Chapter 6: Windows, Light, and Heat Gain

Windows are a key feature of any good solar design because windows bring light into the building. Light is essential for nearly all aspects of life except sleeping. If we do not bring in the sun's natural light we will have to provide artificial light by some other means -- necessarily requiring energy. It only makes sense to use the sun whenever possible.

In addition to light, windows allow the sun's energy to heat the interior of a building. This is an obvious benefit in cold weather, but not so desirable in warm weather. Moreover, while windows provide wonderful light and heat in the daytime they provide little benefit (in the way of light and heat, anyway) at night. Moreover, windows do not insulate nearly as well as other wall materials. Thus, windows have negative aspects as well. The challenge, therefore, is to find ways to reap the benefits of windows while minimizing their downsides.

1. Window U-values

We have already considered windows in conjunction with our analysis of heat losses in a building. Specifically, we know that heat flow through a window may be described by Fourier's Heat Law. The window is characterized by an R-value or a U-value, where U = 1/R. U-values are generally more useful since we typically have to add the UA products for many windows.

Let us look in more detail at the heat losses associated with a window. First, consider a single pane window in a simple frame. The glass conducts heat as does the frame. A metal frame will conduct significantly more heat than will a wood or vinyl frame. The conduction of the metal frame may be reduced by installing a thermal break in the frame -- essentially splitting the frame in half so that heat flowing from one side (of the wall) to the other will have to go through the thermal break -- which is a poor conductor of heat. Such a frame has the strength and fire-resistance of metal but with low thermal conduction.

1.1 Storm Windows

Adding a storm window reduces heat flow by replacing the glass with a 3-layer structure: the original glass, a dead air layer trapped between the original window and storm, and the storm window. As with other multi-layer walls, the R-values of these three add to yield an effective R-value that is higher (by about a factor of 2) than the original window.

Storm windows work better on paper than in practice. In practice, the air layer is not so dead -- air currents develop in the space trapped between the two window panes. And more importantly, over time, the thermal properties of the storm windows deteriorate, mainly due to the breakdown of the seals. It is common to witness air currents in the space between the window and storm after many years.

1.2 Thermal Glass

One problem with window/storm combinations is that the storm window seals deteriorate and air currents develop between the two windows, greatly diminishing the insulating value. A good way to avoid this is to install a double-pane, sealed combination -- two glass panes separated by a dead air space whose integrity is garanteed by a good seal. Such a combination is called a thermal pane.

Though convection is eliminated in the air trapped between the two glass panes, the air still conducts some heat. This conduction could be eliminated if the air was removed -- leaving, instead, a vacuum between the two glass panes. This substantially lowers heat loss, but makes for mechanical nightmare as the two window panes then experience a force to "suck " them together. This problem is reduced by placing physical spacers between the two panes, but these detract from the view. Moreover, it is not easy to maintain the integrity of the evacuated space over long periods of time. In short, practical problems have kept this idea from succeeding in the market place.

1.3 Inert Gas

Another way to lower the heat loss from air conduction is to replace the air with another gas with a lower molar mass. Argon gas (monatomic), for instance, has a lower thermal conductivity than nitrogen gas (diatomic) which is, of course, the main component of air. Inert gas-filled thermal pane windows are strong and have lower heat loss than air-filled thermal pane windows.

1.4 Low-E Coating

The greenhouse effect arises from the simple fact that glass transmits visible wavelengths without attenuation but does not transmit infrared radiation as well. Nevertheless, IR radiation will pass through glass. Materials can be engineered which reflect IR even better than standard glass while still passing visible light. One of the glass panes of a thermal window can be coated with such a low-emissivity material. Alternately, a separate low-e material can be sandwiched in the space between the two window panes.

In addition to reflecting IR, there are good reasons to for windows to block the UV as well. Not much of the sun's energy reaching the earth's surface remains in the ultraviolet range, but what energy there is promotes fading in carpets, apolstry, and the like. Coatings may be included on windows to block this UV.

2. Solar Heat Gains

If heat loss were the only consideration then houses shouldn't have windows. But, of course, windows are important for many reasons. First, they bring in daylight which can reduce lighting costs and brighten the human spirit. Second, windows, by admitting light, can also provide passive solar heat in the winter. It is fair to ask whether, on the whole, a window results in a net energy loss or gain. We have already discussed the energy loss above (i. e., the R-value). Here we discuss a window's energy gain.

The energy gain of a window is related to its ability to allow radiation of certain wavelengths through and to block other wavelengths. This is, as mentioned before, the origin of the green house effect. Glass readily transmits visible light but not infrared radiation. Hence the sun's radiation, with much of its energy in the visible, is admitted into the house while the inside heat, infrared radiation, is not transmitted. Recall that heat may be transferred by 1) conduction, 2) convection, and 3) radiation. By deliberately coating window glass with a layer which has low emissivity for infrared wavelengths the glass' ability to transmit infrared radiation may be further minimized. Well-insulated windows consist of two or even three panes of glass separated by a thin layer (1/4 in. or 1/2 in.) of air.

This reduces conduction and convection while still allowing light to enter. The combined effects of these on heat flow are summarized in the window's R-value.

The heat loss through a window is related to its R-value, the inside, and the outside temperatures. The heat gain depends upon the sun's intensity, its angle (with respect to the window) and the ability of the window to transmit (rather than to reflect) the light.

Consider light of intensity I_0 incident on an air/glass interface. Some fraction of the incident ray will be reflected back into the air. The reflected ray has an intensity I_R. The remaining intensity, I_T, will pass into the glass. Conservation of energy requires that[1]

$$I_T + I_R = I_0 .$$

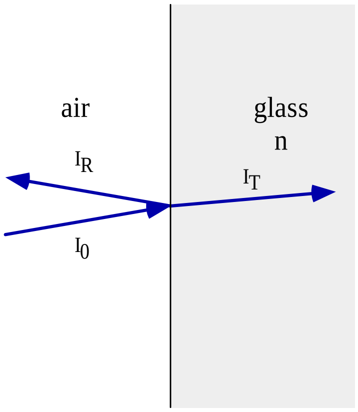

Figure 1. Diagram showing rays for the incident, reflected, and transmitted light at an air/glass interface.

The reflection coefficient is defined by

$$R \equiv \frac{I_R}{I_0} .$$

The transmission coefficient is similarly defined to be

$$T \equiv \frac{I_T}{I_0} ,$$

Conservation of energy leads to the simple relationship between R and T, namely

$$T = 1 - R .$$

In words, the reflection coefficient is the percent of the incident energy which is reflected and the transmission coefficient is the percent of the incident radiation that is transmitted. If the index of refraction of the glass is n then the reflection coefficient is given by[2]

$$R = \left(\frac{n_2 - n_1}{n_2 + n_1} \right)^2 .$$

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[1] Some energy is also absorbed in the glass so that $I_0 = I_R + I_A + I_A$. Ultimately it gets re-radiated as heat, so we will not consider the absorbed energy herer.

[2] This expression is valid only when the light is normal to the plane of the glass. At more glancing angles the amount of reflected light is enhanced further.

It turns out that this same fraction is reflected at an air/glass interface or a glass/air interface (i. e., same amount is reflected as light enters glass or leaves glass).

Now consider what occurs when light rays pass through a window pane as shown in the figure below.

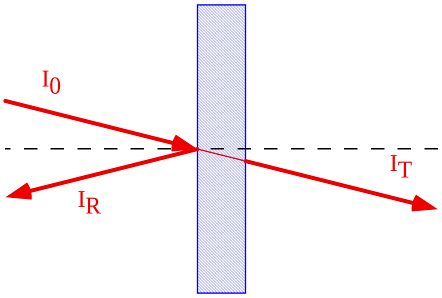


Figure 2. Diagram showing rays for the incident, reflected, and transmitted light through a window.

Light having intensity I_0 is incident upon the air/glass interface from the left. A fraction of this, R, is reflected back into the air and the remaining fraction (1-R) enters the glass, propagating across to the glass/air interface on the right. At the glass/air interface on the right, a fraction R of the light is reflected, and the remaining fraction (1-R) is transmitted into the air. Thus, the ratio of the intensities of the transmitted and incident light rays is

$$T \equiv \frac{I_T}{I_0} = (1-R)^2 ,$$

where R is given by the expression above. A more accurate calculations which keeps track of multiple reflections gives

$$T = \frac{(1-R)^2}{1-R^2} = \frac{1-R}{1+R} .$$

Example 1:
Consider glass with an index of refraction, n = 1.5. Calculate the percentage of the sunlight which will be transmitted from one side to the other, assuming normal incidence.

Solution:
This is a straight-forward calculation of the transmission coefficient T.

$$R = \left(\frac{1.5-1}{1.5+1}\right)^2 = \left(\frac{0.5}{2.5}\right)^2 = 0.04$$

$$T = \frac{1-R}{1+R} \approx 92\%$$

Suppose now that light with intensity I_0 is incident upon a window having area A, index of refraction n, and at an angle θ (called the *obliquity factor*) with respect to the window normal. For simplicity we will assume that the window transmits only visible wavelengths. Let α be the fraction of the incident intensity which is in the visible range. Then, the total power per unit area (J) in the transmitted light is

$$J = \alpha T I_0 \cos\vartheta \approx \alpha\left(\frac{1-R}{1+R}\right) I_0 \cos\vartheta \,.$$

For the solar spectrum, recall that approximately α = 40% is in the visible spectrum. For a south-facing window (here in the northern latitudes) the angle between the window normal and the sun is related to the zenith (Z) and azimuthal (A) angles of the sun. A little trigonometry shows that

$$\cos\vartheta = \sin Z \cos A.$$

Using this expression, expressions for A and Z as a function of time, along with expressions for sunrise and sunset, we may calculate the rate at which light energy enters the window. By integrating this rate over the daylight hours we can find the total amount of light energy gained during a day and compare this with the amount of heat loss during the same period.

Example 2:

Calculate the rate at which solar energy enters a south-facing, vertical window in Oberlin at noon on Dec. 22. Compare this to the rate at which heat is being lost through the same window assuming an outside temperature of 30°F and an R-value of 2.

Solution:

This corresponds to the winter solstice when, in the northern hemisphere, the sun is lowest in the sky. The zenith angle at noon is Z = L + 23.5° which, for Oberlin's latitude of 41.3°, is 64.8° degrees. The azimuthal angle A at noon is zero.

We will take the index of refraction of window glass to be n = 1.5. The power per unit area (or flux J) is given by

$$J_{gain} = \alpha T I_0 \cos\vartheta \approx \alpha\left(\frac{1-R}{1+R}\right) I_0 \sin Z$$

$$J_{gain} = (0.4)(0.92)\left(1000\frac{W}{m^2}\right)\sin\left(64.8^o\right) \approx 333\frac{W}{m^2} \approx 32.2\frac{Btu}{hr\cdot ft^2}$$

The heat loss rate per unit area is obtained readily as

$$J_{loss} = \frac{\Delta T}{R} = \frac{40^o F}{2\ \text{Btu / hr/}^o F\text{ / ft}^2} = 20\frac{Btu}{hr\cdot ft^2}$$

So, at noon, on a bright, sunny day, the window admits more energy than it loses. This "net gain" will go down as the sun moves across the sky and, will become negative once the sun's intensity is too low to offset the heat loss. If we wish to improve the ratio of gain/loss we need to improve the R-value of the window without cutting down on the light it admits.

The above calculation gets much more complicated at times other than noon. The reflection coefficient for the glass will get larger the greater the angle between the sun's rays and the normal to the window. Moreover, the sun's intensity will go down when it is lower on the horizon due to the fact that it must travel through a greater "mass" of air. And, of course, the intensity of the sunlight on the window depends on the weather, particularly clouds.

On the other hand, we have totally neglected *diffuse* and reflected sunlight. Sunlight will be reflected off of other surfaces -- snow, water, sidewalks, etc., so that more than just the direct sunlight will be incident upon the window. Moreover, even on the most cloudy of days, diffuse sunlight will be present. Diffuse sunlight is light that results from scattering off of all kinds of particles in the atmosphere. Unlike direct sunlight, diffuse light is uniform in all directions. On a very cloudy day it is not possible to see shadows. This is because the direct sunlight is blocked, and the light that does arrive on the surface of the earth comes from all directions. Roughly speaking, nearly 50% of the light striking a horizontal surface during the day is due to this diffuse sunlight.

Despite all the effort that goes into equations like those above, in the end it is much easier simply to rely on measurements from previous years to predict how much sunlight and heat will be available throughout the "average day."

3. Characterizing Window Performance

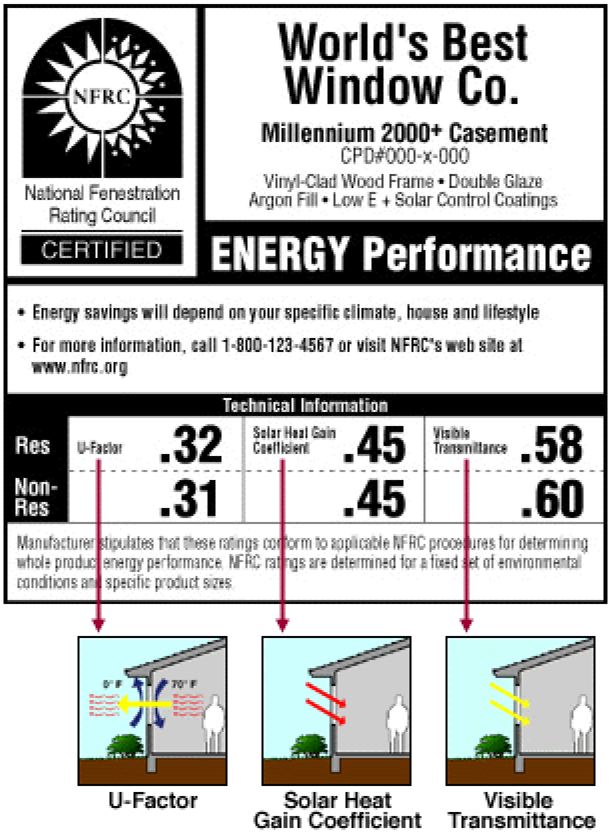
As you can see, it is very difficult to make detailed calculations to determine the performance of a window. Fortunately, with just a few average numbers we can determine the performance of a particular window assembly. Window manufacturers provide these numbers -- many are available from web sites. The most important window parameters are the U-factor, solar heat gain coefficient (SHGC), visible transmittance (VT), and air leakage (AL). This information is taken from web site of the Efficient Window Collaborative.

We have already discussed the U-factor above. Whether you are designing for cold or warm climates, a low U-value is desirable.

The solar heat gain coefficient is or SHGC is the fraction of the incident solar radiation that passes through to the other side of the window. This is a fraction between 0 and 1, usually expressed as a percentage. The number is related to the reflection coefficient R mentioned above, but includes the effects of all window layers. In cold climates we want SHGC to be as high as possible so that we can use the incident sunlight for heating. But in warm climates, we desire a lower SHGC.

A little thought will uncover the fact that the SHGC does not tell us the whole story. The main reason to have windows at all is for the light (visible EM radiation) they admit, not the heat (IR) they admit. Even in the summer we wish to admit light -- but we would prefer not to admit the heat (IR). The visible transmittance (VT) is the fraction of the incident visible radiation that is transmitted. The VT is a fraction between 0 and 1, again, usually expressed as a percentage. But unlike the SHGC which is measured with broadband radiation which includes IR, visible, and UV, the VT is measured for just visible radiation. A good window will have a VT that is greater than the SHGC -- this indicates that the window has a strong preference for passing visible radiation to radiation in the other parts of the EM spectrum – and this is what an ideal window should do.

The final number that is used to characterize a window is the air leakage, AL. The ideal window, when installed in a wall, would prohibit any air from passing from the inside to the outside of the building. Real windows, particularly operable windows (i. e., those which are able to be opened and closed) do not seal perfectly. The air leakage for a window is expressed in cubic feet per minute per square foot of window area. An air leakage rate of 0.30 cfm/sq. ft. is recommended for new construction. The *National Fenstruation Research Council* recommends window labels to indicate all these properties.



NFRC
National Fenestration Rating Council
CERTIFIED

World's Best Window Co.

Millennium 2000+ Casement
CPD#000-x-000
Vinyl-Clad Wood Frame • Double Glaze
Argon Fill • Low E + Solar Control Coatings

ENERGY Performance

- Energy savings will depend on your specific climate, house and lifestyle
- For more information, call 1-800-123-4567 or visit NFRC's web site at www.nfrc.org

Technical Information

	U-Factor	Solar Heat Gain Coefficient	Visible Transmittance
Res	.32	.45	.58
Non-Res	.31	.45	.60

Manufacturer stipulates that these ratings conform to applicable NFRC procedures for determining whole product energy performance. NFRC ratings are determined for a fixed set of environmental conditions and specific product sizes.

4. Solar Irradiance and its effect on Heat Loss and Gain

Our earlier discussion of the thermal envelope of a building considered only energy conduction through the windows and walls. Now we see that, in the winter we must also consider the heat gain due to radiation through windows, particularly those in the south wall of a building. Also, in the summer, we must consider unwanted heating which results from this same radiation.

Windows, of course, are designed to admit light into a building. Other building surfaces will also absorb incident radiation and heat up. Consider, for instance, a south-facing, dark wall. A fraction of the sunlight incident on this wall will be absorbed. In the winter this will change the amount of heat loss through the wall by raising the wall's outside temperature. The amount of light absorbed depends upon the color and texture of the wall's outside surface. Dark, rough surfaces absorb more radiation than light, smooth surfaces. Thus, our calculations of annual heat loads for a building quite properly need to include the effects of sunlight. Moreover, a well-designed building should take advantage of available sunlight for both lighting and heat.

To account for heat and light gains associated with the sun's radiation quite complicated. If we are interested in annual or monthly averages we can make use of on-line resources such as NREL's *Solar Radiation Data Manual for Buildings* http://rredc.nrel.gov/solar/old_data/nsrdb/bluebook/atlas/ which tabulates average incident radiation on various building surfaces. This will help us more accurately account for the annual average heat loss taking radiation into account. Window manufacturers provide detailed information regarding heat loss and solar gains which can be used in our calculations. (For instance, see http://www.ppg.com/gls_ppgglass/architect/topic.htm for typical window data.) Some computer programs include solar radiation to estimate annual energy loads.

To get an even better picture of building performance, particularly for a building which will relies heavily on solar energy for heating and lighting, it is important include more detailed solar irradiance information. Weather files are available which provide the hourly average solar irradiance incident on various building surfaces throughout each day. These data must account for the building site (latitude and longitude), the earth's motion, and average local weather. Such weather files are used by computer programs such as the DOE-2 modeling software for performing detailed analysis of building energy performance. DOE-2 software was developed by the Department of Energy. Various DOE-2 software packages are commercially available, differing mainly in their user interfaces. (Eley Associates http://www.eley.com/ markets *VisualDOE* and SAC Software http://doe2.com/ markets *PowerDOE*, for instance.) DOE-2 simulations have been used extensively in the design of the *Joseph Lewis Environmental Studies Center* at Oberlin College.