

## MODELING OF RESIDENTIAL ATTICS

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### ABSTRACT

A review is given of the available models that have been used to predict the thermal performance of residential attics. The models are first compared qualitatively on the basis of the following features: treatment of ventilation air, inclusion of heat capacities of the roof, ceiling and air space, treatment of radiation heat exchanges, inclusion of heat transfer through gable ends, and dependence of heat transfer coefficients upon temperature and temperature difference. A brief description is then given of a facility for measurements of attic thermal performance under simulated steady-state and dynamic conditions. Included in this description are the boundary conditions to be imposed on attic test sections. Ceiling heat fluxes and attic air temperatures predicted by the various models are then compared to some preliminary results of tests under controlled conditions.

### INTRODUCTION

One goal of our energy research program is to develop a methodology for predicting energy consumption in buildings. One facet of this program is the development of experimentally validated models for the prediction of heat transfer through individual building components. The component to be dealt with in this paper is the residential attic.

A number of models have been developed to predict the thermal performance of attics. The models vary considerably in both level of detail and purpose. They range from the simple steady-state models intended to be used for design purposes to complex transient models intended for use in large computer programs for hour-by-hour energy analyses. Because of the proliferation of models, it was felt desirable to collect in one place descriptions of the models available in the public domain, using a consistent set of nomenclature. This at least allows a qualitative comparison of the various features contained in each of the models.

The final proof of the applicability of a model is how well it predicts actual attic performance. Our laboratory is in the process of performing a series of experiments on an attic module under controlled laboratory conditions that were chosen to simulate typical weather conditions. These experiments are being conducted under a wide variety of conditions, and detailed comparisons of model predictions with data would allow an assessment of the adequacy of each of the models. At this time only a limited amount of data is available. Preliminary comparisons of model predictions with these data are presented to give some idea of model applicability; however, more final judgments about the models must

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await further comparisons under a wider range of conditions.

### DISCUSSION OF AVAILABLE ATTIC MODELS

Six models available in the public domain have been reviewed. In this section, the features of each of these will be discussed in detail. The basic physical situation being modeled is a simple residential attic as shown in Figure 1. The figure identifies the key temperatures on the inner and outer surfaces of the ceiling and roof, and the air temperatures in the attic, inside the house and outdoors. Other temperatures may need to be considered, such as those on gable ends. The motion of ventilation air is shown for the common case of soffit and ridge vents. Other ventilation systems (both natural and powered) may of course be analyzed since the models are general in this regard. Usually some auxiliary information is needed to specify the ventilation rate. All the models discussed here assume that only air from the outdoors enters the attic. However, it is recognized that in some cases air from the rest of the house may leak into the attic and would need to be included as an extra term in the energy balance on the air stream. The figure also shows the heat flow through the ceiling into the room below, which is usually the quantity of most interest.

The models will be described in terms of the familiar electrical analog circuit diagrams. In general, these diagrams are laid out such that the leftmost part represents the roof, the middle part represents the attic space, and the right part represents the ceiling. Flow of ventilation air is represented by the symbol for a current source as is the incident solar radiation. Nomenclature from model to model has been kept as nearly identical as possible to facilitate comparisons. A complete listing of the nomenclature is given at the end of the paper.

#### ASHRAE Handbook Model

The procedure given in Chapter 24 ("Heating Load") of the ASHRAE Handbook of Fundamentals is based on a steady-state analysis and is intended for use in design calculations<sup>1</sup>. A schematic of the electrical circuit analog of this model is shown in Figure 2.

An energy balance on the attic air yields the following relation:

$$T_a = \frac{A_c U_c T_i + T_o (\rho C_p A_c \dot{V}_c + A_r U_r + A_w U_w + A_g U_g)}{A_c (U_c + \rho C_p \dot{V}_c) + A_r U_r + A_w U_w + A_g U_g} \quad (1)$$

The Handbook recommends that the values of  $U_r$  and  $U_c$  be based on surface conductances of  $12.5 \text{ W}/(\text{m}^2 \text{ K})$  which corresponds to one-half the resistance of a selected still air space. The effects of radiation interchange between the roof and attic floor have thus been lumped into the surface conductances. It has been further assumed that the exit temperature of the ventilation air equals the mean attic air temperature.

As the Handbook points out, the effects of solar radiation to and from the roof have not been considered. An immediate improvement in this model could thus be obtained by applying to the roof a sol-air temperature rather than just the outside air temperature.

#### Joy's Model

In order to generalize his experimental results on attic thermal performance, Joy<sup>2</sup> used the model shown schematically in Figure 3. His research is the basis for the table of "Effective Resistance of Ventilated Attics" given in the ASHRAE Handbook of Fundamentals. The schematic applies to a differential length along the flow path of the ventilation air. Heat balances on the model thus lead to a set of differential equations which must be solved simultaneously.

In this model, Joy considers the outside roof temperature,  $T_{ro}$ , and the inside room air temperature,  $T_i$ , to be uniform along the flow path. These two temperatures are furthermore specified as boundary conditions. An important facet of the model is the allowance for direct radiation exchange between the inside roof surface and the attic floor. The ventilation air temperature is considered to follow a well-defined flow path. Since Joy took special precautions in his experiments to guard against heat transmission through surfaces other than the roof and ceiling, only these two surfaces are considered in the model.

Performing heat balances on the interior roof surface, and the attic floor surface, leads to the following two equations:

$$C_{rad}(T_{ri} - T_{co}) dx + \frac{T_{ri} - T_a}{R_1} dx = \frac{T_{ro} - T_{ri}}{R_r} dx \quad (2)$$

$$C_{rad}(T_{ri} - T_{co}) dx - \frac{T_{co} - T_a}{R_2} dx = \frac{T_{co} - T_i}{R_c} dx \quad (3)$$

where  $R_1$  and  $R_2$  are convective heat transfer resistances.

An overall heat balance gives:

$$\frac{T_{ro} - T_{ri}}{R_r} dx = \frac{T_{co} - T_i}{R_c} dx + \rho C_p \dot{V} dT_a \quad (4)$$

These equations may be solved to give a relationship of the following form for the attic floor temperature:

$$T_{co} = K_0 + K_1 \exp(-K_2 x / \dot{V}) \quad (5)$$

where  $K_0, K_1, K_2$ , are constants which depend on the boundary conditions and incorporate the other constants in the above equations. Joy does not give explicit formulas for these constants but they are easily derived.

The average ceiling heat flow is then given by integrating over the length of the attic,

$$Q_c = \frac{1}{L} \int_0^L \frac{T_{co} - T_i}{R_c} dx = \frac{1}{R_c} \left\{ (K_0 - T_i) + \left( \frac{K_1}{K_2} \right) \left( \frac{\dot{V}}{L} \right) [1 - \exp(-K_2 L / \dot{V})] \right\} \quad (6)$$

Joy's model thus incorporates radiation heat transfer between the roof and attic floor and variation of the air temperature along its flow path. The model is subject to the following limitations: (1) it is a steady-state analysis, (2) heat transfer coefficients are assumed to be independent of temperature and temperature difference, and (3) heat transmission through surfaces other than the roof and ceiling (such as gable ends) are not included.

#### OSU-EPRI Model

After considering various alternate approaches, the model shown in Figure 4 was chosen in the OSU-EPRI project for final use in calculating the attic air

temperature<sup>3,4</sup>. It is also the model presently being used at our laboratory for transient load modeling. The model is a transient one and includes the heat capacities of the roof and the air and materials within the attic space. However, the heat capacities of the ceiling and end walls are ignored when calculating the attic air temperature. The heat capacity of the ceiling is included later when the heat flow through the ceiling is calculated. A lumped parameter approach is taken with the roof heat capacity being a single lump sandwiched between two resistances each representing half of the total roof resistance (excluding film resistances). The air and material within the attic space are represented as a single lumped heat capacity with no internal resistance. The ventilation air is taken as entering with the outside air temperature and leaving with the mean temperature of the attic air. This assumes that the attic air is well-mixed and that the temperature of the materials in the attic follow exactly the attic air temperature. All heat transfer coefficients are assumed to be independent of temperature and temperature difference. In addition, heat transfer by radiation within the attic space is not treated separately, but rather is lumped together with the convective heat transfer coefficients. In this and the next two models to be discussed, the heat transfer coefficients for inside surfaces are taken from the ASHRAE Handbook of Fundamentals. Outside heat transfer coefficients are calculated as a function of wind speed,  $V$ , from the relation

$$R_o = 1/(a + bV) \quad (7)$$

where  $a$  and  $b$  are constants chosen to match the ASHRAE outside film coefficients. The data on which these constants are based were obtained on one foot square specimens in a duct, and thus may not be adequate for much larger surfaces.

Performing an energy balance on the exterior roof surface gives

$$\frac{1}{R_o} (T_o - T_{ro}) + Q_{rad} = \frac{2}{R_r} (T_{ro} - T_r) \quad (8)$$

where  $Q_{rad}$  is the net radiation load, which is calculated as the sum of an absorbed solar flux and a long-wavelength term which accounts for radiation interchanges between the surface and the sky and surroundings.

Solving for  $T_{ro}$  gives

$$T_{ro} = \frac{R_o R_r}{2R_o + R_r} \left[ \frac{T_o}{R_o} + Q_{rad} + \frac{2T_r}{R_r} \right] \quad (9)$$

Performing a heat balance on the node at the center of the roof and using the above expression for  $T_{ro}$  gives

$$\left[ \tau_r \frac{d}{dt} + 1 \right] T_r - \beta_1 T_a = \beta_2 \quad (10)$$

where

$$\tau_r = \frac{(M \cdot C_p)_r}{\frac{2A_r}{R_r} + \frac{2A_r}{R_r + 2R_i} - \frac{4A_r R_o}{R_r(2R_o + R_r)}} \quad (11)$$

$$\beta_1 = \frac{2A_r \cdot \tau_r}{(R_r + 2R_i) (M \cdot C_p)_r} \quad (12)$$

$$\beta_2 = \frac{2A_r R_o}{2R_o + R_r} \left[ \frac{T_o}{R_o} + Q_{rad} \right] \frac{\tau_r}{(M \cdot C_p)_r} \quad (13)$$

Similarly, an energy balance on the attic air space leads to

$$\left[ \tau_a \frac{d}{dt} + 1 \right] T_a - \beta_3 T_r = \beta_4 \quad (14)$$

where

$$\tau_a = \frac{(M \cdot C_p)_a}{\frac{2A_r}{R_r + 2R_i} + (\dot{V} \rho C_p)_a + \frac{A_c}{2R_i + R_c} + \frac{A_{ew}}{R_i + R_{ew} + R_o}} \quad (15)$$

$$\beta_3 = \frac{2A_r \tau_a}{(R_r + 2R_i) (M \cdot C_p)_a} \quad (16)$$

$$\beta_4 = \left\{ (\dot{V} \rho C_p)_a + \frac{A_{ew}}{R_i + R_{ew} + R_o} \right\} T_o + \frac{A_c T_i}{2R_i + R_c} \left\{ \frac{\tau_a}{(M \cdot C_p)_a} \right\} \quad (17)$$

The above two first order differential equations may be combined into the following second order differential equation

$$\left[ \tau_r \tau_a \frac{d^2}{dt^2} + (\tau_r + \tau_a) \frac{d}{dt} + 1 - \beta_1 \beta_3 \right] T_a = \beta_2 \beta_3 + \beta_4 \quad (18)$$

In the OSU study, the second derivative was neglected and the resulting first order equation was solved for  $T_a$  as

$$T_a = \frac{\beta_2 \beta_3 + \beta_4}{1 - \beta_1 \beta_3} + \left[ T_{ap} - \frac{\beta_2 \beta_3 + \beta_4}{1 - \beta_1 \beta_3} \right] \exp \left[ - \left( \frac{1 - \beta_1 \beta_3}{\tau_r + \tau_a} \right) t \right] \quad (19)$$

where  $T_{ap}$  is the attic air temperature when  $t$  equals zero.

The attic air temperature was then averaged over a one-hour time period to give

$$T_{avg} = \frac{\beta_4 + \beta_2 \beta_3}{1 - \beta_1 \beta_3} + \left[ T_{ap} - \frac{\beta_2 \beta_3 + \beta_4}{1 - \beta_1 \beta_3} \right] \left[ \frac{\tau_r + \tau_a}{1 - \beta_1 \beta_3} \right] \left\{ 1 - \exp \left[ - \left( \frac{1 - \beta_1 \beta_3}{\tau_r + \tau_a} \right) \right] \right\} \quad (20)$$

A history of average temperatures was then accumulated and used in a conduction transfer function calculation of the heat flow across the ceiling.

Thus, the OSU model offers a calculation procedure for transient cases. Certain approximations have been introduced in the solution of the differential equation in order to obtain a simple formula for the attic air temperature. Limitations of the model are: (1) lack of a separate treatment of radiation heat transfer within the attic space, (2) neglect of the heat capacity of the ceiling when computing the attic air temperature, and (3) treatment of heat transfer coefficients as being independent of temperature and temperature differences.

#### NBSLD Model

The attic subroutine used in NBSLD, the transient load program developed by the National Bureau of Standards, contains two models, the choice between the two depending upon whether the roof is considered to be a delay surface<sup>5</sup>. If the roof is not considered to be a delay surface, then a steady-state model is used, which is essentially the same as the ASHRAE Handbook method modified to include the net radiation load on the roof. If the roof is considered to be a delay surface, the method is modified by calculating the heat flow through the roof using conduction transfer functions, as shown schematically in Figure 5. Using the history of outside roof surface and attic air temperatures, conduction transfer functions are first used to calculate a new outside roof temperature. The new outside roof temperature is then used in a second conduction transfer function calculation to obtain a new value for the attic air temperature. In this step, the heat flow across the ceiling is calculated using the steady-state formula. However, the main program accumulates a history of attic air temperatures and uses these in conduction transfer function calculations for final determination of ceiling heat flows.

The NBSLD model thus includes all the features included in the OSU-EPRI model except the heat capacity of the air and other materials in the attic space. When the mass of the roof is considered to be significant, a more exact conduction calculation is used in the NBSLD procedure. Further limitations of the NBSLD model are the same as those noted for the OSU-EPRI model: (1) lack of separate treatment of radiation heat transfer within the attic space, (2) neglect of the heat capacity of the ceiling when computing the attic air temperature, and (3) treatment of heat transfer coefficients as being independent of temperature and temperature difference.

#### TRNSYS Model

A schematic of the attic model used in TRNSYS<sup>6</sup>, the code developed at the University of Wisconsin for analysis of solar energy systems, is shown in Figure 6. The model includes ventilation by computing an effective conductance  $C_{inf}$  such that

$$C_{inf} = \dot{V} \rho C_p \quad (21)$$

Sol-air temperatures for the north, south, east, and west surfaces are computed and then an effective sol-air temperature is computed as

$$T_{sa,eff} = \frac{C_n T_{sa,n} + C_s T_{sa,s} + C_e T_{sa,e} + C_w T_{sa,w} + C_{inf} T_o}{C_n + C_s + C_e + C_w + C_{inf}} \quad (22)$$

where  $C_n$ ,  $C_s$ ,  $C_e$ ,  $C_w$  are conductances including both inside and outside film coefficients. An effective conductance,  $C_{eff}$ , is defined as the denominator in the above equation. The heat flux through the ceiling is then calculated using transfer functions by

$$q_0'' = \sum_{n=0} b_n (T_{sa,eff,n} - T_i) - \sum_{n=1} d_n q_n'' \quad (23)$$

where  $T_i$  is the inside room air temperature. The transfer functions are built into the computer program, as are the film coefficients.

This model thus includes the heat capacity of the ceiling but not that of the roof or of the air and other materials within the attic space. The treatment of ventilation assumes the air to be well-mixed. The model does not separate out radiation exchange within the attic space and assumes all heat transfer coefficients to be independent of temperature and temperature differences.

#### Peavy's Model

In many respects, the attic model developed by Peavy<sup>7</sup> of NBS is the most sophisticated one available at this time. His computer program, however, was written to analyze the results of the Bureau's Houston attic tests and thus lacks some generality.

A schematic of the basic model is shown in Figure 7. In addition to the features to be discussed here, the model includes provision for heat transfer to air conditioning ducts in the attic space. Heat transfer to the ducts is based on the difference between air temperatures inside and outside the duct and does not include direct radiation exchanges. His computer program also contains logic to determine when powered ventilation should be turned on and off. This model is patterned after Joy's model as described above, with the addition of conduction transfer function calculations for the heat flow through the roof and ceiling. The model incorporates radiation heat exchange between the roof and attic floor. The radiation equations are linearized, but the radiation heat transfer coefficient is calculated as a function of mean temperature by an iterative procedure.

Likewise, natural convection coefficients are calculated as functions of temperature difference and surface orientation. The natural convection coefficients are based on the correlations for finite plates given by McAdams<sup>8</sup> and are of the form

$$h_c = A (\Delta T)^{1/3} \quad (24)$$

where  $A$  is a constant depending upon the surface orientation and the direction of heat flow. Some uncertainty exists with regard to the adequacy of these correlations. First, they are for finite plates with unrestrained air flow at the edges. Second, the one-third power law is for turbulent convection and may not be appropriate for convection from horizontal plates with heat flowing down. A better set of correlations might be those recommended by Holman<sup>9</sup>, although there are still some uncertainties with these.

Forced convection transfer coefficients are calculated as a function of air velocity and length of surface from the following equation

$$h_f = C V^{0.8} L^{-0.2} \quad (25)$$

where  $V$  is the velocity,  $L$  is the surface length and  $C$  is a constant. This equation is of the same form as that predicted by turbulent boundary layer theory. In the region of mixed natural and forced convection, an approximation is used to combine the two coefficients. It would appear that there is still some uncertainty in calculating appropriate mixed convection coefficients.

Conduction of heat through the gable ends of pitched roofs is neglected on the premise that such heat flows are small in relation to that through the roof. Gable ends are also treated as being surfaces for which the net radiant heat flux is zero. The incident solar flux on all roof surfaces is assumed to be uniform and equivalent to that for a flat horizontal surface. Empirically developed correlations are used to relate attic ventilation rate to wind speed and direction. These correlations were derived from data obtained in the Houston study and thus don't necessarily apply to other attic and ventilation opening configurations.

Heat balances at the various surfaces are written as follows:

$$Q_{ro} = h_o (T_{sa} - T_{ro}) \quad (26)$$

$$Q_{ri} = h_{r1} (T_{ri} - T_{co}) + h_{c1} (T_{ri} - T_a) \quad (27)$$

$$Q_{co} = h_{r2} (T_{ri} - T_{co}) + h_{c2} (T_a - T_{co}) \quad (28)$$

$$Q_{ci} = h_i (T_{ci} - T_i) \quad (29)$$

where  $T_{sa}$  is a sol-air temperature,  $T_a$  is the mean attic air temperature,  $h_r$ 's are radiation heat transfer coefficients, and  $h_c$ 's are convection heat transfer coefficients.

Since the attic air is not assumed to be well-mixed, the following differential equation is written for the attic air temperature,  $T_{ax}$ , as a function of a dimension,  $x$ , for the air flow path:

$$\rho C_p A_{co} \dot{V}_a L \frac{dT_{ax}}{dx} + A_{co} h_{c2} (T_{ax} - T_{co}) = A_{ri} h_{c1} (T_{ri} - T_{ax}) \quad (30)$$

where  $\dot{V}_a$  is the air flow rate per unit ceiling area, and  $L$  is an attic floor dimension parallel to the air flow. This equation is then integrated over the air flow path to give a relation of the form

$$T_a = C_1 T_{co} + C_2 T_{ri} + C_3 T_o \quad (31)$$

where the  $C$ 's are constants which depend on the convection heat transfer coefficients and the geometry of the attic.

The heat flows in Eqs. 26 through 29 are next expressed in response factor notation using the inside and outside temperatures of the roof and ceiling. These equations, along with Eq. 31 are then solved simultaneously for  $T_{ro}$ ,  $T_{ri}$ ,  $T_{co}$ ,  $T_{ci}$ , and  $T_a$ . Knowledge of a history of  $T_{ci}$  and  $T_i$  allows a direct calculation of the heat flow through the ceiling.

Peavy's model thus includes most of the features desired in a detailed attic model. The most notable feature not included is conduction through and radiation interchange with the gable ends. It may also be desirable to apply different conditions to the two roof surfaces, for example, to simulate solar conditions during the winter. In addition, no account has been made of the heat capacity of materials within the attic space. Finally, although the convection correlations should be an improvement over using constant values, some uncertainty still remains in their adequacy.

#### Areas for Improvement in Models

Table 1 compares the important features of each of the models discussed above. As noted above, the models vary significantly in both level of detail and purpose. However, no one model includes all of the features potentially desired in an attic model. Peavy's model is the most sophisticated one and probably should be used as a basis for further development. Work at this laboratory has extended Peavy's model to include heat balances on gable ends and a complete radiation interchange analysis assuming opaque surfaces. In addition, provision has been made for unequal heating of the two roof surfaces. Several versions of this extended model are being developed. Different versions will include the heat capacity of the attic space, an option for well-mixed attic air, and the latest recommendations for natural convection correlations. The question of mixed convection coefficients is also being explored and the most recent recommendations will be included.

The first modified version of Peavy's model is shown schematically in Figure 8. This is exactly the same as that shown in Figure 7, except for the inclusion of extra surfaces. Although the model includes five distinct surfaces (two roofs, two gables, one ceiling), the schematic only shows three of these in order to avoid undue confusion on the drawing. As shown, each of the surfaces exchanges heat by convection with the attic air. Also each of the surfaces exchanges heat by radiation with each of the other surfaces. This requires that the surface heat balances given by Eqs. 27 and 28 have additional terms to account for the other radiation exchanges. Also the energy balance on the attic air, Eq. 30, must have extra terms to account for convection from the other surfaces.

#### COMPARISON WITH EXPERIMENTAL RESULTS

To experimentally validate models of attic thermal performance, a facility has been constructed in which a small attic may be tested under controlled conditions. This facility is described in detail elsewhere<sup>10</sup>. Here, only a few of the major features will be mentioned in order to provide a background for comparison of model predictions with measured values.

Basically, the facility consists of a large chamber, the temperature of which can be controlled over a wide range. The floor of the room has a 4.27 m by 6.10 m open area below which is a guarded chamber that can be maintained at an independent temperature. This chamber has provisions for both heating and cooling and for measurement of both these quantities.

A small attic has been built over the metering chamber using scaled-down 2 x 4 raised trusses with 2 x 6 top chords with a pitch angle of 22.6 degrees. The ceiling consists of 15.9 mm gypsum board with provision for installing different types and levels of insulation. The roof consists of 12.7 mm plywood and the gable ends consist of 12.7 mm wood fiber sheathing. The other vertical sides consist of 12.7 mm plywood. A 38 mm opening is left between the vertical sidewalls and the roof to allow entrance of ventilating air. Ventilation air is removed through a ridge vent connected to a blower and orifice system where the flow rate is measured.

An ideal facility would have a large solar simulator to provide heating of the roof. However, such a large simulator was not practical and so a simpler electrical heater pad system was used to provide external heating of the roof. With this system, the external conditions become specified roof temperatures. To provide some degree of reality, typical sol-air temperature profiles were calculated and these were used in controlling the roof surfaces through periodic cycles. The sol-air temperatures were selected to simulate roof surfaces facing north and south. For a summertime condition, both roof surfaces are controlled to the same profile. For a wintertime condition, the south roof is controlled to a sol-air profile, while the north roof is left to float to simulate it being shaded. Steady-state tests may also be performed by maintaining the roof at a constant temperature.

Instrumentation of the attic consists of thermocouples to measure temperatures at various locations and several heat flow meters to measure heat fluxes through the ceiling. Thermocouples are placed at all major surfaces and interfaces. Also included in the temperature measurements are the temperature of the air as it enters and leaves the attic and at various vertical locations within the attic. An examination of the uniformity of attic air temperatures should allow some assessment of the degree of mixing of air within the attic. Also, measurements are made of the temperature inside truss members within the attic space to determine how closely this temperature follows the attic air temperature.

The available models use net radiation loading on the roof as an input. Since this does not match our experimental facility, the programs have been rewritten so that experimentally measured average roof temperatures and ventilation rates may be used as input data. The various models may then be exercised to predict quantities such as ceiling heat flux and attic air temperature.

At the time of writing, the first preliminary experimental data from transient tests were just becoming available for comparison with the models. The comparisons must be considered preliminary at this time since edge effects are not presently incorporated in the models. For these comparisons, the attic was insulated with unfaced R-11 glass fiber batts. Input data for the models consisted of our best estimate of the properties of the various materials at room temperature. For the comparisons to be shown here, the outside air temperature was held constant at about 254 K (-3°F), while the south roof surface was cycled between 257 K (3°F) and 290 K (63°F). For this test, the ventilation rate was zero. For other testing conditions, various ventilation rates will be studied; however, data under these conditions are not available at this time.

Ceiling heat fluxes measured in this test are plotted in Figure 9, along with the predictions of four transient models. As can be seen from the figure, all the models underpredict the heat flux. However, as mentioned above, these underpredictions shouldn't be taken too seriously at the present time due to some remaining uncertainties in edge effects. Peavy's model is seen to lead to the lowest prediction, with the largest disagreement being at the times when the roof is hottest. The reason for this disagreement is fairly clear. Peavy's model ignores heat losses through the gable ends and for a small test attic, these heat losses are appreciable. For a larger size attic where the gables are a smaller fraction of the exposed area, the disagreement would be expected to be less. The model labeled OCF is actually Peavy's model extended to include the gable ends, unequal heating of the two roof surfaces, and a complete radiation exchange analysis. Inclusions of these aspects results in a definite improvement. The OSU-EPRI and NBSLD models are seen to be in reasonable agreement with the OCF model. Although not shown on this graph, the TRNSYS model was found to produce heat fluxes nearly identical to those of NBSLD. The program for the TRNSYS model was specially written so that the R-11 ceiling construction could be used instead of one of the standard ceilings used in the TRNSYS code.

Attic air temperatures measured in this test are shown in Figure 10, along with the predictions of the same four models. Peavy's model overpredicts the air temperature for the same reasons as discussed above for its underprediction of ceiling heat flux. The OCF model does a fairly good job of predicting the air

temperature, while the other two models lead to fairly good predictions except near the peaks.

Many quantities other than the ceiling heat flux and attic air temperature have been measured. However, as of the time of this writing, they had not been compared in detail with model predictions. Before any definite conclusions can be drawn, it will be necessary to make comparisons of experimental data with model predictions for a wide variety of operating conditions and insulation levels. Comparisons under summer conditions, where radiation is relatively more important, and with larger ventilation rates, may show more differences among the models than for the winter conditions shown above. An extensive series of tests are underway and such comparisons will be the subject of an additional paper in the future.

#### CONCLUSIONS

Of the six models for attic performance available in the literature, no one model was found that contained all the features potentially desirable in an attic model. Peavy's model comes closest to a basic description of the heat transport within the attic space. It was therefore used as a basis for further model development. A comparison of model predictions with preliminary experimental data shows fairly good correlation. However, more comparisons under a wide variety of conditions need to be made before definite conclusions can be made as to which model is appropriate for general use.

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## NOMENCLATURE

### Common to Several Models:

$A_c$	area of ceiling
$A_r$	area of roof
$C_p$	specific heat of air
$Q_{rad}$	net radiation load on roof
$R_i$	inside film resistance
$R_o$	outside film resistance
$R_r$	roof resistance, excluding film resistances
$T_a$	attic air temperature
$T_{co}$	attic floor temperature
$T_i$	indoor air temperature
$T_o$	outdoor air temperature
$T_{ri}$	inside roof surface temperature
$T_{ro}$	outside roof surface temperature
$\dot{V}$	volumetric flow rate of ventilation air
$\rho$	density of air

### ASHRAE Handbook Model (Eq. 1, Figure 2):

$A_g$	area of attic glass
$A_w$	area of net vertical attic wall surface
$U_c$	heat transfer coefficient of ceiling
$U_g$	heat transfer coefficient of glass
$U_r$	heat transfer coefficient of roof
$U_w$	heat transfer coefficient of vertical wall surface
$\dot{V}_c$	volumetric rate of introduction of outside air into attic space by ventilation, per unit area of ceiling

### Joy's Model (Eq. 2-6, Figure 3):

$C_{rad}$	radiation heat transfer coefficient
$dx$	differential length along air flow path

$dT_a$	differential temperature along air flow path
$K_0, K_1, K_2$	constants
$L$	attic length
$Q_c$	average ceiling heat flow
$R_1$	convection film resistance at inside roof surface
$R_2$	convection film resistance at attic floor
$R_c$	ceiling resistance, including film resistance at inside surface
$x$	distance along air flow path

OSU - EPRI Model (Eq. 7-20, Figure 4):

$A_{ew}$	area of vertical walls
$a, b$	constants
$(M \cdot C_p)_a$	heat capacity of air and solid materials in attic space
$(M \cdot C_p)_r$	heat capacity of roof
$R_c$	ceiling resistance, excluding film resistances
$R_{ew}$	vertical wall resistance, excluding film resistances
$T_{ap}$	attic air temperature at end of previous hour
$T_{avg}$	attic air temperature averaged over one-hour period
$T_r$	temperature at center of roof
$t$	time
$V$	wind speed
$\beta_1, \beta_2, \beta_3, \beta_4$	parameters defined in Eq. 12, 13, 16, 17
$\tau_a, \tau_r$	time constants defined in Eq. 11 and 15

NBSLD Model (Figure 5):

$A_w$	area of vertical walls
$U_c$	heat transfer coefficient of ceiling, including films
$U_w$	heat transfer coefficient of vertical wall, including films
$\dot{V}_c$	volumetric flow rate of ventilation air

TRNSYS Model (Eq. 21 - 23, Figure 6):

$b_n$	transfer function coefficient
$C_e$	thermal conductance of east surface
$C_{inf}$	effective conductance due to ventilation
$C_n$	thermal conductance of north surface
$C_s$	thermal conductance of south surface
$C_w$	thermal conductance of west surface
$d_n$	transfer function coefficient
$q_n''$	heat flux through ceiling at $n^{th}$ previous hour
$q_o''$	heat flux through ceiling at current hour
$T_{sa,e}$	sol-air temperature for east surface
$T_{sa,n}$	sol-air temperature for north surface
$T_{sa,s}$	sol-air temperature for south surface
$T_{sa,w}$	sol-air temperature for west surface
$T_{sa,eff}$	effective sol-air temperature
$T_{sa,eff,n}$	effective sol-air temperature at $n^{th}$ previous hour

Peavy's Model (Eq. 24-31, Figure 7):

$A$	constant
$A_{co}$	area of attic floor
$A_{ri}$	area of inside surface of roof
$C$	constant
$C_1, C_2, C_3$	constants
$h_c$	natural convection heat transfer coefficient
$h_{c1}$	convection heat transfer coefficient between roof and attic air
$h_{c2}$	convection heat transfer coefficient between attic floor and attic air
$h_f$	forced convection heat transfer coefficient
$h_i$	inside film coefficient
$h_o$	outside film coefficient
$h_{r1}$	inside roof radiation heat transfer coefficient
$h_{r2}$	attic floor radiation heat transfer coefficient

L	linear dimension along air flow path
$Q_{ci}$	heat flux at inside of ceiling
$Q_{co}$	heat flux at attic floor
$Q_{ri}$	heat flux at inside surface of roof
$Q_{ro}$	heat flux at outside surface of roof
$R_{ic}$	film resistance at inside of ceiling
$R_{rad}$	radiation heat transfer resistance
$R_{1c}, R_{2c}$	convection heat transfer resistances corresponding to $h_{1c}$ and $h_{2c}$
$T_a$	average attic air temperature
$T_{ax}$	attic air temperature at position X
$T_{ci}$	temperature at inside surface of ceiling
$T_e$	exit temperature of ventilating air
$T_{sa}$	roof sol-air temperature
V	speed of air flow
$\dot{V}_a$	volumetric flow rate of ventilating air, per unit ceiling area
$\Delta T$	temperature difference

Table 1 Comparison of Attic Models

MODEL	STEADY-STATE ONLY	TRANSIENT	VENTILATION AIR	VENTILATION AIR ASSUMED WELL-MIXED	ROOF HEAT CAPACITY	CEILING HEAT CAPACITY	ATTIC SPACE HEAT CAPACITY	RADIATION INTERCHANGE	HT. TRNS. COEFF. FCN. OF T AND $\Delta T$	GABLE ENDS INCLUDED
ASHRAE HANDBOOK	X		X	X						X
JOY	X		X					X		
OSU-EPRI		X	X	X	X	*	X			X
NBSLD		X	X	X	X	*				X
TRNSYS		X	X	X		X				X
PEAVY		X	X		X	X		X	X	

\*INCLUDED IN FINAL CALCULATION OF CEILING HEAT FLOW

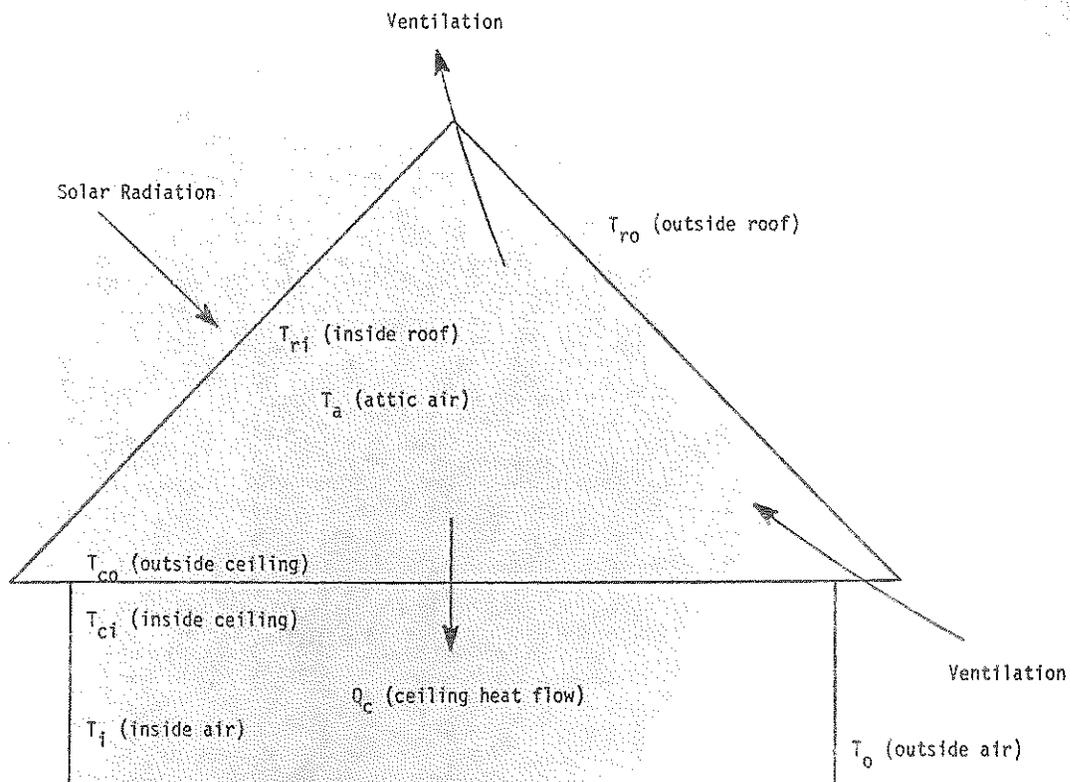


Fig. 1 Physical Model of Ventilated Residential Attic

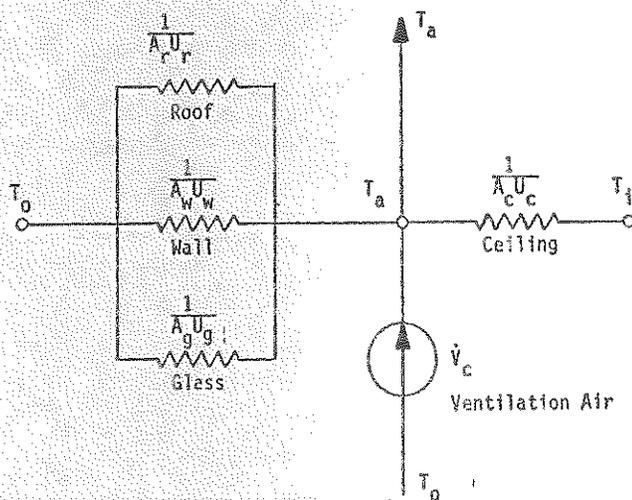


Fig. 2 Schematic of ASHRAE Handbook Attic Model

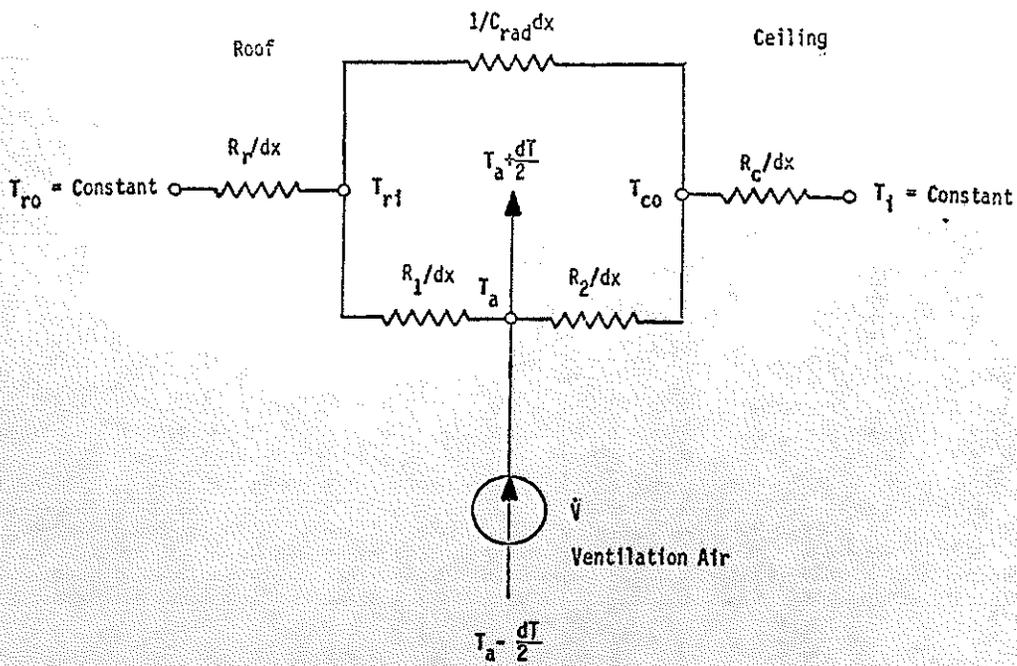


Fig. 3 Schematic of Joy's Attic Model (for Differential Length along Flow Path)

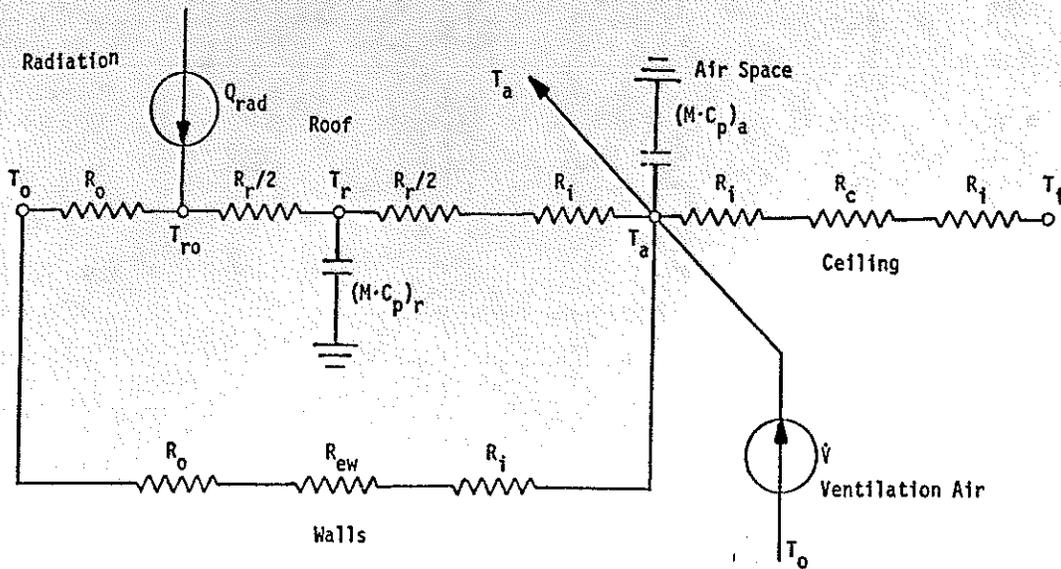


Fig. 4 Schematic of OSU-EPRI Attic Model

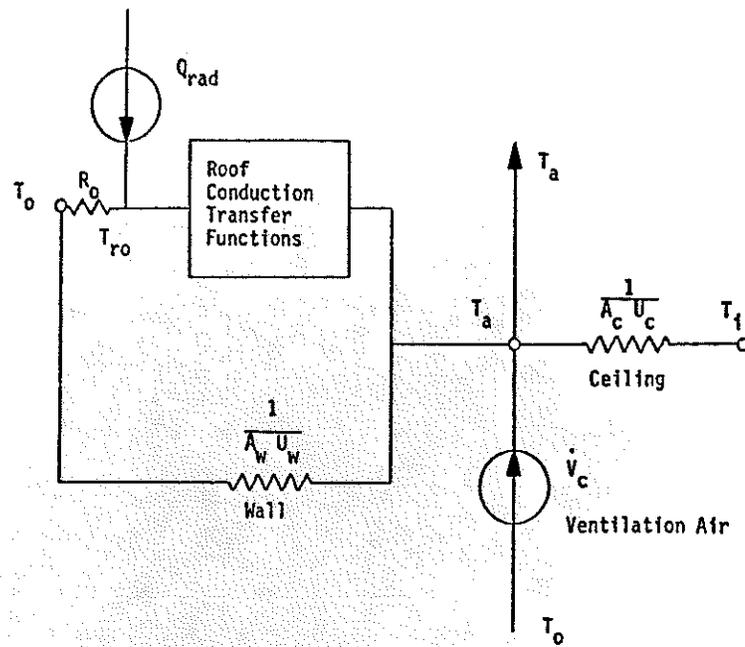


Fig. 5 Schematic of NBSLD Attic Model

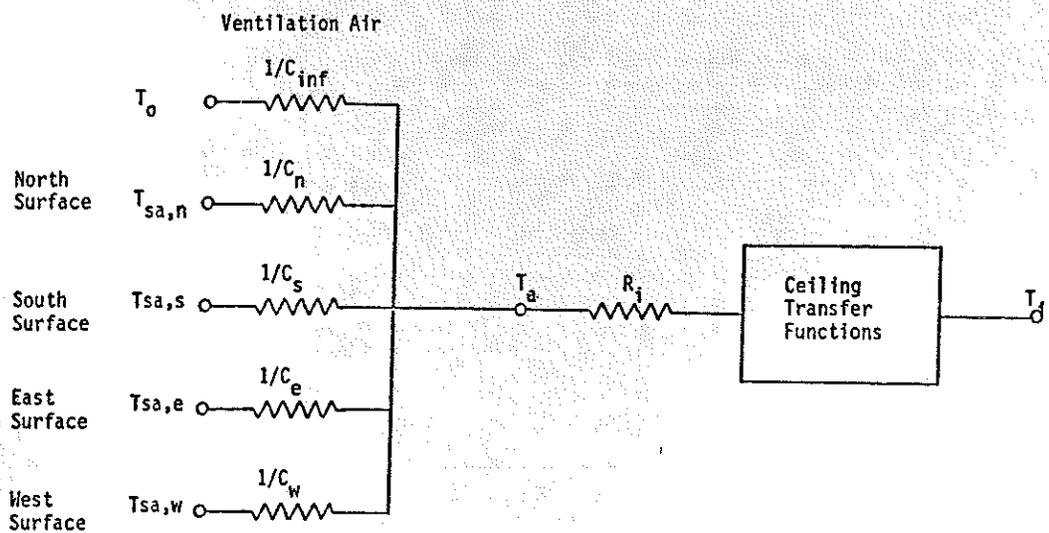


Fig. 6 Schematic of TRNSYS Attic Model

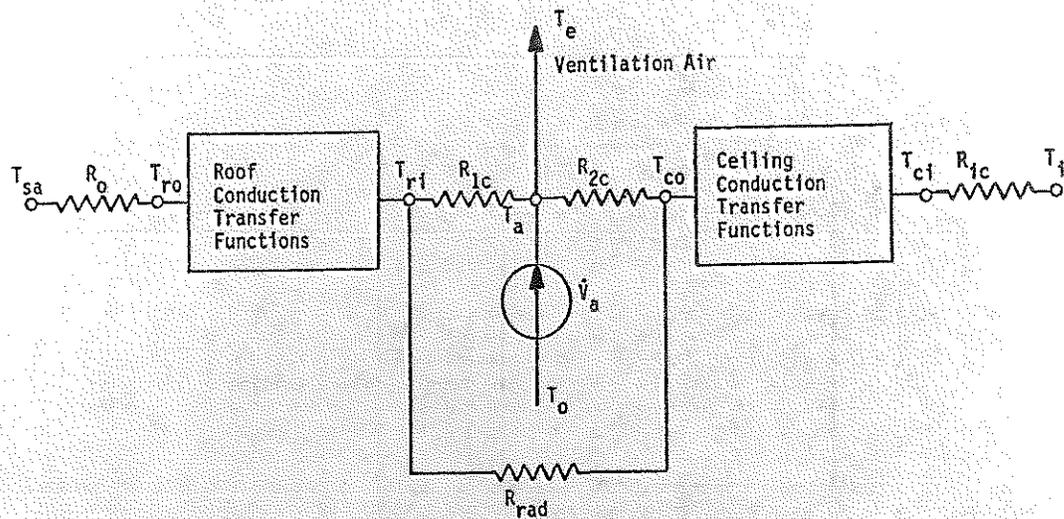


Fig. 7 Schematic of Peavy's Attic Model

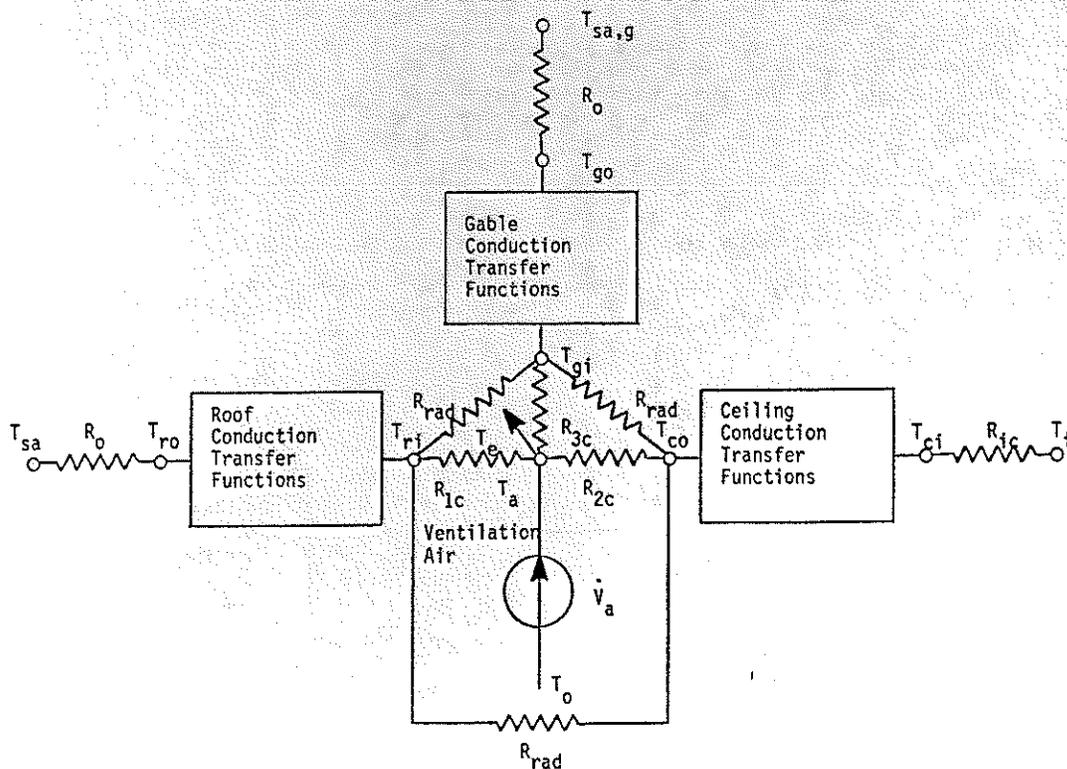


Fig. 8 Schematic of OCF Attic Model

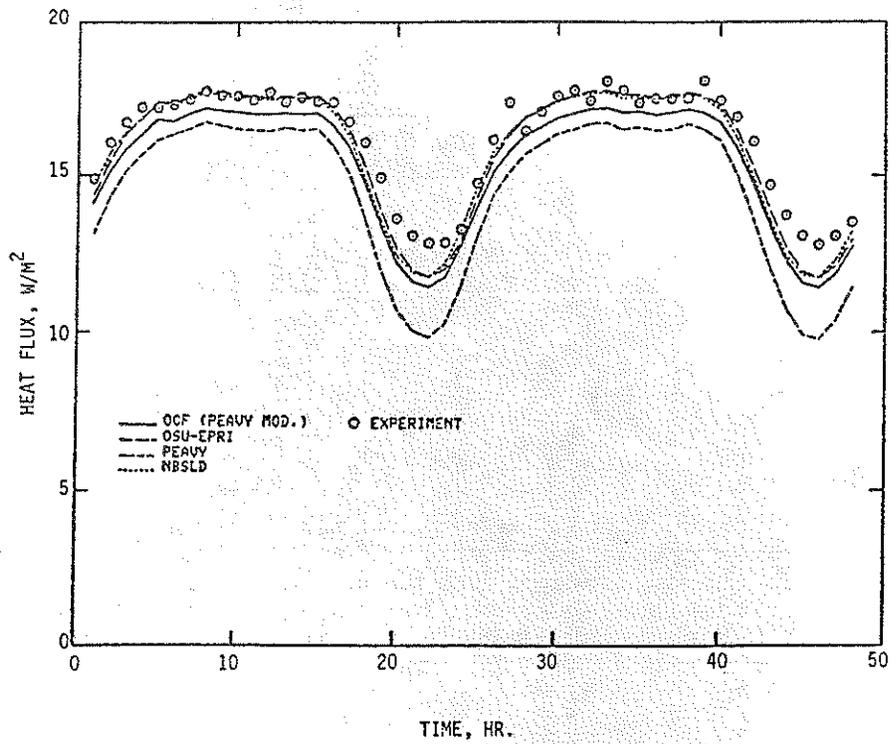


Fig. 9 Ceiling Heat Flux, Winter Test

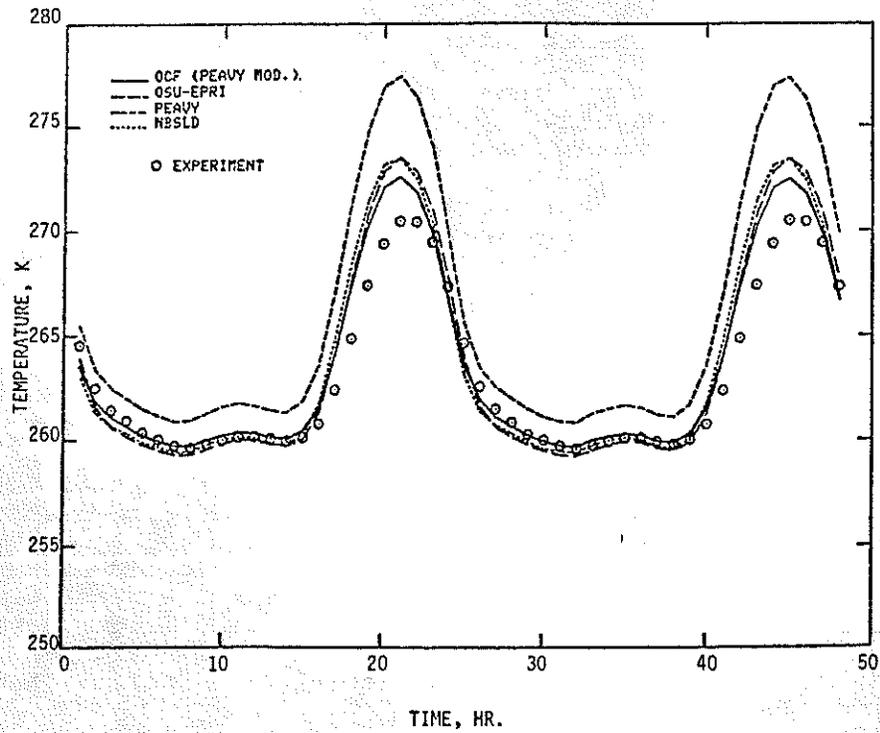


Fig. 10 Attic Air Temperature, Winter Test