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ABSTRACT

Short-term monitoring for estimating thermal parameters of a building, along with an analytical technique to (1) determine the long-term performance and (2) calculate the parameters from a building description, has many valuable applications, which include energy ratings, diagnostics, and retrofit analysis. In this paper we address issues relating to reducing uncertainties in estimating thermal parameters with emphasis on retrofit applications. In general, it is necessary to impose a known heat flow with a suitable profile to reliably estimate the parameters. This is demonstrated with test cell measurements taken before and after changes were made to the test cell. The eventual goal of this project is to develop a practical methodology to determine long-term retrofit performance from short-term tests.

INTRODUCTION

A number of applications will benefit from the development of a credible process for determining the long-term standardized performance of a building from short-term monitoring data. Besides possibly being less expensive than long-term monitoring, such a method can be used for energy ratings and diagnostics. Since this method does not require a detailed building description, it is especially useful for retrofits where such details may be unavailable. Also, short-term monitoring before and after a retrofit can provide relatively quick feedback on the actual benefits of the retrofit. Furthermore, the thermal parameters determined from short-term monitoring are useful in establishing cause-and-effect relationships underlying building performance as needed for engineering a retrofit.

The extreme approaches to building performance analysis are pure calculation or pure measurements. Although, a purely calculational approach may be acceptable in certain contexts, predictions of building performance calculated from a building description are seldom borne out in practice, because of a plethora of input uncertainties. This is especially true in the context of retrofits, where a detailed description of the building that is necessary to provide inputs to a first principles simulation cannot be easily obtained and will not be routinely available. The other extreme is to monitor the building for a long time (e.g., an entire year) to determine its performance. This has several limitations: (1) it is expensive, (2) you still need to normalize the data for standard weather, internal gains, and schedules, and (3) the cause-and-effect relationships behind the building performance are not obvious.

To solve these difficulties requires a balanced measurement and calculational approach. A suitable thermal model of the building is necessary. Once we have such a model, we can determine the model parameters using suitable short-term tests that provide a rather complete thermal description of the building from which we can obtain normalized long-term performance. Long-term monitoring would then be needed primarily for occupancy and behavioral issues.

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To develop a practical package consisting of data specification, short-term test protocol, and analysis to determine long-term performance, we need to address two issues:

1. The characteristics of t driving functions necessary to reduce the uncertainty of estimating building thermal parameters: controlled auxiliary energy input and a monitoring period with the desired weather characteristics.

2. Seasonal variations of solar gains and ground heat flow (and other quantities not amenable to short-term tests) needed for reliable long-term prediction.

We can address the last question adequately using suitable models. In this paper we define the parameters for a suitable model (BEVA - Building Element Vector Analysis). The model and physical significance of the parameters is discussed elsewhere [1,11]. We also point out general issues in regressing the model parameters, describe the test cell experiments, and give the analytical results for both a nonlinear and a linear regression approach.

THERMAL PARAMETERS FOR THE BUILDING

The basic parameters are whole building parameters that are chosen parsimoniously to allow us to determine them from a short-term test, but have a rigorous basis for cause-effect interpretation and extrapolation to long-term performance. A crucial property of these parameters is that they can be easily calculated from a building description [1]. In this paper we are primarily concerned with estimating the parameters from measured data.

Consider first a one-zone building. Let us assume that we only need to consider solar gains from one primary orientation. If we temporarily ignore all storage effects, the energy balance over, say, a period of an hour, is given by

$$L \cdot \Delta T = S_o \cdot I_{sun} + Q_{int} + Q_{aux} , \tag{1}$$

where L is the building loss coefficient; $\Delta T = T_{in} - T_{out}$, where T_{in} and T_{out} are the inside and outside air temperatures, respectively; Q_{int} and Q_{aux} are the internal gains and auxiliary energy, respectively. The quantity I_{sun} is the solar radiation per unit area incident on the primary orientation, and S_o is the equivalent clear aperture area. By definition $S_o \cdot I_{sun}$ gives the solar gains. Hence, if storage is neglected, the building is characterized by two parameters, L and S_o.

Thermal mass effects modify Equation 1. The modifications arise for several reasons: (1) as the indoor temperature changes, the thermal masses coupled to indoor air may charge or discharge; (2) thermal masses coupled to solar radiation may charge or discharge; (3) although perhaps less obvious, thermal masses in exterior walls are coupled to outside temperature and are charged or discharged as the outside temperature changes, which in turn affects indoor heat balance; (4) internal gains or auxiliary energy may be subject to similar storage effects (e.g., lighting energy in commercial buildings).

The transfer function formulation provides a convenient and rigorous framework for handling these storage issues. In this approach interior heat flows are usually expressed as a sum of convolution integrals of the given driving forces with a time-history transfer function, one such integral for each driving force admitted to the problem. It is then necessary to postulate and suitably parameterize the transfer functions. These parameters are then thought of as equivalent thermal parameters. Earlier work in this area can be found in References 2-8. A detailed discussion of the BEVA method, on which this paper is based, can be found in Subbarao [9-11]. The BEVA method identifies the major driving functions, provides a convenient parameterization of the relevant transfer functions, and addresses multizone problems.

BEVA is a hybrid approach in which the linear parts of the problem are characterized in the frequency domain, but the simulation itself is done in time domain where nonlinear aspects (e.g., thermostatic control or variable infiltration) are easily incorporated. By treating the linear parts in terms of transfer functions in the frequency domain, a useful parameterization results: a small number of frequencies (usually zero and diurnal frequency are sufficient) characterize the transfer functions for their use in time-domain analysis.

Harmonic or frequency domain analysis has a long history and does not have a unique universal meaning. Note that in the BEVA approach: (1) the weather is not approximated by a small number of frequencies; (2) the building response is not limited to zero and diurnal frequencies, but all frequencies are implicitly included through a suitable interpolation, and (3) nonlinearities are included.

For most buildings values of the transfer functions at zero and diurnal frequency will be adequate as the building parameters. The zero frequency values are the L and S_o quantities discussed earlier. The diurnal frequency parameters are expressed as three vectors:

1. $\vec{W}$ = amplitude and phase of heat flow in response to unit outdoor temperature diurnal variation
2. $\vec{V}$ = amplitude and phase of heat flow in response to unit indoor temperature diurnal variation
3. $\vec{S}$ = amplitude and phase of heat flow in response to unit solar radiation incident upon the primary orientation.

Physical interpretation and further details are given in Subbarao [9-11]. Subbarao [11] is included in these proceedings.

For a simple one zone building, we need eight parameters: L, S_o, and three vectors $\vec{V}$, $\vec{W}$ and $\vec{S}$ (each vector counts as two parameters). The solar parameters S_o,$\vec{S}$ have a significant seasonal dependence; this must be calculated when using them for other periods.

Some limitations of this framework should be noted. The solar model used here is a "single incidence" model, the simplest of a hierarchy of solar models. For a well-insulated, unshaded building with glazing dominantly at one primary orientation (e.g., a simple test cell), this model is adequate. For more complex solar problems typical of realistic structures (e.g., multiple orientation or shading), the model must be correspondingly enhanced (e.g., multiple solar incidence drivers or calculated drivers).

There are additional extensions to contend with. Additional parameters are needed for variable infiltration and night insulation, if present. Heat exchange with the ground has large time constants associated with it and therefore needs its own parameterization. For multizone buildings heat exchange between zones needs to be included. The method developed in Subbarao [10] is able to handle these complexities.

GENERAL EXPERIMENTAL CONSIDERATIONS IN

The thermal parameters--eight of them, L, S_o, $\vec{V}$, $\vec{W}$, and $\vec{S}$, for a simple one-zone building--can be determined from short-term measurement. Forms of the BEVA models for regression purposes are given in Subbarao [9-11]. The parameters can then be used to determine building performance under any driving functions. This is discussed in detail in Subbarao [9,10]. We are concerned here specifically with the errors in the regression. Any estimation of parameters from measured data has uncertainties associated with it. If the short-term data are obtained with no attempt to choose the driving functions, the error in the estimate can be unacceptable.

A known heat flow must be introduced during the monitoring as seen by setting $Q_{int} = Q_{aux} = 0$ in Equation 1. If this is not done and only temperature response is observed, the problem has no scale and we can only determine the ratio L/S_o.

Albeit oversimplified, another constraint can be derived from Equation 1 by considering the monitoring to have two time periods, i = 1,2. Assume each time period is large compared with the storage time constants; e.g., a few days. For each period i the long term energy balance is

$$L \, \overline{\Delta T_1} - S_o \, \overline{I}_{sun,i} = \overline{Q}_{aux,i}, \quad i = 1, 2. \tag{2}$$

Solving for L and S_o, we have

$$L = \frac{\overline{Q}_{aux,1}/\overline{I}_{sun,1} - \overline{Q}_{aux,2}/\overline{I}_{sun,2}}{\overline{\Delta T_1}/\overline{I}_{sun,1} - \overline{\Delta T_2}/\overline{I}_{sun,2}} \tag{3}$$

$$S_o = \frac{\bar{Q}_{aux,1}/\overline{\Delta T}_1 - \bar{Q}_{aux,2}/\overline{\Delta T}_2}{\bar{I}_{sun,2}/\overline{\Delta T}_2 - \bar{I}_{sun,1}/\overline{\Delta T}_1} \qquad (4)$$

It is easy to see that if $\bar{I}_{sun,1}/\overline{\Delta T}_1$ is significantly different from $\bar{I}_{sun,2}/\overline{\Delta T}_2$, then both L and S_o tend to be well determined. Hence, $I_{sun}/\Delta T$ must vary significantly throughout the monitoring. This can be assured by changing Q_{aux} during monitoring to provide ΔT values which vary as desired.

If the heat introduced is constant in time (i.e., a heater either on or off), then some of the dynamic parameters are ill determined. In other words, heat input is essentially only at zero frequency. Then, in addition to $\vec{L}$ and S_o we can determine from regression only certain combinations of the parameters ($\vec{W}/\vec{V}$, $\vec{S}/\vec{V}$) describing thermal mass effects. Actually, during heat-up, after the heater is turned on, or during cool-down, thermal mass effects are dominant; however, variations in the outside temperature as well as storage effects from solar gains make it difficult to extract the thermal mass parameters from such data, especially for relatively massive buildings.

Finally, correlation between driving forces can make separate determinations of the related parameters impossible. Indeed, strict correlation (i.e., certain functional relations between driving functions) implies that we can determine only the sum of transfer functions. If the correlation is strong, one solution is to modify the building during part of the test to respond differently to one of the correlated drivers (e.g., shade some of the aperture).

TEST CELL EXPERIMENT DESCRIPTION

To understand the key features of the parameter estimation problem, we collected short-term data on a test cell at SERI. The test cell has about 25 ft^2 (2.3 m^2) of south-facing double glazing, a brick floor on an insulated crawl space, and frame walls and roof. The glazing area is net clear area, which is divided into six sections: three 2.8 ft^2 (0.26 m^2) in area and three 5.6 ft^2 (0.52 m^2) in area. There are significant internal ledges around all glazing sections, extending about 4 in. (10 cm) inside from the glazing. There is no shading of the glazing, although the insulated west wall is partially shaded by an adjacent test cell. The floor dimensions are about 4 ft x 9 ft (1.2 m x 2.7 m), and walls are about 8 ft (2.4 m) high. The infiltration rate was measured using tracer gas decay tests and is so small that we ignored variations caused by wind and stack effects. A manually controlled switch can introduce a constant amount of electrical heat into the cell. Inside and outside air temperatures, heater power, and incident solar radiation were sampled at 10-s intervals and integrated over half-hour periods. The heater consisted of two 300-W light bulbs inside a metal box with a small muffin fan to exhaust the box. The pyranometer was parallel to the glazings and mounted near the roof above the glazing. Air temperatures were measured with triple-shielded sensors that are insensitive to incident beam radiation. Internal air temperature is the equally-weighted average of three sensors at three heights.

To demonstrate the application to retrofits, we ran the test cell in two configurations (called A and B) with the parameters for each configuration independently determined. Case B differs from case A in that about 15.7 ft^2 (1.46 m^2) of the 25 ft^2 (2.3 m^2) glazing was painted white. The painted sections were distributed on the aperture to minimize changes in internal distribution of solar radiation. Only the solar parameters (S_o,$\vec{S}$) should be affected by the change, and the remaining parameters should show no significant change. To show the importance of establishing a monitoring protocol to reduce parameter errors, each configuration was run in two modes: (1) no internal gains (heater off) for about two days, and (2) constant internal gains (heater on) for about five days. Either mode alone provided data inadequate for determining reliable parameters, but both modes together provide good parameter estimates. Figures 1 through 4 show the measured data for the four time periods (two configurations A, B, each with modes 1, 2).

REGRESSION OF TEST CELL PARAMETERS

In this section we discuss L and S_o obtained from the test cell data using the nonlinear regression model of Subbarao [9]. We then apply the linear regression procedure of Subbarao [10,11] to get equivalent test cell results with a much simpler technique. The least squares regression is done in the time domain with no harmonic decomposition and/or approximation, such as truncation of driving forces to a few frequencies.

Using data for 114-1/2 hours (starting 4:45 p.m. on June 22, 1984) with 600-W heat input, the estimates of L and S_o had a rather large spread for Case A. Using data for 56 hours (starting at 4:30 p.m. on June 15, 1984) with no heat input, it was not possible to individually estimate L and S_o (only So/L can be determined--see earlier section). Interestingly, when the requirement that the best fit be obtained simultaneously over the earlier two data sets, L and S_o were determined remarkably well. The values were

$$L = 59.2 \pm 2.8 \text{ Btu/hr F } (31.2 \pm 1.5 \text{ W/}^{o}\text{C})$$

$$S_o = 20.6 \pm 3.2 \text{ ft}^2 \; (1.9 \pm 0.3 \text{ m}^2)$$

These are consistent with the test cell construction. It is of particular interest to note that the 2.3 m^2 (25 ft^2) of glazing with a transmissivity (for summer sun angles) of about 0.6 cannot account for all of S_o; the rest of it is caused by solar gains from opaque parts of the building and is consistent with rough estimates. Equations 4 and 5 indicate why the two data sets were individually unable to determine L and S_o well but together were able to.

To further test the procedure, as well as study the ability of the model to determine before and after parameters for retrofit applications, we analyzed Case B data (partially blocked glazings). As before, two data sets (one for 126 hours starting 7:15 a.m., July 10, 1984, with 300-W electrical heat input and the other for 54-1/2 hours starting 10:30 a.m., July 26, 1984, with no electrical heat input), although unable to do so individually, together gave a good estimate for L and S_o as follows:

$$L = 56.8 \pm 3.8 \text{ Btu/hr F } (30.0 \pm 2.0 \text{ W/}^{o}\text{C})$$

$$S_o = 12.3 \pm 2.0 \text{ ft}^2 \; (1.1 \pm 0.2 \text{ m}^2)$$

This value of L is consistent with the earlier estimate. The change in the value of S_o is also consistent with calculations.

Routine use of nonlinear regressions (as shown earlier) is very difficult. Fortunately, the building parameters can be obtained from the linear regression model of Subbarao !10,111. We simply give the results here for L, S_o, $\vec{W}/\vec{V}$ and $\vec{S}/\vec{V}$. As before, reliable results were obtained by requiring best fit for combined data sets from runs with and without heaters. We give results from regressions for the configurations: Case A with the full glazing open and Case B with the glazing partially blocked. Table 1 gives the results for each case from two different response factor series, labeled 1 and 2 in Table 1.

Runs 1 and 2 are quite consistent with each other. Thus, although the individual linear regression coefficients are erratic, the appropriate combinations that give the building parameters are well determined (see Subbarao !101). Also, as expected from the test cell description, Case A and Case B differ basically in S_o and $\vec{S}$ by the expected scale factor (of about about 18/13, including the opaque gains).

Let us note the physical significance of the above numbers. Consider, say, Case A1 in Table 1. The physical significance of L and S_o was noted earlier and is evident. The quantity $\vec{W}/\vec{V} = (0.408, -51.7^o)$ means that (assuming no auxiliary or solar gains) if the outdoor temperature swings (at diurnal frequency) by 20 F (11.1°C), then the indoor temperature swings by 8.16 F (4.5°C) and lags in phase by 51.7° or 3 h 27 min. If the outdoor temperature peaks at 2 p.m., then the indoor temperature peaks at 5:27 p.m. The quantity $\vec{S}/\vec{V} = (0.129, -51.4^o)$ means that (assuming constant outdoor temperature) if the diurnal amplitude of solar radiation is 50 Btu/h ft^2 (157 W/m^2), then the indoor temperature amplitude is 0.129 50 = 6.45 F (3.6°C) !or the swing is 12.9 F (7.2°C)1 and the peak indoor temperature occurs at 3:26 p.m. Knowing these responses, the behavior of the building to actual temperatures and solar radiation (such as those in Figures 1-4) can be determined in the time domain.

CONCLUSIONS

To extract thermal characteristics of a building from short-term tests with a view to determining long-term performance, it is essential to carefully design the short-term tests. The weather and auxiliary input characteristics during short-term tests have a major effect on whether the thermal parameters are estimated with small uncertainty or not. Simple arguments have been given to determine when the data sets tend to be complementary rather than redundant. To make the data sets complementary, it is essential that the heat input profile be chosen suitably. This implies that some intervention is necessary; simply monitoring passively may result in primarily redundant data sets rather than complementary data sets. Efforts are underway to extend the work presented here to a point where a package of data requirements, monitoring protocol, and analysis can be developed for field use, so short-term tests provide a basis for ratings as well as diagnostics.

NOMENCLATURE

Symbols

ΔT	temperature difference, $T_{in} - T_{out}$
I	global solar incidence per unit area
L	building steady state load coefficient
Q	quantity of energy
S	solar radiation transfer function
T	temperature
t	time
V	interior air temperature transfer function
W	outdoor air temperature transfer function

Subscripts

aux	auxiliary
in	inside
int	internal
o	zero frequency or steady state
out	outside
sun	solar radiation

Superscripts

—	bar over symbol denotes time average

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Table 1. Test Cell Thermal Parameters

		1	2
Case A	L	56.8 (30)	57.1 (30.1)
	S_o	17.2 (1.6)	17.5 (1.63)
	$\vec{W}/\vec{V}$	(0.408, -51.7^{o})	(0.450, -46.3^{o})
	$\vec{S}/\vec{V}$	(0.129, -51.4^{o})	(0.125, -67.1^{o})
		[(0.0227, -51.4^{o})]	[(0.0220, -67.1^{o})]
Case B	L	55.6 (29.3)	54.9 (29)
	S_o	11.7 (1.09)	11.2 (1.04)
	$\vec{W}/\vec{V}$	(0.412, -53.4^{o})	(0.393, -58.7^{o})
	$\vec{S}/\vec{V}$	(0.084, -61.9^{o})	(0.086, -52.8^{o})
		[(0.0148, -61.9^{o})]	[0.0151, -52.8^{o})]

Units: L = Btu/h•F (W/^{o}C)
S_o = ft^2 (m^2)
$\vec{W}/\vec{V}$ = (dimensionless, degrees)
$\vec{S}/\vec{V}$ = (h•ft^2•F/Btu, degrees) [(m^2•^{o}C/W, degrees)]

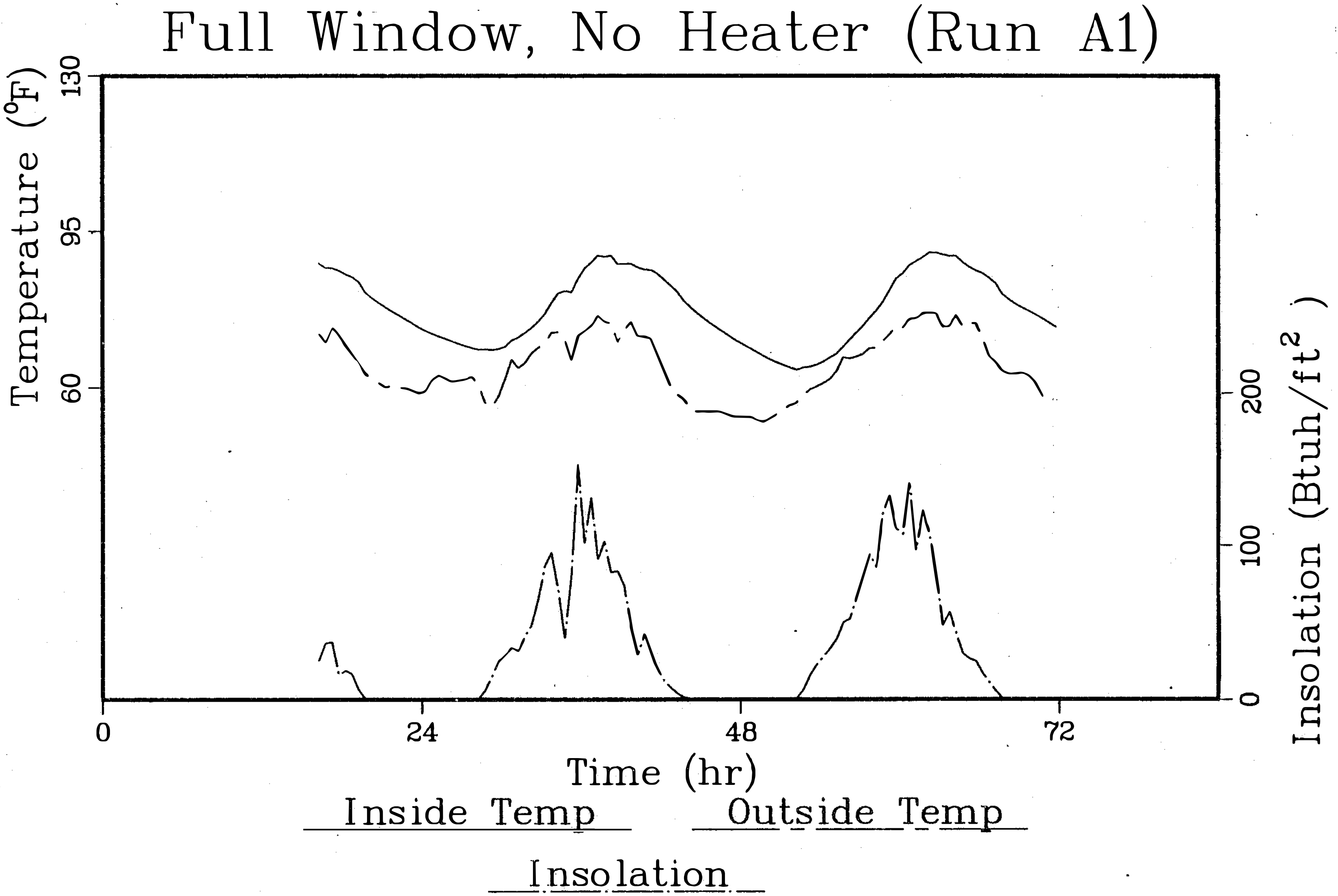

Figure 1. Test Cell Measurements for Run A1
Indoor and outdoor temperature, solar radiation incident on vertical south orientation, and heater power are plotted versus time since start of the experiment, setting midnight of the start day as zero. Start date for the run is June 15, 1984. The glazing is not blocked, and the heater power was zero.

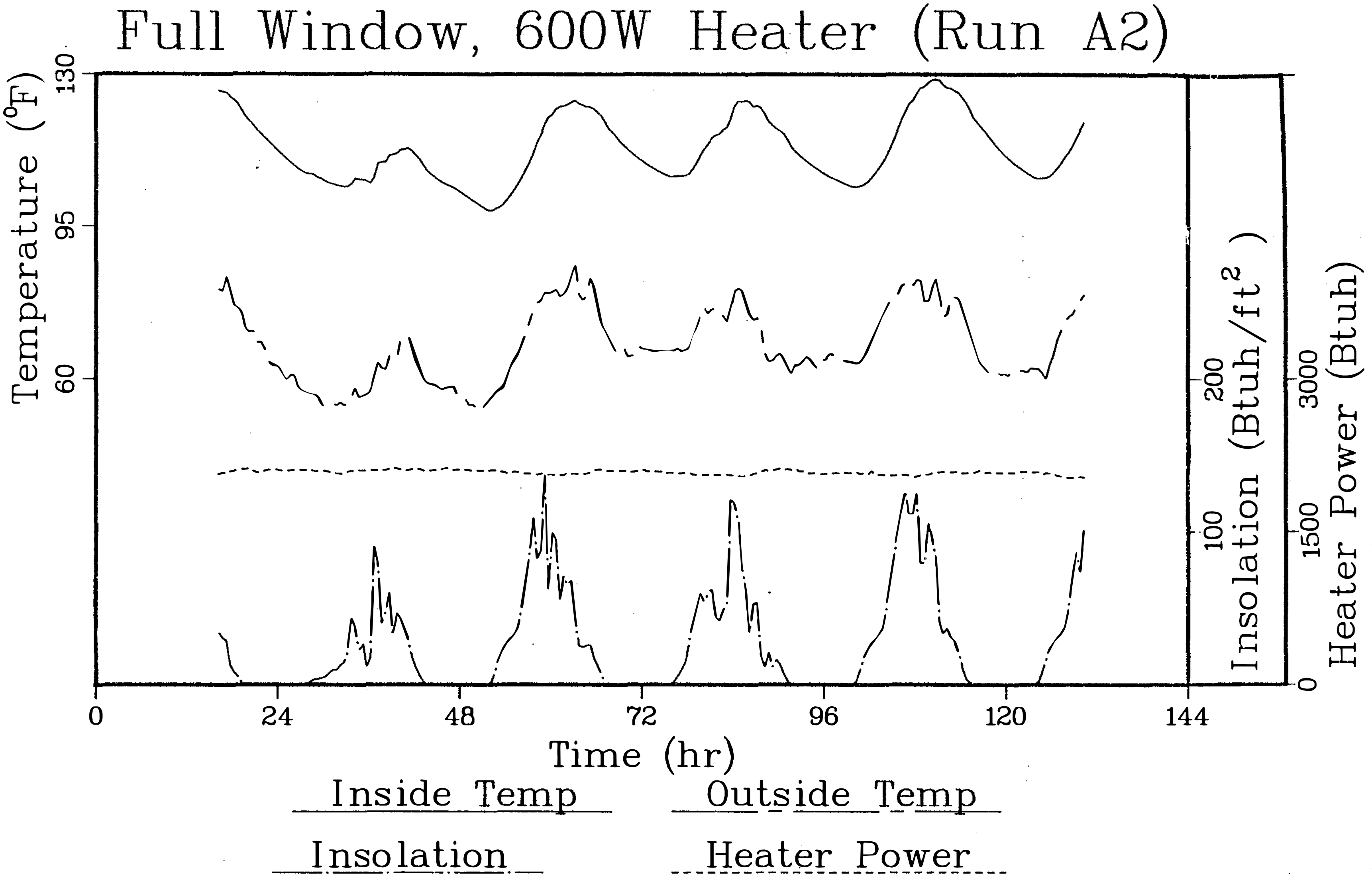

Figure 2. Test Cell Measurements for Run A2
Indoor and outdoor temperature, solar radiation incident on vertical south orientation, and heater power are plotted versus time since start of the experiment, setting midnight of the start day as zero. Start date for the run is June 22, 1984. The glazing is not blocked, and the heater power was about 600 watts. Note the larger temperature difference in this run versus run A1 in Fig. 1.

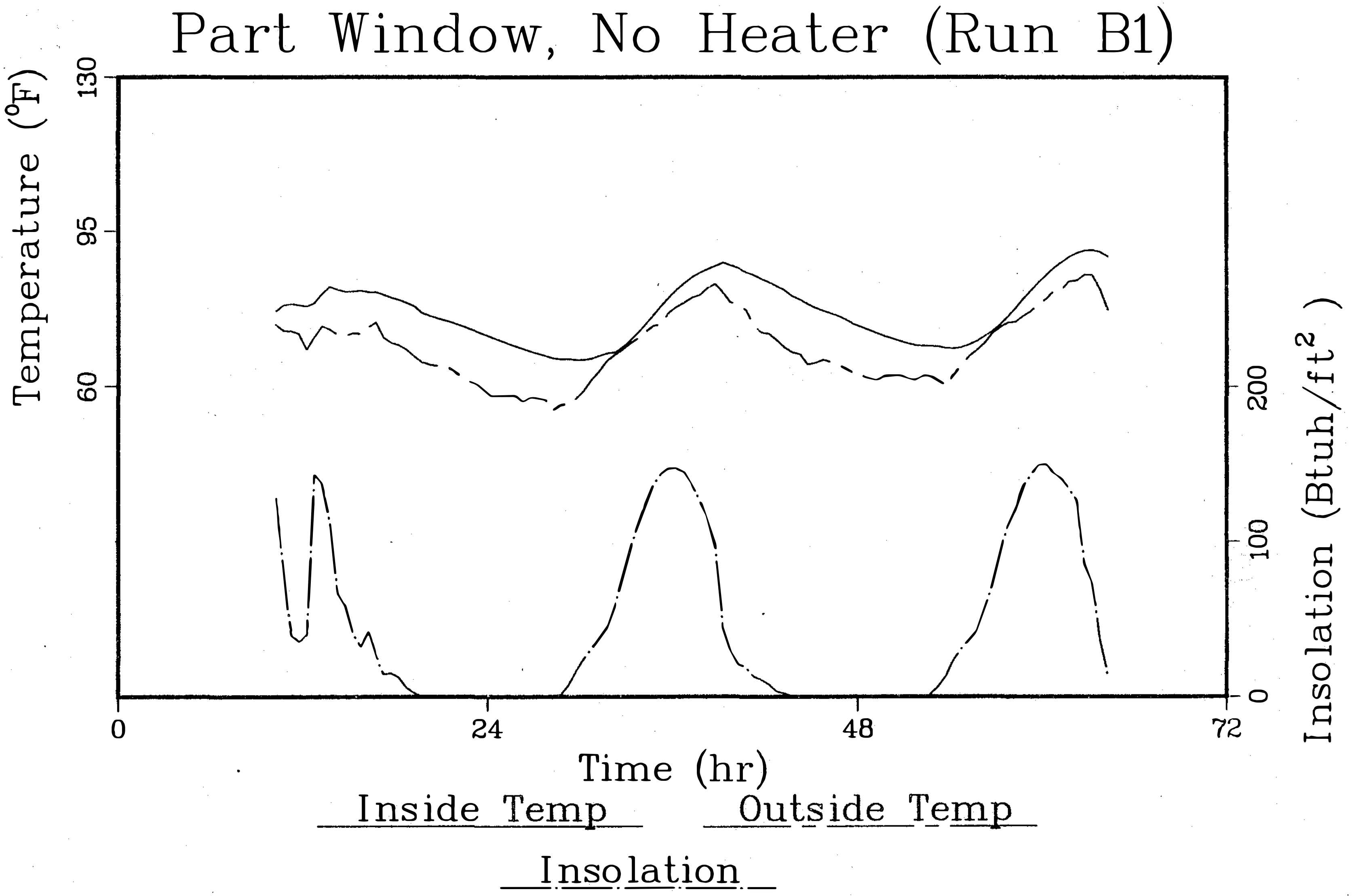

Figure 3. Test Cell Measurements for Run B1
Indoor and outdoor temperature, solar radiation incident on vertical south orientation, and heater power are plotted versus time since start of the experiment, setting midnight of the start day as zero. Start date for the run is July 26, 1984. The glazing is partially blocked by painting about 60% of the glazing. Heater power was zero.

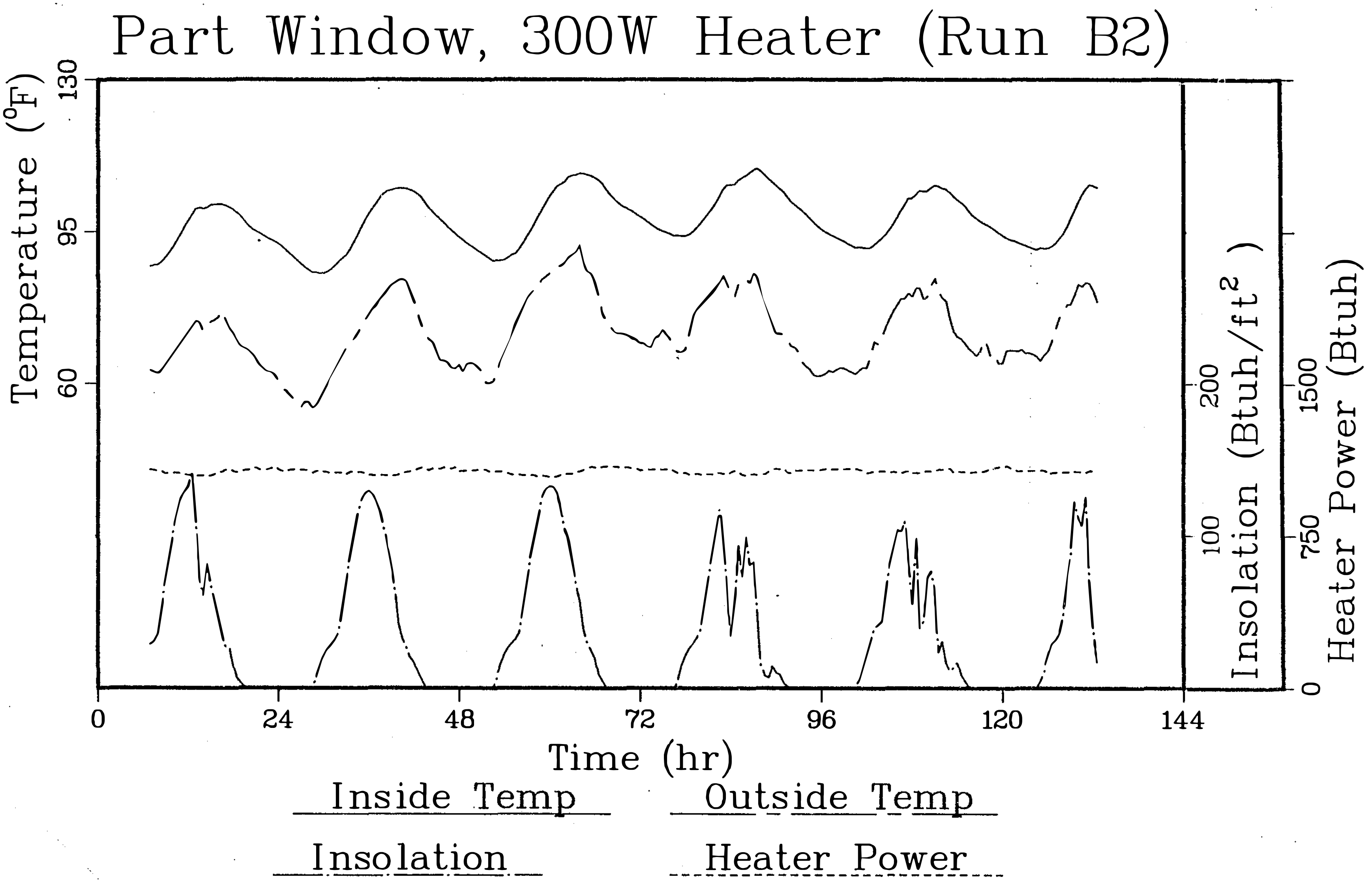

Figure 4. Test Cell Measurements for Run B2
Indoor and outdoor temperature, solar radiation incident on vertical south orientation, and heater power are plotted versus time since start of the experiment, setting midnight of the start day as zero. Start date for the run is July 10, 1984. The glazing is partially blocked by painting about 60% of the glazing. Heater power was about 300 watts. Note that the temperature difference is intermediate between the 600 watts case (Fig. 2) and the 0 watts cases (Figs. 1,3).