COMPARISON OF THE DYNAMIC THERMAL PERFORMANCE OF INSULATED ROOF SYSTEMS

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ABSTRACT

The large-scale climate Simulator at the DOE-sponsored Roof Research Center has been used to provide data for a comparison of the thermal resistance of three common roof insulations over an extended range of temperatures using two different techniques: one steady state and the other transient. The insulations are fiberglass, expanded polystyrene (EPS) and phenolic foam board. R-values are determined for temperatures ranging from 10 F to 130 F. Results from the two techniques are in agreement with one another and both are within 5 percent of reference values for the insulations. The testing illustrates the flexibility of the large-scale climate simulator.

INTRODUCTION

Manufacturer's specifications for roof insulations typically report laboratory steady state thermal conductivities (or R-values) at a mean specimen temperature of 75 F. The reporting of temperature is necessary because the thermal conductivity of materials varies with temperature. A benchmark at 75 F has been chosen so that different materials can be unambiguously compared. Some specification sheets will also report values at other temperatures, such as 40 F, or provide a temperature coefficient so that the user can calculate the effect of the temperature on thermal resistance. The purpose of this report is to address questions such as: How important is the temperature variation of R-value? And is 75 F an appropriate reporting temperature?

MEAN TEMPERATURES OF ROOF SYSTEMS

Manufacturers routinely specify the thermal resistance of insulation for a temperature of 75 F while temperatures in the field vary from much lower to much higher. Is 75 F a representative temperature to report thermal performance? In Figure 1 we show data accumulated for a specimen on the Oak Ridge National Laboratory (ORNL) outdoor facility over a two-year period.[1] The mean temperature is defined as the average of the temperature at the top and the bottom of the insulation sample. Mean temperatures are recorded each hour and weekly averages are plotted against time. For the entire time period the bottom temperature was near 70 F. The top reached temperatures in excess of 160 F due to a combination of high summer air temperatures and solar heating. Note that if a single temperature only is to be chosen as being representative of these data, then 75 F is near the computed average of 74.5 F. Thus, in the sense that the average temperature in the middle of a roof in the middle of the nation (Tennessee) is representative, then 75 F is representative.

THE LARGE-SCALE CLIMATE SIMULATOR

The R-value tests to be reported here have been carried out in the large-scale climate simulator (LSCS) at the Roof Research Center at ORNL.[2] A photo of the LSCS is shown in Figure 2 and a cross-section view in Figure 3. A detailed description of the facility is given elsewhere.[3] Briefly, the upper (or climate) chamber has been designed to reproduce temperature, humidity and rainfall extremes and change rates at a roof surface that correspond to and exceed weather conditions anywhere in the world. The lower (or room) chamber offers a wide variety of simulated room or plenum conditions. The metering chamber shown in Figure 3 is available when the LSCS is to be used as a guarded hot box (ASTM C236 testing) and when there is a need for large area averaging of heat transfer across a roof, ceiling or floor section. The diagnostics platform has a maximum specimen area of 12 feet by 12 feet. *An important design consideration of the LSCS is a need to maximize the number of tests.* This is achieved with several features: (1) high capacity heating and cooling systems on the LSCS to reduce conditioning times; (2) provisions for complete construction of test specimens, wiring for tests, calibration of sensors, and testing of circuits prior to insertion into the LSCS where all electrical connections are made with four multi-conductor quick-disconnect plugs; and (3) installation of multiple experiments on a single diagnostics platform when feasible.

A primary feature of the LSCS is climate simulation. To illustrate this capability we have shown in Figures 4 and 5 the climate and room air temperatures for the actual dates shown that were programmed into the LSCS. Once programmed, the facility will repeat the chosen cycle indefinitely. In these examples, the 24-hour real-time periods were compressed into six machine hours to illustrate the ability to accelerate time periods. Cycles need not be as benign as those shown in the figures. As mentioned earlier, the heating and cooling capacity of the LSCS is large enough to cyclically simulate more catastrophic conditions. Cycle repetition allows good statistical evaluation of whole-roof-systems effects that are not exactly deterministic, e.g., cycles to failure. In addition to climate simulation, the chamber environments can also be programmed to expose specimens to complex prescribed temperature routines required for specific test needs. The work described in the present paper is an example of the latter.

THE TEST CONFIGURATION

To make measurements that lead to determination of the R-value of insulated roof systems well away from edges or penetrations, it is not necessary to utilize the full 12-foot-by-12-foot test area for each specimen. Unpublished calculations using a multi-dimensional heat transfer computer code[4] have shown that if the sensors are at least 18 inches from the specimen edge then the results will be within 1 percent of measurements at very large distances from the edge. A specimen size of 6 by 6 feet was chosen. This will accommodate measurements of the thermal effects of transient moisture movement in the same systems in a subsequent experiment. A photo of the diagnostics platform for this project is shown in Figure 6. Four independent experiments have been assembled for testing.

The details of the three constructions used for this project are provided in Table 1; and a typical construction cross section showing sensor placement is shown in Figure 7. A hollow-cavity cold-deck system, installed in the fourth position, is being used to monitor the differences between heat flow up and heat flow down in cavity roof and cavity floor systems, and the thermal effectiveness of high reflectance foils in cold-deck roof systems. This work will be reported on later. The three conventional systems (expanded polystyrene [EPS] under a built-up roof [BUR], fiber glass under a modified bitumen and phenolic foam under a modified bitumen) were selected because they are similar to systems that were tested in outdoor projects using the ORNL roof thermal research apparatus.[2,5]

ANALYTICAL TECHNIQUES

Several techniques are available for determining the R-value of roof components over a range of temperatures using in situ dynamic data on whole roof systems.[2,5] All require that accurate measurements of temperatures and heat flows at fixed time increments be made. We have chosen two that illustrate the range of available techniques. The first uses the flexibility of the LSCS to require the room and climate temperatures to pass through a series of steps as shown in Figure 8. Then, for those periods in which the temperature difference across the specimens is nearly constant, one can calculate the R-value using steady-state methods. Particularly appropriate for these conditions is the steady-state least squares method[5]

$$R = \sum_{i=1}^{N} (\Delta T)^2 \;/\; \sum_{i=1}^{N} q\,\Delta T \qquad \mathrm{ft^2 \bullet F \bullet h/Btu}$$

where R is the R-value for the system being tested and ΔT and q are, respectively, the temperature difference across and the heat flux through the specimen. The index, i, refers to the hourly readings used in the calculation. The total, N, can be seen from Figure 8 to be about 6 hours for each period of nearly constant ΔT. As an example, to determine the R-value of the EPS insulation depicted in Figure 7, ΔT would be the temperature difference across the test specimen and q would be readings from the heat flux transducer (HFT). For the temperature schedule chosen, there are 11 of these nearly constant temperature periods spanning a range of mean temperatures from 10 F to 130 F. The second technique, PROPOR, is discussed in greater detail elsewhere.[6] The technique, developed for ORNL, is based on a statistical methodology called parameter estimation.[7] The technique takes data from any time/temperature/heat flow history for a roof system and, using a finite difference numerical solution for the conduction equation and a least squares analysis, calculates the R-value as a function of temperature that gives the best agreement between the experimental data and the results of a transient heat transfer model for the roof system. Since the technique works with any specimen history, we simply use the entire temperature history shown in Figure 8 and the corresponding heat flow values.

RESULTS

Figures 9, 10 and 11 give the principal results of this work. They show the R-value per inch for each of the three insulations: EPS, fiber glass and phenolic foam, tested simultaneously in the LSCS. In each case the data extends over mean temperatures that span a range that exceeds that which could be encountered in the field. The triangular data points are the results of calculations using temperature and heat flow data obtained from the systems during the constant temperature periods, that is, steady-state calculations. The two straight line segments connecting the three box points represent the results of the PROPOR calculation. Finally, the single point labeled "NRCA Manual" on each curve is the 75 F R-value for the material taken from the *NRCA Roofing Materials Guide*.[8] The reference includes a 40 F point for EPS. Note that the internal consistency between the two independent data reduction methods is quite good. These methods have been demonstrated on other data to be capable of showing the thermal drift effect in foam insulations.[2,5] Note also that the experimental results at 75 F are above the guide's value in each case: 5 percent for EPS and fiber glass and 7 percent for phenolic foam. The reasons for these differences are still under study.

Regarding the variation of R-value with temperature, the curves show expected tendencies. That is, for EPS and for fiber glass the R-value tends to increase with decreasing temperature, which is true for most insulation materials. For phenolic foam there is a downturn in the curve between 40 F and 60 F. This is probably due to the counter effect of condensation of some of the chlorofluorocarbon (CFC) gas in the closed cell structure of the foam. As seen in Figure 1, the mean temperature in a two-year study in a moderate climate area ranges from about 50 F to 95 F. Over this range the R-values change by 11 percent for EPS, 6 percent for fiber glass and 2 percent for phenolic foam, with the winter values being greatest in each case. Note, however, that since these mean temperatures vary equally above and below an average of about 75 F, variations in R-value from the 75 F value will nearly cancel over the course of one year. In more harsh climates, for example in the far north, the average mean temperature can be significantly less than 75 F. In this case, insulations can perform better than predicted using the 75 F R-value.

CONCLUSIONS

In one six-day period, data were gathered to determine the in situ thermal resistances of three roof system insulations over a range of mean roof temperatures that spans all normal U.S. climate conditions. The resultant curves for R-value versus mean temperature can be used to estimate harsh climate corrections to the published 75 F R-values. In addition, two different methods for determining R-values from field data have been shown to be consistent.

Two primary capabilities of the new large-scale climate simulator have been demonstrated. First, the facility has been operated in a controlled dynamic fashion over a wide range of temperatures, and second, it has been demonstrated that four independent experiments can be carried out simultaneously. Continuing research with these roof systems in the LSCS involves a determination of the effect of moisture on roof thermal performance under dynamic conditions and validation of models that predict moisture migration in roof systems.

REFERENCES

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[6] Courville, G.E. and Beck, J.V., "Measurement of Field Thermal Performance Parameters of Building Envelope Components," *ASHRAE Transactions 1988*, V. 94, Pt. 2.

[7] Beck, J.V. and Arnold, K.J. *Parameter Estimation in Engineering and Science*, Wiley, New York, 1977.

[8] *NRCA Roofing Materials Guide*, Vol. 13, National Roofing Contractors Association, August 1988.

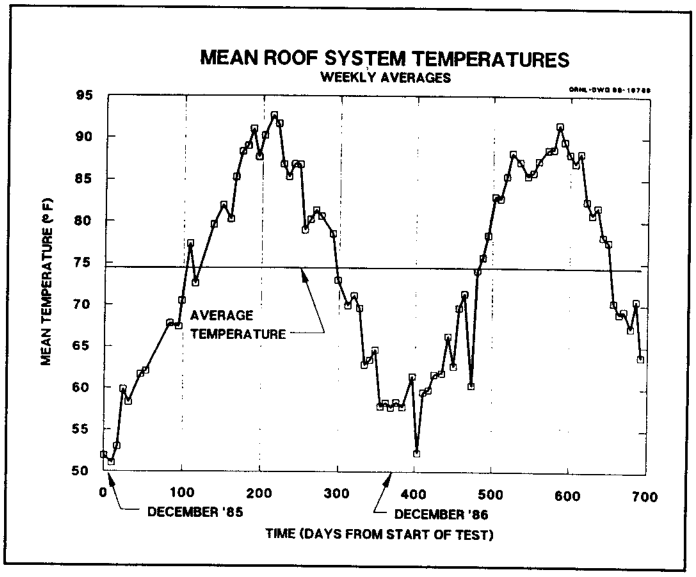

Figure 1 *Weekly average mean roof system temperature for a two-year period. The average temperature over the entire period was 74.5 F*

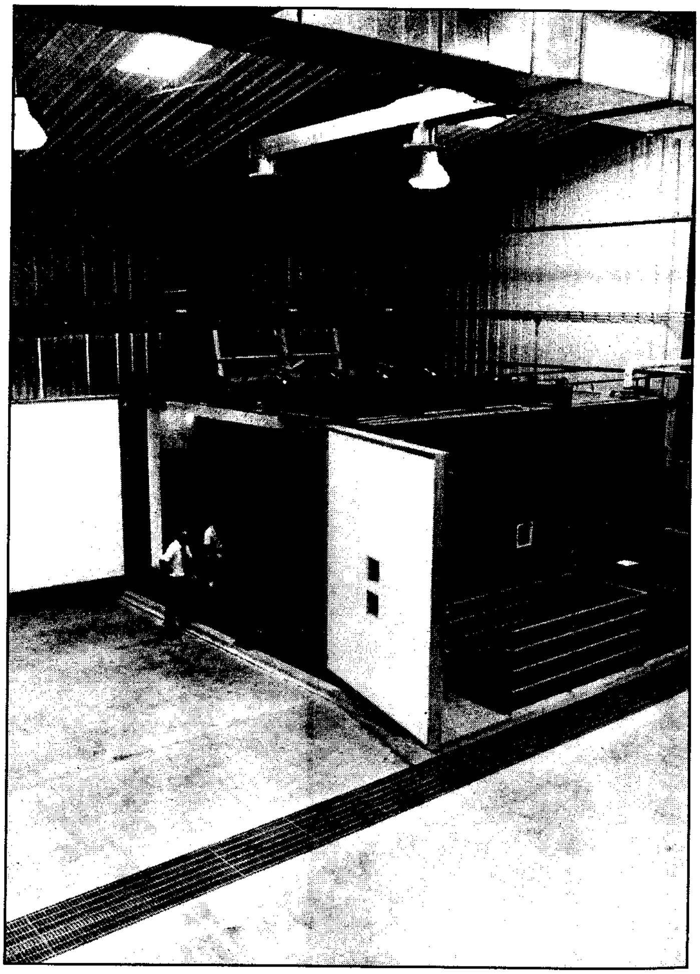

Figure 2 *A photograph of the large-scale climate simulator (LSCS) at Oak Ridge National Laboratory. The climate chamber is seen in the figure. The indoor chamber is accessed from the stairway on the right. An overhead crane is used to move specimens in and out of the facility*

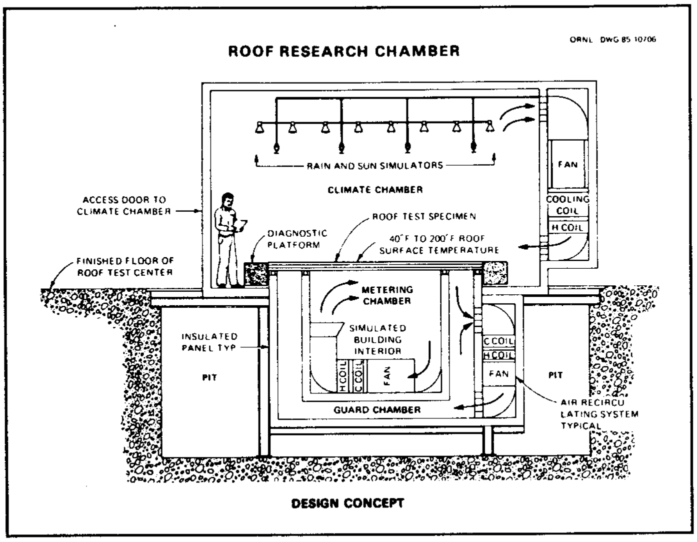

Figure 3 *A schematic cross-section view of the LSCS. The metering chamber can be raised to seal against a specimen or it can be lowered to expose the entire surface of the specimen to the guard chamber. In the former configuration, the LSCS can be operated as a guarded hot box*

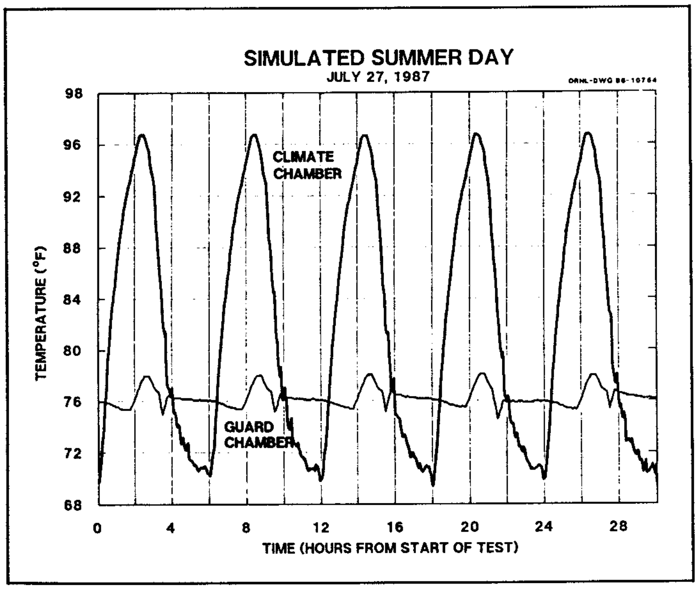

Figure 4 *Hourly temperatures for Oak Ridge, Tenn., on July 27, 1987, have been programmed into the LSCS. To simulate time acceleration, the cycle has been compressed into six hours of machine time and is being repeated a number of times.*

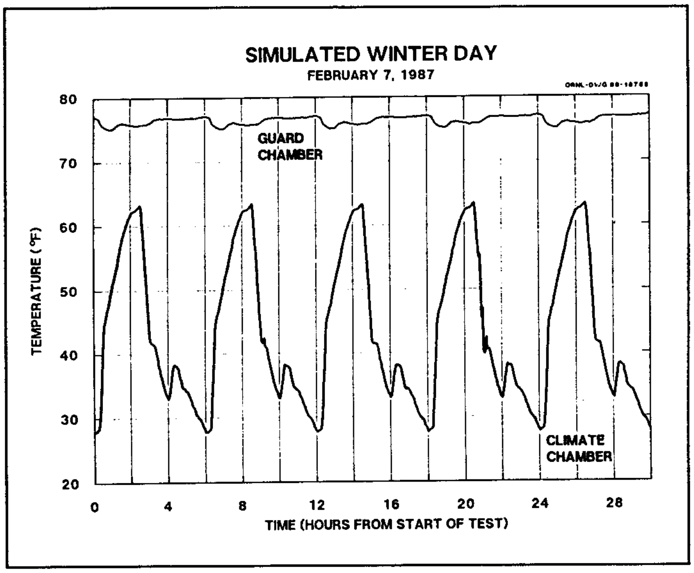

Figure 5 *Hourly temperatures for Oak Ridge, Tenn., on February 7, 1987, have been programmed into the LSCS. To simulate time acceleration, the cycle has been compressed into six hours of machine time and is being repeated a number of times.*

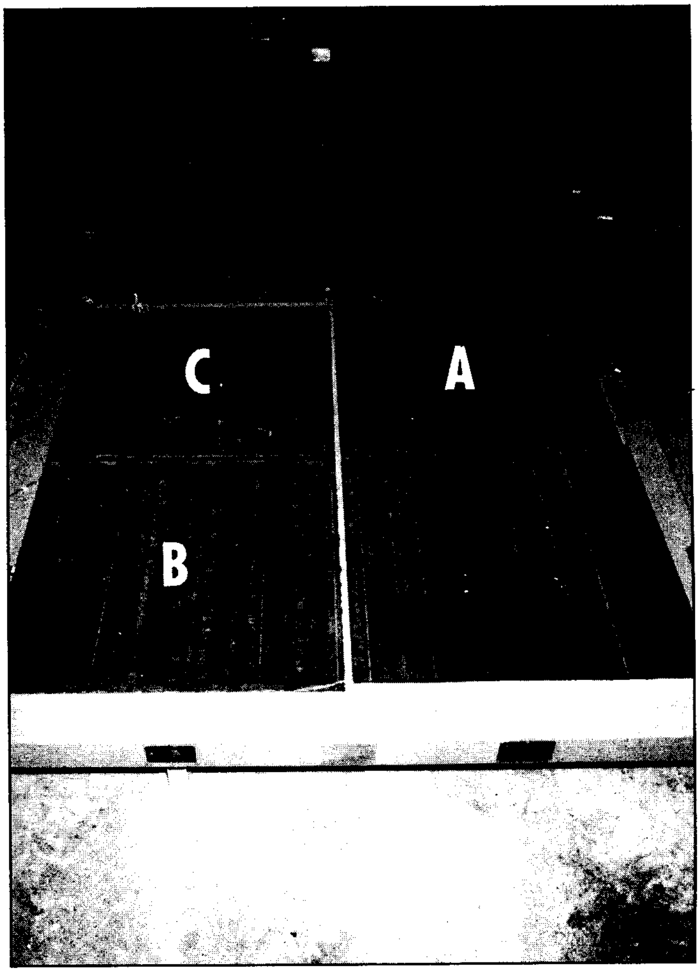

Figure 6 *A photograph of the diagnostics platform with the specimens being tested. The captions A, B and C refer to the system number used in Table 1. The fourth specimen is a cold-deck system briefly described in the text*

	MATERIAL	THICKNESS	
SYSTEM A			
DECK	GALVANIZED STEEL	18 GAGE	—
INSULATION	EPS	(4 BOARDS) 4.5 INCH TOTAL	0.91 lb/FT ^{3}
	WOOD FIBERBOARD	0.5 INCH	16.5 lb/FT ^{3}
MEMBRANE	BUR	~ 0.38 INCH	—
SYSTEM B			
DECK	GALVANIZED STEEL	18 GAGE	—
INSULATION	FIBERGLASS	(4 BOARDS) 3.75 INCH TOTAL	12.8 lb/FT ^{3}
MEMBRANE	MODIFIED (APP) BITUMEN	0.160 INCH	—
SYSTEM C			
DECK	GALVANIZED STEEL	18 GAGE	—
INSULATION	PERLITE	0.75 INCH	10.2 lb/FT ^{3}
	PHENOLIC	2.0 INCH	3.3 lb/FT ^{3}
	WOOD FIBERBOARD	0.5 INCH	16.5 lb/FT ^{3}
MEMBRANE	MODIFIED (APP) BITUMEN	0.160 INCH	—

Table 1 *Construction details for the test specimens used in this study*

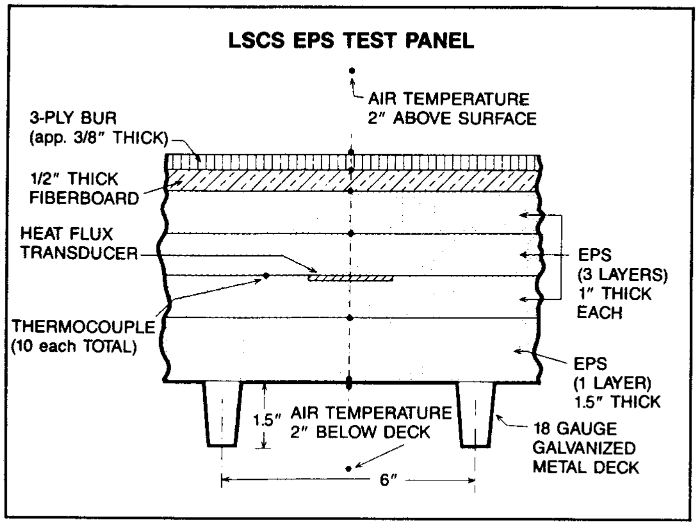

Figure 7 *A schematic cross section of the test panel for EPS insulation*

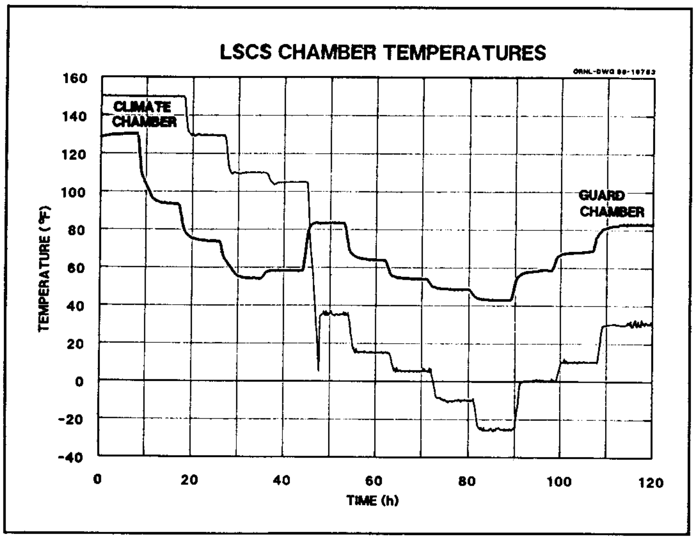

Figure 8 *The temperature routines for the climate and guard chambers during the test period*

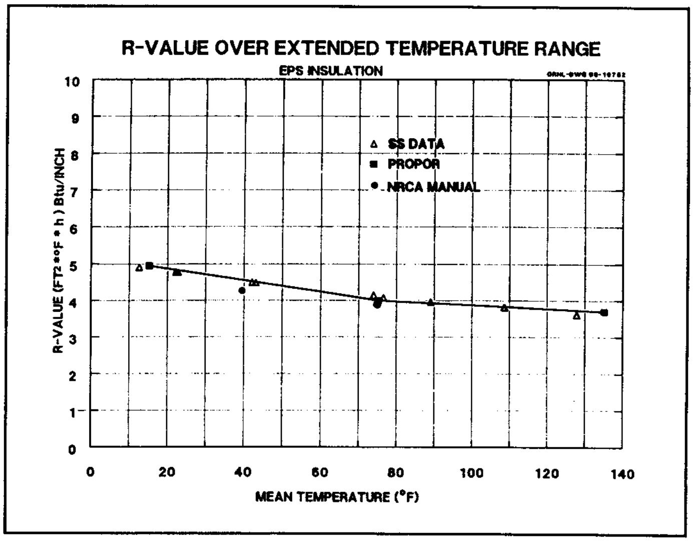

Figure 9 *A plot of the R-value per inch for EPS insulation as a function of mean temperature. The two straight line segments connect the square PROPOR data points. The triangles are the values from a series of individual calculations using steady-state methods. This is discussed in the text*

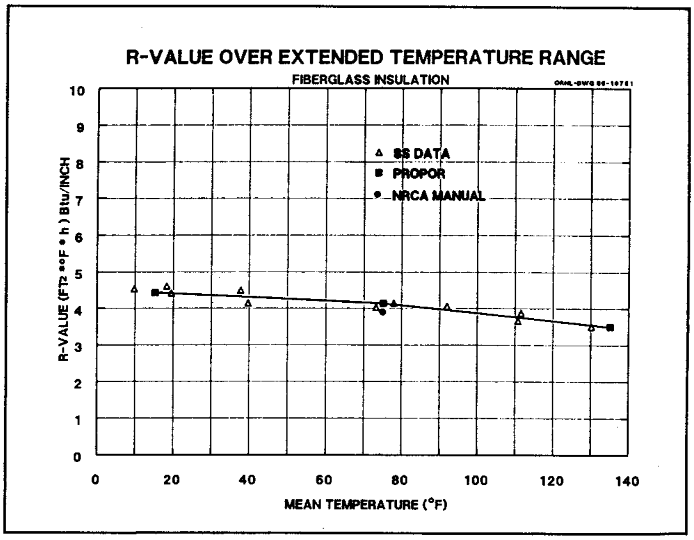

Figure 10 *A plot of the R-value per inch for fiber glass insulation as a function of mean temperature. The two straight line segments connect the square PROPOR data points. The triangles are the values from a series of individual calculations using steady-state methods*

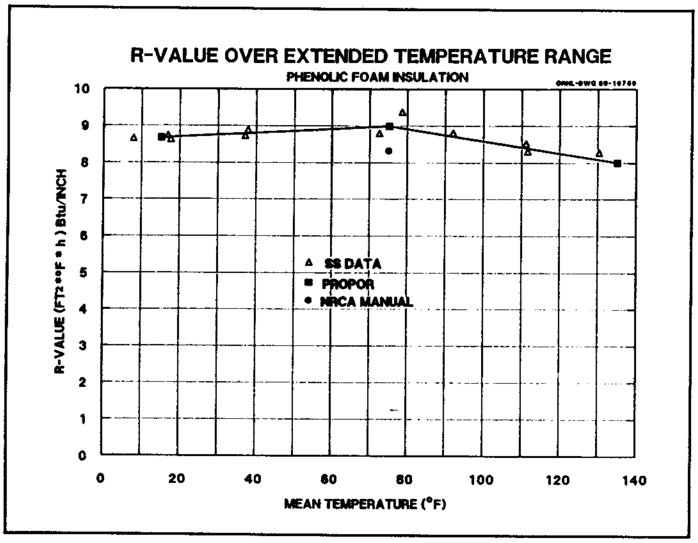

Figure 11 *A plot of the R-value per inch for phenolic foam insulation as a function of mean temperature. The two straight line segments connect the square PROPOR data points. The triangles are the values from a series of individual calculations using steady-state methods*