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Measurement of Thermal Drift in Foam Insulation

G. E. Courville
P. W. Childs

OPERATED BY
MARTIN MARIETTA ENERGY SYSTEMS, INC.
FOR THE UNITED STATES
DEPARTMENT OF ENERGY

ORNL/TM-11290

MEASUREMENT OF THERMAL DRIFT IN FOAM INSULATION

G. E. Courville
P. W. Childs
Energy Division

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FOREWORD

This is one of a series of reports to be published describing research, development, and demonstration activities in support of the National Program for Building Thermal Envelope Systems and Materials. The National Program involves several federal agencies and many other organizations in the public and private sectors who are addressing the national objective of decreasing energy wastes in the heating and cooling of buildings. Results described in this report are part of the National Program through delegation of management responsibilities for the DOE lead role to the Oak Ridge National Laboratory.

George E. Courville
Program Manager
Building Thermal Envelope
Systems and Materials
Oak Ridge National Laboratory

Sam Tagore
Program Manager, Building Systems
Division
Office of Buildings Energy R&D
Department of Energy

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2. LBL-9821: *Measurement of In-situ Dynamic Thermal Performance of Building Envelopes Using Heat Flow Meter Arrays* (December 1979).

3. NBS/BS Series 123: *The Effect of Moisture on the Thermal Conductance of Roofing Systems* (April 1980).

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EXECUTIVE SUMMARY

The thermal resistance of building insulations is usually determined from laboratory measurements on prepared samples of the insulation under steady-state conditions. More recently there has been increased interest in making measurements on installed systems under field conditions because of a concern over a potential difference between design specifications and field performance. This difference can result from a variety of material and performance characteristics. The purpose of this report is to evaluate one procedure for continuously monitoring the thermal resistance of insulation on low slope roofs under field conditions.

Most insulation used on low slope roofs is rigid board material with densities ranging from one pound per cubic foot foam to 15 pounds per cubic foot fiberboard. These boards typically are sized from 2 foot by three foot for high density fiberboard to 4 foot by 8 foot for low density foams with thicknesses that vary from one-half an inch to several inches. Typically roofs will have more than one layer of boards with the joints between boards staggered to reduce thermal bridging. Determining the thermal resistance of an insulation board requires temperature measurements on either side of the board and the heat flux on the top or the bottom.

At ORNL, these measurements are carried out on roof samples mounted on the Roof Thermal Research Apparatus (RTRA). This is an outdoor facility designed for easy installation and continuous monitoring of roof samples. The inside of the RTRA is held at constant temperature and houses the data acquisition system which collects and stores hourly data from sensors mounted on roof test specimens.

The analysis procedure used to determine the thermal resistance is the computer program PROPOR. PROPOR, an application of inverse heat transfer theory, couples use of the transient one-dimensional conduction heat transfer equation with a least squares procedure. Basically, the user initiates the program by defining the program geometry and inputing boundary temperatures and an initial guess for the material thermal conductivity. The program then computes values for the heat flux and any internal temperatures at sites where there are thermocouples. These computed values are compared to the measured values at the same time and an improved thermal conductivity is predicted. This process is repeated until the fit between the computed and the measured quantities is less than some pre-determined value. The final thermal conductivity it takes is the best-fit value for the material. A variation of the technique predicts the thermal conductivity at several temperatures within the range of temperatures covered by the test. This latter technique estimates the temperature dependency of the thermal conductivity for the material and is the technique used in this work.

The test sample used in this work was not a commercially available insulation. The foam material had a high initial thermal resistance and exhibited significant thermal drift: that is, a gradual decrease in thermal resistance with time. Continuous PROPOR analysis showed that the thermal resistance of the sample decreased 27 percent from its original value over the two-year project. Laboratory steady-state measurements made before and after the field test indicated a decrease of 24 percent. The decrease in thermal resistance, after correcting for temperature variation, showed an exponential decrease. This indicates that the behavior is consistent with the usual interpretation that thermal drift as a result of gas diffusion; air diffusion into the closed cell structure of the foam or diffusion of the CFC gas outward.

The project illustrated the value of the PROPOR technique for continuous monitoring of the thermal resistance of roof insulations under field like conditions. The technique is currently being used in several test programs at ORNL.

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G. E. Courville
P. W. Childs

Energy Division
Oak Ridge National Laboratory

ABSTRACT

Oak Ridge National Laboratory (ORNL) has developed a procedure for measuring thermal properties of insulated roofs during exposure to field conditions. This procedure involves field mounting of instrumented test specimens on the Roof Thermal Research Apparatus (RTRA), an outdoor facility at ORNL, and the use of the PROPOR computer program to calculate thermal properties from field data. Hourly data from samples are routinely collected and stored for subsequent computer analysis. Inspection of this record provides continuous and detailed information on the dynamic thermal performance of roof systems.

To test this procedure and to examine the potential of PROPOR for detecting physically significant changes in R-values, e.g., due to seasonal changes in temperature or due to drift of thermal resistance in foam insulations, a special test was conducted on the RTRA. The test sample, not commercially available, had a high initial R-value and exhibited a significant thermal drift. PROPOR analysis of weekly data sets showed that the R-value of the sample decreased 27 percent from its original value over the 2-year project. Laboratory steady-state measurements made before and after the field test gave a decrease of about 24 percent.

Research sponsored by the Office of Buildings and Community Systems, Building Systems Division, U.S. Department of Energy, under contract DE-AC05-84OR21400 with the Martin Marietta Energy Systems, Inc.

1. INTRODUCTION

The thermal resistance of building insulations is usually determined from laboratory measurements on prepared samples of the insulation under steady-state conditions according to one of several ASTM standard methods[1]. More recently there has been increased interest in making measurements on installed systems under field conditions because of a concern over a difference between design specifications and field performance. This difference can result from moisture penetration, from changes in gas concentrations in gas filled foam insulations (thermal drift), from thermal bridges, from changes in surface boundary conditions over time, and from contractor deviations from plans. In all cases one would like to have in-situ procedures in order to avoid altering the performance conditions during a measurement.

Two kinds of problems complicate field measurements: instrumentation problems relating to installation and calibration, and analysis problems relating to the transient nature of the environmental boundary conditions. While researchers have studied these problems[2] there are, as yet, no standard techniques available for making thermal measurements of roof systems under field conditions.[3] The main purpose of this document is to report on procedures that are being developed at Oak Ridge National Laboratory (ORNL) that have the potential of becoming standard practice.

The work is a product of the Roof Research Center at ORNL. This Center is a National User Facility, sponsored by the U.S. Department of Energy with its apparatus and capabilities available to the industry for cooperative or proprietary testing. This project has been a joint effort between ORNL, the Koppers Company*, and Holometrix Inc.** to compare independent procedures for monitoring the in situ thermal performance on roof systems. Details of the combined project have been published elsewhere.[4] This document describes the ORNL activities in more detail.

Tests have been carried out on the Roof Thermal Research Apparatus (RTRA) shown in Fig. 1. The RTRA is an outdoor, fully instrumented test platform with capacity for simultaneous, independent testing of four specimen roof systems. Specimens that are 1.2 m by 2.4 m (4 ft by 8 ft) are constructed off-site in special angle iron frames and transported to the RTRA. In the RTRA the exterior surface of specimens is exposed to local weather and the inside is maintained at room conditions. Numerical calculations using HEATING 6, a general purpose finite difference code available at ORNL[5], have shown that temperatures and heat fluxes measured at distances greater than 0.3 m (1 ft) from the edges of the frames show an edge effect of about 2 percent for typical roof materials. Thus, measurements on homogeneous, layered roof systems within the central 0.6 m by 1.8 m (2 ft by 6 ft) region are essentially independent of boundary effects and can be treated as a one-dimensional heat flow system.

*Koppers Co., Inc.
440 College Park Drive
Monroeville, PA 15146

**Holometrix Inc.
99 Erie Street
Cambridge, MA 02139

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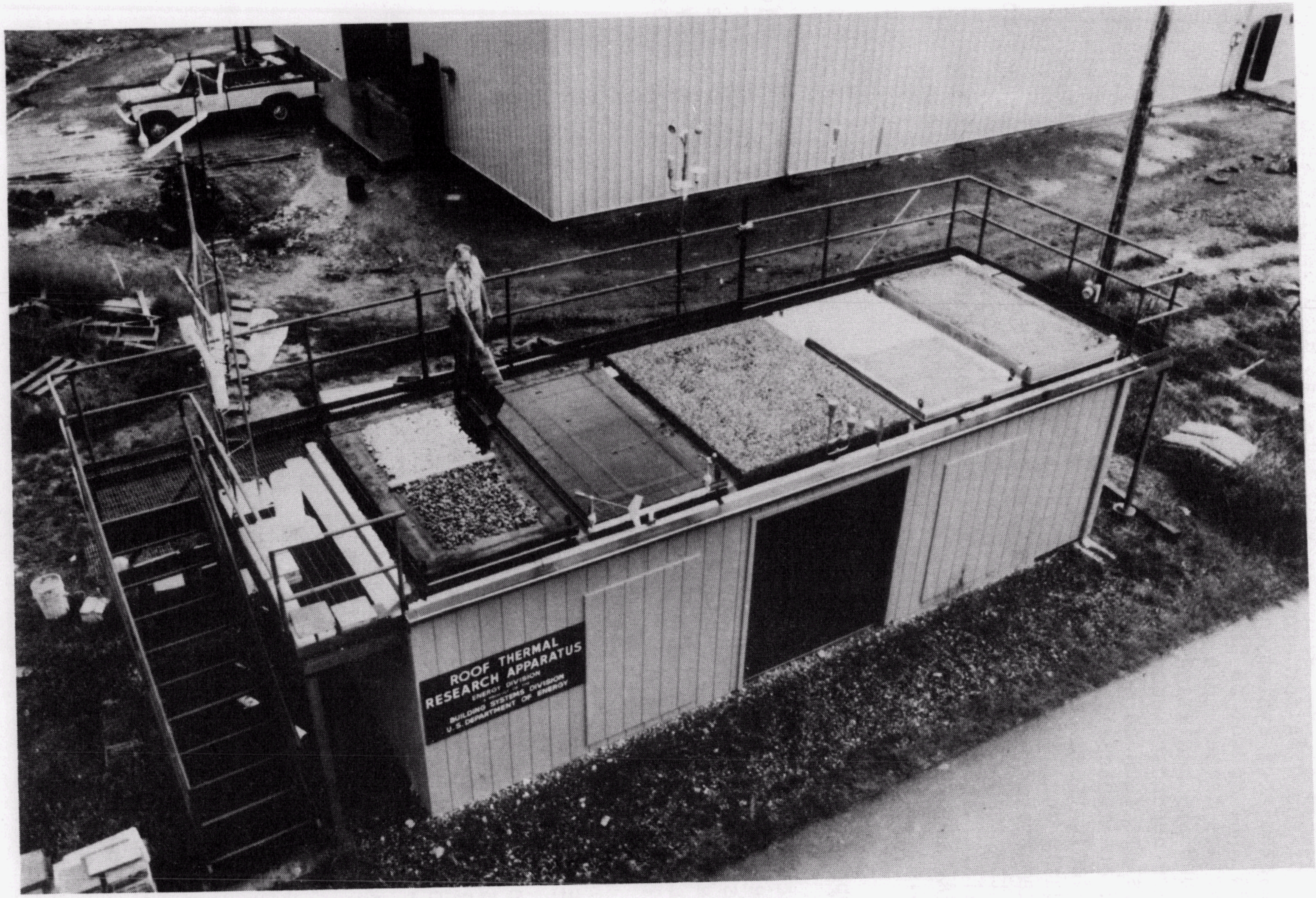

Fig. 1. The Roof Thermal Research Apparatus at ORNL. The test panel discussed in this report is the second from the left.

In addition to describing a test methodology for field thermal performance analysis of roof systems, this work has also demonstrated the utility of the RTRA for providing information on the in situ behavior of insulated roof systems. In situ behavior introduces several uncertainties that cannot be predicted from laboratory testing: (1) the outside surface temperature is strongly dependent upon solar radiation, background sky radiation, and upon the ambient air temperature, all of which are dependent upon local meteorology; (2) Surface properties of roof systems such as solar reflectance, infrared emittance, and surface texture are typically only approximately known; (3) Roofing materials, particularly those near the outer surface of a system can experience large daily and seasonal temperature and moisture fluctuations; (4) the large temperature variations and also the rapid thermal cycling can also affect the long term stability of the thermal properties of the materials. Careful documentation of performance, as is possible with the RTRA, allows one to document conditions that can lead to these effects.

2. PURPOSE OF DOCUMENT

This document will provide a discussion of the characteristics of dynamic roof thermal performance and it will discuss techniques used at ORNL for analysis of in-situ thermal performance. Of particular interest are the consistency and the accuracy of these techniques and their use for studying anomalies in insulation thermal performance such as thermal drift and loss of R-value due to moisture.

3. EXPERIMENTAL DESIGN

A conventional roofing system was used for the project. This insures that system behavior is typical of a real roof and it assures a higher credibil-ity with the industry. A system recommended for use with phenolic foam insulation has been chosen because the Koppers Company, the producer of phenolic foam, expressed an interest in participating in the project. Their participation made it possible to not only test the ORNL procedure but also to conduct the first ever direct comparison of independent techniques for field thermal performance.

Koppers Company of Pittsburgh, Pennsylvania supplied the phenolic foam insulation on which the measurements were made. Holometrix, Incorporated of Cambridge, Massachusetts, a subcontractor to Koppers, provided an indepen-dent diagnostic system and analysis of their results. W. F. Martin Company of Knoxville, Tennessee, supplied the black EPDM membrane and assisted with construction of the test sample. ORNL provided its diagnostics system and analysis. All field testing was done on the RTRA at ORNL. Koppers, Holometrix, and ORNL participated in pre-testing and post-testing of materials, construction of the specimen panel, and comparison of test results. The intention was to operate both diagnostic packages under the same conditions so that a direct comparison of results could be made. The phenolic foam specimen used in the test program was from a pilot plant run and its properties are not necessarily characteristic of commercially available phenolic foam insulations.

The specimen panel was divided into two equal segments, each being 1.2 m by 1.2 m (4 ft by 4 ft) with the Holometrix diagnostics in one segment and the ORNL package in the other. In each instance the package consisted of thermocouples and heat flux transducers (HFT) near the central area of the segment. Fig. 2 shows a schematic cross section of the segment with the ORNL sensors. The specimen had 52 mm (2.05 in.) phenolic foam insulation board between a 19 mm (0.75 in.) perlite bottom board and a 13 mm (0.5 in.) wood fiberboard top board. The deck was 1.2 mm (0.047 in.) galvanized steel and the waterproofing membrane was 1.1 mm (0.045 in.), nominally black, EPDM (ethylene propylene diene monomer.) Results of detailed pre- and post-experiment testing of material properties in the laboratory are included in Section 5.

The ORNL instrumentation package contained thermocouples between each layer of the roof and heat flux transducers on either side of the experimental phenolic foam insulation. All thermocouples are copper-constantan and taken from the same spool to minimize errors in temperature differences. The heat flux transducers are thermopile disks, 2 inch (0.05 m) by 2 inch (0.05 m) in area and 1/8 inch (0.0032 m) thick.[6] They were calibrated in situ by assembling the entire insulation assembly into its final configuration and placing it into an unguarded thin heater apparatus. This steady state thermal conductivity tester has been shown to measure thermal conductivity to within one percent of the National Institute of Standards and Testing (NIST) 1-meter guarded hot plate.[7] In addition to a calibration of the heat flux transducers, the tester was used to provide before and after test base line steady state laboratory measurements of the thermal performance of the test specimen. These measurements are discussed in Section 5.

Data are recorded for all temperature and heat flow sensors in the test specimen and for indoor/outdoor air temperature, solar and background sky radiation, wind, and relative humidity. An Acurex* Autodata Netpac multi-plexing system is used for data collection. The RTRA is currently being serviced by six 20-channel Netpacs, each located near a test specimen to minimize sensor cable lengths. These Netpacs communicate with an Autodata Ten/10 data logger which sequentially scans the Netpacs. This unit is in turn linked to an IBM PC via an RS-232 interface. Initial data storage is accomplished on the PC using floppy diskettes. A PC program allows the user to select data storage intervals and it arranges the data into easily accessible ASCII files. These data are

*Acurex

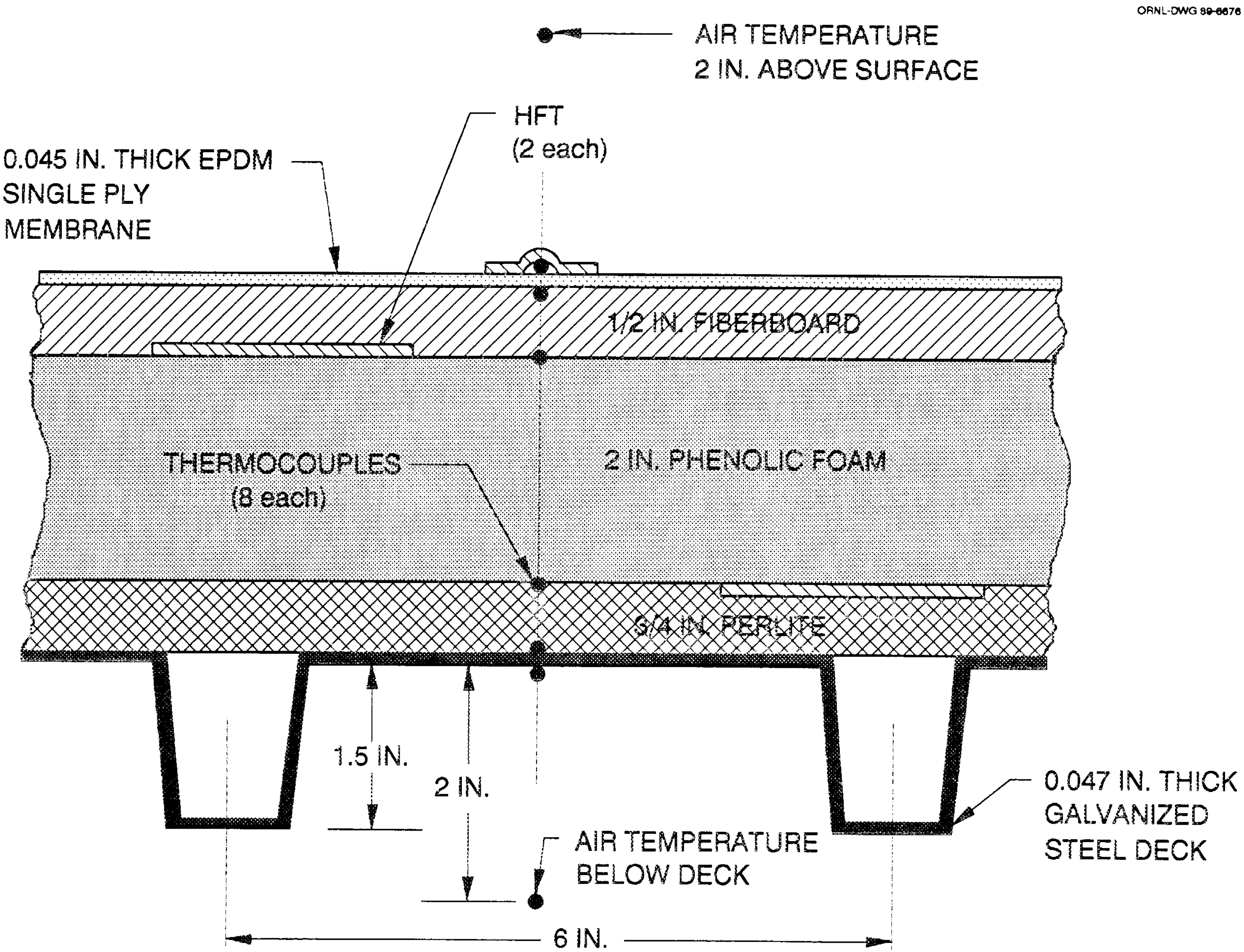

Fig. 2. A cross section of the test panel showing components and instrumentation.

are transferred to an IBM PC/AT for further sorting and subsequently to Bernoulli cartridges for permanent storage.

The test panel for this project was assembled during the Fall of 1985. All roofing materials except the phenolic foam insulation were locally purchased commercial products. The specimen design was consistent with field practices for the phenolic product. The panel was installed in the RTRA in December 1985 and remained in position until removed for post testing in November 1987. Hourly values from all sensors in the ORNL test section of the panel and from the array of environmental sensors were recorded continuously except for brief periods when the data acquisition system was inoperative.

4. CHARACTERISTICS OF IN SITU ROOF THERMAL PERFORMANCE

It is possible with the Roof Thermal Research Apparatus to observe the continuous response of roof systems to local weather conditions. This provides an opportunity to view and to document dynamic behavior and to identify characteristics that dominate roof in situ behavior.

It is instructive, while illustrating the characteristics of this roof system under environmental conditions, to compare the performance under extremes. Thus, we have chosen data for a typical July week and a typical January week. Fig. 3 shows the outdoor air temperatures for the two weeks. Only one plot for the interior temperature is shown because it is essentially the same for the entire year. The hourly data points were obtained by averaging eleven readings taken at 1-minute intervals from five minutes before the hour to five minutes after the hour.

Temperatures from a thermocouple located just below the membrane for the same two weeks are shown in Fig. 4. It is readily apparent from the figure that roof surface temperatures during the daytime are significantly higher than ambient air temperatures. For this black EPDM membrane, summer temperatures in excess of 180°F (93°C) are recorded. Even for the January week where the top air temperature was about 60°F (15.5°C), day surface temperatures frequently reached 100°F (37.8°C). Also note that the nighttime surface temperatures are depressed below the ambient air temperature because of radiant cooling. During the summer the depression is typically between 5°F (2.8°C) and 10°F (5.6°C). During the winter, when the humidity is lower, the depression is between 10°F (5.6°C) and 20°F (11.1°C). Finally, cloud cover is the cause of abrupt temperature dips that are especially apparent in the July data. For example, note the 90°F (50°C) dip in surface temperature during the afternoon of the fifth day followed by a nearly equally sharp recovery when the sun reappeared.

Heat fluxes measured with the lower heat flux transducer for the same time periods are shown in Fig. 5. The sign convention defines heat flow out

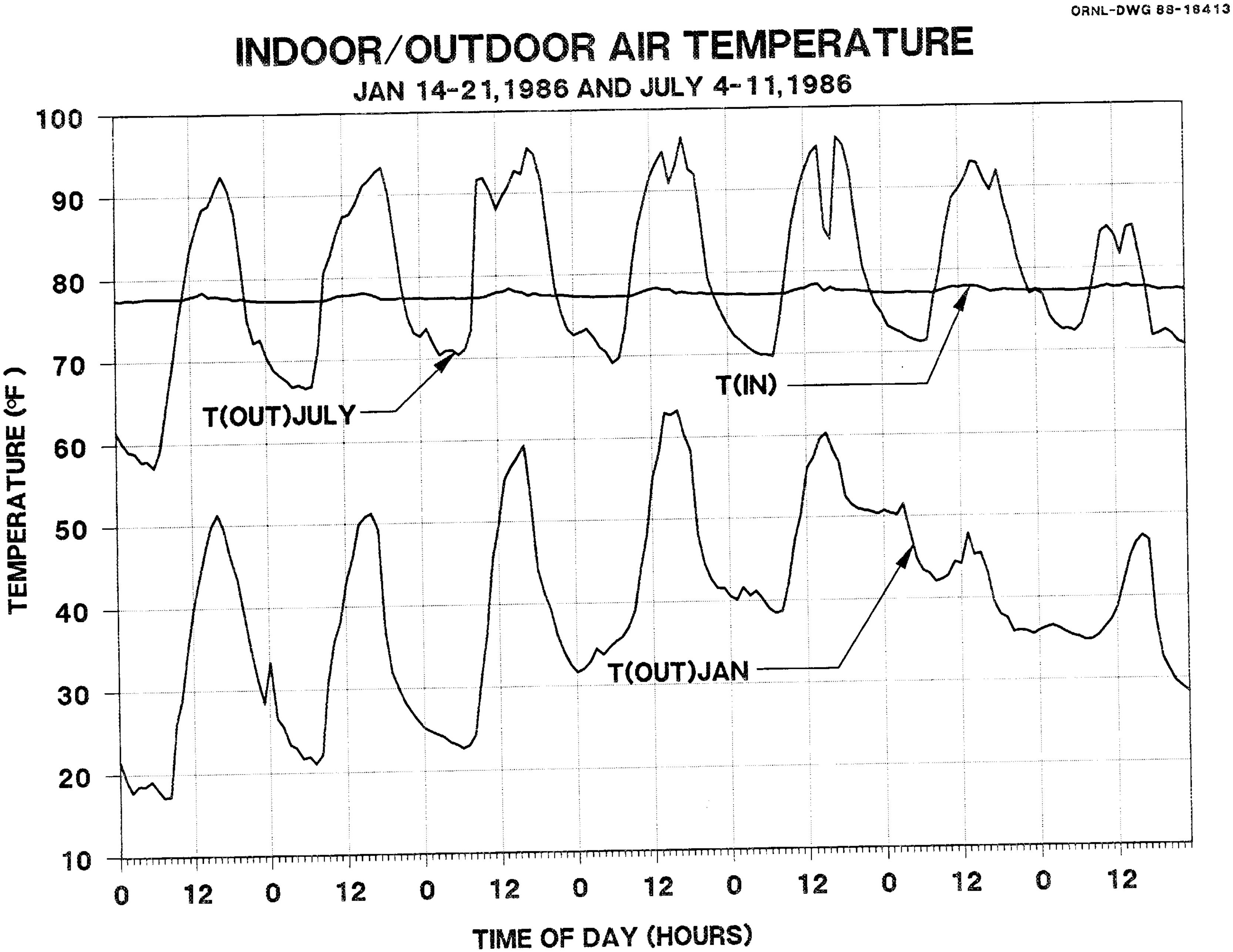

Fig. 3. Indoor and outdoor temperatures for 1-week periods in January and July 1986.

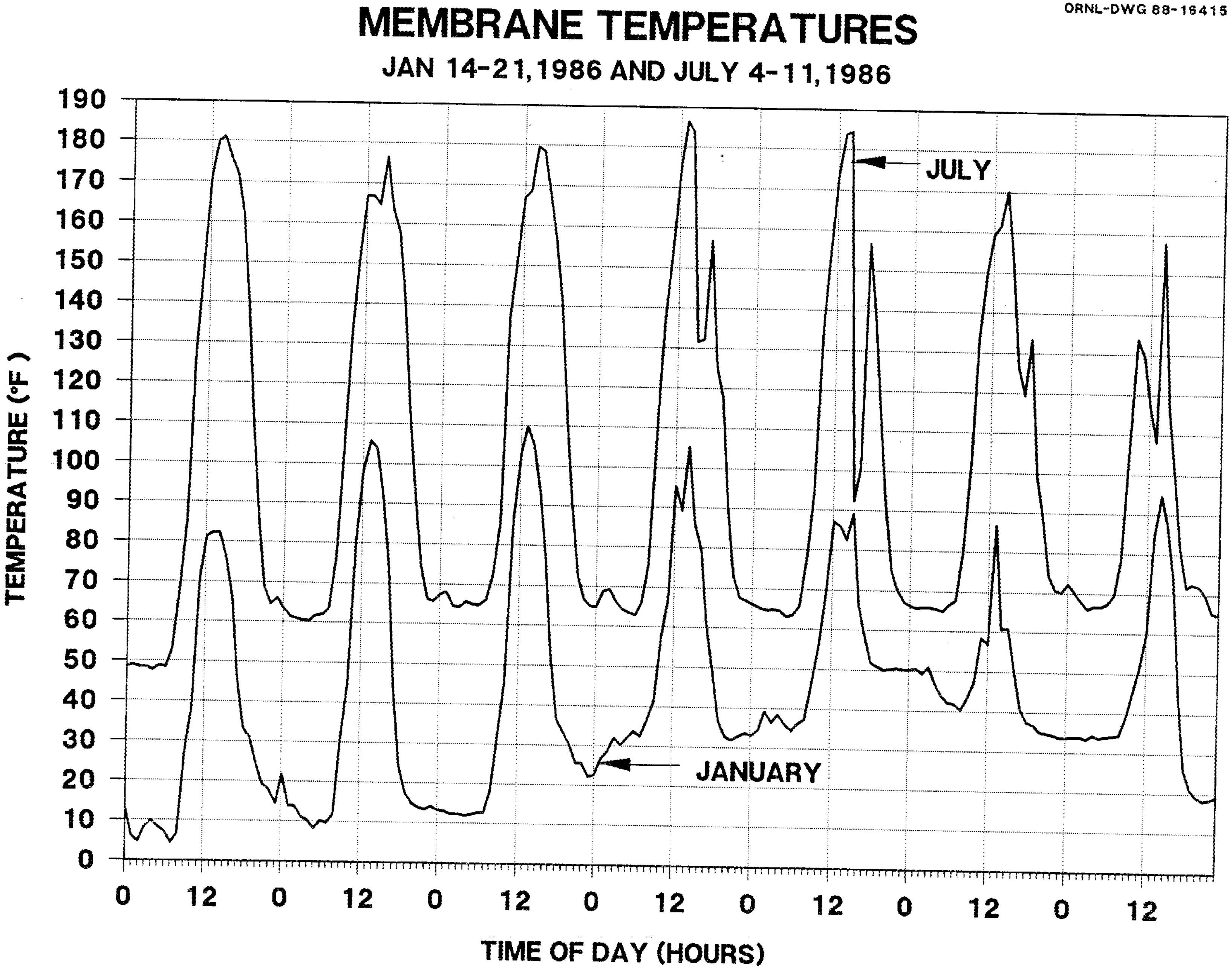

Fig. 4. Temperatures just under the membrane for 1-week periods in January and July 1986.

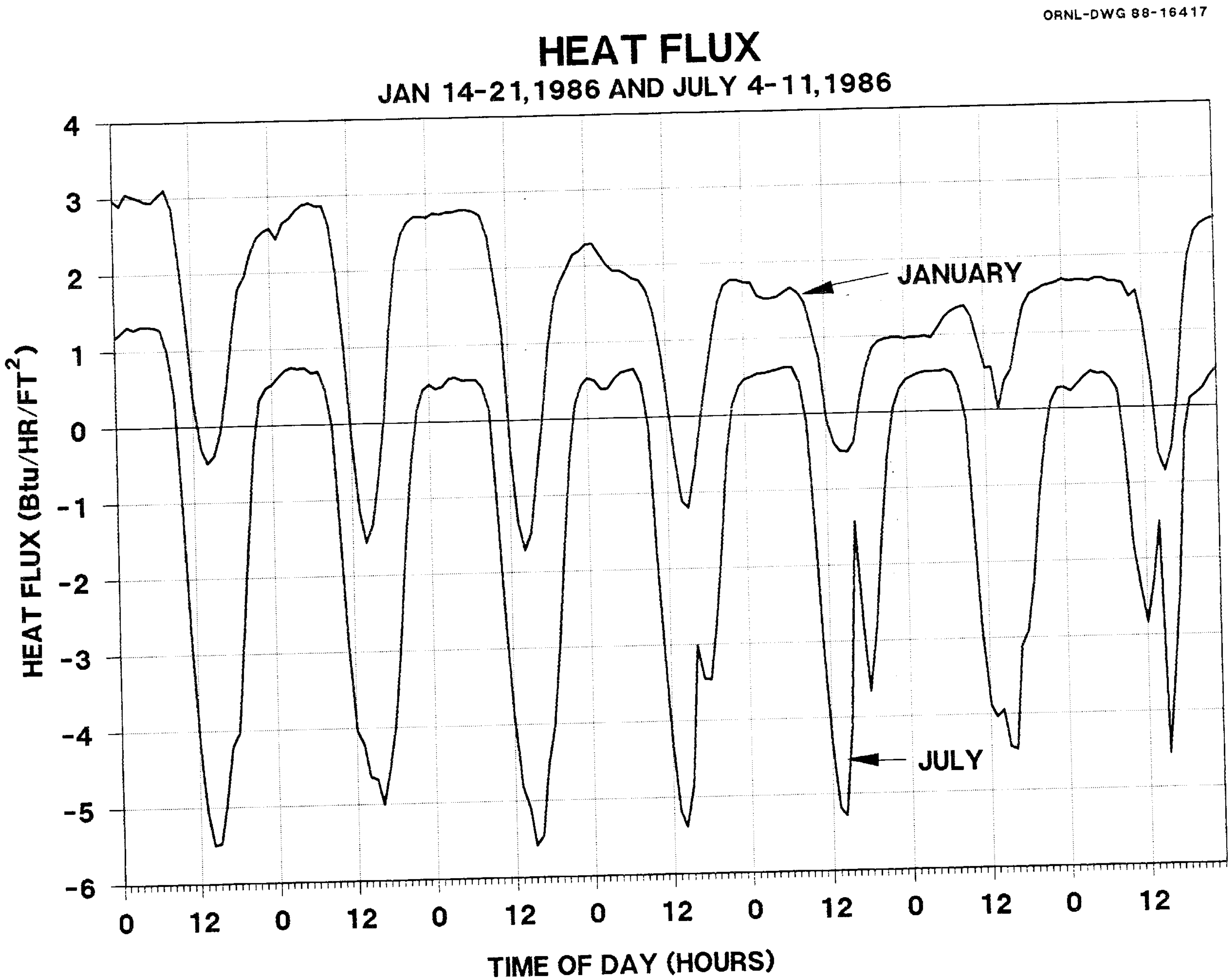

Fig. 5. Heat fluxes measured by the transducers located between the foam and perlite insulations. Positive values are for heat flow out of the building.

of the building as positive. Thus, during the night when the outside is cold relative to the inside the heat flow is positive and during the day when the temperature gradient reverses, this flow is negative. For July, of course, flow out of the building even at night is small relative to the influx of heat during the day. For January, this situation is reversed. Solar heating is responsible for the strong negative heat flux during each afternoon. Referring to Fig. 3 again, we see that during January the outdoor ambient temperature is always at least 15°F (8.3°C) below the indoor temperature. Yet, each afternoon, because of solar heating, there is heat flow into the building from the roof. Fig. 6 is a plot of the cumulative heat flow for each of the two periods. As one would expect the net flow is positive (out of the building) in January and negative (into the building) in July. Also note that the net heat flow in either case is not large because the roof is fairly well insulated. For the July week, which is typical for summer performance, the net heat flow into the building across the roof is about 220 Btu/ft^2 (0.69 KwH/m^2). For a 300 square meter building, this roof load is equivalent to about 1200 watts of interior lighting.

Fig. 7 shows another thermal characteristic of roof systems, namely that surface temperatures change constantly and rapidly. Fig. 7 shows the hourly temperature change (degrees F per hour) at the surface of the roof for a week in July, and Figure 8 shows the hourly change for a week in January. The pattern, which is similar in both graphs, is intuitively expected. That is, change rates near zero in the pre-dawn hours followed by a steep positive change that peaks in the late morning, and a similar steep negative change that peaks in the late evening. During different times of the year the peaks occur at different times and the magnitudes will differ, but the patterns are essentially the same. A principle reason for monitoring temperature change rates is in relation to the impact of thermal shock on roof components particularly during winter months. While the curves in Figs. 7 and 8 show the temperature change for hourly intervals, it is not clear at the present what the appropriate characteristic time interval for thermal shock effects should be. The significance of the RTRA data is that temperature changes are readily measured.

Fig. 9 shows RTRA temperature measurements being used in still a different way. Here, each data point represents the weekly average of the hourly midplane temperatures of the phenolic insulation. This data has been collected over the full test period. As one expects the data is periodic with maximum values during the summer (June 20, 1986 is 200 days) and minimum values during the winter. Also, the summer peaks range around 90°F (32°C) because, for this system with a black membrane, the summer daily surface temperature reaches as high as 180°F (82.2°C). Note that the average for the entire test period is about 75°F (24°C) which, in fact, is the mean temperature used by manufacturers to specify insulation "design R-value." The value would be less if this roof had a more reflective membrane or if it was located in a more northern climate.

ORNL-DWG 88-16414

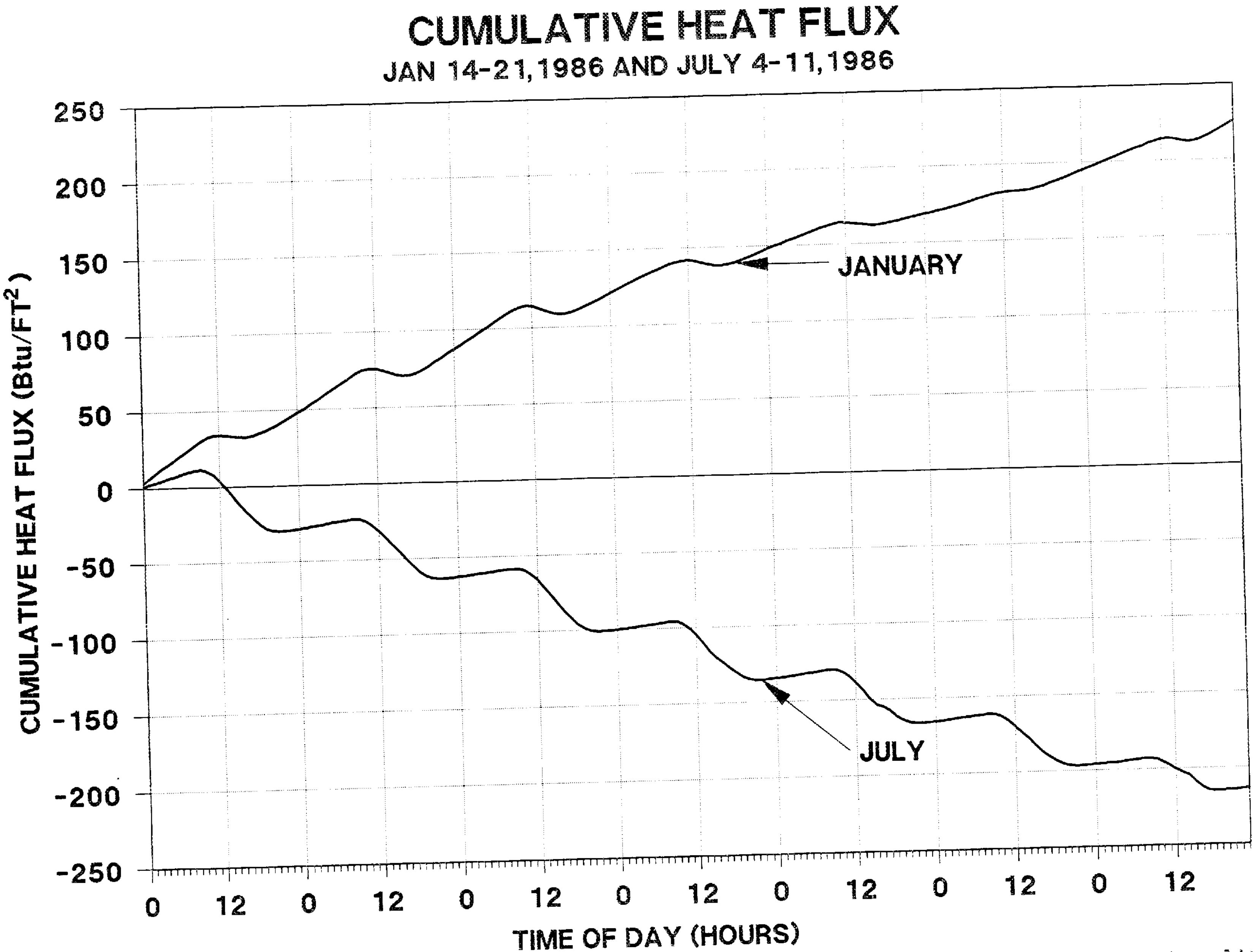

Fig. 6. Cumulative heat flux measured by the transducer located between the foam and perlite insulation. As expected, the sum is positive (heat flow into the building) during January and negative (heat flow from the building) during July.

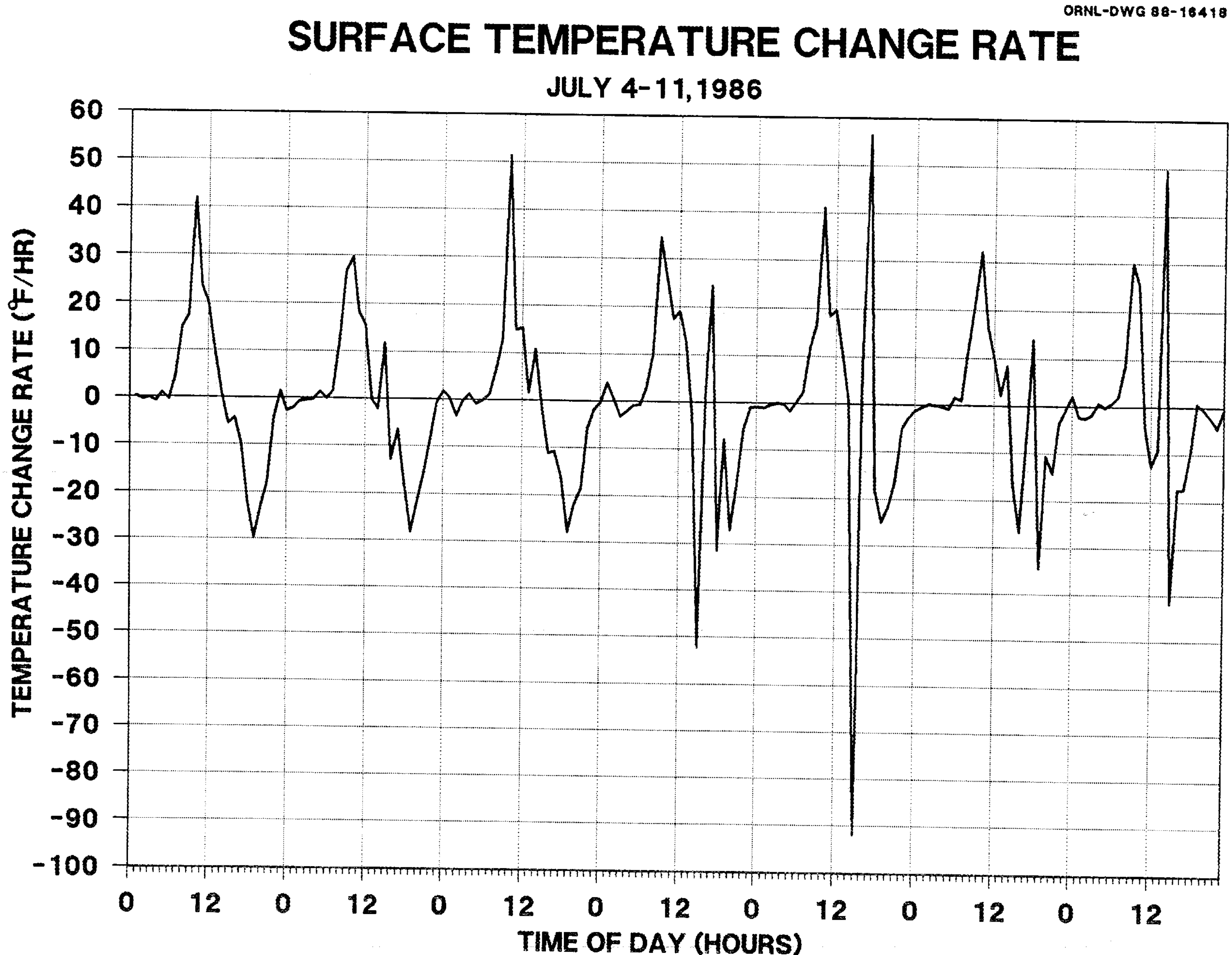

Fig. 7. The surface temperature change rate for a week in July 1986. The difference between hourly readings is being monitored.

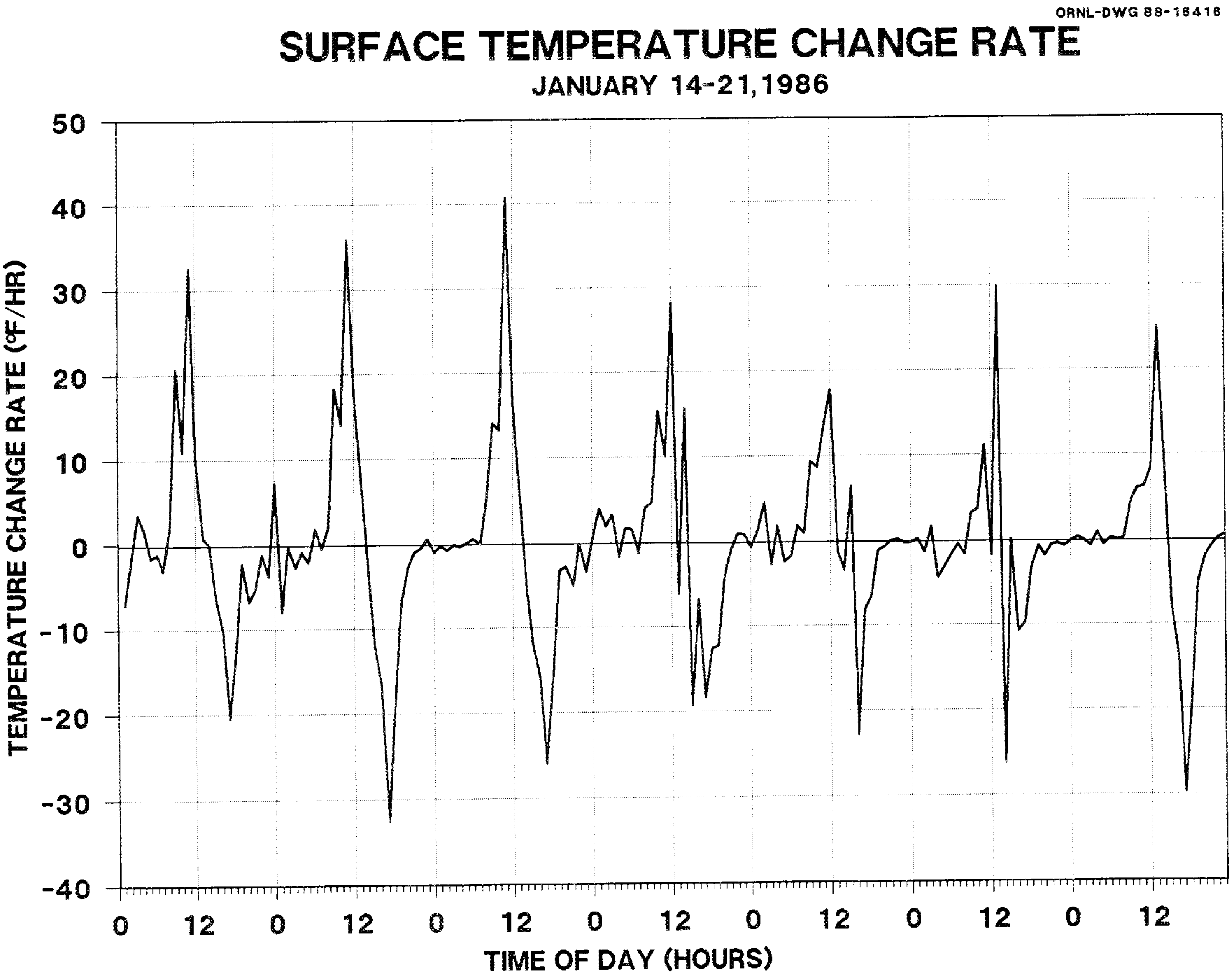

Fig. 8. The surface temperature change rate for a week in January 1986. The difference between hourly readings is being monitored. As one would expect, the rates are lower in January than in July.

ORNL-DWG 88-16410

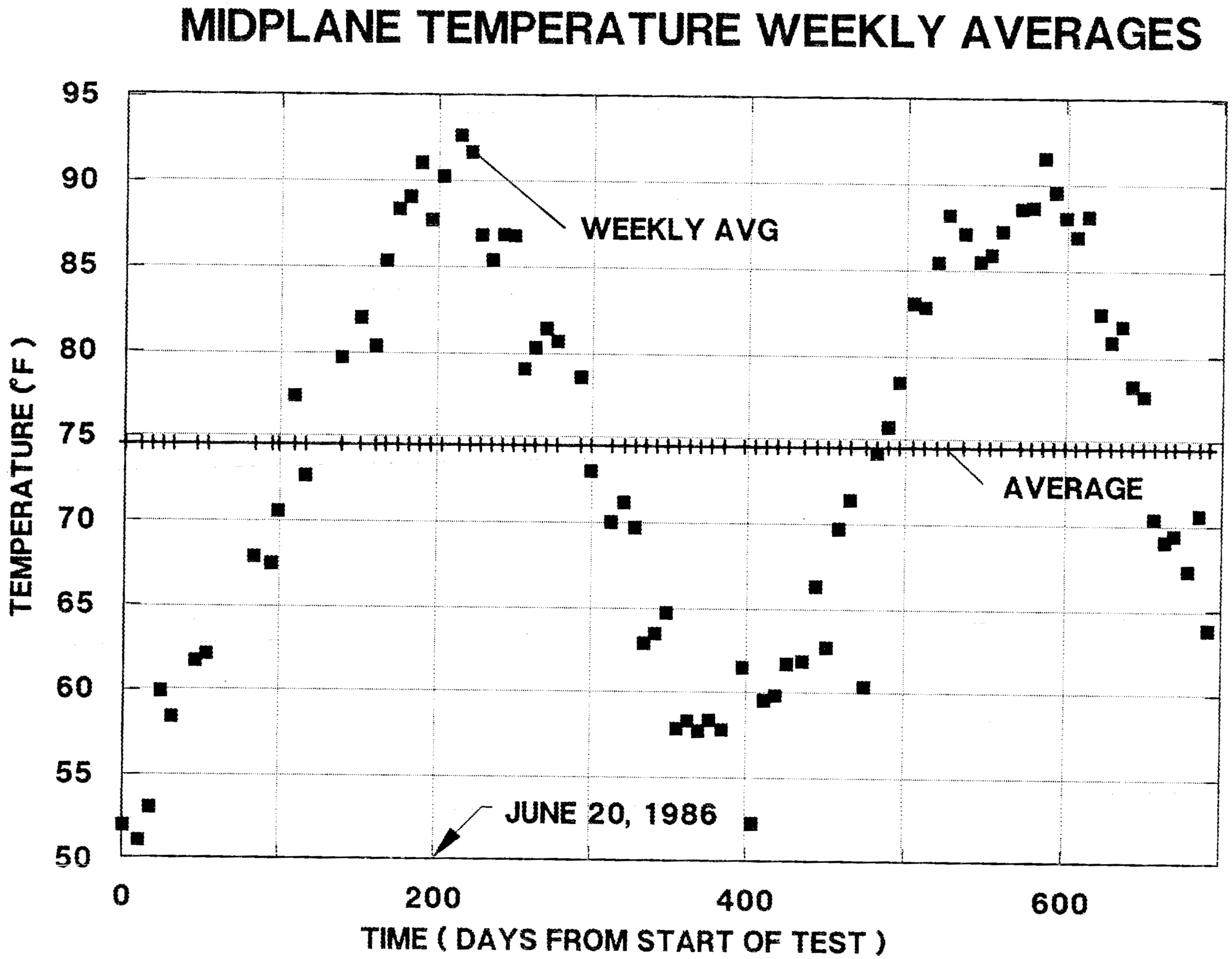

Fig. 9. This figure shows that the average midplane temperature of the foam insulation follows season patterns and has an average near 75°F.

5. LABORATORY MEASUREMENTS

A series of pre-RTRA tests in October-November 1985 and post-RTRA tests in November-December 1987 were conducted on the test samples under laboratory conditions. Detailed results of these tests are reported in an ORNL Letter Memorandum of March 9, 1988.[8] A summary is presented here.

5.1 Density

Pre- and post-measurements of the density of the three insulations in the test panel described in Fig. 2 are listed in Table 1. No change was observed for the fiberboard, but the perlite density increased slightly (2%) and the phenolic board density decreased by 7%. The phenolic board was from a pilot plant test run and was not necessarily representative of commercially available phenolic foam insulation.

No explicit moisture testing was done on the samples. Prior to assembly in 1985, a series of laboratory high temperature tests were run which probably insured that the samples were installed dry. When the panel was disassembled in 1987 all materials appeared to be quite dry. Dimensionally, the only noticeable change over the two years was that the edges of the phenolic insulation were cupped; that is, the center of each board edge was curved inward all around the perimeter of the board.

5.2 Thermal Performance

All laboratory thermal performance testing was done in the ORNL unguarded thin heater apparatus.[7] This device contains an electrically heated screen sandwiched between two insulation specimens with large, isothermal copper plates on the outside. The test specimen was on one side of the screen and the balancing insulation and the outer plate on the other side were kept at the screen temperature so that the known heat flow from the screen all passed through the test specimen.

The pre- and post-tests were different. The only thermal performance pre-test was a determination of the R-value of the total system installed in the field, consisting of perlite, foam, and fiberboard. Two post-tests on the field sample exposed for two years were run; one with the insulation composite as above but also with the EPDM membrane which could not be separated from the fiberboard because it was fully adhered during construction, and the other on the foam insulation alone. In Table 2 the total system R-values for the pre- and the post-tests are compared. The decrease in the measured R-value is apparent. Table 3 gives the thermal conductivity and the thermal resistance for the foam alone from the 1987 post-test.

An estimate of the thermal drift of the phenolic foam from the pre- and post-tests in the laboratory can be obtained as follows. Table 2 gives

Table 1: Component Density Values (lb/ft^3)

	1985	1988	% $\frac{(1988-1985)}{1985}$
Fiberboard	17.1	17.1	0
Perlite Board	10.2	10.4	+2
Phenolic Board	3.43	3.18	-7.3

Table 2: Measured R-Values for the System

Mean Temp.	R(1985)	R(1987)
°F	$ft^2 \cdot hr \cdot F/Btu$	$ft^2 \cdot hr \cdot F/Btu$
82	23.1	18.3
122	19.0	16.4

1985 - 3/4 in. Perlite, 2.02 in. Phenolic, 1/2 in. Fiberboard
1987 - 3/4 in. Perlite, 2.02 in. Phenolic, 1/2 in. Fiberboard, 0.040 in. EPDM

the R-value for the composite in 1987 and Table 3 gives the R-value for the foam alone. The difference is attributable to the perlite and the fiberboard (the membrane R-value is assumed small) at the same temperatures. If we now assume that these fibrous insulations are not subject to drift, then their R-values should not have changed during the test programs.

Thus, after subtraction, the R-values for the phenolic foam in 1985 can be deduced. The results of this calculation are shown in Table 4.

At both temperatures for which measurements are available, the R-value of the foam insulation decreases over the two years of the experiment. This decrease is significant, being 24% at a mean temperature of 82°F. These results will be compared later to calculated R-value decreases from in-situ techniques.

6. THERMAL PERFORMANCE ANALYSIS

6.1. Description of PROPOR

The principal ORNL results that characterize the thermal performance of roof systems have been obtained using the computer program PROPOR. PROPOR is based on a FORTRAN program developed by Beck at Michigan State University.[9] It has been modified for estimating the thermal conductivity, k, and $\rho \cdot Cp$, where ρ is the density and Cp the specific heat of a material, from transient heat flux and temperature measurements[10, 11] PROPOR is a least squares technique applied to measured and calculated temperatures and heat flows. The sum of squares to be minimized is

$$S = \sum_{i=1}^{n} \sum_{j=1}^{J} [Y_{ji} - T_{ji}]^2 \, W_{T_j} + \sum_{i=1}^{n} (F_i - q_i)^2 \, W_q \qquad (1)$$

where Y_{ji} and F_i are measured temperatures and heat flow at time t_i and location x_j, and T_{ji} and q_i are calculated temperatures and heat flow at the same time and location, n is the number of data points in a set (n = 168 for this study), j is the number of sensor sites involved in the minimization, and W_{Tj} and W_q are weighting factors that account for differences in magnitude between the temperature and the heat flux terms. The T_{ji} and q_i values are calculated using Crank-Nicolson finite difference equations derived from the heat transfer equation,

$$\frac{\partial}{\partial x}\left(k \frac{\partial T}{\partial x}\right) = \rho C_p \frac{\partial T}{\partial t} \qquad (2)$$

Table 3: Measured Thermal Conductivity and R-Value for the Phenolic Foam Sample in 1987

t	k(measure)	R(calculated)
°F	Btu/h·ft²·°F	ft²·hr·F/Btu
82	0.136	14.85
122	0.150	13.5

Table 4: Calculated 1987 R-Values for Phenolic Foam Compared to Estimated 1985 R-Values. (See text for discussion)

t(°F)	R(1985)	R(1987)	%Change
82	19.7	14.85	24
122	16.1	13.5	16

In this study the analysis is restricted to the phenolic foam insulation which is sandwiched between a bottom layer of perlite and a top layer of fiberboard as seen in Fig. 2. For this geometry the x-domain starts at the lower side of the foam insulation and ends at the upper side. The only sensors directly relevant to this material are the two thermocouples and the two heat flux transducers in contact with the phenolic foam at the top and at the bottom. The upper heat flux transducer is not used in this analysis because it is suspected that the heat transfer at the upper surface is influenced by a condensation/evaporation process not accounted for in Eq. 2. Also, the temperature outputs from the two thermocouples are needed as boundary conditions for solving Eq. 2. Thus, the only output of the finite difference analysis available for input into the least squares analysis is the heat flux at the lower surface of the foam insulation. This means that only the term involving q_j in Eq. 1 is used and $W_q=1$.

As currently formulated, PROPOR is designed to accommodate two unknown parameters. That is, Eq. 1 when differentiated with respect to these parameters and set equal to zero has two adjustable parameters. This will always be some combination of k(T) and $\rho(T)\cdot C_p(T)$ evaluated at specified temperatures.

Since one does not expect $\rho\cdot Cp$ to have a large influence in the thermal analysis of light weight (low thermal storage) systems, it has been found most useful to first use PROPOR to determine the best values of constant k and constant $\rho\cdot Cp$ for the full range of temperatures during the analysis period. Then, this value of $\rho\cdot Cp$ is reentered into PROPOR as a constant and the program is used to estimate a temperature-dependent k according to the model

$$k = k_a + \frac{k_b - k_a}{T_b - T_a}(T - T_a) \qquad (3)$$

where k_a and k_b are the best-fit thermal conductivities at T_a and T_b respectively. If, for example, T_a and T_b are chosen to be just smaller and just larger than the smallest and largest temperatures in the analysis period, PROPOR gives the best-fit linear relation between k and T over the temperature range covered by the analysis period.

6.2. Calculation of Thermal Resistance

PROPOR has been used to separately analyze 83 successive weekly data sets over a period of two years from December 1985 through November 1987. In the analysis of each weekly data set, the conductivity is assumed to be linear with temperature according to Eq. 3. Results are presented in Table 5 in the "PROPOR High Temp Value," "PROPOR k(high)," "PROPOR Low Temp Value," and "PROPOR k(low)" columns. Thus, each weekly data set yields a linear relation between thermal conductivity and temperature.

At first, one might expect the straight line k versus T curves for all weeks to be identical since they all describe the same system. This will not be so, however, if the true temperature variation of thermal conductivity for phenolic is not linear. The reason is that each weekly data set contains temperatures characteristic only of that week. Thus, a week in January will be dominated by low temperatures and Eq. 3 will give a curve characteristic of low temperatures. Likewise, for a week in July Eq. 3 will yield a curve dominated by the high temperature variation of thermal conductivity. This behavior is important in this case because the thermal conductivity of the test specimen does have a complex temperature variation because the thermal conductivity of phenolic foam insulation is not linear with temperature over the range of temperatures encountered in this program, and because thermal drift will cause conductivity to change with time. Fig. 10 illustrates the effect of both these factors. The four curves of conductivity versus temperature in Fig. 10 are taken from data in Table 5. First, note that Curves 1 and 3, which are for winter data about one year apart, are parallel but are different from Curves 2 and 4 which also are parallel and are for summer data also about one year apart. This suggests different slopes for winter data than for summer data; that is, as indicated above, the thermal conductivity is not linear with temperature. The reason the experimental data show this, as mentioned earlier, is because the range of temperatures included in the PROPOR analysis differs from winter to summer. This is illustrated in Figs. 11 and 12 which show the distribution of hourly temperatures for a week in January and for a week in July. Since PROPOR determines the best fit conductivity versus temperature curve only for the temperatures in the data set, curves for winter will reflect low temperature conductivities and curves for summer will reflect high temperature conductivities.

Fig. 10 shows that the curve for the second winter is above the curve for the first winter and likewise for the summer. This suggests that the conductivity is drifting upward with time. This is consistent with laboratory data for the same sample which is discussed in Section 5. Note that if the insulation material was thermally stable, and if PROPOR were applied to enough data sets, it would provide a series of straight lines and the locus of which would trace out the true temperature dependency for the conductivity of the material.

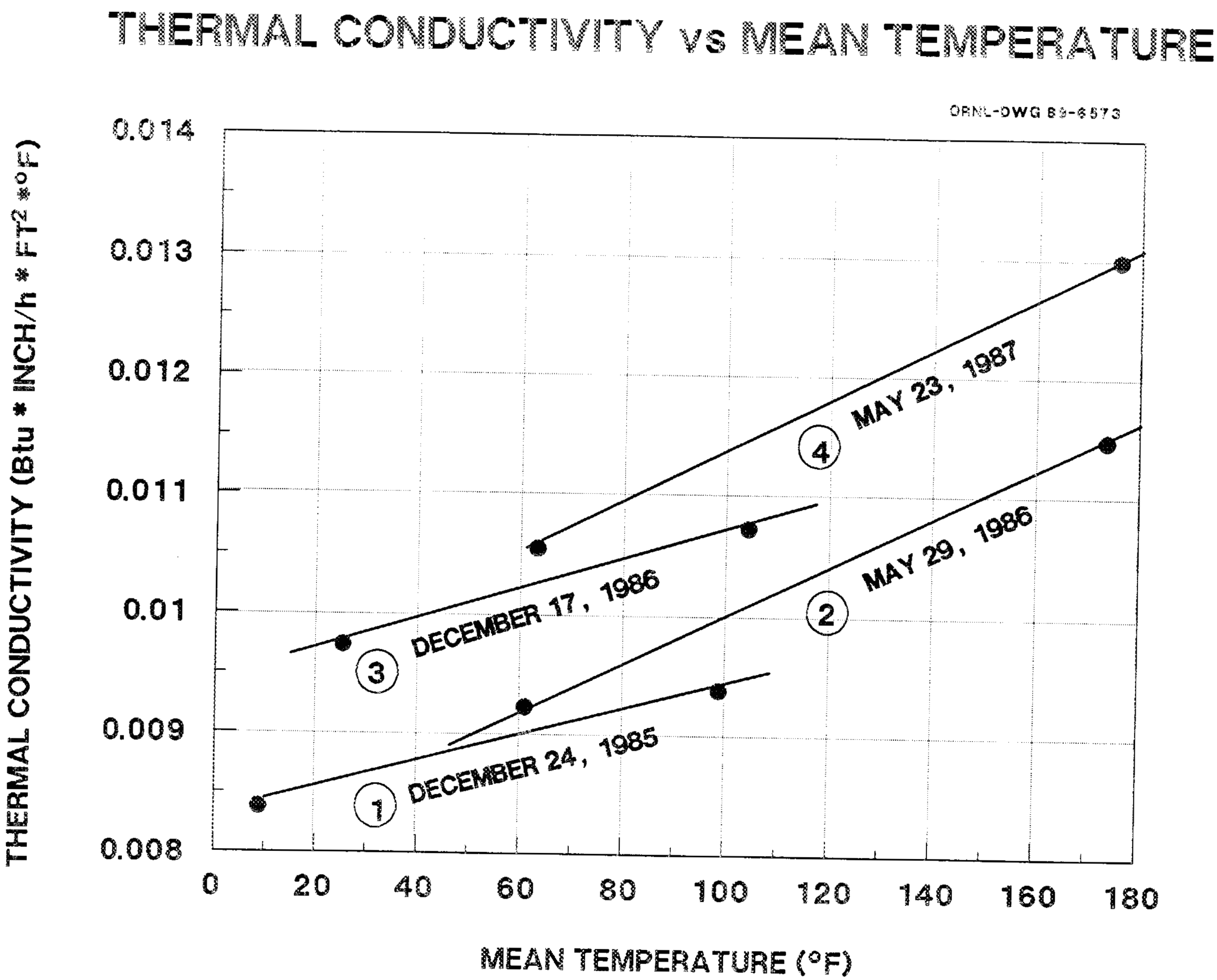

Fig. 10. Examples of weekly thermal conductivity versus temperature curves derived from PROPOR. See text for a discussion.

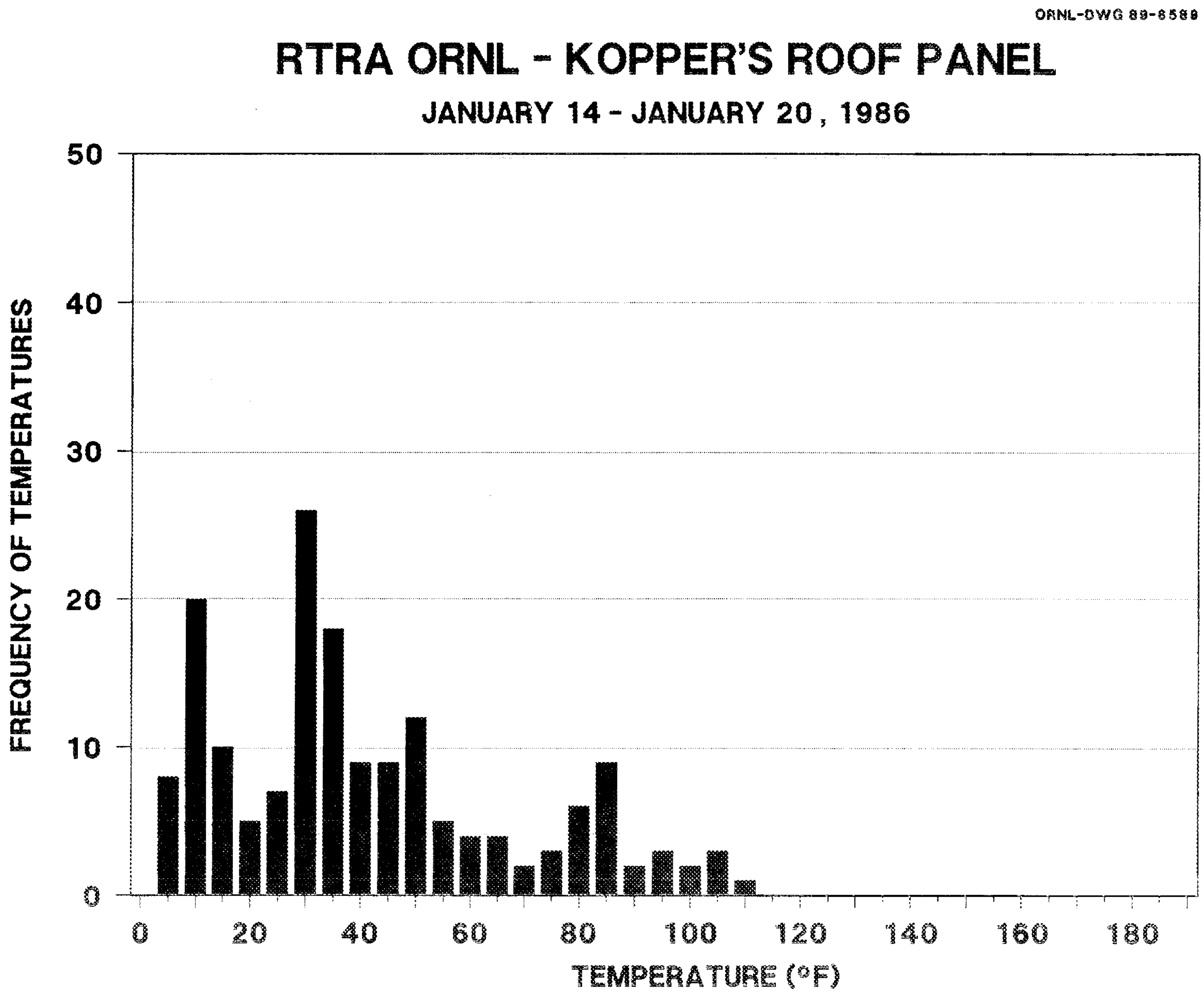

Fig. 11. A histogram of hourly temperatures recorded just under the membrane for one week in January 1986.

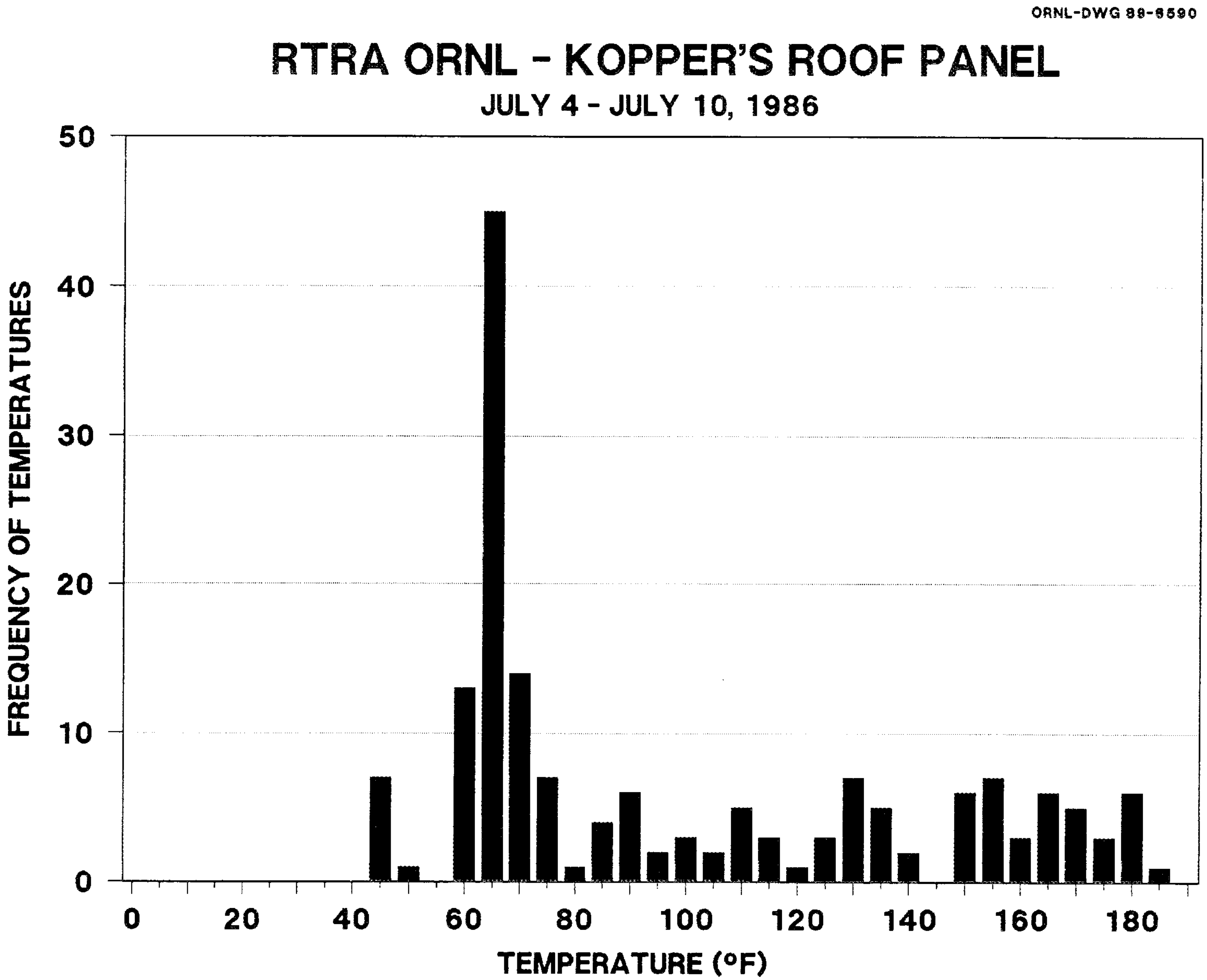

Fig. 12. A histogram of hourly temperatures recorded just under the membrane for one week in July 1986. Note the very different distribution in comparison to Fig. 11.

Table 5: Thermal Performance Analysis Results

FIRST DAY OF WEEK	DAY FROM TEST START	T AVG TOP • BOT OF PHEN	(AVG) R	PROPOR LOW TEMP VALUE	PROPOR k(LOW)	PROPOR HIGH TEMP VALUE	PROPOR k(HIGH)	k(AVG)	R(AVG)	k(75)	R(75)
14-Dec-85	0	51.91	19.19	0.0	0.008131	88.0	0.009290	0.008738	19.55	0.009118	18.73422
24-Dec-85	10	51.07	19.08	0.0	0.008205	96.0	0.009331	0.008736	19.55	0.009084	18.80453
31-Dec-85	17	53.02	19.60	-1.0	0.008494	102.0	0.008847	0.008662	19.72	0.008754	19.51384
07-Jan-86	24	59.87	18.93	7.0	0.008439	109.0	0.009461	0.008897	19.20	0.009120	18.73104
14-Jan-86	31	58.35	19.41	9.0	0.008218	107.0	0.009443	0.008761	19.50	0.009043	18.89122
29-Jan-86	46	61.69	18.98	9.0	0.007792	121.0	0.010460	0.008922	19.15	0.009364	18.24321
05-Feb-86	53	62.09	19.24	10.0	0.007809	118.0	0.010340	0.008954	19.08	0.009332	18.30562
07-Mar-86	83	67.83	18.48	15.0	0.007748	139.0	0.011670	0.009306	18.36	0.009645	17.71075
18-Mar-86	94	67.42	18.65	6.0	0.007715	145.0	0.011550	0.009305	18.36	0.009618	17.76053
22-Mar-86	98	70.52	18.08	6.0	0.007784	153.0	0.011670	0.009483	18.02	0.009608	17.78024
01-Apr-86	108	77.33	18.14	36.0	0.008354	156.0	0.011400	0.009581	17.83	0.009343	18.28277
08-Apr-86	115	72.63	18.38	21.0	0.008089	159.0	0.011380	0.009368	18.24	0.009376	18.21875
01-May-86	138	79.61	17.70	23.0	0.008134	168.0	0.011630	0.009668	17.67	0.009387	18.19749
13-May-86	150	81.95	17.36	52.0	0.008987	164.0	0.011660	0.010031	17.03	0.009535	17.91472
23-May-86	160	80.28	17.85	51.0	0.008632	168.0	0.011480	0.009601	17.79	0.009216	18.53619
29-May-86	166	85.33	16.88	55.0	0.009187	175.0	0.011860	0.010243	16.68	0.009632	17.73509
06-Jun-86	174	88.35	16.89	57.0	0.009449	180.0	0.011520	0.010273	16.63	0.009752	17.51764
13-Jun-86	181	89.05	16.60	49.0	0.009015	180.0	0.012050	0.010331	16.54	0.009617	17.76300
20-Jun-86	188	91.05	16.23	48.0	0.008887	175.0	0.012340	0.010549	16.19	0.009621	17.75610
27-Jun-86	195	87.73	16.54	53.0	0.009276	171.0	0.012000	0.010477	16.31	0.009783	17.46072
04-Jul-86	202	90.28	16.11	50.0	0.009631	176.0	0.011780	0.010643	16.05	0.010057	16.98585
15-Jul-86	213	92.68	15.59	64.0	0.010060	182.0	0.012220	0.010993	15.54	0.010261	16.64822
22-Jul-86	220	91.70	15.74	65.0	0.009596	181.0	0.012720	0.010853	15.74	0.009865	17.31656
29-Jul-86	227	86.84	15.85	52.0	0.009866	174.0	0.012310	0.010874	15.71	0.010326	16.54279
05-Aug-86	234	85.36	16.03	56.0	0.010470	164.0	0.011640	0.010949	15.60	0.010675	16.00187
12-Aug-86	241	86.85	15.89	59.0	0.009985	175.0	0.012230	0.010862	15.73	0.010294	16.59437
19-Aug-86	248	86.82	15.60	50.0	0.010240	170.0	0.012100	0.011060	15.45	0.010627	16.07464
26-Aug-86	255	78.96	16.32	43.0	0.009593	158.0	0.012320	0.010665	16.02	0.010351	16.50273
02-Sep-86	262	80.21	16.24	46.0	0.009943	161.0	0.011950	0.010763	15.87	0.010449	16.34907
09-Sep-86	269	81.36	15.64	45.0	0.009873	160.0	0.012600	0.010998	15.53	0.010584	16.14011
16-Sep-86	276	80.61	15.65	56.0	0.010140	160.0	0.012640	0.011075	15.42	0.010596	16.12132
01-Oct-86	291	78.51	15.81	34.0	0.009575	160.0	0.012890	0.010923	15.64	0.010653	16.03513
08-Oct-86	298	72.97	16.32	35.0	0.009418	143.0	0.012740	0.010656	16.03	0.010648	16.04314
21-Oct-86	311	69.97	16.28	33.0	0.009610	134.0	0.012000	0.010475	16.31	0.010603	16.11048
29-Oct-86	319	71.15	16.07	33.0	0.009601	129.0	0.012100	0.010615	16.09	0.010694	15.97422
05-Nov-86	326	69.68	16.34	33.0	0.009231	119.0	0.012390	0.010522	16.24	0.010773	15.85641
12-Nov-86	333	62.85	16.52	16.0	0.009317	115.0	0.011750	0.010370	16.47	0.010766	15.86642
19-Nov-86	340	63.40	16.44	19.0	0.009620	111.0	0.011150	0.010297	16.59	0.010551	16.19073
26-Nov-86	347	64.63	16.38	35.0	0.009435	108.0	0.011860	0.010329	16.54	0.010763	15.87114
03-Dec-86	354	57.80	16.37	12.0	0.009853	102.0	0.010890	0.010312	16.57	0.010578	16.14849
10-Dec-86	361	58.27	16.40	11.0	0.009864	102.0	0.010730	0.010271	16.63	0.010473	16.31170
17-Dec-86	368	57.69	16.39	18.0	0.009833	102.0	0.011000	0.010314	16.56	0.010624	16.07859
24-Dec-86	375	58.32	16.34	18.0	0.009860	91.0	0.010500	0.010188	16.77	0.010359	16.49014
01-Jan-87	383	57.77	16.42	18.0	0.009908	102.0	0.010770	0.010273	16.63	0.010492	16.28080
14-Jan-87	396	61.45	16.20	24.0	0.009819	93.0	0.010870	0.010350	16.51	0.010595	16.12270
21-Jan-87	403	52.25	16.27	3.0	0.010170	79.0	0.010320	0.010263	16.65	0.010312	16.56629
28-Jan-87	410	59.50	16.35	18.0	0.009532	108.0	0.011530	0.010373	16.47	0.010797	15.82171
04-Feb-87	417	59.82	16.13	5.0	0.009258	122.0	0.012460	0.010593	16.13	0.011173	15.28884
11-Feb-87	424	61.65	16.15	14.0	0.009517	123.0	0.011980	0.010532	16.22	0.010895	15.67943
21-Feb-87	434	61.83	16.13	23.0	0.009436	123.0	.0.012460	0.010547	16.20	0.011008	15.51833

Table 5
(Continued)

FIRST DAY OF WEEK	DAY FROM TEST START	T AVG TOP + BOT OF PHEN	(AVG) R	PROPOR LOW TEMP VALUE	PROPOR k(LOW)	PROPOR HIGH TEMP VALUE	PROPOR k(HIGH)	k(AVG)	R(AVG)	k(75)	R(75)
01-Mar-87	442	66.26	15.93	19.0	0.009509	138.0	0.013210	0.010948	15.60	0.011250	15.18431
08-Mar-87	449	62.64	16.22	17.0	0.009269	128.0	0.012750	0.010612	16.10	0.011087	15.40760
15-Mar-87	456	69.67	15.61	21.0	0.009315	146.0	0.013840	0.011105	15.38	0.011269	15.15850
22-Mar-87	463	71.35	15.50	21.0	0.009640	149.0	0.013120	0.011085	15.41	0.011108	15.37913
01-Apr-87	473	60.34	16.07	11.0	0.009162	133.0	0.012690	0.010529	16.23	0.011012	15.51231
08-Apr-87	480	74.15	15.45	23.0	0.009687	155.0	0.013320	0.011242	15.20	0.011118	15.36522
15-Apr-87	487	75.71	15.26	37.0	0.009904	166.0	0.013750	0.011346	15.06	0.011036	15.47833
22-Apr-87	494	78.35	15.22	33.0	0.010050	160.0	0.013070	0.011322	15.09	0.011048	15.46179
01-May-87	503	82.98	14.71	40.0	0.010340	169.0	0.013370	0.011665	14.64	0.011162	15.30477
08-May-87	510	82.76	14.85	35.0	0.009927	177.0	0.013840	0.011614	14.71	0.011029	15.48911
16-May-87	518	85.42	14.55	54.0	0.010670	176.0	0.013690	0.011876	14.38	0.011189	15.26683
23-May-87	525	88.19	14.25	58.0	0.010810	178.0	0.013720	0.012031	14.20	0.011222	15.22273
02-Jun-87	535	87.12	14.29	44.0	0.010430	173.0	0.013740	0.011960	14.28	0.011225	15.21842
12-Jun-87	545	85.47	14.16	60.0	0.011050	168.0	0.013710	0.012122	14.09	0.011419	14.95986
19-Jun-87	552	85.87	14.07	62.0	0.011090	175.0	0.013980	0.012165	14.04	0.011422	14.95589
26-Jun-87	559	87.27	13.97	42.0	0.010600	175.0	0.014080	0.012253	13.94	0.011463	14.90242
08-Jul-87	571	88.59	13.66	56.0	0.011250	172.0	0.014020	0.012522	13.64	0.011703	14.59651
15-Jul-87	578	88.66	13.64	52.0	0.011250	174.0	0.014110	0.012549	13.61	0.011789	14.49068
22-Jul-87	585	91.55	13.41	58.0	0.011460	179.0	0.014220	0.012715	13.44	0.011847	14.41903
29-Jul-87	592	89.57	13.49	58.0	0.011630	172.0	0.013930	0.012665	13.49	0.011972	14.26823
05-Aug-87	599	88.07	13.47	56.0	0.011670	168.0	0.013940	0.012724	13.43	0.012055	14.17105
12-Aug-87	606	86.97	13.46	58.0	0.011590	172.0	0.014310	0.012754	13.39	0.011995	14.24131
19-Aug-87	613	88.14	13.42	52.0	0.011320	172.0	0.014510	0.012729	13.42	0.011931	14.31794
27-Aug-87	621	82.43	13.87	41.0	0.010940	164.0	0.014470	0.012439	13.73	0.011915	14.33674
03-Sep-87	628	80.80	13.73	43.0	0.011210	163.0	0.014530	0.012570	13.59	0.012095	14.12390
10-Sep-87	635	81.69	13.56	56.0	0.011650	160.0	0.014490	0.012692	13.46	0.012168	14.03858
17-Sep-87	642	78.19	13.72	38.0	0.011060	153.0	0.014480	0.012481	13.69	0.012160	14.04839
24-Sep-87	649	77.57	13.68	42.0	0.011230	152.0	0.014510	0.012521	13.64	0.012214	13.98668
01-Oct-87	656	70.36	14.13	25.0	0.010740	143.0	0.014390	0.012129	14.08	0.012286	13.90402
08-Oct-87	663	69.02	14.06	23.0	0.010730	144.0	0.014480	0.012141	14.07	0.012341	13.84210
14-Oct-87	669	69.40	13.91	23.0	0.010820	139.0	0.014260	0.012225	13.97	0.012362	13.81915
23-Oct-87	678	67.28	14.13	21.0	0.010770	131.0	0.014160	0.012131	14.08	0.012434	13.73900
30-Oct-87	685	70.58	13.87	24.0	0.010800	135.0	0.014400	0.012352	13.83	0.012454	13.71708
05-Nov-87	691	63.83	14.19	18.0	0.010830	119.0	0.013790	0.012052	14.17	0.012500	13.66612

To continue the analysis of data and to allow comparisons with other data bases, the thermal properties are reported in two different ways. First, k at 75°F, k(75) is calculated and then k at the average midplane temperature of the foam insulation k (avg). Both calculations are done on all the weekly results and are listed in Table 5. A plot of R(avg) derived from k(avg), against time over the full test period, Fig. 13, is a direct measure of the full change in thermal conductivity with time and will be discussed in more detail in the next section.

Examination of the R(75) data also plotted against time over the full test period shows that there is a season variation. Under normal circumstances, normalization to a single temperature should eliminate this variation. This indicates that the thermal drift, which is significant in this test, may be temperature dependent.

Finally, the thermal resistance of the sample, the R-value, is obtained from the thermal conductivity by

$$R = L / k \tag{4}$$

where L is the thickness of the sample. R-values at T=75°F, R(75), and at T=T(avg), R(avg), are also provided in Table 5.

6.3. Presentation of PROPOR Results

In Fig. 13 values of R(avg) for the full two years of the test are plotted against time. A periodic variation superposed on a downward drift is clearly seen in the figure. If the sample was thermally stable, the R-value should only show a periodic variation due to seasonal temperature changes. The drift in R-value is even more apparent when R(avg) is plotted against the average temperature in Fig. 14. Note that low weighted mean temperatures correspond to winter conditions and the high ones to summer conditions. Thus, there is a time sequence to the weekly calculated data points. Lines connecting data points are only there to indicate the time sequencing of points. The earliest data point is for December 24, 1985 at the upper left and as time passes and the average temperature increases, the R-value decreases both because of the normal decrease in R-value with increasing temperature and because of the irreversible drift probably due to changing cell gas composition. If the irreversible drift were not present, the R-value, instead of spiraling downward, would retrace the same curve as the average temperature begins to decrease in the second half of each year. The time-sequencing lines make the data appear somewhat chaotic whereas it actually is fairly reliable. A curve fitting exercise[13] as shown that

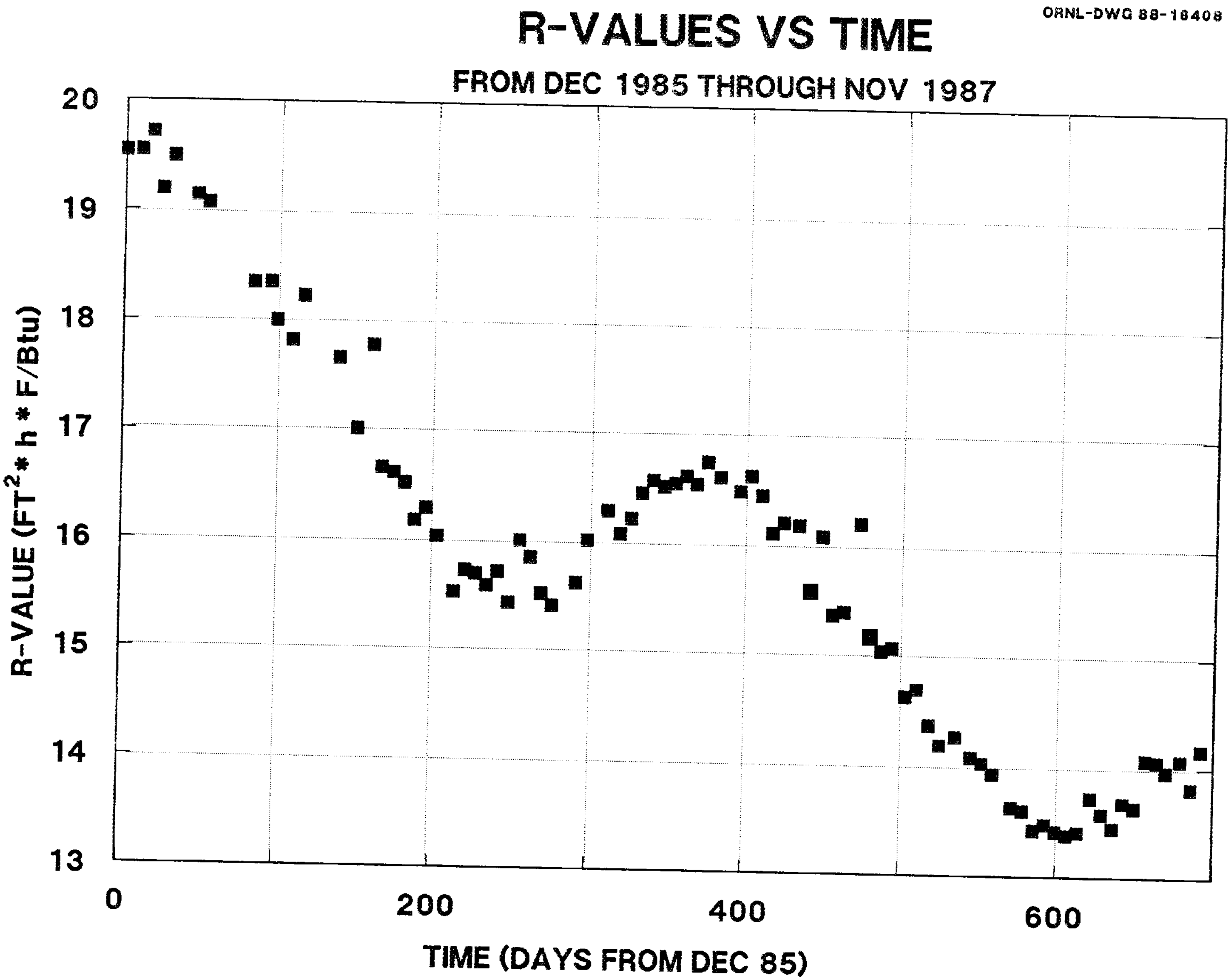

Fig. 13. A plot of R-values of the foam insulation evaluated at the average midplane temperatures over the full test period.

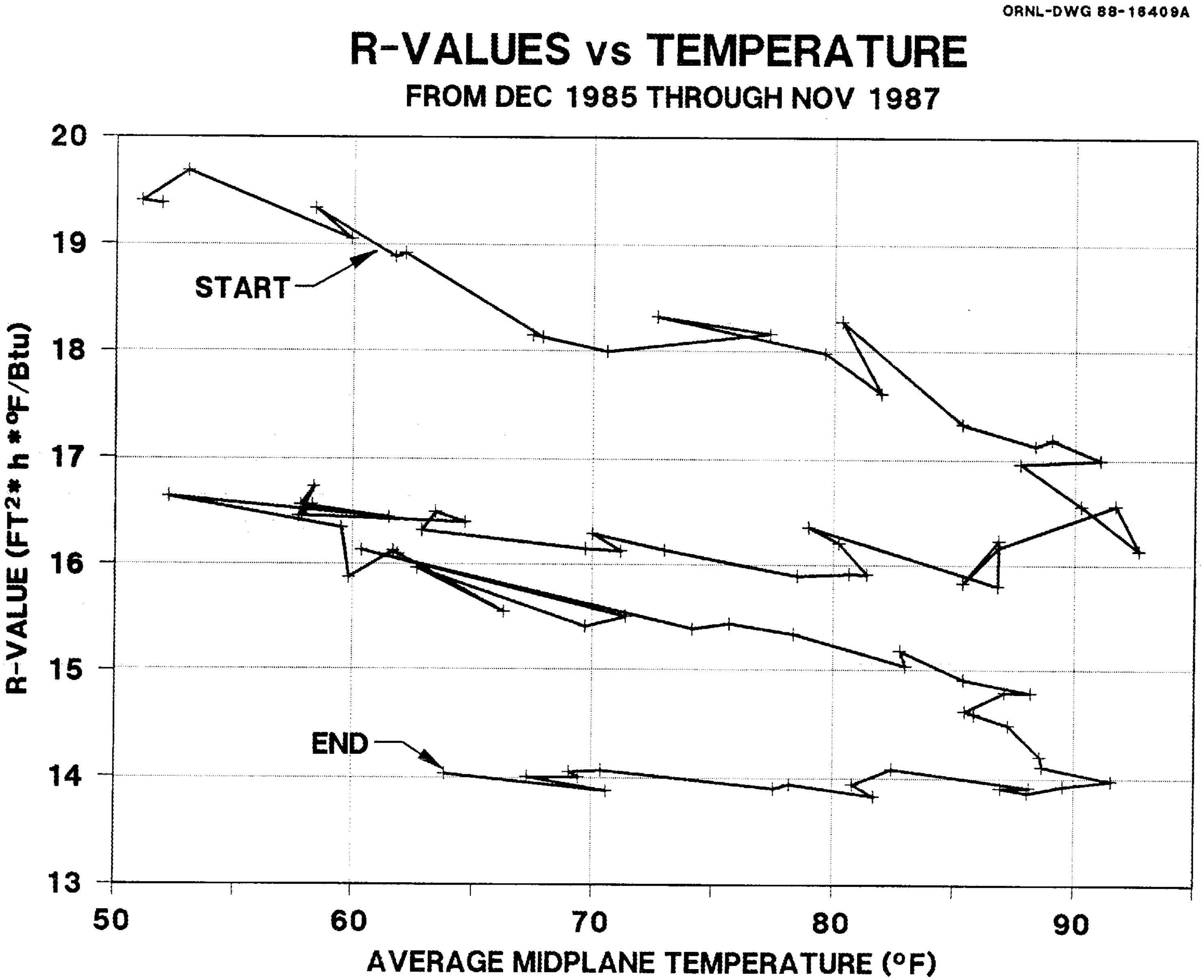

Fig. 14. R-value of the foam insulation from the PROPOR analysis evaluated at the average midplane temperature. This representation clearly shows that thermal drift is a factor in this test.

the data in Fig. 13 (with two outliers) fits the equation

$$R(T,t) = (21.62 - 0.037 \cdot T) \cdot \frac{\exp e(-t/1061) + 0.91}{1 + 0.91} \quad \frac{ft^2 \cdot h \cdot f}{Btu} \qquad (5)$$

to within 3%. The first term (a + bT) represents the periodic temperature variation and the second is an exponential decay representing the thermal drift. The time, t, in the experimental term is measured in days.

For t=0, Eq. 5 reduced to

$$R(T,0) = (21.62 - 0.037 \cdot T) \frac{ft^2 \cdot h \cdot F}{Btu} \qquad (6)$$

or, since the sample is 2.05 inches thick,

$$R(T,0) = 10.5 - 0.02T \quad \frac{ft^2 \cdot h \cdot F}{Btu \cdot inch} \qquad (7)$$

which represents the initial temperature variation of the thermal resistance.

Likewise for $t=\infty$

$$R(T,\infty) = R(T,o) \frac{0.91}{1 + 0.91} = 0.48\ R(T,o) \frac{ft^2 \cdot h \cdot F}{Btu/inch} \qquad (8)$$

From Eq. 7, the R-value per inch at the start of the test period (t=0) for T=75°F is R(75,0)= 9.0 $ft^2 \cdot h \cdot F/Btu$. For comparison, the design value suggested by the National Roofing Contractors Association is 8.3 $ft^2 \cdot h \cdot F/Btu$ inch at T=75°F.[14] Also, using Eq. 8, the ultimate value for the thermal resistance at T=75°F is $R(75,\infty)$ = 4.3 $ft^2 \cdot h \cdot F/Btu$-inch which is near the Laboratory measurement of thermal resistance for open-cell phenolic foam.[15] Thus, one can speculate that the drift process observed in this program is a consequence of the gradual loss of the original CFC blowing agent in the insulation. Furthermore, the thermal resistance is within a few percent of its final value after about 10 years (three times the time constant of 1061 days). Thus, the outward diffusion of gas in this sample takes about 10 years.

The thermal drift over the course of two-year test as determined by PROPOR can be determined from Table 5. The initial value of R(75) is 18.7 $ft^2 \cdot h \cdot F/Btu$ and the final value is 13.7 $ft^2 \cdot h \cdot F/Btu$. Thus, the percentage drift is 27%. From Table 4 the laboratory measured percentage change at T=82°F is 24%. This indicates quite good agreement between the very different techniques.

Fig. 15 is an illustration of the use of the PROPOR technique on an insulation not expected to drift thermally. Fig. 15 is similar to Fig. 14, but the material is expanded polystyrene insulation (EPS) which has no suspected thermal drift. The data is for one full year. Note, in this case, the second half-year data retraces the first half-year data. Thus, one could conclude that this sample is thermally stable.

The thermal drift of the phenolic foam sample for these tests appears anom-alously large. This was apparently due to the fact, unknown to ORNL at the time it was installed, that the material came from an experimental product line, not a production product line. Thus, it is not representative of commercially available material. This does not detract from this project, however, since the purpose was not so much to evaluate material as it was to evaluate the test procedure. In fact, the thermal instability of the sample made the test even more successful because the results of the project make it clear that the technique described in this report will reliably detect thermal drift.

7. AVERAGING TECHNIQUE FOR DETERMINING ROOF THERMAL PERFORMANCE

A second purpose of this project was to provide a comparison to alternate techniques for determining thermal performance properties from in situ data. Of other techniques the one most frequently used is what we refer to as the "Averaging Technique." Two other methods, developed at ORNL, that will not be discussed are the "Absolute Value Technique" and the "Steady State Least Squares Technique"[11]. Both of the latter two techniques have same advantages and disadvantages compared to the Averaging Technique. However, like the Averaging Technique, they are both strictly applicable only when heat capacity effects are negligible. Thus, they are not as generally useful as PROPOR.

7.1. The Averaging Technique

The familiar procedure for characterizing the thermal performance of insulations is through a steady state laboratory measurement of the effective thermal resistance, or R-value, which is defined in terms of the ratio of the constant temperature difference across a sample to the constant heat flow through it. Field characterization is more difficult largely because temperature boundaries are always varying which prevents a steady state analysis. PROPOR addresses these difficulties and has proved to be a useful tool for analyzing field thermal performance.

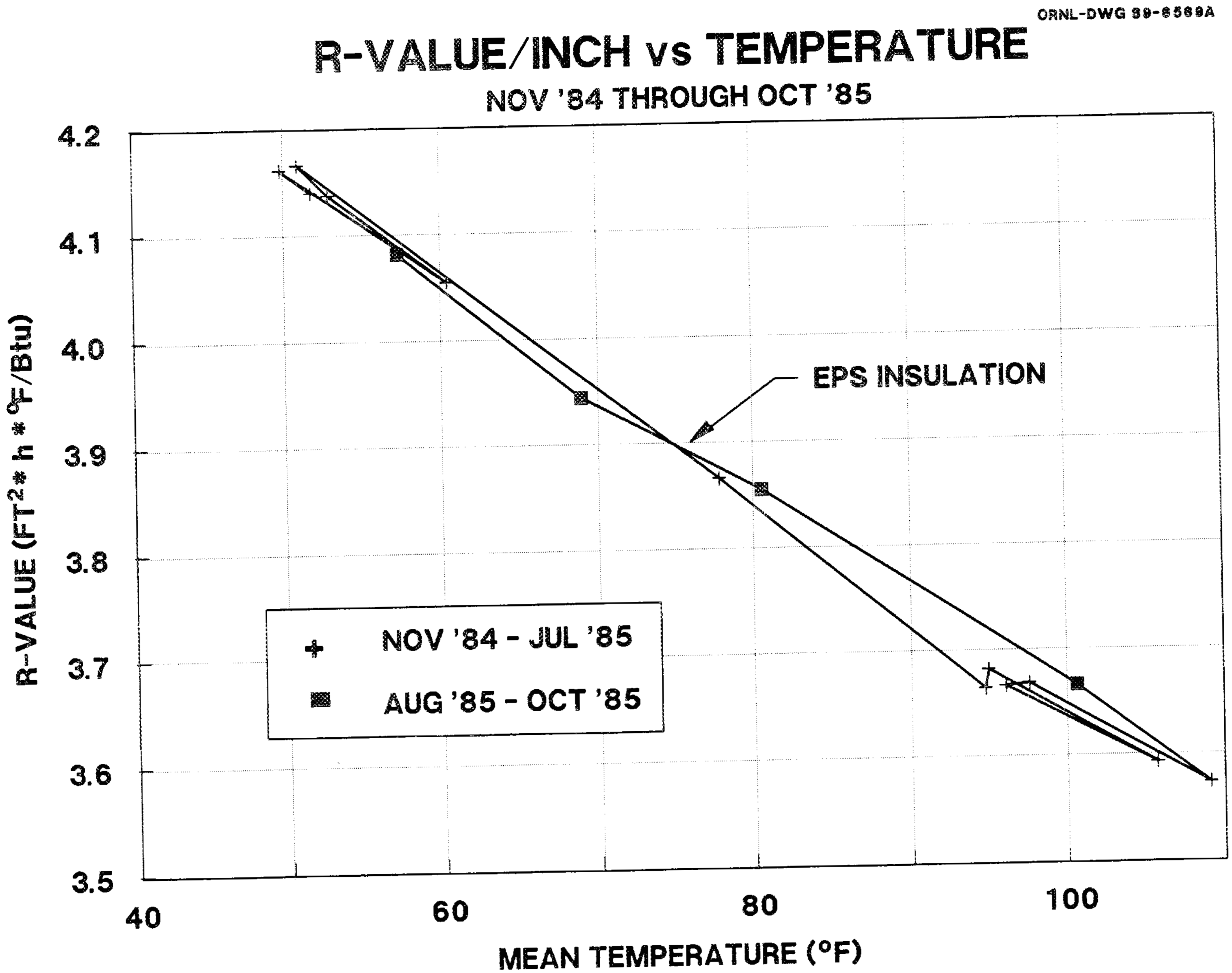

Fig. 15. Similar to Fig. 14 but for EPS insulation. EPS is not expected to exhibit a thermal drift. The figure confirms this.

Other techniques are also available. The one most commonly used is an empirical technique that has been available for several years. It is referred to here as the "Averaging Technique." In this case one assumes that since weather changes are approximately periodic, when measurements are averaged over a sufficiently long period of time, inertial and storage effects will tend to not be significant. Thus, by analogy with the steady state equation, one can construct the expression

$$R_{av} = \frac{1}{n} \sum_{i=1}^{n} \Delta T_i \qquad \frac{1}{n} \sum_{i=1}^{n} q_i \qquad (9)$$

where the numerator is the average temperature difference over n hourly readings, the denominator is the average hourly heat flow over the same time increment, and the time increment is large enough such that storage and inertia effects are negligible. This expression has been used by several authors to characterize the field thermal performance of building envelope components[12, 16]. It has also been shown that the ratio in Eq. 9 indeed converges to the steady state R-value when the temperature difference is sinusoidal, the heat flow is in one direction and the averaging period is some complete number of cycles. Beck of Michigan State[11] has provided a derivation of Eq. 9 under general cyclic conditions which starts from the basic one-dimensional transient heat conduction equations.

The Averaging Technique is fairly simple to use. It requires that the experimenter make long-time temperature measurements on both sides of the system being tested and heat flow measurements on either side or at an interior point. The length of time depends upon the heat storage capacity of the system. Generally, for light weight insulation systems this time is several days, with the best results for a integral number of 24-hour periods. In Fig. 16 the procedure developed at ORNL for using the Averaging Technique is illustrated for the phenolic foam system being studied in this report. Here, the ratio of averages defined by Eq. 9 is updated each hour for each of the 168 hours in a week. The Figure clearly shows that one should include data for several days in the averages so that convergence occurs. Data from application of the Averaging Technique to all 83 weekly data sets for this study are tabulated in Table 5. In all cases the values are final values after a seven-day period (that is, the value from the far right side of curves similar to that in Fig. 16).

The popularity of the Averaging Technique is due to the fairly simple concept it is based upon and to the relative ease with which it can be used. The method is, however, quite sensitive to the conditions of use.

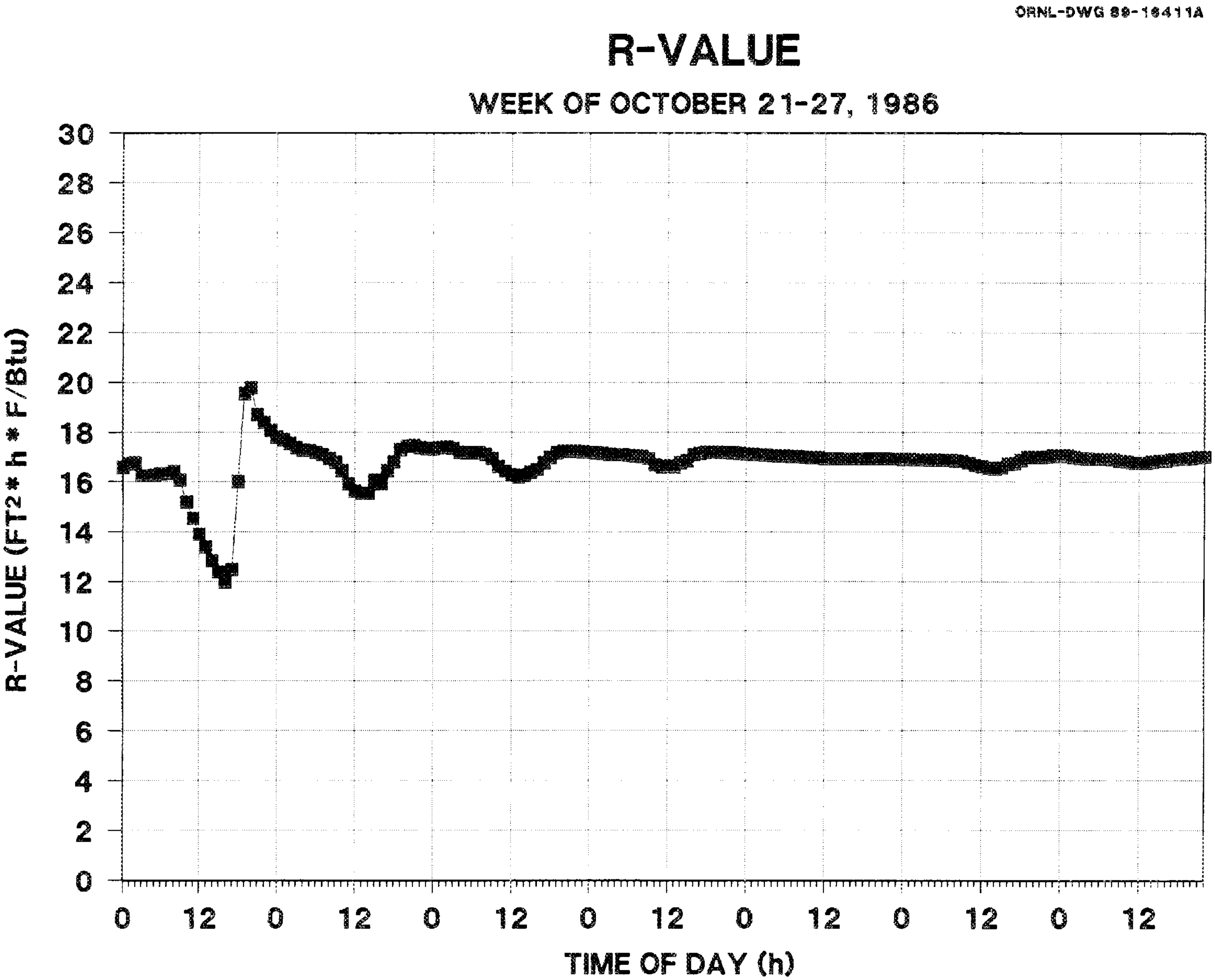

Fig. 16. An illustration of how Equation 9 is used to determine R-value. The calculation is updated after each hour and the graph is a "running average" of the R-value. Convengence to R=17 is clear in this example.

Therefore, since the convergence time for an untested system cannot be pre-determined and since there is no way to estimate the absolute accuracy of a measurement, the operator must be particularly aware of factors that limit the use of the technique and should use some procedure like the "running average" procedure shown in Fig. 16 that indicates convergence of the calculation.

7.2. Averaging Technique and Swing Season Application

The principal shortcoming of the Averaging Technique when applied to building systems is its unreliability with small average temperature differences. This occurs during the spring and fall seasons for varying length5 depending upon local climate conditions. Under these conditions the average heat transfer becomes small and the calculation becomes very sensitive to transducer errors and to otherwise minor fluctuations. Data for the ORNL test sample during the week of May 1-7, 1986 illustrates this problem. Fig. 17 is the "running" average heat flux during the entire time period. Note how this quantity fluctuates about zero. Next, Fig. 18 is a plot of the calculated R-value for this data using Eq. 9. It is rather obvious that under these conditions R is not converging to some single value during this time period.

R(avg) has been calculated for all weekly data sets collected during this project. Values have been included in Table 5. To illustrate differences between the Averaging Technique and PROPOR, results from both methods for a six-month period (December 1985 to August 1986) are plotted against the weighted mean temperature in Fig. 19. Three regions are apparent in the graph. During the winter both methods are in good agreement. During the spring of each year, the Averaging Technique gives fluctuating results which are as much as 70 percent away from PROPOR results. Finally, during the summer, the Averaging Technique gives values that are consistently about 7 percent below PROPOR. The good winter agreement is due to the fact that the heat flow is strongly one directional (from the building), the condition for which the Averaging Technique is known to give reliable results. During the swing seasons, however, reversals in heat flow are daily events and net heat transfer is very small, conditions for which the Averaging Technique is most unreliable. Likewise, during the summer while the net heat transfer for a given week is into the building there is still a significant reversal during most evenings.

One variation of the Averaging Technique that has been proposed is to increase the length of the averaging time[4], the argument being that for longer times the likelihood of small net heat transfer is less and convergence is more likely. Fig. 20 shows R-values obtained by averaging over one-month periods plotted against time over the full two years of the project. A line representing PROPOR data is provided for reference.

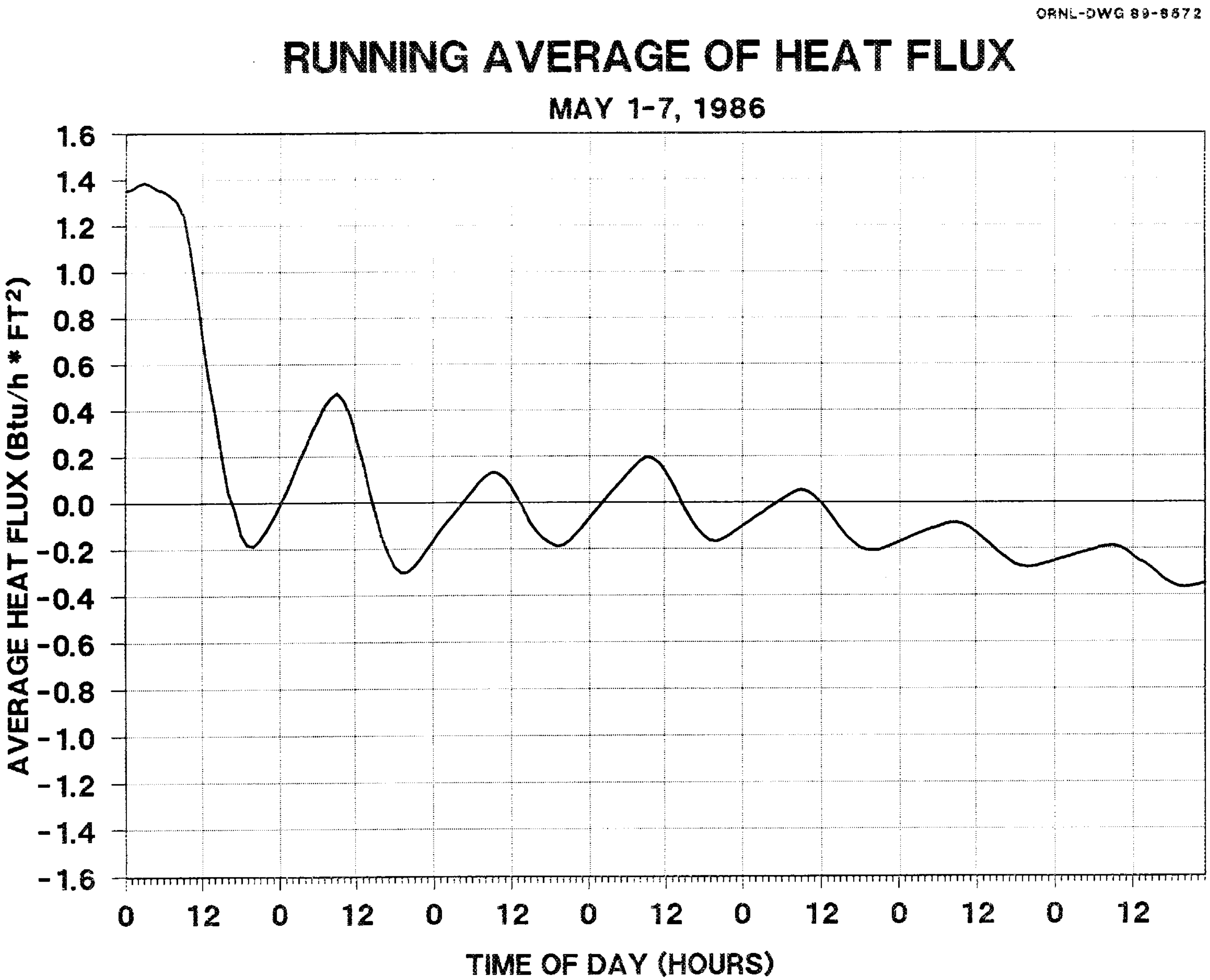

Fig. 17. This figure shows the running average of heat flx across the foam insulation for a time period when the netheat flow is near zero. Under these conditions one can expect convergence problems with Equation 9.

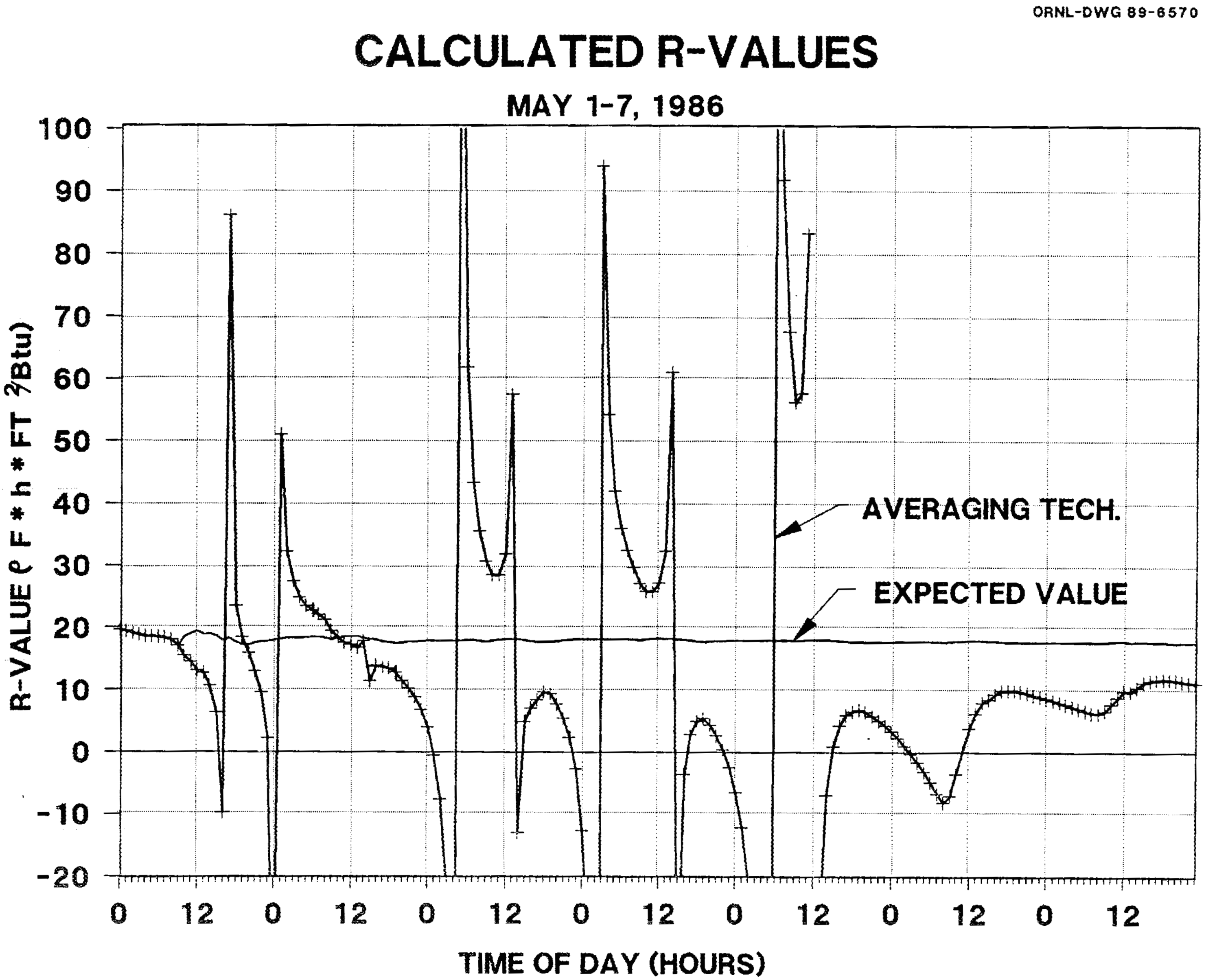

Fig. 18. A graph similar to Figure 16 but for the week indicated in Figure 17 -- Not that the averaging technique does not give a well-defined R-value for this week.

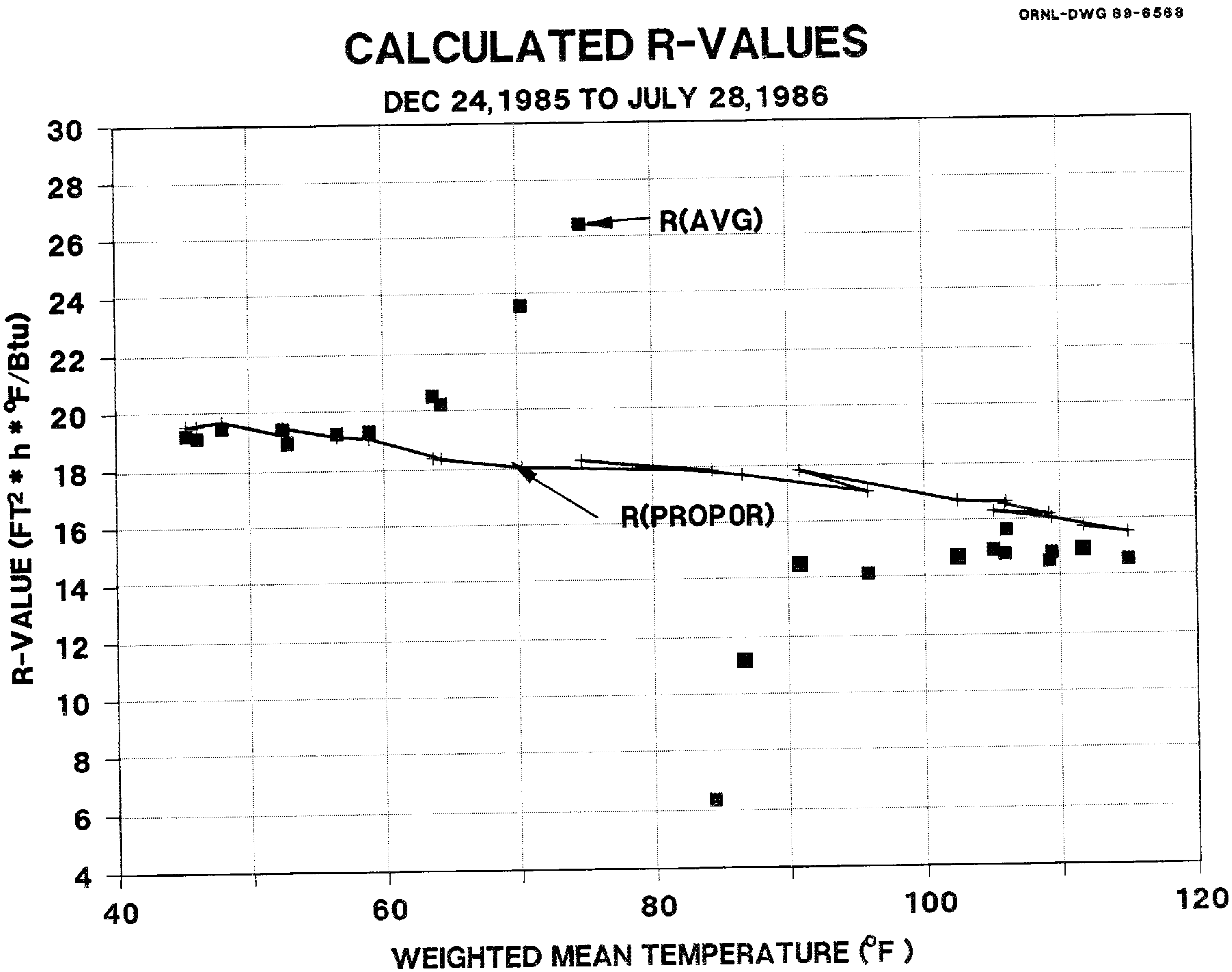

Fig. 19. This figure gives an indication of the error one might expect for R-value calculations using Equation 9 and when to expect it. The maximum uncertainty occurs when the mean temperature of the insulation is near room temperature.

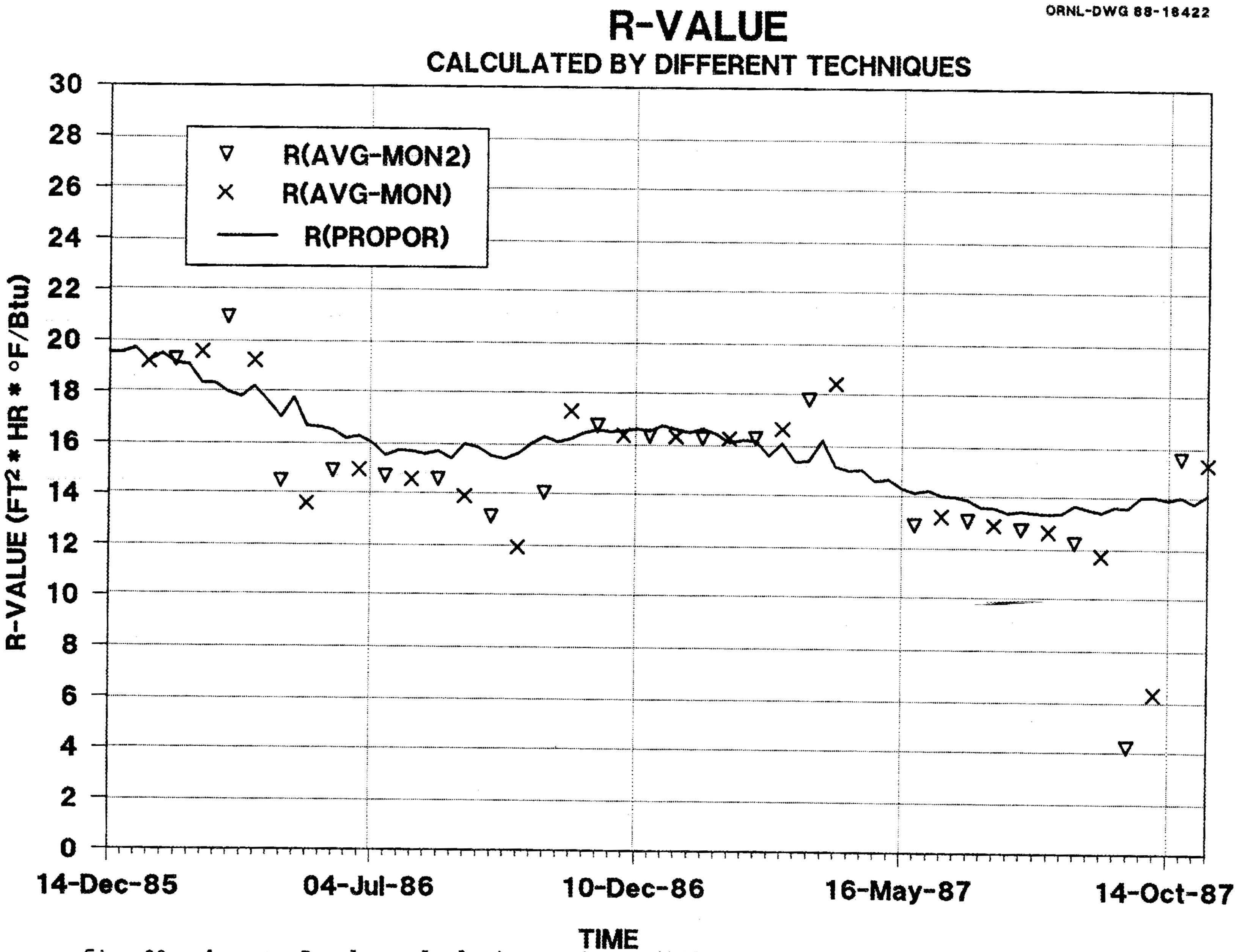

Fig. 20. Average R-value calculations using a different averaging period. The x's are R-values obtained when the average period is extended to a full month. The triangles are R-values for a full month but with a shifted averaging period. In both cases the error during transition seasons persists.

While this does help, the same general error pattern exists although the results are now more in agreement with PROPOR. This behavior can be expected when one notes that increasing the averaging time to one month simply means taking the average of four adjacent weekly values some of which vary little from PROPOR values.

It is important to note that the magnitudes of the differences described here between the Averaging Technique and PROPOR are unique to this location and the particular years of this test because the Averaging Technique yields results that are site and climate dependent.

As described in Section 6, PROPOR results will also change with changes in local temperature distributions because the thermal conductivity of materials changes with temperature. On the other hand results from the Averaging Technique depend upon the nature of local weather, e.g., the length of seasons. The uncertainty of the weather effects together with a dependency upon the measuring time period and problems in doing error analysis seems to build into the Averaging Technique the potential for considerable error. This error can probably be kept small by limiting use of the technique to weather conditions not involving significant reversal of heat flow in the building element and by requiring the convergence of the R-value to a constant value during the monitoring time.

8. SUMMARY

The primary purpose of this work was to demonstrate the capability of the RTRA to conduct long-term field tests of the thermal performance of insulated roof systems and to show that the PROPOR program is a reliable technique for analyzing field thermal performance data.

The test specimen was an experimental sample of phenolic foam insulation with a high initial R-value ($R=9\ ft^2 \cdot h \cdot F/Btu \cdot in$) and a relatively fast thermal drift (about 10 years to ultimate value). This material is not typical of commercially available phenolic foam products which are reported to have lower initial R-values and no significant thermal drift. Commercially available insulations were not tested during this project.

Calculations from field measurements using PROPOR show that the drift in thermal resistance (normalized to T=75°F) of the test specimen was 27 percent over the two-year test period. Steady state laboratory measurements at T=82°F before and after the RTRA tests indicated at 24 percent decrease in R-value. In addition, examination of Fig. 13 shows that deviations of weekly field calculations differ by less than 3 percent from an empirical curve fit. This suggests that PROPOR will provide reliable results under a wide range of environmental conditions. In particular, PROPOR is usable even during periods when the net heat flow across a roof system is small (e.g., spring and fall seasons). The more commonly used averaging technique (Eq. 9) although adequate for periods of high net heat transfer has been shown in this test to be less reliable for low net heat transfer even when the averaging period is extended to one month.

Because of fairly significant downward drift in R-value for the sample, it was not possible to provide direct information on the variation of R-value with temperatures for this sample. Eq. 7, obtained empirically from the PROPOR data, is a best-fitting linear approximation. For insulation without a thermal drift it is easier to determine the temperature dependency of the thermal resistance from field data as illustrated in Fig. 15.

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85. R. Sterling, University of Minnesota, Minneapolis, MN
86. E. Stern, BPCO, Inc., Quebec, Canada
87-91. S. Tagore, Department of Energy, Washington, DC
92. S. Tewes, University of Illinois at Urbana, Champaign, IL
93. A. Tuluca, Steven Winter Associates, Norwalk, CT
94. R. P. Tye, Thermatest Division of Holometrix, Inc., Cambridge, MA
95. C. R. Vander Linden, Vander Linden & Associates, Littleton, CO
96. M. G. VanGeem, CTL, Skokie, Illinois
97. J. P. Verhalen, United States Mineral Products Co., Stanhope, NJ
98. D. C. Wysocki, Mobay Corp., Pittsburgh, PA
99. D. W. Yarbrough, TN Tech University, Cookeville, TN
100. R. Zarr, NIST, Gaithersburg, MD
101. Office, Assistant Manager, Energy Research and Development, DOE/ORO, Oak Ridge, TN
102-111. Office of Scientific and Technical Information, U.S. Department of Energy, Oak Ridge, TN

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