THERMAL PERFORMANCE MEASUREMENTS OF INSULATED ROOF SYSTEMS

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ABSTRACT

Oak Ridge National Laboratory (ORNL) has developed and is operating a field test apparatus for experimentally investigating the thermal performance of low-slope roofs. The apparatus will accommodate four 4- × 8-foot test specimens and includes the measurement capabilities for specimen temperatures, temperature gradients, heat flows and moisture content. A weather station characterizes outdoor weather conditions. Experiments underway include roof surface temperature measurement, the effect of moisture in roofing insulation on the overall roof thermal performance, and the effect of roof insulation thermal mass on the overall roof thermal performance. The purpose of this paper is to describe the special features of this apparatus and to discuss some preliminary results of experiments.

The U.S. Department of Energy has established a Roof Thermal Research Apparatus (RTRA) at Oak Ridge National Laboratory (ORNL) for carrying out a wide range of thermal and hygric experiments on low-sloped roof sections. The goals of this work are to provide reliable thermal and hygric measurements and analysis of well-characterized roof systems under field conditions, and to substantiate energy savings attributes of these systems.

The RTRA has been designed to address many of the energy-related research needs identified in a recent "Assessment of Roofing Research."[1] These include moisture detection techniques, in-place U-value measurements, and the effects of color, reflective coatings, roof mass, and moisture migration on thermal performance. Accurate performance measurements of roof systems with different types and amounts of insulation will demonstrate the effectiveness of insulated roof decks in reducing building energy usage. This will provide baseline data for determining the economic optimum thickness of insulation and for evaluating the relative performance of different insulation systems under field conditions. Measurements from the RTRA also will be available for correlating the results of field measurements with laboratory measurements and with analytic simulations.

Techniques for measuring the amount and location of moisture within roof systems are being developed for use at the RTRA. This will permit detailed studies of the effect of moisture on thermal performance and will provide data on moisture movement within roofs.

THE BUILDING

The apparatus is shown in Figure 1. It is housed in an 8-foot wide, 26-foot long, 9-foot high building with a concrete slab-on-grade floor and concrete block walls. The roof has a conventional built-up roof (BUR) center section with two 4- x 8-foot test panels on either side. A walkway near roof level is mounted along the back and both ends of the building to facilitate inspection of the panels.

The interior temperature of the RTRA is controlled by a through-the-wall heat pump, and a humidifier is available to control humidity during the winter. Plans include the addition of exterior wall test panels to study exterior wall insulations.

TEST PANEL CONSTRUCTION

Test panels are assembled by roofing professionals and instrumented by project staff in a building near the test facility. Each experimental panel is designed to approximate a "real" roof segment. Panels are mounted in special steel angle frames to facilitate transportation and installation. Conventional wood nailers are mounted in the frames for membrane and perimeter flashing attachment. Steel decks are being used in current panels, although other types of decks can be accommodated and will be tested at a later date. The initial experiments are primarily concerned with properties of board insulations which are covered with conventional three-ply BUR membranes. Other membranes will be incorporated into tests when appropriate.

A computer analysis of installed test panels has shown that edge temperature effects are negligible within the central 2- x 6-foot region. This has been confirmed by thermocouple measurements and surface infrared scanning. Thus, thermal experiments carried out in this region will be typical of field conditions.

MATERIAL CHARACTERIZATION

Insulation layouts are designed around separate 3- x 5-foot sections placed in the center of the panel. Laboratory density and thermal conductance measurements are carried out on these sections. Full thickness steady-state conductance measurements are made using a unique hot screen apparatus in use at ORNL.[2] This apparatus has an accuracy of 1.5 percent traceable to Standard Reference Materials issued by the National Bureau of Standards. When heat flow measurements are required, heat flux transducers are imbedded in the insulation stack and calibrated simultaneously with these conductance measurements.

INSTRUMENTATION

Most temperature measurements are made using copper-constantan thermocouples. These measurements typically are made at the panel surface, at various points within the interior of a panel, and at several elevations within the building. Comparative temperature measurements of the panel surface also can be made with a two-dimensional infrared scanner. This equipment includes a camera, a CRT monitor, a video and audio tape recorder, and play back unit. Both monochromatic and color capabilities are available and are used.

Accurate moisture measurements are currently made with a set of load cells for continuously weighing the test panels. Four load cells are used to determine total panel weight and the center of gravity of a panel. Qualitative moisture measurements are obtained by using an infrared imager or a capacitance-based device. Plans for instrumentation include a unique, quantitative, electrostatic capacitance probe.

A conventional recording weather station is available for characterizing the outdoor climatic conditions. Specific measurements include outdoor ambient temperature, relative humidity, barometric pressure, wind speed, and wind direction. Other quantities measured include sky radiation, solar incidence, and outdoor panel surface reflectance.

DATA ACQUISITION SYSTEM

A major feature of the data acquisition system is the use of multiplexing units which receive inputs from many sensors and transmit the data over a single line to the data acquisition unit in the control building. The current system, which is expandable, can handle 100 data inputs.

All measurement transducers input to basic transducing/multiplexing units, each of which can handle 20 input channels. The information from five units is multiplexed again and sent over one wire to a data acquisition system (DAS). This system performs some data reduction, such as calculating hourly averages and applying engineering units. The DAS is hard-wired to a DEC PDP 11/34 computer for data storage. This unit, in turn, is accessible from several IBM personal computers where further data reduction and analyses can be performed. The personal computers also function as terminals for even larger mainframes available at ORNL which can perform data reduction and analysis on a larger scale.

PLANNED EXPERIMENTS

The RTRA has been operational since July 1984. Three experiments are currently underway. These are: (1) validation of an ORNL mathematical model for predicting roof surface temperature with wet insulation under the membrane; (2) comparison of the thermal performance of roof systems with different insulation densities; and, (3) validation of an ORNL analysis of the energy savings potential of high reflectance surfaces.

Additional work includes validation of a comprehensive thermal/hygric/structural mathematical model under development at the University of Illinois,[3] continuation of mass effect studies to different deck systems and to insulating concrete and analysis of the effect of wet insulation and of misting systems on thermal performance.

RESULTS

Roof Surface Temperatures

ORNL is carrying out an analysis of various factors that influence the use of infrared imagers to detect moisture in roof systems.[4] In such work, the relevant parameter is the difference in membrane surface temperature over wet and dry, or less wet, insulation sections. This difference depends upon the amount of moisture, the inside/outside temperature differences, the solar insulation, wind and several other variables. The ORNL analysis is an attempt to quantify these effects. The RTRA is used to validate results of the analysis.

Two nearly identical test panels are placed side by side in the RTRA. Both are BUR membranes without ballast over nominal R-15 fibrous glass board insulation on a metal deck. Provisions have been made for varying the water content. Only total water, not distribution, can be monitored at this time. Figures 2 and 3 show some of the results of this project. Figure 2 is a comparison of the measured surface temperature on a dry panel compared to the calculated temperature using the ORNL model. Two points should be made. First, the overall agreement is good particularly during evening hours which are most relevant for this study because infrared viewing is carried out during these times. Secondly, the disagreement during the day has been shown to be caused mostly by local wind effects during times when the surface-to-air temperature difference is large. Two possible causes are under investigation. One might be a difference in wind speed at the surface compared to measured wind speed 4 feet above the surface and the other might be an error in the algorithm for the surface convective heat transfer coefficient.

Figure 3 compares the temperatures on the two adjacent panels. Again, they follow one another closely, especially during the evening hours. The next step in this work will be to insert known amounts of water into one of the panels and compare measured to predicted values of surface temperature, particularly in the evening hours. Agreement will constitute validation of the ORNL model and provide confidence in its subsequent use to generate guidelines of infrared scanning.

Mass Effects of Roof Insulation

This work has not progressed far enough to provide quantitative results. Preliminary results, shown in Figure 4, suggest the complexity of the problem and also illustrate the hazard of attempting to use simple, steady state equations for calculating heat flow. In this case, a vertical array of thermocouples is installed in a 4-board stack of $^{15}/_{16}$-inch thick fibrous glass boards under BUR. The points connected by the solid lines represent measured temperature as a function of position in this stack at several times during one day, Sept. 1, 1984. The dashed line connects temperatures measured at the top and bottom of the stack. In a steady state calculation ($Q = DT/R$), the dashed temperature distribution is assumed. The figure clearly indicates that substantial errors exist between this assumed temperature distribution and the actual distribution. Also note, for example, at 9 pm and at midnight the steady state assumption predicts heat flow from the building whereas the actual temperature gradient near the inner surface suggests that heat is flowing from the insulation into the building as well as to the air. The reverse of this is true at noon. This illustrates the heat storage property of the insulation.

Thermal Effects of Surface Solar Absorptance

ORNL is currently carrying out a computer simulation study to quantify potential energy savings and surface temperature reduction on roofs around the nation when surface absorptance is varied. The purpose is to provide basic data useful for determining the cost effectiveness of low absorptance coatings. Preliminary results suggest that decreasing the absorptance decreases the summer load and increases the winter load on a building. When the net result is energy savings, it is typically less than 1kWh per year per square foot of roof area when the absorptance is reduced from 0.8 to 0.3.

The experimental apparatus is being used to validate certain aspects of this model. In Figure 5 we have plotted temperature vs. time for two roof sections, one with an asphalt flood-coat surface and the other with aluminum flakes sprinkled in the flood coat. Note that the aluminum flakes clearly produce a decrease in daily temperatures. Also note that the long wave absorptance also is decreased by these flakes because evening temperatures on the treated surface are above those on the untreated surface.

SUMMARY

Oak Ridge National Laboratory has established a Roof Thermal Research Apparatus for carrying out thermal and hygric experiments on sections of low-sloped roofs. Test panels are exposed to a controlled temperature interior space and to the prevailing East Tennessee exterior environment. They are well instrumented with all data processing done with the aid of computers.

Current experiments include studies of the effect of wet insulation on membrane temperature, thermal storage phenomena in built-up roof insulation, and the effects of varying surface reflectance on roof thermal performance.

REFERENCES

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[4] Childs, K. W., and Courville, G. E., "An Investigation of Factors Influencing Infrared Moisture Surveys Using a Mathematical Model," Proceedings of SPIE, Volume 446, p. 82, 1984.

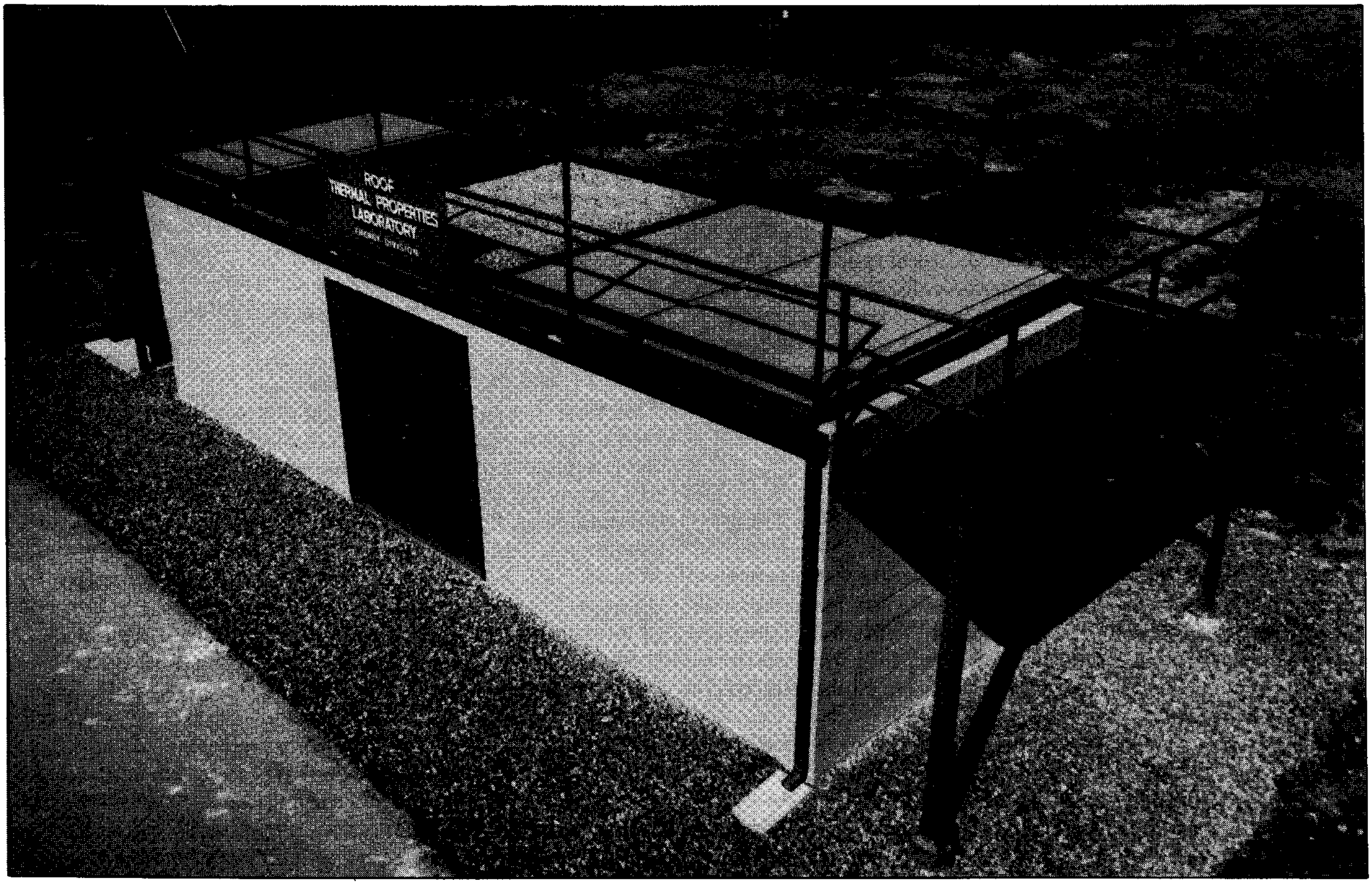

Figure 1 The U. S. Department of Energy Roof Thermal Research Apparatus at Oak Ridge National Laboratory

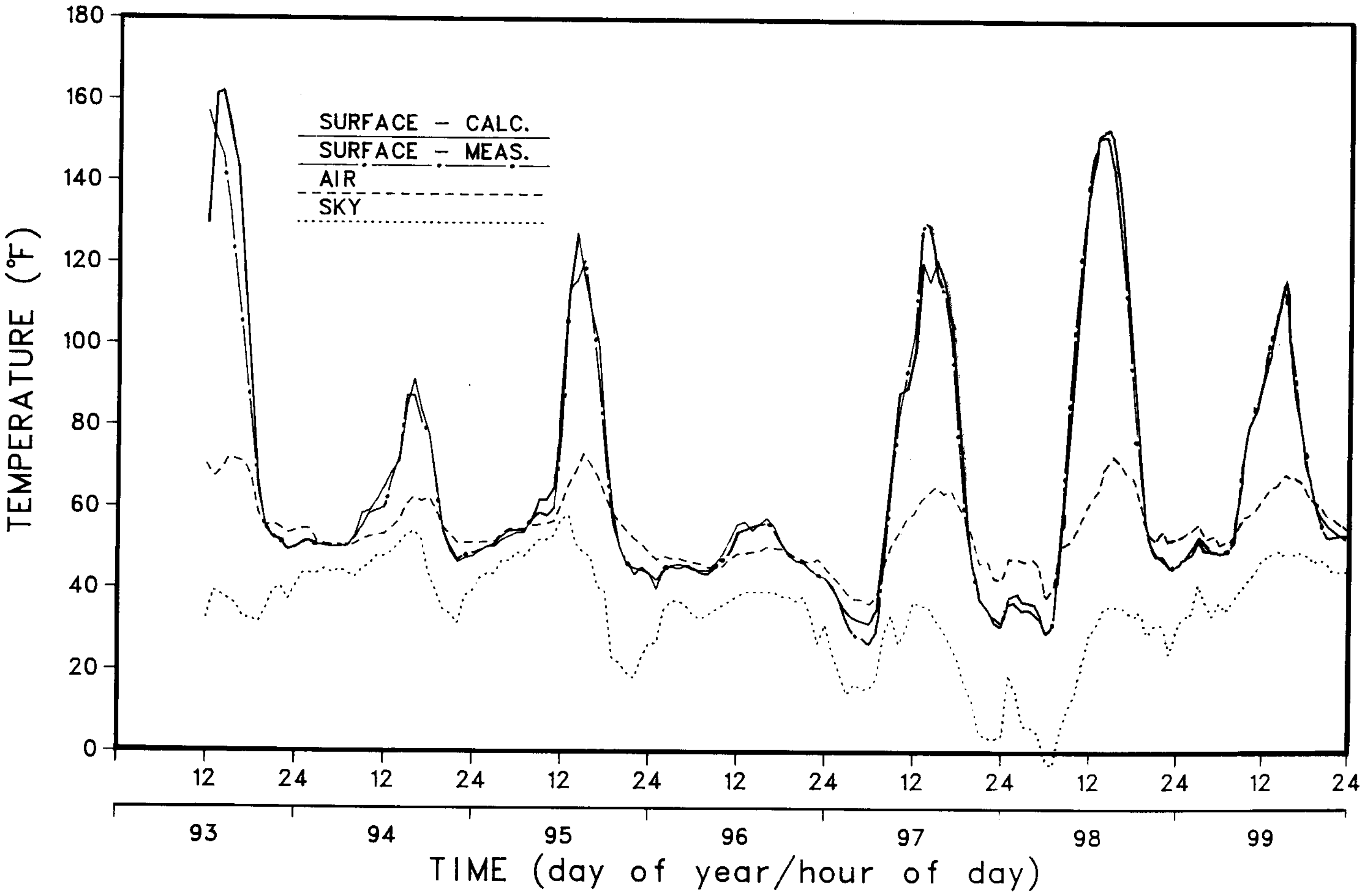

Figure 2 Measured vs. calculated roof surface temperatures. The test panel was nominal R/15 fibrous glass with a 3-ply BUR membrane. The surface coating was an asphalt flood coat.

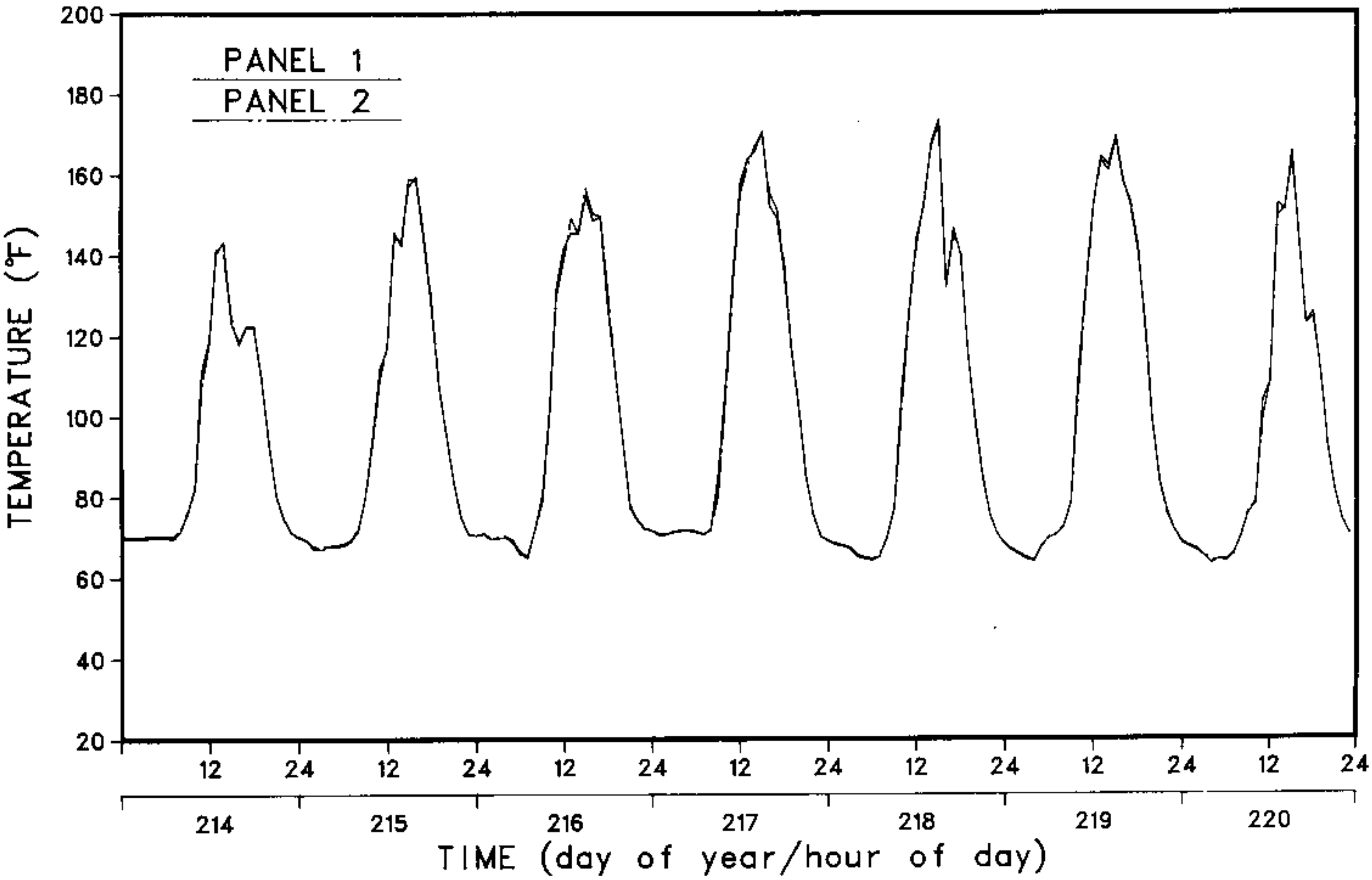

Figure 3 Measured roof surface temperatures on two adjacent test panels over a seven-day period.

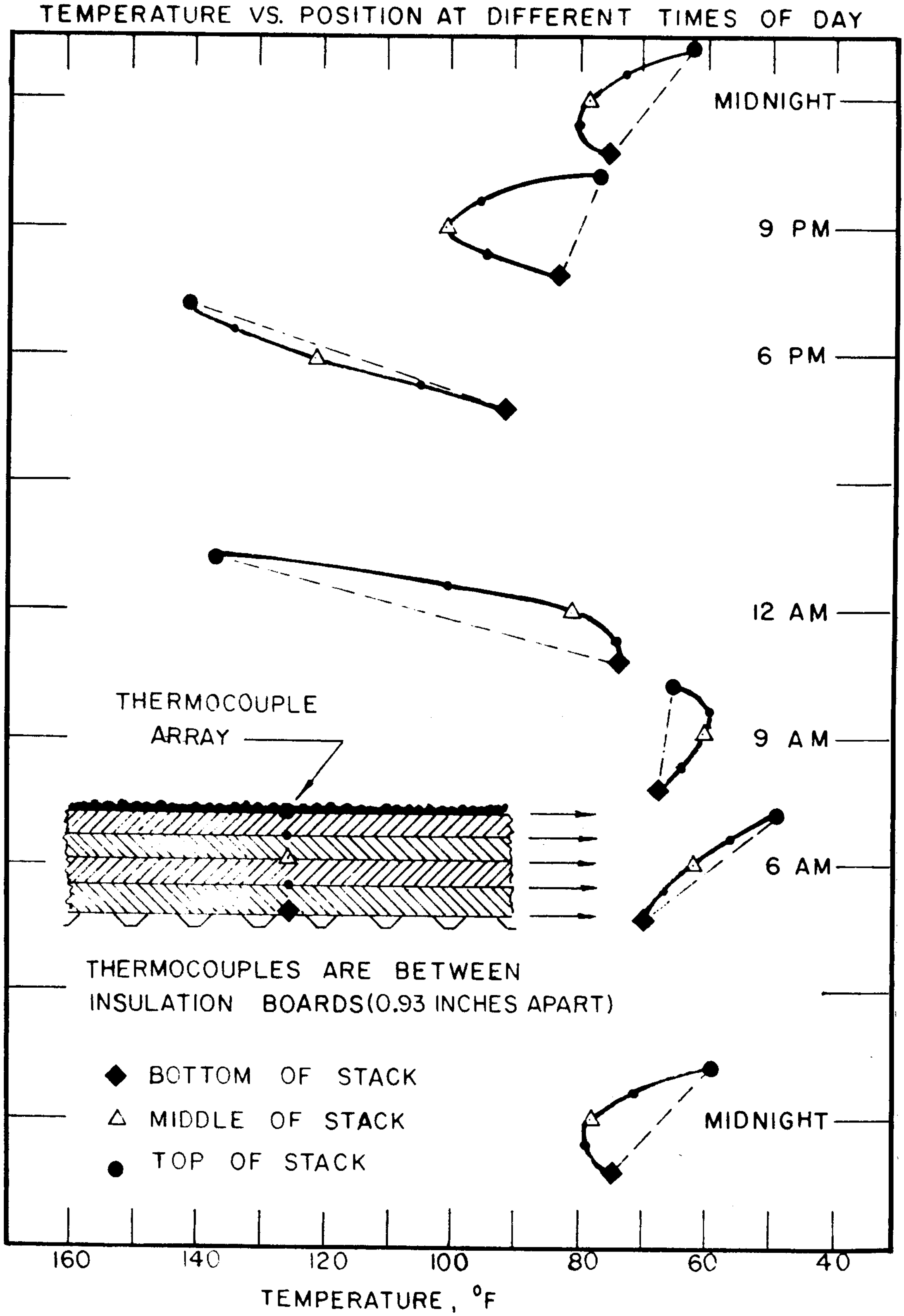

Figure 4 A series of temperature vs. vertical position measurements taken at different times during the day. Measurements are taken between 15/16-inch fibrous glass insulation boards. The dashed lines connect temperature readings at the top and bottom of the insulation stack, and represent the temperature distribution if the roof temperature was assumed to be steady state.

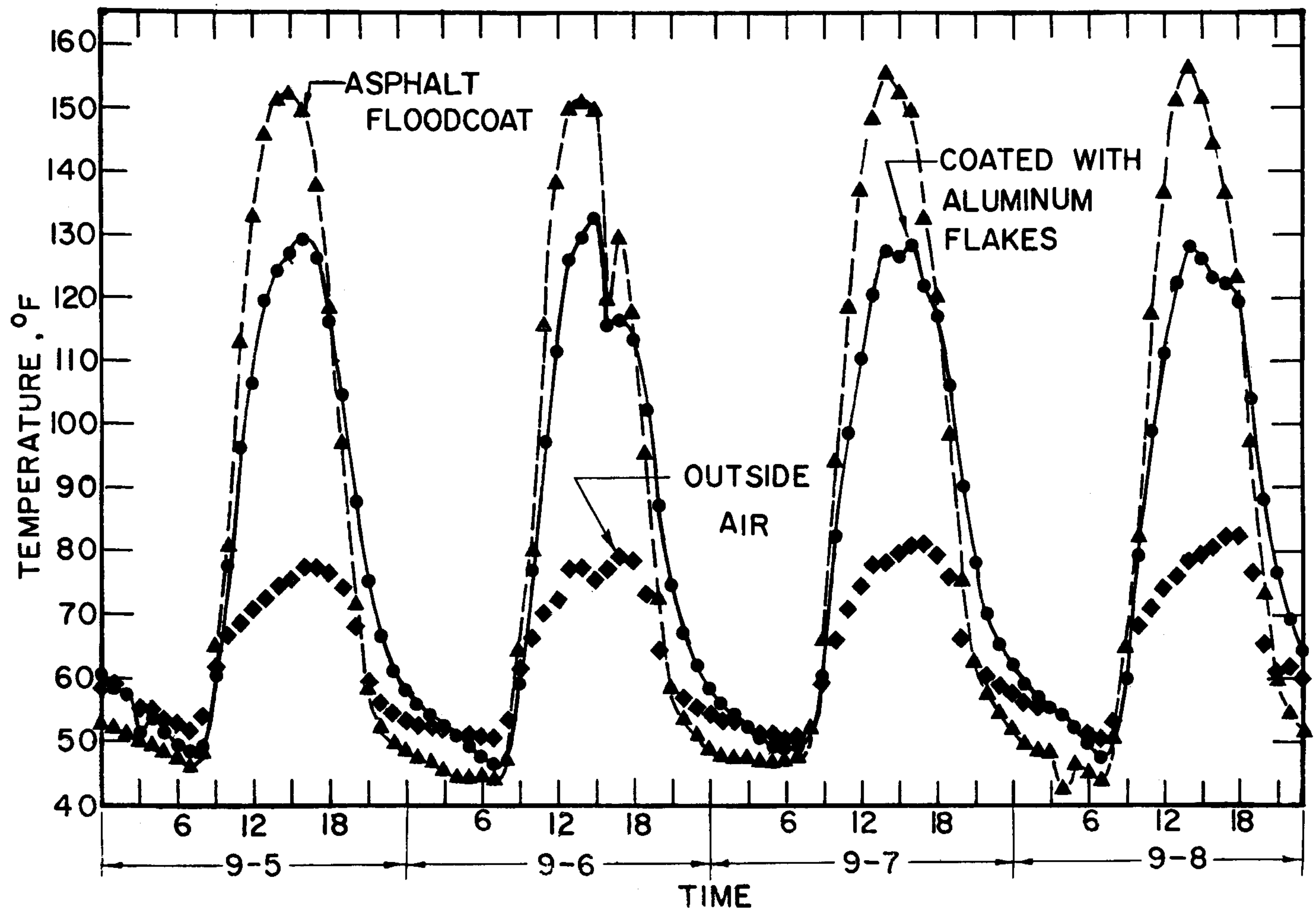

Figure 5 A comparison of surface temperature measurements for all asphalt floodcoat high absorptance surface and a low absorptance surface with aluminum flakes blown onto a flood coat