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The benefits of using window shades

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ABSTRACT

Windows play an important aesthetic role in our daily lives. At the same time, windows typically add significantly to the cost of heating and cooling buildings. After reviewing the physical principles by which windows add heat to buildings and the standard techniques employed to reduce unwanted heating, this paper focuses on one type of device which is readily available, inexpensive to purchase and operate, and capable of being adjusted to changing conditions on even an hourly basis. The device is the common window shade. This paper develops a simple, but realistic, model for computing the advantage of using reflective interior shades. The quantity of interest for characterizing the performance of a shade is the fraction of incident solar energy that remains in the room as heat. The quantity is called the solar heat gain coefficient (SHGC). It is seen that shades can exert a very significant control over the SHGC.

INTRODUCTION

It strains no one's credulity to hear that the annual heating and air conditioning bill for the United States is a huge number. Windows, skylights, glass doors, and other such transparent devices (collectively called fenestrations) have a very significant effect on that bill. On the other hand, energy performance isn't the only thing that matters in the design and operation of fenestrations. On the basis of aesthetics alone, fenestrations are an extremely important part of our daily lives. We refer to a building without windows as a dungeon.

In most cases windows add to the energy bill through conduction heat losses in winter and radiant heat gains in summer, but in some cases fenestrations can actually perform better, energy-wise , than an insulated opaque wall. Properly designed and operated fenestrations can actually offset the cost of the higher quality of life they afford. With so much money and aesthetic appreciation at stake, great effort has been invested in finding ways to maximize the energy and illumination performance of commercially available fenestration systems.

The principle by which fenestrations trap heat in buildings is called the greenhouse effect. Here is how it works: Most of the light (more generally called radiation) from the sun is in the visible

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region of the wavelength spectrum. Ordinary glass is generally transparent at these wavelengths. After passing through a window, radiation strikes objects inside the room. Although a small portion is reflected right back out through the window to the outside, a major fraction of it is absorbed by surfaces in the room.

Now any object, indeed every object, creates and emits radiation. This effect is due to the fact that the jostling of the molecules of any object constitutes accelerated motion of electrical charges (the electrons and protons of these molecules). The fundamental laws of electricity and magnetism (Maxwell's equations) predict that any accelerated motion of electrical charges will produce radiation. The amount of energy radiated is predicted by the Stefan Boltzmann Law found in any physics textbook. Furthermore, the principal region in which most of the radiation is concentrated depends inversely on the absolute temperature of the radiating body (the higher the temperature, the shorter the wavelength). This relationship is known as Wien's Displacement Law. It is this law which predicts that most of the sun's energy is in the visible wavelength region of the spectrum. According to this same law, objects in the room, which are at a much cooler temperature than the sun, emit principally at much longer wavelengths. In practice, these wavelengths are in the far infrared region, to which ordinary glass is almost completely opaque. The entire process just described has come to be known as the "greenhouse effect". The greenhouse effect can be a very effective way to trap sunlight as heat in a room.

Various attempts have been made to control the fraction of incident radiation that is trapped in the room as heat. All of them have been attempts to manipulate this effect to our advantage. They fall into three categories.

The first is to control the amount of radiation that enters the window at all. The idea is to allow more sunlight to strike the window during cold seasons of the year. Consider a typical northern hemisphere mid-latitude location such as one here in the United States. The method consists of putting extended eaves or some other exterior shading device, such as an awning, over south-facing windows. Since the mid-day summer sun is at a higher altitude than the mid-day winter sun, the shading structure simply allows less sunlight to strike the window in the summer. A corresponding arrangement would be used for the mid-latitudes in the southern hemisphere. At extreme latitudes in either hemisphere the arrangement is not often used. In low latitudes, the idea is to keep the sunlight out all day long. In high latitudes one wants to let as much sunlight in as possible. It is difficult to protect east- and west-facing windows in this way but detached exterior shades such as trees and other vegetation can be effective if east and west windows cannot be avoided.

Blocking the sun before it reaches the pane (glazing) of the window is the most effective form of solar gain prevention, since a very high fraction of the heat absorbed outside stays outside and is carried away by the prevailing air currents. The main disadvantage of these highly effective devices is that they are permanent configurations which cannot be readily adjusted. They are configured to give optimal performance for a particular time of day and day of year. Their effectiveness at other times depends on the extent to which the conditions approximate those assumed in the original installation.

The second category of solar gain control strategy is to make the optical effects in the first category variable. The mechanisms available include thermochromism, photochromism, and electrochromism. The "-chromism" refers to changes in the color (spectral) transmittance of the glazings in the windows involved. Desirable chromism for most applications involves changing the magnitude of the light entering the room without changing the perceived color significantly. The changes in solar transmittance can be stimulated by changing temperature (thermochromism), illumination level (photochromism), or applied voltage (electrochromism).

Most people have seen photochromism applied to certain types of sunglass lenses which get darker with more incident solar radiation. Making this same effect work on windows in buildings has been done, but, due to the high cost and some other problems, photochromic windows are not widely available commercially. Thermochromism has not been developed enough to form the basis for a viable technology. This leaves us with electrochromism, which has received considerable interest in recent years from DOE funded researchers as well as investigators in Japan. Although there is a lot of excitement about electrochromic windows, the technology is still in the very early stages of development. Commercially viable, cost-effective, and reliable electrochromic windows cannot be expected for a number of years.

The third category of window energy strategy involves manipulation of the light after it has passed through the window. The idea is to reflect an adjustable fraction of the solar radiation passing through the window back outside, preventing it from staying inside where it is absorbed by interior surfaces and turned into heat gain. Devices capable of accomplishing this sophisticated task have been in use for centuries. They are common window shades and venetian blinds. The more reflective they are and the greater portion of the unwanted solar radiation they intercept and reflect back outside, the less heat that remains in the room. Furthermore, devices of this type can be manipulated on a daily, even hourly, basis. (Of course, there are external shades and shutters which can also be adjusted, but internal shades and blinds are much less expensive, readily available, easily installed, and less prone to mechanical failure due to corrosion and other effects of exposure to the weather.)

The purpose of this paper is to use a simplified mathematical model of a window and shade combination to compute a realistic estimate of the advantage of using shades and blinds to control the window solar gain. The idea is to introduce enough simplification to make the effect easy to visualize and compute and at the same time to be sophisticated enough to give realistic predictions of what can be expected. The quantity of interest is the fraction, *F*, of incident radiation that remains in the room as heat. This quantity is called the solar heat gain coefficient (SHGC). The practical objective is to control the SHGC on a seasonal or even hourly basis in order to reduce cooling loads during hot periods and to assist with room heating when the weather is cold.

GEOMETRY, RADIATION FLOWS, AND ASSUMPTIONS

The main simplification is to assume that the sunlight is always at normal (perpendicular) incidence. Actually it is difficult to imagine such a situation, since for vertical glazings the sun would have to be at the horizon, directly facing the window, a condition seldom seen and which produces relatively little solar gain when it does occur because of the small amount of solar radiation available at sunrise and sunset. One sometimes sees skylights generally facing the sun giving normal incidence, but such systems rarely use interior shades.

In any event, the normal incidence situation is easy to calculate and, as can be seen in Figure 1, the solar gain for a window without shades at normal incidence is close to that for angles of incidence up to about 50 degrees.

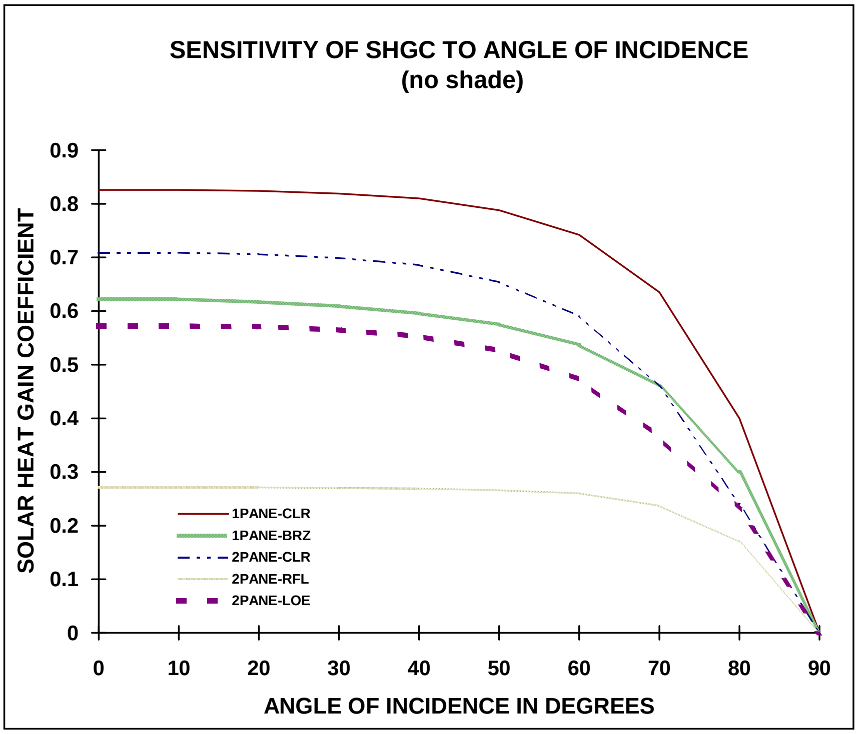

Figure 1. Solar Heat Gain Coefficient as a function of incident angle for several windows.[1] The SHGC is relatively independent of angle up to about 50 degrees.

For a window having no shade, the computation consists of two parts. One is the fraction transmitted by the window into the room. The other is the total fraction of incident radiation absorbed by the pane that is subsequently sent into the room. This second quantity is usually written as the product of two factors: the fraction α of incident radiation absorbed by the pane and the fraction N_i of the absorbed radiation that is re-emitted inwardly toward the room. Thus

$$F = \tau + \alpha N_i \, . \qquad (1)$$

The introduction of a reflective interior shade results in an infinite cascade of subsequent events. Light passing through the pane hits the shade. A portion of that reflects, a portion transmits through the shade, and a portion is absorbed by the shade. Each of these parts has a complicated subsequent fate. That transmitted passes to the interior of the room. That absorbed is radiated, conducted, and convected into the air on both sides of the shade. That re-emitted on the window side approaches the pane (glazing) and has the potential for escaping back outside through the window. That reflected goes back toward the pane (glazing) where a portion is transmitted through the glass back to the outside. The general character of these processes is illustrated schematically in Figure 2.

Fortunately we can make some reasonable assumptions about this complicated process First we assume specular reflection from the glazing for all rays incident on the glazing from the inside. Specular reflection means that the angle of incidence equals the angle of reflection. The alternative is diffuse reflection. Diffuse reflection describes reflection from a dusty or milky white surface, one in which a single incident ray would produce an entire distribution of rays scattered in various directions with a specific distribution of brightness according to direction. Furthermore, each incident angle would have a different complete distribution of scattered rays. All real surfaces are diffuse to an extent. One seldom hears much about diffuse reflection with windows because diffuse reflection is extremely difficult to treat from a computational standpoint. Nonetheless, realistic computer simulations for diffuse glazings are currently being developed for the situation being described by this article. For more information about this research, the reader is directed to a series of research results by J. Klems of Lawrence Berkeley Laboratory being published in the ASHRAE Transactions[2].

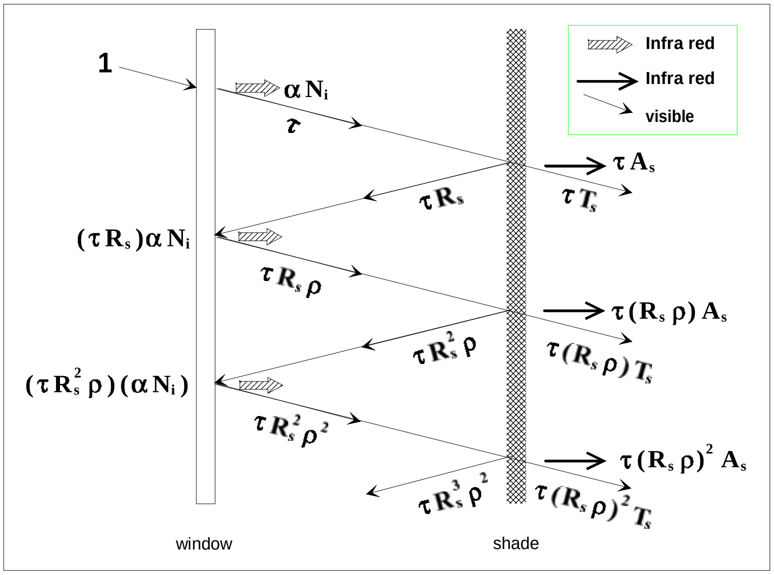

Figure 2. Heat flows associated with solar radiant heat gain for a single pane glass window and a planar interior shade (to the right of the glazing in this drawing).

In addition to our assumptions of normal incidence and specular reflection from the inside of the window glass, we also assume a specularly reflecting shade. This is a drastic step, since almost all shades are diffuse reflectors! The assumption is equivalent to presuming that we can treat the radiation diffusely reflected from the shade as if it were all incident on the inside of the glazing at zero angle of incidence. We do this so that we can use the normal incidence reflectance of the window system to estimate the reflected component. This assumption is based on the fact that, for most glazings, the reflectance and transmittance values depart little from their normal incidence values up to about 50 degrees. (See Figure 3, which shows a plot of reflectance and transmittance of ordinary window glass versus angle of incidence.)

All radiation absorbed and subsequently re-emitted by any element (the shade, the glazing, the air in the room, or even the room itself) is re-emitted almost completely at infrared wavelengths to which the glazing is generally opaque. The subsequent fate of any such re-emitted radiation is to reflect/conduct/convect between shade and glazing through the air inside the room until it is finally absorbed as heat within the room. Accordingly the assumption is made that all radiation once absorbed by the shade remains in the room.

We make the subtle assumption that the shade will have no effect on N_i. In actuality, the portion of radiation directed by the shade back toward the glazing will result in a rise in temperature of the air adjacent to the glazing and of the glazing itself. It is likely that the temperature difference between the glazing and the adjacent air will may also be altered. That difference is the principal determinant of the fraction of radiation absorbed by the glazing that is subsequently re-emitted back into the room, i.e., N_i. We assume this alteration in N_i to be insignificant.

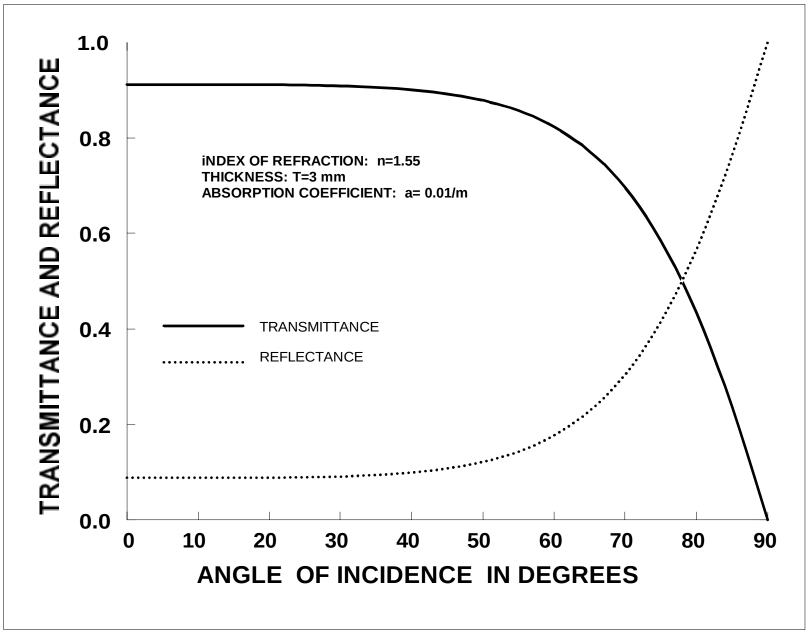

Figure 3. Reflectance and transmittance of ordinary window glass versus angle of incidence. The reflectance and transmittance depart very little from the normal incidence values out to angles of about 50°.

Here is an even more subtle assumption. The N_i value used characterizes the fraction of radiation incident *from the outside* and subsequently re-emitted into the room as heat. Technically there would be a different value for N_i for radiation *incident from the inside and subsequently re-emitted to the outside.* Consider, for example, a double pane system in summer. The outside pane is at a higher temperature. The N_i for radiation incident from the outside describes a two-pane process beginning with a higher temperature pane. The N_i for the radiation incident from the inside characterizes a two-pane process that begins with a lower temperature pane. These two N_i's would be different since they characterize different processes. We make the assumption that one N_i value is adequate for both processes.

Armed with the above assumptions, we follow the radiation back and forth between shade and glazing. As illustrated in Figure 2, each contact with the shade transmits part T_s to the room beyond, absorbs part A_s and reflects part R_s back toward the glazing. Each contact with the glazing sends a fraction αN_i permanently into the room and after the first transmission reflects a portion T_s back to the shade.

We make one further assumption regarding the radiation transmitted through the shade. It is possible that some of the transmitted fraction might be reflected by objects in the room back toward the shade and then transmitted a second time through the shade to the glazing, but we consider this effect to be insignificant. In accordance with observations made earlier about the greenhouse effect, we assume that the transmitted fraction is ultimately absorbed and accordingly also remains in the room as heat. Of course the fraction absorbed by the shade remains in the room as heat.

It is useful to organize the contributions into three categories: one for radiation remaining in the room as heat due to having been transmitted through the shade, one for radiation that remains as the result of having been absorbed by the shade, and one for radiation remaining as the result of having been absorbed by the window and re-emitted into the room as heat. Each of these categories represents an infinite series. Fortunately, each can be written in the form of a geometric series and can be summed in closed form. The final result is the sum of these three terms. As shown in our more detailed paper in the ASHRAE Transactions[3], the result of all these multiple reflections transmissions and absorptions is the expression

$$F_s = \tau \left[\frac{T_s + A_s + R_s\left(\alpha N_i\right)}{1 - \rho R_s} \right] + \alpha N_i \qquad (2)$$

for the solar heat gain coefficient F_s for the window and shade combination.

The interior shading can be removed mathematically by setting $A_s = R_s = 0$ and $T_s = 1$ (none absorbed, none reflected, all transmitted). In that case the square bracket coefficient of □ becomes 1 and the standard expression for F is recovered.

Since the conservation of energy requires that $A_s + R_s + T_s = 1$, the square bracket term can be written so that R_s is the only shade parameter needed to determine the square bracket coefficient of τ:

$$F_s = \tau \; \frac{1 - R_s(1 - \alpha N_i)}{1 - \rho R_s} + \alpha N_i \qquad (3)$$

OBSERVATIONS

A glance at Equation 3 shows that the effect of the shade is to modify the originally transmitted portion of the incident beam. For typical glazing values let us take those assumed by ASHRAE as the "Standard Reference Glazing" (SRG), specifically $\tau = 0.86$, $\alpha N_i = 0.01$, and $\rho = 0.08$. These values all taken at normal incidence. Substituting we get

$$F_s = \left(.86\right) \left[\frac{1 - R_s(1-.01)}{1 - (.08)R_s} \right] + \left(.01\right) \; . \qquad (4)$$

Notice the denominator of the square bracket is essentially equal to 1 even if R_s equals its maximum value of 1. Also the coefficient of R_s in the numerator of the square bracket term is similarly approximately to equal to 1. Thus

$$F_s \approx \left(.86\right) \left[1 - R_s\right] + \left(.01\right) \; . \qquad (5)$$

As we go from no shade ($R_S = 0$) to a perfectly reflecting shade, ($R_S = 1$), F_s decreases essentially linearly from 0.87 to 0.019.

COMPARISON WITH MEASUREMENTS

A comparison of these results can be made with measured values found in the ASHRAE Handbook of Fundamentals[4] and in a test report done by a private test laboratory for some shades sold by a prominent U.S. shade manufacturer. The ASHRAE data is for roller shades for a single pane glazing with τ in the range of 0.79 to 0.87. The test value used for the glass transmittance is not stated.

TABLE 1. Window interior shade solar heat gain coefficient results for window transmittance $\tau = 0.86$

Shade Identification	Shade Reflectance	SHGC (Measured)	SHGC (Calculated)
ASHRAE Handbook of Fundamentals Data:			
Dark Opaque	0.20	0.70	0.71
Light Translucent	0.60	0.38	0.37
Light Opaque	0.65	0.34	0.33
Independent Test Lab Data:			
Privacy White	0.40	0.52	0.54
Translucent	0.50	0.47	0.46
Shiny Opaque	0.67	0.31	0.31
Blackout White	0.77	0.24	0.22

It is difficult to determine from the test report exactly how the private test laboratory data was measured. The report is in two parts, one which indicates a 3/16" pane was used and another which refers to a 3/32" pane being tested.

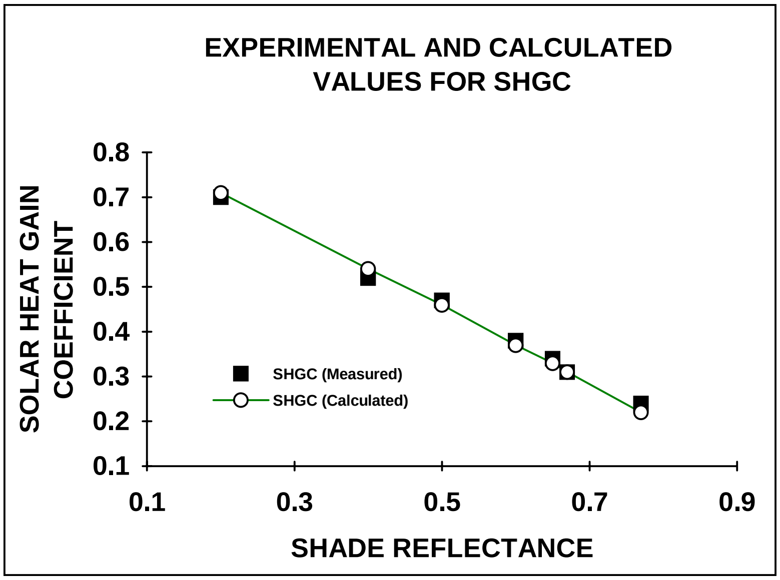

Figure 4. Window Interior Shade Shading Coefficient Model Evaluation Results for Window Transmittance t = 0.86

For both the ASHRAE and the other data, a value of $\tau = 0.86$ was assumed for the sake of computing predicted values for F_s corresponding to measured data. The results are tabulated in Table 1 and are displayed graphically in Figure 4.

The agreement of this simplified model with available data is sufficient to suggest that the model includes the essential processes that occur when shades are introduced. However, for neither set of measurements is it clear exactly how the measurements were performed, how accurate the shade reflectance values are, or how close the actual reference window systems used were to the SRG. Thus the reader should be cautioned not to generalize these results too much.

The model is not expected to be accurate for glazings operated far from the condition of normal incidence. This caveat applies especially to multi-pane windows. Light entering the outside pane of a multi-pane system can easily be obscured by the framing. Furthermore, unlike single pane windows, multi-pane windows exhibit a stronger dependence of reflectance on incident angle, even below the 50° region where the effect becomes significant for single pane windows.

TABLE 2. Solar heat gain coefficient for several real glazings. A value of N_i = .267 was used throughout.

Window	□	□	□
clear 4 mm window glass	0.75	0.07	0.18
bronze 3 mm glass	0.53	0.05	0.42
stainless steel on green tinted glass	0.07	0.39	0.55
spectrally selective film	0.48	0.42	0.11

As suggested earlier there are other modern systems for which this model would not be expected to give accurate predictions. Some modern coatings are being developed specifically to be strongly angularly dependent and/or to have special wavelength dependent properties.

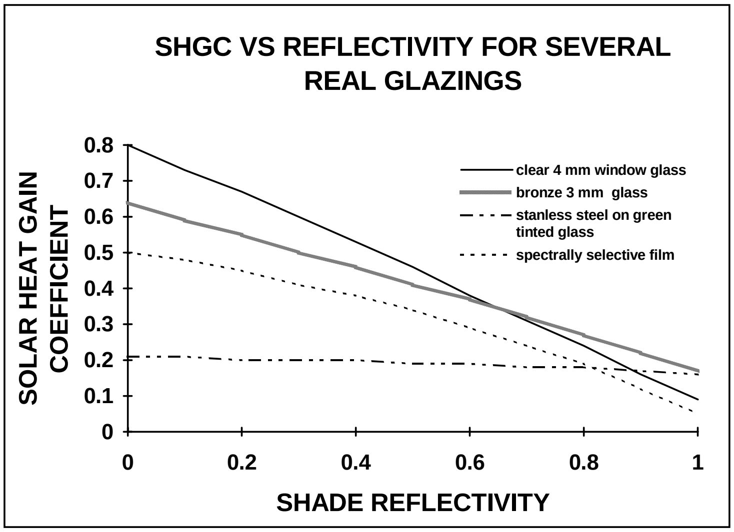

Figure 5. Computed solar heat gain coefficient for several actual glazings. All these calculations assume standard conditions of still air inside the window and 7.5 mph out and a corresponding $N_i = 0.267$.

It is interesting to apply the model presented here to actual glazings. Table 2 presents values for four glazings which are commercially available. Two of these are in common use and two are glazings with advanced special purpose coatings. For all these, the value of N_i has been assumed to be 0.267. Figure 5 presents the predictions of our formula for the solar heat gain coefficient as a function of shade reflectivity for reflectivity values ranging from zero for no shade to one for a perfectly reflecting shade. Notice that the effect of the shade is much more pronounced for the common glazings than for the special purpose ones, as expected.

CONCLUSION

The use of interior shades and venetian blinds, especially shades which are highly reflective on the side facing the glazing, can exert a significant control over the solar radiant heat gain from windows in buildings. That control can be increased even further if the shade or blinds are adjusted several times a day. For example, the shade or blind could be left open when the summer sun is not shining directly on the pane. Then during the hours of maximum summer heating, the shade or blind could be progressively closed to reflect incident radiation back out the window before it becomes heat in the room. In the winter months, the process could be reversed to let in the maximum amount to solar heating. If the control afforded by interior shades and blinds is managed in such a way as to reduce the cooling load in the summer and to supplement the heating of the building in winter, a corresponding reduction in cooling and heating bills can result.

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