CONF-960254--2

LBL-37038
UC-1600

# Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

## ENERGY & ENVIRONMENT DIVISION

Presented at the ASHRAE Winter Meeting, Atlanta, GA,
February 17–21, 1996, and to be published in the Proceedings

# Calorimetric Measurements of Inward-Flowing Fraction for Complex Glazing and Shading Systems

J.H. Klems and G.O. Kelley

May 1995

RECEIVED
APR 11 1996
OSTI

ENERGY
AND ENVIRONMENT
DIVISION

MASTER

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

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

**DISCLAIMER**

This document was prepared as an account of work sponsored by the United States Government. While this document is believed to contain correct information, neither the United States Government nor any agency thereof, nor The Regents of the University of California, nor any of their employees, makes any warranty, express or implied, or assumes any legal responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by its trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof, or The Regents of the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof, or The Regents of the University of California.

Ernest Orlando Lawrence Berkeley National Laboratory
is an equal opportunity employer.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

LBL-37038
Mo-346

Presented at the ASHRAE Winter Meeting, Atlanta, GA, February 17-21, 1996, and published in the Proceedings.

# Calorimetric Measurements of Inward-Flowing Fraction for Complex Glazing and Shading Systems

J. H. Klems and G. O. Kelley
Building Technologies Program
Energy and Environment Division
Lawrence Berkeley National Laboratory
University of California
Berkeley, CA 94720

May 1995

This research was jointly supported by ASHRAE, as Research Project 548-RP under Agreement No. BG 87-127 with the U.S. Department of Energy, and by the Assistant Secretary for Energy Efficiency and Renewable Energy, Office of Building Technologies, Building Systems and Materials Division of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

# Calorimetric Measurements of Inward-Flowing Fraction for Complex Glazing and Shading Systems

J. H. Klems and G. O. Kelley
Building Technologies Program
Lawrence Berkeley National Laboratory
Berkeley, CA 94720

## ABSTRACT

This paper presents a calorimetric measurement of layer-specific inward-flowing fractions of absorbed solar energy for a number of geometric configurations common in fenestrations with shading. The inward-flowing fractions are found to be relatively insensitive to exterior conditions. Results for an interior venetian blind over double glazing agree with thermal model calculations in the literature, and are the first layer-specific verification of these calculations. It is argued that a data base of these inward-flowing fractions for a suitably broad class of geometries will make possible the determination of solar heat gain coefficient from non-calorimetric measurements of solar-optical properties of complex fenestration components, a procedure termed *solar-thermal separation.*

## INTRODUCTION

In previous work (Klems 1994A; Klems 1994B) the concept of the inward-flowing fraction, N, of the solar energy absorbed in a fenestration system has been extended to define a layer-specific inward-flowing fraction, Ni, refering to the ith layer of a fenestration system rather than to the whole system. This is not a new idea; it has been used implicitly in prior discussions of complex fenestration (Farber, Smith et al. 1963). It has been argued (Klems, Warner et al. 1995) that the Ni are the only inherently calorimetric quantities in the determination of the solar heat gain coefficient, and that these quantites, once determined, could be combined with solar-optical transmittances and layer absorbtances determined by non-calorimetric methods to produce solar heat gain coefficients for complex fenestration systems. This two-step procedure has been termed solar-thermal separation. In order to make it a usable technique, it is necessary to demonstrate the determination of the fractions Ni. This paper carries out such a determination for a number of geometric arrangements common in windows with shading.

From general heat transfer theory $N_i$ would be expected to be a slowly-varying function of the temperature of the $i^{th}$ layer, the temperatures of the surrounding layers (or radiatively visible surfaces) and the ajacent air temperatures; it would also depend on the state of motion of the adjacent air. Treatment of this issue in previous discussions in the literature has varied; the inward-flowing fraction has variously been treated as constant (Yellott 1966) or evaluated theoretically using an idealized heat transfer model (Farber, Smith et al. 1963). The underlying physical principle is simple although its application is not: Solar energy absorbed in a fenestration system elevates the temperatures of the various absorbing layers, and this causes heat transfer by the normal processes of conduction, convection and radiation both inward and outward. The temperature of each layer is fixed at the point where the inward and outward flow from the layer equals the rate of solar energy

absorption. The net result is that the heat flow divides into inward and outward heat flow in proportion to the ease with which it can flow in the two directions under the prevailing conditions. But this depends on the temperature of the layer in question, of the adjacent layers and of the adjacent air; in addition, the pattern and velocity of adjacent air flow may have an effect, and all of these may depend on the level of solar irradiation. For the outer fenestration layer, wind and exterior air and radiative temperatures would be expected to be important.

Because of this expected dependence, the $N_i$ were measured under realistic indoor and outdoor conditions. Evaluating the extent to which they vary with external weather conditions was an important part of defining the method. Clearly, if the $N_i$ showed a high degree of variability, providing a representative set of values for solar heat gain calculations would be a much more difficult task than if the variability were low.

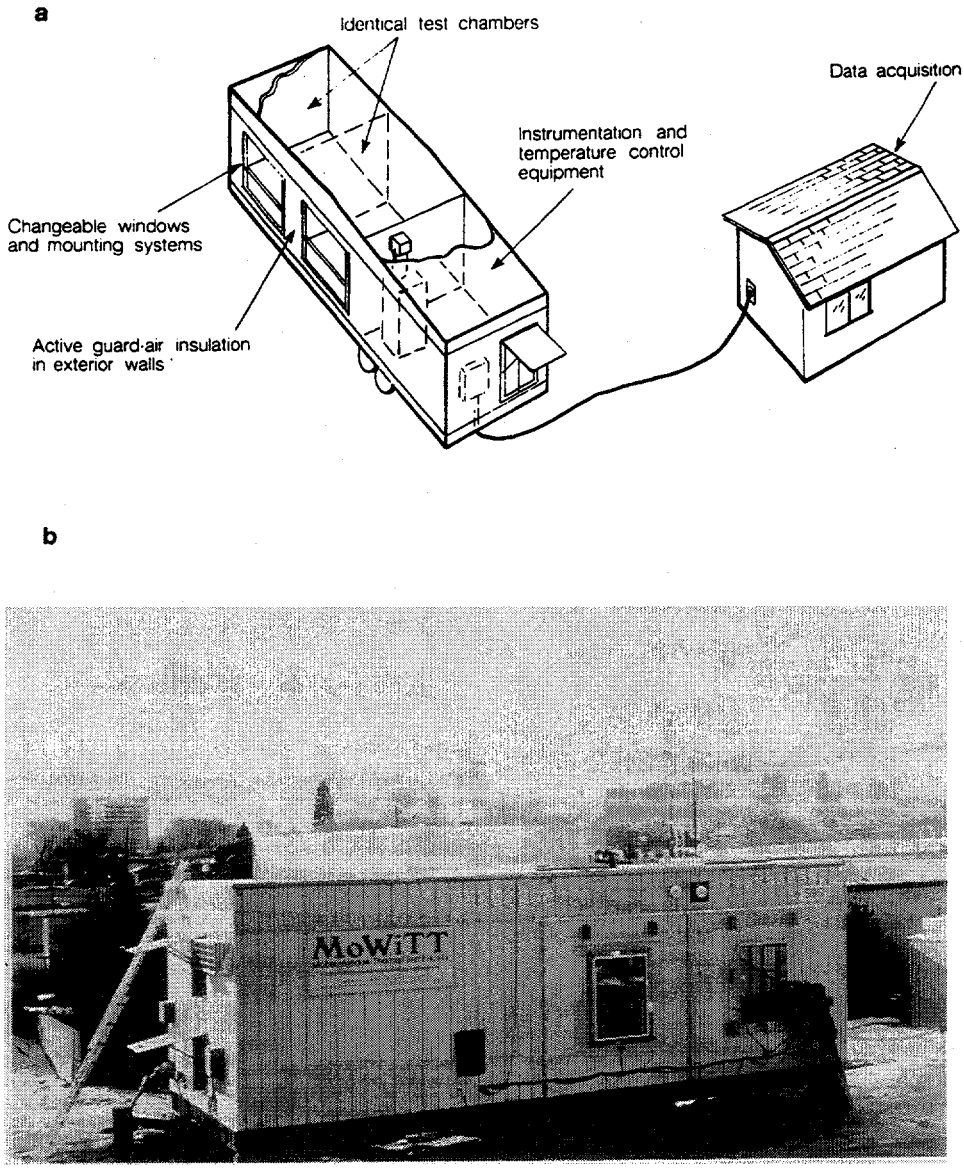
## DESCRIPTION OF THE MOWITT FACILITY

The authors performed the inward-flowing fraction measurements using a well-known mobile window thermal test facility (Klems, Selkowitz et al. 1982; Klems 1988) in Reno, NV. This is a mobile calorimetric facility designed to measure the net heat flow through a fenestration as a function of time under realistic outdoor conditions. Consisting of dual, guarded, room-sized calorimeters in a mobile structure, the it 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. There are also provisions for measuring all auxiliary electric power dissipated inside the chambers (e.g., fan power). A diagram and photograph of the facility is shown in Figure 1.

During the measurement, associated instrumentation measures a variety of internal and external conditions: An array of thermistors with radiation shields monitors the average interior air temperature in each calorimeter, and an aspirated thermistor located in the on-site weather tower measures the exterior air temperature. A standard rotating-cup anemometer and weather vane measures the free-stream wind speed and direction. A sun-tracking pyrheliometer and a horizontally-mounted pyranometer measures beam and total horizontal solar intensity, respectively. A vertically-mounted pyranometer mounted above the two window samples measures the total solar (and ground-reflected) radiation intensity incident on the windows, and a vertically-mounted pyrgeometer measures the total incident long-wave infrared radiation (emitted by the sky and ground). A specially-designed sensor located between the two window samples monitored the nighttime effective heat transfer film coefficient.

## MEASUREMENT OF INWARD-FLOWING FRACTION

To measure the value of $N_i$ for a layer in a particular fenestration system, identical fenestration systems were mounted in the two calorimeters, with provision made to electrically heat the selected layer in one of the fenestrations. Electrical heat applied to that layer would simulate a small increase

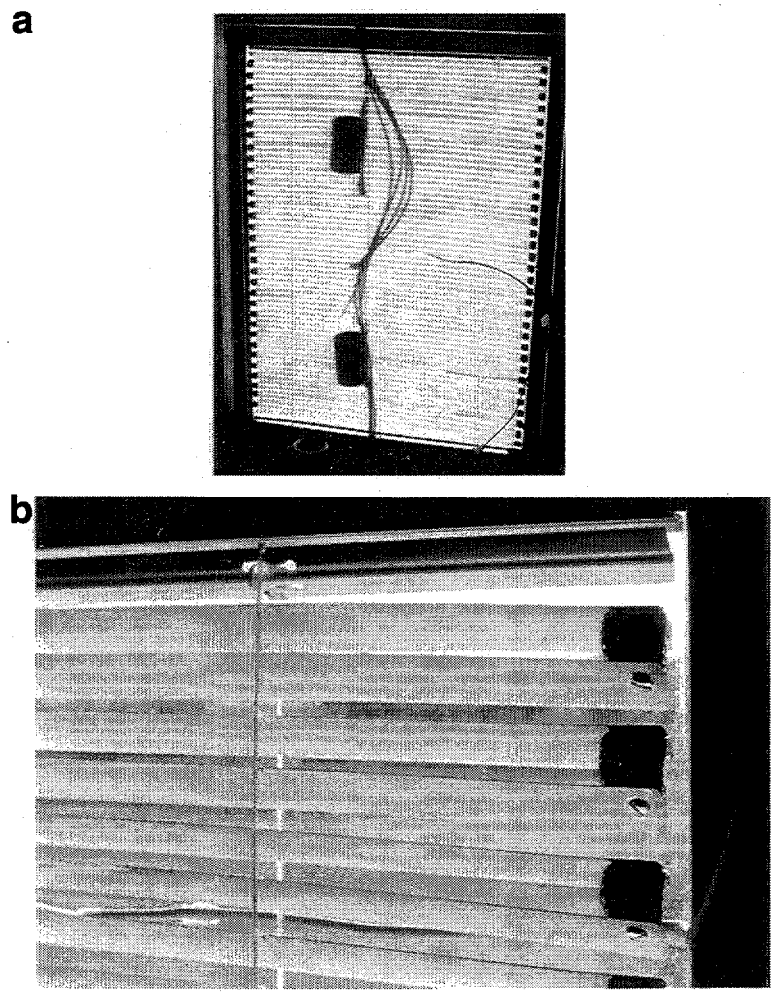



(CBB 892-812B)

***Figure 1. MoWiTT Facility.*** *(a) Diagram showing the major features of the facility. (b) Photograph of the facility in a north-facing orientation at its field site in Reno, NV. The two large featureless (approx. 2.5 m X 3 m) rectangles are bridging walls across the air guard that hold the mask walls (smaller rectangle) in which the windows are mounted. The bridging wall dimesions indicate the approximate cross-sectional dimensions of the calorimeters (the chamber floors are approximately 0.4 m above the bottoms of the bridging walls), while the depth of the facility (visible at left) is approximately 0.6 m greater than the depth of the calorimeter chambers. The inward-flowing fraction measurements were made in the chamber at left in this figure, while the one at right was used as a reference. The vertically-mounted pyrgeometer and pyranometer are visible above the juncture between the two bridging walls. Behind the calorimeter chambers one can see the on-site weather tower, an overpass over Interstate 80 (which passes to the south of the test site) and downtown Reno beyond.*

in solar absorptance, and if a fraction $N_i$ of the applied power, P, flowed inward, then the net heat flowing through the fenestration would increase by an amount $N_iP$. Since the calorimeter accurately measures the net heat flow and P is also known, varying P and measuring the resulting change in net heat flow gave a direct measurement of $N_i$. In this measurement, the companion calorimeter with the unheated layer was used as a control.

The experimental design focused on determining the in-situ values of the inward-flowing fraction, and this meant that the heating power applied to the layer must be a small perturbation to the important variables in the system. The heat was applied in ways that affected the surface geometry and optical properties as little as possible. For metallic venetian blinds electric current was applied at the ends of the blind, with each blind slat itself acting as a heating element, as shown in Figure 2. For




XBD 9506-02545

***Figure 2.*** *Inward-Flowing Fraction Measurements on an Interior Venetian Blind. (a) View from the interior of the calorimeter chamber showing the blind with its attached electrical connections. In the foreground (located at some distance from the blind) are a pair of shielded air temperature monitoring sensors with their associated wires. The electrical connections to the blind slats, visible on either side of the blind, clearly do not obstruct incoming solar energy. The wire at right is a temperature sensor attached to the back of the blind. (b) A detail of the electrical connections shows that alternate slats are wired in series to form a heater utilizing the slats themselves as a heating element.*

non-metallic blinds, a thin heating wire was applied to the underside of each blind slat. Non-metallic shades were treated by cementing a layer of the appropriate shading material on each side of a metallic layer, which was heated. This did change the optical transmission somewhat, but we judged this to have little effect on the inward-flowing fraction. We took the key non-geometric variable to be the layer temperature. To keep the change in layer temperature small meant limiting the amount of the applied power, P; however, it was necessary to have a reasonable value for P to produce a detectable signal in the calorimeter. After some preliminary study we settled on a nominal value for P in the range 30-50W. This produced an increase in the layer temperature of a few degrees Celsius. It was observed that a venetian blind in the MoWiTT cycled over a temperature range on the order of 40° C between day and night under summer conditions. From this it was clear that if there were a temperature dependence in the inward-flowing fraction, the small temperature rise due to the applied layer power would not mask the change between day and night. The sole exception to this procedure was the case of exterior venetian blinds, where the inward-flowing fraction was so small that a much higher applied power was necessary to produce a detectable signal in the calorimeters.

At the outset, the inward-flowing fraction was obtained by comparing the difference between apparent net heat flows through the fenestration in the two calorimeters, one with a heated layer and the other, without applied heating. Comparing this difference with the applied layer power turned on to the difference with the power off (when it should have been zero) gave the amount of the applied power that flowed inward from the heated layer, and the inward-flowing fraction was directly obtainable from that. This method was used to produce initial results. By selecting data only from the afternoon, as compared with data averaged over the full 24-hour period, we were able to determine that, contrary to expectation, there was not a strong dependence of the inward-flowing fraction on layer temperature.

This method of analysis was subsequently discarded as not sufficiently accurate and reproducable. For many shading systems, particularly venetian blinds, the differences between units were sufficiently large that it did not prove possible to mount different units in the two calorimeters and have the net heat flows be the same for no applied layer power. Initially, it was assumed that the problem was due to adjustment of the blind angles, and considerable effort was spent trying to adjust one or the other blind angle to achieve equal net heat flow. However, we observed that even when a good balance was achieved at the outset, subsequent P=0 measurements under different sky conditions would not show equal net heat flows in the two calorimeters. We finally concluded that variations in stiffness, curvature and position among the slats of the two blinds resulted in two units with intrinsically different transmissions. Although the two devices could be balanced under a given set of sky conditions by small changes in slat angle, this did not make the transmissions identical, but rather used changes in beam transmission to offset differences in diffuse transmission. As soon as the sun angle or the direct-to-diffuse ratio changed, the balance was upset.

In the final analysis we used a method that did not require comparisons between physically distinct shading systems. The measured net heat flow, W(t), through the fenestration was compared with a theoretical prediction given by

$$W_{TH}(t) = (UA)\cdot\left[T_O(t) - T_I(t)\right] + B(t)\cdot I_S(t) + N_i \cdot P \qquad (1)$$

where $T_O(t)$, $T_I(t)$, and $I_S(t)$ are the measured values of the outdoor air temperature, indoor air temperature, and incident vertical solar intensity, respectively, at the time t and the subscript i denotes the heated layer, while $(UA)$, $B(t)$, and $N_i$ are parameters that were determined by a least-square fit to the data. An example of a simplified verision of the fitting procedure (in which B was assumed to be a single constant) is shown in Figure 3. In the final analysis, the parameter $B(t)$, which is the

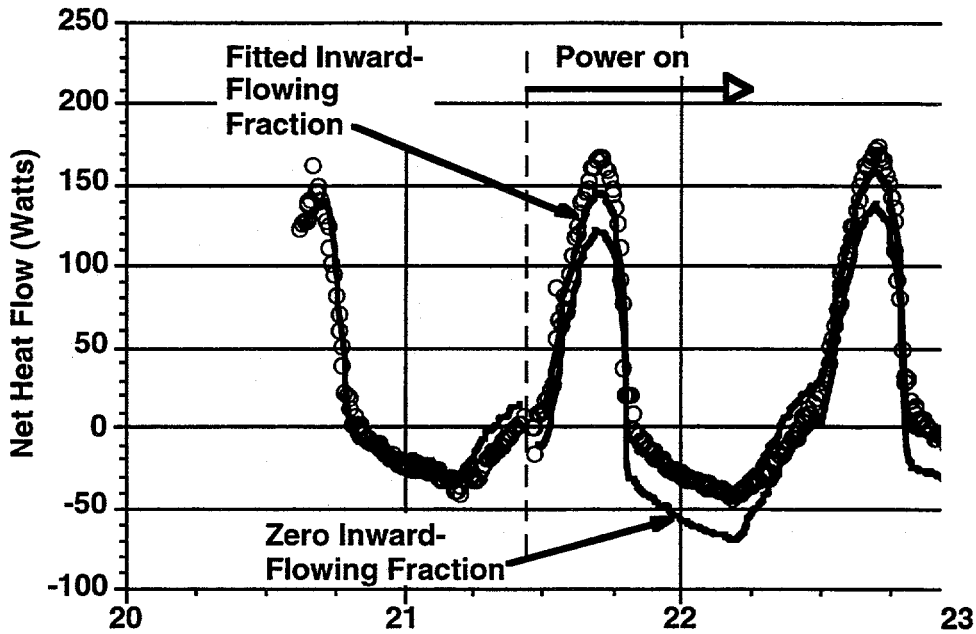



*Figure 3. Determination of $N_i$ for an Interior Shade. The MoWiTT measurement of the apparent window net heat flow is plotted (open circles) together with the calculated curve given by Equation 1 for the fitted value of $N_i$ (heavy curve). Comparison with the same equation assuming $N_i = 0$ (light curve) gives a measure of the significance of the determination. The two curves coincide before the power heating the blind was turned on. This figure illustrates a fit using a single constant value of B, before the additional sophistication of Equation 1a. The fact that the model of Equation 1 does not accurately fit the measured points in the morning or near the solar intensity peak illustrates the limitations of the assumption of a constant value of F.*

effected solar heat gain coefficient multiplied by the applicable area, was defined to be time-dependent as follows:

$$B(t) = \begin{cases} B_1 & \text{for no direct sun on window} \\ B_2 + B_3 \cdot \cos(\theta(t)) & \text{for direct sun on window} \end{cases}, \qquad (1a)$$

where $B_1$, $B_2$, and $B_3$ are constants, while $\theta(t)$ is the solar incident angle relative to the normal to the plane of the window at time t. In the fitting process, (UA) and B(t) were fit using only that portion of the data for which the layer power was off (P=0), and during this fit (UA) was adjusted only between the hours of midnight and sunrise. The typical measurement of an inward-flowing fraction consisted in installing a given window system in both MoWiTT calorimeters with provision to heat a particular layer of the fenestration in one of the two calorimeter rooms (Chamber B). After both calorimeters were closed and allowed to come to equilibrium, data-taking consisted of several days' to a week's measurement with P=0, approximately the same time period with P set to a constant 30-50W (or more

for exterior venetian blinds), followed by another several-day period with the applied layer power off. The layer inward-flowing fraction $N_i$ was determined by fitting the days for which the power was turned on, and during this fit the other parameters were held fixed at the values determined from the days with the power off.

## RESULTS

The values of the layer inward-flowing fractions determined by this method are shown in Table 1. The principal contributor to the quoted errors in the table was the estimated systematic uncertainty in

**Table 1.** Measured Layer Inward-Flowing Fractions, $N_i$, for Geometrically Prototypical Systems

| System | Bind angle below horiz. | Inner Shading Layer | Inner Glass | Between-Pane Shading | Outer Glass | Exterior Shading Layer |
|---|---|---|---|---|---|---|
| Single Glazing with Interior Shade | | 0.80±0.08 | | | 0.08±0.06 | |
| Single Glazing with Interior Venetian Blind | -45° | 0.69±0.05 | | | 0.24±0.09 | |
| | 30° | 0.83±0.08 | | | 0.21±0.07 | |
| | Clsd | 0.72±0.07 | | | 0.14±0.05 | |
| Single Glazing with Exterior Venetian Blind | 45° | | | | 0.46±0.12 | 0.04±0.01 |
| Double Glazing with Interior Shade | | 0.85±0.10 | 0.52±0.12 | | 0.28±0.06 | |
| Double Glazing with Interior Venetian Blind* | 45° | 0.86±0.06 | 0.69±0.14 | | 0.21±0.09 | |
| Double Glazing with Between-Pane Blind | 45°* | | 0.69±0.14 | 0.45±0.06 | 0.34±0.10 | |
| | -45° | | 0.76±0.10 | 0.40±0.07 | 0.27±0.14 | |
| Low-E Double Glazing with Between-Pane Blind | 35° | | 0.46±0.12 | 0.38±0.05 | 0.32±0.11 | |
| Double Glazing with Exterior Venetian Blind | 45° | | 0.73±0.13 | | 0.28±0.12 | 0.03±0.02 |

*Blind measurement was made at 30° rather than 45°.

the absolute net heat flow measurement of the calorimeter, which was typically 2-4W during these tests. The uncertainty arising from the fitting process, estimated by standard statistical techniques, was much smaller. In all cases the quoted error corresponds to one standard deviation. The RMS value of the deviation between the measured and predicted net heat flow was in the range 10-30W.

## Angular Dependence Assumptions

The angular dependence used for the effective solar heat gain coefficient in equation 1a was selected as the simplest form that provided stable fits to the data. We initially tried a theoretical form that used a constant direct-sun value for B. We found that this produced a curve that did not peak as sharply during the daytime as did our measured values of W(t). This resulted in a curve that fit partly cloudy days better than very clear days, and if the power-on and power-off measurement periods differed significantly in this respect, the resulting value of $N_i$ would be biased. For four cases where we had made two separate measurements of the same fenestration system layer at different times, we obtained values of $N_i$ that were not consistent within experimental uncertainties. With the angular dependence of equation 1a, these repeated measurements each produced consistent values of $N_i$.

## Tests for Temperature Dependence

Using this method of data analysis we tested for temperature dependence by repeating the above fitting process while allowing $N_i$ to have a different value, $(N_i)_{PM}$, in the afternoon (during which, for our west-facing tests, the window was in direct sunlight and all parts of the glazing system were at substantially higher temperature) from that of the night and morning, $(N_i)_{AM}$. A typical sample of this data is shown in Figure 4, which summarizes data for shading layers, including venetian blinds with various slat angles, and shades. As can be seen from the figure, there is no pronounced overall tendency for the difference $(N_i)_{PM} - (N_i)_{AM}$ to be different from zero. If one considers specific shading placements, only the between-pane blind appears to exhibit a definite change with temperature elevation, as indicated by the solid line which is the best fit of the assumption that $(N_i)_{PM} - (N_i)_{AM}$ is proportional to $T_{PM} - T_{AM}$. However, the fit is principally constrained by the single point at largest temperature elevation. This point is for a between-pane venetian blind at a 35° downward tilt, for which the interior pane has a low-E coating. The point at a temperature elevation of about 26° is a second measurement of this system, which unfortunately has a larger error estimate and is consistent both with the first measurement and with zero. The distribution of the inside shading points would suggest that the error estimates on the points are low, further weakening the what evidence there is for a temperature dependence. The glazing $N_i$ measurements produced a similar picture. On the whole, this test produced no significant evidence for temperature dependence in $N_i$. There was a tendency for the difference $(N_i)_{PM} - (N_i)_{AM}$ to be positive, but on the average the magnitude of this difference was comparable to the experimental error. For the five systems on which we had made repeated measurements at different times (which includes the between-pane blind discussed above) we have computed the mean and standard deviation of $\Delta N_i = (N_i)_{PM} - (N_i)_{AM}$ for each pair of repeated measurements. These are shown in Table 2. It can be seen from this table that the mean difference is never larger than the standard deviation, which is a measure of the consistency of results obtained on separate measurements of the same system. From this we conclude that the temperature dependence of $N_i$, if any, is not large compared to the experimental uncertainty. It is therefore sufficient to treat the $N_i$ as constants within the measurement uncertainties in Table 1.

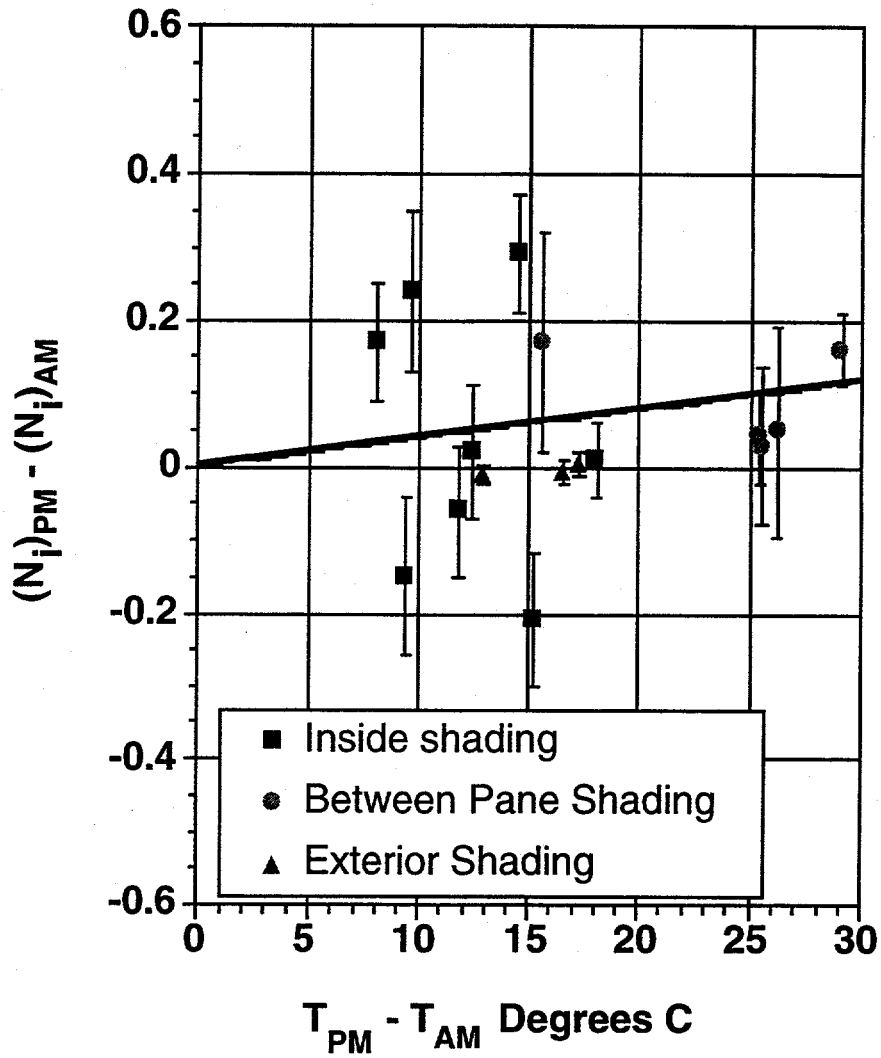



***Figure 4.*** *Changes in Inward-Flowing Fraction for a Shading Layer in Direct Sunlight (PM) Compared with Darkness or Diffuse Daylight (AM), Verses Temperature Elevation Due to Sunlight. The solid curve is a fit to the between-pane shading data only.*

**Table 2.** Differences between Afternoon and Night/Morning Values of Inward-Flowing Fraction

| System | Layer | Mean PM-AM Temperature Difference, °C | Mean PM-AM Difference, $\Delta N_i$ | Standard Deviation, $\sigma(\Delta N_i)$ | Estimated Measurement Error |
|---|---|---|---|---|---|
| Interior Blind with Single Glazing | Blind | 12 | 0.055 | 0.16 | 0.07 |
| Interior Blind with Double Glazing | Blind | 16 | 0.13 | 0.16 | 0.08 |
| Blind between Panes of Double Glazing | Blind | 25 | 0.10 | 0.10 | 0.08 |
| Blind between Panes of Double Glazing with Low-E | Blind | 12 | 0.11 | 0.08 | 0.05 |
| Exterior Blind on Single Glazing | Blind | 17 | -0.011 | 0.004 | 0.01 |

This conclusion must be regarded as encouraging, but preliminary because of the lack of a plausible model of temperature dependent inward-flowing fractions to test against the data. In this research all of the issues regarding inward-flowing fraction measurement procedure, tests for temperature and weather dependence, and methods of extracting information from the measurements had to be addressed simultaneously, and not surprisingly we do not regard our tests as definitive on this issue. It is possible that either improved analysis or more accurate and controlled tests will reveal behavior of the inward-flowing fractions that was masked by measurement uncertainties or analysis artifacts in this treatment.

**Wind Dependence**

The evidence for insensitivity to exterior conditions is somewhat weakened by the possible effects of wind. At the Reno test site under summer conditions, wind speeds tend to be low in the night and morning and significantly higher in the afternoon. Because the overall AM-PM variation in inward-flowing fraction is small, we have not yet attempted to determine the effects of wind speed changes, and it may in fact not be possible to do so. However, there is some reason to expect that rising temperatures and increasing wind speed may exert opposite effects on the inward-flowing fraction. Rising mean temperatures tend to increase radiative heat transfer coefficients, while rising temperature differenced increase convective effects. Since outdoor as well as glazing temperatures rise in the afternoon while interior temperatures remain fixed (except for small surface temperature increases), one would expect that the net effect of the temperature rise would be to decrease the interior film resistance more than the exterior. This would tend to increase the inward-flowing fractions. On the

other hand, rising wind speed decreases the exterior film resistance without affecting the interior. This would tend to decrease the inward-flowing fraction. From this it can be seen that a higher afternoon wind speed will tend to offset the effect of higher afternoon temperatures. Attempts to measure or estimate the magnitude of this effect are beyond the scope of this paper. Caution should be exercised in applying our observation of little change between irradiated and non-irradiated inward-flowing fractions to situations where the correlation between wind and irradiation is different.

We note that the observed insensitivity of $N_i$ to layer temperature and irradiation conditions implies that, to the accuracy level of these results, the $N_i$ could equally well be measured in an indoor thermal facility such as a hotbox. However, the typical exterior 6.7 m/s air flow condition on the exterior in a hotbox test would be an inappropriate condition for such tests. Our data does not demonstrate that the $N_i$ are insensitive to this magnitude of exterior local air flow.

## DISCUSSION

The values of $N_i$ in Table 1 in general confirm existing theoretical ideas and add information for new systems. The model of (Farber, Smith et al. 1963) would predict for the interior venetian blind at 45° inside double glazing values for the shading, inner glass and outer glass of 0.89, 0.56 and 0.15, respectively, in reasonable agreement with our measured values (seventh line in Table 1) of 0.86 ± 0.06, 0.69 ± 0.14, and 0.21 ± 0.09. We note that this is the first direct experimental check of these individual $N_i$ values.

Table 1 contains a number of tantalizing hints at dependence of the behavior of inward-flowing fractions on factors such as blind tilt or shading layer geometry, but in general the results are not accurate enough to make speculation about these dependences fruitful. As discussed above, this stems mainly from the care taken in this experiment to be sensitive to possible temperature dependences. That issue having been largely resolved, there would be no technical obstacle to repeating the measurements with a higher applied blind power in order to more definitively study the detailed behavior of various systems. In the meantime Table 1 provides an ititial data base of inward-flowing fractions for prototypic systems that can be used in deriving solar heat gain coefficients from solar-optical (rather than calorimetric) data.

## CONCLUSIONS

It is possible to make direct measurements of layer-specific inward-flowing fractions of absorbed energy using a co-heating method and a suitably accurate calorimetric facility. The resulting layer-specific inward-flowing fractions do not show marked dependence on temperature, irradiation or exterior weather conditions, although compensating weak dependences on several of these factors cannot be ruled out. These observations make derivation of fenestration solar heat gain coefficients from laboratory solar-optical data, utilizing thermal-optical separation, a viable technique.

## ACKNOWLEDGEMENTS

This research was jointly supported by ASHRAE, as Research Project 548-RP under Agreement No. BG 87-127 with the U.S. Department of Energy, and by the Assistant Secretary for Energy Efficiency and Renewable Energy, Office of Building Technologies, Building Systems and Materials Division of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

The efforts of Dennis DiBartolomeo, Mary Hinman, Jonathan Slack, and Mehrangiz Yazdanian were vital to support of the MoWiTT facility. Special thanks are due to the MoWiTT operational team, Carol Ann Caffrey, Steve Lambert and Michael Streczyn, whose patient and continuous efforts in running the MoWiTT over several years made possible the inward-flowing fraction measurements. We are indebted to the Experimental Farm, University of Nevada at Reno, for their hospitality in providing a field site and for their cooperation in our activities.

## REFERENCES

Farber, E. A., W. A. Smith, et al. (1963). "Theoretical Analysis of Solar Heat Gain Through Insulating Glass with Inside Shading." ASHRAE Trans. **69**: 392.

Klems, J. H. (1988). "Measurement of Fenestration Net Energy Performance: Considerations Leading to Development of the Mobile Window Thermal Test (MoWiTT) Facility." J. Solar Energy Eng. **110**: 208-216.

Klems, J. H. (1994A). "A New Method for Predicting the Solar Heat Gain of Complex Fenestration Systems: I. Overview and Derivation of the Matrix Layer Calculation." ASHRAE Trans. **100**(pt. 1): 1065-1072.

Klems, J. H. (1994B). "A New Method for Predicting the Solar Heat Gain of Complex Fenestration Systems: II. Detailed Description of the Matrix Layer Calculation." ASHRAE Trans. **100**(pt.1): 1073-1086.

Klems, J. H., S. Selkowitz, et al. (1982). A Mobile Facility for Measuring Net Energy Performance of Windows and Skylights. Proceedings of the CIB W67 Third International Symposium on Energy Conservation in the Built Environment. Dublin, Ireland, An Foras Forbartha. 3.1.

Klems, J. H., J. L. Warner, et al. (1995). ASHRAE Solar Heat Gain Project 548-RP Final Report: A New Method for Predicting the Solar Heat Gain of Complex Fenestration Systems. Lawrence Berkeley Laboratory, Technical Report LBL-36995.

Yellott, J. I. (1966). "Shading Coefficients and Sun-Control Capability of Single Glazing." ASHRAE Trans. **72**: 72.