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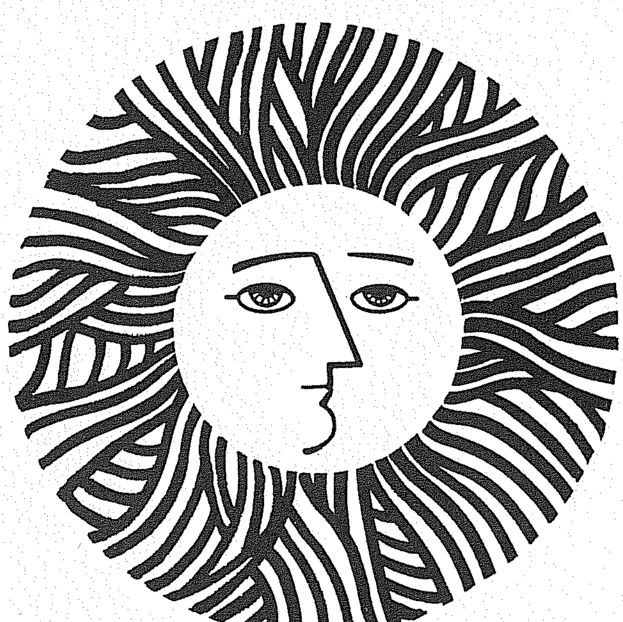
THERMAL PERFORMANCE OF WINDOWS HAVING HIGH SOLAR TRANSMITTANCE

Michael Rubin and Stephen Selkowitz

July 1981



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ERRATA

Table 1 in

THERMAL PERFORMANCE OF WINDOWS HAVING HIGH SOLAR TRANSMITTANCE

(LBL-12288)

The original Table 1 of net energy gain or loss underestimated the contribution of the inward-flowing portion of the solar energy absorbed by the windows. Therefore, all numerical values are increased in the revised table, relative to the original table.

Those windows with relatively large absorption (e.g. conventional glass, absorbing coatings) show the greatest increase. Low-iron glass, on the other hand, changes relatively little. The change is greatest for those orientations with the greatest solar gain. Thus, on the south orientation, the net flux increased appreciably, while on the north the net gain remains practically constant, because the total amount of sunlight available is small. New calculations, using DOE-2.1, are currently in progress and should provide more definitive performance values.

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Table 1 Thermal properties and net energy performance in the winter season for clear windows

window type[a]	gap[h] mm	U-value[c] $Wm^{-2}K^{-1}$	SC[d]	net flux (10^9 J m^{-2}) Minneapolis S	E/W	N
g	-	6.46	1.00	-0.240	-1.260	-2.479
l	-	6.46	1.05	-0.146	-1.192	-2.442
g-g	6.4	3.24	0.88	0.374	-0.351	-1.090
	9.5	2.94	0.88	0.445	-0.250	-0.956
	12.7	2.87	0.88	0.477	0.202	-0.894
l-l	6.4	3.24	0.97	0.495	-0.260	-1.041
	9.5	2.94	0.97	0.560	-0.162	-0.908
	12.7	2.87	0.97	0.589	-0.116	-0.847
g-hg	6.4	2.49	0.76	0.456	-0.160	-0.776
	9.5	2.02	0.77	0.573	0.007	-0.066
	12.7	1.92	0.77	0.608	0.066	-0.484
g-g-g	6.4	2.19	0.79	0.509	-0.077	-0.655
	9.5	1.93	0.80	0.572	0.014	-0.539
	12.7	1.80	0.80	0.605	0.064	-0.476
l-l-l	6.4	2.19	0.90	0.658	0.034	-0.596
	9.5	1.93	0.90	0.711	0.121	-0.482
	12.7	1.80	0.90	0.738	0.168	0.419
g-a-g	6.4	2.31	0.85	0.538	-0.077	-0.655
	9.5	2.07	0.85	0.594	0.007	-0.581
	12.7	1.89	0.85	0.624	0.053	-0.522
g-ph-g	6.4	1.79	0.67	0.534	0.008	-0.502
	9.5	1.45	0.67	0.619	0.129	-0.350
	12.7	1.32	0.67	0.660	0.193	-0.270
g-g-g-g	6.4	1.66	0.72	0.542	0.040	-0.448
	9.5	1.44	0.72	0.597	0.119	-0.350
	12.7	1.33	0.72	0.625	0.161	-0.298
l-l-l-l	6.4	1.66	0.84	0.721	0.172	-0.381
	9.5	1.44	0.84	0.763	0.245	-0.284
	12.7	1.33	0.84	0.784	0.284	-0.233
g-a-a-g	6.4	1.81	0.82	0.605	0.061	-0.480
	9.5	1.61	0.82	0.651	0.131	-0.389
	12.7	1.50	0.82	0.675	0.170	-0.341

[a] Abbreviations used for window materials are: g - 1/8-inch float glass, l - 1/8-inch low-iron sheet glass, p - 4-mil polyester film, a - 4-mil antireflected polyester film, h - heat-mirror coating with ϵ=0.15 (solar transmittance of coating and substrate is 0.7).

[h] Individual gap widths are 1/4, 3/8 and 1/2 inch (1 inch = 25.4 mm).

[c] Calculated for ASHRAE standard winter conditions; $T = T_{out}$ = -18C (0F), T_{in} = 21C (70F), wind speed=24 km hr^{-1} (15 mph).

[d] Calculated for ASHRAE standard summer conditions; $T_{out}=T_{in}$=32C (89F), wind speed = 12 km hr^{-1} (7.5 mph), solar intensity=783.3 Wm^{-2} (248.3 Btu hr^{-1} ft^{-2}).

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ABSTRACT

Antireflected polyester films and low-iron glass sheets have values of solar transmittance that are substantially higher than those of their untreated counterparts. The plastic films utilize coatings to reduce losses due to surface reflectance and the glass is made with low levels of impurities to reduce absorption within the material itself. In this paper, we discuss the optical and thermal properties of these materials and derive the solar and thermal characteristics of windows incorporating high-transmittance glazing layers. Comparisons among these and other types of windows are made on the basis of net energy use for residential buildings in winter.

1. INTRODUCTION

A number of options are available for improving the thermal resistance of single-glazed windows. Double and triple glazing are in widespread use. Newer fenestration components, such as coatings that reflect infrared radiation, gas-fills having a low thermal conductivity, and plastic films suspended vertically in the air space of a double-glazed window, are gaining acceptance. While all of these improvements make the window more insulating, at the same time they decrease beneficial solar heat gain. To provide optimal performance in the heating season, glazing materials having the highest possible solar transmittance should be used.

In this paper, we investigate the two principal classes of commercially available glazing materials which have specially augmented transmittance characteristics: low-absorption glass, and plastic films with antireflection coatings. First, we discuss the structural, optical, and thermal properties of each class of materials. From these properties, we calculate both the overall thermal conductance, or U-value, and the shading coefficient, which is a measure of relative solar heat gain, for windows incorporating these materials. Rough comparisons of windows' net energy performance can be made based on these U-values and shading coefficients. More accurate results are obtained using a detailed building model to assess the relative energy performance over the heating season.

2. LOW-ABSORPTION GLASS

Most window glass has an index of refraction, n, of about 1.5 with slight variations due to differences in the composition of the glass. The reflectance of light at normal incidence is thus about 0.04 from each air-glass interface. If the overall transmittance, T, of the glass is greater than 0.8, the reflectance from the second interface is reduced by at most 0.01, because of multiple reflections and absorption. With the above constraint on T, neither the composition nor the thickness of the glass will have much effect on the reflected component.

Absorption in glass panes may be reduced most easily by reducing the thickness of the glass. A practical lower limit is placed on thickness by the need to consider strength in relation to surface area; the smaller the size of the window the thinner the glazing may be. The maximum value of solar transmittance is 0.86 for 3/32-inch float glass, implying an absorptance of about 0.06. The thinnest possible glazing, in addition to maximizing solar heat gain, will be the least expensive because of the reduced volume of materials, lighter hardware, and easier installation. To reduce absorption still further we must change the composition of the material by removing impurities that contribute to absorption (chiefly iron oxides). Absorption by the glass itself is practically zero, so the theoretical maximum transmittance, limited only by reflective losses, is about 0.92. A "water-white" glass can be made which approaches this value, but at present the only commercially available architectural grade of low-iron glass has a normal transmittance of about 0.90 for 1/8-inch sheet, compared to 0.84 for float glass. In the energy performance calculations, below, the optical properties of the windows are determined for non-normal incidence angles (1).

3. ANTIREFLECTION COATINGS

A wave of light will be partially reflected when it experiences a sharp change in index of refraction. Reflection at the boundary between the air and a glazing material can be reduced by creating a more gradual transition between the two refractive indices. The classic approach is to deposit one or more layers whose thicknesses and indices of refraction are chosen to optimize the gradient in "n" and to cause destructive interference at the desired wavelength (2). Multilayer coatings of excellent quality are made in this way, but they are not appropriate for large-area, low-cost window applications.

Low-cost polyester films are available which have a single-layer antireflection coating applied to each side of the film. A homogeneous layer can result in near-zero reflection over a narrow wavelength band. By choosing a material and thickness so that this minimum reflectance falls at the peak of the solar power spectrum, one can achieve a low average solar reflectance. A further refinement consists of depositing a film such that a dendritic surface structure results. It is this surface structure, rather than the material used in the coating, which is primarily responsible for the antireflection properties. The mechanism that imparts these properties is known as the "graded-index effect". Rough surfaces that have a periodicity smaller than a wavelength of light will interact with incident light as if the surface were smooth, but with an average index of refraction that increases slowly from the tip of the roughly cone-shaped dendrite to its base (see Fig. 1). The angle-dependent optical properties for parallel-sided films can be obtained by familiar methods (1,2), but dendritic coatings are more difficult to model. In this case we used a quadratic-pyramid model for the index profile (3).

As with glass, the absorptance in a plastic film can be minimized by reducing the thickness, but the intrinsic absorbtivity of the material is due to the polymer molecule itself, or additives to improve weatherability, rather than to impurities. Fluoropolymers are available which have both a lower index of refraction than does glass and a very high transmittance. Polyester is much less expensive than glass or fluoropolymers but has an index of 1.65, giving a reflectance of 6% per surface. Use of antireflection coatings can all but eliminate this reflection loss, resulting in a solar transmittnce of about 0.93 compared with 0.84 for the uncoated film.

Plastic film as an alternative to glass in multiple-glazed windows has the advantages of light weight and low cost. The primary disadvantage of plastic film is its poor durability compared to that of glass. The lifetime of the film can be extended if it is mounted between panes of glass (4) and if the film has appropriate stabilizers to reduce ultraviolet and thermal degradation.

4. THERMAL PERFORMANCE

If there were complete freedom to set the spacing between layers in a multiple-pane window, then a window having plastic inserts should display a thermal conductance roughly comparable to an all-glass window having the same number of layers. Fig. 2a shows that windows incorporating plastic films actually have somewhat higher U-values than their all-glass counterparts if the width of the individual air gaps are equal. This is because the plastic is partially transparent to long-wave infrared radiation. However,

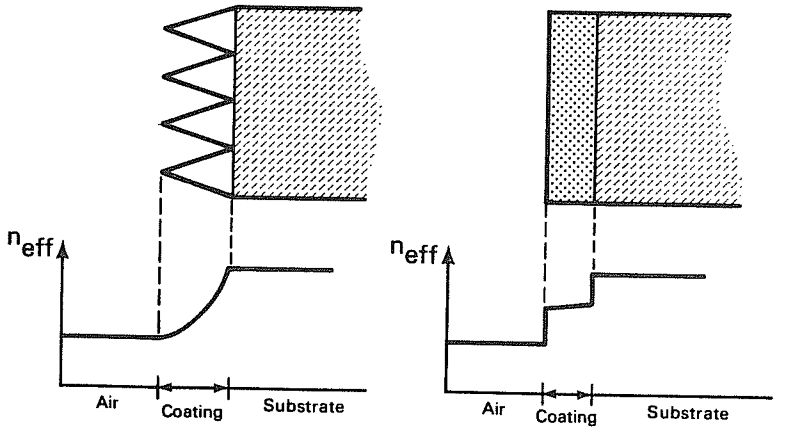

Fig. 1. Depth profile of the effective index of refraction for dendritic and flat coatings.

most manufacturers provide multiglazed units in a limited range of outside dimension (OD). The thickness of a typical glass pane can reduce the air space sufficiently to have a major effect on the U-value, but the thickness of a plastic film is negligible. For this reason, when comparing windows with the same OD (Fig. 2b) those having plastic inserts have a lower U-value than do those that are all glass despite the IR-transmittance effect mentioned above. For individual gaps larger than about 15 mm, the thickness of the glazing is not important since the U-value is a slowly varying function of gap width in this range. In Table 1, we give the U-values for multiglazed window configurations for air-gap spacings up to 12.7 mm (1/2 inch). The thermal conductance of glass is large compared to the overall U-value, so we need not specify the thickness of the glass panes. While the previous statement also applies to plastic films, the IR transmittance of the films is strongly dependent on thickness in the range of a few tenths of a mm. The U-values in Table 1 are for polyester films, 0.1 mm (4 mil) thick.

Shading coefficient (SC) is a measure of the solar heat gain through a glazing system relative to the solar heat gain through clear double-strength float glass, which has T_n=0.84. Solar heat gain is simply the direct solar transmittance plus that fraction of absorbed solar energy which is reradiated and convected to the room. SC will have a weak dependence on gap spacing (see Table 1) or any variable that affects the thermal properties of the window because the materials we are studying have a very low solar absorptance compared to transmittance.

The shading coefficients and U-values in Table 1 are useful for comparisons among window systems, and also for simplified calculations of seasonal or annual energy consumption in buildings. In our calculations of net winter heating requirements, heat-transfer rates are calculated hour-by-hour as a function of environmental variables, such as wind speed and direction, solar position and intensity, and outdoor temperature (5). A lumped-parameter model is used to simulate a residential building that is well insulated and has a heat capacity that is characteristic of wood-frame construction with plasterboard walls. Average monthly solar intensities (6) and local climatic conditions are used in the hour-by-hour calculation.

Net winter heating loads for a house in Minneapolis are shown in Table 1 for windows facing south, east/west, and north. A lumped parameter model allows us to account for thermal storage effects in the building. The overall thermal properties of the building determine the fraction of the heating season solar gain that usefully offsets heating losses.

Variation in the thermal properties of the house will introduce very large changes in the apparent performance characteristics of the window systems shown in Table 1. As expected, the variation is greatest on south orientations because the incident solar energy is greatest there. Figure 3 illustrates the range of variation possible for three window systems (g-g, 1-1, and g-ph-g) for each of three "houses": the average house shown in Table 1, a house having much less thermal mass, and a house having much greater thermal mass. For north orientations receiv-

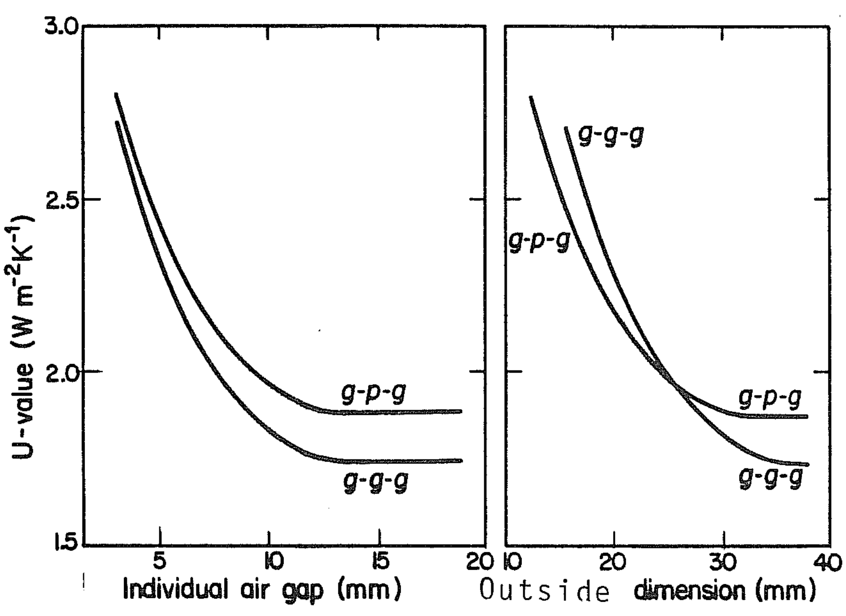

Fig. 2. The effect on U-value of fixed OD for multiple-glazed windows (g= 1/8-inch glass; p= 4-mil polyester).

ing little solar gain, the effect is minimal (±10%). However, for south orientations the effect is very large, as shown in the figure. In addition, the relative rankings of glazing performance may change. For a north orientation, the window having the heat mirror (lowest U-value) is always best. On a south orientation, for a low-mass house, a window with heat mirror out-performs double glazing, but for a high-mass house, conventional double glazing and high-transmittance double glazing both outperform the window with heat mirror. To provide meaningful performance results for the diverse window systems shown in Table 1, it is important to specify the building's orientation and thermal characteristics.

Further analysis of the results in Table 1 and calculations for other cities not shown here suggest that:

(1) For north orientations (or shaded orientations receiving minimal solar gain), U-value is the prime determinant of window performance in the heating season.

(2) For south orientations, and to a lesser extent east and west, shading coefficient plays a significant role. Multilayer windows incorporating high-transmittance glass and plastic films significantly outperform their conventional glass counterparts.

Table 1. Thermal properties and net energy performance in the winter season for clear windows

window type[a]	gap[b] mm	U-value[c] $Wm^{-2}K^{-1}$	SC[d]	net flux (10^9 J m^{-2}) Minneapolis		
				S	E/W	N
g	-	6.46	1.00	-0.242	-1.262	-2.479
1	-	6.46	1.05	-0.146	-1.192	-2.442
g-g	6.4	3.24	0.88	0.351	-0.364	-1.092
	9.5	2.94	0.88	0.419	-0.266	-0.959
	12.7	2.87	0.88	0.451	-0.220	-0.898
1-1	6.4	3.24	0.97	0.423	-0.261	-1.041
	9.5	2.94	0.97	0.558	-0.164	-0.908
	12.7	2.87	0.97	0.586	-0.118	-0.847
g-hg	6.4	2.49	0.76	0.420	-0.181	-0.779
	9.5	2.02	0.77	0.498	-0.022	-0.565
	12.7	1.92	0.77	0.503	0.030	-0.489
g-g-g	6.4	2.19	0.79	0.367	-0.121	-0.662
	9.5	1.93	0.80	0.402	-0.042	-0.546
	12.7	1.80	0.80	0.429	0.007	-0.483
1-1-1	6.4	2.19	0.90	0.654	0.030	-0.597
	9.5	1.93	0.90	0.703	0.117	-0.482
	12.7	1.80	0.90	0.729	0.164	-0.420
g-a-g	6.4	2.31	0.85	0.449	-0.109	-0.694
	9.5	2.07	0.85	0.478	-0.029	-0.587
	12.7	1.89	0.85	0.481	0.009	-0.529
g-ph-g	6.4	1.79	0.67	0.425	-0.025	-0.507
	9.5	1.45	0.67	0.449	0.074	-0.357
	12.7	1.32	0.67	0.480	0.136	-0.279
g-g-g-g	6.4	1.66	0.72	0.327	-0.039	-0.458
	9.5	1.44	0.72	0.368	0.034	-0.371
	12.7	1.33	0.72	0.397	0.053	-0.322
1-1-1-1	6.4	1.66	0.84	0.702	0.158	-0.383
	9.5	1.44	0.84	0.738	0.228	-0.288
	12.7	1.33	0.84	0.758	0.265	-0.236
g-a-a-g	6.4	1.81	0.82	0.418	0.004	-0.488
	9.5	1.61	0.82	0.441	0.056	-0.399
	12.7	1.50	0.82	0.460	0.089	-0.351

Footnotes:

[a] Abbreviations used for window materials are: g - 1/8-inch float glass, 1 - 1/8-inch low-iron sheet glass, p - 4 mil polyester film, a - 4 mil antireflected polyester film, h - heat-mirror coating with ϵ=0.15 (solar transmittance of coating and substrate is 0.7)

[b] Individual gap widths are 1/4, 3/8, and 1/2 inch (1 inch = 25.4 mm)

[c] Calculated for ASHRAE standard winter condtions; T_{out}=-18C (0F), T_{in}=21C (70F), wind speed=24 km hr^{-1} (15 mph).

[d] Calculated for ASHRAE standard summer conditions; $T_{out}=T_{in}$=32C (89F), wind speed=12 km hr^{-1} (7.5 mph), solar intensity=783.3 Wm^{-2} (248.3 Btu hr^{-1} ft^{-2}).

(3) When comparing products the U-values and shading coefficients of which differ, the rankings may change from north to south; i.e., the product with the lowest U-value performs better on the north, but the product with the highest transmittance is a better choice on the south.

(4) Conventinal quadruple glazing performs worse than triple, which in turn is worse than double for a south orientation (the reverse is true for north).

5. CONCLUSIONS AND SUMMARY

Both antireflected plastic films and low-iron glass offer significant increases in solar heat gain on south, east, and west orientations.

When the OD of a sealed-glass unit is fixed, the use of plastic inserts in double-glazed glass windows will provide a lower thermal conductance than will all-glass windows having the same number of layers. Low-iron glass retains all the advantages of standard float glass, such as durability and long life; plastic films offer lighter weight and slightly higher transmittance.

Performance tradeoffs between minimizing U-value and maximizing shading coefficient are summarized in Section 3. Numerical results reported in Table 1 and discussed above are meant to be illusrtative of performance trends and issues rather than definitive values. Studies using DOE-2 are now in progress to more accurately define the impact of a building's thermal characteristics on window performance. Note that we calculate thermal performance only in the heating season. High-transmittance windows that are not properly shaded in summer may contribute to excessive cooling loads.

6. ACKNOWLEDGEMENT

The work described in this paper was funded by the Assistant Secretary for Conservation and Renewable Energy, Office of Buildings and Community Systems, Buildings Division of the U.S. Department of Energy under Contract No. W-7405-ENG-48.

7. REFERENCES

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(2) Heavens, O.S., "Optical Properties of Thin Films", in Reports on Progress in Physics, XXIII, The Physical Society, London (1960).

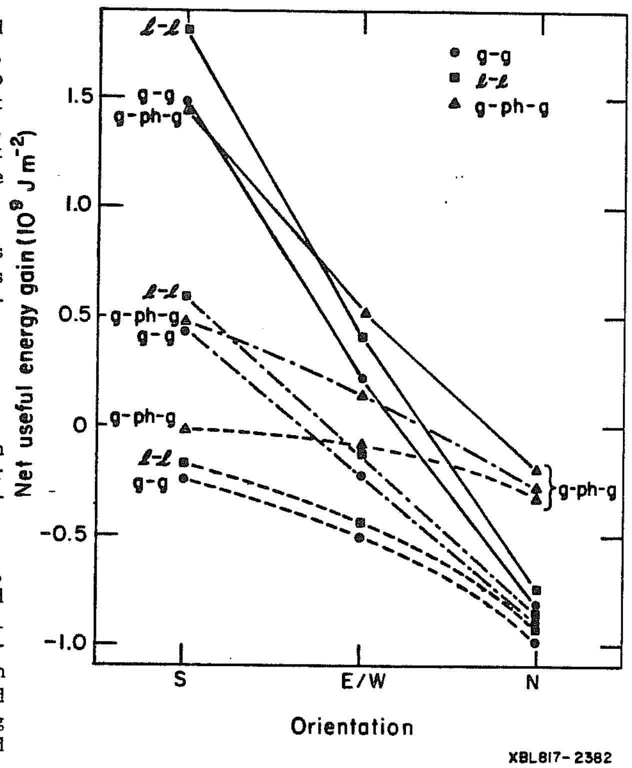

Fig. 3. Net offset to winter heating load attributable to unit area of window for a ___high-, -.-.-medium-, and --- low-mass house.

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