Thermal Modeling of Residential Attics with Radiant Barriers: Comparison with Laboratory and Field Data

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ABSTRACT

Radiant barriers (RB) are receiving increasing attention as an energy conservation measure. A number of experiments performed by several organizations have demonstrated the energy savings potential for radiant barriers. The experiments have utilized a number of different attic and radiant barrier configurations and have been conducted under differing weather conditions. Because of this, it is difficult to compare the experimental results. Models are needed to gain a better understanding of the performance of radiant barriers, to extrapolate experimental data to seasonal and annual performances, and to estimate the performance under other climatic conditions.

This paper describes models that have been developed at a national laboratory for residential attics, with or without radiant barriers. Models based on systems of heat balances have been developed for both horizontal radiant barriers that are laid on top of the attic insulation and for radiant barriers attached to the bottom of the top chords of attic trusses. The models include features such as radiation interchanges within the attic space, convection to ventilation air, and sorption/desorption of moisture at surfaces facing the attic space. The paper compares model predictions with data from steady-state laboratory experiments and field experiments with full-size houses.

INTRODUCTION

A number of laboratory and field experiments have been performed to measure the thermal performance of radiant barriers (Joy 1958; McQuiston et al., 1984; Fairey 1983, 1988a; Hall 1986, 1988; Levins and Karnitz 1986, 1987a,b,c, 1988; Levins et al., 1986; Lear et al., 1987; Katipamula and O'Neal 1986; Katipamula et al., 1987; Ober and Volckhausen 1988). These experiments have generally shown that radiant barriers can reduce the heat flow through ceilings, and that they are most effective under summer cooling conditions. However, the experiments are difficult to compare because they differ in the attic and radiant barrier configurations studied and also in the weather conditions that existed during the experiments. The experiments have usually been performed for short periods of a few days or weeks, and have generally been performed in warm regions of the country, such as Florida and Tennessee.

Mathematical models are useful for comparing experimental results, extrapolating to seasonal and annual performance, and extrapolating to other climates. This paper describes a mathematical model that has been developed for predicting the thermal performance of attics with or without radiant barriers. The paper also gives some results of a study to verify the model by comparing its predictions with experimental results.

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MATHEMATICAL MODEL

The model used here has its origins in the model developed by Peavy at the National Bureau of Standards (Peavy 1979), and that was later extended by Wilkes (1983). Further development and testing of the model has been done at a national laboratory (Wilkes 1989a,b).

The sketch of an attic in Figure 1 shows the heat transfer mechanisms that are included in the model. The model consists of a set of heat balance equations at the interior and exterior surfaces of the ceiling, roof sections, gables, vertical walls at the eaves (for example, for raised trusses), and also a heat balance on the air mass within the attic space. Each of the surfaces is assumed to be isothermal. The set of heat balance equations is solved simultaneously to obtain surface temperatures, and then heat flows are calculated. This procedure is followed on an hour-by-hour basis throughout the time period of interest.

Conduction through each of the surfaces is handled using thermal response factors (Mitalas and Arsenault 1967; Kusuda 1969). The model includes an approximation that was developed to account for the temperature dependence of the thermal conductance of the component (due to temperature-dependent thermal conductivities) (Wilkes 1983), and the effects of framing are incorporated by adding response factors using a parallel path approach.

Convective heat transfer is calculated using coefficients from the literature that are based on correlations for isolated isothermal flat plates (Holman 1981). These correlations account for the following factors: surface-to-air temperature difference, mean (film) temperature, heat flow direction (up vs. down), surface size and orientation, laminar vs. turbulent flow, and natural vs. forced flow. Separate coefficients are calculated for natural and forced flow, and a mixed coefficient is calculated by taking the third root of the sum of the separate coefficients (Chen et al., 1986).

Radiation heat transfer among the surfaces facing the attic space is handled using an interchange analysis for enclosures (Sparrow and Cess 1966). Basic assumptions made in this analysis are that the surfaces are plane, gray, isothermal, diffusely emitting and reflecting, and have a uniform radiant flux. With this method, view factors are calculated among all the surfaces facing the attic space. The enclosure method accounts for all interreflections, and allows each of the surfaces to have a different emittance. The Stefan-Boltzmann (T^4) radiation law is explicitly built into the model.

Heat transfer to the ventilation airstream is treated by the method used by Peavy (1979). Air enters at the temperature of the outdoor air and is heated by convection as it flows through the attic. The areas of each surface are assumed to be distributed uniformly along the flow path. This results in a first-order differential equation for the temperature of the air along its path, from which an average air temperature and an exit air temperature are calculated.

The ventilation airflow rate is calculated from a combination of stack and wind pressure effects. Airflow rates are calculated as the product of the vent area, a discharge coefficient, and the square root of a pressure differential. The pressure differential for the stack effect is computed from differences in density between the air inside the attic space and the outdoor air. The pressure differential due to wind is taken to vary with the square of the wind speed, so that the ventilation rate is proportional to the wind speed. Exfiltration of air from the house is added to the flow that comes from outdoors.

Latent heat effects due to sorption and desorption of moisture at the wood surfaces facing the attic space are incorporated into the model in an approximate manner, using the methods given by Burch et al. (1984) and by Cleary (1985). A moisture balance on the attic space is performed, consisting of moisture that diffuses through the surrounding surfaces, moisture that is transported into or out of the attic by ventilation and exfiltration from the house, and moisture sorbed or desorbed by the wood surfaces. Mass transfer at the wood surfaces is calculated as the product of a mass transfer coefficient and the difference between the humidity ratios in the attic air and at the wood surfaces. The mass transfer coefficient is calculated from the convection heat transfer coefficient using the analogy between heat and mass transfer (Holman 1981). The latent heat associated with the mass transfer at the wood surfaces is coupled into the system of heat balance equations.

Additional heat balances are required with a truss radiant barrier, as shown in Figure 2. When the truss radiant barrier is placed some distance away from the roof, an additional ventilated air space is created between the roof and the radiant barrier surface. The additional heat balances account for radiation across this air space, convection to the ventilation airstream that flows through this space, conduction across the rafters, radiation from the bottom surface of the radiant barrier to the other surfaces facing the attic space, and convection from the bottom surface of the radiant barrier to the air within the main attic space. In this paper, the model with these additional heat balances is called the "truss model," while the model without them is called the "basic model."

Heat balances at exterior surfaces consist of absorbed solar radiation, convection to the outdoor air, and radiation exchanges with the surroundings. The model is set up so that the temperatures of all the surfaces can be calculated using specified weather and indoor conditions or, alternatively, the temperature of any of the surfaces may be specified. The latter mode is useful for analyzing data where surface temperatures were measured, while the former mode is also useful for analyzing experimental data and is necessary for analyzing completely hypothetical cases.

Because of their complexity, the mathematical relationships used in the models are not presented here. A complete mathematical description of the model is given in Wilkes (1989a), and listings of the computer programs are given in Wilkes (1989a,b).

COMPARISON WITH EXPERIMENT

The validity of the model has been assessed by comparing its predictions with the results of several experiments on radiant barriers. These include laboratory experiments, as well as field experiments with small test cells and full-size houses. In the interest of space, only comparisons of the model with steady-state laboratory tests and with ceiling heat flow measurements from two experiments on full-size houses are presented here. Additional comparisons may be found in Wilkes (1989a,b).

Appropriate input parameters for the models were used for each test. These consisted of items such as attic length, width, roof pitch, height at the eaves, response factors, surface emittances, and ventilation areas. Boundary condition inputs to the model consisted of weather parameters or measured boundary temperatures, and sometimes included measured ventilation rates.

Joy

One of the earliest studies of radiant barriers was performed by Joy at a U.S. university (Joy 1958). His results form the basis for the table of "effective resistance of ventilated attics" in chapter 23 of the ASHRAE Handbook of Fundamentals (ASHRAE 1985). These measurements were performed under steady-state conditions in the laboratory, using a test attic with ceiling dimensions of 12 ft by 13 ft. The attic was constructed so that tests could be run either with a flat roof or with a gabled roof having a pitch of about 5.5 in 12. The floor of the attic was insulated to about the R-7.5 level using high-density fiberglass board insulation about 2 in. thick. The attic had vertical eave walls about 1.83 ft high. All vertical walls of the attic (including gables) were covered with aluminum-foil-faced insulating boards and were also guarded with heaters to minimize heat losses. The ceiling heat flow was measured with four specially constructed heat flow meters with active areas that covered about 9% of the ceiling area, and included the heat flow through the ceiling joists as well as that through the insulation.

Tests were performed both with and without a radiant barrier, which consisted of kraft-backed perforated aluminum foil laid on top of the insulation with the foil side up. Summer conditions were simulated by maintaining the roof at 150°F and the room below the attic at 75°F. Tests were run with the attic sealed and with the attic ventilated at various rates with various outdoor air temperatures. For the gabled roof, ventilation air entered through a louver on one gable near the peak and exited through a slot near the peak of the other gable. For the flat roof, the air entered and exited through slots at the level of the ceiling joists.

Measured values of the exterior roof, ceiling bottom, and inlet air temperatures and the ventilation rate were used as inputs to the model. Since all the tests were performed under steady-state conditions, the model runs did not include moisture sorption/desorption at the wood surfaces. The effective emittance of the attic floor was taken to be 0.9 without a radiant barrier, and 0.096 with a radiant barrier. The latter value accounts for the high emittance of the joists, which were not covered with foil, but which were included in the heat flow measurements. The effective emittance of the attic floor was estimated by two methods. The first is an area average of the emittances of 0.05 for the radiant barrier and 0.9 for the joist, which yields an effective emittance of 0.13. This value would be valid if the radiant barrier and the joist surfaces were at the same temperature. The second is an analysis of heat flow through independent parallel joist and insulation paths consisting of radiation across parallel plates in series with R-10 insulation, which yields an effective emittance of 0.061. Since the real situation should be intermediate between these two approaches, an average of the two values was used.

Ceiling heat fluxes predicted by the model are compared with measured values for the gable roof in Table 1 and for the flat roof in Table 2. For the gabled roof, the heat flows span a range of more than a factor of two and, with two exceptions, the model predicts the heat flows to within 5% of the measured values. For the two exceptions, the model predictions are within 15% of the measured values. Comparing similar tests with and without a radiant barrier, measured heat flow reductions due to the radiant barrier range from about 26% to 32%. With the same two exceptions, the predicted heat flow reductions are within one percentage point of the measured reductions.

Measured heat fluxes range over a factor of about 3.5 for the flat roof. All model predictions are within 26% of measured values, and most predictions are within about 10% of those measured. For the tests with no radiant barrier, the model consistently overpredicts the heat flow by about 10%. Part of this overprediction may be due to shading of the attic floor from the hot roof deck by cooler rafters. Shading would be expected to be more important with the flat roof than with the gable roof because of the closer spacing between the roof and the attic floor with the flat roof. For the tests with a radiant barrier, the model overpredicts the heat fluxes by 2.5% to 26%. Part of this overprediction is thought to be due to the special way in which the attic was ventilated, with the cool ventilation air being brought into the attic through a slot that was just over the insulation and exhausted through another slot at a similar location at the other end of the attic. Joy noted that the airflow was laminar and highly stratified for these tests and thus the airflow would not be coupled with the roof as strongly as is assumed in the model. If the roof is assumed to be coupled to the airstream through a 17 in. stagnant air layer, then the model predictions would all be within 4% of the values measured with radiant barriers. Fairey also obtained good agreement with these data by using a two-zone model that assumed the air exchanged heat first with the attic floor and then with the roof (Fairey 1988b). Because of the strong radiation heat transfer in the absence of a radiant barrier, the assumption of a stagnant air layer does not improve the predictions without a radiant barrier. Even without accounting for radiation shading and stagnant air layers, the heat flow reductions due to the radiant barrier as predicted by the model are in reasonable agreement with the measured values. This is partly because the model overpredicts the heat flows both with and without radiant barriers. Measured reductions range from 26% to 48%, and predicted values range from 29% to 49%. With only one exception, the predicted heat flow reductions are within 5 percentage points of the measured values.

Mineral Insulation Manufacturers Association

The Mineral Insulation Manufacturers Association (MIMA) recently conducted a field experiment on radiant barriers at a test site in Ocala, FL (Ober and Volckhausen 1988). The experimental setup consisted of a duplex house with the attic divided into two spaces that were separated by insulation at about the R-30 level. Each space was about 26.67 ft long and 30 ft wide and had a roof pitch of 6 in 12. Each space had soffit vents with an area of about 4.5 ft^2 and ridge vents with an area of about 3.25 ft^2, and were ventilated naturally. Both spaces had well-characterized fiberglass batt insulation, with a nominal R-value of 19 and an installed R-value of about 20. All gable interior surfaces were painted black. The east section had no radiant barrier. The west section had a radiant barrier (reflective on both sides) that was draped between the rafters. Ceiling heat flows were measured by five 12-in. by 12-in. heat flux transducers in each attic space. The transducers were placed between the ceiling joists and measured the heat flow through the insulation, not that through the joists.

Detailed temperature, heat flow, and weather data were provided by Ober for the period of August 24-30, 1987. Hourly measured values of exterior roof, ceiling bottom, and outdoor air temperatures were used as inputs to the model. The ventilation rate was calculated using the algorithms that were built into the model. Since ambient humidity conditions were not measured, all model runs were made without including the effects of moisture sorption/desorption at the wood surfaces in the attic spaces. The effective emittance of the roof was taken to be 0.9 without a radiant barrier (ASHRAE 1985), and 0.1 with a radiant barrier. This latter value represents an area-weighted average of the emittances of the radiant barrier and the exposed surfaces of the rafters. The sensitivity of the model to changes in the effective emittance with a radiant barrier was briefly explored by using emittances of 0.05 and 0.13. The smaller value would apply if no roof wood surfaces were exposed, while the larger value accounts for areas at the top and bottom of the roof that are not covered with the radiant barrier.

Two model runs were made for the attic space with no radiant barrier. For the first run, the gables were modeled as being exposed to the outdoor air, but shaded from solar radiation. For the second run, measured interior gable temperatures were used as inputs to the model.

Hourly heat flows predicted by Run 1 compare favorably with measured values, as shown in Figure 3. (The sign convention in this paper is that heat flows from the attic into the house are taken as positive.) Predicted weekly heat gains are compared with measured values in Table 3. The weekly heat gain predicted from Run 1 agrees with the measured value to within 3%, while that for Run 2 agrees within 10%. It is interesting that the use of measured gable temperatures does not improve these predictions.

Eight model runs are reported here for the attic space with the draped truss radiant barrier. The first two runs were done with the basic attic model (no extra air spaces between the radiant barrier and the roof), with the same two conditions on the gables as were used above. The next four runs were done with the truss model, with the two different gable conditions, and with two assumptions about the flow of ventilation air through the extra air spaces. One of these assumptions was that nine-tenths of the vent area connected to the extra air spaces and that one-tenth of the vent area connected to the main air space. For the other assumption, these vent areas were reversed. The last two runs were similar to Run 1, but with effective roof emittances of 0.05 and 0.13.

Weekly heat gains for these eight model runs are compared with the measured values in Table 3. With the basic attic model and a roof emittance of 0.1, the use of the measured gable temperatures improves the predictions from a 6% underprediction to a 3% overprediction. However, either prediction would be considered good. When the truss model was used with the gables exposed to the outdoor air and shaded, the model predicted heat gains that were 29% to 30% lower than the measured values. When the measured gable temperatures were used with the truss model, the predicted heat gains were within 3% to 7% of those measured. These results show the importance of radiation from the black gables. They also suggest that the airflow assumptions built into the truss model result in too complete an isolation of the main attic space from the hot roof surface. This is confirmed by smoke tests by Ober that have shown that the air flows from the air space between the radiant barrier and the roof back into the main attic space (Ober 1989). The three comparable runs of the basic model with different roof emittances show that the predicted heat flows are sensitive to this parameter and that the high emittance of exposed wood surfaces needs to be taken into account. Hourly heat fluxes predicted from Runs 2 and 5 are compared with measured values in Figures 4 and 5. Hourly values from both these runs are in good agreement with the measured values.

The measured heat gain reduction due to the radiant barrier was about 21%. Various combinations of the predicted reductions range from 9% to 43%. Eliminating Runs 3 and 4 for the radiant barrier case, which appear to underestimate the influence of the gables, and Run 7, which uses too low an emittance for the roof, would narrow the range of predicted reductions to 9% to 24%. Additionally, if Run 1 for the no-radiant-barrier case were accepted as being the more realistic of the two runs, the range of predicted reductions would be 16% to 24%, which is in good agreement with the measured value.

Levins and Karnitz

Levins and Karnitz have conducted a number of field experiments on radiant barriers using the Karns research houses (Levins and Karnitz 1986, 1987a,b,c, 1988; Levins et al., 1986). The Karns houses are three very similar ranch-style houses located in the Karns community, about midway between Knoxville and Oak Ridge, TN. The houses are about 40 ft long and 30 ft wide. The roofs have a pitch of 5 in 12 and are covered with brown shingles. For the tests used here, the attics were vented with soffit vents with an area of about 3.15 ft^2 and gable vents with an area of about 5.01 ft^2. The attics were insulated with R-19 fiberglass batt insulation, and radiant barrier materials used were reflective on both sides. Radiant barriers were installed in either the horizontal configuration (laid directly on top of the insulation) or in the truss configuration (attached to and covering the bottoms of the top truss chords). Although the primary energy measurements were whole-house loads and HVAC energy consumptions, auxiliary measurements of heat fluxes through the ceilings were also made using 2.25-in.-square heat flux transducers. Since this paper deals only with the attic model, only the data from the heat flux transducers will be considered here.

The first radiant barrier tests in the Karns houses were performed during the summer of 1985. Data obtained during the week of August 13-20 were selected for comparison with the model predictions. Peak temperatures during this time period were between 85° and 90°F for all but two days. The indoor temperature was maintained near 70°F throughout this period. During this period, the house designated House 1 was a control house and had no radiant barrier, while House 2 had a horizontal radiant barrier and House 3 had a truss radiant barrier.

Hourly values of ambient and indoor temperature, solar radiation, wind speed, and outdoor and indoor relative humidity were used as inputs to the model. Ventilation rates were calculated using the algorithms built into the model. The emittance of the radiant barrier surfaces (i.e., the attic floor for House 2, and the roof for House 3) were taken to be 0.05. Since the heat flux transducers were located midway between the ceiling joists, the measured heat flux corresponds to that through the insulation path only, and is not influenced by the framing. To match these conditions, the model calculations also did not include the effects of framing on the ceiling heat flow.

Two model runs each were made for Houses 1 and 2. The first run ignored the effects of moisture sorption/desorption at the wood surfaces in the attic, while the second run included these effects. For House 3, these same two runs were performed using the basic attic model, without including the extra air spaces between the radiant barrier and the roof. For House 3, two additional runs were performed including these air spaces. For the first of these last two runs, nine-tenths of the total ventilation area was assumed to be connected to the air spaces between the radiant barrier and the roof, and the remainder to be connected to the main air space. For the second run, these fractions were reversed.

Hourly ceiling heat fluxes as predicted by model Run 2 are compared with measured values in Figures 6 through 8 for the three houses. The hourly variations in heat flux predicted by the model are in good agreement with the measured values. The model predicts the variations in peak heat fluxes well, and also correctly predicts heat flow reversals at night. The model even does a fair job on the fifth day, which was rainy.

Weekly heat gains were calculated by summing the positive hourly heat fluxes. Predicted and measured values are compared in Table 4. Table 5 presents a similar comparison using net heat flows obtained by summing all the positive and negative heat flows. Several points should be noted from this table. First, the inclusion of moisture effects does not influence the positive heat flows, but does improve the predictions of the negative heat flows. Second, the model runs for the truss radiant barrier performed with the basic model that ignores the extra air spaces are in good agreement with measured values. Predictions with the model that includes these air spaces (the truss model) are sensitive to the amount of ventilation area that is connected to the extra air spaces. This differs from the predictions for the MIMA tests, which were not sensitive to the split in ventilation area. The difference may lie in the boundary conditions that were used: for the MIMA tests, measured roof temperatures were used, while for the other tests, the roof temperature was calculated from a heat balance with the ambient weather conditions. Considering Run 2 (and also Run 3 for the truss radiant barrier) as the most appropriate of the model runs, the model predictions of heat gains are within 5%, 10%, and 2% of the values measured for the no RB, horizontal RB, and truss RB cases, respectively. Similarly, net heat flow predictions are within 8%, 14%, and 2% for the three houses.

An empirical analysis of heat fluxes and temperature differences across the ceiling suggests that, at the heat flux transducer locations, the R-value of the insulation in House 2 may be about 10% less than in House 1, while the R-value for House 3 may be about 2% less. Since the model predictions were all based on the assumption of equal (i.e., R-19) levels of insulation in the three houses, an adjustment for differences in insulation levels would improve the predictions of horizontal radiant barrier heat flows relative to those with no radiant barrier.

Measured heat flow reductions due to the horizontal radiant barrier are 23% to 24%, while the predicted reductions are 34% to 40%. As noted above, part of this difference may be due to the insulation level in House 2 being somewhat less than in House 1. Predicted heat flow reductions due to the truss radiant barrier are 25% to 26%, in reasonably good agreement with the measured values of 19 to 20 percent.

SUMMARY AND CONCLUSIONS

Models have been developed for predicting the heat flow through ceilings of residential attics with or without radiant barriers. The validity of the models has been assessed by comparing model predictions with ceiling heat flows measured in a number of radiant barrier experiments, including both steady-state laboratory experiments and field experiments with full-size houses. Model predictions have generally agreed to within about 10% of experimental results. This level of agreement relies upon the selection of appropriate parameters for input to the model, such as the effective emittance of surfaces containing both radiant barriers and exposed wood. The effective emittances used here were based on simple engineering calculations; more detailed analyses are needed to develop a more rigorous estimation of this parameter.

The model that ignores the extra air spaces between a truss radiant barrier and the roof (the basic model) is in good agreement with the experiments. Inclusion of these extra air spaces in the model (the truss model) does not improve the predictions for the experiments examined here.

Remaining discrepancies between the model and the experiments may be caused either by remaining deficiencies in the model or by uncertainties in the characterization of experimental parameters that are inputs to the model. Further progress in refining and validating the models appears to require additional experimentation under well-controlled and reproducible laboratory conditions.

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TABLE 1

Comparison of Predicted and Measured Heat Flows
for Joy's Data with a Gabled Roof

Inlet Air temperature, °F	Ventilation rate, cfm/ft^2	Ceiling Heat Flux, $Btu/h\text{-}ft^2$ Measured	Predicted	Difference, %*	Heat Flow Reduction due to radiant barrier, %** measured	predicted
No Radiant Barrier						
--	0	6.38	6.64	4.1	--	--
86.5	0.20	5.65	5.67	0.4	--	--
84.7	0.46	4.71	4.61	-2.1	--	--
84.5	1.04	3.83	3.73	-2.6	--	--
106.8	0.20	5.85	5.96	1.9	--	--
105.4	0.46	5.42	5.45	0.6	--	--
106.1	1.04	4.77	4.96	4.0	--	--
Radiant Barrier						
--	0	4.55	4.78	5.1	28.7	28.0
86.4	0.20	3.83	3.78	-1.3	32.2	33.3
84.2	0.46	3.47	3.01	-13.3	26.3	34.7
84.7	1.04	2.79	2.36	-15.4	27.2	36.7
106.3	0.20	4.20	4.25	1.2	28.2	28.7
105.9	1.04	3.43	3.58	4.4	28.1	27.8
105.8	1.04	3.44	3.60	4.7	27.9	27.4

*(Predicted-Measured)/Measured x 100

**(No RB-RB)/No RB x 100

TABLE 2

Comparison of Predicted and Measured Heat Flows
for Joy's Data with a Flat Roof

Inlet Air temperature, °F	Ventilation rate, cfm/ft^2	Ceiling Heat Flux, Btu/h-ft^2 Measured	Predicted	Difference,* %	Heat Flow Reduction due to radiant barrier, %** measured	predicted
No Radiant Barrier						
--	0	5.96	6.59	10.6	--	--
84.6	0.20	4.78	5.25	9.8	--	--
85.8	0.46	4.10	4.44	8.3	--	--
85.4	1.04	3.31	3.72	12.4	--	--
94.9	1.04	3.78	4.16	10.1	--	--
104.0	0.20	5.39	5.82	8.0	--	--
105.2	1.04	4.44	4.86	9.5	--	--
Radiant Barrier						
--	0	4.30	4.68	8.8	27.9	29.0
86.0	0.20	2.88	3.43	19.1	39.7	34.7
85.4	0.46	2.13	2.67	25.4	48.0	39.9
84.3	1.04	1.72	1.90	10.5	48.0	48.9
95.1	1.04	2.41	2.59	7.5	36.2	37.7
104.1	0.20	3.59	3.86	7.5	33.4	33.7
105.2	0.46	3.49	3.76	7.7	--	--
105.1	1.04	3.30	3.38	2.4	25.7	30.5

*(Predicted-Measured)/Measured x 100

**(No RB-RB)/No RB x 100

TABLE 3

Comparison of Predicted and Measured Heat Gains
for MIMA Tests (August 24-30, 1987)

Radiant Barrier	Model Run	Ceiling Heat Flow, Btu/ft^2 Measured	Predicted	Difference,* %	Heat Flow Reduction due to radiant barrier, %** measured	predicted
None	1	188.1	182.5	-3.0	--	--
	2	188.1	169.5	-9.9	--	--
Truss (Draped)	1	148.9	140.0	-6.0	20.8	23.3
	2	148.9	153.5	+3.1	20.8	9.4
	3	148.9	104.5	-29.8	20.8	42.7
	4	148.9	106.2	-28.7	20.8	41.8
	5	148.9	144.3	-3.1	20.8	14.9
	6	148.9	138.5	-7.0	20.8	18.3
	7	148.9	126.3	-15.2	20.8	30.8
	8	148.9	145.2	-2.5	20.8	20.4

Run 1: Basic model; gable temperatures not known.

Run 2: Basic model; gable temperatures known.

Run 3: Truss model; gable temperatures not known; nine-tenths of vent area in vent air space.

Run 4: Truss model; gable temperatures not known; one-tenth of vent area in vent air space.

Run 5: Truss model; gable temperatures known; nine-tenths of vent area in vent air space.

Run 6: Truss model; gable temperatures known; one-tenth of vent area in vent air space.

Run 7: Basic model; gable temperatures not known; effective roof emittance = 0.05.

Run 8: Basic model; gable temperatures not known; effective roof emittance = 0.13.

Note: Effective roof emittance for truss RB = 0.1 for all runs except Runs 7 and 8.

*(Predicted-Measured)/Measured x 100

**(No RB-RB)/No RB x 100; truss RB model runs 1, 3, 4, 7, and 8 are referenced to No RB run 1; truss RB model runs 2, 5, and 6 are referenced to No RB run 2.

TABLE 4

Comparison of Predicted and Measured Heat Gains for
Karns House Tests (August 13-20, 1985)

		Ceiling Heat Flow, Btu/ft^2			Heat Flow Reduction due to radiant barrier, %**	
Radiant Barrier	Model Run	Measured	Predicted	Difference,* %	measured	predicted
None	1	108.5	114.1	5.2	--	--
	2	108.5	113.6	4.7	--	--
Horizontal	1	82.3	74.9	-9.0	24.1	34.4
	2	82.3	74.4	-9.2	24.1	34.5
Truss	1	87.0	85.1	-2.2	19.8	25.4
	2	87.0	85.6	-1.6	19.8	24.6
	3	87.0	85.5	-1.7	19.8	24.7
	4	87.0	62.6	-28.0	19.8	44.9

Run 1: Basic model; no moisture sorption/desorption.

Run 2: Basic model; with moisture sorption/desorption.

Run 3: Truss model; with moisture sorption/desorption; nine-tenths of vent area in vent air space.

Run 4: Truss model; with moisture sorption/desorption; one-tenth of vent area in vent air space.

*(Predicted-Measured)/Measured x 100

**(No RB-RB)/No RB x 100

TABLE 5

Comparison of Predicted and Measured Net Heat Flows for Karns House Tests (August 13-20, 1985)

Radiant Barrier	Model Run	Ceiling Heat Flow, Btu/ft^2 Measured	Predicted	Difference,* %	Heat Flow Reduction due to radiant barrier, %** measured	predicted
None	1	96.0	93.2	-2.9	--	--
	2	96.0	103.6	7.9	--	--
Horizontal	1	73.6	55.8	-24.2	23.3	40.1
	2	73.6	63.6	-13.6	23.3	38.6
Truss	1	78.0	69.8	-10.5	18.8	25.1
	2	78.0	77.1	-1.2	18.8	25.6
	3	78.0	78.0	0	18.8	24.7
	4	78.0	55.6	-28.7	18.8	46.3

Run 1: Basic model; no moisture sorption/desorption.

Run 2: Basic model; with moisture sorption/desorption.

Run 3: Truss model; with moisture sorption/desorption; nine-tenths of vent area in vent air space.

Run 4: Truss model; with moisture sorption/desorption; one-tenth of vent area in vent air space.

*(Predicted-Measured)/Measured x 100

**(No RB-RB)/No RB x 100

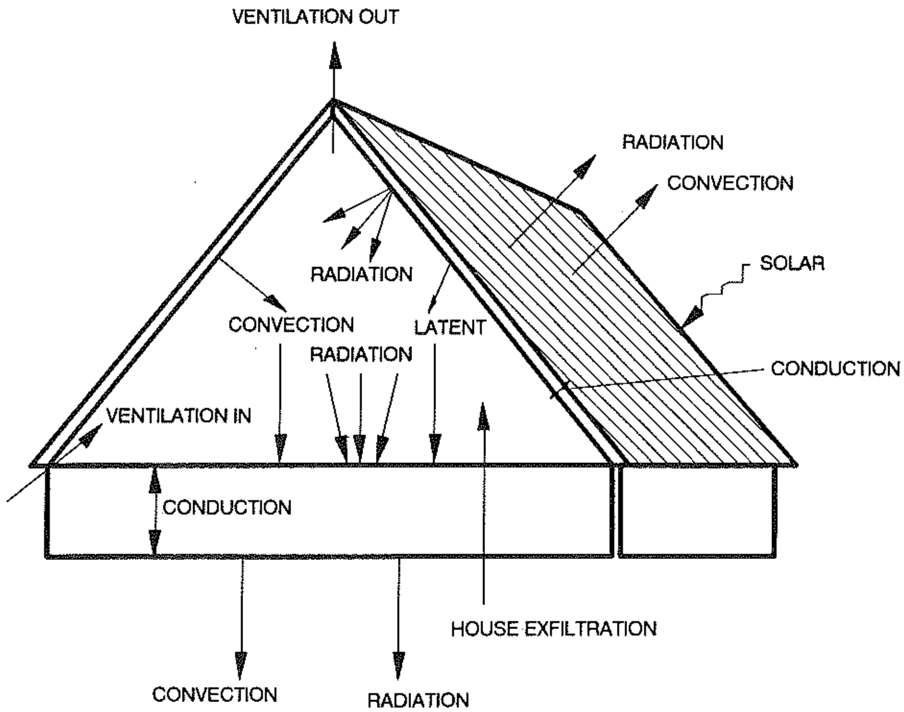

Figure 1. Attic heat transfer mechanisms

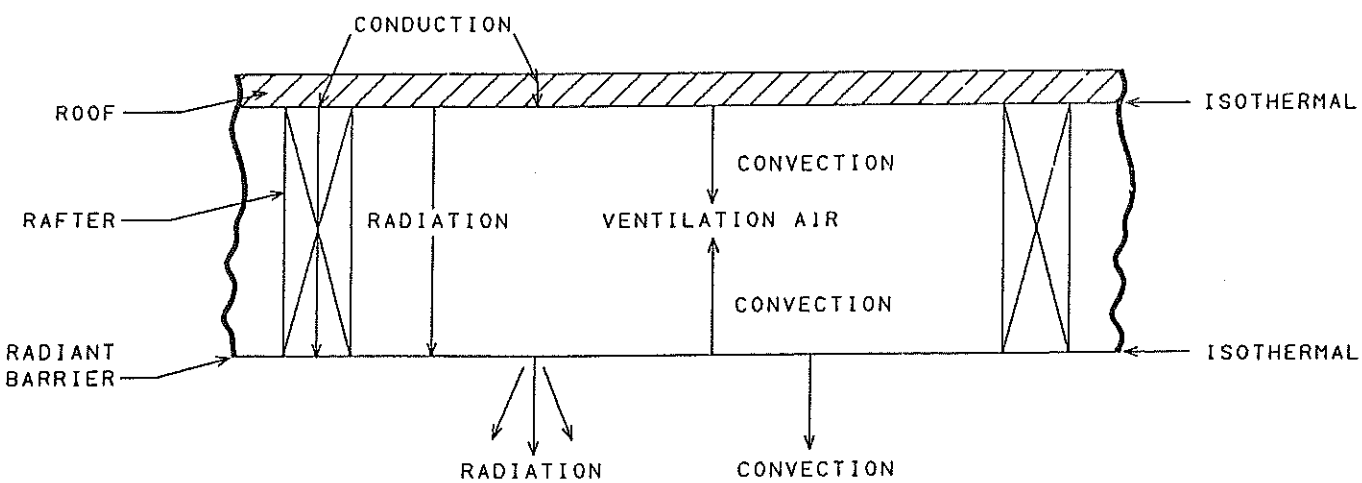

Figure 2. Truss radiant barrier heat transfer mechanisms

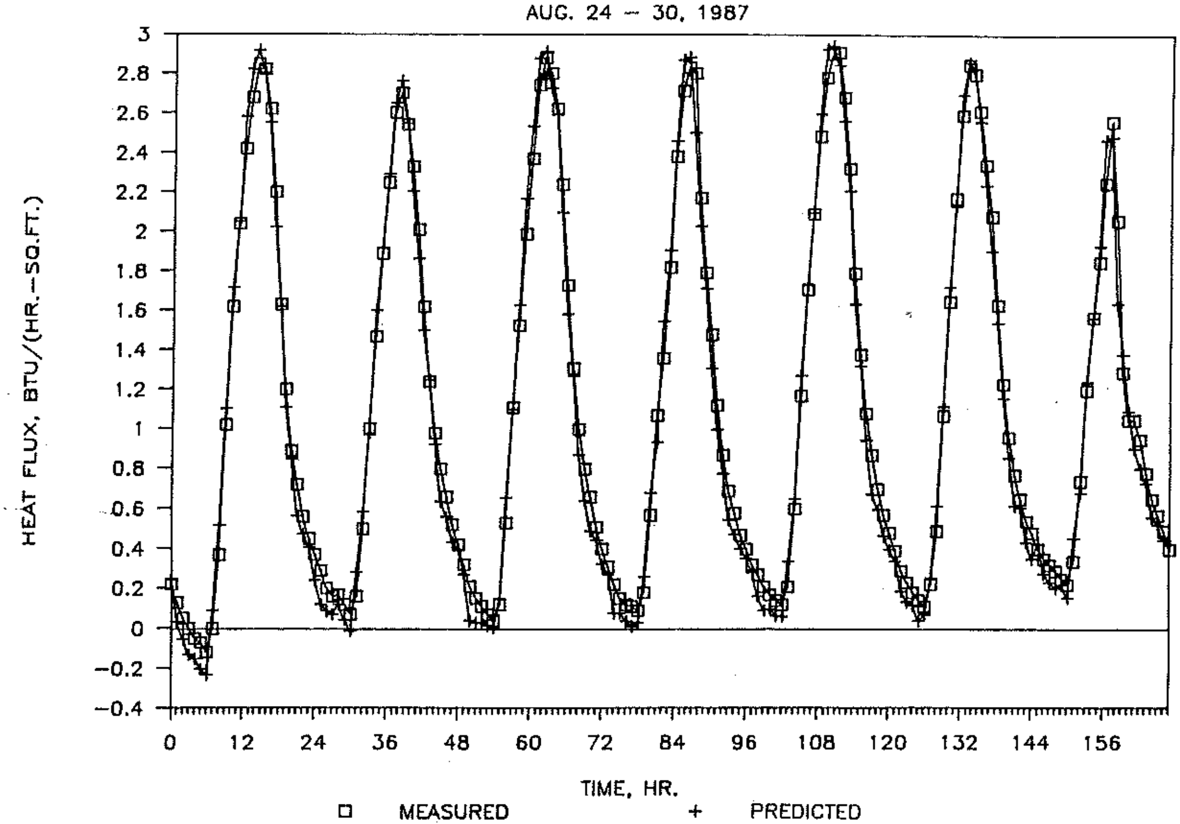

Figure 3. *Comparison of predicted and measured ceiling heat flows for MIMA test with R-19 insulation and no radiant barrier (model run 1, basic model with gable temperatures not known)*

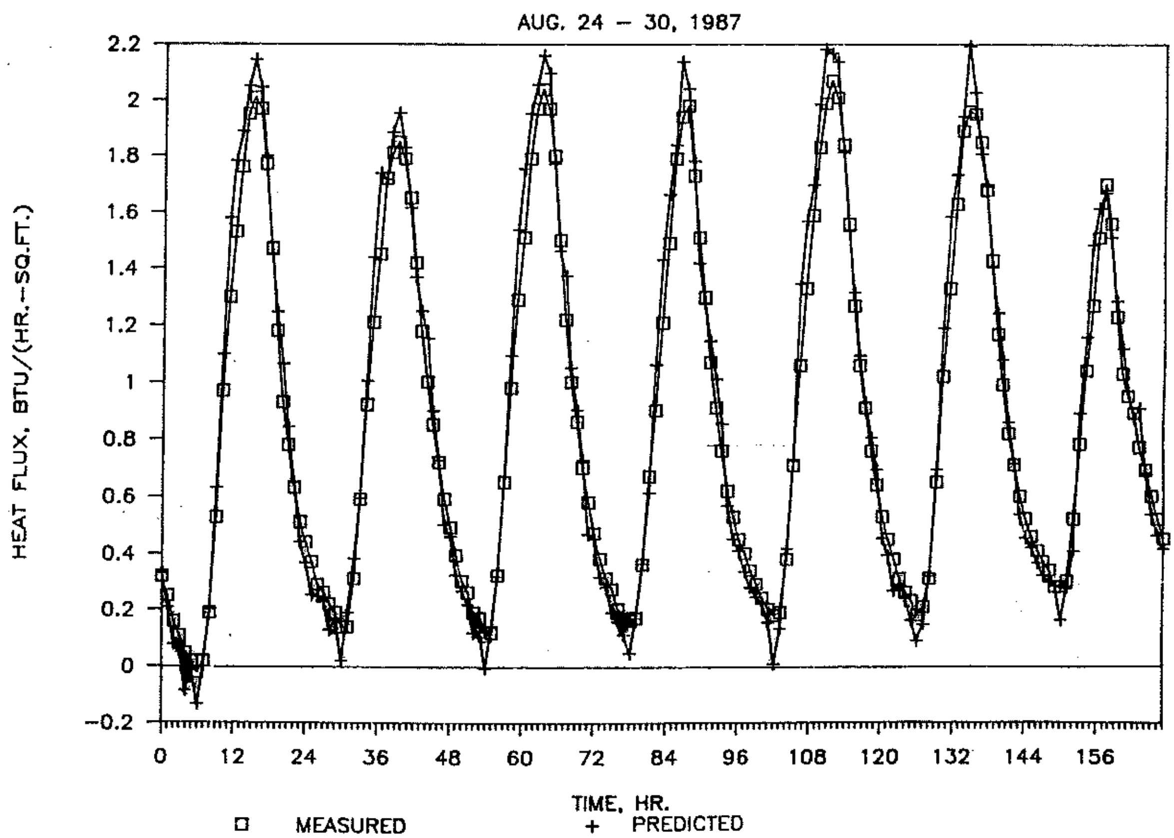

Figure 4. *Comparison of predicted and measured ceiling heat flows for MIMA test with R-19 insulation and draped truss radiant barrier (model run 2, basic model with gable temperatures known)*

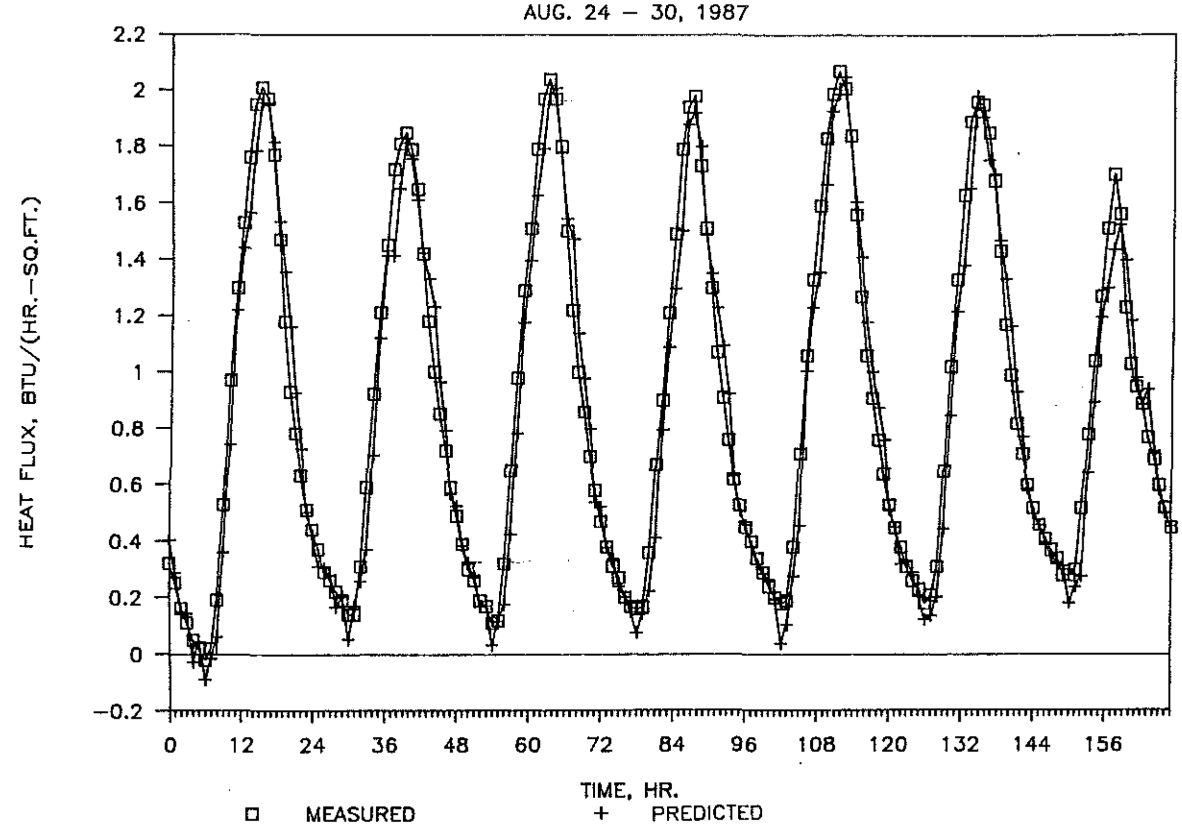

Figure 5. *Comparison of predicted and measured ceiling heat flows for MIMA test with R-19 insulation and draped truss radiant barrier (model run 5, truss model with gable temperatures known and 0.9 of ventilation area connected to air spaces between radiant barrier and roof)*

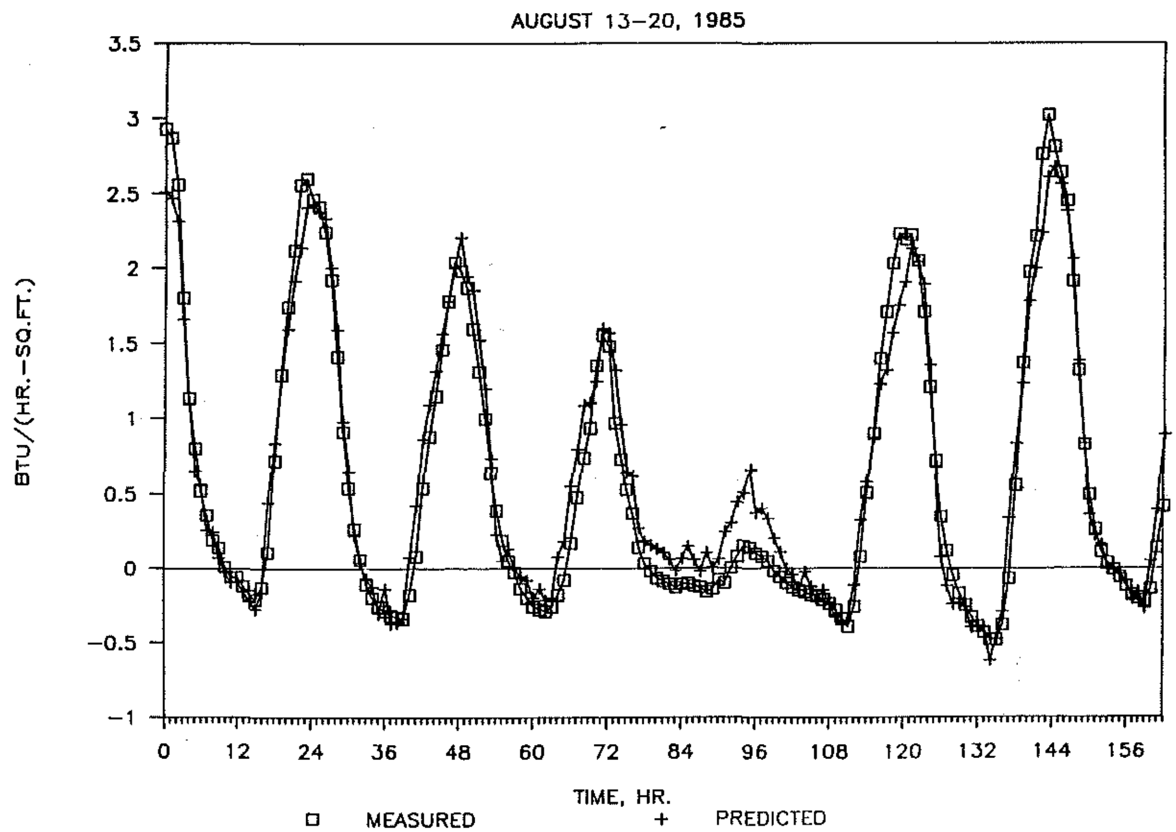

Figure 6. *Comparison of predicted and measured ceiling heat flows for Karns house test with R-19 insulation and no radiant barrier (model run 2, basic model with moisture sorption/desorption at wood surfaces)*

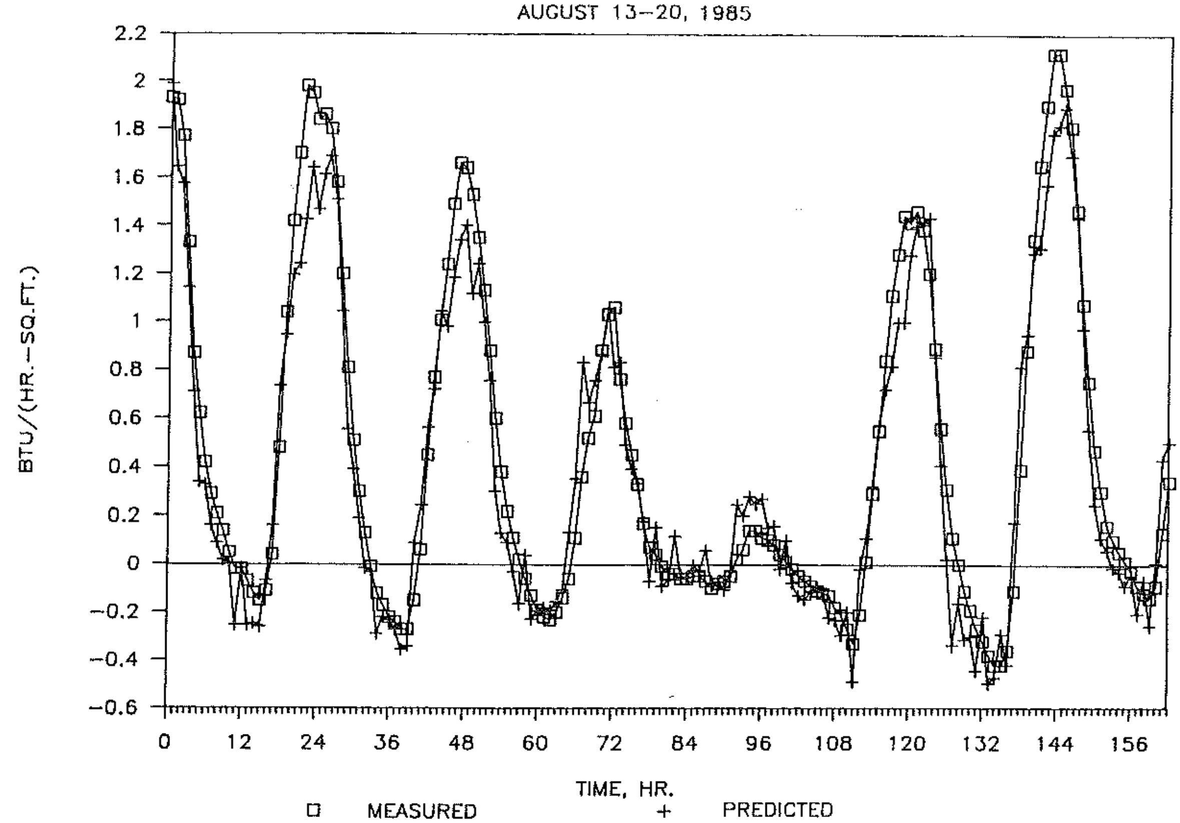

Figure 7. Comparison of predicted and measured ceiling heat flows for Karns house test with R-19 insulation and horizontal radiant barrier (model run 2, basic model with moisture sorption/desorption at wood surfaces)

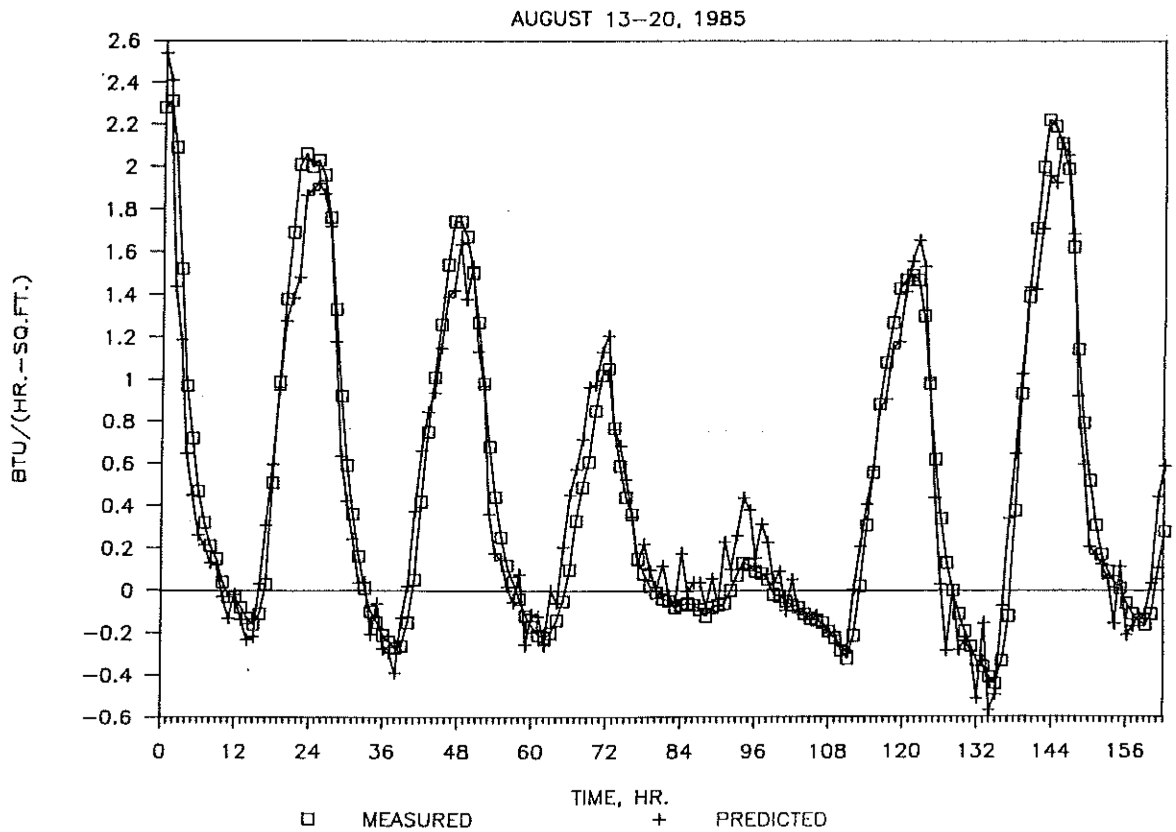

Figure 8. Comparison of predicted and measured ceiling heat flows for Karns house test with R-19 insulation and truss radiant barrier (model run 2, basic model with moisture sorption/desorption at wood surfaces)