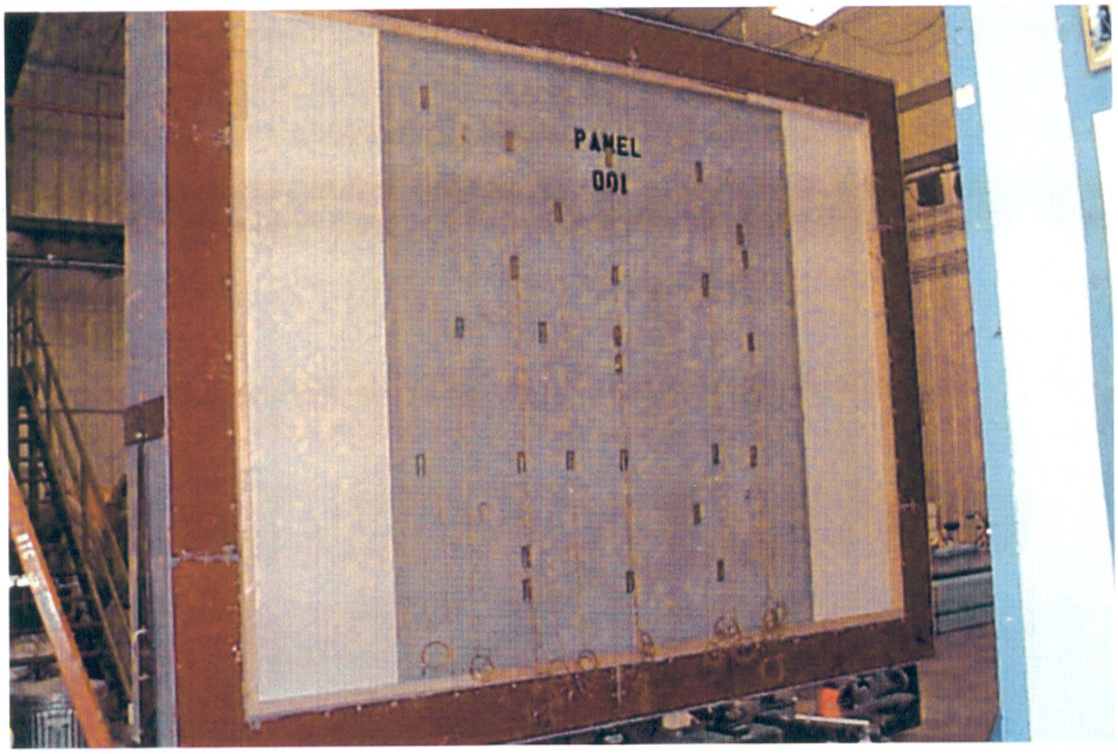
Thermal Performance of Prefabricated Concrete Sandwich Wall Panels



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Abstract

The steady state thermal performances of five concrete-foam-concrete panel wall systems were measured in guarded hot box at the Oak Ridge national Laboratory Buildigns Technology Center (ORNL BTC). In addition, the clear wall thermal analysis was performed using computer modeling. Hot-box test and finite difference computer code Heating 7.2 [Childs 1993] were used to analyze the clear wall area of the panels. Three-dimensional computer modeling enabled analysis of the temperature distribution in the wall and precisely calculate local heat fluxes in clear wall areas where wall thermal performance is influenced by metal or fiber composite connectors joining two concrete parts of the wall. Maps of the temperature distribution in the wall were developed and were used to estimate the areas affected by existing thermal bridges and to calculate R-values.

In addition, a dynamic thermal performance of one Thermomass wall panel was analyzed based on the dynamic guarded hot box test at the ORNL BTC. Using the same wall configuration as for the steady-state analysis, dynamically changing boundary conditions were modeled using the finite difference computer code Heating 7.2. A validation of the model was conducted by comparing the model's heat flow predictions with hot box measurements of the actual heat flow through an 8 ft by 8ft Thermomass clear test wall exposed to dynamic boundary conditions.

The computer models developed for each concrete wall panel were used to generate a series of response factors and equivalent walls. An equivalent wall has a simple multilayer structure and the same thermal properties as actual wall. Its dynamic thermal behavior is identical to that of the actual wall. The thermal and physical properties describing the equivalent wall can be used easily in the whole building energy simulation programs with hourly time steps.

The next step was to use equivalent wall as a part of the input in DOE 2.1E, a whole building thermal performance computer model [LBL 1993]. The DOE-2.1E computer code developed for wall Panel 1 was used to simulate a single-family residence in six representative U.S. climates. The space heating and cooling loads from the residence simulated with massive Thermomass Panel 1 were compared with loads from an identical building simulated as having lightweight wood frame exterior walls.

1.0 Description of Precast Walls

Five precast concrete panels were considered in this project. As shown in Figures 1 - 5 each panel comprised two layers of concrete separated by a layer of insulating foam. Concrete layers were coupled using fiber composite connectors, metal connectors, or concrete bridges. Test Panels 1 through 4 comprised two, 3-in. thick layers of concrete divided by a 2-in. thick layer of extruded polystyrene insulation (Fig. 1 - 4).

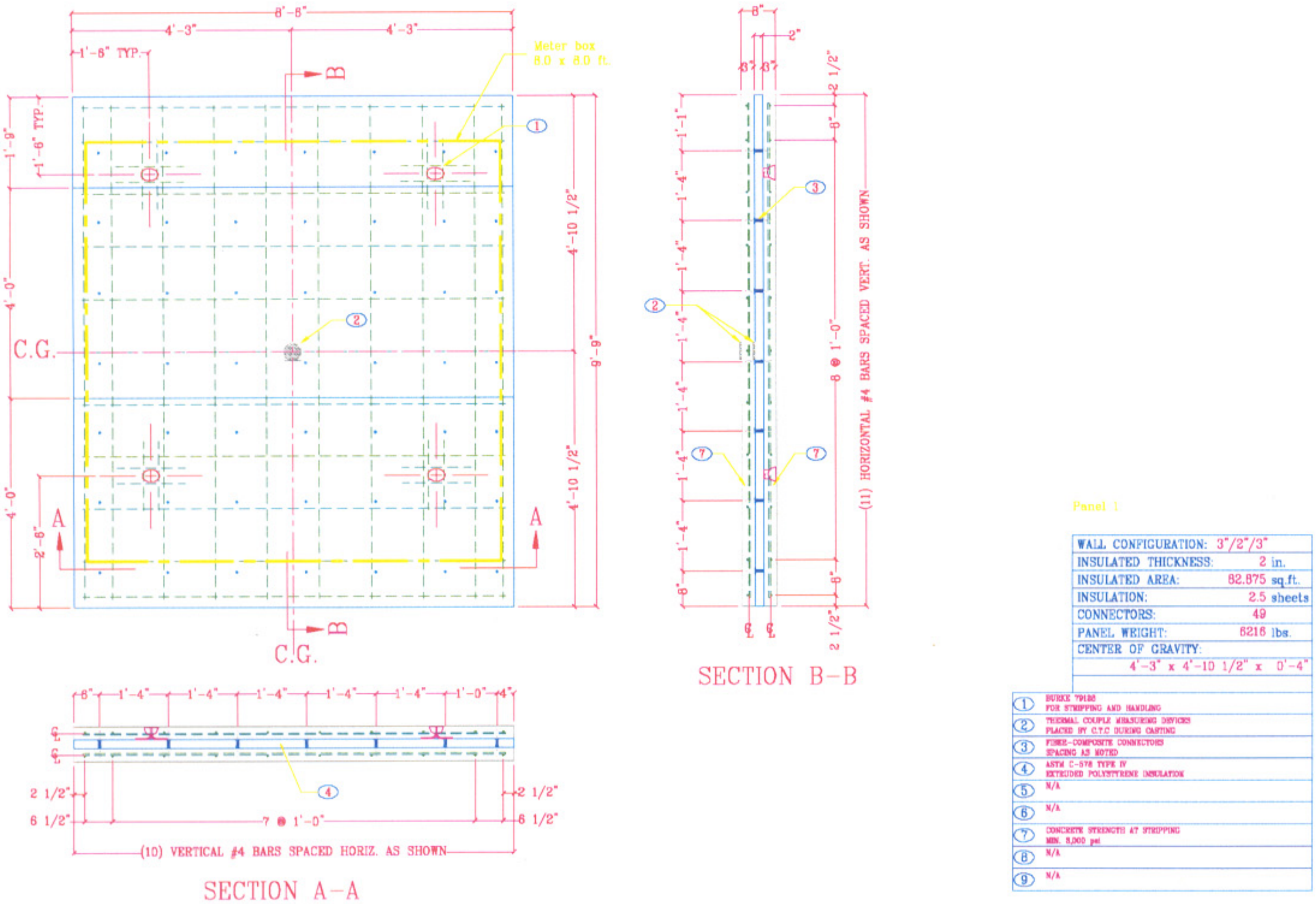

Figure 1. Schematic of test Panel 1.

In Panel 1, concrete layers were coupled using fiber composite connectors installed at 16-in. o.c. in each direction (Fig.1). Because of safety requirements and the weight of the test panel, the test panel had to be supported directly on the testing frame. Therefore, the guarded box covered about 85% of thermally bridged area. Because thermal bridges were distributed relatively uniformly through the whole area of the tested panel, the tested area can be considered as a relatively good representation of the whole panel.

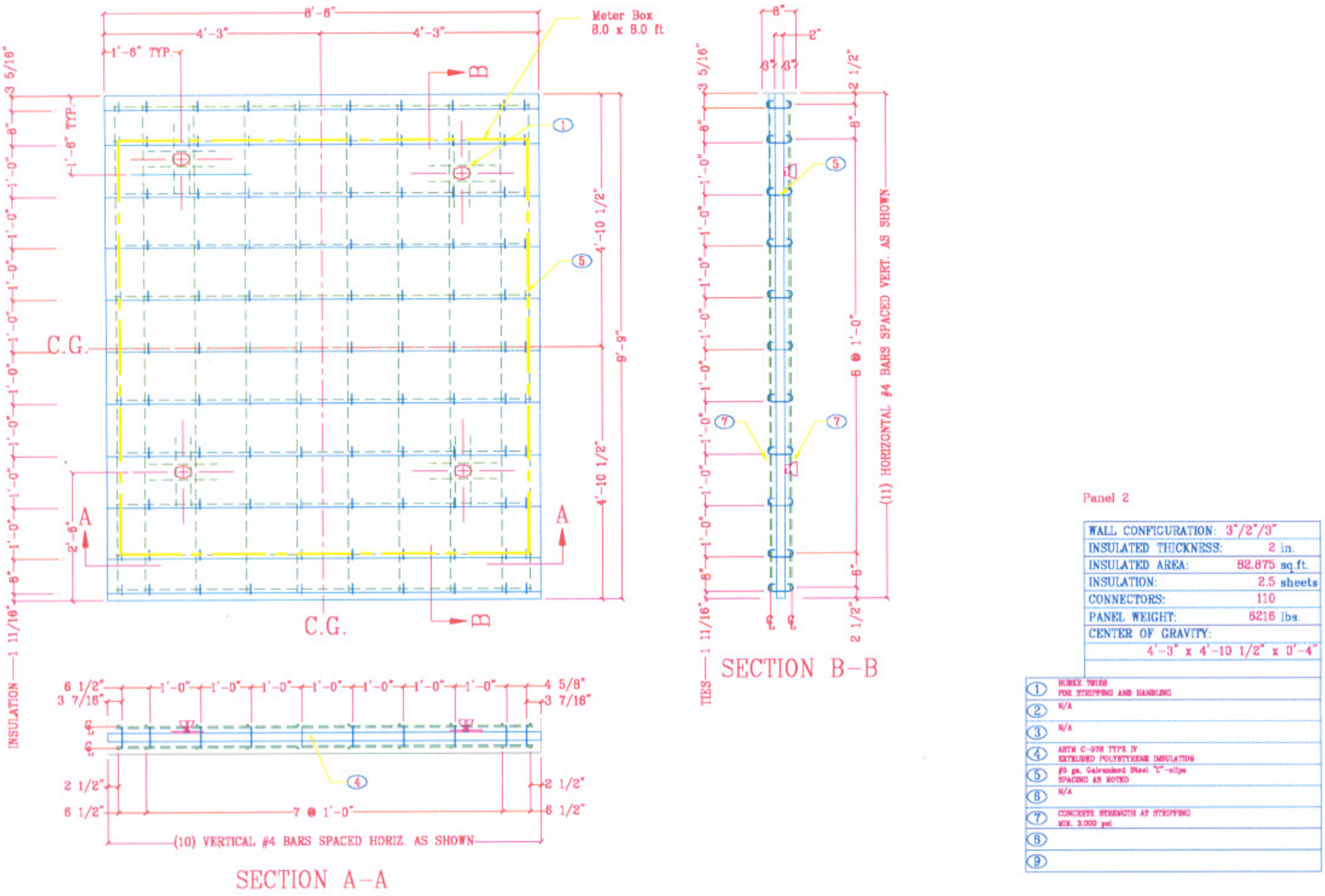

Figure 2. Schematic of test Panel 2.

In Panel 2, concrete layers were coupled using 6 ga. mild steel connectors installed at 12-in. o.c. in each direction (Fig. 2). For this panel, the guarded box covered about 82% of thermally bridged area. Again, because thermal bridges were relatively uniform distributed through the whole area of the tested panel, the tested area can be considered as a relatively good representation of the whole panel.

In Panel 3, concrete layers were coupled by eight, 8x8-in. concrete penetrations (Fig. 3). For this panel, the guarded box completely covered 4 concrete penetrations. The remaining four penetrations were partially covered by the guarded box. Therefore, significant thermal bridging from these penetrations influenced the heat flux rate recorded during the test.

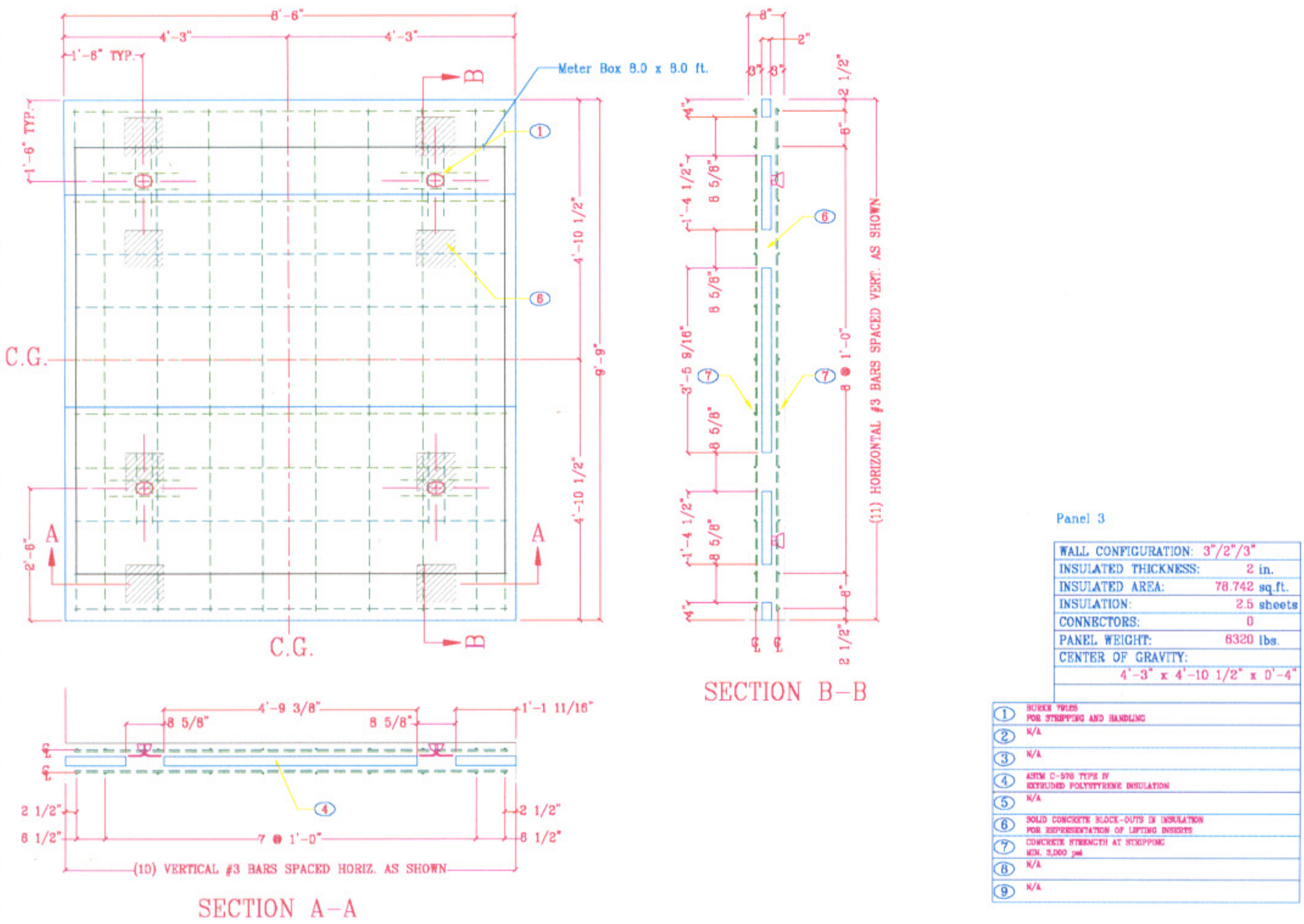

Figure 3. Schematic of test Panel 3.

In Panel 4, concrete layers were coupled using 6 ga. mild steel connectors installed at 12-in. o.c. in each directions and by eight, 8x8-in. concrete penetrations (Fig. 4). As with Panel 3, the guarded box covered completely 4 concrete penetrations and partially covered remaining four. Therefore, some thermal bridge effect from these penetrations influenced the heat flux rate recorded during the test. Also, as in the Panel 2, 82% of thermal bridges created by steel connectors was within the measure space.

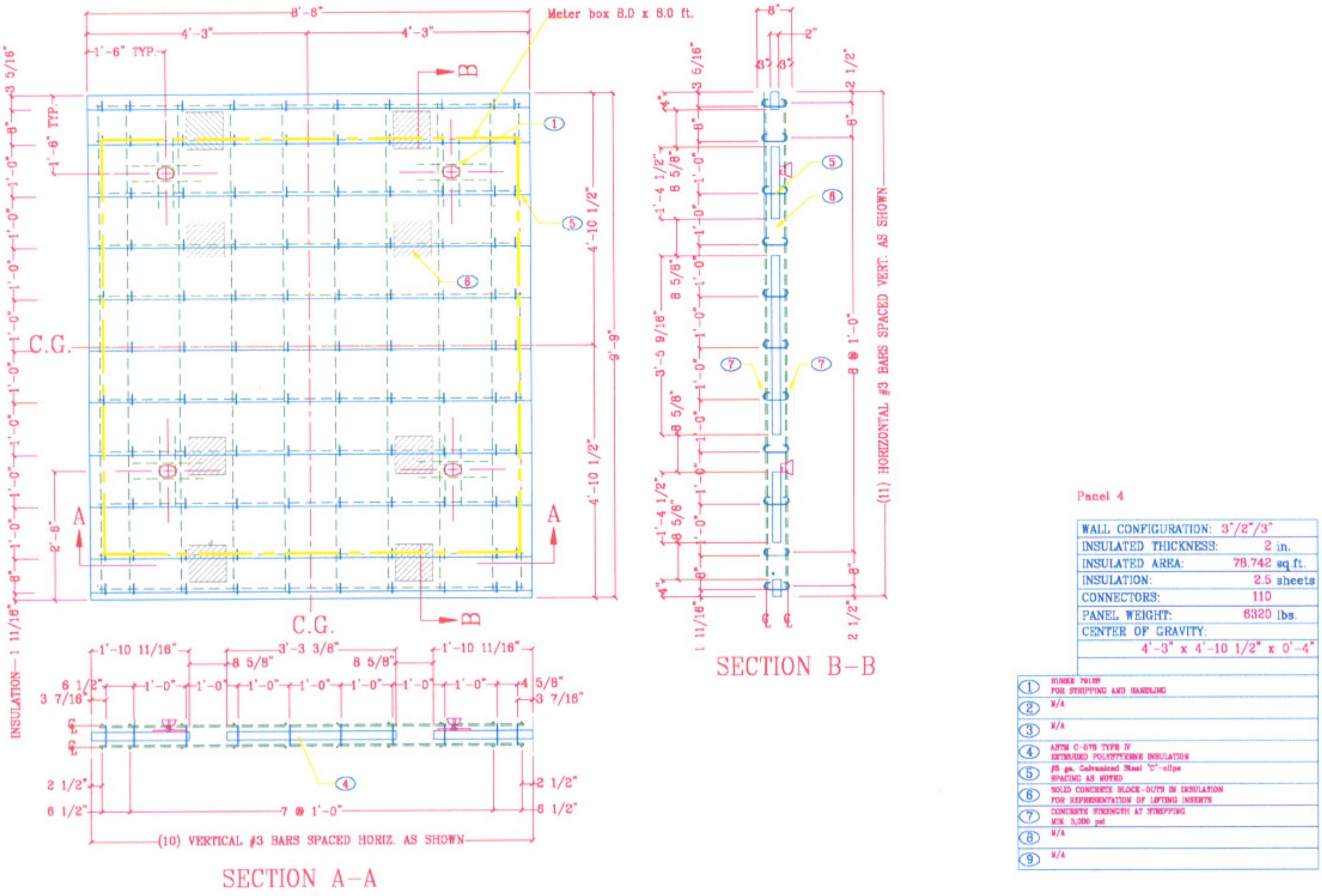

Figure 4. Schematic of test Panel 4.

As presented on Figure 5, the test Panel 6 was the thickest panel considered during this project. It comprised 2-in. thick and 6-in. thick concrete layers divided by 6-in. thick layer of black extruded polystyrene insulation (three layers, each 2-in. thick) and ½-in. thick layer of blue extruded polystyrene. The blue polystyrene sheets incorporated a bonded polypropylene membrane on both faces. The concrete layers were coupled using fiber composite connectors installed at 16-in. o.c. in each direction. The guarded box covered about 85% of thermally bridged area. Because the thermal bridges were relatively uniform distributed through the whole area of the tested panel, the measured area can be considered as a relatively good representation of the whole panel.

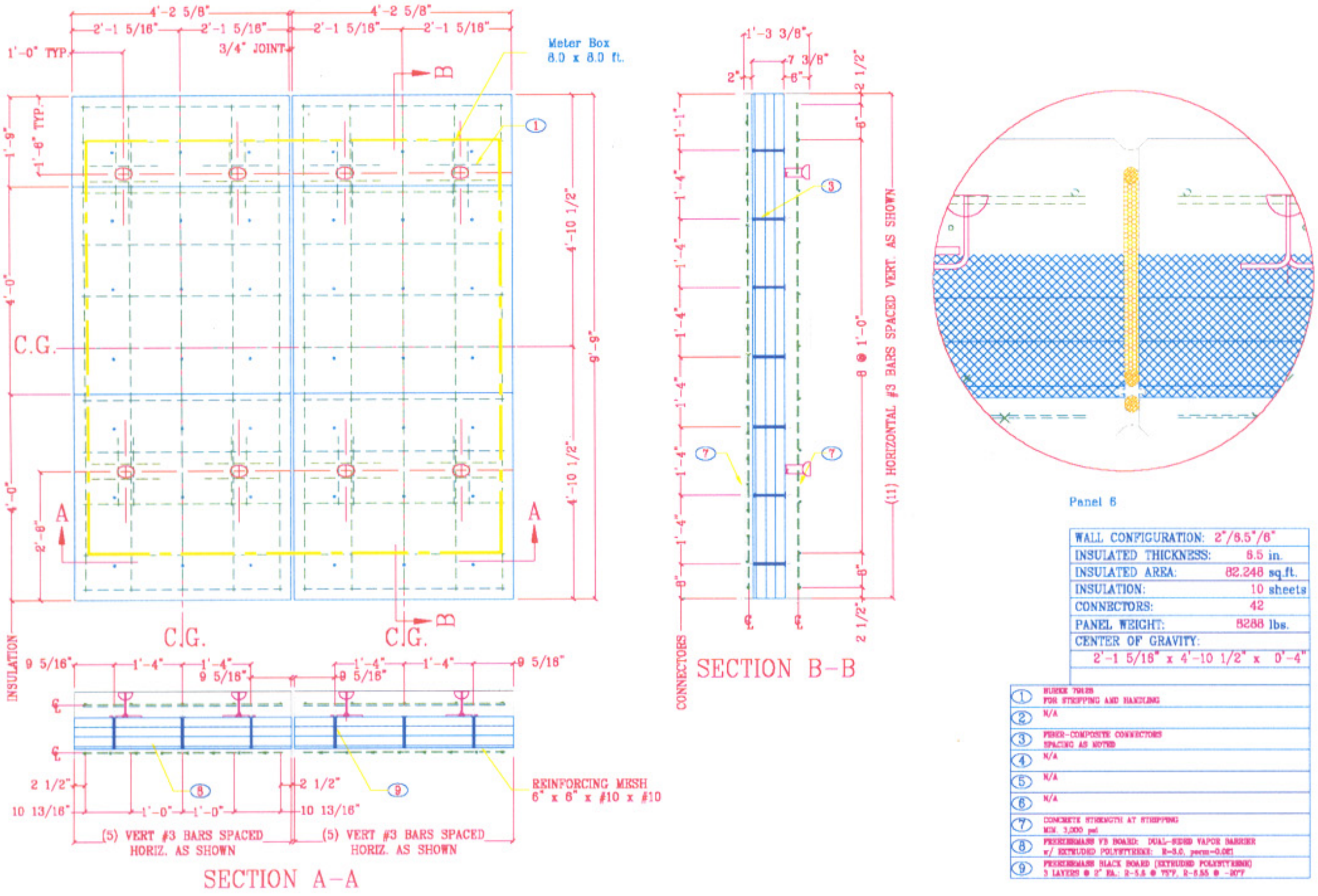

Figure 5. Schematic of test Panel 6.

2.0 Guarded Hot Box Thermal Test of the Precast Walls

Measurements of wall systems are typically carried out using an apparatus such as the one described in ASTM C 236, Standard Test Method for "Steady-State Thermal Transmission Properties of Building Assemblies by Means of a Guarded Hot Box" [ASTM C, 1989]. A relatively large (approximately 8 x 8 ft or larger) cross-section of the clear wall area of the wall system is used to determine its thermal performance. The precision of this test method is reported to be approximately 8% [ASTM C, 1989]. The calibration of the ORNL BTC guarded hot box is described in Appendix A.

At Oak Ridge National Laboratory - Buildings Technology Center the five test panels were installed and tested in the guarded hot-box under steady-state and dynamic conditions. Test results are presented in Table 1.

Table 1. Hot box test results for Panels 1 through 4 and 6.

Measurement	Units	Steady-state					Dynamic		
		Panel 1	Panel 2	Panel 3	Panel 4	Panel 6	Panel 1	Panel 4	Panel 6
Meter side air temperature	°F	71.0	70.1	76.7	76.2	71.5	71.5	78.4	72.3
Meter side air velocity	mph	0.3	0.3	0.3	0.3	0.5	0.6	0.4	0.5
Meter side connector area temp.	°F	67.7	66.4	--	67.4	69.8	69.5	73.2	71.4
Meter side concrete penetration temperature	°F	--	--	58.3	57.6	--	--	67.5	--
Meter side rebar area temperature	°F	67.5	66.0	68.9	70.1	69.9	69.3	74.9	71.5
Meter side joint area temperature	°F	--	--	--	0.0	69.7	--	--	71.1
Meter side concrete panel area temperature	°F	68.4	66.8	72.0	69.1	69.9	69.8	74.3	71.5
Average meter side wall surface temperature (t_1)	°F	68.3	66.7	70.9	68.7	69.9	69.7	74.1	71.5
Climate side air temperature (t_c)	°F	18.9	20.1	15.8	15.8	-5.5	42.1	42.7	31.7
Climate side air velocity	mph	2.2	2.4	2.9	2.9	2.8	2.4	3.1	2.8
Climate side connector area temp.	°F	20.4	22.4	--	19.3	-4.4	43.0	44.7	32.1
Climate side concrete penetration area temperature	°F	--	--	26.2	26.7	--	--	48.9	--
Climate side rebar area temperature	°F	20.1	21.7	20.5	18.9	-4.8	42.7	44.5	32.0
Climate side joint area temperature	°F	--	--	--	--	42.9	--	--	--
Climate side concrete panel surface temperature	°F	20.4	21.9	18.9	19.7	-4.5	43.0	44.9	32.1
Average climate side wall surface temperature	°F	20.4	21.9	19.5	19.9	-4.5	42.9	45.0	32.1
Meter side center hole area temp.	°F	20.3	--	--	--	--	42.9	--	--
Panel mean temperature	°F	44.3	44.3	45.2	44.3	32.7	56.3	59.5	51.8
Total measured energy into meter box (TMP)	Btu/hr	295.6	378.7	570.7	685.6	163.7	172.7	402.0	86.1
Energy through meter box walls (Q_{mbox})	Btu/hr	-0.02	-0.02	0.01	0.01	-0.01	-0.02	-0.06	0.00
Energy Input (total energy through wall) ($Q_h + Q_r$)	Btu/hr	295.7	378.7	570.6	685.6	163.7	174.0	402.1	86.1
Clear wall R-Value (R)	h·ft²·°F/ Btu	10.5	7.6	5.8	4.6	29.1	10.0	4.6	29.3
Meter side air film resist. ($R_{ms\ air}$)	h·ft²·°F/ Btu	0.60	0.57	0.65	0.69	0.64	0.67	0.69	0.61
Climate side air film resist. ($R_{cs\ air}$)	h·ft²·°F/ Btu	0.33	0.31	0.41	0.38	0.38	0.32	0.36	0.32
Ru-Value, ($R_{ms\ air}$ +R + $R_{cs\ air}$)	h·ft²·°F/ Btu	11.4	8.5	6.8	5.6	30.1	11.0	5.7	30.20

Table 1 details the experimental data that were compiled during the hot box testing. The temperature data that are presented represent the average temperatures for the 4-hour time interval after steady-state had been achieved (wall heat flux stabilized). When multiple temperature sensors are used to define a temperature, these sensors are averaged for each scan and then integrated over the 4 hours time interval. Temperature profiles and R-values recorded during hot box testing of the test panels are presented on Figures 6 -16.

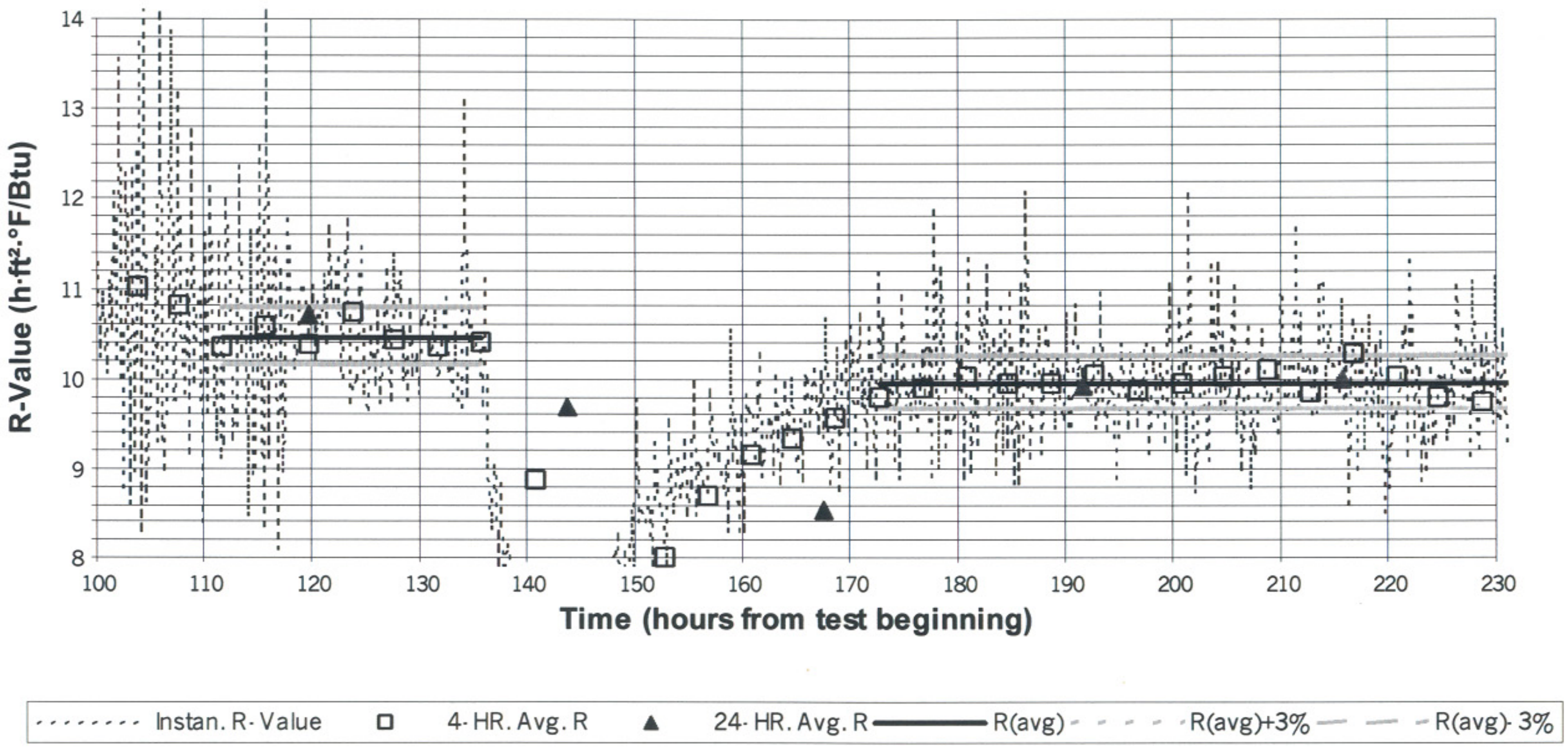

Figure 6 Panel 1 - R-value vs time

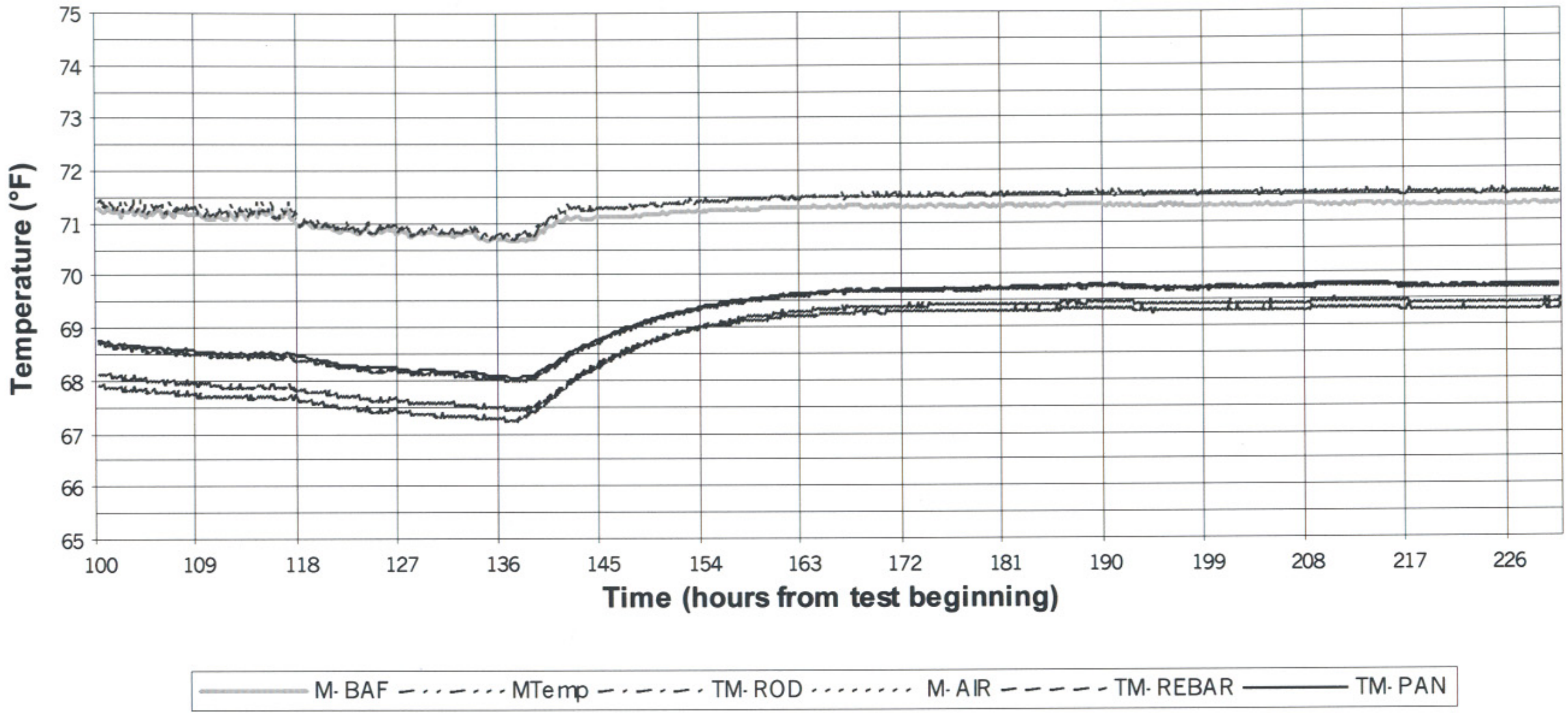

Figure 7 Panel 1 - Meter side temperature profile vs time

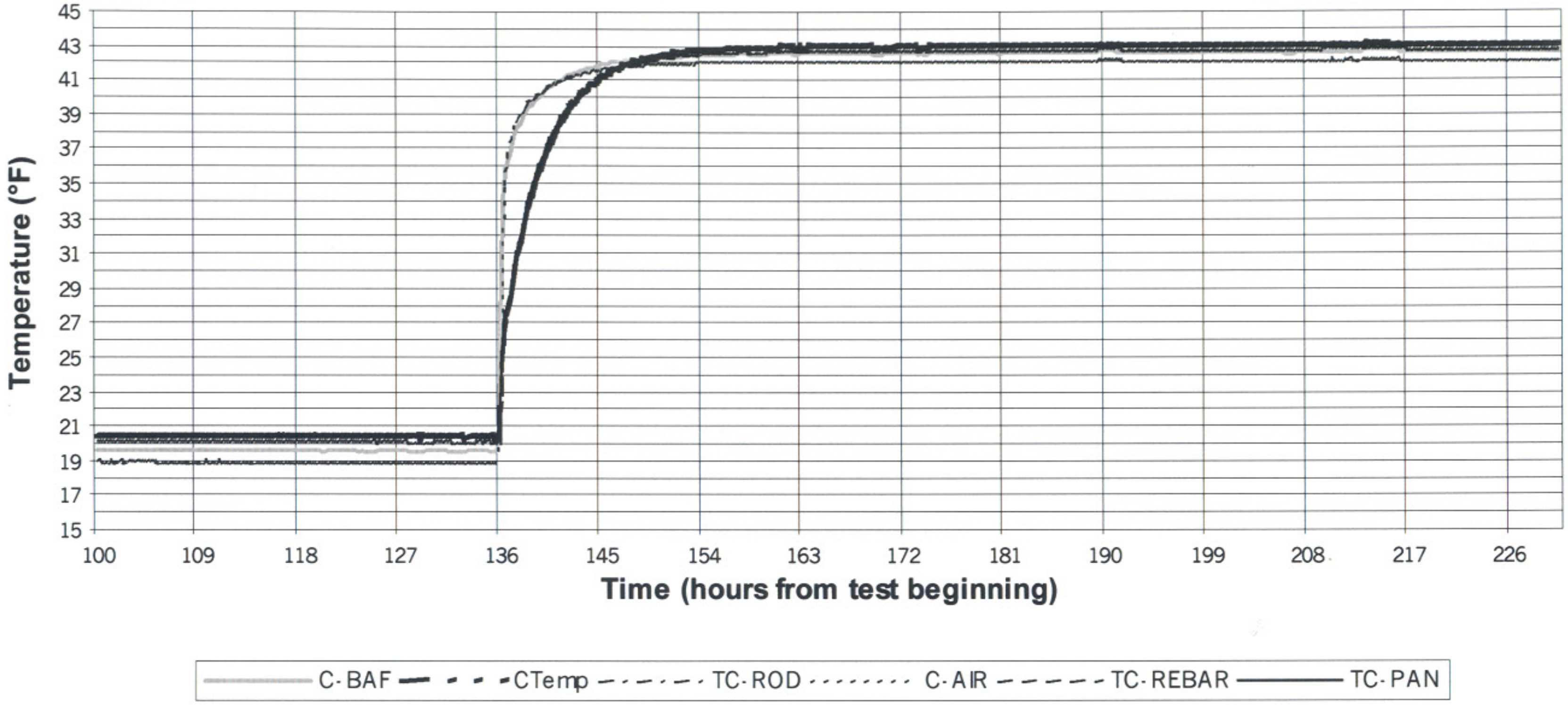

Figure 8 Panel 1 - Climate side temperature profile vs time

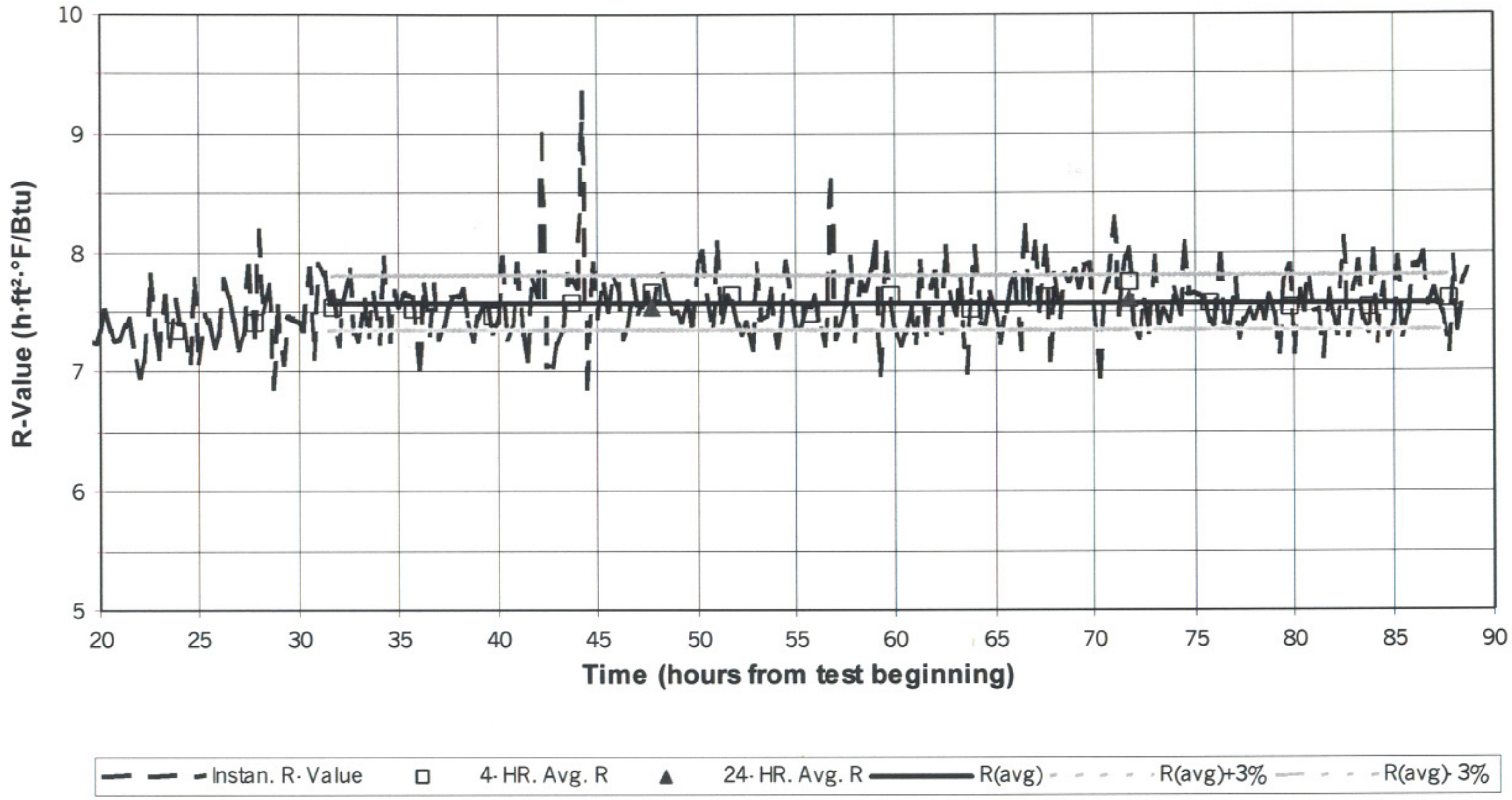

Figure 9 Panel 2 - R-value vs time

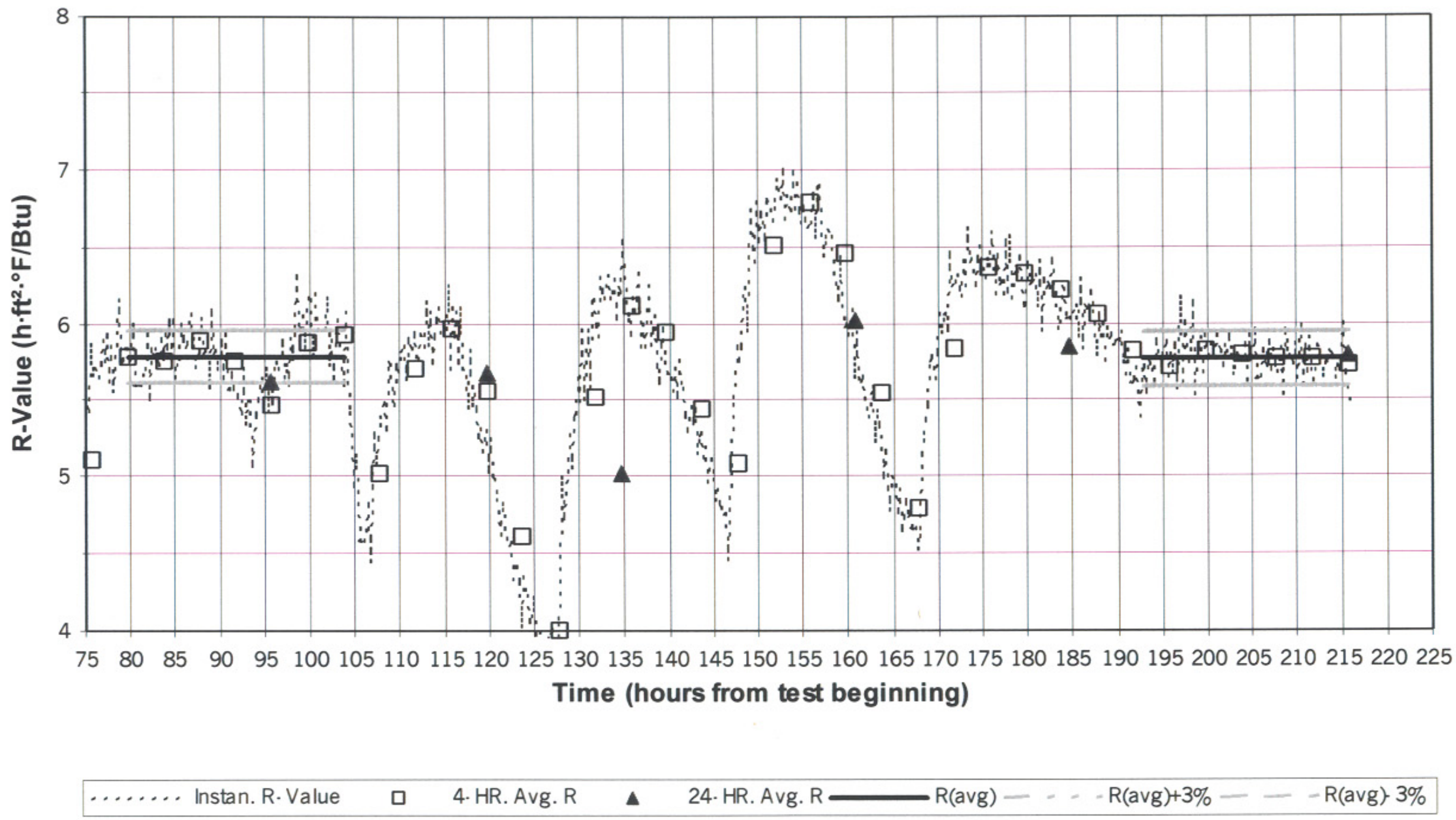

Figure 10 Panel 3 R-Value vs time

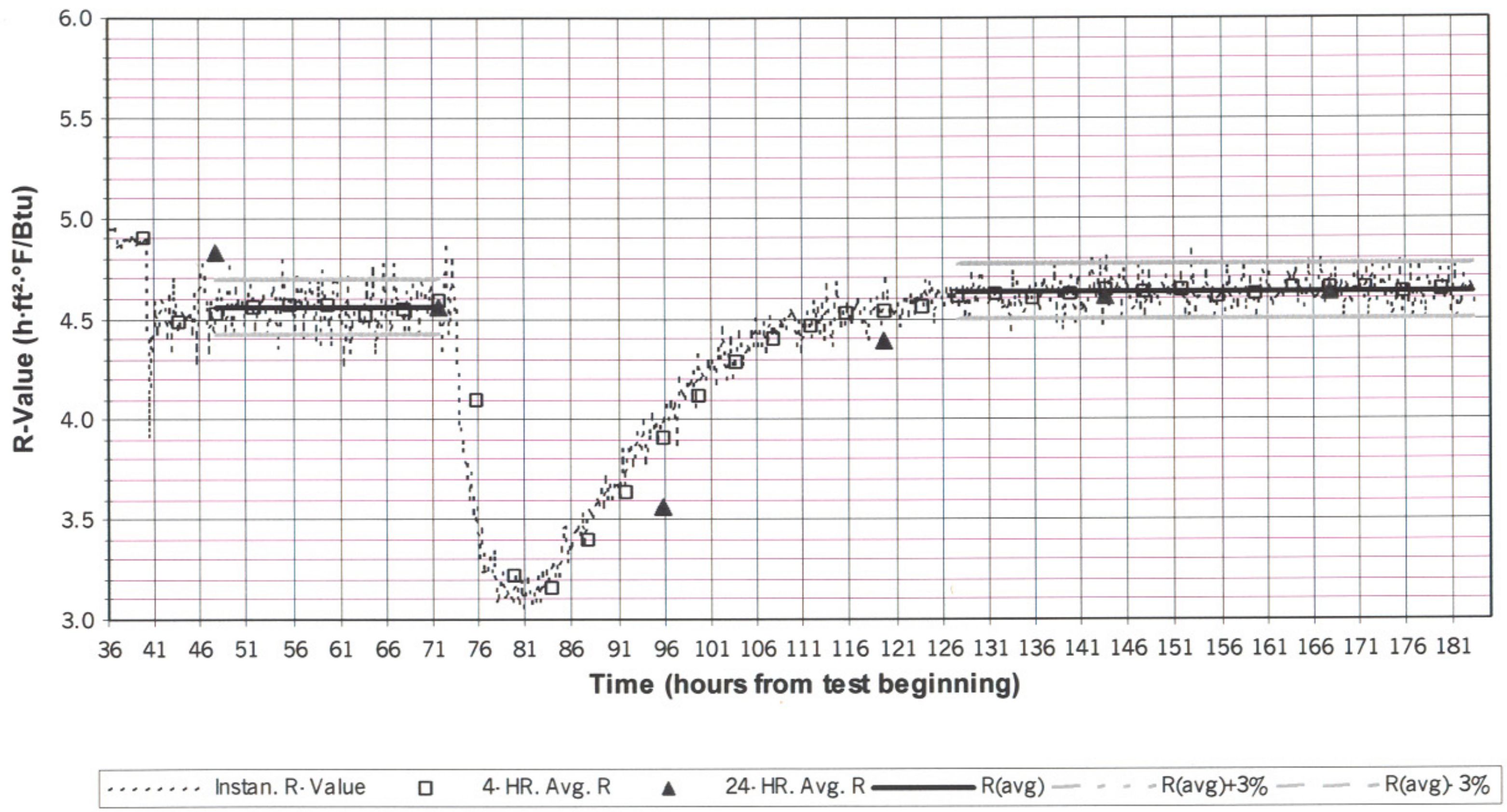

Figure 11 Panel 4 - R-value vs time

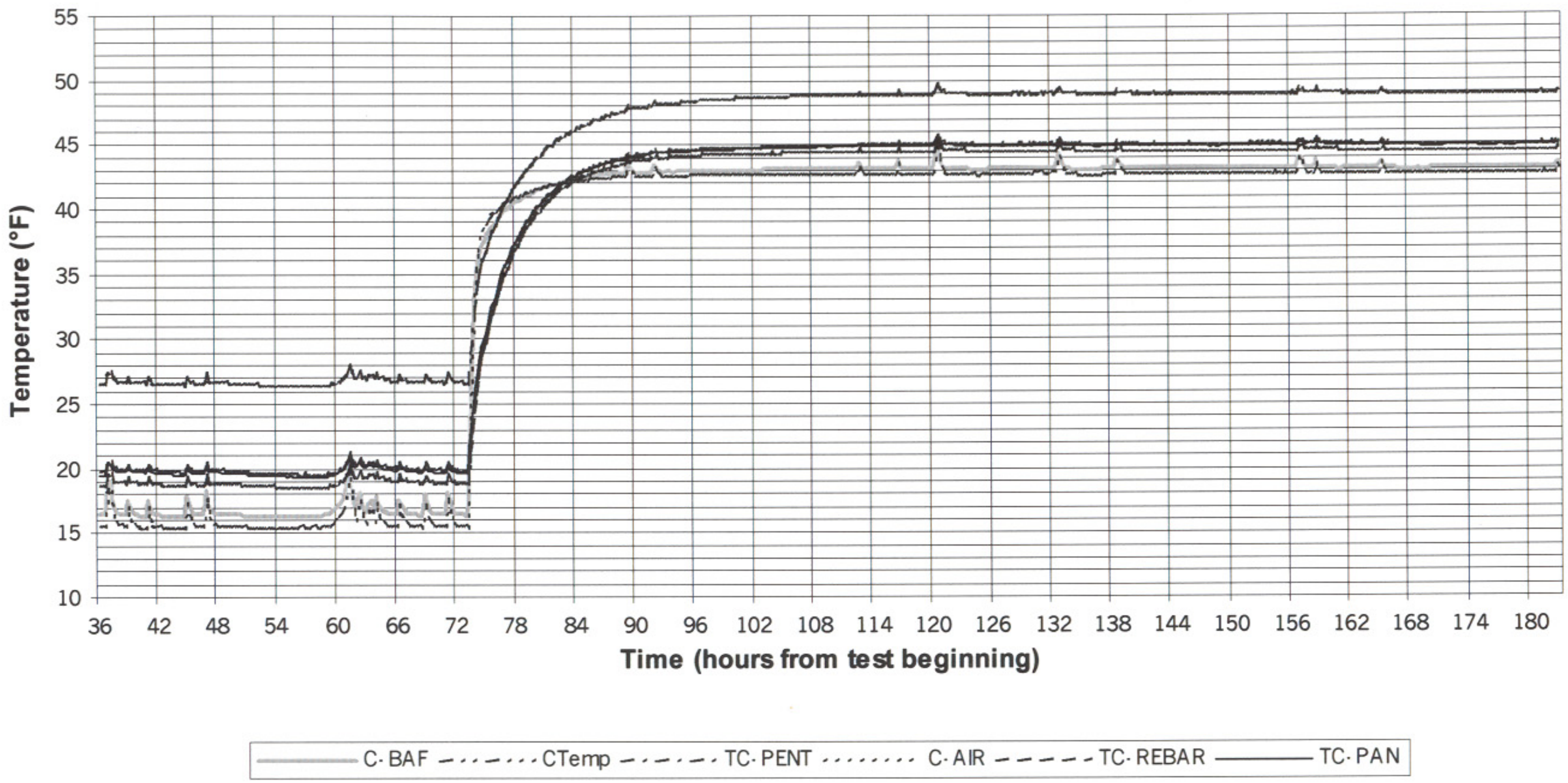

Figure 12 Panel 4 - Climate side temperature profile vs time

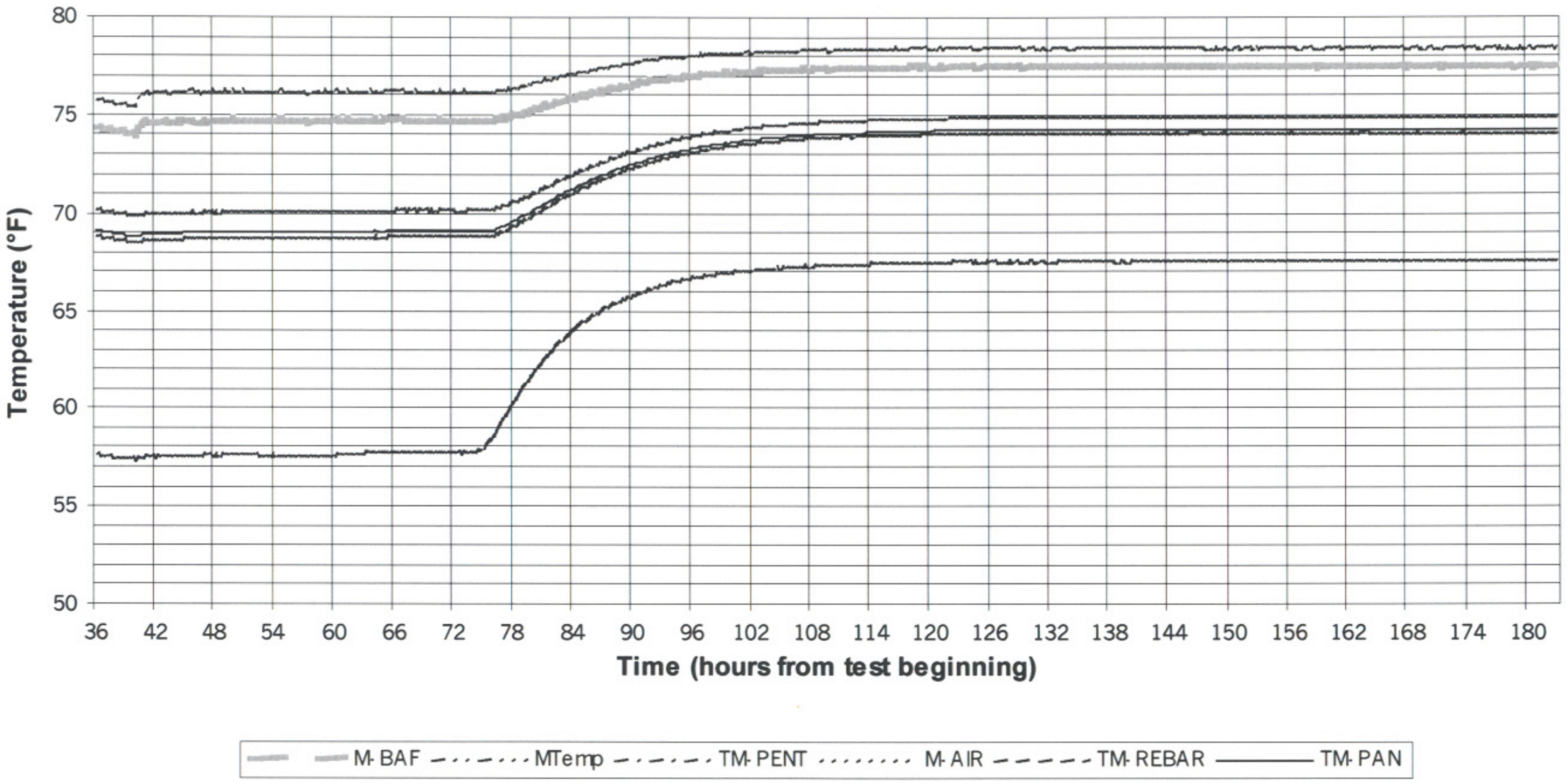

Figure 13 Panel 4 - Meter side temperature profile vs time

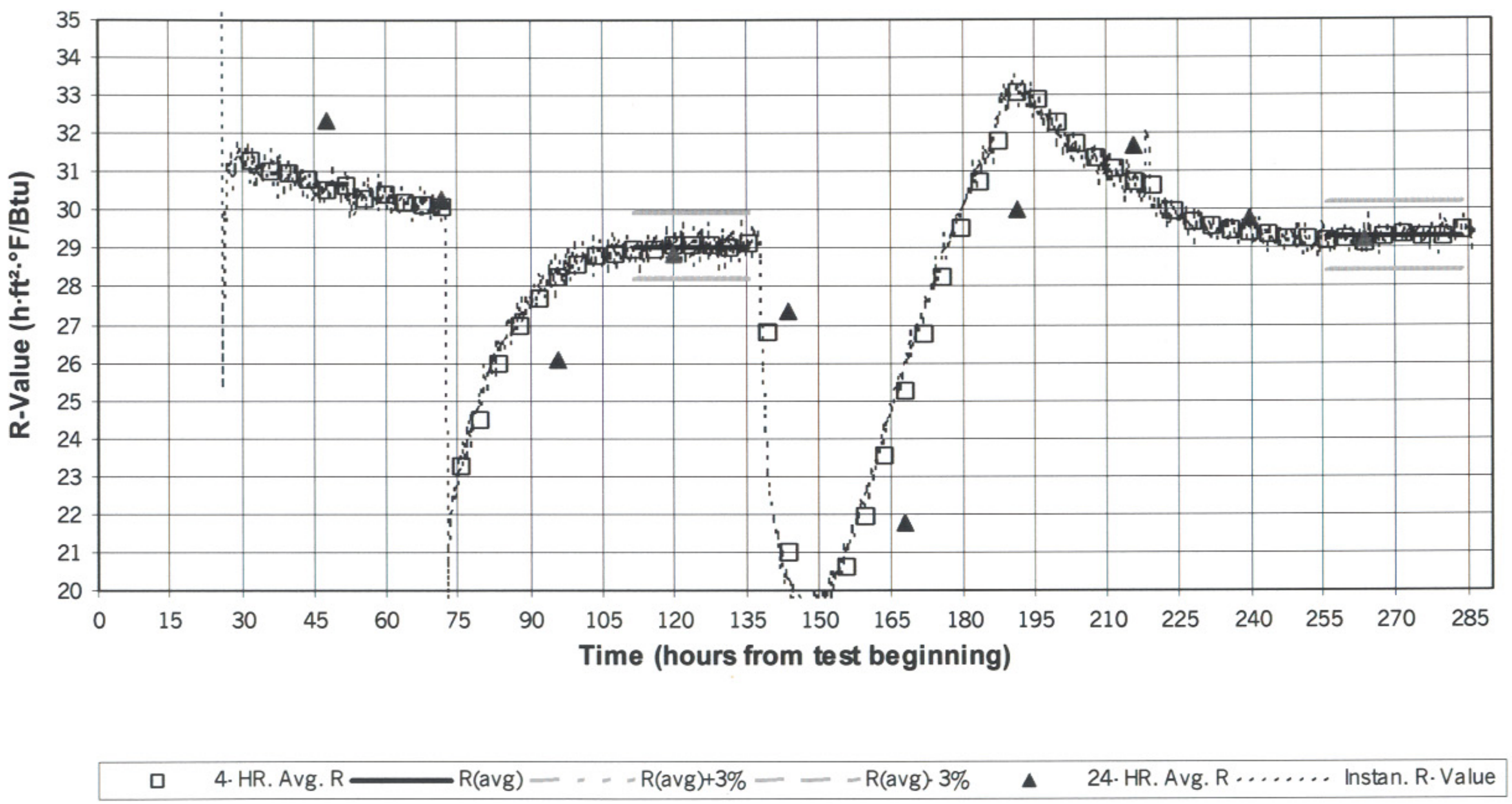

Figure 14 Panel 6 - R-value vs time

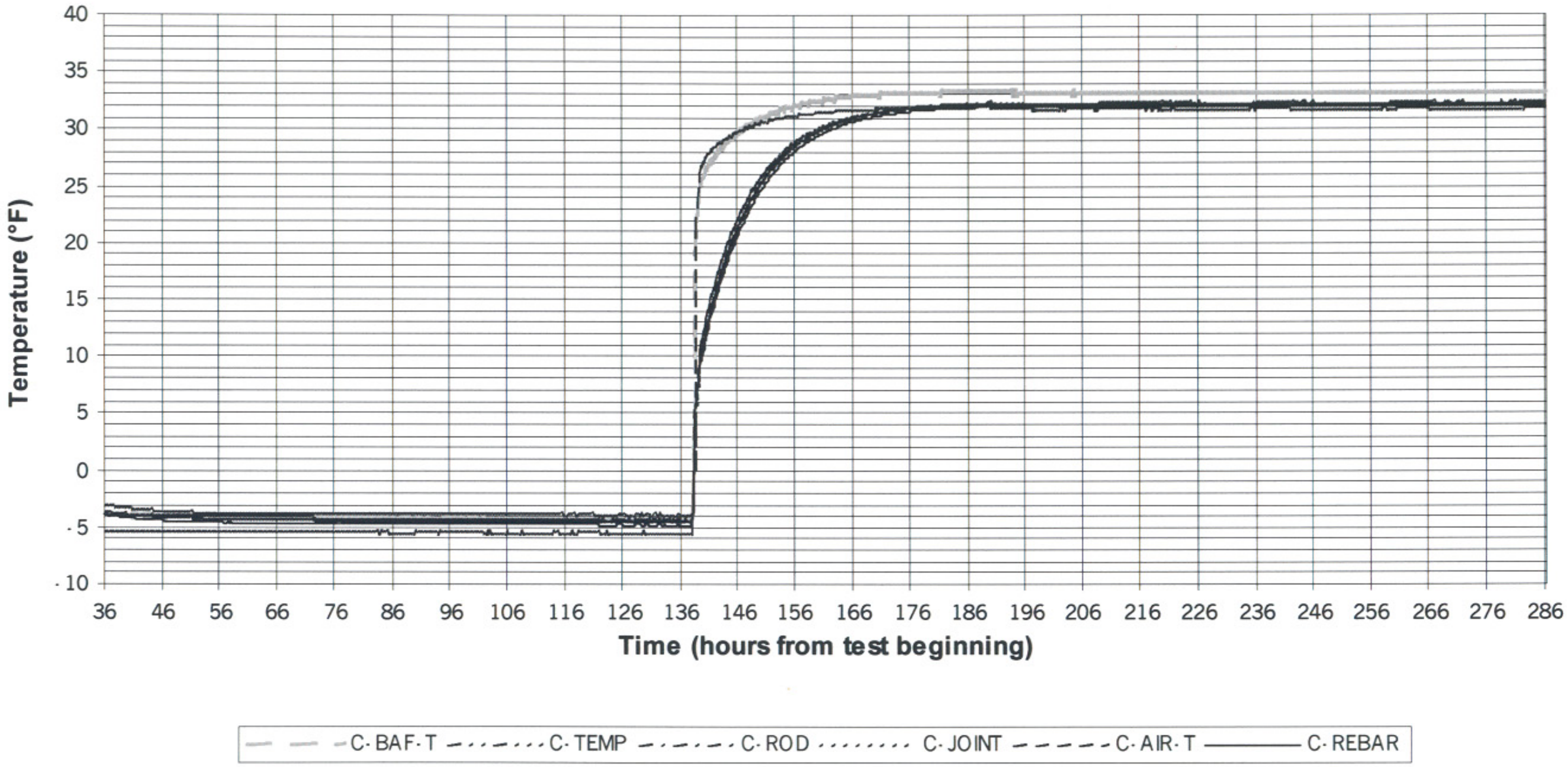

Figure 15 Panel 6 - Climate side temperature profile vs time

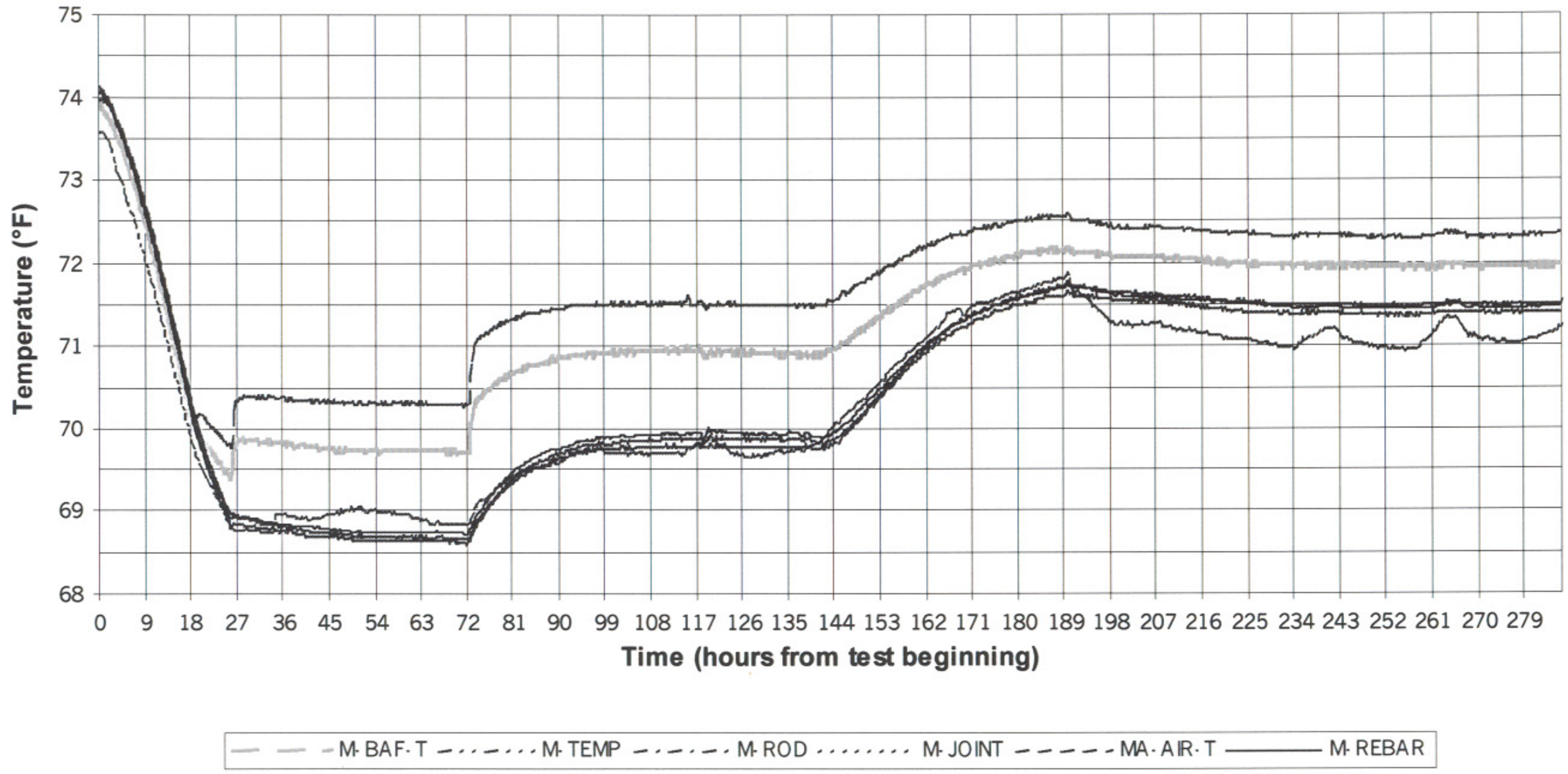

Figure 16 Panel 6 - Meter side temperature profile vs time

Detailed experimental data compiled during the hot box testing are presented on Figures 6-16. Description of the testing apparatus and hot box experimental procedure is presented in Appendix A.

For all tests walls the thermal resistance R is calculated using

$$R = \frac{A(t_1 - t_2)}{(Q_h + Q_f)} \qquad (1)$$

where R = thermal resistance of wall assembly, hr ft^2 °F/Btu (m^2 K/W);
A = area of metering chamber, 64 ft^2 (5.3 m^2);
t_1 = average surface temperature of the wall assembly on the metering side, °F (° C);
t_2 = average surface temperature of the wall assembly on the climate side, °F (° C);
Q_h = metering heater energy input, Btu/hr (W); and
Q_f = metering fan energy input, Btu/hr (W).

The overall thermal resistance of the wall assembly, R_u is calculated using

$$R_u = \frac{A(t_h - t_c)}{(Q_h + Q_f)} \qquad (2)$$

As with R, the units for R_u are, hr ft^2 °F/Btu (m^2 K/W);

The meter side air film thermal resistance, $R_{ms\ air}$ is calculated using

$$R_{ms\ air} = \frac{A(t_h - t_1)}{(Q_h + Q_f)} \qquad (3)$$

with units , hr ft^2 °F/Btu (m^2 K/W);

The climate side air film thermal resistance, $R_{cms\ air}$ is calculated using

$$R_{sc\ air} = \frac{A(t_2 - t_c)}{(Q_h + Q_f)} \qquad (4)$$

Metering box wall losses were not included in any of the energy balance calculations. In the worst case, the metering box wall loss represents less than 0.2% of the energy input ($Q_{h.} + Q_f$).

3.0 Steady-State Thermal Analysis

Three-dimensional computer modeling was used to evaluate the thermal performance of the test panels. A heat conduction, finite difference computer code Heating 7.2 [Childs 1993], was used. The resultant isotherm maps were used to calculate average heat fluxes, and wall R-values. The accuracy of Heating 7.2's ability to predict wall system R-values was verified by comparing simulation results with published test results for twenty-eight masonry, wood frame, and metal frame walls tested at other laboratories. The average differences between laboratory test and Heating 7.2 simulation results for these walls were +/- 4.7 percent [Kośny, Desjarlais 1994]. Considering that the precision of the guarded hot box method is reported to be approximately 8 percent, the ability of Heating 7.2 to reproduce the experimental data is within the accuracy of the test method [ASTM C-236].

3.1 Comparison of Steady-State Analysis with Test Results

In the current study, the results of the guarded hot box tests were utilized to calibrate the computer models. Computer generated heat fluxes were used in R-value calculations.

Test panels were simulated using measured dimensions. The results of the computer modeling were then compared with R-values calculated using data from the hot box tests. Actual tested thermal properties of materials were used.

Thermal conductivities for all wall materials used in computer modeling are presented in Table 2. Test and simulated R-values are within +/-5.7% for all tested panels, as shown in Table 3.

Table 2. Thermal conductivities for wall materials used in finite difference model.

Material:	Density lb/ft^3 [kg/m^3]	Conductivity k_a Btu-in./hft^{2}F [W/mK]*	Specific heat Btu/lbF [kJ/kgK]	Resistivity R/in. hft^{2}F/Btu-in. [mK/W]
Thermomass concrete	**140 [2240]**	**9.09 [1.309]**	**0.2 [0.84]**	**0.11 [0.76]**
Extr. Polystyrene - blue (Panels # 1-6) mean temp. 75 F	**2.0 [32.0]**	**0.2 [0.035]**	**0.29 [1.22]**	**5.0 [28.4]**
Extr. Polystyrene - gray (Panel # 6) mean temp. 50.0F	**2.0 [32.0]**	**0.2135 [0.0308]**	**0.29 [1.22]**	**4.68 [32.7]**
Extr. Polystyrene - gray (Panel # 6) mean temp. 36.5F	**2.0 [32.0]**	**0.2088 [0.03]**	**0.29 [1.22]**	**4.79 [33.5]**

* *Thermal conductivities as tested in ORNL BTC Material Lab. using hot plate apparatus - ASTM C 518-91, Standard Test Method for Steady-State Heat Flux Measurements and Thermal Transmission Properties by Means of the Heat Flow Meter Apparatus, Vol. 04.06, p. 153.*

Table 3. Comparison of hot-box measured R-values with results of finite difference analysis.*

Panel number	ORNL Hot Box Test R-value hft^{2}F/Btu [m^{2}K/W]	Simulated R-value hft^{2}F/Btu [m^{2}K/W]	Difference %
Panel 1	10.5 [1.85]	10.6 [1.87]	+0.9
Panel 2	7.6 [1.34]	7.6 [1.34]	0.0
Panel 3	5.8 [1.02]	6.35 [1.11] whole panel 7.49 [1.31] tested area only	*see comment under the Table*
Panel 4	4.6 [0.81]	4.68 [0.82] whole panel 5.53 [0.97] tested area only	*see comment under the Table*
Panel 6	29.3 [5.16]	30.90 [5.44]	+5.5

* *The measure box completely covered only 4 of the 8 concrete penetrations in each of Panel 3 and 4. Because the remaining concrete penetrations were partially inside the guarded hot box, some thermal bridge effect was included in the heat flux rate recorded during the test. The hot box test R-values are therefore significantly lower than the simulated R-values for Panels 3 and 4.*

3.2 Comparison of The Clear Wall Thermal Performance of Panels 1 and 2 and Conventional Wood Stud Wall:

Presently, 2x4 wood frame construction is the most popular building wall technology used for residential buildings in North America. To compare steady state thermal performance of Panel 1 with that of a conventional 2x4 wood frame wall, finite difference computer modeling was performed on a typical wood frame wall. The following four wall material configurations for the conventional wood stud wall were considered:

- 0.5" OSB, 3.5" fiberglass with 2x4 wood studs at 16-in. o.c., 0.5" gypsum board,
- 0.5" EPS, 0.5" OSB, 3.5" fiberglass with 2x4 wood studs at 16-in. o.c., 0.5" gypsum board,
- 1.0" EPS, 0.5" OSB, 3.5" fiberglass with 2x4 wood studs at 16-in. o.c., 0.5" gypsum board,
- 1.5" EPS, 0.5" OSB, 3.5" fiberglass with 2x4 wood studs at 16-in. o.c., 0.5" gypsum board,

Thermal properties of wood framed wall materials are presented in Table 4.

Table 4. Thermal conductivities of wood frame wall materials used for thermal analysis.

Material:	**Conductivity k_a Btu-in./hft²F [W/mK]**	**Resistivity R/in. hft²F/Btu-in. [mK/W]**
Fiberglass (3.5-in.)	**0.32 [0.046]**	**3.14 [22.0]**
EPS	**0.25 [0.036]**	**4.00 [28.0]**
Gypsum Board (0.5-in.)	**1.11 [0.16]**	**0.90 [6.25]**
OSB (0.5-in.)	**0.8 [0.12]**	**1.25 [8.33]**

R-values and Surface Temperatures:

A R-value comparison between the Panels 1 and 2 and a typical 2x4 wood frame wall are presented in Figure 17. Three thicknesses of the additional insulating EPS sheathing were considered for wood frame wall; 0.5, 1.0, and 1.5-in. Figure 17 shows that clear wall steady-state R-value of the panel #1 is equivalent to R-value of typical 2x4 wood frame wall without insulating EPS sheathing. R-value of Panel 2 is about R-3.4 lower than R-value of typical 2x4 wood frame wall without insulating EPS sheathing..

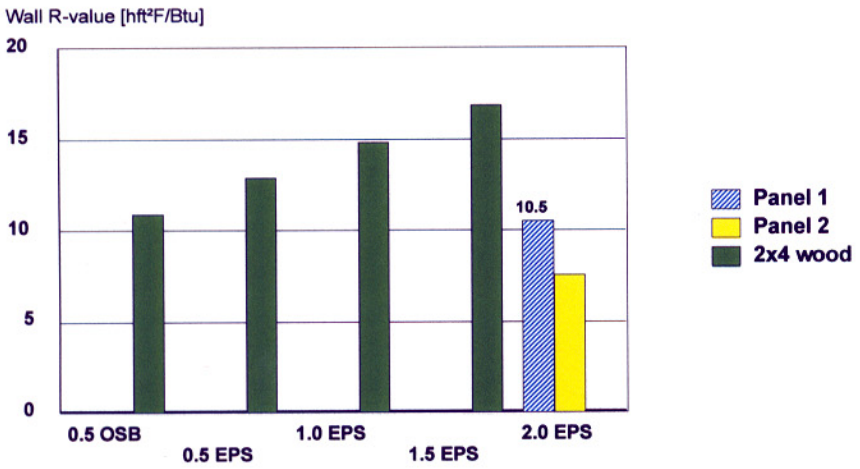

Figure 17. Steady-state R-value comparisons for Panels 1 and 2 v.c. a conventional 2x4 wood framed wall.

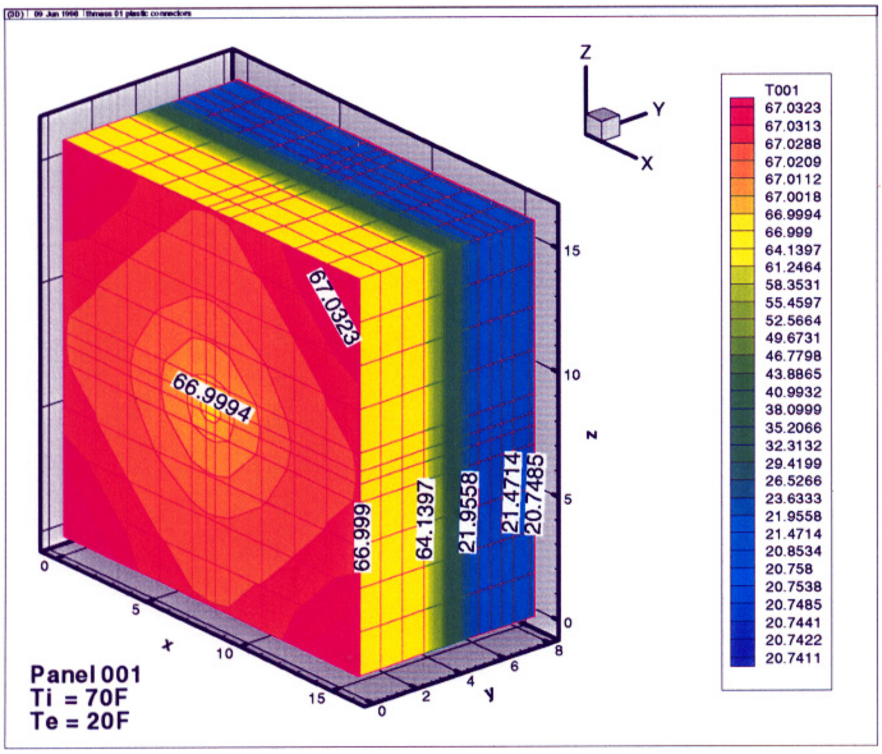

Figure 18. Temperature map for Panel 1.

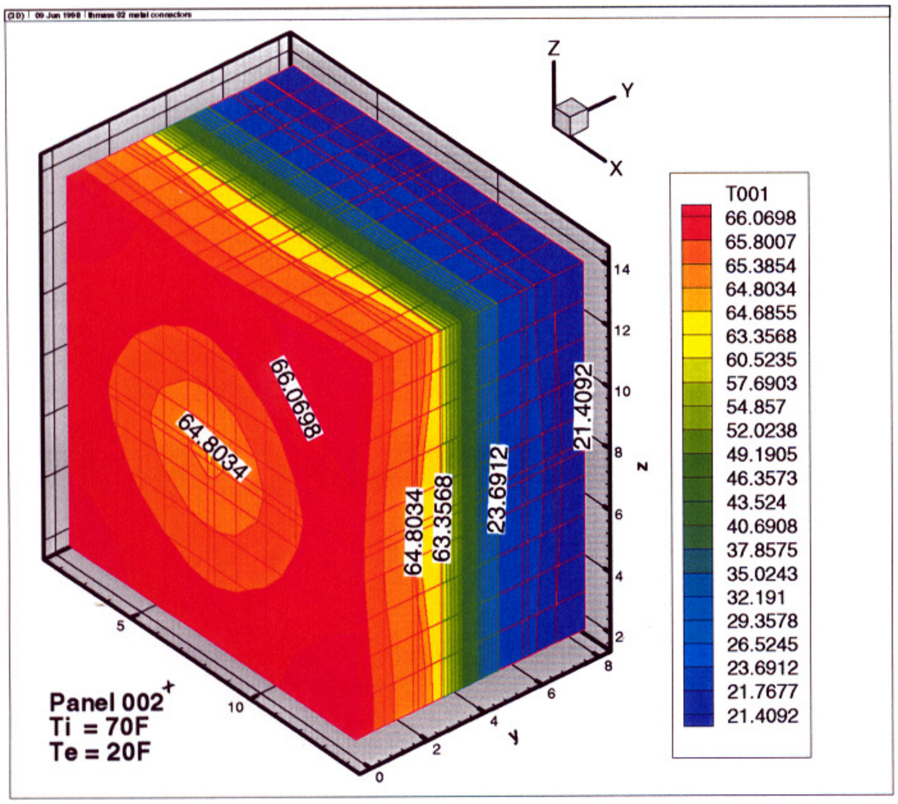

Figure 19. Temperature map for the Panel 2.

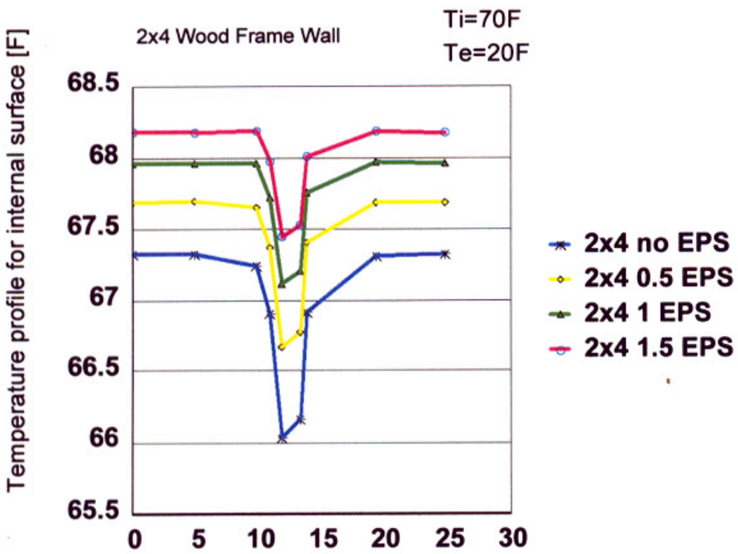

Figure 20. Local surface temperatures for conventional 2x4 wood frame walls.

Internal surface temperatures generated by finite difference computer models for Panels 1 and 2 and. a conventional wood frame clear wall (uninsulated and insulated by EPS sheathing), are shown in Figures 18, 19, and 20 for outside temperature of 20 °F and an interior temperature of 70 °F. For Panel 1, the minimal temperature of the internal surface is 67 °F, while for Panel 2, it is 64.8 °F. The minimal surface temperature for conventional wood frame clear wall, uninsulated and insulated by 0.5-in., and 1-in. EPS sheathing, are 66 °F, 66.7 °F, and 67.1 °F, respectively.

The maximum internal surface temperature difference for the Panel 1 is 0.032 °F while for the Panel 2, it is 1.27 °F. The maximum internal surface temperature difference for the conventional wood frame walls insulated using 0.5-in.OSB, 0.5-in. EPS, and 1-in. EPS sheathing, are 1.30 °F, 1.02 °F, and 0.85 °F, respectively. These comparisons show that Panel 1 has the most uniform surface temperature of all the walls compared.

4.0 Dynamic Thermal Performance Analysis

Dynamic thermal performance of Panel 1 representing a typical Thermomass wall was analyzed (see Figures 6,7,and 8). The same wall configuration as for steady-state analysis was modeled for dynamically changing boundary conditions using the finite difference computer code Heating 7.2. The Heating 7.2 computer model was calibrated using the steady-state test data. Thermal mass validation of the model was conducted by comparing modeled heat flow predictions with the hot-box-measured heat flow. Good agreement was found between test and computer modeling results.

The Heating 7.2 computer model results were used to develop input parameters for use in DOE 2.1E, a whole building thermal performance computer model [LBL 1993]. The DOE-2.1E computer code was used to simulate a single family residence in six representative U.S. climates. The space heating and cooling loads from the residence with massive Thermomass walls were compared with those from an identical building simulated with lightweight wood frame exterior walls. Nine lightweight wood frame walls with R-values from 2.3 - 29.0 (htft^2 F/Btu) were simulated in six U.S. climates. **The heating and cooling loads generated from these building simulations were used to estimate the clear wall R-value which would be needed in conventional wood frame construction to produce the same total heating and sensible cooling loads as the Thermomass wall system in each of the six climates.** The resulting R-value is a steady state R-value for the Thermomass wall multiplied by DBMS (Dynamic Benefit for Massive Systems). This factor accounts for not only the steady state R-value but also the inherent thermal mass benefit. DBMS is a function of climate, building type and base envelope system (i.e. conventional 2x4 wood frame wall system). DBMS values for the Thermomass wall were obtained by comparing the thermal performance of the Thermomass wall and conventional light-weight wood frame walls. They should be understood only as an answer to the question "What R-value would a house with wood frame walls need in oder to obtain the same space heating and cooling loads as an identical Thermomass house?" There is no physical meaning for the product "R-value x DBMS."

4.1 Dynamic Thermal Test and Modeling of Panel 1

Dynamic measurements of wall systems are typically carried out by an apparatus such as described in ASTM C 236, Standard Test Method for "Steady-State Thermal Transmission Properties of Building Assemblies by Means of a Guarded Hot Box" [ASTM ,1989]. A full-scale representative (8 x 8 ft) cross-section of the clear wall area of the wall system is used to determine its dynamic thermal performance. A dynamic test typically consists of the three basic stages:

- steady-state stage (steady temperatures on both sides of the wall),
- thermal ramp (rapid change of the temperature on the one side of the wall), and
- stabilizing stage (wall is kept under the second set of steady boundary temperatures until steady-state heat transfer occurs).

The precision of dynamic testing is close to the precision of the steady-state test method, which is reported to be approximately 8% [ASTM, 1989]. The dynamic test results were used to calibrate the finite difference computer model that served in the analytical part of this project.

The dynamic response of the wall was analyzed for a 20°F thermal ramp (it took 2 hours to change the surface temperature on the climate side of the wall from 20 to 40°F). Temperatures on both sides of the wall were stabilized, and the experiment was continued until steady-state heat transfer occurred. During the first stage of the test process, air temperatures on both sides of the wall were stabilized at 70 and 20°F. Next, a rapid change of the climate side air temperature was performed (thermal ramp). The climate side air temperature was increased from 20 to 40°F. During the second stage, the temperatures were stabilized at about 70 and 40°F.

Heating 7.2, was used for dynamic thermal analysis of Panel 1. The accuracy of Heating 7.2 was validated in two ways:

- The ability to predict steady-state R-values was verified by comparing simulation results with published steady-state test results for twenty-eight masonry, wood frame, and metal frame walls tested at ORNL and other laboratories [Kosny, Desjarlais - 1994] .
- The ability of the program to predict the dynamic process was verified using the dynamic hot box data recorded during the Thermomass wall hot box test.

The measured air temperatures 6-in. away from the surface of the metering side and 14-in. away from the climate side, along with air velocities measured in the meter and climate chambers, were used as boundary conditions for dynamic modeling of the Thermomass wall. The computer program reproduced all recorded test boundary conditions (temperatures and heat transfer coefficients) with 1-hour time intervals. The Thermomass wall internal geometry was numerically described to create the Heating 7.2 input file. The following thermal properties of materials were used for dynamic modeling:

- thermal conductivity of insulating foam 0.2 Btu-in./hft^{2}F,
- thermal conductivity of concrete 9.09 Btu-in./hft^{2}F.

Values that the program generated for heat flux on the surface of the wall were compared with the values measured during the dynamic test. The computer program reproduced the test data very well. The maximum discrepancy between test-generated and simulated heat fluxes was less than 8%. This comparison confirms the ability of Heating 7.2 to reproduce the dynamic heat transfer process measured during the dynamic hot box test of Panel 1.

4.2 Dynamic Thermal Performance of the Thermomass Wall in a Residential Buildings

The computer model developed for the Thermomass wall was used in DOE 2.1E whole building computer modeling. DOE 2.1E is a detailed multi-zone hourly simulation program widely used in the United States and abroad for calculating the energy consumption of buildings. DOE 2.1E can model the impact of hourly variations in ambient climate conditions and internal loads on the building load, as well as vary equipment performance characteristics and realistic operating conditions such as thermostat setbacks and window venting. DOE 2.1E contains two main programs: LOADS and SYSTEMS. The LOADS program calculates the hourly heating and cooling loads of a building or thermal zone at a set indoor temperature. The SYSTEMS program contains algorithms for simulating the performance of the heating, ventilating, and air conditioning (HVAC) equipment used to control the temperature and humidity of the building or zone. SYSTEMS combines the loads output from the LOADS program with the building description inputs to find the capacity, air-flow rate, efficiency, part-load characteristics, and thermostat settings of the system, as well as the temperature and schedule for window venting. It also solves for the indoor air temperature, the true hourly load on the system and its energy consumption. The analysis to determine the dynamic R-value equivalent for Panel 1 uses the space heating and cooling load data that are output from the LOADS portion of DOE 2.1E report.

Six U.S. climates were used for whole building thermal modeling and determination of the dynamic R-value equivalent for the Thermomass wall system. A list of cities and climate data are presented in Table 5.

Table 5. Six U.S. climates used for DOE 2.1E computer modeling

Cities:	HDD (65 deg F)	CDD (65 deg F)
Atlanta	3070	1566
Denver	6083	567
Miami	185	4045
Minneapolis	8060	773
Phoenix	1382	3647
Washington D.C.	4828	1083

To normalize the calculations, a standard residential building elevation was used. The standard elevation selected for this purpose is a single-story ranch style house that has been the subject of previous energy efficiency modeling studies [Hasting, S.R. - 1977, Huang, Y.J. - 1987, Christian - 1991]. A schematic of the house is shown in Appendix B. The house has approximately 1540 ft^2 of living area, 1328 ft^2 of exterior (or elevation) wall area, eight windows, and two doors (one door is a glass slider; its impact is included with the windows). The elevation wall area includes 1146 ft^2 of opaque (or overall) wall area, 154 ft^2 of window area and 28 ft^2 of door area.

For the base case calculation of infiltration, the Sherman-Grimsrud Infiltration Method option in the DOE 2.1E whole building simulation model was used [Sherman, M.H., and Grimsrud, D.T.- 1980]. An average total leakage area expressed as a fraction of the floor area of 0.0005 was assumed. This is considered average for a single zone wood framed residential structure. An average leakage area for concrete buildings is expected to be lower than for conventional woo frame buildings. However, due to lack of experimental data supporting this statement an average total leakage area for concrete building was assumed as the same as for wood frame structure.

For the house described above, cooling, heating, and total load (heating+cooling) were estimated for the Panel 1. Simulated, results are presented in Table 6, for the six U.S. climates. The DOE-2.1E input file for the single-story ranch style house containing Thermomass walls is presented in Appendix C. The same file was used for modeling of the single-story ranch style house with light weight wood frame walls (only wall descriptions were changed).

For the same building and climates, similar energy simulations were performed for lightweight wood frame (2x4 construction with 16-in. o.c.) walls of clear wall R-value from 2 to 29 hft^2 °F/Btu. The total space heating and cooling load consumption data for the light weight wood frame walls are used for the analysis of the dynamic thermal performance of the Thermomass wall. Configurations and R-values for lightweight wood frame walls are presented in Table 7. The DOE-2.1E input file with Thermomass wall, presented in Appendix B, was modified. The Thermomass walls were replaced with lightweight wood frame walls. The thermal mass benefit is expressed in terms of the effective R-value, which is the lightweight wall R-value, for the same climate, and the same heating and cooling loads as the building with Thermomass walls.

Based on comparisons between total loads necessary for heating and cooling lightweight wood frame building and the Thermomass house, DBMS (Dynamic Benefit for Massive Systems) values for the finished Thermomass wall Panel 1 are estimated for six U.S. climates. The product; **"[steady state R-value (for Thermomass wall)] x DBMS" expresses the R-value that would be needed in conventional wood frame construction to produce the same loads as the Thermomass wall Panel 1 in each of the six climates. It is called Dynamic R-value Equivalent.**

Table 6. Simulated heating and cooling energy required for the ranch house built with the Thermomass wall Panel 1 (for the six U.S. locations).

Location	Cooling Energy [MBtu]	Heating Energy [MBtu]	Total Energy [MBtu]
Atlanta	6.32	23.1	29.42
Denver	0.705	44.84	45.545
Miami	35.73	0.52	36.25
Minneapolis	1.615	78.07	79.685
Phoenix	29.65	4.19	33.84
Washington, D.C.	3.55	39.58	43.13

For six US locations, Dynamic R-value Equivalents, are depicted on Figure 21. They can be simply computed as a product of steady state R-value for Panel 1 multiplied by DBMS. This product accounts for not only the steady state R-value, but also the inherent thermal mass benefit. DBMS is a function of climate, building type, and base envelope system (i.e. conventional 2x4 wood frame technology). DBMS values are presented on Figure 22. They were obtained by comparing the thermal performance of the same house built with Thermomass units and light-weight wood frame house. There is no physical meaning for the product "R-value x DBMS."

As shown in Figure 22, the most effective application of the Thermomass walls of those climates we checked is in Phoenix. There, the comparative R-value that would be needed in conventional wood frame construction to produce the same loads as the Thermomass wall is 2.9 times higher than the steady state R-value of the Thermomass wall. Minneapolis is the location where the usage effectiveness of the Thermomass wall is the lowest. However, even in Minneapolis, wood frame construction would require R-value 1.5 times higher than Thermomass wall to produce the same loads as the Thermomass house.

Table 7. Configurations and R-values for light weight wood-frame walls (2x4 with 16-in. o.c.).

Steady state clear wall R-value [hft^2 °F/Btu]	Wall configuration:
2.3	Aluminum siding, ½-in. insul. sheathing (R=1.32), 3-1/2-in. wood stud, empty cavity, ½-in. gypsum board.
4.7	Aluminum siding, ½-in. insul. sheathing (R=1.32), ½-in EPS Foam, 3-1/2-in. wood stud, empty cavity, ½-in. gypsum board.
6.8	Aluminum siding, ½-in. insul. sheathing (R=1.32), 1-in EPS Foam, 3-1/2-in. wood stud, empty cavity, ½-in. gypsum board.
12.5	Aluminum siding, ½-in. insul. sheathing (R=1.32), 3-1/2-in. wood stud, R-11 batts, 1/2-in. gypsum board.
15.0	Aluminum siding, 1/2-in. insul.sheathing (R=1.32), 1/2-in EPS Foam, 3-1/2-in. wood stud, R-11 batts, 1/2-in. gypsum board.
17.0	Aluminum siding, 1/2-in. insul.sheathing (R=1.32), 1-in EPS Foam, 3-1/2-in. wood stud, R-11 batts, 1/2-in. gypsum board.
20.0	Aluminum siding, 1/2-in. insul.sheathing (R=1.32), 5-1/2-in. wood stud, R-19 batts, 1/2-in. gypsum board.
23.0	Aluminum siding, 1/2-in. insul.sheathing (R=1.32), 1/2-in EPS Foam, 5-1/2-in. wood stud, R-19 batts, 1/2-in. gypsum board.
29.0	Aluminum siding, ½-in. insul.sheathing (R=1.32), 1-1/2-in EPS Foam, 5-1/2-in. wood stud, R-19 batts, 1/2-in. gypsum board.
37.0	Aluminum siding, ½-in. insul.sheathing (R=1.32), 2-in Polyurethan Foam, 5-1/2-in. wood stud, R-30 Formaldehyde insul., ½-in. gypsum board.

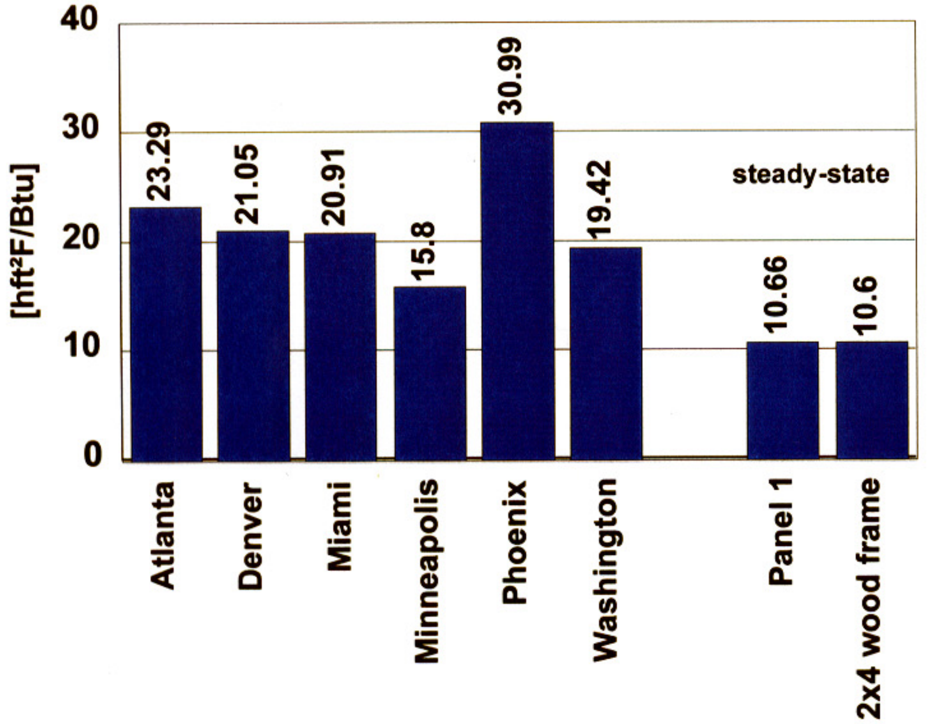

Figure 21. Comparison of the steady state R-values for the Thermomass Panel 1 and 2x4 wood frame wall with dynamic R-value equivalents for six US locations.

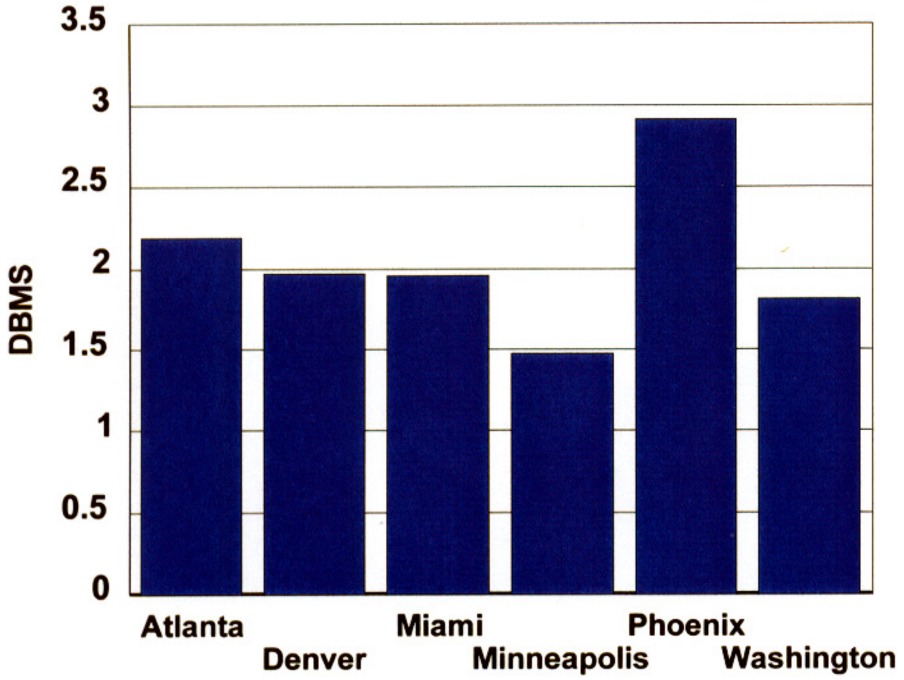

Figure 22. DBMS-values for Thermomass Panel 1.

5. 0 Equivalent walls for Panels 1, 2, 3, 4, and 6

Most whole-building energy-modeling computer programs currently use simplified, one dimensional, parallel path, descriptions of building envelope . For several structural and material configurations of building envelope components that contain high thermal mass and/or two and three dimensional thermal bridges, traditional one-dimensional analysis may generate serious errors in estimation of building loads. The building envelope is one of the most important factors influencing energy efficiency of the whole building. Proper whole building thermal modeling requires accurate descriptions of building envelope components. Otherwise, the results of the whole building simulations may provide misleading information about the energy balance of the building.

The equivalent wall concept was introduced for use in energy modeling performed on buildings containing complex thermal envelope assemblies. A thermally equivalent wall has a simple one-dimensional multilayer structure (1-D) and the same dynamic thermal behavior as the actual wall. The equivalent wall concept expresses the role of storage effects in heat flow through an element [Kossecka and Kosny 1996, 97] . It leads to the definition of the structure factors - the dimensionless quantities, representing the fractions of heat stored in the wall volume, in transition between two different states of steady heat flow, that is transferred across each wall surface. These quantities, together with total transmittance and capacity, are the basic thermal characteristics of the structure.

The equivalent wall technique is a relatively simple way to allow whole-building energy simulations (using DOE-2 or BLAST) for buildings containing complex assemblies. It is possible to generate a series of response factors or transfer functions for the complex wall and modify the whole building simulation program source codes to enable this type of wall data input. However, the equivalent wall technique represents all the thermal information about the wall by only five numbers (R, C, and three thermal structure factors). This is much simpler than the alternate use of a long series of response factors (for massive walls, 60 to sometimes 150 numbers multiplied by 3) or calculation of Z-transfer function coefficients that must be accompanied with troublesome modification of the program source code. A theoretical procedure for calculation of equivalent wall is summarized in Appendix D.

Computer models of Panels 1, 2, 3, 4, and 6 were used to generate equivalent walls. For each wall a simple three layer assembly was developed. The total thickness of equivalent wall is to be the same as for nominal wall. Each layer is characterized by R- value and heat capacitance. The thickness of each layer is 1/3 of the total thickness of the nominal wall. For each layer, R- value and heat capacitance can easily be utilized in whole building simulations after making the following elementary conversions are made.

$$Layer\ thermal\ conductivity = \frac{wall\ thickness}{3 \cdot layer\ R - value}$$

$$Layer\ specific\ heat\ = 1.0$$

$$Layer\ density = 1.0 \cdot heat\ \text{Capacitance}$$

Thermal structure factor and equivalent wall parameters are listed in Tables 8, 9 and 10 for each of considered walls. This data can be simply used in the whole building energy modeling.

Table 8. Thermal structure factors for Panels 1 through 4 and 6.

Description	**Units**	**Equivalent Wall Parameters**				
		Panel 1	**Panel 2**	**Panel 3**	**Panel 4**	**Panel 6**
Thermal Structure Factor , ax	--	4.0117	3.9576	3.8828	3.8066	1.9579
Thermal Structure Factor , ay	--	1.5927	2.1374	3.0131	3.7806	1.0626
Thermal Structure Factor , az	--	5.6697	5.6149	5.5146	5.4372	7.8296
R-value	[hft^2 °F/Btu]	10.58	7.61	6.35	4.67	30.93
Capacitance	[Btu/ft^2 °F]	14.47	14.47	14.70	14.71	19.44

Table 9. Equivalent wall layer R-values for Panels 1 through 4 and 6.

Description	**Units**	**Equivalent Wall Layer R-values**				
		Panel 1	**Panel 2**	**Panel 3**	**Panel 4**	**Panel 6**
Layer 1	[hft^2 °F/Btu]	2.873	2.342	0.3036	0.333	0.7463
Layer 2	[hft^2 °F/Btu]	1.014	7.138	5.7598	4.1966	29.874
Layer 3	[hft^2 °F/Btu]	1.574	2.354	0.2873	0.1489	0.3122

Table 10. Equivalent wall layer capacitance values for Panels 1 through 4 and 6.

Description	Units	Equivalent Wall Layer R-values				
		Panel 1	Panel 2	Panel 3	Panel 4	Panel 6
Layer 1	[Btu/ft^2 °F]	5.787	5.719	5.747	5.586	3.734
Layer 2	[Btu/ft^2 °F]	7.138	0.5600	0.7117	1.3446	0.4993
Layer 3	[Btu/ft^2 °F]	2.354	8.196	8.243	7.7825	15.204

Conclusions

Three-dimensional computer modeling and steady-state hot box test were used for steady-state thermal performance analysis of five precast concrete walls. The hot-box-tested steady-state R-values for walls were as follows:

- 10.5 hft^{2}F/Btu. for Panel 1,
- 7.6 hft^{2}F/Btu. for Panel 2,
- 5.8 hft^{2}F/Btu. for Panel 3,
- 4.6 hft^{2}F/Btu. for Panel 4,
- 29.3 hft^{2}F/Btu. for Panel 6,

The heat conduction, finite difference computer code Heating 7.2 [Childs 1993], was used for computer modeling. The resultant isotherm maps were used to calculate average heat fluxes, and wall system R-values. Computer generated R-values and experimental hot box tested R-values were within +/-5.5%.

Since the ORNL hot box measure area was 8 x 8-ft, and tested panels were 8.6 x 9.9-ft, some of the panel areas were not covered by measure box. In Panels 1 and 2, the guarded box covered about 85% of thermally bridged areas. Because thermal bridges were distributed relatively uniformly through the whole area of the tested panels, the tested areas were considered as a relatively good representation of the whole panels.

For Panels 3 and 4, the guarded box completely covered 4 concrete penetrations. The remaining four penetrations were partially covered by the guarded box. Therefore, significant thermal bridging from these penetrations influenced the heat flux rate recorded during the test. To assess the heat flux difference between the tested area and the whole panel area, two simulations were performed on Panels 3 and 4. The first simulation covered 8 x8-ft. measured area, and the second one 8.6 x 9.9 full panel area. In both cases R-values for measured areas were about 15% higher than for the whole panels. This meant that in both cases thermal bridges were slightly over represented during the hot-box tests. Tested R-value results for Panels 3 and 4 should therefore be considered as conservative.

Computer modeling enabled detailed surface temperature distribution analysis. It was found that Panel 1 had a very uniform surface temperature (evidence of lack of thermal bridges). Surface temperature distribution in Panel 2 was similar as in conventional 2 x 4 wood frame wall (with no foam sheathing).

Dynamic hot-box test and the finite difference computer modeling were utilized to examine the dynamic thermal performance of Panel 1. The whole building computer model DOE 2.1E was used to simulate a representative single family residence in six U.S. climates. It was found that the total space heating and cooling load of the house built with Panel 1 can be significantly reduced when compared to a lightweight wood frame wall with equivalent steady-state R-value. The best dynamic energy performance of Panel 1 was obtained for Phoenix, where comparative wood frame wall R-value would have to be R-31. The lowest dynamic energy performance of Panel 1 was observed for a very severe climate of Minneapolis, where Panel 1 performed as well as R-15.8 wood frame wall.

In addition, equivalent wall parameters were generated for each of considered walls. These data can be simply used in whole building energy modeling.

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Appendix A:

Hot Box Test Procedure

The wall assemblies were tested in accordance with ASTM C 236-89, "Steady-State Thermal Performance of Building Assemblies by Means of a Guarded Hot Box" using the Oak Ridge National Laboratory Rotatable Guarded Hot Box (RGHB). A photograph of the test facility is shown in Figure A1.

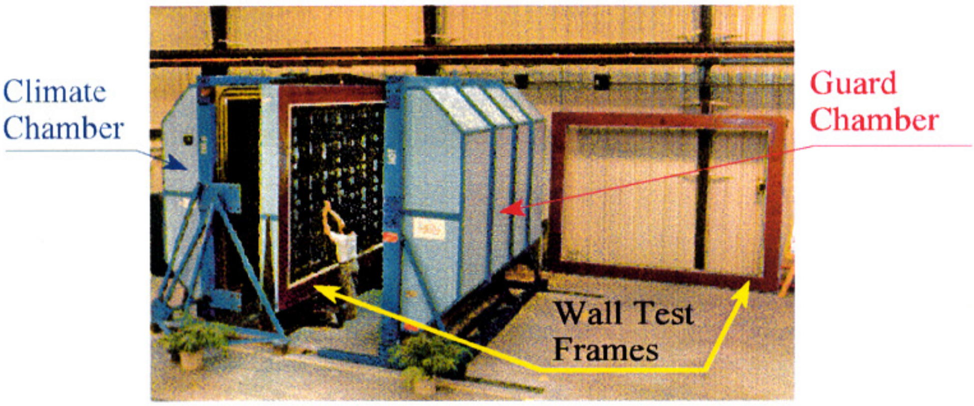

Figure A1. ORNL guarded hot box.

The test wall assemblies were installed into a specimen frame which is mounted on a moveable dolly. The specimen frame had an aperture of 4 by 3 m (13' 1" by 9' 10" ft.) -Figure A2.. Since the wall assemblies being evaluated were all smaller than this aperture, the remaining area was filled with a thermally resistive insulation material and the thickness of the fill material is adjusted to match the thickness of the test wall assembly. The specimen frame/test wall assembly was inserted between two chambers of identical cross-section.

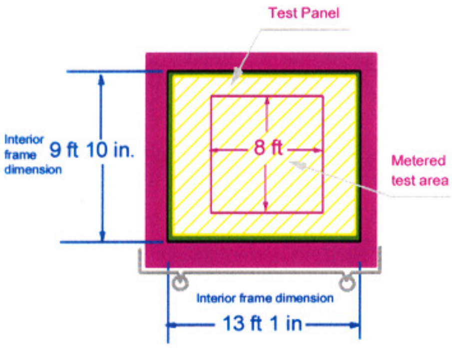

Figure A2. ORNL BTC Hot Box test panel schematic.

The insertion of the test wall assembly between the chambers allowed the chamber temperatures to be independently controlled. These chambers were designated as the climate (cold) and metering/guard (hot) chambers.

In the climate chamber, a full-size baffle is mounted approximately 10 in. (250 mm) from the test wall assembly. Temperature control in this chamber is accomplished by the insertion of a refrigerated air and electrical resistance heaters in series with an array of air blowers. An external refrigeration system is operated continuously and cooled air is transferred from the refrigeration system through insulated flexible ducting into the rear of the climate chamber behind the baffle. Five centrifugal air blowers, installed in the climate chamber behind the baffle, are used to circulate the air through a bank of electrical resistance heaters and through the airspace between the baffle and test wall assembly. Temperature control is accomplished by a combination of controlling the airstream temperature entering the climate chamber and fine-tuning that temperature with the resistance heaters. The air velocity parallel to the climate side of the test wall assembly is controlled by adjusting the electric power input frequency to the air blowers. An anemometer continuously measures the wind speed in the airspace.

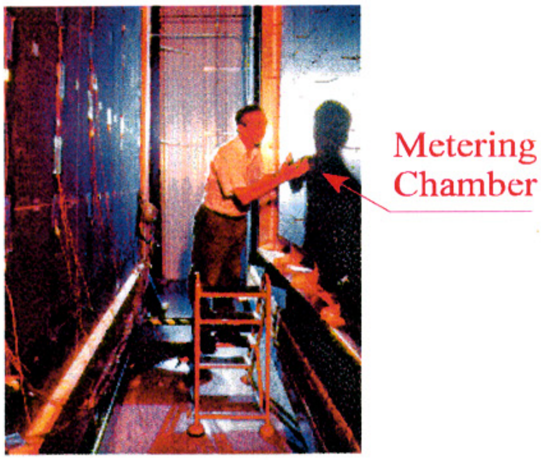

Figure A3. Metering chamber.

In the center of the metering/guard chamber, a metering chamber is pressed against the test wall assembly. A photograph of the metering chamber is shown in Figure A3. The metering chamber is approximately dimensioned 8 ft. (2.3 m) square by 1.3 ft. (0.4 m) deep. The walls of the metering chamber are constructed with 3-in. (76 mm) thick aged extruded polystyrene foam having an approximate thermal resistance of 15 hr ft^2 °F/Btu (2.6 m^2 K/W) at 75°F (24°C). The walls of the metering chamber are reinforced with aluminum frames on the interior and exterior sides and are interconnected with fiberglass threaded rods. The edge of the metering chamber which contacts the test assembly is tapered to a thickness of 0.75-in. (19 mm) and a 0.5-in. (13 mm) square neoprene rubber gasket is affixed to this tapered edge. This gasket is very compressible and readily follows the contour of the test wall surface to minimize air leakage form the metering to the guard chamber. A baffle is mounted inside the metering chamber 6-in. (150 mm) from the exposed edge of the gasket.

Behind the baffle, an array of eight fans and four electric resistance heaters are installed. These components are installed such that air is pulled downward behind the baffle, through the resistance heaters, and upward through the airspace between the baffle and test assembly. The upper and lower rear corners of the metering box are tapered to minimize air impingement onto the metering box walls and to provide a smooth transition into the baffle space.

A ninety-six junction (forty-eight pair) differential thermopile is applied on the interior and exterior walls of the metering chamber to sense the temperature imbalance between the metering and guard chambers. Each thermopile junction is mounted in the center of equivalent surface areas; the interior junction is mounted directly opposite to the corresponding exterior junction. Four heaters and six fans are installed in the guard box to supply heat and circulate the air. These heaters and fans are situated to uniformly distribute the heat and not impinge directly onto the metering chamber.

All temperature measurements were performed using Type T copper/constantan thermocouples calibrated to the special limits of error specified in ASTM E 230, "Temperature-Electromotive Force (EMF - Electromotive Force) Tables for Standardized Thermocouples." All thermocouples were fabricated with No. 26 AWG (American Wire Gage) wire prepared from the same spool. Arrays of thirty-six and forty-eight thermocouples were used to measure the meter and climate chamber air temperatures. Additional arrays of temperature sensors are affixed to each side of the test wall assembly to measure the surface temperature of each wall system component. All of the thermocouples that were attached to the surface of the test wall assemblies were affixed with duct tape. To determine the average surface temperature, the average temperature of the individual wall system components are area-weighted.

In operation, the temperature of the climate chamber is set at the desired level. A controllable AC source is used to energize the metering chamber heaters while the metering chamber fans are powered using a programmable D.C. power supply. The power to the fans is fixed to maintain the desired wind speed in the airspace between the baffle and the test wall assembly. An anemometer is used to set and monitor this wind speed. The power to the metering heaters is adjusted to obtain the required metering chamber air temperature. The output of the differential thermopile is used to energize the heaters in the guard chamber by using a differential temperature controller. By this technique, the temperature difference across the metering chamber walls could be minimized, thereby permitting negligible heat leaks into or out of the metering chamber.

These conditions are maintained until temperatures and heat flows equilibrated. The heat flow generated by the heaters is measured using a watt-hour transducer and the energy dissipated by the fans is metered with precision resistor networks. Once steady-state conditions have been achieved, the test period is continued until two successive four hour periods produce results that varied nonmonotonically by less than one percent. The data for each period is the average of one-minute scans for that period.

The thermal resistance is calculated by

$$R = \frac{A(t_1 - t_2)}{(Q_h + Q_f + Q_{mb})} \qquad \text{(A1)}$$

where R = thermal resistance of wall assembly, hrft²°F/Btu (m² K/W);
A = area of metering chamber, ft² (m²),
t_1 = average surface temperature of the wall assembly on the metering side, °F (C°);
t_2 = average surface temperature of the wall assembly on the climate side, °F (°C);
Q_h = metering heater energy input, Btu/hr (W);
Q_f = metering fan energy input, Btu/hr (W); and
Q_{mb} = metering chamber wall energy exchange between the metering and guard chambers, Btu/hr (W).

To verify the performance of the rotatable guarded hot box, we performed a series of five verification experiments on a homogeneous panel comprised of a 5-in. (127 mm) thick expanded polystyrene foam core faced on both sides with 0.12-in. (3 mm) high impact polystyrene sheet. In these experiments, we varied the test conditions (temperatures of the metering and climate chambers) and the differential thermopile setting. These experiments were performed to assess how closely we needed to maintain the null balance of the thermopile and to determine the precision of the RGHB. A summary of these results is presented in Table A1.

The R-value data presented in Table A1 have already been corrected for any deliberate thermopile imbalance. The metering chamber input heat flow is corrected for any losses through the metering chamber walls to determine the specimen heat flow. The metering chamber wall heat flow was calculated by

$$Q_{mb} = \frac{A_{mb} * \Delta T_{mb}}{R_{mb}} \qquad \text{(A2)}$$

where Q_{mb} = heat flow through metering chamber walls, Btu/hr (W);
A_{mb} = surface area of the metering chamber, ft² (m²);
ΔT_{mb} = temperature imbalance across the metering chamber walls, °F (°C); and
R_{mb} = thermal resistance of the metering chamber walls, hr ft² °F/Btu (m² K/W).

At mean temperatures of 50 and 75°F (10 and 24°C), the differential thermopile bias correction yields R-values that are within 0.05 and 0.02 hr ft² °F/Btu (0.009 and 0.004 m²K/W) of the average values, respectively. To obtain a 10 Btu/hr (2.9 W) bias from the metering chamber requires a 1.5°F (0.8°C) temperature imbalance across the metering chamber walls.

In addition to testing the verification panel in the RGHB, specimens of the EPS foam used to fabricate the verification panel were submitted to the Materials Thermal Analysis Group at the Oak Ridge National Laboratory. They measured the thermal resistance of these specimens in accordance with ASTM C 518-91, "Steady-State Heat Flux and Thermal Transmission Properties by Means of a Heat Flow Meter Apparatus." Using handbook values for the thermal resistance of the polystyrene sheet (0.36 hr ft^2 F/Btu or R = 0.063 m^2 K/W) and adding this thermal resistance to the R-value of the EPS foam, the R-value vs. temperature for the specimen of the verification panel was determined. These data were linearly regressed and compared to the data compiled in the RGHB. Table A2 summarizes these results.

Table A1. Summary of experimental results obtained on the expanded polystyrene foam verification panel. The effects of mean temperature and differential thermopile balance are sought.

Test	Temperature				Heat Flow			R-value
	Meter °F	Climate °F	Mean °F	Thermopile °F	Input Btu/hr	Metering Chamber Btu/hr	Specimen Btu/hr	hr ft^2 °F/Btu
1	98.9	52.3	75.6	-0.04	142.5	-0.3	142.2	21.14
2	98.8	52.7	75.7	-1.03	149.0	-6.9	142.1	21.14
3	99.0	51.1	75.0	0.87	135.3	5.8	141.1	21.16
4	96.6	4.6	50.6	-0.05	267.0	-0.3	266.7	22.07
5	97.5	6.6	52.0	0.87	258.7	5.8	264.5	22.02

Test	Temperature,				Heat Flow,			R-value
	Meter °C	Climate °C	Mean °C	Thermopile °C	Input, W	Metering Chamber W	Specimen W	m^2 K/W
1	37.2	11.3	24.2	-0.02	41.7	-0.1	41.6	3.725
2	37.1	11.5	24.3	-0.57	43.6	-2.0	41.6	3.725
3	37.2	10.6	23.9	0.48	39.6	1.7	41.3	3.728
4	35.9	-15.2	10.3	-0.03	78.2	-0.1	78.1	3.889
5	36.4	-14.1	11.1	0.48	75.8	1.7	77.5	3.880

We find excellent agreement between the test results generated between the two test apparatus; all five of the ASTM C 0236 experiments performed in the RGHB are within ± 0.2% of the ASTM C

0518 results from the heat flow meter apparatus. Even if our estimate of the thermal resistance of the polystyrene sheets were in error by 50%, the results from the two procedures would still agree to within 1.1%. The need to estimate the R-value of the polystyrene sheets does not appreciably compromise the results that are presented.

Table A2. A comparison of the ASTM C 236 (RGHB) and ASTM C 518 test results on specimens of the expanded polystyrene foam verification panel. The ASTM C 518 results are based on a linear regression of the results of the actual experiments as a function of temperature and are computed at the same mean temperature as the RGHB results.

Test	Mean Temperature	R-value, hr ft² °F/Btu		% Difference, (C 236 - C 518)/C518
	°F	ASTM C 236	ASTM C 518	
1	75.6	21.14	21.14	0.0
2	75.7	21.14	21.14	0.0
3	75.0	21.16	21.20	-0.2
4	50.6	22.07	22.07	0.0
5	52.0	22.07	22.01	0.1

Test	Mean Temperature	R-value, m² K/W		% Difference, (C 236 - C518)/C518
	°C	ASTM C 236	ASTM C 518	
1	24.2	3.725	3.725	0.0
2	24.3	3.725	3.725	0.0
3	23.9	3.728	3.735	-0.2
4	10.3	3.889	3.889	0.0
5	11.1	3.880	3.878	0.1

Appendix B

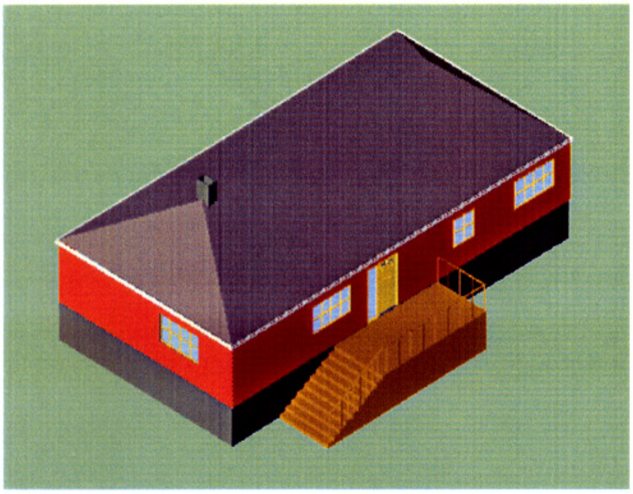

Figure B1. Perspective of one-story ranch-style house used in thermal modeling

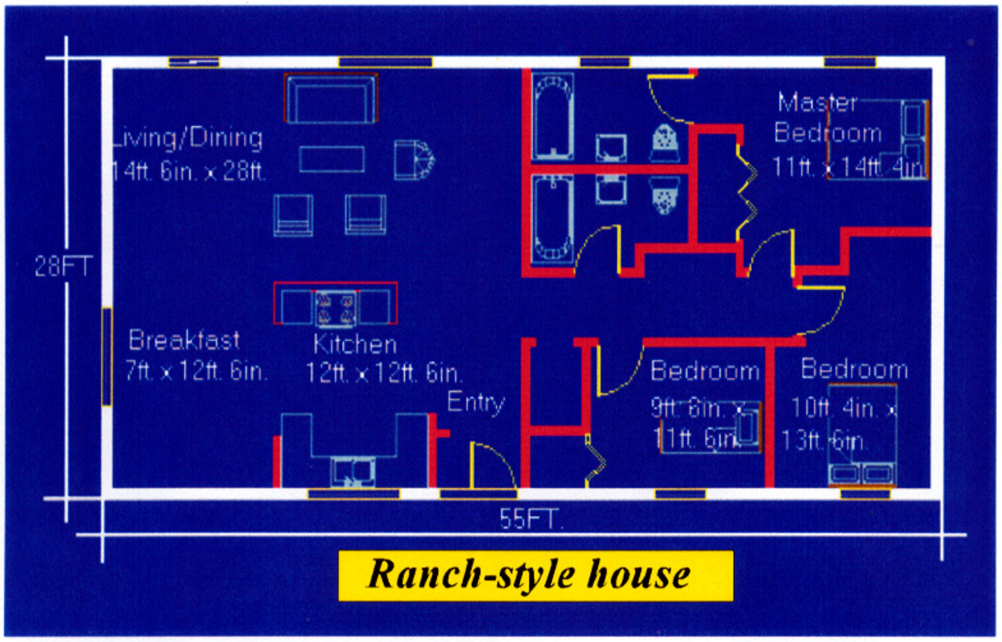

Figure B2. Floor plan of one-story ranch-style house used in thermal modeling.

Appendix C

DOE-2.1E input file for one story ranch-style house used in computer modeling.

```
INPUT LOADS  ..

TITLE    LINE-1  *CAL_FRM.INP AAB BlueMaxx + finish        *
         LINE-2  *ONE STORY CALIFORNIA HOUSE - FRAME       *
         LINE-3  *SEPARATE INSULATION AND STUD PATHS       *
         LINE-4  *HOUSE BUILT ON SLAB                      *
         LINE-5  *South  BASE          R-21.43             *  ..

$ THIS FILE IS A MODIFICATION OF THE CALIFORNIA RANCH HOUSE AS OBTAINED
$ FROM MIKE GETTINGS AND USED IN KEN WILKES RADIANT BARRIER FACT STUDY.

$ HOUSE ASSUMED TO BE BUILT ON SLAB.

DIAGNOSTIC  WARNINGS  ..
ABORT ERRORS  ..

PARAMETER
         FLOORAREA=1540  PERIM=166  IWALLAREA=1000
$         BSMTAREA=1540 $
         INTLOAD=55106  LATLOAD=.2150
         INFILT = .0005     $ MEDIUM INFILTRATION $
         WINDOWGT=WINDOW-2 $ GLASS TYPE $  ..

RUN-PERIOD          JAN 1 1986  THRU  DEC 31 1986  ..

BUILDING-LOCATION  LAT=33.43  LON=112.02  T-Z=7  ALT=1117
                   WS-HEIGHT=33
                   AZIMUTH=0 SHIELDING-COEF=0.19
                   TERRAIN-PAR1=.85 TERRAIN-PAR2=.20
                   WS-TERRAIN-PAR1=1  WS-TERRAIN-PAR2=0.15
                   FUNCTION=(*SHADING*,*NONE*) ..

LOADS-REPORT       SUMMARY=(LS-B,LS-E) ..

    $ LOADS SCHEDULES $

DAYINTSCH  DAY-SCHEDULE  $ CEC INTERNAL LOADS PROFILE $
              (1) (.024) (2) (.002) (3,5) (.021) (6) (.026)
              (7) (.038) (8) (.059) (9) (.056) (10) (.060)
              (11) (.059) (12) (.046) (13) (.045) (14) (.030)
              (15) (.028) (16) (.031) (17) (.057) (18,19) (.064)
              (20) (.052) (21) (.050) (22) (.055) (23) (.044)
              (24) (.027) ..
INTLDSCH  SCHEDULE  THRU DEC 31  (ALL)  DAYINTSCH ..

   $ THE FOLLOWING SHADING SCHEDULE IS MODIFIED BY FUNCTION SHADING
   $ TO GIVE .63 DURING THE COOLING SEASON DEFIND AS PERIODS WITH
   $ MORE THAN 5 COOLING DEGREE DAYS FOR THE FOUR PREVIOUS DAYS.

SHADCO  SCHEDULE  THRU DEC 31  (ALL)  (1,24)  (0.80) ..

   $ GLASS TYPES $

WINDOW-1      GLASS-TYPE
              PANES=1  GLASS-TYPE-CODE=1  GLASS-CONDUCTANCE=1.35 ..
WINDOW-2      GLASS-TYPE
              PANES=2  GLASS-TYPE-CODE=1  GLASS-CONDUCTANCE=.535 ..
WINDOW-3      GLASS-TYPE
              PANES=3  GLASS-TYPE-CODE=1  GLASS-CONDUCTANCE=.327 ..

  $  MATERIALS $

con140=MAT    TH=.541   COND=.83      DENS=140  S-H=.21  ..
AABFOAM=MAT   TH=.208   COND=.0215    DENS=16   S-H=.29 ..
WoodSid=MAT   TH=.0833  COND=.0794    DENS=40   S-H=.39 ..
R11INS=MAT    TH=.2917  COND=.02652   DENS=.6   S-H=.19  ..
R19INS=MAT    TH=.6878  COND=.0362    DENS=.5   S-H=.19  .. $ BLOWN FBGLS $
```

```
R19INSJ=MAT     TH=.2295   COND=.0362    DENS=.5    S-H=.19    ..
FRAM=MAT        TH=.2957   COND=.06833   DENS=28    S-H=.39    .. $ 3.5 IN.studs $
RJST=MAT        TH=.4583   COND=.06833   DENS=28    S-H=.39    .. $ 5.5 IN.joist $
GYPBD=MAT       TH=.04167  COND=.0926    DENS=50    S-H=.26    ..
EARTH=MAT       TH=2.5     COND=.50      DENS=120   S-H=.2     ..
FRAM1=MAT       TH=.5108   COND=.6833    DENS=28    S-H=.39    .. $ 5.5 IN.studs $

  $  LAYERS $

WALLINS=LA      MAT=(WoodSid,AABFOAM,con140,AABFOAM,GYPBD) ..
WALLSTUD=LA     MAT=(WoodSid,AABFOAM,con140,AABFOAM,GYPBD) ..
IWALLC=LA       MAT=(GYPBD,AL21,GYPBD) ..
IWALLS=LA       MAT=(GYPBD,FRAM,GYPBD) ..
ROOFJST=LA      MAT=(AR02,AR01,PW03,RJST,AL32,R19INSJ,RJST,GYPBD) ..
ROOFINS=LA      MAT=(AR02,AR01,PW03,AL32,IN05,GYPBD) ..
$ FLRLINS=LA      MAT=(IN03,PW03,PB04,CP01) I-F-R=.61 ..
$ FLRLJST=LA      MAT=(JSTS,PW03,PB04,CP01) I-F-R=.61 ..
$ BANDJ=LA        MAT=(HB01,AR01,WD02) ..
$ UNDGWALL=LA     MAT=(SC01,CB31) ..
FLR=LA          MAT=(EARTH,CC03,CP01) I-F-R=.61 ..

  $ CONSTRUCTIONS $

SET-DEFAULT     FOR CONSTRUCTION  ROUGHNESS=3 .. $ CONCRETE $

WALL-INS        CONSTRUCTION   LAYERS=WALLINS   .. $ WALL SECTION INS PATH $
WALL-STUD       CONSTRUCTION   LAYERS=WALLSTUD   .. $ WALL SECTION STUD PATH $
ROOF-JST        CONS    LAYERS=ROOFJST  ABS=.75   .. $ ROOF SECTION, WITH JOIST $
ROOF-INS        CONS    LAYERS=ROOFINS  ABS=.75   .. $ ROOF SECTION, WITH INSUL $
IWALLCAV        CONSTRUCTION   LAYERS=IWALLC  .. $ INTERIOR WALLS, CAVITY $
IWALLSTD        CONSTRUCTION   LAYERS=IWALLS  .. $ INTERIOR WALLS, STUDS $
DOORCON         CONSTRUCTION   U-VALUE=.7181  .. $ SOLID DOOR $
$ FLRICON         CONSTRUCTION   LAYERS=FLRLINS  ..   FLOOR SECTION, INS PATH $
$ FLRJCON         CONSTRUCTION   LAYERS=FLRLJST  ..   FLOOR SECTION, JOIST PATH $
$ CRWLSPWALL      CONSTRUCTION   LAYERS=UNDGWALL  ..   UNINSUL CRAWLSP WALL $
$ CRWLSPBAND      CONSTRUCTION   LAYERS=BANDJ  ..   BAND JOIST IN CRAWLSP $
$ GROUND          CONSTRUCTION   LAYERS=GND  ..    EARTH $
SLAB           CONSTRUCTION   LAYERS=FLR  ..  $ SLAB FLOOR $

    $ GABLE AND EAVE SHADING $

B-S  X=18.5  Y=18   Z=8  AZ=180  W=59  H=1.5   TILT=0   ..
B-S  X=77   Y=49.5  Z=8  AZ=0    W=59  H=1.5   TILT=0   ..
B-S  X=18   Y=20   Z=8  AZ=180  W=2  H=14.76  TILT=18.43  ..
B-S  X=75   Y=20   Z=8  AZ=180  W=2  H=14.76  TILT=18.43  ..
B-S  X=20   Y=48   Z=8  AZ=0    W=2  H=14.76  TILT=18.43  ..
B-S  X=77   Y=48   Z=8  AZ=0    W=2  H=14.76  TILT=18.43  ..

    $ SPACE CONDITIONS $

$  SENSIBLE INTERNAL LOADS ARE ASSUMED AT 4692 KWH/YEAR PLUS
$ 0.9KWH/SQFT FOR LIGHTING.  LATENT LOADS ASSUMED 1300 KWH/YEAR

ROOMCOND        SPACE-CONDITIONS
                TEMPERATURE=(74)
                SOURCE-TYPE=PROCESS
                SOURCE-SCHEDULE=INTLDSCH
                SOURCE-BTU/HR=INTLOAD TIMES 0.84
                SOURCE-SENSIBLE=1.
                SOURCE-LATENT=LATLOAD
                INF-METHOD=S-G
                FRAC-LEAK-AREA=INFILT
                FLOOR-WEIGHT=0
                FURNITURE-TYPE=LIGHT
                FURN-FRACTION=0.29
                FURN-WEIGHT=3.30  ..

THEROOM SPACE
                  SPACE-CONDITIONS=ROOMCOND
                  AREA=FLOORAREA  VOLUME=FLOORAREA TIMES 8 ..

    IWALL-CAV     INTERIOR-WALL
                  INT-WALL-TYPE=INTERNAL AREA=IWALLAREA TIMES 0.9
                  CONSTRUCTION=IWALLCAV ..
```

```
    IWALL-STD   INTERIOR-WALL $ 10 % OF WALL AREA $
                INT-WALL-TYPE=INTERNAL AREA=IWALLAREA TIMES 0.1
                CONSTRUCTION=IWALLSTD ..

    NWALL-INS   EXTERIOR-WALL
                WIDTH=41.25 CONSTRUCTION=WALL-INS
                X=75  Y=48  HEIGHT=8  AZIMUTH=0 ..
    NWIND1      WINDOW  GLASS-TYPE=WINDOWGT  X=15  Y=3  W=13.25  H=4
                SHADING-SCHEDULE=SHADCO  ..
    NWIND2      WINDOW  GLASS-TYPE=WINDOWGT  X=35.25  Y=0  W=6  H=6.667
                SHADING-SCHEDULE=SHADCO  ..
    NWALL-STUD  EXTERIOR-WALL $ 25% OF WALL AREA $
                WIDTH=13.75 CONSTRUCTION=WALL-STUD
                X=33.75  Y=48  HEIGHT=8  AZIMUTH=0 ..

    SWALL-INS   EXTERIOR-WALL  LIKE NWALL-INS
                X=20 Y=20 AZIMUTH=180 ..
    SDOOR       DOOR  X=25  Y=0  W=3.0  H=6.667 CONS=DOORCON  ..
    SWIND1      WINDOW  GLASS-TYPE=WINDOWGT  X=11  Y=4.5  W=6  H=2.5
                SHADING-SCHEDULE=SHADCO  ..
    SWINDD      WINDOW  GLASS-TYPE=WINDOWGT  X=22.5  Y=1.667  W=1  H=5
                SHADING-SCHEDULE=SHADCO  ..
    SWIND2      WINDOW  LIKE NWIND1  X=29.25  WIDTH=12  ..
    SWALL-STUD  EXTERIOR-WALL  LIKE NWALL-STUD
                X=61.25 Y=20  AZIMUTH=180  ..

    EWALL-INS   EXTERIOR-WALL  LIKE NWALL-INS
                WIDTH=21  X=75 Y=20  AZIMUTH=90 ..
    EWALL-STUD  EXTERIOR-WALL  LIKE NWALL-STUD
                WIDTH=7   X=75 Y=41  AZIMUTH=90 ..

    WWALL-INS   EXTERIOR-WALL  LIKE EWALL-INS
                X=20  Y=48  AZIMUTH=270 ..
    WWIND1      WINDOW  GLASS-TYPE=WINDOWGT  X=15  Y=3 W=6  H=4
                SHADING-SCHEDULE=SHADCO ..
    WWALL-STUD  EXTERIOR-WALL  LIKE EWALL-STUD
                X=20  Y=27  AZIMUTH=270 ..

$    FLRJST    INTERIOR-WALL   FLOOR BETWEEN THEROOM AND CRAWLSP $
$              TILT=180  CONS=FLRJCON  AREA=BSMTAREA TIMES .15
$              NEXT-TO=CRAWLSP ..
$    FLRINS    INTERIOR-WALL  TILT=180  CONS=FLRICON  N-T=CRAWLSP
$              AREA=BSMTAREA TIMES .85 ..

$   ROOF JOISTS AND RAFTERS ARE 2 X 6 ON 24 IN. CENTERS  $
    ROOFIF=ROOF  X=20  Y=20  Z=8  AZ=180  W=51.56  H=14
                 CONS=ROOF-INS  TILT=18.43  ..
    ROOFJF=ROOF  X=71.56  Y=20  Z=8  AZ=180  W= 3.44  H=24
                 CONS=ROOF-JST  TILT=18.43 ..
    ROOFIB=ROOF  X=75  Y=48  Z=8  AZ=0  W=51.56  H=14
                 CONS=ROOF-INS  TILT=18.43  ..
    ROOFJB=ROOF  X=23.44  Y=48  Z=8  AZ=0  W= 3.44  H=14
                 CONS=ROOF-JST  TILT=18.43 ..

          U-F  A=FLOORAREA  CONS=SLAB  U-EFF=.1078  TILT=180  ..

$ CRAWLSP  SPACE
$         AREA=FLOORAREA  VOLUME=FLOORAREA TIMES 3.
$         X=20  Y=20  Z=-3
$         I-M=AIR-CHANGE A-C=1.
$         Z-TYPE=UNCONDITIONED
$         F-F=0.  F-TYPE=LIGHT  F-WGT=0. ..
$         E-W  H=.33  W=55  X=55 Y=28  Z=2.67 AZ=0   CONS=CRWLSPBAND ..
$         E-W  H=.33  W=28  X=55 Y= 0  Z=2.67 AZ=90  CONS=CRWLSPBAND ..
$         E-W  H=.33  W=55  X= 0 Y= 0  Z=2.67 AZ=180 CONS=CRWLSPBAND ..
$         E-W  H=.33  W=28  X= 0 Y=28  Z=2.67 AZ=270 CONS=CRWLSPBAND ..
$         U-W  H=2.67 W=55  X=55 Y=28  Z=0.00 AZ=0   CONS=CRWLSPWALL ..
$         U-W  H=2.67 W=28  X=55 Y= 0  Z=0.00 AZ=90  CONS=CRWLSPWALL ..
$         U-W  H=2.67 W=55  X= 0 Y= 0  Z=0.00 AZ=180 CONS=CRWLSPWALL ..
$         U-W  H=2.67 W=28  X= 0 Y=28  Z=0.00 AZ=270 CONS=CRWLSPWALL ..
$         U-F  A=FLOORAREA  CONS=GROUND  TILT=180 ..

END ..
```

```
FUNCTION  NAME=SHADING
          LEVEL=BUILDING ..
ASSIGN    Y=SCHEDULE-NAME(SHADCO) ..
ASSIGN    IHR=IHR IDAY=IDAY IMO=IMO DBT=DBT ..
ASSIGN    IPRDFL=IPRDFL  ISUNUP=ISUNUP ..
CALCULATE
      IF(IPRDFL .LE. 0) GO TO 2
      SC=Y
      GO TO 70
    2 IF (IHR.NE.1) GO TO 5
      CDH=0
      HDH=0
      IDAYH=0
    5 CONTINUE
      IF(ISUNUP.EQ.0) GO TO 25
      DELTA=DBT-65.0
      IF(DELTA.GT.0.) GO TO 10
      HDH=HDH+ABS(DELTA)
      GO TO 20
   10 CDH=CDH+DELTA
   20 CONTINUE
      IDAYH=IDAYH+1
   25 IF(IHR.NE.24) GO TO 70
      CDDD=CDH/IDAYH
      HDDD=HDH/IDAYH
      IF(CDDD.LT.5.00) GO TO 29
      IF(SC.NE.0.80) GO TO 27
      ICOUNT=ICOUNT+1
      IF(ICOUNT.LE.4) GO TO 40
   27 IHCOUNT=0
      SC=0.6
      GO TO 70
   29 IF(SC.NE.0.60) GO TO 30
      IHCOUNT=IHCOUNT+1
      IF(IHCOUNT.GE.4) GO TO 30
      SC=0.6
      GO TO 70
   30 ICOUNT=0.0
   40 SC=0.80
   70 CONTINUE
      Y=SC
      END

COMPUTE LOADS ..
INPUT SYSTEMS ..
DIAGNOSTIC  CAUTIONS ECHO ..
SYSTEMS-REPORT      VERIFICATION (ALL-VERIFICATION)
                    SUMMARY=(SS-A,SS-B,SS-C,SS-F,SS-H,SS-I)  ..
PARAMETER      HEATSET=70  SETBACK=70  COOLSET=78  SETUP=78
               VTYPE=-1  $ ENTHALPY VENTING $
               FHIR=1.2987  $ 77% EFFICIENCY, DUCT LOSS EXCLUDED $
               MAXTEMP=120  $ FURNACE TEMPERATURE $
               CBF=.098  CEIR=.3703  $ 2.7 COP AIR-CONDITIONER $ ..

    $  SYSTEM SCHEDULES $

HTSCH    SCHEDULE  THRU DEC 31 (ALL) (1,6) (70) (7,23) (70) (24) (70) ..
CTSCH    SCHEDULE  THRU DEC 31 (ALL) (1,9) (78) (10,16) (78)
              (17,24) (78) ..
VTSCH    SCHEDULE  $ VENT SCHEDULE BASED ON PREVIOUS 4 DAYS
                   THRU MAY 14 (ALL) (1,24) (-4)
                   THRU SEP 30 (ALL) (1,24) (-4)
                   THRU DEC 31 (ALL) (1,24) (-4) ..
VOPSCH   SCHEDULE  $ VENT OPERATION SCHEDULE $
                   THRU DEC 31 (ALL) (1,24) (VTYPE) ..
WINDOPER SCHEDULE  $ NO WINDOW OPERATION BETWEEN 11 PM AND 6 AM $
                   THRU DEC 31 (ALL) (1,6) (0.0) (7,23) (1.0) (24) (0.0) ..

    $  ZONES  $

ZC1           ZONE-CONTROL
                   DESIGN-HEAT-T=70
                   DESIGN-COOL-T=78
                   COOL-TEMP-SCH=CTSCH
```

```
                    HEAT-TEMP-SCH=HTSCH
                    THERMOSTAT-TYPE=TWO-POSITION ..

THEROOM        ZONE ZONE-CONTROL=ZC1
                    ZONE-TYPE=CONDITIONED ..

    $  SYSTEMS  $

SYSCONTRL      SYSTEM-CONTROL
                    MAX-SUPPLY-T=120
                    MIN-SUPPLY-T=50 ..
SYSAIR         SYSTEM-AIR
$                    SUPPLY-CFM=1208
                    NATURAL-VENT-SCH=VOPSCH
                    VENT-TEMP-SCH=VTSCH
                    OPEN-VENT-SCH=WINDOPER
                    HOR-VENT-FRAC=0.0
                    FRAC-VENT-AREA=0.018  $ ASSUME 1/4 OF WINDOW OPEN $
                    VENT-METHOD=S-G       $ WITH DISCHARGE COEF OF 0.6 $
                    MAX-VENT-RATE=20 ..
SYSEQP         SYSTEM-EQUIPMENT
$                    COOLING-CAPACITY=36000
$                    COOL-SH-CAP=28800
                    COIL-BF=.098
                    COMPRESSOR-TYPE=SINGLE-SPEED
$                    HEATING-CAPACITY=-50000
                    FURNACE-AUX=0.0
                    FURNACE-HIR=1.2987  ..
                         $ 77% EFFICIENCY, EXCLUDING DUCT LOSS $
RESIDEN        SYSTEM     SYSTEM-TYPE=RESYS
                    ZONE-NAMES=(THEROOM)
                    SYSTEM-CONTROL=SYSCONTRL
                    SYSTEM-AIR=SYSAIR
                    SYSTEM-EQUIPMENT=SYSEQP
                    HEAT-SOURCE=FURNACE ..
END ..
COMPUTE SYSTEMS ..
INPUT PLANT ..
PLANT-REPORT        SUMMARY(BEPU,PS-B) ..
DUM-1               PLANT-EQUIPMENT  TYPE=COOLING-TWR  SIZE=.001 ..
END ..
COMPUTE PLANT ..
STOP ..
```