Technical Support for Development of an Attic Simulation Model for the California Energy Commission

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Technical Support for the Development of an Attic Simulation Model for the California Energy Commission

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Introduction

The California Energy Commission (CEC) is developing a new attic simulation model for assessing residential energy performance within its Title 24 residential compliance methodology. Within this project, we are providing technical support to assist Bruce Wilcox and CEC in development of the model based on Florida Solar Energy Center (FSEC) experience with similar models. We assisted the effort by using data from FSEC instrumented facilities to help verify the eventual simulation. We also outlined critical issues for modeling with the development of the simulation. Given the importance of attic ventilation, we are also conducting new studies of varied ventilation rates in the late summer of 2005 to assist the evaluation.

The simulation results have been applied to empirical results from a variety of sources, including those in California, which had been extensively monitored. Analysis on the empirical data compared with computer simulation is used to suggest key factors for the attic thermal model that will allow it to reliably predict attic thermal performance and associated impacts on space cooling and space heating.

Background

The importance and complexity of accurate modeling of thermal processes in residential attics has been acknowledged for some time. The preponderance of the research has shown that radiation accounts for the majority of the total heat transfer across typical attic airspaces. Beyond radiatin, other studies suggest that attic ventilation plays a key role in the total heat gain across typical attics (Hinrichs, 1962). However, research on attic radiant barrier systems (RBS) suggests that attic ventilation rates and ventilation air flow paths become relatively more important when the roof in the attic interior surfaces have a very low emittance (Joy, 1958).

For the project, Florida Solar Energy Center used its extensive experience with attic monitoring attics in laboratory and field experiments as well as much work on attic thermal performance simulation models. This work on models and data has been used within the project to assist California in developing detailed and verified attic simulation models.

A relevant summary of FSEC experience with attic/roofing technologies:

1. <u>Radiant barrier Systems (RBS)</u>: FSEC has very extensive experience with RBS technology (Fairey and Beal, 1988). RBS is a mature energy-saving technology having first been evaluated in the late 1950s (Joy, 1958). Industry now manufactures roof plywood decking with the RBS already adhered to its underside. Effective attic

ventilation can significantly improve ceiling flux reductions from radiant barriers (Parker and Sherwin, 1998).

2. <u>Cool roofing</u>: FSEC has led empirical research on the impact of cool roofing materials on reducing air conditioning needs in laboratory facilities and unoccupied and occupied full scale homes (Parker et al., 1998; Parker et al., 2000). These data will be made available to assist with validation of the simulation model.

3. <u>Sealed attic construction</u>: FSEC had performed comparative experiments on sealed attic construction for the U.S. Department of Energy that has shown the promise and pitfalls of this new attic construction method. Empirical data from these experiments have been made available with in the project as well as test cell data from the Flexible Roof Facility (Parker et. al, 2000).

4. <u>Attic ventilation</u>: FSEC has conducted empirical studies of differing attic ventilation rates (Chandra and Beal, 1992) which will be supplemented by further experiments in the course of the summer of 2005.

5. <u>Attic thermal simulations</u>: FSEC has created three different attic simulations and has used its experience in this area to support the attic modeling effort. (Fairey and Swami, 1988, Parker et al., 1991 and Parker, 2004) FSEC also used the ASTM C-1340 procedure (Wilkes et al., 1991). This is a response-factor computer calculation method to estimate the heat gain or loss though residential ceiling systems using a computer analysis tool developed by Oak Ridge National Laboratories (ORNL).

List of Modeling Issues for Attic Model

We identified a number of potential modeling issues associated with creating a successful attic simulation. These take into account the fundamental issues and physical processes associated with thermal performance. Below we outline the specific issues and their attributes. A primary aim is to address the major physical process and first order interactions of the following measures within the CEC attic simulation model.

1) Roofing Materials library
   - Tile
   - Shingle
   - Metal
   - Surface reflectances and emissivities

2) Radiation modeling
   - Simplified characterization
   - Radiant barriers

3) Attic ventilation
   - Ridge vs. soffit impact
   - Gable vs. hip
   - Measured data
   - Need for simplified geometry for eventual model

4) Insulation conductivity to changing temperature
   - Available in FSEC simplied model/ STAR model

5) Roof mass
   - Construction library
   - Tile, shingle and metal

6) Barrel tile vs. flat tile
   - Airspace impacts
   - Ventilation impacts based on batten arrangement

7) Standard construction properties
   - Wood members, rafters etc.
   - Framing fractions.

8) Sealed attic modeling (key parameters and guidance on inputs)
   - How sealed?
   - Impact on duct systems.

9) Roof surface convective heat transfer
   - Accurate adjustment of TMY wind speeds to yield appropriate rooftop values
   - Suitable calculation scheme for various Reynolds numbers

10) Interior surface convective heat transfer in attic (impact of uncertainties)

11) Night sky irradiance modeling

12) Impact of rain/dew condensation on roof surface temperatures

13) Cathedralized ceilings (thermal properties)

14) Impact of parallel heat transfer due to ceiling rafters, recessed cans, attic hatches etc.

15) Pressure interactions with main zone on infiltration from attic

16) Interaction with duct heat transfer and leakage.

Existing Attic Simulation Models

A number of previous investigators have developed models to simulate attic thermal performance. Joy (1958) created a steady state attic heat balance model in order to generalize his experimental study of attic thermal performance. As described by Wilkes (1979), the model solves a series of simultaneous differential equations which considers inside and outside boundary conditions, direct radiation exchange between the inside roof surface and floor and ventilation. The model did not accommodate capacitance, temperature dependent convective heat transfer coefficients or heat transfer through non-roof/non-floor surfaces such as gable roof ends. Blancett et al., (1970) created a transient attic simulation for the Electric Power Research Institute (EPRI) which remedied some of these faults and allowed time-related calculation of attic performance. However, this model did not explicitly model radiative transfer, assumed the attic air was well mixed and treated heat transfer coefficients as non-temperature dependent functions. Three hourly computer simulation models, TRNSYS (1978) and NBSLD (Kusuda, et al., 1981) have subroutines that calculate dynamic attic thermal performance. Although attic air temperatures estimated by NBSLD showed reasonable agreement with a monitored Houston, TX attic, all of these calculation schemes have similar limitations to the EPRI model.

A more comprehensive transient attic model was developed by Peavy (1979). Radiative exchanges within the attic space were explicitly modeled as was thermal capacitance and temperature dependent convective heat transfer coefficients at the various surfaces. As with Joy's model, the ventilation air is not assumed to be well mixed in the horizontal dimension. This results in a more realistic description of the attic's horizontal thermal regime. Peavy's model, however, ignored the effects of gabled roof ends and the effects of thermal buoyancy on attic ventilation rates.

Wilkes developed a modification of Peavy's model which included gabled roof ends and improvements in the correlations for convective heat transfer coefficients for use by Owens Corning Fiberglass. The algorithm did not, however, include buoyancy in the estimation of attic ventilation rates or vertical thermal gradients. Comparison of the various models with a calibrated thermal research facility showed the OCF model to give the best prediction of actual attic thermal performance of the previous models (Wilkes and Rucker, 1983). From 1989 – 1991 ORNL developed the ASTM C-1340 procedure (Wilkes et al., 1991). This is a response-factor computer calculation method to estimate the heat gain or loss though residential ceiling systems using a computer analysis tool developed by Oak Ridge National Laboratories (ORNL).

Fairey and Swami (1988) created a simplified steady-state attic model. A key difference in the model was that the attic air space was split into two vertically stacked air zones to allow simulation of thermal stratification. More recently Parker, et al (1991) has created a transient, stratified air model for attic thermal performance simulation. This model addresses many of the shortcomings of the models discussed above and is used as the conceptual framework for the FSEC 3.0 attic model. Much of the research for that model is suggested as a starting point for modeling various characteristics in the Title 24 attic model.

TenoWolde (1997) created a detailed thermal and moisture model of attics for the Forest Products Laboratory. Although, the primary intent was to evaluate sheathing moisture, the detailed thermal model has direct relevance to this effort.

In 1999, FSEC created a residential attic within DOE-2 for its software EnergyGauge USA (Parker et al. 1999). Within this model, the attic is modeled as a buffer space to the conditioned residential zone. Various conventional constructions are available depending on roofing system type (composition or wood shingles, metal, tile and concrete). The exterior roof surface has a set exterior infrared emissivity (set to 0.90) with the exterior convective heat transfer coefficient computed by DOE-2 based on surface roughness and wind conditions. Convective and radiative exchange between the roof decking and the attic insulation was accomplished by setting the interior film coefficient according to the values suggested in the ASHRAE Handbook of Fundamentals depending on their slope and surface emittance. The attic floor was assumed to consist of a given thickness of fiber-glass insulation over 1.3 cm sheet rock. Heat transfer through the attic floor joists were modeled in parallel to the heat transfer through the insulated section.

Framing, recessed lighting cans, junction boxes and other insulation voids are assumed to comprise a less insulated fraction of the gross attic floor area which can be input. Ventilation to the attic is specified in the model as the free ventilation inlet area to the attic. Common attic spaces are assumed to have soffit and ridge ventilation such that it meets the current code recommendation for a 1:300 ventilation area to attic floor area ratio. However, within the simulation, this simulation, this value can be varied to examine impact of attic ventilation of predicted performance. The rate at which ventilation air enters the attic space is modeled using the Sherman-Grimsrud air infiltration. This model takes into account the effects of wind and buoyancy on the computed ventilation. Local wind-speeds in the model for calculating attic ventilation and house air infiltration are estimated assuming typical suburban terrain and shielding factors as described in the DOE-2 manuals.

The model code used within DOE-2 is reproduced in Appendix B. Given its ready availability we used the EGUSA model and the ASTM C-1340 model to examine the success of existing attic simulation codes in replicating measured attic performance data.

In the sections which follow we discuss specific calculation issues within developemtnof the Title 24 mode.

Materials Properties, Emittance and Reflectance

Any attic model will require sufficient description of the physical roof surface, its underlayment, the decking or battens as well as the attic interior characteristics and insulation. These material properties are readily available from ASHRAE (2005) and a variety of sources. However, for some roofing systems– notably tiles– the batten arrangement may affect ventilation characteristics by creating a double roof. This important impact, and its sensitivity to batten orientation and arrangement is described further in the report.

Very important to roof/attic thermal performance is the roof surface solar absorptance and far infrared emittance. Data on these are available are available from a number of sources (Reagan and Acklam, 1979; Taha et al., 1992, Berdahl and Bretz, 1997; Parker et al., 2000, LBNL, 2005). Test results are also available within ASTM E-903 (solar reflectance) and ASTM E-408 (infrared emittance) for specific roofing samples.

Radiant Heat Transfer

Radiative heat transfer is a dominant heat transfer mechanism in residential attics, particularly during summer conditions. Such modeling is also potentially important for estimating performance of radiant barriers.

The radiation component of attic heat transfer is governed by radiative exchange between pairs of surfaces of a 'N' surface enclosure in accordance with the surface temperature differences, their emissivities, view of the other surfaces and the Stefan-Boltzmann constant. For a pair of surfaces the net radiative heat transfer per unit area is:

$$Q_{rad} = \frac{\sigma(T_2^4 - T_1^4)}{\frac{1}{\in_1} + \frac{1}{\in_2} - 1} \quad \bullet \quad F$$

Where:

σ = Stefan-Boltzmann constant (5.67 x 10^{-8})
T = temperatures of surfaces (°K)
ε = the emissivities of the attic surfaces (dimensionless)
F = view factor (dimensionless)

For the five major surfaces in a simple residential attic (two roof decks, insulation surface, two gable roof ends), the problem is complex. This general equation is transformed to use script-F factors (e.g. Kerestecioglu, 1988) to account for total enclosure emissivity and view factors with respect to each surface:

$$Q_i = A_i \quad \sum_{j=1}^{n} \sigma F_{ij} (T_i^4 - T_j^4)$$

Where:

A_i = areas of surfaces
F_{ij} = script - F factor (dimensionless)

The emissivities of the various surfaces within the attic can be obtained from ASHRAE (2005) and Cess and Sparrow (1968). Calculation within the Title 24 attic model will be conventional. However, the difficulty of computing view factors for changing geometries suggests that roof/attic geometry be fixed for estimation within the proposed attic model. Fortunately, previous research has shown that for A-frame type roofs that specific geometry is not overly critical to estimation of attic thermal performance (Wilkes, 1989).

Convection Heat Transfer Coefficient of the Outside Roof Surface

The amount of solar radiation ultimately transferred to the attic interior depends critically on the amount of heat radiated and convected away. The convective heat transfer coefficient of the outside roof surface can be approximated by assuming fully developed turbulent flow across the entire roof section. Relatively few studies have been completed on measured convection heat transfer for building exterior surfaces (Ito et al., 1972) although the various assessments are in reasonable agreement. A simple correlation can be taken from Burch and Luna (1980).

$$hr = 2.8 + 4.8\,(V')$$

Where:

hr = roof convective heat transfer coefficient ($W/m^2\,K$)

V' = wind speed parallel to the roof surface at the boundary conditions (m/s)

Within this study Niles (2005) had completed a detailed comparison of available surface convective heat transfer coefficients and their attribute. I summarize his more detailed analysis here.

The combined convection coefficient in DOE-2 is based on the relationships described by Klems and Yazdanian (1993) $h_{c,glass} = (h_{cf}^2 + (aV[mph]^b)^2)^{1/2}$ for smooth surfaces. It uses wind speed at "standard conditions" although DOE-2 modifies the TMY2 tower wind speeds to those appropriate to building height (LBNL, 1998).

$hc_{tot} = h_{cf} + R_f(h_{c,glass} - h_{cf})$ for rough surfaces. Surface roughness may be specified.

Free Convection:

$h_{cf}[Btu/hr\text{-}ft^2\text{-}F] = 1.393*(delT[F])^{1/3}/(7.333 - |\cos\varphi|)$ for heat flow up.

$h_{cf}[Btu/hr\text{-}ft^2\text{-}F] = 0.2613*(delT[F])^{1/3}/(1.375 + |\cos\varphi|)$ for heat flow down.

delT = Ts0 - To ~ surface – ambient

φ = angle from horizontal

$\sin(\theta) = \cos(\varphi)$

The Wilkes model in ASTM C-1340 appears to utilize s for the case of a heated plate facing upward as described by Fujii and Imura (1972).

Natural convection, horizontal or nearly horizontal surface (tilt angle $\theta < 2°$):

Heat flow up:

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

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

Heat flow down:

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

Natural convection, tilted surface (tilt angle $\theta < 2°$):

Heat flow up:

$Nu = 0.56\,(Ra\cos(\theta))^{1/4}$ for $Ra/Pr < Gr_c$

$Nu = 0.14\,(Ra^{1/3} - Gr_cPr)^{1/3}) + 0.56\,(Ra\cos(\theta))^{1/4}$ for $Ra/Pr < Gr_c$

with $Gr_c = 1 \times 10^6$ for $\theta < 15°$

$Gr_c = 10^{(\theta/(1.1870 + 0.0870\theta))}$ for $15° < \theta < 75°$

$Gr_c = 5 \times 10^9$ for $\theta < 75°$

Heat flow down:

$Nu = (Ra\cos(\theta))^{1/4}$

Forced convection:

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

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

Combined forced and natural convection:

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

Nu = Nusselt number = hL/k
Ra = Raleigh number = $g\beta\rho C_p\Delta TL^3/vk$
Gr = Grasshof number = $=Ra/Pr$
Pr = Prandtl number = v/α
Re = Reynolds number = vL/v
h = convection 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
v = velocity of air (wind speed)

The model calls for "standard wind speed" although personal communication with the author indicates that this assumption was not fully assessed and that free air stream velocity at the roof level would be a better approximation of what was intended.

Clear et al. (2001) has proposed a new convective heat transfer coefficient based on empirical measurement. Similar to the DOE-2 method, this method explicitly defines velocity as "free-stream wind speed at roof level".

For $\Delta T \geq 0$ and $L_{max} > x_{c,eff} \approx 0$, where L_{max} = maximum linear dimension, the h averaged over rectangular roof surface and wind direction:

$$h_c \; = \; \eta(k/L_n)*0.15*Ra_{Ln}^{1/3} + (k/L_{eff})R_f*0.037*Re_{Leff}^{4/5}Pr^{1/3}$$

For rectangular area A and perimeter P:

$t = 4(\sqrt{A})/P$
$La = 4*A/P$
$L_n = A/P$, the characteristic length for natural convection.
$L_{eff} \approx (0.899\text{-}0.032*t)/La$

Weighting factor for natural convection:

$$\eta \; = \; 1/(1+1/\ln(1+Gr_x/Re_x^2)), \text{ where } x = L_{eff}$$

Niles (2005) finds that the calculations are quite similar, although the Burch and Luna (1980) equation is likely overly simplistic. The treatment used in DOE-2 (Yazdanian and Klems, 1994) or that of Wilkes (1989) appear comparable for the model development.

However, regardless of the correlation method for the surface heat transfer coefficient, the appropriate wind speed to use with the relationship is a very important factor relative to model development.

Measured Variation of Wind Speed with Height at FSEC

At its Cocoa, Florida site, the Flexible Roof Facility has a dedicated weather tower where since the summer of 2005, calibrated wind speeds are taken both at the typical meteorological height of 10 meters as well as at a height of 3 meters (10 feet) on the same tower which corresponds more to the typical height of roof structure and attics relative to venting.

Two plots are shown below giving the measured wind speed at the weather tower height and that more representative of the attic/roof height. The first plot shows the measured 15-minute weather data from July 1 - 12 September of 2005.

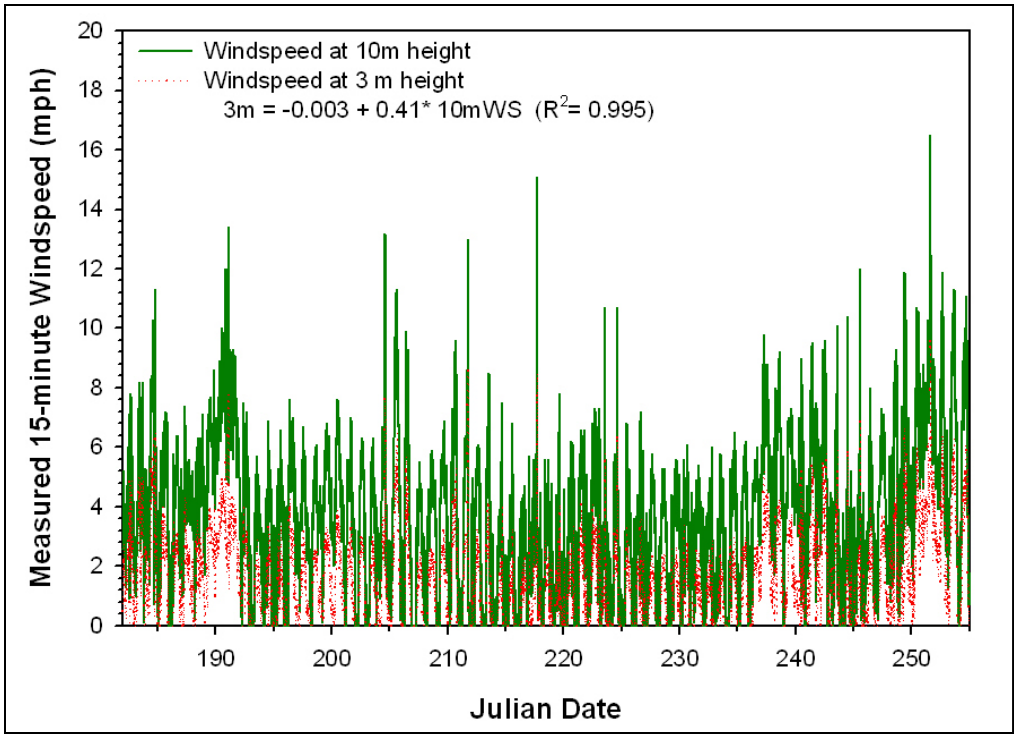

Figure 1. Measured variation in wind speed with height over the summer of 2005.

The second plot shows the average of this data when evaluated over the daily cycle. Note that the wind speed at a 3 meter height (1.5 mph) is much lower than at the 10 meter height (3.7 mph) as would be commonly associated with the height of airport weather towers.

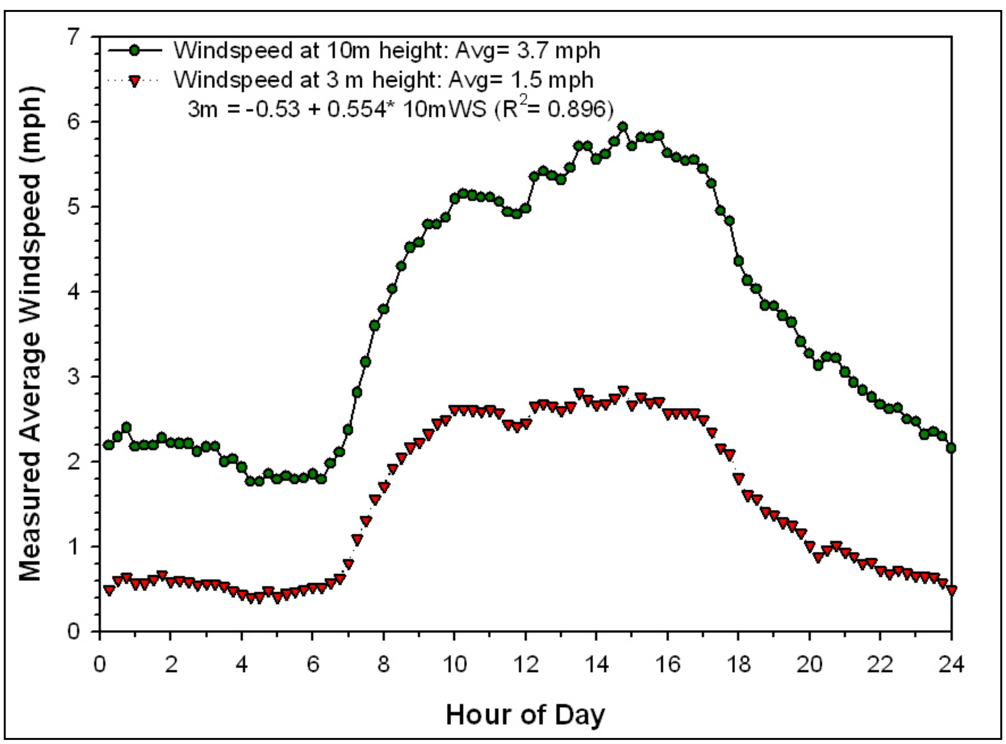

Figure 2. Measured variation in wind speed with height over the summer of 2005

We also found that the measured wind speed at 3meters could be predicted fairly well by the wind speed at 10 meters. In general, the wind speed at 3 meters or 10 feet averages about 41% of the velocity of that measured at 10 meters. R-squared for the data regression was quite good (0.90). Of course, this relationship is only true of the FSEC site and its surroundings. However, given the similarity with many other locations with surrounding suburban areas, the relationship here should be a clear indication of the magnitude of effect. The relationship also showed fair correspondence to the Sherman-Grimsrud method to adjust wind speed against height when suburban localized shielding is assumed. However, the indicated values were lower still, than indicated by that relationship.

Our data regression indicated the following relationship:

```
. regress ws3m ws10m

      Source |       SS       df       MS              Number of obs =    7048
-------------+------------------------------           F(  1,  7046) =60925.16
       Model |  13204.8665     1  13204.8665           Prob > F      =  0.0000
    Residual |  1527.14404  7046  .216739148           R-squared     =  0.8963
-------------+------------------------------           Adj R-squared =  0.8963
       Total |  14732.0106  7047  2.09053648           Root MSE      =  .46555

------------------------------------------------------------------------------
        ws3m |      Coef.   Std. Err.      t    P>|t|     [95% Conf. Interval]
-------------+----------------------------------------------------------------
       ws10m |   .5541159   .0022449   246.83   0.000     .5497152    .5585167
       _cons |  -.5349385   .0099302   -53.87   0.000    -.5544047   -.5154723
------------------------------------------------------------------------------
```

The standard way to adjust wind speed is according the natural log law according to Weiringa,(1986). Wind drag at the surface depends strongly on the surface roughness. For example, a sparse forest creates more drag than a smooth water-covered surface. An aerodynamic roughness length Z_0 quantifies this effect. Values for different landscape types are given below:

Z_0 (m)	***Classification***	***Landscape***
0.0002	sea	sea, paved areas, snow-covered flat plain, tide flast, smooth desert
0.03-0.1	open	grass prairie or farm fields, tundras, airports, heather
0.25	rough	high crops, crops of varied height, scattered obstacles such as trees or hedge-rows, vineyards
1.0	closed	regular coverage with large size obstacles with open spaces roughly equal to obstacle heights, suburban houses, villages, mature forests

The wind speed (WS) is defined to be zero at the ground (more precisely, at the height equal to the aerodynamic roughness length). The wind speed near the surface depends upon the roughness length according the following relationship:

$$WS_2 = WS_1 \bullet \frac{\ln\left(z_2 / z_0 \right)}{\ln\left(z_1 / z_0 \right)}$$

For example, if you know the wind speed WS_1 at a height of Z_1, then you can calculate the wind speed WS_2 at any other height Z_2.

Since airports, where weather data wind speeds are taken are typically classified with a of 0.03 to 0.1 at a height of 10m and suburban environments have a Z_0 roughness of 1.0, the resulting equation for the equation is:

$$WS_2 \quad = \quad WS_1 * \ln(3/1) / \ln(10/0.1) \quad = \quad 1.0986/4.605 \quad = \quad 0.24$$

If we assume both measurements are taken in a suburban environment (Z_0= 1), then the equations become:

$$WS_2 \quad = \quad WS_1 * \ln(3/1) / \ln(10/1) \quad = \quad 1.0986/2.303 \quad = \quad 0.48WS_2$$

This suggests the FRF weather data taken at a 3 meter height would have a typical velocity about 48% of that at 10 meters-- quite close to what was measured. It also indicates, however, that if a nearby airport weather data source (e.g. TMY2 weather data) was to be used to approximate the typical air velocities at roof height, that these values could be expected to be only about 24% of the measure airport wind velocity.

In any case, the calculations show that assuming airport wind speeds will result in serious over-prediction of building adjacent wind speeds. It also indicates that empirically developed correlations for predicting attic ventilation and surface convective heat transfer coefficients are effectively married to the wind speed locations used to develop the correlations.

Interior Roof Surface Convective Heat Transfer

Convective heat transfer coefficients for inside surfaces in the attic enclosure are also very important relative to heat transfer from the heated or cooled roof surface to the attic interior. Here we suggest a calculation logic for the Title 24 model which was used in a previously promulgated FSEC attic model (Parker et al., 1991). These may be estimated based on the correlations adopted by ASHRAE (2005).The ASHRAE formulation accounts for surface orientation and instantaneous temperature differences between the surface and the air node. Within their derivation, natural convection is assumed to be turbulent since measured air velocities over attic surfaces, even under windy conditions with combined ridge and soffit vents, are well below 3 meters per second. The values for the convective heat transfer coefficients are taken from McAdams and are described here for the purposes of suggestion relative to the Title 24 model.

For vertical surfaces:

$$h_{n,v} \quad = \quad 1.31 * (T_{surf} - Tair)^{0.33}$$

For heat flow down:

$$h_{n,d} \quad = \quad 0.76\ (T_{surf} - Tair)^{0.33}$$

And for heat flow up:

$$h_{n,d} \quad = \quad 1.52\ (T_{surf} - T_{air})^{0.33}$$

For roof surfaces which are neither vertical or horizontal with heat flow down:

$$h_{n,rd,d} = \frac{1.805(T_{surf} - T_{air})^{0.33}}{1.375 + \cos(\beta)}$$

And with heat flow up:

$$h_{n,rd,d} = \frac{9.624(T_{surf} - T_{air})^{0.33}}{7.333 - \cos(\beta)}$$

Where
- h_n = convective heat transfer coefficients ($W/m^2 \cdot K$)
- T_{surf} = temperature of component surface (K)
- T_{air} = temperature of air node (K)
- β = roof slope pitch angle (degrees)

Although air movement in attics is generally assumed to be dominated by natural convection, attic ventilation may increase surface heat transfer due to forced convection. For instance, Metais and Eckert (1964) demonstrated that a mixed convection regime between turbulent and laminar flow regimes will tend to increase free convection over the assumption of uniform turbulent flow. In order to accommodate potential forced convection, a forced convection term is suggested for attic surfaces to estimate its magnitude Peavy (1979) recommends the following relationship for turbulent flow over smooth flat plates at low air velocities ($V < 3$ m/s):

$$h_f \quad = \quad 7.176\ (V_a)^{0.8}\ L^{-0.2}$$

Where
- h_f = the forced air convection coefficient ($W/m^2 \cdot K$)
- V_a = attic air velocity over surfaces (m/s)
- L = the air flow path length (m)

The air flow path length is taken as the sum of the soffit to ridge vent distance and the attic height. The calculation of average air velocity over attic surfaces is problematic since interior attic air flows are complex. Ford (1982) and others have estimated attic air flow velocity based on the volumetric rate of ventilation over the cross sectional area of the attic perpendicular to the direction of flow:

$$V_a = \frac{AC\sec(Vol_a)}{A_{fp}}$$

Where:

Vol_a = attic volume (m^3)

A_{fp} = cross sectional area of air flow path (m^2)

Unfortunately, such a calculation greatly underestimates the actual air velocities proximate to the attic heat transfer surfaces, particularly for the roof deck, since air flow through the attic is non-uniform. Parker et. al. (1991) showed the relationship between measured roof deck and insulation surface air velocities inside a test attic over the course of a summer day can average 0.2–0.4 m/s. Other data shows air velocities over attic surfaces at least as great as those measured at the FSEC facility. Ober used smoke pencils to visualize air flow patterns in two test attics in Florida which had relatively low overall ventilation rates (~1.5 ACH). The tests showed that a considerable fraction of the air flowed along the bottom of the roof deck in all tests with two flow layers; a thin fast moving boundary layer with measured velocities of 0.30 - 0.46 m/s and slower boundary region with a measured air velocities of 0.10 - 0.20 m/s. Air movement over the insulation surface was lower, averaging 0.03 to 0.09 m/s.

We suggest a simple empirical model based on measured air velocity measurements in made in the PCL. Average attic roof deck and insulation surface air velocities are approximated as:

$$V_{a,surf} = \left\{ \frac{v^2}{hb^2} + 4\ hb\ g \frac{\Delta T}{(T_{sum})} \right\}^{0.5} - \frac{v}{hb}$$

Where:

ΔT = temperature difference between air node and surface (K)

$V_{a,surf}$ = air velocity over deck or insulation surface (m/s)

hb = boundary layer thickness (0.05 m)

ν = absolute air viscosity (kg/ m/s)

g = gravitational acceleration (9.81 m/s)

T_{sum} = ($T_{surf} + T_{air}$)

Peavy's heuristic method for combining forced and natural convection is suggested:

$$h_{c,i} = h_f + \frac{(9 - V_a^2)}{9} h_n$$

Where:

h_n = natural convection coefficients calculated for surfaces.

Potential Uncertainties in Internal Convective Heat Transfer

The empirical data which produced the heat transfer correlations described by McAdams (1954) were based on laboratory measurements using 0.3 m square smooth plates which were parallel to each other with unrestrained air flow at the edges. Actual surfaces in attics are much larger, feature a number of irregular surfaces and are restrained at the edges.

Past research provides reason to question the appropriateness of laboratory estimates of heat transfer for buildings. As example, ElSherbiny et. al(1980) performed experiments which showed that convective heat transfer coefficients were increased by up to 50% for corrugated compared to smooth surfaces. Similarly, Anderson and Bohn (1984) examined the effect of heat transfer of roughness elements with the same length as the thermal boundary layer. They found that roughness increased the heat transfer rate of a uniformly isothermal wall by 10 - 15% with local increases of 40%. Finally, analysis of measured convective heat transfer by McAdams (1954) reveals that heat transfer rates are approximately 10% higher with rough plates versus smooth ones. Given the very uneven nature of attic surfaces, and in lieu of more specific empirical data, a first order approximation suggested that the convective heat transfer coefficient be increased above by 15%.

Of perhaps greatest importance in this regard, one notes that the ASHRAE still air heat transfer coefficients for low emissivity materials are considerably higher than the values commonly computed based on the relationships presented by McAdams (1954) as reported in the ASHRAE Handbook. The ASHRAE still air values are based on a 5.5 °K temperature difference between air and surfaces when evaluated at a temperature of 294 °K. A large discrepancy in the convective value for the insulation surface is obvious. In a previous assessment, FSEC found that due to their larger magnitude, use of the ASHRAE still air values result in a better calculation of the attic lower zone air and insulation surface temperature (Parker et al., 1991)

In general, it is concluded that convective heat transfer coefficients associated with building elements, such as commonly found in residential attics may have relatively higher heat transfer rates that the common simplified assumptions arising within most building simulations. For instance, a fibrous insulation surface can hardly be argued to possess the convective heat flow characteristics of a small smooth flat plate with unrestrained air flow at the edges.

More recently, using a detailed heat balance assessment Spitler, Pedersen and Fischer (1991) and Fischer and Pedersen (1997) have shown from empirical research that convective heat transfer rates for internal building surfaces are somewhat greater than those commonly described ASHRAE coefficient particularly for high ventilation rate enclosures. As naturally ventilated attics may fall into this domain, it is recommended that these interior convective coefficients in the Title 24 attic model receive appropriate review and evaluation of sensitivity to changes in magnitude.

Changing Conductivity of Ceiling Insulation with Temperature

Ceiling insulation conductivity is typically assumed to be constant within the loads calculations within building energy simulation. However, it is widely known that the conductivity of low density insulation is dependent on the mean temperature across the insulation (Turner and

Malloy, 1981), and increases with increasing temperature. Since higher roof reflectance can reduce the temperature within the attic space, it was deemed important to model this effect. Based on data from Wilkes (1981) the temperature dependent conductivity of fiberglass insulation rated at 70°F (21.0°C) can be estimated as:

$$k_{act} = k_{70°F} [1+0.00418 (T-530)]$$

Where:

k = insulation conductivity (Btu-ft/hr-ft^2-°F)

T = is the mean insulation temperature in degrees Rankine.

The influence was implemented within DOE-2 in EGUSA by calculating an hourly correction term based on the interior and attic air temperatures to use to estimate the changing conductivity. The steady state value is then differenced with the hourly estimate to yield a change to the building heating or cooling loads within the systems model. The differences are typically small -- a maximum of a 14% increase in conductance when the attic air temperature reaches 130°F (54.4°C) with 78°F (25.6°C) maintained on the interior. The impact on annual cooling energy use predicted by the model was only 1 to 2% -- similar to that seen in another analysis (Levinson et al., 1996). In any case, this impact is large enough to justify accounting for this influence within the Title 24 attic model.

Attic Natural Ventilation Rates

Additional attic ventilation is a commonly advocated method to reduce ceiling summertime heat gains in residential buildings. Increased passive attic ventilation (wind and buoyancy driven ventilation) can be obtained by larger inlet and outlet areas or by adding a ridge vent to take advantage of the stack effect.

While various means of augmenting passive ventilation may be useful for new construction, this must be balanced the physical limitations of roof and attic geometry and the need for preventing rain intrusion versus achieving higher ventilation rates and ameliorating attic heat gain. Although the adequacy of attic ventilation rates to reduce moisture accumulation in colder climates has received considerable attention (Harrje et al., 1984; Cleary, 1984; Spies, 1987), the actual impact on attic and whole house thermal performance is less well researched.

Determination of typical *in situ* ventilation rates in residential attics is spotty. Grot and Siu (1979) took test data on three houses in Houston, Texas which had soffit vents. Measured ventilation rates using sulfur hexafluoride (SF_6) tracer gas tests for the attics were 1.7 to 2.3 air changes per hour during the month of August, 1976. Cleary and Sonderegger (1984) made several measurements using SF_6 tracer gas to measure attic air change rates at various wind speeds in a house in Oroville, California. They found rates of 0.023 m^3/s per m/s wind speed in an attic with 3,000 cm^2 of soffit vents. Given the volume of the residential attic, this equates to an approximate air change rate of 4.6 air changes per hour (ACH) at a 7 m/s wind speed. Using similar SF_6 equipment Ford (1979) measured attic air change rates of 3 - 4 ACH under moderate wind conditions in Princeton, New Jersey. Dietz et al. (1986) measured a rate of 2.9 ACH in a long term tracer gas test on an attic in an Illinois house. In a number of experiments using SF_6 tracer gas in two attics in Ocala, Florida, Ober (1990) measured average air change rates of 0.9 to 1.8 ACH in two attics in test periods ranging from 2 to 27 days. The various studies agree that wind speed is the primary driver of attic ventilation with thermal buoyancy a significant secondary influence. Parker et. al. (1991) show a model of attic ventilation compared with measured data from FSEC's Passive Cooling Laboratory. This model showed that common daily attic ventilation rates vary from about 1 ACH at night to 4 ACH during windy afternoons.

Walker and Forest (1995) showed typical attic ventilation rates in two well characterized test attics in Canada of 0.5 - 5 ACH in a relatively tight attic vs. 2 - 9 ACH in a highly ventilated one. Attic ventilation rates were correlated with wind speed, wind direction, and attic-outdoor temperature difference. Wind speed was shown to be the dominant driving force for ventilation; however, wind direction is important particularly when the attic is sheltered. This research and the associated data has been used to develop an attic ventilation prediction model (Walker, Forest and Wilson, 1995).

Dutt and Harrje et al. (1979) found that experimental change from soffit vs. ridge ventilation seemed to make little difference on space cooling, but with the experimental periods too short, and with too varied weather conditions to reach valid conclusions. However, a carefully done simulation study of monitored Houston houses by Peavy (1979) estimated that ceiling heat flux would be reduced by up to 31% by effective ventilation vs. sealed operation. One investigation with particular relevance to the study was work done by the FSEC in its Passive Cooling Laboratory (PCL) in the summer of 1985 (Fairey, 1988). Here experiments examined how ceiling heat fluxes changed with vented or unvented attics in a series of tests. On average, natural ventilation of the attic space (as opposed to a sealed attic) was shown to decrease ceiling heat flux by 37% with R-19 insulation. Parker and Sherwin (1998) found that 1:150 ventilation with an attic radiant barrier would reduce heat flux by 36% vs. 26% against a radiant barrier with only 1:300 ventilation.

An important study by Beal and Chandra (1995) found that a sealed attic versus one ventilated to standard levels (1:300 with soffit and ridge venting) yielded a 32% reduction to attic heat flux. However, the same study showed that the presence of a ridge vent only improved ceiling heat flux reduction by about 4%. Unfortunately, the measurement duration during this study were very short (subject to weather) and there were some questions about the actual ventilation areas in the testing and how they compared to HUD levels (1:300 and 1:150).

Although attic ventilation has been shown to reduce attic air temperatures and cooling loads the only examination of powered attic ventilators has shown the electricity consumption of the ventilator fans to be greater than the savings in air conditioning energy (Burch and Treado, 1979). Research on the impact of natural ventilation rates on the thermal performance of attics and homes has received scant attention– a limitation that FSEC is currently addressing through comprehensive experiments on attic ventilation in its Flexible Roof Facility (FRF).

Importance of Modeling Wind Speed and Attic Ventilation

Accurate estimation of attic ventilation is critical to calculation of heating and cooling loads for buildings because the attic air temperature in an attic is highly sensitive to its ventilation rate (Walker, Forest and Wilson, 1995; Beal and Chandra, 1995).

Similar to the impact on the roof surface heat transfer coefficient, the impact of wind on attic ventilation model results is dramatic-- with large under prediction of attic heat build up if the wind speed at 10m height is used. Within our analysis, wind speed taken at a 10m height for the model is reduced to 48% of the value at a 10m height in accordance for suburban shielding in the natural log model (Weiringa, 1986). Wind also influences the attic ventilation rate.

The attached graph in Figure 3 shows the simulation model predictions on 19 July 1997 for DOE-2.1E and ASTM C-1340 with the wind speed as modified for eave height (48% of the 10m value). Also, plotted is the prediction for the ASTM C-1340 model when the 10m wind speed is used. Note the severe under prediction when the unmodified and speed is used. Although not plotted, the DOE-2 model shows similar sensitivity. This indicates that having a good procedure to estimate wind speed will be vital to any effective attic model-- arguably more important than accurate characterization of the attic geometry.

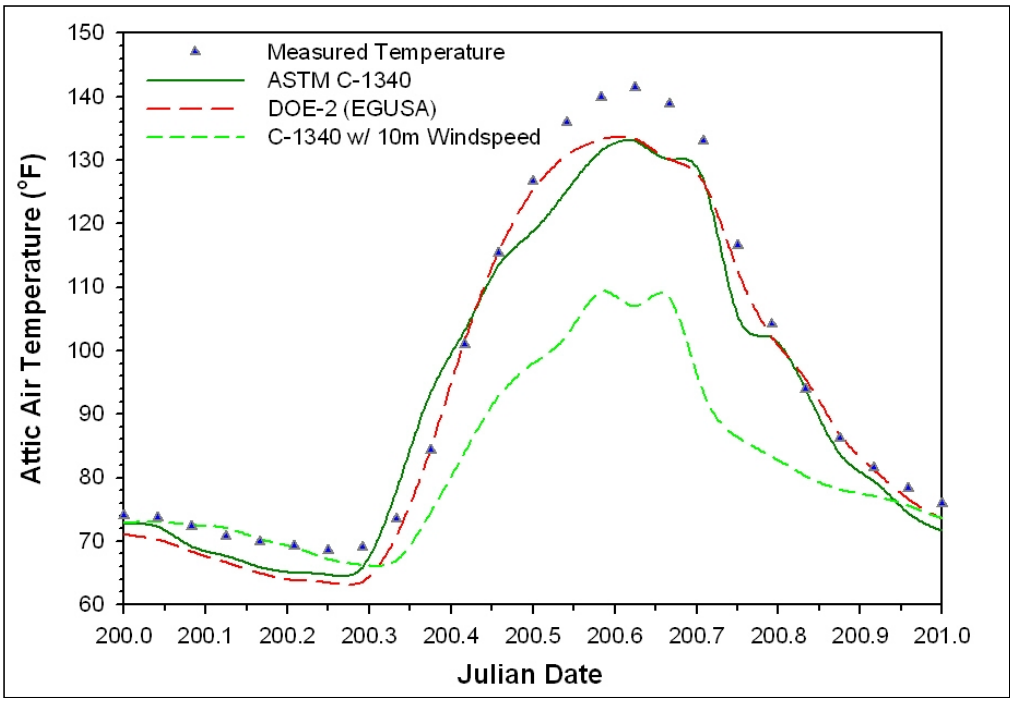

Figure 3. Comparison of measured data with simulation models: dark shingles, 1:300 ventilation July 19th, 1997

Ventilation of Tile Roofing Systems and Importance of Batten Configuration

Tile roofing systems are very common in California and are rapidly changing the roof system stock in the state given the fire danger posed by older cedar shake roofs. During the project, the intriguing results were reported from work done on ventilation of tile roofing by Oak Ridge National Laboratories (ORNL) (Miller et al., 2005). However, the new ORNL paper is entirely consistent with previous work at FSEC. A key issue is the way the tiles are set up over the roof to allow for ventilation (see Figure 1 and Figure 6 of ORNL's draft paper). As shown in FSEC research on this issue (Beal and Chandra, 1995), tiles over a batten-counter-batten arrangement have *very different* thermal performance from those that are applied via direct nailing (the most common arrangement in Florida). See Figure 7 in Beal and Chandra, 1995 and the associated discussion that illustrates these points. The ORNL work claims a very large effect from convective flow in the air space under the tile, while the specific horizontal batten arrangement in California installations works against the ventilation anticipated.

The typical tile application method in California is a key issue in characterizing tile roof attic thermal performance for Title 24. In Florida the batten/counter-batten arrangement is not used due to storm resistance concerns -- direct nailed on plywood decking accounts for almost all installations. Within the project, we found that identical application methods are used in California. Recent experience with tile roofing with Centex Corp. (a large California builder) shows the counter-batten arrangement is not typically done there (Rainer, 2004). See Figure 5 for an illustration from a new housing project. Most in California use a single batten arrangement. <u>However, in all the installations observed, the single battens run horizontally across the direction of potential tile natural convection (gable to gable rather than eave to ridge) and thus do not aid convection under the tile as might be potentially expected in the ORNL work. This is an important point</u>.

For instance, in the FSEC research, the vented S-tiles on counter-battens reduced daytime heat flux by 48% relative to black shingles, whereas the direct-nailed installation with the same tile only reduced daytime heat flux by 39% (Beal and Chandra, 1995). These results are entirely consistent with the research data coming out from ORNL's Envelope Systems Research Apparatus (ESRA) roof test facility. However, the study does not present data on the less advantageous methods of installing tile that dominate the actual residential construction market.

Unfortunately, the research put forth by Miller et al. (2005) does not provide the summarized flux data in tabular form. Within that study, it would be useful to see how S-mission tile does on a direct nailed application, and a single batten arrangement with disadvantageous orientation compared with the counter-batten arrangement provided in the paper. Developers of the California attic model (and Title 24) should also be alerted to the issue that the counter-batten arrangement is potentially the most beneficial for the thermal performance of tile roofs -- which may not characterize current conventional roof construction methods which are more likely to be single batten applications with the battens running in a non-beneficial direction. In these cases, the solar reflectance and emissivity properties would be emphasized.

As shown in Figure 4, the tiles being used in California are typically those with low solar reflectance. For instance, a chocolate brown roof tile commonly used by Centex Corporation in construction in Livermore, CA had a tested solar reflectance of only 8.8%. However, a variety of colored tile products are available with reflectances of 40% or better (Parker et al., 2000).

Figure 4. Illustration of cross-long width orientation of battens used for installation of tile roof in a California residential development. This arrangement does not provide enhanced ventilation of tile roofing.

Surface Moisture Impact on Attic Heat Transfer

Current versions of the most widely used simulation codes (i.e., DOE-2, BLAST, EnergyPlus) cover most of the heat transfer phenomenon that impact the envelope of residence, including natural convection, forced convection, direct, diffuse and reflected radiation. However, such codes do not adequately cover the heat transfer mechanisms for surfaces in wet climates when such surfaces fall below the dew-point temperature, as is common in summertime evening periods.

This can easily be observed in empirical data by comparing simulated nighttime surface temperatures against measured nighttime temperatures. Furthermore, current simulations do not contain any provision for calculating heat transfer during rainy periods. The potential impacts of rain on space cooling have been experimentally documented (Jayamah et al., 1998).

Although potentially less important in dry California, these effects should be included by the new Title 24 attic model by the simple first order expedient of setting the roof surface temperature to the wet bulb temperature if the rain flag is encountered in the hourly TMY2 file. If necessary, further refinements could be made to calculation of the impact of this phenomenon, but this approximation is easily incorporated.

The impact of roof snow loading during winter conditions can be potentially important. TenoWolde (1997) provides so recommended simplifications for simulation modeling.

Sources for Empirical Data for the Attic Model

A major objective for the project was to develop sources of empirical data to allow attic model validation. Below we describe the physical characteristic to be studied and potential sources of data with from projects which can be used to evaluate each. The overall summary of potential sources is shown in Table 1.

- Low Albedo roof materials (reflective vs. non-reflective roofing materials)
  - Flexible Roof facilty (FRF) measurements for 1997 - 2004 (includes aged measurements on Test Cell #6) as well as white tile vs. white metal vs. dark shingle roof which is the control.
  - Florida Power and Light Company study (seven identical houses)-- attic temps for white metal, white barrel tile and white flat tile.
  - Flexible Roof Facility (FRF) for measurements of unfinished metal roofing materials (2001-2004) and also spectrally selective IR reflective paints (2001-2004)

- Mass roof materials (low mass metal, shingle vs. higher mass tile roofing).
  - FRF: Measurements on tile vs. metal vs. dark shingles (1997).
  - FPL Study from 2000: Terra Cotta barrel tile vs. white barrel tile vs. dark shingle roof (control)

- Surface Ventilation of roof systems (ventilation of tile roof systems directly under roofing).
  - FPL Study in 2000 where measurements are made of white flat tile vs. white barrel tile with weep hole ventilation (side by side test)
  - FRF 1994: Measurements of tile roof direct nailed vs. counterbatten installation

- Radiant Barriers
  - FRF: Measurements for 1997 for two ventilation rates including fluxes and air temperature compared with control roof with no RBS and 1:300.
  - Livermore, California Zero Energy Home: Techshield Radiant Barrier with two years on continuous attic air temperature data. The physical sample of the chocolate brown tile roofing in the Livermore house had a tested solar reflectance was 8.8%.

- Attic Ventilation
  - FRF measurements in 1994: Ridge Vent: High vs. Low profile
Soffit Vent: Closed vs. perforated
1:250 Vent vs. 1:50 vent
Side by side test

- Attic duct and air handler leakage and insulation
  - Data on air handler location in available hourly data sets.

- Sealed or cathedralized Attics
  - FPL Project in 2000: Control home with 1:300 attic ventilation vs. sealed attic with foam insulated roof deck.
  - Verified duct leakage in both. Identical roofing materials.

Table 1
Summary of Data Sources for Development of California Title 24 Attic/Duct Model

Project Measure	Hi Albedo	Tile	Shingle	Meta l	Dark Tile	Surface Vent	Radiant Barrier	Varied Vent Rate	Sealed Attic	Night Breeze	IR Refl. Colors	Location	MET Data	Notes
Livermore ZEH		X			X		X			X		Livermore, CA	X	No control, Dark tile; radiant barrier only; p two years of attic temp data
Development of Cool Colored Roofing Materials	X	X		X	X	X		X			X	Fairfax, CA	X	Four homes, 2 controls; Reflective tile vs. non; Dark metal vs. IR Refl
FPL Cool Roof Research Project	X	X	X				X	X				Ft. Myers, FL	X	7 Identical homes with different roofs including sealed attic type
Flexible Roof Facility (FSEC): 1994		X	X		X	X		X	X			Cocoa, FL	X	Six attic test cells, tiles direct nailed and on battens; two vent rates with and without ridge vents (data in two week increments)
Flexible Roof Facility (FSEC):1997	X	X	X		X		X		X			Cocoa, FL	X	Comparison of white tile, dark tile, white metal, RBS with two vent rates, control with dark shingle
Flexible Roof Facility (FSEC):1998	X	X	X		X		X					Cocoa, FL	X	Sealed attic standard
Flexible Roof Facility (FSEC):1999	X	X	X		X	X						Cocoa, FL	X	White metal shingle
Flexible Roof Facility (FSEC):2000	X	X	X	X	X	X			X		X	Cocoa, FL	X	IR Reflective metal shingles
Flexible Roof Facility (FSEC):2001	X	X	X	X		X		X	X		X	Cocoa, FL	X	White tile is sealed, double roof on sealed attic
Flexible Roof Facility (FSEC):2002	X	X	X	X		X		X	X		X	Cocoa, FL	X	Unvented white metal, unfinished metal (Galvanized/Galvalume)
Flexible Roof Facility (FSEC):2003	X	X	X	X		X		X	X		X	Cocoa, FL	X	Aged unfinished metal
Building Science Corp.: Pulte Homes		X		X	X			X	X			Las Vegas, NV	X	Summer 1996: three homes, two days of data
PIER Research Houses for REGCAP Research		X			X							CA, Texas	X	Six new homes, five in CA (two in Sacramento, 2 Palm Springs, 1 Mountain View), another in Cedar Park, TX; 100 days of data in 1998
Tempe Arizona RBS Research Houses			X				X	X				Tempe, AZ	X	Two side by side homes; data from summer 1987, one with RBS, light gray shingles; Wu 1989
University of Alberta			X					X				Alberta, Canada	X	Two well-characterized test sites with varied ventilation; 1991 data
Cardinal Roseville		X			X							Roseville, CA	X	Two well characterized base case tile roof houses with high and low vents
Cardinal Houston			X									Houston, TX	X	Three well characterized base case homes with dark asphalt shingles
Cardinal Fort Wayne			X									Ft. Wayne, IN	X	4 well characterized base case houses at 2 orientations Possible future experiment?
San Ramon ZEH					X		X			X		San Ramon, CA	X	2 exp and 2 control with dark tile roofs, not identical, data collection now.

Empirical Data Sets for Model Validation

Within the project, we created cleaned validated empirical data sets upon which the various attic models could be tested. A key data source was that of FSEC's Flexible Roof Facility (FRF) located in Cocoa, Florida, ten miles (17 km) west of the Atlantic Ocean on mainland Florida. The FRF is a 24 ft by 48 ft (7.3 x 14.6 m) frame building constructed in 1987 with its long axis oriented east-west (Figure 5). The roof and attic are partitioned to allow simultaneous testing of multiple roof configurations. The orientation provides a northern and southern exposure for the roofing materials under evaluation. The attic is sectioned into six individual 6 foot (1.8 m) wide test cells spanning three 2 ft (0.6 m) trusses thermally separated by partition walls insulated to R-20 ft2-hr-^{o}F/Btu (RSI-3.5 m2-K/W) using 3 inches (7.6 cm) of isocyanurate insulation. The partitions between the individual cells are also well sealed to prevent air flow cross-contamination. The gable roof has a 5/12 pitch (22.6^{o}) and 3/4 inch (1.9 cm) plywood decking. On the attic floor, R-19 (RSI-3.3) unsurfaced batt insulation is installed between the trusses in all of the test bays (with the exception of Cell #2) in a consistent fashion. The attic is separated from the conditioned interior by 0.5 inch (1.3 cm) gypsum board. The interior of the FRF is a single open air conditioned space.

Figure 5. FSEC's flexible roof facility (FRF).

The roof lends itself to easy reconfiguration with different roofing products and has been used in the past to examine different levels of ventilation and installation configurations for tile roofing (Beal and Chandra, 1995). Testing has also compared reflective roofing, radiant barriers and sealed attic construction (Parker and Sherwin, 1998). Appendix B lists the test cell configurations over recent years. A black asphalt shingle roof on one of the test cells serves as a reference for other roofing types.

While it would have desirable to have California specific data, the FRF was the only one to have need insulation and wind speed data. To format the data, we adopted the weather file requirements identified in ASTM C-1340 attic model and edited the data into EXCEL comma separated value (CSV) spreadsheets to make the data widely compatible with possible program inputs. The ASTM C-1340 model and the input and output file descriptions are provided in Appendix A. Appendix B to the report consists of a disk containing the cleared data files in electronic format.

The weather data and their order:

Ambient air temp (°F)
Horizontal Solar Irradiance (Btu/hr-sqft)
Wind speed (mph)
Wind direction (degrees from north)
Humidity (Outdoor relative humidity %)
House Indoor Temperature (e.g. 75°F)
Indoor Relative Humidity (e.g. 50%)

Other information that the model can use for comparative purposes:

VDOT	=	Attic ventilation (if invoked)
IVFLA	=	Flag for calculating flow velocity
Flux	=	Measured ceiling heat flux (Btu/hr/sqft)
Tair	=	Measured attic air temperature (°F)
Texit	=	Ridge vent air temperature (°F.)

Model Comparison for Shingle Roofs

Figure 6 shows the success of the current EGUSA and ASTM C-1340 attic models in predicting attic temperatures as those measured at the FRF in the summer of 1997. The predicted attic has dark shingles with 1:300 ventilation. Hourly data is for July – September of 1997. Figure 7 shows the data for the first week in July of that summer where we had good data on temperature and solar irradiance.

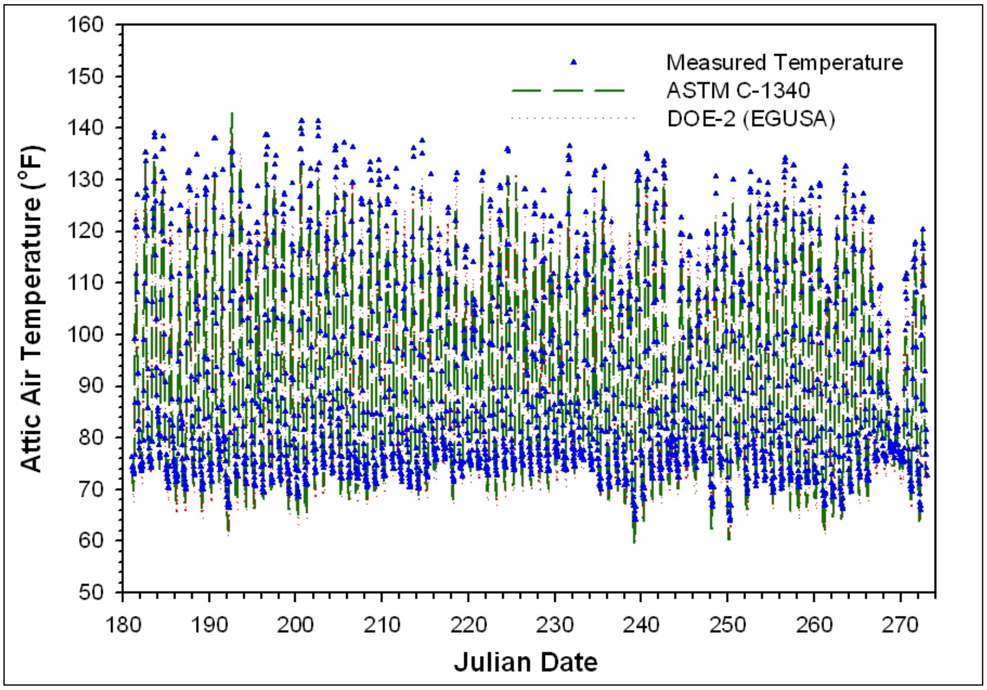

Figure 6. Comparison of measured data with simulation models: dark shingles, 1:300 ventilation. June 30th – September 30th , 1997.

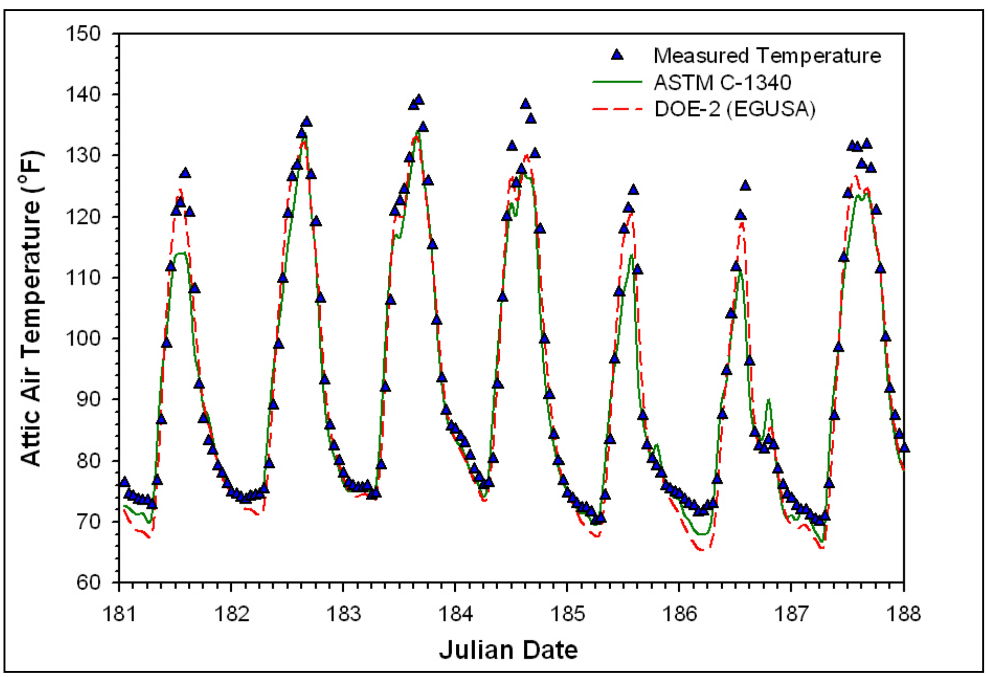

Figure 7. Comparison of measured data with simulation models: dark shingles, 1:300 ventilation. June 30th – July 6th , 1997.

The EGUSA and ASTM C-1340 models (red and green lines) are both quite good compared with the measured attic temperatures (blue triangles) with the bias appearing to underestimate the daily extreme high. This may indicate that DOE-2 and ASTM C-1340 are overestimating the roof exterior convective heat transfer coefficient as reducing this parameter would have the impact of increasing the effective solar absorption of the roof. Conversely, we know that DOE-2 does not limit the computed roof nighttime temperature from night sky irradiance to be no less than the dew point-- which is a real world constraint. This likely explains how DOE-2 computes lower values, while the monitored values tend to flatten out at a similar point. However, the impact should be lower like the dry climates typical in California. Another strong possibility for the disparity is that the *in situ* ventilation rates may be affecting the results.

The documentation for the ASTM C-1340 calculation including the newly added duct calculation section is shown in Appendix A. This includes the input text file for the model (Test.ATM) which produces the results which were previously described for a attic with a dark shingle roof (Abs = 0.95) without a radiant barrier and with 1:300 ventilation.

Model Comparison with Tile Roofs

Figure 8 shows the comparison from the summer of 1997 for the test cell with Terra Cotta Barrel tile. The tile has a measured absorptance of 0.80 and an infrared emittance of 0.9. Within both ASTM C-1340 and the DOE-2 attic models, the tile roof is modeled as a layer of tile, an air space, a weatherproof membrane and a plywood decking. As previously discussed, the performance of the tile roof has special relevance for the project since this is a very common roofing type in California.

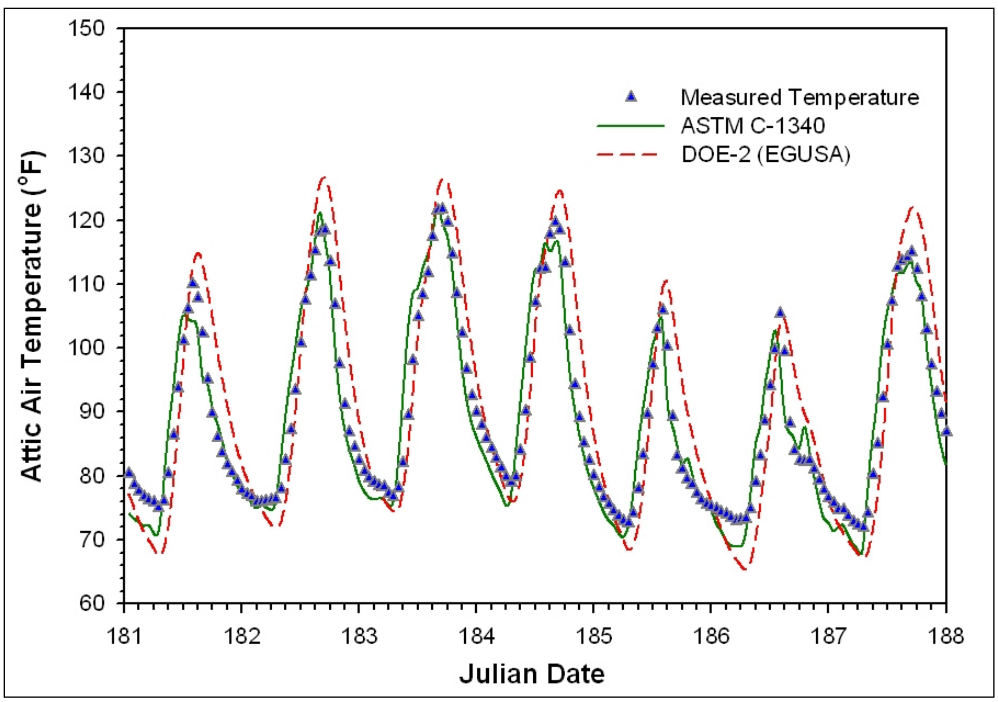

Figure 8. Comparison of measured data with simulation models: terra cotta s-tile, 1:300 ventilation June 30th – July 6th, 1997

ASTM C-1340 appears the better model, although both simulation methods do a good job of capturing the daily variation in attic air temperature. Both models also err most by allowing the roof temperature to drop below the dew point temperature-- a drawback that can be simply addressed.

Note that the tile roof is still somewhat better than the shingle roof, although not nearly so moderate in temperature as the white tile roof. All the data use a wind speed for the ventilation models that is 48% of the 10m tower wind speed. This was done according to the previous analysis of wind speed and how it can expect to vary with building height.

Model Comparison for Coof Roofs

Figure 9 continues the comparison done with the black shingle roof where measured data is used to drive the DOE-2 and ASTM C-1340 attic models for data from our Flexible Roof Facility. In this case, we model the attic air temperature in the test bay using a white standing seam metal roof. This is a very different case as the roof is highly conductive metal and also has a solar reflectance (65%). For our work in the project, Ken Wilkes at ORNL revised the transfer functions for ASTM C-1340 to allow this to be accomplished after the specific roofing material properties were provided.

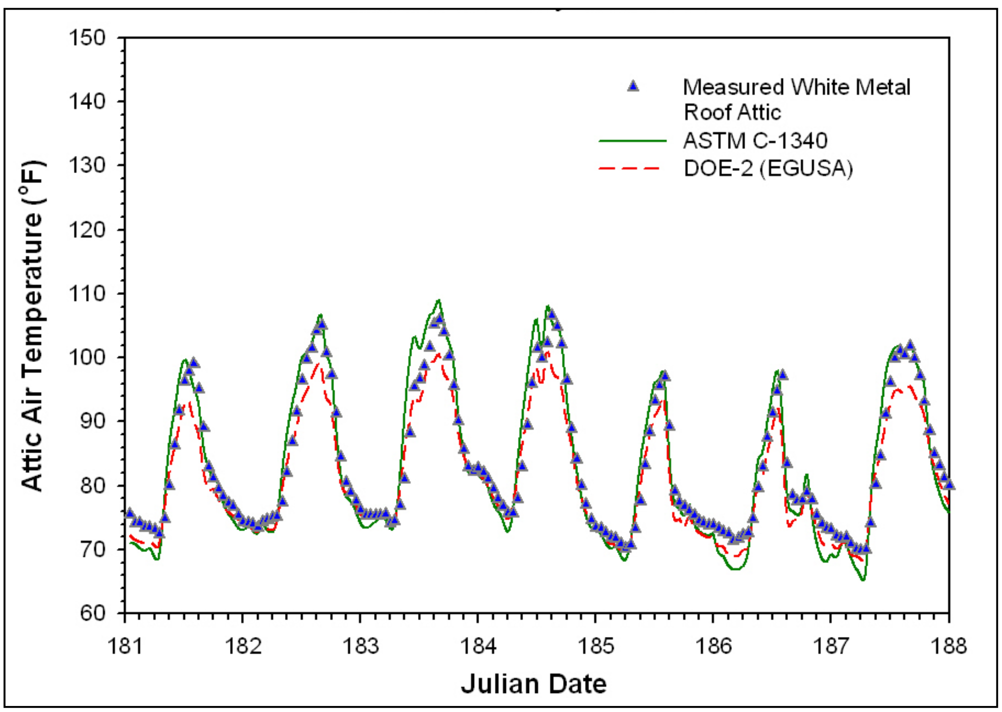

Figure 9. Comparison of measured data with simulation models: white metal, 1:300 ventilation June 30th – July 6th, 1997

Note that the predictions for both models are quite good for the white metal roof, with ASTM C-1340 showing the best agreement. As before, most the remaining discrepancy between the models comes during nighttime hours where the model allows the roof temperature to drop below the dewpoint and for rainy periods where the model is unable to drop the roof temperature as rapidly as actually happens. Both models somewhat under-predict that midday heat gain (particularly for the highly absorptive dark shingle roof) if the unmodified 10m wind speeds are used. Here, we used a value that is 48% of the tower value based on common suburban terrain and shielding with the natural log model (Weiringa, 1986). Coming up with better wind speed models may be useful within the attic model development. However, we expect that the current formulation will suffice for our initial evaluation.

One can readily see the large influence of the highly reflective roof. See Figure 10 which shows the reflective white metal roof as configured at the FRF in the summer of 1997.

Figure 10. FRF showing terra cotta barrel tile and white standing seam metal roofs.

Discussion and Conclusions

This report summarized research done in support of development of an improved attic simulation within the California Title 24 process. The research here concentrates on three fundamental objectives:

1. A comprehensive literature review of available attic thermal simulations and the calculation methodologies employed by each.
2. An evaluation of recommended methods to estimate the fundamental influences that impact predicted thermal performance.
3. 3) Empirical source data that can be used to validate the developed model.

Several models were described in the literature review, nearly all that have some attributes to suggest for consideration within the Title 24 model development. These are covered in detail within the report. However, no single model was found uniformly superior relative to what can be developed within this project– there is room for improvement.

Several facets of the calculation procedure was found critical to development of an effective model. Chief among there were:

- Exterior air convective heat transfer coefficient. The project has fruitfully spent a large effort in determining how collected heat on the roof surface is lost via convection as this is a fundamental physical process that influences how much of absorbed solar energy is effectively transmitted to the attic interior. We find the correlations of Clear et al. (2001), Yazdanian and Klems or the Wilkes (1989) represent calculation schemes which are most appropriate as they consider surface roughness which can differ a lot (e.g. barrel tile vs. single tab shingles). Winkelmann clearly indicates the "free air velocity at roof height," which would not be the velocity at 10 meters. Mowitt and DOE-2 (Yazdanian and Klems, 1994) does the same (DOE-2 manual; Supplement, p. 2.97). Thus, the selected scheme should use a calculation method for adjusting weather tower wind speed at 10 m to a velocity at 3 m sub-urban shielding using appropriate equations. Two and three story homes should have roof height accounted for within the estimation of rooftop velocity.

- Interior air film coefficient. The procedure for calculation interior air film convective heat transfer coefficients was examined and found lacking in most methods. It is suggested that an effective scheme consider (1) higher velocities typically encountered in vented attics along the interior decking and (2) influence of surface roughness relative to conventional correlations.

- Attic ventilation. Knowledge of attic ventilation is shown to be critical to evaluate attic thermal performance. Moreover, recent experiments at FSEC's Flexible Roof Facility shows that the distribution of the attic ventilation is very important with balance soffit and ridge ventilation making ventilation most effective. Soffit only, or ridge only ventilation was found to be scarcely better than no ventilation at all. The model of Walker et al (1999) is the recommended calculation procedure although adjustment to soffit level free velocity wind speeds are critical to an effective procedure. Thus, calculation of roof relevant wind speeds are doubly important within the model development, both for the exterior air film convective heat transfer coefficient and accurate modeling of attic ventilation.

- Material properties and radiation. Estimation of material thermal properties is a tractable part of the model development process. Exercise of attic models quickly reveals that knowledge of surface solar reflectance and far infrared emissivity is vital to good prediction. Evaluation of attic cavity radiation is important within the model, important to evaluation of radiant barrier and cool roof performance, and easily accomplished. A simple geometry is recommended which appears to have little impact on the robustness of the model calculation.

- Influence of secondary roof ventilation below roof tiles must consider batten arrangement and how this configuration will influence results. Data being collected in California can be used eventually verify approximations to the complex phenomenon involved.

- Night sky radiation must be modeled well to properly account for variation of roof system influence in California's dry clear night skies. Again, the need to for accurate estimation requires special attention to the convective surface heat transfer coefficient and how it influences this phenomenon.

- Issues of secondary importance are: variation of ceiling insulation conductivity with mean temperature, influence of dew, rain and snow on roof thermal performance and effective procedures for modeling sealed attics.

The report also summarizes data sources for validation of the developed attic model. These include a variety of sites around the U.S. However, the need for good insolation and wind data limits these. Cleaned data for a number of roof system configurations at the FSEC's Flexible Roof Facility will allow estimation of performance with good weather data. These data sets also include measured attic air temperatures for dark tiles, white tiles, metal, shingle roof and shingle roofs with radiant barriers. The data is attached to this report as a CD Rom with an appropriate field description. Other data may be available in the future to allow examination of the model performance with differing attic ventilation rates, wind speeds at various heights and with sky infrared emittance.

Future Work and Remaining Issues

Due to the fundamental influence of attic ventilation on attic thermal performance, and the poor availability of long-term comparative data, we recommend that priority research for the summer of 2005 use FSEC's Flexible Roof Facility (FRF) to examine attic ventilation influences. The FRF has been set up in the following configuration to establish relative performance. All cells would have black shingles save for Test 6 six with the white metal roof which has served for years as the best performing roofing system. Each test cells has R-30 insulation installed on the attic floor with the ventilation areas carefully verified by blower door pressurization.

Cell No.	Description of Experiment Condition in Test Cell	Justification within experiment
6	White metal roof, 1:300 ventilation	Best performing roofing system
5	Reference; 1:300 ventilation area	Standard requirement for building code
4	Black shingles, 1:150 vent area	Added attic ventilation area per codes
3	Black shingles, sealed	New ASHRAE recommendation to reduce attic humidity
2	Black shingles, 1:300, all soffit vent	Evaluation impact of soffit vs. ridge venting
1	Black shingles; 1:300, all ridge vent	Evaluate impact of soffit vs. redge venting

Monitoring would continue in the given configuration for an entire year to examine both cooling and heating related performance. Collected data will be used to refine the critical attic ventilation models used for building simulations in the Title 24 attic model.

In the summer of 2005, the FRF was configured as describe above. Initial results from the summer attic ventilation experiments are shown in Figure 9. The plot shows mid attic air temperatures in each test cell against ambient air temperature. Examination of the data suggest several important influences.

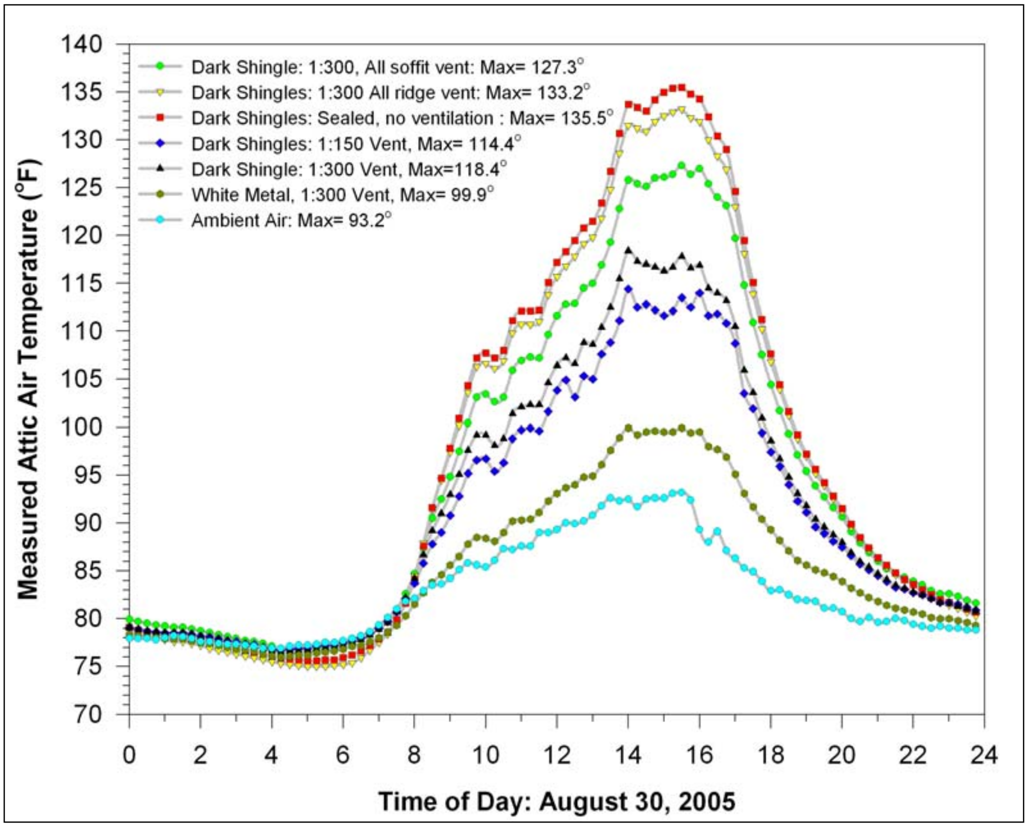

Figure 9: Measured influence of attic ventilation rates and vent distribution at FSEC's FRF on August 30th , 2005.

- A sealed attic will yield the highest interior temperatures
- All ridge ventilation and all soffit ventilation are only marginally better than no ventilation at all. Thus balance inlets and exhaust is very important to performance. This means that this facet must be explicitly accounted for within the Title 24 attic simulation.
- 1:300 ventilation with balance inlets and exhaust performs fairly well at reducing attic heat build up.
- 1:150 ventilation provides modest improvements to heat gain, but with evidence of diminishing returns.
- The white reflective roof with 1:300 ventilation readily exceeds the other options in performance. This continues to evidence the fundamental influence of roof surface solar reflectance in controlling attic heat gain.

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Appendix A

Inputs for ASTM C-1340 Model

Inputs for ASTM C-1340 Model

X1.5.2 Input Parameters for Duct Model

This section describes the inputs required for the duct model. Figure 4 and Table 4 of the main body of the standard describe the input data for an example problem. The example input contains 72 lines. When using the duct model, additional input parameters are entered after Line 72 of the example problem. The new input parameters are as follows:

Line 73. Flag to indicate whether the duct model is being used (0 = ducts not included; 1 = ducts included).

Line 74. Number of supply duct runs in the attic; number of return duct runs (both integers).

Line 75. Temperature of the air as it leaves the conditioning equipment (°F).

Lines 76-XXX. These lines are grouped into sets of three lines, with one set for each of the supply and return ducts. Inputs for the supply ducts are listed first, followed by input for the return ducts. The number of lines in this total group should equal three times the sum of the two entries on Line 74. Lines 76, 77, and 78 will now be described. Lines 77-XXX follow the same pattern.

Line 76. There are eight entries on this line.

> Integer identification of the duct run. Ducts should be numbered sequentially, starting with the run nearest the air-handling equipment.
>
> Integer node numbers for inlet and exit of duct run. The node numbers identify how the duct runs are connected to each other. The exit for one duct run will be the inlet for one or more duct runs next downstream, and the junction will occur at a particular node.
>
> Flag for shape of the duct (0 = a round duct; 1 = rectangular duct). All ducts do not have to have the same shape.
>
> Thermal conductivities (Btu/h•ft•°F) for an inner and an outer layer of duct insulation. Even if only one layer of insulation is to be modeled, non-zero values for both conductivities must be entered as input, in order to avoid a divide-check.
>
> Heat capacity per unit length of the duct materials (including the duct wall and insulation), in Btu/ft•°F.
>
> Length of the duct run (feet).

Line 77. There are four entries on this line.

Volume flow rate of air that enters the duct length (CFM). Note, CFMs are assumed to be based on standard indoor conditions of 68°F and 14.696 psia, for which the density of air is 0.075 lb/ft^3.

Rate of leakage to or from the duct per unit of length (CFM/ft).

Emittance of the external surface of the duct, dimensionless.

Integer to identify the zone of the house that the duct supplies air to. At present, this parameter is not used in the program.

Line 78. If the duct run is round, Line 78 will contain three entries:

Inside diameter of the inner layer of the duct insulation system (feet).
Outside diameter of the inner layer (and inside diameter of the outer layer) of the duct insulation system (feet).
Outside diameter of the outer layer of the duct insulation system (feet).

If the duct run is rectangular, Line 78 will contain six entries:

Inside width of the inner layer of the duct insulation system (feet).
Inside height of the inner layer of the duct insulation system (feet).
Outside width of the inner layer of the duct insulation system (feet).
Outside height of the inner layer of the duct insulation system (feet).
Outside width of the outer layer of the duct insulation system (feet).
Outside height of the outer layer of the duct insulation system (feet).

Lines 76 to 78 are repeated for each of the duct runs in the duct system. The program is dimensioned to allow up to 25 duct runs, in any combination of supply and return ducts.

X1.5.3 Example Problem

The house described in Section 8 is used, with a simple HVAC duct system that consists of a supply system with three sections and one return section. The supply system consists of a main trunk 40 ft long with a branch 15 ft downstream. The branch is 15 ft long. The main trunk is a round duct with an inside diameter of 1 ft covered with R-4 insulation (1 inch thick with a thermal conductivity of 0.021 Btu/h·ft·°F), and an exterior emittance of 0.9. The branch is a round duct with an inside diameter of 0.5 ft also covered with R-4 insulation and an exterior emittance of 0.9. Conditioned air at 55°F and 1000 CFM enters the main trunk, and 400 CFM enters the branch. All supply ducts have a leakage of 1 CFM/ft. The return duct is similar to the main trunk, but is 20 ft long, has a flow of 1000 CFM and is leak-free. Parameters for the system are summarized in Table X2. Figure X1 shows the required input data file. The output file is given in Figure X2, and a plot of calculated duct temperatures is given in Figure X3.

Table X2. Duct Input Parameters for Example Problem

Input Parameter	Duct Section			
	1	2	3	4
Inlet node number	1	2	2	5
Outlet node number	2	3	4	6
Shape	Round	Round	Round	Round
Insulation Thermal Conductivity (Btu/h·ft·°F):				
Inner layer	0.021	0.021	0.021	0.021
Outer layer	0.021	0.021	0.021	0.021
Heat capacity (Btu/ft·°F)	0.075	0.075	0.075	0.075
Length, ft	15	15	25	20
Inlet Volumetric Flow Rate, CFM	1000	400	585	1000
Leakage, CFM/ft	1	1	1	0
Emittance	0.9	0.9	0.9	0.9
Diameters, ft:				
Inner	1.0	0.5	1.0	1.0
Middle	1.083	0.583	1.083	1.083
Outer	1.167	0.667	1.167	1.167

X1.6 Precision and Bias. Limited validation of the algorithms for ducts in an attic has been obtained by Petrie, et al. [24] Laboratory tests were conducted on a 14 ft × 16 ft (4.3 m × 4.9 m) attic having a 6 in. (152 mm) diameter galvanized duct insulated with foil-covered fiberglass batt duct insulation. The duct was installed in a U-shape with long runs near the eaves and a shorter run along one gable. The duct system was 31 ft (9.4 m) long, including two 90 degree elbows. Test were conducted under both summer and winter conditions, with and without a radiant barrier mounted under the roof, and with varying levels of ventilation. Duct air temperature changes from duct inlet to outlet ranged from 0.9°F to 1.5°F (0.5°C to 0.8°C). Differences between model predictions and measured duct air temperature changes averaged +0.16°F (0.09°C) at the mild winter conditions and +0.02°F (+0.01°C) at severe summer conditions.

Figure X1. Example Additional Input Data for Model with Ducts

								Line
1								73
3	1							74
55.0								75
1	1	2	0	0.021	0.021	0.075	15.0	76
1000.0	1.00	0.90	0					77
1.000	1.083	1.167						78
2	2	3	0	0.021	0.021	0.075	15.0	79
400.0	1.00	0.90	0					80
0.500	0.583	0.667						81
3	2	4	0	0.021	0.021	0.075	25.0	82
585.0	1.00	0.90	0					83
1.000	1.083	1.167						84
4	5	6	0	0.021	0.021	0.075	20.0	85
1000.0	0.00	0.90	0					86
1.000	1.083	1.167						87

Figure X.2 Output File for Example Problem with Ducts

Ceiling Heat Flux Btu/h-ft^2	Temperatures, F Nodes 1- 6					
0.4393	55.000	55.237	55.569	55.889	74.000	74.072
0.2831	55.000	55.237	55.568	55.887	74.000	74.071
0.2057	55.000	55.222	55.532	55.831	74.000	74.052
0.1479	55.000	55.210	55.504	55.788	74.000	74.037
0.0929	55.000	55.195	55.467	55.730	74.000	74.018
0.0713	55.000	55.203	55.486	55.760	74.000	74.027
0.1082	55.000	55.227	55.544	55.850	74.000	74.059
0.2304	55.000	55.273	55.653	56.021	74.000	74.118
0.4449	55.000	55.337	55.806	56.261	74.000	74.202
0.6891	55.000	55.388	55.928	56.454	74.000	74.270
0.9480	55.000	55.447	56.068	56.674	74.000	74.347
1.2500	55.000	55.516	56.232	56.933	74.000	74.438
1.5696	55.000	55.578	56.378	57.163	74.000	74.519
1.6891	55.000	55.550	56.312	57.058	74.000	74.482
1.8027	55.000	55.591	56.410	57.213	74.000	74.536
1.8946	55.000	55.592	56.412	57.216	74.000	74.538
1.8637	55.000	55.562	56.342	57.105	74.000	74.498
1.7205	55.000	55.512	56.224	56.918	74.000	74.432
1.5150	55.000	55.461	56.103	56.726	74.000	74.364
1.3032	55.000	55.420	56.006	56.573	74.000	74.311
1.1150	55.000	55.381	55.913	56.427	74.000	74.259
0.9497	55.000	55.351	55.842	56.315	74.000	74.220
0.7938	55.000	55.316	55.758	56.184	74.000	74.175
0.6881	55.000	55.310	55.743	56.161	74.000	74.167
0.5874	55.000	55.281	55.673	56.052	74.000	74.129
0.4941	55.000	55.266	55.638	55.998	74.000	74.110
0.4024	55.000	55.244	55.584	55.914	74.000	74.081
0.3160	55.000	55.228	55.545	55.853	74.000	74.060
0.2323	55.000	55.208	55.498	55.780	74.000	74.035
0.1882	55.000	55.215	55.514	55.804	74.000	74.043
0.2087	55.000	55.237	55.569	55.889	74.000	74.072
0.3145	55.000	55.279	55.669	56.047	74.000	74.127
0.5225	55.000	55.346	55.828	56.297	74.000	74.215
0.7704	55.000	55.401	55.958	56.501	74.000	74.286
1.0412	55.000	55.464	56.108	56.736	74.000	74.369
1.3664	55.000	55.540	56.288	57.021	74.000	74.469
1.6087	55.000	55.559	56.334	57.094	74.000	74.495
1.7569	55.000	55.577	56.376	57.160	74.000	74.518
1.8386	55.000	55.580	56.383	57.170	74.000	74.521
1.8750	55.000	55.580	56.384	57.171	74.000	74.521
1.8834	55.000	55.577	56.377	57.160	74.000	74.517
1.7547	55.000	55.515	56.231	56.928	74.000	74.436
1.5322	55.000	55.460	56.101	56.723	74.000	74.363
1.3111	55.000	55.420	56.005	56.572	74.000	74.310
1.1195	55.000	55.381	55.912	56.425	74.000	74.259
0.9538	55.000	55.351	55.842	56.316	74.000	74.221
0.7975	55.000	55.316	55.758	56.184	74.000	74.175
0.6911	55.000	55.310	55.743	56.161	74.000	74.167
0.5898	55.000	55.281	55.673	56.052	74.000	74.129
0.4961	55.000	55.266	55.638	55.998	74.000	74.110
0.4040	55.000	55.244	55.584	55.914	74.000	74.081
0.3174	55.000	55.228	55.545	55.853	74.000	74.060
0.2334	55.000	55.208	55.498	55.780	74.000	74.035
0.1892	55.000	55.215	55.514	55.804	74.000	74.043
0.2094	55.000	55.237	55.569	55.889	74.000	74.072
0.3152	55.000	55.279	55.669	56.047	74.000	74.127
0.5230	55.000	55.346	55.828	56.297	74.000	74.215
0.7708	55.000	55.401	55.958	56.501	74.000	74.286
1.0415	55.000	55.464	56.108	56.736	74.000	74.369
1.3666	55.000	55.540	56.288	57.021	74.000	74.469
1.6089	55.000	55.559	56.334	57.094	74.000	74.495
1.7571	55.000	55.577	56.376	57.160	74.000	74.518
1.8388	55.000	55.580	56.383	57.170	74.000	74.521
1.8751	55.000	55.580	56.384	57.171	74.000	74.521
1.8835	55.000	55.577	56.377	57.160	74.000	74.517
1.7548	55.000	55.515	56.231	56.928	74.000	74.436
1.5323	55.000	55.460	56.101	56.723	74.000	74.363
1.3112	55.000	55.420	56.005	56.572	74.000	74.310
1.1195	55.000	55.381	55.912	56.425	74.000	74.259

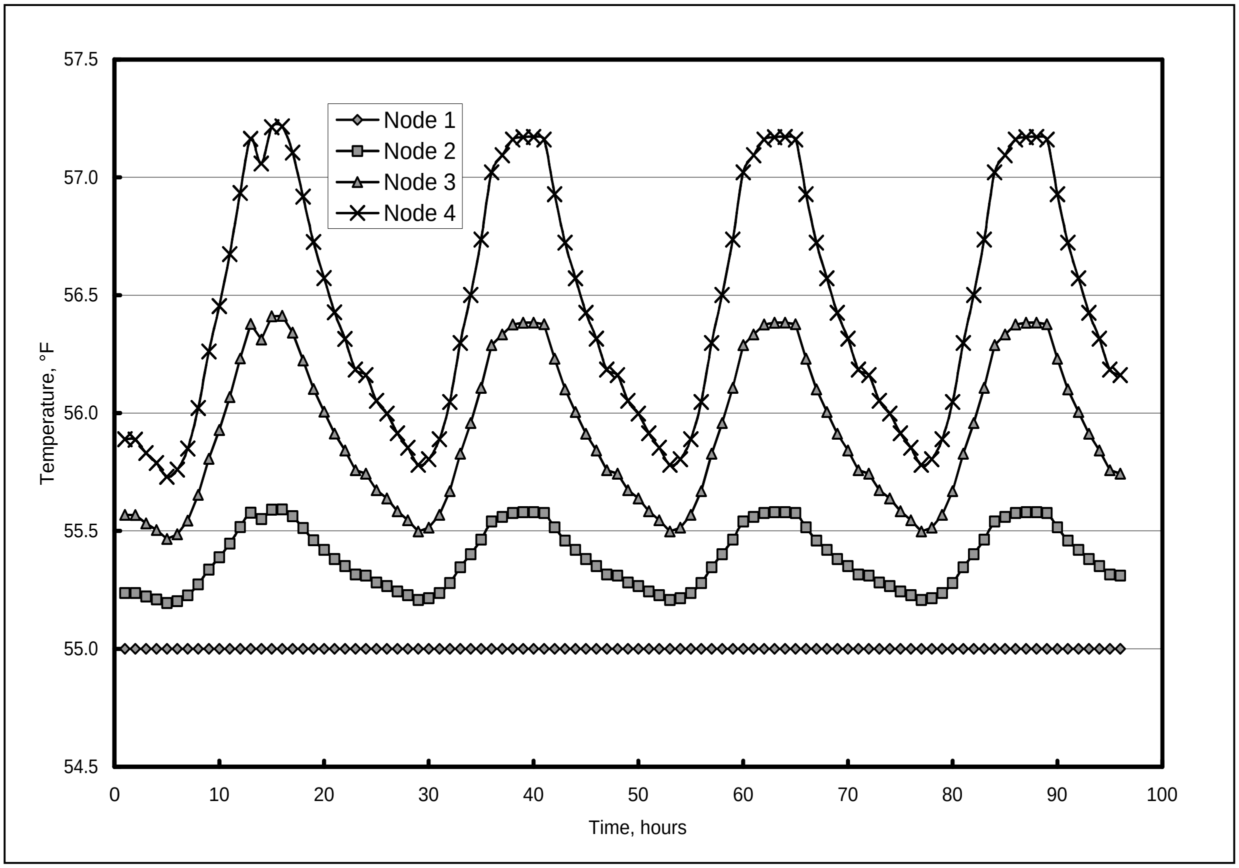

Figure X.3 Hourly Duct Temperatures Calculated for the Example Problem

Appendix B

Attic Model for DOE-2 within EnergyGauge USA

This series of excerpts shows the way in which DOE-2 has been adapted within EnergyGuage USA. It gives surprisingly good agreement with measured attic temperatures.

Zone Description

This is a 2000 square foot home with a gable end roof.

```
$--- ATTIC/ROOF ZONE ---$
ATTIC-1 =SPACE          A = 2000.00 V = 5206.89 FLOOR-WEIGHT = 0
                        INF-METHOD = S-G
                        FRAC-LEAK-AREA = ATVENTA
                        ZONE-TYPE = UNCONDITIONED T=(TAVE TIMES 1.1) ..

$ROOF DIMENSIONS GO HERE...$
FRONT-RF-1 = ROOF       H = 40.25 W = 23.57 AZ = 180  TILT = 18.40
                        CONS = INS-RF-1 OUTSIDE-EMISS = 0.90 ..
FRONT-RF-1F = ROOF      H = 4.47 W= 23.57 AZ = 180  TILT = 18.40
                        CONS = INS-RF-1F OUTSIDE-EMISS = 0.90 ..
GABLE-1    = ROOF       H = 7.44 W = 22.36 AZ = 90  TILT = 90.00
                        CONS = NONINS-WL ..

REAR-RF-1  = ROOF       LIKE FRONT-RF-1  AZ = 0 ..
REAR-RF-1F = ROOF       LIKE FRONT-RF-1F AZ = 0 ..
GABLE-2    = ROOF       H = 7.44 W = 22.36 AZ = 270  TILT = 90.00
                        CONS = NONINS-WL ..
```

ATVENTA= The attic free inlet ventilation area stated as an specific leakage area.
INF-METHOD= S-G; Sherman-Grimsrud estimation of hourly ventilation.
OUTSIDE-EMISSIVITY is set to 0.9 unless unfinished metal roofing (0.4). Hip roof has no gable ends, but two other roof panels facing the other two cardinal directions.
Roof dimensional elements are specified. The volume is computed based on simple geometry.

Ceiling Construction Description

```
$---CEILING ASSEMBLY---$

LAY-4         = LAYERS     MAT=(CINS-1, DRYWALL-1)
                           I-F-R=0.762 ..
CEIL-INS-1    = CONS       LAYERS=LAY-4 ..

LAY-9         = LAYERS     MAT=(CINS-STUD-1, STUD-2, DRYWALL-1)
```

```
                          I-F-R=0.762 ..
CEIL-STUD-1  = CONS       LAYERS=LAY-9 ..
```

There are two parts to the ceiling: the stud part and the sheet rock part. I-F-R is the interior air film coefficient. Layers from the top down, CINS-1 = ceiling insulation

ROOF ASSEMBLIES

```
$---ASPHALT SHINGLE ROOF ASSEMBLY---$
LAY-3        = LAYERS     MAT=(AS-SHG-1, AS-SHG-1, RFINS-1, PLYW-2)
                          I-F-R=SURFR ..
INS-RF-1     = CONS       LAYERS=LAY-3  ABS = RFABS ..
LAY-3F       = LAYERS     MAT=(AS-SHG-1, AS-SHG-1, STUD-2, PLYW-2)
                          I-F-R=SURFR ..
INS-RF-1F    = CONS       LAYERS=LAY-3F  ABS = RFABS ..
```

Again two parts. A sheathing only part and a sheathing and stud part (10% of area).
Asphalt shingle roof consists of overlapped shingles (two layers, an underlayment(membrane) and plywood. RFABS is the roof solar absorptance. SURFR is the surface convective air film coefficient.

```
$---FLAT TILE ROOF ASSEMBLY---$
FLT-1        = LAYERS     MAT=(CT01, CT01, BR01, RFINS-1, PLYW-2)
                          I-F-R=SURFR ..
FTILE-RF      = CONS       LAYERS=FLT-1 ABS=RFABS ..
FLT-1F       = LAYERS     MAT=(CT01, CT01, BR01, STUD-2, PLYW-2)
                          I-F-R=SURFR ..
FTILE-RFF     = CONS       LAYERS=FLT-1 ABS=RFABS ..
```

BR01 is a weatherproof membrane. CT01 is a DOE-2 concrete tile. Tiles are assumed to be overlapped.

```
$—BARREL TILE ROOF ASSEMBLY---$
LAY-8        = LAYERS     MAT=(CT01, CT01, AT-AIR-1, BR01, RFINS-1, PLYW-2)
                          I-F-R=SURFR ..
TILE-RF      = CONS       LAYERS=LAY-8 ABS=RFABS ..
LAY-8F       = LAYERS     MAT=(CT01, CT01, AT-AIR-1, BR01, STUD-2, PLYW-2)
                          I-F-R=SURFR ..
TILE-RFF     = CONS       LAYERS=LAY-8 ABS=RFABS ..
```

AT-AIR-1 is a 1" air space

GABLE-ENDS

```
$---UNINSULATED WALL SECTION---$
LAY-10       = LAYERS     MAT=(STUCCO-1, BP01, PLYW-1)
                          I-F-R=0.68 ..
NONINS-WL    = CONS       LAYERS=LAY-10 ABS=WLABS ..
```

Construction of the uninsulated gable ends of the roof

Adjustment to Attic to Ceiling Flux Based on Mean Temperature of Insulation

```
C  THE ROUTINE BELOW CALCULATES THE TEMPERATURE DEPENDENCY OF CEILING
C  INSULATION THERMAL RESISTANCE BASED ON THE RELATIONSHIP DESCRIBED BY
C  WILKES (1981) AT ORNL. AN ADJUSTMENT IS MADE TO QUICK LOADS BASED ON
C  NOMINAL VS. CALCULATED R-VALUE FOR THE ATTIC-LIVING SPACE TEMP. DIFFERENCE
C  THE FUNCTION CAN BE TURNED OFF BY SETTING 'ATFAREA' TO ZERO
         TMEAN = (TLIVIN+TATTIC)/2
         KACT  = KVAL* (1+0.0042*((TMEAN+460)-530))
         RNOM  = THINS/KVAL
         RACT  = THINS/KACT
         QNOM  = (TATTIC-TLIVIN)*((ATFAREA)/RNOM)
         QACT  = (TATTIC-TLIVIN)*((ATFAREA)/RACT)
         QADJ  = QACT-QNOM
```

Where:
TLIVIN = interior air air temperture inside home
Tattic = hourly predicted attic air temperature in F.
`KVAL  = 0.2856  $ CEILING INSULATION K-VALUE/inch $`
THINS = inch thickness of insulation
RNOM = Nominal R-value of the insulation