MODELING OF RESIDENTIAL ATTICS WITH RADIANT BARRIERS

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ABSTRACT

This paper gives a summary of the efforts at ORNL in modeling residential attics with radiant barriers. Analytical models based on a system of macroscopic heat balances have been developed. Separate models have been developed for horizontal radiant barriers laid on top of the insulation, and for radiant barriers attached to the bottom of the top chords of the attic trusses. The models include features such as a radiation interchange analysis within the attic space, convective coupling with the ventilation air, and sorption/desorption of moisture at surfaces facing the attic enclosure. The paper gives details of the models and the engineering assumptions that were made in their development. The paper also reports on the status of efforts that are underway to verify the models by comparing their predictions with the results of laboratory and field tests on residential attics and test cells, both with and without radiant barriers. Comparisons are given for a number of selected sets of experimental data. Suggestions are given for needed model refinements and additional experimental data. Plans for utilization of the models for extrapolation to seasonal and annual performance in a variety of climatic conditions are also described.

INTRODUCTION

[illegible] residential attics is becoming increasingly popular. Experiments that have been performed by a number of organizations have clearly demonstrated that radiant barriers are effective in reducing ceiling heat flows, especially under cooling conditions.[1-13] While the results from these experiments are generally in qualitative agreement in indicating heat flow reductions, there is a controversy regarding the magnitude of the thermal performance of these systems. The reasons for the differences among the various results are not understood at present, but may be at least partly due to the different conditions under which the experiments were performed. There is a need to understand the extent to which experimental results differ and the reasons for these differences.

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

Analytical models offer means for addressing both these issues. They are useful in sorting out reasons for differences among the various sets of data, and in extrapolating the experimental results to other conditions. This paper gives a summary of the efforts underway at the Oak Ridge National Laboratory (ORNL) in modeling the thermal performance of residential attics with radiant barriers. The first section gives a description of the models that have been developed, the features that are included within them, and the engineering assumptions that were made in developing them. The next section discusses the efforts that are underway to verify the models by comparing their predictions with experimental data. Finally, plans are discussed for the utilization of the models for extrapolation to seasonal and annual performance in various climates.

ANALYTICAL MODELS

Models for building components may be developed at various levels of detail. For very detailed studies, finite element or finite difference models may be useful. For example, the Florida Solar Energy Center is developing a finite element model for attics with radiant barriers that would solve for details of temperature, heat flux, and air flow fields within the attic. A number of less detailed models have been developed using systems of heat balances on an hour-by-hour basis. During a review of the models that were available at the time,[14] the author concluded that the best model was the one that had been developed by P. Peavy at the National [illegible] the last year, under the sponsorship of the Department of Energy and the Tennessee Valley Authority, this model has been further enhanced in order to apply it to attics that contain radiant barriers of various types.

The sketch of an attic given in Figure 1 shows the various heat transfer phenomena that occur within an attic. The model treats all of these phenomena through a system of heat balance equations at the interior and exterior surfaces of the ceiling, roof sections, and gables, as well as a heat balance on the air mass within the attic. To handle the case of raised trusses, short vertical walls at the eaves were also included. Each of the surfaces is assumed to be isothermal. Thus for an attic consisting of a ceiling, two roof sections, two gables, two vertical eave sections, and one air space, a total of 15 heat balance equations are used.

Conduction through each of the surfaces is handled using thermal response factors.[17] The response factor equations relate the surface heat fluxes at a particular time to the present and previous temperatures at the two surfaces of the component. The response factor equations represent

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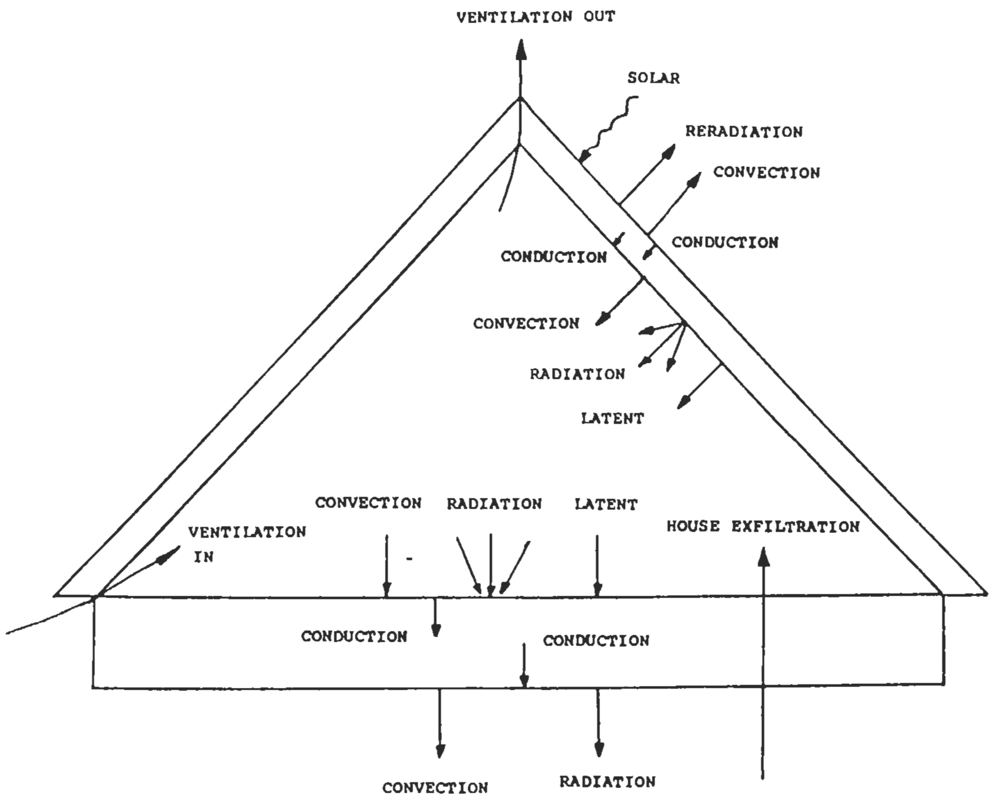

Figure 1. Schematic of Residential Attic Showing Heat Transfer Phenomena

an exact solution of the heat conduction equation for one-dimensional heat flow through a multilayer slab with temperature-independent thermal properties, with the only approximation being that the surface temperatures are taken to vary linearly between their hourly values. The model also utilizes an approximation that was developed to account for the temperature dependence of the thermal conductance of the component.[16] The effects of framing are incorporated by adding response factors using a parallel path approach.

Convection heat transfer from surfaces is calculated using convection heat transfer coefficients that are available in the literature.[18] The coefficients are based on correlations that have been developed for isolated isothermal flat plates. Correlations for natural convection are in the form of Nusselt numbers as a function of the Rayleigh number, while those for forced convection are in the form of Nusselt numbers as a function of Reynolds number. Correlations for both laminar and turbulent flow are used, depending upon the magnitude of the Rayleigh or Reynolds numbers. The Rayleigh number is calculated from the temperature difference between the surface and the average temperature of the air in the attic space, a characteristic dimension of the surface, and thermophysical properties of air evaluated at the film temperature. The Reynolds number is based upon an estimate for the velocity of the air flow over the surface, the characteristic dimension, and properties of air at the film temperature. For flows over the exterior surfaces, the wind speed is used. For flows over interior surfaces, an estimate of the air speed is made by dividing the ventilation volume flow rate by an average cross sectional area for the attic. The correlations account for the effects of the following variables: surface-to-air temperature difference, heat flow direction, film temperature, surface size, and surface orientation, as well as laminar vs. turbulent flow, and natural vs forced flow. Separate coefficients are calculated for natural and forced flow. A mixed coefficient is calculated by taking the third root of the sum of the cubes of the two separate coefficients.[19]

The applicability of correlations based on isolated isothermal plates exposed to an isothermal air mass has been questioned. A possible improvement is to use correlations for isolated isothermal plates exposed to an air mass that is stratified.[20-21] However, a better improvement would be to use correlations that account for coupling of the various surfaces rather than those for isolated plates. A number of studies have been reported for convection within a triangular enclosure.[22-28] These correlations have two deficiencies for attic modeling. The first is that they were obtained for systems that have isothermal surfaces, even at the intersections of the surfaces. This leads to a large contribution due to conduction in the "tip region" that would not be present in a real attic. The other deficiency is that the correlations were obtained for enclosures that are sealed, and so would appear to have limited applicability to attics that are ventilated.

A number of engineering approximations are made in the treatment of radiation within the attic. Each of the surfaces is assumed to be plane, gray, and isothermal. In addition, the surfaces are assumed to be diffusely emitting and reflecting and to have a uniform radiant flux over the surface. With these assumptions, the radiation interchanges are calculated using the enclosure method described by Sparrow and Cess.[29] With this method, view factors are calculated among the various surfaces. The enclosure method accounts for all inter-reflections, and allows each of the surfaces to have a different emittance. The Stefan-Boltzmann (T^4) radiation law is built into the equations. By factoring the nonlinear equations, it is possible to preserve a set of heat balance equations that have a linear form.

Heat transfer to the ventilation air stream is treated by Peavy's method. The air is assumed to enter with the temperature of the outdoor air. It then flows along a fictitious flow path where it picks up heat by convection from each of the surfaces facing the attic space. The areas of each surface are assumed to be distributed uniformly along the flow path. The result is a first order differential equation for the temperature of the air along its path. From this an exit air temperature is calculated, as well as an average air temperature.

The rate of ventilation air flow is determined from a combination of stack and wind pressure effects. Ventilation rates are calculated as the product of the vent area, a discharge coefficient (about 0.6), and the square root of a pressure differential. For the stack effect, the pressure differential is that from the bouyancy due to differences in density between the air within the attic space and that outside the attic. It is calculated using the outdoor temperature and the average temperature within the attic space. The pressure differential due to wind is taken to vary with the square of the wind speed. There appears to be a good deal of uncertainty in this ventilation algorithm. One question is whether the stack effect should be based upon the average attic air temperature or on some other more appropriate temperature. Also, the effective discharge coefficients for wind pressures are uncertain. An additional source of ventilation flow through the attic is air that exfiltrates from the house. This flow is added to the flow that comes from outdoors.

Approximations have been built into the models to account for the latent heat effects due to sorption and desorption of moisture at the wood surfaces that face the attic space. These generally follow the suggestions given by Burch, et. al.[30] and Cleary.[31] In this model, the humidity ratio at the wood surface is calculated from the moisture content of the wood and the surface temperature. A mass transfer coefficient is then calculated from the convection heat transfer coefficient assuming an analogy between heat and mass transfer. With this, a moisture balance is performed on the attic space that includes diffusion of moisture through the surfaces, convection of moisture into the attic space from the outside air and from exfiltration from the house, convection of moisture out of the attic space by the ventilation air, and moisture transfer to or from the wood surfaces. From this, the flow of moisture to or from each of the surfaces facing the attic space is calculated, and the latent heat effect is estimated. The intent of this treatment of moisture is only to estimate the effect of latent heats on the heat flow rates, and not to determine the accumulation of moisture itself. An estimation of moisture accumulation rates might require a more detailed treatment than is used here.

The treatment of the truss radiant barrier configuration requires additional heat balances, as shown in Figure 2. An extra ventilation air space is created between the radiant barrier surface and the roof. The model includes radiation across this space, and convection from the roof and the radiant barrier to the air flowing through this space. Conduction across the rafters is treated as a parallel path. The bottom side of the radiant barrier is then coupled by radiation and convection to the main attic air space as described above. With a truss radiant barrier on both roof sections,

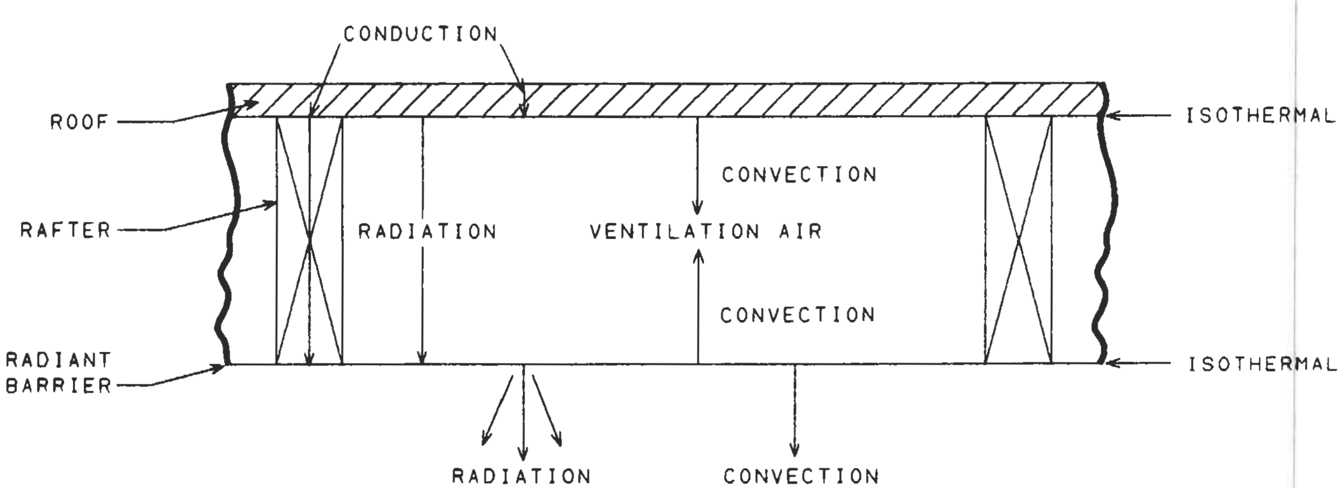

Figure 2. Heat Transfer Phenomena for Truss Radiant Barrier

four new heat balance equations are added to the set of 15 mentioned above: two balances on the radiant barrier surfaces and two balances on the ventilation air streams. A couple of problems remain unresolved. One is how to estimate separate flow rates for the main attic space and the spaces between the roof and the radiant barriers. Another is how the separate flows interact: are the flows separate, or do they mix with each other?

The set of heat balance equations that results is a system of simultaneous nonlinear algebraic equations with the unknowns being the surface and air temperatures. As mentioned above, each of the equations may be cast into a linear form. The linear equations are may then be solved by standard techniques. For the model described here, the Gauss-Jordan elimination technique was used, but other techniques might also be applied. Since many of the coefficients in the equations depend upon the unknown temperatures, the system of equations is solved iteratively. No convergence problems have been encountered with this iterative solution. After the temperatures are determined, heat flows may be readily calculated.

MODEL VERIFICATION

Since a number of phenomena have been combined in this model and many engineering approximations have been made, it is necessary to determine the validity of the models by comparing their predictions with data measured on real systems. Since comparisons of the ORNL model with measured data are still underway, the comparisons that are reported here should be considered preliminary. However, they do give some idea of the validity of the model.

Experiments on radiant barriers fall into two broad categories: laboratory and field experiments. Experiments in the laboratory may be conducted under either steady-state or transient conditions, while experiments conducted in the field are all transient. Field experiments may be further classified into those conducted with small test cells and those conducted with full-size houses. Comparisons of model predictions with data from each of these types of experiments are either underway or are planned.

A series of steady-state and transient laboratory experiments was conducted by Owens-Corning Fiberglas.[16,32] While no radiant barriers were included in these tests, the results are still useful for determining the validity of the basic model. The attic test module was a gabled attic built with trusses with a roof pitch of 5 in 12. The module had a 14 foot by 20 foot ceiling. For these experiments, the roof temperatures and attic ventilation rates were measured and were used as inputs to the model. Since the measured ceiling heat flow was that over the entire ceiling area, corrections for edge heat losses were made as described in Reference 32. Comparisons of model predictions with measured values for the total ceiling heat flow and for the average attic air temperature are given in Table 1. While full details of the test conditions are given in Reference 32, that Tests 1 and 2 were for winter conditions where the roof and outdoor temperature were both near 0°F, while Tests 3, 4, and 5 were for summer conditions with the roof near 150°F and with the outdoor air at 80-100°F. Results are given for a wide range of insulation levels. With a few exceptions, the heat flows predicted by the model are within about 5 to 10 percent of the measured values. Likewise, with a few exceptions, the predicted attic temperatures are within a few degrees of the measured values.

Table 1. Preliminary Comparison of ORNL Model Results with Owens-Corning Fiberglas Steady-State Tests

	Test	Heat Flows*	Attic Temperature**
R-0	1	-3.1%	-0.2°F
	2	-6.0	-0.9
	3	9.7	5.1
	4	19.6	-0.1
	5	7.7	3.4
R-11	1	-10.6	0.2
	2	-8.5	-1.1
	3	31.3	4.8
	4	9.3	-0.9
	5	8.6	-7.0
R-19	1	-0.8	-0.1
	2	-1.2	-1.8
	3	9.4	5.3
	4	8.2	-2.8
	5	4.2	-8.2
	1a	7.8	-5.0
	4a	4.6	-1.7
R-38	1	-0.9	0.3
	2	-0.7	-1.2
	3	2.6	1.4
	4	6.8	-1.4
	5	7.1	-3.7

* Values are predicted minus measured, as percentage of measured value,
$(Q_{predicted} - Q_{measured})/Q_{measured} \times 100$.

** Values are predicted minus measured temperatures, $T_{predicted} - T_{measured}$.

The laboratory data obtained by F. A. Joy[1] are widely quoted and are the basis for the tables of effective resistance of ventilated attic spaces given in the ASHRAE Handbook of Fundamentals. He reported steady-state data on two types of attics: one with a gabled roof and one with a flat roof. He reported data for attics with no radiant barrier and for a radiant barrier placed over the attic insulation (but not over the joists, which protruded above the insulation). Heat flow measurements were obtained with large heat flow transducers which measured the heat flow through the joists as well as that through the insulation. While full details of the test conditions are given in Reference 1, the roof temperatures were maintained near 150°F for the summer tests, and the outdoor air was held at 85-105°F with various ventilation rates. Measured values of both roof temperatures and ventilation rates were used in the models. A comparison of predicted and measured ceiling heat flows and exit air temperatures is given in Table 2 for the gabled roof, and in Table 3 for the flat roof. With the exception of two tests, summer heat flows for the gabled roof were predicted within 5 percent, and exit temperatures were predicted within a few degrees. The agreement for the flat roof was not as good, with predicted heat flows being as much as 25 percent different from the measured values. It was found that better agreement for the heat flows for the flat roof could be obtained if the roof was assumed to be coupled to the ventilation air through a 17 inch stagnant air layer, as shown in Table 4. It is speculated that the observed results are due to the special method of ventilation for the flat roof, where the cooler ventilation air is brought in just above the insulation and is not well coupled thermally to the roof.

Table 2. Preliminary Comparison of ORNL Model Results with Joy's Data for a Gabled Roof

Test	Heat Flows*	Exit Temperature**
No Foil, Summer:		
17	4.0%	-
18	0.4	-0.3°F
19	-2.1	-2.7
20	-2.7	-1.7
21	1.9	2.7
22	0.6	-0.3
23	3.9	-1.7
Foil, Summer:		
24	5.0	-
25	-1.4	-5.3
26	-13.3	-10.4
27	-15.2	-9.3
28	1.3	1.4
29	4.1	-3.0
30	4.5	-3.2
Foil, Winter:		
33	6.2	-
34	12.9	-0.1

* Values are predicted minus measured, as percentage of measured value,
$(Q_{predicted} - Q_{measured})/Q_{measured} \times 100$.

** Values are predicted minus measured temperatures,
$T_{predicted} - T_{measured}$.

A large number of field tests were performed by Fairey using a test cell that is approximately 5.75 feet long and 9.25 feet wide.[3,4] The cell has one roof section with a slope of about 6.5 in 12. Tests were performed both with and without radiant barriers. The test data are unique among field data in that the ventilation was imposed by a fan and was directly measured. Heat flows were measured with small heat flux transducers that measured the heat flow through the insulation only and did not include heat flow through the joists. A preliminary comparison of model predictions with measured heat flux and exit air temperatures are given in Figures 3a and 3b for a test with R-19 insulation and no radiant barrier. As with the other comparisons, measured roof temperatures and ventilation rates were used as input to the model. Model predictions

Table 3. Preliminary Comparison of ORNL Model Results with Joy's Data for a Flat Roof

Test	Heat Flow*	Exit Temperature**
No Foil, Summer:		
1	10.6%	-
2	10.0	2.6°F
3	8.4	0.2
4	12.4	-0.2
5	10.1	0.0
6	8.0	3.8
7	9.4	0.1
Foil, Summer:		
8	8.7	-
9	19.0	-3.5
10	25.7	-2.1
11	10.2	-0.9
12	7.4	-1.8
13	7.6	-0.2
14	7.7	-1.3
15	2.5	-1.9
Foil, Winter:		
31	4.9	-
32	8.6	1.3

* Values are predicted minus measured, as percentage of measured value,
$(Q_{predicted} - Q_{measured})/Q_{measured} \times 100$.

** Values are predicted minus measured temperatures,
$T_{predicted} - T_{measured}$.

Table 4. Preliminary Comparison of ORNL Model Results with Joy's Data for a Flat Roof (Assuming 17 inch dead air space below roof.)

Test	Heat Flow*	Exit Temperature**
No Foil, Summer:		
1	10.3%	-
2	8.0	-0.5°F
3	7.7	-3.1
4	14.9	-2.6
5	12.1	-2.1
6	6.8	-1.4
7	11.0	-1.5
Foil, Summer:		
8	1.6	-
9	-2.0	-14.6
10	-0.8	-10.3
11	-1.3	-5.9
12	-2.8	-6.0
13	2.0	-10.4
14	3.6	-7.5
15	0.7	-5.3

* Values are predicted minus measured, as percentage of measured value,
$(Q_{predicted} - Q_{measured})/Q_{measured} \times 100$.

** Values are predicted minus measured temperatures,
$T_{predicted} - T_{measured}$.

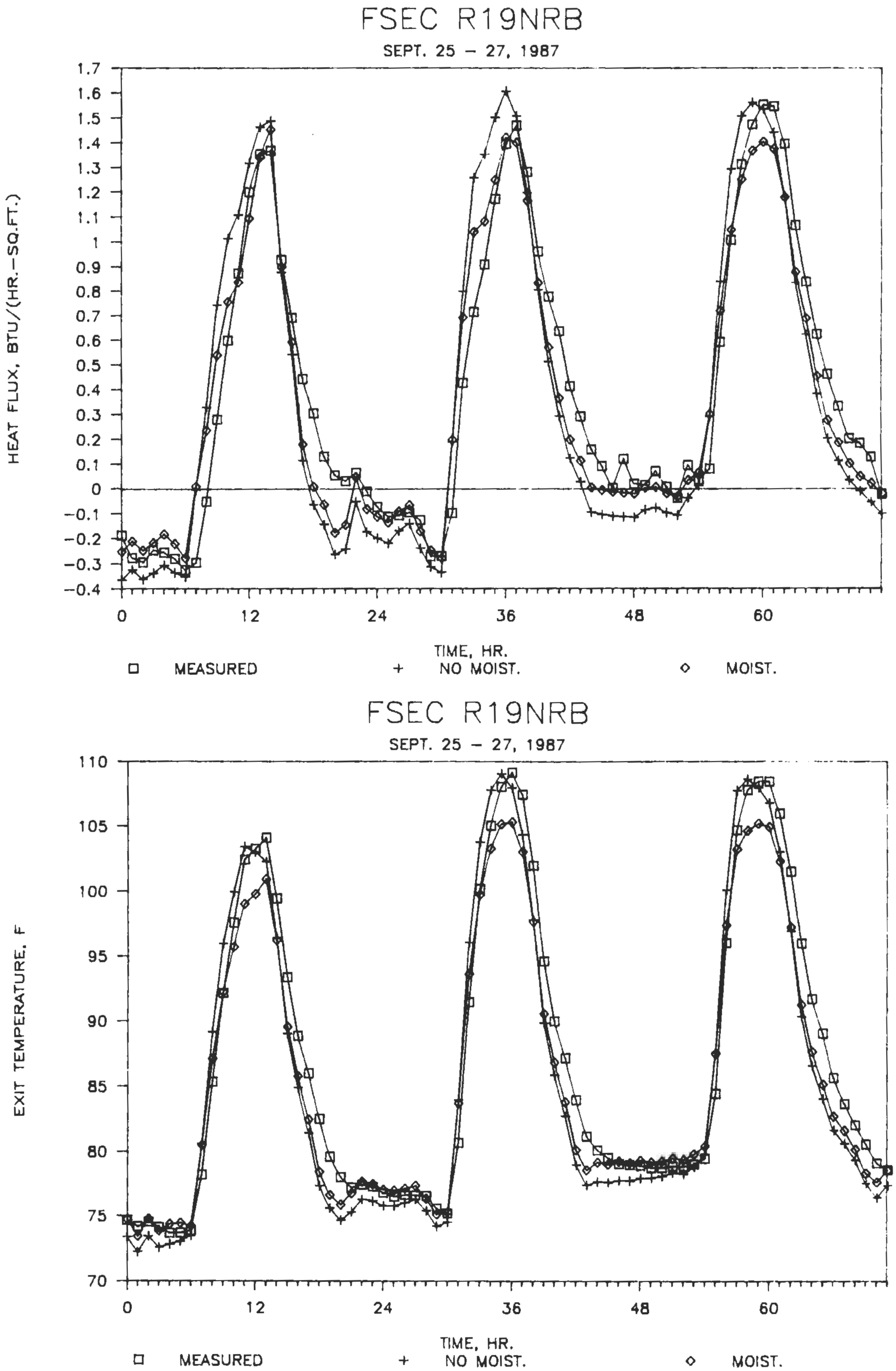

Figure 3. Preliminary Comparison of ORNL Model Results with Florida Solar Energy Center Data (R-19 insulation, no radiant barrier)

were made both with and without latent heat effects from moisture sorption/desorption included in the model. In general, these results show that the model does a reasonably good job of tracking the experimental results. The inclusion of moisture effects improves the predictions, at least during some parts of the day. Clearly, more comparisons with Fairey's data, especially those obtained with radiant barriers, are needed. These comparisons are underway and will be reported in the future.

Other experimental data have been reported by the Tennessee Valley Authority (field tests with test cells), the Mineral Insulation Manufacturers Association (field tests with full-size houses), and the Oak Ridge National Laboratory (field tests with full-size houses). Comparisons of model predictions with results of these experiments are underway, and will be reported in the future.

PLANS FOR GENERALIZATION STUDY

When the models have been judged to yield predictions that are in reasonable agreement with the experimental data, they can be used for extrapolation purposes. The plan is to couple the specialized attic/radiant barrier models with a whole house model (DOE-2) to estimate the potential for energy savings due to radiant barriers on a seasonal and annual basis for a number of climates. To do this, the models would be run with weather tapes from cities such as Miami, Phoenix, Los Angeles, Atlanta, Washington, Chicago, and Minneapolis. Because of the special interest in the Tennessee Valley, analyses would also be performed for Memphis and Knoxville. It is anticipated that the performance of radiant barriers will depend upon a number of parameters such as the radiant barrier location, the emittance of the radiant barrier, the amount and type of ventilation, the insulation level, the color of the roof, the geometry of the house, and the thermostat setting. Several other parameters that may have an influence can also be identified. It would be desirable to analyze the performance of radiant barriers with all combinations of these parameters. Since this would not be feasible, it is planned to carry out this study using ideas from the statistical design of experiments. Using a fractional factorial design, it is expected the most important parameters can be identified. A more detailed study can then be undertaken using only a few of the most important parameters.

SUMMARY

Heat transfer models for attics with or without radiant barriers have been developed based on a system of heat balances. The models have been based upon those available in the literature, but have been enhanced in several areas. One of the models incorporates the additional heat balances that occur with truss radiant barriers. Predictions of the models are presently being compared with experimental data from a number of sources. Comparisons that have been performed to date have been favorable. Predicted heat flows have generally been within about 10 percent of measured values. However, more comparisons are needed before making definitive statements about the accuracy of the models. Upon validation, the models will be used to extrapolate the experimental results to seasonal and annual performances in a wide range of climatic conditions.

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