EFFECT OF SURFACE MASS ON ROOF THERMAL PERFORMANCE

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ABSTRACT

The roof of a building is exposed to the most severe environment that is experienced by any component of a building envelope. Diurnal peak surface temperatures of 140 to 185 °F are not uncommon. The addition of thermal mass to the exterior surface of the roof should lessen the severity of the environment that is experienced by the roof membrane and the roof insulation. The exterior mass should result in attenuation both of temperature extremes and of heat flux variations. It also may result in lowered net heat flow through the roof. This paper presents some results of a combined experimental and analytical study to quantify the effects of surface mass. Measurements were made on roof test panels that were exposed to the weather of eastern Tennessee. The test panels consisted of glass fiber insulation with a modified bitumen membrane. Experiments were conducted on a bare panel and on a panels that were loaded with either concrete pavers or aggregates. A heat transfer model for the bare panel and the panel with concrete pavers was developed to calculate the internal temperatures and heat fluxes using measured indoor and ambient conditions. The model was validated by comparing its predictions with measured values. Following validation, the model was used to perform a parametric study of the effects of various levels of surface mass.

INTRODUCTION

A considerable amount of attention has been directed at the thermal performance of massive walls of building envelopes. From this work, it has been concluded that the addition of mass on the exterior of insulated walls produces only very small reductions in heat loads.[1,2] Much less attention has been directed at the thermal performance of mass added to the exterior of flat roofs.

Interest in the effect of surface mass on flat roofs stems from the fact that the roof is exposed to the most severe environment that is experienced by any component of a building envelope. Maximum diurnal peak temperatures of 140 to 185°F are commonly encountered.[3] Such severe temperatures impose limitations on the types of materials that may be used for roof membranes and insulations. It has been suggested that addition of thermal mass to the exterior surface of a roof would decrease the peak temperatures that are experienced by the membrane and insulation, thus possibly extending their useful lives or allowing use of other types of materials. Addition of exterior mass should also decrease the magnitude of roof heat flow fluctuations, and under some conditions may also result in a reduction in the net heat flow through the roof.

This paper presents some results of a combined experimental and analytical study to quantify the effects of surface mass. The first section gives a description of the experiments that were conducted with different types of surface mass. The next section describes a mathematical model that was developed to predict the thermal performance of roof systems with well-defined layers of materials. Following this are comparisons of model predictions with experimental data for a bare roof and a roof with a concrete paver. Next, results of parametric analyses with the model are presented to illustrate the effect of various levels of surface mass. Finally, plans for continued analyses and for development of a set of guidelines for the use of surface mass are presented.

EXPERIMENTAL SETUP

The experiment on surface mass was carried out at the U.S. Department of Energy Roof Research Center using the Roof Thermal Research Apparatus (RTRA) at the Oak Ridge National Laboratory (ORNL).[4] The RTRA, shown in Figure 1, is housed in a concrete block building approximately 8 feet wide by 26 feet long by 9 feet high. The RTRA has an insulated concrete slab-on-grade floor. The roof consists of a central fixed built-up roof (BUR) with four 4 foot by 8 foot test sites, two on each side. The interior temperature of the RTRA is controlled at about 75°F.

The panel for the surface mass experiment was positioned at the left end of the RTRA (as pictured in Figure 1). A cross section of the panel is shown in Figure 2. It consisted of four 15/16 inch sheets of fiberglass insulation over an 18 gauge metal roof deck. The top surface was sealed with a modified bitumen membrane. The cross section shown in Figure 2 also shows a layer of concrete pavers above the insulation and membrane. The panel was divided into two 4 foot by 4 foot sections. Near the center of each section, thermocouples were located at the exterior boundaries and between each layer of the panel. Calibrated heat flux transducers were located between the two inner layers of insulation.

Experiments were performed with various types of surface mass. During some time periods, one section was left bare, while the other section was loaded with mass. During other time periods, both sections were loaded with different masses. The types of masses studied included concrete pavers (with and without a modified bitumen cover), concrete pavers with grooves, white and brown river rock, and white and gray crushed aggregate. Although all of these masses were studied experimentally, this paper will focus on only one type, the concrete pavers. Results for the other types of mass will be discussed in forthcoming papers. For the time periods reported upon in this paper, one section of the panel was left bare, and the other section was covered with concrete pavers with a modified bitumen cover. The bitumen cover was added in order to match the radiative properties of the two panel sections.

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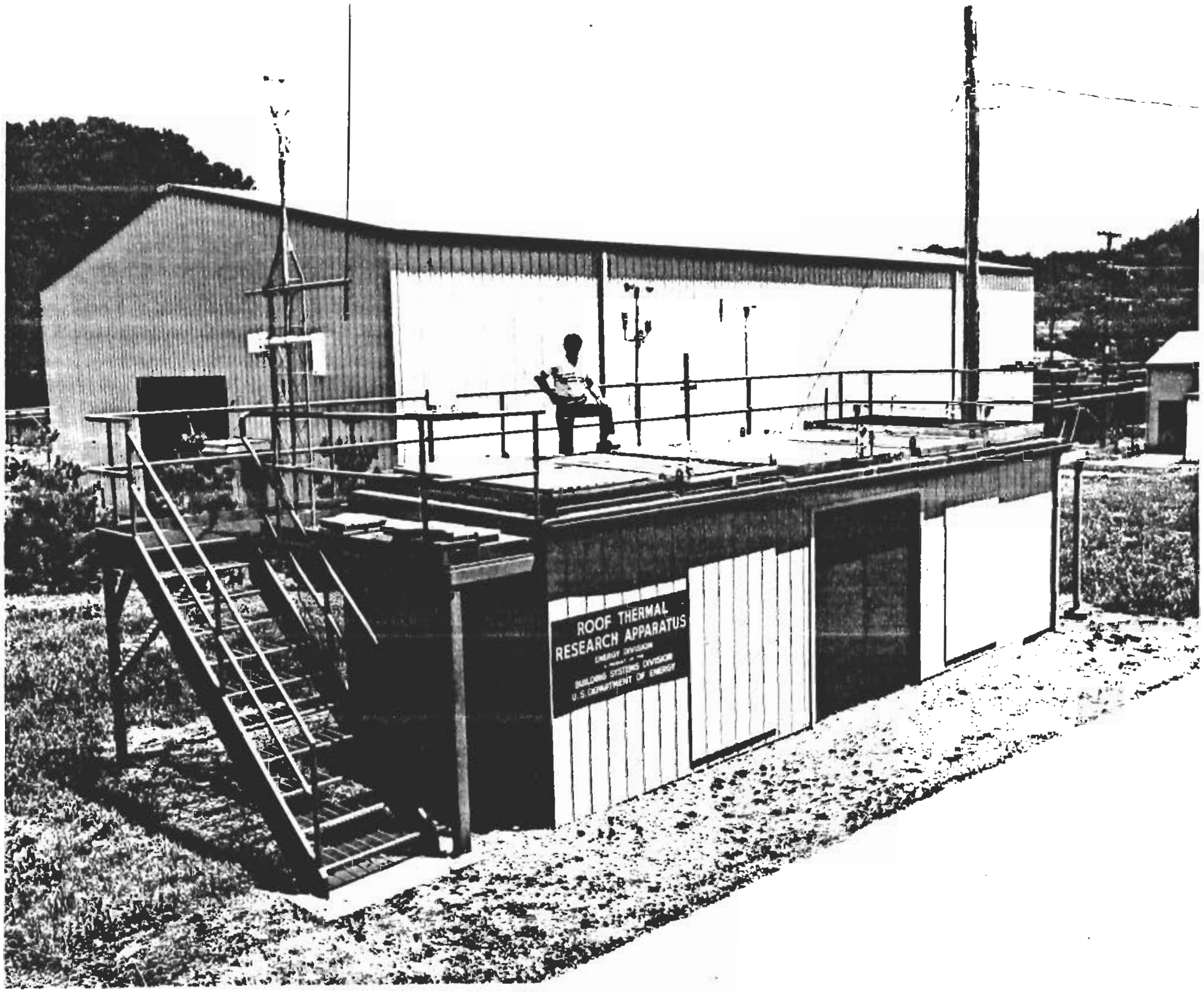

Figure 1. Roof Thermal Research Apparatus (RTRA)

In addition to the temperatures and heat fluxes measured on the panel, weather data were collected at the site. This consisted of outdoor temperature, relative humidity, wind speed, barometric pressure, incident solar radiation (pyranometer measurements over the 0.28 to 2.8 micron wavelength range), and incident infrared radiation (pyrgeometer measurements over the 4 to 50 micron wavelength range). These data were monitored continuously and hourly averages were recorded.

EXPERIMENTAL RESULTS

Two weeks of data have been selected for discussion in this paper. They correspond to a cool week (January 29 - February 4, 1986) and a warm week (May 1 - May 7, 1986). Measured ambient air temperatures for these two periods are shown in Figure 3a. During the week in January, the ambient temperature varied between 19 and 69°F, and exhibited a warming trend. During May, relatively warm days and cool nights prevailed with ambient temperatures varying between 35 and 88°F. Measured incident solar radiation values are shown in Figure 3b. The January time period exhibited both cloudy and sunny conditions while the week in May had predominantly clear skies. Measured incident infrared radiation data are shown in Figure 3c. The large magnitude of the infrared radiation should be noted. On cloudy days it can exceed the peak solar radiation. The pyrgeometer measures the incident infrared radiation, not the net amount which includes the outgoing radiation emitted and reflected by the surface.

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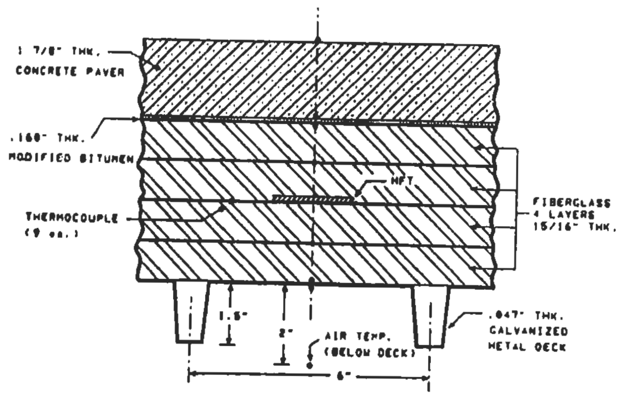


Figure 2. Cross Section of Roof Panel, Showing Concrete Paver Block Added to Surface

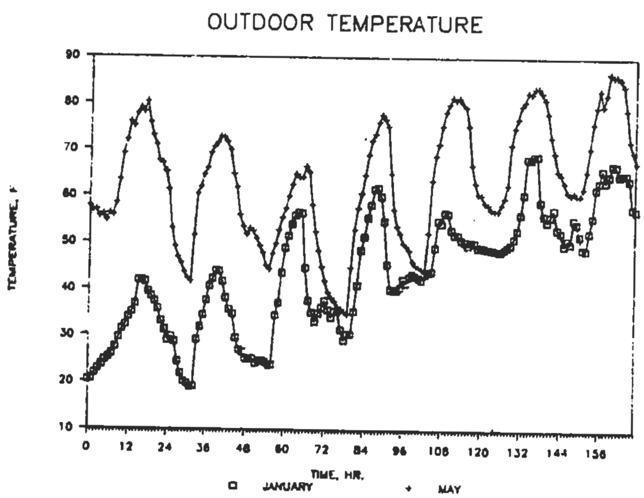
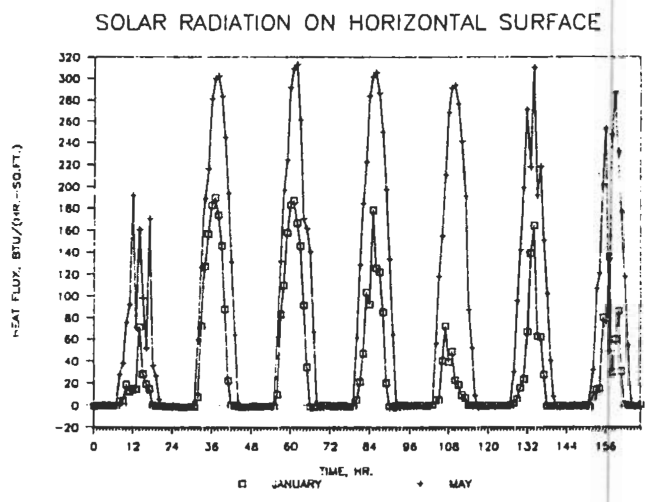


Figure 3. Weather Conditions During Cool and Warm Test Periods



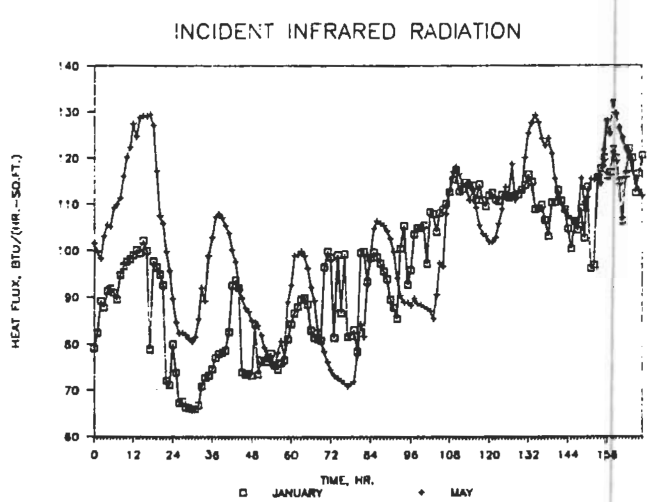


Figure 3. Continued

The two quantities examined in this paper are the temperature between the membrane and the insulation, and the heat flux through the roof. This temperature is important because it influences the useful lives of the membrane and the insulation and the choice of materials for these two components. The heat flux through the roof determines the magnitude of any energy savings. Measured values for the membrane temperature for the week in May are shown in Figure 4a. This figure shows temperatures for both the bare roof and the roof loaded with the concrete pavers. The paver results in a decreased amplitude for the temperature fluctuations experienced by the membrane. The peak daytime temperatures with the paver are as much as 30°F lower than with the bare roof. The pavers also reduce the nighttime temperature extremes. In some cases, such reductions in temperature extremes might be critical to extending the life of the membrane, or in allowing an alternate selection of membrane and/or insulation materials.

Roof heat fluxes measured for the week in May are compared in Figure 4b. Here, heat flow out of the building is positive while heat fluxes into the building are assigned negative values. The added mass reduces the peak heat flows in both the positive and negative directions. The presence of the pavers can also be seen to delay the occurrence of the peak heat flows by one to two hours. By summing the hourly heat flows, it is found that the positive heat flows are 178 and 90 BTU for the bare and paver roofs, respectively. Likewise, the negative heat flows are 225 and 154 BTU for the bare and paver roofs. Defining a net heat flow as the positive values minus the negative values, the nets for the bare and paver roofs are -47 and -64 BTU. With these definitions, the effect of the mass is to reduce both the positive and negative heat flows, but to increase the net heat flow. Whether the effect of mass on energy consumptions during this period is beneficial or not will depend upon the thermal behavior and operation of the rest of the building.

For the week in January, the positive heat flows for the bare and paver roofs were 275 and 238 BTU, while the negative heat flows were 38 and 7 BTU. For this period, the net heat flows would be 237 and 231 BTU, indicating little benefit from the mass.

ANALYTICAL MODEL

An analytical model for the thermal performance of roofs was developed to provide a means for generalizing the results of the experiments. The model is called STAR (for Simplified Transient Analysis of Roofs). It is a one-dimensional finite-difference transient heat conduction model that has been implemented on an IBM AT personal computer. In its present form, it is run interactively with information on roof geometry and material properties being input from the keyboard. The program handles multi-layer constructions, with node spacings being specified by the user. Temperature dependent thermal conductivities and specific heats are allowed. The user is given a choice of techniques for the transient solution: explicit, fully implicit, or Crank-Nicolson. The user may also select the size of the time step (as an integer number of time steps per hour). Although the program is strictly a heat conduction analysis at present, it will ultimately incorporate transport and storage of moisture. It will also be coupled with programs for determining the induced mechanical strains and stresses in the roof.

Two types of boundary conditions are allowed. One type is the specification of the boundary temperature. This is useful when experimental data are available. The second type utilizes the weather and interior room conditions to drive the thermal model. The exterior boundary condition consists of the following heat balance:

$$\alpha Q_{solar} + \epsilon Q_{infrared} + h_c (T_{air} - T_s) - \epsilon \sigma T_s^4 + Q_{latent} + Q_{cond} = 0$$

The terms in this equation represent absorbed solar radiation, absorbed incident infrared radiation, convection from the air to the surface, radiation emitted by the surface, heat delivered to the surface by condensation of moisture (or removed by evaporation), and the heat conducted up to the exterior surface of the roof. The quantities α and ϵ are the solar absorptance and the infrared emittance of the surface. The surface is assumed to be gray, so that the infrared absorptance and emittance are equal. The convection coefficient, h_c, is calculated from existing correlations and accounts for the orientation of the surface (tilt angle), direction of heat flow (up vs. down), the surface-to-air temperature difference, and the wind speed.[5] For a horizontal surface, the correlations for natural convection are

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

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

for heat flow up, and

$$Nu = 0.58\, Ra^{0.2}$$

for heat flow down. For forced convection, they are

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

$$Nu = Pr^{1/3} (0.037 Re^{0.8} - 850) \qquad \text{for } Re > 5 \times 10^5$$

where Nu, Ra, Re, and Pr are the Nusselt, Rayleigh, Reynolds, and Prandtl numbers. A mixed convection coefficient is obtained by taking the third root of the sums of the cubes of the natural and forced coefficients. An analogy between heat and mass transfer is used to estimate mass transfer coefficients for the latent heat term, with the mass transfer coefficient being approximately equal to the convection heat transfer coefficient divided by the specific heat of air. The amount of moisture that is condensed or evaporated from the surface is calculated with this mass transfer coefficient, the relative humidity and temperature of the air, and the temperature of the surface. A constant latent heat of 1060 BTU/lb is used in the program.

MODEL VERIFICATION

The validity of the model has been assessed by comparing its predictions with the measured membrane temperatures and roof heat fluxes. Although

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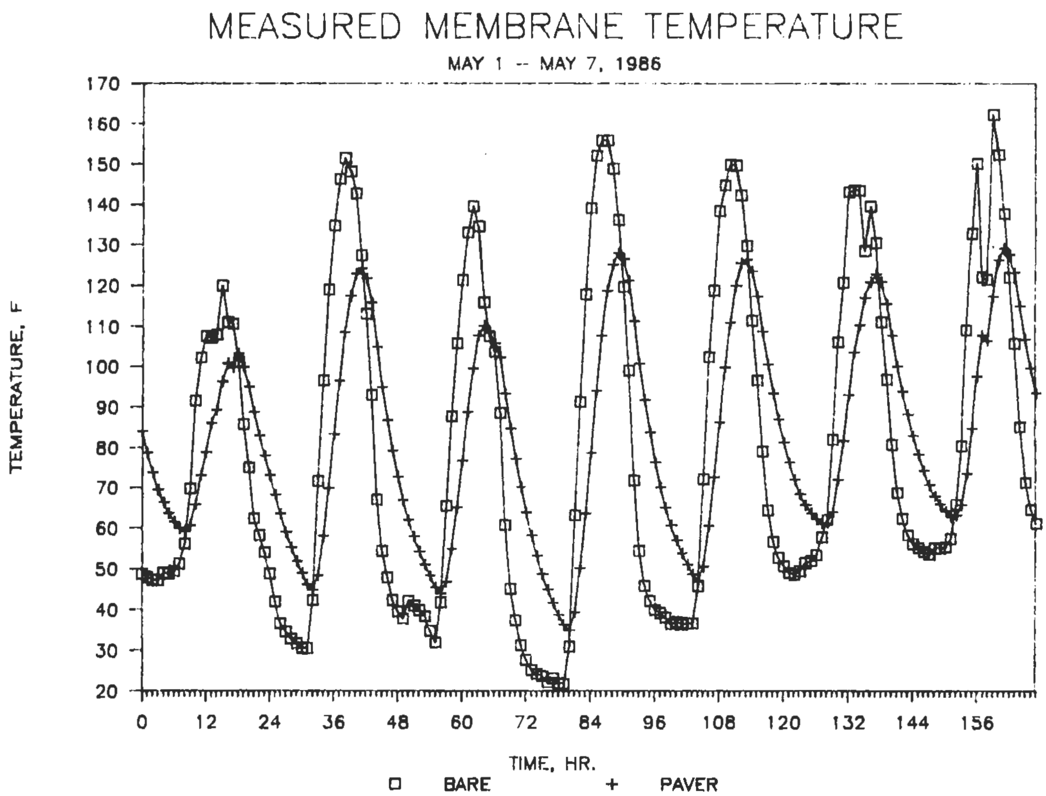

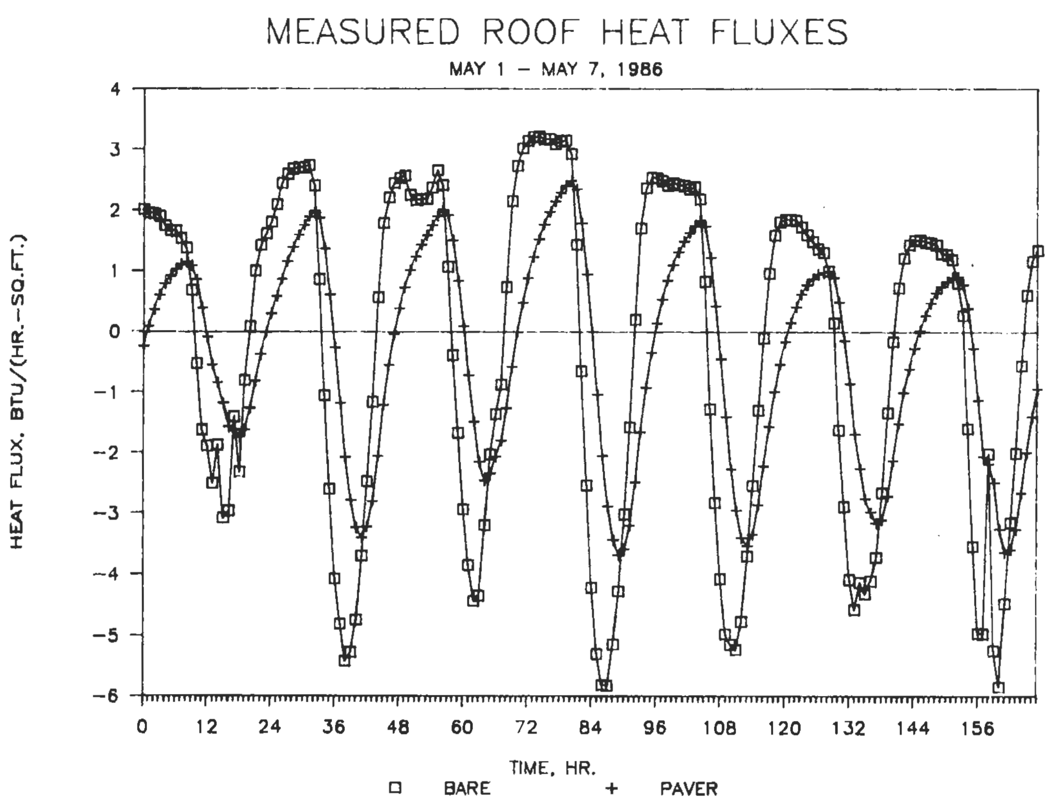

Figure 4. Measured Membrane Temperatures and Heat Fluxes During Warm Test Period

comparisons were made for the week in January as well as for the week in May, for brevity only detailed results for May will be presented here. Values used for the geometry and material properties are given in Table 1. All calculations were performed using the fully implicit technique, using a time step of 0.1 hours. A few runs were made with time steps of 1 hour and 0.01 hours, with more and fewer nodes to verify that the node spacings and time step used were satisfactory.

In the first step of this assessment, the model was run using measured temperatures for boundary conditions at the exterior and interior surfaces of the bare and paver roof panels. Measured and predicted membrane temperatures and heat flows for the bare roof are compared in Figure 5a and 5b, and similar comparisons for the paver roof are shown in Figure 6a and 6b. The predicted membrane temperatures for the bare roof are essentially identical to the measured values since the model used the temperatures measured on the other side of the membrane as input. From a visual inspection of the plots, other predicted temperatures and heat fluxes are judged to be in very good agreement with the measured values. Similar agreement was found for the January time period.

As the next step, the weather boundary conditions on the exterior side were used instead of the measured boundary temperature. Measured and predicted membrane temperature and heat fluxes are compared for the bare roof in Figures 7a and 7b. Similar comparisons for the paver roof are shown in Figures 8a and 8b. These comparisons, although less favorable than the ones with measured boundary temperatures, are still judged to be reasonable considering the uncertainties that exist in factors such as the correlations for convection of heat and mass. However, it appears that there is a need for further research to develop better information on convection and mass transfer coefficients and the interchanges of infrared radiation.

PARAMETRIC ANALYSES

Following verification of the model, it was used to perform a set of parametric analyses to estimate the effect of level of mass on the thermal performance. The hypothetical roofs analyzed were the same as the experimental roof, except that the concrete paver was replaced with layers having thicknesses such that the paver mass was 5, 10, 15, or 20 pounds per square foot. The exterior boundary condition consisted of the measured weather data for the January and May time periods. The interior boundary condition was taken to be a 75°F air temperature.

The maximum membrane temperature during each of the two periods was identified, and the values are listed in Tables 2 and 3. The largest decrease in membrane temperature occurs with the first addition of mass to the bare roof. With each additional increase of mass, the membrane temperature continues to decrease significantly but at a rate that is lower than the initial decrease. The reductions in membrane temperature due to the addition of surface mass are roughly the same for both time periods. However, even during the cool period, the peak membrane temperatures may be 90°F or higher.

Tables 2 and 3 also show the results of the parametric analyses for the effect of mass on the heat flows. The values given here are those at the interior surface of the roof, and are given in terms of positive, negative, and net heat flows for the weekly periods. From these values, it appears that the first incremental increase in mass produces a smaller impact on the heat flows than the last incremental increase. For the warm period, increasing mass leads to lower values for both the positive and negative heat flows, but increases the net heat flow for the period. As was noted above, the energy savings benefit from mass for this period would depend upon the characteristics of the rest of the building. For the cool weather period, the heat flows are predominantly positive, and the addition of mass produces a change in net heat flow of only a few percent.

CONCLUSIONS

A combined experimental and analytical approach has been used to perform an initial assessment of the effect of surface mass on the thermal performance of roofs. The experimental data clearly show that the peak membrane temperature may be decreased significantly by adding surface mass. The benefits of surface mass in conserving energy are

Table 1. Material Properties and Geometric Values Used in Models

Material	Thickness in.	Number of Nodes	Thermal Conductivity, BTU-in/(hr-ft^2-°F)	Specific Heat, BTU/(lb-°F)	Density, lb/ft^3
Modified Bitumen*	0.160	1	0.96	0.3	30.0
Concrete	1.875	4	20.3	0.21	140.0
Modified Bitumen*	0.2225	1	0.96	0.3	30.0
Fiberglass Insulation	3.75	8	0.252	0.3	12.7

* Solar Absorptance = 0.84
Infrared Emittance = 0.9

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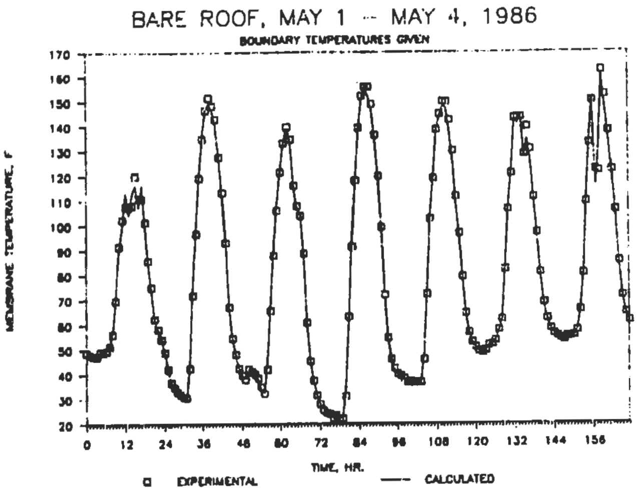


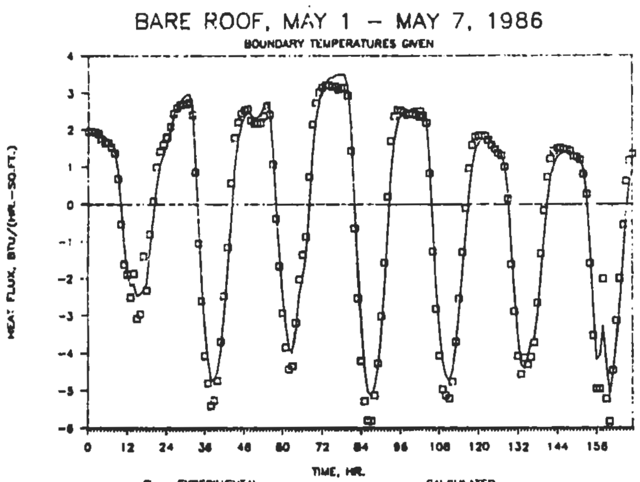
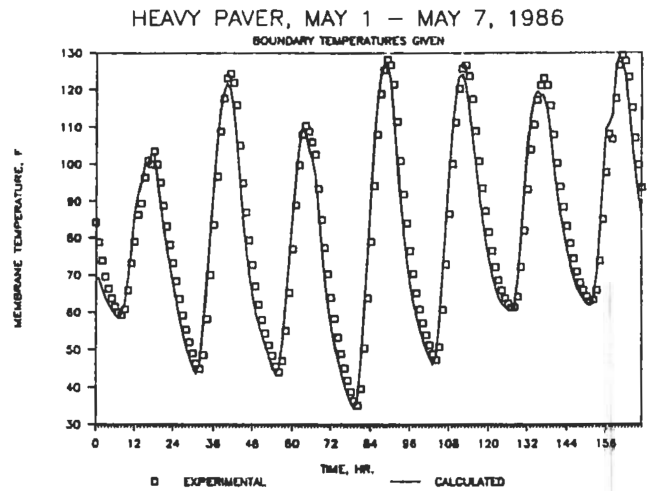


Figure 5. Comparison of Measured and Predicted Membrane Temperatures and Heat Fluxes for the Bare Roof During Warm Test Period: Boundary Temperatures Given for Predictions



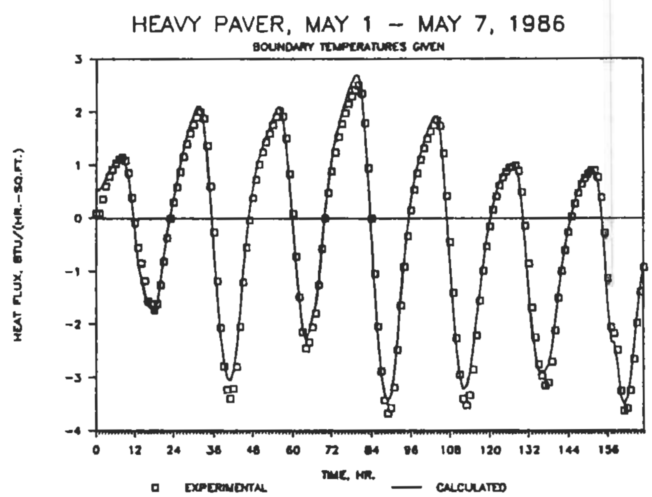


Figure 6. Comparison of Measured and Predicted Membrane Temperatures and Heat Fluxes for the Paver Roof During Warm Test Period: Boundary Temperatures Given for Predictions

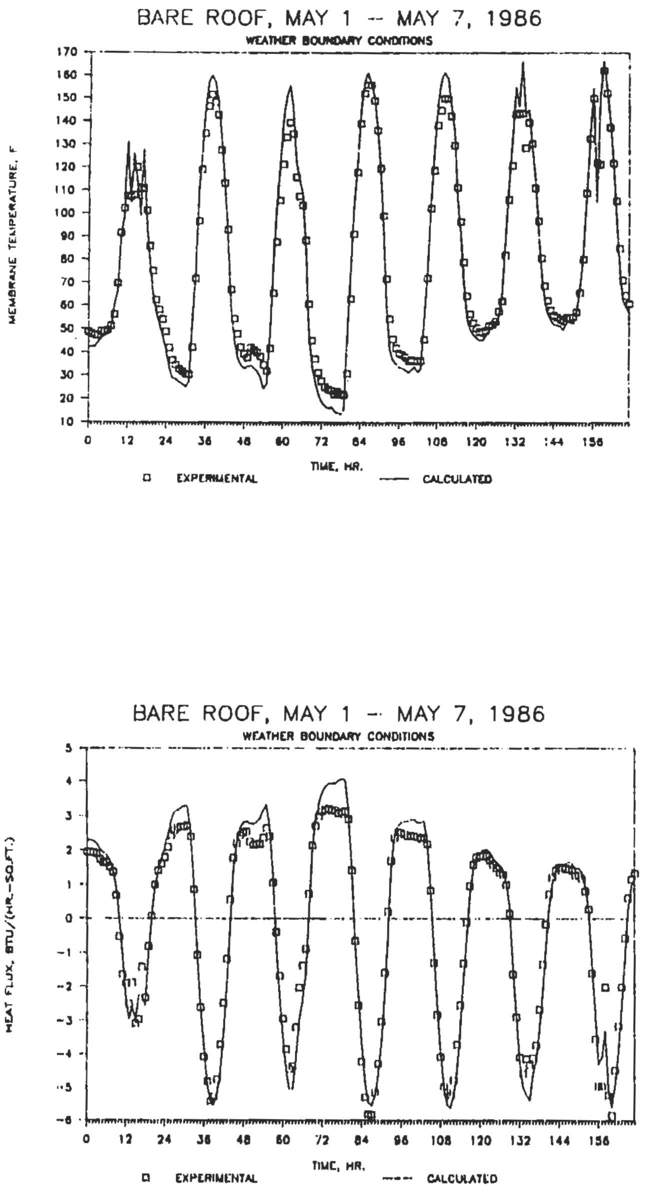


Figure 7. Comparison of Measured and Predicted Membrane Temperatures and Heat Fluxes for the Bare Roof During Warm Test Period: Weather Boundary Conditions for Predictions

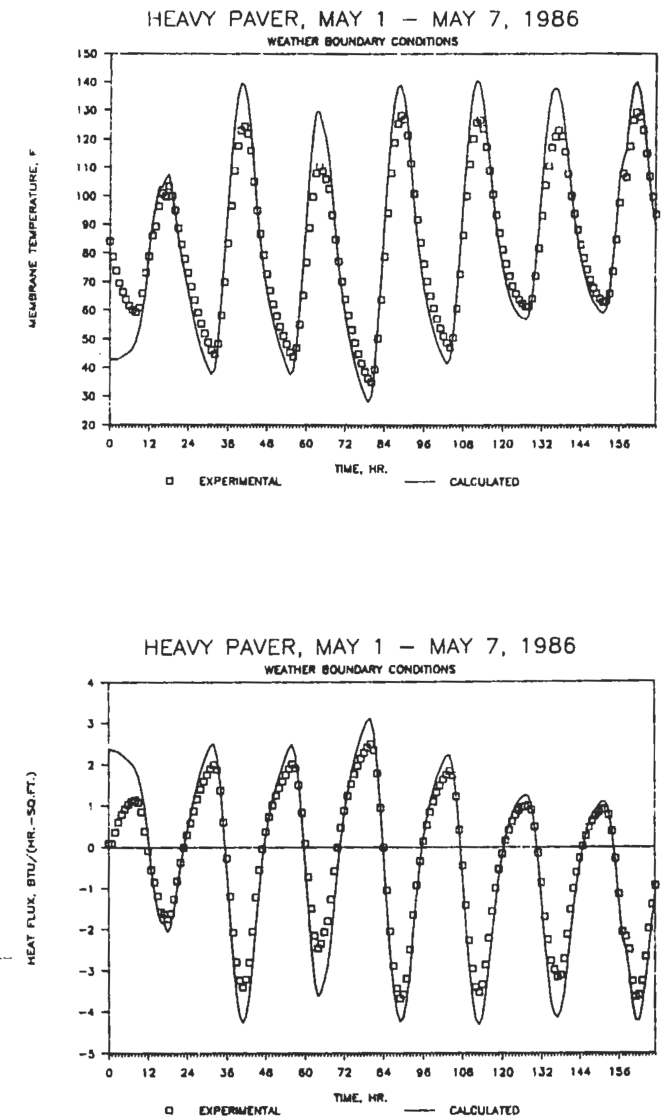


Figure 8. Comparison of Measured and Predicted Membrane Temperatures and Heat Fluxes for the Paver Roof During Warm Test Period: Weather Boundary Conditions for Predictions

Table 2: Parametric Analyses for One Week of Warm Weather (May) **

Mass psf	Tmax °F	Q+ BTU	Q- BTU	Qnet BTU
0	166	166	-205	-40
5	157	155	-202	-47
10	153	146	-195	-55
15	148	123	-185	-62
20	143	107	-175	-68

Table 3: Parametric Analyses for One Week of Cool Weather (Jan.) **

Mass psf	Tmax °F	Q+ BTU	Q- BTU	Qnet BTU
0	117	305	-14	292
5	106	304	-13	291
10	99	297	-9	288
15	95	290	-5	285
0	90	286	-3	284

** Q+ = Heat flow out of the building
Q- = Heat flow into the building

less clear. The addition of mass certainly decreases the peak heat flows in both the positive and negative directions, but the impact on the net building energy consumption would depend upon the characteristics of the rest of the building.

An analytical model for the thermal performance of roofs has been developed and verified against the experimental data. From visual inspections of the plots, the model is judged to work very well when the boundary temperatures are known. It also is judged to work reasonably well when the ambient weather data are used as a boundary condition. However, additional research is needed to better define the coupling of the surface to the environmental conditions.

Parametric analyses using the model suggest that the biggest impact on peak membrane temperature occurs with the first incremental addition of mass to the roof, with lower (but significant) impacts for additional mass. On the other hand, the first incremental addition of mass appears to have a lower impact on heat flows than intermediate additions. During cool weather, where the heat flow is predominantly in one direction, the addition of mass has only a small impact on net heat flows. During warm weather, where heat flows may be in both directions, the addition of mass may lead to increased net heat flows. However, the use of a net heat flow may not be appropriate for assessing the impact on building energy consumptions under these conditions, since a heat loss at one point in time does not necessarily offset a heat gain at another time.

While these parametric analyses have shown the effect of mass during two specific time periods, the net benefits of mass for energy conservation need to be determined from analyses that include the entire heating and cooling seasons and account for the characteristics of the rest of the building. This work is planned for the near future at ORNL.

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