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In-Situ Measurements of U-Values and Overall Thermal Performance of Windows

Prepared for Bonneville Power Administration

by

J. H. Klems and H. Keller

Windows and Daylighting Program

Applied Science Division

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Abstract

Five commercial windows were studied using the MoWiTT (Mobile Window Thermal Test) facility, an accurate new field test apparatus. Both overall diurnal performance and U-values were measured. The latter were compared to test laboratory hot box measurements for the same five windows, and to calculations made with the program WINDOW-2.0. Calculations, MoWiTT and hot box measurements agreed for three of the windows; for one of the others, the calculations agreed with the MoWiTT measurement but not with the hot box. For the fifth, a low-E window, the calculations may be made to agree with either measurement but not both, depending on assumptions about the frame. The authors suggest a possible explanation for the conflict, and advance an interpretation of the data which would allow a consistent understanding of calculated, field and laboratory U-values.

In the studies of overall performance, uncertainties arising from wintertime solar gain were found to overshadow the differences in U-value for all window orientations, including north-facing. In some of the windows tested, improved U-values were offset by decreased solar gain acceptance. Further research is suggested to achieve a method of evaluating overall window energy performance which would reliably reflect U-value improvements.

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1 Executive Summary

1.1 Do Window Conservation Measures Deliver Energy Savings?

Investing in energy-efficient construction as an economical supply of "new" energy is becoming increasingly popular. However, anecdotal evidence has led to uncertainty about whether window improvements provide expected savings in energy usage. Even for the knowledgeable, disagreement over window-energy usage calculations and U-value specifications make investing in window improvements appear risky. This makes manufacturers reluctant to invest in producing window energy improvements, architects, to specify them, utilities and regulatory bodies, to encourage them, and consumers, to buy them. The result is that decisions in the window market place remain driven by consumer amenities. Energy consumption is sometimes increased in this decision-making process, whereas an optimal window choice would produce the same level of amenities together with reduced energy consumption at little or no added first cost.

1.2 Description of the Project

This uncertainty about window performance arises partly because it is difficult to measure window energy use in a building, and even more so to measure the effect of improvements. Measurements tend to be made either in laboratory hotboxes or in simple outdoor test cells. The latter are of limited accuracy, while the former focus on the U-value and measure it under idealized conditions. In a new approach to the problem, the MoWiTT (Mobile Window Thermal Test) facility, an accurate field measurement facility which studies windows under realistic conditions, was used to measure directly the net energy flow through several types of windows under climatic conditions resembling the Pacific

Northwest. The goal is to help resolve the U-value specification question and clarify how window energy design improvement measures could improve window energy use.

1.3 Key Findings

The most significant finding was the strong verification of a window thermal analysis computer model, WINDOW-2.0, by the field measurements. *Excellent agreement was found between WINDOW-2.0 calculations of U-value and MoWiTT measurements when appropriate corrections for frame and environmental conditions (wind and radiant temperature) were included.* ***This is a promising result since it suggests that an accurate tool for determining field U-values for a wide range of commercially available windows can be readily provided to decision-makers.*** Field-measured U-values were below ASHRAE values by about 0.07 BTU/(hr ft^2 F) for double-glazed and 0.13 BTU/(hr ft^2 F) for single-glazed windows due to wind, radiant and frame effects. MoWiTT measurements and WINDOW-2.0 calculations agreed (after appropriate corrections) with test laboratory measurements for single and standard double glazed windows except for the case of a double-glazed window with a highly conductive frame. There the test laboratory measurement was lower than the calculation and the MoWiTT measurement, which agreed.

There was significant disagreement between the test laboratory, the MoWiTT, and initial theoretical expectations for a low-emissivity window. Repeated field tests have substantiated the MoWiTT result and further investigation has indicated that the anomalous U-value obtained (which is *higher* than that expected for ordinary double glazing) is due to conduction through the frame resulting from a design defect. WINDOW-2.0 calculations based on this assumption agree well with the MoWiTT measurement; however the test laboratory measurement is much lower than both.

Solar gain effects are a significant factor even when the aim is U-value improvement. *Studies of overall performance showed that many U-value improvements are accompanied by significant decreases in solar gain, which must be taken into account when evaluating the net energy effect of the improvement. In addition, solar gain is found to be a significant part of the window net heat balance, even for north-facing windows, very overcast days, and shaded windows, as well as for the familiar cases of unshaded windows in direct sunlight.* ***There is probably no window in the BPA service area for which solar gain can be safely neglected.***

The study also underlines the importance of the assumptions about when solar gain is useful or acceptable. It is shown that differences in assumptions may change the calculated thermal performance by many times the amount due to a U-value improvement; therefore, an inappropriate choice of assumptions could easily lead to a wrong conclusion.

These considerations are relevent both for new design and for retrofit. Design or retrofit strategies must be carefully examined using an appropriate calculational model which includes both U-value and solar effects. *To set building or retrofit standards on the basis of calculations including only the U-value effects could be counterproductive.*

Other findings confirm the utility of the simplified "standard" model often used to analyze net window performance and evaluate its accuracy (±10%). The systematically smaller U-values measured in the field due to actual nighttime wind speeds lower than expected from seasonal averages may be a general feature, not a pecularity of the field test environment.

1.4 Summary of Recommendations

This study points to the possibility of a consistent understanding of both laboratory and field measurements of U-value, and also points out that it is solar gain rather than U-value which currently limits the accuracy of energy savings calculations. A twofold approach is recommended:

(1) *Reduce the prediction uncertainties due to solar gain.*

- Develop an angle-dependent aperture model.
- Base energy savings calculations on a building simulation computer code. Empirically verify the calculation of window/perimeter space interactions for conventional fenestrations in all orientations.
- Develop representative solar utilizability assumptions based on window use.

(2) *Develop an accurate regional U-value calculation model and resolve the remaining consistency problems with the test laboratories.*

- Resolve the conflict between MoWiTT and test laboratory measurements of the low-E window (and of the double-glazed window with unbroken aluminum frame).
- Develop a library of representative
  - frame conductances
  - exterior film coefficients
  - outdoor radiative temperatures

to be used in conjunction with the U-value calculation model.

Carrying out these recommendations will lead to a method for accurately predicting window properties for comparative product evaluations as well as making average or seasonal energy efficiency calculations which can form the basis for the reliable planning of utility conservation programs.

2 Introduction

Energy consumption attributable to windows and energy savings resulting from improving window systems are typically calculated on the basis of laboratory measurements of the U-value and shading coefficient of the window. During the winter heating season, even in conventional buildings, windows function as passive solar collectors during the daytime, admitting solar gain which offsets conductive losses, so that the overall thermal performance cannot be calculated simply from the U-value and indoor and outdoor air temperatures. This makes window performance dependent on orientation and on the thermal storage capacity of the adjacent space. In addition, most windows in residential settings have blinds, shades or drapes; the occupants' opening or closing these fixtures very strongly affects the thermal performance of windows.

Such circumstances make it difficult to measure window thermal.performance accurately in ordinary residences, favoring a calculational approach. However, several considerations raise questions about the degree of confidence to be placed in calculations. Accurate answers to these questions are particularly important to a utility offering incentive payments to implement specific window conservation strategies.

Both U-value and shading coefficient depend on the exterior wind conditions and to a lesser extent on the exterior sky temperature. There is no generally accepted method of taking these into account in a laboratory measurement.

Correlations between window performance and interior space conditions are also poorly known. The theoretical model is drawn from heat transfer studies in idealized geometries which are seldom realized in actual window systems; the extent to which altered natural convective and radiative heat flows within the interior space may change overall window performance (particularly during the daytime) is unknown. In addition, use of nighttime thermostat setbacks tends to enhance the importance of daytime performance, the area of greatest uncertainty.

3 Methodology

3.1 The Mobile Window Thermal Test (MoWiTT) Facility

Lawrence Berkeley Laboratory has developed and calibrated a unique facility for studying the field performance of window systems, the Mobile Window Thermal Test (MoWiTT) Facility. Consisting of dual, guarded, room-sized calorimeters in a mobile structure, the MoWiTT can simultaneously expose two windows to a room-like interior environment and to ambient outdoor weather conditions while accurately measuring the net heat flow through each window. This measurement comes from a net heat balance on each calorimeter chamber, performed at short intervals. To get an accurate net heat balance measurement and control the interior air temperature during the full diurnal cycle, each calorimeter chamber contains an electric heater, a liquid-to-air heat exchanger with measured flow rate and inlet/outlet temperatures, and a nearly continuous interior skin of large-area heat flow sensors. A conceptual drawing of the MoWiTT is shown in Figure 1; a photograph of the facility at its test site in Reno, Nevada is shown in Figure 2. The design of the MoWiTT has been discussed in detail elsewhere (1).

3.2 Project Description

This project is a study of the performance of commercially available windows under actual outdoor conditions using the MoWiTT. The study consists of four discrete test periods of simultaneously measuring the performance of two windows in the two MoWiTT calorimeter chambers. The facility was oriented in a different direction for each test period, yielding data for north, south, east and west orientations. A reference window was mounted in one calorimeter chamber during all four test periods. Thus the project allows four separate comparisons between windows exposed to the same weather conditions, each

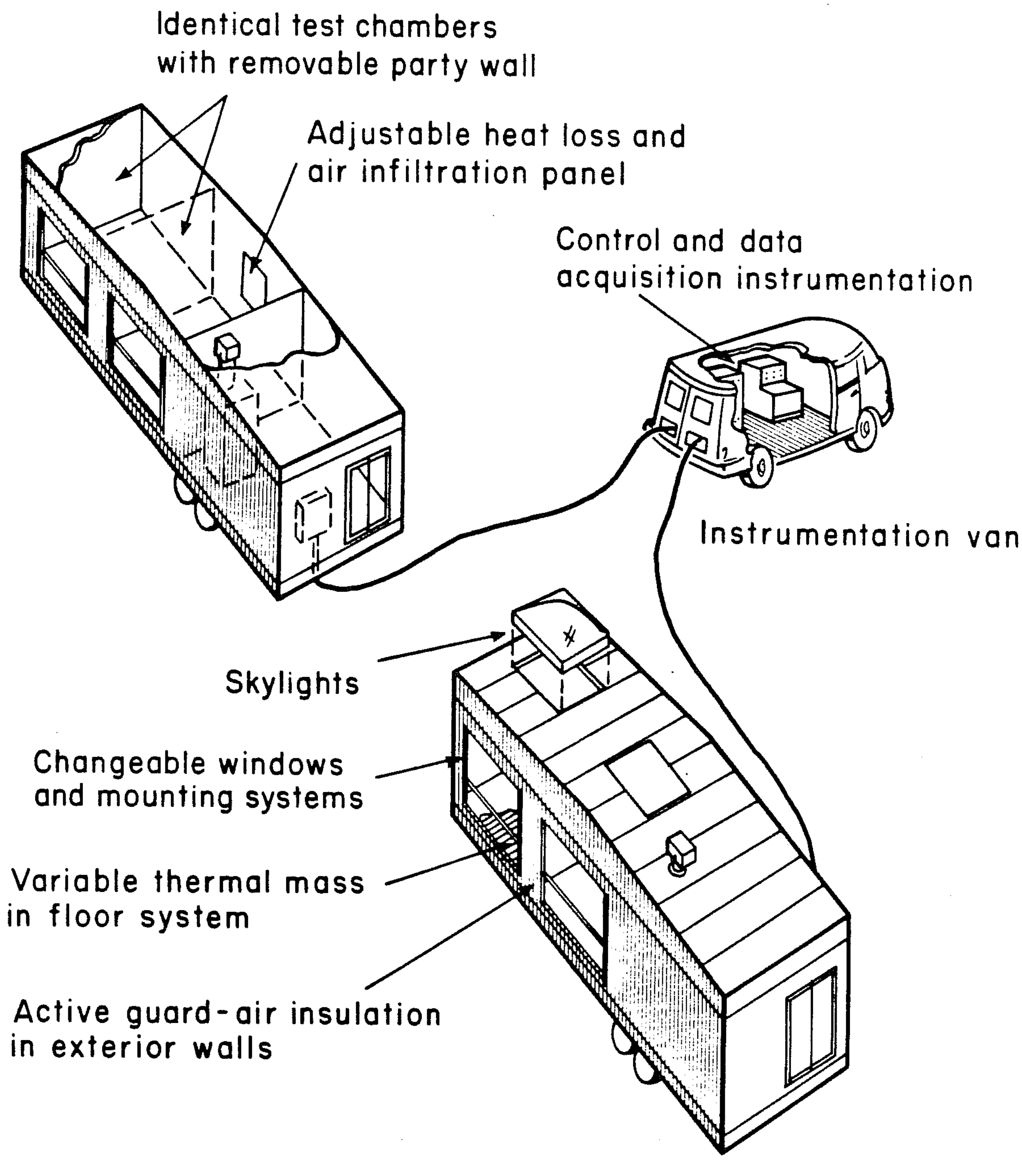


Figure 1. A conceptual drawing of the MoWiTT showing the modular mobile units (one of which has been built), each containing a dual, room-sized calorimeter, with connection to a separate data-processing facility.

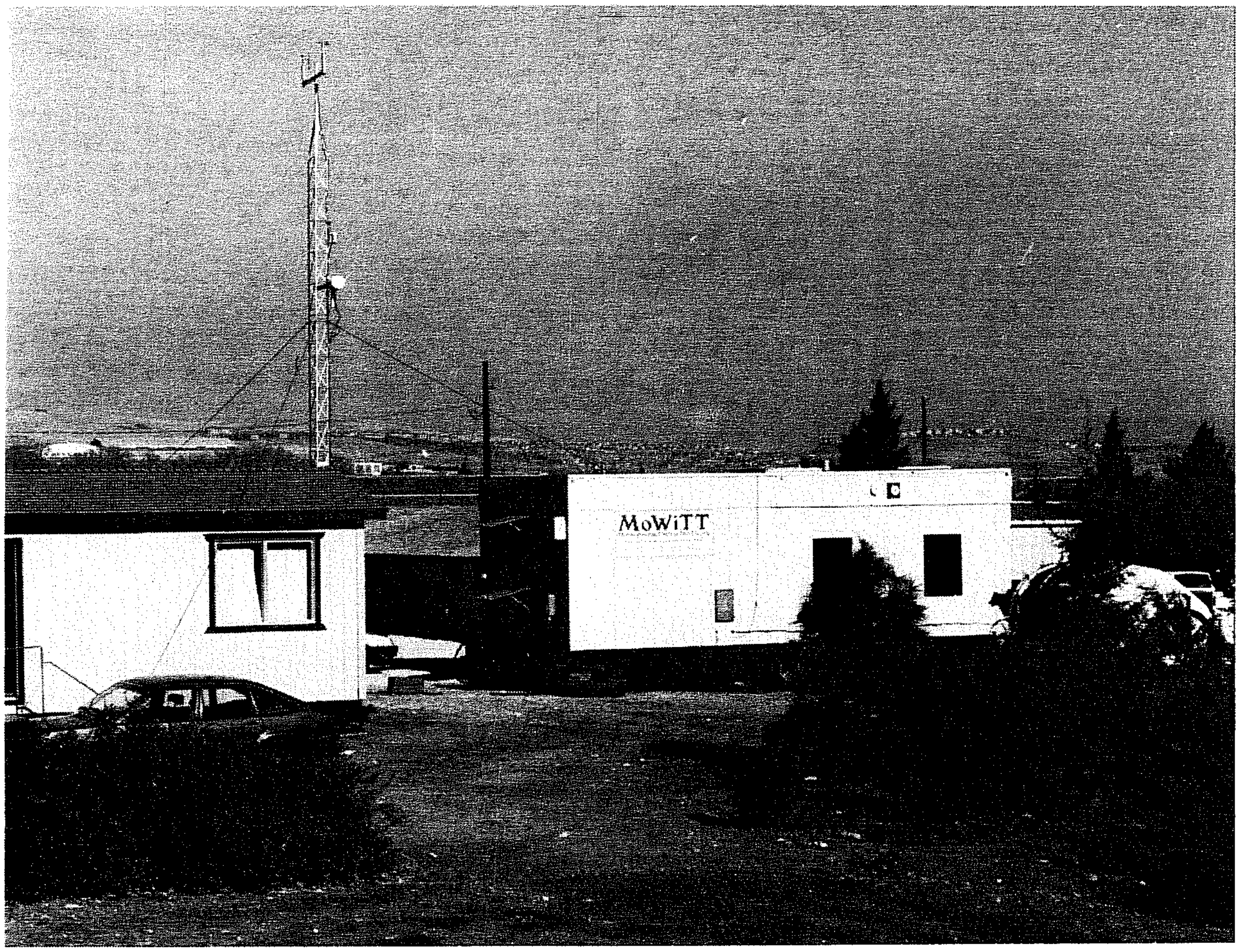


Figure 2. The MoWiTT facility at its field location at the University of Nevada, Reno campus. The facility is shown in the south-facing orientation. The bushes in the foreground are quite low and do not obstruct wind or sunlight. The building at left with the weather tower contains the data collection and control computer as well as support facilities. The dark square on the MoWiTT above and between the test windows is the vertically mounted infrared pyrgeometer, which measures outdoor radiant temperature. Next to it is the pyranometer, which measures solar intensity.

comparison in a different orientation, as well as comparisons of the performance of the same window under different orientations and weather conditions.

Through discussions with Bonneville Power Administration (BPA) staff, five classes of windows of interest to BPA were defined. These are shown in Table 1, together with the shorthand mnemonics which will be used to refer to them. A window in each category was selected from the BPA list of approved windows and obtained for testing from its manufacturer. After initial tests in November, non-operable "picture" windows were chosen to minimize the effects of air infiltration. The CDAT window was chosen as the reference window. The five windows tested are shown in Figures 3-5. All four of the aluminum-frame windows have a very similar frame as viewed either from the inside or outside; they are distinguished by the differences in thickness and cross section necessary for the incorporation of thermal breaks. Cross sections of the window frames are shown in Figure 6.

Table 1
Window Categories Tested

Window		Mnemonic
Glazing	Frame	
Clear double	Aluminum with thermal break	CDAT
Clear double	Aluminum without thermal break	CDA
Clear double	Wood	CDW
Clear double with low-emissivity coating	Aluminum with thermal break	CDLAT
Clear single	Aluminum without thermal break	CSA

The test period, figure 7, began in late January. During the initial CDAT/CDA test in late March an equipment failure delayed operations for five weeks, rendering this data unusable. The test was repeated as soon as operations resumed. Thus, the CDAT/CDA and CDAT/CSA tests occurred in May rather than in April as originally planned.

a b

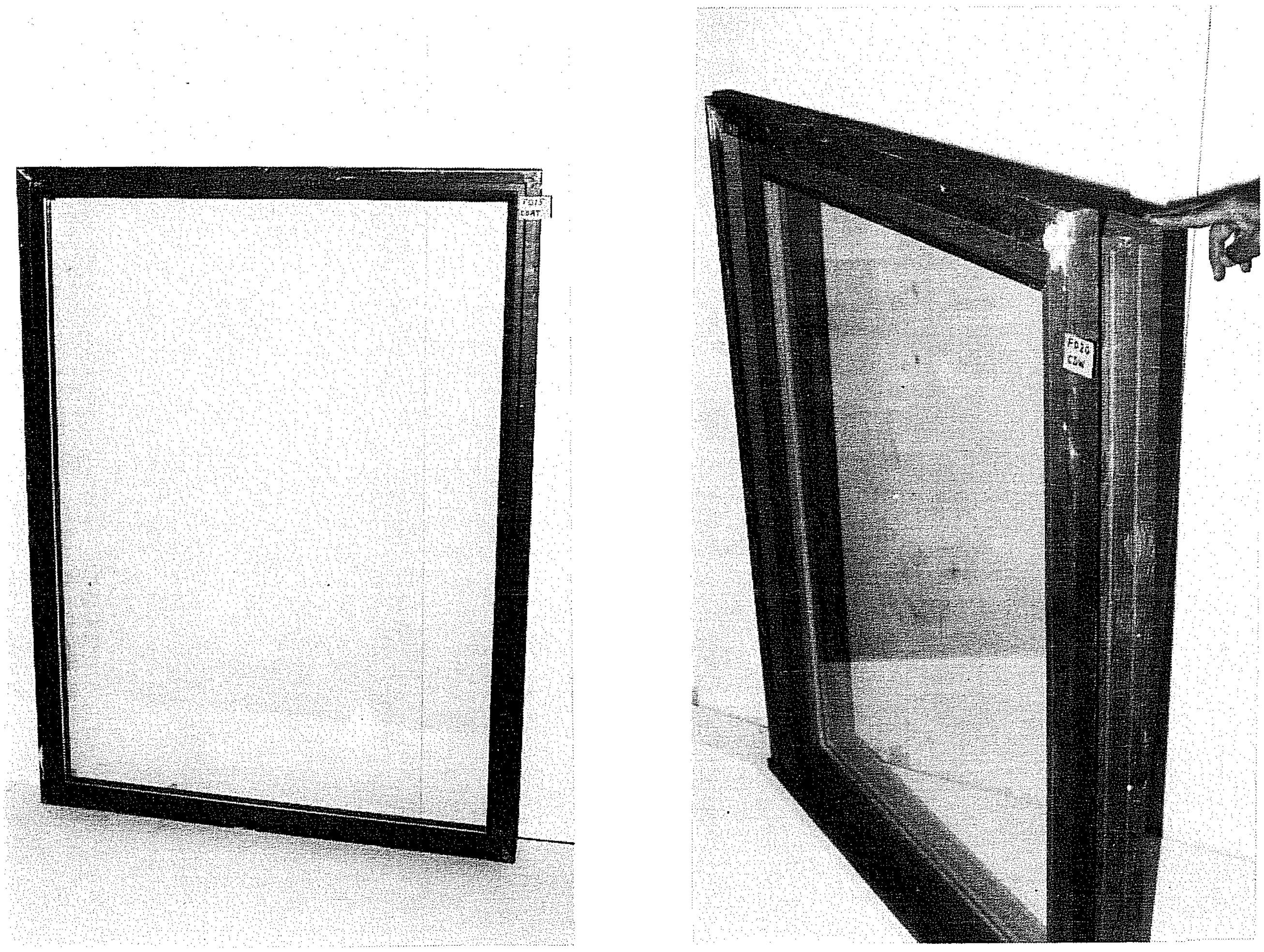


Figure 3. Overall appearance of the window samples: (a) The CDAT window. All of the aluminum-frame windows tested appear identical from this angle. (b) The CDW window.

a b

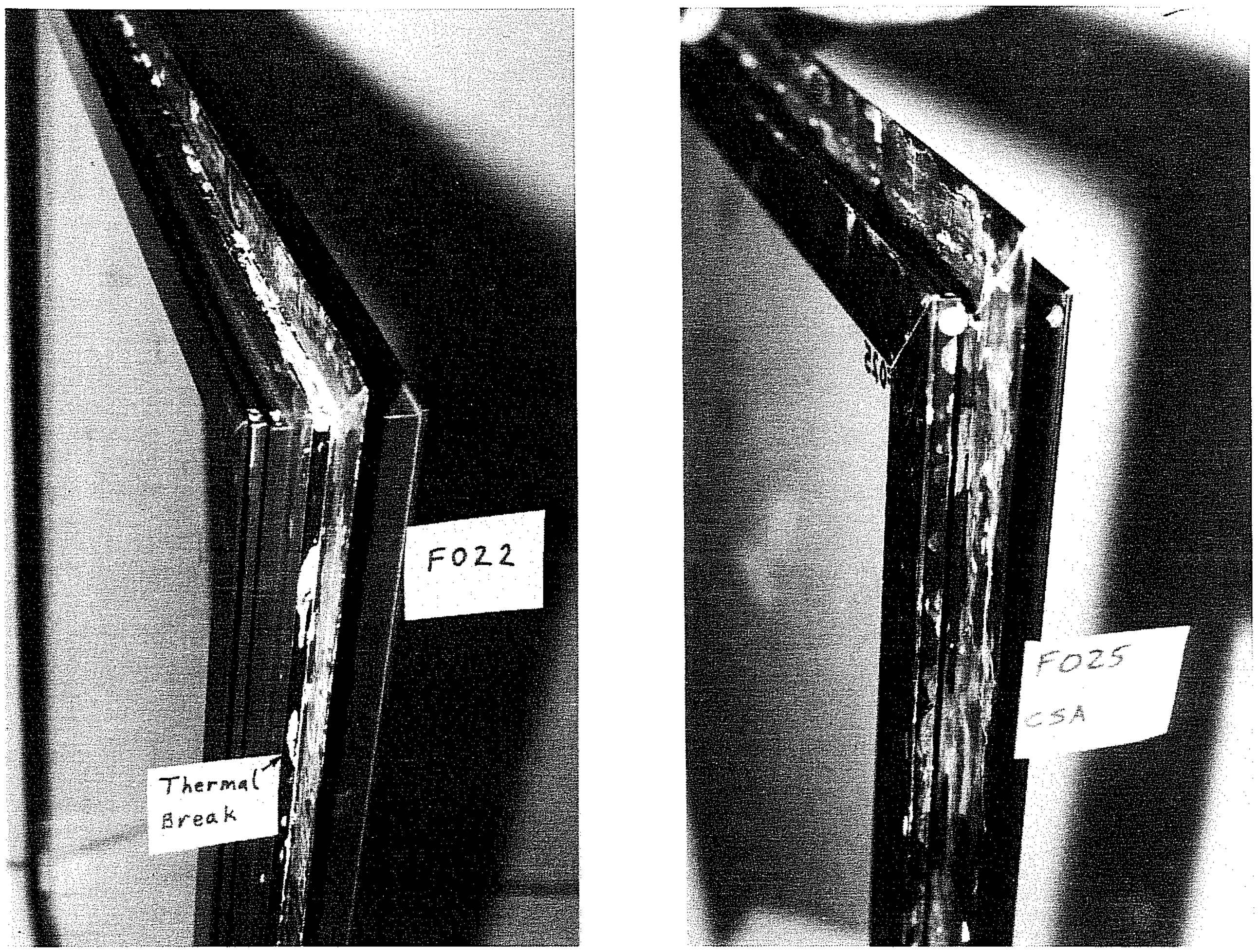


Figure 4. Edge views of two of the aluminum-frame windows. (a) CDLAT, which in this view appears identical to CDAT. The frame consists of inner and outer sections joined by a urethane plastic thermal break. (b) CSA. An identical inner frame section connects without thermal break to a simpler outer section that holds the single glass pane.

a b

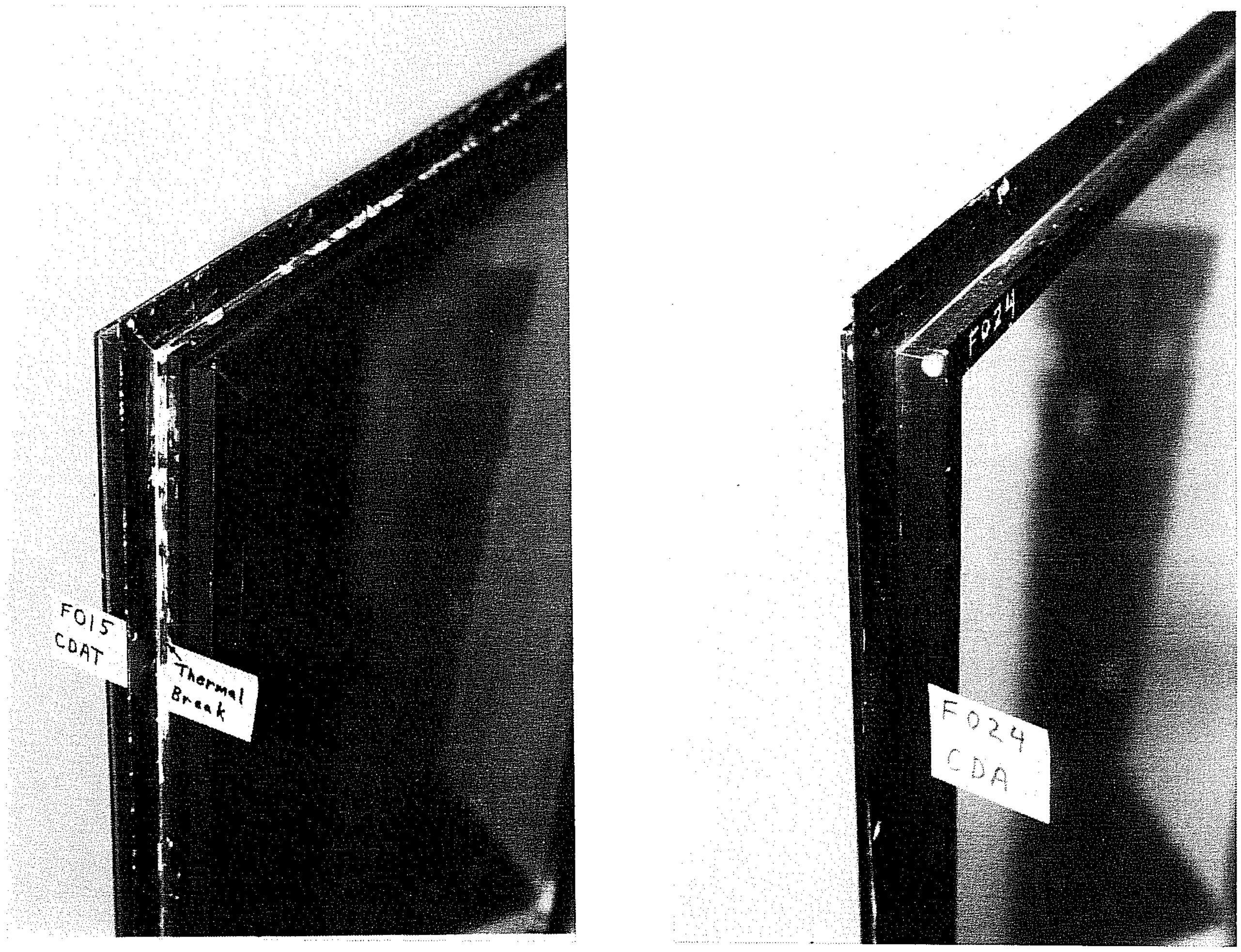


Figure 5. Edge views of CDAT and CDA. (a) CDAT, showing thermal break. (b) CDA, which is similarly constructed, but without the thermal break.

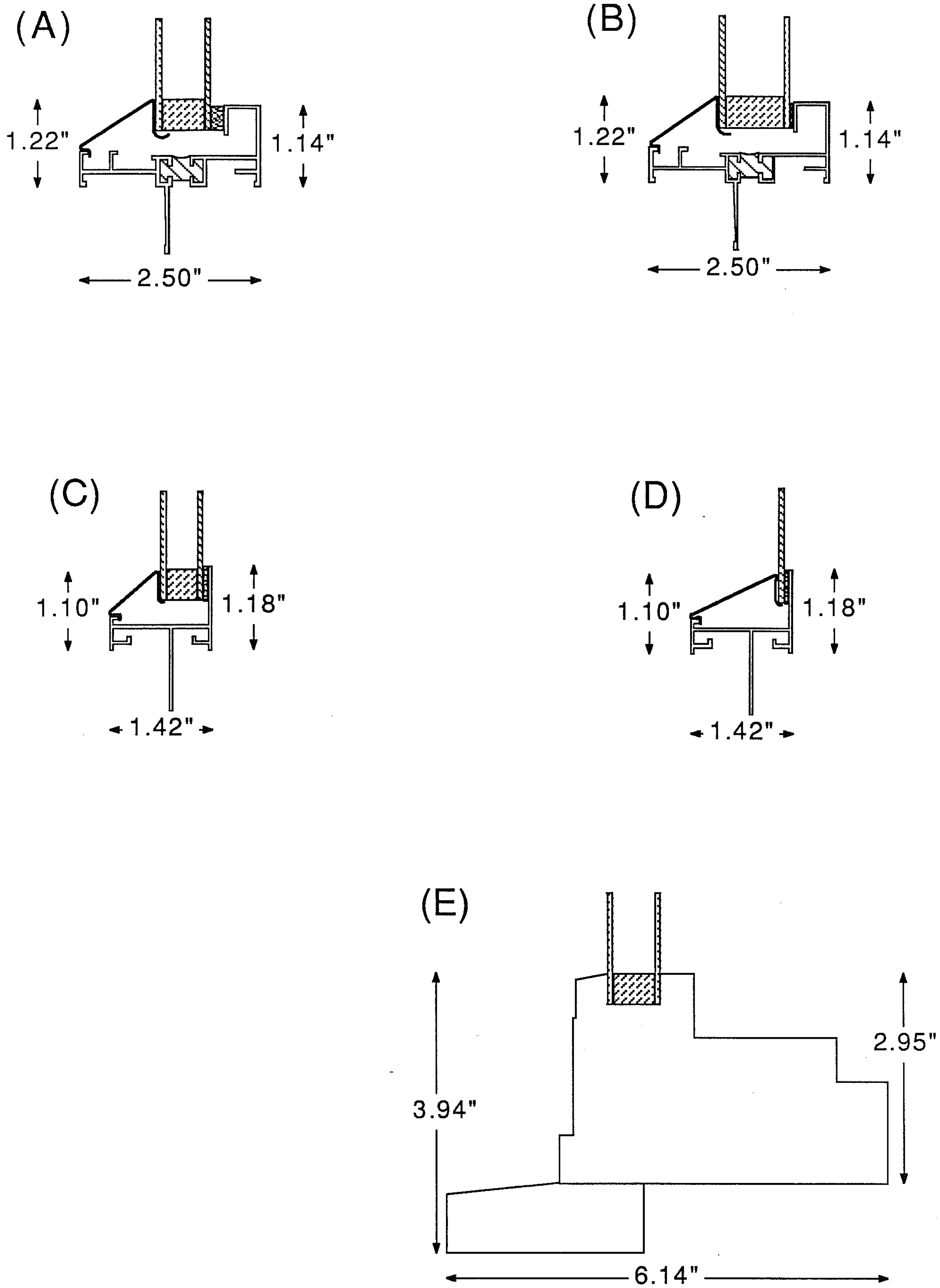


Figure 6. Cross sections of the frames of the tested windows: (a) CDAT, (b) CDLAT, (c) CDA, (d) CSA, and (e) CDW.

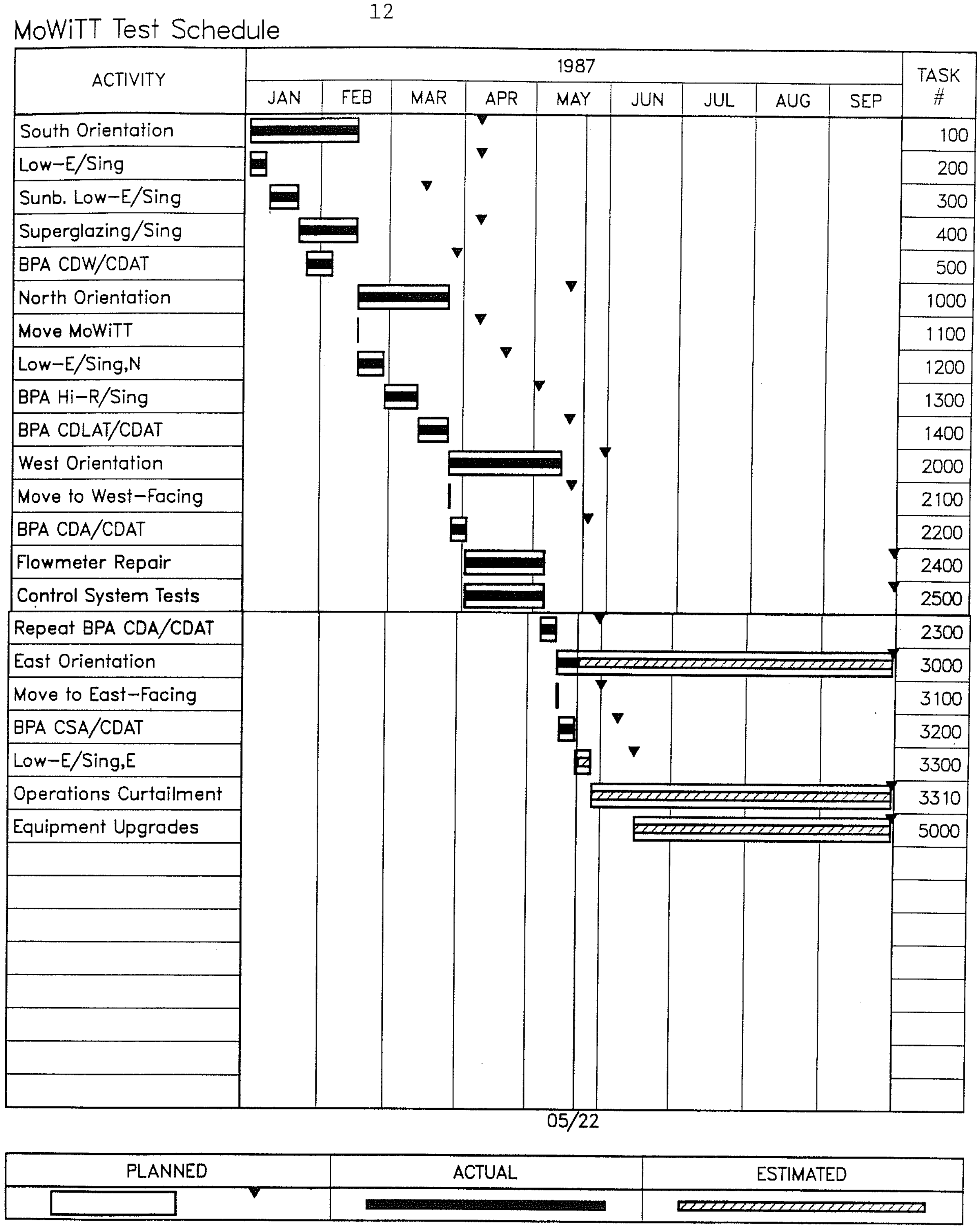


Figure 7. MoWiTT test schedule for the period January-September 1987. Not shown on the schedule are the July retests of CDAT/CDLAT, which occurred during the indicated equipment upgrades.

4 Experimental Results

4.1 Data Obtained

The basic data produced by the MoWiTT is the net energy, W (BTU/hr), flowing through the window system as a function of time. This data is collected on a short time scale, typically between five and fifteen minutes, and is derived from detailed measurements of the net heat flows into and out of the room-sized calorimeter chamber. The calorimeter rooms were specifically designed to have short thermal time constants, but irreducible time constants remain (due to the control system and experimental equipment within the chamber) which cause the W value derived to lag behind the true instantaneous heat flow through the window. This effect disappears when the data is averaged over periods of 30 minutes.

An example of the measured value of W (which we term the sample heat flow) for the window CDAT over a thirty-six hour period is shown in Figure 8. Each point represents a 30-minute average measured value. In this north-facing measurement the window lost heat during the nighttime hours and gained net heat during the daytime. By convention, positive W represents inward heat flow through the window. In addition, we measured a large number of other quantities useful in interpreting the basic measurement of W. The most relevant are inside and outside air temperature, incident solar intensity, outdoor radiant temperature and wind speed. For the same day, these measurements are shown in Figures 9 through 13, respectively. From Figure 9 it can be seen that the inside air temperature was maintained constant at approximately 72º F, while Figure 10 shows that the outside air temperature varied between 21º F and 46º F. The outside radiant temperature was lower, varying between about 8º F and 44º F, as can be seen from Figure 11. Although the window faces north, receiving no direct sunlight, Figure 12 shows it nevertheless receives a maximum of 52 BTU/(hr ft^2) of diffuse solar radiation, about 20% of the intensity which an unshaded south-facing window might receive. Wind speed during this period varied between a low of 1 MPH to a high of 11 MPH, as can be seen from Figure 13.

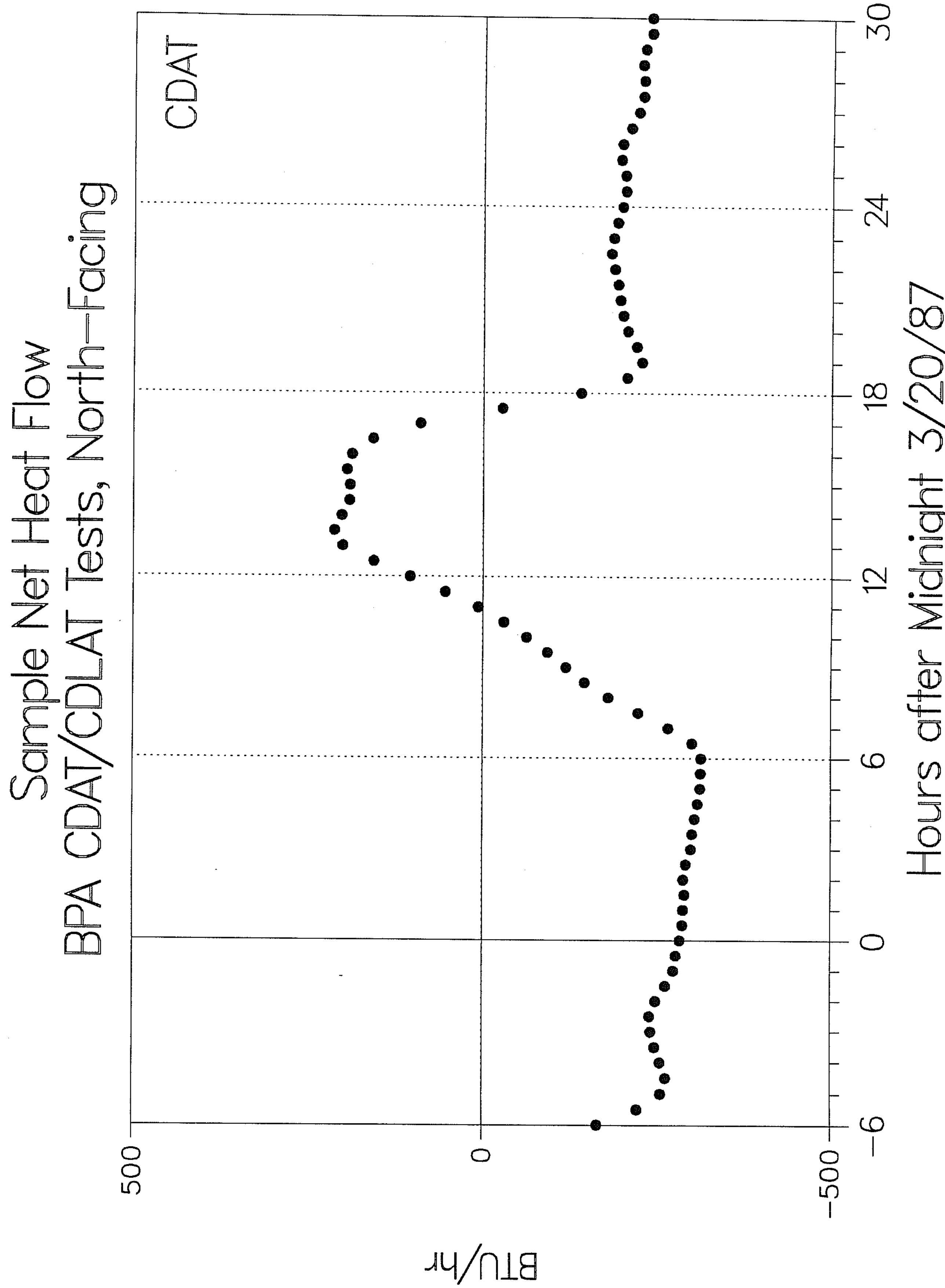
A complete set of plots covering all of the data collected for each of the four test periods will be found in the Technical Appendix. Hourly averages of the data are presented for greater legibility, since each plot covers a series of several days.

4.2 Accuracy of the Standard Model of Window Net Energy Flow

Figure 8 illustrates the complexity of window thermal behavior. Unlike a wall, which may be considered to have a heat flow dependent only on the difference between inside and outside temperatures, the net heat flow through a window depends also on the incident solar energy. .This may, even on cold winter days, represent a net energy gain. The standard simplified model, derived from heat transfer theory, which describes this behavior has the form

$$W = A_T U (T_O - T_I) + A_S F I_V , \quad (1)$$

Figure 8



Sample Net Heat Flow
BPA CDAT/CDLAT Tests, North-Facing
CDAT
BTU/hr
500
0
-500
Hours after Midnight 3/20/87
-6
0
6
12
18
24
30

Figure 9

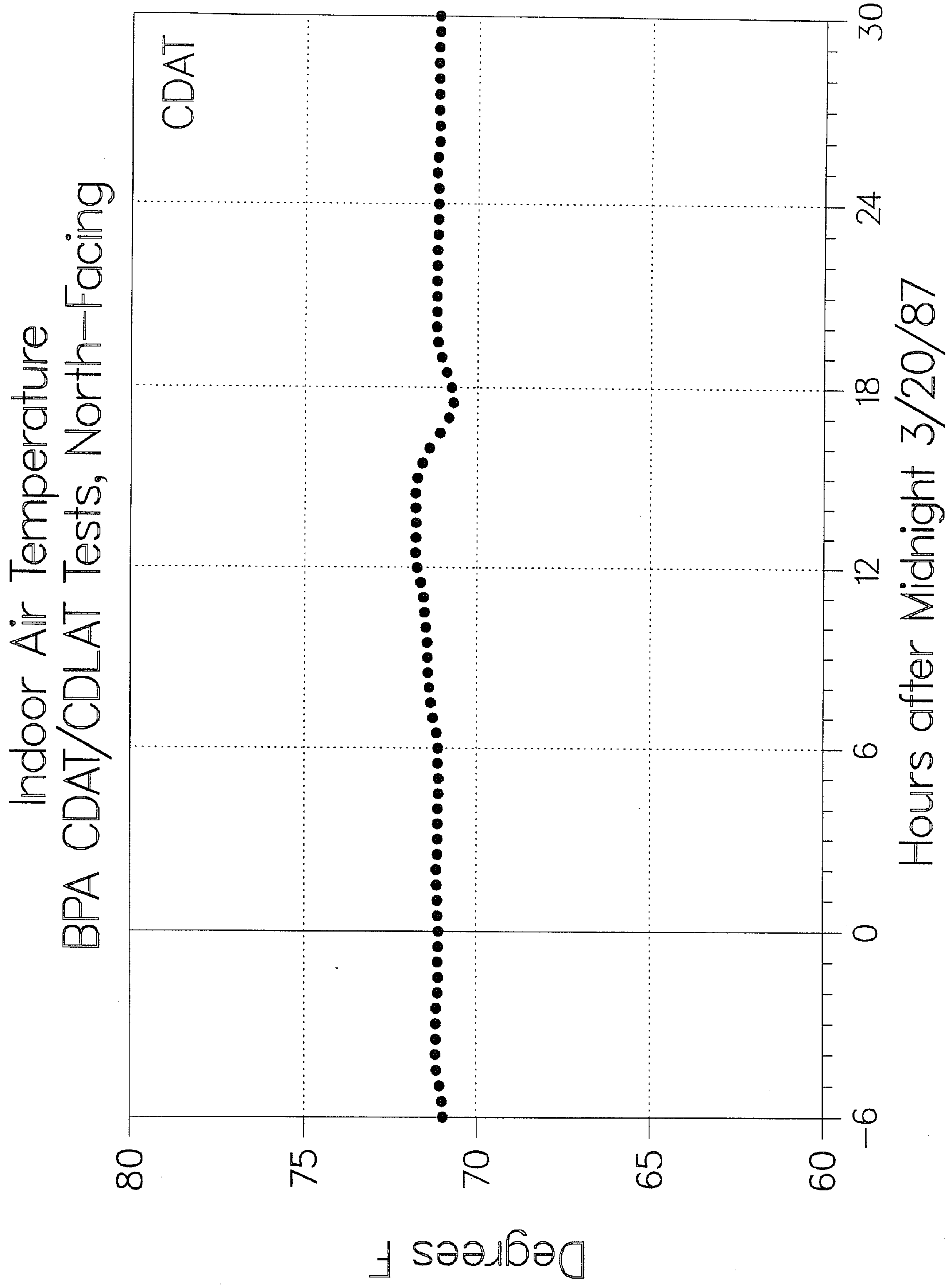

Indoor Air Temperature
BPA CDAT/CDLAT Tests, North-Facing
CDAT
Degrees F
80
75
70
65
60
−6
0
6
12
18
24
30
Hours after Midnight 3/20/87

Figure 10

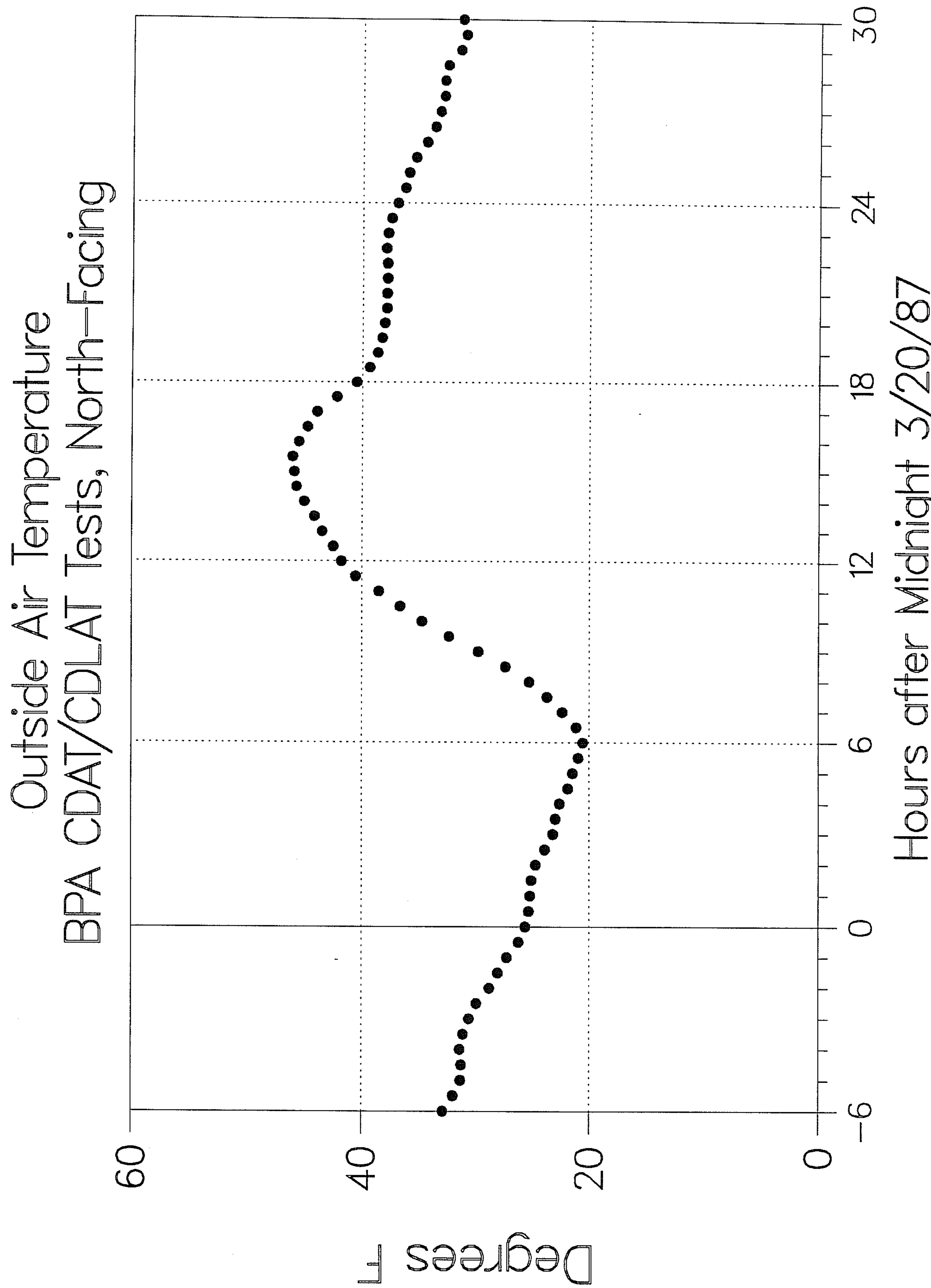

Outside Air Temperature
BPA CDAT/CDLAT Tests, North-Facing
Degrees F
60
40
20
0
-6
0
6
12
18
24
30
Hours after Midnight 3/20/87

Figure 11

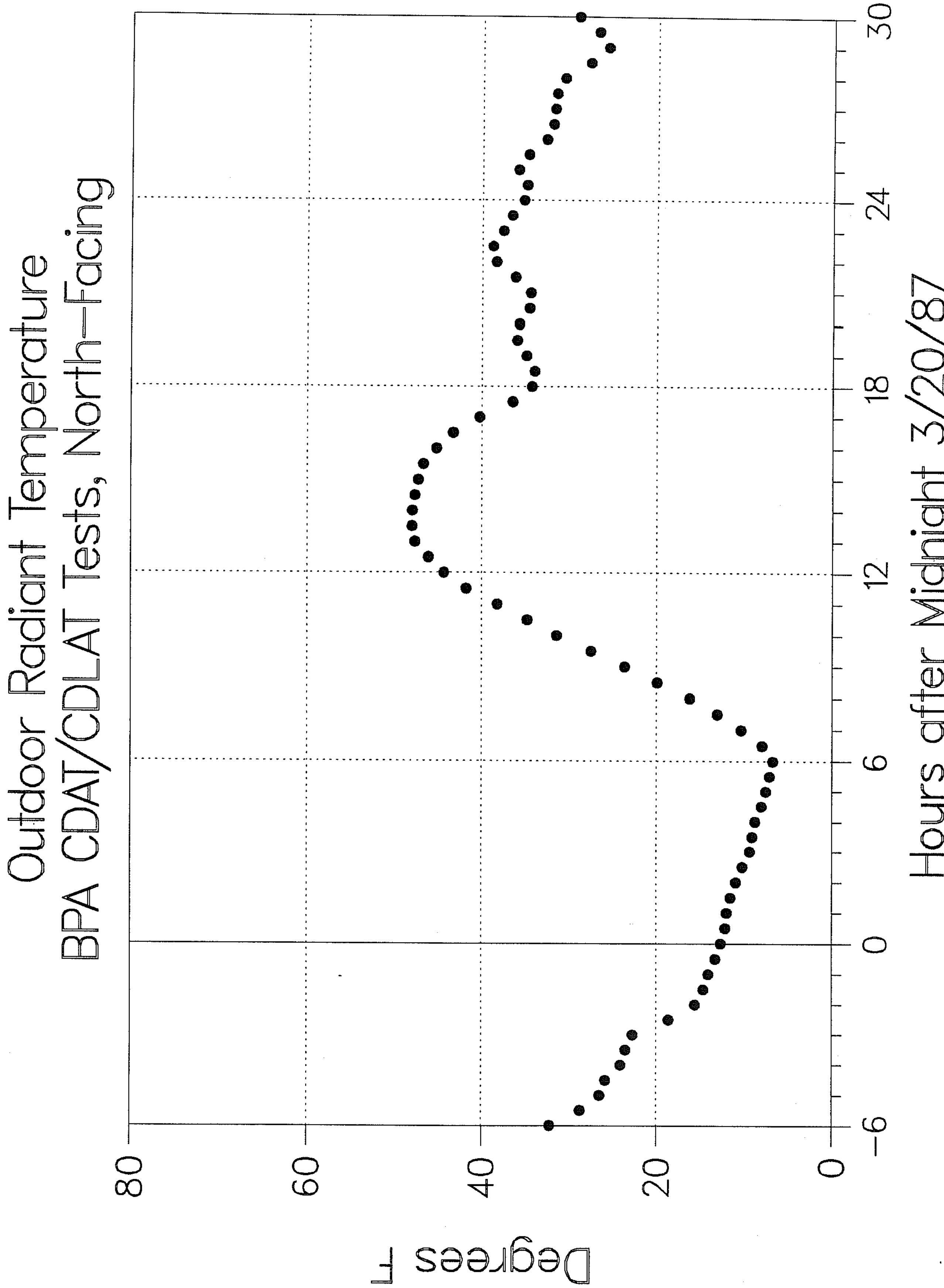

Outdoor Radiant Temperature
BPA CDAT/CDLAT Tests, North-Facing
Degrees F
0
20
40
60
80
-6
0
6
12
18
24
30
Hours after Midnight 3/20/87

Figure 12

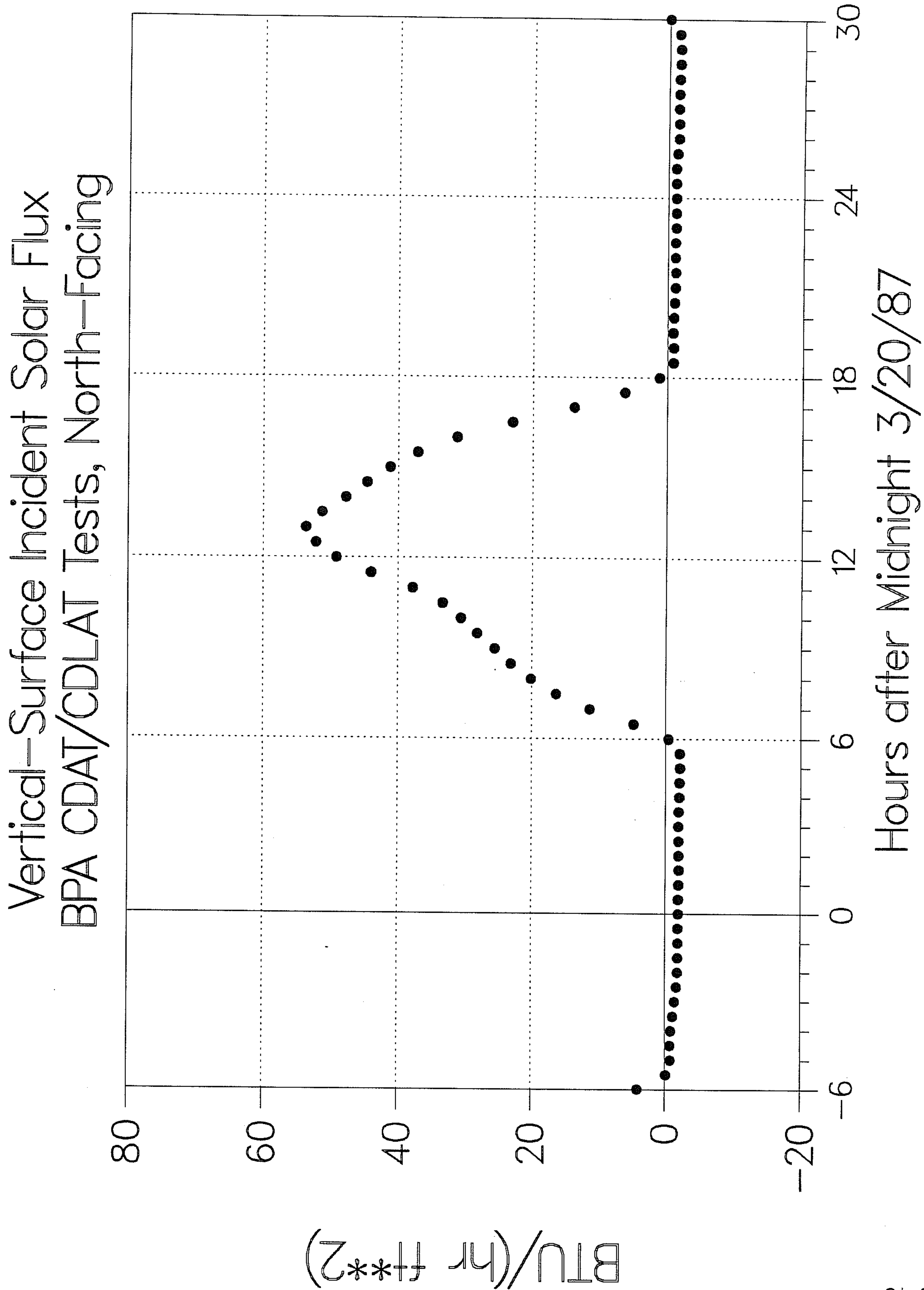


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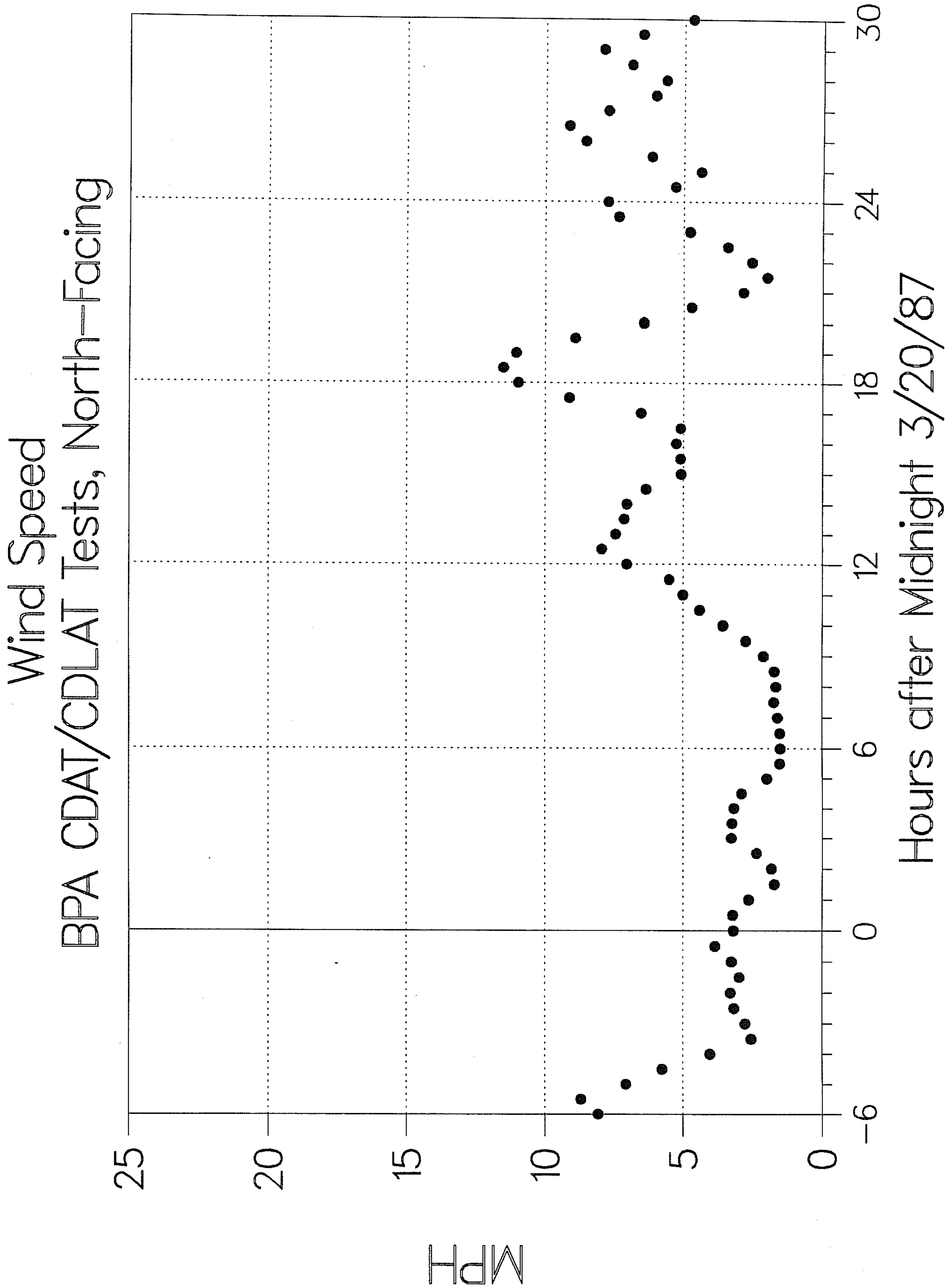
Figure 13



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where U is the window overall thermal transmittance, F is the solar heat gain coefficient, or "solar factor", A_S is solar aperture, *i.e.,* the glazed area, of the window, A_T is the overall area of the window, T_O and T_I are the outside and inside air temperatures, respectively, and I_V is the total solar intensity incident on the (vertical) exterior surface of the window.

For simplicity the quantities U and F are typically taken to be constants, although they are in fact functions of weather- and time-dependent quantities: U may depend on the average temperature, the temperature difference, and wind speed, and F may depend the same variables as well as on the solar incident angle. Further, equation (1) neglects the differences between outdoor air and radiant temperatures, assumes stable, still air conditions on the interior, and lumps together beam and diffuse solar radiation. These simplifications of the underlying theory raise questions about how realistically the equation represents window behavior.

For the five windows tested in the study, this question may be answered directly. As indicated in the previous section, all of the variables on both sides of equation (1) are measured, leaving only values of U and F to be determined. Methods are available for predicting U and F. Two equivalent approaches are possible: one could use predicted values of U and F to calculate the right hand side of equation (1) and then compare the result with the measured values of W; alternatively, one could mathematically fit the right hand side of the equation to the measured values of W, determining effective "best fit" values for U and F, and then compare these values to the predicted ones. We chose the latter approach. (For reasons explained below, we included one additional complication to the model: U was allowed to have different values during the night and day. The nighttime U value was determined by a more elaborate, but fundamentally equivalent, treatment of the data as described below, and only the daytime U-value and F determined from the fitting process.)

The results of this comparison are shown in Figures 14-21 for the four test periods. These figures show that equation (1) provides an excellent calculation of the data over a variety of weather conditions and for all orientations. It is significant that the model works well not only for clear days (*e.g.*, days 5 and 6 in Figure 14), but for both partially cloudy and overcast days (*e.g.*, days 2 and 3, respectively, in Figure 14), for north-facing orientation (Figures 16 and 17), and for east and west orientations, when the window is shaded for part of the day (Figures 18-21).

Table 2 provides a quantitative measure of the quality of the fit by the root-mean-square difference between the calculated curve and the measured points. This quantity varied between 82 and 216 BTU/hr, indicating the accuracy with which one could expect to predict the heat flow using the equation. For all orientations except north-facing, the rms deviation (100-200 BTU/hr) is 5 to 10% of the peak daytime energy flow (1000-2000 BTU/hr). The figures (*e.g.*, days 5 and 6 in Figure 14) show that the deviations occur primarily around noon, when the model tends to underpredict the heat gain. This is a consequence of lumping together direct and diffuse radiation and not taking into account that the glass transmission depends on the solar incident angle and the self-shading of the windows by their frame elements as the angle increases. These two effects make it impossible to calculate the solar heat gain accurately using a single constant value of F.

Figure 14

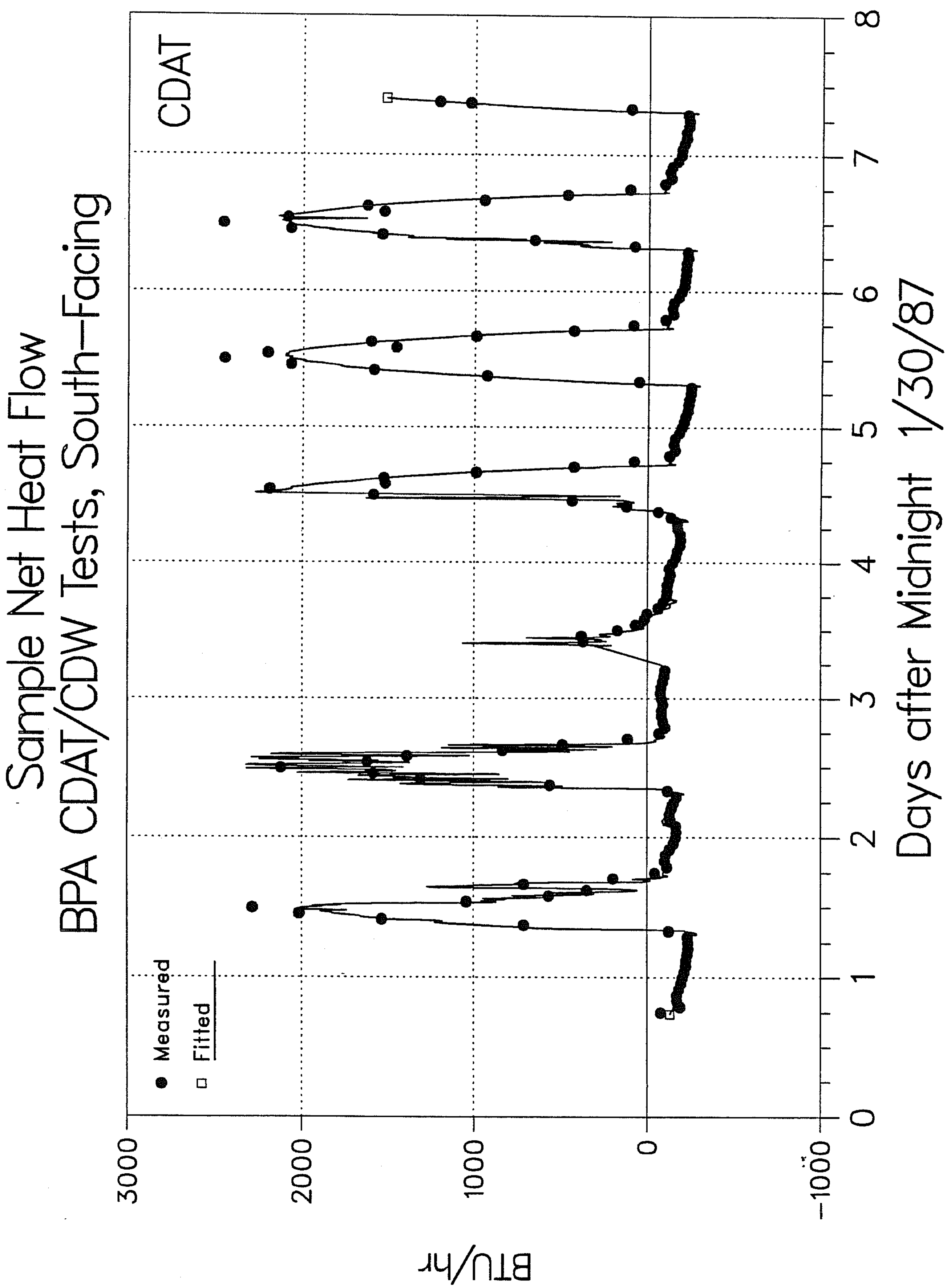

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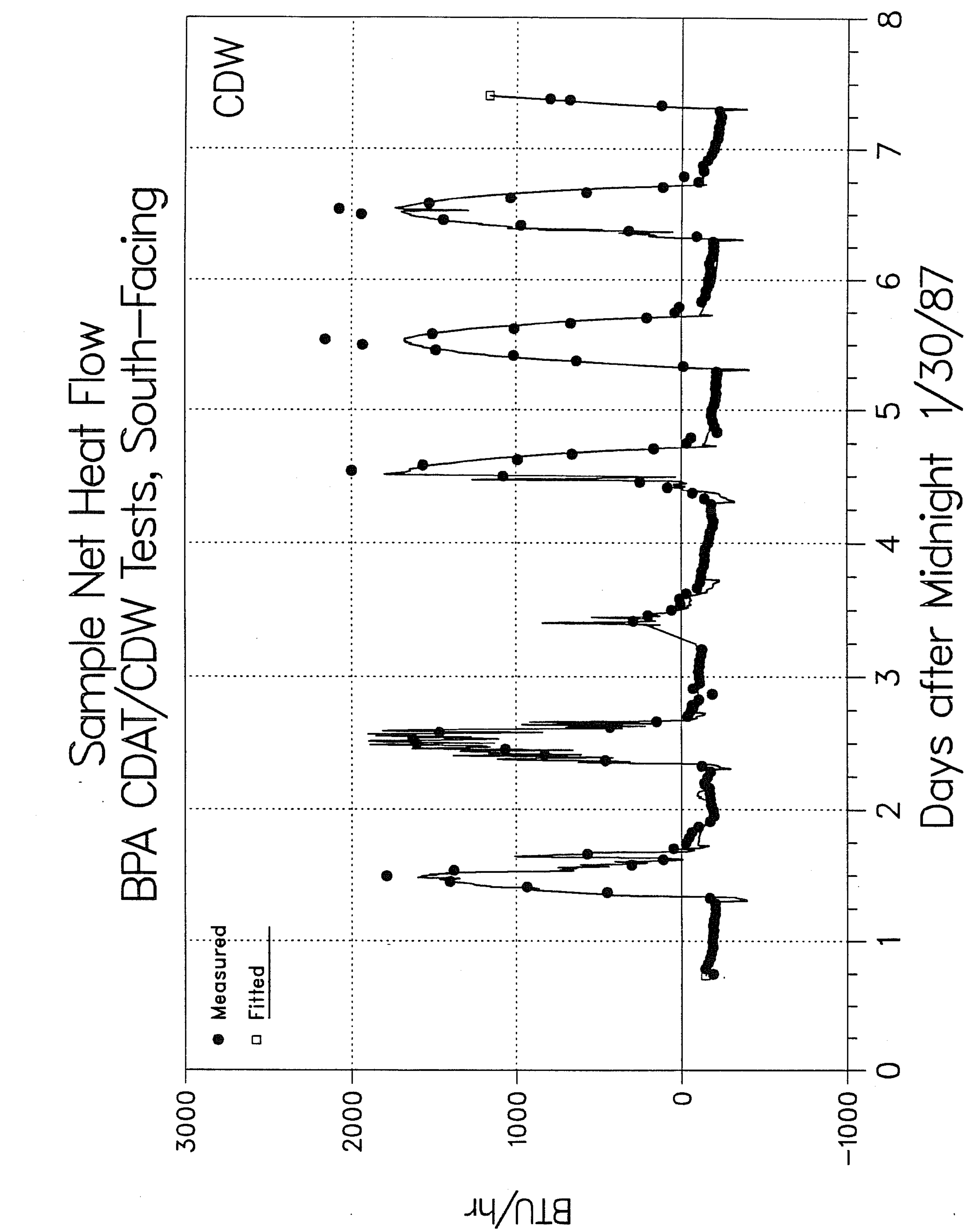
Figure 15



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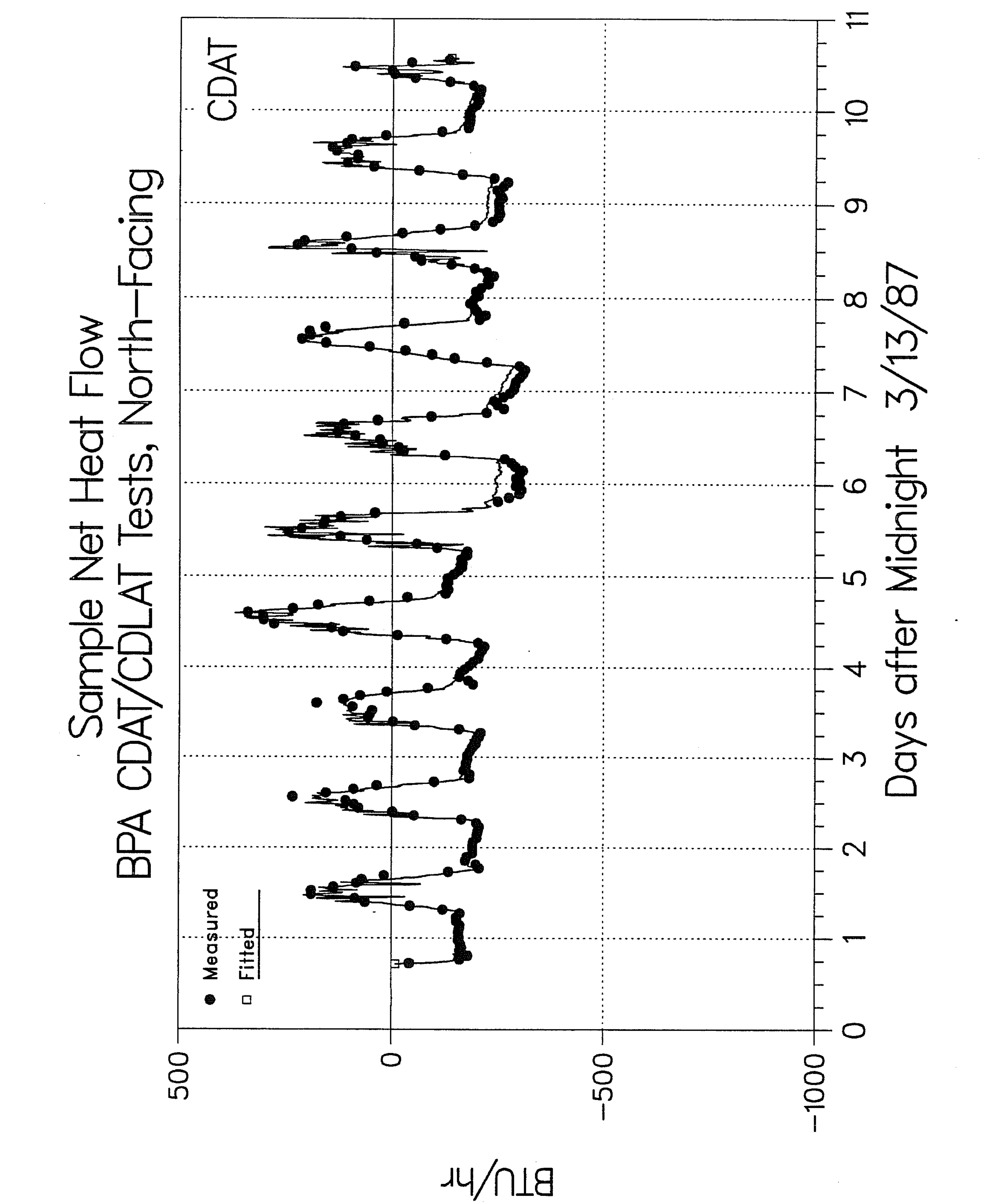
Sample Net Heat Flow
BPA CDAT/CDLAT Tests, North-Facing
CDAT
Measured
Fitted
Days after Midnight 3/13/87
BTU/hr
500
0
-500
-1000
0
1
2
3
4
5
6
7
8
9
10
11

12488 27

Figure 17

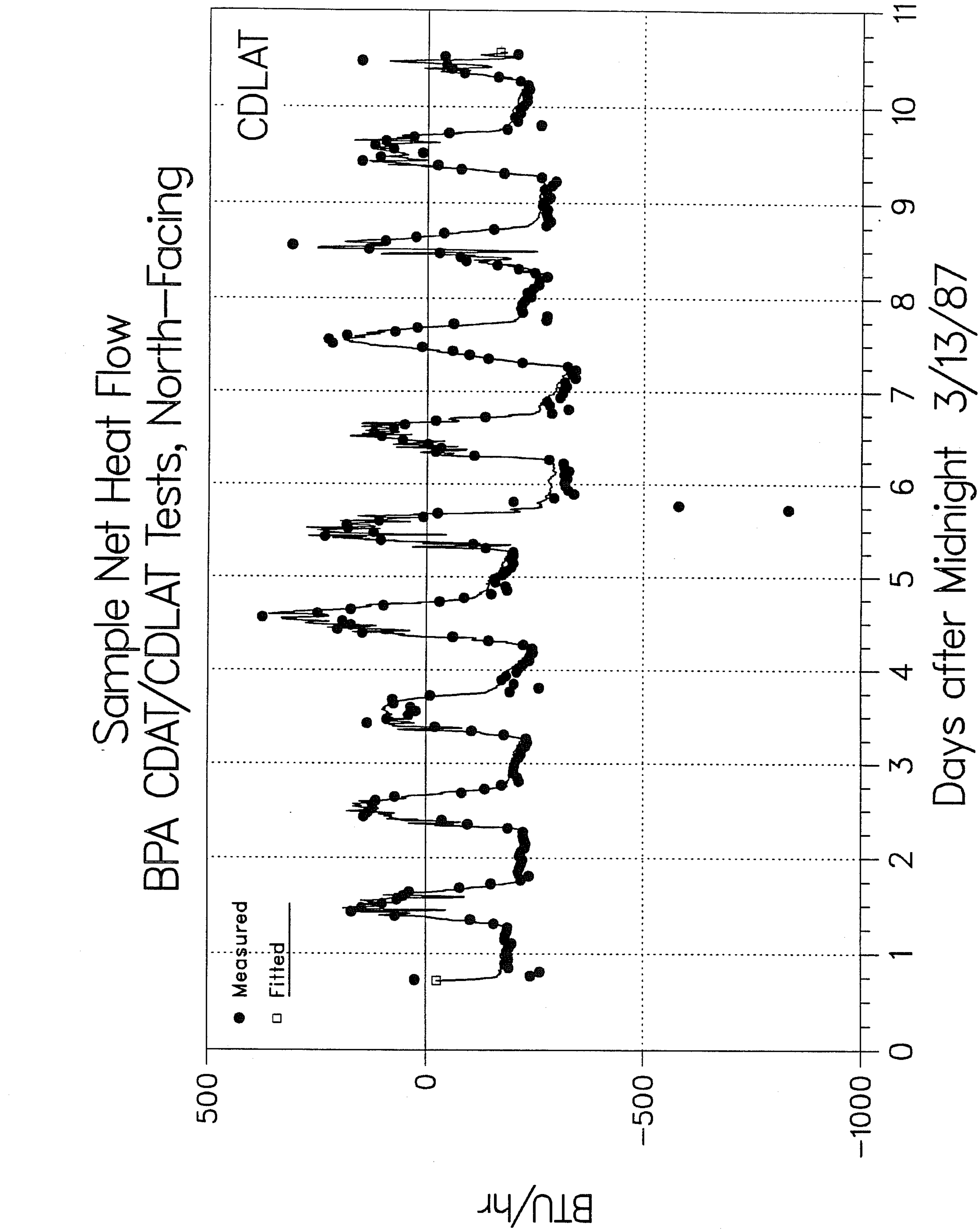
Sample Net Heat Flow
BPA CDAT/CDLAT Tests, North–Facing
CDLAT
Measured
Fitted
Days after Midnight 3/13/87
BTU/hr
500
0
–500
–1000
0
1
2
3
4
5
6
7
8
9
10
11

Figure 18

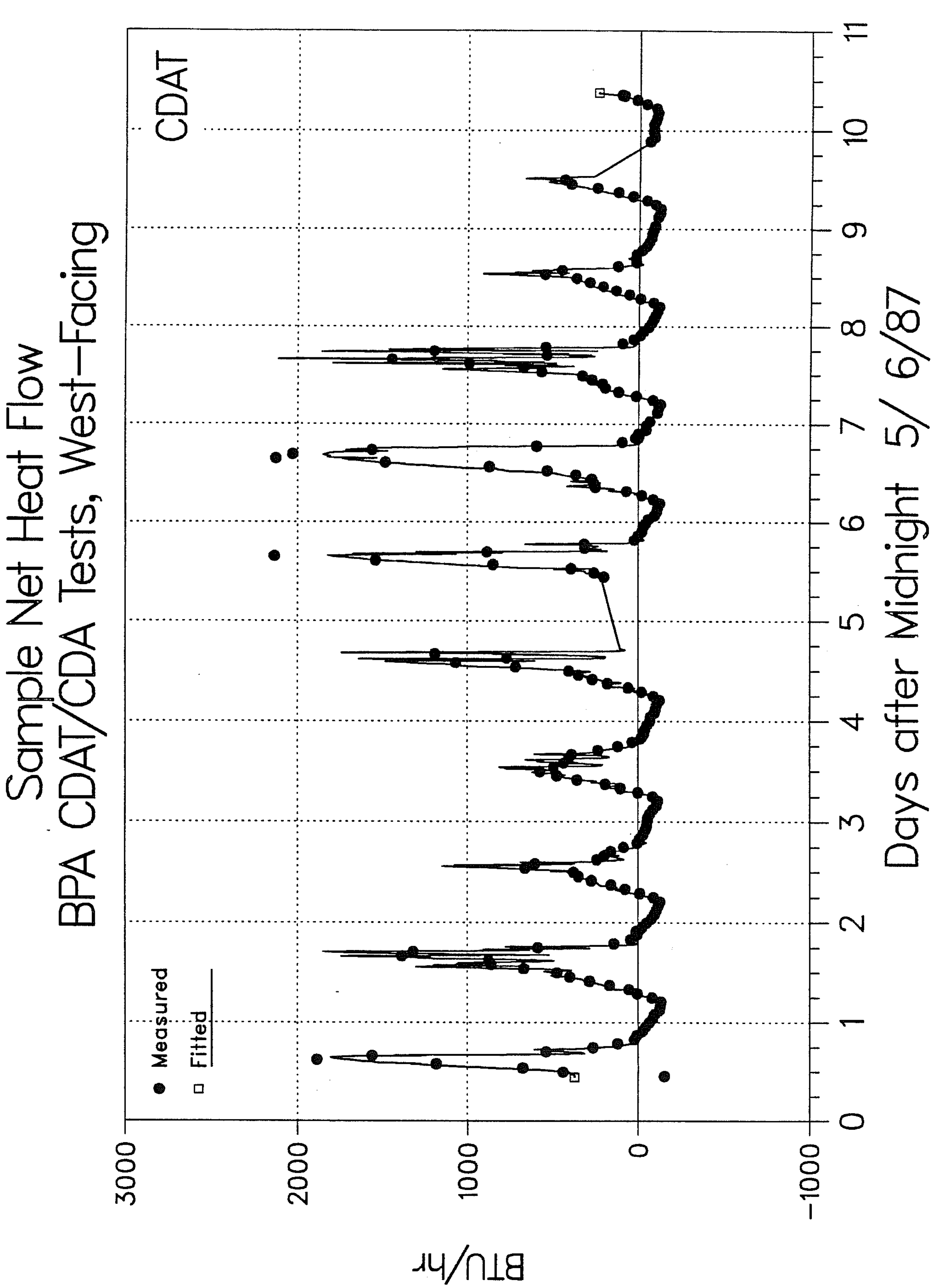

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Figure 19

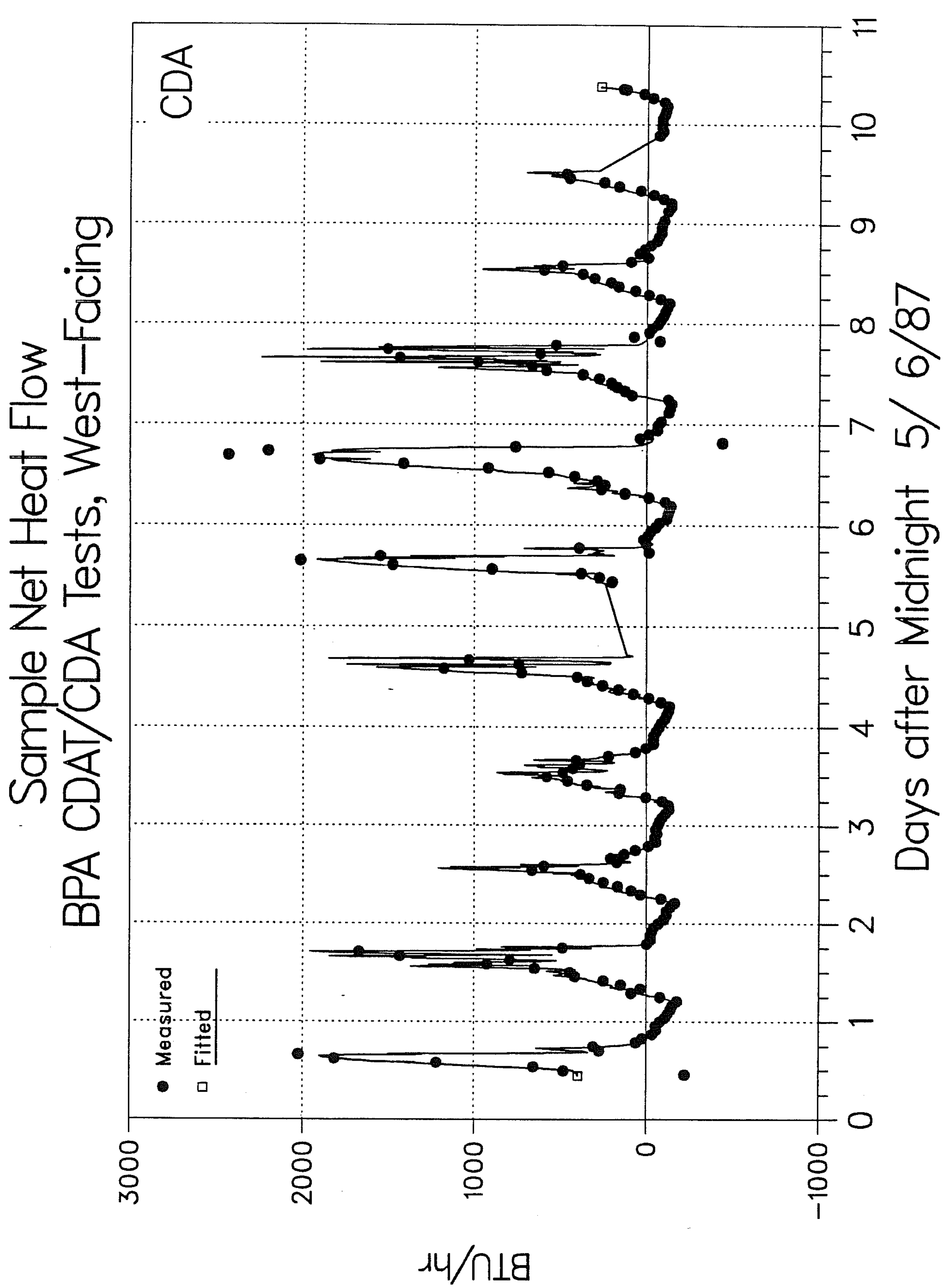

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Figure 20

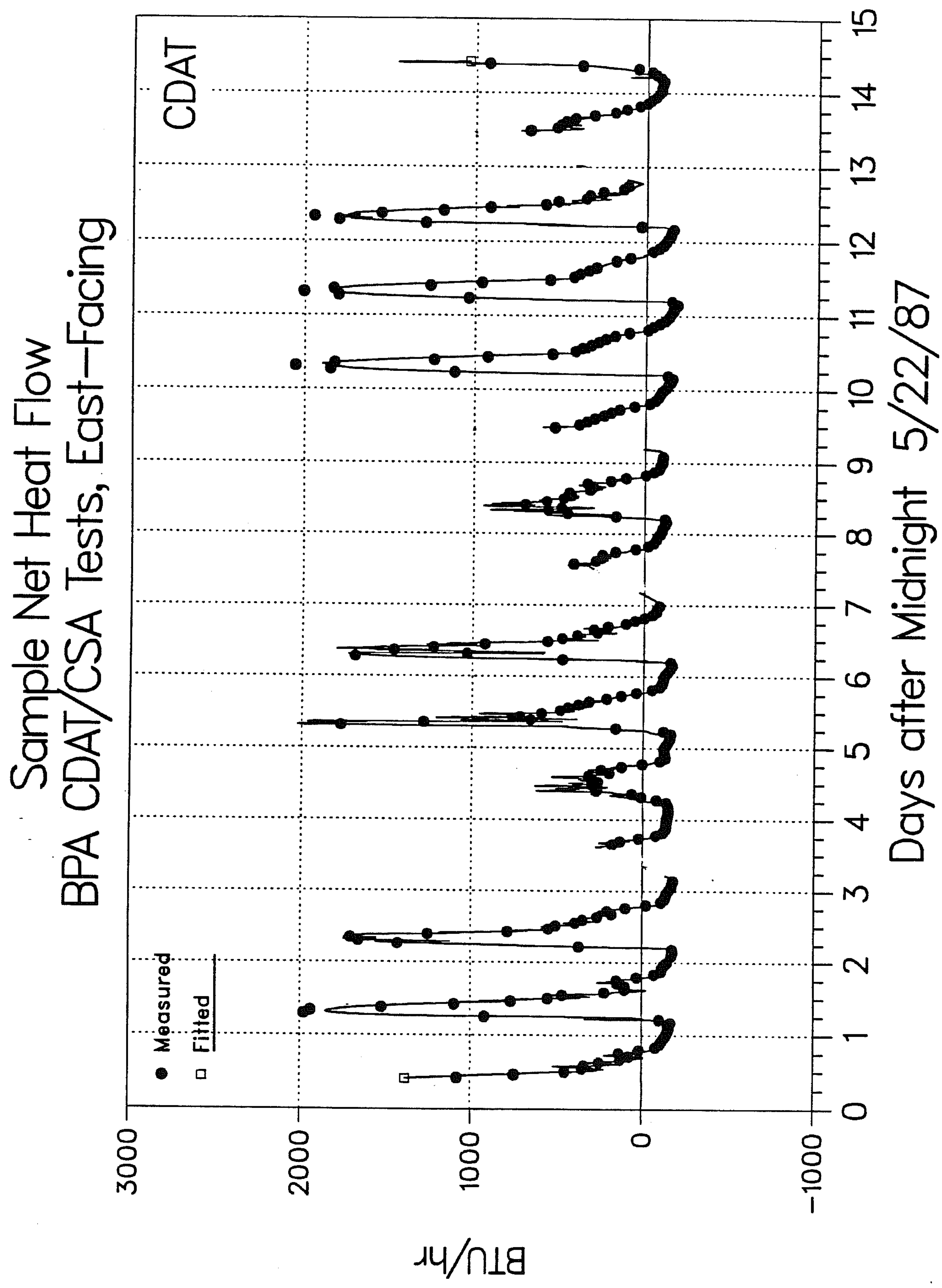

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Figure 21

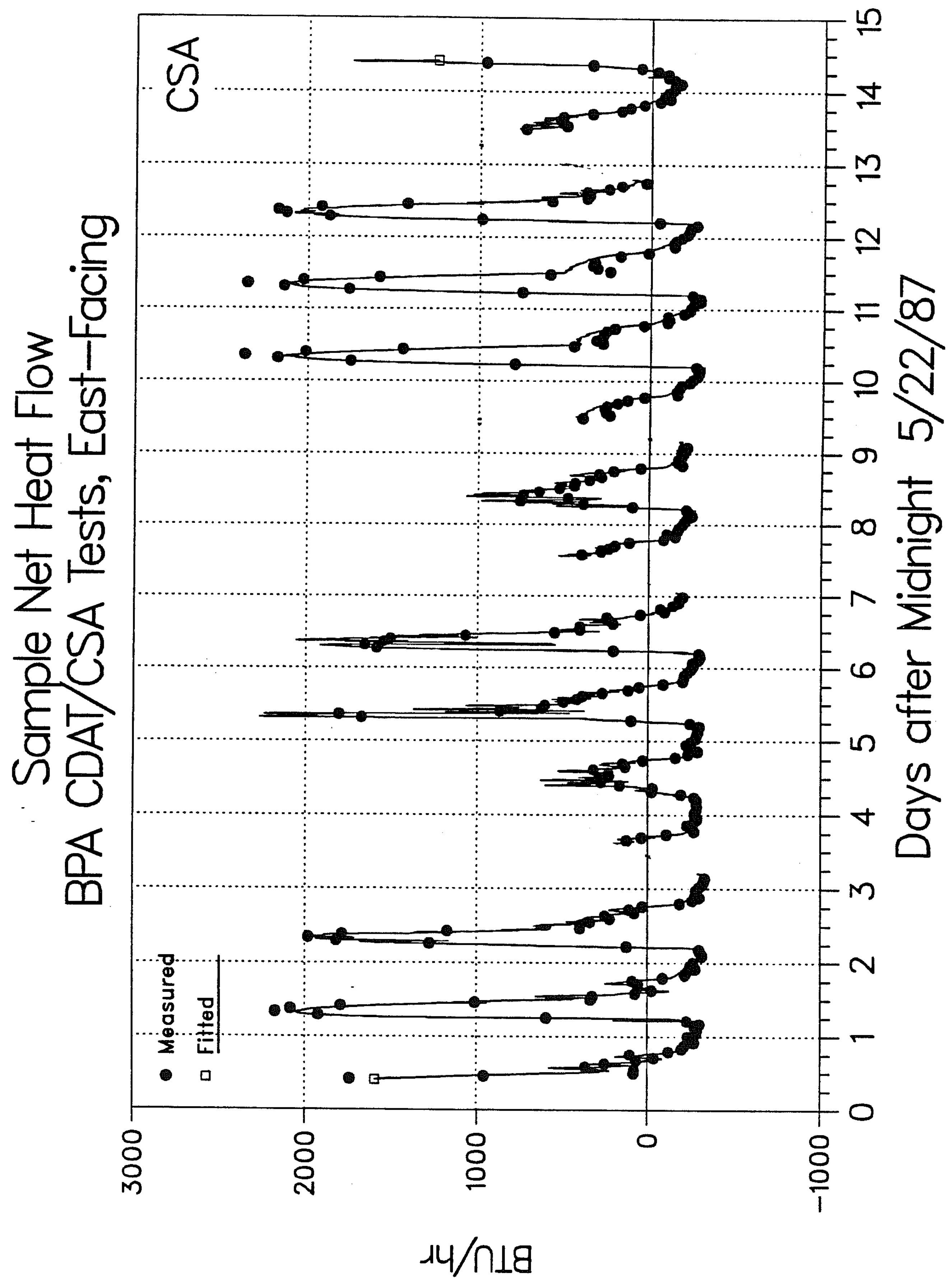

Sample Net Heat Flow
BPA CDAT/CSA Tests, East-Facing
CSA
Measured
Fitted
Days after Midnight 5/22/87
BTU/hr
3000
2000
1000
0
−1000
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15

Table 2

Root-Mean Square Deviations of Measured

Net Heat Flow from Calculated Values

Sample	Orientation	RMS Deviation (BTU/hr)
CDAT	South	236
CDW	South	212
CDAT	North	82
CDLAT	North	99
CDAT	West	198
CDA	West	225
CDAT	East	130
CSA	East	174

On the other hand, it is clear from the plots that the assumption of a constant U-value provides a calculation which, on the energy scale appropriate to the diurnal cycle of window heat flows, is indistinguishable from the data. This is true overall, with the exception of March 19-23 (Figures 16 and 17), when there was rain and snow. The two points in these figures deviating from the curve by very large amounts at approximately 6:00 PM on March 18 are experimental artifacts and should be disregarded. At this time the calorimeter interior air temperature set points were changed, and the data was not valid until the system had re-equilibrated some two hours later.

The figures also make clear the relative magnitudes of the daytime solar gain and nighttime thermal loss. For all orientations except north-facing, the nighttime heat flows are of the same order of magnitude (100-200 BTU/hr) as the rms deviations of equation 1 from the data. For these orientations, solar heat gain is a huge effect relative to thermal loss. For the north-facing orientation, peak solar gain and nighttime thermal losses are roughly the same size, as can be seen from Figures 16 and 17.

4.3 Nighttime U-Values

Equation (1) may be used at night (when the solar flux is of course zero) with the measured values of W(t) and the air temperatures $T_O(t)$ and $T_I(t)$ to determine an effective measured U-value for the short time period (here one hour) surrounding the time t:

$$U(t) = \frac{W(t)}{A_T(T_O - T_I)} \quad . \tag{2}$$

However, considerable care must be exercised here to obtain meaningful values. Figures 14-21.show that the solar-dominated daytime heat flows are much larger than the thermal-transmission-dominated nighttime heat flows for all cases except the north-facing orientation and a few very overcast days, when the daytime and nighttime heat flows are of approximately equal magnitude. This means that very small-percentage residual solar effects, for example through heat storage inside the calorimeter, may have a devastating effect on the apparent U-value. In addition, the measurement of W has limited accuracy. Near sunrise and sunset, when W is small, the measured value will be dominated by the measurement error arising from this finite accuracy. At the same time, the temperature difference becomes small, and the resultant error in U value becomes large as a result.

To avoid these effects and instrumental problems which compromised the validity of the procedure for some parts of the data, nighttime U-values were calculated only when known effects could be excluded. Thus, the fitting procedure described above was not used to determine the average nighttime U-values. For these restricted sets of data, the measured hourly average nighttime U-values for the eight window/orientation combinations are shown in Figures 22-29. These plots show considerable scatter in the measured U-values, reflecting the fact that experimental uncertainties (~10-20 BTU/hr) are not negligible relative to the heat flows (100 - 250 BTU/hr) which contributed to the measurement. As noted above, the data are reasonably consistent with constant nighttime U-values; while the measured points show some variations from hour to hour and day to day, these are consistent with expected experimental errors. We have been unable to find any point-to-point variations in the nighttime U-value which correlate with changes in either wind speed or outdoor radiant temperature, although both of these affect the overall average U-value. Other measurements made with the facility indicate that for this data effects from both sources should be smaller than the experimental error, since neither nighttime wind speeds nor sky temperature depressions typically showed large variations during a measurement period. (A few atypical variations are discussed in Section 4.3.3.)

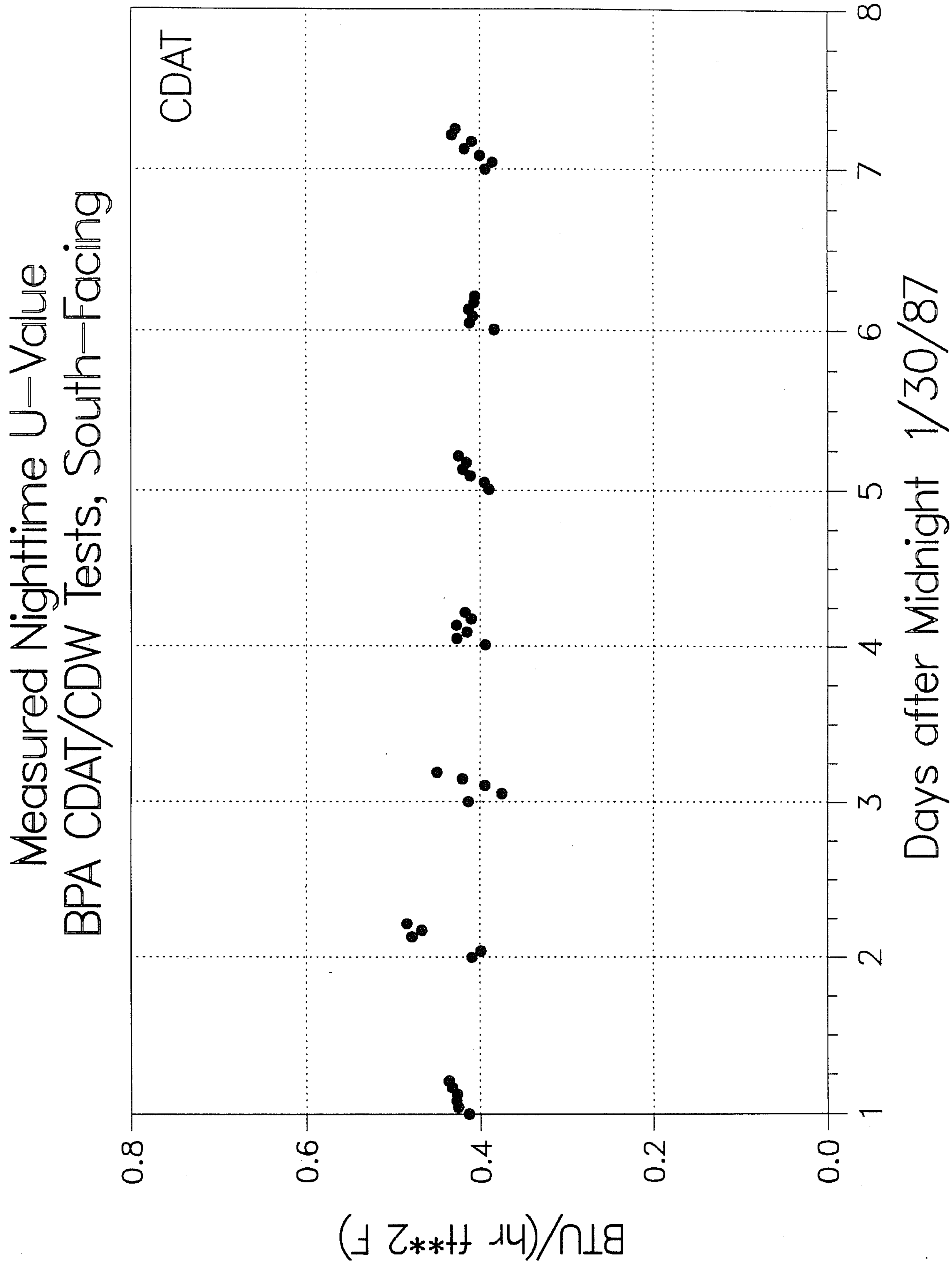
Table 3 lists the average measured nighttime U-values, together with the average temperature and wind conditions during the measurement. Table 4 shows the extremes of outdoor temperature and the average outdoor radiant temperature and relative humidity for the period of the U-value measurements.

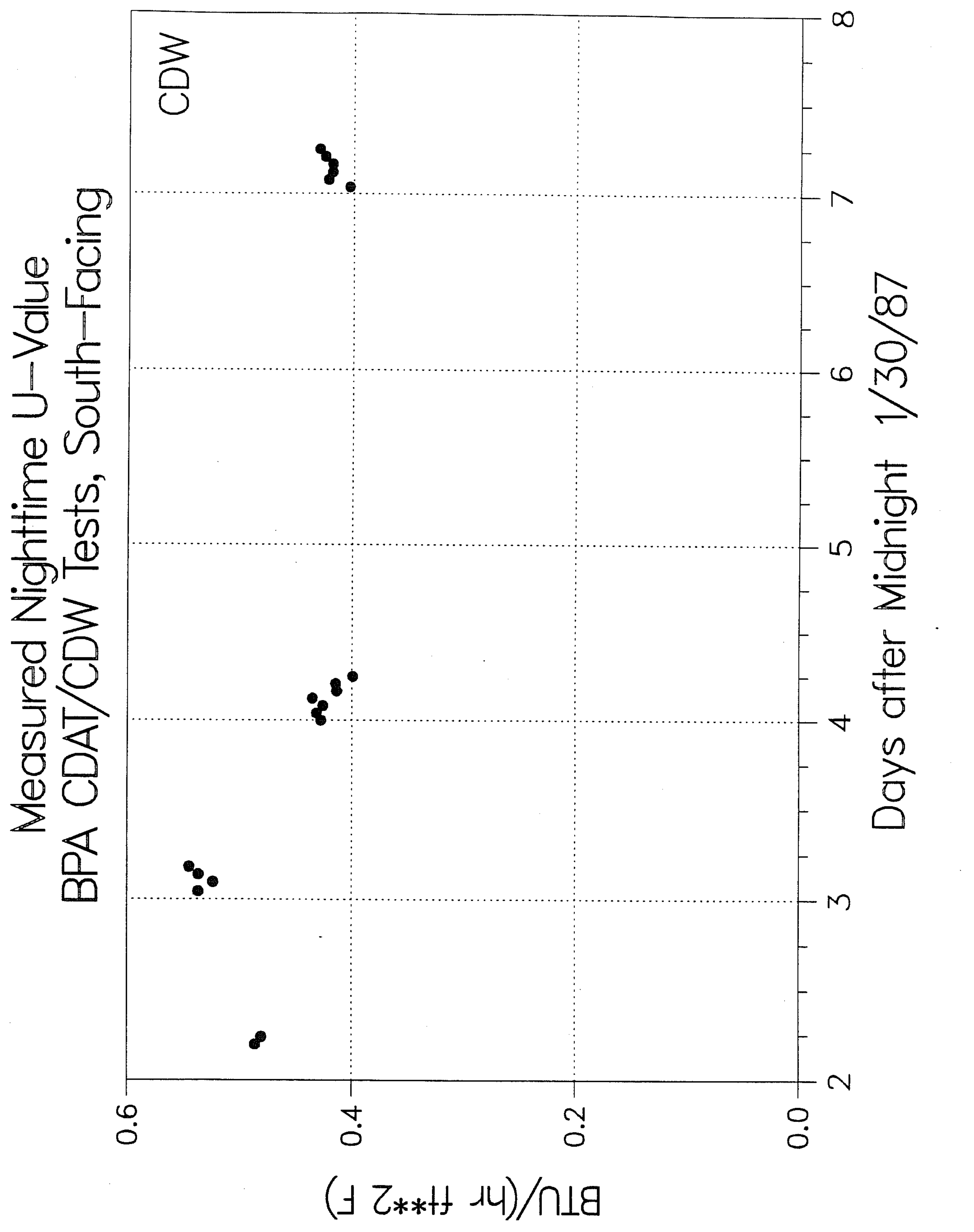
Table 3

Measured Nighttime U-Values and Average Conditions of the Measurement

Sample	Orientation	Air Temperatures Indoor ºF	Outdoor ºF	Wind Speed MPH	Measured U-Value BTU/(hr ft^2 F)
CDAT	South	67.8	33.3	3.5	0.42 ± .04
CDW	South	67.8	38.1	4.8	0.46 ± .06
CDAT	North	69.4	33.4	6.6	0.47 ± .04
CDLAT	North	69.8	33.3	6.4	0.53 ± .03
CDAT	West	71.0	54.9	2.5	0.55 ± .10
CDA	West	70.9	54.7	2.5	0.64 ± .06
CDAT	East	71.4	47.1	4.2	0.46 ± .08
CSA	East	71.8	47.1	4.3	0.87 ± .09

Figure 22


Measured Nighttime U-Value
BPA CDAT/CDW Tests, South-Facing
CDAT
BTU/(hr ft**2 F)
0.0
0.2
0.4
0.6
0.8
1
2
3
4
5
6
7
8
Days after Midnight 1/30/87


Measured Nighttime U-Value
BPA CDAT/CDW Tests, South-Facing
CDW
BTU/(hr ft**2 F)
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0.2
0.4
0.6
Days after Midnight 1/30/87
2
3
4
5
6
7
8

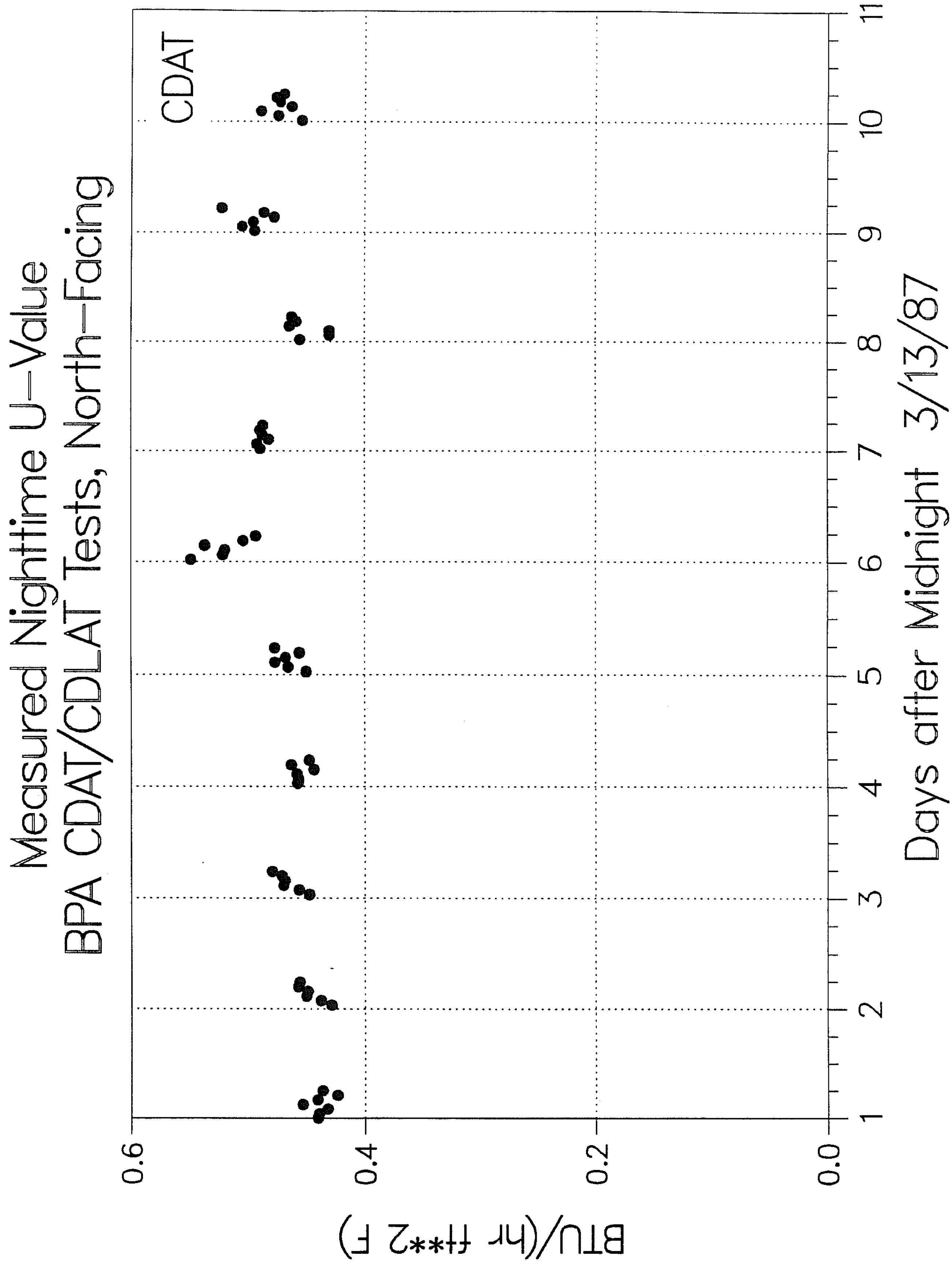
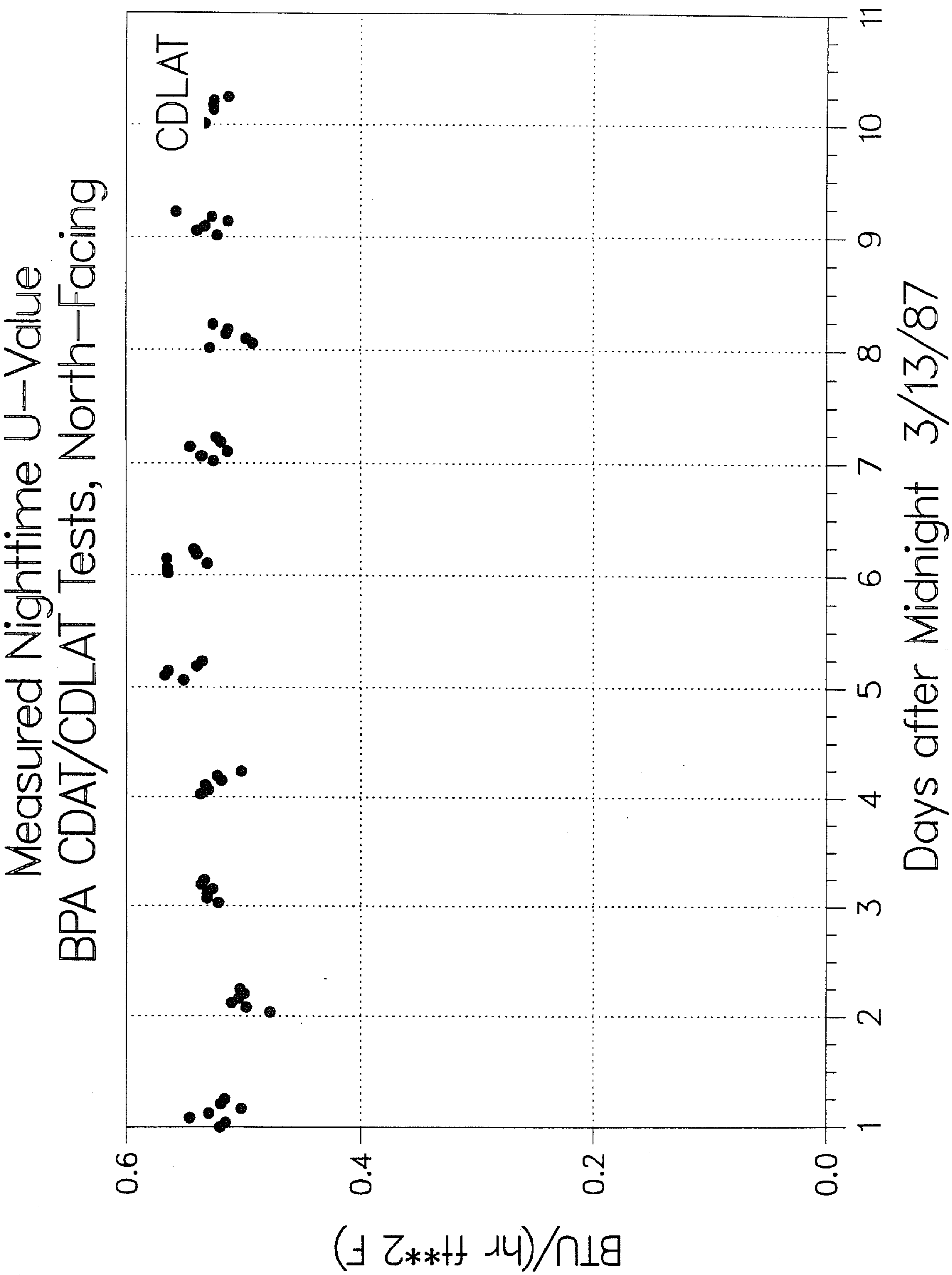
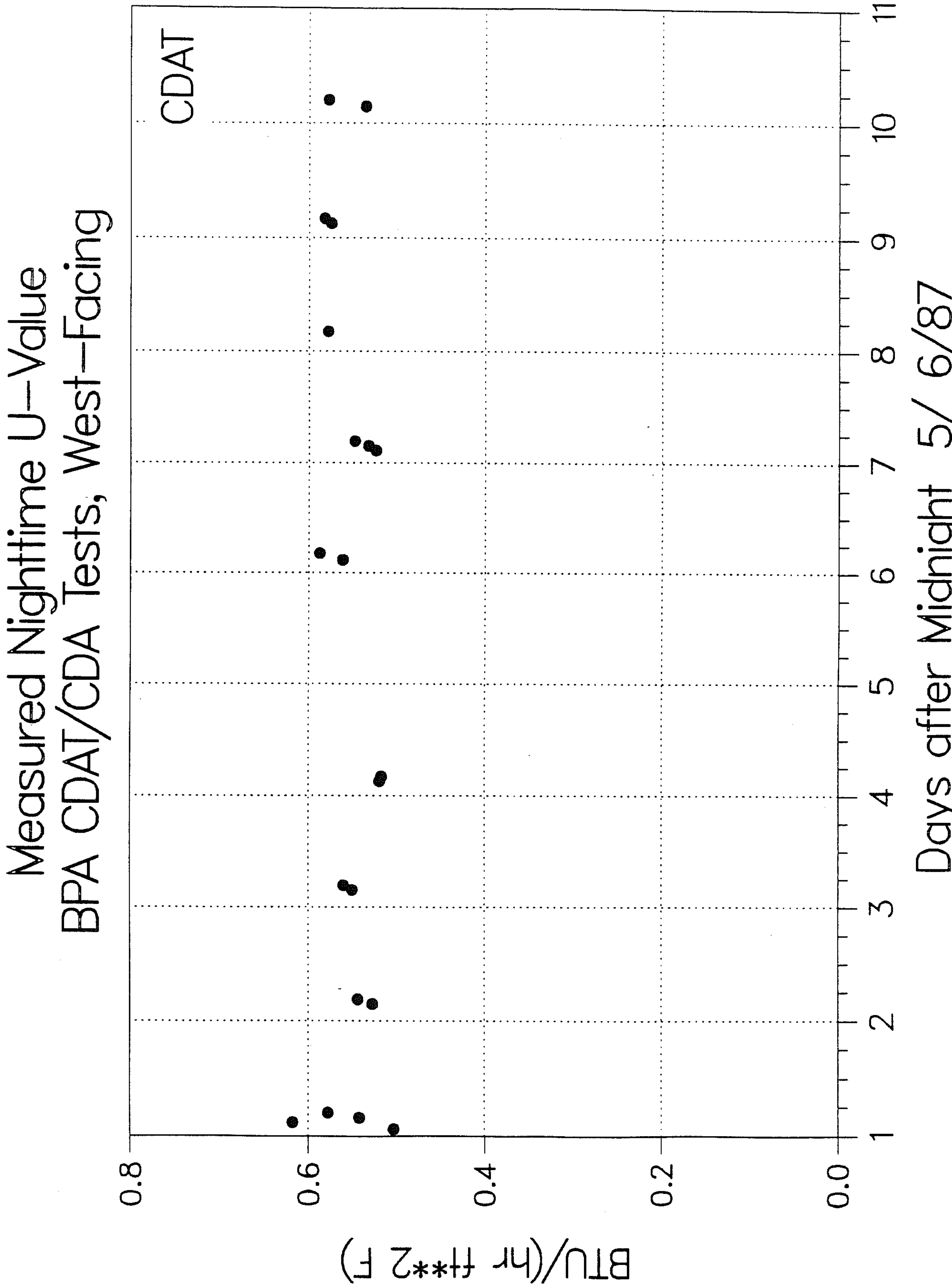

Measured Nighttime U—Value
BPA CDAT/CDLAT Tests, North—Facing
CDAT
BTU/(hr ft**2 F)
0.6
0.4
0.2
0.0
1
2
3
4
5
6
7
8
9
10
11
Days after Midnight 3/13/87

Figure 25



2488 18


Measured Nighttime U—Value
BPA CDAT/CDA Tests, West—Facing
CDAT
BTU/(hr ft**2 F)
0.0
0.2
0.4
0.6
0.8
1
2
3
4
5
6
7
8
9
10
11
Days after Midnight 5/ 6/87

2488 20

Figure 27

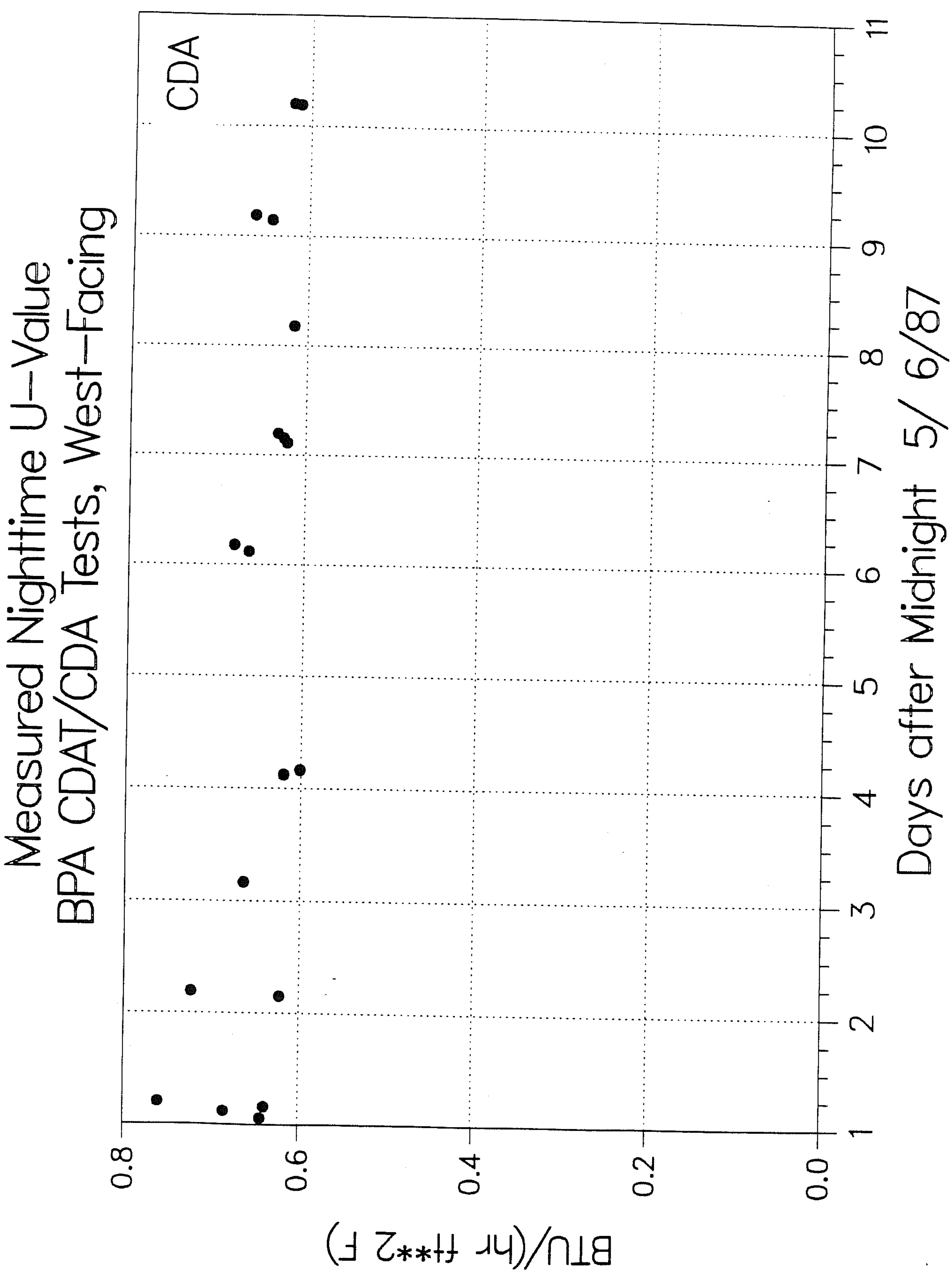

Measured Nighttime U-Value
BPA CDAT/CDA Tests, West-Facing
CDA
BTU/(hr ft**2 F)
0.0
0.2
0.4
0.6
0.8
1
2
3
4
5
6
7
8
9
10
11
Days after Midnight 5/ 6/87

Figure 28

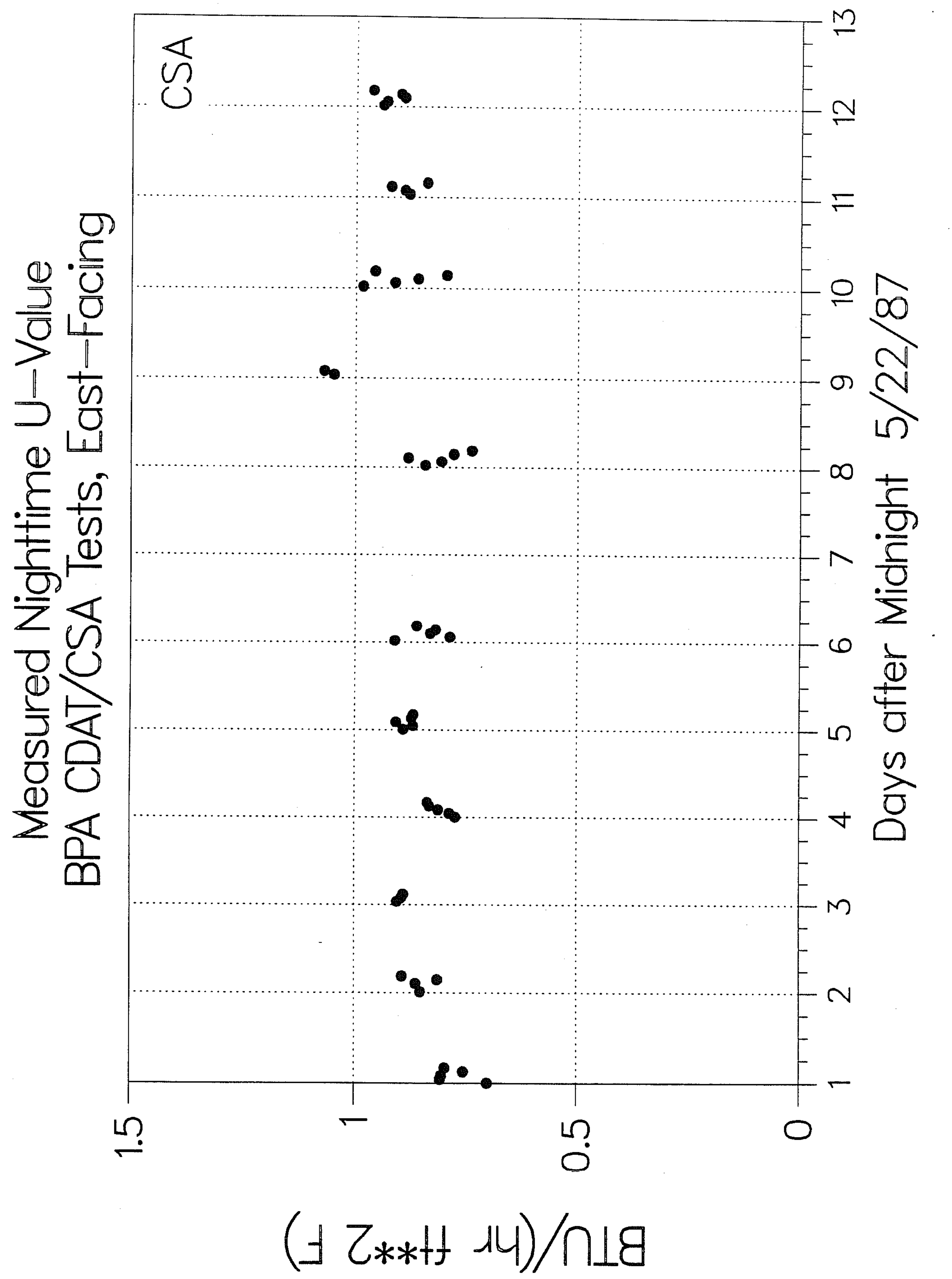
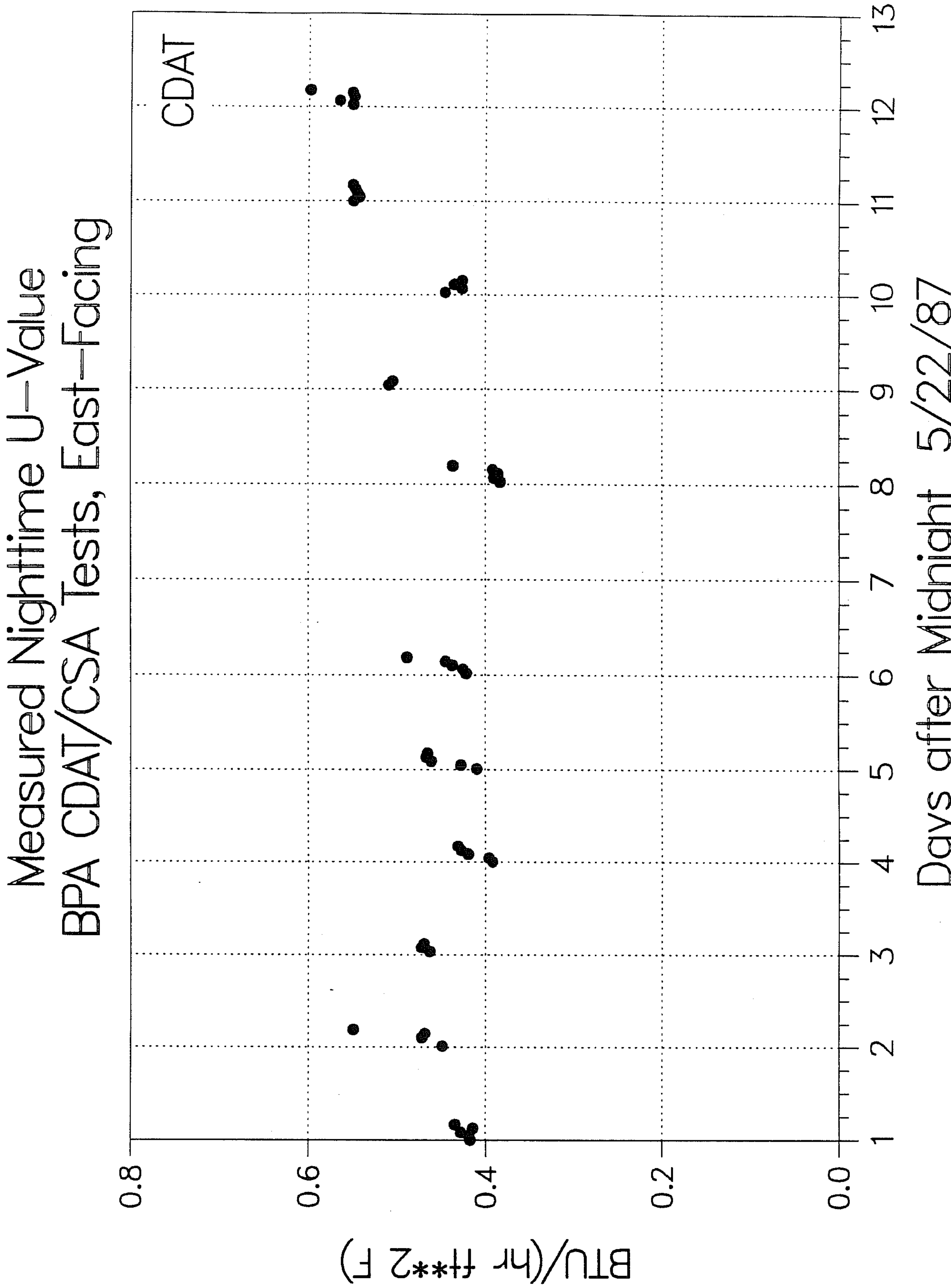

Measured Nighttime U-Value
BPA CDAT/CSA Tests, East-Facing
CSA
Days after Midnight 5/22/87
BTU/(hr ft**2 F)
0
0.5
1
1.5
1
2
3
4
5
6
7
8
9
10
11
12
13

Figure 29


Measured Nighttime U—Value
BPA CDAT/CSA Tests, East—Facing
CDAT
Days after Midnight 5/22/87
BTU/(hr ft**2 F)
0.0
0.2
0.4
0.6
0.8
1
2
3
4
5
6
7
8
9
10
11
12
13

For each orientation, the two windows tested were simultaneously exposed to the same weather conditions; however, the selection of data for the nighttime U-value measurement sometimes differed between the two samples due to small differences in conditions in the two calorimeter chambers. Generally the conditions for the two samples are quite close, if not identical. The one exception to this statement occurred for the south-facing measurement, where an instrumentation problem in the calorimeter chamber holding the CDW window necessitated excluding some of the coldest nighttime data. However, if one restricts both window measurements for this orientation to the same data set (by excluding data for both chambers if the data for either is unacceptable), the measured U-values are unchanged, indicating that the difference in wind speeds has no effect on the measurement.

Table 4

Other Conditions During the Nighttime U-Value Measurements

Sample	Orientation	Outside Air		Outside Radiant Temperature (Mean) º F	Relative Humidity %
		Min º F	Max º F		
CDAT	South	23.4	53.2	22.6	58
CDW	South	25.5	53.2	27.5	47
CDAT	North	20.3	43.3	28.9	53
CDLAT	North	20.3	42.1	28.9	53
CDAT	West	51.5	56.7	49.1	54
CDA	West	51.1	56.5	48.7	54
CDAT	East	39.9	56.8	41.5	53
CSA	East	39.9	57.0	41.5	53

The experimental uncertainty of ± 0.04 BTU/(hr ft^2 F), Table 3, quoted for the South-facing CDAT measurement corresponds to an uncertainty of about 13 BTU/hr in heat flow measurement and is close to the limiting resolution of the MoWiTT. This uncertainty is typical of the south- and north-facing measurements, where cold outdoor temperatures are favorable for making U-value measurements. However, the above-mentioned instrumentation problem resulted in a somewhat larger uncertainty for the CDW sample. Two factors make the west-facing and east-facing runs more problematic for the measurement of nighttime U-values. First, nighttime temperature differences are smaller, since these two runs occurred later in the season than the south- and north-facing; second, calibration problems (from long-term drifts in an RTD sensor) in the chamber holding the CDAT window increased the experimental uncertainty for those runs.

The measured values in Table 3 fall into a pattern which, with one exception, qualitatively match what one would expect. The four measurements of CDAT are consistent within experimental uncertainties. One would expect this, since nighttime U-values could depend on orientation only if there were strong wind effects and a preferred wind direction; we see no nighttime wind dependence. (This is because, as indicated in Table 3, nighttime wind speeds are low, as is discussed in Section 4.3.3.) The simultaneous measurements of CDAT and CDW are also consistent. These are measurements of two double-glazed windows with thermally "good" frames; the differences between them are smaller than our experimental resolution. There is a difference when the comparison is between CDAT and the window without a thermal break in the frame, CDA. While the simultaneous measurement of CDAT has poor accuracy, since there are no orientation dependences, it can be compared with the error-weighted average of the CDAT measurements, which is U = 0.45 ± .03 BTU/(hr ft^2 F). Here the CDA U-value is about three standard deviations higher, a significant difference. The single-glazed CSA window has about twice the U-value of CDAT, as one would expect.

The single, glaring exception to this picture is the CDLAT measurement. This is a low-emissivity window, and the measured value has a low experimental uncertainty. One would expect a value lower than that of CDAT, yet the measured value is higher. This clearly anomalous result led to further tests, and is discussed at some length below.

4.3.1 Comparison to Laboratory Measurements and WINDOW-2.0 Calculations

After completion of MoWiTT testing, BPA sent the test windows to a commercial test laboratory, where an AAMA-1503 standard(3) hotbox U-value measurement was made on each. In Table 5 the MoWiTT measured values are compared to the values obtained from these tests. For comparison, test values for windows of the same type published by the City of Seattle (2) are also shown for three of the windows.

The MoWiTT measurements do not agree very well with the raw test laboratory values. However, a quantitative comparison must take into account the difference in environmental conditions between the test laboratory and the field. As discussed in Section 4.3.3, both the wind speed and the outdoor radiant temperature during the MoWiTT field tests differed substantially from those in the laboratory test. In the adjacent column of the table the laboratory measurements have been adjusted to apply for the exterior film coefficients and radiative temperatures applicable to each MoWiTT measurement, using the formulas given in Section 4.3.3. For all windows except CDLAT, the adjusted values and the MoWiTT measurements are in excellent agreement within the experimental errors in the latter. We note, however, that the adjusted test laboratory value for CDA is some 2.2 standard error units below the MoWiTT value. The results for CDLAT are discussed in Section 4.3.2.

Table 5

Comparison Between MoWiTT Measured U-Values,
Laboratory Measurements and Published Values

Sample	Orientation	Published Value BTU/(hr ft^2 F)	Test Laboratory Measurement BTU/(hr ft^2 F)	Test Laboratory Measurement Adjusted to Expt'l Conds. BTU/(hr ft^2 F)	MoWiTT Measurement BTU/(hr ft^2 F)
CDAT	South	0.49	0.54	0.49	0.42 ± .04
	North			0.47	0.47 ± .04
	West			0.49	0.55 ± .10
	East			0.47	0.46 ± .08
CDW	South	0.41	0.41	0.40	0.46 ± .06
CDA	West	--	0.57	0.51	0.64 ± .06
CSA	East	--	1.22	0.86	0.87 ± .09
CDLAT	North	0.33	0.40	0.36	0.53 ± .03

A similar picture emerges when the MoWiTT measurements are compared with calculated values. Table 6 compares the MoWiTT measurements with calculated values obtained with the program WINDOW-2.0(4) under two alternative sets of assumptions. In the first column, the value presented was computed with the ASHRAE standard conditions, including a 15 MPH wind speed. As can be seen, the agreement between these values and the measured ones is not very good. In the second column, the WINDOW-2.0 calculation was carried out for the experimental conditions. In order to make these calculations, the normal exterior film coefficient calculation in WINDOW-2.0 was replaced with a slightly modified form of Equation 4. The film coefficient was taken to have the wind dependence of Equation 4, but the constant term was instead taken to be the sum of the temperature-dependent turbulent natural convection and radiative film coefficients. Since WINDOW-2.0 assumes that the outdoor radiative temperature is equal to the air temperature, a further correction for this effect was made using Equation (3) in Section 4.3.3.

Table 6

Comparison of MoWiTT Measurement with U-values

Calculated under Various Assumptions

Sample	Orientation	WINDOW-2 Assuming ASHRAE Standard Conditions BTU/(hr ft^2 F)	WINDOW-2 Assuming Experimental Conditions BTU/(hr ft^2 F)	Including Frame Correction BTU/(hr ft^2 F)	MoWiTT Measurement BTU/(hr ft^2 F)
CDAT	South	0.50	0.46	0.48	0.42 ± .04
	North		0.44	0.46	0.47 ± .04
	West		0.48	0.50	0.55 ± .10
	East		0.46	0.48	0.46 ± .08
CDW	South	0.50	0.48	0.42	0.46 ± .06
CDA	West	0.51	0.48	0.65	0.64 ± .06
CSA	East	1.13	0.81	0.93	0.87 ± .09

These calculations, presented in the second column of the table, are considerably closer to the MoWiTT measurements than are the values for ASHRAE standard conditions, as one might expect. However, both sets of calculations apply to the central part of the glazing unit only. We next corrected the WINDOW-2.0 calculation under the experimental conditions for the parallel frame conductance. We used the frame cross sections in Figure 6. For the wood window a simple one-dimensional calculation was done for each section of the frame (which varies in thickness). For the aluminum windows we assumed that all aluminum sections are isothermal and used the thermal conductivity of the thermal break material supplied by the manufacturer. In addition to the experimental exterior film coefficient, we used for the interior film coefficient a value of 1.39 ± .24 BTU/(hr ft^2 F), which is derived from the same set of data used to obtain Equation (4).

The result of this calculation is presented in the third column of Table 6. The agreement with the measured results is good; if the frame corrected values are the true ones, then there is an 83% probability that a set of seven measurements would differ from them, purely due to statistical fluctuations, by more than do the MoWiTT measurements. By contrast, if the ASHRAE standard condition values were the true ones, the probability of a deviation equal or greater than that of the measurements is less than 1%.

Both the exterior film coefficient (including the effect of outdoor radiant temperature) and the frame conductance are significant, as can be seen from the table. For the CDAT window the frame correction has little effect because fortuitously the sealed-insulating glass unit and the frame have approximately the same conductance. For other windows the frame effect is larger, notably for CDA, where the difference between the central-glazing U-value and the overall U-value is some 2.8 times the experimental error. In all the calculations in Table 6 the effect of the aluminum edge spacers in the sealed-insulating glass units was included, although in most cases it is negligible (less than .01 BTU/(hr ft^2 F)).

The same calculational method was used to predict the values to be expected for the test laboratory measurements, and these are compared with the measured values in Table 7. Agreement between the measured and calculated values is quite good (within .04 BTU/(hr ft^2 F)) for all windows except CDA. There the difference of .07 BTU/(hr ft^2 F) is difficult to understand. On the one hand, the sealed-insulating glass unit in CDA is nearly the same as that in CDAT (the gap width is slightly smaller), while on the other hand the frame is nearly identical to that of CSA, as can be seen from Figure 6. For both of these windows the calculations and the test laboratory measurements agree. If either the central glazing or the frame U-value calculation were wrong for CDA, the corresponding calculation should also disagree with the test laboratory measurement for either CDAT or CSA, respectively.

It might be possible to understand a measured U-value which was higher than the calculated one, since the frame calculation employed here is one-dimensional, and one might suggest that in the case of CDA, with its well-insulated sealed-insulating-glass unit and conductive frame, two-dimensional heat conduction degrades performance more than would be accounted for by the one-dimensional calculation. However, the measured value is smaller than the calculated one. We can conceive of no way in which two-dimensional heat conduction could reduce the effective U-value of the frame. It is also worth noting that in Table 5 the adjusted test laboratory value falls some 2.2 standard error units below the

MoWiTT measurement (which does agree with the calculation). There is a 15% probability of such a deviation occurring through random statistical fluctuations, so this difference is suggestive rather than conclusive.

Table 7

Comparison of Frame-Corrected WINDOW-2.0 U-value Calculation with Test Laboratory Measurements

Sample	Calculated U BTU/(hr ft^2 F)	Test Laboratory Measurement BTU/(hr ft^2 F)
CDAT	0.53	0.54
CDW	0.45	0.41
CDA	0.64	0.57
CSA	1.20	1.22

The combination of the disagreement with the WINDOW-2.0 calculation together with the disagreement with MoWiTT for CDA at least raises the question of whether there is some experimental circumstance which makes the AAMA test procedure measure a systematically low U-value when the frame conductance is considerably higher than that of the glazing unit. We can suggest one such possibility. In the AAMA-1503 test method a simulated 15 MPH wind is blown perpendicularly onto the test specimen. The incident flow is adjusted so that the measured exterior film coefficient is correct for a *planar* calibration specimen. During the test the air flow near the window is driven by what is in reality a turning flow. In an idealized geometry one might think of a flow which stagnates at the center and flows radially outwards. If, due to the window frame geometry, there were flow separation near the frame such that the effective film coefficient there were considerably lower than the average, then the result would be to underrepresent the high-conductance frame.

In summary, the WINDOW-2.0 calculations are in excellent agreement with the MoWiTT measurements of U-value provided that the actual wind speed and outdoor radiant temperature are properly taken into account, and that a simple approximation to the actual *frame properties is used.* For three of the windows the test laboratory measurements also agree with both the MoWiTT measurements and the calculations when these effects are taken into account. There is a suggestive difference between the test laboratory and MoWiTT measurements for CDA, and for this window the calculations and test laboratory measurements do not agree.

From the rms difference between the MoWiTT measurements on the one hand and the raw test laboratory measurements and ASHRAE-condition WINDOW-2.0 calculations on the other, we estimate that for the double-glazed windows uncertainties on the order of 0.06 BTU/(hr ft^2 F) would result if the latter were used without correction to field conditions. For single- glazed windows the uncertainty would be larger, up to .30 BTU/(hr ft^2 F).

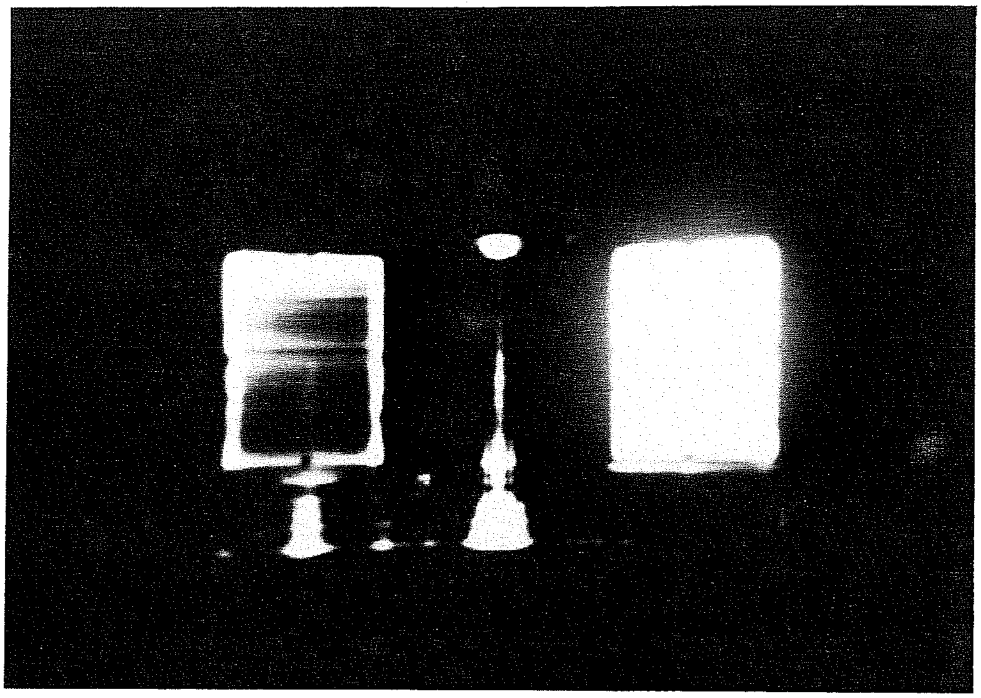
4.3.2 Results for the Low-Emissivity Window

The CDLAT U-value measurement contrasts sharply with the general agreement above. The MoWiTT measured value of 0.53 ± .03 BTU/(hr ft^2 F) is some 5.3 standard error units above the adjusted test laboratory value in Table 5, indicating complete disagreement. If one carries out the calculation of Table 6, the expected (frame-corrected, experimental-condition) U-value is 0.33, some 6.7 standard error units below the measurement. Moreover, the measured CDLAT U-value is higher than the simultaneously-measured CDAT U-value by some 2 standard error units. This seemed a paradox, because the CDAT and CDLAT windows were designed to have identical frames: aluminum with a thermal break. Therefore, the two windows should be identical except for the presence of the low-emissivity coating. Yet previously studied frameless, sputter-coated, low-emissivity, sealed-insulating glass units were judged to be consistent with the WINDOW-2.0 predictions(5), with some minor questions about the correctness of the wind-speed correlation used in the computer code. Degradation of the coating could, of course, make the U-values for the two units equal, but in no case should that of CDLAT be higher.

To resolve this paradox, the CDAT/CDLAT tests were rerun during July. To achieve a sufficiently large indoor-outdoor temperature difference to make nighttime heat flows large enough for accurate measurement, both calorimeters were run at an elevated temperature (86ºF). While not providing a realistic field-measured U-value, this method did allow us to study the relative thermal conductance of the two windows.

Infrared photographs of the two windows are shown in Figure 30. These photographs, along with glass surface temperature measurements taken at the same time, confirm that the low-emissivity sealed-insulating glass unit is functioning as expected. Closer examination of the two window units revealed a small but significant difference. In the CDAT unit there was a thick foam spacer between the inner side of the sealed-insulating glass unit and the aluminum frame, as shown in Figure 6(a) and in Figure 31. In the CDLAT unit the sealed-insulating glass unit was somewhat thicker and this spacer was absent, as shown in Figure 6(b). The absence of the spacer allows a conductive heat path through the aluminum spacer of the sealed-insulating glass unit to act as a thermal short circuit in parallel with the frame thermal break.

If the thermal break in CDLAT is assumed to be ineffective, creating essentially a non-thermally-broken frame, then the calculated U-value for the MoWiTT measurement a



b

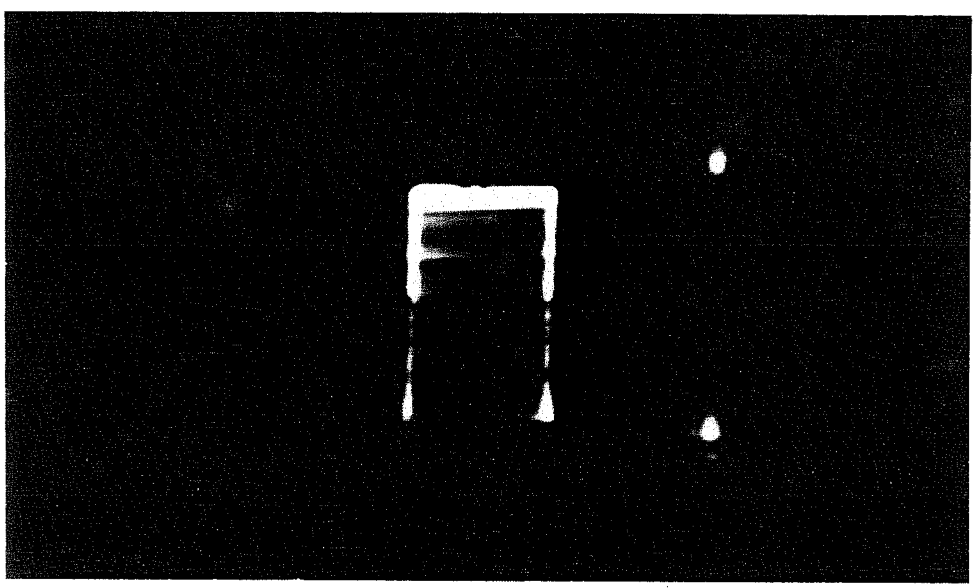


Figure 30. Thermal infrared photographs of CDAT and CDLAT, taken from the exterior side. The inside air temperature is some 25ºF higher than the outdoor temperature. (a) The bright square of CDAT (right) indicates a relatively uniform elevated surface temperature, while CDLAT (right) shows a cool sealed-insulating-glass unit surrounded by a warmer frame. One infers from this that the CDLAT glazing has a considerably higher thermal resistance than that of the CDAT. (b) A higher-temperature-resolution view of the CDLAT unit shows nonuniform temperatures around the frame, with highest temperatures at the top.

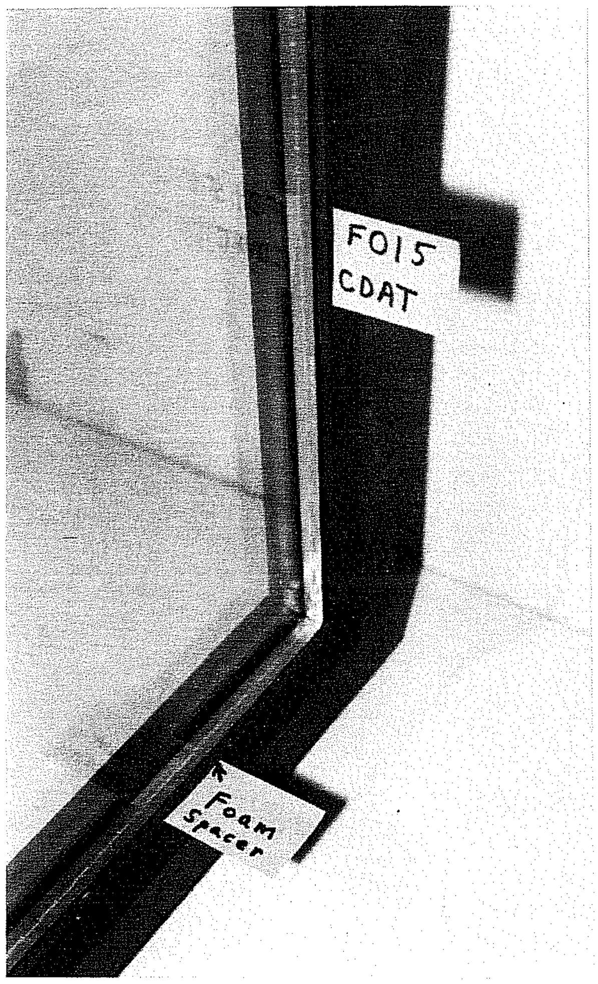


Figure 31. Interior side of the CDAT window. A close inspection of the window revealed the indicated foam spacer, which is absent in the CDLAT window.

conditions is 0.47 BTU/(hr ft^2 F), in reasonable agreement with the measurement. The difference is two standard error units. The probability of occurrence of such a deviation is 17%.

This effect should also have appeared in the test laboratory measurement. In Table 8 we compare the test laboratory and MoWiTT measurements with the calculated values assuming the presence or absence of the thermal break. The two measurements lead to quite contradictory conclusions. The MoWiTT measurement is consistent with the assumption of no thermal break and inconsistent with the assumption of a thermal break, while for the test laboratory measurement the reverse is true.

Table 8

Comparison of Calculation, Laboratory and MoWiTT Measurements for Low-emissivity (CDLAT) Window

Calculation Assumptions	Test Laboratory [BTU/(hr ft^2 F)]		MoWiTT [BTU/(hr ft^2 F)]	
	Calculated	Measured	Calculated	Measured
Thermally-broken Frame	0.41	0.40	0.33	0.53 ± .03
Thermally-unbroken Frame	0.64		0.47	

We have considered the possibility of a systematic error in the MoWiTT measurements. However, after carefully checking our calibration we retested the CDLAT window in February, 1988 and obtained essentially an identical result, 0.52 ±.01 BTU/(hr ft^2 F).

We note that the effect suggested in Section 4.3.1 to explain the low test laboratory value for the CDA window would also explain a low test laboratory result in this instance. If a local film coefficient at the frame is chosen to make the calculation and measurement agree for CDA, then the corresponding calculated value (assuming thermally unbroken frame) for the CDLAT test laboratory U-value drops from 0.64 BTU/(hr ft^2 F) to the range 0.46-0.49 BTU/(hr ft^2 F).

In summary, there is a consistent picture of the CDLAT window performance given by the MoWiTT U-value measurement, the infrared photographs, the glass surface temperature measurements, the CDLAT frame detail, and the WINDOW-2.0 calculations. This picture is that the CDLAT performance is degraded by a frame which contains a thermal short circuit around the thermal break. We find the bulk of the evidence persuasive that this is the correct picture of the way in which the CDLAT window performed under the MoWiTT field conditions. We do not fully understand why the window appears to perform differently under test laboratory conditions, but note that the comparison with calculations indicates a similar difference in performance for the CDA window. Our picture of the CDLAT window performance can be made marginally consistent with the laboratory measurements if it is assumed that the local exterior film coefficient is preferentially low at the frame during the laboratory test. Additional research would be necessary to determine whether this is in fact the true explanation.

4.3.3 Sky Temperature and Wind

Theoretically, U-values may be affected by sky temperature, and it is interesting to ask whether our observation of constant nighttime U-values is consistent with this expectation. One would expect a dependence of the form

$$U_{EFF} = U_0 \left[1 + \gamma \frac{T_O - T_R}{T_I - T_O} \right] , \qquad (3)$$

where U_{EFF} is the U-value as measured, U_0 is the U-value as normally defined, T_R is the outdoor radiant temperature for the hemisphere viewed by the window, and γ is the ratio of the radiant surface heat transfer coefficient to the total exterior film coefficient. We refer to the ratio of temperature differences in Equation 3 as the fractional sky temperature depression. For our nighttime U-value runs γ had a value in the range 0.36 - 0.44. The magnitude of the average fractional sky temperature depression was in the range 0.12 - 0.37. The resulting corrections to the U-value vary from 9% to 16%. Since during the nighttime measurements the variation of the sky temperature from the mean was considerably smaller, the consequent variations in U-value from the mean were less than our experimental uncertainty. Thus, it is not surprising that we observed no correlation between changes in the U-value and changes in the outdoor radiant temperature.

Wind also had little effect on the instantaneous (as opposed to the average) measured U-values. Table 9 shows that, while overall wind speeds were moderate, there is a definite tendency for nighttime wind speeds to be low. This observation is reinforced by examination of the hourly average wind speed plots A.1.6, A.2.6, A.3.6, and A.4.6 in the Technical Appendix. Low overall winter wind speeds, with nighttime speeds lower than daytime is typical of Reno. From other experiments with the MoWiTT we have determined that the exterior film coefficient is given by

$$h_0 = 1.28 + 0.056\, V_{WIND} \qquad \left[\frac{BTU}{hr\, ft^2\, F} \right] , \qquad (4)$$

where V_{WIND} is in miles per hour and blows into the leeward hemisphere. (We have as yet no data for the windward hemisphere.) The intercept in this formula is consistent with the sum of radiation and turbulent natural convection. The formula applies to most of the nighttime U-value data (for which the wind speed is either low or in the leeward hemisphere), and has been used in correcting calculated values to experimental conditions.

Table 9

Observed Nighttime and Daytime Mean Wind Speeds

Sample Orientation	Nighttime Wind Speed MPH	Daytime Wind Speed MPH
South	3.5	5.6
North	6.6	7.9
West	2.5	5.6
East	4.2	7.8

Because of the low average wind speed, it is not surprising that wind has little effect on the nighttime instantaneous U-values. However, a few nights with high wind speeds did occur. In Figure A.2.6 in the Technical Appendix it can be seen that night 5 (3/18/87) had nighttime wind speeds of around 15 MPH, while on night 4 wind speeds were quite low. Yet as can be seen from Figure A.2.11 the measured U-values for CDAT on nights 4 and 5 were the same. Similar remarks hold for the other night with consistently high wind speed, night 4 in Figure A.4.6, as compared with night 6, a low-wind-speed night. The corresponding U-values in Figures A.4.11 and A.4.12 again fail to show any increase in U-value with wind speed. While the finite time constant of the calorimeters will not respond to very rapid and transient wind gusts, on these nights the *nighttime average* wind speeds were quite different. This absence of the expected wind speed dependence is puzzling, and will need further study.

The net effect of a diurnal variation of wind speed at Reno is that the average annual or seasonal wind speed which appears in weather publications does not resemble the actual average conditions for a window at a particular time of day. Since window performance is highly time-dependent, as Figure 8 and the corresponding figures in the Technical Appendix show, and since window heat loss may be much more or less detrimental at different times of day, depending on the type of building, its occupants, and their activities, specific time-of-day performance is needed. If, as in Reno, use of average wind speed is not a correct guide to specific performance, substantial error in energy demand calculations is possible.

In retrospect, the diurnal correlation in Reno is expectable. Without weather fronts, wind is caused by spatial temperature gradients which arise ultimately from solar heating of the ground during the day and radiative cooling at night. Thus, some kind of periodic diurnal pattern is natural. The question is whether similar wind/time correlations exist in other locations, a possible subject for future research.

4.4 Daytime U-Values

The above discussion of the difficulty of obtaining accurate nighttime U-values should clarify why, in the fitting process described in Section 4.2, the nighttime U-values were not obtained by fitting Equation (1) to the unselected data. The fits, in turn, yield the effective daytime U-values in Table 10, where we also list for comparison the observed nighttime values.

Table 10

Daytime U-Values Obtained from Fits Compared to Measured Nighttime U-Values

Sample	Orientation	Daytime U BTU/(hr ft^2 F)	Nighttime U BTU/(hr ft^2 F)
CDAT	South	0.55	0.42 ± .04
CDW	South	0.76	0.46 ± .06
CDAT	North	0.49	0.47 ± .04
CDLAT	North	0.54	0.53 ± .03
CDAT	West	0.71	0.55 ± .10
CDA	West	0.65	0.64 ± .06
CDAT	East	0.24	0.46 ± .08
CSA	East	0.84	0.87 ± .09

It is difficult to give these values a consistent physical interpretation. For the two north-facing data points the daytime U-values are reasonably consistent with the nighttime. Since for this case the solar gain absorbed by the glass is small, the situation is comparable to the nighttime one in terms of the physics of thermal heat transfer., The difference between the 6.6 MPH mean nighttime wind speed and the 7.9 MPH mean daytime wind speed produces a negligible difference in U-value. For the other orientations, where the amount of solar gain absorbed in the glazing may not be negligible relative to the heat flows due to thermal transmission, no consistent pattern is observed. For the CDAT window, two of the fits give a much higher U-value than the nighttime, while the third is much lower. While these effects could be statistical artifacts of the fitting procedure, it is also possible that the basic assumption of Equation (1)--that U is quasi-constant and independent of the solar intensity--may not be valid during the daytime. Additional research will be necessary to settle this point.

4.5 Solar Heat Gain Factors

The measured solar heat gain factors, F, obtained from the fits described in Section 4.2 are shown in Table 11. Also shown are the predicted value calculated using WINDOW-2 for the actual conditions of measurement. The table shows the expected value to be identical for all of the clear double glazed windows except those in north-facing orientation, where the radiation is completely diffuse. This represents a considerable oversimplification for the east- and west-facing orientations, but the quality of the measured data does not merit a more exact treatment.

Table 11

Measured Solar Heat Gain Coefficients Compared with Window-2 Calculations

Sample	Orientation	Measured F	Window-2 Calculated F
CDAT	South	0.81	0.76
CDW	South	0.85	0.76
CDAT	North	0.68	0.66
CDLAT	North	0.66	--
CDAT	West	0.72	0.76
CDA	West	0.76	0.76
CDAT	East	0.76	0.76
CSA	East	0.92	0.85

Although the statistical error of the fitting process is quite small, we do not yet know the experimental uncertainty to be attached to these measurements. However, if we assume that in the south, west, and east orientations the CDAT window has the same F value (which would be predicted by WINDOW-2.0), then the scatter of the measured data gives an estimate of the error. Computing the mean and standard deviation of the measured values for this window, we obtain a value of 0.74 ± .05, in good agreement with the expected value of .76. This implies that our experimental uncertainty is 0.05, indicating that the other measurements (CDW, CDA and CSA) are also in agreement with the WINDOW-2 calculations. The uncertainty derived in this manner is 6%. This is a good first attempt; additional instrumentation studies will be required to locate the source of this uncertainty and improve matters.

4.6 Overall Diurnal Performance

We have discussed comparisons between a single type of performance, either thermal or solar. However, as Figure 8 clearly indicates, in the course of a daily cycle both influences play a role, and during the winter season they are opposing roles.

The effect of these two opposing influences in comparing the net effect on energy usage of two alternative windows is illustrated in Figure 32, which presents a comparison of the measured net heat flows through single and double glazing (CDAT and CSA). While this figure, since it does not represent heating season performance, is not directly quantitative, it does illustrate the issues that enter into determining quantitative performance differences.

It can be seen from Figure 32 that the CDAT window represents a smaller heat loss at night, and hence an improvement. However, it also represents a decrease in solar gain during the daytime. To the extent that the solar gain is useful in offsetting heat losses elsewhere in the building and does not cause associated effects such as glare, furniture fading, etc., which are objectionable or detrimental to occupants, the reduction in solar gain will offset the improvement resulting from reduction in nighttime U-value.

These differences become more apparent in Figure 33. In the title of this and succeeding figures, "base unit" always refers to the CDAT window. A negative value on the vertical axis represents a loss when the base unit is replaced with the candidate window (here CSA), and a positive value represents an improvement. Here, as expected, replacing CDAT with CSA represents a backward step at most times during the day; however, for a few hours during the morning (note east-facing orientation) there are large gains which may upset a quantitative calculation of the advantages of CDAT over CSA.

Figure 34 presents the more interesting difference in wintertime performance between south-facing CDW and CDAT windows. Here the nighttime effect of replacing CDAT with CDW is neutral, but the daytime effect is strongly detrimental, since the CDW window has a smaller glazed area.

In Figure 35 the early March comparison between CDAT and CDLAT shows that replacing the former with the latter would be detrimental. This is not surprising, since our tests showed the CDLAT window to have a poorer U-value and a lower solar heat gain coefficient.

We believe, as explained earlier, that this results from frame design. To avoid a false impression of the effect of low-emissivity coatings, we present in Figure 36 the results of earlier measurements (5) comparing frameless clear double and low-emissivity sealed insulating glass units. The low emissivity coating produces an effect qualitatively similar to

Figure 32

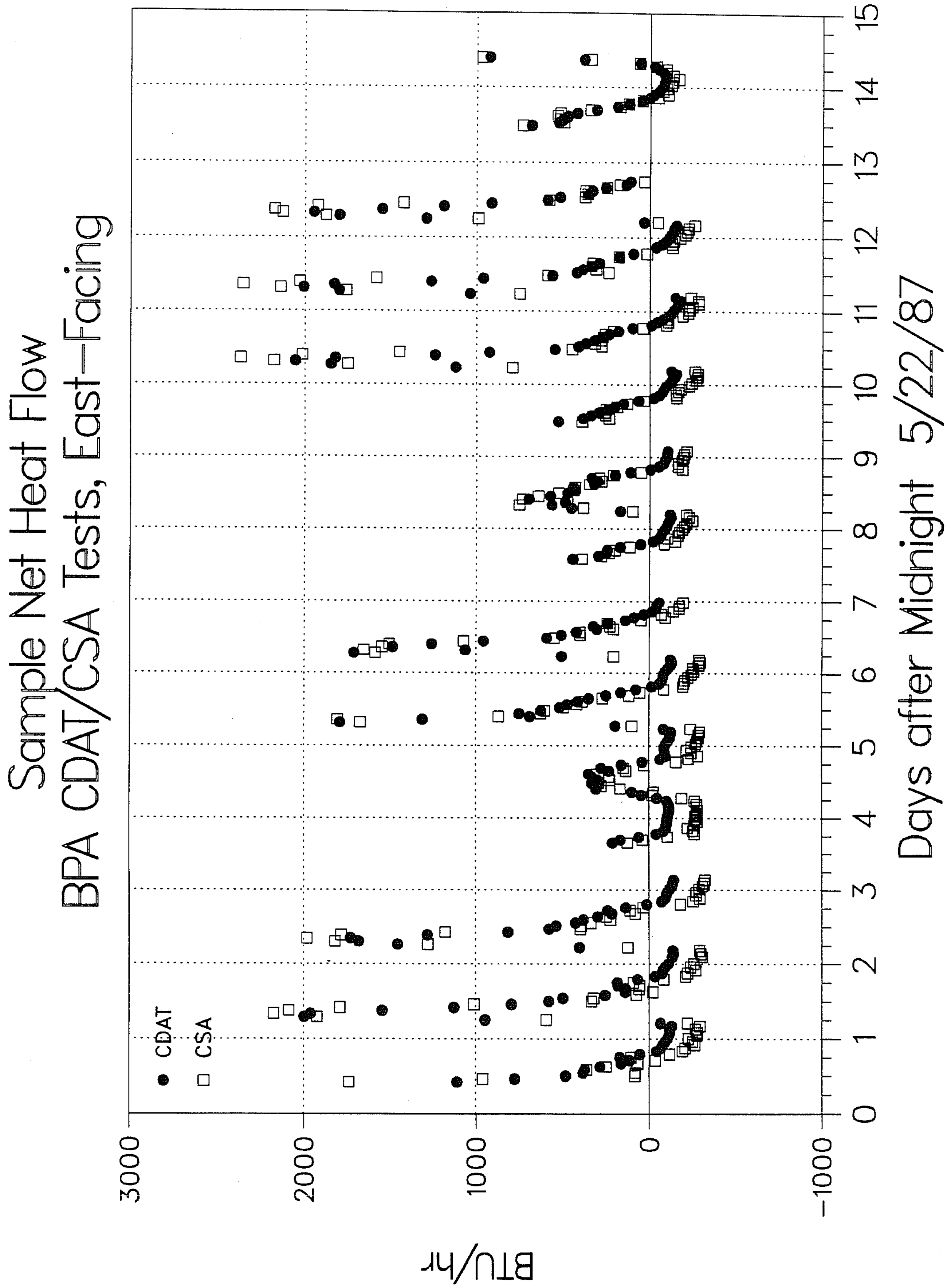
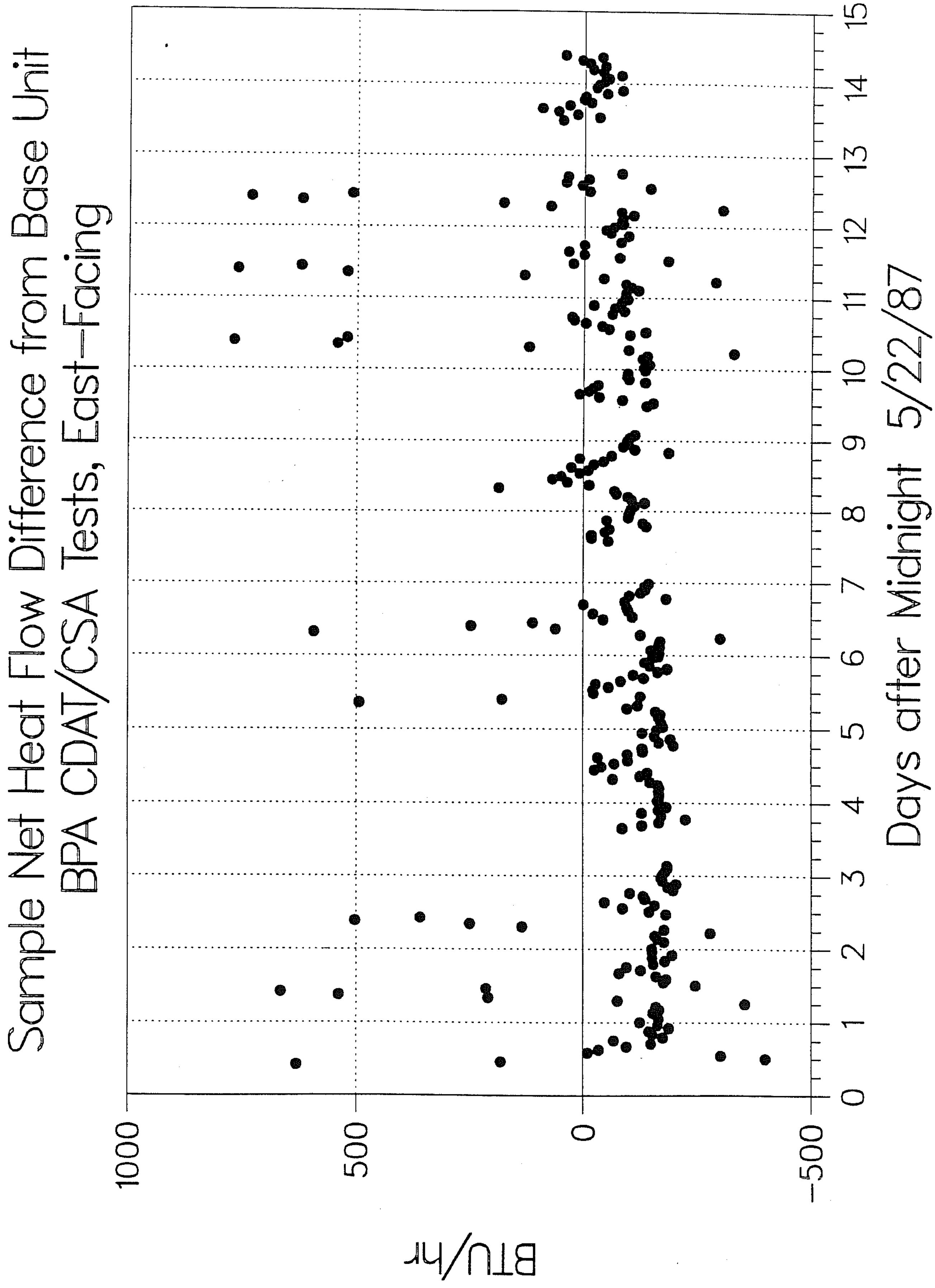
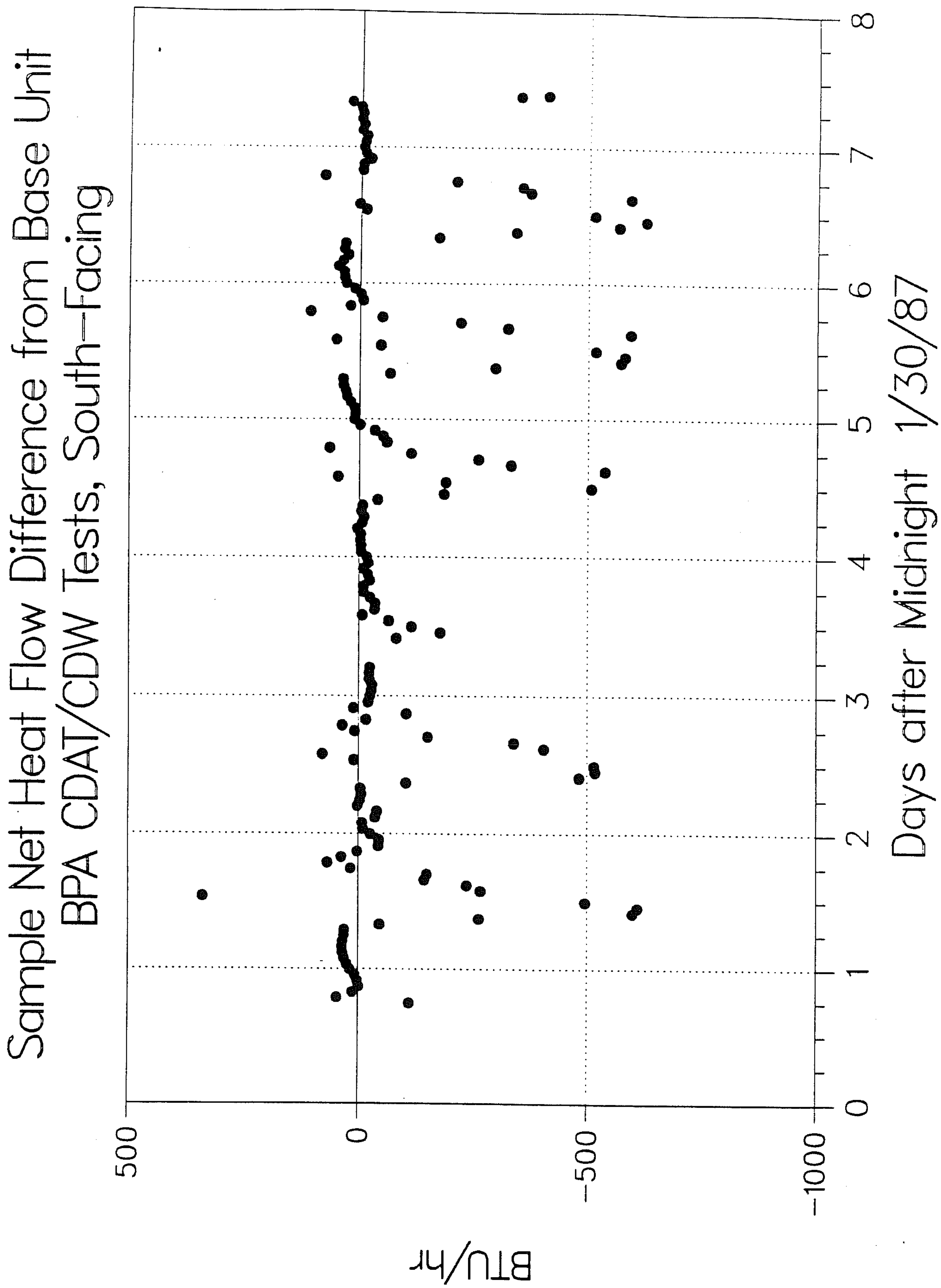

Sample Net Heat Flow
BPA CDAT/CSA Tests, East-Facing
BTU/hr
Days after Midnight 5/22/87
CDAT
CSA
3000
2000
1000
0
-1000
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15

Figure 33



Sample Net Heat Flow Difference from Base Unit
BPA CDAT/CSA Tests, East-Facing
BTU/hr
1000
500
0
-500
Days after Midnight 5/22/87
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15

Figure 34



Sample Net Heat Flow Difference from Base Unit
BPA CDAT/CDW Tests, South-Facing
BTU/hr
500
0
-500
-1000
0
1
2
3
4
5
6
7
8
Days after Midnight 1/30/87

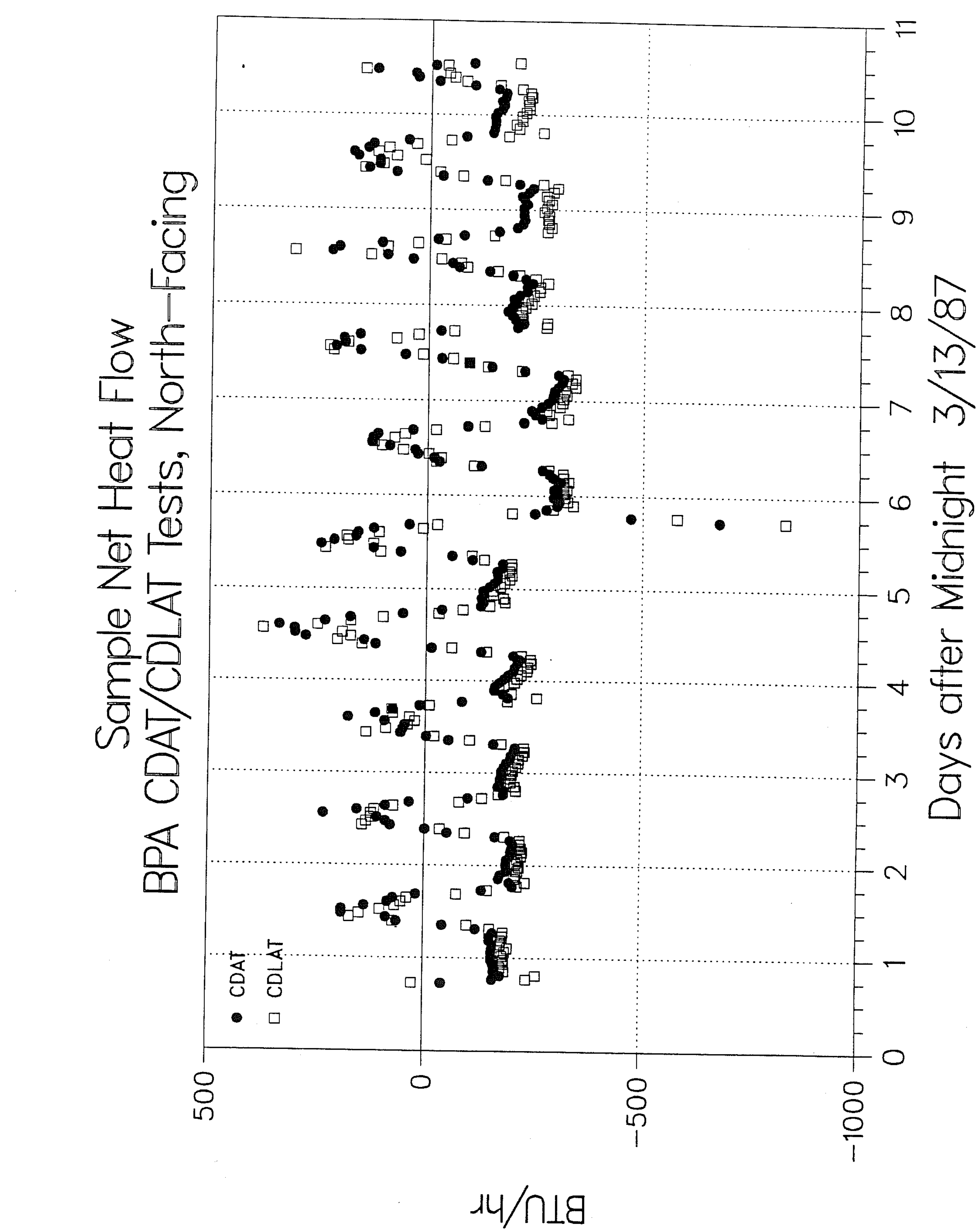
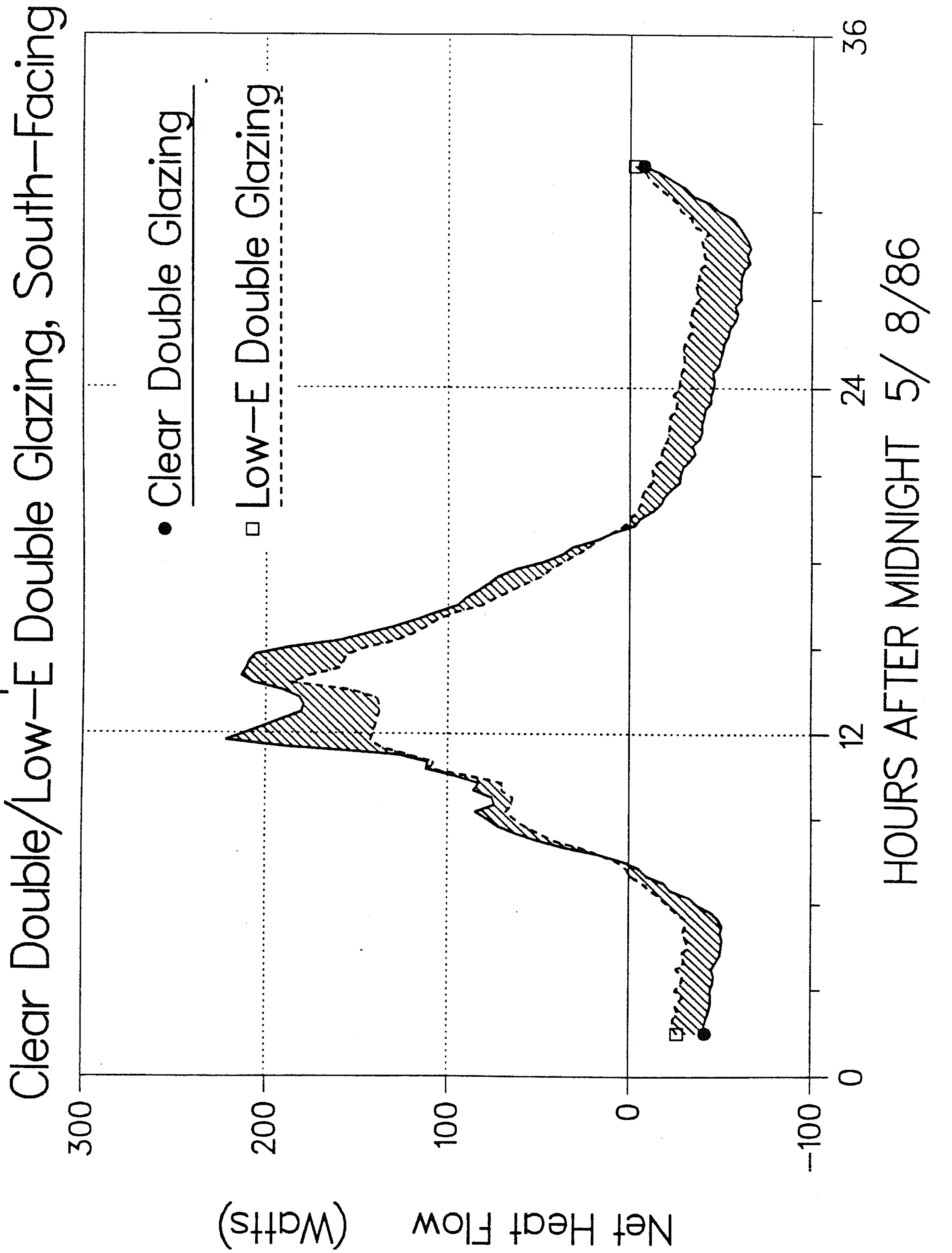

Sample Net Heat Flow
BPA CDAT/CDLAT Tests, North-Facing
Days after Midnight 3/13/87
BTU/hr
CDAT
CDLAT
500
0
-500
-1000
0
1
2
3
4
5
6
7
8
9
10
11

Figure 36


Sample Net Heat Flow
Clear Double/Low–E Double Glazing, South–Facing
Clear Double Glazing
Low–E Double Glazing
Net Heat Flow (Watts)
300
200
100
0
–100
0
12
24
36
HOURS AFTER MIDNIGHT 5/ 8/86

adding an extra glazing layer: decreased thermal losses at night and decreased solar gain during the day.

These plots make several points about the energy impact of windows:

(1) Most improvements in window U-value also reduce the amount of solar gain of the window.

(2) During the heating season, the solar gain is beneficial, provided its comfort and other effects (including local heating and glare) are acceptable to the building occupants.

(3) Hence, a correct evaluation of the effect of a U-value improvement must also include a correction for the offsetting loss of beneficial solar gain; i.e., a determination of net energy performance.

(4) This determination is both orientation and climate dependent.

Before proceeding to a more quantitative discussion, point (4) necessitates comparison of the Reno measurements with conditions in the Pacific Northwest.

5 Discussion

5.1 Comparability of the Test Weather Conditions to the BPA Service Area

To evaluate the degree to which the data reported here is representative and to discuss the climate-dependent comparison between nighttime heat loss and daytime solar gain, it is first necessary to determine whether the measurement periods fairly represent conditions encountered in areas important to BPA. Wind has already been mentioned in the discussion of U-values. There are three reasons why we believe our observations of much lower wind speeds, and hence somewhat lower U-values, may be applicable: (1) The observed day/night pattern of high/low wind speeds results from widespread solar effects, which may well occur elsewhere. An examination of monthly mean hourly wind-speed profiles would settle this. (2) Part of the low wind-speed effect results from the height effect: windows in single-story buildings are typically subject to lower wind speeds than are measured at the standard weather tower height of 10 m. (3) Although the average winter wind speed in Reno is lower than that in Seattle, Portland, and Spokane (it is higher than Missoula's), the MoWiTT's location in flat, open terrain partly compensates for this; an urban location would have greater terrain roughness, leading to lower local wind speeds. (The wind speed data appearing in climatological data tables is typically measured at airports.)

For climate-dependent comparisons, only the cold-weather south- and north-facing data periods are of interest. Table 12 compares the temperature and solar conditions of these two test runs with the most comparable months in Seattle, Portland, Spokane and Missoula. It shows Reno characterized by a greater temperature swing than any of these cities; its daytime highs are comparable to winter days in Portland and Seattle, while its nighttime lows are more comparable to those in Spokane and Missoula. Thus, a measurement of the twenty-four-hour average winter net energy flow would give a somewhat lower result for Reno than for Portland and Seattle, and a somewhat higher one than for Spokane and Missoula. While Reno tends to have more sunny days, our measurements can be accommodated to this difference, since days may be separated and treated individually.

Table 12

Comparison of Weather Conditions for MoWiTT Test with Major Population Centers in BPA Service Area

Location	Month	Temperature Mean ºF	Temperature Low/High ºF	Wind Speed MPH	Horizontal Solar % of Poss.	Fraction of Days Clear	Fraction of Days Cloudy
Reno (MoWiTT test)	Feb	37	27/47	4.6	66	.80	.20
Missoula (1984)	March	40	32/48	6.4	65	.16	.84
Reno (MoWiTT test)	March	35	25/47	8.0	78	.71	.29
Seattle (1984)	Dec	37	32/42	8.8	27	.26	.74
Portland (1984)	Dec	38	34/43	9.5	22	.19	.81
Spokane (1984)	Feb	35	28/41	7.8	39	.24	.76

Since U-values depend only weakly on temperature, the nighttime temperature range of the MoWiTT measurements should adequately represent any of the BPA cities. Given the greater frequency of cloud cover in the BPA region, it appears likely that the outdoor radiant temperature would be closer to the outdoor air temperature than it is in Reno. As noted above, this could cause at most a 10% shift in the U-value.

In principal, the difference in latitude between Reno and the Pacific Northwest could affect the solar heat gain factor measurements. However, this effect is likely to be important only during the summer. For the winter south-facing data the solar incident angle is relatively low, where glass optical properties are insensitive to angle. The difference in solar altitude due to latitude should therefore not cause an appreciable difference in transmission or reflection. For the east- and west-facing orientations the sun moves over a very large range of incident angles in the course of a day; the small difference in trajectories due to latitude should not be important. And, of course, the north-facing data should be independent of latitude.

In summary, we expect the MoWiTT measurements to be reasonably representative of conditions in the BPA service area, except where issues of trading off solar gains and nighttime heat losses is concerned. There caution must be exercised to insure that the result is not biased by the greater frequency of clear weather in Reno.

5.2 Examination of Net Performance Calculations for a Prototypcial Day

We return to consideration of Figures 8 through 13 characterizing a particular day (March 20, 1987) from our data which, arguably, may represent any of the four cities mentioned. Its low solar flux (Figure 12) would not be atypical in any of them. While it was colder at night than normal in Portland or Seattle, temperatures this low do occur in both cities.

We first note that the window was a net energy gainer during the daytime. If this is true, then certainly comparable (double-glazed) windows in Portland and Seattle, which have similar daytime temperatures and at least as much solar gain, are also daytime energy gainers. Next, we consider four alternative sets of assumptions for calculating the energy impact of the window: First, we do a degree-hour calculation using the measured average U-value and ignoring solar effects altogether. This corresponds to a common calculation of window performance for the purpose of evaluating improvements. Second, we do a degree-hour calculation assuming the U-value is larger by 0.07. The difference between this calculation and the first one represents the effect of using the ASHRAE U-value in place of the value obtained in the MoWiTT measurement. Third, we add up the actual thermal losses, but do not count any net gain. This might correspond to a window completely shaded, because of a desire for privacy or perhaps shading device mismanagement. Fourth, we integrate the net energy flow over a twenty-four hour period. This might correspond to the situation of an unshaded window in a residence.

Table 13 shows the results of this calculation. The four sets of assumptions can be seen to produce answers which differ by up to 38 % (using case 1 as the base). In particular, the differences among the first, third and fourth assumptions are up to twice as large as the difference between the first and second. Of course, for the south-facing window also listed in the table the solar gain effects are much larger.

Table 13

Calculated Window Daily Net Energy Flow for Selected Days under Various Assumptions

Day	Assumptions	Net Energy Flow BTU (Losses are Negative)
March 20, 1987, North-facing, Low solar gain, CDAT window.	(1) Degree day calculation, U=0.45	-4973
	(2) Degree day calculation, U=0.52	-5285
	(3) Measured Heat Flows, exclude gain	-3840
	(4)Measured Heat Flows, net	-2867
Feb. 4, 1987, South-facing, High solar gain, CDAT window.	(1) Degree day calculation, U=0.45	-4404
	(2) Degree day calculation, U=0.52	-5090
	(3) Measured Heat Flows, exclude gain	-2393
	(4)Measured Heat Flows, net	10740

This is a very conservative calculation, using a twenty-four hour period with a very cold night and low solar gain. Since the window faces north, it receives only diffuse solar gain. We believe that this measurement characterizes not only north-facing windows, but also shaded windows (*e.g.*, by overhangs) in other orientations, since diffuse solar gain is not strongly directional. While it is not surprising that solar gain is an important effect for unshaded south-facing windows--and by extension, for unshaded east- and west-facing windows--the significance of solar gain in north-facing and shaded windows is not generally appreciated. *This means that there are no windows for which daytime solar gain may be safely neglected in winter heating calculations.*

To summarize, for both of the prototypical days the different possible assumptions about the way to treat solar gain have a very large effect on the consequent window energy impact calculation--much larger than do questions of wind effects on U-value, or whether laboratory, field measurements, or ASHRAE U-value calculations give a more accurate representation. In addition, the third and fourth sets of assumptions were not arbitrarily chosen. The fourth represents a plausible picture of window performance in many rooms of a residence; the third represents reasonable, and, indeed, likely behavior of an office worker near a window on a sunny or bright-overcast day.

5.3 Implications for Standards and Performance Calculations

In a number of places in this work we have alluded to the considerable disparity in the magnitudes of solar gain and nighttime heat loss. In Section 4.2 we saw that the solar gain dominated the behavior of the fits to the data except in the north-facing orientation, when daytime solar gain and nighttime heat losses are of comparable magnitude. The same comparable magnitudes are also observed in the east and west orientations when the window is shaded, *i.e.*, afternoon in the east-facing and morning in the west-facing. In Section 4.3 great care was necessary to isolate the U-value measurements from residual solar effects, while in Section 4.4 the solar gain made extraction and interpretation of daytime U-values problematic. In Section 4.6 we saw that U-value improvements generally also reduce daytime solar gain somewhat, and that this must be taken into account in evaluating the effect of the improvement, while in Section 5.2 we saw that assumptions about the usefulness of solar gain have a major impact on estimates of the net daily energy cost to be attributed to a given window.

It would be useful to compare these effects in a consistent way. We will take U-value as a basis of comparison. In Section 4.3 we saw that field measured U-values differed from ASHRAE or test laboratory values by some .06 BTU/(hr ft^2 F) for double glazed windows and some 0.3 BTU/(hr ft^2 F) for single-glazed. We can take these values as a reasonable measure of the uncertainty to be attached to U-values taken from sources such as laboratory tests (*i.e.*, uncertainty about the actual value in application). In Section 4.2 we saw that for south, east and west facing, the rms deviation (due primarily to uncertainty in calculation of admitted solar gain) of Equation (1) from the data ranged from 130 to 236 BTU/hr. To cause an equal rms deviation would take a change in nighttime U-value of from 0.45 to 0.57 BTU/(hr ft^2 F). In other words, the inaccuracy due to use of Equation (1) with constant F is some 8 to 10 times bigger than that resulting from using test laboratory U-values without correction to field conditions. For north-facing orientation, which we have argued is also a reasonable estimate for shaded windows, the corresponding uncertainty of 82 Btu/hr is equivalent to a U-value uncertainty of 0.19 BTU/(hr ft^2 F), some 3 times larger than that which results from neglecting correction to field conditions. In Section 5.2 we saw that for a north-facing window during a twenty-four hour period reasonably representative of cloudy Pacific Northwest conditions, assumptions about inclusion of solar gain made a difference of 1133 to 2076 BTU, equivalent to a U-value uncertainty of 0.25 to 0.47 BTU/(hr ft^2 F), some 4 to 8 times the difference between laboratory and field conditions.

These considerations have immediate consequences for specifying energy-efficient windows. In order to evaluate the advantages of a particular window, it is necessary to calculate the winter heating cost and compare it to that of some base case window. It is clear from the preceding paragraph that in order to make meaningful calculations of this kind a consistent treatment of solar gain is necessary. Further, as we saw in Section 4.6, U-value improvements usually also reduce solar gain somewhat, and it is necessary to evaluate the net overall effect.

A window performance evaluation technique should be based on detailed energy use calculations by a building simulation program (e.g., DOE-2). In addition, it is necessary to make a consistent set of assumptions about the acceptability of solar gain (and possibly the attendant glare, local heating, furniture fading, etc.) and to use more sophisticated aperture treatments in the calculation than a constant F (which corresponds to a constant shading-coefficient in a building simulation model). In WINDOW-2 (with planned extensions in WINDOW-3.1 to make frame corrections) there is clearly a powerful technique for calculating U-values accurately, as the close agreement with the MoWiTT data in Section 4.3.1 shows. However, to exploit this accuracy properly will require improved information on exterior film coefficients and their relation to wind, height, and location, some knowledge of outdoor radiant temperatures, and detailed (but not extremely accurate) knowledge of window frame effects.

6 Conclusions

Continuous and accurate measurements of the net heat flow through five commercially available windows allowed a study of the overall diurnal performance and a near-instantaneous measurement of the nighttime U-value. It was found that fluctuations in the nighttime U-value with time were consistent with experimental uncertainties, so that the U-values were best characterized by a constant value over each (1-2 week) measurement period. This was due to the low variability of the nighttime wind speed and outdoor radiant temperature. The constant U-values determined depend on the average wind speed and radiant temperature during the measurement period.

Consistency between calculated values, laboratory and field measurements was obtained for most of the windows. The measured nighttime U-values are lower than would be predicted on the basis of standard ASHRAE design conditions or obtained from laboratory measurement, due to low observed values of the nighttime wind speed and differences between the outdoor air and radiant temperatures. *When WINDOW-2.0 calculations for the correct wind speed are adjusted for radiant temperature effects and specific frame conductances, there is excellent agreement with the MoWiTT measurements.* When wind and radiant temperature differences are taken into account there is also excellent agreement between the calculations, the MoWiTT data, and the test laboratory measurements except for the case where a highly conductive frame is combined with an insulating glazing (CDA). In this case the test laboratory value is systematically lower than the calculated value and the MoWiTT measurement, which agree.

A measured low-emissivity window was found to have a much higher U-value than expected. Infrared photographs and surface temperature measurements revealed that the sealed-insulated-glass unit was performing properly and led to discovery of a potential thermal short circuit in the frame. WINDOW-2.0 calculations based on the assumption of a highly conductive frame agree well with the MoWiTT measurements. The test laboratory value is inconsistent with this assumption. However, under this assumption the window would be a highly conducting frame combined with a highly insulating glazing, and a lower value obtained in the hotbox would be consistent with the discrepancy observed for CDA. A mechanism by which the hotbox test could produce such an effect has been suggested.

A standard simplified model using constant solar heat gain coefficient and constant (but different) day- and nighttime U-values fit the measured net heat flow to about 10%. The discrepancy arose mainly from the daytime solar gain. A more accurate prediction of daytime performance would require a more sophisticated modeling of the window than permitted by a single solar heat gain coefficient, since for many window orientations it is not possible to treat both beam and diffuse solar radiation adequately with the same window solar-optical properties. Values of the solar heat gain coefficient obtained by fitting the model to the measurements are consistent with WINDOW-2.0 calculations within the experimental uncertainty.

The daytime U-values obtained by adjusting the model to fit the measurements are not easily interpretable as physical parameters in a thermal heat transfer picture. This may result from experimental uncertainties or may be an indication that the basic assumptions of the simplified model are violated during the daytime. Further work would be necessary to determine which alternative explanation is correct.

A detailed examination of measured overall window performance points to the great importance of solar heat gain in the wintertime window energy budget. This is a point well known for south-facing glazing but not generally considered for other orientations. A double-glazed window under the Reno, Nevada test conditions was nearly always an energy gainer during the daytime for all orientations, even on overcast days or when the window was shaded from direct sunlight. Detailed comparison of Reno weather with that in Portland, Seattle, Spokane and Missoula indicates that for most winter days, unshaded windows will also be energy gainers in Portland and Seattle in most orientations. In Spokane and Missoula they will either gain energy or have their losses greatly reduced over calculations based only on temperatures and U-values.

Comparisons of the overall thermal performance of the different alternative windows revealed that U-value improvements were often accompanied by significant decreases in solar gain, which must be taken into account when evaluating the effect of the improvement.

Calculations of double-glazed window performance revealed that the uncertainties in window energy usage associated with lumped solar gain are much larger than those resulting from uncertainties about U-value. The key uncertainties are whether or not windows remain unshaded, the net effects of typical shading devices, how building occupants will utilize shading, and to what extent solar gains are useful in offsetting heating loads as opposed to causing overheating. While the latter are typically taken as assumptions in calculating energy performance, it is important that these assumptions faithfully reflect reality: a change in assumptions is capable of inverting the choice between two alternative window candidates.

These conclusions are relevant both for new design and for retrofit. Since improvements in window U-value also frequently involve changes in the solar heat gain coefficient, design or retrofit strategies must be carefully examined using an appropriate calculational model which includes both effects. To set building or retrofit standards on the basis of calculations including only the U-value effects could be counterproductive.

Further research aimed at better quantifying the energy savings attributable to windows, window improvements or retrofits should be directed toward reducing these uncertainties if it is to achieve its goal.

7 Recommendations

This work raises, for the first time, the possibility of a consistent way to predict U-values accurately for both laboratory and field conditions. However, the study has also demonstrated that uncertainties in energy use arising from inadequate ability to predict the amount of usable solar gain entering through a window prevent heating energy use calculations from reflecting even the level of accuracy of our current knowledge of U-values; still less would they reflect the improvement which is now possible.

For example, predicting the savings resulting from replacing a single-glazed window with an improved one (*e.g.*, a double glazed, low-E window) would require predicting the heating energy use of each window over the same time period (*e.g.*, a winter heating season) and taking the difference. But if an inadequate consideration of the usable solar gain caused an overestimate of the heat losses due to each window, then the expected savings could also be overestimated. We have demonstrated that either an inappropriate choice of assumptions about usability or inaccuracies in predicting the solar gain from Equation (1) could cause differences in the prediction which are large compared to the effects of the U-value difference between single glazing and double with low-E. We are not suggesting that there are not worthwhile savings from replacing single glazing with low-E, but rather that if overinflated expectations are raised and then not fulfilled it will undermine the confidence necessary to achieving the true savings on a large scale.

We therefore recommend the following:

(1) *Reduce the prediction uncertainties due to solar gain.* There is already work underway through ASHRAE to develop a methodology for predicting the solar heat gain through complex shaded glazings. Therefore, additional work could concentrate on reducing the rms error for Equation (1) through use of a more sophisticated, angle-dependent F, study of angle-dependent properties of coated glazings, and better methods of treating aperture effects and diffuse radiation. A building simulation model should be chosen as a basis for energy savings estimates, and several characteristics of the model should be verified empirically: (i) the time-profile of perimeter space heating demand in relation to incident solar gain (*i.e.*, how much of the solar gain is available to offset heating, and when); (ii) the relation of (i) to perimeter space characteristics, such as thermal mass and (iii) the calculation of interior conditions such as local air and radiant temperature, light level and glare, which would affect the decision about whether a given level of solar gain is acceptable. We term these issues window/perimeter space interactive effects. It is important to verify that the building model simulates them properly. Considerable work in this area has already been done, but attention has focused on south-facing glazing and the clear conditions useful for passive solar heating; here the focus is on conventional glazings in all orientations, on perimeter spaces which are not designed specifically for passive solar heating, and on average conditions, including clear, overcast and shaded conditions. Once this technical work has been carried out, then a realistic and accurate set of calculations could be made based on comfort and user requirements (perhaps for several types of window applications) drawn from BPA's experience with its customers.

(2) *Develop an accurate regional version of WINDOW and resolve the remaining consistency problems with the test laboratories*, so that representative U-values can be accurately calculated by users or converted from published laboratory test data. The first step here should be resolution of the conflict between WINDOW and MoWiTT, on the one hand, and the test laboratory, on the other, for the CDLAT and CDA windows. ASHRAE is already planning a new format for their U-value tables based on a calculation of the central U-value of the glazing together with standardized edge and frame calculations for specific glazing sizes. Once this has been done, research is necessary to develop a library of representative film coefficients, outdoor radiative temperatures, and frame conductances to adapt this calculation for the Pacific Northwest.

Carrying out these recommendations will lead to a method for accurately predicting window properties for comparative product evaluations as well as making average or seasonal energy efficiency calculations which can form the basis for the reliable planning of utility conservation programs.

8 Acknowledgements

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