

WINDOWS FOR ACCEPTING OR REJECTING
SOLAR HEAT GAIN: FINAL REPORT

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SUMMARY

Ordinary fenestration may be modified at low cost using various combinations of windows, duotone venetian blinds, and drapes to control the solar heat gain. In the winter, solar radiation may be absorbed by dark blinds and transferred to the air, minimizing fading of furnishings while collecting useful energy. In the summer, more than 90 percent of the total potential window heat gain may be rejected by exhausting evaporatively cooled air over the blinds. The performance of several window configurations has been theoretically analyzed, modeled on a computer, and verified experimentally.

INTRODUCTION

In hot, arid climates, low-cost window designs are needed which admit winter solar heat gain to the house in a controllable fashion as hot air, and which allow summer window heat gain to be exhausted by evaporatively cooled air flowing out of the window. Such treatments should permit significant solar heat gain during the winter yet prevent fading of furnishings. The view out the window should also be relatively unimpeded.

None of the devices or designs discussed here are intended to maximize the solar heat gain through the window. When the sunlight shining directly through the window is absorbed by dark interior furnishings, the energy gain will usually be maximized.

The basic principle of the designs tested during this program involves the use of an interior shading device as a solar absorber. Air transport across the shading device is utilized to either draw heat into the building or reject heat to the exterior. The objective of this research program was to analyze, test, and evaluate window systems which combine conventional and readily available components to achieve an added dimension of control over solar gain. These investigations have established the thermal performance characteristics of this type of window system in an actual building environment. Conventional components have been used to increase the probability of acceptance by builders of both new and retrofit construction.

A theoretical analysis was developed to predict the general heat and mass transfer characteristics of the systems and to further develop useable design tools to predict quantitative performance. This analysis is presented in Appendix A. A

review of the heat and mass transfer literature for the determination of previously established information and ongoing studies relevant to this project is included in Appendix B.

THE KLOS WINDOW

The Klos window¹, one of the window systems tested, is composed of two half-slider (horizontal movement) windows which open on opposite sides and which enclose venetian blinds, as shown in plan view in Fig. 1. Other combinations include: windows with a fixed center pane and a sliding panel on each end; a window with a "half slider" window on the outside (one pane slides), and a double sliding window (both panes slide) on the inside; or two double hung windows may be used. (Fig. 1).

The blinds have a dark concave upper surface, and a white convex lower surface. This reversal of the conventional arrangement is done primarily for esthetic reasons, since the white lower surface is made visible from the inside of the house and decreases the visual impact of the blinds. The concave shape of the dark upper surface also reduces glare. When the blinds are adjusted for the dark upper surface to intercept all direct solar radiation, no harsh contrasts of light intensity are found in rooms with Klos windows. In this project, the dark upper surface of the experimental blinds was a standard "bronze" color ($\alpha=0.89$), while the lower surface was an off white ($\alpha=0.43$). The absorptivities (α) were determined by measuring the total and the reflected insolation with an Eppley pyranometer.

To accept heat during the winter, the interior window is open while the exterior window is closed (Fig. 1). House air is heated as it flows over the blinds by natural convection. To prevent overheating, the windows may both be closed, the white side may be turned out, or the inside window may be closed and the outside window opened.

During the summer, the windows are opened at opposite ends. (Fig. 1) Evaporatively cooled air flows out over the solar heated venetian blinds, carrying this heat outside without blocking the view. Additionally, a layer of cool air is interposed between the hot ambient and cool interior air. Since radiation, conduction, and convection heat gains are all affected by this window treatment, the heat gain is greatly reduced.

Klos windows can be installed by the builder, or retrofitted by the homeowner, using easily available standard windows and venetian blinds.

Recently, several local companies² in Tucson, Arizona, have begun to fabricate a complete Klos window, ready for installation as a unit.

Klos windows must be properly designed. The two windows should be set approximately 3-5 inches apart to permit air flow through the window and allow the blinds to be removed. Any fixed panes in the windows must be accessible for cleaning, and no area of a fixed pane should be more than 0.6M (2 ft) from an opening for cleaning and easy access to the blinds. Double sliding storm windows on the inside make cleaning much simpler.

Each blind should be no wider than the height of the window, to allow their removal, unless storm windows with "lift out" panes are used as the interior window.

Surprisingly, the cost of two single glazed windows can be little more than a double glazed window of equal quality. If two half-slider windows are used and opened as shown in Fig. 1, entry into the house is not possible without breaking the window. If a Klos window is installed in a bedroom, windows with sliding panels on each end, or a double-sliding interior window (some storm windows are double sliding) should be used so that the window can be completely opened on one side for egress in case of fire. However, unwanted entry is not prevented as easily with this type of window.

As in all devices, Klos windows have their credits and debits. The windows give good control over solar gain and effectively reject heat during the summer when used in evaporatively cooled houses. Due to the absence of a continuous aluminum path from the inside to the outside, they should lose less heat than a standard aluminum framed double glazed window. However, the space between the windows is not sealed, requiring more cleaning. Also, condensation may occur, especially in colder climates. The venetian blinds will need occasional cleaning, a task which may be required less frequently than normal since the dust is less visible on the concave upper surface of the blinds.

CLEARVIEW SOLAR ABSORBER

This design uses an ordinary window with a duotone venetian blind like that used in the Klos window. The insolation absorbed by the dark upper surface of the venetian blind heats air, which is convected upward into the house, as in Fig. 2. Since direct sunlight doesn't strike furnishings, fading is greatly reduced. To control solar gain during the winter, white drapes can be closed, or the blinds turned white side out.

During the summer, white lined drapes can be used to direct evaporatively cooled air along the venetian blind slats between the drape and the window. (Fig. 3.) This reduces window heat gain in a manner similar to that of the Klos window. The drape edge must be pinned back along the edge opposite the opening so that airflow is permitted along the drape and out the window. It is best if

the sides of the drape end at the left and right sides of the window opening, so the folds of the drape do not interfere with air entering the area between the window and the drape. The drape liner must be prevented from blowing against the window by pinning it to the outer decorative drape at the bottom. A heavy "black-out" white lined drape may be used. Depending on the drapery material used, drapes for windows more than 3'-5' high may require additional support, such as a fine wire or a "cafe" curtain rod midway between the top and the bottom of the window. It is not necessary to enclose the top of the drape with a valance.

Similarly, woven wood window coverings are also effective for exhausting window heat gain with evaporatively cooled air. If the window is partially opened, and such a covering is used on the interior of the house, evaporatively cooled air flows out between the wood strips, and then outside. Cool air fills the space between the covering and the window, reducing conduction and convection heat gains, and cools the outside facing surface of the wood strips.

EXPERIMENTAL PROCEDURE AND TEST RESULTS

Solar heat gain data were collected using the calorimeter shown in Figs. 4, 5, and 6. The calorimeter consisted of an insulated box attached to the window. Air was drawn through the box vertically at a low velocity, over the interior window surface and a black absorber plate into a plenum in the upper section of the box. It is important that low air velocities are used, so that free convection conditions prevail.

The air flow was measured with a sharp-edged orifice at the outlet. Temperatures were measured with thermocouples, shielded where necessary from thermal radiation. Energy input was determined from the temperature rise of the air, while solar radiation was measured with pyranometers.

During the summer test of the Klos window, the insulated box was moved sideways so that the window could be opened slightly, to allow evaporatively cooled air to be exhausted through the window. The heat gain through the remaining glazed area was measured, and the radiant heat gain through the opened portion calculated from the measured slat temperatures in the open area.

Data from the test window, both with and without the calorimeter in place, were used to formulate energy balance equations, which could be solved to estimate solar heat gain factors and heat transfer coefficients. Tables 1 and 2 present the experimental data and calculated performance for the Klos window and ClearView solar absorber case respectively. While experimental conditions deviated substantially from the standardized conditions used to derive the shading and heat loss coefficients, the agreement between experimental and computed efficiencies appears adequate for most design purposes.

The ClearView absorber-drape combinations was also tested. Figure 7 is a plan view of the

Table 1

Klos Window Calorimeter Data
 4:00 p.m., MST (3:36-3:38 p.m. Sun Time); West Facing Window
 1980 Data for clear, cloudless days

Date	4/26	4/25	4/16	4/15
Slat Angle, (Deg.)	18	30	45	60
Temperatures (°F):				
outdoor	85.5	72.6	87.5	84.6
inlet	79.2	77.0	79.8	78
outlet	104.0	99.8	103.4	100.9
net rise	24.8	22.8	23.6	22.9
Airflow (lb/hr)	334	335	335	335
Energy Gain ¹ (Btu/sq.ft.hr.)	150	138	143	139
Solar Radiation (Btu/sq.ft.hr.)	245	257	259 ³	261
Efficiency (percent)	61.2	53.7	55.2	53.3
Computed Efficiency ² (percent)	59.2	54.1	57.7	55.8

¹Based on the exterior area of glass in the window

²From Table 8, using the equation: efficiency = 100 x
 $[0.868 \times SC + U(t_o - t_i) / I_{ST}]$ where t_i is taken as the mean of inlet
 and outlet temperatures.

³Instrument malfunction on this date. This value was estimated from
 other clear day data.

experimental ClearView Solar Absorber, showing the location of measurement points of the drape surface temperature. The calorimeter could not be used in this case, due to the drapes. Thus, drape temperatures were taken to allow the driving force for heat transfer to be estimated (drape temperature-house internal temperature). These drape temperatures were measured with 30 gauge, type T thermocouples placed just under the surface of the decorative drape material, which was ~1/16 inch thick. The material was not a "hard woven" material, but was composed of large fibers without gaps between them. The "black out" type drape liner prevented any insolation from reaching the decorative drape material, and striking the thermocouples in it. Evaporatively cooled air was exhausted along the venetian blinds between the drape and the single glazed window at 200-290 feet per minute. The west facing window was tested in the full mid-afternoon sun at the time of the solar equinox.

The temperature differences shown in modes 1a and 1b of Table 3 illustrate the effectiveness of this technique. Additionally, a valence does not

enhance the effect, as in modes 1a and 2a. High air velocities do enhance the effect (modes 2a and 2a').

ESTIMATING HEAT GAIN VALUES

The hourly heat gains per unit area are calculated from the equation:

$$q_i = SC \times SHGF - U (T_i - T_o)$$

SC = shading coefficient (dimensionless)
 U = overall coefficient of heat transmission,
 Btu/Ft² hr^oF
 SHGF = Solar Heat Gain Factor, Btu/Ft²hr
 T_i = interior temperature of the house, °F
 T_o = ambient temperature °F
 q_i = heat gain, Btu/Ft² hr

English units are used to conform with the units of the SHGF used by ASHRAE.

Table 2

Clearview Window Calorimeter Data
 4:00 p.m., MST (3:31-3:34 p.m. Sun Time); West Facing Window
 1980 Data for clear, cloudless days

Date	4/10	3/31	4/6	4/8
Slat Angle, (Deg.)	18	30	45	60
Temperatures (°F):				
outdoor	84.6	63	78.4	82.6
inlet	80.6	74.3	77.8	78
outlet	107.5	99.8	103.5	104.8
net rise	26.9	25.5	25.7	26.8
Airflow (lb/hr)	336	338	337	337
Energy Gain ¹ (Btu/sq.ft.hr.)	163	156	156	163
Solar Radiation (Btu/sq.ft.hr.)	261	270	263	263
Efficiency (percent)	62.5	57.8	59.3	62.0
Computed Efficiency ² (percent)	64.6	57	60.8	60.8

¹Based on the area of glass in the window

²From Table 6, using the equation: efficiency = 100 x
 $[0.868 \times SC + U(t_o - t_i)] / I_{GT}$ where t_i is taken as the mean of inlet
 and outlet temperatures.

Table 3

Drape Temperatures

Mode	Air Velocity, fpm	$t_{NR} - t_i$	$t_{NW} - t_i$
1a NO VALANCE BLINDS SHADE DRAPES	200 + 30	1.7	3.6
1b " SUN STRIKES DRAPES	0	7.3	16.3
2a VALANCE BLINDS SHADE USED DRAPES	210 + 10	2.1	3.7
2a " "	290 + 50	1.5	2.3
2b' " SUN STRIKES DRAPES	0	10.2	17.3
2b' " "	240 + 40	2.2	6.1

NOTE: t_i = inside temperature, °F; t_{NR} = temperature of drape on side nearest room;
 t_{NW} = temperature of drape on side near window.

Hourly winter heat gain values for design purposes may be estimated using the hourly Solar Heat Gain Factors (SHGF) tabulated by ASHRAE³ and the coefficients in Tables 4, 5, 6, 7, and 8 for the window configurations discussed above. The window heat gain calculations are based on the SHGF, since these values account for window orientation, the time of day, and the latitude. Thus only one table of coefficients is required for each window configuration. However, in the ClearView solar absorber case, the blinds can be relatively close to the window (placed in the opening in the wall for the window), or inside the house at a distance from the window. Since the solar heated air from the blinds does not flow against the window in the latter case it is more efficient. Separate coefficients are presented for these two cases.

Table 4 Shading Coefficients (SC) and Overall Coefficients of Heat Transmission (U-factor) for Single Glass ClearView Absorbers; Free-standing Blinds.

<u>Slat Angle, Deg.</u>	<u>Shading Coefficient(SC)</u>	<u>U-Factor</u>
18	0.856	1.235
30	0.848	1.232
45	0.833	1.224
60	0.816	1.211

(Average U-Factor = 1.23)

Table 5 Shading Coefficients and U-Factors for Two Glazing ClearView Solar Absorber; Free-standing Blinds.

<u>Slat Angle, Deg.</u>	<u>Shading Coefficient(SC)</u>	<u>U-Factor</u>
18	0.792	0.586
30	0.786	0.585
45	0.775	0.583
60	0.762	0.579

(Average U-Factor = 0.58)

Table 6 Shading Coefficients (SC) and U-factors for Single Glazing, ClearView Absorbers; Convectively-coupled Blinds and Glass.

<u>Slat Angle, Deg.</u>	<u>Shading Coefficient(SC)</u>	<u>U-Factor</u>
18	0.796	1.237
30	0.782	1.221
45	0.765	1.206
60	0.746	1.187

(Average U-Factor = 1.21)

Table 7 Shading Coefficients and U-Factors for Two Glazing ClearView Solar Absorbers; Convectively-coupled Blinds and Glass.

<u>Slat Angle, Deg.</u>	<u>Shading Coefficient(SC)</u>	<u>U-Factor</u>
18	0.762	0.589
30	0.753	0.586
45	0.739	0.581
60	0.725	0.574

(Average U-Factor = 0.58)

Table 8 Shading Coefficients and U-Factors for Klos Window-winter Operation.

<u>Slat Angle</u>	<u>Shading Coefficient</u>	<u>U-Factor</u>
18	0.713	1.093
30	0.700	1.085
45	0.684	1.073
60	0.665	1.057

(Average value of U-Factor = 1.08)

Coefficients are given for various blind slat angles (from the horizontal) for each configuration. The tilt angle of the blind does not appear to have a large effect if the direct sunlight does not penetrate the blinds. These tabulated coefficients are not valid if sunlight penetrates the blinds. The area of the window should be the actual glazed area, and not include the window frames. The tabulated coefficients are based upon 2-inch wide blind slats; a blind slat width of 1-inch gives heat gains of ~0.5-1% higher, due to the slightly higher convection heat transfer coefficient of the narrower slat.

Similarly, the coefficients in Table 9 are used to estimate the total hourly summer heat gain from Klos windows through which evaporatively cooled air is flowing. The summer heat gains of a Klos window in this mode are only a small percentage of the total potential heat gain of an ordinary window.

Table 9 Shading Coefficients and U-factors for Klos Window-summer Operation.

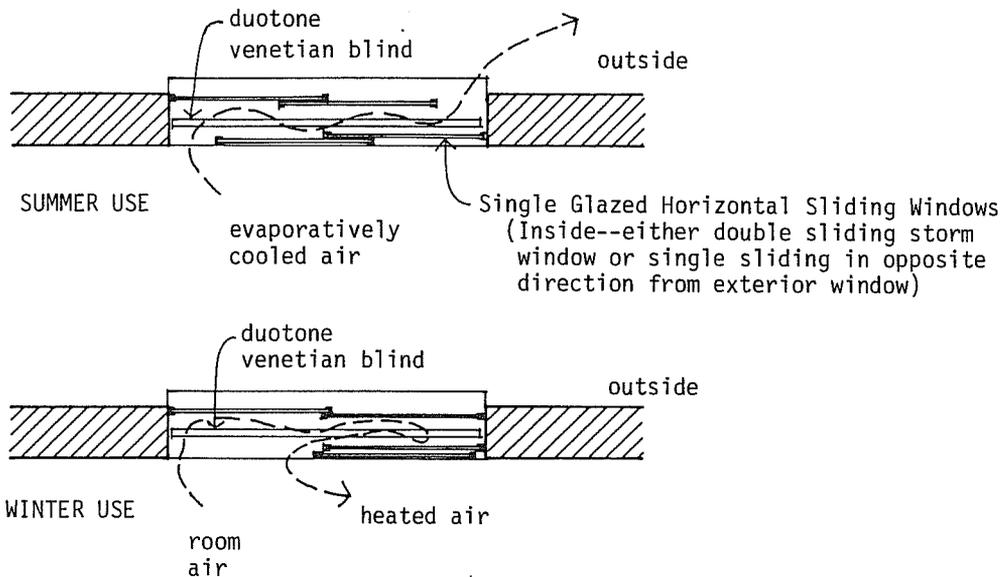
<u>Air Flow/CFM/SQ.FT</u>	<u>Shading Coefficient</u>	<u>U-Factor</u>
30	0.087	0.083
40	0.080	0.067
50	0.076	0.056

ACKNOWLEDGEMENT

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NOTES AND REFERENCES

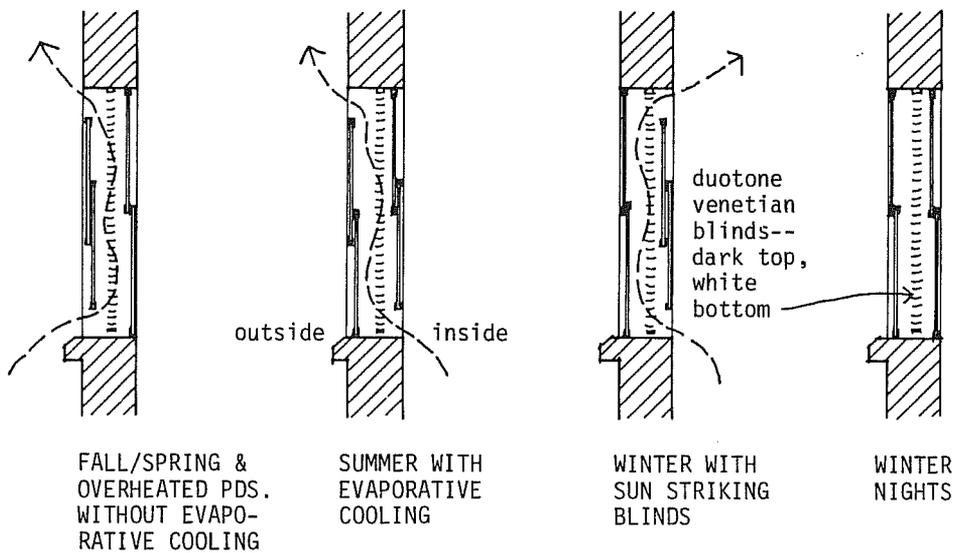
1. Stanley Klos of Tucson, Arizona is the first person, to the authors' knowledge, to have used this design.
2. For example: The Arizona Glass Co. and Zephyr Window Covering Co., both of Tucson, Arizona.
3. 1977 ASHRAE Handbook of Fundamentals. American Society of Heating, Refrigerating, and Air Conditioning Engineers, Inc., 345 E. 47th Street, New York, NY 10017.



KLOS WINDOW

Horizontal Sliding

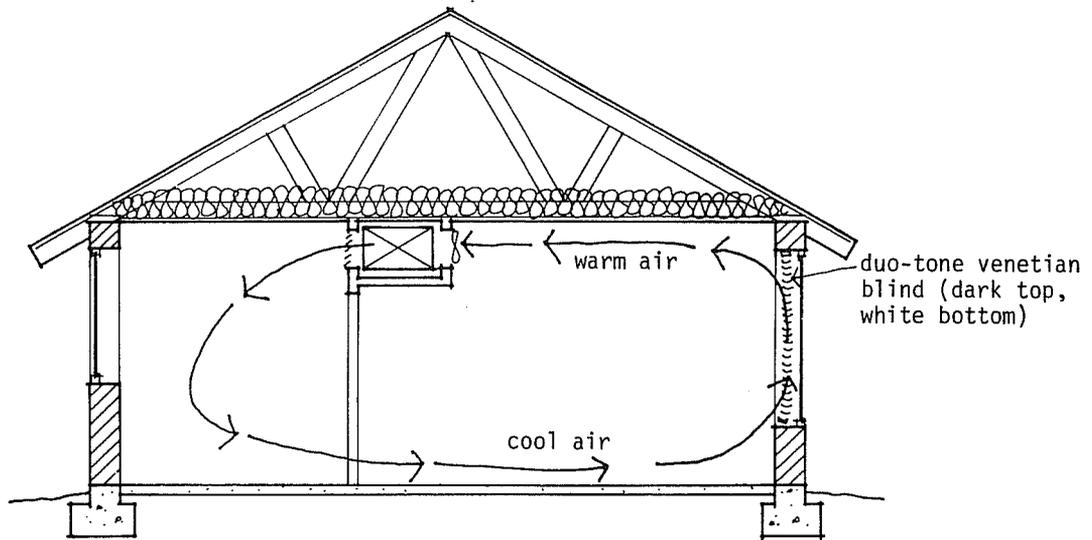
PLAN VIEWS



Double Hung

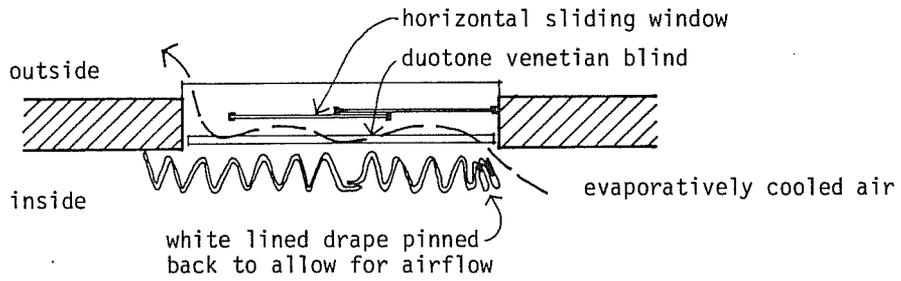
SECTION VIEWS

Fig. 1

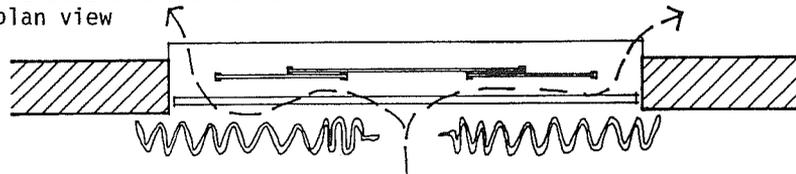


CLEARVIEW SOLAR ABSORBER with automatically controlled fan to distribute heat

Fig. 2



ONE SIDE OPENING WINDOW OR PATIO DOOR
plan view



TWO SIDE OPENING SLIDING OR CASEMENT WINDOW
plan view

EXHAUSTING WINDOW HEAT WITH EVAPORATIVELY COOLED AIR

Fig. 3

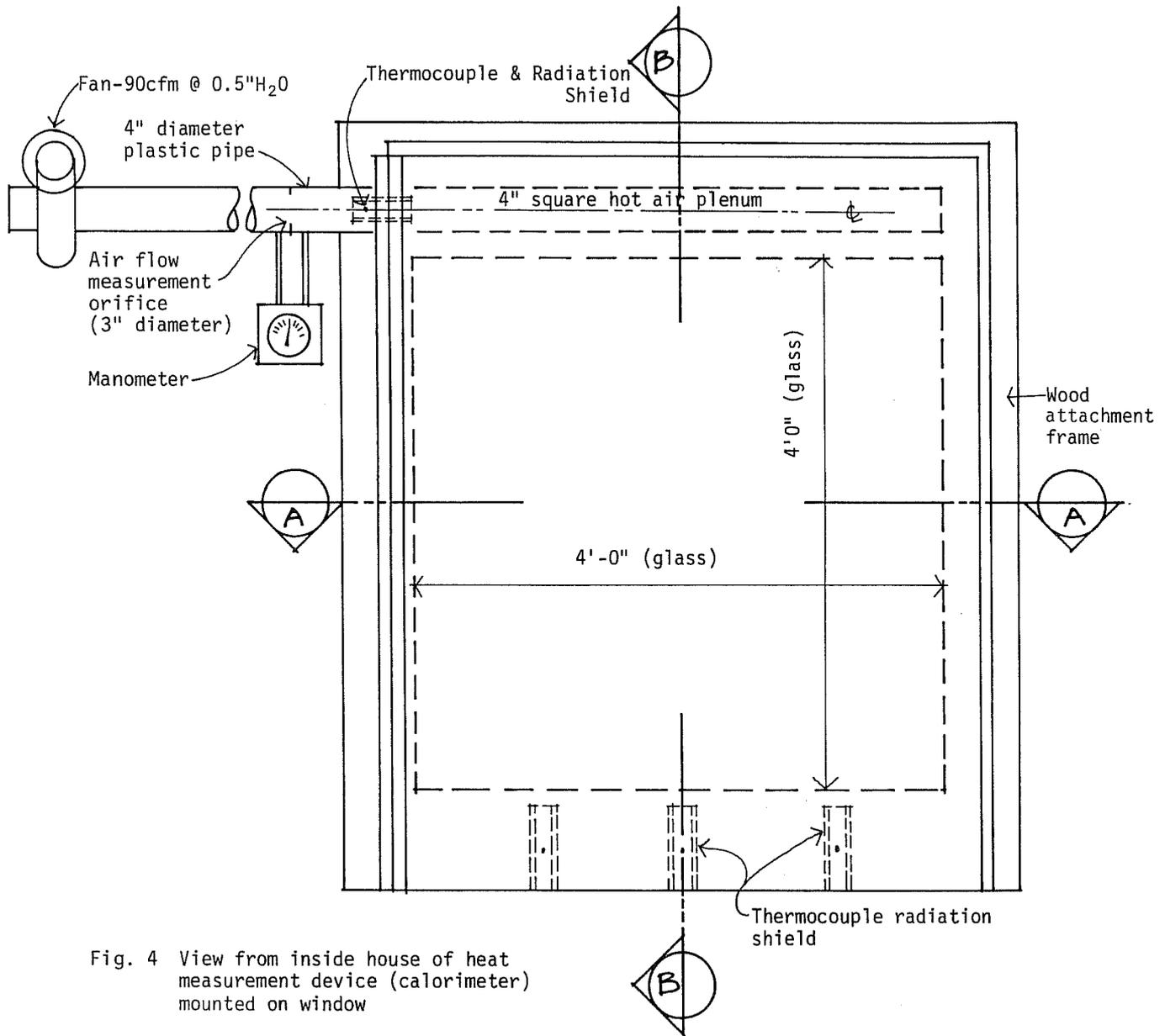
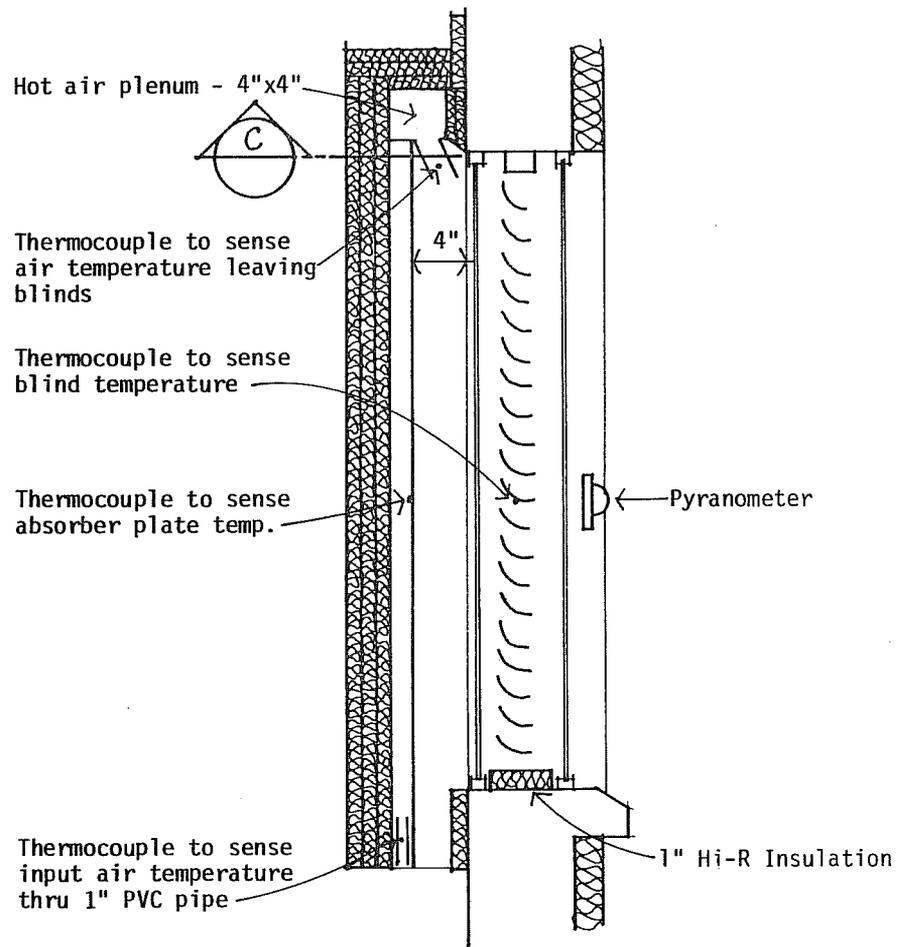
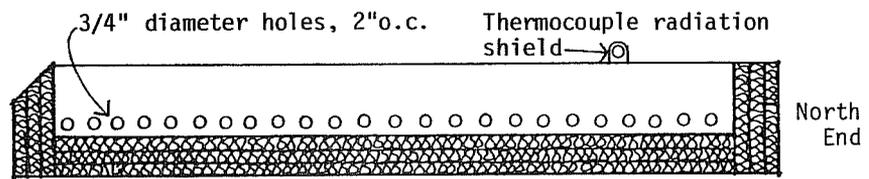


Fig. 4 View from inside house of heat measurement device (calorimeter) mounted on window



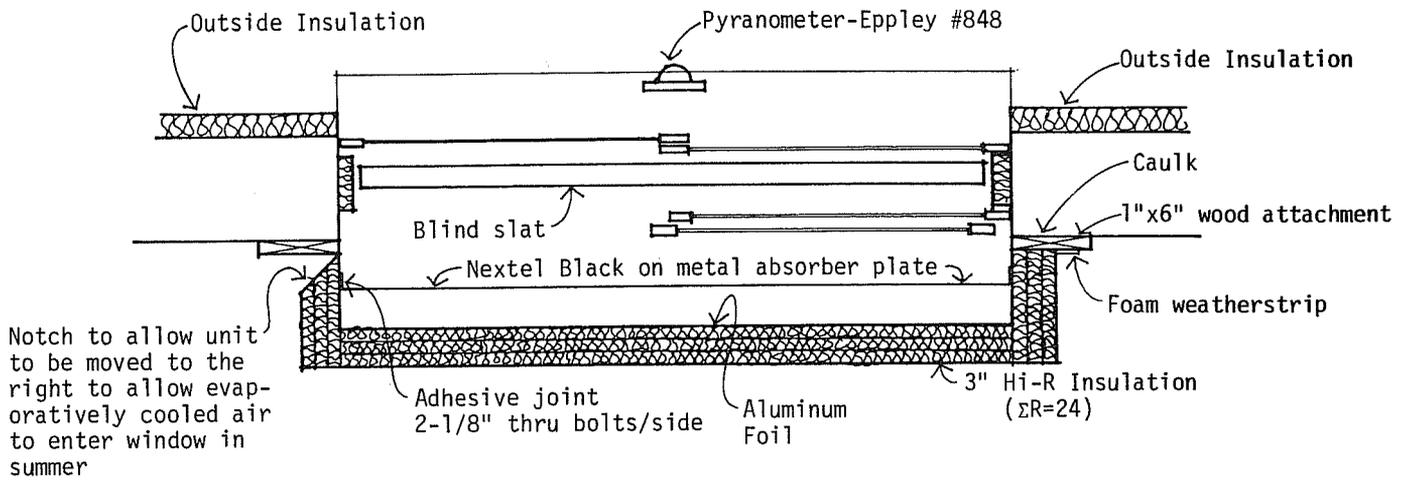
SECTIONAL ELEVATION B-B



Air Entrances to Hot Air Plenum

SECTION C-C

Fig. 5 Section Views of Window Calorimeter



SECTION A-A

Fig. 6 Additional View of Window Calorimeter

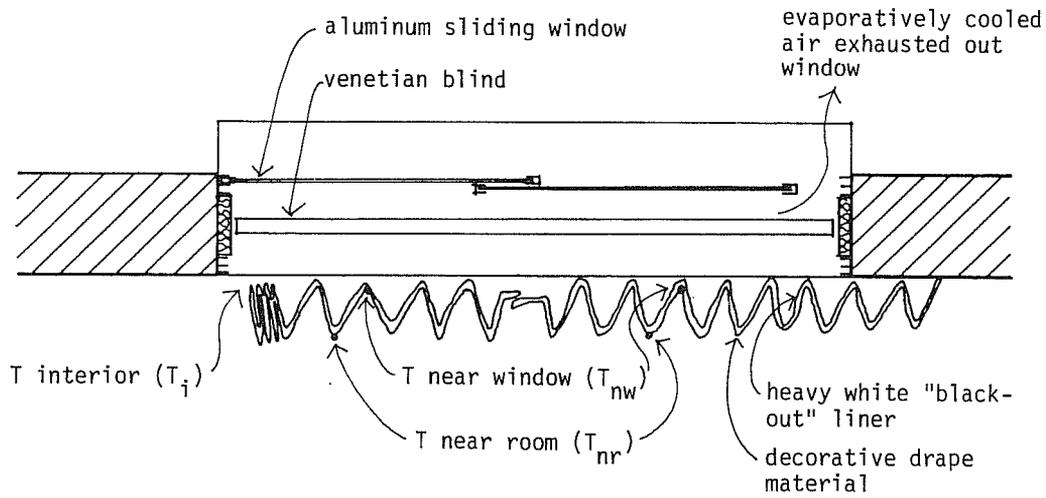


Fig. 7 WINDOW TEST CONFIGURATION (for testing temperatures of shaded, unshaded, ventilated and unventilated drapes)

APPENDIX A
METHODS FOR CALCULATING THE PERFORMANCE
OF KLOS AND CLEARVIEW WINDOWS

INTRODUCTION

A window calorimeter, illustrated in Figures 4, 5 and 6 was used to measure the performance of the Klos and ClearView windows under a relatively restricted set of conditions. The range of outside temperatures was limited due to the rather high temperatures prevailing in Tucson during the test period; hence, analytical models must be used to extrapolate the results to a wider range of ambient temperatures.

At the close of the calorimeter tests, the results were compared with an instrumented window without the calorimeter box; this comparison revealed a strong convective-coupling effect between the ClearView blinds and glass which had been obscured during the calorimeter runs. Two cases will be considered for the ClearView analysis: the first, or "free-standing" case in which the blinds are well separated from the window glass, and the second, or "convectively-coupled" case, in which case the blinds are near the window pane and influence the convective heat transfer to the glass.

There are a number of uncertainties and approximations in the analyses which follow. While more extensive experimentation and data collection could yield more precise and satisfying correlations for portions of the analytical models, we have proceeded with data collection only to the extent required to fulfill the objectives of this program: to establish the thermal performance of these window systems for design estimating purposes.

This appendix presents the methods for treating thermal radiation exchange, solar radiation absorption, convective heat transfer, and overall energy balances which can be used to analyze window performance.

THERMAL RADIATION EXCHANGE

To calculate the long-wave length (non-solar) radiation exchange between the various surfaces, it is necessary to obtain the view factors (F) and the overall graybody interchange factors (F'). Peck, *et al.*¹, gives the following expression for the blind blade-to-blade view factor: (Not to be confused with the fraction of open viewing area through the blinds to the outside.)

$$F_{bb} = 1/2 \left[\sqrt{1 - 2(S/W) \sin \alpha + (S/W)^2} + \sqrt{1 + 2(S/W) \sin \alpha + (S/W)^2} \right] - (S/W) \quad (1)$$

where α is the slat angle with the horizontal and W/S is the spacing ratio or the ratio of the slat width (W) to the spacing (S). Considering the

case where the blinds are located between two glass sheets, and taking the glass panes as infinite parallel plates, if the supporting strings or tapes are ignored, the required factors are:

$$F_{2b} = F_{1b} = (W/S) (1 - F_{bb}) \quad (2)$$

$$F_{b1} = F_{b2} = (1/2) (1 - F_{bb}) \quad (3)$$

$$F_{12} = F_{21} = [1 - (W/S) (1 - F_{bb})] \quad (4)$$

Where the subscript b refers to blind surface and subscripts 1 and 2 to the outer and inner glass panes, respectively.

For these calculations, the ratio of blind surface area to that of either pane is $2(W/S)$. Using Gebhart's absorption-factor method², the required interchange factors can be determined as:

$$F'_{b1} = \epsilon_b \epsilon_1 / \{ [(r - F_{1b} \rho_b) / F_{12}] - \rho_1 (F_{1b} \rho_b - F_{12} \rho_2 r) \} \quad (5)$$

$$F'_{12} = \epsilon_2 r F'_{b1} / \epsilon_b \quad (6)$$

where:

$$r = \{ (F_{1b} \rho_b / F_{12}) + [(1 - F_{bb} \rho_b) / F_{b1}] \} / \{ (1 / F_{12}) + \rho_2 \} \quad (7)$$

When the emissivities of the glass panes are unequal, F'_{b2} can be determined by exchanging the subscripts 1 and 2 in equations (5) and (7). ϵ and ρ are the emissivities and reflectances (here $\rho = 1 - \epsilon$) of the various surfaces. Note that:

$$2(W/S) F'_{b1} = F'_{1b} \quad (8)$$

$$2(W/S) F'_{b2} = F'_{2b} \quad (9)$$

This derivation was based on the case where the emissivities of the blind slat top and bottom are equal. In some cases, where one surface is made highly reflective, to reduce the solar load for example, the emissivities will be unequal and these expressions will not apply.

For the case where only one pane is present, set the emissivity and reflectivity of the missing pane to one and zero, respectively. If, for example, the inner pane is missing, the room will become surface 2 with $\epsilon_2 = 1$ and $\rho_2 = 0$, and radiation into the room may be calculated.

Table A-1 gives interchange factors for the ClearView and Klos windows, calculated with the above equations.

Table A-1

Greybody Interchange Factors for Klos and Clearview Windows
 $\epsilon_b = 0.9$ $\epsilon_g = 0.94$ $W/S = 1.2$

Slat Angle, , Deg.	0	18	30	45	60
Clearview Window:					
Blind-to-Glass	0.236	0.243	0.254	0.276	0.305
Blind-to-Room	0.257	0.264	0.275	0.298	0.327
Glass-to-Room	0.358	0.341	0.312	0.257	0.182
Klos Window:					
Blind-to-Glass	0.242	0.248	0.259	0.280	0.308
Glass-to-Glass	0.337	0.321	0.294	0.242	0.172

Radiation heat transfer can be treated in this instance with an equivalent heat transfer coefficient for radiation h_r , BTU/(ft²) (hr) (°F).

$$h_r = \sigma F' (T_1^4 - T_2^4)/(T_1 - T_2) = \sigma F' (T_1 + T_2) (T_1^2 + T_2^2) \quad (10)$$

Where T_1 and T_2 are the absolute temperatures of the surfaces considered, °R; and σ is the Stefan-Boltzmann constant, BTU/(sq.ft.) (hr) (°R)⁴.

The closed portion of the Klos window has two inner glass panes, designated by subscripts 2 and 3, between the blinds and the room. The interchange factor for these two panes is given by the expression for exchange between two infinite parallel plates³:

$$F'_{23} = 1/[(1/\epsilon_2) + (1/\epsilon_3) - 1] \quad (11)$$

SOLAR RADIATION ABSORPTION AND TRANSMISSION

The reader is referred to Parmelee and Vild's⁴ paper for calculating the absorption of direct and diffuse solar radiation by venetian blind and single glass combinations. For a venetian blind behind a single glass pane, taking into account only one pair of reflections, Parmelee and Vild give for direct radiation:

Transmission into room:

$$\tau_D = \tau_{gD} (\tau_{bD} + \rho_{gd} \rho_{bD} \tau_{bDa}) \quad (12)$$

Absorption by glass:

$$(\alpha_D)_1 = \alpha_{gD} + \tau_{gD} \alpha_{gd} \rho_{bD} \quad (13)$$

Absorption by blind:

$$(\alpha_D)_b = \tau_{gD} (\alpha_{bD} + \rho_{gd} \rho_{bD} \alpha_{bDa}) \quad (14)$$

Calculations must be performed for the direct (I_{SD}), diffuse ground (I_{SG}), and diffuse sky (I_{SS}) components of the total solar radiation (I_{ST}). The above expressions hold for the direct component. For the diffuse ground and sky components, the transmission equations are:

$$\tau_{dG} = \tau_{gd} (\tau_{bdG} + \rho_{gd} \rho_{bdG} \tau_{bDa}) \quad (15)$$

$$\tau_{dS} = \tau_{gd} (\tau_{bdS} + \rho_{gd} \rho_{bdS} \tau_{bDa}) \quad (16)$$

To compute the absorptivity or transmissivity for diffuse radiation, it is only necessary to substitute the diffuse value of a component property for its direct counterpart in equation (12)-(14). For the blinds, the diffuse sky (subscript dS), diffuse ground (subscript dG), or diffuse average (subscript da) must be used, depending on whether the radiation originates from above or below the horizon, or results from a diffuse reflection from the blinds.

The overall transmission of solar radiation into the room for the ClearView absorber becomes:

$$\tau_c = (1/I_{ST}) (\tau_D I_{SD} + \tau_{dG} I_{SG} + \tau_{dS} I_{SS}) \quad (17)$$

Similarly, absorption by the glass for the diffuse components is:

$$(\alpha_{dG})_1 = \alpha_{gd} + \tau_{gd} \alpha_{gd} \rho_{bdG} \quad (18)$$

$$(\alpha_{dS})_1 = \alpha_{gd} + \tau_{gd} \alpha_{gd} \rho_{bdS} \quad (19)$$

and the overall absorption by the glass is:

$$\alpha_{c1} = (1/I_{ST}) [(\alpha_D)_1 I_{SD} + (\alpha_{dG})_1 I_{SG} + (\alpha_{dS})_1 I_{SS}] \quad (20)$$

The corresponding equations for absorption by the blinds are:

$$(\alpha_{dG})_b = \tau_{gd} (\alpha_{bdG} + \rho_{gd} \rho_{bdG} \alpha_{bdDa}) \quad (21)$$

$$(\alpha_{dS})_b = \tau_{gd} (\alpha_{bdS} + \rho_{gd} \rho_{bdS} \alpha_{bdDa}) \quad (22)$$

$$\alpha_{cb} = (1/I_{ST}) [(\alpha_D) b^{I_{SD}} + (\alpha_{dG}) b^{I_{SG}} + (\alpha_{dS}) b^{I_{SS}}] \quad (23)$$

When two glass panes are between the slats and sun, as would be the case for a double glazed window, for absorption by the inner glass pane, the slats, and transmission through the combination, multiply equations (12), (13), and (14), by τ_{gD} . For the outermost glass pane:

$$(\alpha_D)_{01} = \alpha_{gD} + \alpha_{gD} \rho_{gD} \tau_{gD} + \tau_{gD}^2 \alpha_{gD} \tau_{gD} \rho_{bD} \quad (24)$$

To determine the diffuse absorptivity of the outer glass, substitute the diffuse properties as previously illustrated into equation (24), and calculate the overall absorption as:

$$\alpha_{c01} = (1/I_{ST}) [(\alpha_D)_{01} I_{SD} + (\alpha_{dG})_{01} I_{SG} + (\alpha_{dS})_{01} I_{SS}] \quad (25)$$

The Klos window geometry consists of a single glass in front of the blind and one or, more commonly, two inside panes behind the blinds. The solar absorption and transmission expressions will be given only for the case of direct solar radiation, since the diffuse equations follow with obvious modifications. Also the overall transmission (τ_K) and absorptances (α_{K1} , α_{Kb} , α_{K2} and α_{K3}) follow from the ClearView examples, equations (17), (20) and (23).

Transmission into room:

$$\tau_D = \tau_{gD} \tau_{gdi} (\tau_{bD} + \rho_{gdi} \rho_{bD} \tau_{bda} + \rho_{gdi} \tau_{bD} \rho_{bda}) \quad (26)$$

Absorption by the outer glass:

$$(\alpha_D)_1 = \alpha_{gD} \tau_{gD} (\rho_{bD} + \rho_{gdi} \tau_{bD} \rho_{bda}) \quad (27)$$

Absorption by Blind:

$$(\alpha_D)_b = \tau_{gD} [\alpha_{bD} + \alpha_{bda} (\rho_{gD} \rho_{bD} + \rho_{gdi} \tau_{bD})] \quad (28)$$

Absorption by inside glass(es):

$$(\alpha_D)_i = \alpha_{gdi} \tau_{gD} [\rho_{gD} \rho_{bD} \tau_{bD} + \tau_{bD} (1 + \rho_{gdi} \rho_{bda})] \quad (29)$$

Equations (26) through (29) are written so that they may be applied to a system having one or more glass panes between the blinds and room. The subscript "i" refers to the property designated evaluated for the combination of inside glasses. For example, if there are two inside glass panes, ρ_{gdi} refers to the overall reflection of diffuse radiation from two glass sheets. This greatly simplifies the analysis.

The reader is referred to Parmelee and Vild's paper⁴ for instructions and tables for evaluation of the terms in equations (12)-(29). Tables A-2 and A-3 for the transmission and absorption of diffuse and direct solar radiation were calculated for the experimental blinds used in this study. When the slat angle is adjusted so

that no direct solar radiation penetrates the space between the blinds, the product of the absorptivity of the upper blind surface and the transmittance through the outermost glass pane is a good approximation to the more rigorously computed value of the overall blind absorptivity from equation (14).

CONVECTIVE INTERCHANGE BETWEEN GLASS AND AIR

The convective heat transfer coefficient at the outermost glass surface¹ can be estimated from:

$$h_{co} = 0.9 + 0.3v_W \quad (30)$$

where v_W is the wind velocity, mph.

Radiative transfer from the outside glass to the sky and surroundings is also important, and may be estimated if the atmospheric conditions, temperature, and nature of the surroundings are given. The practice in the ASHRAE handbook⁵ is to use a combined convective and radiative coefficient (h_o). The examples given here will normally use that approach, unless otherwise stated.

Free convection conditions at the inner glass surfaces will normally be in the turbulent flow regime, and the equation for a vertical plane³

$$h_c = 0.19 \Delta t^{1/3} \quad (31)$$

will apply, where Δt is the temperature difference between the surface and surrounding air, °F.

The free convection coefficient between two glass panes can be calculated from the expression for a vertical enclosed air-space³ as:

$$h_c = 0.137 \Delta t^{1/4} \quad (32)$$

where Δt is the temperature difference between the two panes.

CONVECTIVE TRANSFER FROM BLINDS

For convective heat transfer from the blinds, both the exposed blinds of the ClearView configuration, and enclosed blinds of the closed portion of the Klos window must be treated.

First considering the ClearView window configuration, two distinct cases must be analyzed. The first, or "free-standing", case considers the blinds to be set back at a distance from the glass, so that room air circulates freely over both the blind slats and glass pane, and convective heat transfer from the room to glass is determined by the room air and glass temperatures. This is illustrated in figure A-1. The second case, shown in figure A-2 considers direct "convective coupling" between the blinds and the window pane; room air is heated by passage through the blinds and is drawn upward between the blinds and glass by a natural draft. Convective heat transfer to the glass is much larger due to the higher temperature of the air impinging on the glass.

Table A-2

Absorptance and Transmittance of Experimental Blind Assembly
for Direct Solar Radiation

Absorptivity: upper blind slat surface = 0.89
lower slat surface = 0.43

Transmittance

Profile	slat angle, ψ , deg.			
Angle, (Deg.)	18	30	45	60
0	0.640	0.415	0.167	0.013
10	0.445	0.236	0.021	0.011
20	0.237	0.046	0.016	0.010
30	0.029	0.022	0.015	0.009
40	0.025	0.019	0.013	0.008
50	0.022	0.017	0.012	0.007
60	0.020	0.016	0.011	0.006

Absorptance

Profile	slat angle, ψ , deg.			
Angle, (Deg.)	18	30	45	60
0	0.343	0.553	0.779	0.911
10	0.528	0.722	0.920	0.908
20	0.726	0.902	0.914	0.906
30	0.924	0.920	0.912	0.904
40	0.922	0.920	0.909	0.902
50	0.920	0.914	0.907	0.900
60	0.918	0.912	0.905	0.898

Convective Transfer from Free-standing Blinds

Experimental correlations for free convection heat transfer from the blind surfaces could not be located in the literature for either the free-standing or convectively coupled case. However, an approximate solution for the free-standing case was estimated from a similar geometry.⁶ Infinitely long parallel plates were judged to be the most suitable geometry for which extensive data are available. The analogy will become increasingly poor as the blinds are closed; at total closure equation (31) would be expected to apply.

The correlations of Elenbaas⁷ can be simplified to the following for air at room temperature, $W/S = 1.2$, and used to estimate convective heat transfer coefficients for free-standing blinds:

ψ , deg.	$W = 1$ inch	$W = 2$ inches
60	$h_{cb} = 0.610\Delta t^{0.248}$	$h_{cb} = 0.511\Delta t^{0.248}$
45	$0.572\Delta t^{0.252}$	$0.483\Delta t^{0.252}$
30	$0.527\Delta t^{0.258}$	$0.451\Delta t^{0.258}$
18	$0.464\Delta t^{0.27}$	$0.407\Delta t^{0.27}$

Heat Transfer Between Convectively-coupled Blinds and Glass

The relatively large difference between the "free-standing" and "convectively-coupled" heat transfer coefficients was first inferred from the relatively high temperatures of the blind slats in the latter case; 10 to 20°F above that predicted

Table A-3

Absorptance and Transmittance of Experimental
Blind Assembly for Diffuse Solar Radiation

Absorptivity: upper blind slat surface = 0.89
lower blind surface = 0.43

Slat Angle, ψ , Deg.	0	20	30	40	50	60
Diffuse Absorptance:						
Radiation from above horizon	0.593	0.789	0.830	0.888	0.906	0.902
Radiation from below horizon	0.433	0.334	0.346	0.393	0.477	0.592
Average	0.513	0.562	0.598	0.641	0.692	0.747
Diffuse Transmittance:						
Radiation from above horizon	0.378	0.167	0.106	0.047	0.014	0.009
Radiation from below horizon	0.444	0.610	0.620	0.576	0.486	0.359
Average	0.411	0.389	0.363	0.312	0.250	0.184

in the free-standing case for the same room air and solar radiation conditions. Rather than flowing essentially parallel to the slats, as happens in the free-standing case, the air flows from the room against the bottom of the blind slat, through the space between the slats, over the top of the slats, and into the space between the blinds and window pane. A relatively strong natural updraft occurs in the space between the blinds and window pane, with the velocity increasing with height as more warm air is fed into the updraft from succeeding slats.

No direct measurement of the heat transfer coefficients from the blind slats was attempted; rather, computer models were employed in which various equations for the heat transfer coefficients were tested, with the computed temperatures compared with experimental values. The coefficients selected as a result of these studies are given by equations from McAdams³:

For the bottom of the slats:

$$N_{Nu} = 0.27 (N_{Gr} N_{Pr})^{1/4} \quad (33)$$

and for the top of the slats:

$$N_{Nu} = 0.54 (N_{Gr} N_{Pr} \cos \psi)^{1/4} \quad (34)$$

$$\text{or } N_{Nu} = 0.55 (N_{Gr} N_{Pr} \sin \psi)^{1/4} \quad (35)$$

When N_{Nu} is the Nusselt number, N_{Gr} is the Grashof number, N_{Pr} is the Prandtl number and ψ is the slat angle. Equation (33) is for a heated plate facing down; Equation (34) is for a heated plate facing up, with a correction for the slat angle⁶; while equation (35) is for a vertical

plate, also with a slat angle correction. At a given slat angle, the larger value of the heat transfer coefficient calculated from equation (34) or (35) should be used. No correction for the slat angle is used with equation (33) for a heated plate facing down, as this case is not well understood⁶. In these equations the temperature differences are computed using the blind and room temperature, with the slat width used for the geometry term. Equations (33) through (35), evaluated for air at room temperature are:

For the bottom of the slats:

$$h_{cb} = 0.12 (\Delta t/W)^{0.25} \quad (36)$$

and for the top of the slats:

$$h_{cb} = 0.27 [(\Delta t/W) \cos \psi]^{0.25} \quad (37)$$

$$\text{or } h_{cb} = 0.29 [(\Delta t/W) \sin \psi]^{0.25} \quad (38)$$

The heat transfer coefficient at the inside glass pane can be calculated from equation (31) for turbulent free convection, as recommended by Liburdy & Faeth⁹ for a thermal plume along a wall.

Convective Heat Transfer Coefficients in the Closed Portion of the Klos Windows

In the closed portion of the Klos window, air flows in the bottom half of the space connecting the open and closed portion of window, is heated by convection by the blinds, and flows out the top half of the window, as illustrated in figure A-3. Circulation is caused by the density difference between the room air and air in the window; the flow pattern is approximately semi-circular around

a point at the center edge of the inside panes. The air velocity is low enough to allow calculation of the convective heat transfer coefficient using free convection equations. In the analysis of the window, the air flow will be considered to be split into two streams, with the inside stream contacting the bottom side of the slats and the outside stream contacting the top of the slats, consequently equation (33) is used for the inside stream, and equation (34) or (35) for the outside stream.

Convective heat transfer between the air streams and glass surfaces is again calculated as turbulent free convection with equation (31).

OVERALL ENERGY BALANCE, FREE-STANDING BLINDS

To determine the overall efficiency of the window-blind combination, energy balances are written around the glass surface, the blinds, and the air within the room. As previously explained, room air is considered to circulate freely over both the blinds and glass pane.

The energy balance around the glass pane is:

$$f_{LS} \alpha_{cl} I_{ST} = h_o(t_1 - t_o) + (h_{cli} + h_{rli})(t_1 - t_i) + h_{rlb}(t_1 - t_b) \quad (39)$$

f_{LS} is a factor to correct for losses from the aluminum window frame, in addition to the glass pane, and any correction for shading when required.

An energy balance around the blind slats is given by:

$$f_{LS} \alpha_{cb} I_{ST} = 2(W/S)[h_{cb}(t_b - t_i) + h_{rbl}(t_b - t_1) + h_{rbi}(t_b - t_i)] \quad (40)$$

To solve these equations, values of various surface and air temperatures are assumed and the various coefficients evaluated. The coefficients are substituted into equations (39) and (40), and the equations solved for t_1 and t_b . The coefficients are re-evaluated for the new temperatures and the process repeated until the required accuracy is attained.

The free-standing blind equations can be solved to clear t_b and t_1 , yielding the following expression for heat gain by the room:

$$U = \frac{1}{\frac{1}{h_o} + \frac{1}{(h_{rli} + h_{cli}) + \frac{1}{\frac{1}{h_{rlb}} + \frac{1}{[2/(W/S)h_{cb} + h_{rib}]}}}]} \quad (41)$$

$$h_{sb} = (h_{rli} + h_{cli}) + h_{rlb} \{1 + (h_{rli} + h_{cli})/[2(W/S)h_{cb} + h_{rib}]\} \quad (42)$$

$$q_i = \{ \tau_c + \alpha_{cl}(U/h_o) + \alpha_{cb} [(U/h_{sb})] \} f_{LS} I_{ST} - U(t_i - t_o) \quad (43)$$

These expressions are similar in several respects to those given by the ASHRAE guide⁵ for a double glazed window.

Analytical values of the shading coefficients (SC) and overall coefficients of heat transmission (U-factor) are presented in table 4 for the ClearView solar absorber. As explained in the ASHRAE guide⁵, the total instantaneous heat gain in the room, in Btu/(sq ft)(hr) is given by:

$$q_i = (SC)(SHGF) + U(t_o - t_i) \quad (44)$$

Equation (44) may be converted to the Hottel-Whiller-Bliss¹ form for flat plate solar collectors, where efficiency is expressed as:

$$\eta = F_c \alpha_{cb} + (F_c U_L) [(t_o - t_i)/I_{ST}] \quad (45)$$

$F_c \alpha_{cb} = 0.868 \times SC$, and $F_c U_L = U$, where SC

and U are from table 4. These approximations also apply to results tabulated for the Klos window and convectively-coupled blinds and glass cases.

Tables 4 and 5, as well as the tables presented for the other Klos and ClearView windows giving shading coefficients and U-factors, were computed based on a south facing, vertical window at 12 noon suntime, Dec. 21, and 32°N. Latitude. The reflectance of the ground in front of the window was taken as 0.2; the combined radiative and convective coefficient (h_o) at the outside of the glass was taken as 4.0; and the glass was the ASHRAE reference material double-strength sheet glass. The absorptivity of the top blind surface was taken as 0.89 and the bottom surface 0.43, from the experimental blinds used in this study. The slat width was 2 inches, and the ratio of slat width to spacing (W/S) was 1.2. The room temperature was taken as 72°F.

Table 5 presents values for shading coefficients and U-factors for the free-standing ClearView absorber equipped with a double glazed 3/4 inch air space. Modifications of the basic equations (39) and (40) for double glazing requires only the addition of an equation for the energy balance around the second outer glazing. This procedure is described in detail in the ASHRAE guide⁵, and need not be repeated here.

The analysis presented here for the free-standing blinds gives approximately the same results as the information presented in the ASHRAE guide when allowance is made for the difference in the

absorptance of the blinds; values of the U-factor given here are slightly higher than the ASHRAE values because of the effect of the blind temperatures on the radiative heat transfer coefficients. For example, if the heat gain is computed for venetian blind slats, medium color, with an absorptance of 0.6 for the slat assembly, (ASHRAE table 37⁵), the shading coefficient is 0.64 (ASHRAE table 34³), and the U-factor is 1.10 (ASHRAE table 13⁵). For an outdoor temperature at 55°F, an indoor temperature of 72°F, at 12 noon, Dec. 21, 32°N. Lat., south facing window (SHGF=252).

$$q_i = (0.64)(252) - (1.1)(72-55) = 142.6 \quad (46)$$

Using the techniques of Parmelee and Vild⁴, for an overall slat assembly absorptance 0.6, the blind top and bottom should have absorptivity of 0.51. The computer program prepared for these studies gives a shading coefficient of 0.647 and a U-factor of 1.23:

$$q_i = (0.647)(252) - (1.23)(72-55) = 142.1 \quad (47)$$

The two methods are in general agreement, and the ASHRAE values and technique appear in harmony with the analysis presented here for the free-standing blinds, in which room air is assured to circulate freely over both the blinds and the glass. The other case presented here, for the convectively-coupled blinds and glass, will give a lower value for the total gain than would be computed from ASHRAE methods.

Figure A-4 shows the partition of solar radiation for the standard 12N, Dec 12 case used for SHGF calculations. Here both the glass pane and blind slats exchange heat with room air at 72°F.

OVERALL ENERGY BALANCE, CONVECTIVELY-COUPLED BLINDS AND GLASS

In this case room air does not circulate freely over both the blinds and window pane; rather, air is drawn through the blinds by a natural draft, heated by contact with the blinds, and further drawn upward in the space between the blinds and window pane until it exits at the top of the window cavity. Heat from the warm air stream is transferred by natural convection to the window pane. The rate of convective heat transfer to the glass is considerably greater than in the free-standing case.

An energy balance around the glass pane is similar to equation (39), but must be written around a differential height segment "dz" as:

$$f_{LS}^{\alpha} c_l I_{ST} = h_o(t_l - t_o) + h_{cla}(t_l - t_{am}) + h_{rlb}(t_l - t_b) + h_{rli}(t_l - t_i) \quad (48)$$

Where t_{am} is the mean air temperature in section "dz" between the blinds and window.

Convective heat transfer between the blinds and room air will be calculated based on the temperature difference between the blind slats and room air ($t_b - t_i$), so that an energy balance around the blinds is given by:

$$f_{LS}^{\alpha} c_b I_{ST} = 2(W/S) [h_{cb}(t_b - t_i) + h_{rbi}(t_b - t_i) + h_{rbi}(t_b - t_i)] \quad (49)$$

With the exception of the convective heat transfer term between air and glass in equation (48), these expressions are identical to equation (39) and (40) for the free-standing case.

Now assume that the warm air leaving the blind slats in a given section mixes with the air from the section below it, while giving up heat by convection to the window pane, and then flows to the next section. Using a finite height section " ΔZ ", an amount of air " ΔM " (lb/ft hr) will be heated from t_i to t_{ab} by convection while passing through the blinds:

$$2(W/S)h_{cb}(t_b - t_i) = (\Delta M/\Delta Z)C_p(t_{ab} - t_i) \quad (50)$$

If the air streams entering the section, M at t_{ab} and M_{in} at $t_{a,in}$, mix, transfer heat to the glass, and leave the section at $t_{a,out}$, then:

$$C_p \Delta M (t_{ab} - t_{a,out}) + C_p M_{in} (t_{a,in} - t_{a,out}) = h_{cal}(t_{am} - t_l) \Delta Z \quad (51)$$

Assuming complete mixing:

$$t_{am} = [0.5 \Delta M / (\Delta M + M_{in})] (t_{ab} + t_{a,out}) + [0.5 M_{in} / (\Delta M + M_{in})] (t_{a,in} + t_{a,out}) \quad (52)$$

To compute the mean vertical air velocity, and hence the mass air flow rate, let:

$$K(\rho V^2/2g) = \bar{\Delta \rho} Z \quad (53)$$

Where ρ is the density of air, lb/ft³, and $\bar{\Delta \rho}$ is the mean difference in density between the column of air in the space between the blinds and glass, and the room air, over the height Z . V is the mean vertical velocity of air in the air space at height Z , ft/hr; g is acceleration due to gravity, ft/hr²; and K is an experimentally determined velocity-head coefficient required to account for resistance to flow through the blinds, friction in the air space, etc. If X_{as} is the distance between the blinds and glass, ft., then equation (53) can be

$$(M_{in} + \Delta M)^2 = (2g\rho X_{as}^2/K) \left[\sum_{j=1}^{n-1} (\Delta \rho \Delta Z)_j + \rho \beta (t_{am} - t_l) \Delta Z \right] \quad (54)$$

where β is the coefficient of volumetric expansion for air, °R⁻¹ or $\beta = -\Delta \rho / \rho \Delta t = 1/\bar{T}$.

These equations are approximated in linear form by expressing the terms $(M_{in} + \Delta M)^2$ and $(\Delta M) t_a$ as the first two terms of Taylor series. For example:

$$(M + \Delta M)^2 = (M + \Delta M_{est})^2 + 2(M + \Delta M_{est})(\Delta M - \Delta M_{est}) \quad (55)$$

where ΔM_{est} is an estimate of ΔM to begin iterative computations. Then equations (48) through (54) can be solved simultaneously, and through an iterative procedure will yield solutions for the temperatures and flow rate which can be used to determine the heat gain by the room as:

$$q_i = \overline{h_{rib}(t_b - t_i)} + \overline{h_{rli}(t_1 - t_i)} + \tau_{cLS} I_{ST} + (M_{out,t} C_p / Z_t) (t_{a,out,t} - t_i) \quad (56)$$

Where the first two terms are the average rates of heat transfer by radiation to the room interior, and the last term is the heat transfer by convection from the air space between the blinds and glass into the room. Here Z_t is the total window height, ft, $M_{out,t}$ is the air flow rate out of the top of the window, lb/ft hr, and $t_{a,out,t}$ is the air temperature out of the top of the window °F.

Experimentally, it was found that all of the air exits the window cavity through the top two slat openings, so the effect of exit conditions was negligible relative to the total window height.

A number of models were tested in which K and the blind heat transfer coefficients were varied. A constant value of $K=3$ agreed as well with experimental data as models in which K varied with height, air flow, etc. As previously mentioned, the blind heat transfer coefficients as determined by the equation for a flat plate facing down for the slat bottom, and a flat plate facing up for the top, with appropriate angle corrections, gave the best agreement with experimental data.

It should also be pointed out that there are many uncertainties in the values for both K and h_{cb} . Data were influenced by stray and erratic convection currents in the room in which the tests were conducted; stratification of air in the room; variations in the placement of the blinds relative to the glass; and uncertain measurements of air velocities and temperatures within the air space. Further experiments should be conducted under more controlled conditions with better instrumentation. The existence of the convective-coupling effect between blinds and glass was not anticipated at the outset of these experiments, and the experimental design and instrumentation was not well suited to investigate the convection currents encountered.

Computed values for the shading coefficients and U -factors are presented in Table 6 for the single glazing case and Table 7 for two outer glazings. In the previous section, it was demonstrated that the free-standing blind case gave good agreement with ASHRAE methods. In this case, for an overall slat assembly absorptance of 0.6, the shading coefficient was calculated to be 0.61 and $U=1.19$ for an energy gain, under the same conditions:

$$q_i = (0.61)(252) - (1.19)(72-55) = 133.49 \quad (57)$$

This is approximately 6% lower than predicted using ASHRAE methods.

Figure A-5 shows the calculated distribution of solar energy for the reference case of 12N, Dec. 12. In comparing Figure A-4 with Figure A-5 for the free-standing case, note that while the convective heat transfer to the glass for the convectively-coupled case is seven times that for the free-standing case, it amounts to only slightly more than 3% of the total solar radiation. Such a small percentage difference is difficult to detect from calorimeter data; however, the blind temperature is approximately 12°F higher, which is strikingly different and readily detected.

The window calorimeter used in this program, while useful for estimates of performance, influenced convection currents around the blinds and glass. Figure A-6 shows ClearView data for the afternoon of March 20, for a west facing window. Taking 15:28 sunset (4pm MST) for analysis, the experimental efficiency was 54.7%. Separating the model room temperatures into a radiant transfer temperature at the plate temperature, and a convective transfer temperature at the mean of the air entering and leaving the calorimeter, the free-standing model gave a computed efficiency of 57.2% and a calculated blind temperature of 129°, very near the measured temperature at the center of north blind shown in Figure A-6. The convectively-coupled model gave an efficiency of 54.5%, but predicted a blind temperature of 139°; since the measured temperature at the center of south blind was 136°, only with difficulty could one select between the two models from the window calorimeter data.

However, figure A-7 shows the temperature distribution measured for blinds without the calorimeter box. The free-standing model predicts an erroneous blind temperature of 112°F, while the convectively-coupled model predicts an average temperature of 124°F, in fair agreement with experimental results. Note that the experimental blind temperatures do not vary substantially with height.

OVERALL ENERGY BALANCE - KLOS WINDOW, WINTER OPERATION

During winter operation, the Klos window can be treated in two sections: one section with the inside window open which functions as a ClearView solar absorber, and which can be analyzed independent of the closed portion of the window; and the closed section where the plane of the blinds is separated from the room by two planes of glass, and which is open to the room only by the narrow slot through which the blind slats extend. There is some slight entrainment of warm air from the ClearView portion in the inlet air to the closed portion of the windows; and air exiting the closed section appears to influence the convection currents near the top of the ClearView sections, but these effects can be neglected in the overall analysis.

As mentioned in the section on convective heat transfer coefficients, and shown in Figure A-3, air flows into the bottom half of the closed

window section through the connecting slot, is heated by convection from the blinds and flows out the top half of the window. The air-flow pattern is roughly semi-circular around a point near the center of the connecting slot. Within the closed window section, the air flow is split into two streams, one moving through a channel formed by the outside window pane and blinds, and the major air flow through the channel formed by the blinds and one inside glass pane. These patterns were observed by introducing smoke into the air stream.

The analysis which follows is similar in some respects to one used by Brown, et.al.⁸, for air flow by convection between rooms through openings. A variation of the equations from Brown, et.al.⁸ based on a single mean value for the density of air within the window cavity was used with good results in modeling the window calorimeter tests, where the overall air temperatures into and out of the calorimeter were of primary interest. However, the method which follows better predicts the temperature and velocity distribution of air leaving the window.

In a given differential area, at fixed air temperatures for the two streams of t_a and t_{as} , assuming no mixing of the two streams and neglecting conduction in the glass and blinds, energy balances around the blinds and glass panes can be written as:

outer glass:

$$f_{LS}^{\alpha} K_1 I_{ST} = h_o(t_1 - t_o) + h_{1as}(t_1 - t_{as}) + h_{r1b}(t_1 - t_b) + h_{r12}(t_1 - t_2) \quad (58)$$

blinds:

$$f_{LS}^{\alpha} K_b I_{ST} = (W/S) [h_{cba}(t_b - t_a) + h_{cbas}(t_b - t_{as}) + h_{rb1}(t_b - t_1) + h_{rb2}(t_b - t_2)] \quad (59)$$

inside glass panes (2 and 3):

$$f_{LS}^{\alpha} K_2 I_{ST} = h_{r2b}(t_2 - t_b) + h_{r21}(t_2 - t_1) + h_{c2a}(t_2 - t_a) + (h_{c23} + h_{r23})(t_2 - t_3) \quad (60)$$

$$f_{LS}^{\alpha} K_3 I_{ST} = (h_{c23} + h_{r23})(t_3 - t_2) + (h_{c3i} + h_{r3i})(t_3 - t_i) \quad (61)$$

Now considering the air streams passing over a differential absorber area " dA_K ":

$$M_a C_p dt_a / dA_K = (W/S) h_{cba}(t_b - t_a) + h_{c2a}(t_2 - t_a) \quad (62)$$

$$M_{as} C_p dt_{as} / dA_K = (W/S) h_{cbas}(t_b - t_{as}) + h_{c1a}(t_1 - t_{as}) \quad (63)$$

If "2Z" is the height from the entrance to the exit of an air streamline (2Z is used to allow integration from the window center at height = Z)

$$K \rho V_a^2 / 2g = 2Z \overline{\Delta \rho} \quad (64)$$

$$K \rho V_{as}^2 / 2g = 2Z \overline{\Delta \rho} \quad (65)$$

where V_a and V_{as} are the velocities of the two air streams and $\Delta \rho$ is the mean difference in density of the air streamlines and room air. Expressions (64) and (65) can be written for mean air temperatures and a finite element of height as:

$$M_a^2 = [4gz\beta(\rho X_{aK} \Delta Z)^2 / K] (\bar{t}_a - t_i) \quad (66)$$

$$M_{as}^2 = [4gz\beta(\rho X_{ask} \Delta Z)^2 / K] (\bar{t}_{as} - t_i) \quad (67)$$

If the path of the streamline is approximated as semi-rectangular, for simplicity, then the area tranversed by the streamline is:

$$\Delta A_K = 2Z(1 + 2X_w/Z_t) \Delta Z \quad (68)$$

Where X_w is the width of the closed portion of the window and Z_t is the total height of the window.

Using average temperatures in equations (58) - (67), and linearizing M_a^2 and M_{as}^2 terms with Taylor series, these equations can be solved iteratively for the various temperatures and flows.

The heat gain by the room is then:

$$q_1 = h_{r3i}(t_3 - t_i) + \tau_{KLS} I_{ST} + [\Sigma M_a C_p (t_{a,out} - t_i) + \Sigma M_{as} C_p (t_{as,out} - t_i)] / A_K \quad (69)$$

The values of K were found to be approximately the same for the two air flows, and were taken as 12. The same experimental difficulties mentioned in connection with the ClearView window were encountered with the closed portion of the Klos window, and further experimentation is required; however, values for the heat gain coefficients are felt to be adequate for design purposes. Table 8 presents shading coefficients for the Klos window, with the open half of the window analyzed based on the convectively-coupled ClearView model.

Figure A-8 shows the computed energy distribution for the reference case of 12N, Dec. 12 for the closed portion of the Klos window. Fig. A-9 shows experimental temperature data for the window. The higher temperatures in the Klos window reduces the efficiency relative to the ClearView absorber.

KLOS WINDOW, SUMMER OPERATION

For summer operation, the Klos window is operated with the inner and outer glass panes opened slightly (~4 inches) as shown in Figure 1, and the blinds inclined so that evaporatively cooled air flows over the blinds, carrying the major portion of the solar heat gain by the blinds to the outside. The analysis of this case is virtually identical to that described by Peck, et.al.¹ and will not be repeated here. Table 9 presents values of the shading coefficients and U-factors for this case. The experimental convective heat transfer coefficients at the blind surfaces were found to be considerably higher than expected from the earlier work by Peck, et.al.¹. This was probably caused by the turbulence produced by the turns the air was subject to in this design, which are known to produce high coefficients¹⁰.

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Definition of Terms

- A.....Area, Sq.ft.
 - A_C , of ClearView absorber
 - A_K , of Klos Window
- C_pSpecific heat of air, Btu/lb^oF
- FView factor
 - F_{bb} , from blade to blade
 - F_{1b} or F_{2b} , from glass pane 1 (or 2) to blade or slat
 - F_{12} or F_{21} , between glass panes 1 and 2
- F_CEfficiency factor used in solar collector equation
- F'Overall graybody interchange factor; same subscripts system as view factor
- f_{LS}Correction factor for effective area for window loss exceeding glass area, or factor for partial shading of glass, dimensionless
- gAcceleration due to gravity, ft/hr²
- hHeat transfer coefficient, Btu/(sq.ft.) (hr) (^oF)
 - h_o , combined radiative and convective coefficient outside first glass pane
 - h_{sb} , combined radiative and convective coefficient relating to heat transfer between glass, blinds and room
- h_cConvective heat transfer coefficient, Btu/(sq.ft.) (hr) (^oF)
 - h_{cb} , from blind slats
 - h_{cba} , from blind slats to air
 - h_{cbas} , from blind slats to secondary air stream
 - h_{co} , from glass to outside air
 - h_{cna} , from glass "n" to air, n=1, 2, 3, or 4
 - h_{cni} , from glass "n" to inside
 - h_{cnm} , from glass "n" to glass "m", m=1,2, 3 or 4
- h_rRadiative heat transfer coefficient, Btu/(sq.ft.) (hr) (^oF),
 - h_{rnb} , from glass pane "n" to blinds (note that $h_{rnb} = h_{rbn}$ because the coefficients include the overall graybody interchange factor)
 - h_{rni} , from glass pane "n" to interior of room
 - h_{rnm} , from glass pane "n" to glass pane "m"
- I_sSolar radiation, Btu/(sq.ft.) (hr)
 - I_{SD} , direct component
 - I_{SG} , reflected ground component
 - I_{SS} , sky component
 - I_{ST} , total solar radiation
- KVelocity-head coefficient
- MAir flow rate per unit window width, lb/ft hr.
 - M_a , air stream
 - M_{as} , secondary air stream
 - M_{est} , estimate
 - M_{in} , into section or space between blind and glass
 - M_{out} , out of section
 - $M_{out,t}$, out of top of window
- NDimensionless number
 - N_{Nu} , Nusselt number
 - N_{Gr} , Grashof "
 - N_{Pr} , Prandtl "
- q_iHeat flux to the interior or inside, Btu/(sq.ft.) (hr)

r.....Dimensionless ratio in graybody interchange factor equation
 S.....Slat spacing, ft.
 SC.....Shading Coefficient
 SHGF.....Solar heat gain factor, Btu/(sq.ft.) (hr)

T.....Absolute temperature, °R
 T, average
 T_n, from surface "n"

t.....Temperature, °F
 t_a, air (t_a, average air)
 t_{ab}, air leaving blinds
 t_{a,in}, inlet air
 t_{a,out,t}, outlet air at top of window
 t_{am}, air mean
 t_{as}, secondary air stream (t_{as}, average secondary stream temperature)
 t_b, blind
 t_i, inside
 t_n, glass pane "n", n=1, 2, 3 or 4
 t_o, outside

U.....Overall coefficient of heat transmission, Btu/(sq.ft.) (hr) (°F)
 U_L, for solar collector losses

V.....Air velocity, ft/hr
 V_a, of air stream
 V_{as}, of secondary air stream

v_w.....Wind velocity, miles/hr

W.....Width of blind slats, Ft.

X.....Distance or spacing, ft.
 X_{as}, air space between blinds and glass, ClearView collector
 X_{aK}, air space for main air flow, Klos window
 X_{asK}, air space, for secondary air flow, Klos window
 X_w, width of window

Z.....Height or vertical distance, ft.
 Z_t, total height of window

α.....Absorptivity for solar radiation
 α_b, of blinds
 α_{bd}, of blinds for direct radiation
 α_{bd}, of blinds for diffuse radiation
 α_{bda}, of blinds for diffuse radiation, average of ground and sky
 α_{bdG}, of blinds for diffuse ground radiation
 α_{bds}, of blinds for diffuse sky radiation
 α_c, overall combined absorptivity, ClearView absorber
 α_{c1}, overall combined absorptivity, ClearView, for glass pane
 α_{cb}, overall combined absorptivity, ClearView, for blinds
 α_{c01}, overall combined absorptivity, ClearView, for outermost glass pane in double glazed window
 (α_D)₁, (α_D)_b, (α_D)₀₁, absorptivity of direct radiation component for glass, blinds, or outermost glass, respectively
 (α_{dG})₁, (α_{dG})_b, (α_{dG})₀₁, absorptivity of ground radiation components
 (α_{dS})₁, (α_{dS})_b, (α_{dS})₀₁, absorptivity of sky radiation component
 α_g, of glass
 α_{gD}, of glass, for direct solar radiation
 α_{gd}, of glass, for diffuse solar radiation
 α_{gdi}, of glass, for diffuse solar radiation, inside glass panes
 α_K, overall combined absorptivity, Klos window, enclosed portion
 α_{Kb}, K_n, overall combined Klos absorptivity, for blinds and glass pane "n"

β.....Coefficient of volumetric expansion
 Δ.....Difference
 ε.....Emissivity
 ε_b, of blinds
 ε_n, of glass surface "n"
 η.....Solar collector efficiency
 ρ.....Density of air in air flow equations (no subscripts), lb/cu.ft.
 ρ.....Reflectivity of radiation, subscript system same as α.
 σ.....Stefan-Boltzmann constant, Btu/(sq.ft.) (hr) (°R)⁴
 τ.....Transmissivity, subscript system same as T_D, τ_{dG}, τ_{dS}, Transmissivity into room for direct, diffuse ground, and diffuse sky, solar radiation, dimensionless
 ψ.....Slat angle with horizontal, degrees

Subscripts

a	air, average
b	blind, blade or slat
c	ClearView, collector, convective
D	direct
d	diffuse
G	ground
g	glass
i	inside
K	Klos
L	loss
m	mean
o	outside, overall
r	radiative
S	solar, sky, shade
s	space, secondary
W	wind
1,2,3,4	glass window pane, numbered from outside to inside

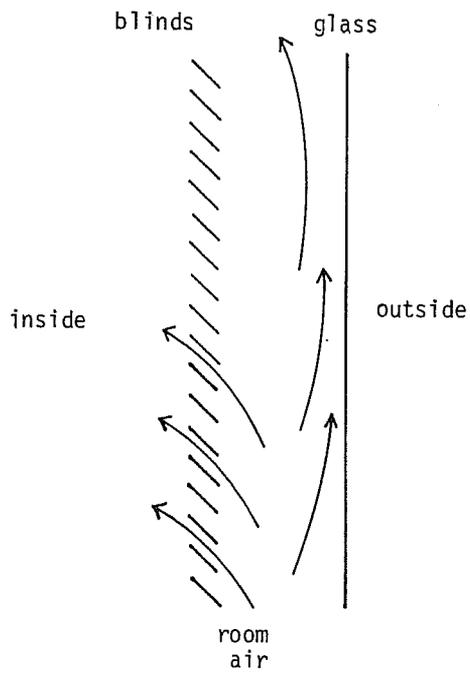


Fig. A-1 Freestanding Blinds - air circulates freely over both slats and glass.

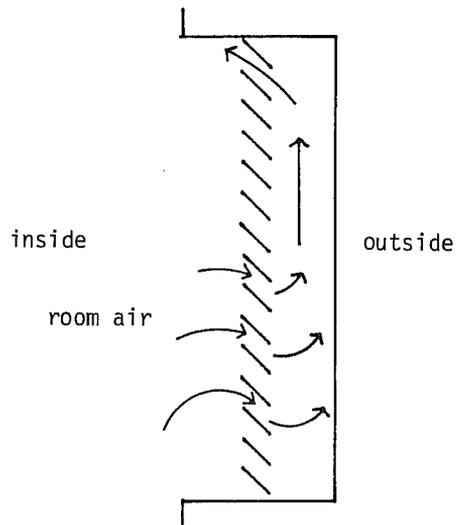


Fig. A-2 Convectively-Coupled Blinds and Glass - room air is heated by passage through blinds

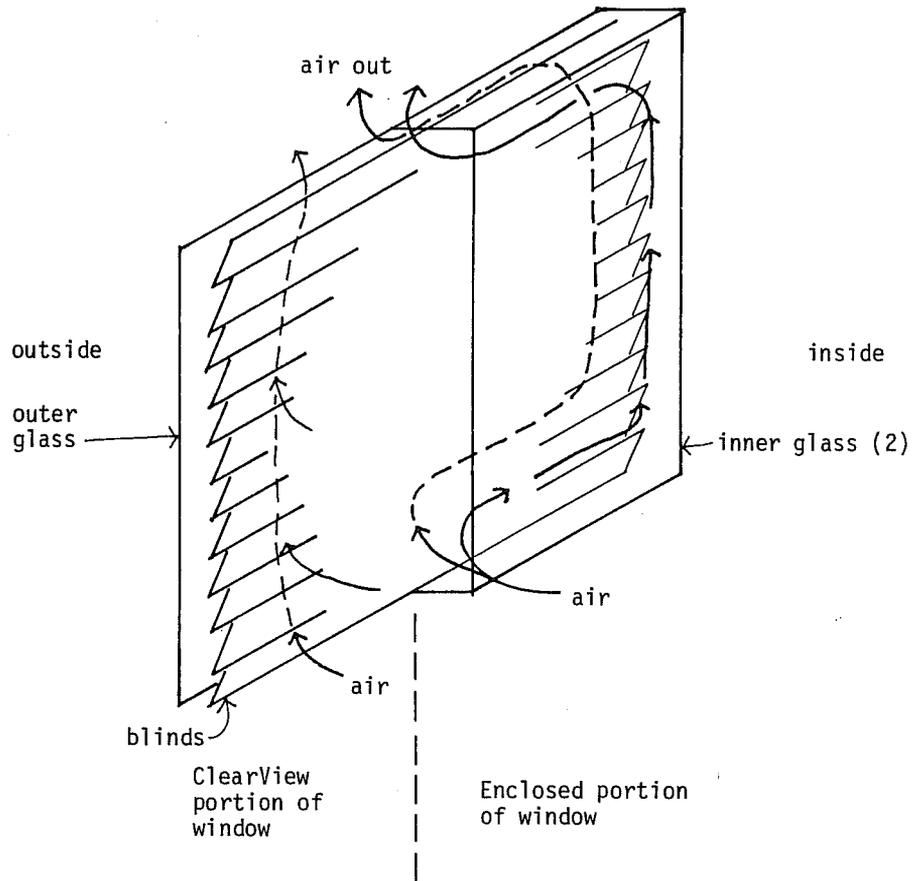


Fig. A-3 Klos Window Air Circulation

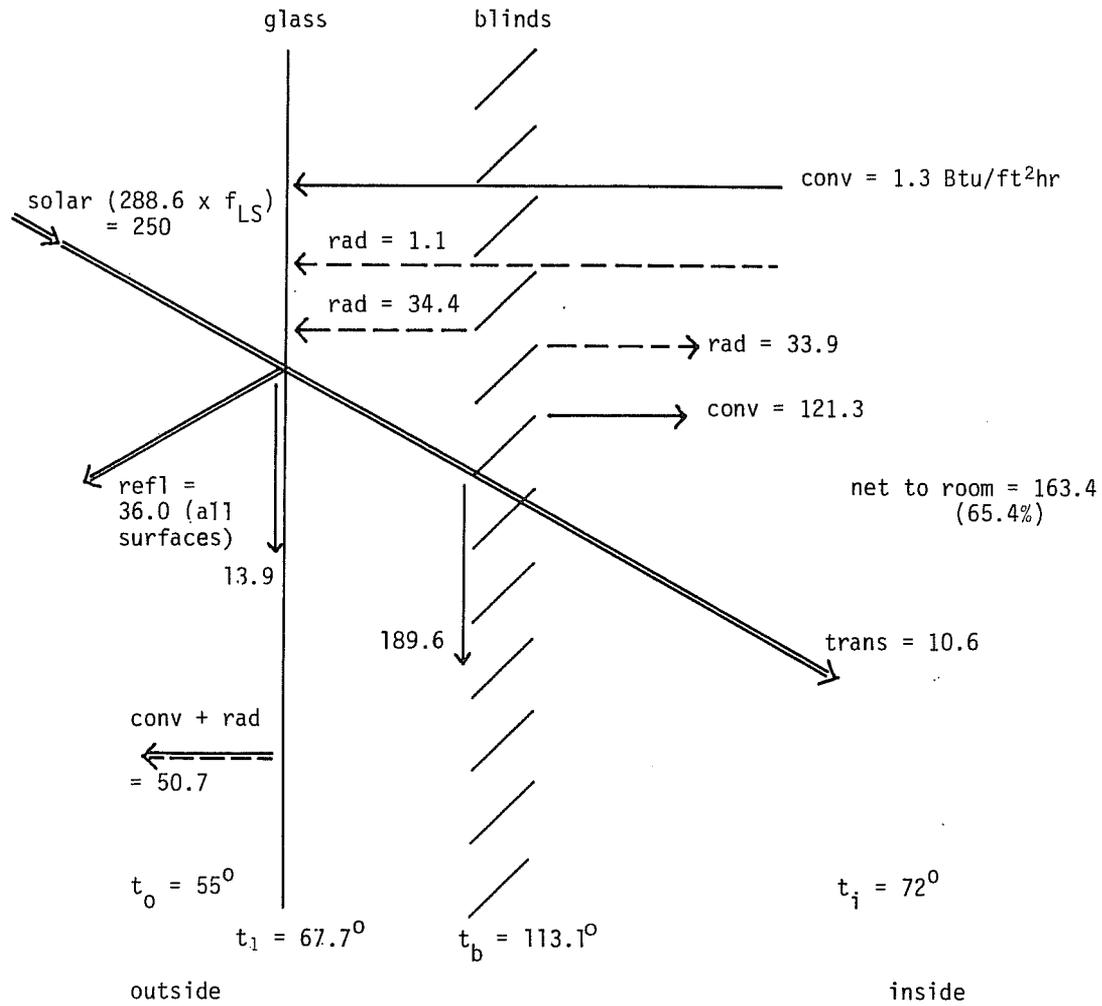


Fig. A-4 Energy Balance - Single Glazed ClearView Absorber - Free-standing

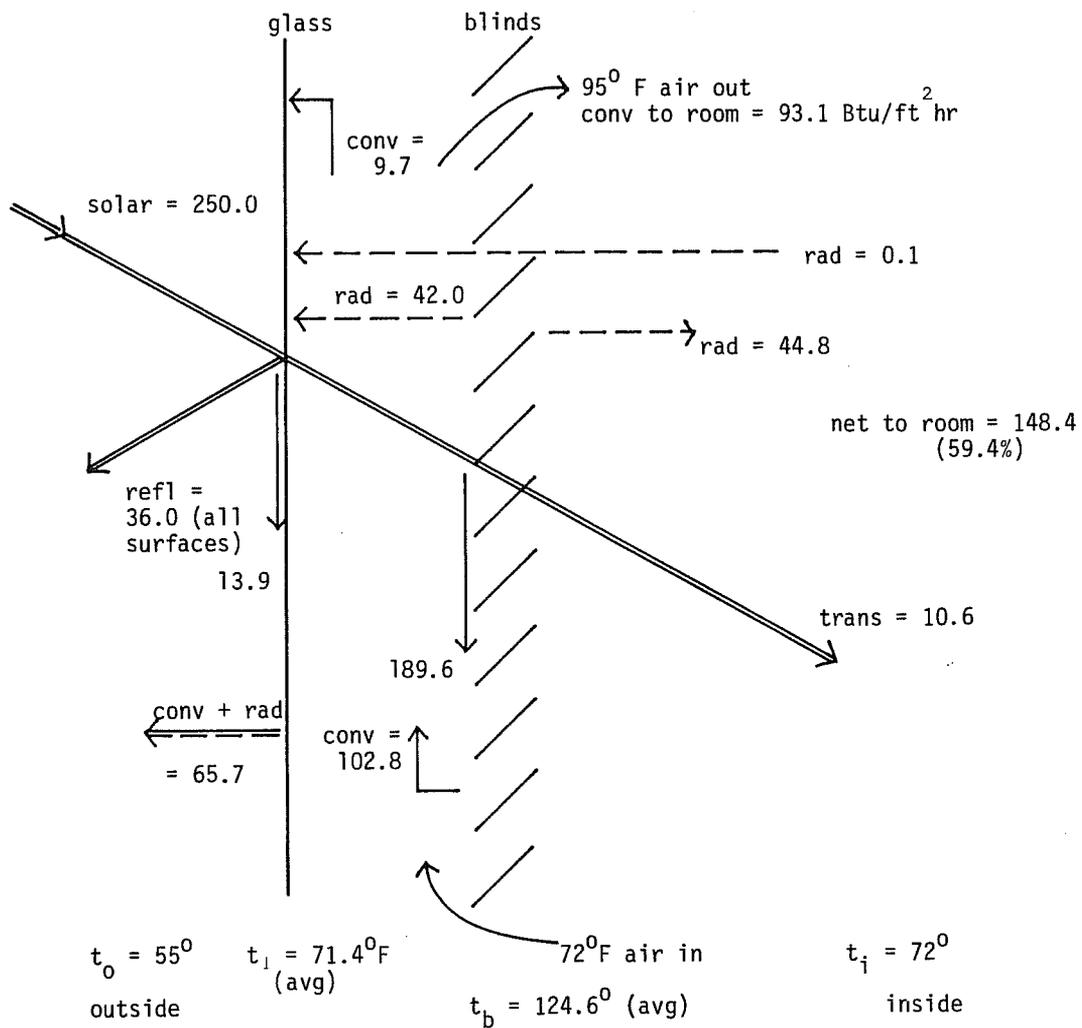


Fig. A-5 Energy Balance, single glazed ClearView Solar Absorber - Convectively-coupled

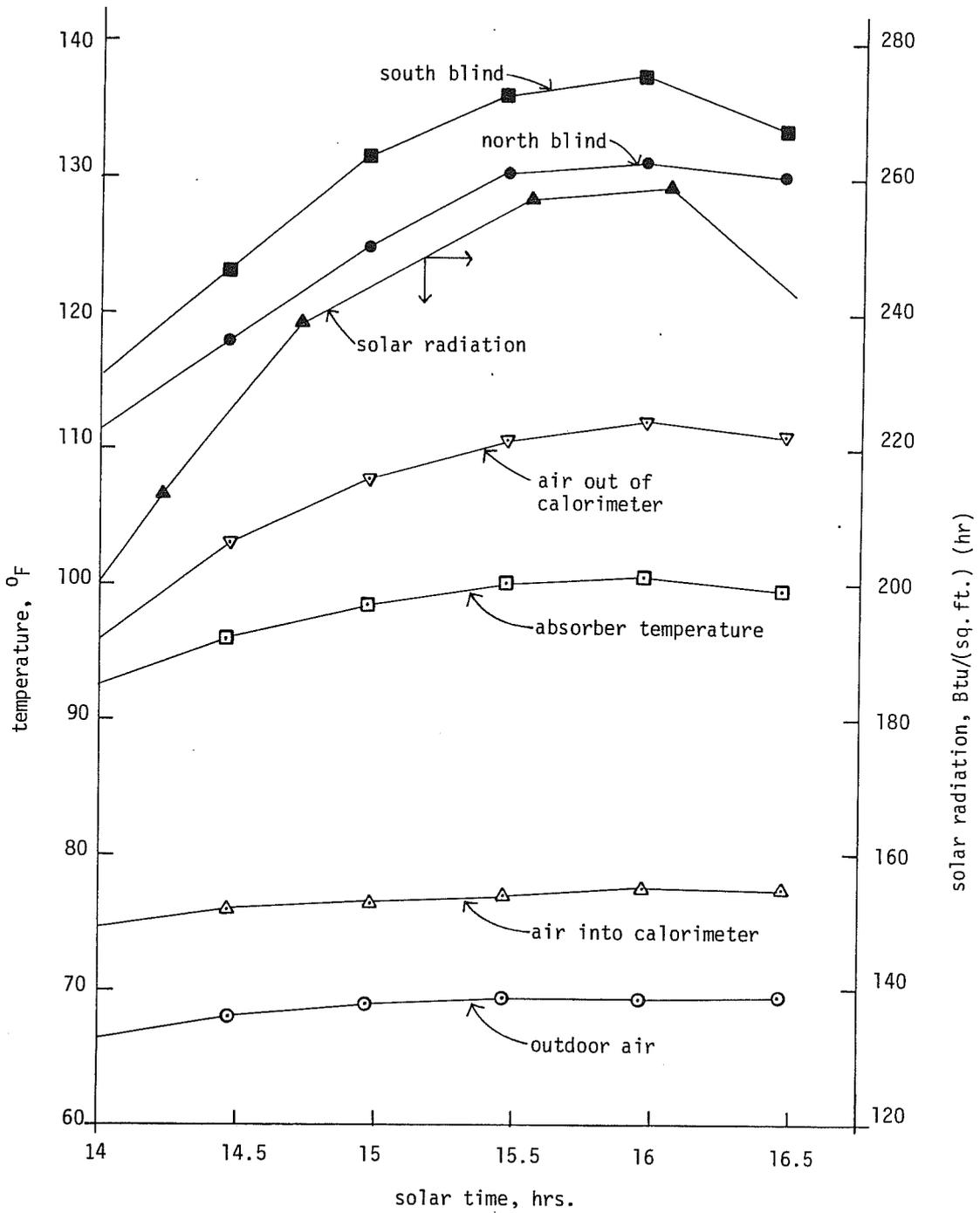


Fig. A-6 Typical Window Calorimeter Performance - ClearView Configuration
 3/20/80 West facing window, slat angle = 45°, air flow rate = 225 lb/hr

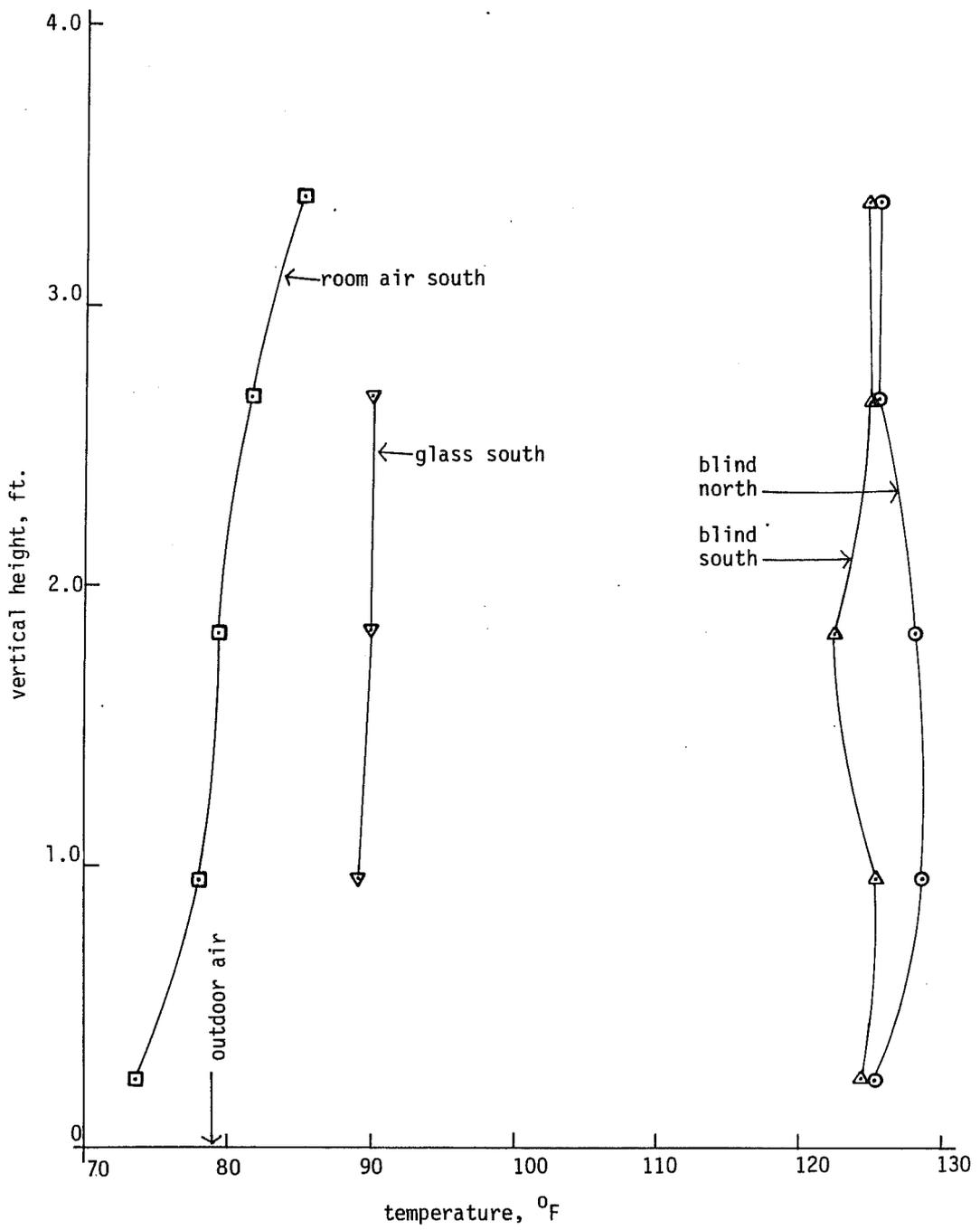


Fig. A-7 ClearView Absorber Data - slat angle = 45° - 2/24/80 - 15:30 mst
14:52 sun time

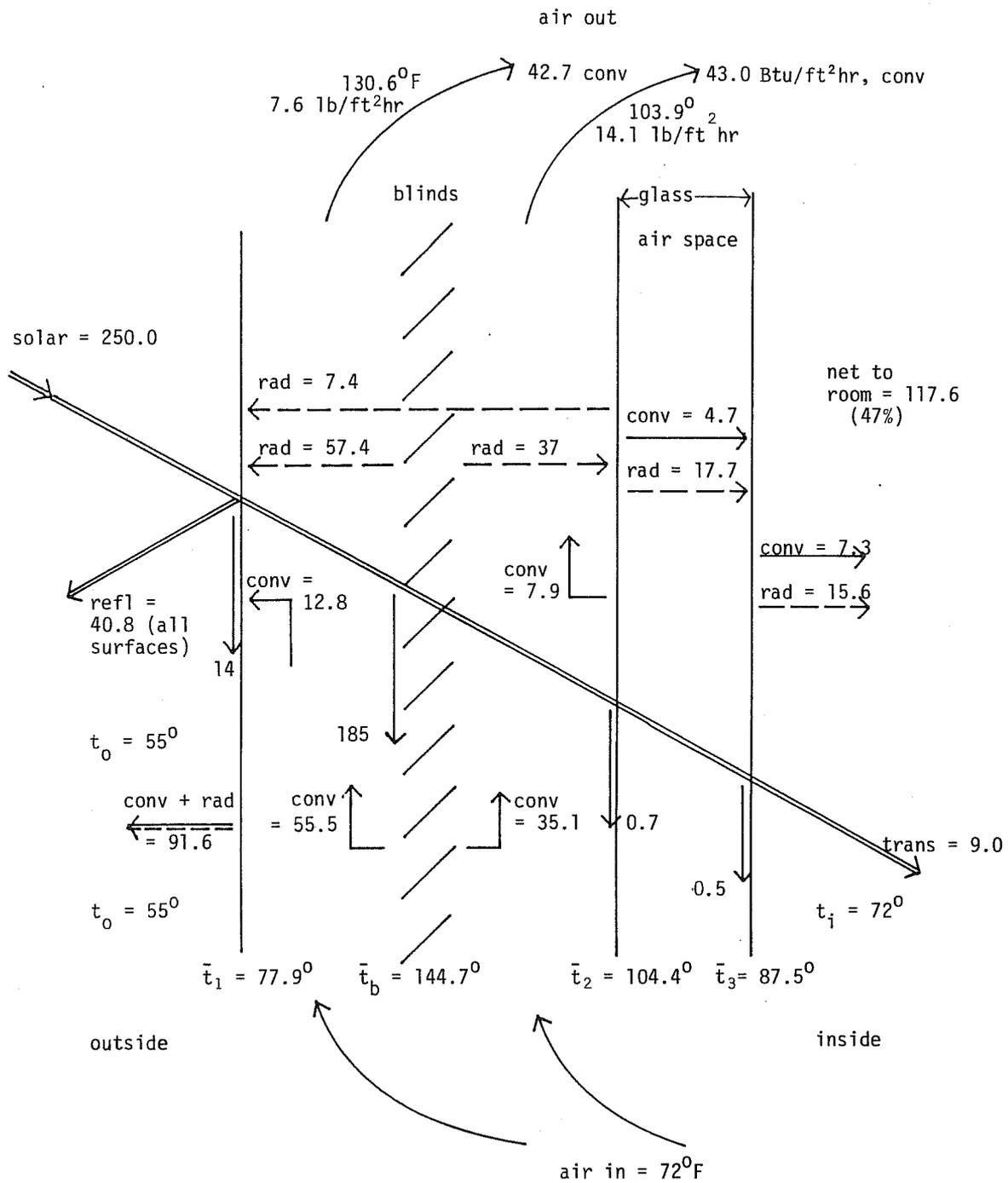


Fig. A-8 Energy Balance - Klos Window - Enclosed Section

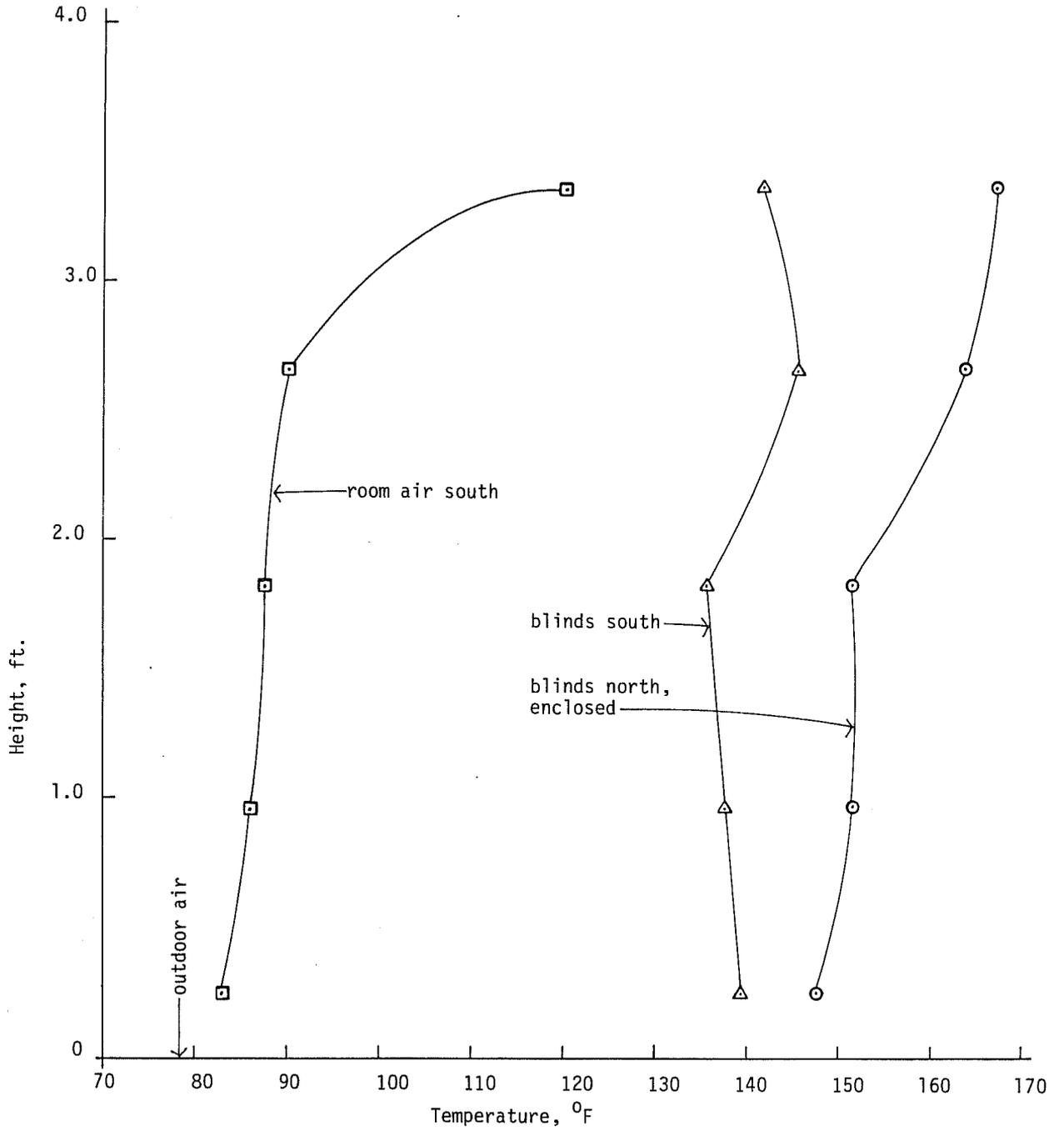


Fig. A-9 Experimental Klos Window Temperatures 3/18/81, 16:30 mst, 15:57 solar time

APPENDIX B
LITERATURE SURVEY-SOLAR CONTROL WINDOWS

INTRODUCTION

This literature survey describes various windows and window systems designed to control solar heat gain and improve thermal comfort. Generally, they are composed of slat-type absorbent surfaces located between panes of glass. Some of the windows are ventilated; others are not. All are transparent to some degree.

The unventilated windows, which utilize blinds located between two fixed panes of glass, are designed to reduce solar heat gain as well as blind maintenance. The ventilation feature allows for further fine-tuning of thermal comfort conditions within a space, since ventilation air is exhausted across the blinds between the panes of glass. This brings the inside glass temperature close to that of the interior space. Some have used these windows as solar collectors by installing dark top, reflective bottom blinds which are used to either convert sunlight to hot air (to heat the structure) or to reflect light back out the window. Others use a reflective, or low emissivity, surface to control heat loss from the interior of a space.

UNVENTILATED WINDOW SYSTEMS

Studies have been made to determine the effectiveness of slats installed between two fixed glass panes in reducing solar heat gain and improving insulation values.^{1,2,3} These devices do not permit heat to be introduced into or ejected from the building interior by air movement over the slats.

The general conclusion was that slats enclosed between glass panes reduce heat gain more effectively than slats located on the interior side of a double-glazed window, but less effectively than slats located on the outside surface of a double-glazed window. A significant advantage of the enclosed slats is lower maintenance and dust collection.

It has also been noted that enclosed slats (venetian blinds) reduce the heat losses of a window by interfering with convection. Both a recent paper by Berlad⁵ and Pella window data confirm these results. Berlad also shows that enclosed insulating and reflecting, or low emissivity, slats can significantly increase the insulation value of a window over one with ordinary metal blinds.

Some companies which make these windows (which may incorporate colored or reflective slats) include the Rollscreen Company, Pella, IA; Disco Aluminum Products, Company, Inc., Selma, AL; Efco Corporation, Monett, MO; and Versa Vent from Flour City Architectural Metals, Glen Cove, NY.

VENTILATED WINDOW SYSTEMS

Ventilated window systems include systems used to collect and distribute solar heat as well as those used to exhaust ventilation air. Systems which combine the two features were the primary focus of the testing conducted during this project. Examples of all these types of ventilated window systems will be discussed.

The Klos window^{6,7}, which has been previously described, provides a view and controls light and heat input to the house while reducing glare and fading of interior furnishings. It gives excellent control over solar gain during all seasons and costs little more than a double-glazed window with a drape or venetian blind figure 1.

A pre-manufactured window identical to the Klos window is available in Holland. This window, which uses two double-sliding windows with a venetian blind located between them is sold by Intal B.V., Watermolenweg 6 - Postbus 31, Geldersmalsen, The Netherlands. (This company is half owned by an American company, International Aluminum Corporation, Monterey Park, CA which could potentially manufacture such windows in the United States if there were a demand.)

A solar heating system very similar to the Klos window is the ClearView Solar Collector^R developed at the University of Arizona's Environmental Research Laboratory.^{4,5,6,7,8,}

The site-built transparent wall-mounted ClearView Solar Collector uses venetian blinds or "heat absorbing" glass to absorb solar radiation in the winter. The heat is then distributed through the house, or in the active version, is stored in a rockbed. During the summer, evaporatively cooled air is exhausted through the ClearView Solar Collector to reject any heat absorbed by the blinds. See Figures B-1 and B-2.

One of the earliest designs for using venetian blinds to heat air in a transparent solar collector was studied by Friedrich Tonne of Berlin.⁹ While heat from the blinds is distributed through the house in the winter, provisions for summer solar control are made by lowering an exterior blind, since evaporatively cooling was not needed or used in Germany. To our knowledge, this particular system was not built. See Figure B-3.

Another early version of a semi-transparent heat collecting/rejecting window was described by Nicholas Fuschillo in 1974.¹⁰ He discusses several versions, using heat absorbing glass or heat absorbing films on glass, a retractable shade or venetian blinds. The system may be used to collect solar heat or to reject heat absorbed by the blinds, shade or glass to the outside.

At the Farallones Institute in northern California, an experimental cabin has been constructed with a louver window solar collector which uses venetian blinds between panes of glass.¹¹ The venetian blinds absorb solar radiation without obstructing the view (very similar to the ClearView) and heat is drawn into a vertical airflow rockbed below the floor slab. The blinds are used for solar heating and control of incoming solar radiation in winter, but do not appear to be used to enhance cooling in the summer. The reflective lower blind surfaces may be used to reflect sunlight back outside; however, this would obstruct the view. The blinds are used in the winter to reflect infrared radiation back into the space at night, thus providing additional insulation. See Figure B-4.

A concept approaching that of the "solar window absorber" unit is discussed by Seth Silverstein of the General Electric company. He uses a shade or venetian blind to absorb solar radiation in the winter and to reject solar radiation in the summer.¹² Although this system does not use blinds between panes of glass, with air moving between, the concepts for solar heating are similar to those studied in this project. It also provides improved insulation against nighttime heat loss. See Figure B-5. Solar collection is achieved in the winter when the dark side of the shade or blinds faces out and heat rejection is accomplished in the summer when the white side faces out. This, however, interferes with the view. No provision is made for ventilation over the shade in the summer.

Arthur Rosenfeld describes how Silverstein's method might work best with venetian blinds that are metallic on the reflective side so they can reflect heat as well as light in a similar manner to the Farallones' louver window.¹³ He discusses the possibility of ventilating the heat absorbed by the blinds by natural convection during the summer. Rosenfeld and Selkowitz¹⁴ have also described a method for using polished aluminum blinds to reflect solar radiation into the room interior for heating. This method may be advantageous if the glare problem is controlled, e.g. use reflective blinds above eye level, and dark/white blinds below.

Several manufactured ventilating window systems have been developed which improve interior comfort and are generally applicable to offices and hospitals rather than residences. Some of these include the following;

The Protecta-Sol^R System^{15,16}

This system is designed with clear double-glazing on the exterior, a single pane of clear glass on the interior, and a venetian blind (or vertical blind) between the two windows. Air from inside the space is exhausted between the two windows over the blinds and to the outside by forced draft, thus maintaining the temperature of the interior glazing surface at a temperature similar to that of the inside space. (The room air enters the window unit at the top and exits to the outside at the bottom.) This system greatly

reduces radiant heat loss from the occupants to cold windows or heat gain from hot windows, reduces glare, allowing diffuse light to enter the space, and provides a view to the outside. See Figure B-6.

It would be used in commercial buildings where a positive interior air pressure for constant ventilation is required. No mention of using the blinds for solar heating is made, and perhaps in commercial situations, solar heating is not necessary. Also, these windows apparently use white or shiny aluminum blinds which can either reflect light into the space or back out the window.

The advantage of the Protecta-Sol^R system is that it effectively lowers the U-value of the window to 0.3 to 0.6 K cal/m²hr °C (0.06-0.12 BTU/sq.ft.hr.°F)¹⁶ and decreases the winter and summer energy requirements of the building if ventilation is required for reasons other than the window's exhaust system. The blinds may require cleaning less frequently, due to the airflow over them.

The "Exhaust-Air Window" or "Extract-Air Window"

These are similar to the Protecta-Sol^R window. The exhaust-air window, discussed by Sodergren and Bostrom¹⁷, is also composed of an exterior insulated (double pane) window and an interior single pane window. Air flows over venetian blinds located between the windows. The comfort experienced by occupants living or working in spaces with such windows is improved, since skin surface radiation to cold or hot window surfaces is greatly reduced. It is also pointed out that heat flow from the building interior to the exterior, through the window itself, is reduced. However, whether or not such windows are a net energy saver for buildings equipped with them is not addressed in the paper. This depends on the design of the HVAC system, ventilation requirements, interior air temperatures deemed comfortable because of the window temperature, exterior air temperature, whether additional heat is actually required in the winter, etc.

When EKONO, a Finnish company, started using this window, they called it the "extract-air window" and added a solar heating feature by using dark venetian blinds.^{18,19} See Figure B-7. The total system requirements are discussed more completely in their papers because the integration of the windows into the HVAC system is explained. They propose storing heat absorbed by the solar heated blinds from windows located on the south and from the lighting system in hollow core concrete floor slabs. The improved interior comfort is again attributed to the fact that the windows are at or near room temperature. It is noted that the heat lost to the ambient air comes from air within the window. The collection of solar energy by black venetian blinds enclosed between the windows is described. This system is totally integrated into the HVAC system of the building and is suitable for large buildings including office structures and hospitals. The window itself is a packaged unit.

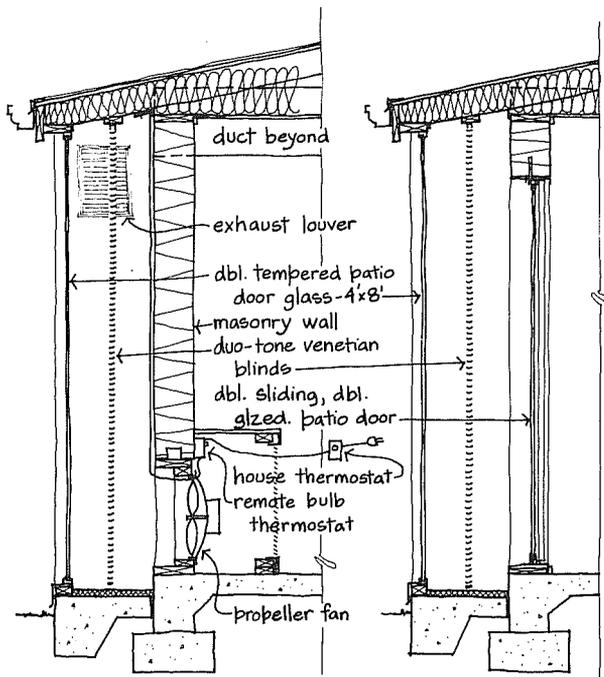
Both the exhaust-air window and the extract air window can eliminate the need for radiative heaters located adjacent to exterior windows and can even out temperature differences across a space. The extract-air window when integrated with the building HVAC system, can reduce heating and cooling loads in EKONO's Scandinavian climate (and presumably some others as well.)

The Walter White Pivoting Window

Another flexible, pre-manufactured window unit for solar control is the pivoting window designed by Walter White, which is composed of double insulating glass on one side and heat absorbing glass on the other, with an air space between them through which air may flow.^{16, 20} In winter, sunlight is absorbed by colored glass which faces the house or building interior. Heat is carried into the space by radiation and convection. In the summer, the heat absorbing glass faces the exterior and heat resulting from the absorption of sunlight by the glass, may be carried away by the wind or natural convection. The heat absorbing glass also prevents much of the direct solar radiation from penetrating the space. See Figure B-8.

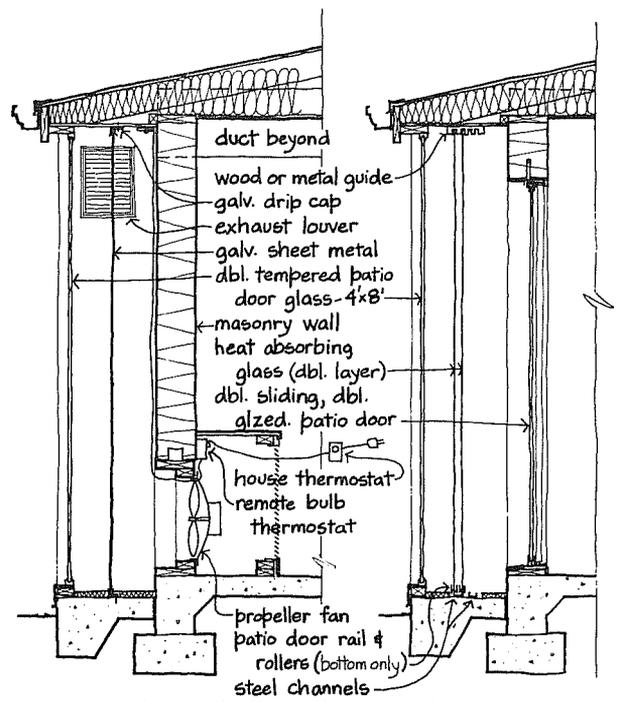
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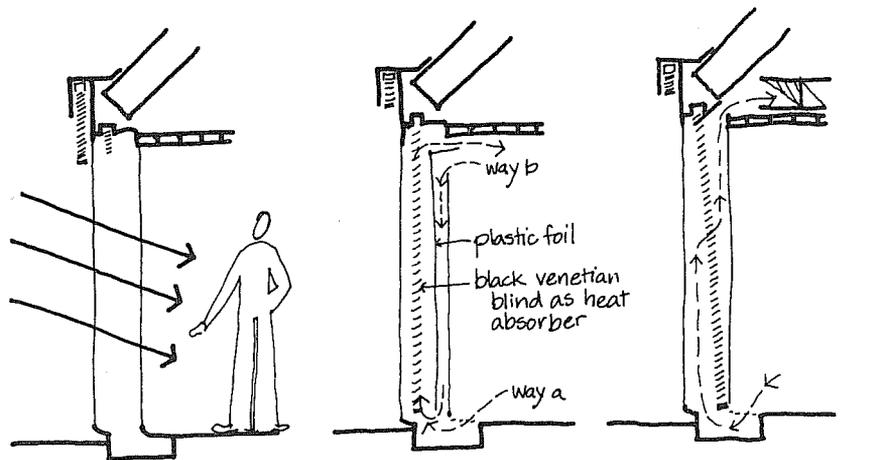
Venetian Blind Hybrid
ClearView Solar Collector®

Fig. B-1



Heat Absorbing Glass Hybrid (patented)
ClearView Solar Collector®

Fig. B-2



direct radiant energy allows low air temperature

outside venetian blind for summer sun control

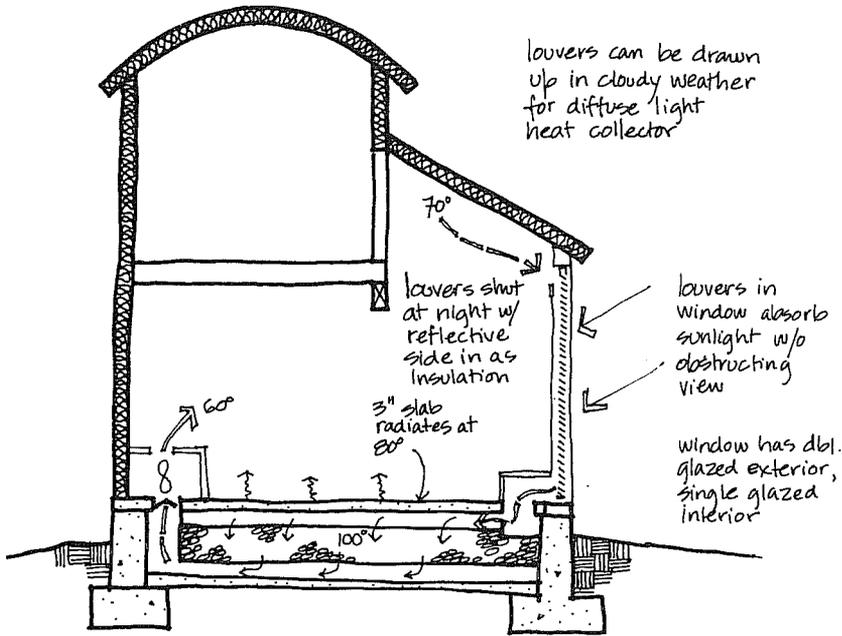
way a: heating of the air

way b: heating of the radiant ceiling by a warm air cushion

warm air conducted to other rooms or to a storage unit

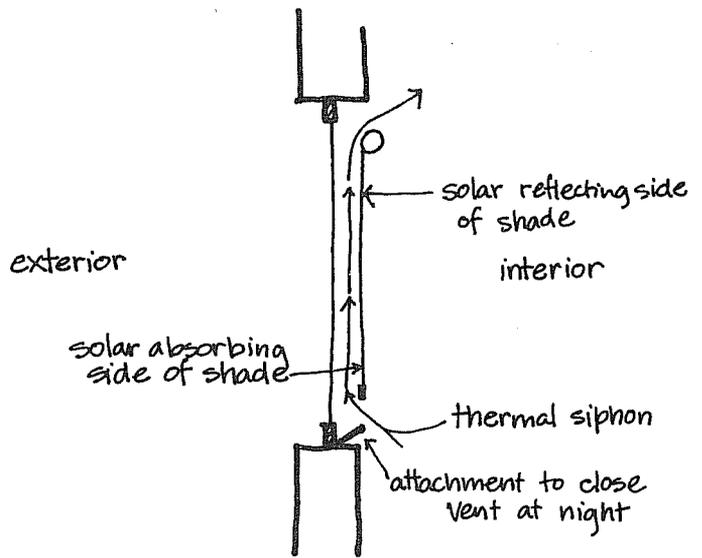
Solar Energy used in Three Ways -
window collector of Tonne solar heated house

Fig. B-3



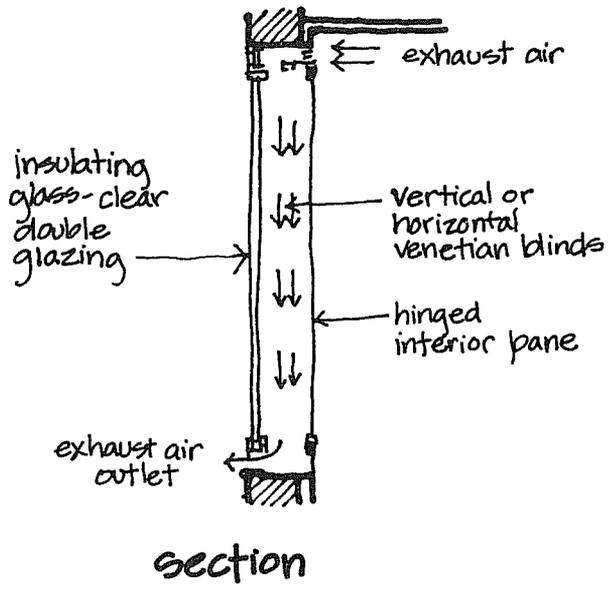
Farallones Institute louver window cabin

Fig. B-4



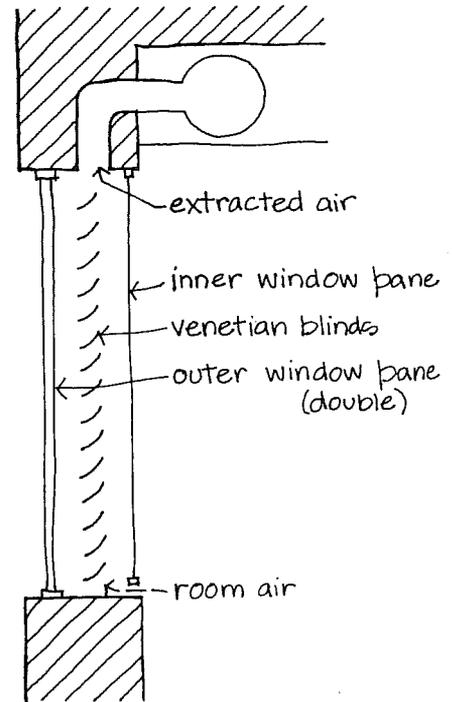
Heating Season - Day
DUAL SHADE
 (shade is reversed during summer)

Fig. B-5



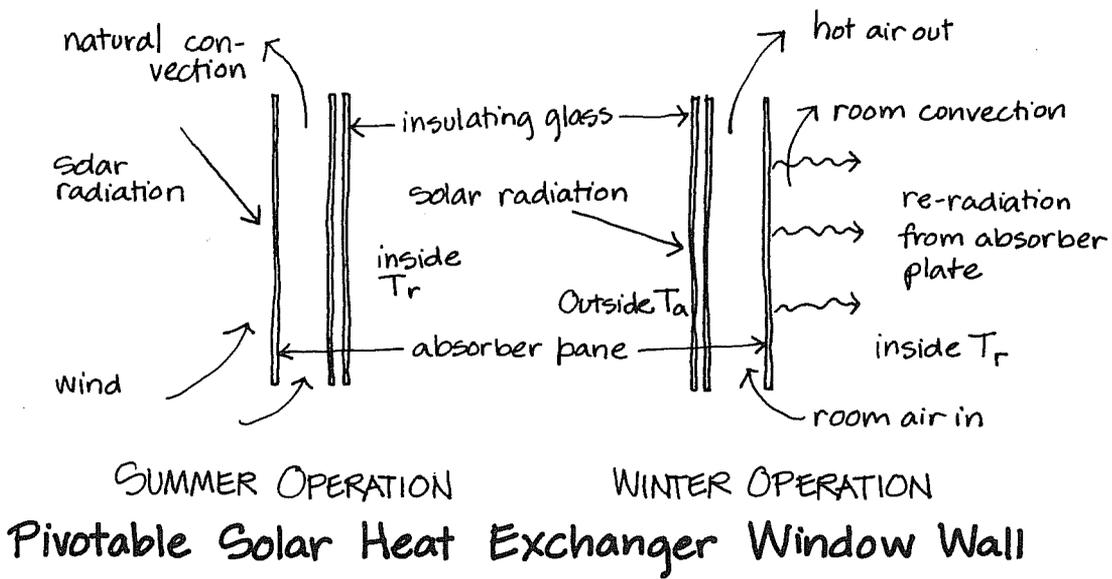
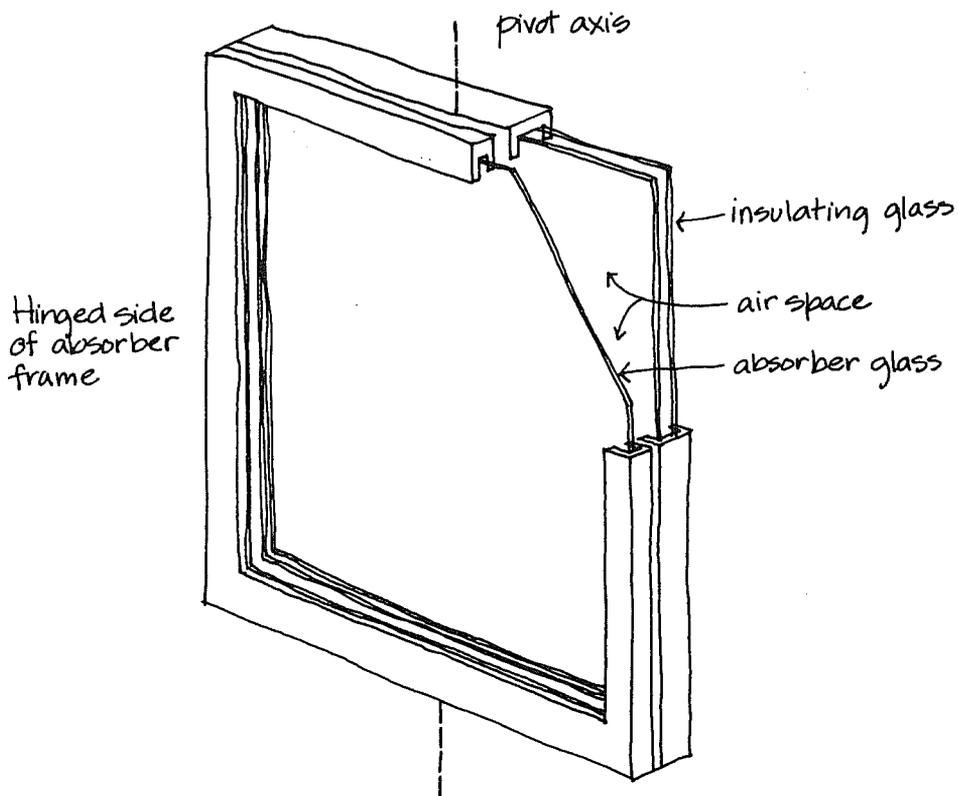
PROTECTA-SOL WINDOW

Fig. B-6



Extract-Air Window

Fig. B-7



SUMMER OPERATION WINTER OPERATION
Pivotable Solar Heat Exchanger Window Wall

Fig. B-8