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ABSTRACT

Windows admit radiant and conducted heat energy as well as light and, for this reason, effective means for control is mandatory. Venetian blinds, providing continuous solar control, are ideal for energy efficient windows. They may be closed in the summer to block out undesirable solar radiation and opened in the winter to admit the valuable energy of the sun while providing year-round glare free illumination. Architects, engineers and manufacturers have been reluctant to promote the use of venetian blinds as energy saving products because of remaining uncertainties in the technology. This cooperative program involving industry, government and a university research team has developed predictive equations and has confirmed their ability to accurately predict shading coefficients through experiments in an environmental simulator with an artificial sun. Ten venetian blinds with a wide range of surface finishes, including gloss and satin finish paints, polished aluminum, chrome deposition and units with different colors on the upper and lower surfaces of the slats were included in the experimental work.

In addition, the effect of solar incidence and slat angle on blind reflectance and shading coefficient was determined. The impact of varying incidence and slat angle on building energy load is discussed.

SUMMARY

Venetian blinds, providing continuous solar control, are ideal for energy efficient windows. They may be closed in the summer to block out undesirable solar radiation and opened in the winter to admit the valuable energy of the sun while providing year-round glarefree illumination. Earlier studies have shown that with proper control and use, interior shading devices can save a minimum of 10 and up to 30 percent of the overall yearly heating and cooling energy consumption of typical glass paneled commercial office buildings. Since energy consumed by commercial buildings is estimated to be as much as 15 percent of total energy consumption in the United States, these savings are very significant and equivalent to 0.35 million barrels of oil per day.

Architects, engineers and manufacturers have been reluctant to promote the use of venetian blinds as energy saving devices because of remaining uncertainties in the technology. Levolor Lorentzen, Inc., the leading producer of venetian blinds and Stevens Institute of Technology, a small private college devoted to engineering and science have joined together and, with the cooperation and support of the Department of Energy and the University of California at Berkeley, have undertaken an analysis, test and evaluation of venetian blinds. The work was divided into four major tasks:

1. Comparison of measured shading coefficients with predicted values, using the Stevens-Levolor Environmental Simulator with an artificial sun.
2. Refinement of predictive equations for shading coefficients.
3. Determination of the significance of solar angle of incidence.

4. Development of improved procedures for estimating annual energy requirements based on the findings of the initial work.

These objectives are fully consistent with the LBL/DOE research program which has as its goal a major reduction in the consumption of non-renewable energy resources in buildings.

Early research into solar heat gain through windows by the American Society of Heating, Refrigerating and Air-Conditioning Engineers, led to the development of shading coefficients defined as the ratio of solar heat gain through a glazing system to the solar heat gain through double strength glass under the same set of conditions. Most early shading coefficients were determined by experiment in a solar calorimeter. Analytical techniques have been developed and are now used to calculate shading coefficients based on the solar optical properties of the elements within the glazing system. Discrepancies in proprietary data for venetian blinds have raised questions as to the validity of the mathematical models. As an example, the analysis does not consider the free convective air flow around venetian blinds. In addition, various interpretations of proportioning of energy within the system of an interior blind fitted to a single glass window have been suggested.

Resolution of these uncertainties required additional analysis of the basic heat transfer through glass-blind glazing systems and corresponding experimental investigations to confirm the predictive methods. The needed environmental simulator with artificial sun, designed and built by Stevens Institute of Technology under contract to Levolor Lorentzen, Inc. for evaluating their products, was made available for this work.

The quality of the artificial sun and usefulness of the simulator to determine shading coefficients was established at the start of the program. Among the basic characteristics investigated and measured are solar spectral energy proportioning, directionality and ratio of diffuse to total radiant energy. Measured shading coefficients for three glasses: clear, heat absorbing and reflective, agreed with published values and verified the environmental simulator system and procedures for obtaining shading coefficients and measurements of solar optical properties of elements used in glazing systems.

Ten venetian blinds with a variety of surface finishes, including gloss and satin finish paints, polished aluminum, chrome deposition and units with different colors on the upper and lower surfaces of the slats were included in the experimental work. Transmittance and reflectance were measured and used in the predictive equations for calculating shading coefficients.

The analytical approach taken in developing the predictive equations follows the techniques used by the American Society of Heating, Refrigerating and Air Conditioning Engineers in developing expressions for the solar heat gain through single and double glazing. In extending these basic concepts to glass-blind systems we have neglected the resistance of the blind to convective heat flow based on the reasonable assumption that air is free to flow through and over the blind slats. The equations reflect the concept that solar heat absorbed by the blind remains within the room. In addition, the fractions of heat flowing from the glass are determined by the film and overall heat transfer coefficients. The ability of the derived equation to accurately predict shading coefficients for a wide range of blind colors, slat angles and solar incidence angles was confirmed by the experimental part of the program.

The variation in shading coefficient with solar incidence angle is found to be relatively small but the effect of slat angle is shown to be very important. Thus, variations in blind setting should be permitted and accounted for in any estimations of solar energy loads on the interior of a building with single glass-blind window treatment.

It is recommended that the development of very high reflectance blinds suitable for mass production at reasonable cost be pursued. Other, more complex glazing systems, must also be studied to further the national goal of large scale energy savings through control of heat flow through windows.

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NOMENCLATURE

The following symbols and definitions are used in this report:

DS	double strength (reference standard clear glass)
F	solar heat gain coefficient
h	surface film coefficient of heat transfer, Btu/hr-sq ft deg F
I	solar intensity, Btu/hr-sq ft
k	constant of proportionality
N	inward flowing fraction of solar heat absorbed by the glass
Q	heat flow, Btu/hr
SC	shading coefficient = 1.15 F of fenestration
SHGF	solar heat gain factor, Btu/hr-sq ft
SHG	solar heat gain, Btu/hr
t	temperature, deg F (Fahrenheit)
U	overall heat transfer coefficient, Btu/hr sq ft-deg F
α	absorptance
θ	solar incidence angle, deg
ρ	reflectance
τ	transmittance
ψ	slat angle, deg

Subscripts

M	measured
P	predicted
o	outer or outdoor glass unit
s	space (between)
i	inner or indoor blind unit
io	inward flowing heat absorbed by outer glass unit
ii	inward flowing heat absorbed by inner blind unit
2	inner combined film coefficient (including porous blind)

A bar over a symbol denotes the combined glass-blind average value.

INTRODUCTION

Background

The design of energy efficient buildings now and in the foreseeable future will require increased energy efficient utilization of fenestration. Windows admit radiant and conducted heat energy as well as light and, for this reason, effective means for control is mandatory. In summer we wish to block out undesirable solar radiation but in winter we wish to retain the valuable energy of the sun, while enjoying year-round glarefree illumination. It has been shown[1] that with proper control and use of shading devices such as venetian blinds, a minimum of 10, and up to 30 percent savings in overall yearly heating and cooling energy consumption, depending on locale, of a typical glass-faced modern commercial office building can be realized while at the same time improving the aesthetic and physical working environment. Architects, engineers and manufacturers have been reluctant to promote the use of venetian blinds as energy saving devices because of remaining uncertainties in the technology.

Early research into solar heat gain through windows by the American Society of Heating, Refrigerating and Air-Conditioning Engineers, led to the development of shading coefficients defined as the ratio of solar heat gain through a glazing system to the solar heat gain through double strength glass under the same set of conditions. Most early shading coefficients were determined by experiment in a solar calorimeter. Analytical techniques have been developed and are now used to calculate shading coefficients based on the solar optical properties of the elements within the glazing system. Discrepancies in proprietary data have raised questions as to the validity of the mathematical models. As an example, one widely used analysis does not consider the free convective air flow around venetian blinds. In addition, various interpretations of proportioning of energy within the system of an interior blind fitted to a single glass window have been suggested. Resolution of these uncertainties required additional analysis of the basic heat transfer through glass-blind glazing systems and corresponding experimental investigations to confirm the predictive methods.

Stevens Institute of Technology, a small private college devoted to engineering and science and Levolor Lorentzen, Inc., the leading manufacturer of venetian blinds, joined together to unravel the muddled technology. Working together, Stevens and Levolor explored the relationship between building energy use and interior shading and concluded that significant benefits could be derived. Their modest research budget permitted the design and construction of an environmental simulator with an artificial sun for product testing and evaluation. Recognizing the need for a fundamental investigation of the heat transfer through a glass-blind system and cognizant of the limitation of their own budget, the research team petitioned the Department of Energy for additional support.

The U. S. Department of Energy's Windows Program managed through the Lawrence Berkeley Laboratory at the University of California had also shown that in many instances, when treated as a dynamic element of a building, a window can provide net energy benefits. The DOE/LBL program is directed at developing improved design strategies for using window systems in walls, and assisting in the commercialization of energy efficient window products and accessories. The cooperation and support of the Department of Energy was sought to ensure completion of the program and to accelerate implementation of the results by architects and engineers.

This document serves as the final report for the detailed study of energy efficient windows fitted with interior blinds undertaken by contract with Lawrence Berkeley Laboratory for the U. S. Department of Energy.

Research Objectives

The prime objective of this study was the analysis, test and evaluation of new types of reflective venetian blinds, several of which were designed to achieve low shading coefficients and one which was expected to achieve a value of 0.2. The work was divided into four major tasks:

1. Comparison of measured shading coefficients with predicted values, using the Stevens-Levolor environmental simulator.
2. Refinement of the predictive equations for shading coefficients.
3. Determination of the significance of solar angle of incidence.
4. Development of improved procedures for estimating annual energy requirements based on the above results.

Significance of Work

Windows, because of their comparatively high thermal conductivity, permit heat losses that account for 8% of the energy used nationally for heating, cooling and ventilation of buildings. A well insulated wall system may be expected to have a U-value an order of magnitude less than the 1.0 Btu/ft^2 hr^{o}F attributed to a single light of glass. For this reason, many architects and building code officials have suggested minimizing window area for energy efficient designs. Other studies have suggested that double glazed fenestration may have a net energy gain over the heating season for many orientations. It is clear that among the many requirements for energy efficient windows are:

1. High transmission of solar radiation during the heating season.
2. Maximum reflectance of solar radiation during the cooling season.

Our further understanding of the heat transfer through windows with the attainment of the specific research objectives defined for this program provides the basis for the rapid implementation of energy efficient interior shading products. The potential savings are 0.35 million barrels of oil per day.

ANALYSIS

Heat Transfer Through Windows

Early research by the American Society of Heating, Refrigerating and Air-Conditioning Engineers,[2] has shown that direct radiant solar heat gain through windows is a function of the angle of incidence of the sun and that this relationship for various glass and glass shading components differs approximately by a constant factor. This led to the development of the "shading coefficient" of a window system which is defined as the ratio of solar heat gain through a glazing system under a specific set of conditions (e.g., blind angle and sun conditions) to the solar heat gain through a single light of double strength sheet glass under the same set of conditions:

$$SC = \frac{\text{SHG through glazing system}}{\text{SHG through DS clear glass}} .$$

Most early shading coefficients were determined from ratios of direct heat measurements using a solar calorimeter that tracked the sun.

Solar intensity and solar heat gain factors for the standard reference glass, double strength clear glass, are now tabulated for latitudes from 0° to 64° North at 8° intervals for both horizontal and vertical surfaces at sixteen orientations.[2] ASHRAE has also assembled a table of typical shading coefficients for a variety of glasses and combinations of glass with interior shading devices. These data enable architects and engineers to estimate the heat gain or loss through fenestration by means of the following equation:

(1) Total Heat Gain = SC x SHGF + $U(t_o - t_i)$, where:

SC = shading coefficient
SHGF = solar heat gain factor, Btu/hr-sq ft
U = overall heat transfer coefficient, Btu/hr-sq ft-deg F
t_o = outside temperature, deg F
t_i = inside temperature, deg F

Air movement across the outdoor surface of the glass is usually assumed to be 7.5 mph and indoors to be still air conditions, with a standard ground reflectance of 0.2. Maximum SHGF occurs near 35 degrees solar incidence angle.

The above equation shows the relative heat gains (or losses) through glass areas within a building. These gains are dependent on the following characteristics:

- Solar radiation intensity and incident angle
- Outdoor-indoor temperature difference
- Air movement across the surfaces of the glass
- Shading device characteristics
- Low temperature radiation from the surfaces of the fenestration

Equation (1) was developed from the more basic relationship

$$\text{Total Heat Gain} = \begin{array}{c}\text{Transmitted}\\ \text{Solar}\\ \text{Radiation}\end{array} + \begin{array}{c}\text{Inward Flow}\\ \text{of absorbed}\\ \text{Radiation}\end{array} + \begin{array}{c}\text{Conduction}\\ \text{Heat Gain}\end{array}$$

(2) Total Heat Gain = Solar Heat Gain + Conduction Heat Gain,

where: conduction heat gain, $U(t_o - t_i)$, occurs whether the sun is shining or not. When the outside temperature is greater than the inside temperature, the heat flow is inward.

Predictive Methods for Determining Shading Coefficients

More recently, analytical techniques have been developed to permit rapid, economical determination of SC based on the solar optical properties of the glass and the shading device, i.e., reflectance, transmittance and absorptance measurements of each component. However, some questions have arisen as to the validity of SC values computed for a single glass-blind system using double-glazing theory with a dead air space, since that analysis does not consider the free flow of air around and through modern one-inch wide blinds. In addition, various interpretations of proportioning of energy within the system of an interior blind fitted to a single glass window have been suggested. The schematic diagram in Figure 1, Heat Transfer Through Selected Glazing Systems, illustrates the heat transfer through a single glass and glass-blind system. For the same indoor and outdoor air temperatures, the relative air velocities at the inner and outer faces of the glass will govern the fraction of the energy absorbed by the glass ultimately conducted into the room. Some researchers have allowed for a portion of the energy absorbed by the blind to be radiated back to and absorbed by the glass. We are concerned about this apportioning, since the warmer sunlit glass requires a net loss of radiated and absorbed energy to the cooler blind. As a result, we postulate that all energy absorbed by an interior-mounted blind with sunlit glass having emittance equal to or greater than that of the blind ramains within the room. This energy apportioning is shown in Figure 1. It remains to be determined just what proportions of the energy are reflected and conducted back through the glass and what proportions remain in the room for various blind angle settings at various solar incidence angles.

For a single light of glass, Equation (2) may be written per unit area as:

$$\text{Total Heat Gain} = [\tau + N\alpha]I + U(t_o - t_i)$$

$$\text{Total Heat Gain} = FI + U(t_o - t_i)$$

where, for single glass

$F = \tau + N\alpha$ = Solar Heat Gain Coefficient, characteristic of the fenestration and incidence angle

τ = transmittance of the glass

α = absorptance of the glass

N = inward flowing fraction of solar heat absorbed by the glass

I = solar intensity, Btu/hr-sq ft

And, by definition

$$SC = \frac{\text{F of Fenestration}}{\text{F of Double Strength Clear Glass}}$$

and since F of DS clear glass for standard summer conditions is 0.87,

$$SC = 1.15 \text{ F of Fenestration}$$

This same approach, when developed for an interior-mounted blind with a single light of glass, produces the following equations - borrowing the form from double glazing theory used by ASHRAE and as shown in Figure 5 but assuming $N_{ii} = 1$:

$$\text{Total Heat Gain} = FI + U(t_o - t_i)$$

$$\text{Total Heat Gain} = [\bar{\tau} + N_{io}\,\bar{\alpha}_o + N_{ii}\,\bar{\alpha}_i]\, I + U(t_o - t_i)$$

where, for a glass-blind system:

$F = [\bar{\tau} + N_{io}\bar{\alpha}_o + N_{ii}\bar{\alpha}_i]$ = Solar Heat Gain Coefficient

$\bar{\tau} = \tau_i \left(\dfrac{\tau_o}{1 - \rho_o\rho_i}\right)$ = transmittance of the glass-blind system (ρ_i measured from outside)

$\bar{\alpha}_o = \alpha_o + \alpha_o\rho_i \left(\dfrac{\tau_o}{1 - \rho_o\rho_i}\right)$ = net absorptance of the outer component of the system (the glass)

$\bar{\alpha}_i = \alpha_i \left(\dfrac{\tau_o}{1 - \rho_o\rho_i}\right)$ = net absorptance of the inner component of the system (the blind)

$N_{io} = N = \dfrac{U}{h_o}$ = inward flowing fraction of heat absorbed by the glass

$N_{ii} = 1.0$ = inward flowing fraction of heat absorbed by the blind

$U = \dfrac{1}{1/h_o + 1/h_s + 1/h_i + R_{blind}}$ = overall heat transfer coefficient neglecting glass resistance

This analysis assumes that air is free to flow through and over the blind slats, resulting in natural convection at the inside surface of the glass. We may take an overall inside coefficient h_2, such that

$$1/h_2 = 1/h_i + 1/h_s + R_{blind}$$

then

$$U = \frac{1}{1/h_o + 1/h_2} = \frac{h_o h_2}{h_o + h_2}$$

giving

$$N_{io} = \frac{h_2}{h_o + h_2}$$

Substituting for a single glass-blind combination with $N_{ii} = 1.0$

$$F = \bar{\tau} + N_{io}\,\bar{\alpha}_o + 1.0\,\bar{\alpha}_i \qquad (3)$$

The F of the glass-blind combination may be written as a function of blind reflectance ρ_i for a given set of glass solar optical properties τ_o, ρ_o, α_o:

$$F = \bar{\tau} + \bar{\alpha}_i + N_{io}\,\bar{\alpha}_o$$

$$F = \tau_i\,\left(\frac{\tau_o}{1-\rho_o\rho_i}\right) + \alpha_i\,\left(\frac{\tau_o}{1-\rho_o\rho_i}\right) + N_{io}\,\left[\alpha_o+\alpha_o\rho_i\,\left(\frac{\tau_o}{1-\rho_o\rho_i}\right)\right] \qquad (3a)$$

but since

$$\tau_i + \rho_i + \alpha_i = 1$$

then

$$\tau_i + \alpha_i = 1 - \rho_i$$

so that

$$F = (1 - \rho_i)\,\left(\frac{\tau_o}{1-\rho_o\rho_i}\right) + N_{io}\,\left[\alpha_o + \alpha_o\,\rho_i\,\left(\frac{\tau_o}{1-\rho_o\rho_i}\right)\right] .$$

Shading coefficient for a glass-blind system may now be expressed as

$$SC = 1.15 \text{ F of Fenestration}$$

where the factor 1.15 is the reciprocal of F for standard reference glass, then

$$SC = 1.15\,\left\{(1 - \rho_i)\left(\frac{\tau_o}{1-\rho_o\rho_i}\right) + N_{io}\,\alpha_o\left[1 + \rho_i\left(\frac{\tau_o}{1-\rho_o\rho_i}\right)\right]\right\} \qquad (4)$$

This predictive equation was confirmed by the experimental program.

EXPERIMENTAL APPARATUS AND PROCEDURES

Environmental Simulator with Artificial Sun

Simulator

The Building Technology Research Division of the Davidson Laboratory at Stevens Institute of Technology working with the support of Levolor Lorentzen, Inc., the acknowledged leading manufacturer of venetian blinds, have designed and built the Stevens-Levolor environmental simulator. This new test facility was designed to provide accurate calorimetric measurement of total solar heat gains through glass-blind systems in order to obtain the shading coefficients of many of Levolor's newer products. In addition, the relationships between energy use and interior shading have been investigated with the aim of increased utilization of innovative venetian blinds with shading coefficients significantly lower than values currently found in architectural and engineering handbooks. Values as low as 0.2 have been previously reported for unique reflective finishes.

The actual layout of the Levolor simulator includes two thermally-insulated test chambers connected by a window, with an adjustable angle solar simulator in the outdoor chamber; see Figures 2, 3 and 4. The steady-state heat flow into the "indoor" room is accurately measured by the heat removed in the water flowing through a heat exchanger that maintains constant temperature in the indoor room. This water is supplied prechilled from an outside reservoir and is circulated into and out of the test room where the water temperatures in and out and the flow rate are very accurately measured with platinum resistance thermometers and a turbine flow meter. Specific information on the instrumentation may be found in Appendix 1.

In order to minimize wall heat losses, six inches of polyurethane foam were sandwiched between fiberglass-coated plywood panels to give the indoor room a measured overall heat transfer coefficient of 0.033 Btu/hr-deg F-ft^2. The total indoor room wall heat loss is then 9 Btu/hr-deg F.

The solar heat gain test procedure is to seal both chambers, bring them to equilibrium with the "outdoor" solar simulator ON and the glass fully warmed up, and then to adjust the cooling water flow rate to maintain constant indoor temperature while keeping the temperatures of the two chambers and outer laboratory environment within 1.0 degree Fahrenheit of one another. This procedure provides true "steady-state" measurement of the total radiant and absorptive-conductive heat flow into the indoor test room through the fenestration opening with minimal wall corrections. One computational adjustment required is for the heat load due to the test room electric blower motor, which is located within the room and moves the air through the heat exchanger. The power consumption of this blower is measured and found to be approximately 760 Btu/hr. This load is constantly monitored and is subtracted from the measured total heat load removed by the cooling water.

Total solar heat gain to the test room, a function of the solar simulator incidence angle and installed fenestration treatment, is measurable to within ± 18 Btu/hr. The heat balance is as follows:

$$Q_{in} = Q_{out} \quad \text{where } Q \text{ is heat flow in Btu/hr}$$

$$SHG + Q_{Blower} = Q_{walls} + Q_{Heat\ Exchanger}$$

where SHG is total solar heat gain through the fenestration. With temperatures set so that $Q_{walls} = 0$ and no temperature difference indoors to outdoors, then

$$SHG = Q_{Heat\ Exchanger} - Q_{Blower}.$$

The desired shading coefficient is the ratio

$$SC = \frac{\text{SHG of glass-blind system}}{\text{SHG of reference glass}}$$

$$SC = \frac{(Q_{OUT} - Q_{BLOWER}) \text{ glass-blind under test}}{(Q_{OUT} - Q_{BLOWER}) \text{ reference glass}}$$

The "outdoor" solar room is cooled by a thermostatically-controlled air conditioning system.

Artificial Sun

The following characteristics are considered desirable for good simulation of the sun at a fenestration opening in a building:

1. Relatively uniform intensity over the glass area.
2. Adjustable intensity (insolation) of from 50 to 250 Btu/ft^2.
3. Good directionality (along the axis of the "sun").
4. A spectrum with energy content in the various wavelength bands closely proportional to that of the sun.
5. Reflected and diffuse radiant energy minimized and documented for any tests that may be influenced by this radiation.

The solar simulator consists of four, 400-watt, high intensity multi-vapor lamps and associated power equipment mounted on an adjustable lamp bank that utilizes five, 300-watt and four 200-watt incandescent lamps in an array similar to that laid out by earlier researchers[3] to fill in and provide relatively uniform lighting at the window and good simulation of the sun's spectrum at reasonable cost.

Measuring Solar Optical Properties

Solar optical properties of venetian blinds and window glasses are measured in separate tests. A black box mounted behind the window absorbs unwanted reflected energy. Average transmittance and reflectance are determined with pyranometers. See Figure 3.

Blind slat angles are set and held by means of a small motor and potentiometer arrangement. Angular position of the potentiometer is calibrated using a pointer mounted on the central slat that is set against a protractor on the window frame.

RESULTS

Confirmation of Test Methods

Quality of Artificial Sun

The basic characteristics of the solar simulator have been measured and documented in Table 1, Solar Simulator Light Beam Characteristics, revealing a reasonably good representation of the solar spectral energy proportioning, good directionality and an approximately 25 percent proportion of diffuse to total radiant energy. Currently, an average insolation of 100 Btu/hr-ft^2 is provided normal to the window opening for 35 degrees incidence angle. This intensity is considered ample to obtain an accurate measurement of shading coefficient, which is merely a ratio of solar heat gains for conditions of equal indoor and outdoor temperatures. Shading coefficient, by definition, is independent of solar intensity. Higher values of insolation may be realizable with additional investment in the future.

Shading Coefficients for Several Glasses

Since the measurement of shading coefficient as well as of solar optical properties (reflectance, transmittance and absorptance) is generally performed using natural sunlight on a clear day, this experimental work using an artificial sun has little or no precedent. Therefore, confirmation of the procedures and techniques was made by measuring the shading coefficient and the solar optical properties of three typically-available 1/4-inch thick single lights of glass: clear, gray heat absorbing and silver reflecting -- with the coating on the indoor surface of the glass.

Table 2, comparing measured and predicted shading coefficients, verifies the environmental simulator system and procedures for obtaining shading coefficients and measurements of solar optical properties of fenestrations. The verification is on the basis of a comparison of published and accepted shading coefficients with measured values for three glasses - clear, heat absorbing and reflective.

The time required to achieve this precision was found to depend on glass warm-up time with the solar simulator lights at equilibrium. These conditions are reached at from one to two hours after turn-on of the system, when accurate measurement of total solar heat gain of any given fenestration can commence. However, once the glass is heated up, addition of a blind angle change or other change in reflectance at the window can produce a new set of equilibrium glass temperatures in as little as twenty minutes.

Measured Solar Optical Properties of Blinds

The venetian blinds supplied by Levolor Lorentzen, Inc. for this program are listed and described in Table 3. It is to be noted that they include six painted finishes - some glossy and some satin, one polished aluminum finish, one chrome deposited finish and two blinds with different colors and finishes on the upper and lower surfaces of the slats. These blinds all have one-inch wide, 1.2 width to spacing ratio, slightly convex-shaped (upper surface) slats and are representative of current large scale production items.

It should be stated here that none of the high-production blinds supplied had the anticipated high reflectance finish produced in limited quantities to special order in recent years. As a result, the measured reflectances listed with the other solar optical properties in Table 4 for a typical 35 degree incidence angle, do not exceed 0.6 - even for the closed blind position. However, reflectances of up to 0.9 have been measured for specific highly reflective blinds in closed position in recent years with higher than 0.6 for 45 degree position. These blinds generally had highly polished mirror-like metallic finishes and were quite costly to produce. It is hoped that highly reflective paints may become available which could fill the need for lower production cost energy-efficient blinds discussed throughout this report.

Measured Shading Coefficients for Blinds

The shading coefficients as measured in the simulator which provides essentially still air conditions on both sides of the fenestration are presented in Table 5, Measured Shading Coefficients of Experimental Venetian Blinds. Actual air velocities were measured to be everywhere less than one-foot per second within six inches of both sides of the bare window glass without solar heat but with air circulation blowers running in both sealed chambers (indoor and outdoor). Thus, heat conduction and natural convection are free to develop in the vicinity of the glass and blind system under solar loading. This, plus the fact that observed average temperatures on both sides of the glass are within one to two degrees F for clear glass under a solar heat load, is why still air conditions ($N_{io} = 0.5$) are used for computing the fraction of the heat energy absorbed in the glass that passes by convection and radiation into the indoor room of the simulator.

Comparison of Measured and Predicted Shading Coefficients

Table 6 shows a direct comparison between predicted shading coefficients for still air conditions with the simulator measured values. The measured values were adjusted to allow for the 1/4-inch clear glass installed in the simulator in the following manner:

$$SC_M = \frac{\text{SHG through glazing system}}{\text{SHG through 1/4-inch clear glass}} \times 0.94$$

where the factor $0.94 = \dfrac{\text{SHG through 1/4-inch clear glass}}{\text{SHG through DS clear glass}}$

Calculated shading coefficients for ASHRAE summer conditions ($N_{io} = 0.267$) are given in the last column of Table 6 to show the effect of a 7.5 mph outside wind on the shading coefficients of various fenestrations. Figure 6 was plotted to examine the variations in measured shading coefficients with blind reflectance for each slat position tested. The solid lines in the figure represent the predicted shading coefficient using Equation (4) with $N_{io} = 0.5$. The dashed lines represent the standard deviation for the measured data relative to the predicted line. It may be seen that the predicted shading coefficient is almost but not quite linear with reflectance.

The agreement between measured solar heat gain ratios and predicted values based on solar optical reflectance of the blind is considered very good. Since convection velocities set up at the inner side of the glass are partly due to the blind absorptance and reflectance and the relative porosity to air flow between the slats, it is surprising how well a single value of N_{io} can be fitted to the measurements in Figure 6. The term in the equation involving this fraction is the heat absorbed in the glass and only represents a portion of the total heat load passing through the fenestration to the room. However, this term becomes a major portion of the heat load for a highly reflective blind. The agreement is sufficiently good for predictive purposes with different finishes, colors and surfaces as exemplified by the ten test blinds.

<u>Effect of Solar Incidence and Slat Angle on Shading Coefficients</u>

The sensitivity of shading coefficient to blind reflectance as a function of glass type and the fraction N_{io} is shown in Figures 7 and 8. These predicted shading coefficients computed by Equation (4) show that high reflectance blinds, $\rho_i = 0.9$ for example, will result in shading coefficients as low as 0.2 for 1/4-inch clear glass but only 0.30 for 1/4-inch heat absorbing glass for $N_{io} = 0.3$. It is obvious in these figures that the N_{io} fraction has a much more important effect on shading coefficient for a typical heat absorbing glass as compared to a clear glass with the same interior reflecting blind. Thus the energy-saving effect of a retrofit of blinds to existing glass is seen to be dependent on the properties of the installed glass.

Table 7 gives a listing of measured shading coefficients and measured blind reflectances for the No. 2 off-white, satin finish blind at three different solar incidence angles for the several slat angles tested. This table and Figure 9 reveal the relatively small effect of incidence angle on shading coefficient, while Figure 10 shows that the measured variations are due primarily to the reflectance differences that occur with changes in solar incidence/slat angle combination.

Figure 11 is a graphical display of the combined effects of slat angle and solar incidence angle (θ) on measured reflectance for the No. 2 blind. This figure shows that basically one curve can be fitted to the reflectances if the appropriate angle scale is selected as shown. In this manner, reflectance may be computed for any other incidence (θ) and slat angle (ψ) if the curve has been measured for one incidence angle over a wide range of slat angles. Empirically, this may be expressed as

$$\rho_i = k(\theta + \psi) \cos\theta \ . \tag{5}$$

Table 8 lists the fitted values of k for each test blind for reflectance. These k values are a good relative measure of the average brightness of each blind, except for several points near the wide open zero degree position. The k values are seen to cluster into roughly five levels of brightness for the ten test blinds. It is anticipated that k may be as high as 0.01 for a highly-reflective blind.

Figure 9 has been replotted for measured shading coefficient against this same angle scale, $(\theta + \psi)\cos\theta$, in Figure 12. The scatter about a mean curve is greatly reduced in Figure 12, indicating the validity of the empirical fit.

DISCUSSION

Estimating Building Heating and Cooling Energy

Energy Savings Estimation

It is suggested that, to any existing procedure for estimating heating and cooling loads used in annual energy savings calculations for a venetian blind (e.g., ASHRAE, Reference 6), a variable shading coefficient term be introduced where formerly a constant value was used. Thus, solar heat gain through a single light of glass with interior shading by means of a venetian blind should be calculated in the following manner:

$$SHG = SC \times \begin{bmatrix} \text{Total Direct + Diffuse Insolation through} \\ \text{standard 1/8-inch Thick DS Clear Glass} \end{bmatrix}$$

where now $SC \neq$ constant but becomes a variable function of θ and ψ, where ψ may be a function of insolation, time of day and season and θ, as a first approximation is the tabulated solar altitude angle which is a function of time of day, month, and latitude of the fenestration.

Note that SC now is calculated using Equations (4) and (5):

$$SC = 1.15 \left\{ (1 - \rho_i)\left(\frac{\tau_o}{1 - \rho_o \rho_i}\right) + N_{io}\alpha_o\left[1 + \rho_i\left(\frac{\tau_o}{1 - \rho_o \rho_i}\right)\right] \right\}$$

$$\rho_i = k(\theta + \psi)\cos\theta$$

with the appropriate substitution of k, θ and ψ values into Equation (5) for the specific blind-glass combination, season and latitude under consideration. Since it is believed that for highly reflective blinds, ψ would be controlled for most effective use of daylighting - e.g., $\psi = f$ (Insolation) - and also would be governed by season for total solar energy management - e.g., closed as much as possible in summer and open as much as possible in winter, except at night - ψ will become a function of insolation, time and season. The actual variation of ψ

must be determined for optimization of daylight and glare control as well as solar heat gain, since artificial lighting affects heating and cooling loads during all seasons of the year.

Several architectural calculations have been made to demonstrate the effects of variable shading coefficient as compared with constant shading coefficient of 0.55 for a typical "light" color blind behind a single 1/4-inch clear glass. Computations were made for the daily solar energy heat load per square foot of window area at 40 deg north latitude for two orientations - facing south and southwest - for two representative days, January 21 (Winter) and June 21 (Summer).

Current practice is to use a single constant value of shading coefficient to compute solar heat gain (or loss), see Reference 7, for example, with no provision for variation with season or solar incidence angle (profile angle for a horizontal blind). This condition was followed for Case I of Table 9. Case II of the same table was computed allowing for variations in shading coefficient according to Equations (4) and (5) with the No. 2 blind characteristics used to represent a typical light color blind. In addition, the blind was assumed open (ψ = 0 deg) for the winter day and closed (ψ = 70 deg) for the summer day. The solar altitude angle variations with time of day tabulated in Reference 8 were used for θ variations to approximate hourly profile angle values in Equation (5). Table 9 shows that fairly large variations in daily solar heat gain/sq ft may be realized simply by opening the blind during the winter season (January 21 as a typical day) on south or southwest oriented windows. The typical summer season (June 21) daily solar heat gains computed for this fenestration show little difference with those including the added complexity of using a variable shading coefficient. In fact, the detailed hourly calculations show relatively small variations in shading coefficient due to varying solar altitude angle during either season at both orientations. The major difference in mean shading coefficient was due to the assumption of open blind (ψ = 0 deg) for the winter day. This gave an average value of about 0.8 versus 0.55 for shading coefficients at both orientations on January 21.

Obviously, many other examples could be used to show other types of blind control, but these simple examples show that the usual procedure of computing solar heat loads through fenestrations using a constant shading coefficient probably gives acceptable energy values as long as the correct mean value is used for the blind reflectance and average blind angles used for a given season. However, it is definitely shown that blind angle changes must be accounted for by using a different mean value of shading coefficient other than the usual tabulated "closed blind" values, even for a typical light-colored blind. Naturally, the percentage variations in heat gain in winter or loss in summer will depend not only on the reflectance of the blind - particularly high-reflectance energy saving blinds open instead of closed - but also on the specific type and number of lights of glass used in the fenestration.

CONCLUSIONS AND RECOMMENDATIONS

The primary findings of this investigation and study enables us to reach the following conclusions and recommendations.

1. The energy ratio, known as the shading coefficient, has been demonstrated predictable as a function of interior blind solar optical reflectance and ratio of film coefficients for a given glass.

2. The energy proportioning to the room, for a fenestration consisting of a single glass fitted with an interior venetian blind, has been shown and proven with precise measurements under carefully controlled conditions using an artificial sun as a source of radiant energy.

3. The variation in shading coefficient with solar incidence angle is found to be relatively small but the effect of slat angle (or blind position) is shown to be a more important parameter that should be accounted for in any estimations of solar energy loads on the interior of a building with a single glass-blind window arrangement.

4. The relative brightness of the outdoor-facing surfaces of a blind is based on the rate of change of average solar reflectance with change in an angle combining solar incidence and slat setting effects. Thus, brightness is a measure of the ability of a given blind to control radiant solar energy heat gains to a room at all angle settings. It is suggested that the empirical equation using this factor be applied to energy calculations where slat angle changes are required for different seasons or controlling systems.

5. It has been found that more work is needed for the development of a high reflectance blind suitable for mass production at reasonable cost, since current mass-produced blinds do not provide the shading coefficient 0.2 value desired and previously reported by other laboratories for special order products.

6. Further, it is believed that shading coefficient claims for many other add-on products should be verified in order to provide fair comparisons between products on other bases such as cost, longevity, eye-appeal, etc. for a given level of energy savings at the window.

7. Additional research is required to investigate and confirm predictive techniques for other glazing systems such as insulating and reflective glass.

8. Further work should be undertaken to determine the significance of air movement on both the interior and exterior glazing surface.

9. Experimental work exploring shading coefficients for angles of incidence greater than 45 degrees should be considered. These investigations should include skylight applications.

ACKNOWLEDGEMENTS

This study could not have taken place without the cooperation and assistance of many.

Levolor Lorentzen, Inc. graciously supplied the Environmental Simulator as well as the numerous blinds and other attachments used in these tests. Mr. Joseph Anderle, Director of Material, Standards and Quality Control at Levolor was especially helpful. We are also indebted to Dr. Rowland Bevans who, in addition to an excellent overview, helped devise a solution to control the chilled water system temperatures and flow rates. The research division of Libbey-Owens-Ford Company provided us with important additional information on the several glass types used for the verification tests.

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Special thanks are extended to Mr. Stephen Selkowitz, the University of California program manager, whose continuing input guided us throughout the program.

Finally, we would like to thank the many individuals working through ASHRAE who developed the shading coefficient concept and most of the equations used to define the solar heat flow through windows.

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TABLE 1

SOLAR SIMULATOR LIGHT BEAM CHARACTERISTICS[1]

A. Distribution of Spectral Energy

Nominal Wavelength Band millimicrons	ASHRAE Sun[2]	Solar Simulator Lamps ALL	Solar Simulator Lamps 4MV[3]
300 - 400 Ultra Violet	.03	.06	.07
400 - 700 Visible	.44	.28	.36
700 - 2800 Infra Red	.53	.66	.57

B. Insolation Measured Normal to Plane of Window

Spectral Filter Band millimicrons	Insolation Btu/hr-ft² ALL	Insolation Btu/hr-ft² 4MV[3]
295 - 2800	107.4	75.0
400 - 2800	100.9	69.2
530 - 2800	92.8	62.7
695 - 2800	70.6	42.5

C. Directionality Averaged Over Three Vertical Stations

1. Basic Simulator Lights

Incidence	ALL	4MV[3]
35 degrees	± 8 deg	± 8 deg

2. Simulator + Honeycomb[4]

35 degrees	± 3 deg	-

Honeycomb causes a 55 to 65 percent light reduction

D. Ratio of Diffuse Light to Total Light

ALL	4MV[3]
0.25	0.18

1. Measured on window centerline at 35 degrees incidence angle
2. P. Moon, for air mass 2.
3. Four multi-vapor lamps only.
4. Hexcel D.S. 6000 aluminum, 3/4-inch cell, 3-inch thick.

TABLE 2

VERIFICATION TEST RESULTS

A. Comparison of Measured Shading Coefficients with Predicted Values

1/4-Inch Glass	SC_M	SC_P
Clear	0.94	0.97
Heat Absorbing	0.80	0.80
Reflecting	0.46	0.45

Measured values, SC_M, were determined in the Stevens-Levolor simulator at 35 degrees incidence and in still air conditions. Predicted values were determined using ASHRAE technique: $SC_P = 1.15\ (\tau + N\alpha)$ for $N = 0.5$ and the simulator measured solar optical properties in B.

B. Comparison of Measured and Typical Published* Solar Optical Properties of Glass

1/4-Inch Glass	Transmittance		Outdoor Reflectance		Absorptance	
	Stevens	LOF	Stevens	LOF	Stevens	LOF
Clear	0.77	0.765	0.09	0.072	0.14	0.163
Heat Absorbing	0.46	0.460	0.07	0.054	0.47	0.486
Reflecting	0.11	0.089	0.32	0.334	0.57	0.577

*Total solar properties measurements of representative samples of these glasses supplied by glass manufacturer's research division.

TABLE 3

DESCRIPTION OF EXPERIMENTAL VENETIAN BLINDS

All Blinds Are One-Inch Width With 0.8-Inch Spacing (Open)

Blind No.	Color Upper Surface/Lower Surface (Convex/Concave)	Surface Finish Upper Surface/Lower Surface (Convex/Concave)
1	White/White	Glossy/Glossy
2	Off White/Off White	Satin/Satin
3	Light Green/Light Green	Glossy/Glossy
4	Aluminum/Aluminum	Polished/Polished
5	Light Tan/Light Tan	Glossy/Glossy
6	Medium Tan/Medium Tan	Satin/Satin
7	Chrome/Chrome*	Fine Ripple/Fine Ripple
8	Chrome/Black*	Fine Ripple/Satin
9	Dark Brown/Dark Brown	Satin/Satin
10	Black/Chrome*	Satin/Fine Ripple

Arranged in order of decreasing reflectance for closed blinds.

"Glossy" and "Satin" refer to typical painted surface finishes as seen by the eye.

*These blinds received a special protective coating.

TABLE 4

MEASURED SOLAR OPTICAL PROPERTIES
OF EXPERIMENTAL VENETIAN BLINDS
35 Degrees Solar Incidence

Blind No.	Slat Position	Transmittance τ_i	Reflectance ρ_i	Absorptance α_i
1	Closed	.051	.602	.347
	45 deg	.110	.495	.395
	Open	.483	.216	.301
2	Closed	.042	.589	.369
	45 deg	.108	.477	.415
	Open	.442	.197	.361
3	Closed	.034	.503	.463
	45 deg	.108	.375	.517
	Open	.544	.148	.308
4	Closed	.036	.498	.466
	45 deg	.120	.381	.499
	Open	.570	.069	.361
5	Closed	.035	.444	.521
	45 deg	.080	.340	.580
	Open	.499	.134	.367
6	Closed	.021	.316	.663
	45 deg	.052	.229	.719
	Open	.399	.097	.504
7	Closed	.024	.316	.660
	45 deg	.058	.219	.723
	Open	.482	.046	.472
8	Closed	.017	.312	.671
	45 deg	.025	.231	.744
	Open	.496	.013	.491
9	Closed	.015	.089	.896
	45 deg	.026	.065	.909
	Open	.434	.020	.546
10	Closed	.006	.062	.932
	45 deg	.032	.041	.927
	Open	.407	.014	.579

TABLE 5

MEASURED SHADING COEFFICIENTS OF
EXPERIMENTAL VENETIAN BLINDS

35 Degrees Solar Incidence Angle and Still Air Conditions (N_{io}=0.5)

Blind No.	Color	Slat Position	Shading Coefficient
1	White	Closed	.55
		45 deg	.66
		Open	.80
2	Off White	Closed	.53
		45 deg	.68
		Open	.79
3	Light Green	Closed	.58
		45 deg	.67
		Open	.84
4	Aluminum	Closed	.56
		45 deg	.71
		Open	.92
5	Light Tan	Closed	.60
		45 deg	.71
		Open	.84
6	Medium Tan	Closed	.66
		45 deg	.77
		Open	.88
7	Chrome	Closed	.66
		45 deg	.80
		Open	.92
8	Chrome/Black	Closed	.69
		45 deg	.80
		Open	.90
9	Dark Brown	Closed	.83
		45 deg	.85
		Open	.90
10	Black/Chrome	Closed	.83
		45 deg	.85
		Open	.90

The above shading coefficients were measured under still air conditions and therefore are not directly comparable with ASHRAE values published for various wind conditions.

TABLE 6

COMPARISON OF MEASURED AND PREDICTED SHADING COEFFICIENTS

35 Deg Incidence, 1/4-Inch Clear Glass,
1-Inch Wide Interior Blinds

Blind No.	Slat Position	ρ_i Blind Reflectance	SC_M Still Air (N_{io}=.5)	SC_P Still Air (N_{io}=.5)	SC_P Summer (N_{io}=.267)
1	Closed	.602	.55	.50	.44
	45 deg	.495	.66	.59	.53
	Open	.216	.80	.81	.76
2	Closed	.589	.53	.51	.45
	45 deg	.477	.68	.60	.55
	Open	.197	.79	.82	.78
3	Closed	.503	.58	.58	.52
	45 deg	.375	.67	.68	.63
	Open	.148	.84	.86	.82
4	Closed	.498	.56	.58	.53
	45 deg	.381	.71	.68	.63
	Open	.069	.92	.92	.88
5	Closed	.444	.60	.63	.57
	45 deg	.340	.71	.71	.66
	Open	.134	.84	.87	.83
6	Closed	.316	.66	.73	.68
	45 deg	.229	.77	.80	.75
	Open	.097	.88	.90	.86
7	Closed	.316	.66	.73	.68
	45 deg	.219	.80	.81	.76
	Open	.046	.92	.94	.90
8	Closed	.312	.69	.73	.68
	45 deg	.231	.80	.80	.75
	Open	.013	.90	.96	.92
9	Closed	.089	.83	.91	.86
	45 deg	.065	.85	.92	.88
	Open	.020	.90	.96	.92
10	Closed	.062	.83	.93	.88
	45 deg	.041	.85	.94	.90
	Open	.014	.90	.96	.92

Subscripts: M = measured in Simulator
P = predicted based on measured blind reflectance, ρ_i , where glass τ_o = .77, ρ_o = .08, α_o = .15

TABLE 7

EFFECTS OF SOLAR INCIDENCE AND SLAT ANGLE
ON BLIND REFLECTANCE AND SHADING COEFFICIENT

No. 2 Blind in Still Air

A. Measured Shading Coefficient with 1/4-Inch Clear Glass

Slat Angle Setting ψ deg	Incidence Angle, θ, deg 0	35	45
Closed 69*	.62	.53	.56
45 deg 45	.72	.68	.66
Open 0	.84	.79	.84

B. Measured Average Solar Reflectance of Blind Alone

Slat Angle Setting ψ deg	Incidence Angle, θ, deg 0	35	45
Closed 69*	.518	.589	.578
45 deg 45	.342	.477	.450
30 deg 30	.237	.389	.374
Open 0	.127	.197	.211

*Maximum angle possible (varies slightly with blind)

TABLE 8

BRIGHTNESS FACTORS FOR EXPERIMENTAL VENETIAN BLINDS

Blind No.	k per degree	Colors (see Table 3)	Finish
1	.0073	White	Glossy
2	.0072	Off-White	Satin
3	.0056	Light Green	Glossy
4	.0058	Aluminum	Polished
5	.0051	Light Tan	Glossy
6	.0035	Medium Tan	Satin
7	.0035	Chrome	Fine Ripple
8	.0036	Chrome/Black	Fine Ripple/Satin
9	.0010	Dark Brown	Satin
10	.0007	Black/Chrome	Satin/Fine Ripple

TABLE 9

EFFECTS OF VARIABLE SOLAR INCIDENCE AND SLAT ANGLE ON SOLAR ENERGY CONSERVATION IN A BUILDING

Daily Energy Loads, Btu/Sq Ft of Window

Day (Season)	CASE I Constant SC=0.55 Window Facing South	CASE I Window Facing Southwest	CASE II Variable SC = f(θ,ψ) Window Facing South	CASE II Window Facing Southwest	Blind Setting ψ deg
Jan 21(winter)	901		1330		0 open
"		653		967	" "
"	901		706		70 closed
"		653		514	" "
June 21(summer)	346		354		70 closed
"		560		522	" "

Effective Daytime Shading Coefficient

Day (Season)	CASE I South	CASE I Southwest	CASE II South	CASE II Southwest	ψ deg
Jan 21	.55		.81		0 open
"		.55		.81	" "
"	.55		.43		70 closed
"		.55		.43	" "
June 21	.55		.56		70 closed
"		.55		.51	" "

Conditions of comparison:

40 deg North Latitude

$\frac{1}{4}$-inch clear glass: τ_o=.77, ρ_o=.08, α_o=.15

No. 2 Blind: $\rho_i = .0072(\theta + \psi)\cos\theta$

N_{io} = 0.267

$\theta \approx$ Solar Altitude Angle, deg

ψ = Slat Angle, deg

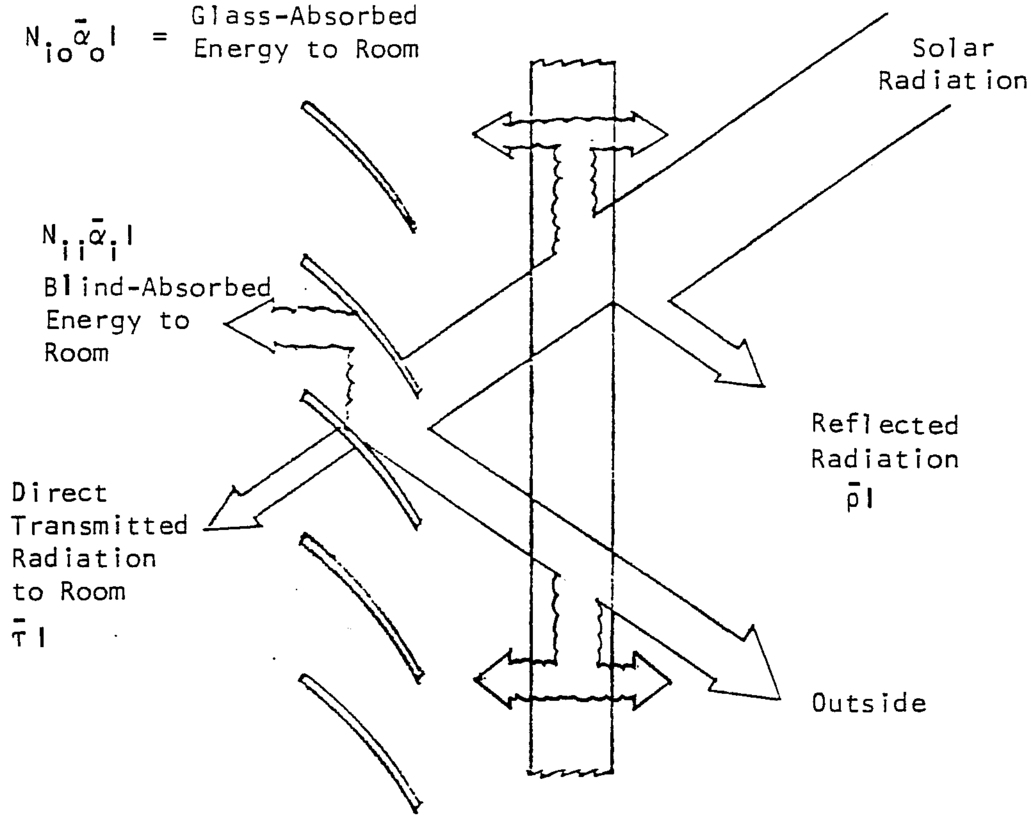
TABLE 10

PRECISION

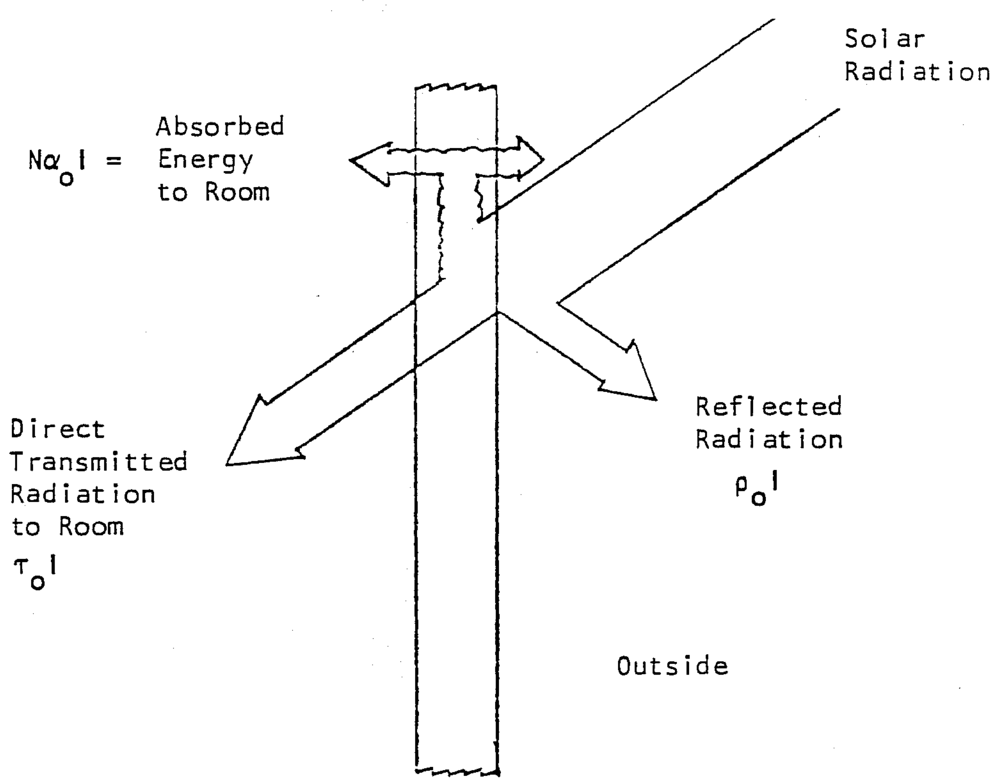
The precision of the measured results is estimated to be within the following values:

τ	total solar transmittance	± 0.02
ρ	total solar reflectance	± 0.03
α	total solar absorptance	± 0.05
SC_M	measured shading coefficient	± 0.03
θ	solar incidence angle*	± 0.1 deg
ψ	slat angle setting	± 0.5 deg

*Same as altitude angle and profile angle for this test arrangement.



Glass Blind System



Single Glass

FIGURE 1. HEAT TRANSFER THROUGH SELECTED GLAZING SYSTEMS

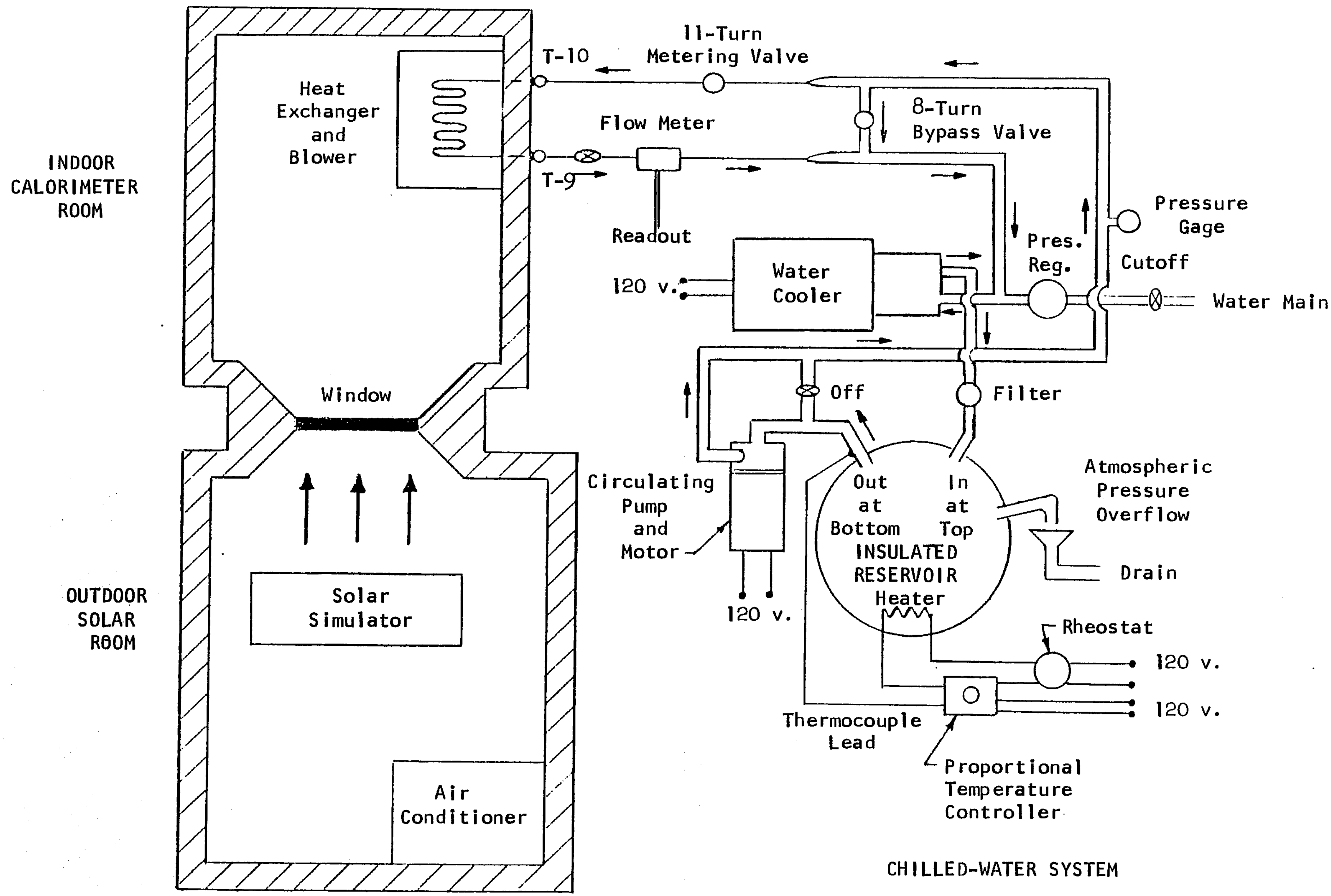


FIGURE 2. LEVOLOR ENVIRONMENTAL SIMULATOR

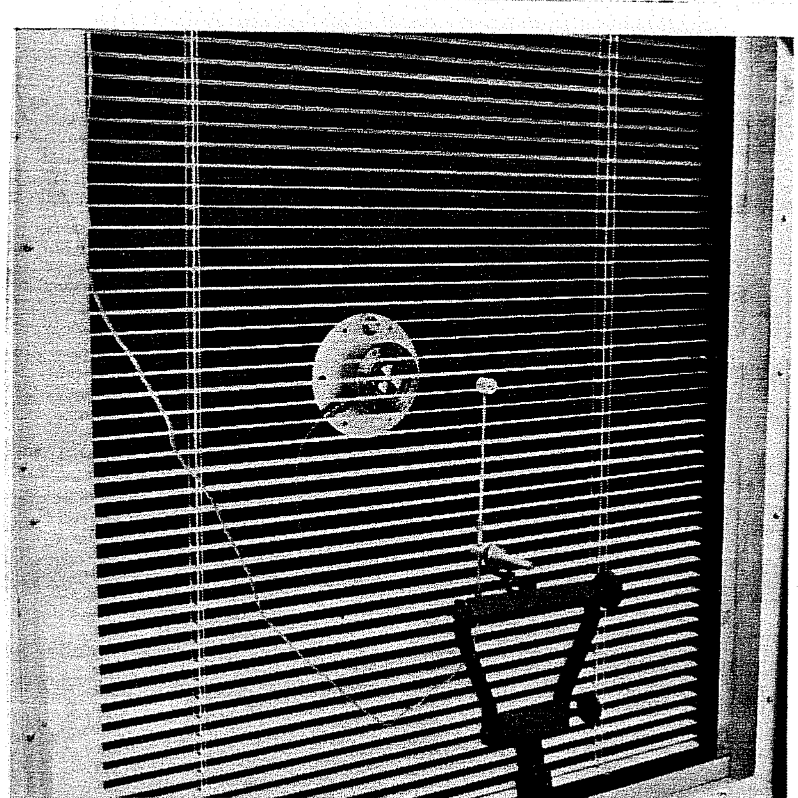


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FIGURE 3. EXPERIMENTAL SETUP FOR MEASURING TRANSMITTANCE AND REFLECTANCE

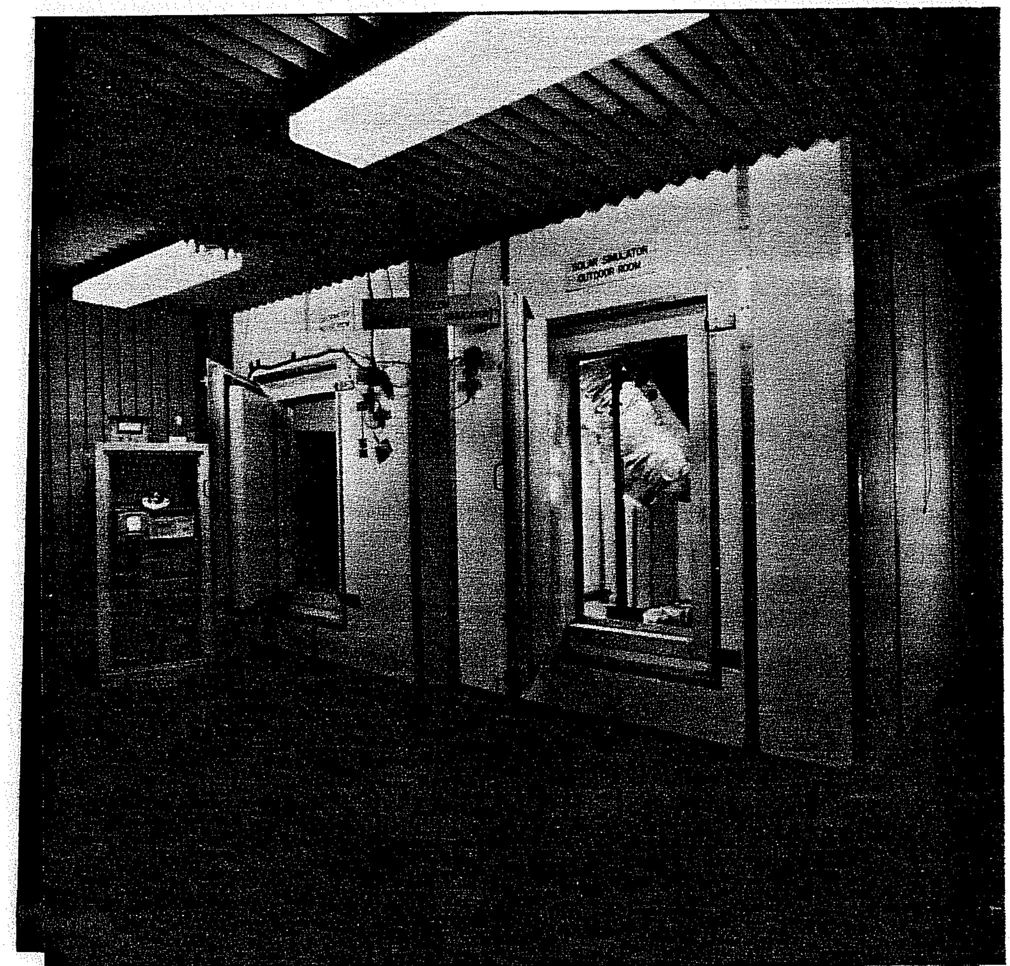

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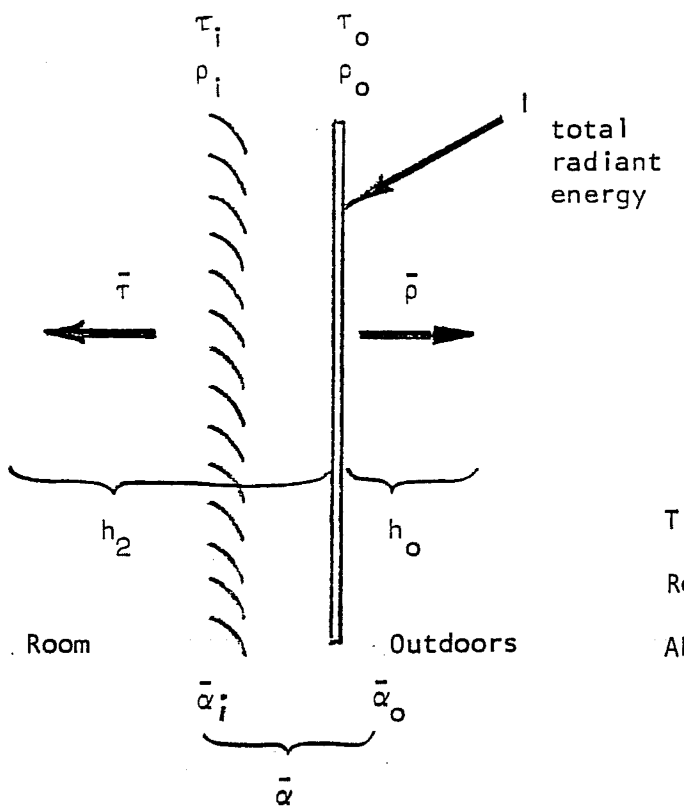
FIGURE 4. OVERALL VIEW OF LABORATORY



Solar Optical Properties

	Isolated Blind	Isolated Glass	Combined Glass-Blind
Transmittance	τ_i	τ_o	$\bar{\tau}$
Reflectance	ρ_i	ρ_o	$\bar{\rho}$
Absorptance	α_i	α_o	$\bar{\alpha}$

Surface Coefficients

h_2 combined room side of glass

h_o outdoor side of glass (outer)

where: $1/h_2 = \Sigma$ (resistances of air space, blind and all surfaces between the glass and the room)

$$U = \frac{1}{1/h_o + R_{glass} + 1/h_2}$$ and neglecting R_{glass}

$$U = \frac{1}{1/h_o + 1/h_2} = \frac{h_o h_2}{h_o + h_2}$$, then

$$N_{io} = \frac{h_2}{h_o + h_2}$$

FIGURE 5. IMPORTANT PARAMETERS GOVERNING SOLAR HEAT TRANSFER THROUGH GLASS-BLIND GLAZING

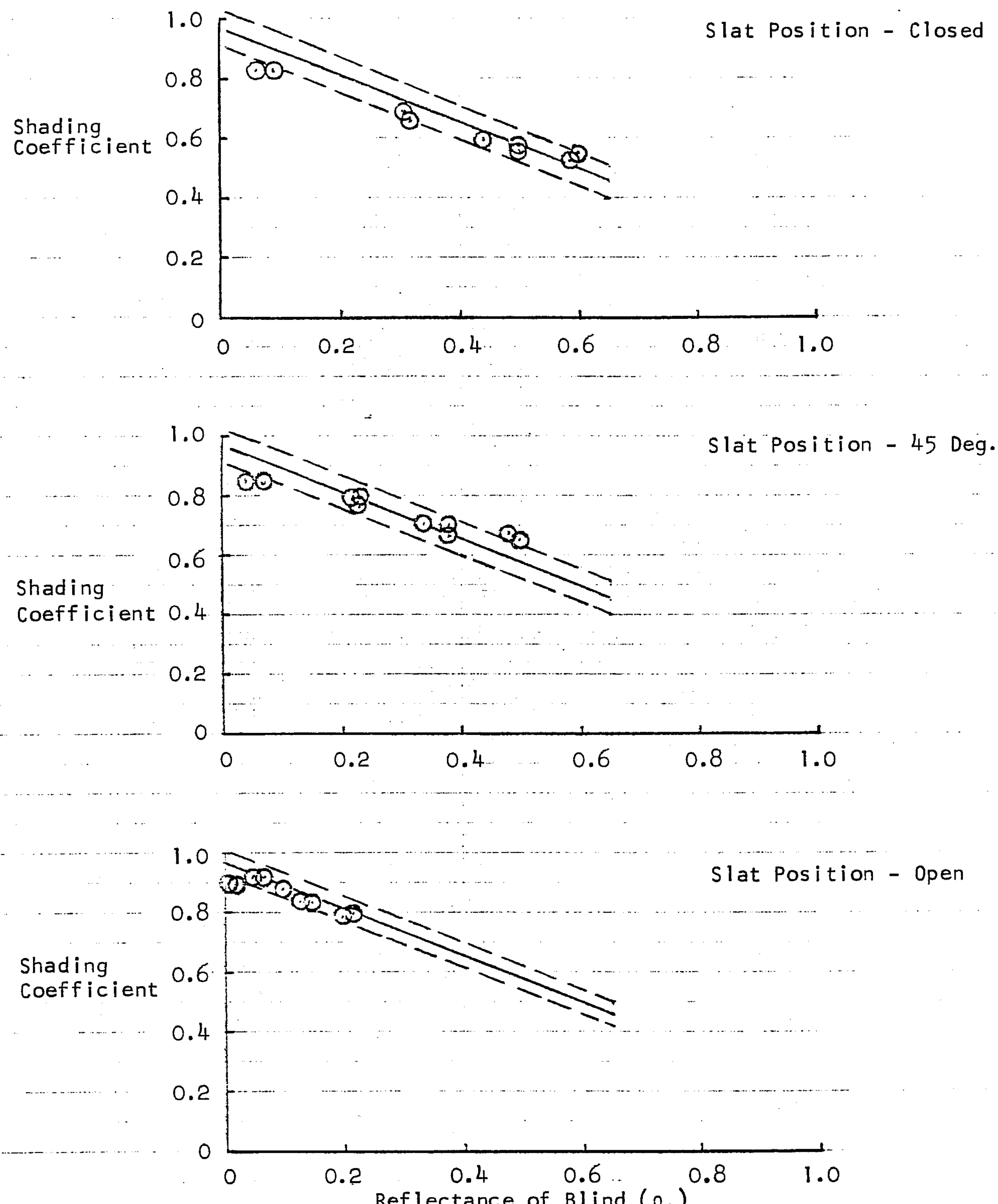


FIGURE 6. COMPARISON OF PREDICTED AND MEASURED SHADING COEFFICIENTS

One-Inch Blinds with 1/4-Inch Clear Glass
35 Deg. Solar Incidence Angle
Still Air Conditions

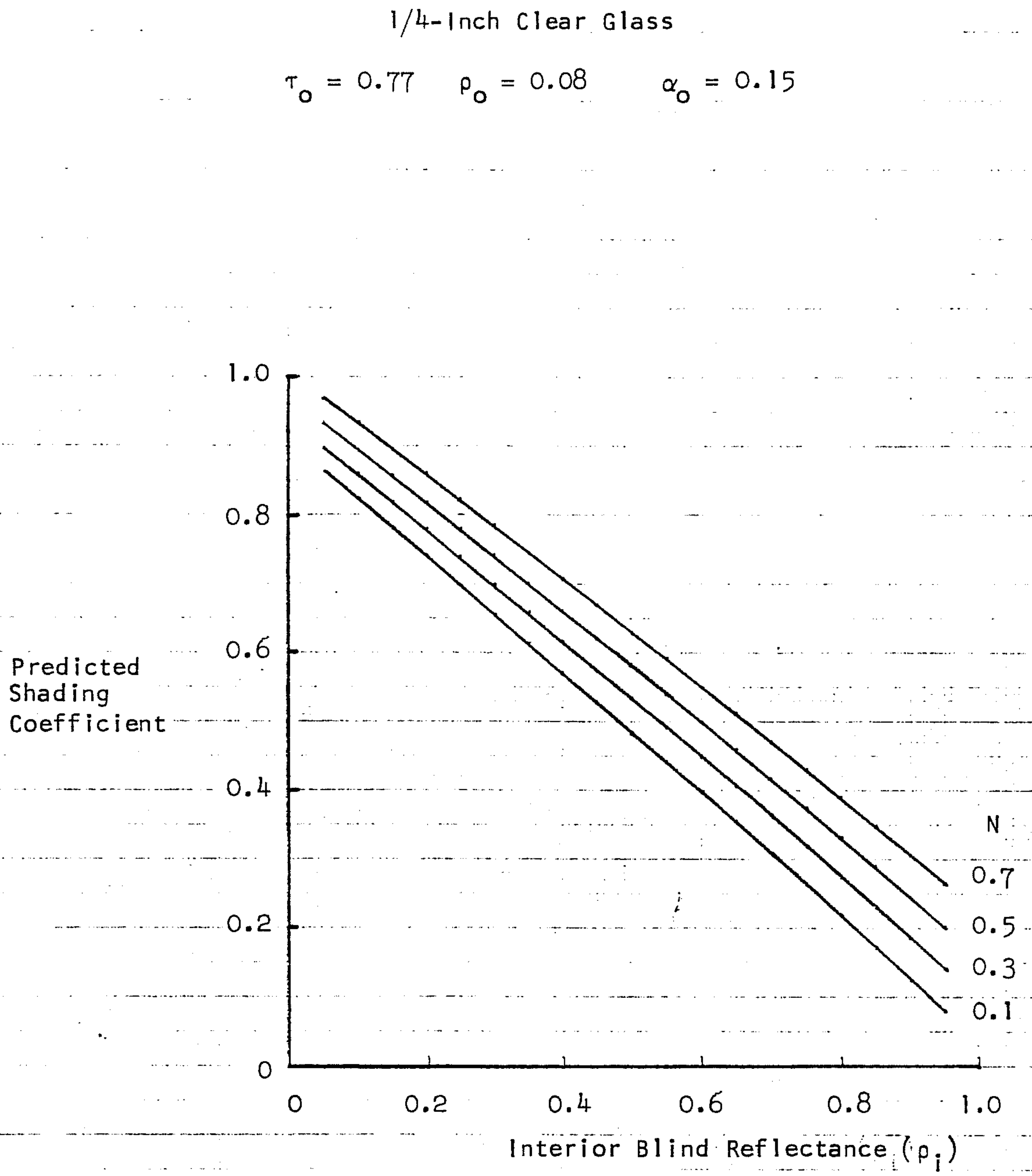


FIGURE 7. EFFECT OF N FACTOR ON SHADING COEFFICIENT FOR CLEAR GLASS

1/4-Inch Gray Heat Absorbing Glass

$\tau_o = 0.46$ $\rho_o = 0.05$ $\alpha_o = 0.49$

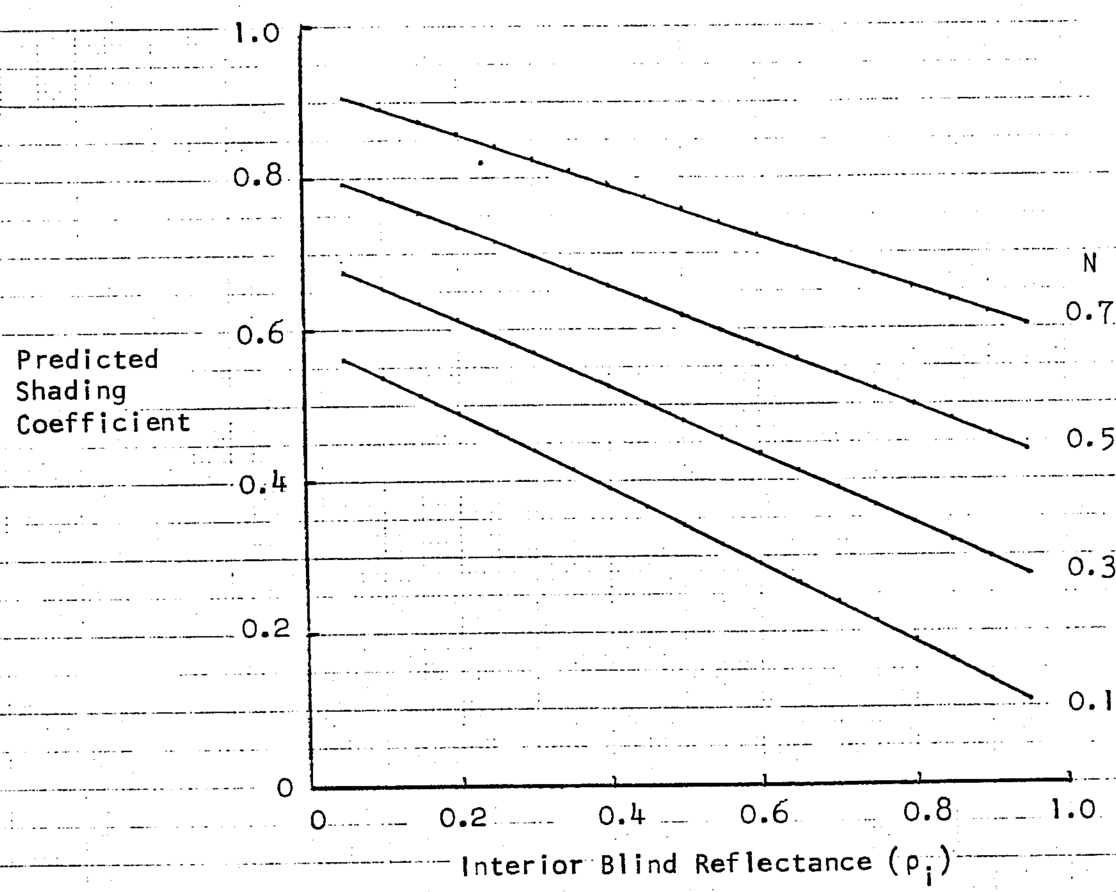


FIGURE 8. EFFECT OF N FACTOR ON SHADING COEFFICIENT FOR HEAT ABSORBING GLASS

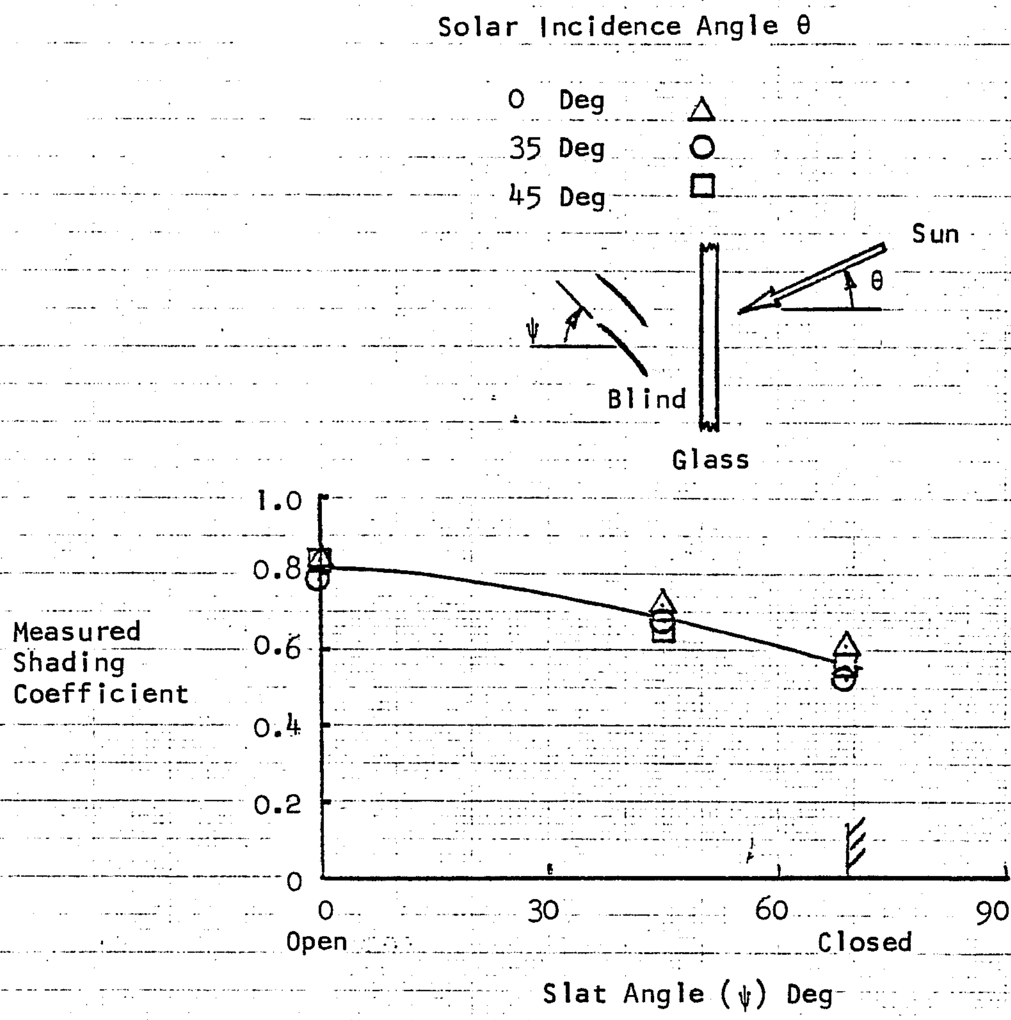


FIGURE 9. EFFECT OF BLIND SLAT ANGLE ON SHADING COEFFICIENT IN STILL AIR

No. 2 Blind With 1/4-Inch Clear Glass

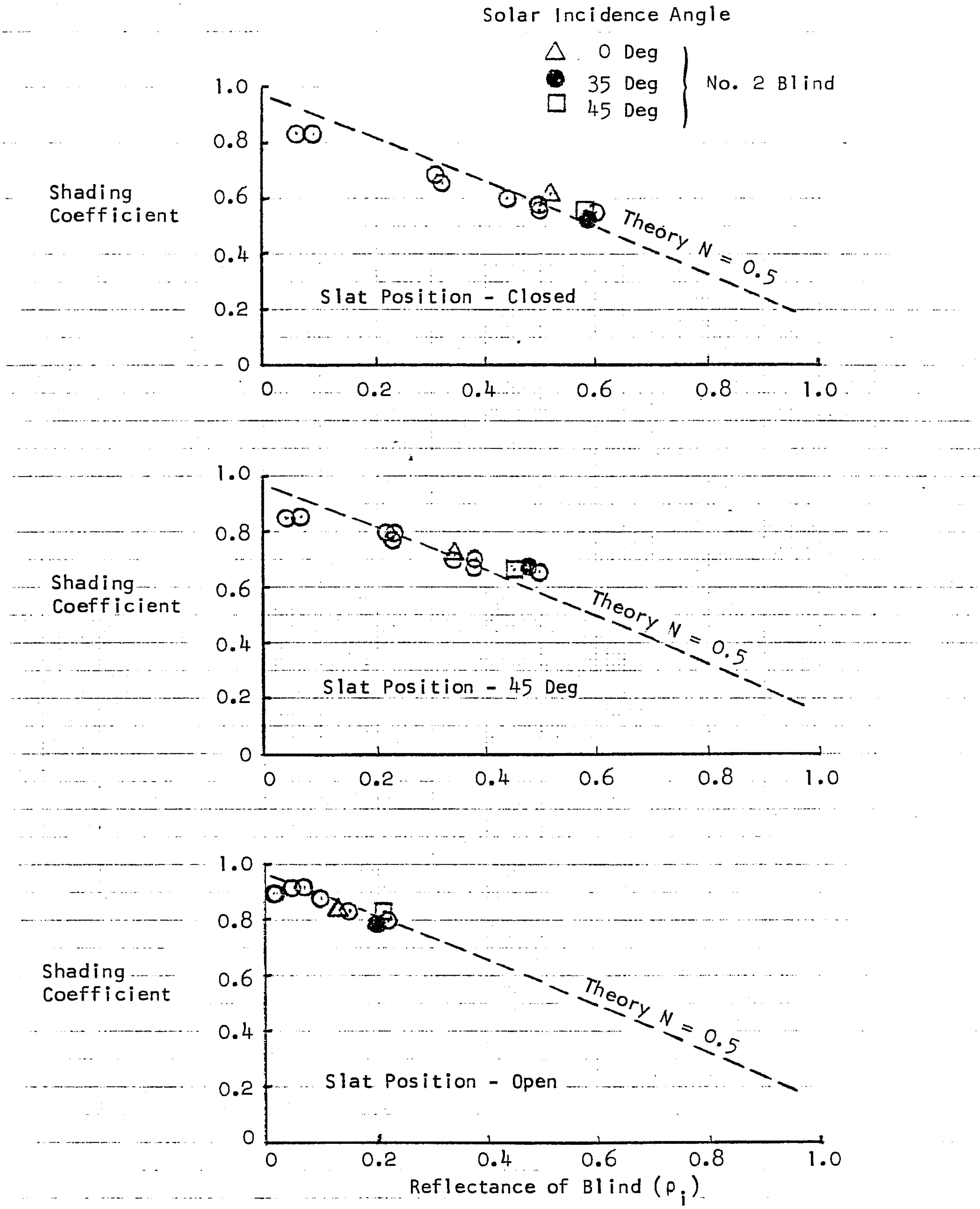


FIGURE 10. EFFECT OF BLIND REFLECTANCE ON SHADING COEFFICIENT
Measured in Environmental Simulator - Still Air
One Inch Blinds With 1/4-Inch Clear Glass

Measured in Environmental Simulator - Still Air
No. 2 Blind With 1/4-Inch Clear Glass

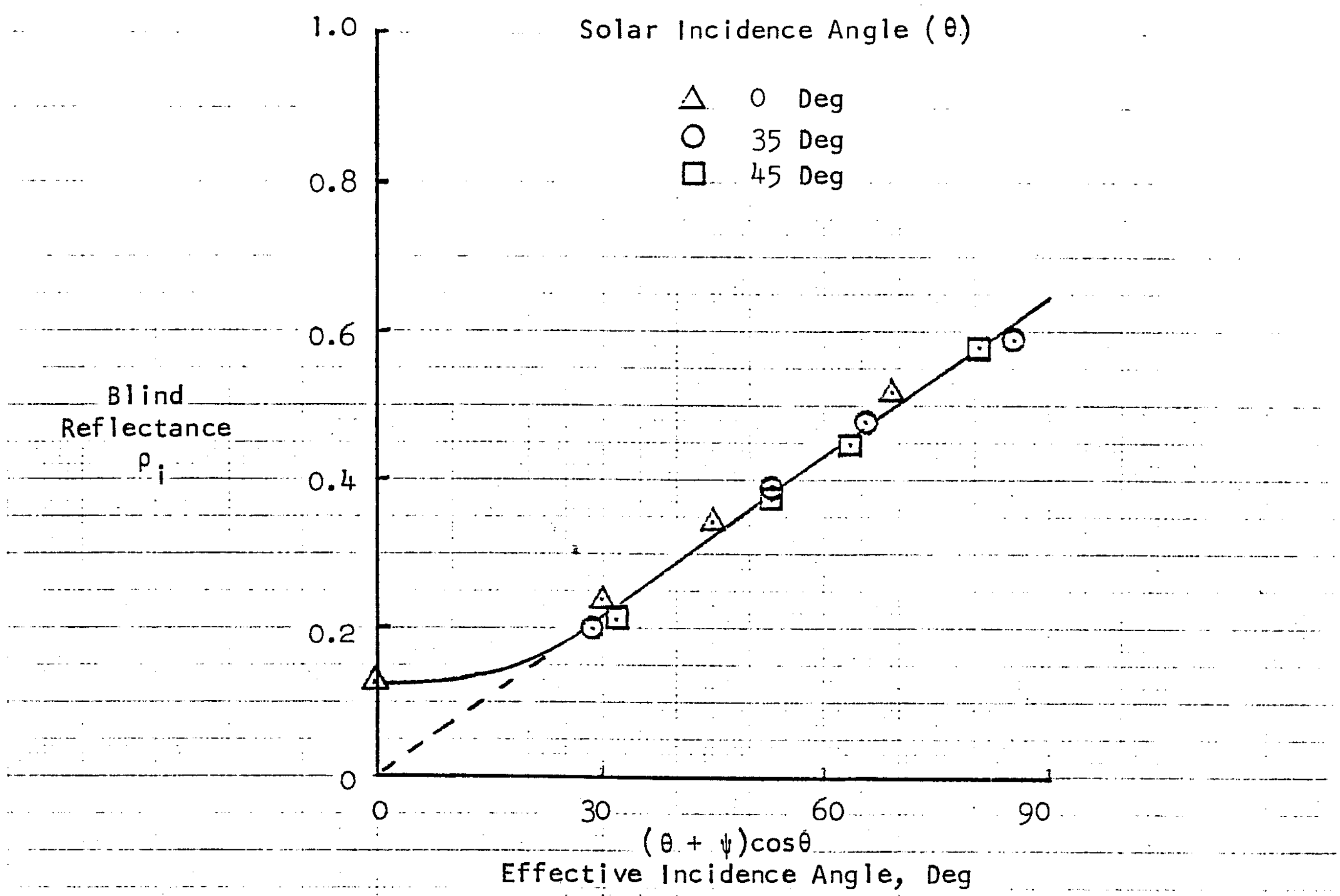


FIGURE 11. EFFECT OF SLAT ANGLE AND SOLAR INCIDENCE ON BLIND REFLECTANCE

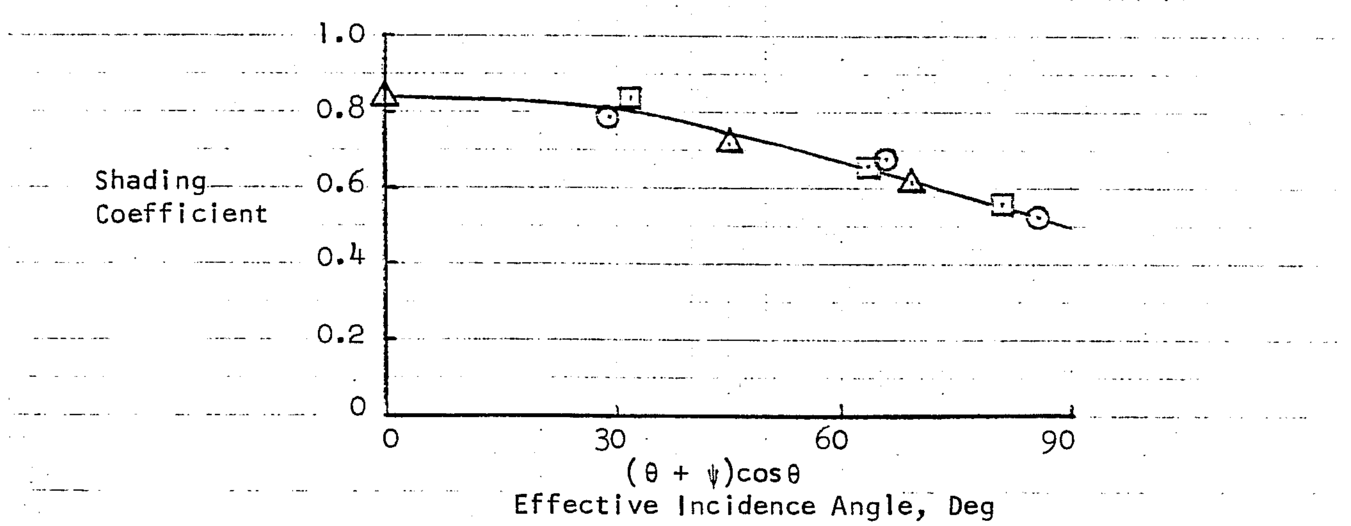


FIGURE 12. SHADING COEFFICIENT AS A FUNCTION OF EFFECTIVE INCIDENCE ANGLE

APPENDIX I

Simulator Instrumentation

No.	Item Name	Model No.	Type	Manufacturer
1	Black and White Pyranometer	8-48	Thermopile	The Eppley Laboratory, Newport, R.I.
2	Precision Spectral Pyranometer	PSP Schott Filters	Thermopile	The Eppley Laboratory, Newport, R.I.
3	Alphatometer Miniature Pyranometer	1A	Thermopile	Devices & Services Co. Dallas, Texas
4	Emissometer	AE	-	Devices & Services Co. Dallas, Texas
5	Halltron Power Computer, Precision Wattmeter	PC5-59	Hall Effect	Ohio Semitronics, Inc. Columbus, Ohio
6	Omniflow Flowmeter and Readout	FTM-N6-LJS	Turbine Magnetic Pulse	Flow Technology, Inc. Phoenix, Arizona
7	Measurement System Temperature	TS-0068-7105	Platinum Resistance Transducer & Signal Conditioner	Whittaker Corporation ISD
8	Data Logger	2200B	30 Channels, DC. 100 possible	John Fluke Mfg. Co., Inc. Mountlake Terrace, WA
9	Fine Metering Valve	SS-6L-3/8in.	11 turn	NUPRO
10	Adjustable DC Power Supply	1010T	Transistorized 1-100V	Power Designs, Inc. New York, NY
11	A.C. Line Conditioner	Series 6000	-	ELGAR Corporation San Diego, CA
12	Integrating Digital Voltmeter	HP-2401C	Solid State	Hewlett-Packard Corporation Palo Alto, CA

APPENDIX 2

Summary of Previous Work

The early work on heat flow through glass was conducted by the American Society of Heating and Ventilating Engineers at its research laboratory in Cleveland, Ohio. In the early 1950's the investigation was extended to include an analysis of the effect of uniformly spaced flat opaque slats. In the first report,[1] of this long-range research effort, G. V. Parmelee and W. W. Aubele reported calculated values of absorptance and transmittance for specular and diffuse reflecting slat surfaces and suggested rules for estimating the properties for a combination glass and slat assembly. Among their conclusions regarding the effect of the several variables on the performance of a venetian blind are:

1. For given values of slat absorptance, profile angle and slat geometry, the type of reflection (diffuse or specular) is most important. The importance decreases as profile angle, slat angle and slat width-spacing ratio decrease.
2. For a given profile angle and slat geometry, decreasing values of absorptance increase reflectance but also increase transmittance.
3. In many cases, particularly when the slat width-spacing ratio is of the order of 1.2 and the slat angle is greater than zero, the absorptance of the slat assembly is greater in value than the absorptance value of the slat surface.

In the experimental study of slat-type sun shades[2] the researchers compared experimental determinations of the absorbed and transmitted fractions of solar radiation with those predicted by the mathematical theory. Heat gain measurements were made with a solar calorimeter. The agreement between the theoretical and measured values suggested the approach taken in the earlier paper was practical for developing design data for shading products.

In the final research paper[3], the investigators presented design data as a Shade Factor which was defined as the total heat gain from a shade-glass combination minus the convection and radiation gain from a single unshaded common window glass. The shade factor may be considered a predecessor of the shading coefficient.

$$\text{Shade Factor} = \frac{\begin{array}{c}\text{Total Gain from Shade-}\\\text{Glass Combination}\end{array} - \begin{array}{c}\text{Convection and Radiation Gain}\\\text{from Single Unshaded Common Glass}\end{array}}{\begin{array}{c}\text{Total Solar Energy Transmitted}\\\text{by Single Unshaded Common Glass}\end{array}}$$

Among the discussions of the performance characteristics in this paper were the following points which are of current interest.

1. Normal slat curvature does not significantly change the shade performance. The thickness ratio of metal slats is so small as to be insignificant.

2. Transmitted solar radiation consists of straight-through and reflected-through components. Both components are influenced by profile angle, slat angle and spacing ratio. The reflected-through component is also dependent upon the absorptance of the slat for solar radiation and does not change rapidly with profile angle.

3. An increase in slat angle increases the total energy reflected to the outside and decreases the amount admitted to the room.

4. A spacing ratio of 1.2 with a slat angle of 45 degrees will exclude the straight-through component on all orientations in the north latitudes between 6 a.m. and 6 p.m. from May 1 to the middle of August. A 30 degree slat angle will do the same between 7 a.m. and 5 p.m. but will approximately double the reflected-through component and increase the radiation absorbed by the shade.

5. A decrease in slat absorptance (higher slat reflectance) increases the amount of solar radiation admitted to the room by increasing the reflected-through component, but it also increases the energy reflected to the outside. The total heat gain is therefore reduced.

6. Slat-type shades have a high transmittance for ground-reflected solar radiation, which may constitute a sizeable fraction of the incident diffuse solar radiation. The transmittance for both above-the-horizon and below-the-horizon diffuse solar radiation is generally greater than the reflected-through transmittance of direct solar radiation.

Other research workers in this field have conducted mathematical and experimental analysis of the heat transfer through single and insulating glass with interior drapery shading.[4,5,6] These programs together have provided the foundation for the present ASHRAE method for determining the heat gain through windows.

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APPENDIX 3

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