LBL-12765

Presented at the Third International Symposium
on Energy Conservation in the Built Environment,
Dublin, Ireland, March 30-April 1, 1982

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October 1981

Prepared for the U.S. Department of Energy under Contract DE-AC03-76SF00098

LBL-12765
EEB-W-81-20
W-104

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OCTOBER 1981

The work described in this paper was supported by the Assistant Secretary for Conservation and Renewable Energy, Office of Buildings and Community Systems, Buildings Division of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

A Mobile Facility for Measuring Net Energy Performance of Windows and Skylights

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ABSTRACT

A Mobile Window Thermal Test (MoWiTT) Facility is being built at Lawrence Berkeley Laboratory in order to use direct measurement to verify predictions of the net energy performance of fenestration systems and other complex elements of the building envelope. It consists of one or more wheeled modules together with an instrumentation van. Each module contains two room-sized (2.4m x 3.1m x 2.4m) guarded calorimeters, each capable of accurately measuring the net energy flow through a sample under all conditions of solar gain. Expected performance of the facility is calculated using the program BLAST. We conclude that it provides a much more accurate measuring capability than the passive cell commonly in use.

RESUMÉ

Le Lawrence Berkeley Laboratory construit actuellement une unité mobile d'expérimentation thermique de fenétres (MoWiTT) dont le but sera d'utiliser les mesures directes en vue de vérifier les prédictions de fonctionnement énergétique nette de fenétres et d'autres éléments relatifs à l'enveloppe de la construction. L'unité MoWiTT se compose d'une ou plusieurs remorques ainsi que d'un véhicule équipé d'appareils de mesure. Chaque remorque comporte deux calorimétres (2,4m x 3,1m x 2,4m) avec leurs protections, dont le but est de mesurer le flux énergétique net à travers l'èchantillon à tester, en fonction du rayonnement solaire, considéré dans diverses conditions. Le programme de calcul BLAST est utilisé pour la simulation du fonctionnement de l'unité expérimentale; en conlusion, il s'avère que les mesures obtenues dans ces conditions sont beaucoup plus exactes que celles obtenues par les cellules d'expérences passives utilisées ordinairement.

INTRODUCTION

Energy-consciousness in the building sector has led to the development of window and skylight products having improved properties, such as lower nighttime U-value, lower (or higher) shading coefficients, and lower air leakage. Selecting these products for application, or identifying new directions for development, has often been guided by calculations of instantaneous net energy performance under specified extreme or design conditions. This approach has two disadvantages. First, it does not yield quantitative estimates of the energy consumption so that one can do a cost-benefit calculation as a basis for selection. Second, it may lead to serious errors. A few such errors identified in the literature[1,2] emphasize this point:

1. Inappropriate use of fixed solar-control devices in a small building to reduce summer cooling loads may result in an increased winter heating load which more than offsets the cooling season savings.
2. Overemphasis on nighttime U-value as a determinant of net annual energy consumption may lead one to conclude that reducing window area saves energy, whereas including proper credit for solar gain may show that the reverse is true.
3. Calculation of air leakage rates under extreme conditions may seem to justify a large investment for reducing window leakage when, in fact, the average net energy savings show a much smaller investment to be optimal.

Each of these errors results from the user's failing to focus on average net energy performance as the basis for selecting fenestration for a particular application. Average net energy performance determines the direct cost or benefit attributable to the fenestration. Unlike the steady-state parameters generally used to characterize a window or skylight system (nighttime winter U-value, shading coefficient, and air leakage coefficient), which are quasi-intrinsic properties, net energy performance is a system property of the fenestration, the adjacent building interior, and the local exterior environment. As such, it reflects the combined effects of the fenestration properties and the dynamic matching of these properties to the building demand and to the climate. <u>Average</u> net energy performance includes, in addition, the variability of this matching with time and provides a uniform measure of the net benefits of alternative fenestrations which, for example, are optimally matched to the building demand at different times or have time-varying properties (e.g., managed window systems).

The foregoing should make it clear that average net energy performance constitutes a better basis for comparing fenestrations. One drawback, however, is the lack of a well-defined methodology for measuring it. At present, the best way of determining this quantity is to calculate it using the intrinsic fenestration properties as input to a building-model computer program. In the United States the most advanced building-model programs are DOE-2 and BLAST. Although these programs initially were not flexible enough to allow modeling of advanced window systems, subsequent versions have moved toward a broad modeling capability. While there remain controversies about how the window properties should be measured, what film coefficients should be used, and so forth, the overriding uncertainty is whether the average net energy calculated is correct. Neither program was specifically designed to calculate net performance of components, and, in modeling a building, both programs make assumptions which might affect the calculation of window performance. Although both programs have been validated to a certain extent,[3,4] the validations have not been sufficiently accurate to check the calculations at the level of individual components. To provide the necessary validation, direct measurements of average net energy performance are clearly necessary.

Two generic approaches have been used to measure annual net energy performance of fenestration systems. The first uses an existing building and measures the effect of alternative window systems on its energy consumption. When the number of windows involved is small, it is difficult to obtain meaningful results by this method because of uncertainties in heat flows through other building systems and components that are large compared with the heat flow through the windows. The need to correct for weather differences and the behavior of occupants also plague this approach. In a variant of the method, the "demonstration project," a very large area of windows is changed so that the heat flow attributable to the windows represents a significant fraction of the heating or cooling load of the building. While this variant is a useful marketing strategy, it is too expensive and inflexible as a research tool.

The second approach uses a small test room in which the alternative fenestrations are mounted. Several such installations have been constructed in the United States, Canada, and Europe. In the United States the data from these tests has had limited value for measuring the net performance of fenestration because of its inaccuracy. This subject is discussed below.

MoWiTT CONCEPT

At Lawrence Berkeley Laboratory we are building a Mobile Window Thermal Test (MoWiTT) facility specifically designed to measure the dynamic net energy performance of fenestration systems under field conditions. Originally conceived as an extension of the small test cell, the MoWiTT will provide the following capabilities:

- Full-scale testing of window and skylight units of various sizes and types;
- Accurate side-by-side, simultaneous testing of different window systems and window management strategies;
- Dynamic performance measurements using real weather conditions, including solar gain;
- Flexibility in simulating interior building environments ranging from light-weight to thermally massive structures, from poorly to well insulated, and from leaky to air-tight;
- Variable orientation;
- Variable location and climate.

A key feature of MoWiTT is its ability to determine the net energy flowing through the fenestration by a dynamic net heat balance on the test space.

MoWiTT DESIGN

The initial design of the MoWiTT included a unit having four test cells, each of which was a calibrated hotbox. This design, which has been described,[5,6] was subsequently revised for improved accuracy and economy. In the original design it had never been practical to provide insulated walls thick enough to make the envelope heat flow negligible during nighttime winter testing; moreover, the insulated walls required a massive steel frame to protect them from flexure and vibration in transit, and this proved incompatible with a reasonably priced mobile facility.

The revised design is shown in Figure 1. Each test room was made into a guarded hotbox by including a guard air plenum in the exterior walls, a modification that allowed us to greatly relax the tolerances on flexure for the shell.. We then divided the facility into modular units, each connecting to an instrumentation van, as shown in Figure 1(a). The two identical test cells per module, each measuring 2.4m x 3.1m x 2.4m high, are capable of accepting a window test sample up to 2.4m square and a skylight sample up to 1.2m square. A removable common wall between the two chambers allows testing of larger (4.8m x 2.4m) samples or varying the surface-to-volume ratio of the test chamber. Figure 1(b) shows the layout of a test module.

Each test chamber can be operated in either of two distinct modes. In the metering mode the chamber acts as a guarded calorimeter and measures the net energy flowing through the fenestration. In the simulation mode, the chamber mimics the properties of a specified building type by varying thermal mass, envelope heat loss, and air leakage. The net energy flow can also be measured in this mode, although possibly with less accuracy.

Details of the test chamber design are shown in Figures 1(c) and 1(d). In order to prevent a large heat flow through the test frame, window samples smaller than 2.4m x 2.4m will be mounted in a double-walled test frame to allow guard air circulation except in a small area near the window perimeter. A similar arrangement will be used when skylights are tested. The guard air circulation rate will be high enough to maintain fully developed turbulence for good thermal mixing and uniformity of surface temperatures. The design limit for heat transfer between the test chamber and the guard under equilibrium nighttime conditions is 3W.

Under solar-gain conditions, maintaining equal temperatures in the test chamber air and the guard air is not sufficient to prevent heat transfer, since the interior surface temperatures of the test chamber envelope will rise above the air temperature. Because thermal storage in the test chamber walls is important under these conditions, the test chamber walls are covered with a continuous layer of large-area, high-sensitivity heat-flow meters. Economical heat-flow meters having the necessary

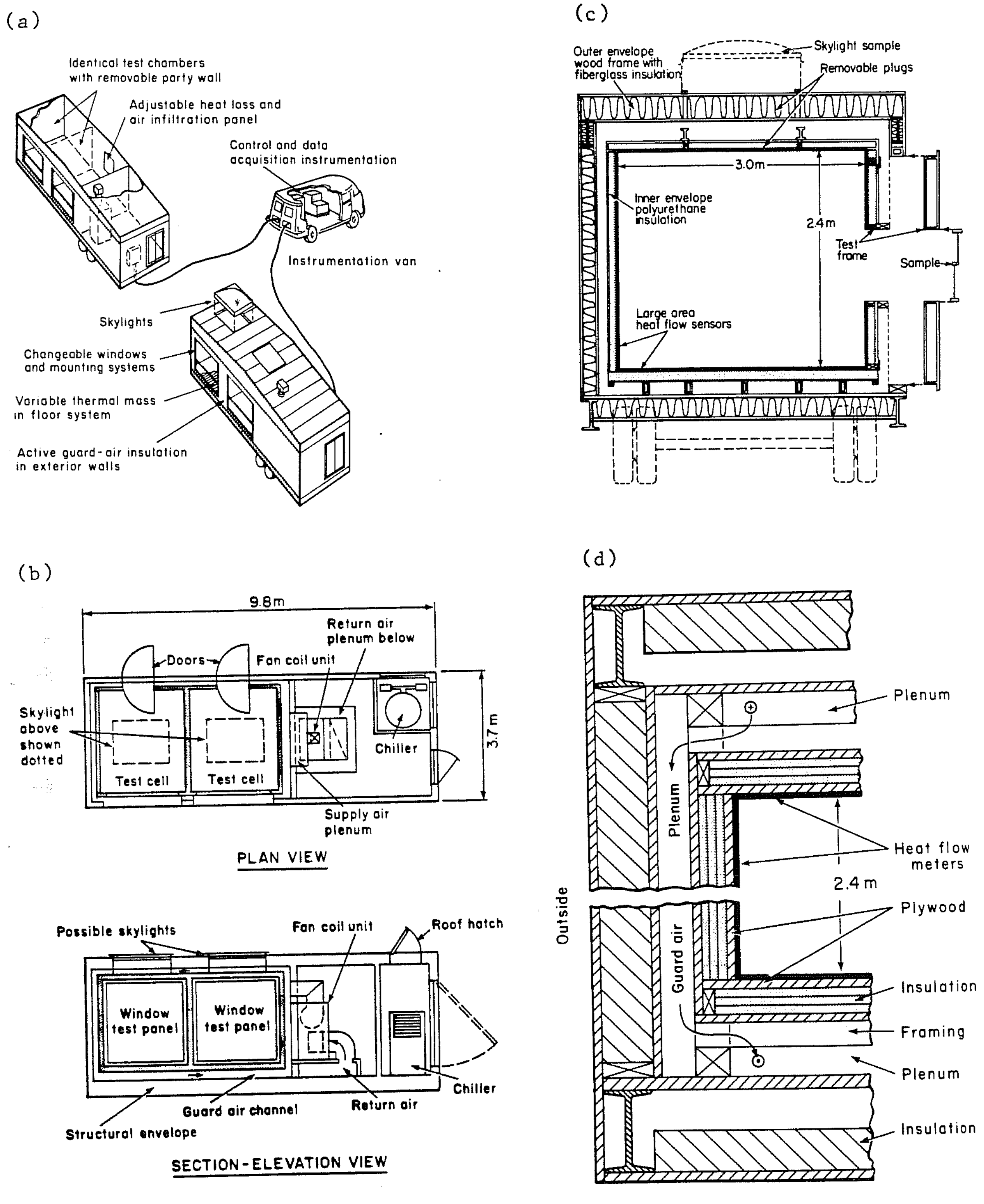

Figure 1. Design of the Mobile Window Thermal Test (MoWiTT) Facility. (a) Planned field configuration. (b) Layout of a test module. (c) Cross-section through the center of a test chamber, showing mounting of alternative window or skylight systems. (d) Detailed envelope cross-section.

characteristics are being developed.[7]

INSTRUMENTATION AND CONTROL SYSTEMS

The instrumentation system of the MoWiTT was designed to provide the flexibility necessary for conducting a wide variety of experiments in the test chambers together with accurate metering of the chamber's energy balance and good control of interior temperature.

The system has a data logger and control equipment located in the equipment room of each test module. These communicate with passive sensors in the test chamber and can also drive devices such as actuators for movable blinds as dictated by experimental requirements. Most power-consuming data acquisition equipment is external to the test chambers, and all power entering the chambers is metered. A flexible system of terminal blocks inside the test chambers and a data logger designed around plug-in units with an accurate digital voltmeter facilitate changing of sensors or reassigning of data channels between test chambers.

The data logger in each module communicates through a bidirectional instrumentation bus (IEEE-488) to a microcomputer in the instrumentation van, where data is processed and stored. The microcomputer is also accessible by telephone link from LBL and will support remote monitoring and spot-analysis of the data as it is collected. The stored data will be periodically shipped to LBL for complete analysis.

An important capability of the MoWiTT is that it can simulate interior climate conditions for a large variety of buildings while, at the same time, accurately measuring the net energy balance of the test cell. Heat is provided by an electric heater which, of course, is metered, as is the fan power. Cooling is accomplished with a liquid-to-air heat exchanger, for which we determine the extracted heat by measuring the coolant flow rate and inlet and outlet temperatures. Humidification can be provided when desired, and dehumidification can be effected by operating the system in a cool-and-reheat mode.

EXPECTED PERFORMANCE

The MoWiTT is distinguished from an ordinary passive test cell by its ability to perform a net energy balance on each test chamber and thereby measure net energy flow through the window sample. This ability derives from its two unique features, the thermal guard and the continuous envelope of heat-flow meters. Here we will compare the dynamic performance of the MoWiTT with that of a passive cell having exactly the same structure, except that the air-guard space is omitted from the envelope and the lining of heat-flow meters is removed. For this calculation we used the program BLAST and assumed a cold, clear design day (Dec. 20) at Donner Summit, in the Sierra-Nevada mountains of California. Both the MoWiTT and the passive cell are assumed to have a $1m^2$, triple-glazed window sample. The driving forces assumed for the model--outdoor temperatures and solar gain admitted through the window--are shown in Figure 2(a).

A net energy balance for the test chamber shows that the net energy, Q(t), passing through the window at time t is given by

$$Q(t) = L(t) - E(t), \qquad (1)$$

where L(t) is the instantaneous heating or cooling load and E(t) is the amount of heat flowing into the test chamber through the inner surface of the envelope. The quantity L(t) is defined so that positive L denotes a cooling load and negative L a heating load. Positive E and Q denote heat flows into the chamber. The hour-by-hour calculations for L(t) and E(t) for the MoWiTT and the passive cell are shown in Figure 2(b).

We draw two conclusions from these curves. First, the net heat flow Q through the window is calculated by measuring both E and L and taking the difference according to Eq. (1). If we assume that these measurements have a fixed (and equal) fractional accuracy, ε, then the error, δQ, to be expected in the derived value of Q will be given by

$$\delta Q = \varepsilon \sqrt{L^2 + E^2} \ . \qquad (2)$$

If we consider the pre-sunrise hours 1 to 8, we see that for the passive cell, Q is a small difference between two large (negative) numbers, while for the MoWiTT, one curve (E) lies very close to zero. Eq. (1) and (2)

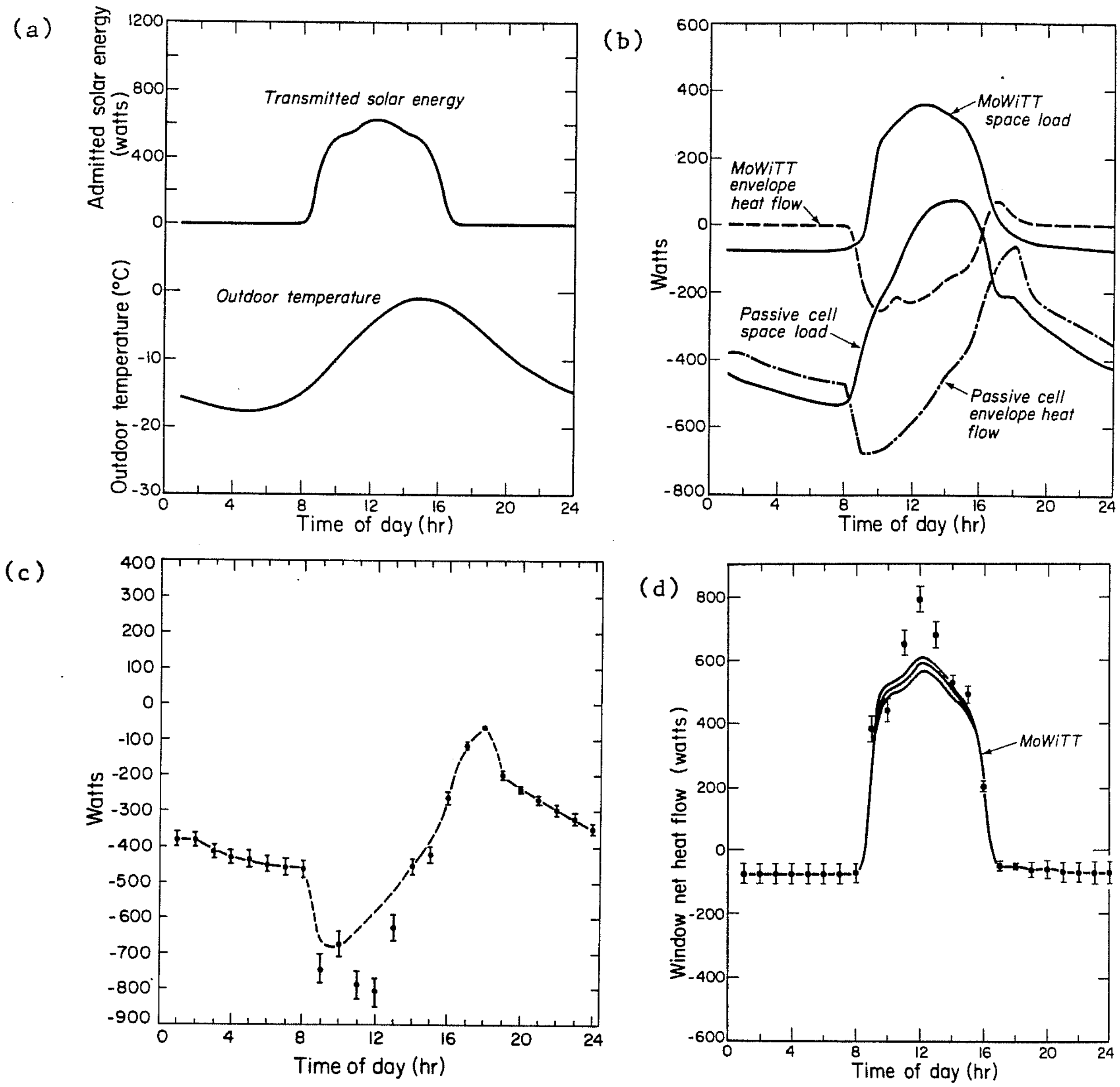

Figure 2. BLAST Simulation of a Triple-Glazed Window Measurement Comparing the MoWiTT and a Passive Test Cell. (a) Assumed outdoor temperature and solar energy transmitted through the window. (b) Calculated space loads, L(t), (solid curves) and envelope heat flows, E(t), (dashed curves) for the MoWiTT and for the passive cell. (c) Measurement of envelope heat flow in the passive cell. Dashed curve: BLAST calculation of the envelope heat flow; points with error bars: envelope heat flow measured with the heat-flow meter grid described in the text. (d) Derived values for the net heat flow, Q, through the window. Solid curves are the mean, + 1 standard deviation, and -1 standard deviation for measurements by the MoWiTT. Points with error bars are the corresponding quantities for the passive cell with heat-flow meter grid.

then tell us that for the same value of E the error δQ will be much smaller for the MoWiTT than for the passive cell. This is the effect of the thermal guard.

From the shape of the envelope heat-flow (E) curves, we can draw a second conclusion. Coincident with the solar peak in L we see a dip in E; i.e., the heat flow out through the envelope increases. This dip is attributable to the solar gain absorbed in the envelope of the test chamber. From the size of the dip relative to the peak in space load, we can see that between one-third and one-half of the solar gain initially flows into the walls rather than into the air. This portion of the solar gain cannot be determined from a measurement of L(t) and the air temperatures alone and we conclude that any test chamber that cannot measure either interior surface temperatures or heat flows will be unable to measure a dynamic net daytime heat balance with better than 50–100% accuracy.

For this reason, we assumed that the passive cell is equipped with surface heat-flux sensors. Specifically, we assumed that a grid of commercial heat-flux sensors is placed on each interior surface at a spacing of one per $0.74 m^2$. Because of the high cost of commercial heat-flux sensors, a much greater density seems unlikely. By hand calculation we then constructed the pattern of direct solar illumination and deduced the resultant heat flow that would be measured by the grid of heat-flow sensors.

The results of this calculation are given in Figure 2(c), where the curve represents the actual heat flow through the envelope as calculated by BLAST, and the points are the responses of the heat-flow sensor grid. The error bars around each point indicate the error expected on the basis of heat-flow meter accuracy. (All measurements in this calculation are assumed to have an accuracy of 5%.) As can be seen, before and after sundown the points follow the curve well, but, under solar-gain conditions, large deviations appear as the sun hits particular heat-flow sensors. These deviations occur because the local value of the heat flux is applied to the entire $0.74 m^2$ of area whereas the sun may actually illuminate only part of that area.

The effect of these considerations on the measurement of net energy flow through the window is given in Figure 2(d). In this figure the net energy

ACKNOWLEDGEMENT

The work described in this paper was supported by the Assistant Secretary for Conservation and Renewable Energy, Office of Buildings and Community Systems, Buildings Division of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

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