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ABSTRACT

Heat Resistance Measurements with the Portable Calorimeter Box

by
Philipp G. Mohr

The heat resistance of wall section materials has been investigated under laboratory conditions, but reliable measurements in-situ with non-steady weather conditions are not yet available. The portable calorimeter box is designed to make field measurements to test the thermal performance of building envelopes. The experimental setup and the equipment for thermal measurements are described, as well as the computer program for data reduction. The characteristics of the portable calorimeter box and the problems of non-controllable test conditions have been investigated.

Forty experiments were completed. Sixteen preliminary experiments investigated problems associated with insufficient setups; such as a short duration, only partly reported data, and the influence of solar radiation. Twenty-four tests measured the heat resistance of test specimens. The problems with measurements of temperature differences smaller than 15 F between outside and inside are shown. The influence of different thermal radiation emissivity inside the portable calorimeter box and non-zero controller settings is demonstrated. It is concluded that the portable calorimeter box is a device that can measure the heat resistance of building envelope sections with an accuracy better than 10%.

Heat Resistance Measurements with the Portable Calorimeter Box

by
Philipp G. Mohr

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Master of Science**

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Heat Resistance Measurements with the Portable Calorimeter Box

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This thesis is dedicated to my brother
Oliver Mohr

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Chapter 1

INTRODUCTION

The energy consumption of buildings for heating and cooling represents an essential factor. Ever increasing energy costs require more knowledge about the technology to improve the thermal performance of the building envelope. Data of steady state heat transfer through wall sections do not reflect the actual performance of building envelopes exposed to non steady weather conditions. The influence of substandard workmanship is usually not taken into account in laboratory data bases. Measurement devices as the guarded hot box and the calibrated hot box are designed for laboratory testing and the heat flow transducer does not cover a representative area and requires an experienced user. The portable calorimeter box (PCB) is an easy to use alternative to measure the thermal performance of in-situ building envelope sections.

The PCB has been used since 1979 in various locations [11,13,...,16] but no documentation was available about the characteristics and limitations of this method. The National Bureau of Standards (NBS) conducted a series of field and laboratory tests to evaluate the accuracy of in-situ thermal resistance measurement techniques. Their tests included several wall constructions with varying thermal mass content. That allowed the present work to concentrate on the PCB itself.

A standard practise has not been established. The objective of this work was to determine the limits of the PCB.

Chapter 2 will give an overview of methods to measure the heat resistance of walls in laboratory and in-situ conditions.

Chapter 3 describes the equipment and the setup used to perform the experiments. In detail the software setup to acquire the data is explained.

Chapter 4 introduces how the experiments are done. The problems encountered and solutions are shown. The experiments done are described and the results presented.

Chapter 5 concludes the results of the experiments and points to work which could further be done.

The appendix states the calibration of the equipment, the locations of the thermocouples, an introduction to the software used, the results and data of the experiments and some literature about this field.

Chapter 2

METHODS OF MEASUREMENTS OF ONE-DIMENSIONAL HEAT TRANSFER

2.1 Measurement Methods

There are several methods to evaluate the heat resistance of walls. The 1989 *ASHRAE HANDBOOK FUNDAMENTALS* offers a theoretical method to calculate the R-values of building envelopes with known materials. The experimental methods are:

1. Guarded Hot Plate
2. Guarded Hot Box
3. Calibrated Hot Box
4. Heat Flux Transducer
5. Portable Calorimeter Box

2.2 Guarded Hot Plate Method

The guarded hot plate apparatus is a laboratory, steady-state heat flux measurement system to determine thermal transmission properties of flat-slab specimens. It consists of one hot plate and two cold plates, whereas the hot plate is in the middle and has on both sides the specimen to measure attached. On both sides outside are the cold plates. This is enclosed by insulation and guarded heating units to create unidirectional heat flux and to reduce the radial heat flow. The area is given by the plates and the temperature difference and the heat flow data will allow to calculate the heat resistance of the specimen.

2.3 Guarded Hot Box Method

The guarded hot box measures the laboratory, steady-state heat-flux of panels to determine the thermal properties of the section. The surface of the panel doesn't have to be even and flat like the requirement of the flat-slab specimen of the guarded hot plate. The materials to be measured separate two climate boxes, the guard and the cold box. Inside the guard box is a five sided metering box located with the open side attached to the panel. While a zero temperature difference is maintained between the guard and the metering box the heat supplied in the metering box flows through the test panel. The metering box determines the area and with the temperature and heat flow data the thermal resistance of the panel can be calculated.

2.4 Calibrated Hot Box Method

The calibrated hot box has, similar to the guarded hot box, a climate box and a metering box, but lacks the guard box. Due to the omitted guard box, even though a partial guard chamber may be attached, the metering box has to be calibrated to determine the heat losses. Like the guarded hot box, the calibrated hot box is designed for laboratory, steady-state tests. Dynamic test conditions are allowed but not established as a standard measurement.

2.5 Heat Flux Transducer Method

The heat flux transducer (HFT) is a flat plate, which can be flexible, incorporating a thermopile. A thermopile produces a voltage output corresponding to the temperature difference. The voltage output of the thermopile is nearly linear to the heat flux through the HFT. The size of an HFT does not allow the thermal properties of a representative area of a building section to be measured.

Thermography can help to estimate the number of HFT's necessary and where to place them to measure the average thermal resistance of an envelope section.

2.7 Portable Calorimeter Box Method

The portable calorimeter box (PCB) is a five sided metering box that has to be sealed against the material to be measured. Inside the PCB are a heater and temperature sensors. Temperature sensors are also located outside the PCB in the room and on the other side of the material, which is the cold side, are temperature sensors. A thermopile across the back indicates temperature differences between inside and the room outside the PCB, that has to be controlled to be zero to ensure a solely unidirectional heat flow through the material. The PCB is a passive method to measure the thermal properties of materials in-situ.

In this thesis the portable calorimeter box is discussed. It is the only one stated that is not an ASTM standard yet and it is the only one that can reliably measure the heat transfer through a representative building section in-situ in a simple and inexpensive way. The HFT can also be used for in-situ measurements but it requires an experienced user and is expensive so that there is no other practical field measurement method than the PCB. The field measurements are necessary to verify laboratory tests in-situ, to control the workmanship and to detect the influences of the environment. The field measurement is also ideally suited to track the aging behavior of building envelopes.

A field measurement measures an actual wall section with mainly several layers of different materials. The temperatures inside the room may change slightly but the temperatures outside will change significantly. Solar radiation will also contribute varying heat. Therefore measurements of small mass sections are ideally taken after sunset and before dawn, measurements of large mass sections have to be taken over several days. With this work the data, the behavior and the

measurement process of the portable calorimeter box are provided to develop the PCB as an ASTM standard method.

Chapter 3

THE EQUIPMENT

3.1 Data Acquisition Equipment

The portable calorimeter box was constructed at NJIT. All the other equipment was purchased and assembled and configured for the special purpose. The equipment used to perform the measurements were:

- Portable Calorimeter Box (PCB) design by Brown and Schuyler
- PC AT 386/25Mhz (Monitor, etc.), Supercom
- Data Acquisition board DT 2805/5716, Data Translation, Inc.
- Screw Terminal DT 707A-T, Data Translation, Inc.
- Screw Terminal DT 727-T (1) channel 8 - 39, Data Translation, Inc.
- Screw Terminal DT 727-T (2) channel 40 - 71, Data Translation, Inc.
- Thermocouples (TC's) T-Type, Omega Engineering, Inc.
- On-Off Controller Model 49, Love Controls Co.
- Kilowatt-hour meter with photocell, Landis & Gyr
- Power Supply (10w DC), HP
- Variac Autotransformer Type W5MT3, General Radio Company
- Labtech Notebook version 6.3.0 Software, Laboratory Technologies Co.

The purpose was to record the temperatures and heat input and to control the temperature difference between the room and inside the PCB. Recording and controlling were done independently. The temperature and energy to the heater measurements were done with the data acquisition board, screw terminals, kilowatt-hour meter, power supply, thermocouples and Notebook software, see figure 1. The control devices which maintain a nominal zero temperature

difference are the proportional on-off controller, variac and the thermopile across the back of the PCB.

3.2 Data Acquisition Setup

At the end of this section are diagrams of the configuration used to measure the heat resistance of walls. The Figure 1 shows a schematic of the equipment. Fifty-one thermocouples are connected to the screw terminals DT 727 -T (see Figure 3 and Figure 4). Each terminal has a temperature sensor for the cold junction compensation. On DT 727 -T (2) is a short circuit used for internal calibration. To distribute the temperature more evenly and more stably an aluminum sheet and insulation is added inside the box of the screw terminals DT 727 -T. The aluminum sheet is painted black for the radiation effect to increase the heat exchange. The screw terminal DT 707 A-T (see Figure 2) receives the analog signals from the DT 727 -T terminals and multiplexes them on one channel per each DT 727 -T. The DT 707 A-T monitors the state of the event counter of the kilowatt-hour meter and also has a short circuit for calibration. The signals are send to the DT 2805/5716 board. The data acquisition board DT 2805/5716 converts the analog signals from the terminals to a digital signal. The digital signals are directly transferred to the main memory of the PC for analysis and final storage in a file on the hard disk.

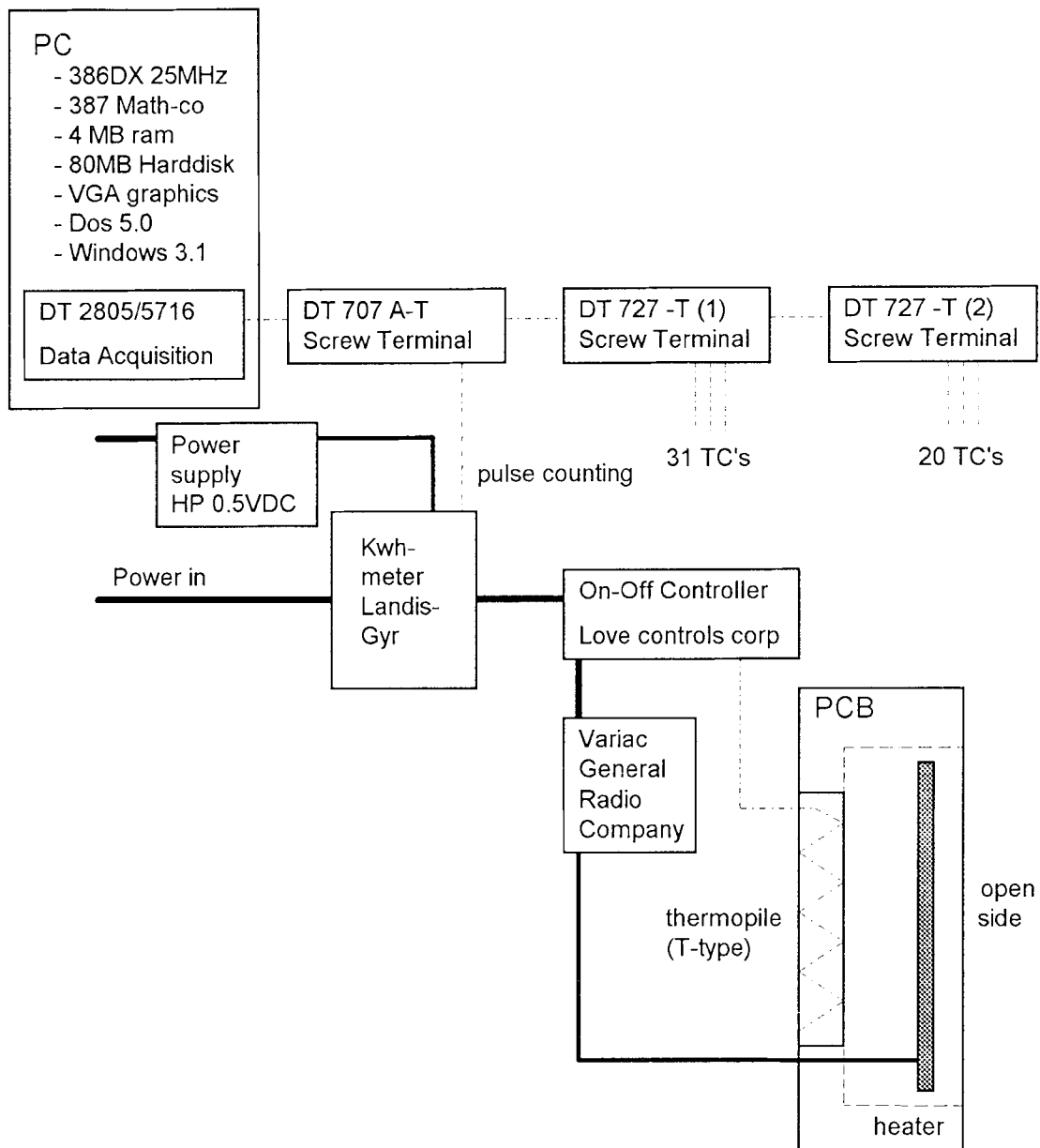


Figure 1 Data Acquisition Setup

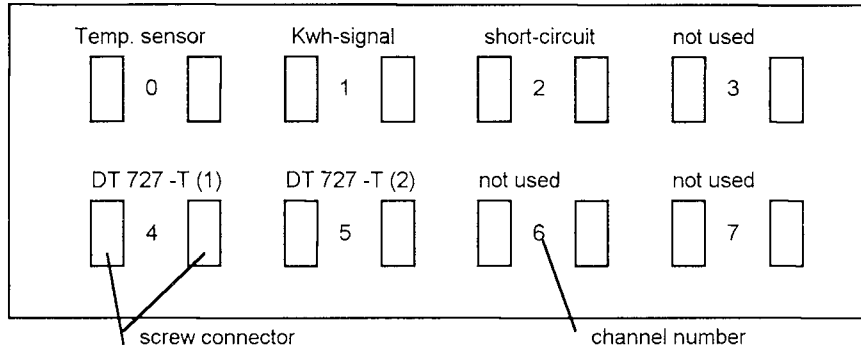


Figure 2 DT 707 A-T Screw Terminal Setup

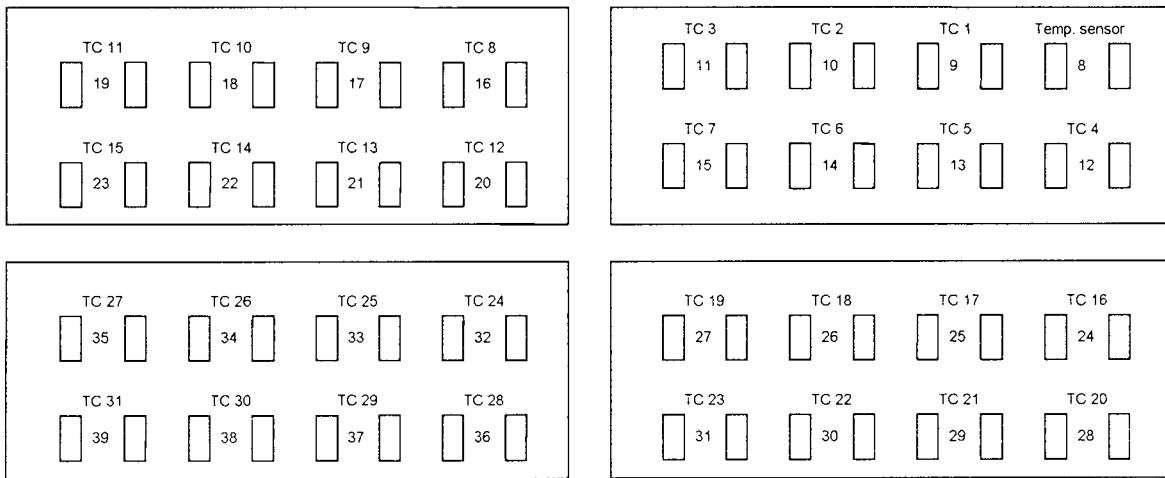


Figure 3 DT 727 -T (1) Screw Terminal Setup

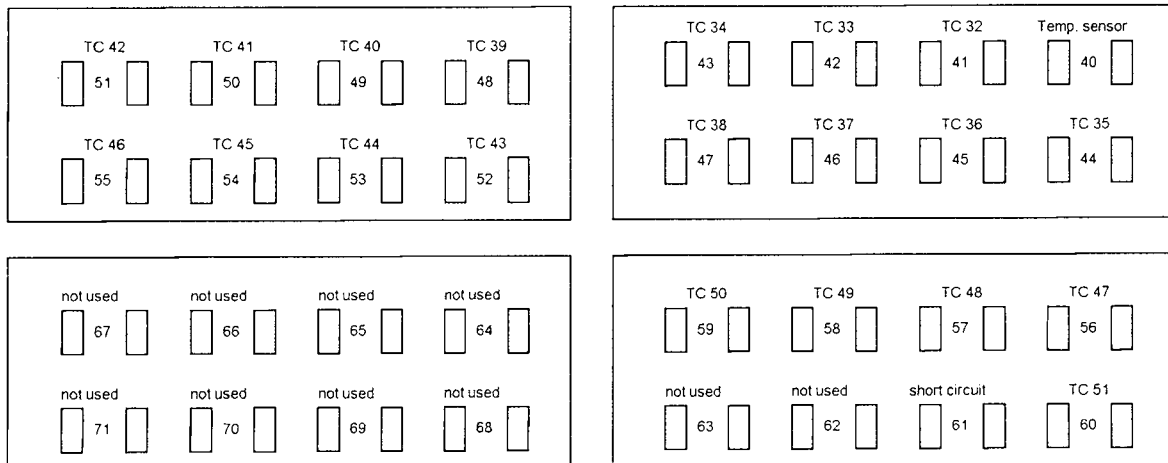


Figure 4 DT 727 -T (2) Screw Terminal Setup

3.3 The Portable Calorimeter Box

The PCB was designed by W. Brown and G. Schuyler at the Building Research Division of the National Research Council of Canada [11]. The PCB used here was constructed according to their design at NJIT, Bear Center. The size is 38"x34"x9" (height x width x depth) and the area at the open side is 35"x31", which gives an open area of 7.535 ft². The thermocouples were located in a 4x4 grid at the open side of the PCB to resolve the temperature distribution on the surface of the test specimen.

3.4 Data Acquisition board

The data acquisition board was chosen with a 16 bit resolution. The 16 bit instead 12 bit resolution increases the time needed to collect a data sample, therefore the sampling rate will be lower. A sampling rate of one per two seconds is feasible with the Notebook software. However, a sampling rate of one per ten seconds is sufficient. For long time experiments (over night or longer) one sample per ten minutes is sufficient to follow temperature changes due to weather changes. Oak Ridge National Laboratory uses one averaged sample per ten minutes in their data collection [25]. The 16 bit resolution allows a detection of $0.61\mu\text{V}$, but the system noise reduces the repeatability to $10\mu\text{V}$, which corresponds to 0.5°F for a T-type thermocouple. That is also the accuracy that can be obtained from a T-type as supplied, according to the manufacturer of the thermocouple wire.

3.5 The Screw Terminals

There are three screw terminals connected. One with eight channels, six are directly connected to the data acquisition board. The two other terminals are

multiplex thirty-two channels, each connected to one channel of the two remaining of the eight channel terminal. Thus two times thirty-two plus six channels are available. Three are connected with temperature sensors for cold junction compensation. Two more channels are needed for zero adjustment of the A/D board. Then are sixty-five channels left. Of these sixty-five channels fifty-one are used with thermocouples and one to measure the heater power.

3.6 The Thermocouples

All the thermocouples came from one coil to insure a consistency of the temperature signal. The size is AWG 24, a compromise between wire resistance, heat conductance and response time of the signal. Teflon insulation was chosen to avoid problems with moisture. Calibration of the thermocouple is discussed in the appendix.

3.7 Kilowatt-hour meter, Power Supply and Variac

The heater was connected with the power line (110V AC). A heater of nickel-iridium bare wire was installed inside the PCB. Since the electrical resistance of the wire was not changeable, a variac was connected between the heater and the controller (see Figure 1). The variac was only manually adjustable and could be set between 0 volt and 140 volts output, see appendix for the calibration. The experiments were done in the range from 25 volts to 45 volts, whereby a lower setting will result in a more stable temperature history (slower heat up), too low may not provide enough energy.

To measure the energy to the heater a modified household kilowatt-hour meter is used. A solid state relay changes its state every quarter of a circle of the turning wheel. The states are low and high resistant. To read this change of state a power supply has to be connected. From the kilowatt-hour meter are three cables

coming out (black, red, yellow). One half volt DC power was supplied between the black (+) and the yellow (-) cables. The signal was measured between the red (+) and the yellow (-) cable. To reduce oscillating of the signal a capacitor C1 (104 pF) was connected between the red and the yellow cable and ground, from the power supply, was connected with the yellow cable with a resistor R1 (10 Mohm) and with the red cable with a capacitor C2 (33 pF). The power supply was set to 0.5 VDC.

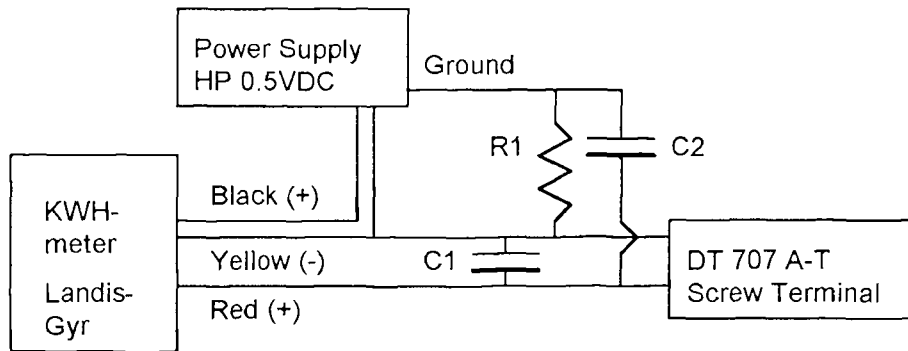


Figure 5 Power Measurement Wiring

3.8 The Controller

The heat which is required to maintain the temperature inside the PCB changes with the temperature difference between the PCB and the outdoor environment. To control the PCB temperature close to the room temperature, an on-off controller is used, that switches a heater inside the PCB on and off. The voltage of the heater has to be set manually at the variac and cannot be adjusted with the controller. The feedback signal is provided by a thermopile, consisting of sixteen thermocouples, across the back of the PCB. The thermopile is of T-type (copper-constantan, that gives a 0.02 mV signal per Fahrenheit temperature difference per thermocouple) and has therefore a 0.32 mV signal per Fahrenheit temperature difference.

The controller is a time proportional type. It does not switch on if the feedback signal passes the setpoint and turns off if the feedback signal drops below the setpoint. The setpoint is the process value that has to be reached and maintained and the offset is the difference between the setpoint and the actual value of the process. Here the setpoint has to be zero to have a zero temperature difference between the room and inside the PCB. If there is a temperature difference, indicated by the thermopile, then this difference is the offset. The offset can be stated in Fahrenheit or millivolt as the thermopile signal. The full scale range is range in which the controller can pursue its task and the bandwidth is the range around the setpoint where the controller reacts proportionally. The bandwidth is of 2% of the full scale range (10 mV) the controller can adjust, which is 0.2 mV and represents according to the thermopile 0.63 F. If the feedback signal (offset) is 0.1 mV below the setpoint, the controller is on 100% of the time and if the feedback signal is 0.1 mV above the setpoint, the controller is off all the time. A feedback signal within the bandwidth causes a linear proportional ratio of on time to off time. At the setpoint the on time to off time ratio is 1:1, the heater is 50% of the time on and 50% off.

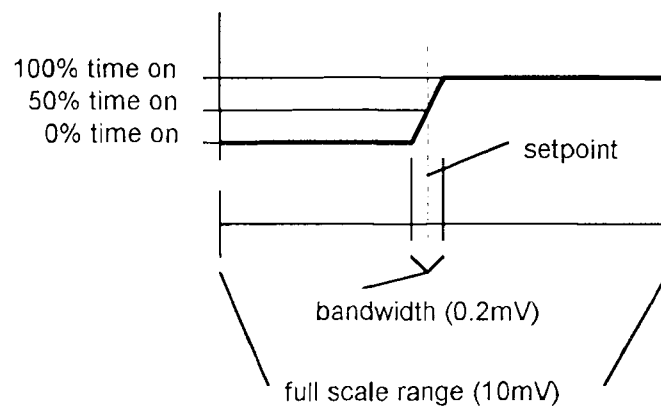


Figure 6 Controller

The disadvantage of the time proportional controller is that an offset from the setpoint can result, which happens when the heater setting gives not exactly 2

times the energy required (50% on time at setpoint). But since the bandwidth is about 0.63 F and the offset will not exceed half of the bandwidth which is 0.3 F (if the heater can provide enough energy). The advantage is a more stable heat transfer (shorter on-off circle) and no overshoot of the setpoint, the setpoint will be slower approached.

3.9 Software Setup

Blocks are used for the data acquisition. Each block contains a menu about the specifications the block will perform. A block can perform one task and has its own individual setup which can be changed within the menu. While running an experiment all blocks get processed in sequence, when the task of one block is finished, the next will start. This allows the acquisition of the data with one block while a block later in the sequence still holds the former value and performs calculations with both values. It also implies that a calculation with data can only be done when they have been acquired in blocks preceding the block that is performing the calculation. As an example is the setup shown to measure the temperature with thermocouple TC 1. Device 1 is DT 707 A-T and device 2 refers to both DT 727 -T (1) and DT 727 -T (2).

Block 2 analog signal in from channel 8, device 2 - measures the voltage of channel 8 on DT 727 -T (1) where the temperature sensor for the cold junction compensation is connected. The scale factor is 3635.0 and the offset is $8.99 \cdot 10^{-3}$ to convert the voltage to Fahrenheit temperature as calibrated.

- Block 4 analog in from channel 2, device 1 - measures the voltage of channel 2 on DT 707 A-T where the connectors are shorted. The short circuit should give a zero voltage reading. If not, such a value has to be subtracted from the measurements to cancel the bias of the data acquisition board.. Scale factor is one and offset is zero to leave the measured value unchanged.
- Block 5 analog in from channel 61, device 2 - measures the voltage of channel 61 on DT 727 -T (2) where the connectors are shorted. Scale factor is one and offset is zero to leave the measured value unchanged.
- Block 6 blocks 4 plus 5 in -adds blocks 4 and 5. Scale factor is 0.5 to calculate the average. Offset is zero.
- Block 7 block 6 in, moving average of last 5 - takes the last five values acquired by block 6 and computes the average. This is now an average of two channels with short circuits and their last five measurements to provide an offset value. The averaging is to reduce the influence of the system noise. Scale factor is one and offset is zero to leave the value unchanged.
- Block 9 unit conversion of block 2 - converts the value of block 2 from Fahrenheit temperature to mV signal with linear interpolation of the given table. The table has to have the filename as the block name with the extension ".lcl", here it was "Fto_mV.lcl". The block type is calibration E, where E stands for a table with equally spaced values. It starts with 0 F and 5 F increment. The corresponding values are voltages of T-type thermocouples. Scale factor is one and offset is zero to leave the value unchanged.

Block 11 analog in from channel 9, device 2 - measures the voltage of channel 9 on DT 727 -T (1) where TC 1 is connected. Scale factor is one and offset is zero to leave the measured value unchanged.

Block 62 block 11 minus block 7 in - subtracts the value of block 7 from block 11. The result is the value of block 62. Scale factor is one and offset is 1.8×10^{-7} to adjust the value for the data acquisition board characteristics of . The offset was calibrated before with a short circuit of channel 9.

Block 113 blocks 62 plus 9 in - adds block 62 and block 9. The result is the voltage of a thermocouple with ice-point reference. Scale factor is one and offset is zero to leave the value unchanged.

Block 171 unit conversion of block 113 - converts the voltage result from block 113 to temperature. The block is of calibration type. The voltages are not equally spaced. So here the table needs data pairs of voltage and temperature between it is interpolating. The table has to have the filename as the block name with the extension ".clb", here it was "mV_toF.clb". Scale factor is one and offset is -0.140 as calibrated.

The temperature value of a thermocouple gets influenced by 10 blocks of acquiring, calculating and converting data. Finally block 171 gives a temperature value.

To measure the power supplied a different method is used. During one turn of the wheel from the kilowatt-hour meter, the state of the relay changes four times (two pulses).

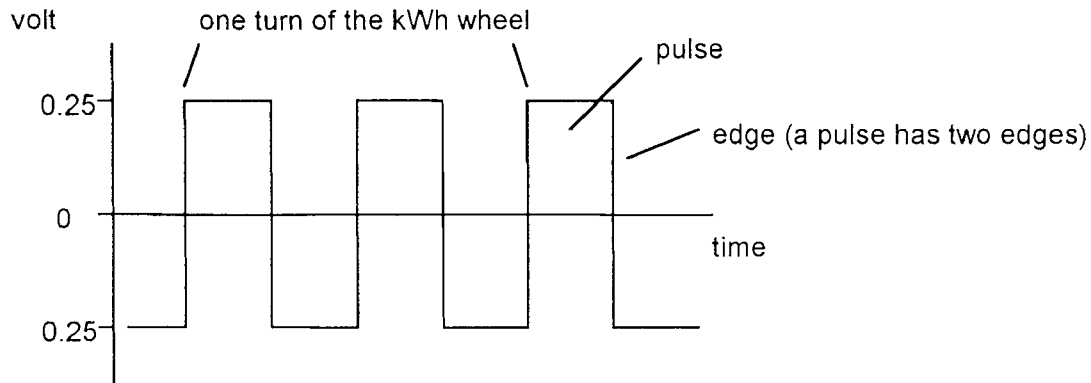


Figure 7 Kilowatt-hour meter Signal

Instead of counting the pulses, that gives two signals per turn, counting the change of the state or an edge count gives four signals. A smaller fraction of energy can be resolved. The incoming signals are 0 volt and 0.5 volt. To distinguish better 0.25 was subtracted (offset from the analog input block is set to -0.25), now we have -0.25 and 0.25 as incoming values for the next block (with the software cannot units be handled only values). The values can change with the system noise and are actually not important but the change of the value. To strip off the unnecessary information the sign of the value is taken. The sign is zero if the value is zero or below zero and one if the value is above zero. During one turn of the wheel the sign is twice zero and twice one. Differentiation with the software gives the difference between the new value and the former value, that means if the sign changes from zero to one the result is one and from one to zero the result is minus one. With the absolute value taken we get a one when the sign changes in any direction. Every quarter of a turn we get a single one signal. To convert this to an engineering signal the scale was set to 0.033962 [Btu/ft²] (see calibration of heater) and offset to zero. For experiments lasting one or more nights the sample period was ten minutes for the temperatures, but to get the energy signal the sampling period has to be 0.5 seconds to distinguish a change of state even at high energy consumption. To connect both signals, the temperature and the energy, the

energy signal was integrated. Each quarter of a turn another signal was accumulated. Here the differentiation will not lead to a proper result, the energy consumption in a ten minute period is needed. The following setup was done with a ten minute sampling period. Since the software does process the blocks in sequence (from the first to the last block) the value of the accumulation will be assigned to a block with a high number. On a block with a lower number will the difference between the integrated value and the higher number be taken. This is the energy consumption between the sampling. A time block counts the time elapsed since the last sampling. The energy consumption gets divided by the time elapsed, that gives the energy or heat flow.

Block 164 analog in from channel 3, device 1 - measures the voltage of channel 3 on DT 707 A-T where the kilowatt-hour meter is connected . Scale factor is one and offset is -0.25 to have a clear value.

Block 165 sign of block 164 - to get a one if block 164 is above zero, otherwise zero. Scale factor is 1.0. Offset is zero.

Block 166 differential of block 165 - last value minus former value. To get a non zero value when block 165 changes. Scale factor is one and offset is zero to leave the value unchanged.

Block 167 absolute of block 166 - each change gives now a positive value. Scale factor is 0.033962 and offset is zero to get the engineering unit of Btu/ft².

Block 168 integral of block 167 - accumulate the number of energy units. Scale factor is one and offset is zero to leave the value unchanged.

Block 170 time elapsed - time elapsed since last sample.

Block 225 block 168 minus block 226 - subtracts the value from block 226 from block 168. Scale factor is 0.815 to account for the calibrated energy consumption of the heater, the variac set to 35 volts, and offset is zero.

Block 226 in block 168 - assigns the value of block 168 to block 226.

Note that this happens after the calculation of the difference between block 168 and this block. This is similar to the option like block 166.

Here we have differently sampling rates, blocks 164 until block 168 are sampled every 0.5 second and blocks 225 and 226 are sampled every 10 minutes, so the same option can not be used to get the difference between the last samples due to the different sampling rates. Scale factor is one and offset is zero to leave the value unchanged.

Block 227 block 225 divided by block 170 - calculates the heat flow. The amount of energy accumulated between the last samples divided by the time elapsed. Scale factor is one and offset is zero to leave the value unchanged.

The result of block 227 is the averaged heat flow between the last samples acquired. The signal from the kilowatt-hour had to be observed closely two times a second to encounter every change of the signal. Yet the number of signals in a longer time distance, ten minutes, is of interest and could be gained.

Chapter 4

THE EXPERIMENTS

4.1 Introduction

The experiments were done to determine the accuracy of finding wall section R-values measured with the Portable Calorimeter Box (PCB). The principle was to measure the temperature difference on both sides of the test specimen and the heat required to maintain a zero temperature difference between inside the PCB and the room. The heat flow area was determined by the geometry of the PCB. Thus the equation $R=A \cdot \Delta T/Q$ can be applied. The measuring method is passive, the temperatures of each side of the test specimen are not controlled, but exposed to outside and room conditions. The room temperature is controlled by an air-conditioner. And the temperature inside the PCB is controlled to the room temperature to ensure no heat transfer between the room and the PCB, therefore all heat supplied passes through the test specimen.

4.2 Test Location: Advantages and Disadvantages

A window was chosen as test section to control the conditions and locations of the thermocouples so that the test specimen would be uniform layers of materials with well known thermal properties in series and also for easy of changing specimen. The surface of the window is even that ensures a straight full body contact with the test specimen which themselves are even. The window allows an easy access to the frame of the grid and to the thermocouples. Due to the radiation through the window pane the R-value of the window cannot be calculated with this method, because the window is translucent to the thermal radiation but opaque to the infrared radiation by the material behind the window (greenhouse effect). During the day time in the afternoon the solar radiation heats the material behind the

window. That creates a heat source that cannot be measured. The window was facing the western side and at 6:00 p.m. the sun was in front of it. Between the window and the next material occasionally temperatures were measured 40 F higher than outside and in the room during the daytime of the summer experiments. Materials that do not have the same behavior can be measured. The solar radiation will be absorbed by any material but an opaque material will absorb the radiation at the surface and there the temperature has to be measured. Only then can the R-value of the section be measured. The effect that the solar radiation will decrease the temperature difference between inside and outside still remains a problem because the accuracy decreases with the temperature difference (see experiment 24). Nevertheless the 4x4 grid outside touching the window was used to show that the temperature distribution outside is even enough ($T_{\text{top}} - T_{\text{bottom}} < 1 \text{ F}$) to allow to measure with one thermocouple during the measurements.

4.3 Test Specimen Setup and Location of Thermocouples

Forty tests were made. The first sixteen tests were done to evaluate the characteristics of the PCB and to determine the necessary setup. Temperature recording during all tests included sixteen thermocouples outside at the window surface in a 4x4 grid and sixteen thermocouples inside the PCB at the test specimen surface also in a 4x4 grid. For in-situ measurements these are the main necessary locations. The distribution of the thermocouples was to determine the possibility and location of one representative thermocouple. The ASTM C236-90 [9] requires a minimum number of thermocouples of $N = A / (0.07 + 0.08 \cdot \sqrt{A})$ where A is the metering area in m^2 , here $A = 1 \text{ m}^2$ and N is then 7 which is exceeded. For the experiments 23 to 33 two layers of materials and the window were used. The layers of a test specimen are: the double glass window, then two layers of 1/2 inch

gypsum board and a one inch board of standard glass fiber insulation. The gypsum board was used to introduce the mass effect and the standardized insulation is a material with a known R-value. Three thermocouples were fixed vertically between the window and the adjacent gypsum board to measure any vertical temperature gradient. Four thermocouples were located between the gypsum board and the insulation, one in each quadrant.

4.4 Additional Recorded Temperatures

Additionally the room temperature, the outside temperature and the air temperature inside the PCB were recorded. These temperatures were measured each with four thermocouples, one in each quadrant. The outside temperature was recorded approximately four inches apart from the surface and the room temperature was measured four inches from the back surface of the PCB. The air temperature in the PCB was measured in the plane where the heater is located. Sketches of the location of the thermocouples are in appendix B, see figures 8 to 15.

4.5 The Test Specimen Materials

Window : double glass 1/4 in. air space $R=1.75 \text{ Fft}^2\text{hr/Btu}$.
 Insulation no.1 : glass fiber, bonded (11.19 lb/ft³) 1 in. $R=4.0 \text{ Fft}^2\text{hr/Btu}$.
 Insulation no.12 : glass fiber, bonded (11.17 lb/ft³) 1 in. $R=4.0 \text{ Fft}^2\text{hr/Btu}$.
 Gypsum board : (45 lb/ft³) 0.5 in. $R=0.45 \text{ Fft}^2\text{hr/Btu}$.

R-values from 1989 *ASHRAE HANDBOOK FUNDAMENTALS*.

4.6 Information Gathering

The results of the experiments show that the set of information gathered is important. The temperatures at the boundaries of the test specimen and the heat consumption are necessary. It is convenient to let the software, that controls the measurements, calculate the R-value. The procedure takes several steps to get

useful data. The temperature differences of the boundaries of the test specimen and the heat signals have to be integrated over the test period but data points when the heat signal is zero have to be blanked out. The R-values are integrated for averaging. The reason to blank out the accumulation of temperature difference when the heat is zero is that there is no cooler inside the PCB so the cooling load can not be measured. Accumulating only temperature difference without the corresponding heat will introduce a bias. During the measurement over a summer day when the temperatures outside are higher than the room temperature the heat will be off and the accumulated temperature differences will be negative and the resulting R-value would be a summation of negative temperature differences divided by zero. The blanking out can be done with a multiplication of the temperature difference by $\text{sign}(\text{heat signal})$, ($\text{sign}(\text{heat signal})$ equals one if heat signal is larger than zero and zero if heat signal is zero or smaller). The ratio of the integrated values, integrated temperature difference divided by the integrated heat consumption, is the averaged R-value.

$$\bar{R} = \frac{A \cdot \int_0^t \Delta T \cdot \text{sign}(Q) dt'}{\int_0^t Q dt'} \quad (1)$$

The integration time t should cover at least one night to include a falling and rising temperature period to get a good average. The mass effect of the test was small so that a duration of one night from sunset to dawn was sufficient. Measurements of wall sections with a large mass will require several night duration as shown by R. A. Grot et al. [14].

That the cooling load cannot be measured and the fact that the temperature difference between inside and outside should be 15 F or larger during the tests

questions the use of the PCB during the summer. However with the blanking out can measurements during the summer be made to get an estimate.

4.7 Data Analysis Options

For the field measurement the result from the measuring software is sufficient. To evaluate the behavior of the test method calculations are easier and can include more information when done with a spreadsheet. The use of the spreadsheet Excel 4.0 is detailed in appendix C. To do the calculations of the temperature differences and averages of the R-values the required information are the temperatures and the heat consumption. The squared average and the reporting temperature can easily be calculated. The averages can be calculated over different time intervals and do not have to last from start to end of the test even though these calculations are not necessary for the field measurements. Measurements of small mass sections and a high temperature difference ($\Delta T > 30$ F) will yield a good instant R-value (see test 39 in appendix) but with smaller temperature differences and mass effect an accurate instant R-value cannot be found (see test 12 second night).

4.8 Mass Effect

When heat from the heater flows only to the outside direction and not lateral, it is proportional to the temperature gradient at the surface of the test specimen, which is not always the same as the temperature gradient over the whole test specimen that can be measured. This is caused by the mass effect. The propagation of the temperature gradient is not instant and heat is stored in materials. The mass effect of the test specimen and the PCB can to be encountered with averaging. The mass effect of the PCB can effect the measurement only when the room temperature is varying. The larger the temperatures change and the larger the mass of the test specimen the longer the time averaged has to be. If the test specimens are removed

between the tests then they have to be placed before the measurements starts to reach a new temperature distribution. The first sixteen tests were done during the summer period from June/24 until July/14. At that time the setup of the equipment was ready and the behavior of the measurement system had to be determined. The temperatures outside reached or exceeded the room temperatures during the day time. When this happens and the mass effect of the test specimen is large then the temperature difference can be negative and the heat signals still be larger than zero until the temperature gradient in the surface of the test specimen will become negative. The duration of the test has then to include at least one period that the temperature difference is larger than zero. During the night when the temperature outside is below the room temperature the heat signal will become larger than zero when the temperature gradient in the surface turns positive and the temperature difference will already be larger than zero. The mass effect apparently causes a time delay of the heat required.

4.9 Temperature Measurement Frequency

A heat unit at the experiments was $0.34 \text{ Btu}/(\text{hrft}^2)$, see appendix on heater calibration, which corresponds to a quarter turn of the indicator of the kilowatt-hour meter. The time interval between the measurements has to be long enough to collect at least one heat unit per interval. If the time interval is too long the temperature measurements may not be able follow the temperature history if the temperature is varying too much between the measurements. As an example the temperature may rise just after a measurement and drop shortly before the next, due to sunshine and a cold breeze respectively. The controller will adjust the heat required but the measured temperature can not resolve this event. A good compromise is a ten minute interval which was used during the later of the sixteen

experiments and beyond. Oak Ridge National Laboratory uses one averaged sample per ten minutes in their data collection [25].

4.10 Reported Data

All R-values are reported as the cumulative value at 7:00 a.m. from the beginning of the test to cover the night measurements and to avoid the effect of the rising sun and to allow to compare the results. The time 7:00 a.m. was chosen because during the summer experiments the air-conditioner was switched on at 7:00 a.m. and cooled the room so that the controller stopped the heat supply to keep the inside PCB temperature close to the room temperature. Temperature distributions of different locations of the PCB reported represent a characteristic value averaged from 1:00 a.m. until 6:00 a.m. because the outside temperatures varied only slightly ($\Delta T < 1.2$ F) during this time of the compared tests. The temperature differences between outside and the room are averaged during the night from the start of the test until 7:00 a.m. in the morning.

4.11 Preliminary Experiments 1-16

The first sixteen tests were done to get to know the process of testing materials. Because of the limited use to characterize the PCB the results are mentioned only briefly, but the tests contain information about how not to perform a test. The results of these tests can not give valuable information about the materials tested and so the materials are not mentioned here but are included in the data appendix. The problems were the measurement frequency, the data collected, the values recorded and the duration of the tests. During the preliminary tests the temperatures only across the whole test specimen including the window were measured, but not intermediate temperatures between the layers. The solar radiation was trapped between the window and the test specimen and heated this section up which could not directly be detected, but the results showed an

increasing R-value after the sun rose in the morning. In the evening, due to the mass effect, the heat consumption partly remained zero until late night even though the temperature difference between the surface of the test specimen inside the PCB and the window surface outside was positive for several hours (up to 5 hours 45 minutes see tests 8,10, and 12 in the appendix).

Tests 1 to 5 were of four hours duration and were done in three stages to evaluate the necessary measurement frequency. The three stage measurement were important to determine the validity of the recorded data, whether one sample every 10 or 15 minutes can provide the necessary information or not. First the sample rate was one measurement every 15 minutes for one hour, the second stage was one measurement every 15 seconds for a period of 15 minutes and third again one measurement every 15 minutes for the remaining 2 hours and 45 minutes. During the second stage of the tests when the temperatures were recorded every 15 seconds the temperature data did not change significantly, therefore a 15 minutes data collection period will be able to provide a reliable temperature history. To evaluate the R-value the second stage did not contribute further information. The heat and the temperature data can be averaged and used as a single data point. From test four on the data recorded included additional the heat measured instead of only the temperatures and the cumulative R-value, to enable to do further calculations with the data.

Test six lasted for ten hours and was the last test that measured in three stages. The first and the second stayed the same and the third stage lasted eight hours and forty-five minutes. The previous tests lasted only four hours and left the question what did happen after the test. Test six showed that the air-conditioner was switched on at 7:00 a.m. which cools the room temperature and that, also due to the mass of the PCB, let the controller halt the heat supply (see chart in the appendix).

The tests 7, 8 and 9 had the same setup except the voltage setting of the variac. At test 7 the setting was 35 volts and at tests 8 and 9 it was 20 volts. The tests started at 11:00 p.m. and lasted for eleven hours until 10:00 a.m. These tests were done at the end of June and beginning of July and the heat gain in the afternoon got stored in the materials so that the controller switched the heater on between 2:30 and 2:45 a.m. at test 8. The cumulative integration of the temperature difference and the heat started at the beginning of the test. While the heat was zero the temperature difference was accumulated and that resulted in calculated R-values as high as 900 Fft²hr/Btu. The instant R- value of test 8 was all the time smaller than the cumulative R- value (see appendix). That led to the conclusion that the temperature differences have to be blanked out when the heat is zero. This can be done with multiplying the temperature difference with sign(heat). From test 10 on the temperature difference was multiplied with sign(heat). Nevertheless, since the instant temperature differences and the heat were recorded the cumulative and instant R-values can be calculated with spreadsheets.

Test 10 was designed to get a test with a test duration longer than 24 hours to evaluate the characteristics during the daytime as well. In the tests before the heater started occasionally after midnight. On July/3 the heater was on already at 6:00 p.m. because of the cool day temperature. July/4 was a warm day so the heater was switched on by the controller between 1:30 and 1:45 a.m. in the morning of the next day. The outside air temperature was between 85°F and 90°F in the late afternoon between 3:00 p.m. and 7:00 p.m. and the temperatures on the outside surface of the window was between 90°F and 100°F during the same time period depending on the sun shine (see appendix). The window was facing the western side and at 6:00 p.m. the sun was in front of it. After 7:30 p.m. a building was covering the sun. The temperature inside the PCB rose up to 108°F which was

the highest temperature measured. The temperature between the window and the next layer was not measured. This led to the decision to measure the temperature between the layers, which was done at test 12.

The mass effect of the PCB can be seen at test 11. The air-conditioner was switched on between 7:15 and 7:30 a.m. and the heat was reduced immediately even though the temperature difference was still about 15 F. Nevertheless, the temperature between the layers was not recorded to make a more profound interpretation.

During test 12 the temperatures between all layers were recorded and the test lasted 64 hours. The temperatures at the interface of the window and the next layer exceeded 160°F on the second day, which shows the greenhouse effect because the temperature of the window surface did not exceed 105°F and the room temperature was below 85°F at that time (see appendix).

Tests 13 to 16 were done to evaluate the R-value of the window alone. The results were $R_{13}=1.4 \text{ Fft}^2\text{hr/Btu}$, $R_{14}=1.4 \text{ Fft}^2\text{hr/Btu}$, $R_{15}=1.5 \text{ Fft}^2\text{hr/Btu}$ and $R_{16}=1.3 \text{ Fft}^2\text{hr/Btu}$. But there are some flaws with these tests. At Test 13 the voltage of the heater was too low and the temperature inside the PCB was below the room temperature even though the heater was on all the time between 1:00 and 6:30 a.m.

4.12 Experiments 17-20

4.12.1 Measurements with Small Temperature Difference

The preliminary tests showed that the R-value of the window can not be measured and the temperatures between the layers have to be recorded. From test 17 on the necessary requirements to measure the R-value are fulfilled. Tests 17 to 20 were to measure the R-value solely of the insulation. For these tests the setup included the window and insulation no. 1 and were done in consecutive days from July/15 to

July/17. The temperature difference between outside and the room was between 11 F and 15 F, except test 17 on July/15 where it was about 19 F. The R-value of insulation no. 1 is about 4.0 Fft²hr/Btu according to [1]. The result from test 17 was a R=4.3 Fft²hr/Btu, which is about 7% too high. The other results are R₁₈=4.7 Fft²hr/Btu, R₁₉=3.8 Fft²hr/Btu and R₂₀=4.5 Fft²hr/Btu. Due to the low temperature difference the results R₁₈, R₁₉ and R₂₀ are not representative. The low R₁₉ value is due to the relative higher temperatures inside the PCB to the room temperature. The results show that measurements with low temperature differences, smaller than 15 F, can not find a reliable R-value.

4.12.2 Temperature Distribution at Surfaces

The temperature distribution at the surfaces: outside at the window, between the window and the insulation, at the surface of the insulation inside the PCB and the air inside the PCB are shown for test 17. The distribution outside of the window surface is within 1 F, the average temperature at the top was 68.3°F and at the bottom 67.8°F, the highest 68.5°F and the lowest 67.6°F respectively. Between the window and the insulation was the temperature distribution within 2 F. At the top the average temperature was 73.1°F and at the bottom 72.0°F, the highest was 73.4°F and the lowest 71.5°F respectively. Inside the PCB the temperature distribution of the surface of the test specimen was within 5 F. The average temperature at the top was 91.0°F and at the bottom 86.8°F, the highest 91.2°F and the lowest 86.5°F respectively. The distribution outside and between the window and the insulation was in a good range (1 F).

4.13 Experiments 21-22

4.13.1 The Gypsum Board Measurements

Both tests were designed to measure the R-value of the gypsum board. The test setup included the window insulation no. 1 and 0.5 in gypsum board and the tests were done on July/22 and July/23. Between all layers the temperatures were recorded. The temperature difference between outside window surface and inside the PCB gypsum board surface was about 13 F during test 21 and 21 F during test 22. The temperature difference of test 21 was too low to get a representative result. The measured value of $R=0.93 \text{ Fft}^2\text{hr/Btu}$ was twice the R-value $0.45 \text{ Fft}^2\text{hr/Btu}$ shown in [1]. Test 22 gave the result $R=0.87 \text{ Fft}^2\text{hr/Btu}$ which is also about twice as high as in [1].

4.14 Experiments 23-28

4.14.1 Test Behavior

The PCB was still furnished with aluminum foil during these tests and the setup was the same for all. Outside the window, then 2 layers of 0.5 inch gypsum board and inside insulation no. 1. The temperatures were recorded between all layers. The tests 23 to 27 were done in the time from July/24 until August/4 and test 28 was done on September/25. See table 1 for results of R-values and temperature differences. Test 24 lasted two nights and tests 26 and 28 three nights. During test 24 for the first time the heat flow was non zero for more than thirty-four hours and that with a temperature of about 140°F and falling at the start of the test at 7:00 p.m. This marks the trace of the calculated R-value (see test 24 in appendix). In the first night the R-value started with a high of $16.9 \text{ Fft}^2\text{hr/Btu}$ and decreased within 50 minutes to $3.9 \text{ Fft}^2\text{hr/Btu}$. The R-value of the insulation no. 1 remained around $4.2 \text{ Fft}^2\text{hr/Btu}$ during the night and decreased in the morning to a low of

0.96 Fft²hr/Btu at 1:10 a.m. Due to the time delay of the mass effect the R-value calculated was too high as long as the temperature difference increased. The temperature difference decreased in the morning hours around 7:00 a.m., to this time the sun rose and that leads to a heat source (diffuse sky radiation) between the window and the gypsum board and questions the reliability of the calculations. That is also the argument why the cumulative R-value at 7:00 a.m. is given as the test result. During the second night the R-value remained stable around 3.9 Fft²hr/Btu from 7:00 p.m. until 6:00 a.m.

4.15 Experiments 29-33

4.15.1 The Radiation Effect

The inside of the PCB was initially furnished with reflective aluminum foil. Before the 29. test the inside surface was black painted. No other changes were made, the test specimen were the window, one inch gypsum board and insulation no. 1. The controller setting $X_0=0.0$ remained the same. The temperature inside the PCB was controlled in a way that the room temperature was below the surface temperature of the test specimen during test 29. With the black painted PCB surface inside the PCB the radiation heat transfer caused the averages of the surface temperatures inside the PCB to be within 0.5 F. For the original reflective surfaces the PCB, the surface temperature of the test specimen was lower 1 F to 2 F than the PCB. With a temperature difference of 10 F between the outside surface and the surface of the test specimen the measured R-value is not valid.

4.15.2 The Controller Setting Part 1

The fact of test 29 that the room temperature was slightly lower than the temperature of the surface of the test specimen led to change the controller settings from $X_0=0.0$ to $X_0=-0.30$ at test 30 (see appendix). The objective was to find the

controller setting that will have the same effect as the reflective surface with $X_0=0.0$. That is that the room temperature is close to the air temperature inside the PCB. At test 30 the room temperature was in between the air temperature inside the PCB and the temperature of the surface of the test specimen. For test 31 the controller setting was changed to $X_0=-0.50$ and the room temperature was still between the air temperature inside the PCB and the surface of the test specimen. With the controller setting of $X_0=-0.60$ the room temperature during test 32 was higher than the air temperature inside the PCB. Test 33 with $X_0=-0.55$ measured a room temperature close to the air temperature inside the PCB. The R-value measured from test 32 was $R_{32}=4.7 \text{ Fft}^2\text{hr/Btu}$ and test 33 was $R_{33}=4.6 \text{ Fft}^2\text{hr/Btu}$. That result led to the conclusion that the controller setting has to be higher. The tests 36 and 37 were done to confirm the result.

4.16 Experiments 34-40

4.16.1 Temperature Distribution at Surfaces

During Test 34 the controller setting was set to $X_0=0.0$. The test specimen was the window and insulation no. 1 the same as test 17 when the temperature distribution of the surfaces was shown, see paragraph 4.12.2 page 31. The temperature difference between the outside surface and the test specimen surface inside the PCB was 19 F at test 17 and 28.5 F at test 34. While during test 17 the PCB had a reflective aluminum surface inside the PCB it was black painted during test 34.

The temperature distribution at the surfaces: outside at the window, between the window and the insulation, at the insulation inside the PCB and the air inside the PCB are shown for test 34. The distribution outside is within 1 F, the average temperature at the top was 41.5°F and at the bottom 40.9°F, the highest 41.6°F and the lowest 40.9°F respectively. Between the window and the insulation was the temperature distribution within 2 F. At the top the average temperature was 46.7°F

and at the bottom 45.2°F, the highest was 47.2°F and the lowest 44.9°F respectively. Inside the PCB the temperature distribution was within 5 F. The average temperature at the top was 72.4°F and at the bottom 67.4°F, the highest 72.7°F and the lowest 67.3°F respectively. The temperatures of the air inside the PCB were 73.5°F at the top and 71.4°F at the bottom.

Test 35 was started on November/28 and the outside temperature was below 50°F. The objective was to check the possibility to measure walls with larger overall R-values than 7 Fft²hr/Btu. R=7 Fft²hr/Btu or smaller were the overall R-values measured so far except the preliminary tests 4, 5 and 6. The results of tests 4, 5 and 6 were the R-values 13.3 Fft²hr/Btu, 20.0 Fft²hr/Btu and 12.2 Fft²hr/Btu respectively and the temperatures differences were 17 F, 13 F and 16 F respectively. They had the same setup the window, insulation no. 1 and insulation no. 12. Test 35 had the same setup but the temperature difference was larger than 20 F (27 F). The overall R-value measured at test 35 was 9.1 Fft²hr/Btu and the R-value of the insulation measured was 4.3 Fft²hr/Btu. The overall R-value including the window is only an indicator but not a test result of the test specimen because of the radiation effect introduced by the window. To confirm the result of test 35 the tests 39 and 40 were done later.

4.16.2 The Controller Setting Part 2

The results of tests 30 to 33 showed that with a controller setting of $X_0=-0.55$ the air temperature inside the PCB is close to the room temperature when the PCB is black painted inside but the results of the measurements are too high. Tests 36 and 37 were done to check whether the controller setting has to be zero. The controller settings were $X_0=-0.20$ and -0.10 respectively. At test 36 the setup was the window, two layers of 0.5 in. gypsum board and insulation no. 1 to measure the insulation while the setup at test 37 was the window, insulation no. 1 and two

layers of 0.5 in. gypsum board to measure the gypsum board. With $R_{36}=4.4 \text{ Fft}^2\text{hr/Btu}$ the result was 10% too high for the insulation. The result of test 37 $R_{37}=1.3 \text{ Fft}^2\text{hr/Btu}$ was considerable higher than 0.9 $\text{Fft}^2\text{hr/Btu}$ the R-value of the gypsum board. The tests 21 and 22 showed already the difficulty to measure such a small R-value. To meet the objective to verify the controller setup of $X_0=0.0$ another test has to be done.

Test 38 was done to confirm the result of test 37. The setup of the test specimen was the same as test 37 but the controller setting was $X_0=0.0$ instead of -0.10 . The duration was two nights (40.5 hours). The test result was $R_{38}=1.2 \text{ Fft}^2\text{hr/Btu}$ slightly lower than R_{37} to verify the controller setting of $X_0=0.0$, but still too high for the gypsum board. Insofar the result also confirms the result from the tests 21 and 22 that low R-values are difficult to find.

The objective of tests 39 and 40 was to measure the R-value of the insulation while the overall R-value is larger than 8.0 $\text{Fft}^2\text{hr/Btu}$. The setup of the test specimen was the window, insulation no. 12 and insulation no. 1. The controller setting was $X_0=0.0$. Test 39 lasted one night and test 40 two nights. The results were $R_{39}=4.0 \text{ Fft}^2\text{hr/Btu}$ and $R_{40}=3.9 \text{ Fft}^2\text{hr/Btu}$. The temperature differences were 38 F and 36 F respectively.

Chapter 5

CONCLUSION

5.1 Validity of Data

The data show that with this method R-values can be found with 10% accuracy or ± 0.4 Fft²hr/Btu, whatever is larger, when the temperature difference between inside and outside is larger than 15 F. When the temperature difference was 35 F or larger the accuracy was 2.5% (see tests 39 and 40). Even though there is a difficulty to find R-values of 1.0 Fft²hr/Btu or smaller. Field experiments with whole walls will not encounter the small R-values measured here where the temperatures between the layers of the test specimen could be measured. The results tend to be larger than the actual value. With a large series of tests a trend will be detectable to calculate adjustments. The parameter to be observed are the temperature difference, the R-value and the voltage settings of the heater.

The black coating inside the PCB to increase the radiation heat transfer did not alter the test results significantly. So both setups with or without the black coating will find the R-values. The temperature distribution inside the PCB will be more even with the black coating and so favorable but not necessary.

For all experiments the controller setting X_0 should be 0.0 to ensure no heat transfer between the room and inside the PCB. If changes seem to be necessary, then the voltage settings of the heater should be adjusted including the correction in block 225 (see A.5 calibration of the heater). The voltage setting of $V=35$ volts did serve well and no further investigations were done.

In field measurements will be one point of temperature measurement at the surface outside sufficient. The temperature variations were smaller than 1 F within the area outside opposite to the location of the PCB. Inside the PCB are at least

two points required in vertical direction, because the temperature variations were about 4 F. The horizontal temperature variations were negligible.

5.2 Further Work

For the field measurements some few refinements can be done to enhance the performance and to ease the handling. A software driver for the screw terminals to measure the temperature with thermocouples (TC) directly would reduce the software setup and allow to more TC's. The program Notebook can not directly convert the signals from the screw terminals to temperatures. To measure temperatures with a TC the temperature of the cold junction has to be measured and converted to a TC voltage signal and added to the TC signal and then to be calibrated. That requires four steps of measuring and calculation and with a software driver this could be done in one step, it will not be possible to add another TC with the present setup.

A cable connector for TC's between the screw terminals and where the TC's are located would increase the portability of the PCB. This would allow the PCB to be transported independent of the data acquisition system. Particularly a connector between inside and outside the window would make it easier to move the frame between outside and inside.

In the long run the on/off controller could be replaced with a continuous controller to ensure a more even and steady heat supply. Though it will be more difficult to calibrate and measure then the heat supplied.

APPENDIX

A Calibration

A.1 General Description

The conversion of a thermocouple emf signal to a temperature °F signal involves three steps. First the influence of the data acquisition board on the signal of the thermocouple has to be excluded. This is done with the adjustment of the zero voltage with a short circuit reference. Second the cold junction temperature signal has to be converted to a voltage signal of the same type of thermocouple. The conversion can be done with interpolation of tables (Reference Tables N.I.S.T. Monograph 125, published by *OMEGA*). This signal has to be added to the thermocouple signal. The result is the same as a thermocouple with actual reference of an ice-point. Finally the signal has to be converted to temperature, which can also be done with interpolation of the tables. Now the actual calibration of each thermocouple can be done.

Two tasks are performed with the equipment:

1. Temperature measurements
2. Energy to the heater measurements

The temperature calibration involves three steps. First step is to calibrate the cold junction compensation (cjc), second is to calibrate the analog/digital converter (A/D), and third the calibration of the thermocouples (TC).

A.2 Cold Junction Compensation (CJC) Calibration

Every junction between different metals induces a voltage that changes with temperature. The voltage cannot be directly measured with a voltmeter, because to connect to the voltmeter introduces another junction. But the voltage induced by the temperature difference of these junctions can be measured. Therefore, two

junctions are required to measure temperature, one is called the measuring junction and the other the reference or cold junction. For certain pairs of different metals, tables of the temperature - voltage function have been established. These are all shown if one of the junction (the cold junction) has a temperature of 32°F. If this temperature cannot be maintained during a measurement, a compensation for this reference or cold junction has to be made. That is to record the temperature of the cold junction and evaluate the voltage difference that a thermocouple of the same type would induce with reference to 32°F. Adding the voltage difference to the measured voltage leads to the voltage induced, and so the temperature, of the measuring junction. Since the voltage induced is not a linear function of the temperature this calculation has to be done. A direct calculation from measured voltage to temperature difference can lead to a wrong temperature.

The temperature sensor of the cold junction of the DT 727 -T screw terminal has, according to the manufacturers supplied information and what could be verified, a linear function of the temperature. The output of the temperature sensor is a voltage in the millivolt range, and the temperature (T) - voltage (V) function is: $T = b*(V+a)$. The values of a and b have to be determined. The voltage of the temperature sensor was recorded over a period of 30 seconds with 2 measurements per second. The average (mean value) of that result was related to the result of the temperature measurement which was done at the same time. The temperature measurement was done with a liquid thermometer of which two were used. The readings of the two thermometers differed by less than $\Delta T < 0.05$ F after stabilization in an enclosed container. Due to the measurable range 53°F to 102°F an ice - or steam calibration was not possible. The thermometers are ASTM certified with 0.1 F divisions. A linear regression was made on the temperature - voltage data pairs. The regression coefficient r of all measurements together was better than $r^2 > 0.999$, that indicates a reliable linearity within the measured

temperature range of 71.5°F to 81.5°F (a straight line gives $r^2=1$; no linear correlation between both values gives $r^2=0$, means no linear relation).

A.3 Data Acquisition Board Calibration

To limit the error of the analog/digital converter, the zero voltage of each channel used to measure the micovolt signal of a thermocouple, was calibrated. To avoid a drift of the zero offset (offset is the difference between the needed value (setpoint) and the actual value) a short circuit reference was used. With the idea to circumvent warm up periods and an age drift, that if the board measures lower values it will do it for all channels. To gain a more stable reference two channels were chosen and the average of the last five measurements calculated. Every measurement included 61 data points collected in a 30 second period with 2 samples per second. The average and the standard deviation of each channel were separately calculated. The magnitude of the coefficient of variance (standard deviation/mean value) was in the range of 0.015 to 0.03, if the magnitude would be about 1 or larger a correction is not needed, because the spread of the data includes the value looked for. These measurements were made 21 times. The difference from each channel to the reference short circuits was calculated and will be subtracted from the thermocouple signal for the zero offset.

A.4 Thermocouple Calibration

All thermocouples and the thermometer were taped together and surrounded by an isolated copper coil to provide a constant and even temperature distribution. They were also enclosed in a container to reduce air movements. The measured temperature of each thermocouple was compared with the temperature shown by a liquid thermometer. The calibration of the thermocouples was done with twenty-eight measurements in the temperature range from 62.5°F to 80.9°F. Each

measurement took 30 seconds and collected 61 data points (2 samples per second, one at the beginning). The offset from the thermocouple measured value to the temperature shown by the liquid thermometer did not vary linearly with the temperature, but was constant over the calibrated range. That means that the offset was not significantly different at around 65°F than at 78°F. For this reason was the offset for each thermocouple averaged and subtracted from the measured value.

A.5 Energy to the Heater Calibration

For the energy to the heater measurement a kilowatt-hour meter is used. The energy per turn of the indicator wheel is 0.3 watt-hour per turn ($k_h = 0.3$). A sensor provides two pulses per turn (the pulse length is a quarter of a turn) of the indicator wheel. The duration of the pulse of a quarter of a turn allows the rising and the falling edge of a pulse to be used as an energy to the heater signal. Each signal counts for 0.075 watt-hour. To convert to Btu we have to divide by 0.29308 watt-hour/Btu. The PCB has an open area of 7.535 ft². To get the energy intensity Btu/(hour·ft²) we have to multiply by 7.535 and to divide by the time elapsed between the signals. In this case the number of signals per time period is accumulated. This is only possible because the time period is much larger than the time elapsed between two signals and also necessary because due to the on/off controller the elapsed time between two signals is not defined. The converted signal counts for 0.034 Btu/ft² (0.033962 Btu/ft²). Due to losses in the variac the actual energy arriving at the heater has to be determined. The resistance of the heater is $R_{\text{heater}} = 58.4$ ohm. Sequential measurements with 5 volt step increments from 25 volts to 50 volts were done. The voltage across the heater was measured and the time elapse for one turn, up to 40 volts and two turns at higher voltages, was measured. Each turn accounts for 0.3 Whr or 1080 Ws. With $P_{\text{kW-h meter}} = 1080 \text{ Ws/time elapsed}$ and $P_{\text{heater}} = V^2/R_{\text{heater}}$ the ratio

$r_{\text{eff.}} = V^2 \cdot \text{time elapsed} / (R_{\text{heater}} \cdot 1080 \text{ Ws})$ can be calculated. Since $r_{\text{eff.}}$ changes with the applied voltage, the voltage set has to be recorded for each measurement. The setting for $V = 35$ volts (0.815) was implemented in the software (Block 225) for the experiments.

The other settings are:

V [volts]	$r_{\text{eff.}}$
20	0.70
25	0.735
30	0.77
35	0.815
40	0.87
45	0.885

APPENDIX

B Locations of Thermocouples

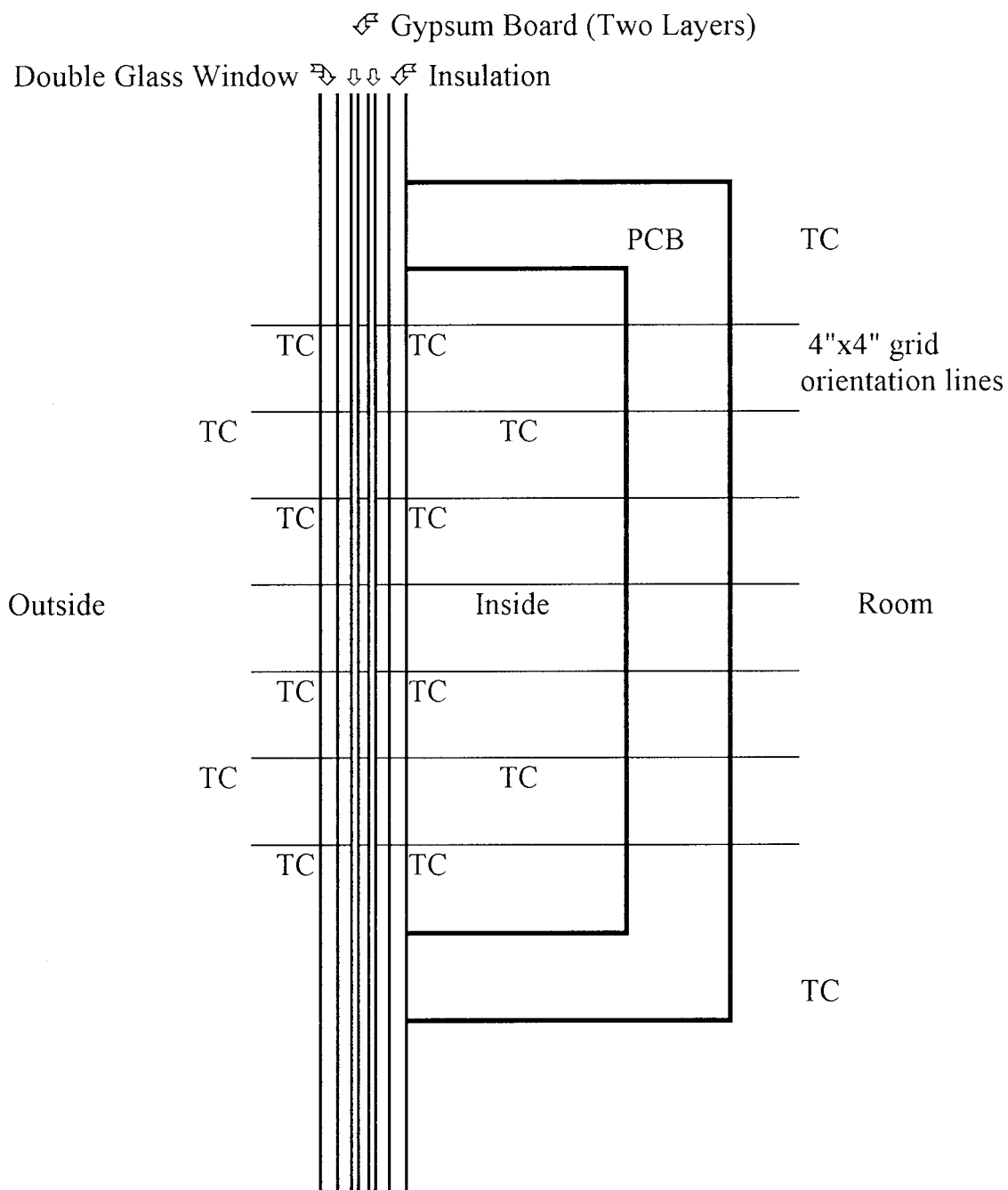


Figure 8 Cross View of PCB

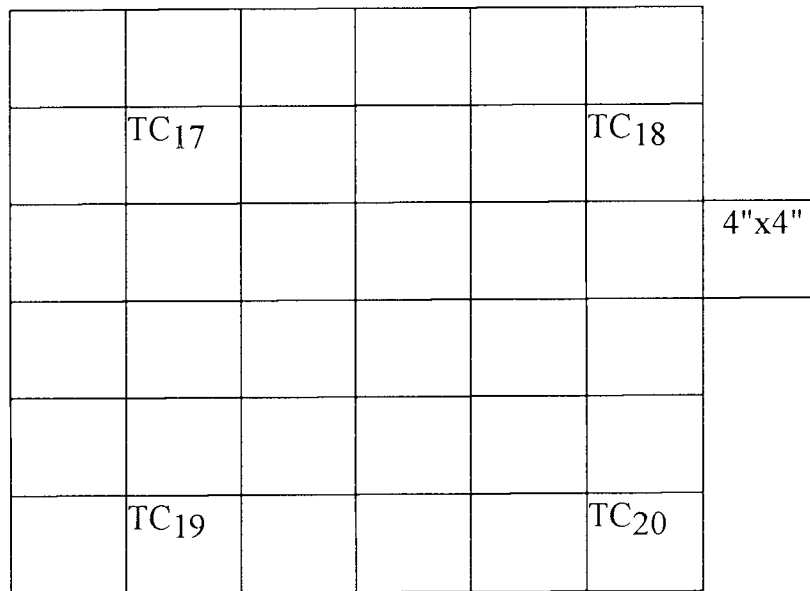


Figure 9 Thermocouple Locations Outside

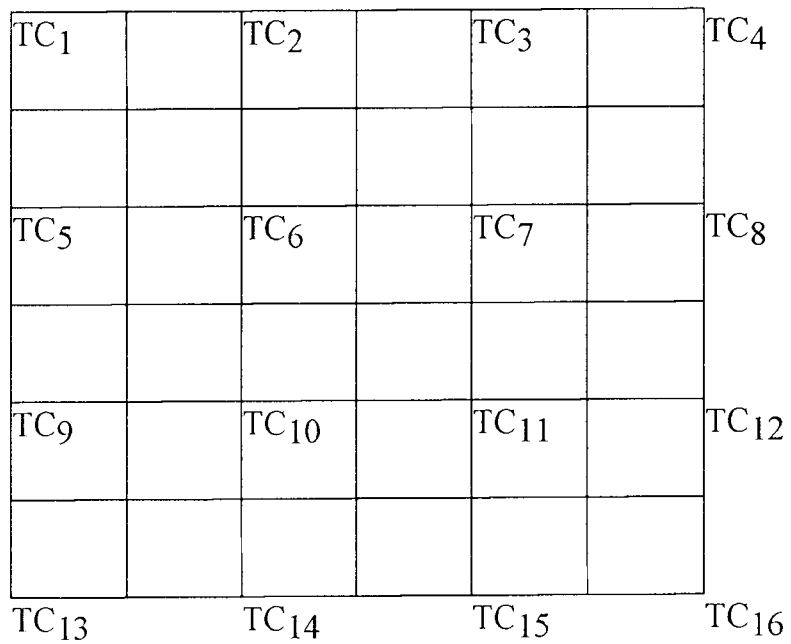


Figure 10 Thermocouple Locations Outside Surface

			TC49		
			TC50		
			TC51		

Figure 11 Thermocouple Locations between Window and Gypsum Board

	TC45				TC46
	TC47				TC48

Figure 12 Thermocouple Locations between Gypsum Board and Insulation

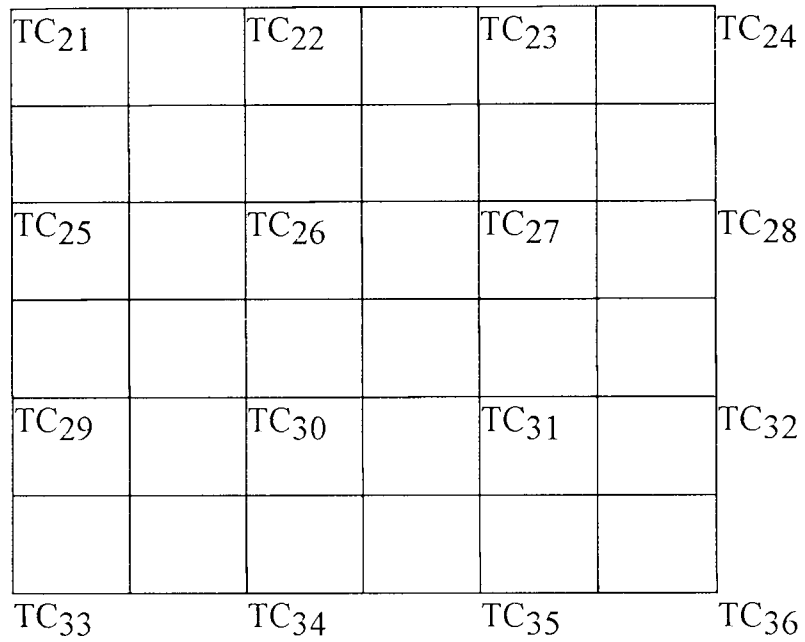


Figure 13 Thermocouple Locations Inside Surface (PCB)

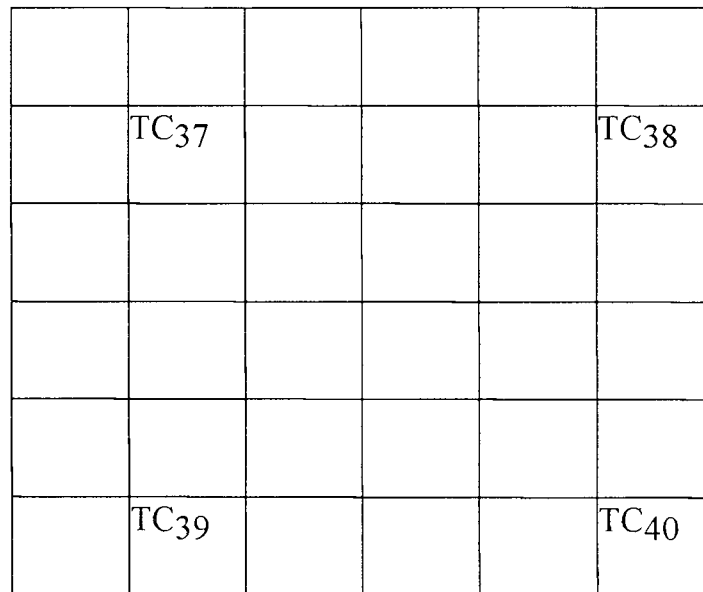
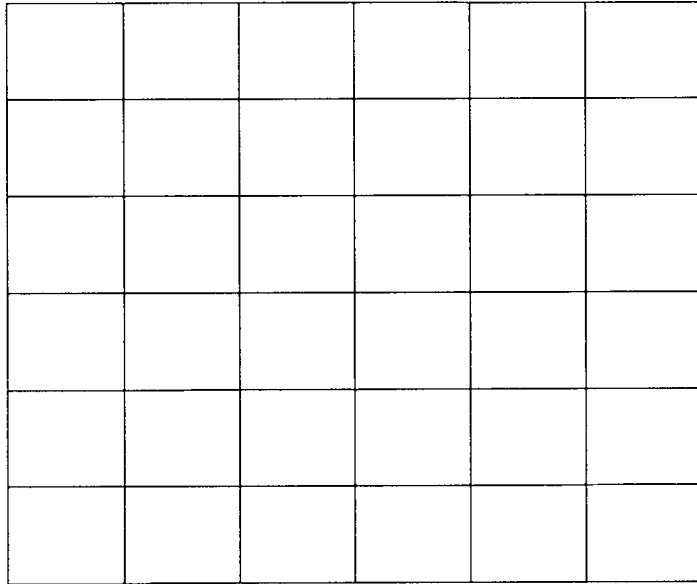


Figure 14 Thermocouple Locations Inside (PCB)

TC41

TC42



TC43

TC44

Figure 15 Thermocouple Locations Room

APPENDIX

C Data Handling with Software

C.1 General information

For the data handling three software packages were used: Notebook 6.3.0. for the measurements, Word 2.0 to change the data format and Excel 4.0 to perform calculations and graphs. The programs Word and Excel are Window programs and knowledge of the use of Windows and the mouse is assumed for this limited overview. To use the measurement method is Notebook necessary, it can save the data to a file and they can be copied to the printer. To create graphs is Excel or a similar program necessary. Word converts the data from Notebook to a format Excel can read easier. Notebook saves the data in an ASCII format with predetermined field size. With varying values the amount of space between the numbers varies and Excel expects a constant number of spaces (delimiter) between the values, because it will insert an empty cell after each space.

C.2 Data Handling with Word

Word is not a data management program, but it can change the format of data and perform the transition of data files created by Notebook to read them with Excel. Notebook is programmed to save the tests in a file with the name "testnit1.prn". After each test this file has to be copied to a new file. To do this click the "open" button with the mouse or press "Ctrl+F12" on the keyboard. Then the listed files have to be changed to "All Files (*.*)", and the directory has to be "c:\nb\". Chose "testnit1.prn" in the list or type it under "File name" and press "Enter". This file has to be saved in a new one, press "F12" and Word will prompt with "Save As", chose the directory, here "c:\gostat\data\" was used, make sure Word will save as a "Text Only (*.txt)" file and type the filename.

After an paragraph mark (¶) or "Enter" Excel starts a new row. Also each delimiter, here space, causes it to start a new cell. Two spaces will cause Excel to create a blank cell between the entries. To replace two spaces with one: chose replace with pressing "Alt e e". In "Find What:" press two times the "Space bar" press "Tab" or click "Replace With:" and press once "Space bar". Then click "Find Next" and "Replace" or "Replace All" immediately. If there are more than 2728 changes, Word will ask to save the file and then you have to start to replace again. Since the file is already saved with another filename then "testnit1.prn" it can be saved with "Shift+F12", without another prompt. Start replace with "F4", the last replace command is saved by Word and clicking "Replace All" will replace the same as the previous one. Save the file with "Shift+F12". To print the data click the print button or press "Ctrl+Shift+F12" and chose the print range of the pages or press "Enter" immediately and Word will print the whole data file.

C.3 Data Handling with Excel

To open the data file click the "Open" button with the mouse or press "Ctrl+F12" on the keyboard. Then the listed files have to be changed to "All Files (*.*)", and the directory has to be the one where the data file was saved, here "c:\gbstat\data\" was used. Click the "Text" button to get the window to define the data format of the data file and click where "Space" stands under "Column Delimiter" and then click "Ok". Chose the data file in the list or type it under "File name" and press "Enter". To retain the data file and preserve the calculations save the data file as an Excel file. Press "F12" and Excel opens a window to define the file where to save. Under "Save File as Type:" chose "Normal", Excel will change the file extension automatically to "*.xls". If you want to keep the file in the same directory press "Enter" or click "Ok", if not double click the directory where to save shown under "Directories:".

To perform the calculation click a cell in an empty column and type "=" and then the formula. To calculate the difference from the value in "A2" and "B2" type "=a2-b2" and press "Enter". The result will be shown in the cell you chose and the formula in the bar below the toolbar. To calculate the differences of all cells in column "A" and "B" point with the mouse to the cross in the lower right corner of the cell where you did the first calculation, the pointer will change to a cross, and while you press the left mouse button drag the cross down the column until where the calculations have to be made. After release of the mouse button Excel will perform the calculations. To print the results click the print button or press "Ctrl+Shift+F12" and chose the print range or press "Enter" immediately and Excel will print all cells.

To create a chart click a cell in one of the four corners of the cell range of the data and while you press the left mouse button drag the unchanged mouse pointer to the opposite cell of the cell range. The first selected cell will be in white and all other in black with yellow characters. Now click the "Wizard Chart Button", the mouse pointer will change to a hair cross, and press the left mouse button where you want the right upper corner of the chart and drag to the lower left corner and release the press the left mouse button. Excel will prompt to chose the appearance of the chart, click the fields of the style you want and after you clicked "Ok" Excel will create the chart. To change the chart double click while the mouse pointer is on it and Excel will open a window. With the "Gallery", "Chart" and "Format" menus all presettings can be changed. Click the "Minimize" button to return to the data sheet. For details see the User's Guide 1 manual from Microsoft.

C.4 Measurements with Notebook

Notebook is a menu driven DOS program, which can be started from Windows 3.1 but not be used as a Window program. Here the use of an already defined

measurement setup will be shown. The setup is called "Niteexp2". After start of Notebook, under DOS with "c:\nb\nb", the main menu is shown and preset on "SETUP". The menu options are "SETUP", "GO", "ANALYZE", "CURVE-FIT", "FFT", "INSTALL" and "QUIT". With the arrow keys the highlighted task can be changed. Start the highlighted task with "Enter". If the last setup was "Niteexp2" then chose "GO" and press "Enter". Notebook will ask you whether it should overwrite "Testnit1.prn" or not. If the former experiment is saved with a new name just press "Enter", if not see how to save under word or abandon the previous test. To start the experiment press "Enter". To stop the experiment press "ESC" while it is running and press "Enter" to return to the main menu.

To chose the setup "Niteexp2" highlight "SETUP" press "Enter" and then highlight "SAVE/RETRIEVE" press "Enter". Now go to "RETRIEVE" press "Enter" and type from one of the shown setups "Niteexp2" and press "Enter". Return to the main menu with pressing "ESC" two times and "GO" will be highlighted.

Notebook can only be stopped from the main menu with highlighting "QUIT" and pressing "Enter".

APPENDIX

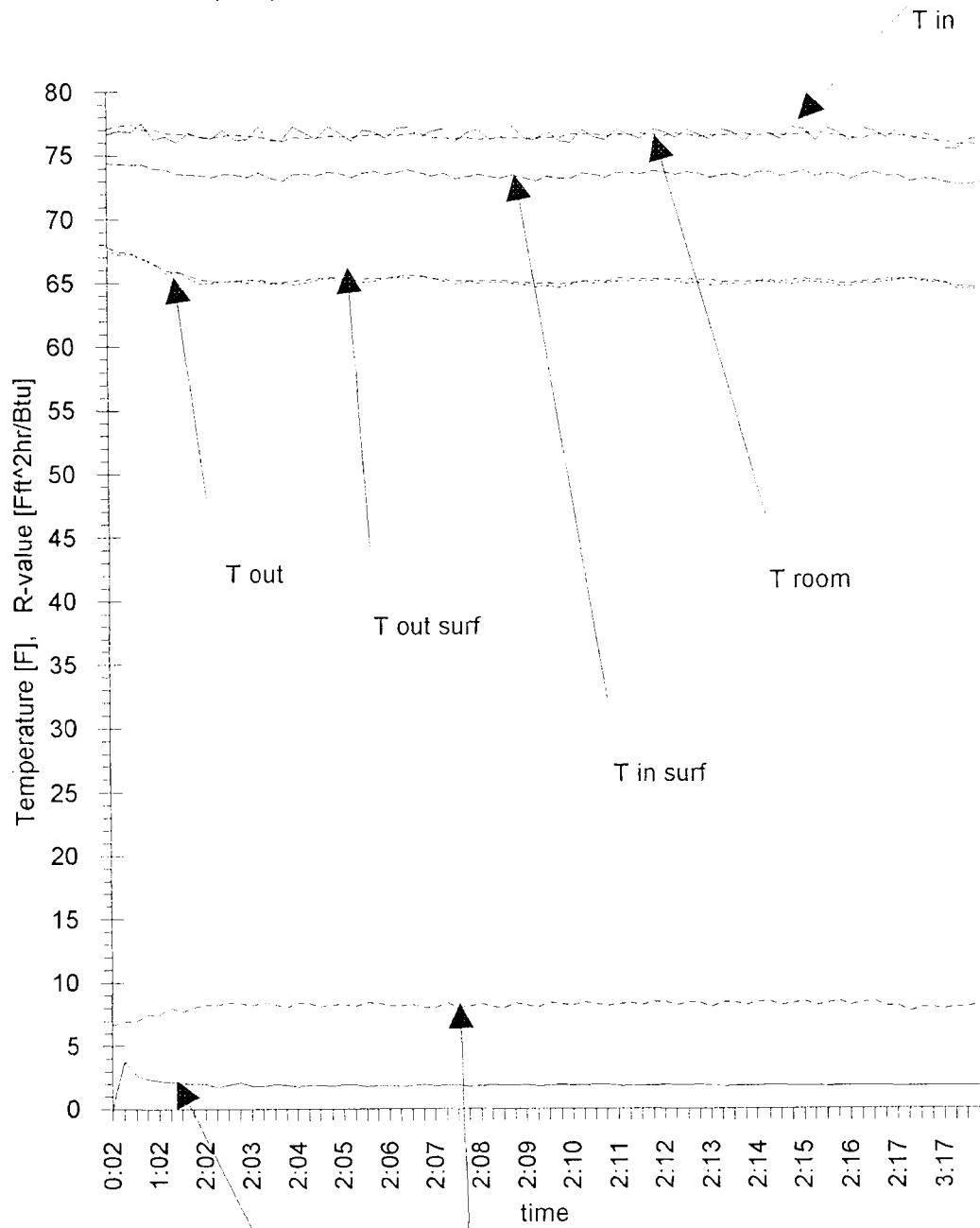
D Experiment Results and Data

no	date	start	dur hrs	end	material	R tot.	R insul	T ref.	ΔT
1	6/24/92	00:00	4	04:00	window	1.3		69.3	7.7
2	6/25/92	00:00	4	04:00	win., insulation no 1	5.3		70.6	11.5
3	6/26/92	00:00	4	04:00	win., insul no. 1	5.1		75.6	14.7
4	6/27/92	00:00	4	04:00	win., insul no. 1, insul. no. 12	13.3		75.5	17.2
5	6/28/92	00:00	4	04:00	win., insul no. 1, insul. no. 12	20.0		75.7	13.4
6	6/29/92	00:00	10	10:00	win., insul no. 1, insul. no. 12	12.1		79.8	16.7
7	6/30/92	23:00	11	10:00	win., insul no. 1, gyp. 0.5in	6.1		81.7	11.9
8	7/1/92	23:00	11	10:00	win., insul no. 1, gyp. 0.5in	7.0		73.4	12.3
9	7/2/92	23:00	11	10:00	win., insul no. 1, gyp. 0.5in	6.8		75.1	17.2
10	7/3/92	18:00	41	11:00	win., insul no. 1, gyp. 0.5in	6.4		75.0	16.0
11	7/5/92	21:00	12	09:00	win., insul no. 1, gyp. 0.5in	5.9		79.4	18.0
12	7/6/92	18:00	64	10:00	win., insul no. 1, gyp. 1in	8.6		76.6	15.6
13	7/10/92	21:00	13	10:00	win.	1.4		82.9	8.7
14	7/11/92	20:45	14	11:00	win.	1.4		83.4	13.5
15	7/13/92	20:00	14	10:00	win.	1.5		81.2	12.6
16	7/14/92	20:00	14	10:00	win.	1.3		89.0	9.3
17	7/15/92	19:40	14	10:00	win., insul no. 1	5.5	4.3	81.5	19.3
18	7/16/92	18:30	16	10:00	win., insul no. 1	6.1	4.7	77.1	11.1
19	7/17/92	21:00	13	10:00	win., insul no. 1	4.6	3.8	80.7	13.8
20	7/18/92	21:00	13	10:00	win., insul no. 1	5.7	4.5	82.4	14.9

no	date	start	dur hrs	end	material	R tot.	R insul	T ref.	ΔT
21	7/22/92	20:00	14	10:00	win., insul no.1, gyp. 0.5in	6.3	0.93	84.5	13.2
22	7/23/92	20:30	14	10:00	win., insul no.1, gyp. 0.5in	5.2	0.87	80.7	21.4
23	7/24/92	20:00	14	10:00	win., gyp. 1in, insul no.1	6.1	4.0	74.2	17.9
24	7/25/92	19:00	39	10:00	win., gyp. 1in, insul no.1	6.2	3.9	85.2	17.0
25	7/30/92	22:00	12	10:00	win., gyp. 1in, insul no.1	4.2	3.8	78.0	12.1
26	7/31/92	19:00	63	10:00	win., gyp. 1in, insul no.1	5.9	4.2	88.3	14.2
27	8/04/92	18:00	17	11:00	win., gyp. 1in, insul no.1	5.5	4.3	80.9	16.8
28	9/25/92	19:00	63	11:00	win., gyp. 1in, insul no.1	4.6	3.9	69.8	8.0
29	10/09/92	20:00	21	16:50	win., gyp. 1in, insul no.1	7.2	4.5	71.7	10.2
30	10/18/92	19:30	15	10:40	win., gyp. 1in, insul no.1	6.8	4.3	65.1	28.1
31	10/19/92	19:00	15	10:10	win., gyp. 1in, insul no.1	6.2	4.2	64.1	39.0
32	10/20/92	18:20	16	10:20	win., gyp. 1in, insul no.1	7.0	4.7	63.6	24.3
33	10/21/92	18:40	16	10:40	win., gyp. 1in, insul no.1	7.3	4.6	65.7	24.9
34	11/27/92	21:00	18	15:00	win., insul no.1	5.3	4.4	59.1	28.6
35	11/28/92	21:10	17	14:40	win., insul no.1, insul. no.12	9.1	4.3	62.0	27.7
36	11/29/92	19:30	16	11:30	win., gyp. 1in, insul no.1	6.6	4.4	57.7	28.6
37	11/30/92	18:30	17	11:30	win., insul no.1, gyp. 1in	7.0	1.3	64.3	26.3
38	12/01/92	19:10	40	11:40	win., insul no.1, gyp. 1in	6.1	1.2	70.5	30.7
39	12/03/92	20:30	15	11:30	win., insul. no.12, insul no.1	8.5	4.0	64.4	38.1
40	12/04/92	21:50	39	13:00	win., insul. no.12, insul no.1	8.6	3.9	61.7	36.3

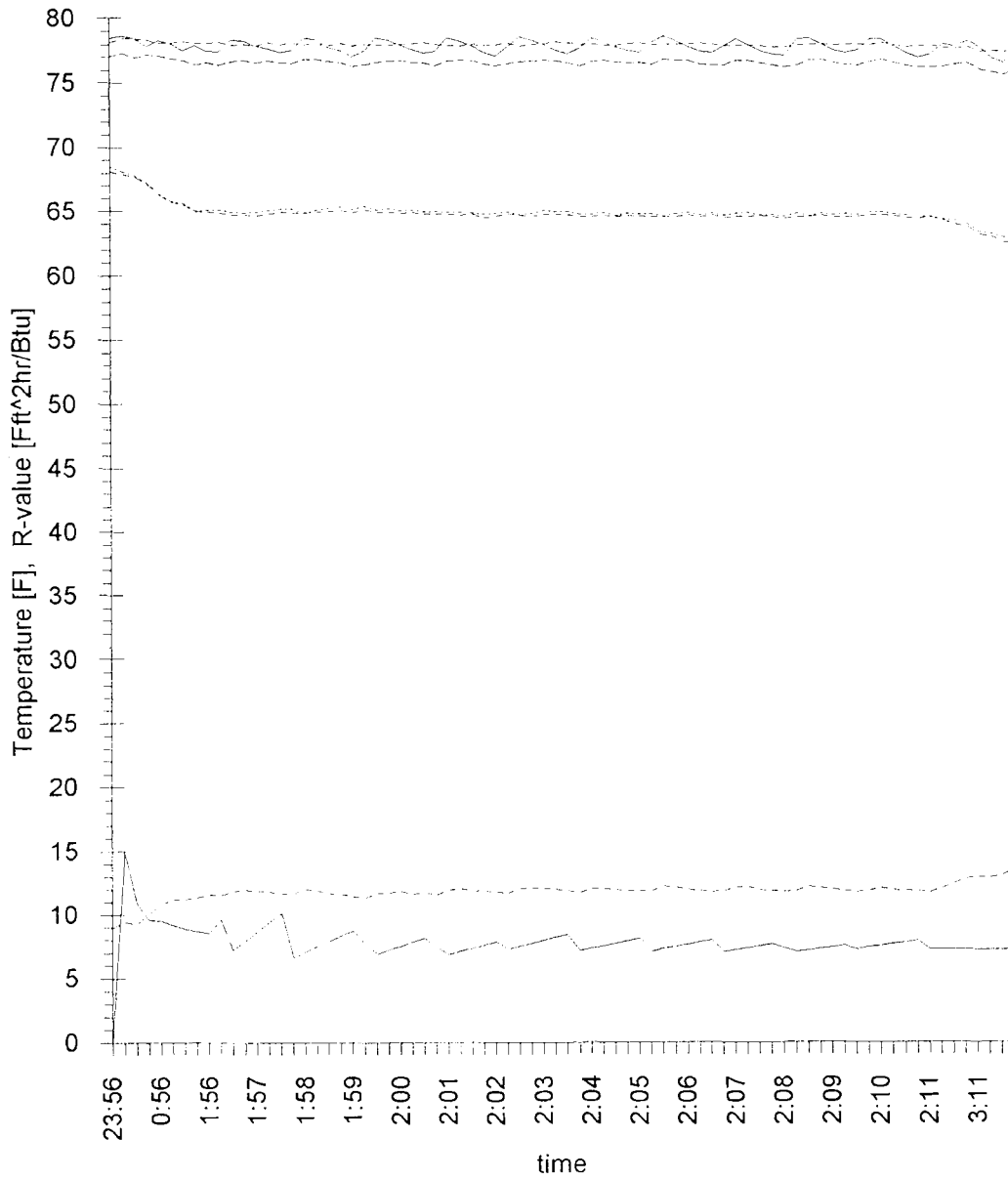
In the following pages are the plots of test data shown. On top is the date when the experiment started, the test number and the materials measured in sequence from outside to inside. The X-axis is the temperature in Fahrenheit, the R-value in $\text{Fft}^2\text{hr}/\text{Btu}$ and from test 4 on the heat (q) in Btu/hrft^2 . The Y-axis shows the time in hour and minute. Below is the legend with the displayed values and their trace.

6/24/92 Test 1 Window



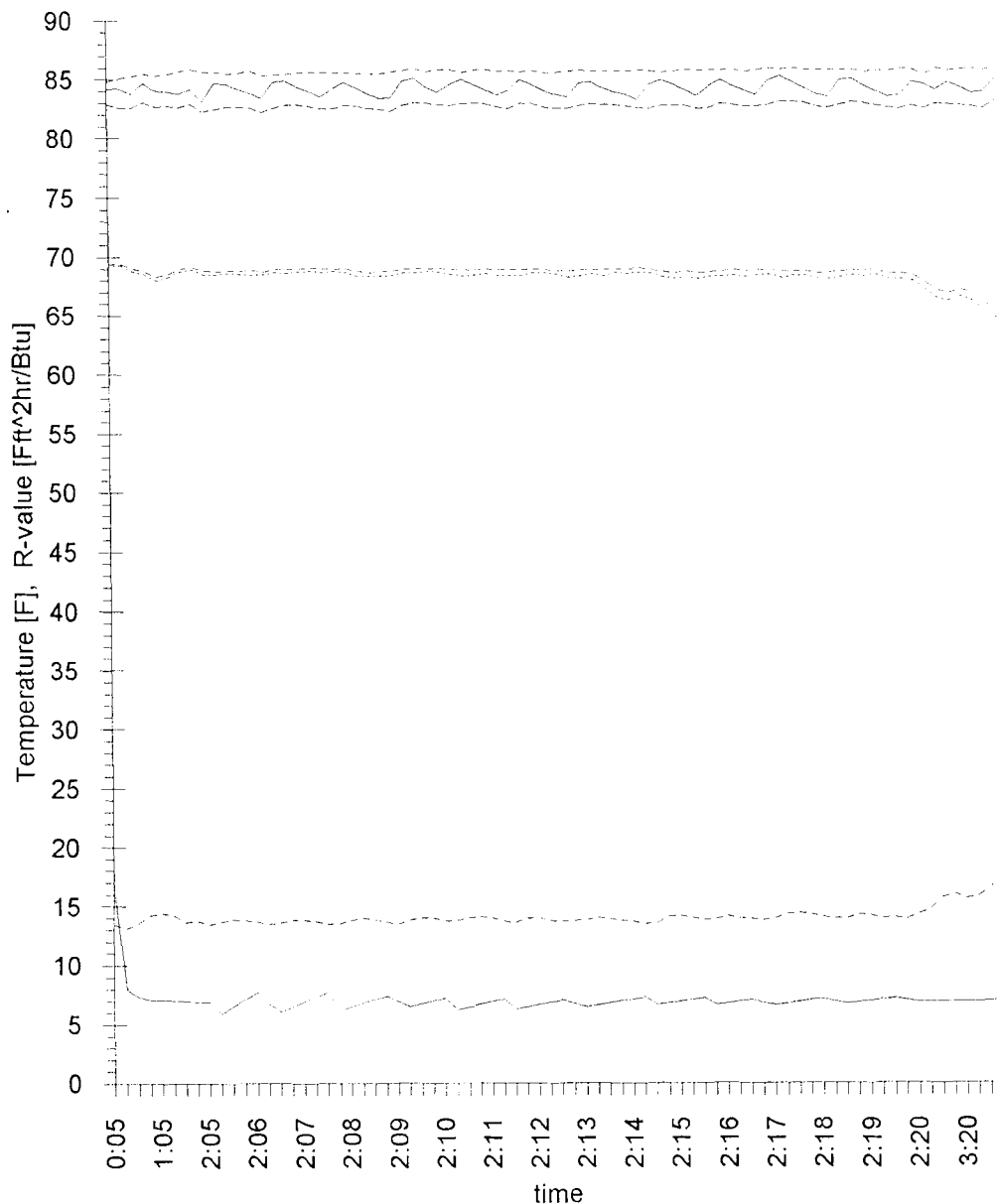
— R tot cum	- - - dT i,o surf	..... T out	- - - T out surf
..... T in surf	— T in	- - - T room	

6/25/92 Test 2 Window and Insulation no. 1



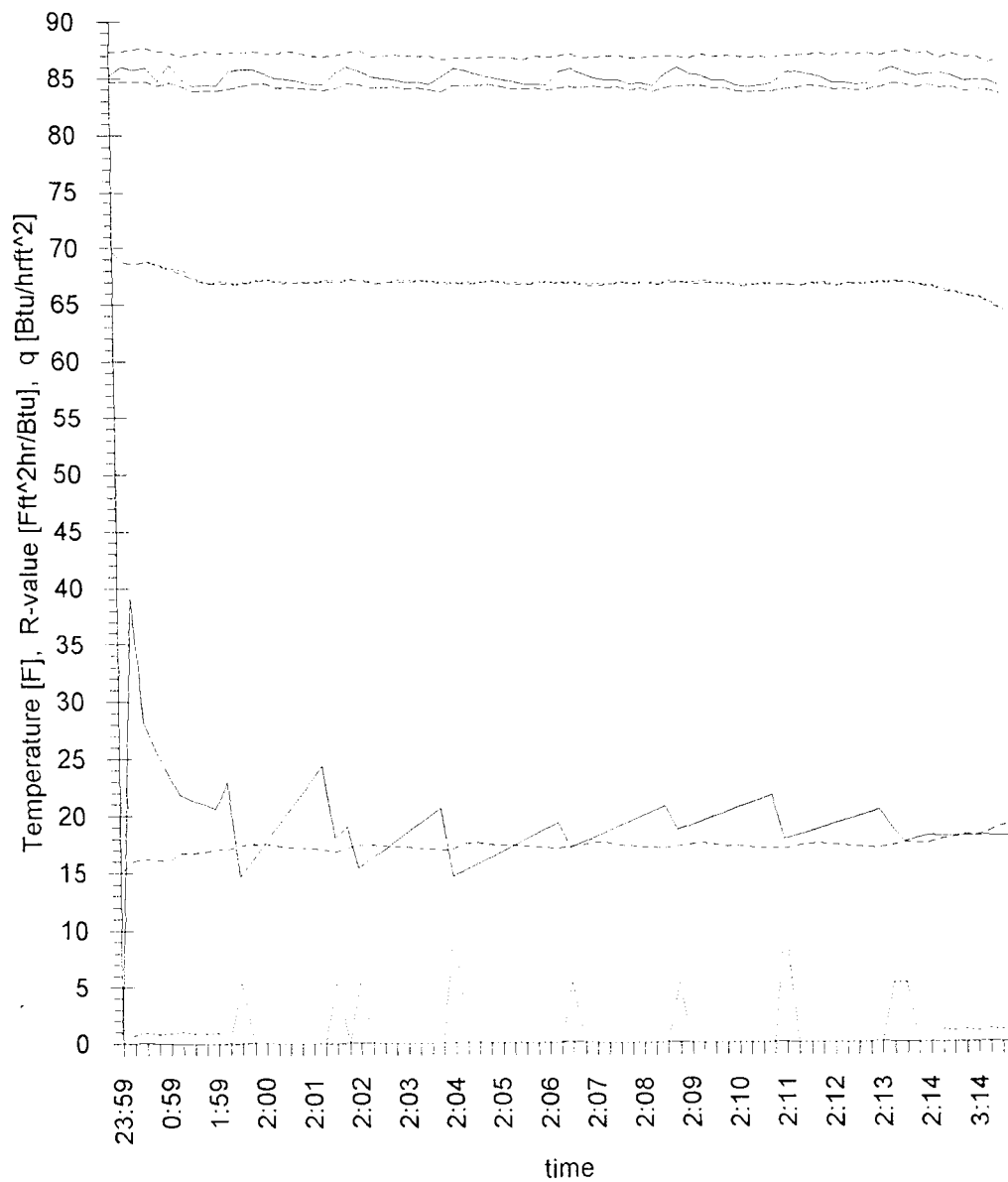
——— R tot cum - - - - - dT i,o surf T out - · - · - T out surf
 - - - - - T in surf ——— T in - - - - - T room

6/26/92 Test 3 Window and Insulation no.1



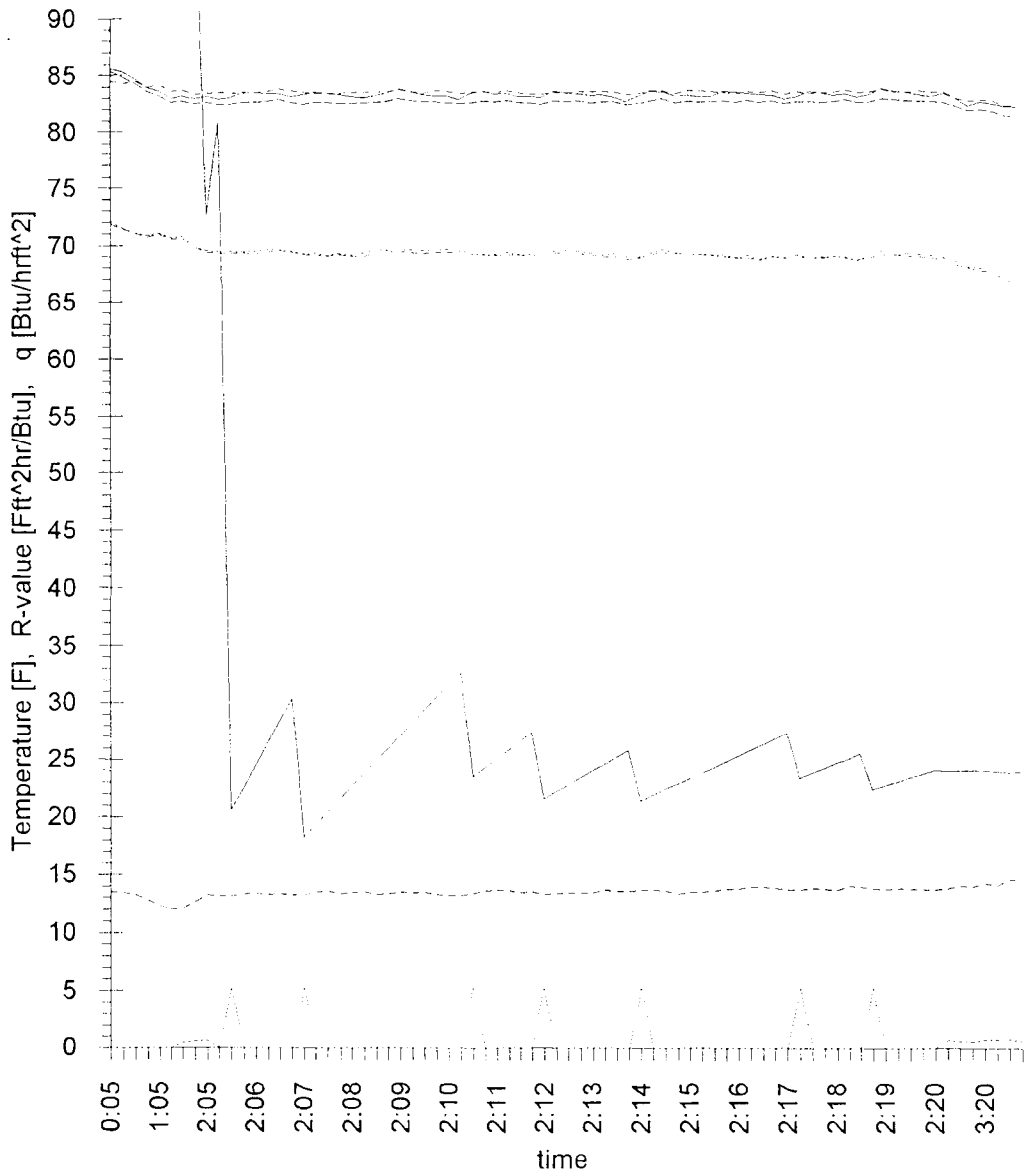
— R tot cum - - - dT i,o surf T out - · - · - T out surf
 T in surf — T in - - - T room

6/27/92 Test 4 Window, Insulation no. 1
and Insulation no.12



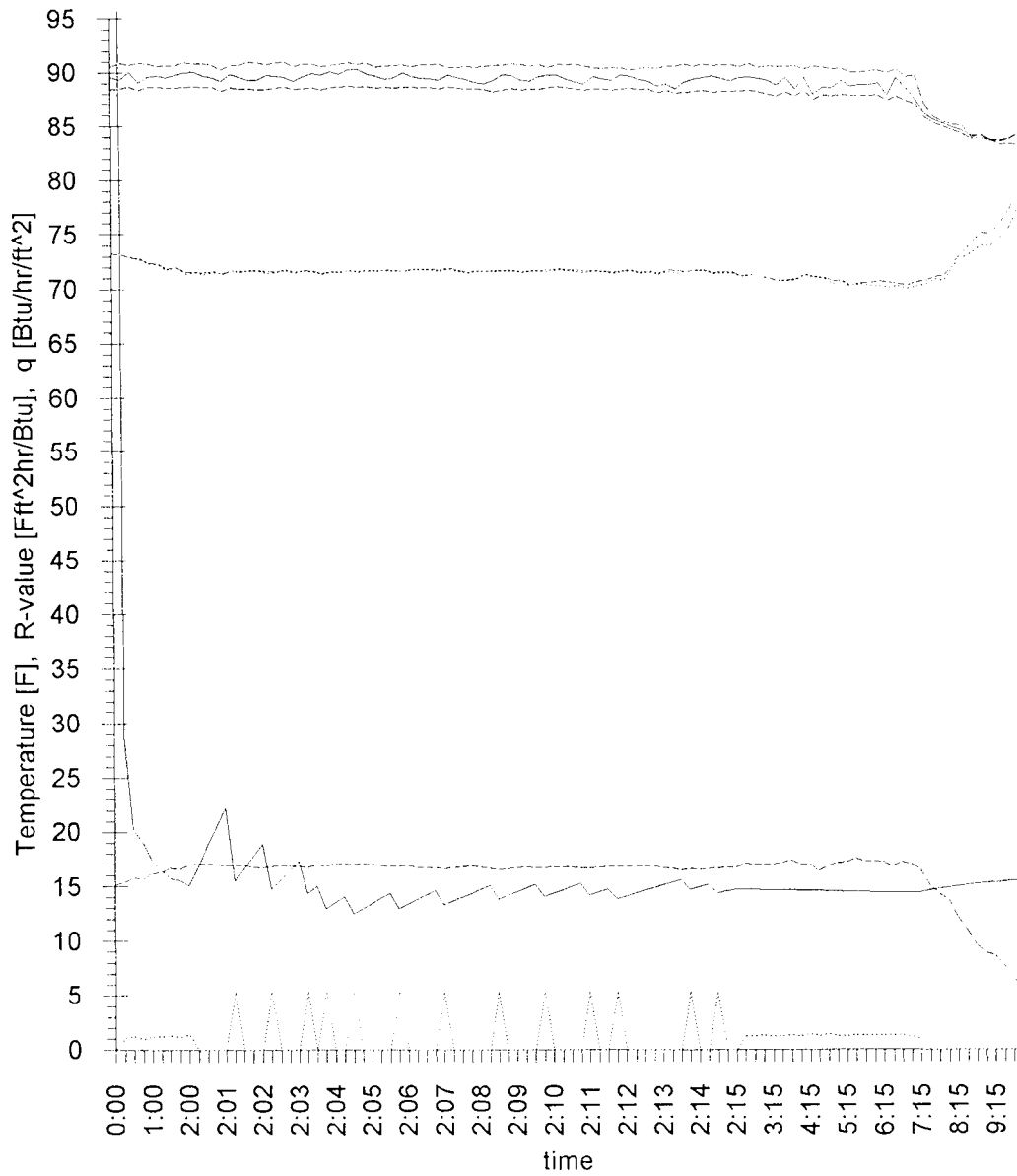
—— R tot cum	- - - - dT i,o surf	..... T out	- . - . T out surf
- - - - T in surf	—— T in	- - - - T room	..... q

6/28/92 Test 5 Window, Insulation no. 1
and Insulation no. 12



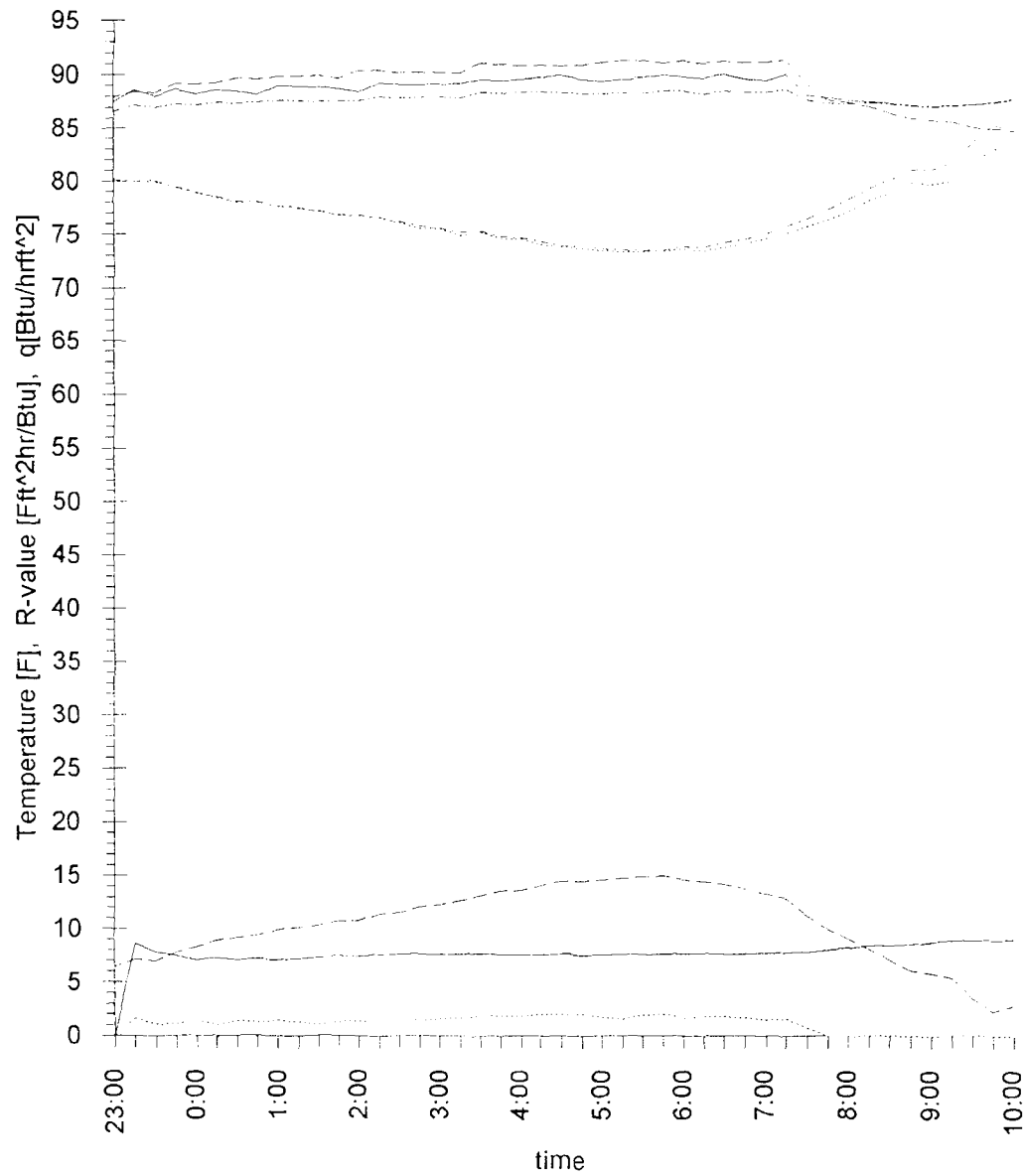
— R tot cum	- - - dT _{i,o} surf	..... T out	- - - T out surf
..... T in surf	— T in	- - - T room	..... q

6/29/92 Test 6 Window, Insulation no.1
and Insulation no. 12



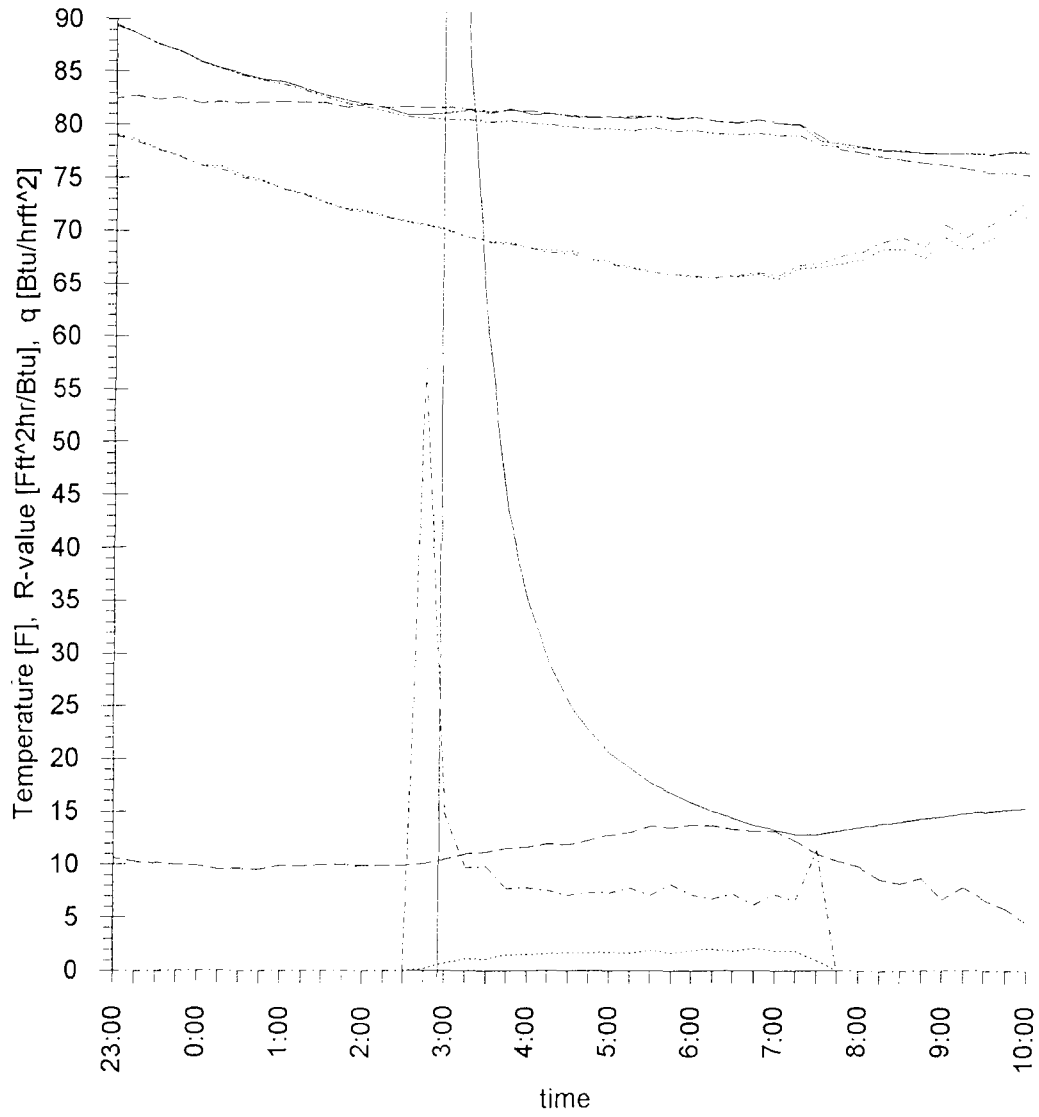
— R tot cum	- - - dT i,o surf	..... T out	- · - · - T out surf
..... T in surf	— T in	- - - T room	..... q

6/30/92 Test 7 Window, Insulation no.1
and Gypsum Board 0.5 in.



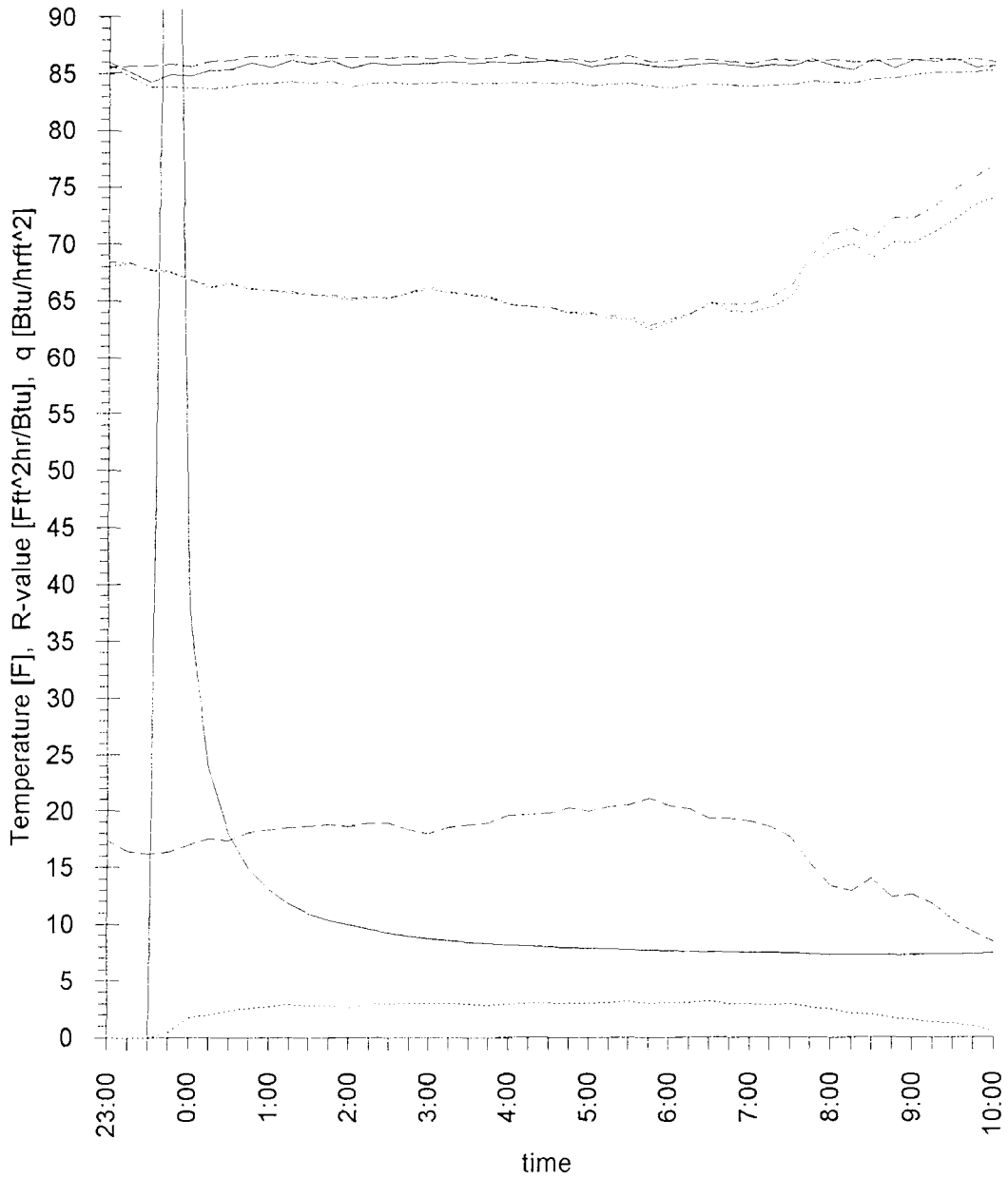
— R tot cum	- - - dT i,o surf	..... T out	- . - . T out surf
..... T in surf	— T in	- - - T room	..... q

7/01/92 Test 8 Window, Insulation no. 1
and Gypsum Board 0.5 in.



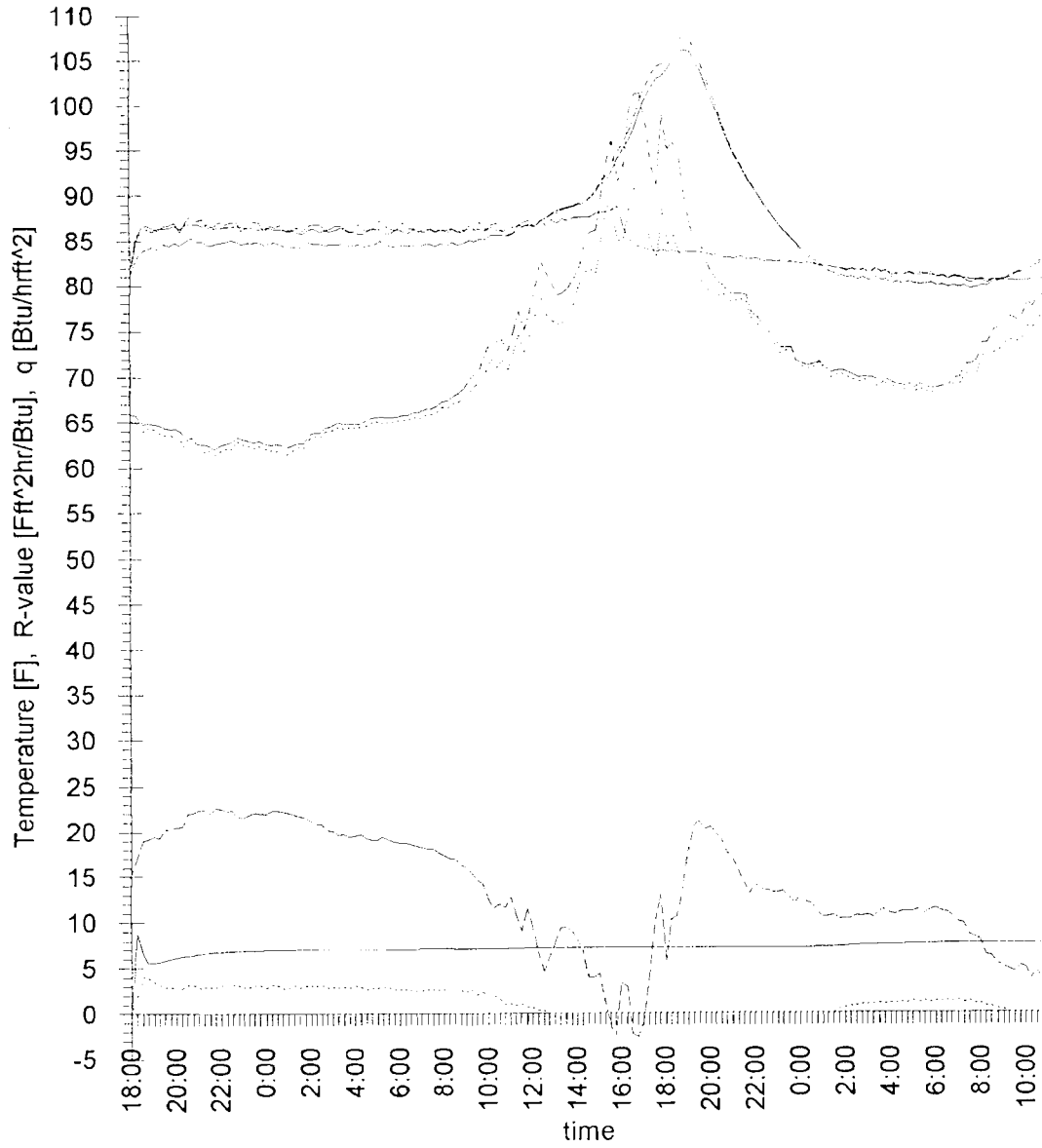
— R tot cum	- - - dT i,o surf	..... T out
- - - T out surf	..... T in surf	— T in
- - - T room	..... q	- - - R tot inst

7/2/92 Test 9 Window, Insulation no.1
and Gypsum Board 0.5 in.



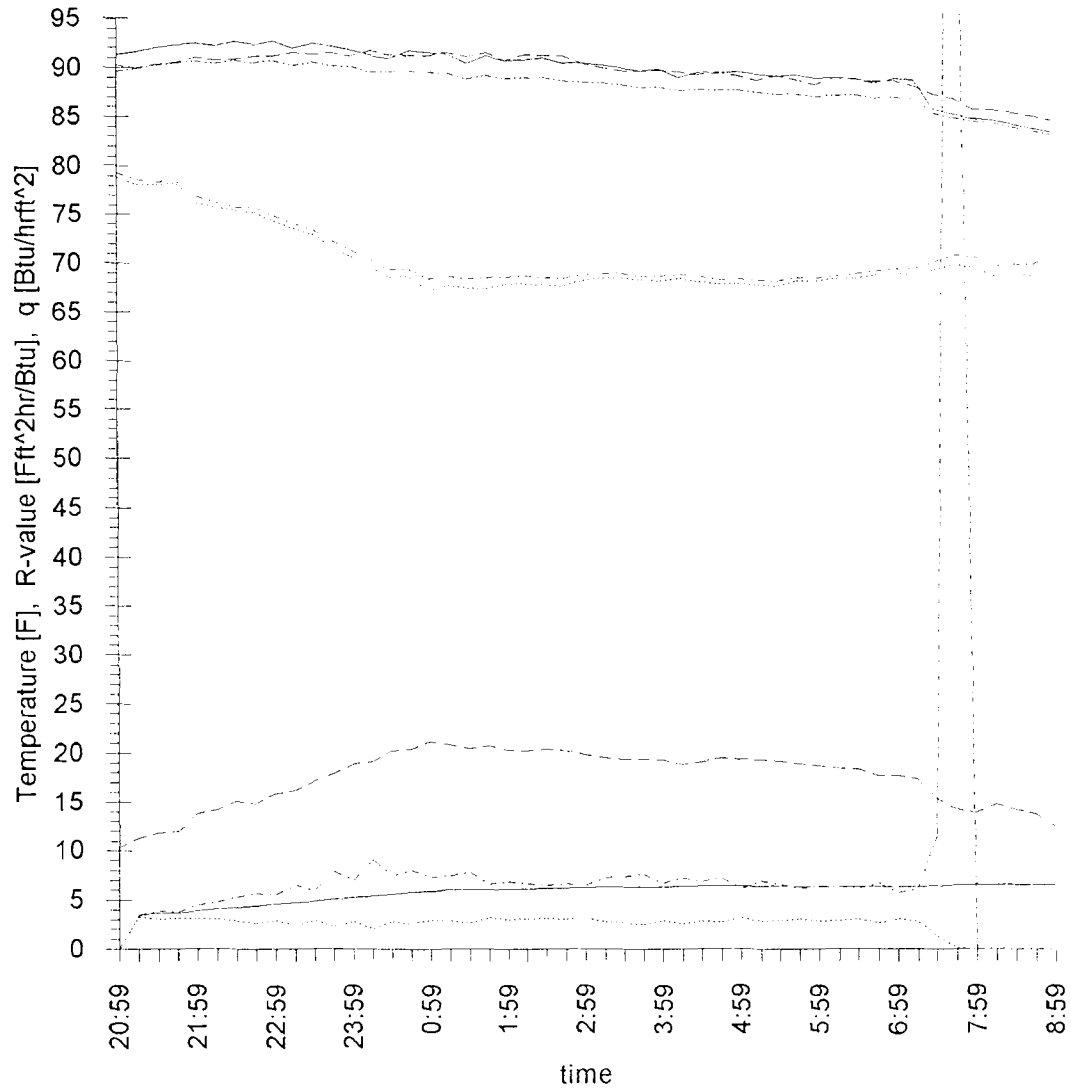
— R tot cum	- - - dT _{i,o} surf	..... T out	- · - · - T out surf
- · - · - T in surf	— T in	- - - T room	..... q

7/3/92 Test 10 Window, Insulation no.1
and Gypsum Board 0.5 in.



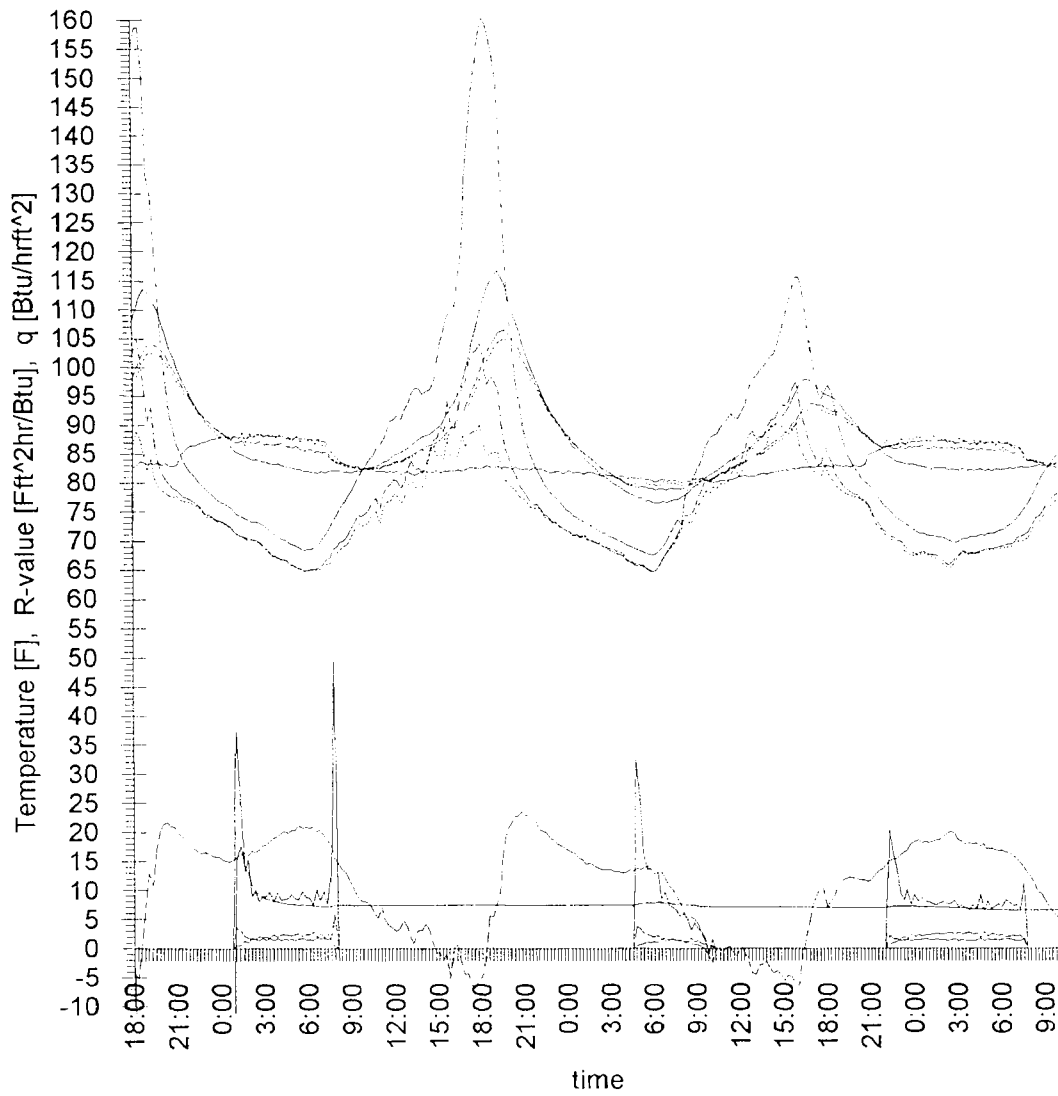
----- R tot cum	----- dT i,o surf	..... T out	----- T out surf
..... T in surf	----- T in	----- T room	..... q

7/5/92 Test 11 Window, Insulation no.1
and Gypsum Board 0.5 in.



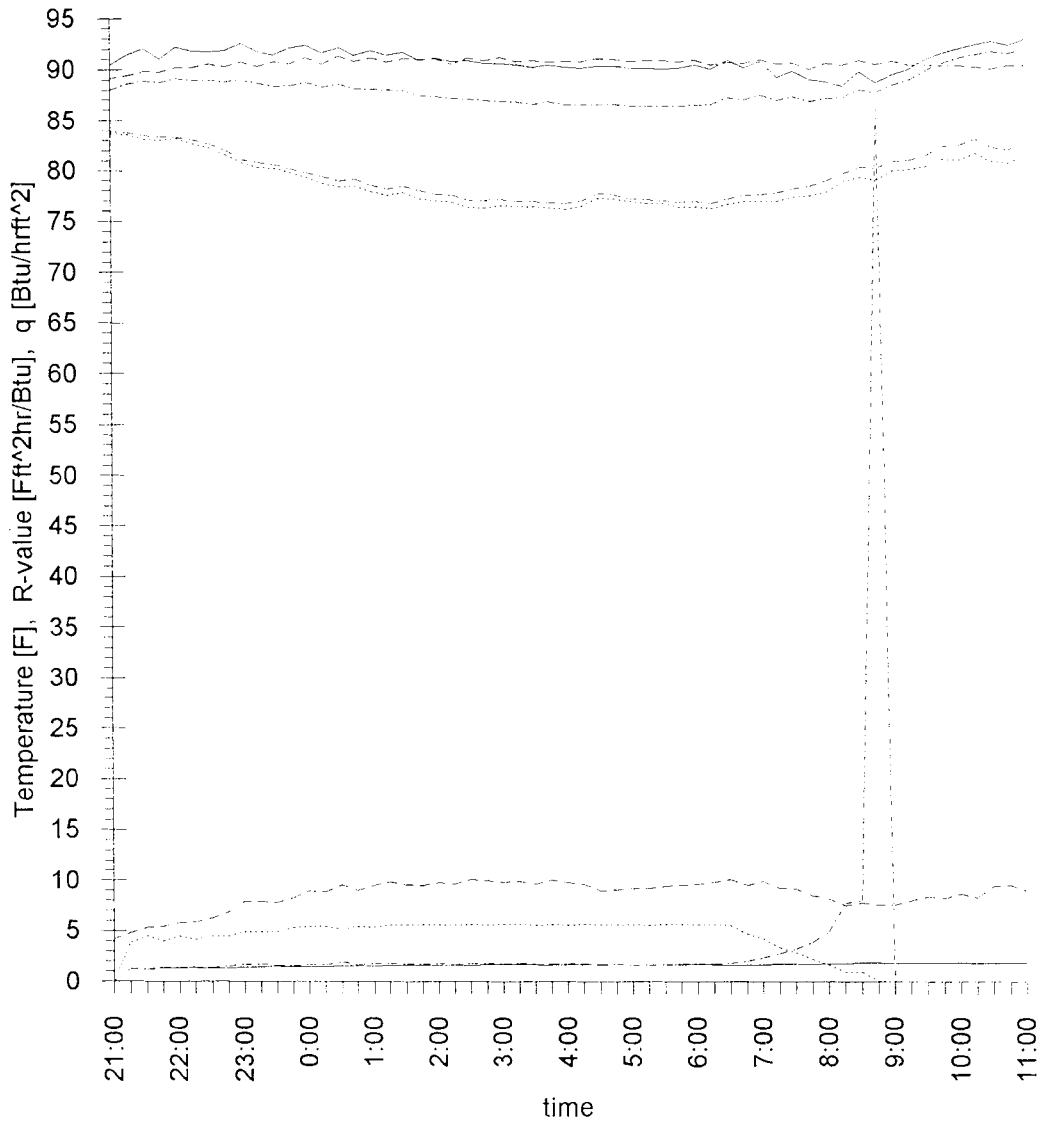
- | | | |
|----------------------|---------------------|-----------------------|
| — R tot cum | - - - dT i,o surf | T out |
| - · - · - T out surf | - · - · - T in surf | — T in |
| T room | q | - · - · - R tot inst. |

7/6/92 Test 12 Window, Insulation no. 1
and Gypsum Board 1 in.



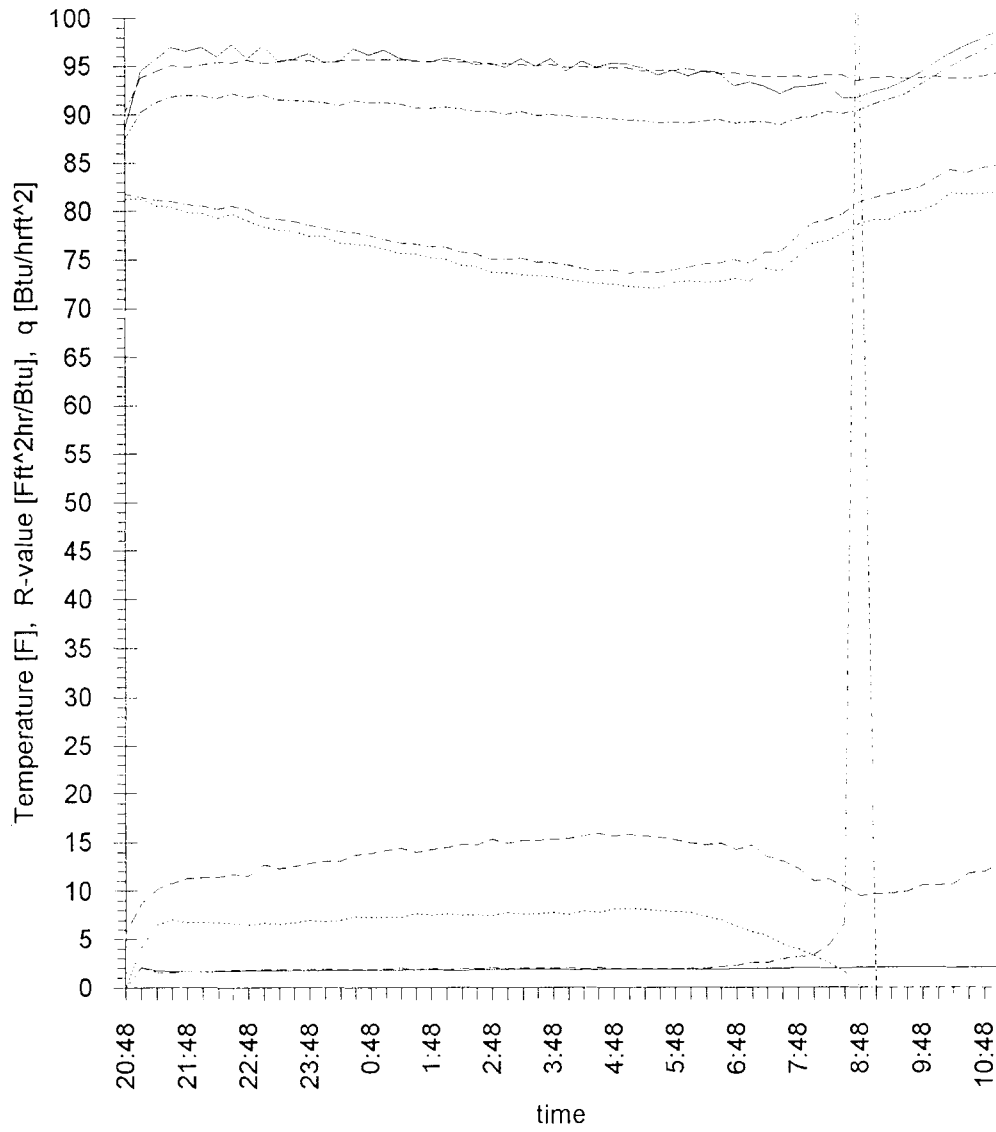
- | | | | |
|-----------------------|--------------------------|-------------------------|--------------------------|
| ----- R tot
com | - - - - - dT i,o
surf | T out | - - - - - T out
surf. |
| T win,
insul | ----- T insul,
gyp | - - - - - T in
surf. | T in |
| - - - - - T room | ----- q | ----- R tot
inst | - - - - - R gyp
inst |

7/10/92 Test 13 Window



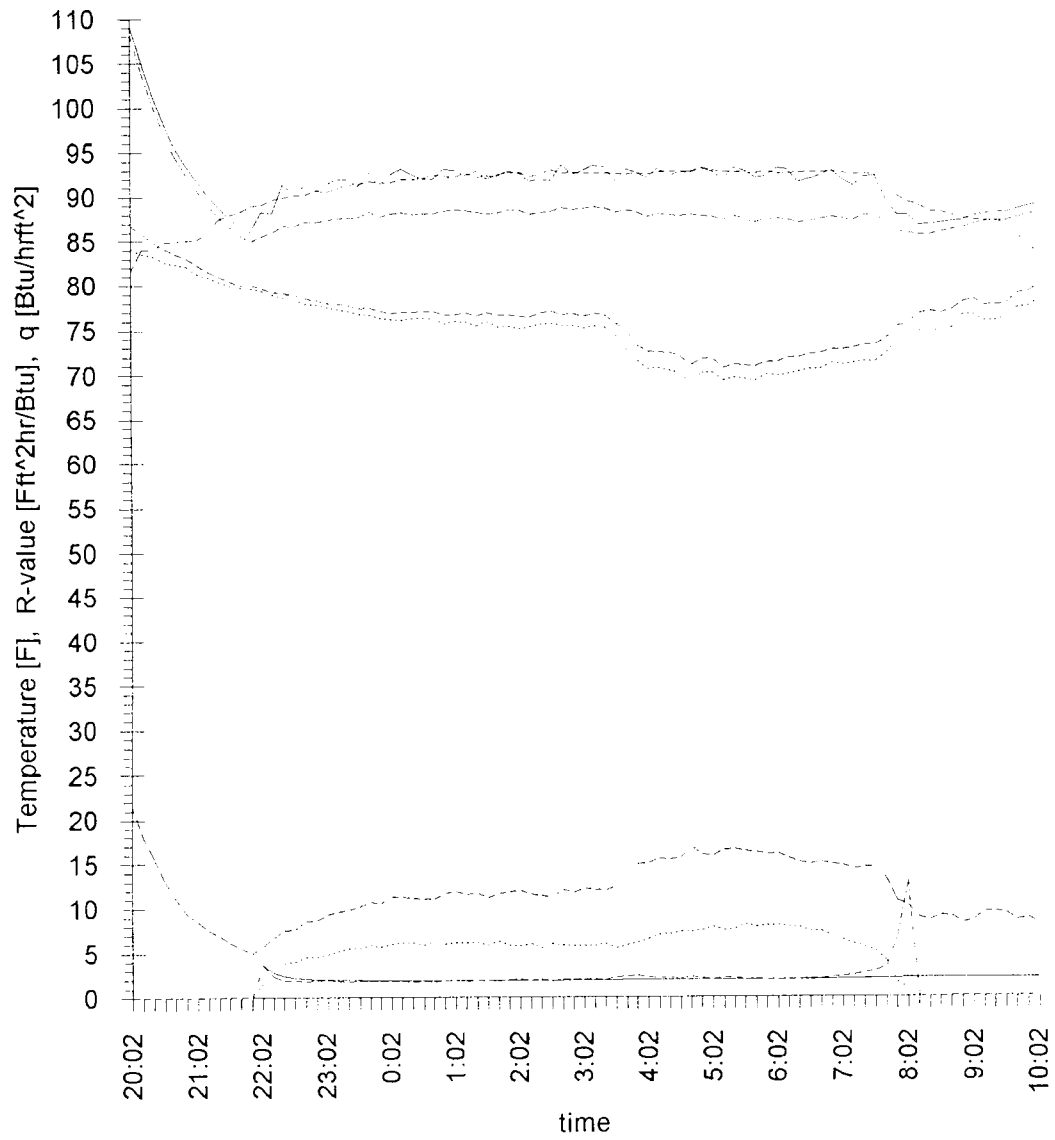
——— R tot cum	- - - - - dT i,o surf	..... T out
- - - - - T out surf.	..... T in surf.	——— T in
- - - - - T room	..... q	- - - - - R tot inst

7/11/92 Test 14 Window



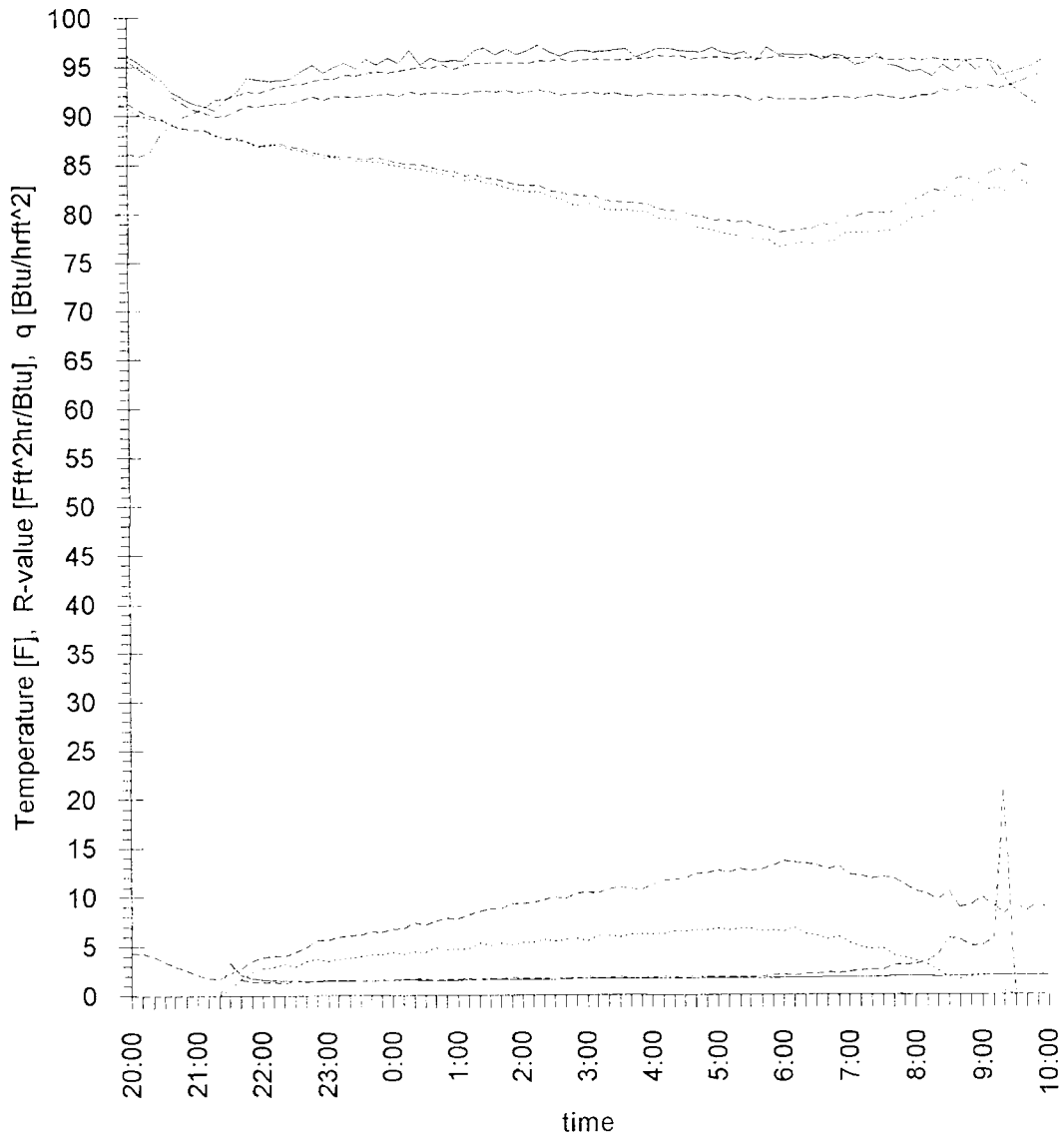
—— R tot cum	- - - - dT i,o surf	..... T out
- - - - T out surf.	..... T in surf.	—— T in
- - - - T room	..... q	- - - - R tot inst

7/13/92 Test 15 Window



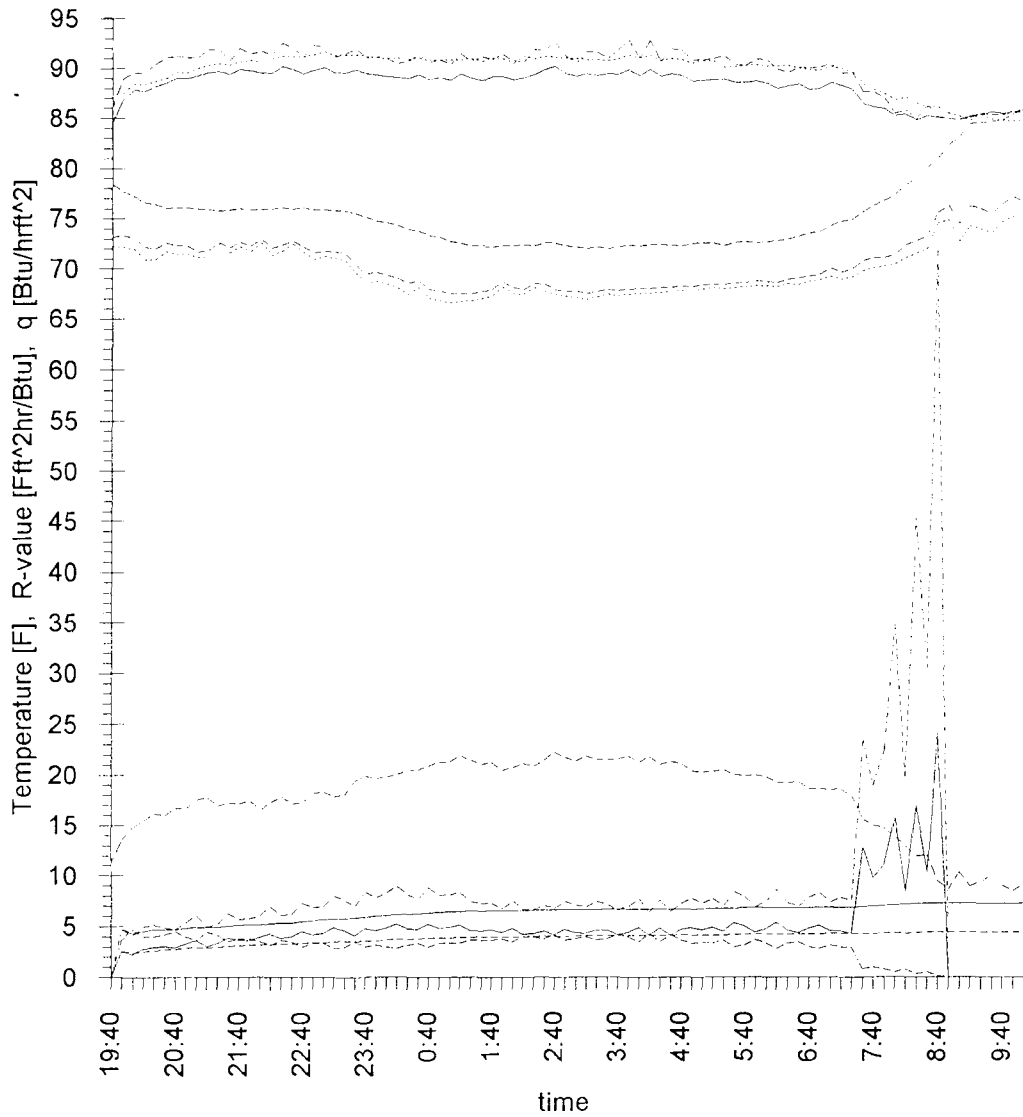
— R tot cum	- - - dT i,o surf	..... T out
- . - . T out surf.	..... T in surf.	— T in
- - - T room	..... R tot inst	- . - . q

7/14/92 Test 16 Window



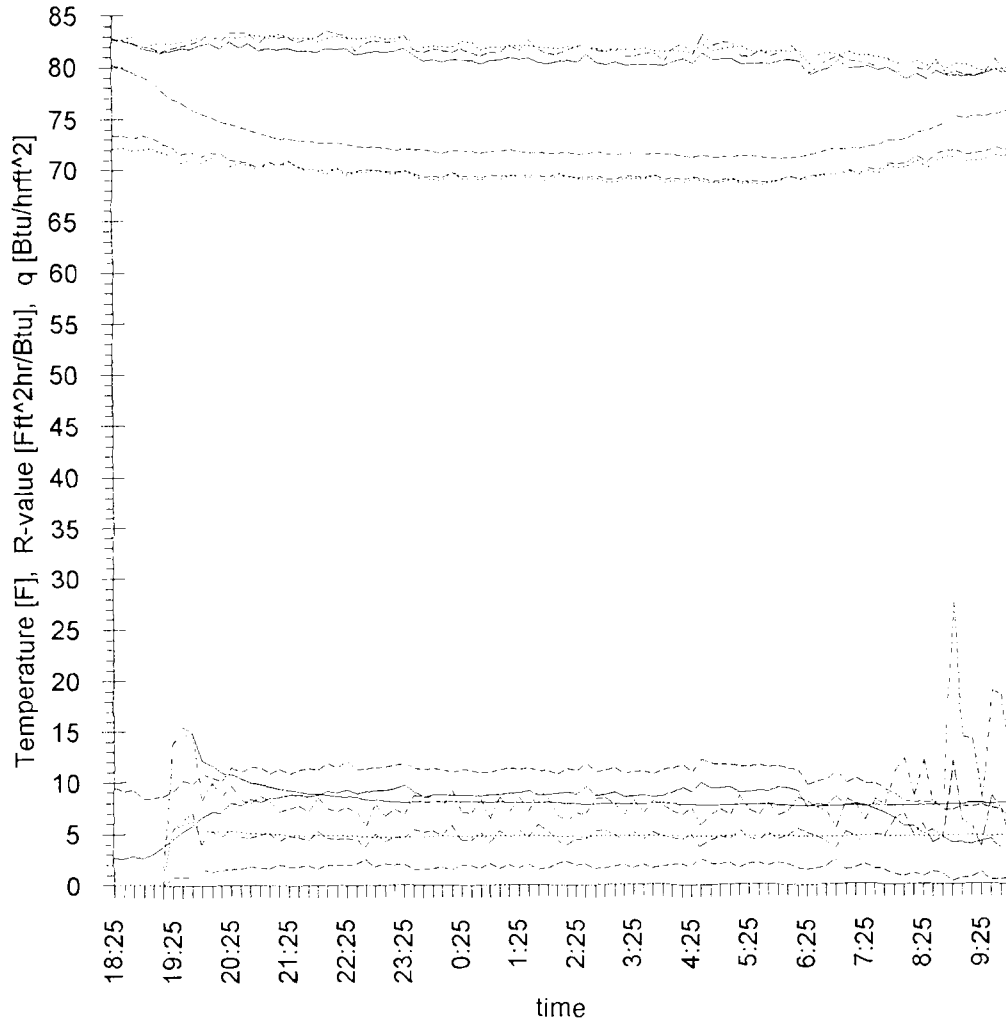
— R tot, cum	- - - dT i,o	..... T out
- · - · - T out, surf	- · - · - T in, surf	— T in
- - - T room	..... q	- · - · - R tot, inst

7/15/92 Test 17 Window and Insulation no.1



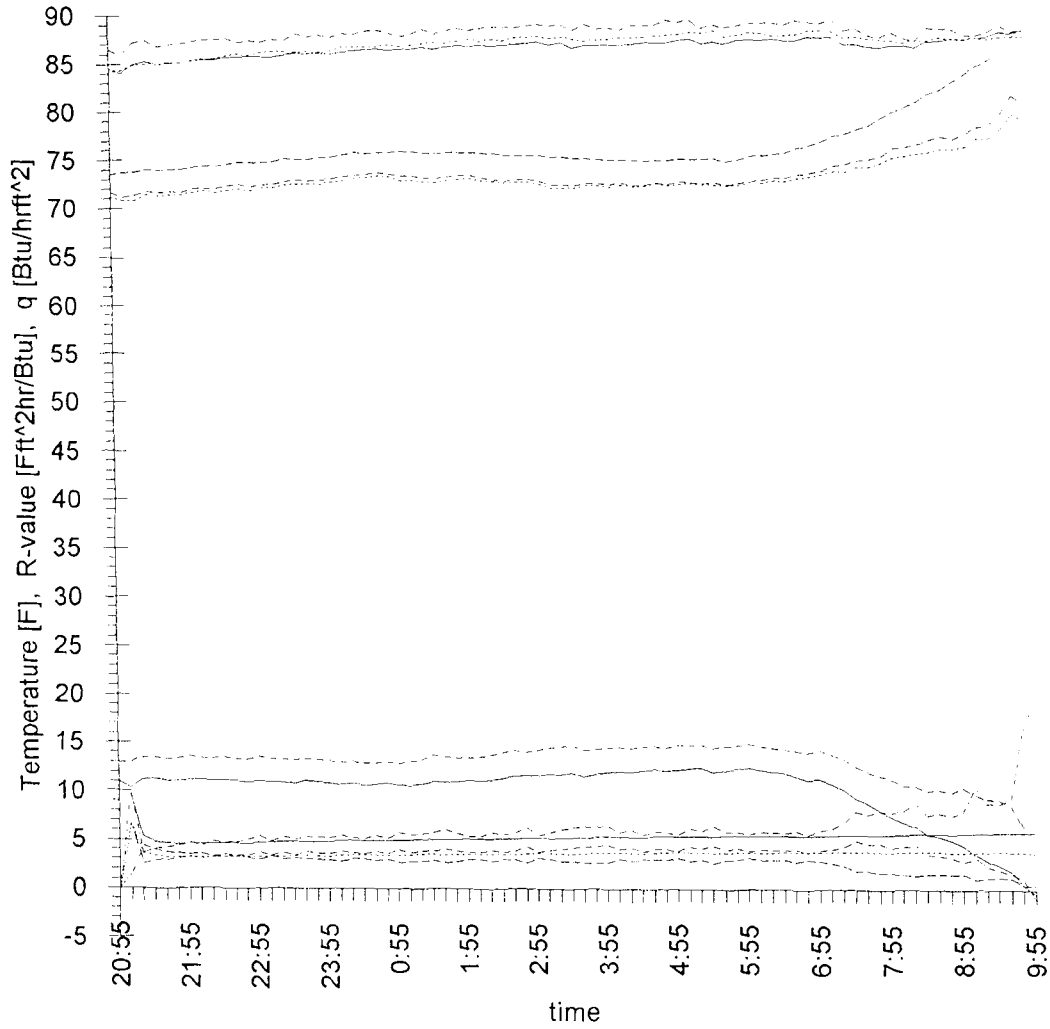
— R tot cum	- - - dT in, out surf	..... T out	- . - . T out, surf
..... T win, insul	— T in, surf	- - - T in	..... T room
- - - R tot inst	- - - q	— R insul inst	- - - R insul cum

7/16/92 Test 18 Window and Insulation no.1



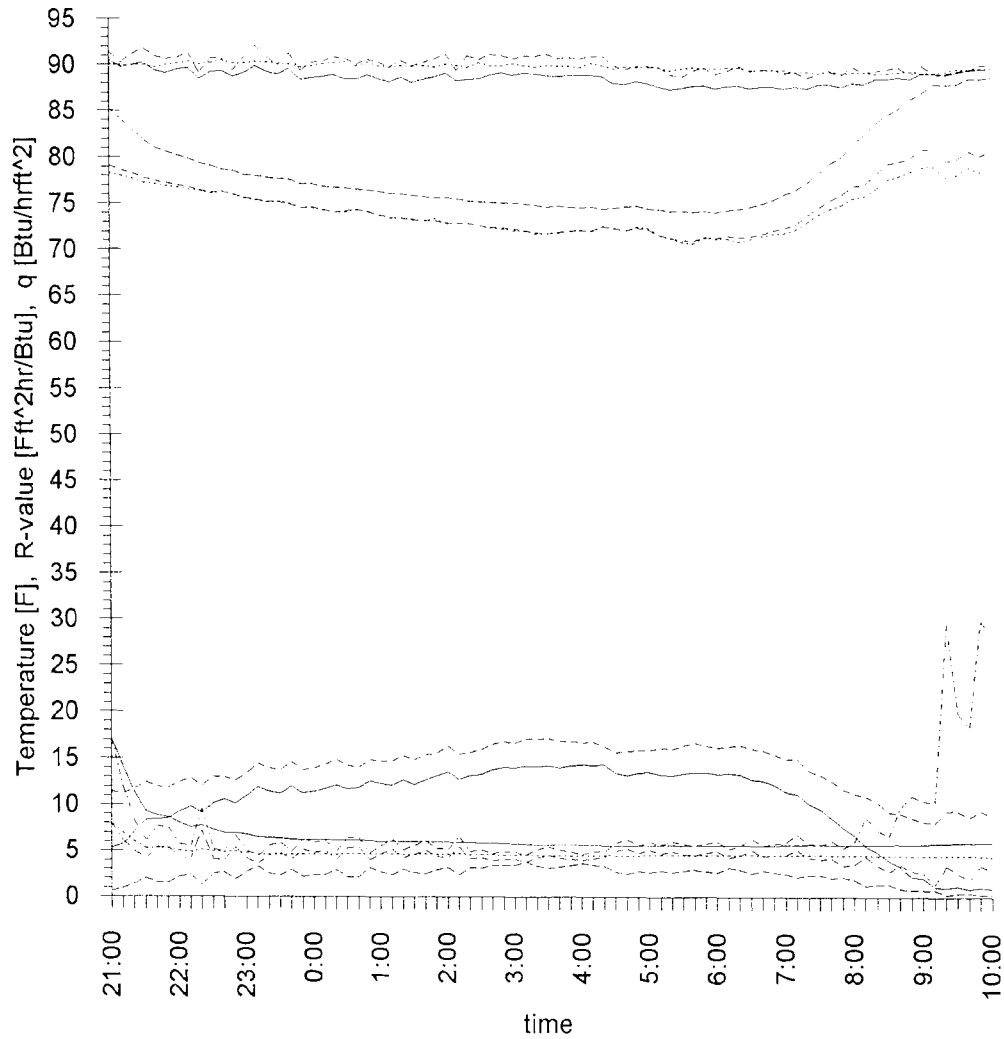
- R tot cum
- T win, insul
- R tot inst
- R insul cum
- - - dT i,o surf
- T in surf
- q
- dT in, insul
- T out
- - - T in
- T out surf
- T room
- - - R insul inst

7/17/92 Test 19 Window and Insulation no.1



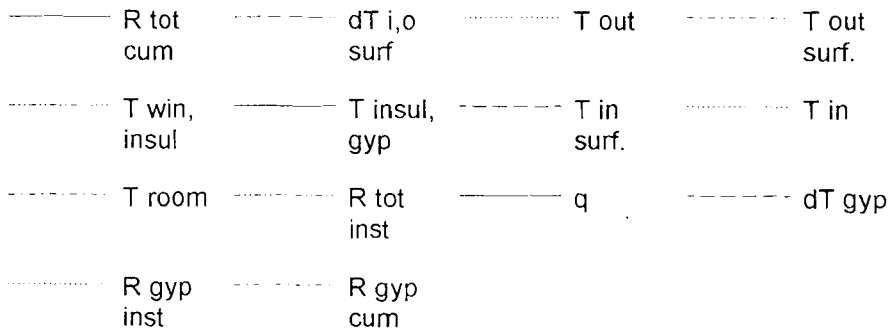
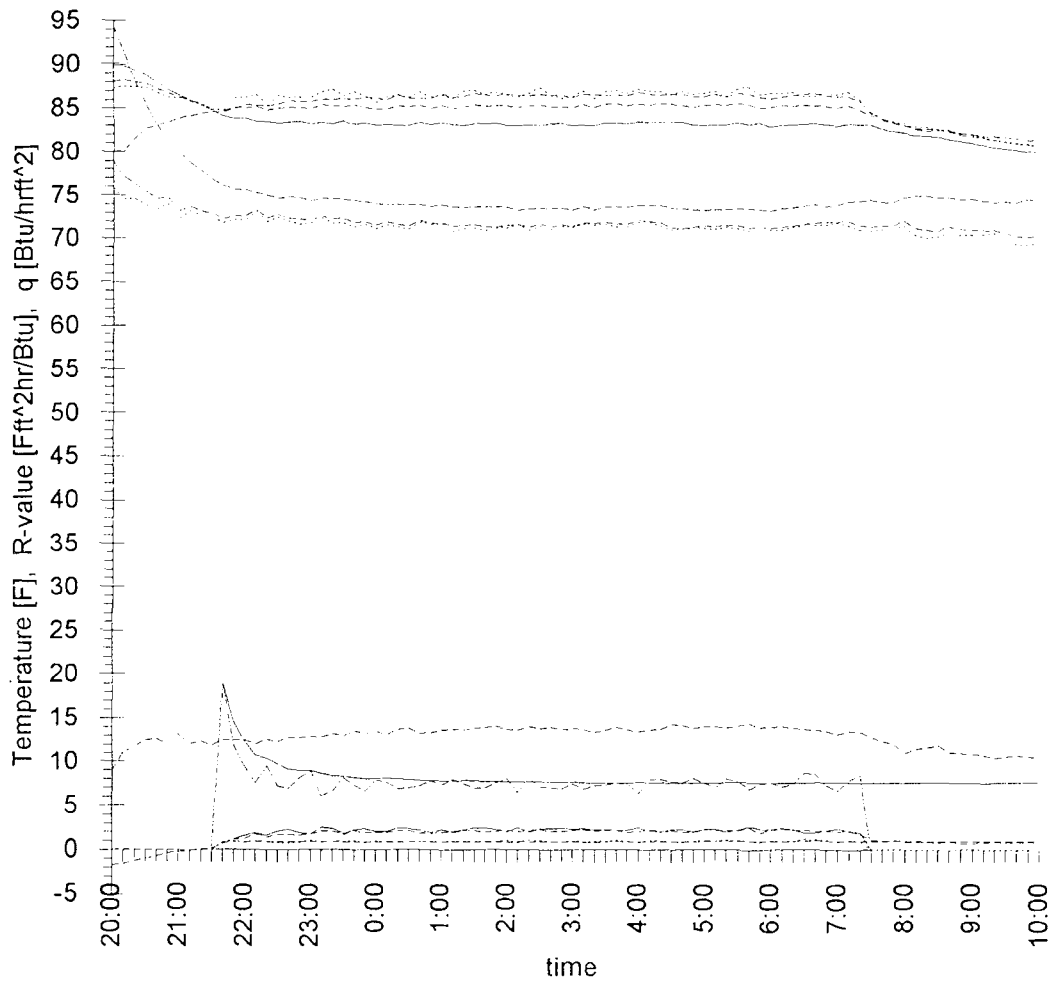
- | | | | |
|--------------------|-------------------|----------------|--------------------|
| — R tot cum | - - - dT i,o surf | T out | - - - T out surf |
| T win, insul | — T in surf | - - - T in | T room |
| - - - R tot inst | - - - q | — dT in, insul | - - - R insul inst |
| R insul cum | | | |

7/18/92 Test 20 Window and Insulation no.1

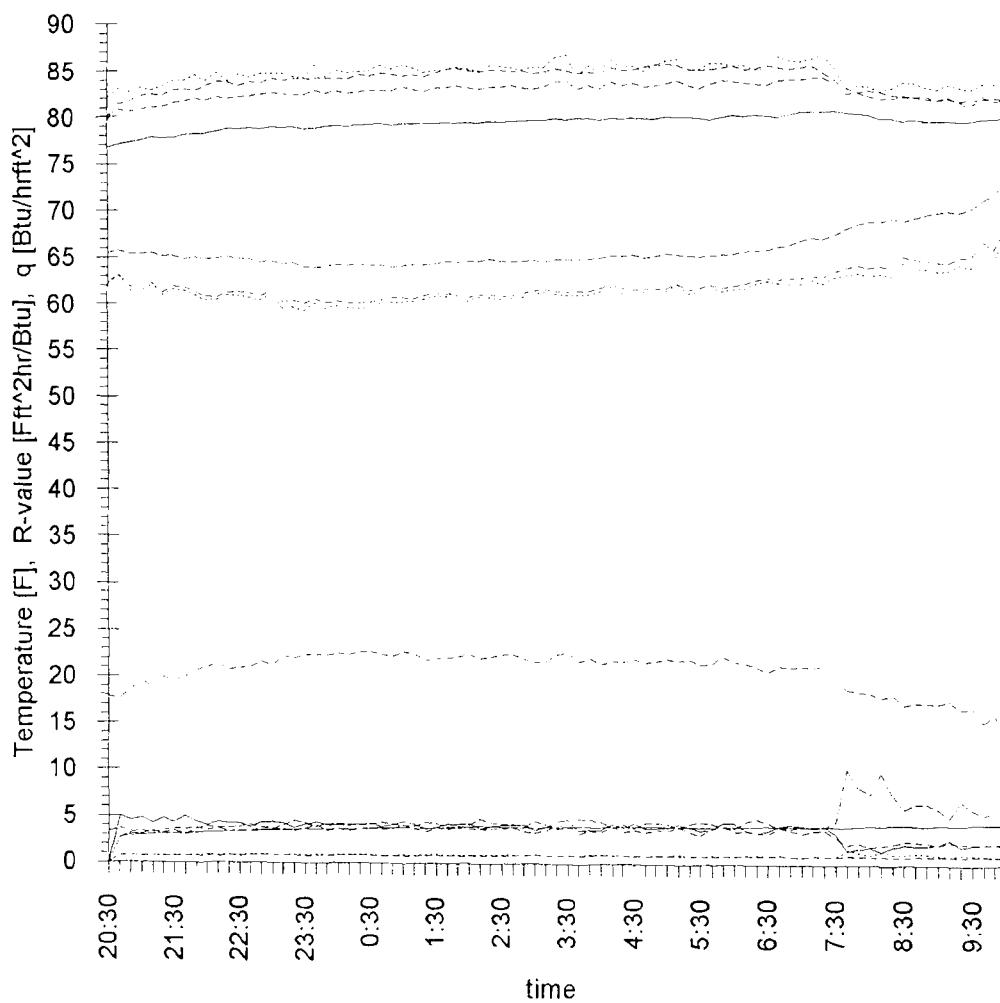


— R tot cum	- - - dT i,o surf	..... T out	- - - T out surf.
- . - T win, insul	— T in surf.	- - - T in	..... T room
- - - R tot inst	..... q	— dT insul	- - - R insul inst
..... R insul cum			

7/22/92 Test 21 Window, Insulation no.1
and Gypsum Board 0.5in.

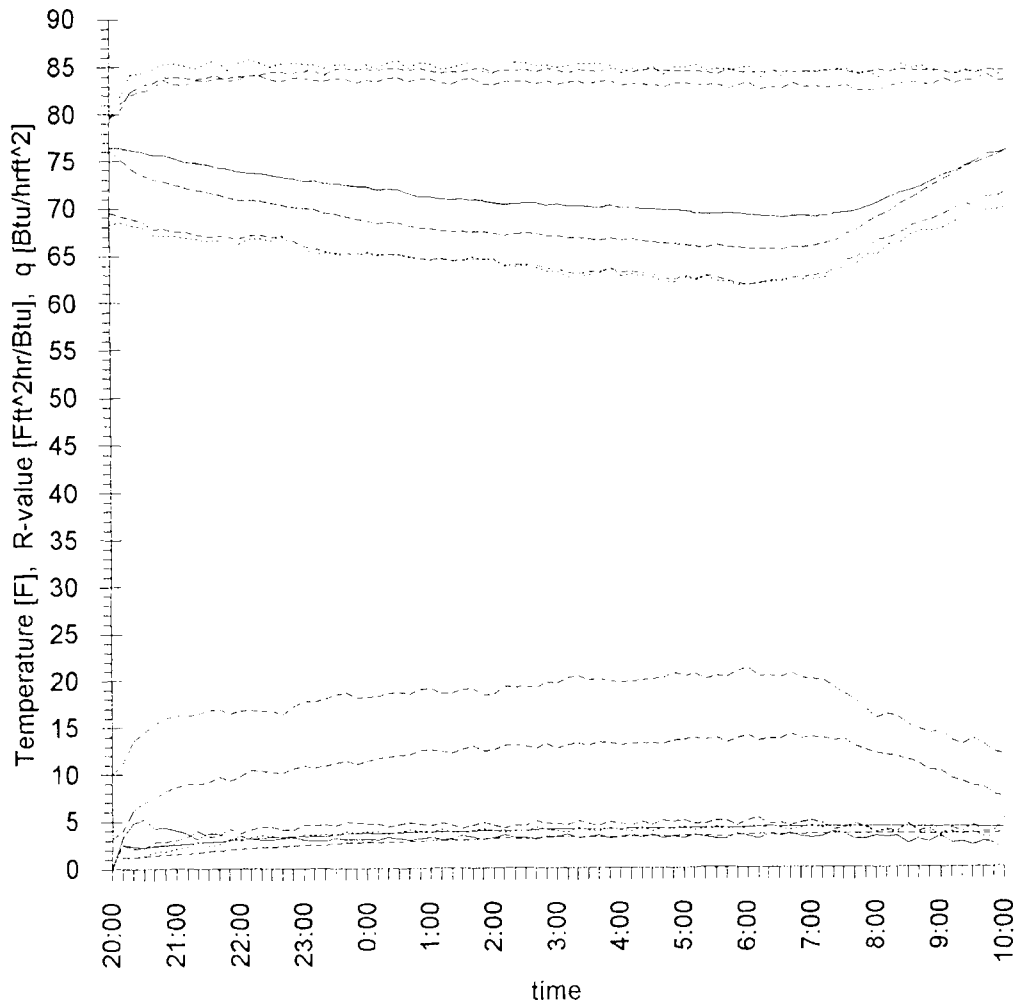


7/23/92 Test 22 Window, Insulation no.1
and Gypsum Board 0.5in.



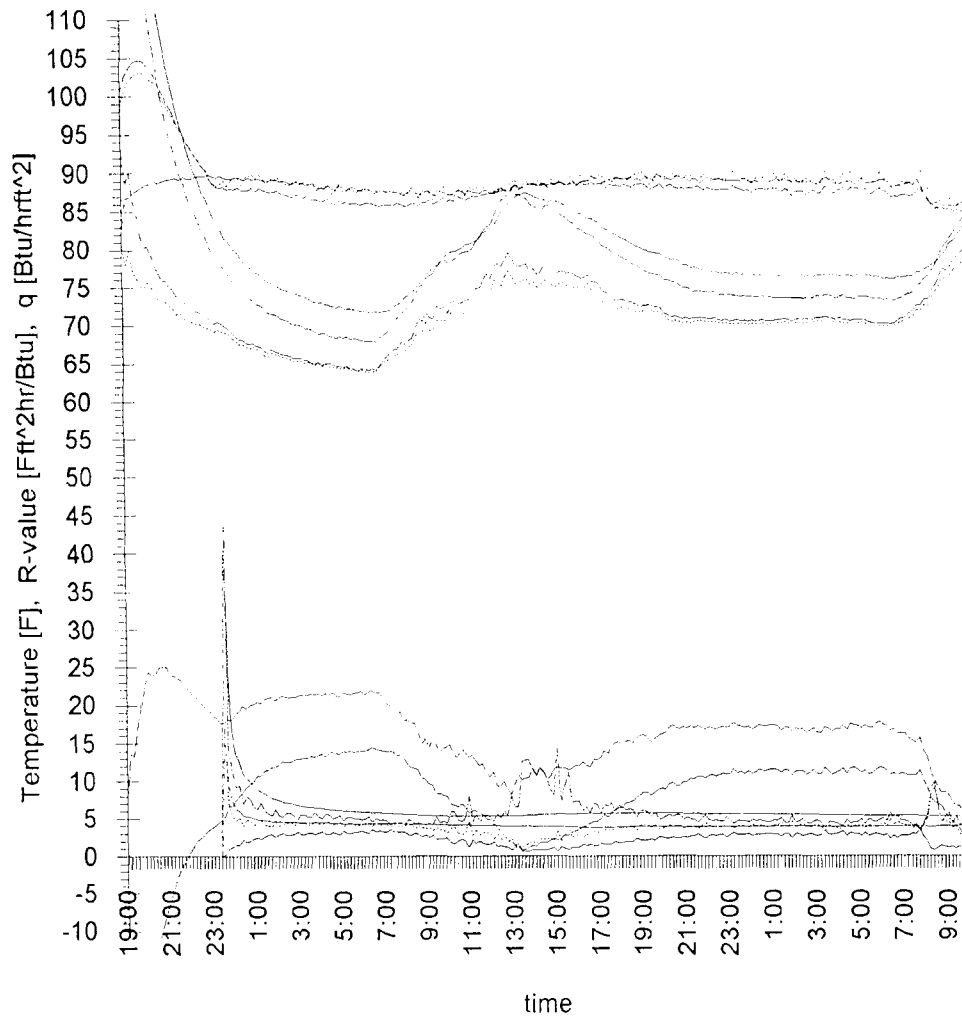
— R tot cum	- - - dT i,o surf	..... T out	- - - T out surf.
- - - T win, insul	— T insul, gyp	- - - T in surf.	..... T in
- - - T room	- - - R tot inst	— q	- - - dT gyp
..... R gyp inst	- - - R gyp cum		

7/24/92 Test 23 Window, Gypsum Board 1in.
and Insulation no.1



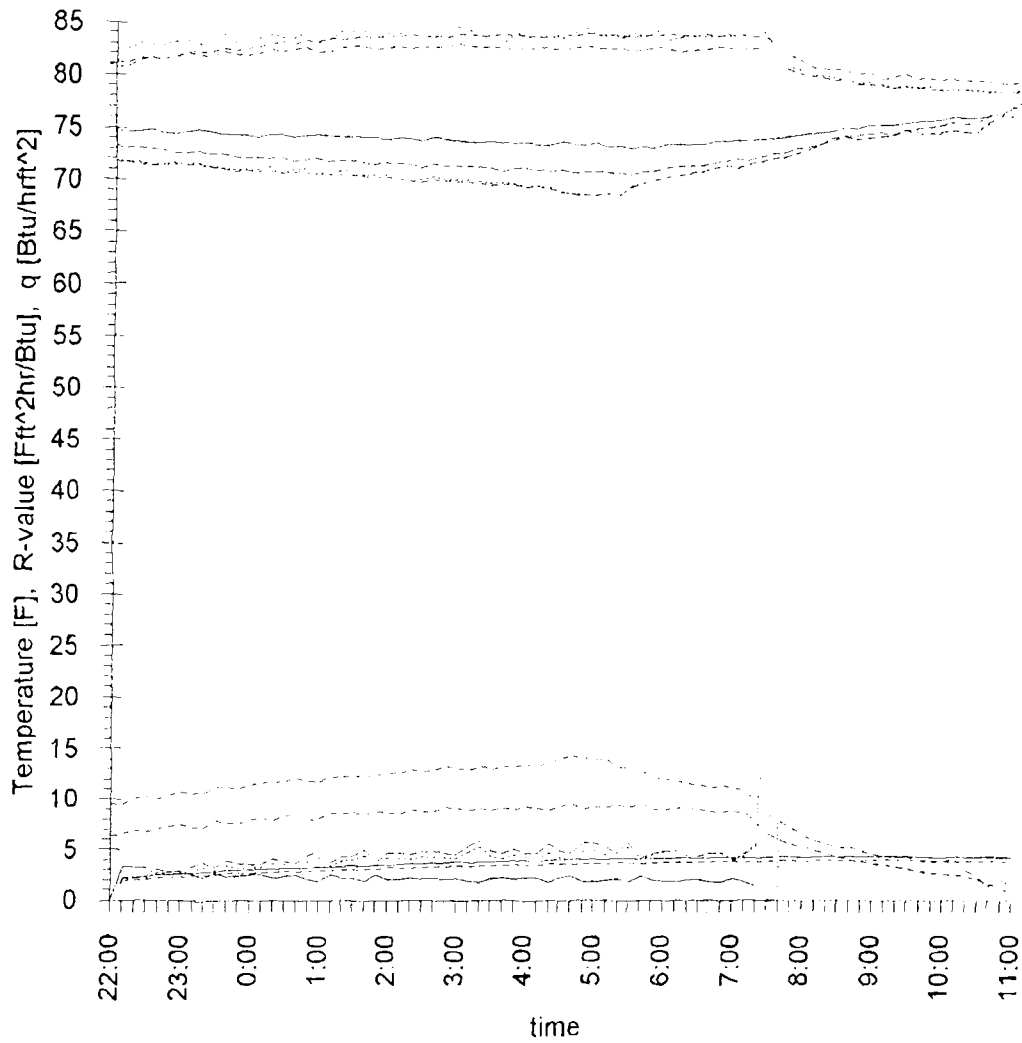
— R tot, cum	- - - dT i,o surf	..... T out	- - - T out, surf
- - - T win, gyp	— T gyp, insul	- - - T in, surf	..... T in
..... T room	..... R tot, inst	— q	- - - dT in, insul
..... R insul, inst	- - - R insul, cum		

7/25/92 Test 24 Window, Gypsum Board 1in.
and Insulation no.1



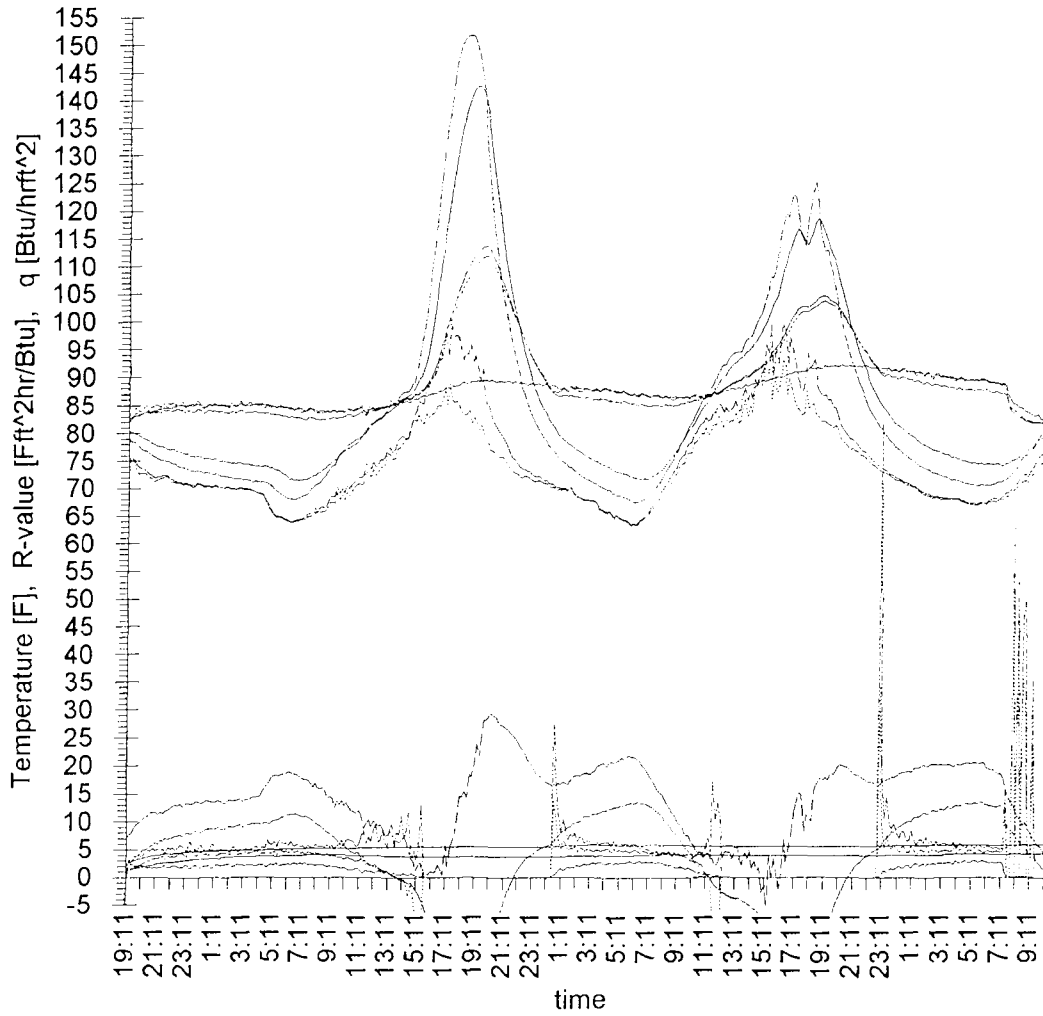
----- R tot, cum	----- dT i,o surf	..... T out	----- T out, surf
..... T win, gyp	----- T gyp, insul	----- T in, surf	..... T in
----- T room	..... R tot, inst	----- q	----- dT in, insul
..... R insul, inst	----- R insul, cum		

7/30/92 Test 25 Window, Gypsum Board 1in.
and Insulation no.1



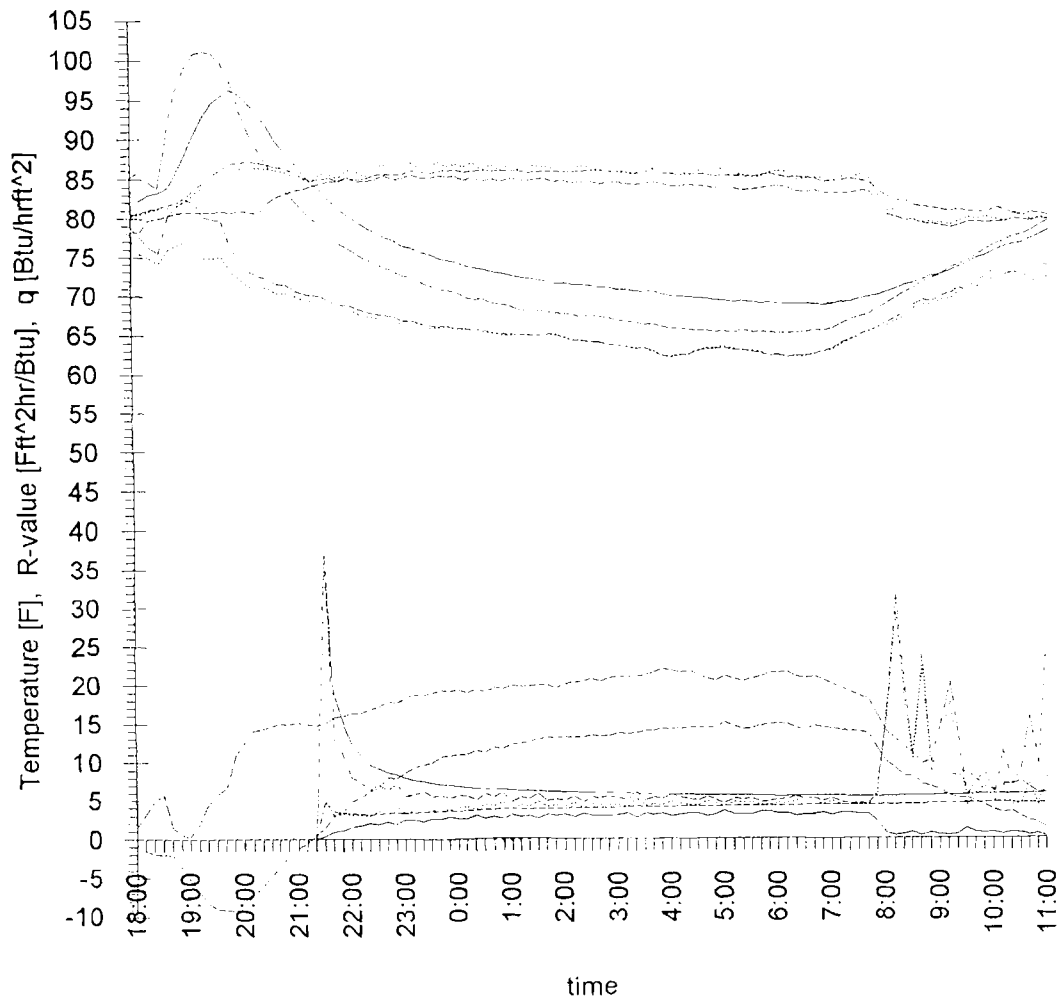
- | | | | |
|---------------------|--------------------|------------------|--------------------|
| — R tot, cum | - - - dT i,o surf | T out | - - - T out, surf |
| T win, gyp | — T gyp, insul | - - - T in, surf | T in |
| - - - T room | - - - R tot, inst | — q | - - - dT in, insul |
| R insul, inst | - - - R insul, cum | | |

7/31/92 Test 26 Window, Gypsum Board 1in. and Insulation no.1



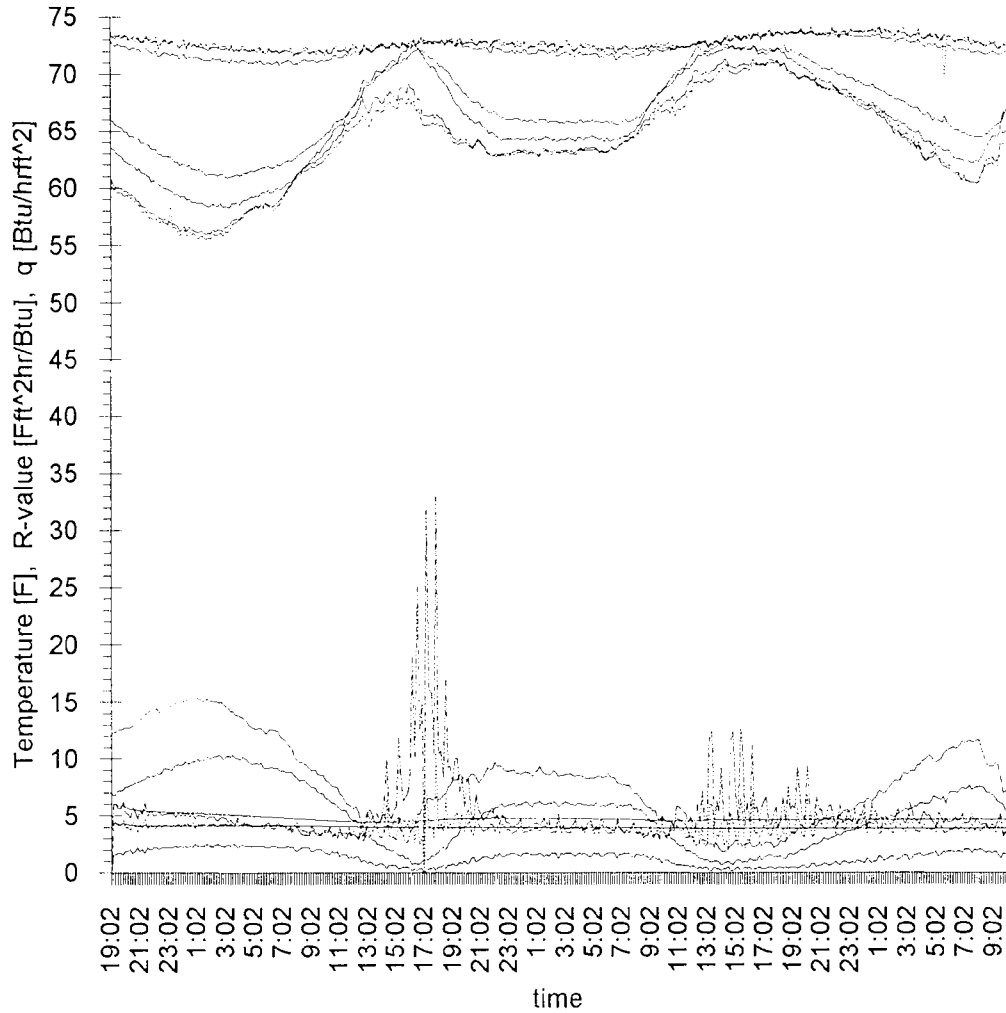
- | | | | |
|---------------------|--------------------|------------------|-------------------|
| — R tot, cum | - - - dT i,o surf | T out | - - - T out, surf |
| - - - T win, gyp | — T gyp, insul | - - - T in, surf | T in |
| - - - T room | - - - R tot, inst | — q | - - - dT i, insul |
| R insul, inst | - - - R insul, cum | | |

8/04/92 Test 27 Window, Gypsum Board 1 in.
and Insulation no.1



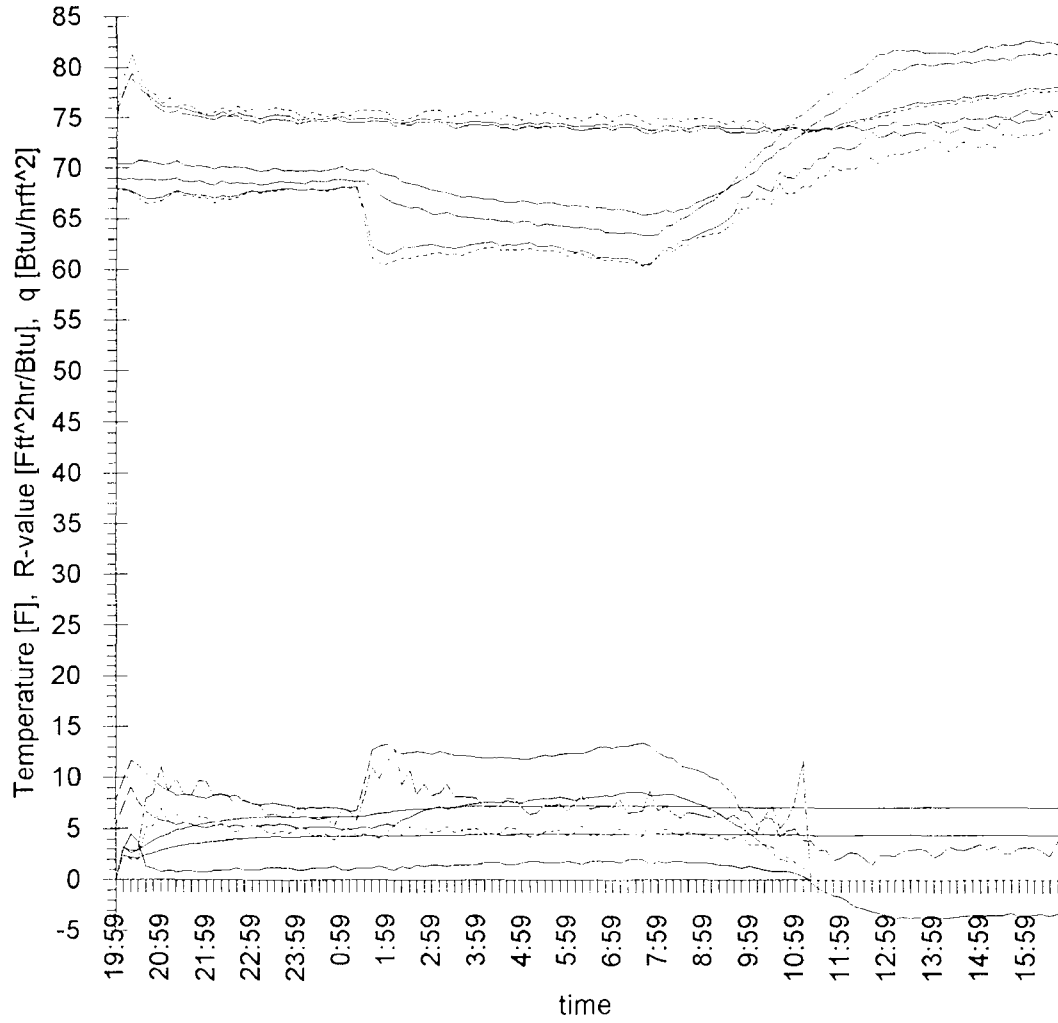
- | | | | |
|---------------------|--------------------|------------------|--------------------|
| — R tot, cum | - - - dT i,o surf | · · · T out | - - - T out, surf |
| - - - T win, gyp | — T gyp, insul | - - - T in, surf | · · · T in |
| - - - T room | - - - R tot, inst | — q | - - - dT in, insul |
| · · · R insul, inst | - - - R insul, cum | | |

9/25/92 Test 28 Window, Gypsum Board 1in.
and Insulation no.1



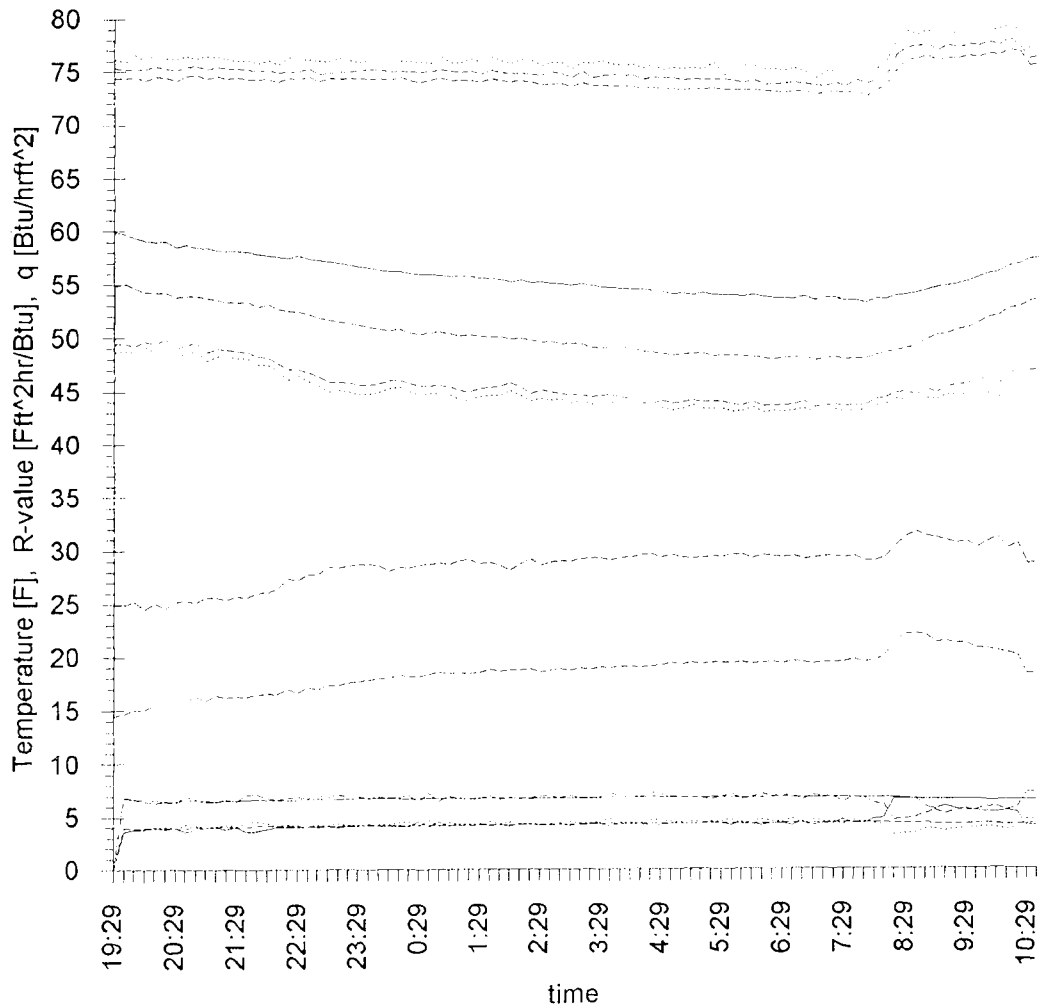
- | | | | |
|---------------------|------------------------|----------------------|------------------------|
| ----- R tot, cum | - - - - - dT i,o surf | T out | - - - - - T out, surf |
| T win, gyp | ----- T gyp, insul | - - - - - T in, surf | T in |
| - - - - - T room | R tot, inst | ----- q | - - - - - dT in, insul |
| R insul, inst | - - - - - R insul, cum | | |

10/09/92 Test 29 Window, Gypsum Board 1in.
and Insulation no.1



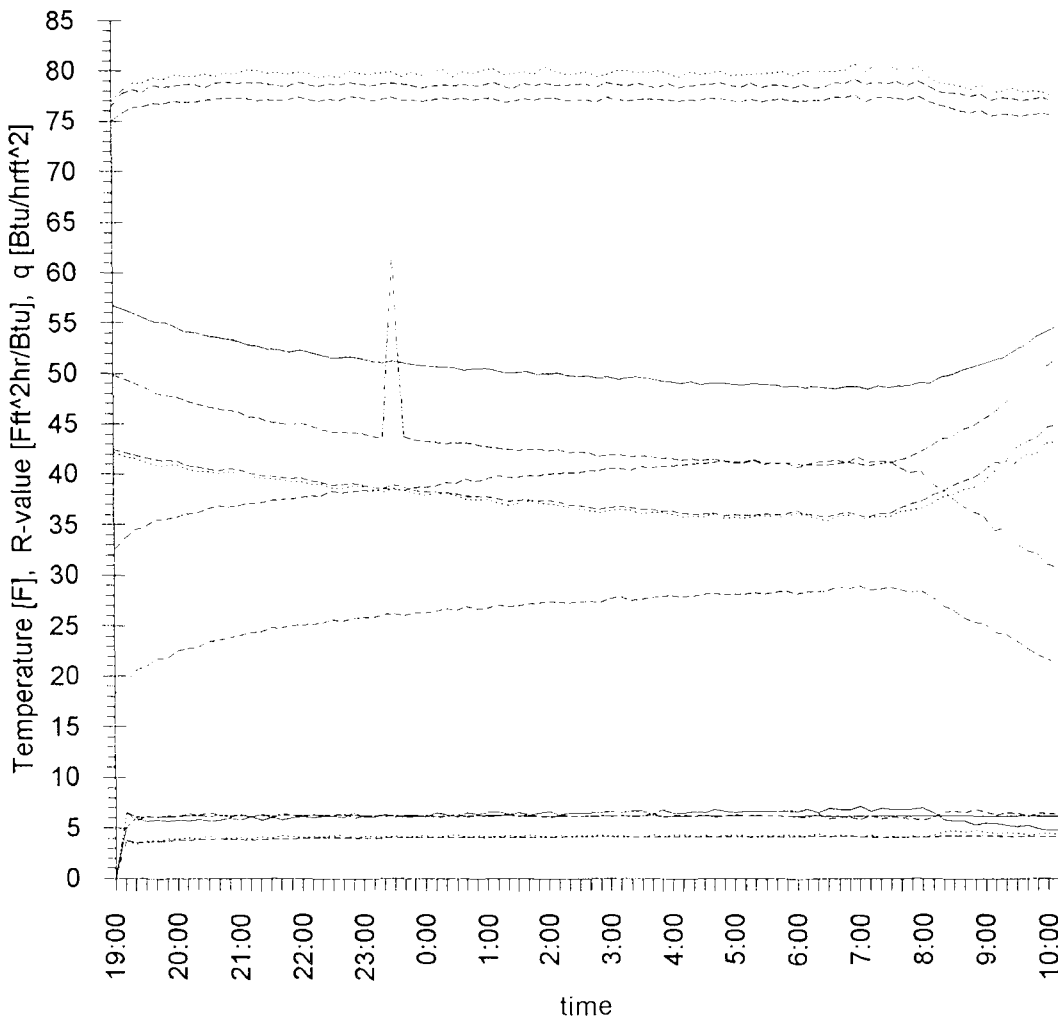
- | | | | |
|--------------------|-------------------|-----------------|--------------------|
| — R tot cum | - - - dT i,o surf | T out | - - - T out surf |
| T win, gyp | — T gyp, insul | - - - T in surf | T in |
| - - - T room | R tot inst | — q | - - - dT in, insul |
| R insul inst | - - - R insul cum | | |

10/18/92 Test 30 Window, Gypsum Board 1in.
and Insulation no.1



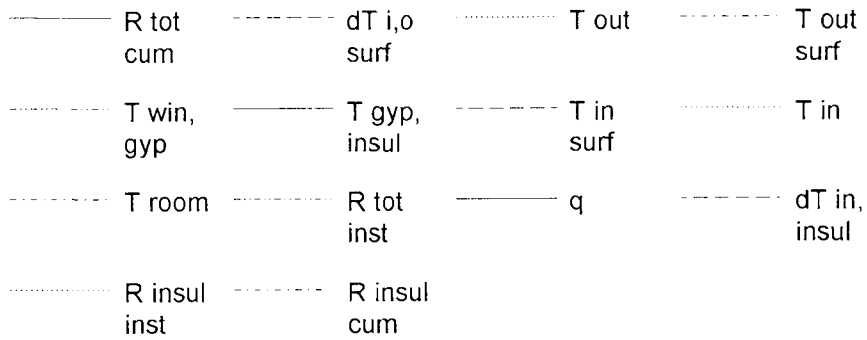
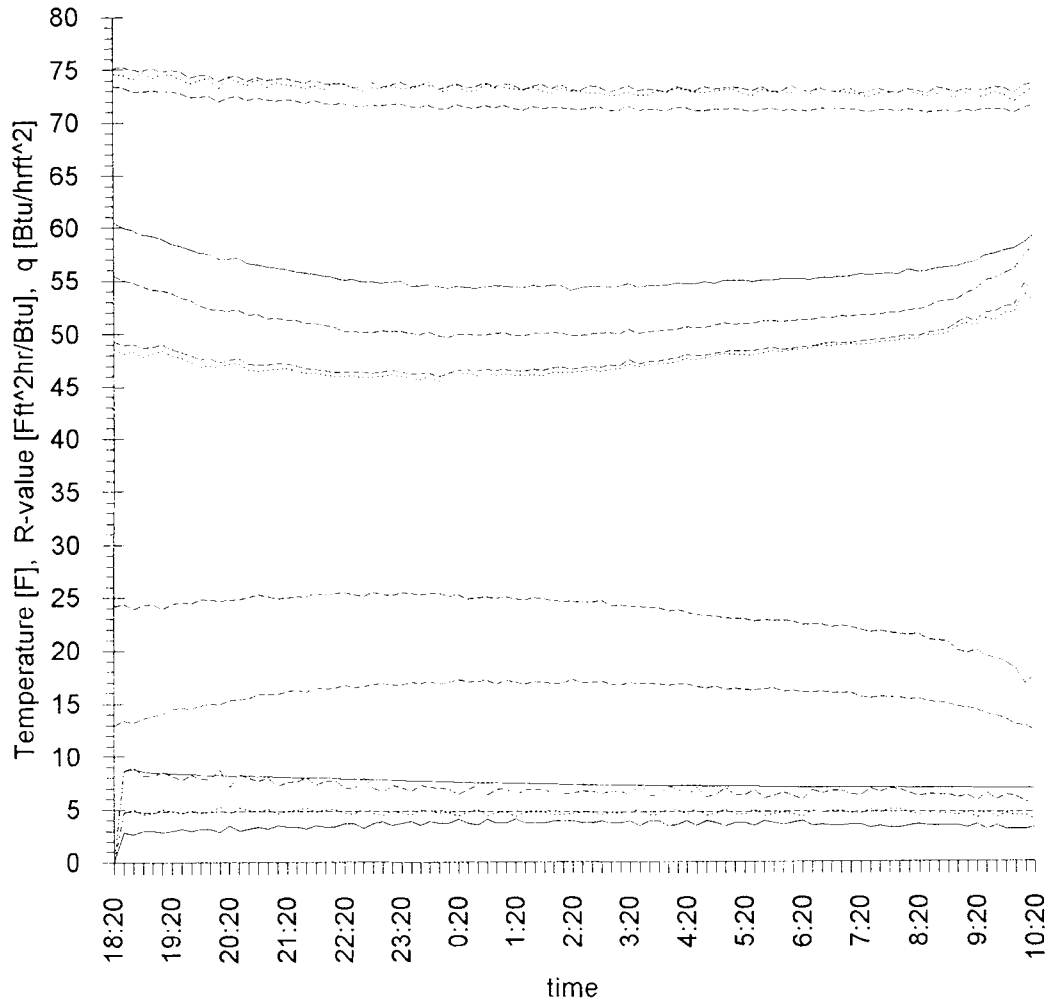
----- R tot cum	- - - - - dT i,o surf	..... T out	- - - - - T out surf
..... T win, gyp	----- T gyp, insul	- - - - - T in surf	..... T in
- - - - - T room	- - - - - R tot inst	----- q	- - - - - dT in, insul
..... R insul inst	- - - - - R insul cum		

10/19/92 Test 31 Window, Gypsum Board 1in.
and Insulation no.1

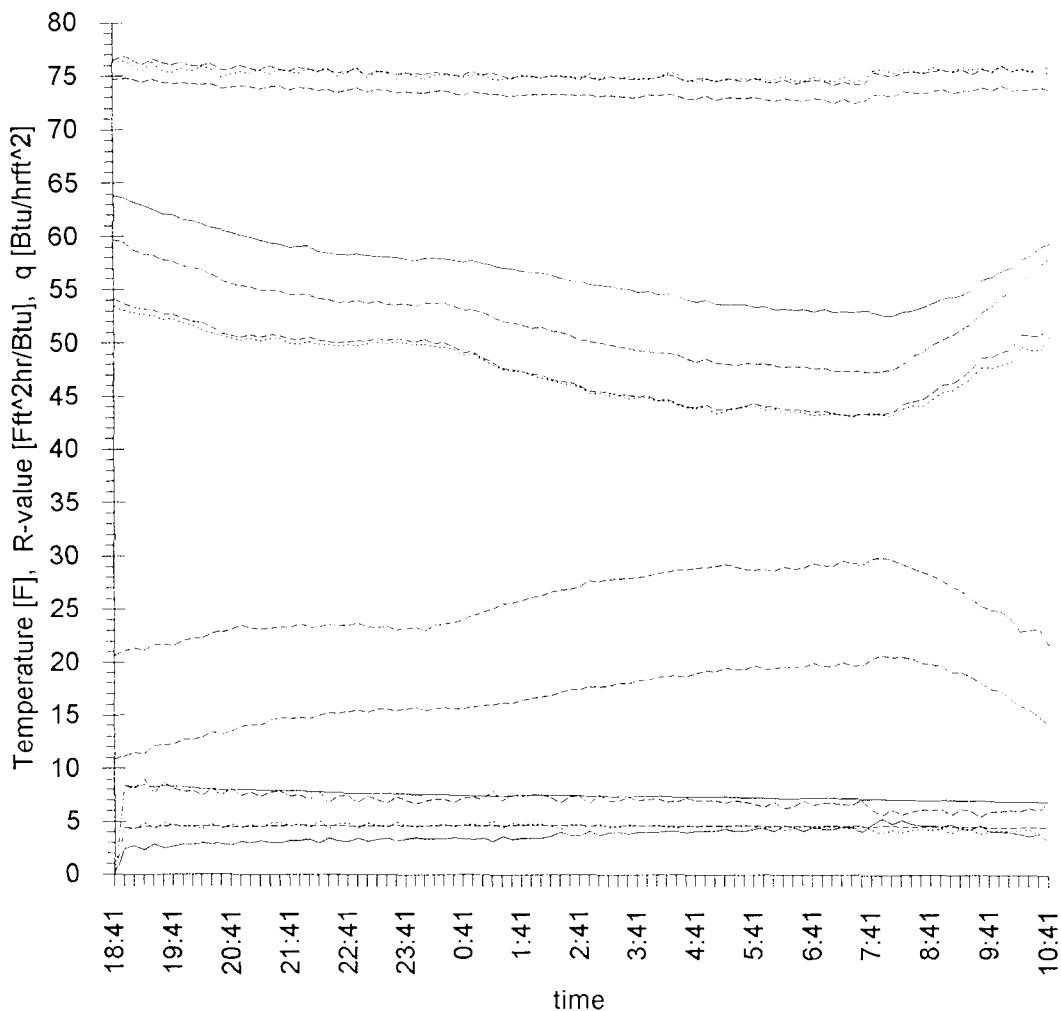


— R tot cum	- - - dT i,o surf	..... T out	- - - T out surf
- - - T win, gyp	— T gyp, insul	- - - T in surf	..... T in
..... T room	..... R tot inst	— q	- - - dT in, insul
..... R insul inst	- - - R insul cum		

10/20/92 Test 32 Window, Gypsum Board 1in.
and Insulation no.1

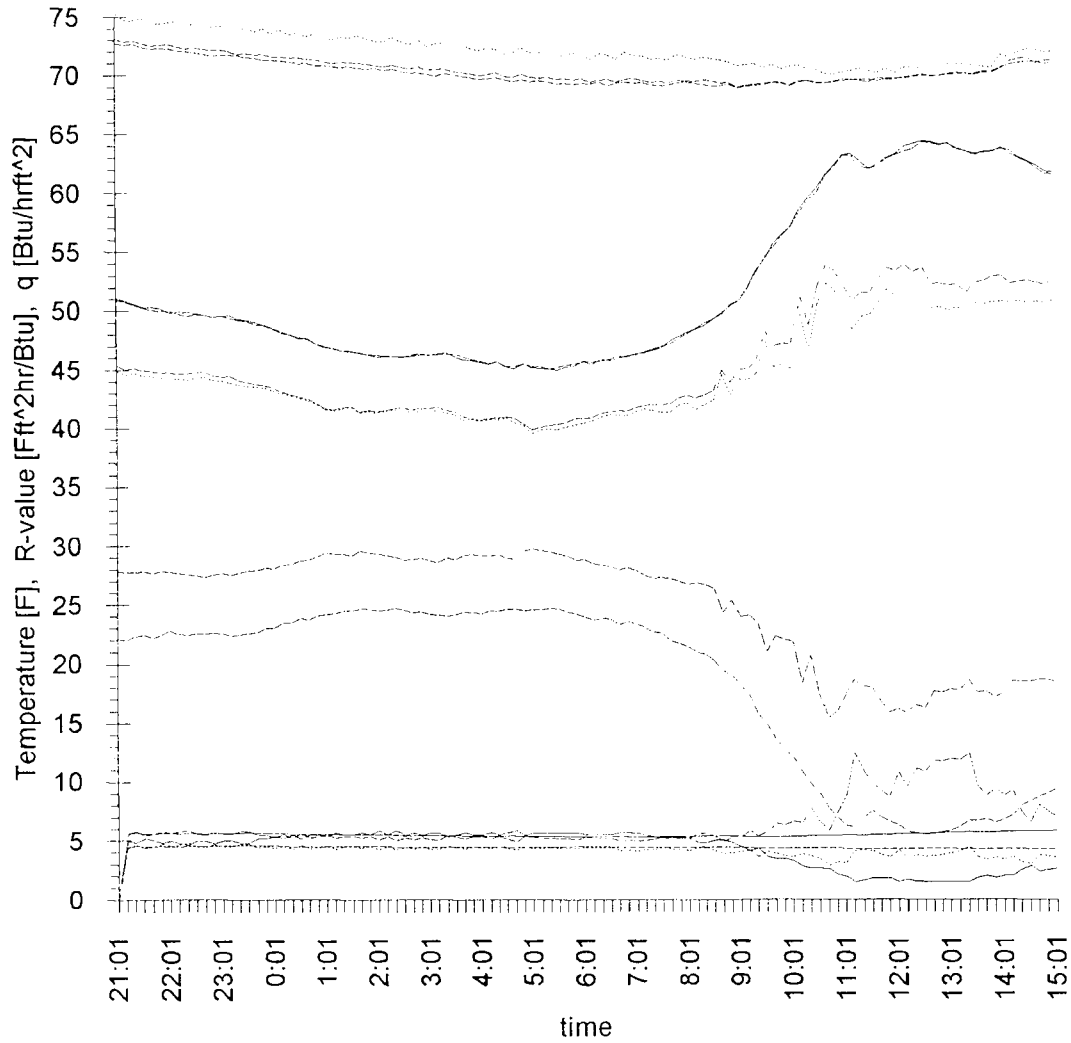


10/21/92 Test 33 Window, Gypsum Board 1in.
and Insulation no.1



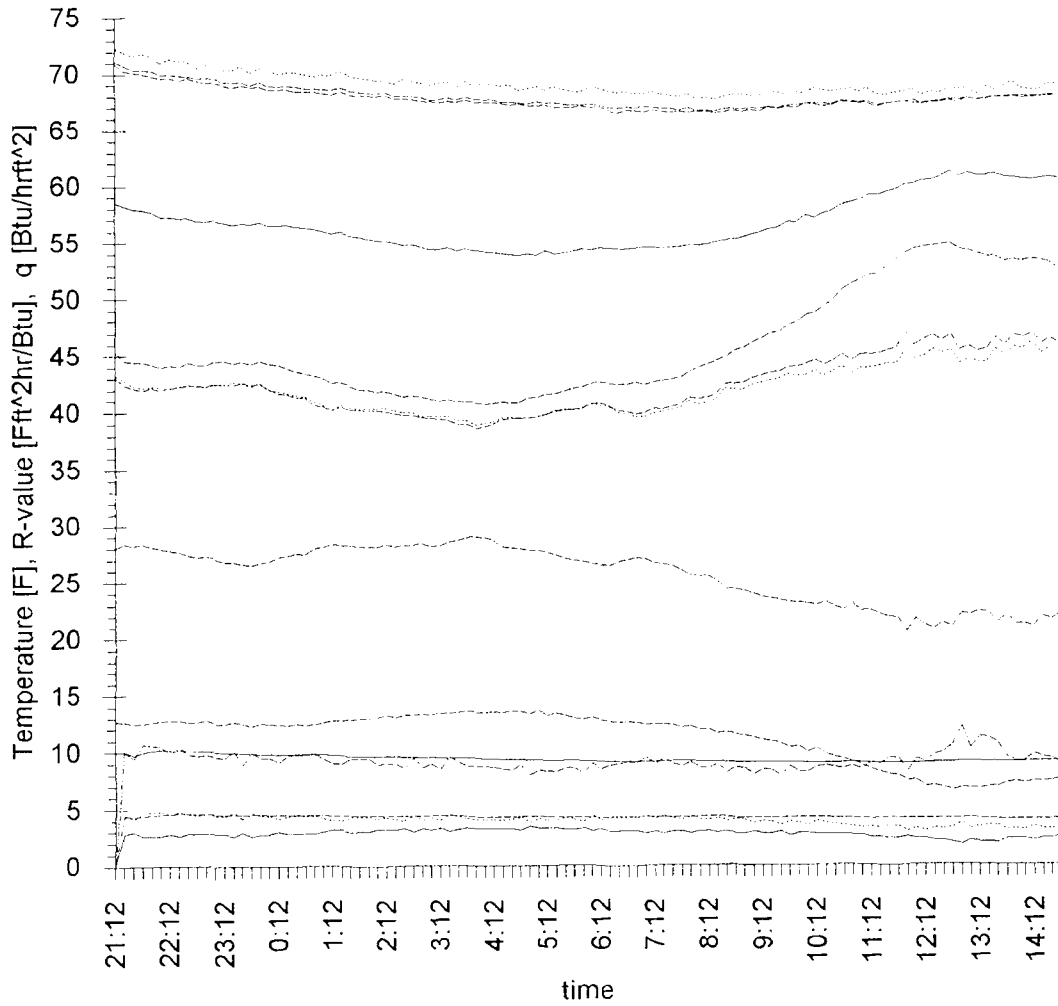
— R tot cum	- - - dT i,o surf	..... T out	- - - T out surf
- - - T win, gyp	— T gyp, insul	- - - T in surf	..... T in
- - - T room	..... R tot inst	— q	- - - dT in, insul
..... R insul inst	- - - R insul cum		

11/27/92 Test 34 Window and Insulation no.1



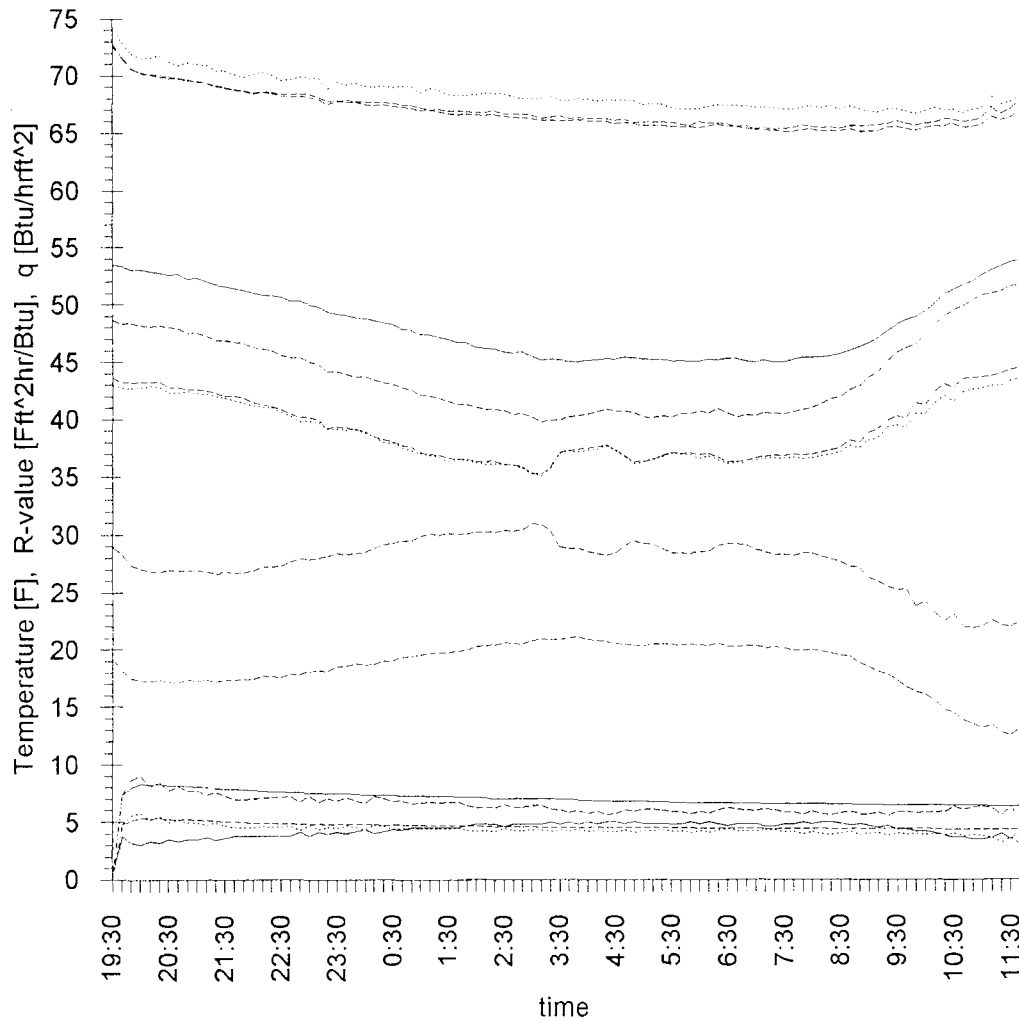
—— R tot cum	- - - - dT i,o surf	..... T out	- - - - T out surf
..... T win, insul	—— T win, insul	- - - - T in surf	..... T in
- - - - T room	- - - - R tot inst	—— q	- - - - dT in, insul
..... R insul inst	- - - - R insul cum		

11/28/92 Test 35 Window, Insulation no.1
and Insulation no.12



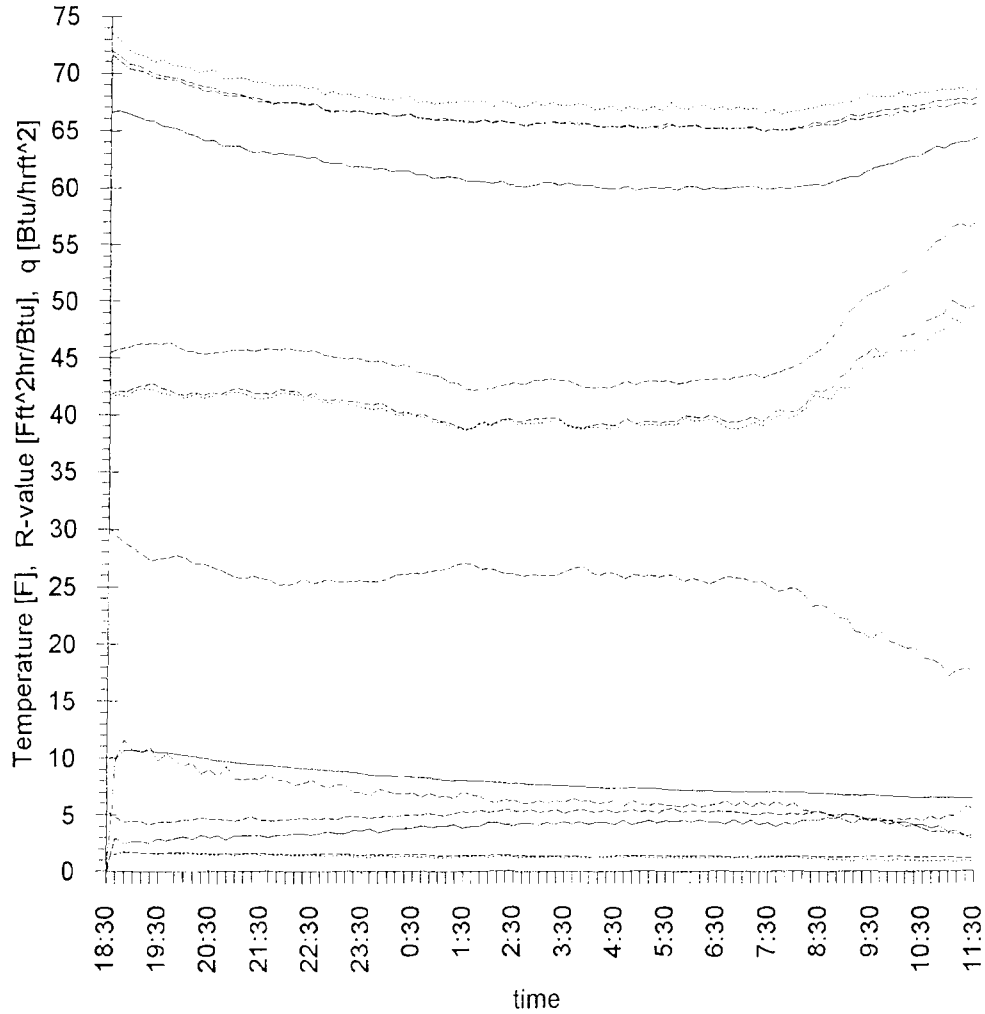
----- R tot cum	- - - - - dT i,o surf	..... T out	- - - - - T out surf
- - - - - T win, insul 1	----- T insul, insul 12	- - - - - T in surf	..... T in
- - - - - T room	- - - - - R tot inst	----- q	- - - - - dT in, insul
..... R insul inst	- - - - - R insul cum		

11/29/92 Test 36 Window, Gypsum Board 1in.
and Insulation no.1



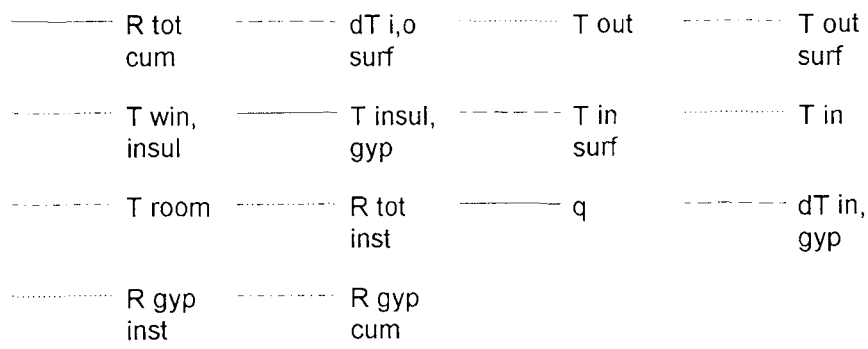
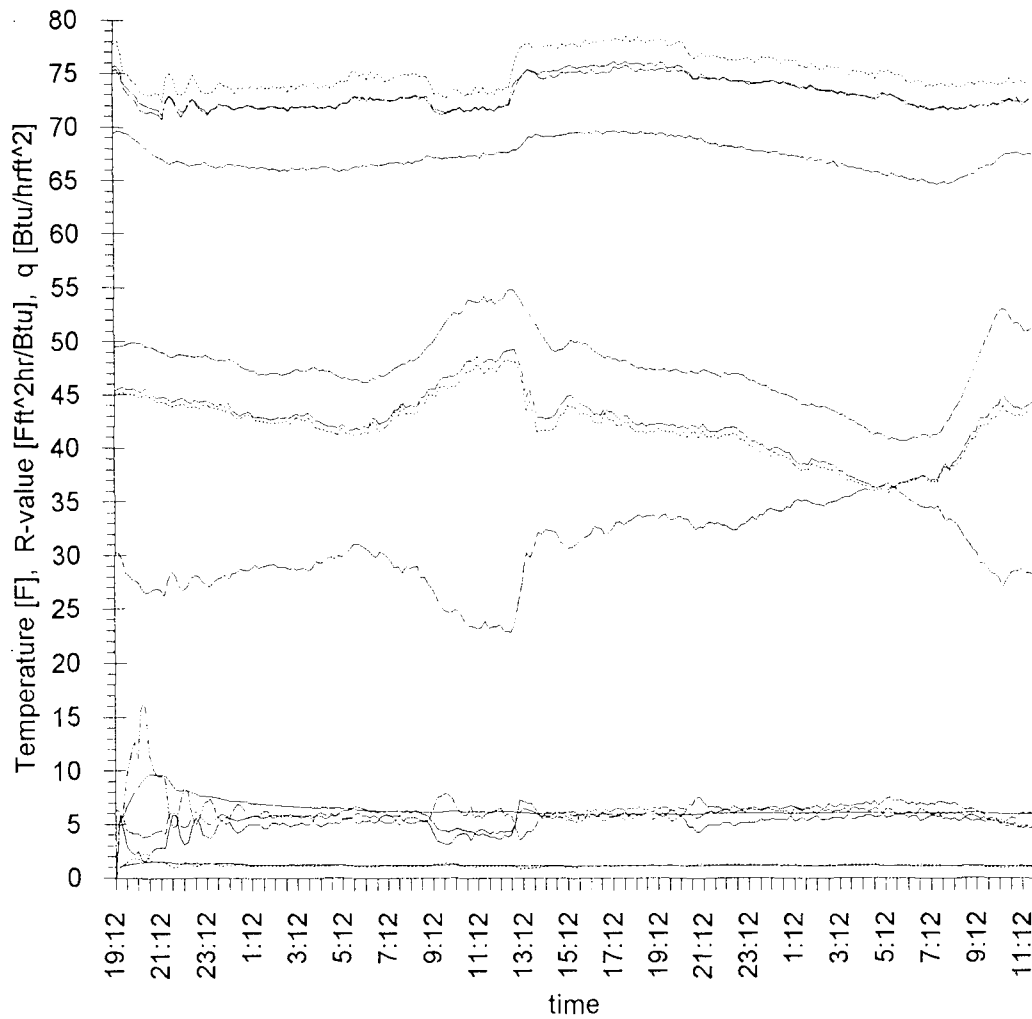
----- R tot cum	----- dT i,o surf	..... T out	----- T out surf
..... T win,gyp	----- T gyp, insul	----- T in surf	..... T in
----- T room	----- R tot inst	----- q	----- dT in,insul
..... R insul inst	----- R insul cum		

11/30/92 Test 37 Window, Insulation no.1
and Gypsum Board lin.

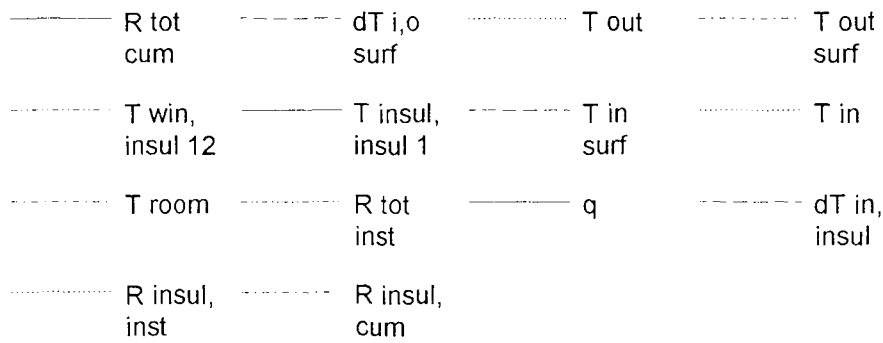
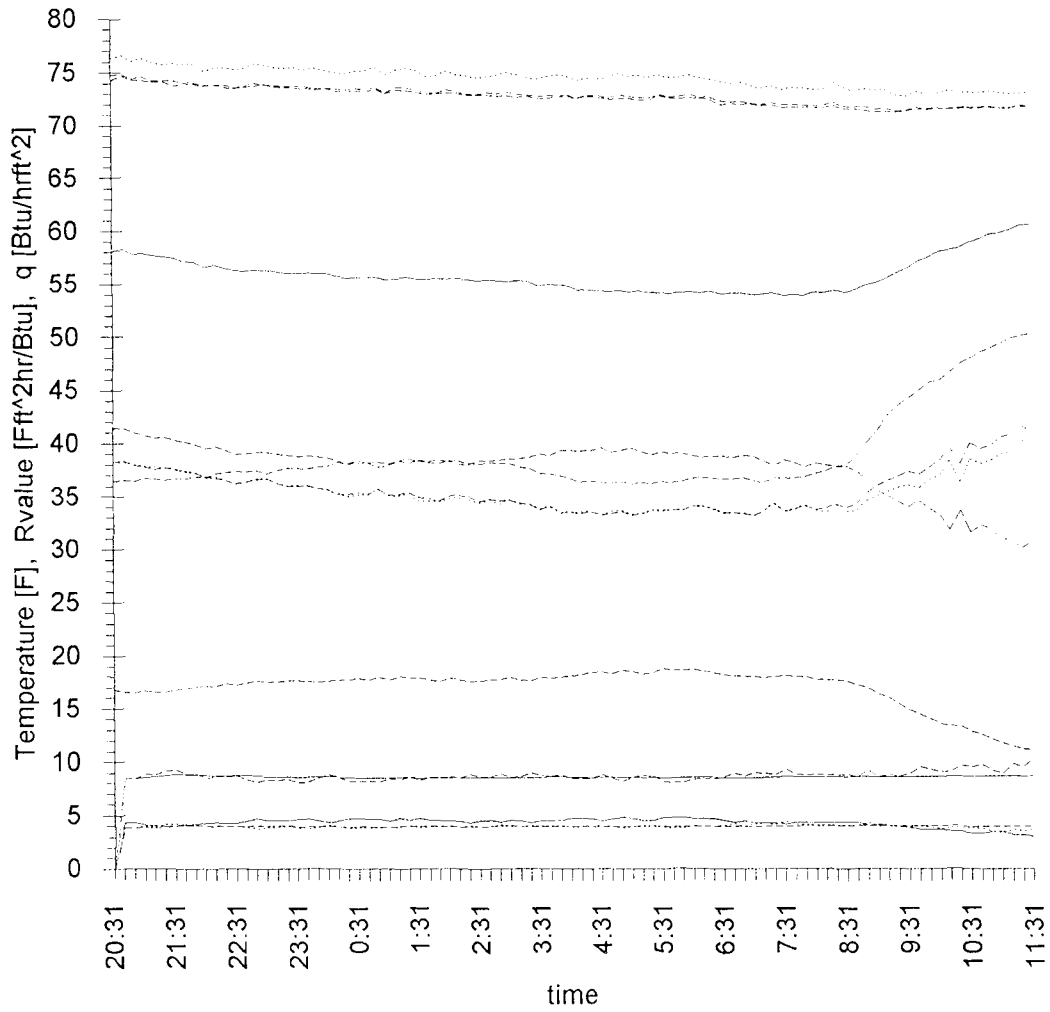


- | | | | |
|--------------------|--------------------|-----------------|------------------|
| ----- R tot cum | ----- dT i,o surf | T out | ----- T out surf |
| ----- T win, insul | ----- T insul, gyp | ----- T in surf | T in |
| ----- T room | ----- R tot inst | ----- q | ----- dT in, gyp |
| R gyp inst | ----- R gyp cum | | |

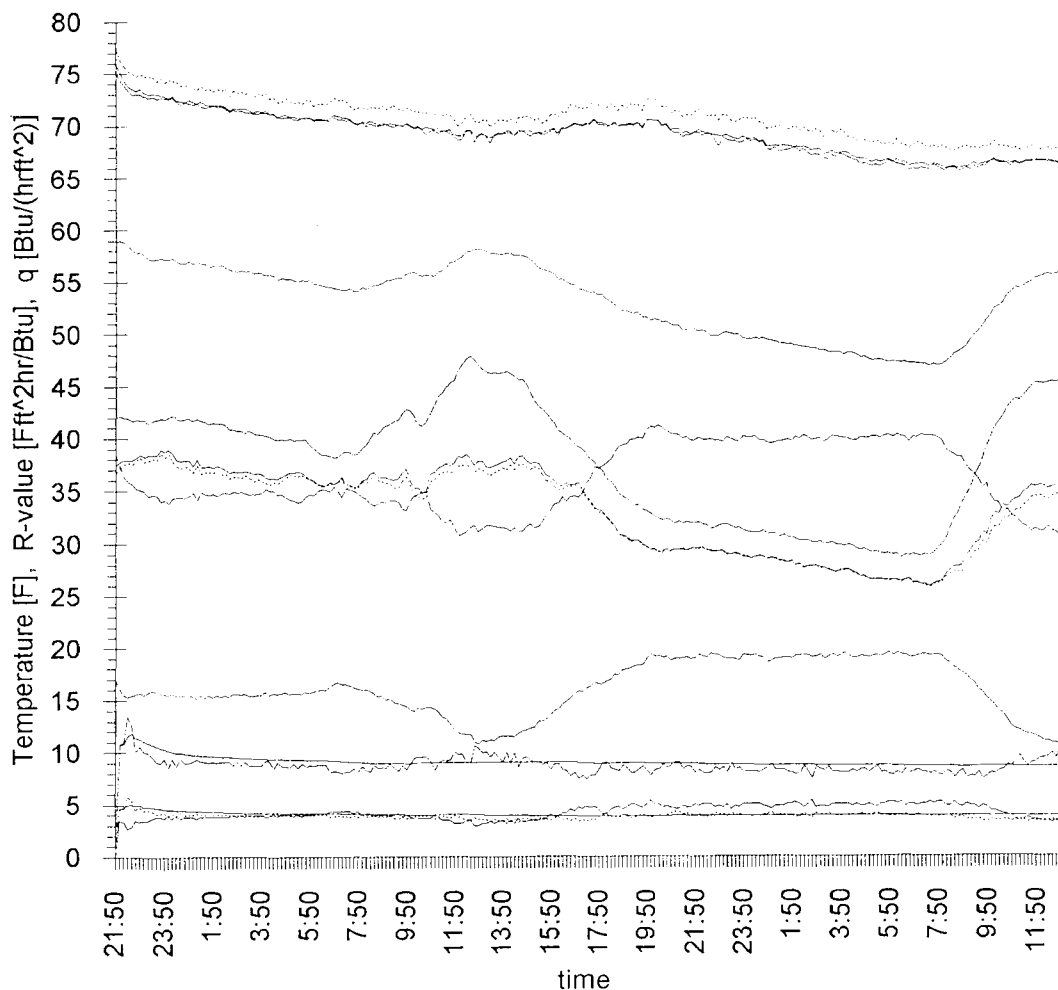
12/01/92 Test 38 Window, Insulation no.1
and Gypsum Board 1in.



12/03/92 Test 39 Window, Insulation no.12
and Insulation no.1



12/04/92 Test 40 Window, Insulation no. 12
and Insulation no. 1



— R tot cum	- - - dT i,o surf	..... T out	- - - T out surf
- - - T win, insul 12	— T insul, insul 1	- - - T in surf T in
- - - T room	- - - R tot inst	— q	- - - dT in, insul 1
..... R insul 1, inst	- - - R insul 1, cum		

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