPEN(7, FILE=FILENM, STATUS='NEW')
    WRITE (7,1500) ((SRAD(L,I), I=1,24), L=1,LCOUNT)
    CLOSE (7, STATUS='KEEP')
1500 FORMAT (' ',184(24(F7.2, ' '),/))

```

C

```
WRITE (*,300)
300 FORMAT(' MORE RUNS WITH SAME MEASURED SOLAR DATA? (0=NO 1=YES)'\)
READ (*,*) NRUN
IF (NRUN.EQ.1) GO TO 1000
END
```