DYNAMIC THERMAL PERFORMANCE OF INSULATED METAL DECK ROOF SYSTEMS

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ABSTRACT

The thermal performance of an in-service roof is difficult to analyze because it is dominated by complex time-varying boundary conditions at the outer surface. The Roof Thermal Research Apparatus has been built at a national laboratory to provide accurate detailed measurements of thermal response of roof systems exposed to fixed interior conditions and to fully monitored East Tennessee weather on the outside. Absolute and comparative data will be presented for well-insulated (R-value about 17 h•ft^2•F/Btu) test panels of expanded polystyrene, fiberboard, iso cyanurate, and fibrous glass board insulation under built-up roof membranes. Issues discussed will include mass effects caused by differing insulation densities, R-value measurement, comparison to steady-state calculations, and the relative influence of solar, wind, and ambient temperature. Results will be compared to numerical solutions of the heat transfer analyses.

INTRODUCTION

There are over 25 billion square feet (1200 square miles) of low slope roofing in place in this country with about 2.5 billion square feet of new roofing going up each year (Chang and Busching 1983). Currently, over 80% of roofing systems are estimated to be insulated, and this percentage has increased very sharply only over the past ten years. While limited reliable data are available, it has also been estimated that roof R-value levels are typically about 10 ft^2•F•h/Btu or less. The use of insulation in roofs, of course, varies for different climates. With this massive amount of insulation in place on roofs and with new and reroof jobs typically installed with increased insulation levels, it is imperative that data on the thermal performance of insulated roofs and data on the effect of insulation on the longevity of roof systems be accurate and available to the industry. The U.S. Department of Energy (DOE) through its Roof Research Program at Oak Ridge National Laboratory (ORNL) has initiated a significant activity involving a unique combination of experimentation and analysis to provide these data (Courville et al. 1984). This paper discusses results of the first phase of a project with the objective of providing a useful formulation of performance of insulated roof systems.

DYNAMIC PERFORMANCE OF ROOFS

The thermal performance of roofs historically and currently is characterized by material parameters measured in the laboratory under steady-state conditions. Yet in-service roofs function as integrated systems of materials under conditions that are dynamic. The application of

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steady-state material characterization to determine the performance of actual roofs has not been explored fully; first, because thermal performance has not been given a high priority among roof researchers, second, because the use of high R-value systems and systems with complex insulation combinations is relatively new, and third, because in situ thermal measurements on roof systems on roof systems are very difficult. The dynamic performance of a homogeneous material can be characterized by its thermal diffusivity, α. This diffusivity is the ratio of the thermal conductivity, k, to the heat storage capacity of the material. The heat storage capacity is a product of the density, ρ, of the material and its heat capacity per unit weight, c.

$$\alpha = k / (\rho \ c) \tag{1}$$

k is a measure of the flow of heat within the material due to a temperature gradient. A large value of k means a high flow of heat and a small value of k indicates a low flow under the same thermal gradient. This means that interior volumes of materials with small values of k will respond slowly to temperature changes, which implies that dynamic effects can produce significant thermal gradients in these materials. One useful indicator of whether dynamic effects are significant is the measured or inferred lag time between a temperature pulse applied to one side of a building component and the resultant pulse in heat flow on the other side. For a large homogeneous slab with heat flow perpendicular to the slab resulting from a sinusoidal temperature variation (a fair approximation for roof insulation), the lag time is monotonic with the unitless parameter (Childs et al. 1983)

$$\delta = (L^2 / P\alpha)^{1/2} \tag{2}$$

where L is the thickness of the slab and P is the period of the applied temperature oscillation. When α from Equation 1 is substituted into Equation 2, the expression for δ becomes

$$\delta = [(R \cdot L\rho c)/P]^{1/2} \tag{3}$$

where R = L / k is the R-value of the slab material. Equation 3 indicates that dynamic effects not only can be significant for large values of heat content but also for high R-values. This means both high heat capacity and high R-value systems require dynamic analysis.

Table 1 contains a list of properties for some roof insulations and a few other materials. The last column gives the lag times as determined according to Childs (1983) assuming an infinite slab geometry and sinusoidal temperature variation. Note that the lag times for all these materials are about the same for the same thickness. This does not mean they all respond dynamically the same, since lag time combines two independent dynamic characteristics. Also note that expanded polystyrene and fiberboard represent extremes for materials used for roof insulation boards.

METHODOLOGY

Careful experimental data on roof systems mounted on the ORNL Roof Thermal Research Apparatus (RTRA) provide the basis for analysis (Courville et al. 1985). Since these results, obtained for a small number of roof configurations in one climatic region would be of limited value to the roofing industry, a mathematical model is being developed concurrently. Experimental results are being used to validate the model, which in turn will be used to predict the performance of other roof systems under other climatic conditions. This first activity involves roof systems of rather simple construction (steel deck, board insulation, membrane, asphalt flood coat) that can be represented by one-dimensional heat flow in order to keep the modeling simple. The next step will be to include high heat capacity decks, e.g., concrete and, finally, to add ballast to the exterior surface.

A photograph of RTRA is shown in Figure 1. The apparatus can handle up to four replaceable 4-ft by 8-ft test panels at any one time. Calculations have shown that the central area of any panel is not significantly affected by the boundaries. Thus, measurements in this area are representative of one-dimensional measurements on real roof systems away from edges and penetrations.

The data acquisition system for RTRA is shown in Figure 2. Since it was desired to have both the capability to quickly change the number and configuration of data channels and to locate the data analysis room in a different building, a system was chosen that allows multiplexing in the test building and single line transmission to the data recorder. At the present time data are being collected at hourly intervals from about 120 channels and are being stored on a computer mainframe. Selected blocks of data (usually one week of data for 20 to 30 channels) are then copied on floppy disks for analysis with individual microcomputers.

A schematic of a roof system typical of those currently being analyzed, along with a typical sensor configuration, is shown in Figure 3. Results reported here are for measurements taken only across the insulation stack. Each insulation stack investigated has been separately tested for thermal conductance at three fixed temperature differences in a laboratory apparatus traceable within 1% to NBS reference materials. This technique is described elsewhere in these Proceedings (McElroy and Graves 1985). This has provided a reference curve on conductance as a function of mean temperature. Heat flux transducers have also been calibrated in their installed position in the same apparatus.

THE EXPERIMENT

Most of the data presented in this report have been collected on the two systems described in Table 2. Expanded polystyrene (EPS) and fiberboard insulations were chosen because they should provide the extremes in dynamic performance for lightweight (steel deck) systems. The conductivity equations were empirically derived from 3-point laboratory characterizations. These panels have been in place since December 1984; therefore, data are available for a wide range of climatic conditions. A typical graph showing transient temperatures at three spatial positions within the fiberboard insulated panel is shown in Figure 4. As one would expect, the daytime exterior surface temperatures are higher than outside air temperatures due to the absorption of solar radiation. Also note the phase shift in the temperature wave as it moves through the insulation. The time lag between the top and the bottom of the stack has been measured for EPS, fiberboard, and fibrous glass and plotted in Figure 5 against values of δ calculated from Equation 2. Also shown in the figure is the curve representing lag time versus δ for a slab geometry and sinusoidal temperatures (Childs 1983). As one would expect, the measurements are consistent with calculated values.

RESULTS

Insulation Mean Temperature

In this study, insulation mean temperature is defined as the midplane temperature of the thick insulation stacks used in the experiments. Calculations show that the time average of the mean temperature when taken over several days agrees very well with the average of the bottom and top temperatures. A definition of mean temperature is necessary because the conductivity of insulations varies with temperature, and, for a thick stack of insulation under dynamic conditions, the temperature is changing continuously. To accommodate this behavior, manufacturers conventionally list the R-value of their product at a temperature of 75 F. Thus, if a material is consistently at a mean temperature less than 75 F, the actual R-value would differ from the advertised value. For the samples, the climate, and the time period we studied, 75 F is a fairly good choice. Figure 6 is a plot of weekly average mean temperature against time for fiberboard and for EPS insulations. This figure shows that the mean temperature varies by about 40 F over the year. The mean temperature is about the same for the two materials because they have about the same R-values. If we approximate the data points with the dashed curve, as shown in Figure 6, and calculate the average over one year, the result is a mean of about 75 F.

Thermal Performance

A major element of this work has been a study of techniques for characterizing the thermal performance of in situ roof systems. Since the experimental panels are well instrumented, it has been possible to compare different methods. For example, suppose that experimental values of the temperature difference across the insulation stack and heat flux measurements at the bottom surface are used to determine an "R-value." How well does this quantity agree with the steady-state R-value for the stack? Figure 7 shows the results if one simply divides the hourly recorded temperature difference by the hourly heat flux. Examination of this figure or Figure 8, which shows the percent error in these hourly calculations, clearly indicates that either this method is unacceptable or the concept of R-value is not meaningful for dynamic conditions. Actually, this issue has been discussed by others (Flanders 1980; Orlandi et al. 1984), and the resolution is that, while R-values are not appropriate with periodic temperature variations to the period, they are, in fact, very useful for characterizing the average behavior of insulated systems over long time periods. Thus, the error is in the method. A more appropriate use of the R-value, for example, is to determine the average heat transfer across a roof system over a long time period. The validity of this method is illustrated in Figure 9. Here, the ratio of the average temperature difference divided by the laboratory-derived, steady-state, temperature-corrected R-value is compared to the average heat flux measured by a transducer at the bottom of the insulation stack. The curves represent cumulative averages, that is, after each hour a new data point is added and a new average is computed and plotted. Note that the two curves are very different for short times but that they tend to converge for longer times. Also note that there is a consistent phase difference between the two curves. This time shift is about four hours, which agrees well with the predicted value listed in Table 1. The interpretation of this result is that for the August 9 through 15, 1985, temperature difference, Figure 4, across a stack of fiberglass insulation on a metal deck and under a BUR membrane, the average heat flux into the building through the roof is 1.2 Btu/h·ft^2.

R-VALUE DETERMINATION

Given that the R-value is a useful concept for thermal analysis of in-service roof systems, a question arises as to how it is to be determined when a field measurement is needed. As suggested in the previous section, some form of time averaging technique is required. One technique frequently used (Flanders 1980; Orlandi et al. 1984) defines a quantity R_1 by

$$R_1 = \frac{\frac{1}{n}\sum_{i=1}^{n}(\Delta T)_i}{\frac{1}{n}\sum_{i=1}^{n} q_i} \qquad (4)$$

It has been shown that this reduces to the laboratory-determined R-value for periodic temperature changes when the temperature potential, ΔT, driving the heat flow is unidirectional, for example, during the winter (Flanders 1980; Orlandi 1984). During other times of the year, the average heat flux can become small (or zero), which prevents R_1 in Equation 4 from converging or increases the times for convergence. Thus, the technique is useful only over part of the year. An alternate technique that appears to avoid these difficulties is to define an R_{eff} that is the ratio of the total temperature potential and the total heat flow, that is:

$$R_{eff} = \frac{\frac{1}{n}\sum_{i=1}^{n}\left|\Delta T_i\right|}{\frac{1}{n}\sum_{i=1}^{n}\left|q_i\right|} \qquad (5)$$

This overcomes the drawbacks of the previous definition by eliminating situations such as large or negative R-values that result when Σq approaches 0 or when $\Sigma(\Delta T)$ and Σq have opposite signs. Phase change effects and errors in measuring small ΔT's and q's are absorbed quickly in the ever-increasing sums and are thus rendered progressively negligible. This also enhances convergence and reduces the overall time required for a meaningful measurement.

As one would expect, the two methods defined by Equations 4 and 5 produce the same result under conditions when ΔT is unidirectional. The difference occurs when this is not true. Figure 10 illustrates this rather dramatically. The curves for both R_1 and R_{eff} represent continuously updated values as time increases. Note that R_{eff} converges quickly to the value based on property values determined in the laboratory while R_1 is effectively an unreliable indicator of the thermal response of the insulation.

An extensive set of data has been accumulated for fiberboard and EPS insulations under built-up-roof membranes using Equation 5 over a wide range of mean temperatures. These data are shown in Figure 11. Although some aspects of these results are as yet unresolved, it is clear that the method provides R_{eff}-values that are within 5% of laboratory values. For confirmation, we have used a one-dimensional finite difference model, driven by the measured surface temperatures, to calculate resultant internal temperatures and heat fluxes. These results have then been used to provide a calculation of R_{eff}. Note that the computed values have variations with mean temperatures that are similar to the experimental values for EPS and fiberboard except for being displaced upward for EPS and downward for fiberboard. This would suggest some systematic variation we have not yet identified.

SUMMARY

The Roof Thermal Research Apparatus is available for careful measurements of the thermal performance of insulated roof systems. A series of experiments has been designed to identify the effect on thermal performance of dynamic variation in environmental conditions. The first experiment in this series dealt with unballasted insulated roofs on steel decks, that is, lightweight roof systems. Subsequent work will look at the effects of different decks and of roof ballast.

It has been found for lightweight roofs of high nominal R-value in the East Tennessee environment that the mean roof temperature varies by about 40 F over the year and that the annual average for the past year has been about 73 F.

It has also been found that laboratory-determined R-values usefully characterize the average thermal performance, but they are not reliable for instantaneous calculations under dynamic conditions.

In addition, averaging techniques are useful for determining in situ R-values for lightweight systems. The ratio of the average net temperature potential to the average net heat flow is accurate for unidirectional heat flow. For bidirectional flow, the ratio of the average total temperature potential to the average total heat flow is more useful. This latter method is within ±5% of the steady-state R-value for the lightweight systems and over the range of mean temperatures encountered in this experiment.

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TABLE 1

Thermal Properties of Some Building Materials

	k Btu/ft·h·F@75 F	ρ lb/ft^3	C Btu/lb·F	α ft^2/h	δ*	Lag* (h)
Fibrous Glass	0.021	10.0	0.30	0.007	0.81	2.5
Expanded Polystyrene	0.022	1.0	0.29	0.076	0.25	<1
Polyisocyanurate	0.014	2.0	0.38	0.018	0.51	1.1
Fiberboard	0.030	17.5	0.33	0.005	0.93	3.2
Soft Wood	0.067	32	0.33	0.0063	0.85	2.8
Building Bricks	0.42	120	0.22	0.016	0.53	1.2
Insulated Lightweight Concrete	0.083	30	0.24	0.012	0.62	1.6
Structural Lightweight Concrete	0.35	100	0.22	0.016	0.53	1.2
Normal Weight Concrete	1.1	145	0.19	0.04	0.33	<1

*All samples are assumed to be 4 in thick for these calculations of δ and lag time. Different thickness will produce different values of δ according to Equation 2. To determine lag times in these instances, one is referred to K. W. Childs (1983).

TABLE 2

Insulation Systems for Dynamic Measurements

PANEL 3	PANEL 4
5.9 in fiberboard	4.6 in expanded polystyrene
k(97 F) = 0.401 ± 0.006 Btu/h·ft·F	k(96 F)=0.275 ± 0.004 Btu/h·ft·F
3-ply BUR membrane	3-ply BUR membrane
Metal deck	Metal deck
Coverboard	Coverboard

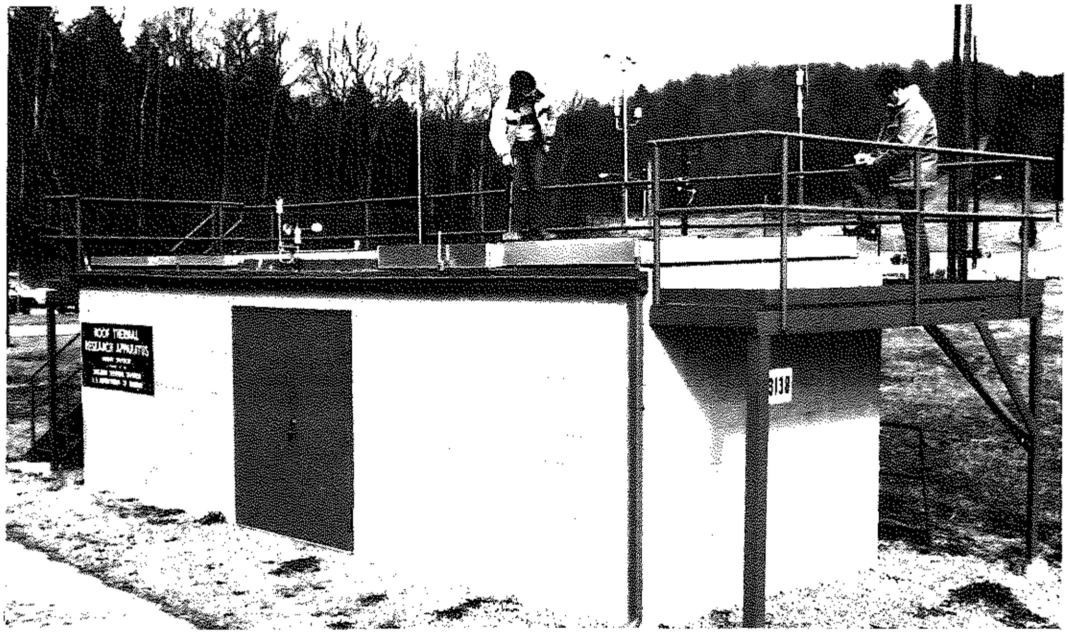

Figure 1. *Roof thermal research apparatus used for gathering detailed thermal performance data on various roof systems*

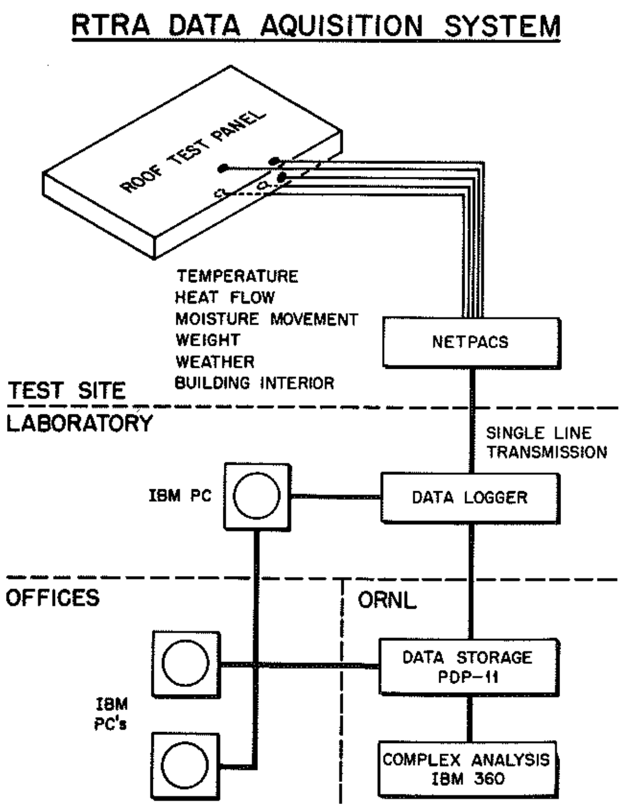

Figure 2. *Schematic of data acquisition system for roof thermal research apparatus. Significant features include single wire transmission between data site and laboratory and use of personal computers for analysis*

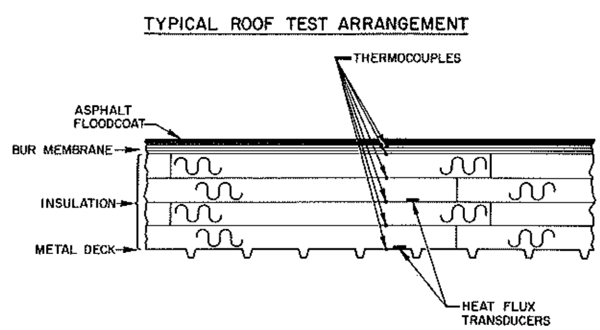

Figure 3. *Typical built-up roof system configuration studied for this report. Heat flux transducers (2 x 2 x 1/2 in) are place in hollowed-out niches and calibrated in situ in a steady-state laboratory testing unit*

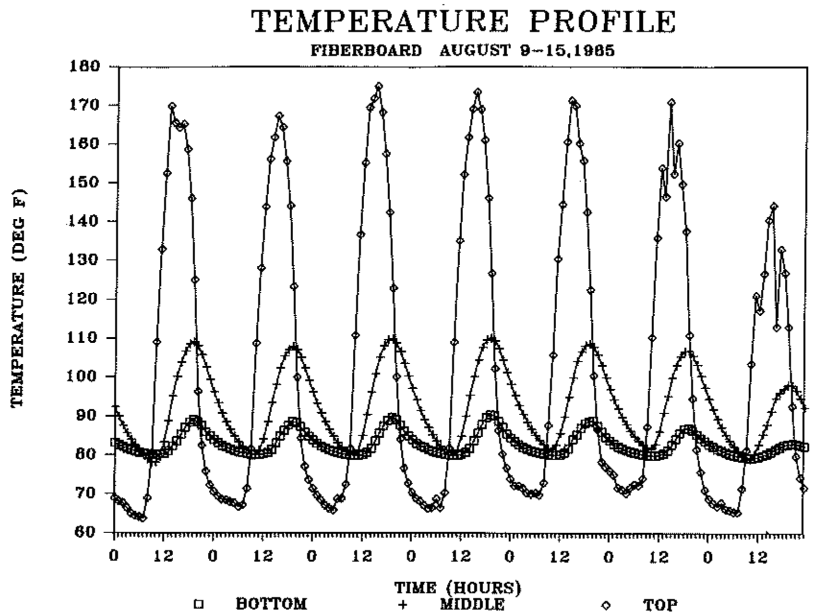

Figure 4. Typical summertime temperature distribution through fiberboard insulation. High outer surface temperatures are due to solar absorption by high absorptance black asphalt flood coat. Phase shift of temperature wave through sample is due to dynamic properties of material

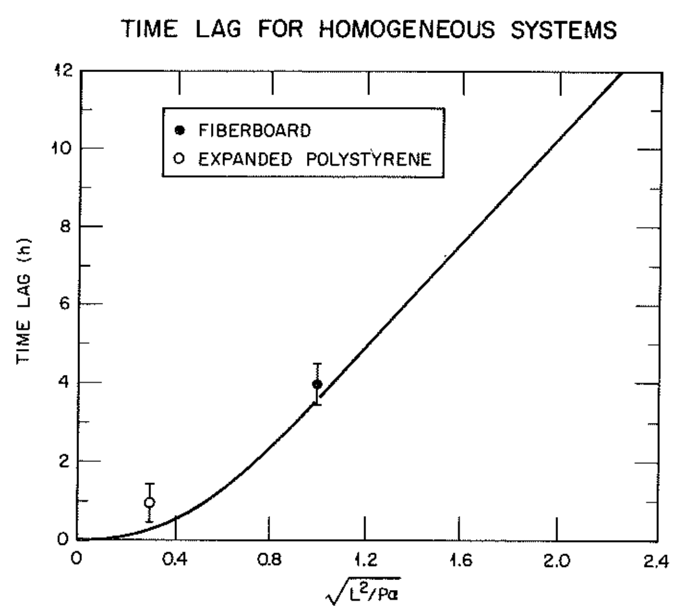

Figure 5. Time lag between temperature wave at outer surface of material slab and heat flow wave at inner surface. The curve is for ideal geometry (K.W. Childs 1983), and the points are from measurements presented in this report

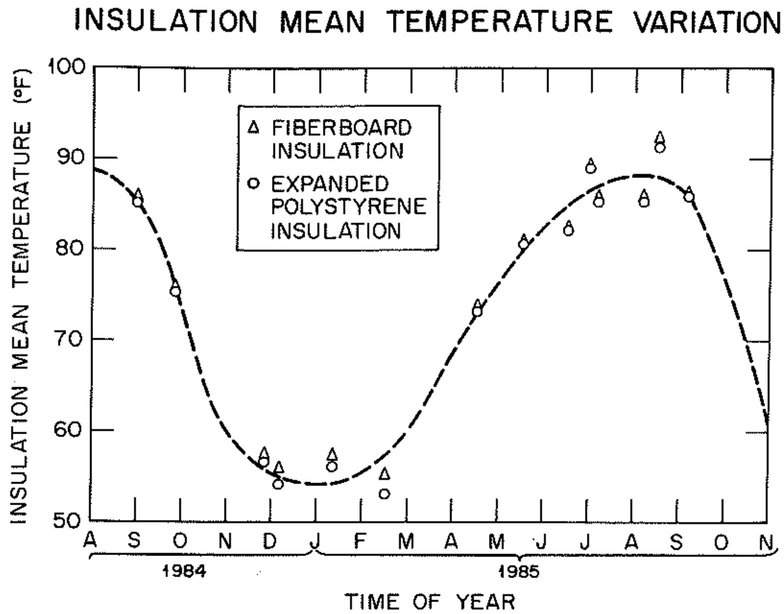

Figure 6. Average midpoint temperature (insulation mean temperature) measured at different times of year. The dashed line is an approximate interpolation to show the annual variation

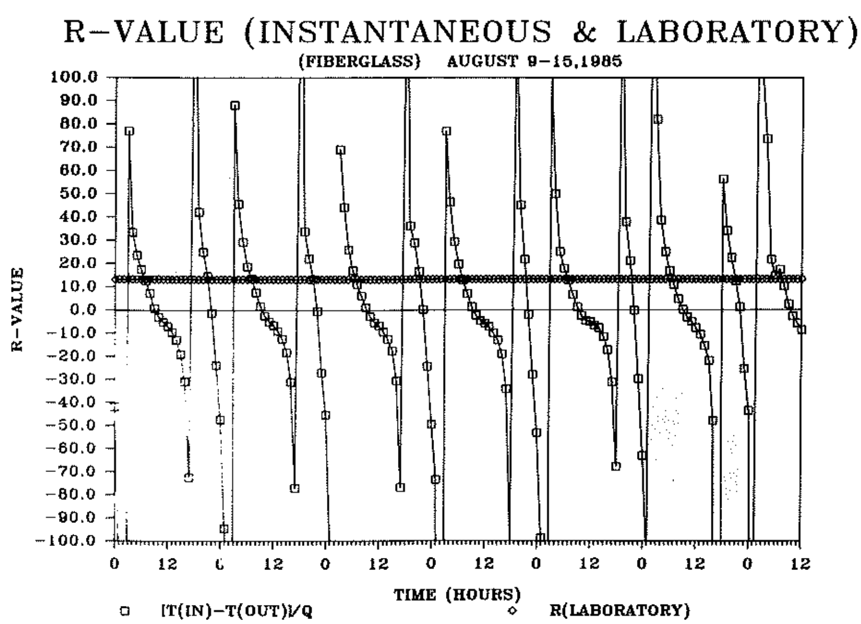

Figure 7. Comparison of R-values calculated from hourly temperature differences divided by hourly heat flow and the R-value obtained from laboratory steady-state results corrected for insulation mean temperature

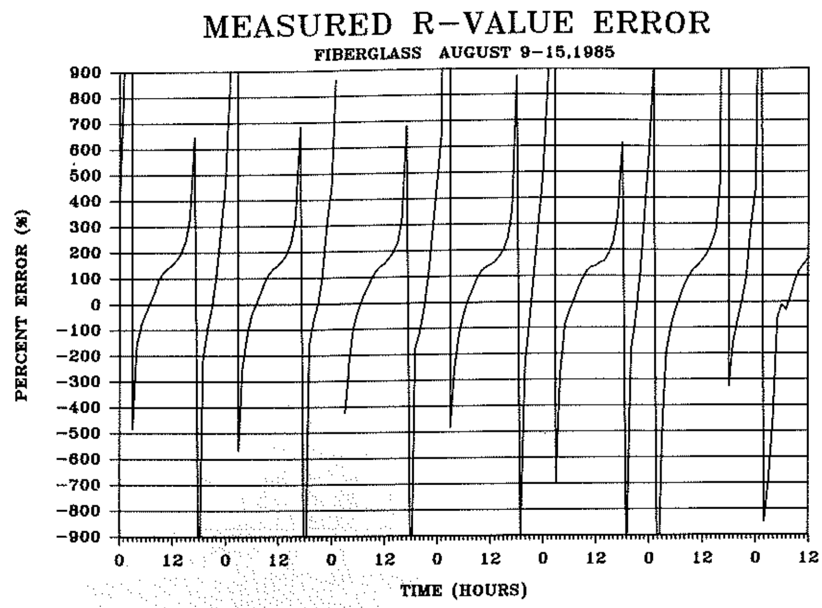

Figure 8. The difference between the two quantities plotted in Figure 7 is calculated each hour and expressed as a percent error

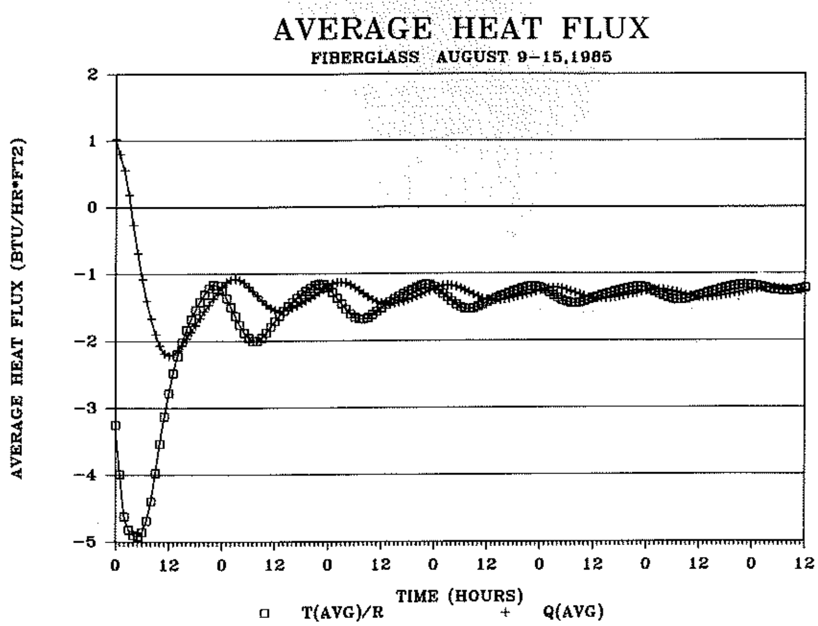

Figure 9. Comparison of cumulatively averaged measured heat flux through a 4-in stack of fiberglass insulation to the heat flux calculated by dividing the cumulatively averaged temperature difference across the stack by the laboratory-measured R-value

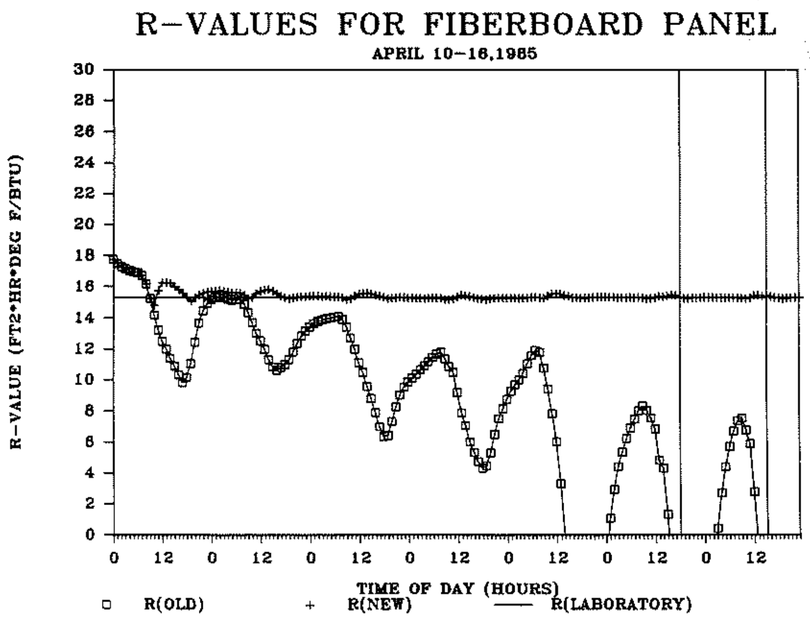

Figure 10. R-value for fiberboard test panel as determined by three techniques: Equation 4, Equation 5, and the laboratory steady-state value corrected for insulation mean temperature. Values for the latter two methods converge after about 36 hours. Note that results using Equation 4 are not consistent with results from the other techniques, nor does it converge to a unique value

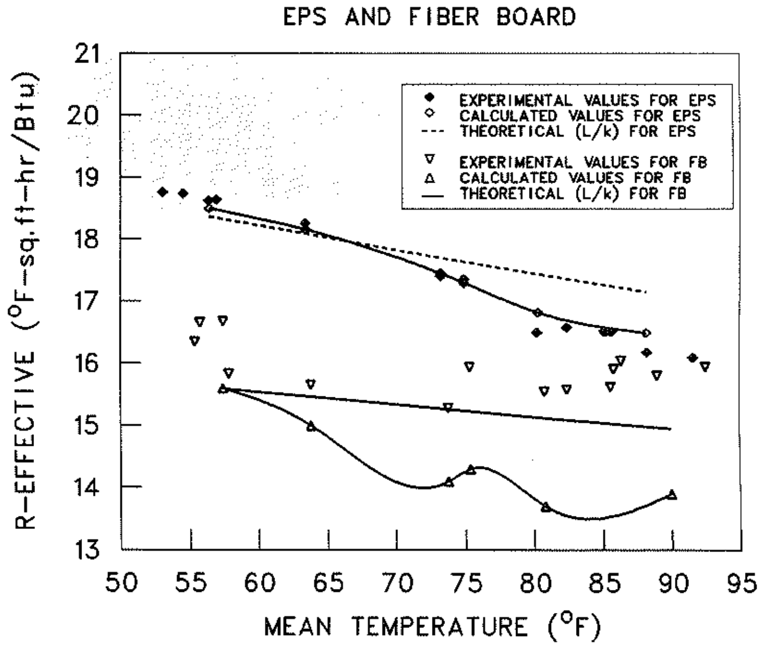

Figure 11. In-situ R-values for EPS and fiberboard measured at different insulation mean temperatures (different times of year). Solid lines represent laboratory steady-state measurements. Triangular points are calculated values having a one-dimensional dynamic heat transfer model to generate heat flows and this using Equation 5 to calculate R-values and the measured inside/outside temperatures. While some features of these different techniques are not understood at this time, it needs to be pointed out that differences are always less than about 5%