PHRC **Research Series Report No. 111**

The Pennsylvania Housing Research Center

Evaluation of Residential Window Retrofit Solutions for Energy Efficiency

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Preface

This report presents a review of several different approaches to enhance energy efficiency through windows. The most widely known method of reducing energy loss through windows is to replace inefficient single glazed window units with their newer, energy efficient counterparts. However, there are also other methods that involve retrofit solutions, including the use of curtains, drapes, blinds, screens, and shutters. While these products are often selected for aesthetic or privacy concerns, they can also provide an effective means of limiting heat transfer. This report describes the performance criteria such as reduction in heat conductance, solar heat gain, daylighting, thermal comfort, condensation potential, air leakage, cost, ease of operation, privacy, and aesthetics for each retrofit solution. Window retrofit attributes are evaluated based on data and information available in the open literature and those provided by product manufacturers as well as using the software such as WINDOW and THERM. The study outlines some guidelines for selection of retrofit options and for better understanding of different solutions with respect to heat loss prevention and other attributes.

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Table of Contents

Table of Figures

1. Introduction

According to the 2011 Buildings Energy Data Book (US DOE, 2011a), buildings consume approximately 40% of the nation's energy. Approximately 56% of this energy is used for space heating and cooling as well as lighting applications, while 25% to 35% of this energy is wasted due to inefficient windows. All of these factors are directly impacted by the building envelope (Totten and Pazera, 2010). In addition to other functions (Kazmierczak, 2010; Sanders, 2006), successful building envelopes shield occupants from outside weather conditions, whether that be excessively hot temperatures in the summer or extremely cold temperatures in the winter, as well as provide a connection to the outside in terms of natural lighting and views.

Fenestration systems are a key element in achieving these goals. While fenestration systems are the most widely used method to provide a connection to the outside (Figure 1), they are also always the weakest link in terms of the thermal performance of the building envelope (Oldfield et al. 2009). This is primarily due to the extremely high U-value found in windows in comparison to wall systems. In addition, glazing systems can have a significant impact on energy savings through daylighting. For example, Johnson et al. (1984) found that fenestration can reduce total building peak demand by up to 14-15%.

Figure 1: Typical residential window. Image courtesy of Gold Beach Real Estate

One of the major challenges facing homeowners is the high capital cost associated with fenestration upgrades. The cost of replacing all the windows in a residential building can be substantial. However, the energy savings associated with replacing windows with their higher efficiency counterparts is typically relatively small. The payback period for replacing single glazed windows with double glazed windows can be as long as 50 years for cold climates. This payback period will also increase as the quality of the existing windows increases. When double glazed uncoated windows are replaced with triple glazed units with argon fill and a low-e coating, the payback period is typically around 100 years for cold climates (Guler et al., 2001). Another study conducted by Frey et al. (2012) demonstrated that high performance window upgrades have a return on investment (ROI) of only between 1.2-1.8% based on climate. This translates to a simple payback period of 55-83 years. Therefore, for most homeowners it is necessary to determine low cost methods of reducing heat flow through their windows.

A similar analysis was performed in this study with the goal of determining the payback period for window upgrades in several different climates. Philadelphia, PA was selected to represent a mixed temperature, humid climate. Miami, FL was selected to represent a hot, humid climate. Chicago, IL was selected to represent a cold, humid climate. Albuquerque, NM was selected to represent a hot, dry climate. Lastly, Anchorage, AK, was selected to represent a cold, dry climate.

For this analysis, a single story, 1500 SF residential home was analyzed. The home has 14 windows (437.5 SF), distributed evenly amongst each side. This corresponds to 25% glazed area. The house has walls insulated to achieve an R-value of 19 and ceilings insulated to achieve an R-value of 49. The house uses a Gas Furnace for heating and AC for cooling. Utility costs have been assumed to be \$0.054/kWh for electricity and \$0.4/Therm for gas. These values have been assumed to be constant across all climates.

The cost of replacing existing windows often is largely determined by the cost of installation. A replacement, vinyl clad, double glazed window with a low-e coating can cost anywhere between ~\$149 (U –value = 0.48, SHGC = 0.59) to \$263 (U-value = 0.32, SHGC = 0.21) before delivery and installation costs are taken into account. Installation costs can vary considerably as well. Lowe's uses a base installation cost of \$100 per window. Existing conditions such as the current type of windows and age of original construction can significantly add to this cost. For the purposes of this project, a ReliaBilt 3500 series window (\$263) will be selected, with the base installation cost of \$100/window.

An existing, double hung window system using PPG ¼" monolithic glass with a wood frame was used for the original baseline. This system has a whole window U-value of 0.85 Btu/hr-ft^2-°F, a SHGC of 0.64, and a T_{vis} of 0.67. Since many older windows are particularly leaky, an air leakage rate of 1 cfm per ft^2 of glazed area was assumed. The upgraded windows have been assumed to be double glazed, double hung windows with a low-e coating and argon fill. A U-value of 0.32 and an SHGC factor of 0.21 were used for the analysis. An air leakage rate of 0.2 cfm per ft^2 of glazed area was used. The critical variables used for the analysis are summarized in Table 1.

Table 1: Summary of critical variables used for cost analysis

Window Properties	Original Glazing	Upgraded Glazing
U-value (Btu/hr-ft^2-°F)	0.85	0.32
SHGC	0.64	0.21
Air Leakage (cfm/ft^2)	1	0.2
Utilities		
System Type	Gas Furnace/AC	
Electricity Cost (\$/kWh)	0.054	
Gas Cost (\$/Therm)	0.4	

RESFEN software (LBNL, 2007) was used to perform an analysis of the energy use and cost of using each system across a variety of different climates. These results are shown in in Table 2. For each climate, the energy savings from upgrading windows was between ~\$139 and \$167. The amount of time needed to pay off the investment of upgrading windows was then calculated as a simple payback. The equation for simple payback is shown below.

$$Simple\ Payback\ (Years) = \frac{Initial\ Cost\ (\$)}{Annual\ Savings\ (\$/_{yr})}$$

Table 2: Payback analysis for upgrading fenestration systems based on climate.

	Single-Glazed Wood Frame, Annual Energy Use (MBtu)	Single Glazed Wood Frame, Annual Energy Cost ($)	Double-Glazed Aluminum Frame, Annual Energy Use (MBtu)	Double Glazed Aluminum Frame, Annual Energy Cost ($)	Savings per Year ($)	Simple Payback (Years)
Philadelphia	76.6	394.67	44.2	227.5	167.17	30.4
Phoenix	75.8	390.65	43.4	223.5	167.15	30.4
Miami	68.6	360.79	41.8	220.13	140.66	36.1
Anchorage	142.2	568.87	100.9	403.66	165.21	30.8
Chicago	99.5	413.34	66.8	273.39	139.95	36.3

It should also be emphasized here that the installation costs could increase the total upfront cost substantially. Although these results predict slightly shorter payback periods than those of Guler et al. (2001), they confirm the same conclusions. With payback periods ranging from ~30-37 years, upgrading windows are unlikely to be an economically viable option for many homeowners.

The objective of this study was to quantify the performance of various window retrofit solutions. The report will start with an investigation of the performance of several different window retrofit solutions (also referred to as window attachments). This investigation involves not only a description of each method, but also gives an indication of the cost of each method, the expected improvement in U-value and/or SHGC, as well as any potential risks that may be involved with them. Computer analysis was conducted to determine the performance of these systems when implemented on a typical residential building in several different climates throughout the United States. Finally, a method was developed to aid homeowners in selecting a glazing system.

2. Background on Window Performance

2.1 Window Styles

There are many different window styles used in residential buildings. Figure 2 provides an illustration of several of these systems. In general, these window styles fall into three primary categories: Fixed, Hinged, and Sliding.

- **Fixed window**s, also known as picture windows, are not operable. Fixed windows can come in a variety of sizes and shapes. While they are more airtight than operable windows, they have no capacity to provide for ventilation when desired.
- There are several windows in the **hinged** category. Awnings are hinged at the top and open outward. Hopper windows, on the other hand, are hinged at the bottom, while casement windows are hinged at the sides. One benefit of hinged windows is that they are typically more airtight than other operating window styles since the weatherseal is compressed when the window is closed. In addition, hinged windows provide superior ventilation since the opening area is larger and the projecting window serves as a scoop for the air. While awning style windows can be opened during the rain, hopper and casement windows will allow water into the home if not shut ahead of time.
- **Sliding** windows open by having one sash slide over an adjacent sash. Horizontal sliding windows have sashes that open from side to side. Hung windows open by sliding top to bottom. Both sliding and hung windows may be single hung (only one sash is operable) or double hung (both sashes are operable).

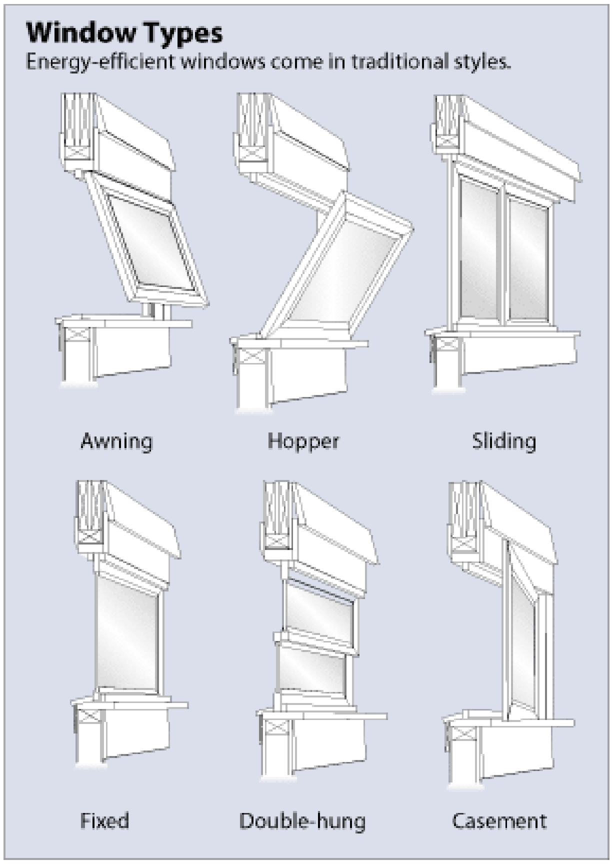


Figure 2: Common styles of window systems. Image source: http://www.energysavers.gov/your_home/windows_doors_skylights/index.cfm/mytopic=13460

The LBNL conducted field testing of the air leakage of various styles of windows (Weidt et al., 1979). The study reached several important conclusions. The first is that comparisons of the air leakage performance of different styles of windows vary dramatically based on whether the measured air leakage is a function of "linear foot of cracks", "square foot of glazing area", or "square foot of ventilated area" as is shown in Figure 3. In the above descriptions "crack length" refers to the length of the separation between the sash and the frame, "square foot of glazing area" refers to the total size of the window (frame excluded), and the "square foot of ventilated area" refers to the total size of the operable portion of the window. When these values were measured as a function of total glazing area, it was found that casement windows performed best, and double hung windows performed worst. While double hung windows are the worst performing using 2 out of 3 methods of measurement, the air leakage of single hung windows can be described as being higher. In addition, operable windows (e.g., sliders or double-hung) leak more than their non-operable counterparts (e.g., casement windows). This is very intuitive, as any capability for movement will provide more opportunities for air leakage.

However, it is important to consider the construction and behavior of a window rather than its manufacturer designation when attempting to compare various products. For example, a single hung slider is often constructed in an identical fashion as a double hung slider, with only minor steps to fix one sash in place. This means that a single hung slider may perform similarly to a double hung slider from an air leakage perspective.

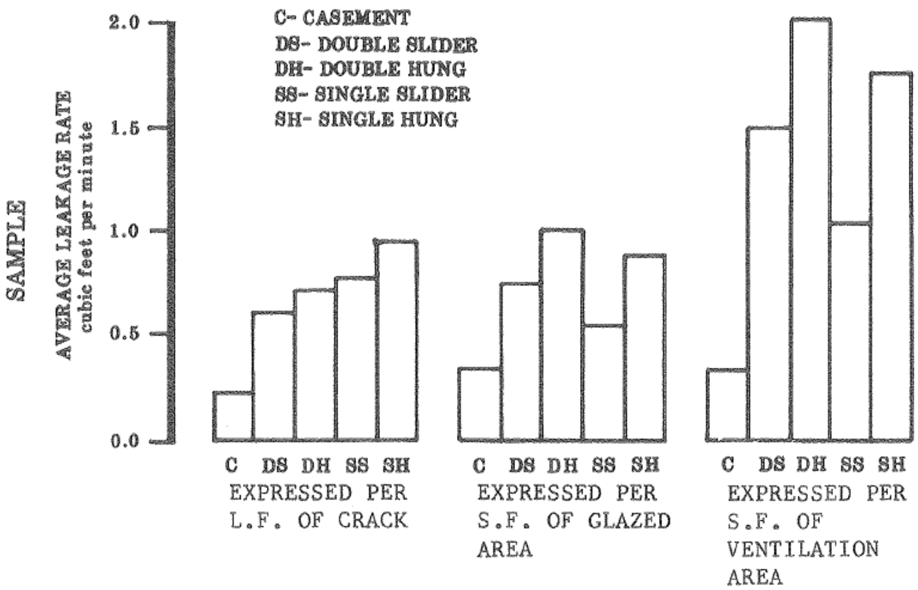


Figure 3: Air leakage rates for various window styles. Note the variance in performance based on how air leakage is expressed. Image Source: Weidt et al., 1979.

Sliding windows are the most popular type of residential window. As such, this study will focus on window attachments used in conjunction with this window type. A schematic of a typical double hung window identifying all key components is shown in Figure 4.

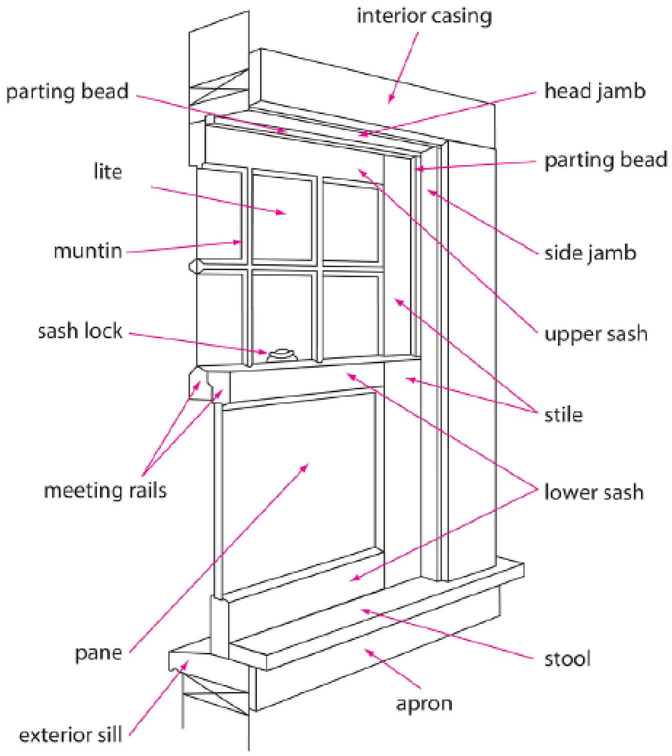


Figure 4: Names and parts of a typical double hung window. Image source: US DOE, 2011b

2.2 Glazing Performance Characteristics

The National Fenestration Rating Council (NFRC) is an independent agency that provides a uniform rating system for window and other fenestration products. Using independent, NFRC–accredited laboratory testing results on each window product, the NFRC provides a series of values that can be used by homeowners and building designers to compare the performance of various products. A typical NFRC label in shown in Figure 5. The label provides up to five different performance values for consideration. Two of these values, the U-value and the Solar Heat Gain Coefficient (SHGC) will have the greatest impact on the energy efficiency of the window. The other three criteria, Visible Transmittance (T_{vis}), Air Leakage (AL), and Condensation Resistance (CR) will play a secondary role in the performance of the window. While the U-value, SHGC, and T_{vis} are criteria that are required for NFRC certification, manufacturers are permitted to choose whether to report values for Air Leakage or Condensation Resistance.

NFRC
National Fenestration Rating Council®
CERTIFIED

World's Best
Window Co.

Millennium 2000+
Vinyl-Clad Wood Frame
Double Glazing • Argon Fill • Low E
Product Type: **Vertical Slider**

ENERGY PERFORMANCE RATINGS

U-Factor (U.S./I-P)	Solar Heat Gain Coefficient
0.35	**0.32**

ADDITIONAL PERFORMANCE RATINGS

Visible Transmittance	Air Leakage (U.S./I-P)
0.51	**0.2**
Condensation Resistance **51**	**—**

Manufacturer stipulates that these ratings conform to applicable NFRC procedures for determining whole product performance. NFRC ratings are determined for a fixed set of environmental conditions and a specific product size. NFRC does not recommend any product and does not warrant the suitability of any product for any specific use. Consult manufacturer's literature for other product performance information.
www.nfrc.org

Figure 5: Example of a NFRC rating label. Image source: NFRC, 2005b.

The U-value measures the rate of heat flow through a building component due to conduction, convection, and radiation (NFRC, 2005b). Therefore, a lower U-value implies less heat transfer and is therefore desirable. The unit for the U-value is Btu/(hr*ft^2*°F), although the values are usually shown without the unit attached. In addition, the relationship between heat transfer and the U-value is linear. Therefore, a U-value of 0.2 is twice as effective at limiting heat transfer as a U-value of 0.4.

There are several standards used to determine the U-value of a glazing system. The most common methods used in the North America are based on ASTM C1363 (*Standard Test Method for Thermal Performance of Building Materials and Envelope Assemblies by Means of a Hot Box Apparatus*) (ASTM, 2011) and ASTM C1199 (*Standard Test Method for Measuring the Steady-State Thermal Transmittance of Fenestration Systems using Hot Box Methods*) (ASTM, 2009a). However, NFRC 100 (*Procedure for Determining Fenestration Product U-Factors*) (NFRC, 2010a) covers a more specific approach for fenestration systems. Each of these methods works under the same general principle of measuring heat flow through a specimen.

The solar heat gain coefficient measures the amount of incident solar heat gain transmitted through the system as heat. This ratio varies from 0 (no solar gain transmitted as heat) to 1 (solar gain completely transmitted as heat). Like the U-value, the relationship between the SHGC and the solar heat gain is linear. The shading coefficient (SC) is a similar, but older method of measuring a units transmittance of solar heat gain that has been replaced by the SHGC. The shading coefficient varies, however, in that it measures the ratio of solar heat gain through glazing as compared to a clear 1/8" single pane of glass.

Visual Transmittance, or T_{vis}, is a term used to describe the percentage of the visible portion of the solar spectrum that is transmitted through glazing. A T_{vis} of 1 means that no visible light is prevented from transmitting through the window, whereas a T_{vis} of 0 means that the window does not transmit any visible light.

The SHGC and Visual Transmittance of a glazing system are both determined in a similar fashion. ASTM 1084 (*Standard Test Method for Solar Transmittance (Terrestrial) of Sheet Materials Using Sunlight*) (ASTM, 2009b) is used for determining the SHGC, while ASTM 1175 (*Standard Test Method for Determining Solar or Photopic Reflectance, Transmittance, and Absorptance of Materials Using a Large Diameter Integrating Sphere*) (ASTM, 2009c) can be used for measuring the visual transmittance. Each of these methods operates under a similar principle of determining what percentage of light is capable of passing through a given material specimen.

The Condensation Resistance (CR) of a window is a rating on the scale of 1-100 of the ability of a window to resist condensation on its interior surface. Condensation will occur under certain environmental conditions (both interior and exterior) for any building material. It should be noted that the CR is not a prediction of whether condensation will occur, but a means of comparing how likely different products are to experience condensation.

The CR of a window system is determined using NFRC 500 (Procedure for Determining Fenestration Product Condensation Resistance Rating Values) (NFRC, 2010b). This standard normalizes the lowest surface temperature (i.e., the point at which condensation will occur), for the center-of-glass, edge-of-glass, and frame locations in 30%, 50%, and 70% relative humidity. A window with a higher CR will be more effective at resisting condensation.

Air leakage is a measurement of the amount of air that will leak through a window (measured in cubic feet of air transport through a square foot of window area). This value generally lies between 0.1 and 0.3 ft^3/ft^2. The air leakage rate is determined using NFRC 400 (*Procedure for Determining Fenestration Product Air Leakage*) (NFRC, 2010c), which is based off ASTM E 283 (*Standard Test Method for Determining Rate of Air Leakage through Exterior Windows, Curtain Walls, and Doors under Specified Pressure Differences Across the Specimen*) (ASTM, 2012).

Specifying window systems usually involves a balance of different properties to achieve the desired overall performance characteristics. Improvements to the U-value and SHGC often come at a cost to the clarity of the window transparency. By extension, this means that less light in the visible spectrum enters into the interior of the building. This may result in additional demands for interior lighting, thus offsetting the benefit of the improved performance of the window systems.

2.3 Transparent Insulating Materials

There are four basic categories of transparent insulating materials (TIM) (Platzer et al. 1990), which are illustrated in Figure 6.

Parallel Plate Structures are composed of multiple layers of plastic films or glass. This type of TIM setup results in higher convection losses as well as minor losses to transparency based on optical reflection losses. Multi-paned glass windows are an example of a parallel plate structure.

Slat Structures are comprised of multiple transparent layers or "films" stretched perpendicularly across the glazing cavity. Convection losses are easily controlled, and optical losses are minimal. Examples of slat structures are honeycombed or capillary materials.

Cavity Structures are a combination of the parallel plate and slat structure types. While convection losses are easily controlled with this type of structure, reflection losses tend to be higher. Multiwall polycarbonate units are a typical example of a cavity structure.

Quasi-Homogeneous Layers are most similar to cavity structures. However, these are even more effective at suppressing convection. The primary difference between the two is that scattering and absorption are the primary mechanisms of optical losses rather than reflection. Aerogel is an example of a quasi-homogenous layer.

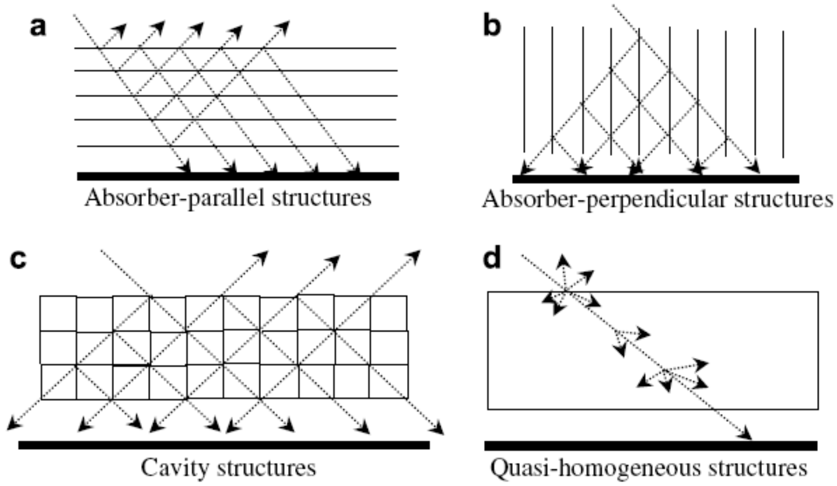


Figure 6: The four basic catagories of transparent insulation. Image source: Wong et al. (2007). Image used with permission from publisher.

The primary method of transparent insulation presently used in the industry is multi-paned glazing. Glazing for both residential and commercial construction usually varies from single-, double-, or triple-paned glass depending on the performance needs of the building.

Modern slat structures still operate under the same principles used in its conception. While these systems allow for light transmission, they do not provide a clear view. In addition to placement on solar collectors, they are found in skylights, curtain walls, and window applications where clear vision is not required. In these applications, the honeycomb system is sandwiched in between two thin light diffusing veils. This helps to diffuse the light throughout the space and minimize the appearance of the honeycomb system itself. In addition to insulation and light transmission properties, these systems also are efficient at controlling sound attenuation and managing moisture buildup within the system. An example of such a system is Advanced Glazing's Solera product line, which is shown schematically in Figure 7.

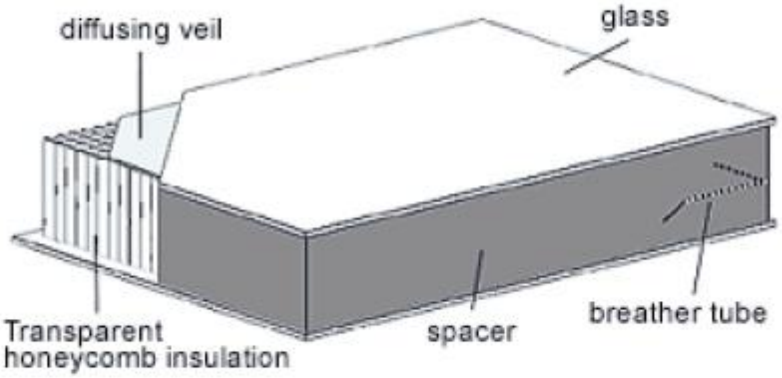


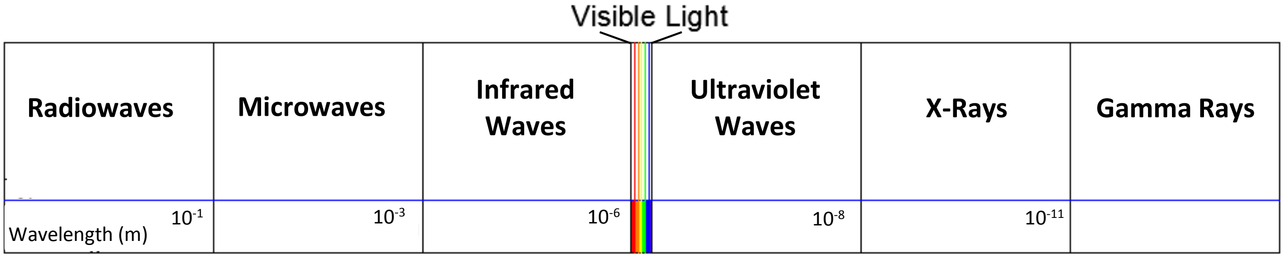
Figure 7: Advanced Glazing Solera honeycomb insulation system. Image source: Advanced Glazing (2010).

2.4 Control of Solar Heat Gain

A low SHGC is most important in cooling dominated climates where the sun is particularly intense. Methods of reducing the SHGC typically involve utilizing tinted glass or the application of a coating or film. These methods limit the transmittance of solar energy through the glazing system. Regardless of which option is used, consideration must be given to whether additional lighting will be needed to account for the reduction in daylighting, which may negate reductions in cooling costs.

2.4.1 Background on Solar Spectrum

All types of radiation are transmitted as waves of various wavelengths that together make up the electromagnetic spectrum. At the long end of the spectrum are radio waves, which have wavelengths exceeding 1 km long. Gamma rays are at the other end of the spectrum, with wavelengths only 0.001 nm long. In the building industry, the middle portion of this spectrum, known as the "solar spectrum" is of greatest interest. The solar spectrum features infrared light, visible light, and ultraviolet light. These wavelengths are capable of making the long journey from the sun through space and the earth's atmosphere to the earth's surface. Figure 8 shows the relative position of each type of radiation in the electromagnetic spectrum.



Radiowaves	Microwaves	Infrared Waves	Visible Light	Ultraviolet Waves	X-Rays	Gamma Rays
Wavelength (m) 10^{-1}	10^{-3}	10^{-6}		10^{-8}	10^{-11}	

Figure 8: Electromagnetic spectrum showing wavelengths for various types of radiation.

Visible light is the portion of the electromagnetic spectrum that is visible to the naked eye. This portion has wavelengths in the 390 – 750 nm range. As the wavelength of this type of radiation changes, different colors are produced. Listed from long wavelengths to short wavelengths, the colors present in the spectrum are red, orange, yellow, green, cyan, blue, and violet. Other colors such as magenta and pink are produced through combinations of different wavelengths.

The sensitivity of the eye to visible light at different wavelengths is described by the luminosity function, also known as the photopic response. The eye is often more sensitive to some colors (wavelengths) than others. The peak visual response is found at approximately 555 nm, corresponding to green light.

Infrared waves are longer than those found in the visible spectrum, with wavelengths ranging from 0.7 – 30 µm. Infrared radiation has many different properties, with heating capabilities being one of the most critical for building purposes. Radiation resulting in heating comes primarily from region of infrared radiation found closest to the red band of the visual spectrum. This region is described as the "near infrared" region and contains wavelengths varying in length from approximately 0.7 to 1.0 µm. While the portion of infrared light closest to the red band of visible light can typically be visually detected, the majority of this region is invisible to the naked eye.

Infrared radiation coming directly from the sun accounts for only approximately 49% of the energy used to heat the earth. The remaining energy comes from light in the visible and ultraviolet regions, which are absorbed and reflected off of other surfaces at longer wavelengths (ASC, 1980). This portion of the solar spectrum is known as far infrared.

Ultraviolet light is the region of radiation with wavelengths shorter than visible light. Wavelengths in the ultraviolet (beyond violet) region have wavelengths in the range of approximately 10 – 400 nm. Although ultraviolet light is not visible to the human eye, other species are capable of detecting it.

There are three primary categories of ultraviolet light: UVA, UVB, and UVC. Ultraviolet light has both harmful and beneficial qualities. While prolonged exposure to UV radiation can cause material degradation in fibers and polymers as well as skin cancer, the radiation is also important for Vitamin D production. The longer wavelengths of UV radiation are known as UVA radiation and are least dangerous. The intermediate wavelengths are known as UVB radiation. These wavelengths are those responsible for causing sunburns and skin cancer. Lastly, UVC radiation has the shortest wavelengths and is often used for sterilization, as it is capable of killing bacteria and viruses. This type of radiation is nearly completely blocked by the ozone layer. In fact between 97 – 99% of UV radiation is blocked by the ozone layer. 95% of remaining UV radiation is UVA (SCF, 2012).

2.4.2 Controlling Heat Transmission in Glazing

In order to reduce heating and cooling loads in buildings through fenestration systems, the ability to control heat flow through glazing is important. This goal is accomplished through the use of spectrally selective coatings, tints, and intelligent coatings.

Spectrally Selective Coatings

Spectrally selective coatings control the transmission of solar energy through the glass. In general, these coatings work by absorbing or reflecting the light in the near infrared and ultraviolet range, while transmitting light in the visible spectrum.

Spectrally selective coatings can be broken into two categories: winter coatings and summer coatings. Winter coatings are designed to reduce transmission of far infrared radiation while allowing for transmission of near infrared radiation for passive solar heating. Summer films, on the other hand, focus on reducing the transmission of near infrared heat as well. In both cases, it is desired to reduce thermal radiation without limiting transmittance in the visible spectrum (Berning, 1983). If desired, reductions in visual transmittance can then be accomplished by varying the thickness of the glass or using additional "tinting" based coatings (Selkowitz and Lee, 1998).

Figure 9 is useful for understanding how spectrally selective coatings work. The solid black line shows the solar spectrum (near infrared) and far infrared irradiance, while the dashed gray curve shows the photopic response of the human eye. The solid and dashed lines indicate the ideal transmittances for coatings for warm and cold climates, respectively. Note that both coatings work to limit transmittance of the far infrared radiation portion of the spectrum, which is heat radiating off of nearby objects.

Low-emissivity coatings were one of the first coatings used to improve the thermal performance of regular glass (Berning, 1983). After glass has absorbed heat, it emits that heat in both directions. Low-emissivity coatings work to reduce the emissivity of a given surface. This results in a system that transfers less heat through radiation, resulting in a lower U-value.

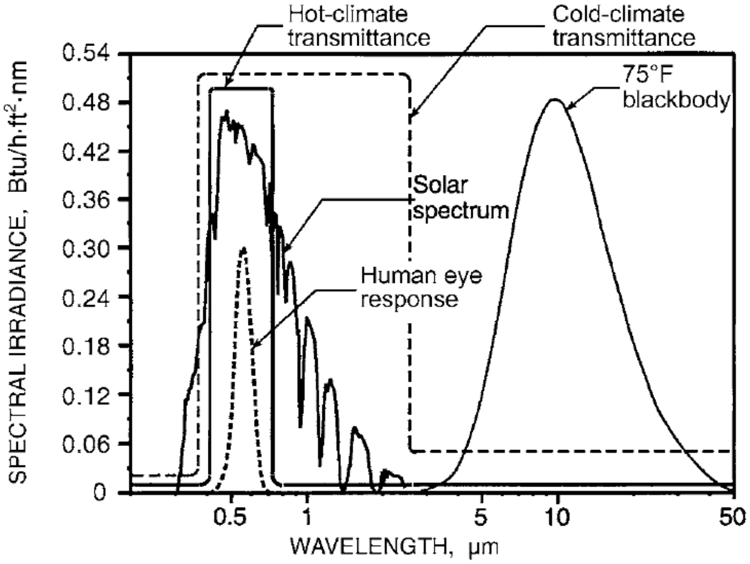


Figure 9: Illustration of solar spectrum and ideal spectral transmittances of coatings for hot and cold climates. Image source: ASHRAE, 2009

In real glazing systems, however, it is not possible to completely achieve these requirements. Different coatings typically block different wavelengths in various ways that do not perfectly meet the needs of the user. Uncoated glass transmits all of the near infrared radiation, while reflecting a small percentage (~30%) of the radiant heat from the glass. Glass with a low-e coating, on the other hand, prevents the reflection of the radiant heat. It should be noted that the reflectance and transmittance curves for the glass with low-e coating tend to be relatively symmetrical. Coatings that do not exhibit this important characteristic will experience undesired discolorations, which may negatively affect the aesthetics of the glazing unit (Martin-Palma, 2009).

Tints

Tint-based coatings are one means of reducing the solar gain through a glazing unit. They function primarily by changing the hue of the glass itself, which prevents the transmission of portions of the solar spectrum. Another method of reducing visual transmittance is increasing the thickness of the glass itself (Selkowitz and Lee, 1998).

Intelligent Coatings

Glazing coatings can have one of two forms: static or dynamic. Static coatings (Spectrally Selective Coatings) are used more prevalently than dynamic coatings and have characteristics that are fixed. In contrast, dynamic coatings, also known as intelligent coatings have transmittance and reflectance characteristics that can be varied based on external conditions. Photochromic coatings vary the absorptance based on the amount of light landing on their surface. As the amount of light increases, the visual transmittance decreases. Thermochromic coatings are another type of dynamic coatings. These coatings vary their transmission based on their surface temperature. As the surface temperature increases, the transmittance decreases.

In photochromic glazing, a coating is applied to glass that allows for a reversible chemical reaction between two forms with differing absorption spectra. There may be either a positive or negative change. Positive photochromism is more common. It features a stable, transparent or near transparent form that acquires color with irradiation. Negative photochromism, on the other hand, features a stable, colored form that becomes transparent with irradiation (Pardo et al, 2011). Figure 10 shows a sample absorption spectra for two different forms of a photochromic material.

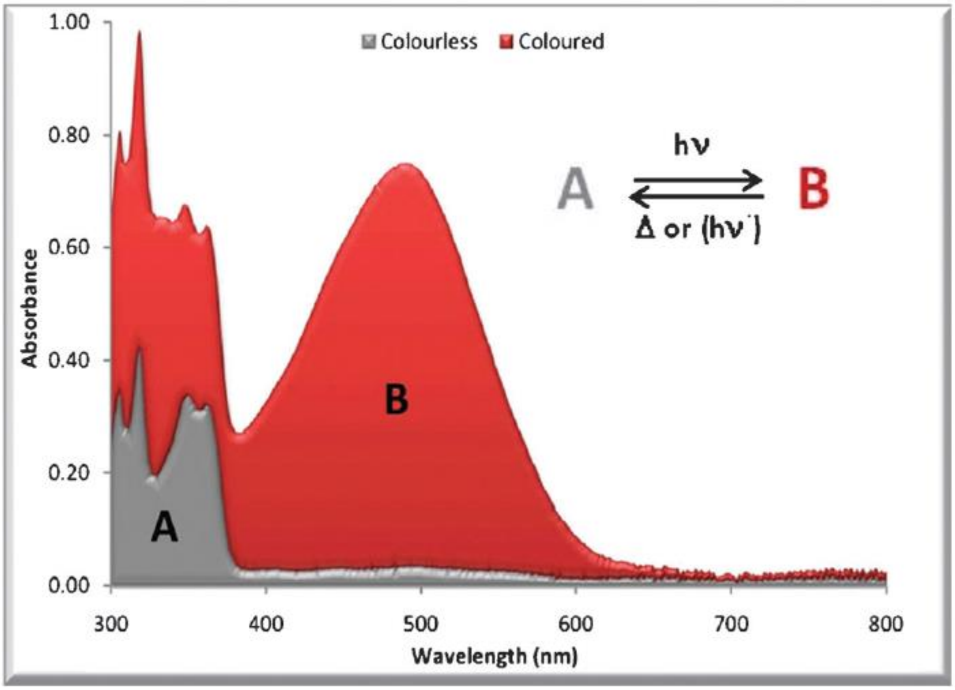


Figure 10: Illustration of change in absorptivity between state A (colorless) and state B (colored) of a photochromic material. Image source: Pardo et al, 2011. Image used with permission from publisher.

Thermochromic materials undergo a transition from a semi-conductor form to a metal form at a specified, critical temperature. When this state change occurs, the material exhibits different transmittance and reflectance properties. At temperatures above the critical temperature, the material reflects the infrared wavelengths (Figure 11), which were previously allowed to pass through. This makes thermochromic glazing particularly useful in mixed climates since it can allow for passive solar heating in the winter, while blocking heat gain in the summer (Parkin et al., 2008). Selkowiz and Lampert (1998), found that the use of thermochromic glazing can result in a 30% reduction in energy used for heating and cooling applications in buildings. Dynamic coatings can also be applied to other cladding materials (Karlessi et al., 2009).

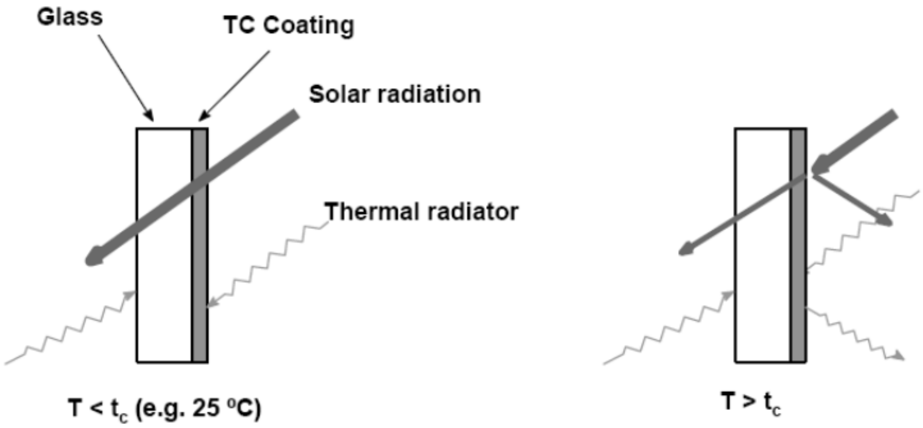


Figure 11: Schematic of thermochromic coating behavior on glazing. Image source: Parkin et al, 2008. Image used with permission from publisher.

Emerging technologies such as electrochromic glazing and suspended particle devices may also be used to control solar heat gain. Both of these systems operate by modifying transmittance during operation by inducing a low voltage current through the glass. Both of these systems are still in development and have numerous technical (switching time, glare, color rendering…) and non-technical (high cost, lifetime) issues to resolve (Bahaj et al. 2008).

2.5 Window Frame Performance Characteristics

The weakest element of a window assembly is the frame. Although high performance center of glass U-values can be achieved, the highly conductive window frame will often result in significantly lower performance. Gustavsen et al. (2007) performed an investigation on state-of-the-art window frames currently on the market. They found that manufacturers are employing two basic methods to improve the performance of window frames. The first is to reduce the U-value as much as possible by using new materials, new constructions, and through the substitution of large parts of the frame with low-conductance materials. The second method is to reduce the overall size of the frame as much as possible, which produces a slim frame that allows for a high net energy gain. A high net energy gain indicates that more energy enters the building through the window than is lost through it. This is an important requirement for passive solar heating in cold weather climates.

2.5.1 Frame Materials

Window frames are currently produced in a variety of different materials. These include wood, aluminum, vinyl, or wood/polymer composites. In addition, they can be made of a combination of different materials used for different parts of the assembly.

Wood

Wood is the traditional material used for crafting window frames. This is primarily due to the fact that wood is readily available in most locations. In addition, wood can be easily milled into complex shapes, and will last a long time if properly built and maintained. However, wood frames require a frequent maintenance to prevent rot and deterioration. The exterior facing surfaces of the frames are often clad in aluminum or vinyl to achieve a weather resistant finish, although this reduces the thermal performance of the system. Window frames constructed of wood typically have good thermal performance, with frame U-values of about 0.3-0.5 Btu/hr-ft^2-F.

Aluminum

Historically, aluminum has often been used as an alternative for wood frames, primarily due to the material being light, strong, and durable. Complex frame shapes can be generated through an extruding process and require little maintenance, particularly for anodized frames and those with high-performance finishes. However, aluminum is highly conductive, resulting in average frame U-values of 1.0-2.0 Btu/hr-ft^2-F for typical frames with standard thermal breaks. Apart from energy usage, this also means that condensation will be a major issue with these systems. In fact, condensation issues with aluminum frames led to the widespread use and development of low-conductivity thermal breaks. High-end, innovative aluminum frames are available with U-values as low as 0.5 Btu/hr-ft^2-F.

Vinyl

Much like aluminum, vinyl is light, durable and can be easily extruded for any shape and requires very little maintenance. However, vinyl varies in that it provides better insulating performance. In addition, vinyl window frame sections must be larger than their aluminum counterparts in order to carry support the glazing. Vinyl frames also have a higher coefficient of thermal expansion, and therefore require detailing to account for movement.

Byars and Arasteh (1992) performed a study to determine the effect of the use of materials of various conductance's on the performance of a window frame. Figure 12 shows the performance of various materials with conductances as a percentage of wood. As the figure shows, the U-value of the frame is a function of both the conductance of the sash and the jamb. Reducing the conductance of the jamb will result in a proportional reduction in frame performance for any sash conductance. Reducing the conductance of the sash, on the other hand, results in less than proportional reductions in frame conductance.

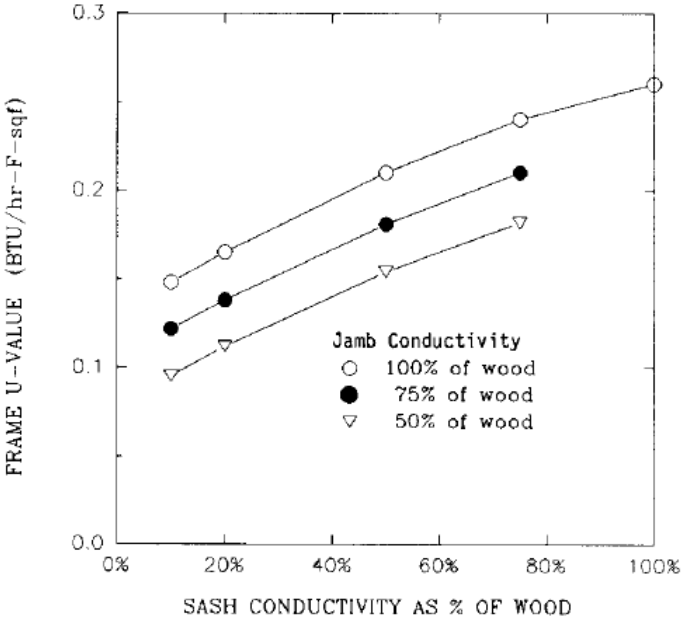


Figure 12: Frame U-value as a function of varying conductivities for jamb and sash elements. Image source Byars and Arasteh, 1992. Image used with permission from publisher.

Byars and Arasteh also evaluated the effect of using vinyl or fiberglass cladding on wood and insulation filled sashes. Table 3 lists the frame U-values for various cladding materials and thicknesses for wood-filled insulation-filled sashes. They found that, regardless of cladding material, the improvement obtained using Insulated (In) spacers rather than Aluminum (Al) spacers is greater for insulation filled sashes than for wood filled sashes. They also found that after upgrading to insulated spacers, adding additional cladding will have no effect or possibly even result in a decrease in thermal performance for the frame.

Table 3: Frame U-values for various cladding materials and thicknesses. The effect of aluminum and insulated spacers is also shown. Data source: Byars and Arasteh, 1992.

	Wood-filled sash frame U-values (Btu/hr-ft^2-°F)	Insulation-filled sash frame U-values (Btu/hr-ft^2-°F)
Vinyl clad sash		
0.04” cladding		
Aluminum spacer	0.37	.19
Insulated spacer	0.27	0.11
0.08” cladding		
Insulated spacer	0.27	0.14
Fiberglass clad sash		
0.04” cladding		
Aluminum spacer	0.39	0.21
Insulated spacer	0.29	0.13
0.08” cladding		
Insulated Spacer	0.31	0.17

The effect of various framing materials on the overall U-value for a given window was also investigated in the same study. Table 4 compares the center-of-glass, frame, and whole product U-values for different framing materials and configurations. It was found that for a window with a center of glass U-value of 0.12 Btu/h-ft^2-F, the use of a conventional, solid wood frame with an aluminum space resulted in a whole U value of 0.23 Btu-ft^2-F, a 92% decrease in performance. In contrast, the use of 0.08" vinyl clad, insulation filled window with an insulated spacer resulted in a whole window U-value of 0.13 Btu/h-ft^2-F, only a 9% decrease in performance.

Table 4: Comparison of center-of-glass U-values, frame, and whole product U-values. Data source: Byars and Arasteh, 1992

	Center of Glass U-value (Btu/hr-ft^2-°F)	Frame U-value (Btu/hr-ft^2-°F)	Total Window U-value (Btu/hr-ft^2-°F)
Conventional solid wood frame, Aluminum spacer	0.12	0.36	0.23
Conventional solid wood frame, Insulated spacer	0.12	0.26	0.17
Vinyl cladding (0.08"), insulation filled frame; Insulated spacer	0.12	0.14	0.13
Jamb: 50% conductivity of wood Sash: 10% conductivity of wood Insulated spacer	0.12	0.10	0.13

Studies have shown that variations in air leakage performance from one system to another are typically more a function of manufacturer than of material (Weidt et al., 1979).

2.5.2 Frame Configurations

As previously mentioned, window frame thermal resistance can be improved by varying the geometry of frame as well as the materials used within the frame. This involves the creation of air spaces or substituting regions of solid material for a lower conducting material. Several different configurations of materials are shown in Table 5. Polyurethane (PUR) was found to be the most common insulating material used as an infill for frames. However, in the case of a fire, PUR will release extremely dangerous hydrogen cyanide gas. Some substitutes to PUR that are used in some frames are polyethylene (PE), polypropylene (PP), extruded polystyrene (XPS), and ethylene propylenediene (EPDM). EPDM can also be used to add rigidity to the frame.

Table 5: Comparison of several state-of-the art window frame configurations, a description of the type of insulating material used, as well as the expected frame U-value. Data source: Gustavsen, 2007.

Window Frame Description	**Thermal Insulation Fill Material**	**Frame U-value (W/m^{2}K)**
Wood Frame	PUR	0.65
Wood Frame with insulation filled Al Cladding	PUR and XPS	0.68
PVC Frame	PUR	0.71
PVC Frame with insulation filled Al Cladding	PUR	0.82
Al Frame	PUR	0.71
Fixed Wood and Al Frame	PUR	0.63
Glass Façade System	PE and EPDM (support)	0.65

2.6 Spacer Performance Characteristics

A windows thermal transmittance, measured with the U-value, is based on a combination of effects from the glazing, the frame, and any spacers used within the glazing. This value is determined using two different methods: The ASHRAE SPC 142P method (ASHRAE, 1998) and the ISO 10077-2 method (ISO, 2003a). The difference in these two methods deals primarily with the way the effect of the spacer is taken into account. In the ASHRAE method, the spacer affects the frame heat transfer rate as well as the "edge-of-glass" heat transfer rate, where the "edge-of-glass" is an area 2.5" (63.5 mm) wide around the perimeter of the glazing measured from the glazing/frame interface. The ISO method, on the other hand, takes the effect of the spacer as being proportional to the glazing frame sightline distance and thus the length of the spacer itself. Blanusa et al. (2007) found that these two methods provide up to a 3% difference, particularly for window areas smaller than ~20"x20" (500mmx500mm). As the size of the window increases, the difference between the two methods decreases. It was found that the primary reason for these differences is that 2.5" (63.5mm) is too small of an edge distance width to appropriately capture the effects of the spacer. In reality, closer to 6" (150 mm) is needed.

Spacer bars are commonly constructed of aluminum or steel. These highly conductive materials result in very low edge-of-glass temperatures due to thermal bridging. This results in a loss of thermal performance as well as an increased risk of condensation development. To solve this problem, innovative spacer designs, collectively known as warm edge technology (WET) have been developed from either low conductance materials or spaces with an integrated thermal break. Figure 13 depicts a conventional spacer bar (IG1) and 9 WET spacer bars (IG2-IG10).

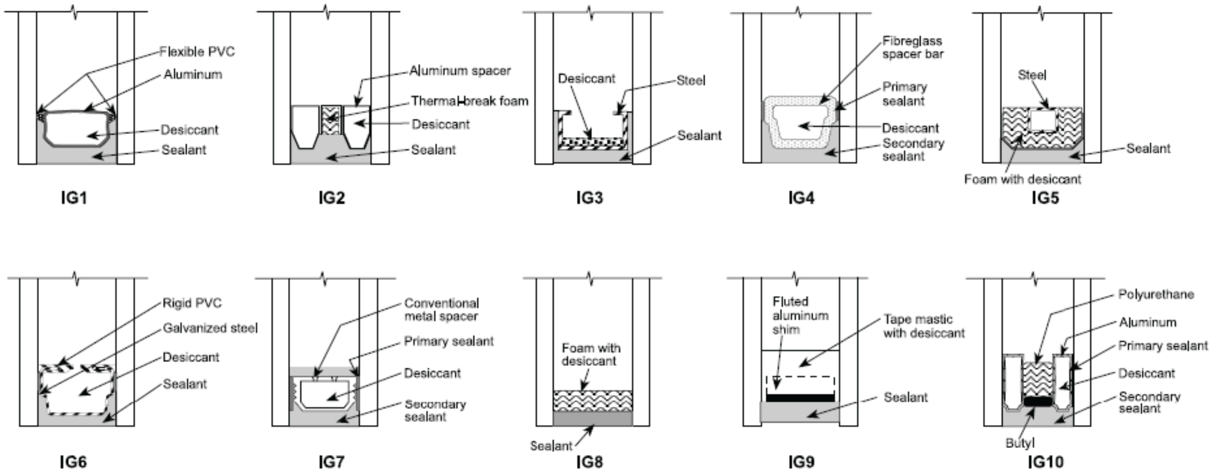


Figure 13: Comparison of warm-edge technology spacers (IG2-IG10) and conventional spacers (IG1). Image source: Elmahdy, 2003.

Elmahdy (2003) investigated the effect of the each spacer for an insulated glass unit without a frame using physical testing of specimens 152mm x 1200mm (6"x 47.25"). Figure 14 shows the surface temperature of the glazing on the warm side for each of these spacers as a function of distance from the glazing/frame sightline. As the figure shows, the effect of each spacer becomes negligible at a sufficient distance (approximately 50mm, or ~2").

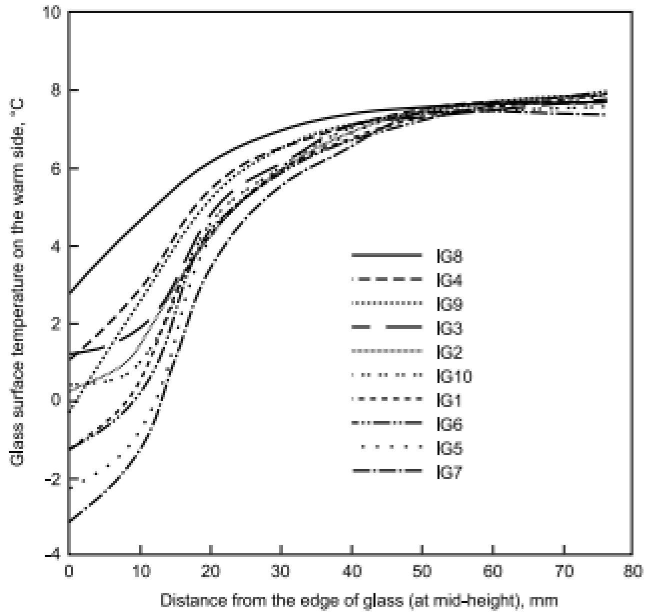


Figure 14: Inside glass temperatures for various spacer bars as a function of distance from the edge of glass. Image source: Elmahdy, 2003.

In addition, the effect of each spacer on the thermal performance of vinyl, thermally broken aluminum, redwood, and foam-insulated fiberglass was investigated. This investigation showed that redwood frames with foam/desiccant spacer bar performed the best among the various alternatives. Moreover, the general trend of behavior was the same for each spacer regardless of the framing material. These results are shown in Figure 15.

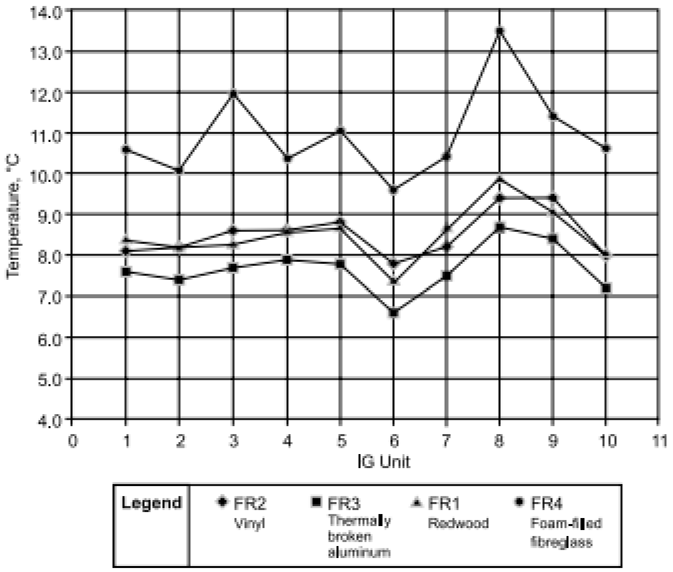


Figure 15: Effect of spacer on frame performance measured as a function of surface temperature on the warm side of the frame. Image source: Elmahdy, 2003.

2.7 Energy Balance through Fenestration

In order to understand the effect of window shading devices on energy transfer through the complete fenestration unit, it is important to understand the behavior of window systems. Heat transfer can occur through three mechanisms: conduction, convection, and radiation. Conduction occurs through molecular contact. The conductivity for some common materials are listed below. For a glazing system, this means the frame, spacer, and the air molecules themselves.

Table 6: Conductivity of common glazing materials. Data source: The Engineering Toolbox, 2013

Material	**Conductivity (W/m-K)**
Air	0.024
Aluminum	205
Argon	0.016
Glass	0.96
Krypton	0.0088
Polycarbonate	0.11
Vinyl (PVC)	0.19
Wood	0.12

Convection is heat transfer through a fluid. For glazing systems, this takes place on the exterior and interior sides of the unit as well as in the air space. In addition, all objects absorb and emit infrared radiation (heat). The effect of convection and radiation is taken into account as fictitious “surface films”. For highly insulating walls, the effect of these surface films is marginal. However, for poorly insulated systems such as windows, convective and radiative heat transfers have a significantly greater effect and therefore, the role of surface films are much more important. Some typical surface film heat transfer coefficients are shown in Table 7. It should be noted that the thickness of surface films is not meaningful since they are a fictitious element. Therefore, the units are listed in W/(m^{2}K) rather than W/(mK) as with conductivity, which must always be associated with a material thickness.

Table 7: Typical surface film heat transfer coefficients. Data source: Straube and Burnett, 2005

Surface Position	**Flow Direction**	**Conductance (W/m^{2}K)**
Still Air (Indoors)		
Horizontal (ceilings)	Upward	9.3
Horizontal (floors)	Downward	6.1
Vertical (walls)	Horizontal	8.3
Moving Air (Outdoors)		
Stormy Conditions – winter (6.7 m/s)	Any	34
Breezy Conditions – summer (3.4 m/s)	Any	23
Average Conditions	Any	17

Outdoor surface film heat transfer coefficients are a function of wind speed and temperature. Values of 29 W/(m^{2}K) and 6.8 W/(m^{2}K) are often used for outdoor surface film heat transfer coefficients for stormy, winter and calm conditions, respectively. An indoor heat transfer coefficient of 8.3 W/(m^{2}K) is used by designers for both summer and winter conditions (ASHRAE, 2009).

The heat transfer coefficient of the interior cavity is dependent on the temperature of the glazing as well as the emissivity of the glass. For uncoated systems, the air space heat transfer coefficient is typically taken as 7.4 W/(m^{2}K). However, the presence of low-e coatings can have a significant effect on this value, resulting in values as low as 2.0 W/m^{2}K and as high as 11.9 W/m^{2}K (ASHRAE, 2009).

The importance of the surface film coefficients can be demonstrated by examining the calculation for the U-value for a single glazed window.

$$U = \frac{1}{\frac{1}{h_o} + \frac{1}{h_i} + \frac{L}{k}}$$

Where

h_o - Outdoor surface film coefficient
h_i - Indoor surface film coefficient
k - Conductivity of the glazing material
L - Thickness of the glazing material

Consider a 6mm pane of glass. Since the value for the conductance (L/k) will be small (.006/.96 = 0.00625) in comparison to the first two terms (1/17 = .059 and 1/8.3 = 0.12), it is clear that convection has a large effect on the thermal performance of the glazing unit. If we disregard the role of these surface films in the heat transfer calculation, we would obtain a U-value of 160 W/(m^2K). Taking the roles of the surface films into account, the U-value drops to 5.39 W/(m^2K). The glazing systems resistance to thermal transmittance is 29 times higher when the surface films are neglected!

Other studies use a formulation for the overall heat transfer coefficient that completely neglects the function of conduction in the center of glass region. Shahid and Naylor (2005) use a formulation that is entirely dependent on convective heat transfer and radiative heat transfer. This formulation is shown below.

$$U = \frac{Q_c + Q_r}{T_{out} - T_{in}}$$

Where,

Q_c – average convective heat flux
Q_r – average radiative heat flux
T_{out} – outside air temperature
T_{in} – inside air temperature

Of course, the energy balance of a multi-layered glazing system is much more complicated, and requires an understanding of the energy flux to and from each layer. The energy balance for a generalized glazing system can be reduced to what is shown in Figure 16. This figure shows that the energy balance through a window is based on the solar irradiance on each glazing surface (S_i), the interior and exterior convection ($h_{c,in}$ and $h_{c,out}$), the radiosity of each glazing layer (J_i), the irradiance from the interior room (G_i) and the convective heat transfer in each gap. The heat flux across each gap (q_i) is the convective heat transfer within a unit, plus the radiation emitting the front side of a unit, minus the radiation from the adjacent unit.

$$q_i = h_{c,i}\left[T_{f,i} - T_{b,i-1}\right] + J_{f,i} - J_{b,i-1}$$

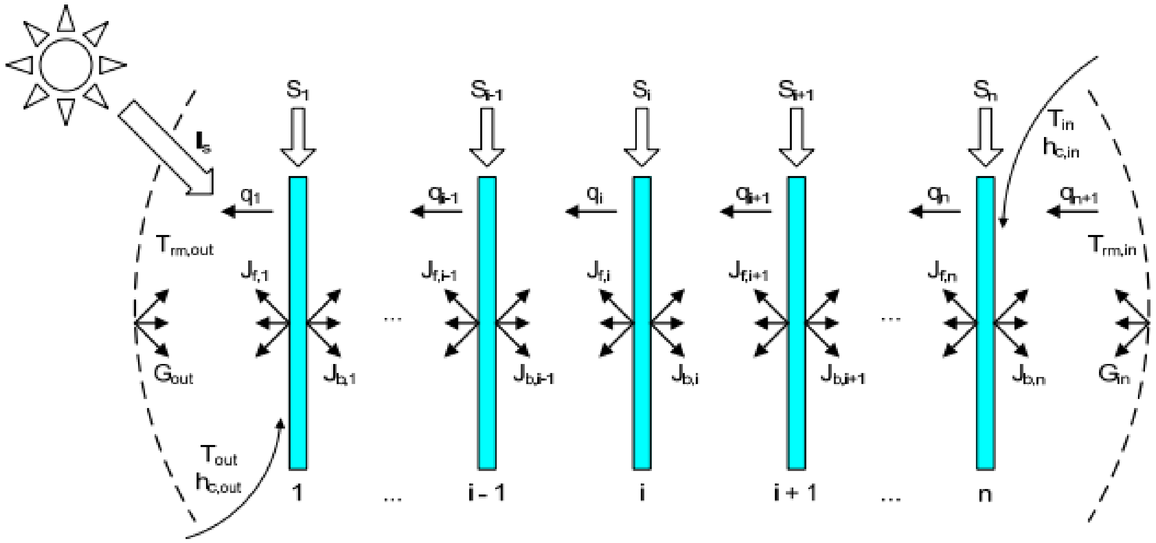


Figure 16: Energy balance on multilayer glazing system. Image Source: Carli, 2006.

All energy landing on a surface will be absorbed (α), transmitted (τ), or reflected (ρ). These terms make up the radiosity of a surface (radiative effects leaving a surface) and irradiance (radiative properties landing on a surface). The sum of each of these terms must equal one. The energy balance demonstrated in Figure 16 is used by WINDOW in the calculation procedure.

When shading devices are incorporated into a glazing system, the cavities formed by the shading device are considered ventilated cavities. In such cavities, the role of convection must be taken into account not just within the cavity, but between adjacent cavities separated by a shade. The energy balance of such a system is generalized in Figure 17.

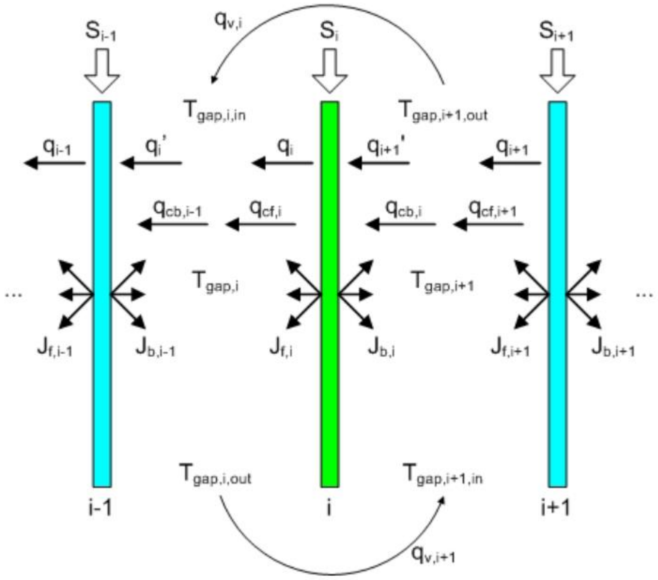


Figure 17: Energy balance for a glazing system with a shading layer. Image source: Carli, 2006

Yahoda and Wright (2004) developed a simplified model allowing for a venetian blind to be treated as a simplified, planar, homogenous layer within a series of other glazing layers. This work was later expanded by Wright (2008), which treats both convective and radiative heat transfers as “effective resistances” and allows for a one-dimensional heat transfer model through the glazing systems. The effect of convection across a shading device is taken into account as a “jump resistor” (Figure 18). Although this formulation is not used in the calculations of software such as WINDOW, it is a useful illustration of the behavior of the system.

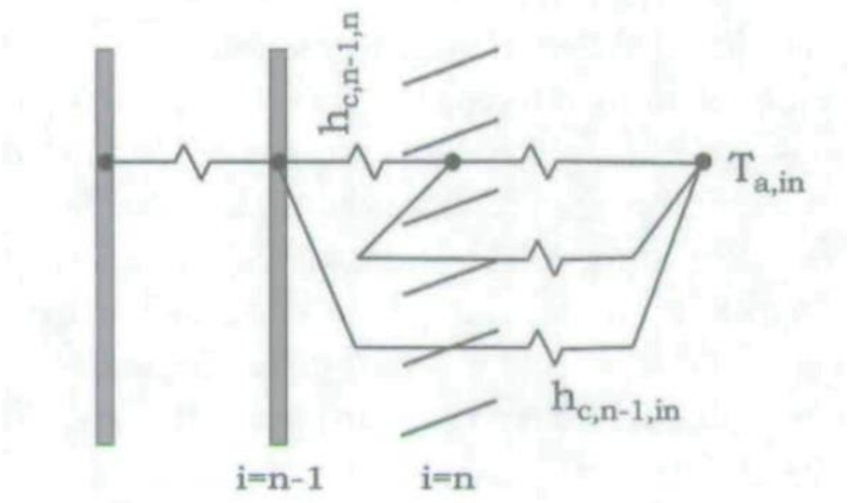


Figure 18: Example of "effective resistances" from convective and radiative heat transfer across a glazing system with a shading device. Image source: Wright, 2008. Image used with permission from publisher. ©ASHRAE www.ashrae.org. ASHRAE Transactions, (114), (2).

The energy balance is used to create a set of simultaneous equations that relate each of the components of the energy balance to the temperatures at each surface. The surface temperatures are then used to determine the thermal resistance of each layer or cavity (Carli, 2006). The U-value is the reciprocal of the total resistance.

$$U = \frac{1}{R_{total}}$$

$$R_{total} = R_{out} + \sum_{i=1}^{n} R_{gl,i} + \sum_{i=1}^{n} R_{gap,i} + R_{in}$$

Where,

R_{out} - The thermal resistance of the outside surface layer
R_{gl} - The thermal resistance of the glazing layer
R_{gap} - The thermal resistance of the glazing cavity
R_{in} - The thermal resistance of the indoor surface layer.

2.7.1 Background on LBNL WINDOW Analysis

WINDOW uses two standard sets of calculations for the U-value and SHGC analysis. The first is ISO 15099 (ISO, 2003b), “Thermal Performance of Windows, doors, and shading devices – Detailed calculations.” The second is ISO/EN 10077 (ISO, 2003a) “Thermal performance of windows, doors, and shutters – Calculation of thermal transmittance.”

ISO 15099 specifies the calculation procedures that should be used to determine thermal and optical properties for window and door systems, including single- and multi-pane glazing products with low-emissivity coating, suspended films, gas fills, metallic and nonmetallic spacers, frames and shading devices. ISO/EN 10077 deals with the calculation procedures for thermal and optical transmittance for glazing systems. These algorithms, however, are greatly simplified in comparison to ISO 15099.

One important piece of the discussion that will follow is how the shading layers being modeled relate to the windows. This is especially important when the heat transfer processes of conduction, convection, and radiation are considered. WINDOW works under the assumption that the shading device is mounted inside the frame. The top, left, right, and bottom openings shown in Figure 19 represent the opening area between the shading layer and the frame. Modifying this area is achieved using the D_{top}, D_{left}, D_{right}, and D_{bot} distances found in the glazing system definitions in the glazing system library within WINDOW. The center openings represent the amount of air that is able to move through the shading device. This area is specified as the "openness factor" found in the shading layer library. An openness factor of 1 implies that the shading layer has no effect on limiting transmittance to the surface of the glazing. Conversely, an openness factor of 0 implies that the shading layer is completely effective at limiting air flow.

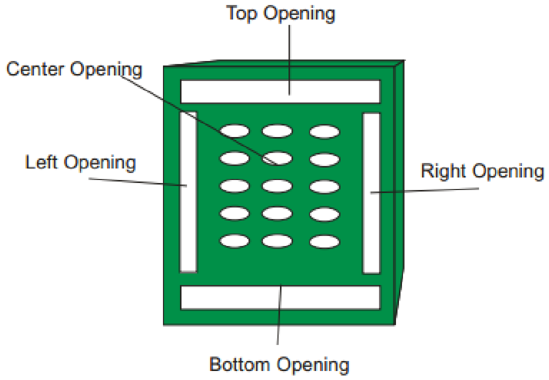


Figure 19: Generalized shading layer geometry. Image source: Carli, 2006.

The openness factor is taken into account in the calculation for the pressure loss through ventilated cavity. A cavity formed by a shading device is considered a ventilated cavity. This value is important for thermally driven ventilation with the glazing system.

The challenges associated with the openness fraction can be illustrated by examining the case of venetian blinds. When the blinds are in use, WINDOW uses a default openness fractions of 0, 0.5, and 1.0 for slat angles of 90°, 45°, and 0°, respectively. However, it is realistic to assume that these values will change continuously based on the configuration of the specific blind. In particular, an openness factor of 0 is unrealistic, as the blinds will never form a perfect seal even when closed. Machin et al. (1998) noted that even if the blinds can reach the full 90° rotation, which most systems will not, "slight axial undulations" of each slat would prevent a tight seal from ever being formed. Therefore, for this analysis, an openness fraction of 0.05 will be assumed for blinds in 90° position.

3. Methodology

There have been several different studies that have compared the benefit of various window attachments. The Cold Climate Housing Research Center has produced a document comparing several different window attachment systems (Craven and Graber-Slaght, 2011). This study was geared only towards insulating behavior and analyzed a combination of window attachments available on the market and custom designs.

Another study was conducted by BuildingGreen, Inc. and Lawrence Berkeley National Lab (LBNL). This study provided a more comprehensive analysis of several window attachments (US DOE, 2011b). This study described the behavior of each system in terms of solar heat gain and visual transmittance. In addition, it makes recommendations (summarized in Table 8) to homeowners and renters on when they should consider using each system.

Table 8: Recommendations on window attachments use. Adapted from DOE et al., 2011.

	Homeowner	Apartment Renter - Long Term	Apartment Renter - Short Term	Live in a Condo	Live in a Historical District
Exterior Awnings	x			x	x
Exterior Low-e Storm Windows	x	x		x	x
Exterior Window Shades and Shutters	x				
Interior Window Panels	x	x		x	x
Interior Surface Applied Films	x			x	x
Interior Blinds, Shades, and Drapes	x	x	x	x	x
Interior Insulating Blinds	x	x		x	x
Air Sealing Upgrade	x	x			x

In 1980, William Langdon wrote a book titled “Movable Insulation: A Guide to Reducing Heating and Cooling Losses Through the Windows in Your House,” (Langdon, 1980). This book goes into great detail describing different measures for improving the insulation on existing windows as harnessing solar heat gain. Only a few systems were described that focused on reducing the cooling load in buildings. Several different products available on the market as well as DIY versions were described in detail. In addition, the information was very qualitative in nature (making it difficult to perform a side by side comparison of the performance of different systems) and is also in some need of updating.

The National Trust for Historic Preservation: Preservation Green Lab (Frey et al., 2012) conducted another study in 2012. This study involved a performance and cost analysis on a model home across several different climates using the SEEM (Simple Energy and Enthalpy Model). The study included a detailed cost analysis with the goal of finding systems with a low return on investment (ROI) over several climates. However, only seven different systems were investigated: weather stripping existing windows, exterior storm windows, interior window panel, insulating window shade, combination of exterior storm window and insulating cellular shade, interior surface film, and new high-performance window.

The study presented in this report builds on the aforementioned studies and expands the scope of options considered as viable solutions. It will examine window attachment products that are available on the market as well as those that can be easily custom produced by the homeowner (e.g., plastic wrap around windows). In addition, it will include a discussion of important characteristics that retrofit measures should have for energy performance.

3.1 Criteria for Comparing Window Attachments

The aforementioned studies identified several important considerations for window retrofits. These issues include Thermal Improvement, Comfort, Cost, Condensation Potential, Ease of Operation, Impact on Daylighting, Privacy and Aesthetics. While thermal improvement, comfort, cost, and condensation potential can be quantified, ease of operation, privacy, and aesthetics are more subjective and qualitative. A simple diagram (Figure 20) is developed for each window retrofit solution to illustrate a method of evaluating each system at a glance.

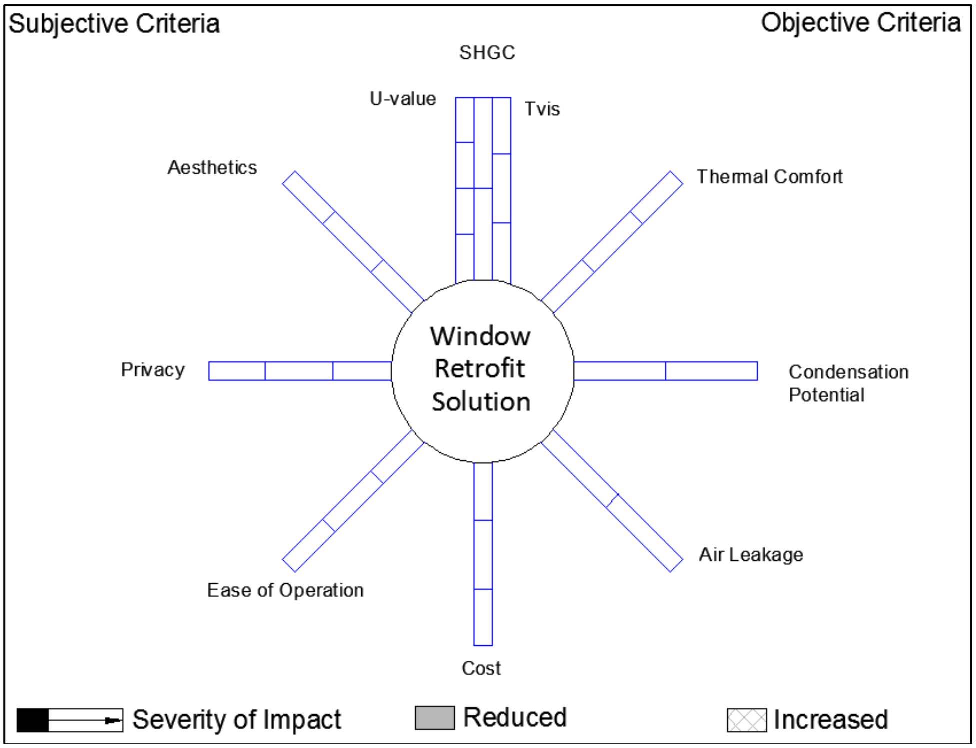


Figure 20: At-a-glance performance diagram for window retrofit solutions

3.1.1 Thermal Improvement

One of the most important criteria from an energy management standpoint is the amount of thermal improvement provided by a window attachment system. When evaluating thermal improvement, two basic aspects are to be considered. The first is the reduction in U-value. The U-values for the glazing systems and the window retrofits cannot simply be added together. Therefore, estimations for U-value improvement will be based on estimations in literature or through WINDOW analysis. The second aspect of window attachment performance is how well it reduces solar heat gain into the interior space. This criterion will be evaluated using WINDOW.

The thermal performance of each window attachment will be measured in terms of the thermal improvement obtained in comparison to a double glazed window. One result of this is that windows that are already more efficient will see a substantially lower improvement than predicted for their less efficient counterparts. The equation used to generate the percent improvement is shown below.

$$\frac{Improved\ Performance - Orginal\ Performance}{Original\ Performance} \times 100\%$$

Systems are also rated for shading ability. Systems that provide shade on the exterior side of the glazing will be more effective at limiting solar heat gain than those on the interior since they prevent heat from even reaching the interior of the building. Figure 21 shows the performance bars for thermal improvement and shading as well as visual transmittance (discussed next).

3.1.2 Impact on Daylighting

Most window attachments will affect the visual transmittance of the window assembly in one way or another. Attachments that are more opaque can significantly affect the daylighting in an interior space. In these situations, increased energy is required to light the interior of the building. Depending on the amount of lighting that is required, any energy saved in heating or cooling costs will be offset for lighting. Therefore, each system will be rated as significantly reducing daylighting potential, moderately reducing daylighting potential, or not influencing daylighting potential.

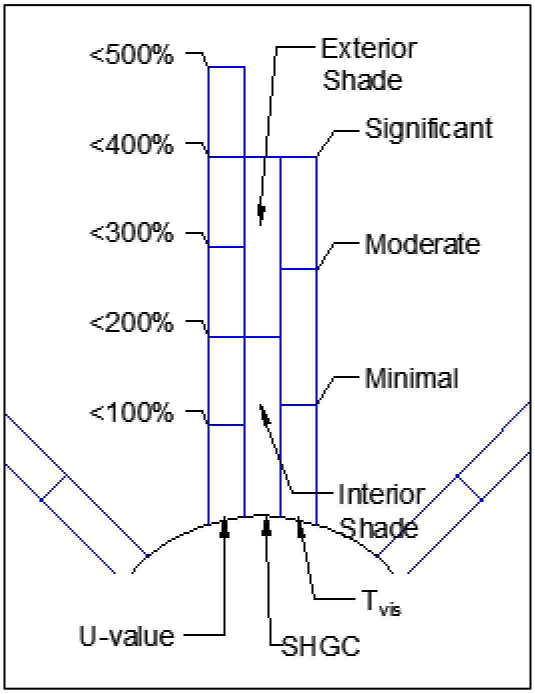


Figure 21: Thermal improvement (U-value and SHGC) and impact on daylighting (T_{vis}) criteria on the at-a-glance performance diagram

3.1.3 Thermal Comfort

Along with inside air temperature, the second component related to thermal comfort is the Mean Radiant Temperature (MRT). The MRT is determined by weighing the effects (by area, spatial relationship, and difference in temperature as compared to the skin of a person in the space) of each object in a space. When the MRT is warmer than the occupant's skin temperature, that person will "feel" warm. On the other hand, when the MRT is cooler than the occupant's skin temperature, they will "feel" cold.

The Mean Radiant Temperature of a window is a property that is largely based on the amount of furnishings in a particular space as well as the size and location of the window in that space. In addition, regional climate characteristics such as outside temperature, humidity, and wind speed will also have an effect. Therefore, to compare the mean radiant temperature of several window attachments; a common set of parameters will be used.

Investigations into window size and placement have led to several important conclusions in this regard. (Gan, 2001).

- A window's area as well as its aspect ratio has a significant impact on thermal comfort. The larger the area of the window, the greater the discomfort. In addition, square windows tend to cause more discomfort than an equivalent window area spread over several tall, narrow windows, in which case discomfort is negligible.
- The location of windows in a room has a significant impact on the amount of thermal discomfort they cause. When windows are far apart, such as on opposing walls (walls 1 and 3 in Figure 22), the effect of each window is nearly independent, with the amount of discomfort caused by each being cumulative. However, if the windows are close together, such as on adjacent walls (walls 1 and 2 in Figure 22), their effects merge, which slightly amplifies the effect of each window. The discomfort caused by windows less than 0.5m apart can have a significant impact on the comfort level in the room.
- Double glazed windows greatly reduce the discomfort caused by windows. In fact, the effect of the mean radiant temperature extends nearly twice as far into the room when single-glazing is used as it does with double-glazing.
- Although below window heating sources, such as radiators, are effective at reducing thermal discomfort caused by windows, the excessive heat often results in its own thermal discomfort. Therefore, measures that reduce the need for excessive use of under window heat sources will improve the overall comfort of the space.

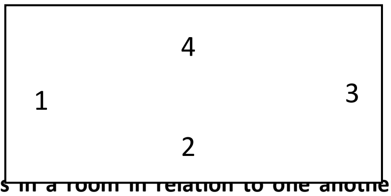


Figure 22: The location of multiple windows in a room in relation to one another will have an impact on the amount of thermal discomfort. Windows on adjacent walls will result in a greater degree of thermal discomfort then windows on opposite walls.

Based on these criteria, it can be concluded that mean radiant temperature is a concern whose relative importance will vary based on several conditions.

- The size and shape of the window are one determinate on whether thermal comfort should be considered. Reduction in thermal discomfort need not be considered for narrow windows. As the area increases and the aspect ratio nears square, thermal discomfort must be considered.
- Reducing the thermal discomfort caused by single-glazed windows is essential.
- Reducing thermal discomfort is essential when multiple large windows are located near one another.

For the purposes of this study, window systems will be rated as having a minimal, moderate, or severe impact on the thermal comfort of the space (Figure 23).

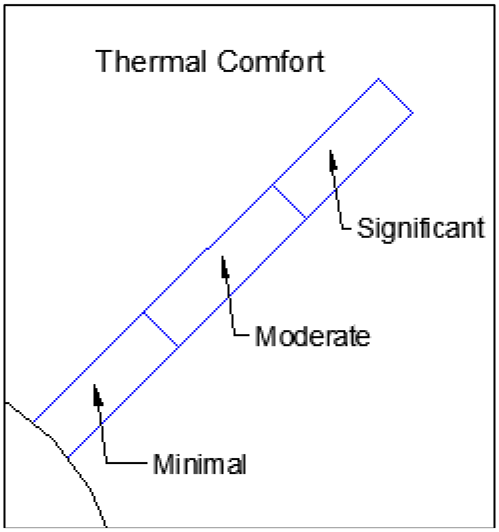


Figure 23: Thermal comfort criteria on the at-a-glance performance diagram

3.1.4 Condensation Potential

Condensation occurs when moist air contacts a surface temperature below its dew point. For fenestration systems, this typically involves warm, moist interior air condensing on the interior surface of a cold glazing unit. The risk of condensation is highest at the coldest location on the fenestration unit. This may be a location where a highly conductive material forms a thermal bridge (e.g., aluminum window frames) or where airflow is restricted. Condensation is often associated with low quality (high U-value) windows. However, even high performance windows with a low whole product U-value may have localized thermal bridges where condensation may occur. Condensation can result in mold growth and rot in the window frame and sill. For particularly cold climates, condensate on windows has the potential to freeze, resulting in possible egress issues.

Werner and Roos (2007), conducted a study to investigate the impact of various glass coatings on condensation development. It was found that low-emissive coatings (S_nO_2) delay the formation of condensation on glass, as the glass retains absorbed heat longer. Self-cleaning, hydrophilic coatings (TiO_2) on the other hand, did not slow the formation of condensation. However, these coatings did result in a window that was easier to see through (in comparison to uncoated or low-emissivity coatings) even after condensation had formed.

There are several solutions that have been found to be effective at reducing the condensation potential on windows. Generally speaking, exterior window attachments that result in an increased glazing temperature will have a lower risk of condensation, while interior attachments that lower the temperature of the glazing will have an increased risk of condensation. Interior window treatments that either completely seal out moist air from the surface of the windows or allow for increased levels of ventilation will have less condensation. In this study, window attachments are rated as having either a moderate or significantly increased or decreased risk of condensation (Figure 24).

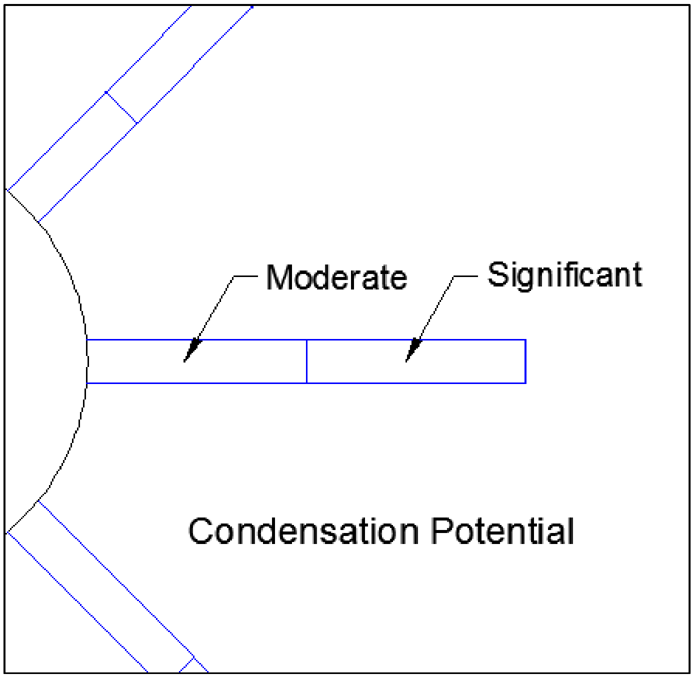


Figure 24: Condensation potential criteria on the at-a-glance performance diagram

For windows that have a high condensation potential, a solution is to add an additional molding on the inside of the window to cover the aluminum frame. By covering the cold surface with a material with a lower conductance, the potential for condensation to develop on frame is minimized. An illustration of this is shown in Figure 25. The image on the left shows a triple-glazed window with an aluminum frame. The lowest temperature on the window, found at point B, is -1.7°C. When an additional wood molding is added, the lowest point, found at point C, is now +5.1°C. Therefore, it can easily be seen that the window with the additional molding will be more resistant to developing condensation at a given outdoor temperature and indoor humidity level.

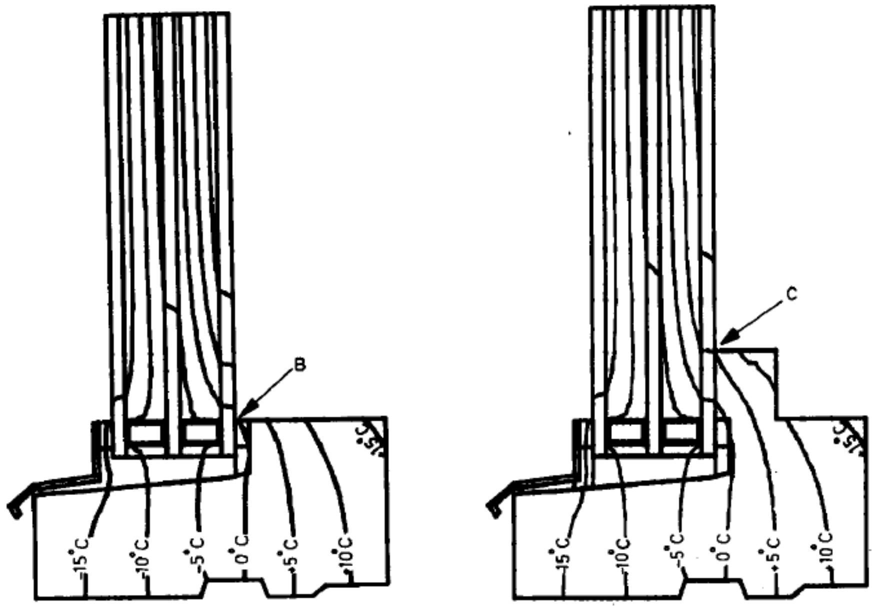


Figure 25: Comparison of isotherms for a triple glazed window without (left) and with (right) additional molding covering aluminum frame. Image source: Moshfegh et al. 1989. Image used with permission from publisher.

One important point to note is that improved (reduced) U-values will not always correlate to reduced condensation potential. The condensation potential will be based on a variety of factors including framing materials, coatings, spacer bars, as well as glazing window retrofit configurations. Without the use of physical testing or extremely robust finite element analysis, a more detailed rating of condensation potential is not possible. If such testing was available, each window attachment could be rated for condensation resistance using the temperature index (I_x). Given by the formula shown below, the temperature index relates the temperature of the interior surface of the window to the interior and exterior air temperatures. A temperature index of 1.0 indicates that the interior surface of the window is the same temperature as the interior air. This is the point at which the window has maximum condensation resistance, regardless of interior humidity levels.

$$CRF = I_x = \frac{T_x - T_e}{T_i - T_e}$$

In this equation, T_x is the interior window surface temperature, T_e is the exterior air temperature, and T_i is the interior air temperature. AAMA Standard 1503 (*Voluntary Test Method for Thermal Transmittance and Condensation Resistance of windows, Doors and Glazed Wall Sections*) (AAMA, 2009) describes this index, referred to by the document as the Condensation Resistance Factor (CRF). The standard describes that the interior and exterior air temperatures should be 70° F (21° C) and 0° F (-18° C), respectively.

3.1.5 Air Leakage

The degree to which a window attachment prevents or decreases the transport of air movement through the building envelope must be considered. Figure 26 depicts the two major routes in which outside air can infiltrate through windows. The first method is between the sash and the jamb. The second route is between the jamb and the wall. The ability of a window attachment to reduce air leakage will be judged based on how effective it is at preventing air leakage through each of these locations (Figure 27).

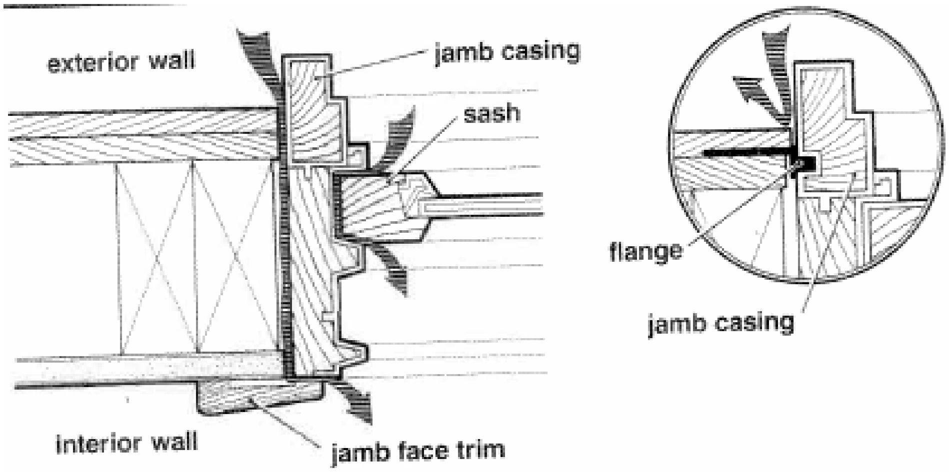


Figure 26: There are two major routes of air infiltration through the window assembly. Image source: Langdon, 1980.

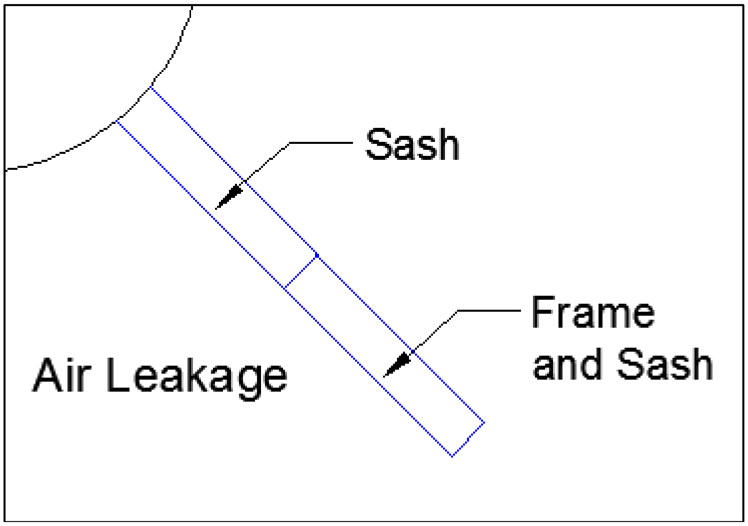


Figure 27: Air leakage performance criteria on the at-a-glance performance diagram

3.1.6 Cost

The cost of each window attachment will be compared as an additional metric. Since these are all retrofits for residential construction, the cost of all materials will come from sources available to the common homeowner, such as home improvement centers (Lowe's, Home Depot, etc.). When appropriate, installation costs will be included (Figure 28).

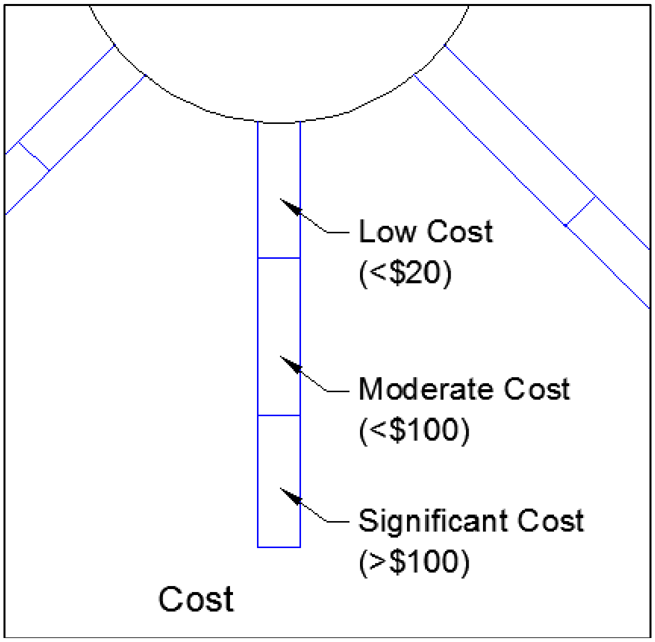


Figure 28: Cost performance criteria on the at-a-glance performance diagram. Note that cost is for the retrofit of a single, 30"x60" window.

3.1.7 Ease of Operation

The most successful window attachments are those that are easy for the owner to operate. A window attachment that is difficult to use will be ignored by the occupant, rendering it useless, or worse be used incorrectly, potentially resulting in an increase in energy use. While some window attachments, such as window films, require no action from the user after installation; other systems, such as shutters, must be adjusted several times per day for optimal performance. Therefore, window attachments will be rated as follows (Figure 29).

- Minimal or no operation required
- Some operation required
- Significant operation required

3.1.8 Privacy

Privacy is an important criterion for window retrofit solutions. Therefore, each solution will be rated for its effectiveness at providing privacy for the building occupants (Figure 29). Since the majority of retrofit solutions have variable settings, the privacy criteria will be evaluated for the shade in the most closed position.

3.1.9 Aesthetics

The aesthetic impact of a window attachment is the hardest criteria to weigh against that of the others. An exterior window attachment may negatively affect the street appeal of a home, thus reducing its value to the homeowner. Similarly, an interior window attachment may negatively affect the interior aesthetics of a room. In both of these situations, the severity of any positive or negative impacts is highly subjective on the part of the occupant. Therefore, for the purposes of this study, each window attachment will be described as having either “little to no aesthetic effect”, or “substantial aesthetic effect” (Figure 29).

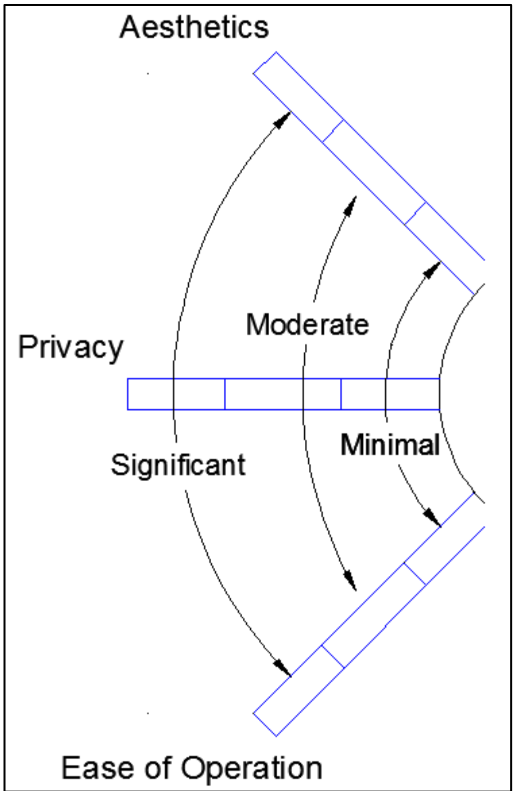


Figure 29: Ease of operation, privacy, and aesthetic performance criteria on the at-a-glance performance diagram

Variations

In cases where there are variations in each system, these will be described. Some of these are different commercially available products that serve the same function, albeit in different ways. Others will be modifications to existing systems that will improve the efficacy of their design.

Other Issues

Glass Breakage caused by heat buildup in window attachments where there is little air movement. This will be a particular issue for systems that are highly insulative interior attachments, which have a thoroughly sealed "air cavity". These systems allow heat to enter through the window into an enclosed space, where it cannot easily escape.

3.2 Modeling of Window Retrofit Characteristics

Homeowners have many different styles of window retrofit options to choose from. For each of these styles, numerous variations currently exist on the market or could be easily envisioned. Therefore, it is necessary to examine specific products on the market as well as hypothetical systems with a broad range of design features. Such an analysis will provide an understanding of how the wide variance of attributes for each system will affect the performance of that system.

Table 9 provides a summary of the different retrofit solutions investigated in this study. Each of these methods has been placed into one of six different catagories: venetian blinds, fabric shades, glazing layers, insulating layers, perforated screens, and cellular structures. Each of these catagories has their own set of variables that will affect their performance. These variables will be discussed further in subsequent sections.

Table 9: Summary of window retrofit solutions and software that can be used to model each system.

Window Retrofit Solutions	Venetian Blinds	Fabric Shades	Glazing Layers	Insulating Layers	Perforated Screens	Cellular Structures
Operable Shutters (Shading)	X					
Operable Shutters (Insulating)				X		
Exterior Insulating Rolling Shutters				X		
Exterior Storm Windows			X			
Insect Screens					X	
Roller Screens					X	
Exterior Plastic Film on Insect Screens			X			
Interior Conventional Blinds	X					
Insulating Cellular Blinds						X
Interior Shutters (Shading Style)	X					
Interior Shutters (Insulating Style)				X		
Interior Roller Shades		X				
Interior Curtains and Draperies		X				
Low-Emmissivity Films						
Plastic Film on Window Frames			X			
Draft Snakes						
Modeling Software						
WINDOW	🟦	🟦	🟦		🟦	
THERM	🟦		🟦	🟦		
ABAQUS	🟦	🟦	🟦	🟦	🟦	🟦

The three software packages that can be used to determine performance values are LBNL WINDOW (LBNLb, 2012) and THERM (LBNLa, 2012) as well as the FEM software ABAQUS (Dessault Systemes, 2013). WINDOW and THERM work together to determine thermal and optical performance values for window components and assemblies. WINDOW is the simpler of the two programs. It uses material properties such as spectral data and material conductivity to determine the whole window U-value, SHGC, and Visual Transmittance for fenestration assemblies. The current version of the software, WINDOW 6.3 (LBNLb, 2012), has predefined models based on actual products for venetian blinds, fritted glass, and woven shades. Custom models can also be developed for horizontal venetian blinds, woven shades, and fritted glass.

The latest beta version (LBNLa, 2013) of the software (WINDOW 7) has predetermined models based on actual products for venetian blinds (vertical and horizontal), cellular shades, perforated screens, woven shades, light-diffusing screens, and electrochromic coatings. In addition, custom-shading layers can be developed for venetian blinds, perforated screens, woven shades. When making custom layers, optical properties for absorption, reflection, and transmittance are needed to generate accurate values for the SHGC and T_{vis}. This will likely create a challenge for determining the effects of solar heat gain and daylighting. It should be emphasized that this version of the software is still in the beta phase, and therefore likely has bugs that may potentially affect the accuracy of results for some of the newer features.

THERM is a simplified FEA modeling software used to measure heat transfer through building components. The intended function of THERM is to calculate frame and edge-of-glazing U-value properties, which can then be imported into WINDOW, where whole value product U-values can be determined. Therefore, this function primarily refers to the use of specialized framing and/or connections between glazing elements. Standard, predefined wood, vinyl, aluminum, or aluminum with thermally broken frames are available in WINDOW based on ASHRAE standards. In these cases, the use of THERM is not required to determine the whole product U-value, although THERM may still be useful to generate temperature isotherms for ratings of condensation potential. However, THERM cannot generate isotherms for windows using shading systems.

ABAQUS is the most advanced of the three software packages previously mentioned. As a fully functional FEA analysis program, it is capable of modeling the thermal transmittance of the most advanced glazing systems. However, it is also the most complicated to use, and requires a thorough understanding of the software as well as the behavior of the system being modeled. When using ABAQUS, the user must manually specify the precise interaction between every surface in question. Therefore, its increased compatibilities will come paired with a much longer time to develop models as well as an increased likelihood of errors. Therefore, the use of ABAQUS will be better served as a further phase of research, in which results from physical testing can be used for validation.

Several authors have conducted research in this area (Oosthuizen et al., 2005, Shahid and Naylor, 2005, Wright, 2008, Cho et al., 1995). In general, these studies have focused nearly entirely on the performance of venetian blinds, and in all cases have only examined the center-of-glass region. Window framing can have a significant effect on the performance of a given system. This study will differ from the aforementioned studies in that it will investigate the performance of a given shading device on an actual window system with various types of frames. For each shading device, a picture window, 1200 mmx1500 mm will be used with wood, vinyl, and a thermally broken aluminum frame. The ultimate goal will be to be able to "predict" an actual product's performance based on its design attributes. These results will need to be validated using physical testing during a later stage of research. Rather than trying to force a comparison between products in different catagories, this study has focused on only comparing the performance of products in similar catagories.

4. Venetian Blind Style Attachments

4.1 Operable Shutters

Exterior shutters in new construction are typically inoperable and exist primarily for aesthetic purposes. However, many older homes have operable shutters (Figure 30). In addition to providing protection for the glazing during inclement weather, exterior shutters can also be an effective means of limiting solar heat gain. These shutters usually fold in from the sides, but can also fold in from the top as well as slide into place on tracks.

Figure 30: Example of operable shutters. Image source: Timberlane, 2013

A wide variety of shutter systems are available. Shutter systems can be characterized as having two primary sets of differences: material and operation type. Shutters can be constructed using wood, aluminum, and even steel. Shutters can be louvered, raised paneled, board-n-batten, Bahama, or accordion type.

Material

- Wood
- Aluminum
- Vinyl
- Composites

Shutter Styles

Louvered Shutters – This style of "side-swinging" shutters has louvers in the main body of the shutters. These louvers are either operable, such as in Figure 31, or inoperable. When the louvers are operable, the shutters can be particularly effective as a shading device to allow the desired amount of light into the interior of the building.

Figure 31: Typical louvered shutter. Image source: Timberlane, 2013

Raised Panel Shutters – These “side-swinging” shutters are made of a solid material, with decorative “raised panels” as seen in Figure 32. When closed, they provide complete shade. In addition, they can be constructed of a highly insulative material and installed in such a way that they can be thoroughly sealed to the window frame when shut, effectively increasing the insulation of the window system at night. In addition, these shutters can be an effective means of protecting the window from severe weather or vandalism.

Figure 32: Typical raised panel shutters. Image source: Timberlane, 2013

Board-n-Batten Shutters – These shutters are made by attaching several pieces of “wood” together such as in Figure 33 to create a more rustic look. Although the shutters are intended to simulate the aesthetic of wood boards, they can be constructed of any material.

Figure 33: Typical board-n-batten shutter. Image source: Timberlane, 2013

Bahama Shutters – These shutters swing from the top of the window frame and are typically designed with some form of louvers to be used as shading or light filtering devices as can be seen in Figure 34.

Figure 34: Typical Bahama style shutter. Image source: Timberlane, 2013

Accordion Shutters – These shutters extend from one side of the window frame to cover the whole window. One advantage of this style is that it can easily cover any size or shape window (Figure 35). Their primary function is either protection from severe weather or vandalism. In addition, highly insulating materials could be incorporated into their construction to offer increased insulation. Exterior insulated rolling shutters, described in Section 7.1, are an example of such a system.

Figure 35: Typical accordion style shutter. Image source: Hurricane Shutters Florida, 2013

Thermal Improvement

The performance of shutters at reducing energy use for heating and cooling applications is a function of the style, construction, and installation of shutter used. Some varieties are better for reducing cooling loads while others will be more beneficial for increasing insulation.

Shutters with louvers are an effective means of reducing the solar heat gain into the building. These shutters are installed on the exterior side of the glazing, providing shade for the building and preventing heat from even reaching the glazing. This reduces the solar energy reaching the interior space as well as radiant energy emitting from the surface of the glazing itself. Although shutters without louvers can also serve this purpose, they will block all light from entering the room, which may result in increased electrical loads for lighting.

Shutters can also be an effective means of limiting the effect of night sky radiation when closed. Since typical installations allow significant air movement around the shutters, they will be an ineffective form of insulation unless a mechanism is in place to seal the perimeter of the shutter. In such a situation, shutters can provide a significant increase in insulative value depending on the type of material used.

The CCHRC performed a field investigation of a highly insulating shutter system. They found that such a system could provide upwards of 400% improvement in thermal insulation (Craven et al., 2011). While typical shutters with standard installation details will not achieve performance anywhere near this level, these systems can be used as a reference for the upward limit of shutter performance. Highly insulating shutters will be discussed in more detail in Section 7.2.

Impact on Daylighting

Hinged shutters are commonly equipped with louvers, which allow for partial sunlight to pass through. When these louvers are operable, the amount of sunlight can be varied as required by the occupant. Other styles of shutters have no method of filtering light without blocking all of it. In either case, however, additional lighting will often be required.

For best performance, louvered or light filtering shutters should be used in daylight hours during the summer or in hot climates. In cold climates, they should remain open to gain as much solar heat as possible during the day, and then closed to trap it in the house at nighttime.

Comfort
Proper use of shutters will decrease the temperature of the glazing during summer and increase it during the winter. In both cases, this will result in an improved MRT. As such, occupants will feel more comfortable when they are in place.

Condensation Potential
Operable shutters will increase the temperature of the glazing when used during the winter. This will result in a reduced risk of condensation.

Cost
The price of these shutters (http://www.architecturaldepot.com/louver-shutters.html) can vary based on the exact style and materials used. The cheapest shutters are typically composed of vinyl, but are not adequate for operability. Wood shutters can cost as low as $99 per pair, but tend to require more maintenance over time. Higher quality, maintenance free, storm quality shutters start at roughly $337 per pair. Custom made storm shutters can be created at even lower rates. Therefore, for this study, an average cost of $100 will be assumed for each window.

Air Leakage
In general, shutters will be an ineffective means at reducing air leakage through window systems unless special efforts are taken to seal the perimeter of the shutters when they are shut. If such measures are taken, air leakage can be effectively reduced through the sash.

Ease of Operation
The owner must open or close shutters several times per day to achieve maximum performance. If windows are located on the second floor, their use might be impractical.

Privacy

Shutters are an effective means of providing privacy when closed.

Aesthetics
Shutters have a low aesthetic impact on the home. They are aesthetically pleasing when in an open position, and have a low impact when closed.

Figure 36 shows the at-a-glance performance diagram for operable exterior shutters with respect to the criteria discussed above.

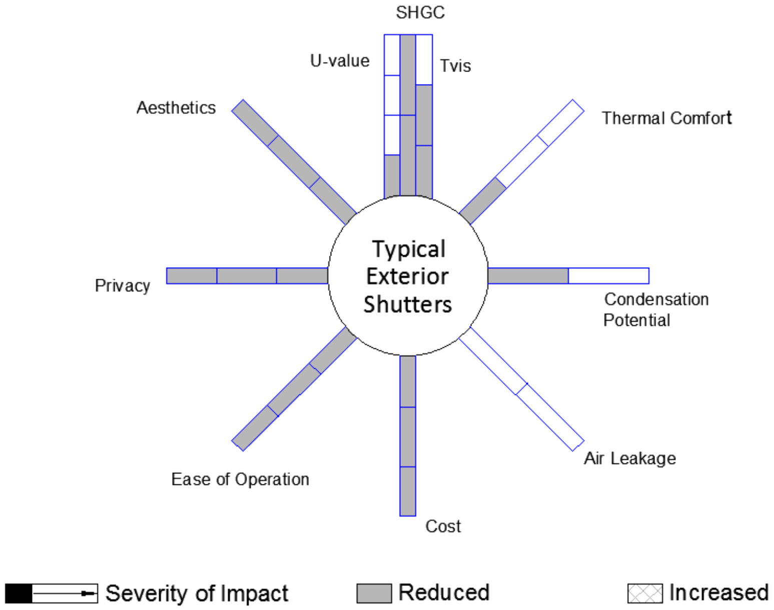


Figure 36: At- a-glance performance diagram for operable exterior shutters.

Variations

As was previously discussed, Bahama shades (Figure 34) are an effective means of providing shade for the window. A variation of this style of shutters with hinges at the bottom and a reflecting surface facing the window such as in Figure 37 could be designed. This system would reflect sunlight further into the building for daylighting or passive solar heat gain. Further improvements are possible if the shutters are constructed of a highly insulating material such as rigid foam insulation. These shutters would then be closed at night-time to reduce heat loss through the windows. A compressive seal could be utilized to insure that no air leaks through the windows when the shutters are closed. Figure 38 shows the at-a-glance performance diagram for this variation of shutter.

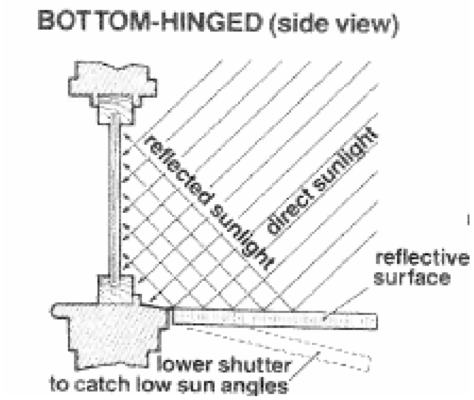


Figure 37: Horizontal folding shutter with a reflecting surface to increase daylighting potential or solar heat gain. Image source: Langdon, 1980.

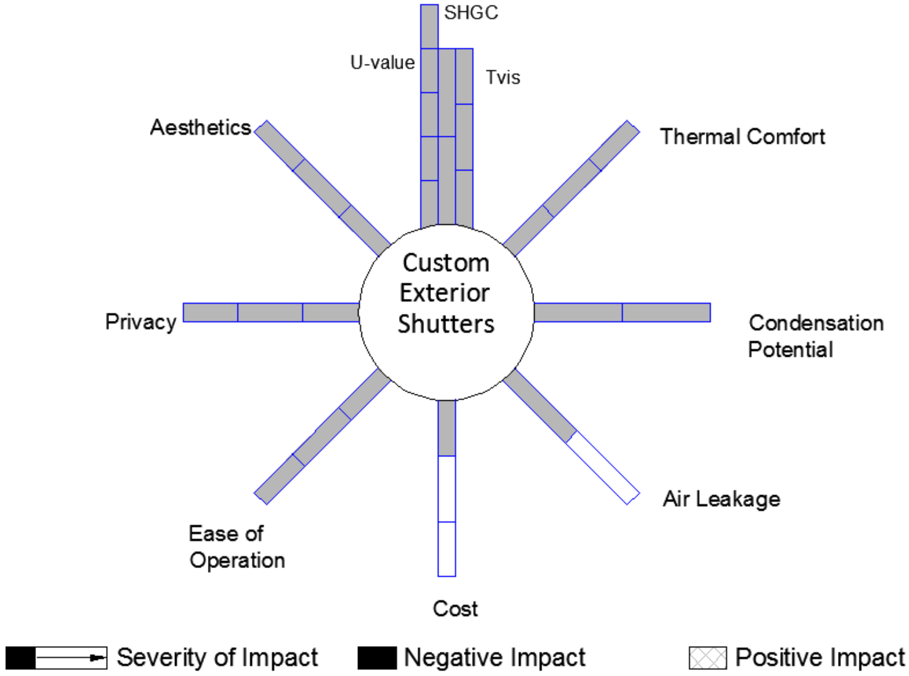


Figure 38: At-a-glance performance diagram for custom exterior shutter designs.

4.2 Venetian Blinds

This system uses individual flat slats that can be adjusted to block light and solar heat gain. They are generally made of aluminum, wood, or vinyl and are available in a variety of different colors and finishes. While aluminum blinds are typically thin (between 6 and 9 gauge), wood and vinyl blinds can be as thick as ¼”.

Thermal Improvement

Aluminum blinds provide little insulation. Wood and Vinyl blinds, on the other hand, with their thicker cross-sections will provide slightly more insulation. However, these systems may be useful at limiting thermal transmittance by disrupting convective heat transfer and infrared radiation. In addition, all three types of blinds will block solar heat gain during the summer and provide a radiant barrier during the winter. It is estimated that conventional blinds, when completely closed, result in a 50% decrease in SHG and a 20% decrease in heat losses through a double glazed window (Langdon, 1980).

Some blinds have cord holes that will be blocked by adjacent slats when in the closed position. The design intent of this feature is to prevent excess light from penetrating through the closed blinds. However, the feature should also have the added benefit of reducing the amount of cold air or solar heat gain that can pass through blinds. A comparison between a “LightMaster” and a standard hole is shown in Figure 39.

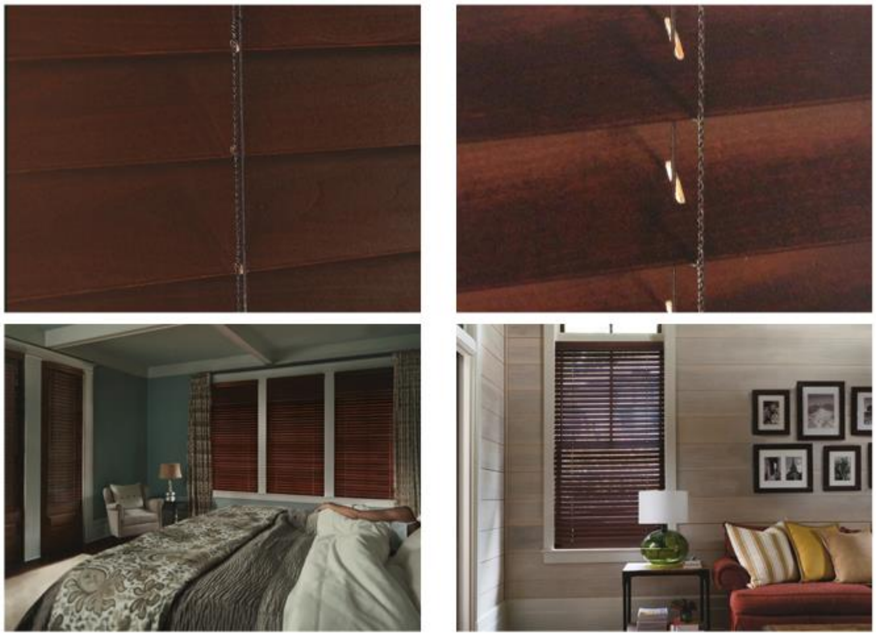


Figure 39: Slats for conventional blinds can be designed to have smaller holes, which are concealed when the slats are in the closed position. Image source: Levelor, 2013

Impact on Daylighting

These units can be easily adjusted to several different positions. The blinds can be retracted to the top of the window, allowing complete light transmittance. They can be adjusted to an “open” position to allow for partial light transmittance, or to the closed position which results in a nearly completely blockage of transmittance.

Comfort

Insulating blinds will help to improve the thermal comfort of the space by providing a barrier between the cold window surface and the room.

Condensation Potential

Since the blinds will not affect the interior temperature of the glazing, condensation will likely be an issue. In particularly humid conditions such as in kitchens or bathrooms, condensation may be severe. Therefore, aluminum or vinyl moisture resistant blind should be used rather than wood in these situations.

Cost

The cost of conventional blinds will vary based on their type. Levolor blinds can be divided into three categories: Metal, Faux Wood (Vinyl), and Wood. Metal blinds range in price from $43-$106. Faux Wood blinds range in price from $84-$120. The price of wood blinds will range from $111 - $151 (Lowe's, 2013).

Ease of Operation

Venetian blinds utilize a set of pull cords to easily open the blinds or adjust the tilt of the slats. In order to achieve optimal performance, venetian blinds require adjustment on the part of the building owner over the course of the day. This may be a significant amount of work depending on the number of windows.

Privacy

Venetian blinds are an effective means of creating privacy for the occupants.

Aesthetics

Venetian blinds will have a significant impact on the aesthetics of the space depending on the materials and installation details used. Figure 40 shows the at-a-glance performance diagram for venetian blinds.

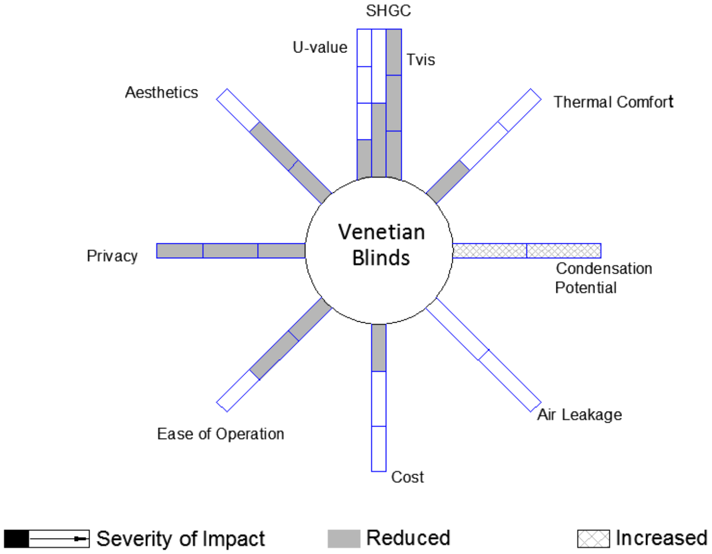


Figure 40: At-a-glance performance diagram for venetian blinds.

4.3 Interior Shutters

When installed inside a window, interior shutters act similarly to blinds, except they are completely opened by swinging the shutter out of place. In addition, the angle of the shutters is adjusted either manually or using an adjustment rod. The shutters are typically composed of wood or vinyl, with each slat being in the ¼" range. An example of interior shutters used with a patio door can be found in Figure 41.

Figure 41: Interior shutters can be used to cover an entire window assembly. Image source: Graber, 2013

Thermal Improvement

When the shutters are closed, with their slats in the closed position they function almost like a door placed over the window. Weather-stripping can be placed at the "jambs" of the shutters for additional improvement.

The CCHRC performed a study on the performance of custom made, 3" thick polyisocyanurate foam insulation filled interior shutters. They found that a 147% improvement in the field when installed over a triple-glazed window. When a computer analysis was performed of the shutter over a double-glazed window, a 696% improvement was obtained (Craven and Graber-Slaght, 2011).

These shutters would also be an effective means of providing shading for solar heat gain. However, designs with louvers are desirable in such applications for two reasons. First and foremost, using interior shutters to limit solar heat gain will trap heat in the cavity between the glazing and the shutter. This heat could cause damage to the window seals or the glazing itself. Louvered shutters will provide a mechanism for air movement within the cavity, which will help to dissipate that heat. Secondly, louvered shutters allow for partial daylighting based on the occupants needs.

Impact on Daylighting

Interior shutters with louvers can control exactly how much light can enter a space. They can be completely opened to allow for 10% light transmittance, or completely shut based on the needs of the occupant.

Comfort

The shutters should significantly improve the thermal comfort of the space by providing a covering over the cold glazing surface.

Condensation Potential

The shutters will have the effect of decreasing the temperature of the interior glazing surface, therefore the condensation potential of the system will be high. This is particularly true for shutter systems with a large R-value. In these cases, insuring that weather-stripping is used in such a way as to limit the amount of indoor humidity that can reach the cold surface of the glass. Figure 42 shows an example of condensation forming on a window system with a highly insulative shutter system. In any case, vinyl shutters should be used in humid climates to reduce the chance of mildew and rot occurring in the wood.

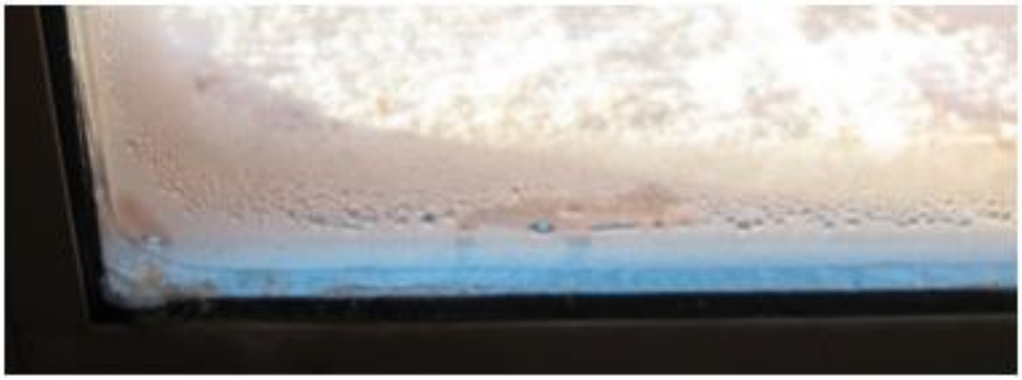


Figure 42: Condensation can easily form on the surface of windows using highly insulative shutter systems. Image source: Craven and Graber-Slaght, 2011.

Air Leakage

When the shutters are completely closed, a seal is created around the interior area of the window. This should dramatically reduce any air leakage through the sash, particularly if weather-stripping is used around the shutter itself.

Cost

The cost of store-bought, interior shutters is particularly high. They often require custom fitting for the specific window. The estimated cost for vinyl “Faux Wood” blinds are priced at $339 for a 30”x60” window. Painted wood shutters cost $412 per window. Stained wood shutters cost $478 per window (Lowe’s, 2013). However, DIY interior shutters could be custom-made for improved thermal performance at a much cheaper price.

Ease of Operation

Interior shutters are easy to operate for any window that is easily accessible. However, if there are many windows, the process of closing each of them can be a cumbersome process.

Aesthetics

The use of interior shutters will have a dramatic effect on the space they are placed in. While this is true for many interior systems, most of them can be opened or closed in such a way that their effect is minimized. Shutters, on the on the other hand, have a “heavy” appearance that is present in any configuration.

Figure 43 shows the at-a-glance performance diagram for interior shutters.

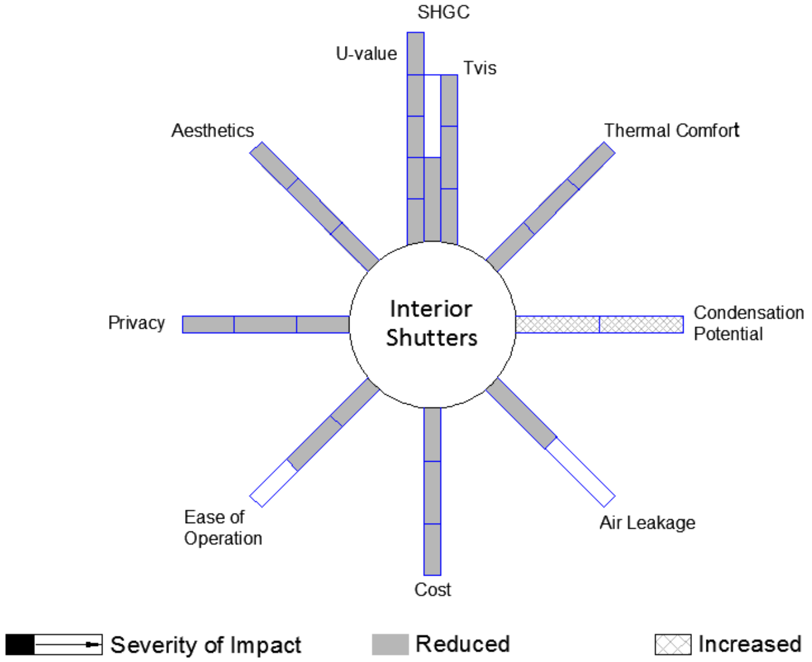
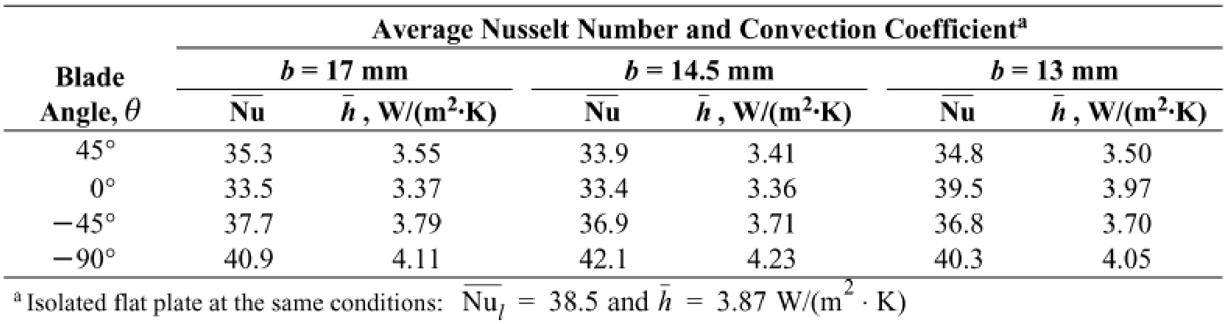


Figure 43: At-a-glance performance diagram for interior shutters.

4.4 Background on Venetian Blind Performance

Machin et al. (1998), performed a study to investigate the impact of venetian blinds on convective heat transfer. When no blind was present, a convective heat transfer coefficient of 3.87 W/(m^{2}K) was obtained. It was found that the presence of a Venetian blind reduced the surface film convective heat transfer coefficient to as low as 3.36 W/(m^{2}K) when the distance from the glass surface to the center point of the blind was 14.5 mm and the slat angle was at zero degree. This is primarily due to a disruption in airflow pattern caused by the blinds. It was found that as the center of the blind moves closer to the glass surface, the heat transfer coefficient increases. This is primarily due to the fact that conduction along the blade profile increases at this distance. When the slats are at a 90° angle, it was found that heat transfer is also slightly increased, as a chimney effect is created. A summary of these results are shown in Table 10.

Table 10: Average nusselt number and average convection coefficients, Ra$_l$=3.04x10^7. Image source: Machin et al.,1998.



Blade Angle, θ	Average Nusselt Number and Convection Coefficient[a]					
	b = 17 mm		b = 14.5 mm		b = 13 mm	
	$\overline{Nu}$	$\bar{h}$, W/(m^2·K)	$\overline{Nu}$	$\bar{h}$, W/(m^2·K)	$\overline{Nu}$	$\bar{h}$, W/(m^2·K)
45°	35.3	3.55	33.9	3.41	34.8	3.50
0°	33.5	3.37	33.4	3.36	39.5	3.97
−45°	37.7	3.79	36.9	3.71	36.8	3.70
−90°	40.9	4.11	42.1	4.23	40.3	4.05

[a] Isolated flat plate at the same conditions: $\overline{Nu}_l$ = 38.5 and $\bar{h}$ = 3.87 W/(m^2 · K)

Shahid and Naylor (2005) performed an experimental and analytical study on venetian blinds on single- and double-glazed windows in order to determine the effect on convective and radiative heat transfer. They found that venetian blinds have the greatest effect on windows when the slats are in the fully closed (Φ = 90) position. Radiative heat transfer is reduced by 42% and 37% for single and double glazing, respectively. However, convective heat transfer is increased by 22% and 31%, respectively for single-and double-glazing due to the chimney effect. The relationship between the heat flux ratio (average heat flux with blinds to that without blinds) and the blind angle is shown in Figure 44. The variation in U-value ratio (U-value with blinds to that without blinds) with respect to blind angle is shown in Figure 45.

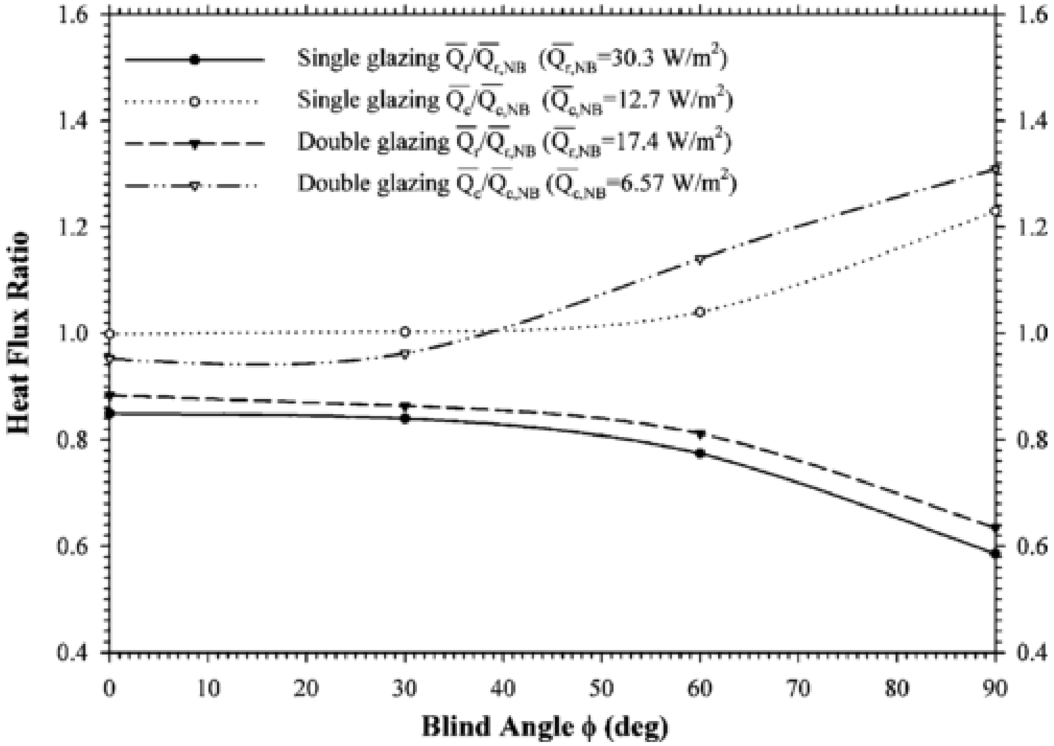


Figure 44: Variation in the convective and the radiative heat flux ratios from the indoor glazing with louver angle. Image source: Shahid and Naylor, 2005. Image used with permission from publisher.

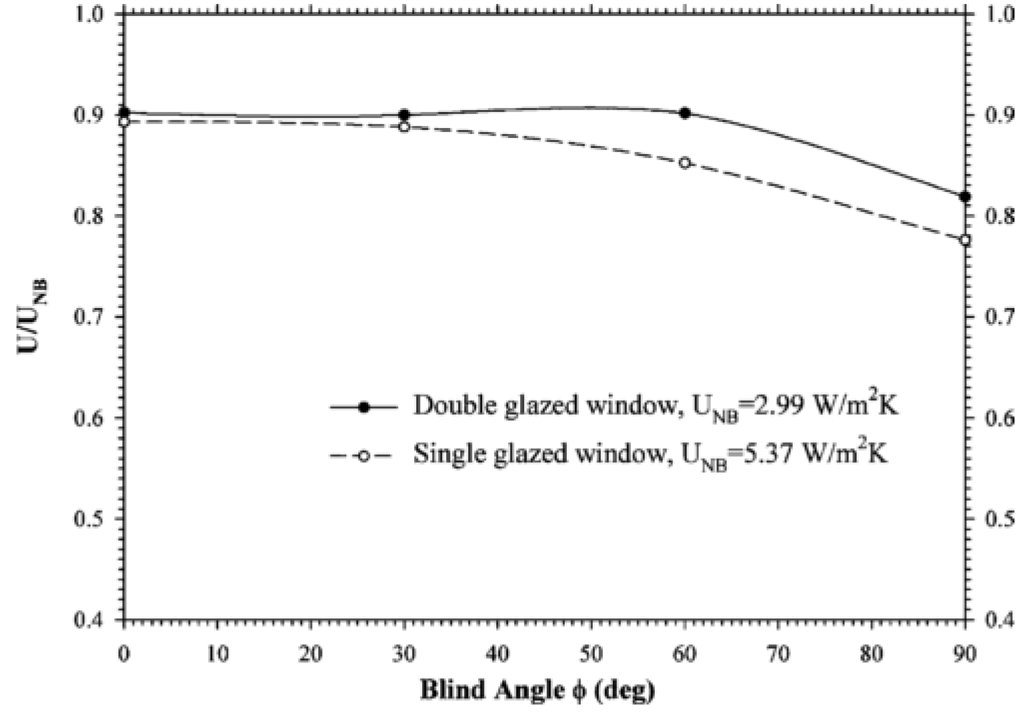


Figure 45: Variation in U-value ratio with louver angle for a single and double glazed window. Image souce: Shahid and Naylor, 2005. Image used with permission from publisher.

Shahid and Naylor (2005) also developed correlations between the variation of the radiative and convective heat transfer distribution along the height of the window (Figure 46) as well as variations in the U-value ratio with blind angle and blind emissivity (Figure 47).

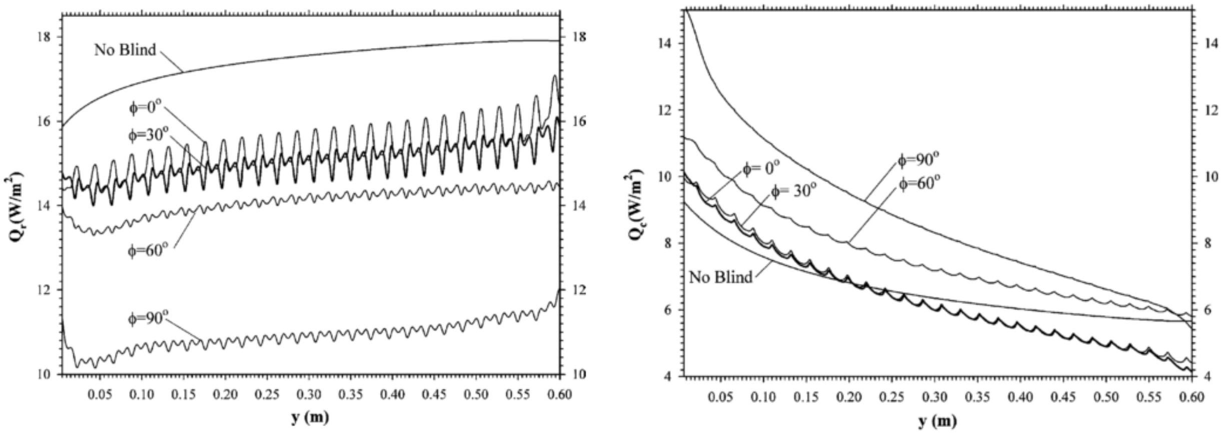


Figure 46: Variations in the local radiative (left) and convective (right) heat transfer distribution on the indoor glazing of a double glazed window. Image source: Shahid and Naylor, 2005. Image used with permission from publisher.

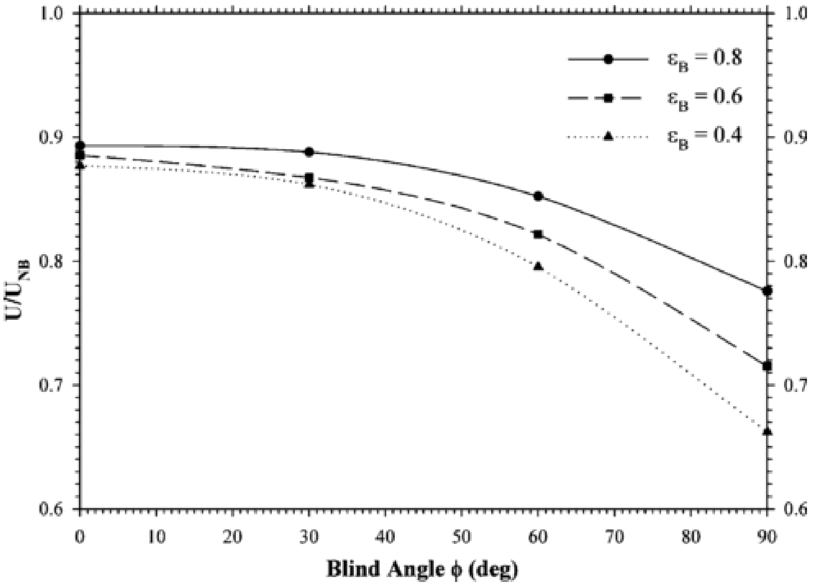
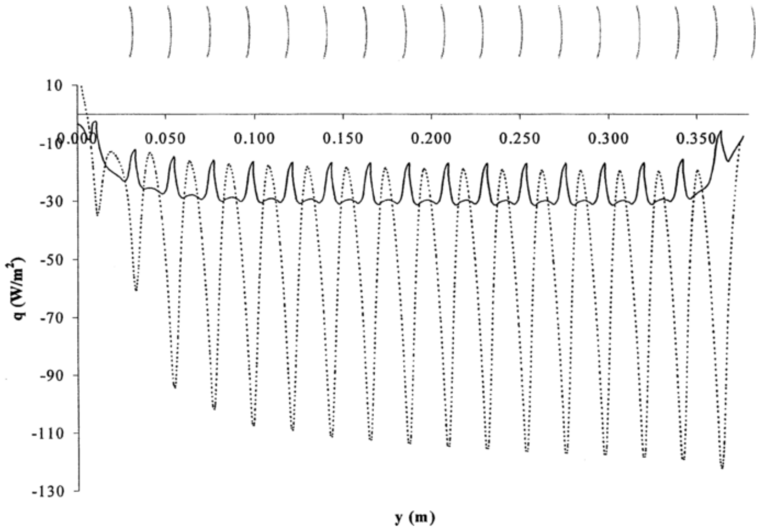


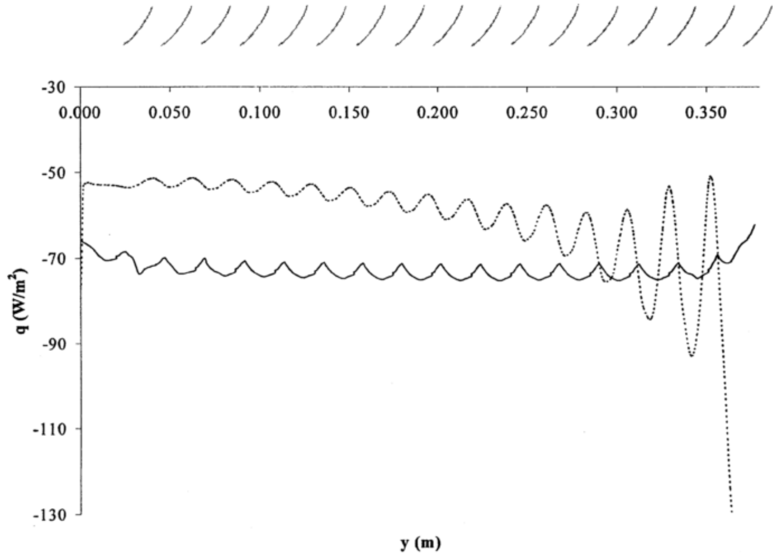
Figure 47: Variation of U-value ratio with louver angle for a single glazed window with blinds of various emissivity's. Image source: Shahid and Naylor, 2005. Image used with permission from publisher.

Oosthuizen et al. (2005) performed a study to determine the effects of natural convective and radiative heat transfer through shading devices. A numerical study was conducted for the case of internal venetian blinds at angles of 0°, 45° (room side edge up), and -45° (room side edge down). The results of this study are shown in Figure 48. Negative heat flux (q) indicates that heat is moving from the interior air to the glass surface, while a positive heat flux indicates that heat is moving from the glass surface to the interior air. In these images, the y axis indicates the height along the surface of the blind.

These figures demonstrate that venetian blinds limit convective heat loss to ~-25 W/m^2 when they are oriented at 0 degrees. However, the radiative heat loss is significantly higher at an average of ~60 W/m^2

with significant peaks at the locations of the slats. When the blinds are oriented at 45 degrees, the convective heat transfer is increased to ~-70 W/m2, and the radiative heat transfer is reduced at ~-50 W/m^2. When the blinds are oriented at -45 degrees, the convective and radiative heat transfer is limited to ~-30 and ~-25 W/m^2 respectively.





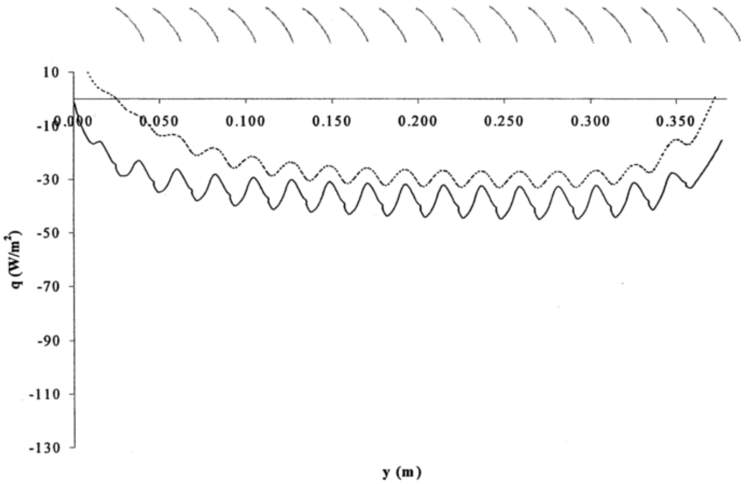


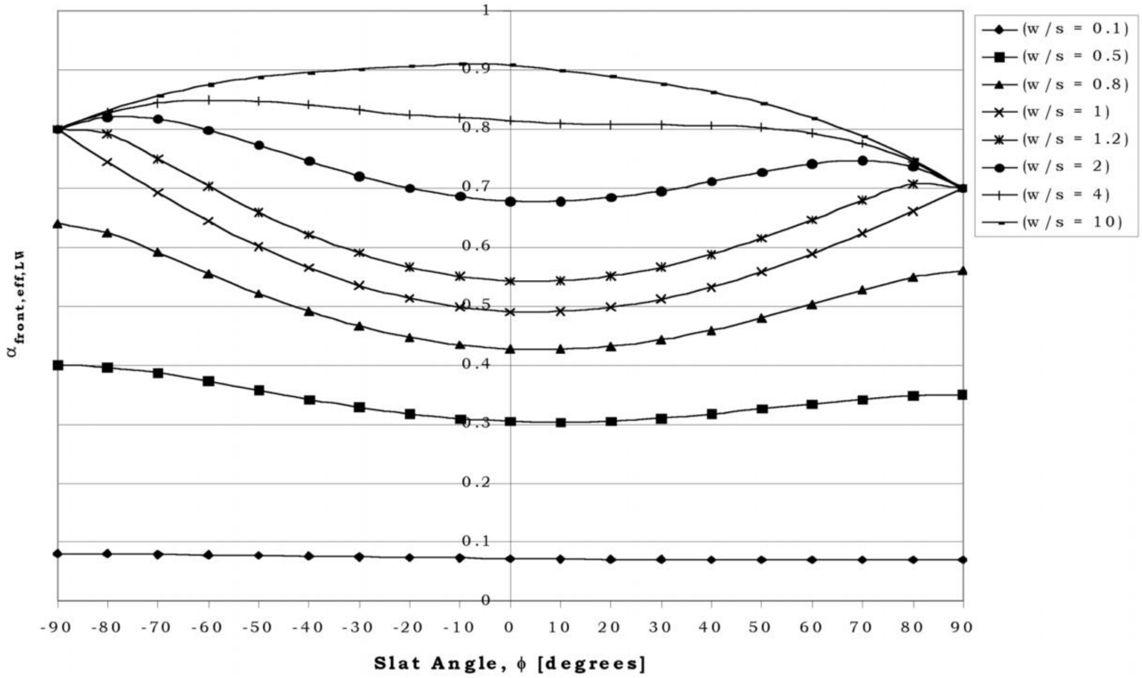
Figure 48: Convective (solid lines) and radiative (dashed lines) heat flux for Venetian blinds with Φ=0 (top), Φ=45 (middle), and Φ=-45 (bottom). Image source: Oosthuizen et al., 2005

Yahoda and Wright (2004) developed a simplified model for computing the properties of venetian blinds most concerned with long wave radiation. These properties are absorption, reflection, and transmission. They then performed a parametric study of various slat parameters to determine the sensitivity of various slat parameters. It was found that for the transmission of long wave radiation, the critical parameters are the slat width (w), slat spacing (s), angle, and the emissivity of the top and bottom of the blind surface. The results of this study are shown in Figure 49.

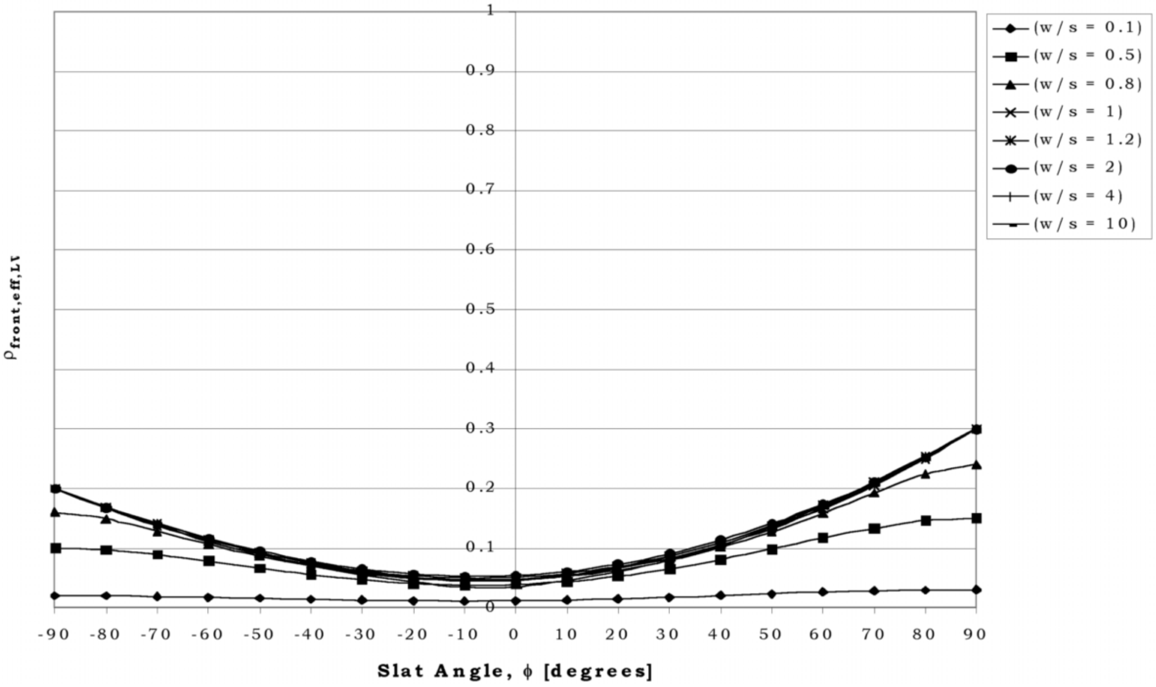
The top figure demonstrates that when blinds are in the closed position (slat angle = 90°) and have slat width to spacing ratios greater than 1.0, the absorption of the blinds is equal to the absorptivity of the slat material, which was assumed to be 0.7. When w/s <1.0, the absorption is less than the absorptivity of the material even when the blinds are completely closed, as the gaps between each slat allow for transmission of radiation. When the blinds are completely open (slat angle =0°) and the w/s ratio is much greater than 1, the absorption can actually be greater than the absorptivity of the material, primarily due to the radiation bouncing around in between slats.

The middle figure demonstrates that the reflectance of the slats increases as the slat angle deviates from 0° for all w/s ratios. When w/s > 1 and Φ = ±90°, the layer reflectance and material reflectance must be equal. This value will be ($1-\varepsilon_{top}$) or ($1+\varepsilon_{top}$).

The bottom figure demonstrates that for w/s > 1.0 and Φ = 90°, the transmittance is equal to zero. For w/s < 1.0 and Φ = 90°, the transmittance is equal to 1- w/s (the amount of blind that is “open”). When w/s is much greater than one, then even when the blinds are in the open position, the transmittance will still approach zero. This is due to the additional space in which the radiation will reflect within the blind.



$\alpha_{front,eff,LW}$
Slat Angle, ϕ [degrees]
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
-90 -80 -70 -60 -50 -40 -30 -20 -10 0 10 20 30 40 50 60 70 80 90
(w / s = 0.1)
(w / s = 0.5)
(w / s = 0.8)
(w / s = 1)
(w / s = 1.2)
(w / s = 2)
(w / s = 4)
(w / s = 10)



$\rho_{front,eff,LW}$
Slat Angle, ϕ [degrees]
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
-90 -80 -70 -60 -50 -40 -30 -20 -10 0 10 20 30 40 50 60 70 80 90
(w / s = 0.1)
(w / s = 0.5)
(w / s = 0.8)
(w / s = 1)
(w / s = 1.2)
(w / s = 2)
(w / s = 4)
(w / s = 10)

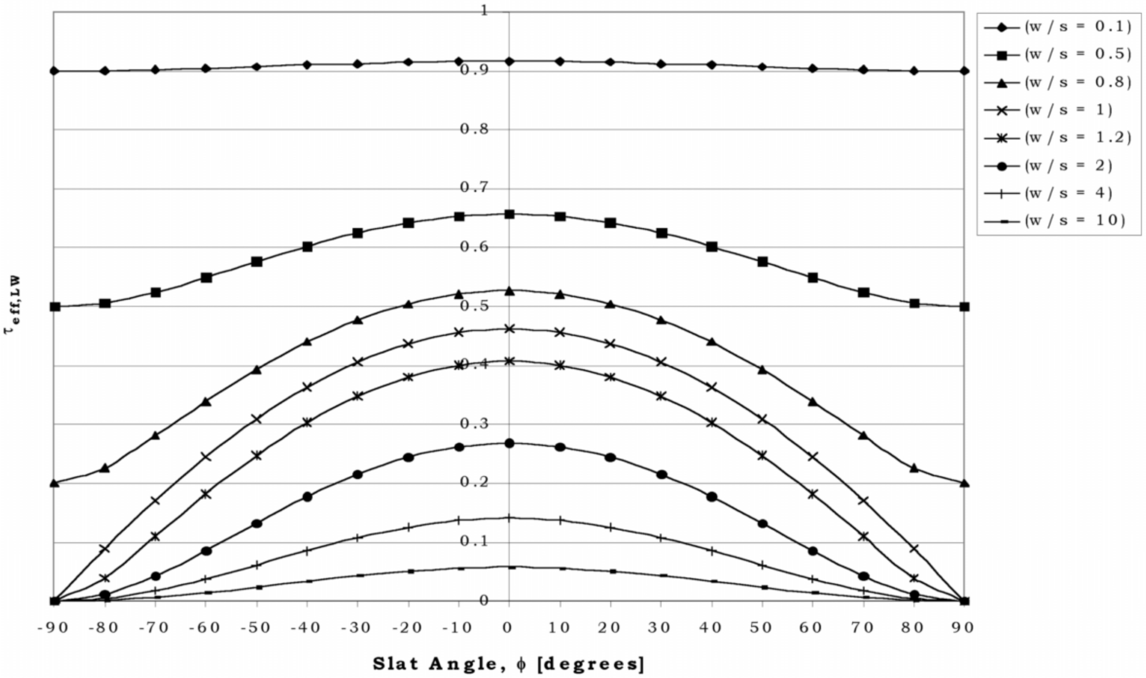


Figure 49: Relationships between slat angle and Absorptance α (top), reflectance ρ (middle), and transmission τ (bottom) for various slat width to spacing ratios (w/s). Image source: Yahoda and Wright (2004). Image used with permission from publisher. ©ASHRAE www.ashrae.org . ASHRAE Transactions, (110), (1).

4.5 Venetian Blind Analysis

Based on the previously discussed studies (Machin et al., 1998, Shahid and Naylor, 2005, Oosthuizen et al, 2005, Yahoda and Wright, 2004), there are a set of criteria that are critical to the performance of venetian blinds. These criteria are slat angle, the distance from the blind to the glass surface, the emissivity of the blinds, the slat width and spacing, and lastly the height of the window.

Figure 50 shows the venetian blind characteristics that can be modified using LBNL *WINDOW*. In addition, the slat material can also be modified based on parameters such as conductivity, solar, visible, and infrared transmittance, reflectance and/or emittance, as well as the size of the space between the glass surface and the centerline of the blind.

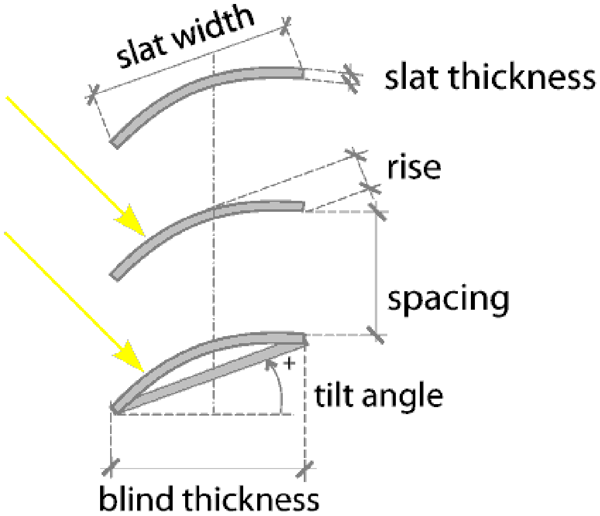


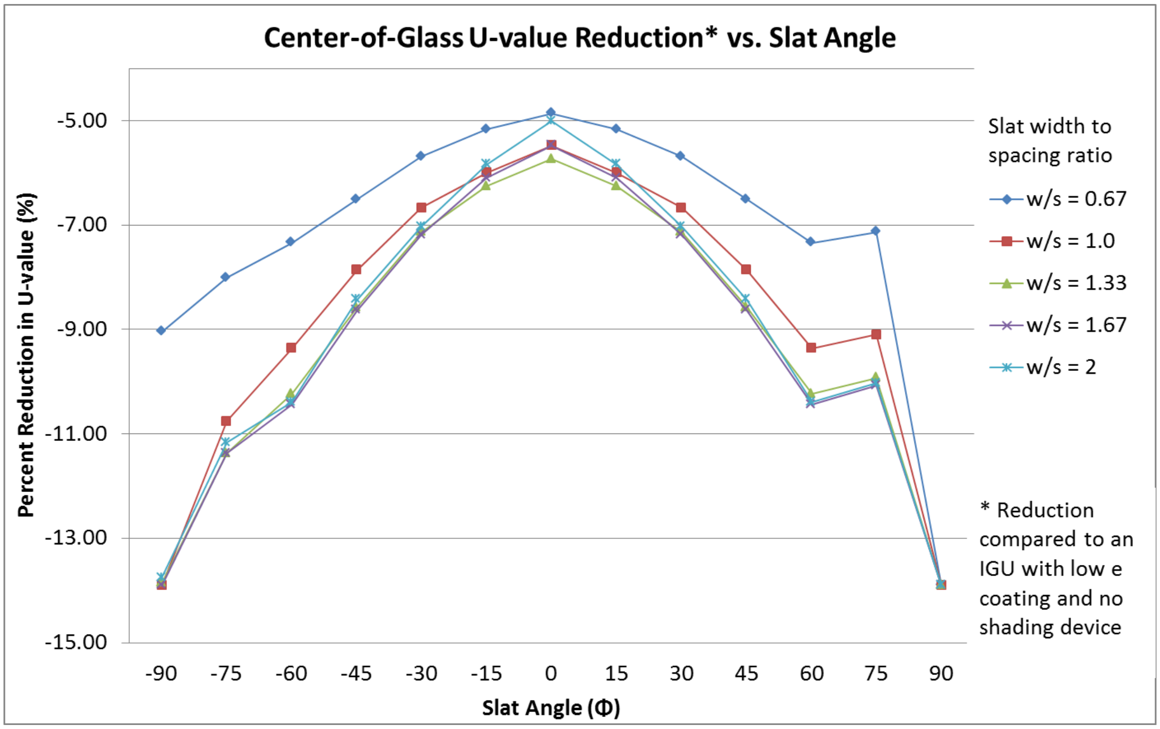
Figure 50: Illustration of venetian blind geometric parameters used in WINDOW. Image Source: LBNL, 2012b.

Each of these properties was evaluated individually and/or in combination with each other to determine the effect of various blind designs. An IGU with a low-e coating on the interior surface of the exterior pane of glass was used for the glazing system in order to establish a baseline for performance. In order to determine the impact of the blinds for a wide variety of different window systems, whole product U-values were assumed for wood, vinyl, and aluminum frames with thermal breaks. In addition, a "center-of-glass" U-value was determined, which assumes an infinitely large glazing area so that "edge-of-glass" framing effects are not present. A sample of the data collected is shown in Table 11. For each part of the analysis, this data was then converted to a percentage improvement over the glazing system with no venetian blind.

Table 11: U-values determined based on variations in slat thickness.

LBNL WINDOW Version	File Name	Blind Properties				U-values (W/m^{2}K)			
		Rise	Material Conductance (W/mK)	Slat Thickness (mm)	Slat Width (mm)	WINDOW Glazing System U-value	WINDOW Wood Framed Picture Window Whole Product U-value	WINDOW Vinyl Framed Picture Window Whole Product U-value	WINDOW Al/break Framed Picture Window Whole Product U-value
6.3.72.0	IGU with Low E (Base)	0	0	0	0	1.934	2.13	2.017	2.681
6.3.72.0	Venetian0_A_0.2_16	0	160	0.2	16	1.667	1.93	1.816	2.469
6.3.72.0	Venetian0_A_0.8_16	0	160	0.8	16	1.664	1.927	1.814	2.467
6.3.72.0	Venetian0_A_1.4_16	0	160	1.4	16	1.661	1.925	1.811	2.464
6.3.72.0	Venetian0_A_2.2_16	0	160	2.2	16	1.656	1.921	1.808	2.46
6.3.72.0	Venetian0_A_2.8_16	0	160	2.8	16	1.652	1.918	1.805	2.457
6.3.72.0	Venetian0_A_3.4_16	0	160	3.4	16	1.647	1.915	1.801	2.454
6.3.72.0	Venetian0_A_4.0_16	0	160	4	16	1.643	1.911	1.798	2.451
6.3.72.0	Venetian0_A_4.6_16	0	160	4.6	16	1.638	1.908	1.795	2.447
6.3.72.0	Venetian0_A_5.2_16	0	160	5.2	16	1.633	1.905	1.792	2.444

The first criteria to be investigated was the slat angle. This analysis was first performed for the center-of-glass region for several different slat width to spacing (w/s) ratios. Note that w/s ratio less than one means that the blind will not completely close in the 90° position, as the slat width is less than the spacing between adjacent slats. When the w/s is greater than one, there will be an overlap in the slats when closed. The results of this study are shown in Figure 51. The results were then repeated for a w/s of 1.33 and for several different framing options (Figure 52).



* Reduction compared to an IGU with low e coating and no shading device

Figure 51: Reduction in center-of-glass U-value vs. slat angle for several different slat width-to-spacing ratios.

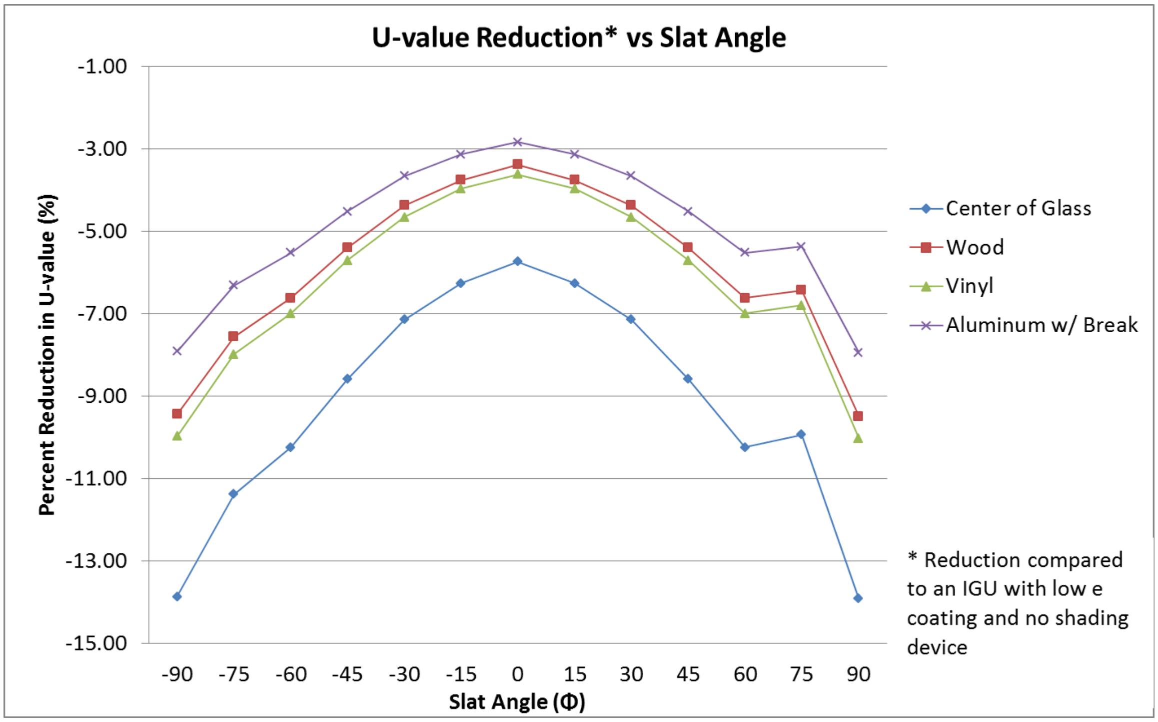


Figure 52: Reduction in U-value vs. slat angle

Figure 51 illustrates the importance of the w/s ratio for various slat angles. When the slat angle does not equal 0°, the variance for w/s ratios greater than 1 is marginal. When the slat angle is 0°, there is about a 1% variance in performance for w/s greater than one. Based on the findings of Yahoda and Wright (2004), this variance can be attributed to a decreased shading absorptance and transmittance properties at this angle. When w/s is less than 1, the variance from the rest of the ratios is more pronounced. This variance is also in line with Yahoda and Wright, who found that the absorptance, reflectance, and transmittance properties of the blind vary more dramatically for w/s less than one.

When the effect of this criterion was evaluated for the SHGC (Figure 53), it was found that blinds with a width-to-spacing ratio of greater than 1 all performed similarly, reducing between 0% and 50% for blinds in the 0° and ±90° positions, respectively. For blinds with width-to-spacing ratios less than 1, the blinds increased the solar heat gain in the 0° position by nearly 15% and reduced the SHGC by about 23% in the ±90° position. Since the blinds are located on the interior of the glazing, they have a limited effectiveness at reducing solar heat gain. As will be seen later, blinds located on the exterior of the glazing are much more effective in this regard.

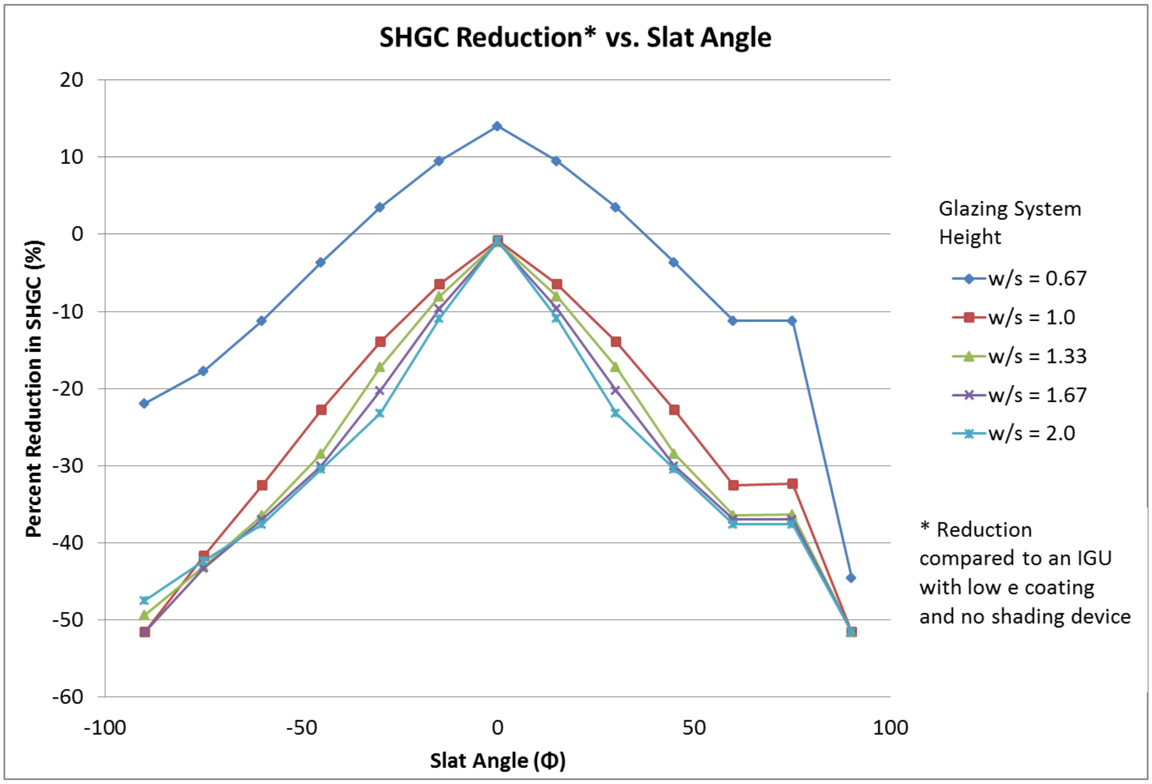


Figure 53: Reduction in SHGC vs. slat angle for several width-to-spacing ratios

The next criterion investigated was the effect of the width of the shading cavity. This width is defined as the distance between the interior surface of the glass to the centerline of the shade. For this analysis, the shades were in the closed (90°) position. The study was then repeated for several other glazing system heights. The results are shown in Figure 54. For a window with a height of 1500mm (that of the previous investigations), the width of the shading cavity can affect the performance of the system by about 1%. As the height of the glazing system is increased, the effect of the size of the shading cavity becomes slightly more pronounced, resulting in closer to 2% of a variance.

The results of the study by Machin et al. (1998) show that there was a performance peak at about 14.5 mm. This particular feature was not found in the present study. In fact, for short windows, it was found that a shading cavity of ~15mm actually produces the *worst* results. However, it should be noted that those results were specifically for convective heat transfer. In addition, the role of the framing was not taken into account in that study. This seems to indicate that the role of radiative heat transfer is less dependent on the cavity width. In addition, the effect of the more highly conductive framing has the effect of lessening the effect of this particular feature for the size of windows investigated.

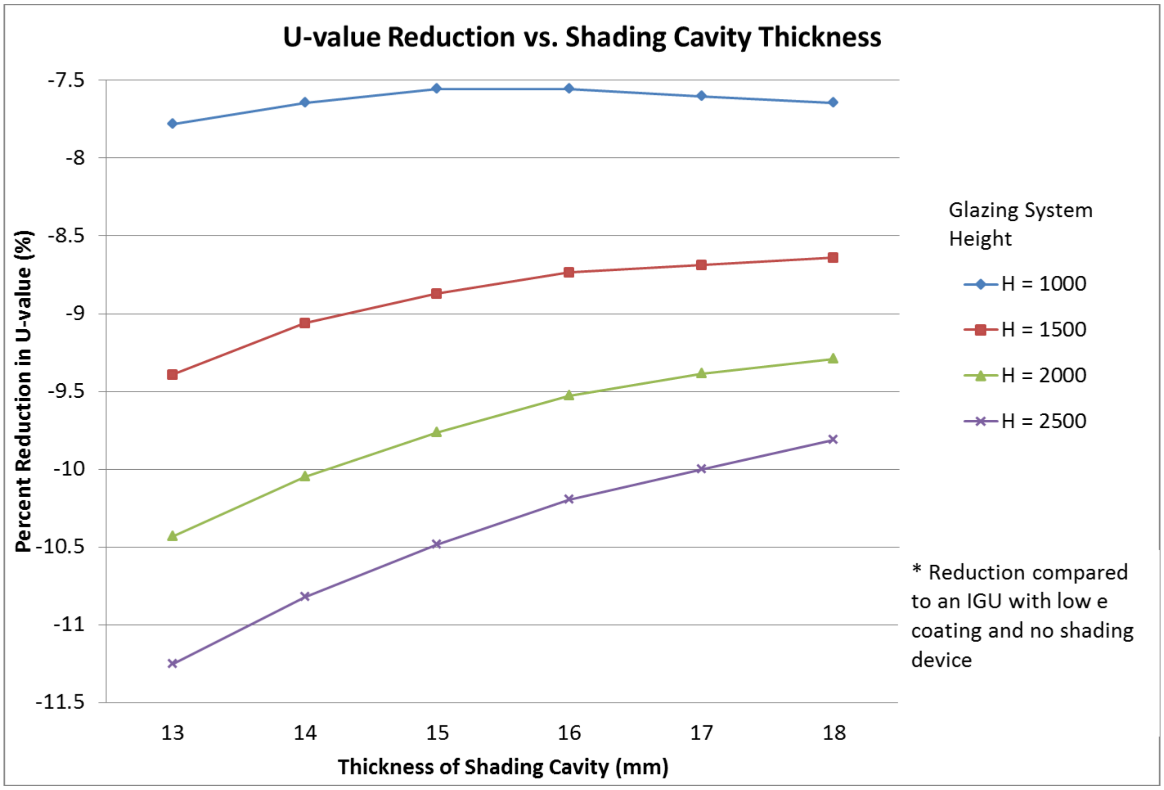


Figure 54: Reduction in center of glass U-value vs. shading cavity thickness for several different window heights.

The next criterion investigated involved the optical qualities of the material used for the slats. There are three types of radiation that are of interest to the performance of shading systems. The first two types are radiation in the solar or visible portions of the electromagnetic spectrum. These wavelengths can be either transmitted through the blind or reflected. Variations in these variables will primarily affect the SHG (solar spectrum) and visual transmittance (visible spectrum) of the system. The default values for opaque white blinds were used ($T_{sol} = 0$, $R_{sol} = 0.7$, $T_{vis} = 0$, $R_{vis} = 0.7$) to account for these effects. The third type of radiation is in the infrared spectrum (heat). This quantity will be of primary interest for the purposes of reducing the thermal transmittance of a glazing system. To determine the effect of these variations, the transmittance (T_{IR}) was set to 0, and values for the emissivity were varied between 0 and 1.0. The results of this variation are shown in Figure 55.

Compared to the other variables examined thus far, it is clear that emissivity has a dramatic effect on the performance of venetian blinds. Variations in emissivity can account for between ~8 and ~15% reduction in U-value. These center-of-glass results are consistent with those of Shahid and Naylor (2005). The effect of the framing materials on the performance of the system is also shown. The increased performance obtained from using low-emissivity solutions is lessened for highly conductive frames (~11%) compared to low-conductivity framing solutions (~15%).

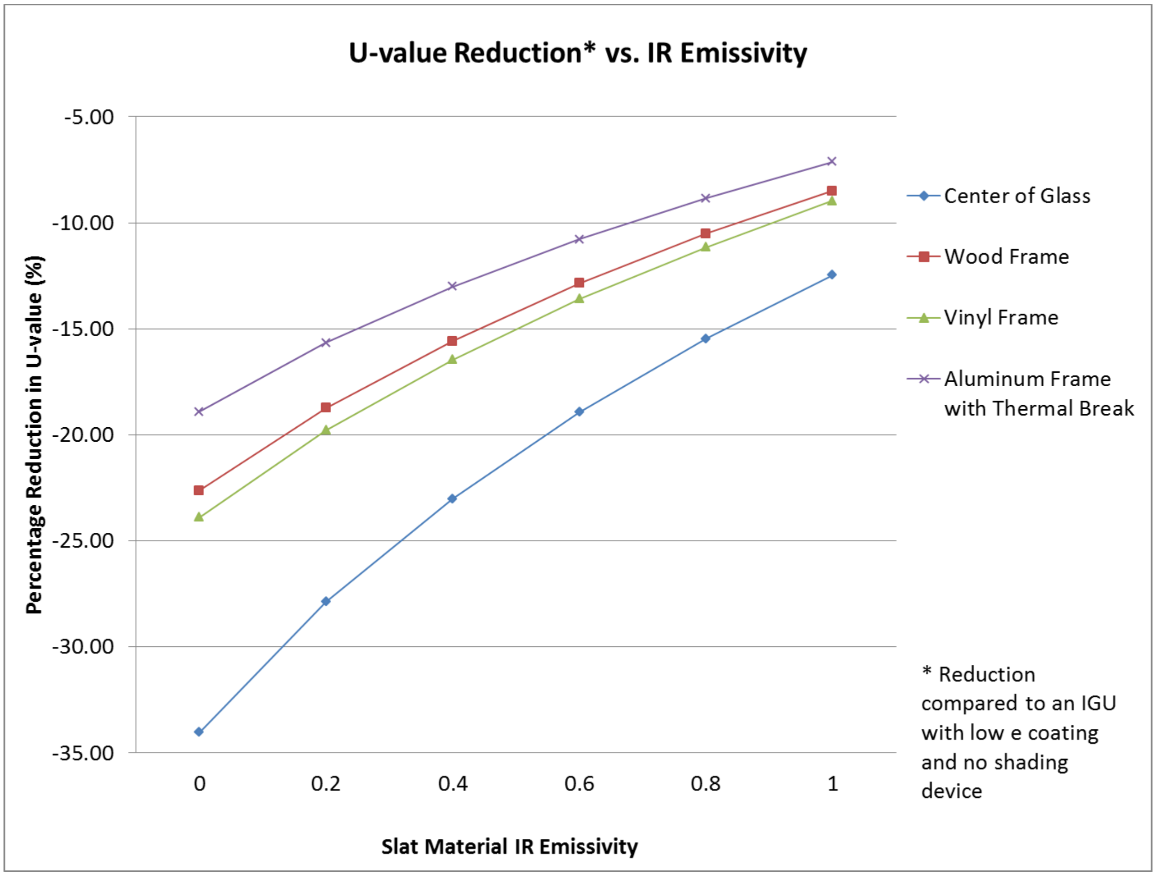


Figure 55: Reductions in U-value obtained based on variations in IR emissivity.

The effect of slat rise was investigated next. Recall from Figure 50 that this characteristic is essentially a description of the curvature of the slats. This criterion was investigated for slats with rises between 0.25-2.25 mm (0.009-0.088 inches). The slat thickness and width were maintained at 0.6mm and 16mm, respectively. The results are shown in Figure 56. For variations in the range of slat rises investigated, it was found that regardless of frame type used, the rise of the slats will only account for a variation in U-value of less than 0.5%. It can therefore be concluded that the impact of slat rise is negligible.

One interesting effect can be observed in Figure 56. As the slat rise increases, there is a slight oscillating behavior in the performance of the blind. Yahoda and Wright (2004) noted that the effect of slat curvature was minimal for large curvatures (low rises using our terminology), but that it is likely that the effect would become more pronounced when the radius of curvature is very slight (large rise values). However, the oscillating behavior of the shades was not noted in their study. This likely indicates that the oscillations are a function of the algorithms used by WINDOW.

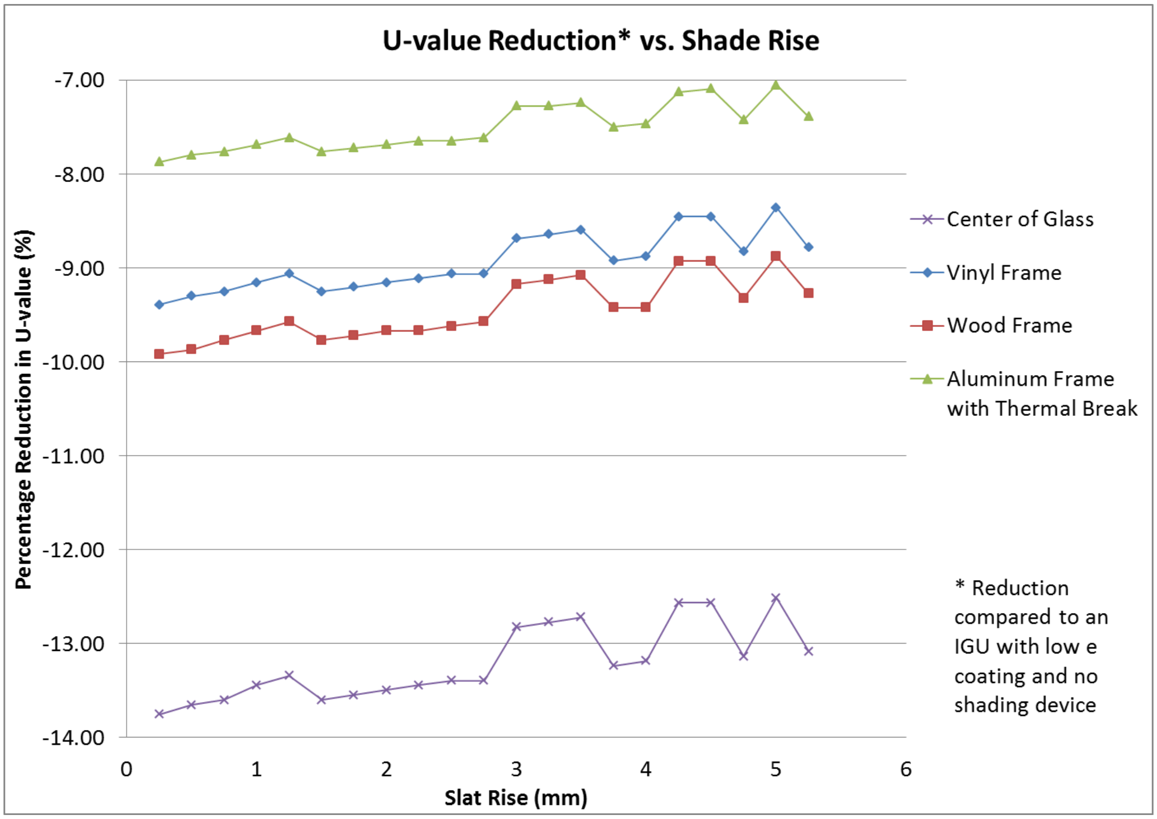


Figure 56: U-value reduction based on variations in slat rise.

The effect of the openness fraction (effective openness) was then investigated. Recall that the openness factor is a measure of the open areas or “holes” in the central portion of the shade through which air can move. In effect, this is a measure of how ventilated the cavity is. The results for openness factors of between 0 (perfectly sealed) and 1 (perfectly open) are shown in Figure 57 for shades in the 90° position. Shades with less than five percent openness are able to achieve significant improvements in performance, while those with greater than 5% openness were very consistent. It is important to remember, however, that most shades currently on the market are not able to achieve a completely sealed condition when closed (Machin et al., 1998) and that a 5% openness was assumed to be the standard conditions for shades at 90°. Investigation of designs that could allow for the 0% openness condition could be an area for future study.

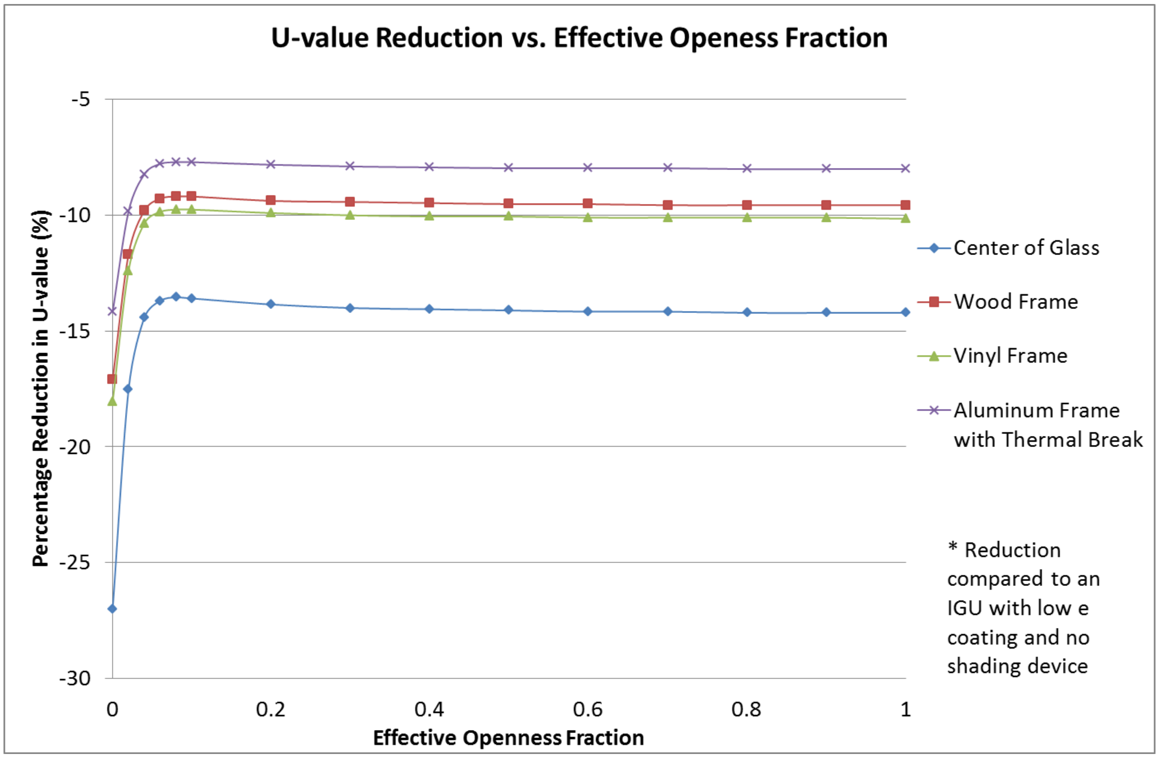


Figure 57: Reductions in U-value as a function of effective openness

The effect of slat thickness was next investigated. For this analysis, it was assumed that the blinds are in the completely closed position, with a 16 mm (0.63 inches) slat width, a 12 mm (0.47 inches) spacing, and a 0 mm rise. It was assumed that the slats would be in the fully closed condition, as is appropriate for nighttime use when improvement in U-value is most critical. For the initial portion of this analysis, a material conductivity of 160 W/mK was used. The results of this study are shown graphically in Figure 58.

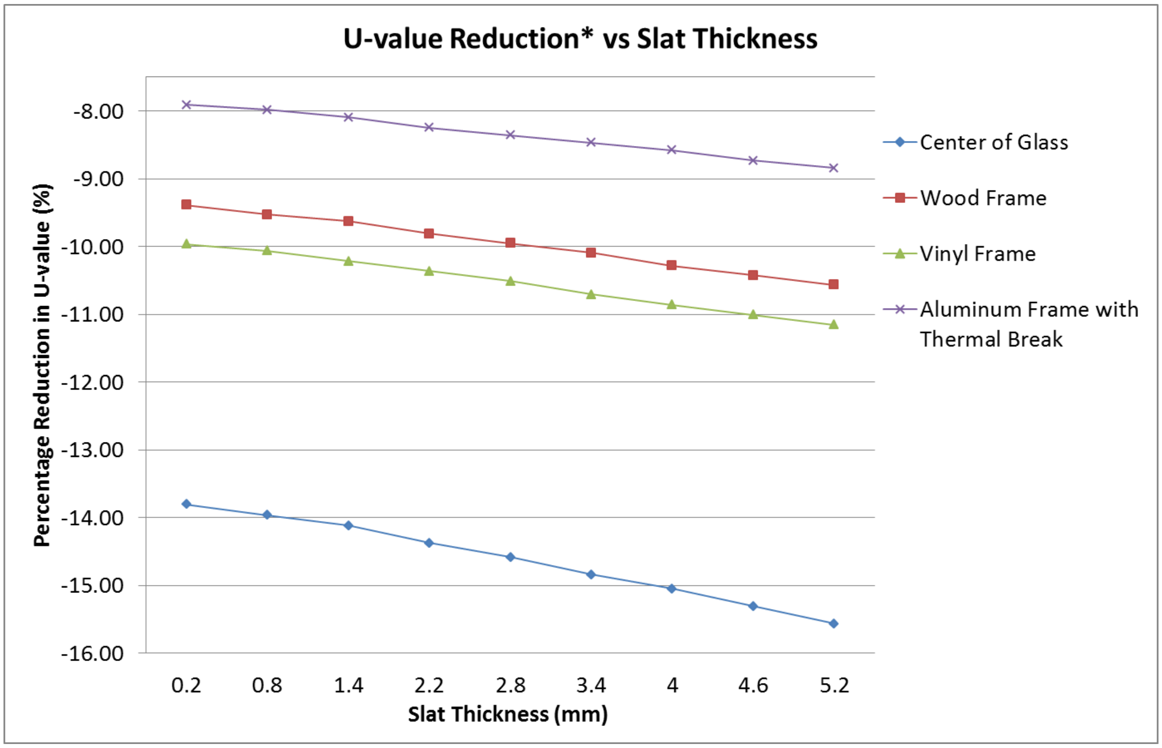


Figure 58: U-value reduction achieved using venetian blinds of various slat thicknesses.

As can be seen in Figure 58, the blind performance improves as the thickness of the slats increases. Over the range of thicknesses examined, the center-of-glass U-value improvement will range of ~13-15% as compared to an IGU with no shading device. The type of window frame present in the system will have a large effect on the performance of the shade. More thermally conductive frames will dominate the performance of the glazing system, allowing the shade to have only a small impact on the improvement of the system. Regardless of the impact of the frame material, variations in the thickness of the slats will only result in a 1-2% variation in shading performance. Therefore, it can be concluded that slat thickness will not be a primary factor affecting shade performance.

In order to determine exactly what role conductance plays in the performance of venetian blinds, the analysis was repeated for conductivities of 200 W/(mK) and 120 W/(mK). For this particular analysis, only center-of-glass U-values were considered. The results of this analysis are shown in Figure 59. This analysis showed that the conductance of the material used for the slats has no effect on the performance of the shade system, as all variations coincide. This makes sense, as thermal performance of the slats is based on reducing radiative and convective heat flow. Since the blinds are such a thin, highly conductive feature of the system, it makes sense that conductance will not be a driving feature of their performance.

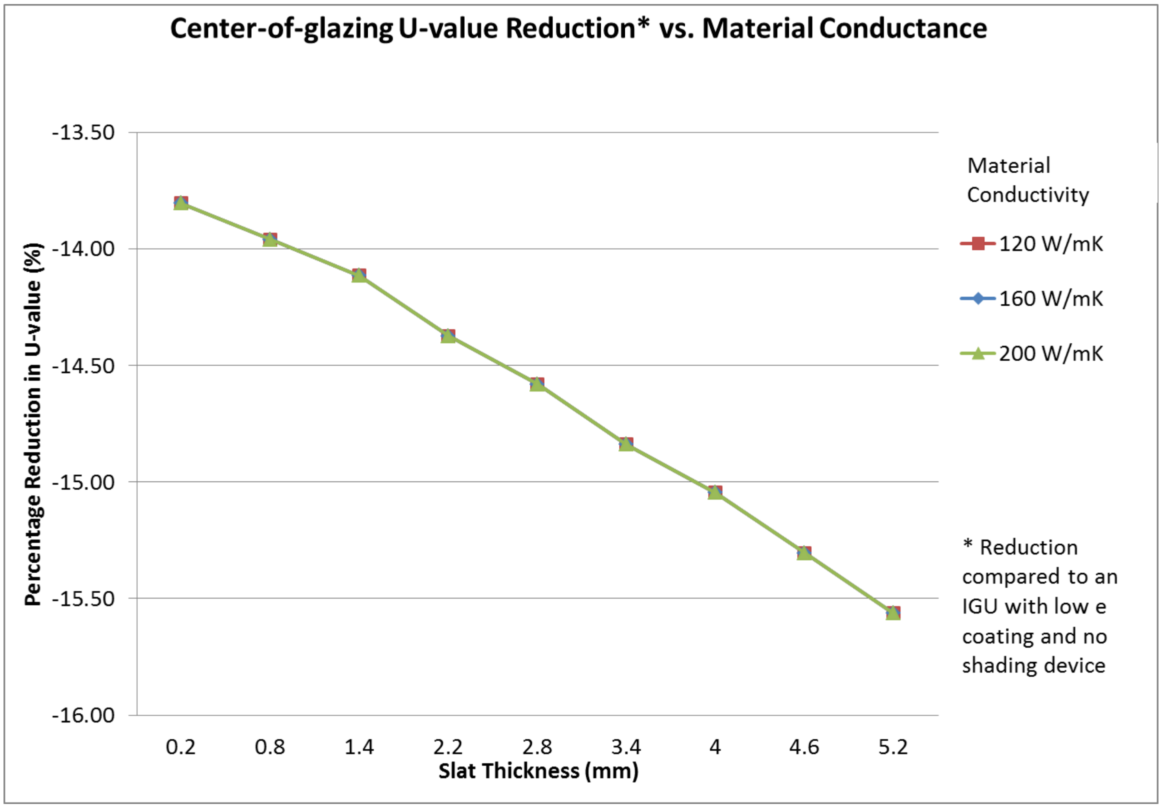


Figure 59: U-value reduction achieved based on the conductance of the shading material used.

From the criteria previously investigated, it can be concluded that the two venetian blind features that are most likely to drive the performance of the system are the openness of the shade and the emissivity of the slat material. A further study was then conducted to evaluate the combined effect of both of these features. The center-of-glass U-values were calculated for systems with openness fractions between 0 and 0.12 and varying emissivity. The results of this study are shown in Figure 60, which seem to indicate that for low-emissivity blinds, with an openness condition of about 2%, approximately 15% to 40% reduction in U-values could be achieved depending on the slat material emissivity. If a 0% openness condition could be reached, this improvement can be increased from 25% to 60%, depending on the slat material emissivity.

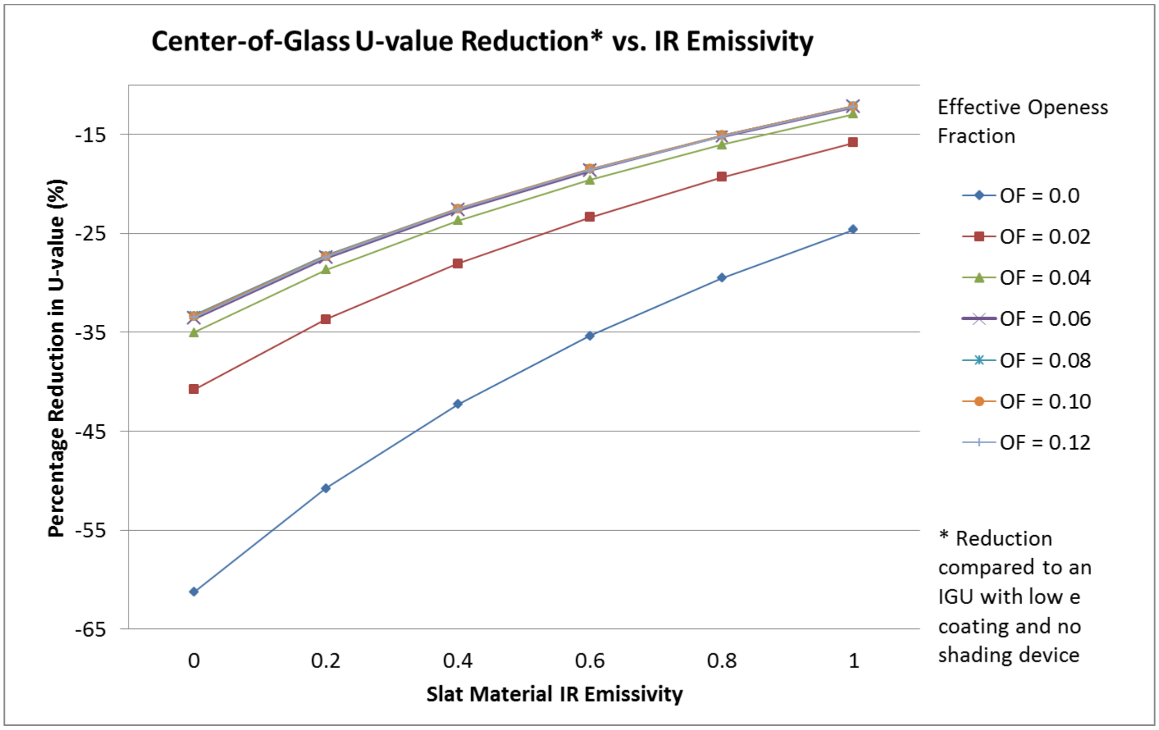


Figure 60: Reductions in center of glass U-value vs. IR emissivity and openness fraction

The analysis was then repeated to examine the effect of venetian blinds on the exterior side of the glazing. It was found that the venetian blinds reduced the U-value by 20-25% in the center of glass region. The results of this study are shown in Figure 61. Note that the data shown for wood framing was limited to slat angles of -60° to +90°. The data corresponding to slat angles beyond this seemed to be corrupted. The reason for this was not clear, but one possibility seems to be related to internal modeling assumptions.

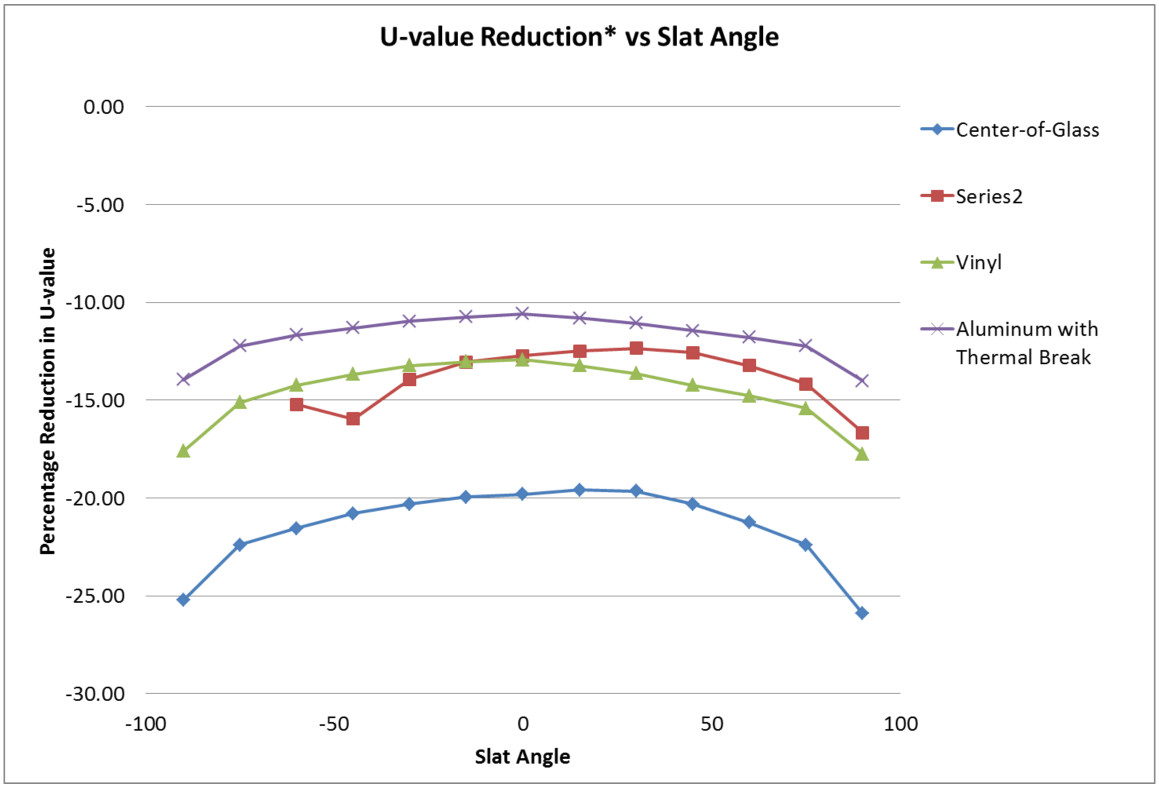


Figure 61: Reductions in U-value vs. slat angle for exterior venetian blinds

The slat angle had a significant effect on solar heat gain reduction for exterior shades, as is shown in Figure 62. When the slats are in the closed position, the SHGC is reduced by nearly 100%. As the slat angle approaches 0°, however, the reduction decreases. At 0°, there is actually an increase in solar heat gain. This seems to imply that the shades have a magnifying effect at this angle.

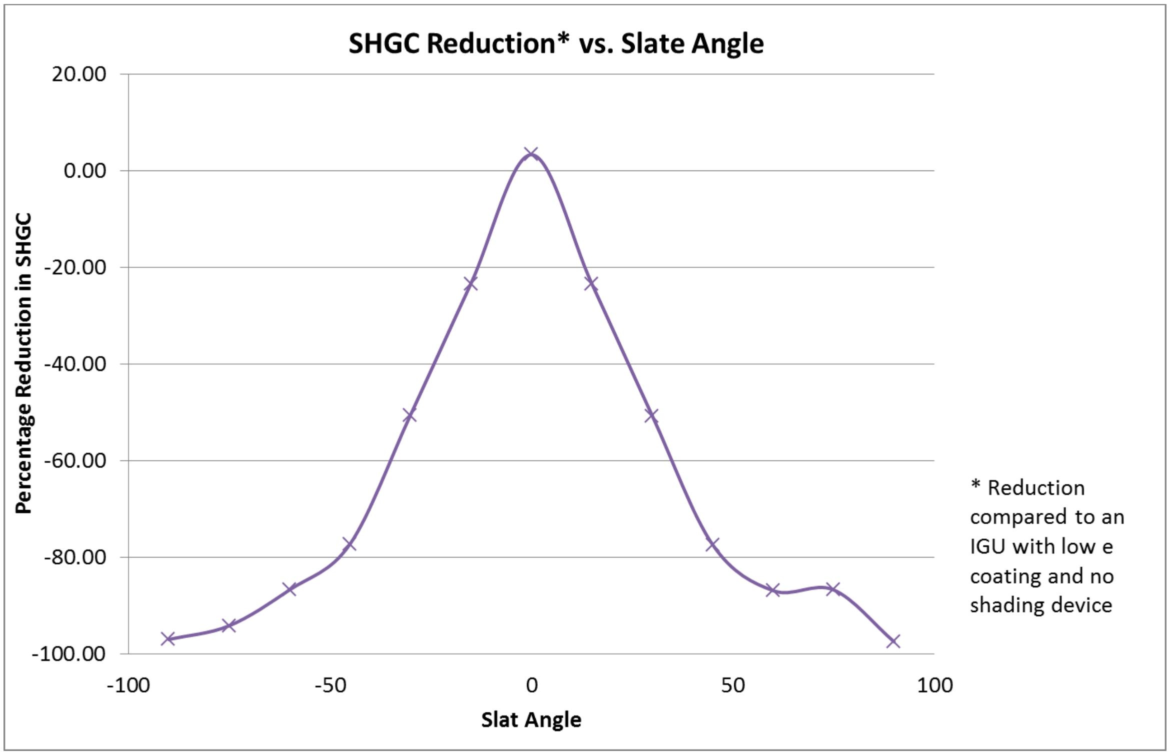


Figure 62: Reductions in SHGC vs. slat angle for exterior venetian blinds

4.6 Venetian Blind Analysis Summary

Numerous criteria were investigated in this portion of the study, including slat angle, the slat width to spacing ration (w/s), shading cavity thickness, infrared emissivity, openness fraction, slat thickness, and material conductivity. It was found that the least effective criteria was material conductivity, which resulted in no change in performance. The most effective criteria was emissivity of the blinds and the effective openness of the system, which reduced the U-value by as much as 35% and 27.5%, respectively. When these criteria were combined, it was found that up to a 60% reduction in U-value could be achieved. The results of the U-value analysis are shown in Table 12.

In the winter, when it is desired to utilize solar heat gain while also reducing the U-value, venetian blinds can be left in the 0° position during the day rather than retracted entirely. In such cases, the blinds will still be effective at slightly reducing the U-value without any reduction in SHGC. If the shades are located on the exterior of the building, they will actually allow for more solar heat gain.

Table 12: Summary of center of glass U-value (top) and SHGC (bottom) reductions for venetian blinds

Criteria Explored	Range of U-value Reduction (%)	Reference Figure
Slat Angle Width to Spacing Ratio (w/s)	4 - 14	Figure 51
Slat Angle Frame Type	6 - 14	Figure 52
Shading Cavity Thickness Glazing Height	7.5 - 11.5	Figure 54
IR Emissivity Frame Type	12.5 - 35	Figure 55
Shade Rise Frame Type	12.5 - 13.75	Figure 56
Openness Fraction Frame Type	13 - 27.5	Figure 57
Slat Thickness Frame Type	13.75 - 15.5	Figure 58
Slat Thickness Conductivity	13.75 - 15.5	Figure 59
Openness Fraction IR Emissivity	25 - 60	Figure 60
Slat Angle (Exterior) Frame Type	11 - 26	Figure 61

Criteria Explored	Range of SHGC Reduction (%)	Reference Figure
Slat Angle	-15 - 50	Figure 53
Slat Angle (Exterior)	-5 - 95	Figure 62

5. Fabric Shade Style Attachments

5.1 Interior Curtains and Draperies

Curtains or draperies are a common feature of many homes. They are made with a variety of different materials in various styles and are typically used primarily for decoration (Figure 63). However, they can provide insulation and solar shading depending on the fabric type and installation details.

Figure 63: The use of curtains made of thick fabrics can greatly increase the insulative capacity of windows when properly utilized. Image source: Brezza, 2012

Thermal Improvement

In order for curtains to be effective for heat management, they must have three important features (Langdon, 1980.)

- **Perimeter Sealing:** When curtains hang in front of a window, the cold air in the interstitial space between the curtain and the glass can travel freely into the room through convection. In order for the curtain to be truly effective as a means of insulation, the top, bottom, and edges of the curtain must be able to be sealed from air movement.
- **Air Barrier:** In order to prevent heat transport through the curtains, they must have a layer that will be impervious to air transport.
- **Insulation:** The curtains may use a variety of means to prevent heat flow. This can include air gaps, foil reflectors, or a fill material.

Many products are available that claim to prevent heat flow through windows, but they will be ineffective if they do not meet all of the properties described above. Products purchased on the market typically require modification to create a perimeter seal around the curtain upon installation. Figure 64 illustrates several of the measures that can be taken to accomplish this. The bottom of the full length curtains can be sealed by weighting the bottom of the curtains to insure they firmly press against the floor. Other methods include the use of magnetic strips, elastic cords or brackets. The sides of the curtains should be attached to the molding around the window. The top of the curtain can be sealed using a variety of different window valences. Lastly, the center-of-curtains should be sealed as well. This can be accomplished using magnets sewn into the fabric.

When the CCHRC modeled the performance of a fleece curtain using THERM, they found a 38% improvement could be achieved over a double glazed window. When they tested the performance of this curtain in the field with a triple-pane window, they found that only a 17% improvement occurred (Craven and Graber-Slaght, 2011).

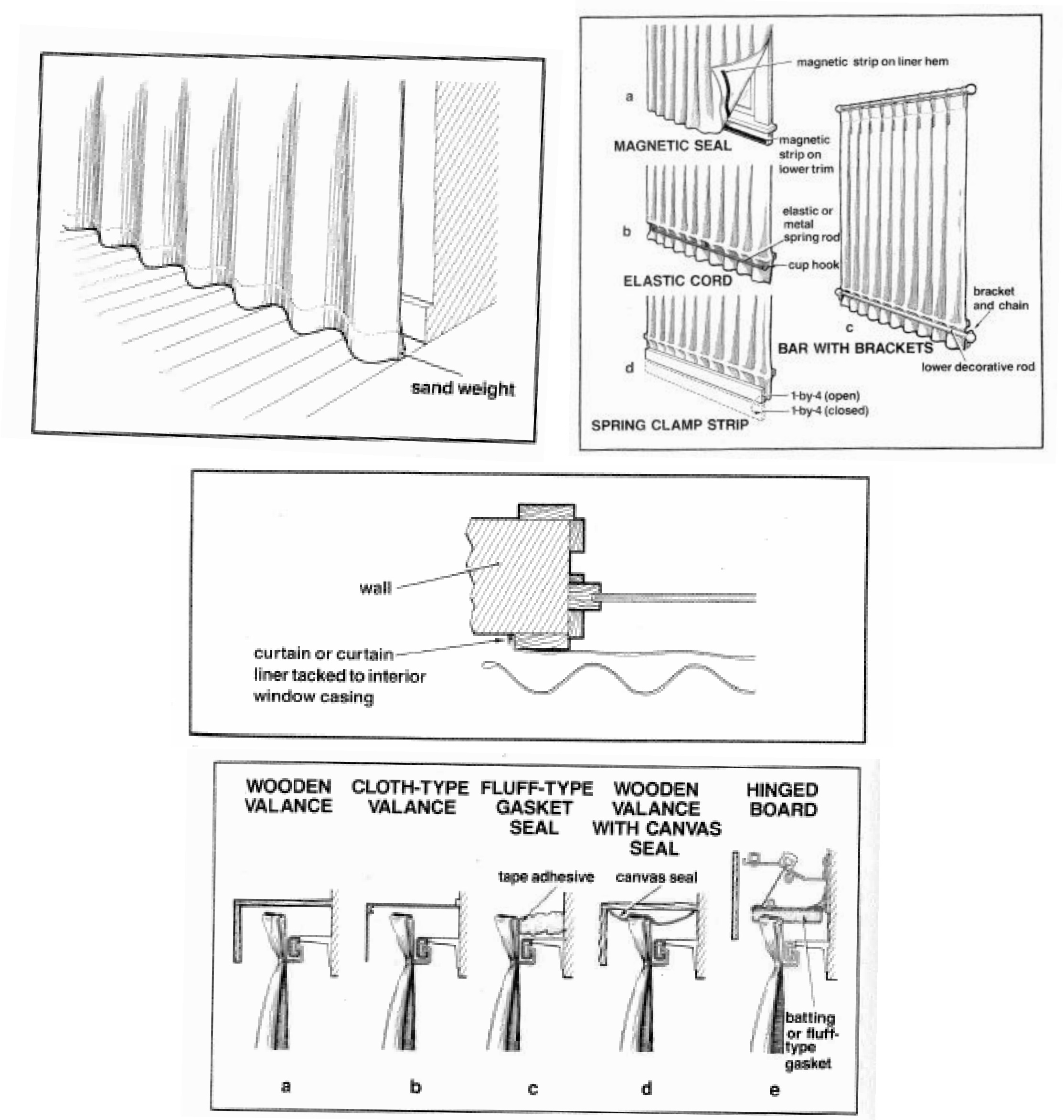


Figure 64: Various options for sealing the perimeter of curtains. Top-Left – Weights such as sand can be used to ensure full length curtains create a firm contact with the floor. Top-Right – Methods for sealing the bottom edge of curtains. Middle – The curtain should be tacked to the molding. Bottom – Methods for sealing the top of curtains. Image source: Langdon, 1980.

Comfort

Even if measures are not taken to thoroughly seal the top, sides, and bottom of curtains, they will still do an excellent job of improving the thermal comfort of the space.

Condensation Potential

Since curtains will not increase the temperature of the glazing, condensation can be a big problem for this system. This is particularly true for curtains that are not completely sealed around the perimeter, yet do not allow enough air movement to dry out the space. One method of reducing the risk of condensation is to utilize designs featuring a moisture barrier layer as well as an air barrier. This will help reduce the amount of humid air that contacts the glazing.

Air Leakage

If the curtains are well-sealed and are made of a suitably air impermeable material, they will do an excellent job of preventing air leakage through both the sashes as well as the frame.

Cost

Three different varieties of thermally efficient curtains are sold at Walmart (Figure 65) as an example of a retail store with affordable options.

- Eclipse *Thermaback* Panels – These have a thermal coating on the interior facing (glazing side) of the fabric. They cost $9.87 for a 42”x63” panel, two of which are needed for a single window. Therefore, these drapes would cost $19.74 per 30x60 window.
- Eclipse *Thermaweave* Panels- These panels include the thermal coating of the Thermaback panels as well as an extra insulative weave to help add to the insulative properties of the system.
- Eclipse *Thermalayer* Panels – These panels include the features described above as well as a blackout fabric to completely stop light transmittance.

Figure 65: Three different grades of Eclipse curtain panel products for energy efficiency are available. Image Source: Ellery Homestyles, 2013

Other varieties

- Style selections *Energy Saving Blackout Curtain* – These drapes have a thermal backing which helps provide additional insulation. They cost $14.99 per 40”x63” Panel, two of which are needed for each window. This brings the total cost to $29.98 (Lowes, 2013).
- Style Selections *Back Tab Panel* – This is a standard drape made of a light fabric. These are generally selected for their aesthetic value only. They cost $12.97 each, resulting in a total window cost of $25.94 (Lowes, 2013).

Impact on Daylighting

Depending on the style used, curtains and draperies will dramatically reduce daylighting potential of the windows. In general, curtains that are most effective at providing thermal insulation will also block the most amount of light.

Ease of Operation

Curtains and draperies are simple to operate for any easily accessible window.

Aesthetics

Curtains are often selected specifically for their aesthetic attributes. However, the measures that must be taken to seal the perimeter of the drapes may create a more significant aesthetic impact that will be perceived as negative to some users.

The at-a-glance performance diagram for curtains and draperies is shown in Figure 66.

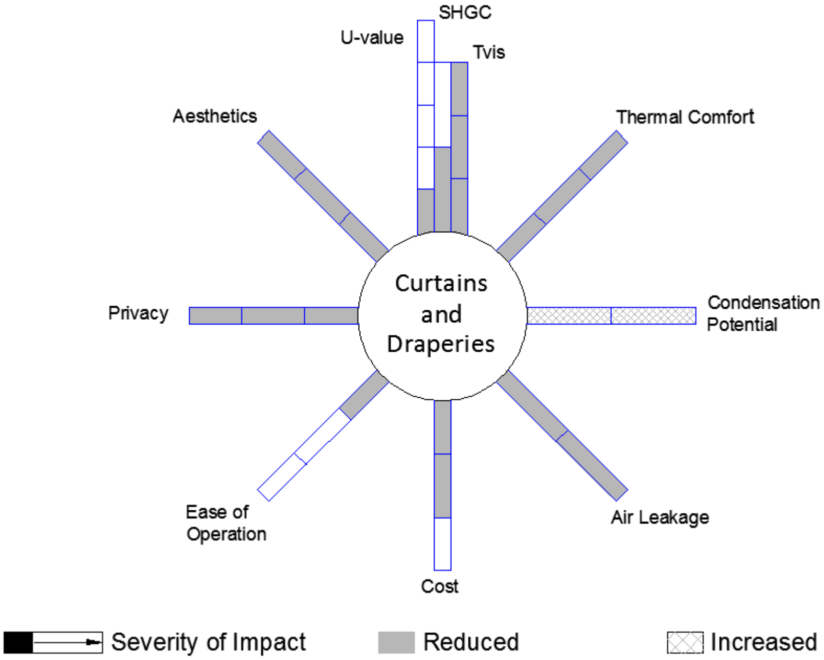


Figure 66: At-a-glance performance diagram for curtains and draperies

5.2 Interior “Roller” Shades

Rolling shades are a style of fabric shade that are installed on either the interior or exterior of the building to block solar heat gain or create privacy. These shades can either roll up within the valence (Figure 67) or have a “Roman Shade” setup in which fabric folds up at the top (Figure 68). They are available in a variety of different materials and colors with varying transparencies.

Figure 67: Interior roller shades can be made from a variety of different fabrics. Image source: Levolor, 2013.

Figure 68: Roman shades fold up and down the window. Image source: Levolor, 2013.

Thermal Improvement
The primary benefit of this system will be in solar heat gain reduction. Since the material used for these shades is typically not very thick, they offer little improvement in terms of thermal resistance. Models featuring thicker fabrics could be effective at improving thermal insulation of the system if measures are taken to seal around the perimeter of the shades.

Comfort
Thermal shades will provide an effective barrier between the interior space and the surface of the glass. This will result in an improvement in the thermal comfort of the space.

Condensation Potential
Interior fabric shades limit airflow along the surface of the glass without raising the temperature of the interior surface. This combination will increase the likelihood of condensation. Exterior shades, on the

other hand, are likely to slightly reduce the interior glazing temperature, which will have a slight decrease on the likelihood of condensation.

Impact on Daylighting

The effect on daylighting will vary based on the specific materials used for the shades. Some shades only provide light shading, while others will completely block all light. Some shades even provide a mechanism that allows them to be opened from the top *as well as* the bottom, in order to achieve a greater variety of lighting conditions.

Air Leakage

These shades will not affect the air leakage into the space. Even if the shades are thoroughly sealed around the perimeter, the materials used for these shades are typically air permeable and will not prevent air transmission.

Cost

These shades can cost anywhere between $128 per window for basic roller shades to $278 for high-end roman shades (Lowes, 2013).

Ease of Operation

The amount of work needed to operate this system will vary based on the size and location of the window, as well as the location on which the shade is mounted. Mechanical operation may be a practical necessity for outdoor applications.

Aesthetics

Rolling style shades have a minimal impact on the aesthetics of the interior or exterior space. In addition, valence used to contain the roller is much smaller than that required for similar window attachment methods such as insulating roller shutters.

The at-a-glance performance diagram for roller fabric shades is shown in Figure 69.

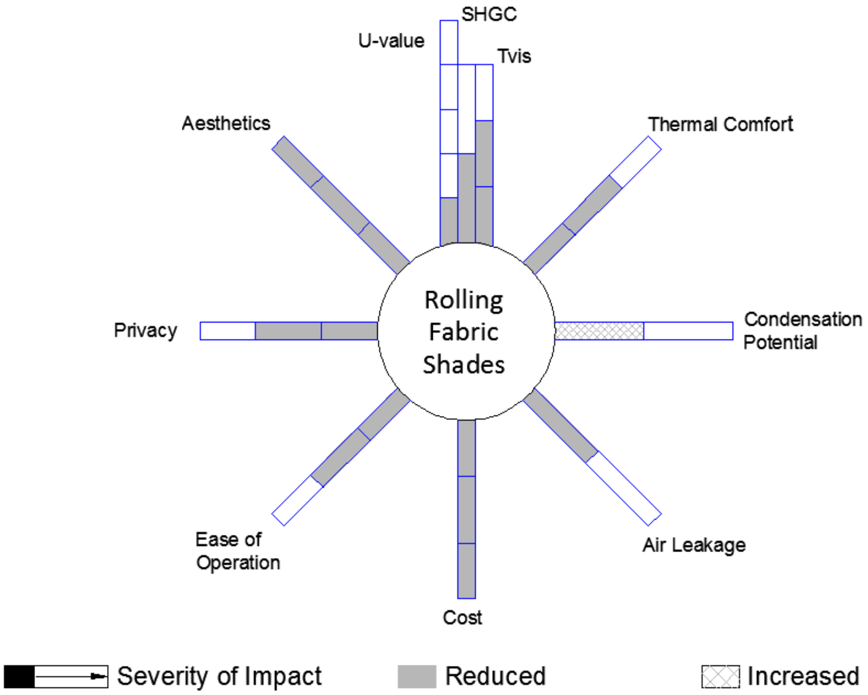
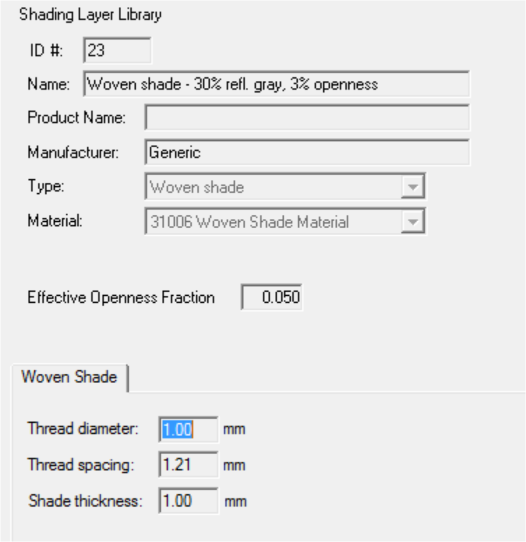


Figure 69: At-a-glance performance diagram for rolling fabric shades

5.3 Fabric Shade Analysis

WINDOW provides several options for creating a custom woven fabric shade. The criteria that affect the performance of the shade are thread material, thread width, and thread spacing (center-to-center spacing), shade thickness, and the openness fraction. These criteria are shown in Figure 70. As with venetian blinds, the openness fraction is not inherently tied to the thread spacing in the program algorithms despite the obvious relationship between the two criteria.



Shading Layer Library

ID #: 23

Name: Woven shade - 30% refl. gray, 3% openness

Product Name:

Manufacturer: Generic

Type: Woven shade

Material: 31006 Woven Shade Material

Effective Openness Fraction 0.050

Woven Shade

Thread diameter: 1.00 mm

Thread spacing: 1.21 mm

Shade thickness: 1.00 mm

Figure 70: Screenshot from LBNL WINDOW showing important parameters for shade selection. Image source: LBNL, 2012b.

The first criterion investigated was the effect of thread spacing. For this analysis, the thread diameter and the shade thickness were both maintained at 1mm. The effective openness factor was set to 0.05. The results of this study are shown in Figure 71. It can be seen that the performance of the shade is highly dependent on the spacing of the threads. The best performance is achieved for shades with close spacing. As the spacing is increased, the performance is reduced by nearly 6% over the range of spacings investigated. It is important to note, however, that WINDOW treats the openness fraction as an independent variable from thread spacing. It is likely that an openness fraction of 0.05 is inappropriately low for these shades, particularly those with a wider thread spacing. Improved correlations between thread spacing and openness factor are important in order to obtain more accurate results.

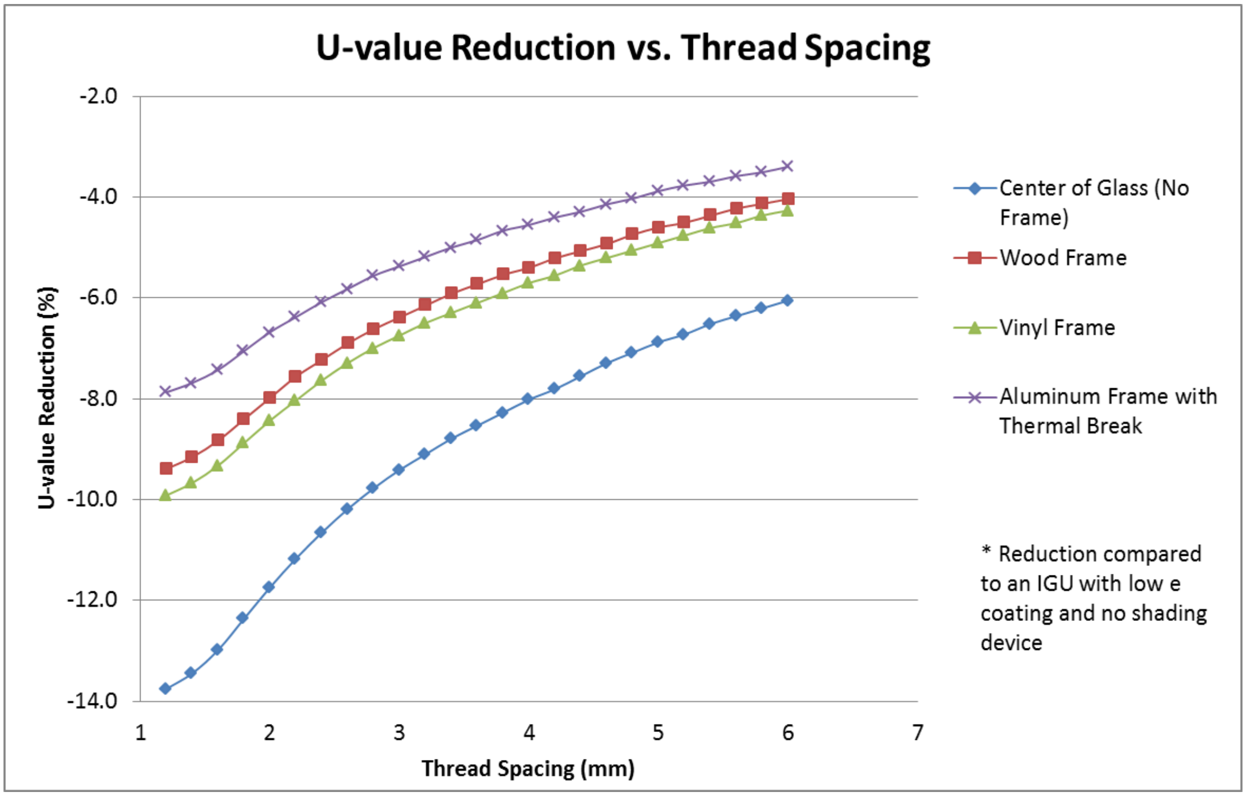


Figure 71: Reduction in U-value vs. thread spacing

To evaluate the effect of the openness fraction on this behavior, various openness fractions were studied (Figure 72). In this study, it was shown that the behavior of the system is essentially the same for all openness fractions. However, there was an unexpected result as well. This analysis demonstrates that for woven shades, the performance of the system (measured by reduction in U-value) improves for higher openness fractions. This is the opposite of the effect that was observed for venetian blinds, in which the performance worsened with higher openness fractions (Figure 57).

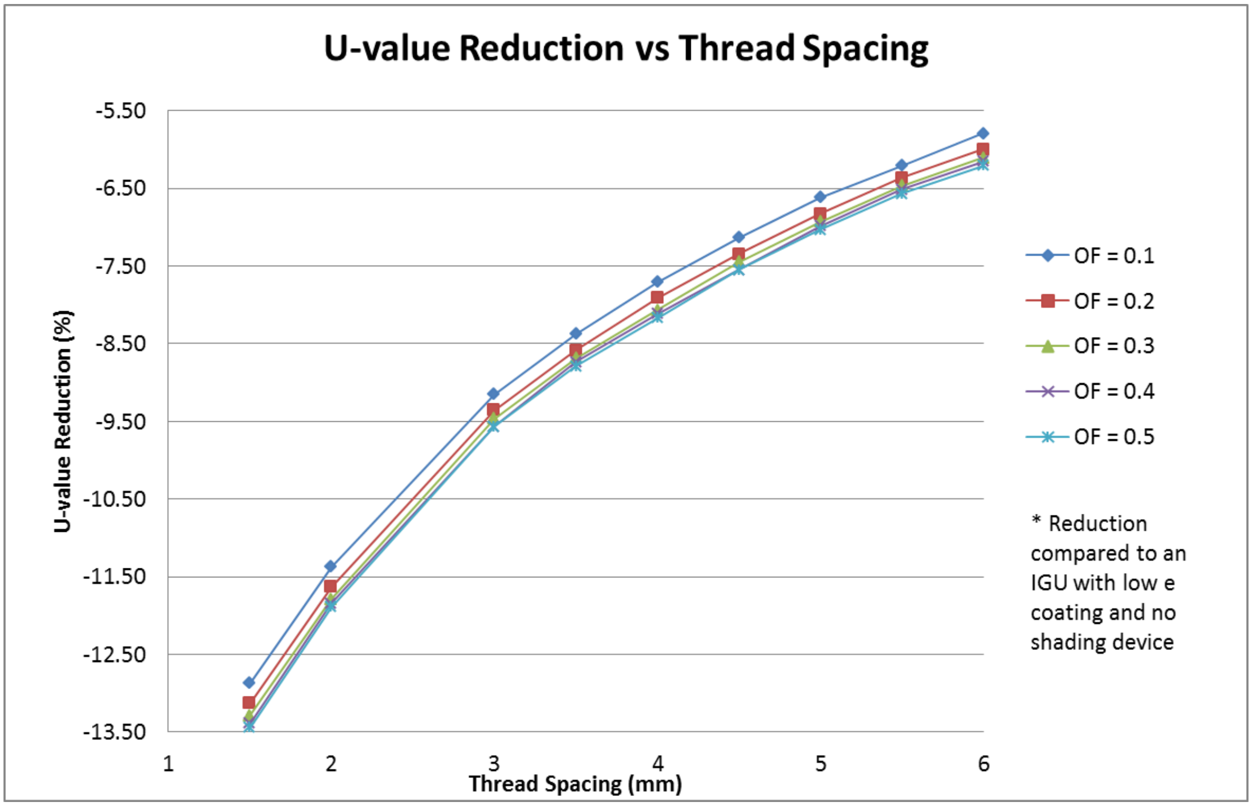


Figure 72: Reduction in center of glass U-value vs. thread spacing for various openness fractions.

To further evaluate this effect, the openness fraction was then investigated independently from the other variables. The openness fraction was varied between 0 and 1, while the thread diameter and spacing were set at 1mm and 2mm, respectively. Shade thicknesses of 1, 2 and 3mm were investigated. The results of this study for the center-of-glass region are shown in Figure 73. The figure shows that higher openness fractions result in better performing shades. The figure also shows that shade thickness does not have an effect on system performance.

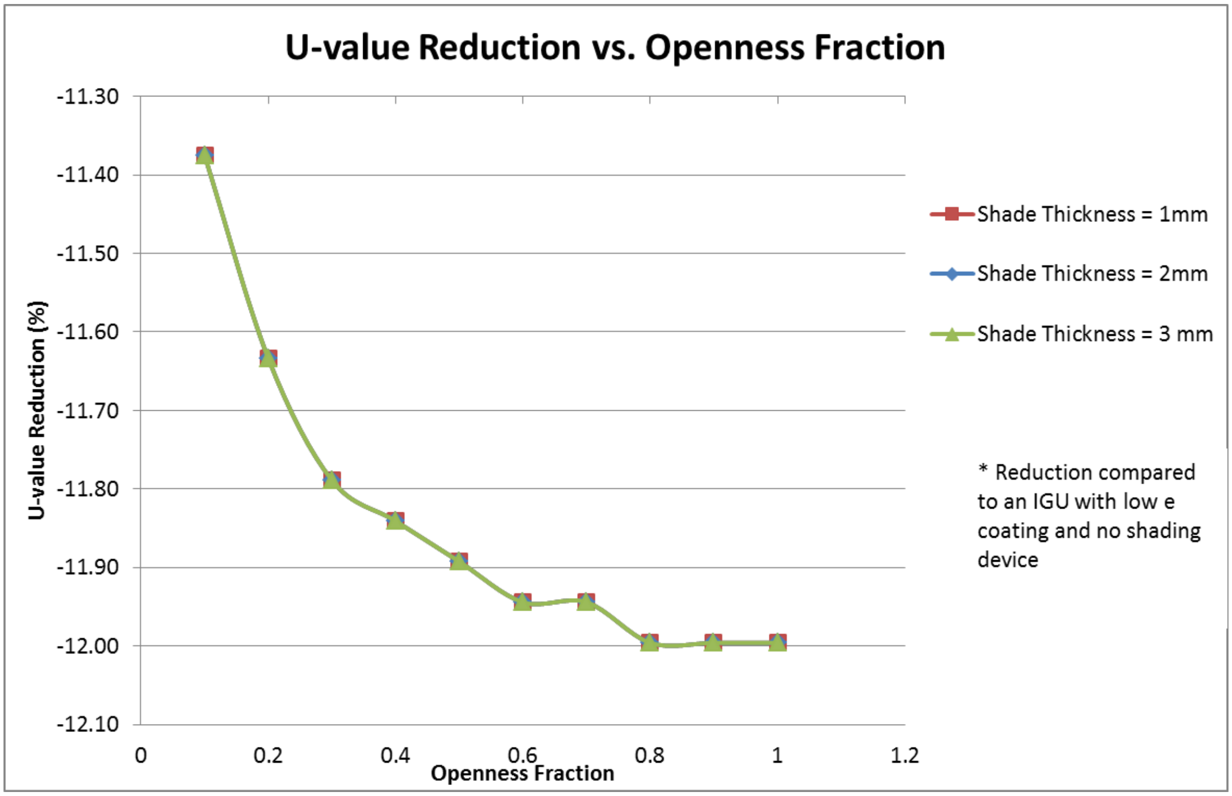


Figure 73: Reduction in center of glass U-value vs. openness fraction

Next, the effect of openness fraction and thread spacing on the solar heat gain coefficient was evaluated. The results of this study are shown in Figure 74. It was found that a woven shade can provide ~10-33% improvement in the system's ability to reduce solar heat gain. The openness fraction was found to have no effect. While it might be expected that this figure would be higher, it should be considered that these systems are placed on the interior of the window. This means that the heat has already entered the indoor environment at this point.

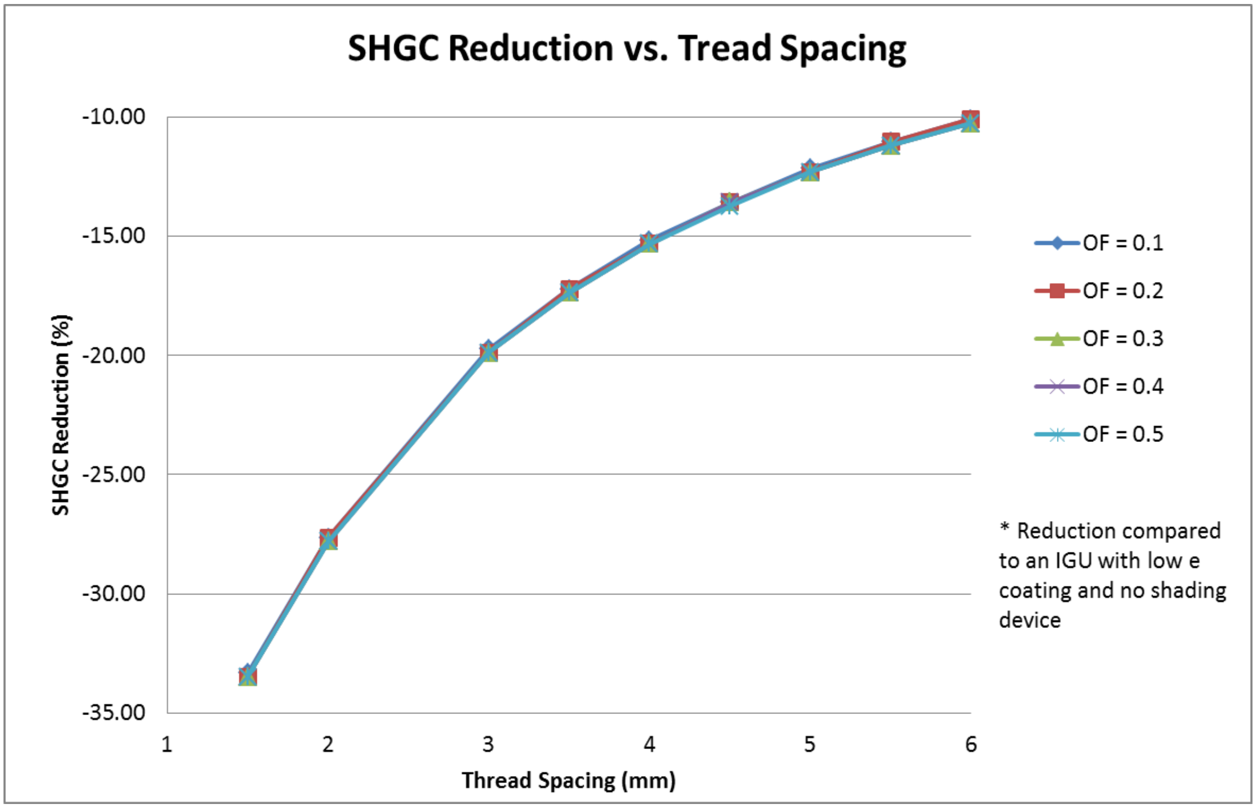


Figure 74: Reduction in SHGC vs. thread spacing.

It was found in Section 4.5 that the location of venetian blinds could also have an effect on the performance of the complete fenestration system. Therefore, the effect of placing woven shades at distances of 7.5, 10, 12.7, and 15mm from the glazing surface was investigated. As is demonstrated in Figure 75, the performance of the system improves, as the shade is placed closer to the surface of the glass. Over the range of cavity thicknesses shown, nearly a 6% difference in U-value was observed.

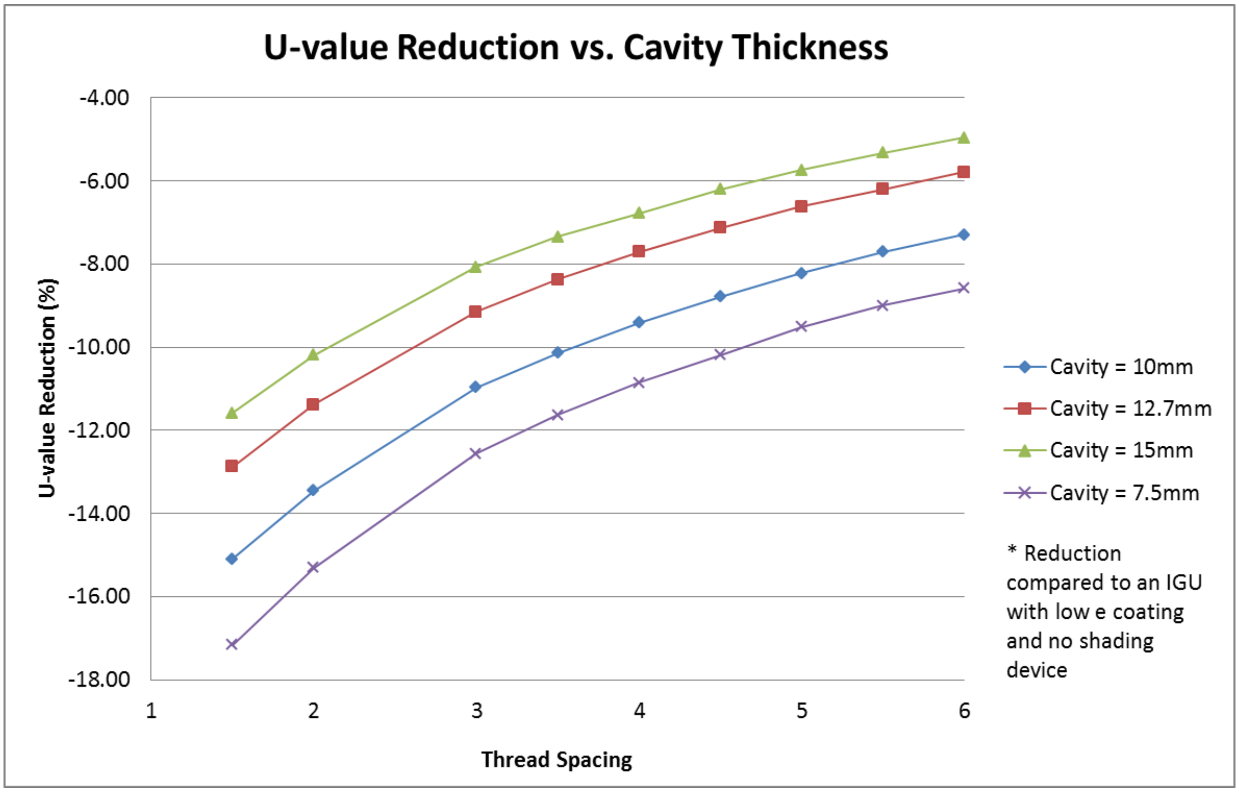


Figure 75: Center-of-glass U-value vs. thread spacing for several cavity thicknesses

Lastly, it was desired to see the effect of placing the woven shades on the exterior side of the glazing. Figure 76 shows the effect of woven shade thread spacing on the U-value, while Figure 77 shows the effect of woven shade thread spacing on the SHGC. When placed on a windows exterior, woven shades reduce the U-value by 24-26%. The thread spacing has a minimal effect in this case. This makes sense, as the shade is working by disrupting the convective airflow along the surface of the glazing. The shade has a greater effect than when placed on the interior of the window due to the more turbulent conditions present outside. The thread spacing has a much greater impact on the SHGC. When the threads are closely spaced, the SHGC is reduced by nearly 90%. When the threads are spaced further apart, the reduction is in the 25% range.

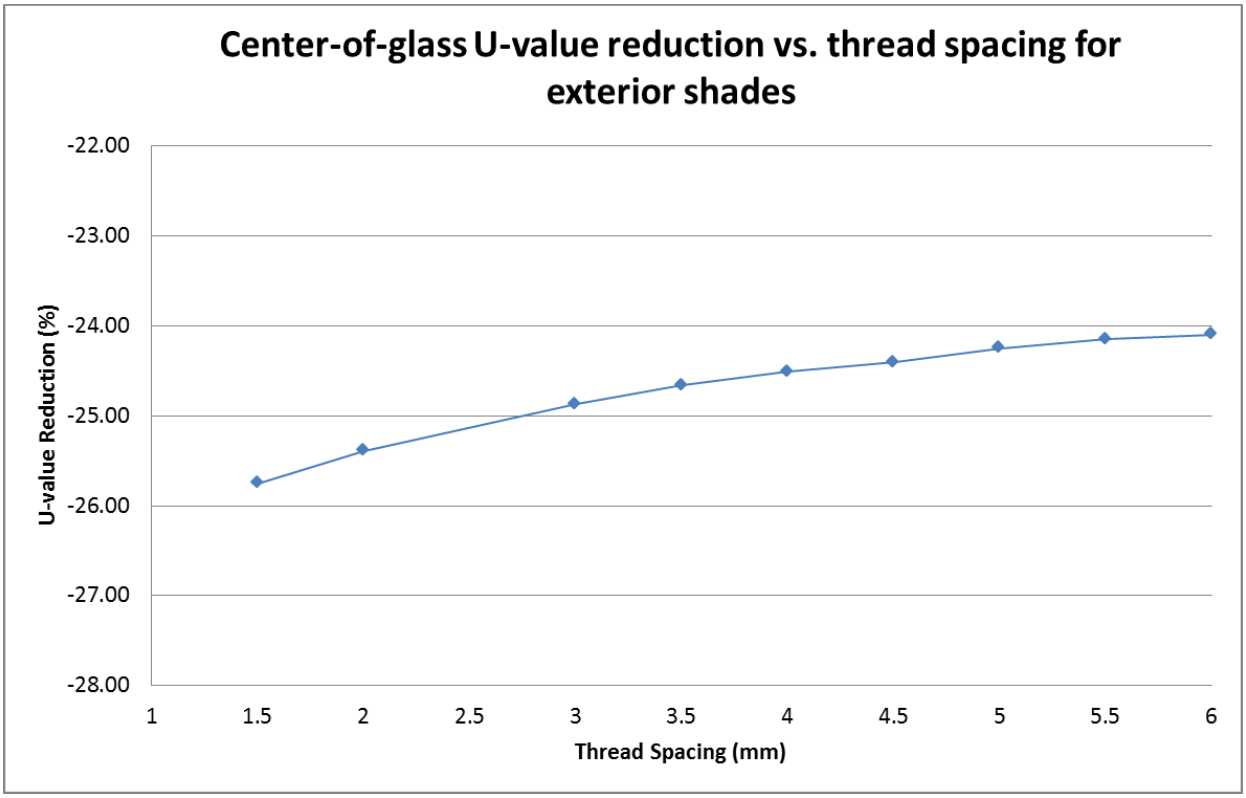


Figure 76: Center of glass U-value reduction vs. thread spacing for exterior woven shades.

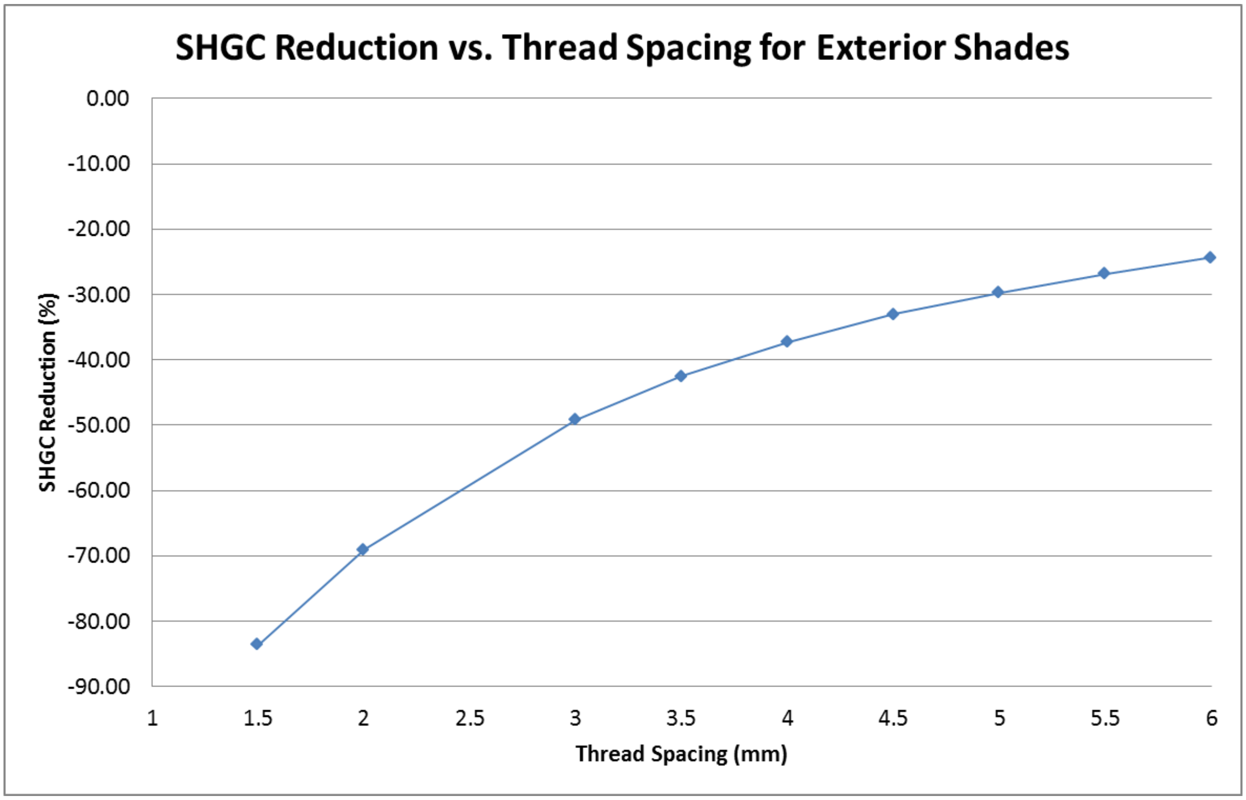


Figure 77: SHGC reduction vs. thread spacing for exterior woven shades

5.4 Fabric Shade Summary

For fabric shades, the effect of numerous criteria, including threading spacing, openness fraction, and shade thickness on the U-value as well as the SHGC were investigated. It was found that over the range of values explored, fabric shades were capable of reducing the U-value by 6-14% when placed on the interior of the glazing, and 24-25.5% when placed on the exterior of the glazing. The most important criteria were found to be the thread spacing and the openness fraction (in other words, how tightly the fabric is weaved), which the thickness of the shade was found to have little effect. The thread spacing was found to have an effect on reducing solar heat gain. Moreover, it was found that shades on the exterior of the glazing were far more effective from this regard than those on the interior of the glazing. These results suggest that durable, fabric shades should be placed on the exterior of the glazing rather than the interior for best performance. The results of the fabric shade analysis are summarized in Table 13.

Table 13: Summary of center-of-glass U-value (top) and SHGC (bottom) reductions for fabric shades

Criteria Explored	Range of U-value Reduction (%)	Reference Figure
Thread Spacing Frame Type	6 - 14	Figure 71
Thread Spacing Openness Fraction	6 - 13.5	Figure 72
Openness Fraction Shade Thickness	11.3 - 12	Figure 73
Thread Spacing (Exterior)	24 - 25.5	Figure 76

Criteria Explored	Range of SHGC Reductions (%)	Reference Figure
Thread Spacing Openness Fraction	10 - 33	Figure 74
Shading Cavity Thickness Thread Spacing	5 - 17	Figure 75
Thread Spacing (Exterior)	25 - 85	Figure 77

6. Glazing Layer Style Attachments

6.1 Exterior Storm Windows

A storm window in its most basic form is an additional window system installed on the exterior of the existing window system (Figure 78). Depending on the existing windows in question, the system can be installed either directly on top of the jambs (blind stop installation) or on top of the window trim (overlap installation). An illustration of the difference between blind stop and overlap installation methods can be seen in Figure 79. Storm windows were common during the 1970’s, but have become less popular as IGU’s have become ubiquitous in residential construction. Storm windows can result in egress issues depending on the specific model used. Storm windows are classified as Two-Track, Triple-Track, Two-Track Sliding, and Basement.

Figure 78: Storm window installed on existing window jamb. Image source: Larson, 2013.

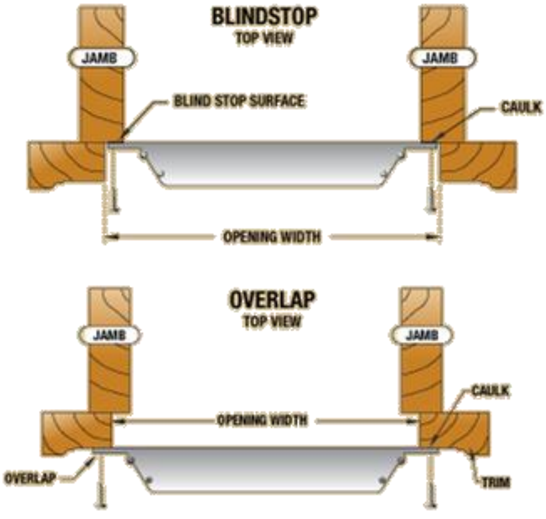


Figure 79: Comparison of Blind Stop (top) and Overlap (bottom) installation methods. Image source: Larson, 2013

Two – Track storm windows contain an exterior insect screen on one sash and glass pane on the other, both of which are permanently fixed in place. Inside of this layer is an additional glass pane, which can slide up or down based on the user preference. Triple-Track windows feature a half screen as well as two half glass panes, each of which can move independently. This offers the user the most flexibility for configuration. Examples of a two-track and triple-track storm window are shown in Figure 80.

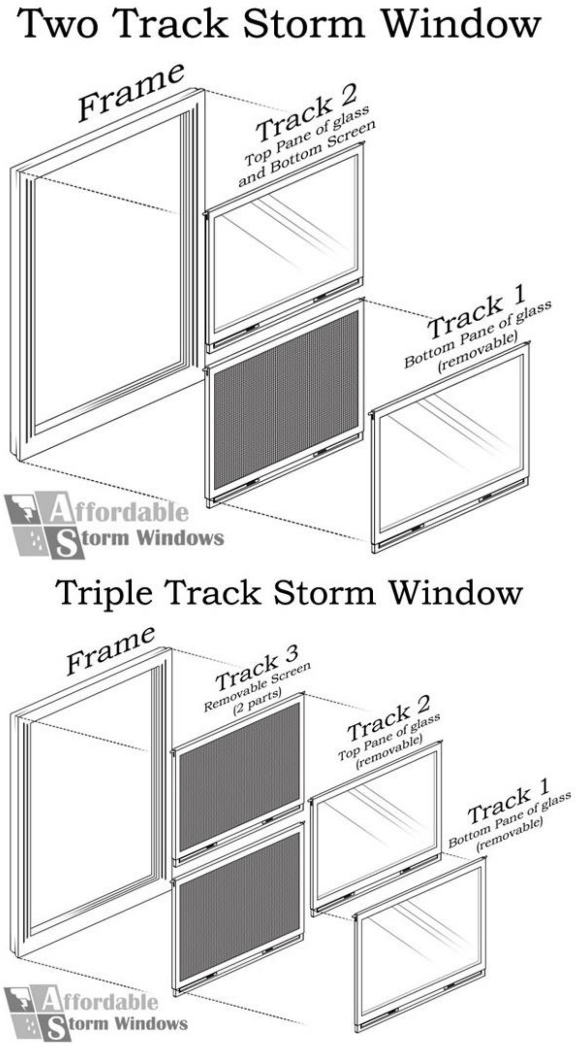


Figure 80: Illustration of how a two-track storm window (top) and a triple-track storm window (bottom) operates. Image source: Affordable Storm Windows, 2013.

Thermal Improvement

Since storm windows add an additional layer of glazing and air space to any existing window system, they can result in a substantial increase in thermal efficiency. This efficiency can be improved when models including a low- e coating are used. The addition of a storm window installed over a single-glazed window reduces the U-value from 1.1 to 0.50. This corresponds to a 120% reduction in U-value. Drumeheller et al. (2007) found that when low-e storm windows are installed over single-glazed windows, a center-of-glass U-value of 0.36 could be achieved.

A similar study was completed by the Cold Climate Housing Research Center. Through computer analysis, they found that a storm window (with uncoated glass) could achieve a 121% improvement over a double-glazed window. When they tested this in the field using an actual double-glazed window, they found that a 110% improvement was achieved (Craven and Graber-Slaght, 2011).

Comfort

Thermal comfort will be improved since this system results in a warmer interior pane of glass.

Condensation Potential

Storm windows located on the exterior of the glass would increase the temperature of the inner pane of glass, thereby reducing the risk of condensation.

Cost

Low-e coatings and operability (two-track vs. triple-track) are the two factors that most significantly affect the price of storm windows. The cost of a Comfort-Bilt, 32”x63” Two-Track Single-Glazed Storm window is ~$71.00. A Larson, 36”x63” Two-Track storm window with a low-e coating costs ~$109.00 per window (Lowes, 2013).

Impact on Daylighting

There is no significant impact on daylighting using storm windows.

Air Leakage

Storm windows can be extremely effective at reducing air leakage between the window frame and the sash. Drumeheller et al. (2007) conducted a field study of the performance of six different residential homes. Air tightness was measured using a whole house pressurization test. It was found that the addition of storm windows reduced the air infiltration rate between 5.7 and 8.6%. This corresponds to an average reduction of 15 CFM per window when the house was pressurized to 50 Pascal’s.

Ease of Operation

Storm windows should be installed at the beginning of the heating season and removed at the end of it. Each sash is opened and closed in the same manner as standard window sashes. However, these sashes typically are not modified throughout the heating season. Therefore, they have a low degree of effort needed for optimal use.

Aesthetics

The inclusion of storm windows results in a minimal change to the aesthetics of the home.

The at-a-glance performance diagram for storm windows is shown in Figure 81.

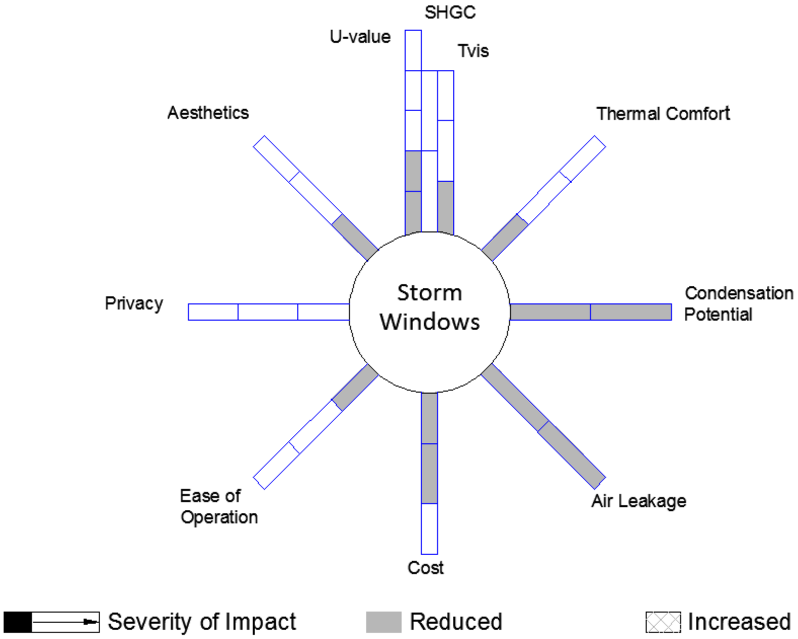


Figure 81: At-a-glance performance diagram for storm windows

6.2 Exterior Plastic Wrap on Insect Screens.

Plastic wrap can be used to cover the outside of window insect screens to create a cheap, easy to install alternative to storm windows.

Thermal Improvement

The primary improvement obtained through this method is the creation of an additional airspace on the exterior side of the sashes. Since weather-stripping is seldom used for insect screens, this airspace would still be subject to drafts that could seep between the edges of the insect screen and the jambs. The percent improvement in thermal insulation for this system would be greater than the 7% improvement obtained through using insect screens alone, but not as great as the 55% obtained through the use of exterior storm windows. For now, a 20% improvement will be assumed.

The addition of plastic wrap to the window screen should result in an additional reduction to the solar heat gain coefficient since some of the heat will be reflected off of the surface of the plastic. However, this improvement will likely be minimal. For now, a SHGC reduction of 50% (compare with 46% reduction for window screens alone) will be assumed.

Comfort

This system will result in a warmer interior surface for the glazing; therefore, the comfort of the space should be improved.

Condensation Potential

Since this system is placed on the exterior of the window system, the condensation potential will be reduced.

Impact on Daylighting

When the plastic wrap is properly installed, there is no substantial decrease in visual transmittance.

Air Leakage

In a typical window assembly, insect screens are not sealed for air leakage. This means that even though the screens are being covered by plastic wrap, there is still potential for air to leak around the edges. However, the amount of air leakage will be reduced.

Cost

Most home improvement centers carry kits that contain all the necessary components to weatherproof windows. This includes heavy-duty plastic sheeting and double-sided tape. Frost King Window Insulation Kit provides enough of these materials to weatherproof three standard size windows (42”x62”) for $5.98. This results in a cost of $1.99 per window. If the windows do not currently have insect screens, then there will be an additional cost of $2.80 per window (See Section 8.1 Insect Screens.) This will bring the total cost of the assembly to $4.79 per window (Lowe’s, 2013).

Ease of Operation

The process of covering insect frames with plastic wrap is simple. First, the screen is removed from the window assembly. Next, the plastic wrap is applied to the inside portion of the insect screen frame using double-sided tape and shrink-wrapped using a blow dryer. The screens are then reinstalled. This whole process can be accomplished from the inside of the building regardless of which story the windows are located. The installation process can be very time consuming depending on the number of screens being applied, but little maintenance is required afterwards unless the plastic is damaged over the course of the heating season.

Aesthetics

This system has a minimal effect on the aesthetics of the exterior appearance of the home and no effect on the interior aesthetics of the space.

Figure 82 shows the at-a-glance performance diagram for exterior plastic wrap on insect screens.

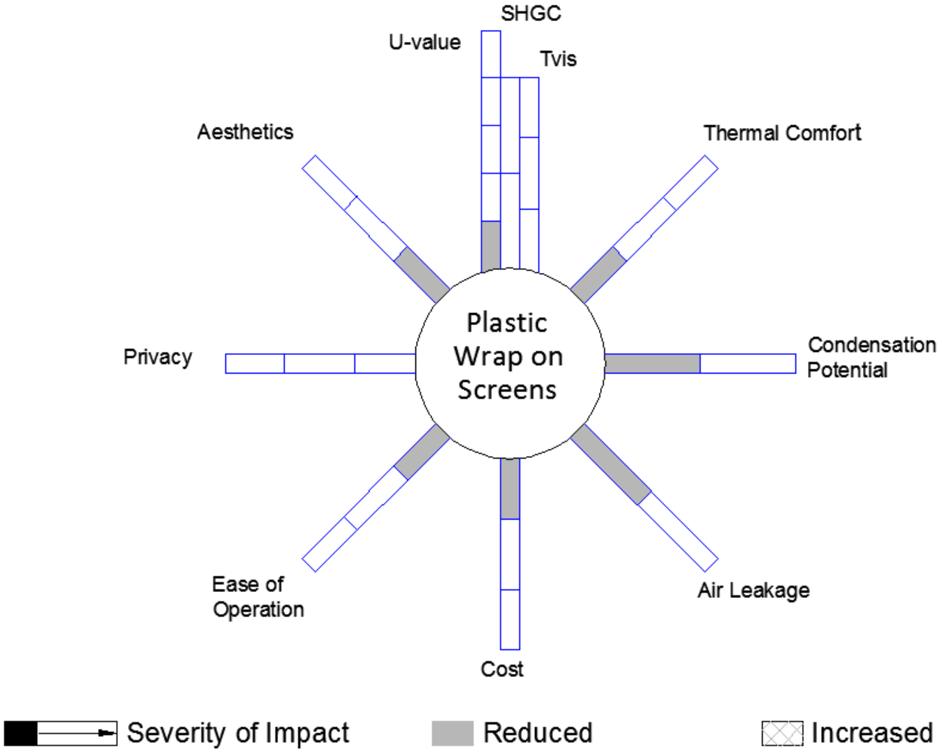


Figure 82: At-a-glance performance diagram for plastic wrap covered insect screens

6.3 Plastic Wrap around Window Frame

Plastic wrap can also be used to cover the entire window frame on the interior of the building. Double-sided tape is used to attach the plastic to the outside of the window frames. A hair dryer is then used to stretch the plastic tight (Figure 83). Alternatives to this method involve the use of bubble wrap rather than plastic wrap. While bubble wrap will provide improved thermal performance, transparency will be greatly reduced.

Figure 83: DIY installation of plastic around window frame. Image Source: This Old House, 2013

Thermal Improvement

The primary benefit of this system lies in the air space that is created between the window and the interior space. This air space adds an extra insulative layer to the space. The effect of this is similar to that obtained by adding an additional window pane. The CCHRC found that when a triple-paned window was covered with plastic wrap, a 33% improvement in U-value could be obtained. A computer analysis was also completed for a double-glazed window, in which a 24% improvement was obtained.

It could be envisioned that a plastic wrap could be developed with spectrally selective attributes that would limit the transmission of long wave, infrared radiation that would further improve the thermal performance of the system. This is similar to the films suspended within "heat mirror" glazing systems. However, such products are not currently available to consumers. It is possible that the cost of producing heavy-duty plastic wrap with these qualities would be too great for a system that requires yearly replacement.

Comfort

Since the plastic wrap covers the entire cold surface of the window, this method should improve the thermal comfort of the space by serving as a radiant barrier. Since the plastic has so little thermal mass, it is unable to create the radiative imbalance that results in thermal discomfort.

Condensation Potential

While this system does not increase the temperature of the glass, it does limit the amount of humid air that can condense on the window. This means that the condensation potential of the window will be reduced.

Impact on Daylighting

The plastic wrap used for this product is completely transparent; therefore, there will be no impact on daylighting.

Air Leakage

This method is particularly useful for older windows that suffer from air leakage between the sash and the frame. Since the plastic is used to cover the entire assembly, air leakage through the sash should be virtually eliminated. For this reason, this method is particularly effective for old, drafty windows.

Cost

Frost King produces a window insulation kit with enough plastic wrap and double-sided tape for 3 42”x62” windows. This product costs $5.98, which corresponds to a total cost of $1.99 per window (Lowe’s, 2013).

Ease of Operation

This method requires annual installation at the start of the heating season. Heavy duty plastic wrap is fixed to the frame of the window using double-sided tape. A blow dryer is then used to stretch the plastic tight. Unless the plastic is damaged, there should be no need for additional work on the part of the homeowner after installation.

Aesthetics

When installed correctly, this system does not have a substantial impact on the aesthetics of the windows. However, it may interfere with operability of secondary window attachments, particularly conventional blinds, which may be undesirable to some users.

Figure 84 shows the at-a-glance performance diagram for plastic wrap on window frames.

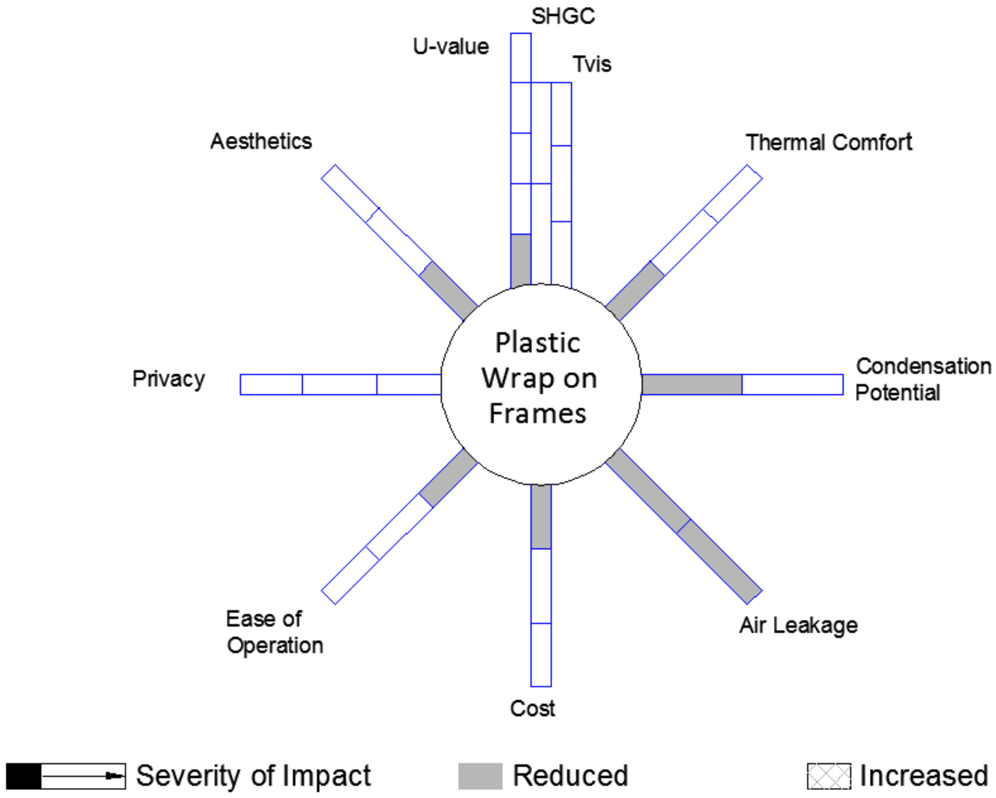


Figure 84: At-a-glance performance diagram for plastic wrap on window frames

6.4 Glazing Layer Analysis

In order to investigate the effect of additional layers on the interior or exterior of the glazing system, a variety of different very thin materials were added to both the interior and the exterior of the glazing system. For this portion of the analysis, only center-of-glass properties were investigated. This is because the performance of the edge-of-glass region will be highly dependent on the method by which the additional layers are connected to the frame. It is difficult to arrive at general conclusions based on these parameters, therefore the edge-of-glass region was not considered.

The first portion of the analysis was an investigation into the effect of using various thickness of glass or polycarbonate for the additional glazing layer. In both cases, clear, uncoated glass or polycarbonate was used. The material conductivity for the glass and polycarbonate was 1.0 W/mK and 0.195 W/mK, respectively. The results of this analysis are shown in Figure 85. For both cases, there is a nearly linear relationship between reduction in U-value and the addition of extra thickness to the glazing layer. The addition of a glazing layer on the exterior of the window system results in a roughly 3% improvement in performance over an identical layer on the interior of the system. Also, polycarbonate systems will provide better performance than glass systems. This is expected since polycarbonate has a lower material conductivity then glass.

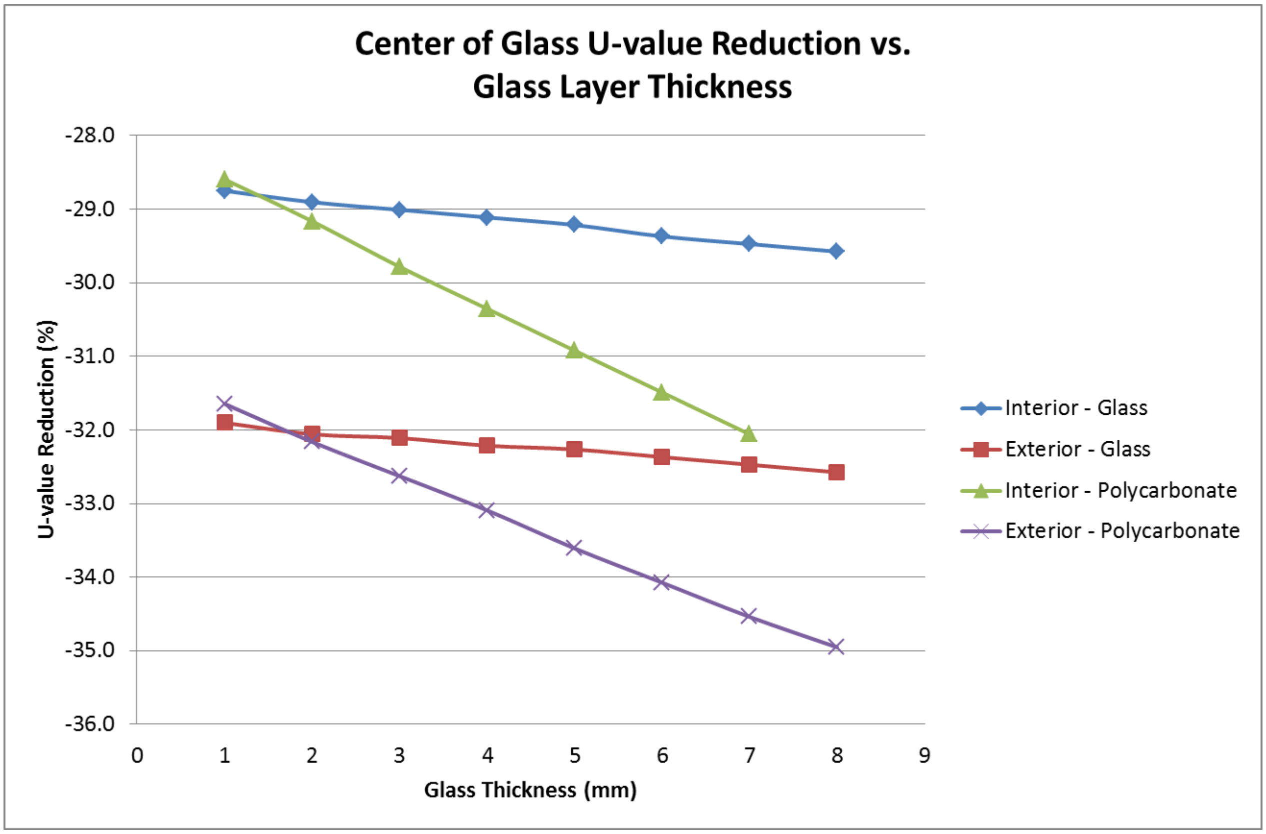


Figure 85: Reduction in center-of-glass U-value vs. thickness of additional interior or exterior glazing layers

The addition of extra glazing layers can have greater effect (up to an 18% reduction) on the SHGC for thicker (5-8 mm) layers when they are placed on the exterior of the glazing system as is shown in Figure 86. It is interesting to note that polycarbonate layers result in less reduction than glass layers. Since this classification of the systems is typically used to limit heat loss during the winter, polycarbonate is a more attractive option than glass since solar heat gain is desired. Glass and polycarbonate systems performed much more similarly (only ~1% different) when placed on the interior of the glazing system.

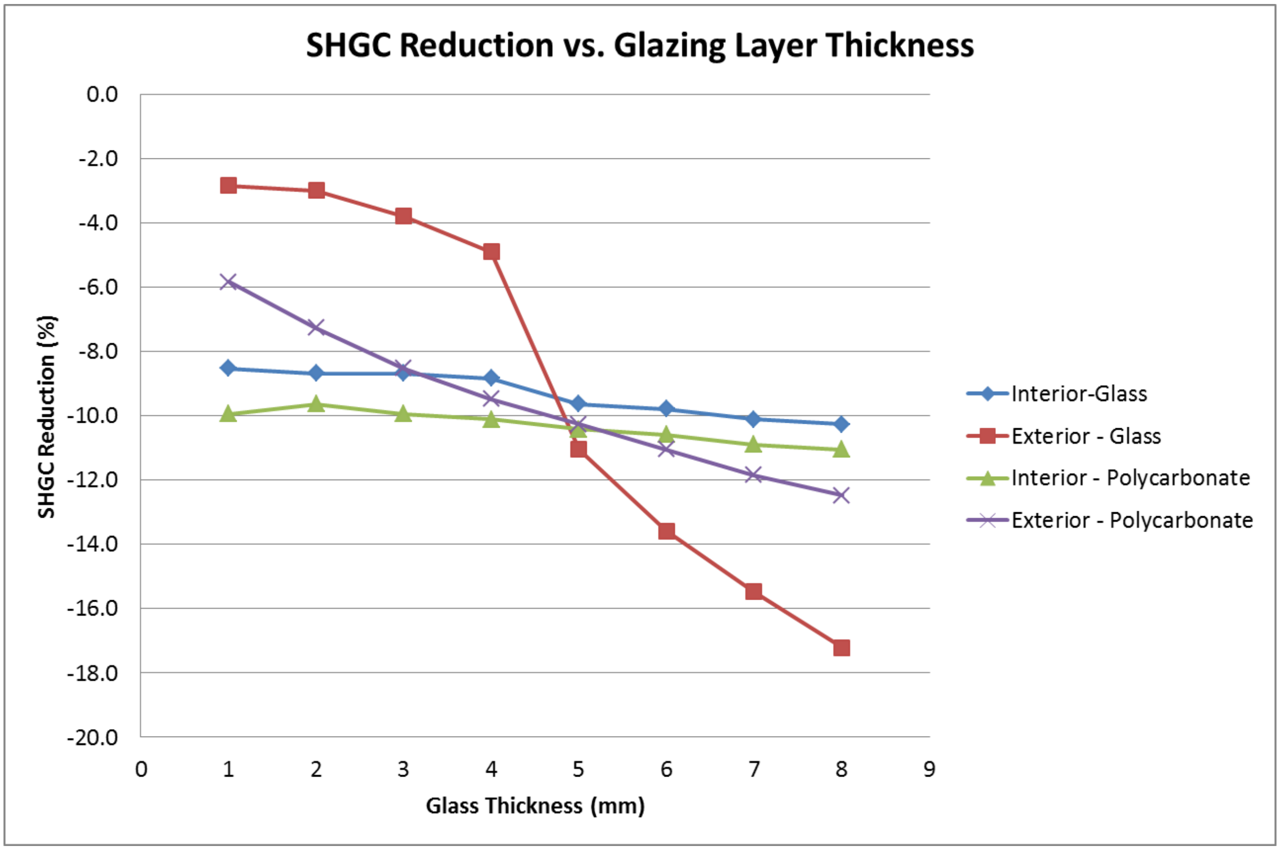


Figure 86: Reduction in SHGC vs. thickness of additional interior or exterior glazing layers

It should be noted that the results shown above are for uncoated, clear layers. Layers with spectrally selective properties are capable of providing even better performance. In order to evaluate this criterion, a representative sample of Southwall *Heat Mirror* films were analyzed for mounting conditions and the front and back side of the glazing system. These films were oriented so that the "front" side properties face the interior side of the glazing unit, which is most appropriate for reducing heat loss. The properties of these films are shown in Table 14. The results of the study are shown in Figure 87.

Table 14: Properties of representative sampling of Southwall Heat Mirror films. Data source: LBNL, 2012b.

Film Name	T_{sol}	R_{sol} (Front)	R_{sol} (Back)	T_{vis}	R_{vis} (Front)	R_{vis} (Back)	ε_f	ε_b
HM 22	0.115	0.825	0.808	0.229	0.692	0.711	0.019	0.760
HM 33	0.174	0.759	0.744	0.338	0.584	0.607	0.020	0.760
HM 44	0.225	0.701	0.687	0.440	0.474	0.500	0.030	0.760
HM 55	0.307	0.614	0.603	0.567	0.349	0.377	0.033	0.760
HM 66	0.362	0.553	0.543	0.652	0.260	0.288	0.038	0.760
HM 77	0.476	0.435	0.422	0.778	0.144	0.165	0.052	0.760
HM 88	0.625	0.268	0.249	0.875	0.057	0.063	0.110	0.760

The results shown in Figure 87 demonstrate that the relationship between the emissive properties and the reduction in U-value is also nearly linear. Unlike the previous study, low-emissivity films mounted on the inside of the glazing system performed better (~47.5-51.5% improvement) than those mounted on the exterior (~44-47% improvement). It should be noted, however, that these films are very thin (3 mil or 0.0762mm) and are therefore typically suspended within the glazing cavity. In order for these films to be durable enough to be mounted on the outside of the glazing cavity, they would likely need to be manufactured to have increased thickness.

While the heat mirror films reduced the U-value to a greater degree than clear glass or polycarbonate, they also had a greater impact on the SHGC (Figure 88). The films that were most effective at reducing the U-value also reduced the SHGC by nearly 90%. Since solar heat gain is desirable in the heating periods during which these systems would be used, such a system may not be a good option for cold climates.

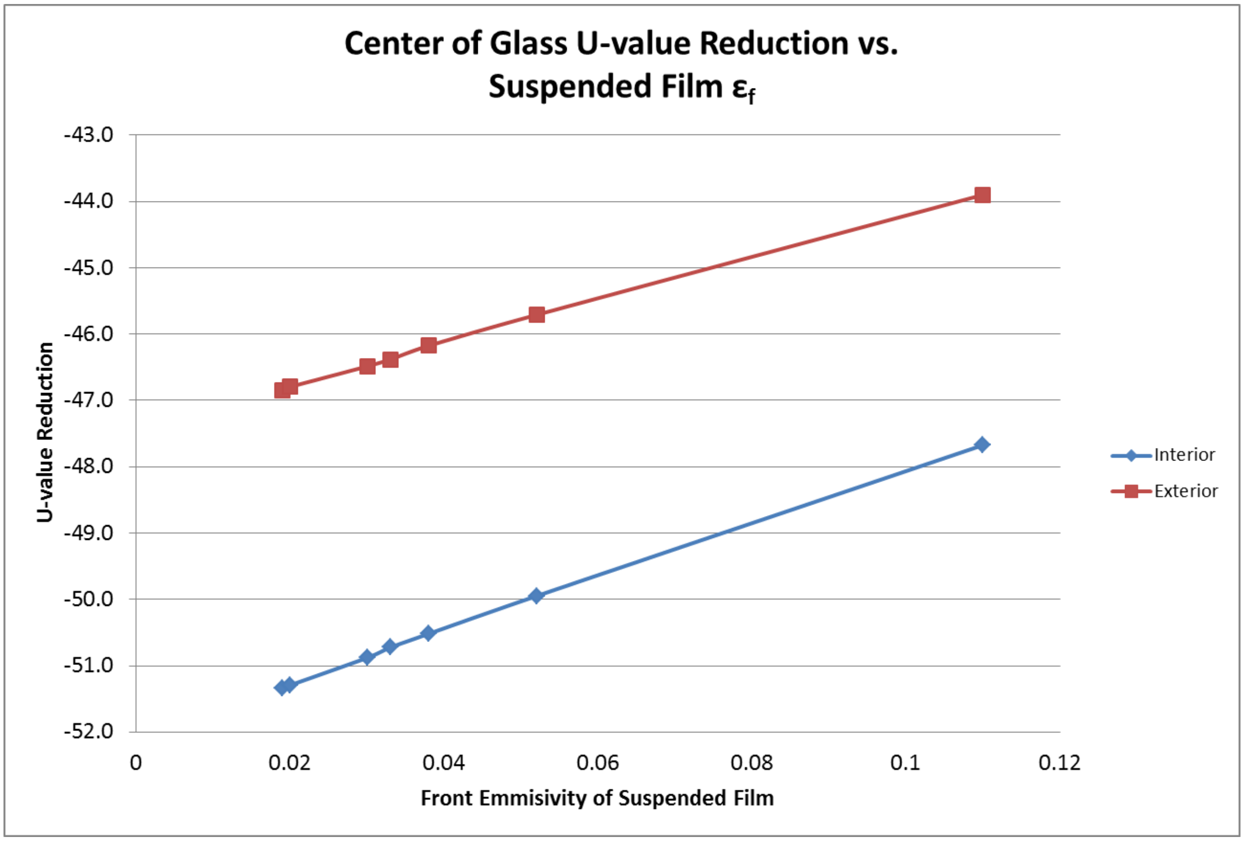


Figure 87: Reduction in center-of-glass U-value vs. film (front) emissivity for additional interior and exterior glazing layers.

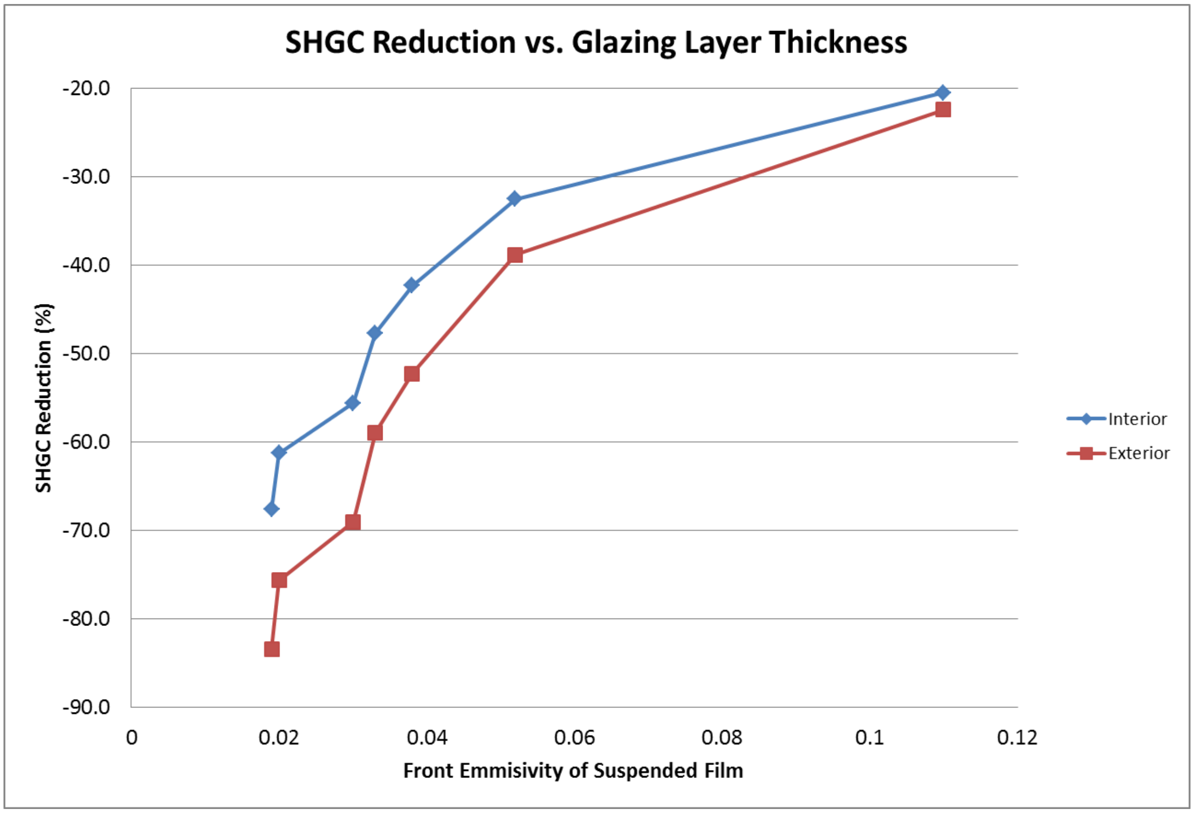


Figure 88: Reduction in SHGC vs. film (front) emissivity for additional interior and exterior glazing layers.

6.5 Glazing Layer Summary

This portion of the analysis investigated the effect of material type, material thickness, and film emmisivity on center-of-glass U-values and SHGC. It was found that location of additional glazing layers (interior vs. exterior) has a far greater effect on performance than the type of material used. In addition, glazing layers with a low-emissivity could achieve the greatest results, reducing the U-value by half and the SHGC by as much as 85%. These results are summarized in Table 15.

Table 15: Summary of center-of-glass U-value (top) and SHGC (bottom) reductions for glazing layers.

Criteria Explored	Range of U-value Reduction (%)	Reference Figure
Material Type Material Thickness	28.75 - 35	Figure 85
Material Type (Exterior) Material Thickness (Exterior)	32 - 35	
Film Emissivity	44 - 47	Figure 87
Film Emissivity (Exterior)	47.5 - 51.5	

Criteria Explored	Range of SHGC Reduction (%)	Reference Figure
Material Type Glazing Layer Thickness	8.5 - 11	Figure 86
Material Type (Exterior) Material Thickness (Exterior)	3 - 17	
Film Emissivity	20 - 67.5	Figure 88
Film Emmisivity (Exterior)	22.5 - 85	

7. Insulating Layer Style Attachments

7.1 Rolling Shutters

Exterior insulated shutters can be envisioned as a variation of the accordion style shutters described in Section 4.1: Operable Shutters. These shutters are comprised of interlocking slats that completely cover the outside of a window. The slats can then be retracted by rolling them up to fit inside of a valence located at the top of the window. The slats usually slide inside of tracks that are often weather sealed. An example of this type of system can be seen in Figure 89. While these units are often used for protection from weather or security purposes, they can also be used as an effective means of improving the thermal performance of windows.

Figure 89: Example of insulated rolling shutter installed on residential building. An interior view is shown on the left, while and exterior view is shown on the right. Image source: Rollac, 2013.

Thermal Improvement

The performance of a rolling shutter system was investigated by the Cold Climate Housing Research Center. Through computer modeling, they found that the shutters improved the U-value of a double glazed window by 51%. When they tested the performance of the shutters on an actual triple glazed window, they found a 30% improvement.

The best performing roller shades feature an insulating foam core, which can provide a substantial improvement in thermal efficiency. Testing of the Rollac DuraComfort A150-R system (Figure 90) performed by Architectural Testing Inc. (ATI) demonstrated that when combined with a single glazed, uncoated window with a wood frame, the U-value decreased from 0.91 to 0.47 in whole window U-value (a 55% improvement) (ATI, 2009). When paired with a better window system such as an IGU with a low e coating, the relative improvement was much reduced. In this case, the original U-value was 0.36, while the U-value with the addition of the roller shades was 0.26 (a 28% improvement).

Figure 90: Aluminum slat with foam core on Rollac DuraComfort A150-R system. Image source: Rollac, 2013.

The performance of this system will be highest if the slats are installed with a track that provides a weather-tight seal. In addition to keeping the slats away from the glazing, the track will also form an additional air layer. Based on the manufacturer recommended installation method, it has been assumed that the ATI study described above used such a track system.

Exterior shutters do not allow for any light filtering capacity. While the shades could be closed during the day to block solar heat gain, this would result in an increase in electrical load for lighting. This would likely offset the energy savings of the shutters. Therefore, from a thermal improvement standpoint, their usefulness is limited to cold weather climates.

Comfort

Since these shutters will lower the temperature of the glazing, they will result in a lower MRT compared to conventional glazing alone. As such, they will make the occupant feel warmer when in place.

Condensation Potential

Since this system places the insulation on the outside face of the window, the glazing will be warmer, and the risk of condensation will be reduced.

Air Leakage

When rolling shutters are installed with sealed tracks, they will provide significant improvement in air leakage between the sash and frame and between the frame and the wall.

Cost

Roller shutters are produced by Rollac in the DuraComfort Product Line. According to a Rollac representative, Stefan Poetsch on December 4th, 2012, the estimated cost for a 30”x60” window opening is approximately ~$400 per window for non-motorized models, and ~$1000 for motorized models. Installation would likely add $150-$250 dollars per window. For this study, the non-motorized models will be assumed, with a total cost of $600 per window.

While this cost is significant, it should be noted that the primary function of this system is security and protection. Improved energy efficiency is one bonus feature along with sound reduction and privacy. Therefore, this system might be substantially more attractive to those in hurricane prone regions.

Ease of Operation

The units can be either motorized or non-motorized. Motorized units will be very simple for the occupant to make use of, while non-motorized units will require more work on the part of the owner. When the shutters are not motorized, a pulley system is usually used, which is routed through the exterior wall to allow the shutters to be closed or opened from the inside.

Impact on Daylighting

This system completely eliminates views to the outside as well as any daylighting potential. For cold climates, the shades would be open in the day to allow maximum solar gain from the sunlight, and closed during the night hours to prevent heat from escaping. In such a situation, there would be no effect from a daylighting perspective. However, in warm weather climates, the shades would be used to block incoming solar heat. In this case, the effect would be more dramatic. As a result of the increased artificial lighting use that may be necessary, this system may result in increased overall energy use for the home depending on the climate.

Privacy

When these shades are in use, they will completely block views into the building.

Aesthetics

While this system can be produced in a variety of different colors, there is still a substantial aesthetic impact on the home due to both the shutters themselves as well as the valence.

Figure 91 shows the at-a-glance performance diagram for insulated rolling shutters.

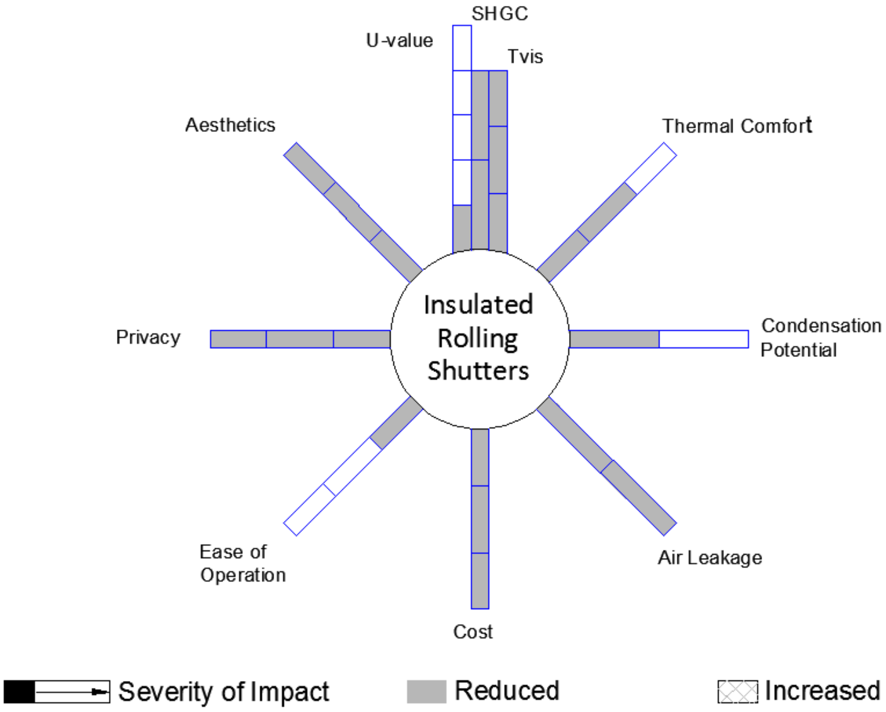


Figure 91: At-a-glance performance diagram for insulated rolling shutters.

Variations

Although rolling shutters are typically placed on the exterior side of the window, they could potentially be placed on the interior side instead for improved thermal performance. An alternate approach would be to create custom roller blinds with a thicker insulated cross section. The downside of this proposal is a much larger diameter of the rolled shades.

7.2 Insulated Foam Shutters

Some shutter designs feature construction with an insulated core material such as polyisocyanurate and a radiant heat reflecting foil. While providing superior thermal performance, these designs typically completely block light rather than simply filtering it as with louvered shutters. An example of a DIY insulated shutter design is shown in Figure 92.

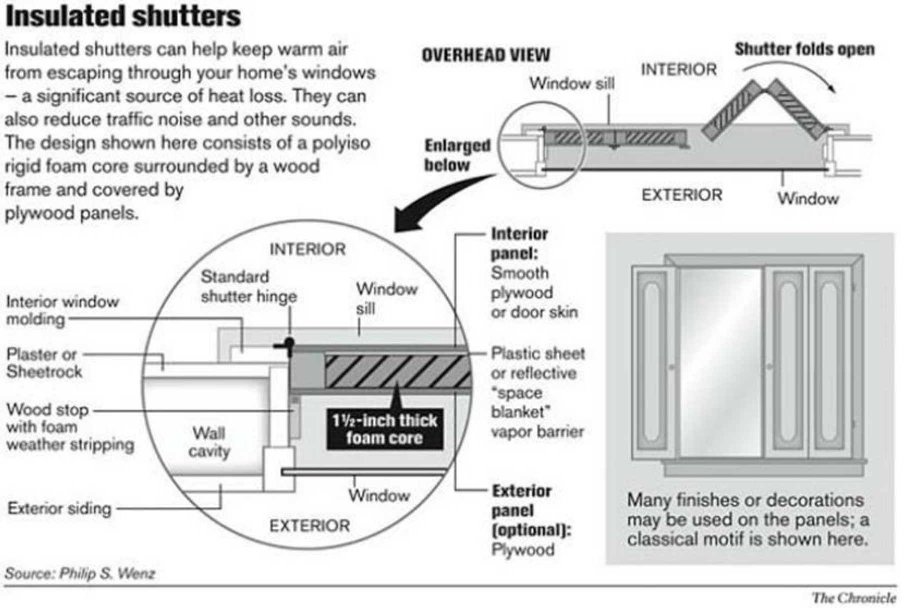


Figure 92: DIY insulated shutter design. Image source: SFGate, 2008.

The two basic installation categories are shown in Figure 93. Glass hugging installation is when the shutters are attached just off the surface of the glass using clips or magnet strips. Since the insulation is placed so close to the glass, there is no opportunity for cold air to accumulate behind the shutter and enter the room through convection. Edge-sealed installation, on the other hand, involves attaching the shutters inside the window jamb using magnets or other types of clips along with gaskets or weather-stripping to prevent air movement. A friction fit clip can be used along with a compression gasket for optimal results.

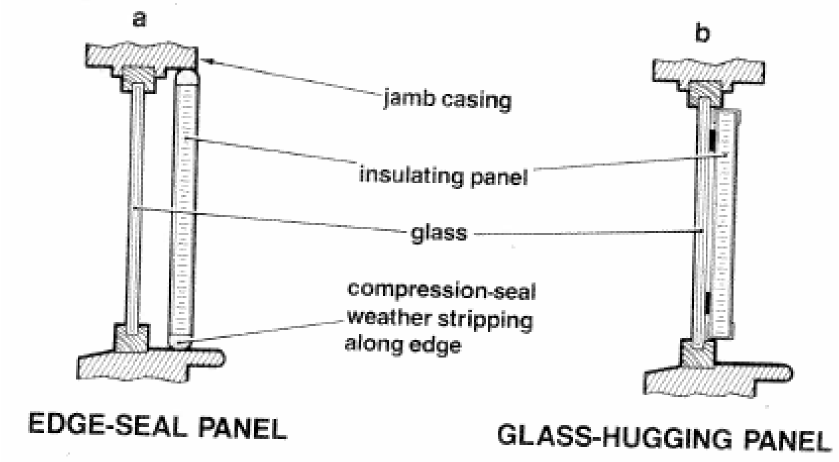


Figure 93: Illustration of the edge-seal panel and glass-hugging panel installation methods. Image source: Langdon, 1980.

Thermal Improvement

The effectiveness of insulating shutters will be determined by the R-value of the insulation used in its construction as well as the degree to which air movement is restricted around the seal. For example, Pactiv 2" thick extruded polystyrene has an R-value of 10. The second criterion will be largely determined by the installation method. These systems are usually designed to be inserted during the night hours and removed during the day.

This style of shutter can also be easily modified to serve as a passive solar heat collector if the exterior facing side is covered with a black cloth or other highly heat absorbing material and a gap is left at the top and the bottom. Figure 94 shows how the shutter system would be used during various periods throughout the year.

The CCHRC performed a field investigation of a custom built rigid foam shutter system which slides on a track to cover the exterior of a window. They found that this system resulted in a thermal improvement of 410%. It is unclear from the report whether the existing window was a single-, double-, or triple-glazed. The system was then modeled using THERM over a double-glazed window. This analysis showed a 532% improvement (Craven and Graber-Slaght, 2011).

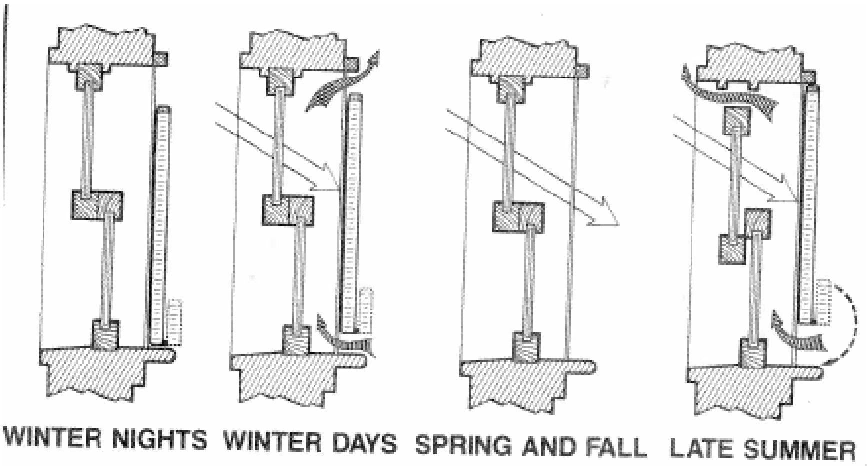


Figure 94: An edge sealed insulated window shutter can be modified for use in passive solar heating. Image source: Langdon, 1980.

Comfort

Using insulated window shutters covers the cold glass with insulation. Because of this, the temperature differential will be much reduced. This results in a more comfortable environment for the building occupants.

Condensation Potential

Insulated window shutters do not affect the temperature of the glass. In addition, both methods of installation still expose the cold glass to the humid interior air while limiting air movement between the glass and the shutter. Therefore condensation will be likely with this system. However, this risk can be reduced if the systems include installation details that seal around the perimeter of the shutter.

Air Leakage
Air leakage will be reduced between the sash and the jamb, but not between the jamb and the interior wall.

Cost
These systems are not widely available on the market, and must therefore be constructed in a DIY fashion. They can be easily constructed using a variety of materials such as corrugated cardboard (extremely low cost) or foam rigid insulation (higher cost, but improved performance).

Manufacturers (Lowe's, 2013)

Pactiv 2" x 8' x 4' Extruded Polystyrene Insulated Sheathing: $33.25 each. This translates to approximately $17.33 for a 30"x60" window assuming scrap pieces can be glued together to minimize waste.

1"x2"x8' spruce pine furring strips: $1.12 each. This translates to $2.24 for a single window.

Reflective Foil Insulation: $68.69 for a 125'x48" roll; this translates to $1.72 per window.

Total cost (less finishes) = $21.29 for window

Regardless of the type of insulation used, the entire board can be wrapped in foil for increased fire protection and can then be finished in a variety of ways. Pine furring strips can be used to add durability to the corners to the panel and then the whole panel can be covered in a fabric to improve the appearance of the system.

Ease of Operation
These panels can be put into place very easily for any accessible window. For most windows, they can be put into place by a single person and removed just as easily.

Impact on Daylighting
These panels are typically only applied at night, therefore there is no impact on daylighting. However, if they are used as heat collectors during the daytime, the daylighting capability of the system will be practically eliminated.

Privacy
These shades will completely block views through the glazing.

Aesthetics
These panels will have a moderate to significant effect on the aesthetics of the building based on the way they are finished.

Figure 95 shows the at-a-glance performance diagram for insulated foam shutters.

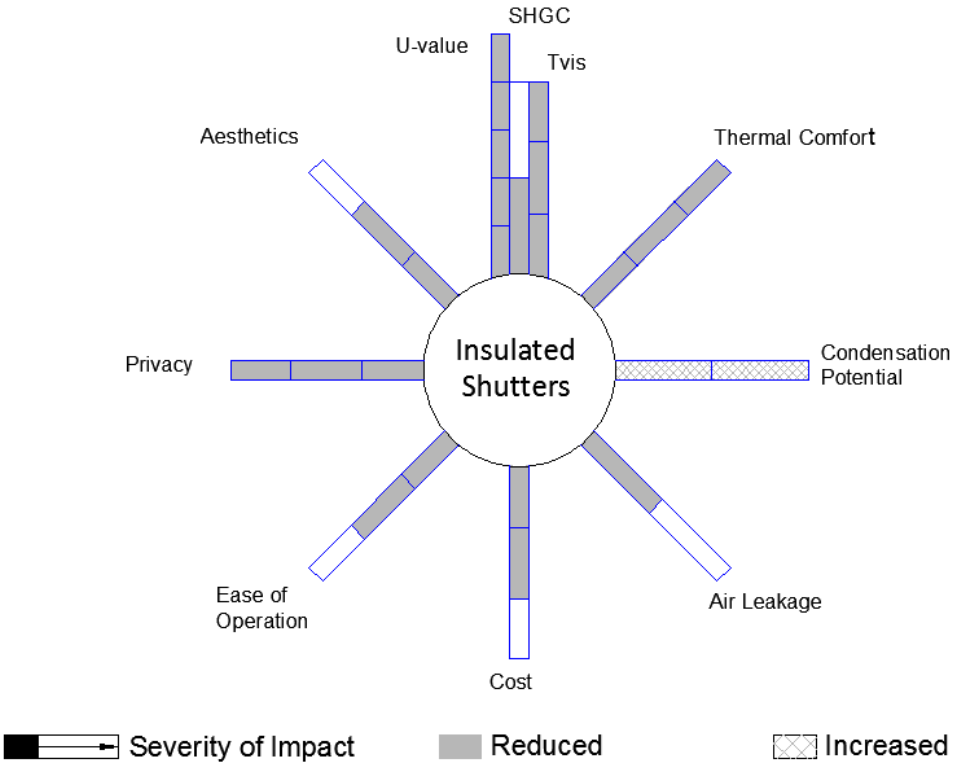


Figure 95: At-a-glance performance diagram for insulated shutters.

7.3 Insulated Layer Analysis

In order to examine the effect of adding layers of insulation (in this case, rigid foam insulation) to a glazing system, the center-of-glass region was first investigated. The effect of adding layers of rigid foam insulation (Expanded Polystyrene) was then investigated. Insulation thicknesses between 6.45mm (1/4”) and 50.8mm (2”) were used. Three different installation methods were considered. In the first method, the insulation was attached directly to the surface of the glazing. In the second method, the insulation was offset from the glazing surface, but attached to the frame. In the third method, the insulation was offset from the glazing surface as well as the frame. These three methods are illustrated in Figure 96. The cavity created between the glazing/frame and the insulation was modeled as a slightly ventilated and non-ventilated cavity conditions. These cavity properties are generated by THERM based on NFRC 100 specifications. THERM models a slightly ventilated cavity as a material with twice the “effective” conductivity as a non-ventilated cavity. For this study, the IGU with a low-e coating used in previous studies was imported directly from WINDOW. The result of the analysis to determine the effect of insulation thickness and airspace thickness on reduction of the U-value is shown in Figure 97.

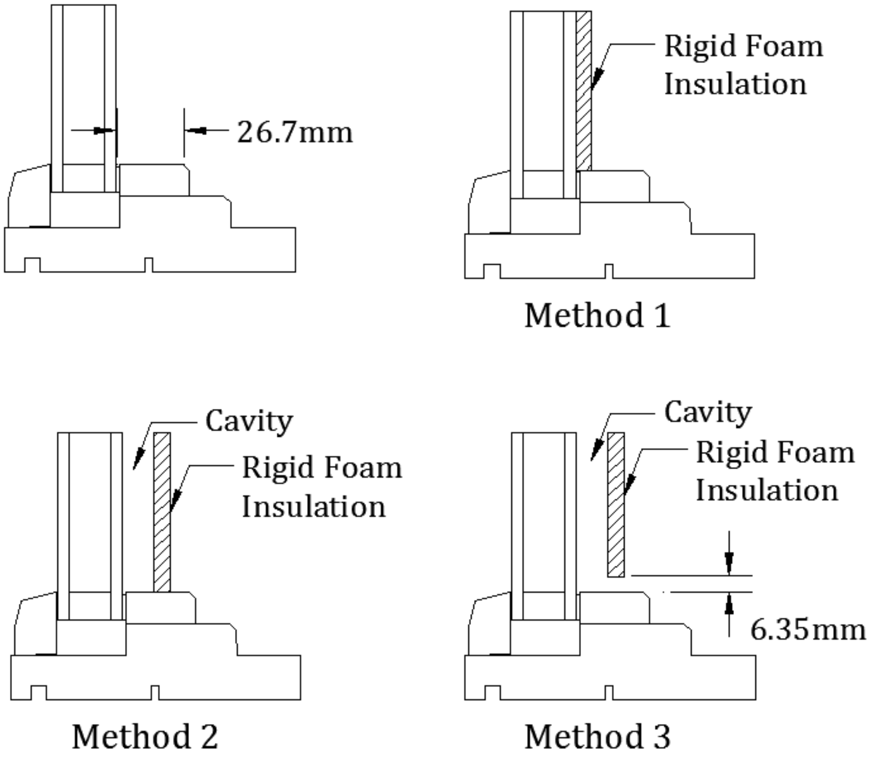


Figure 96: IGU with wood frame (top left), installation method 1 (top right), installation method 2 (bottom left), and installation method 3 (bottom right).

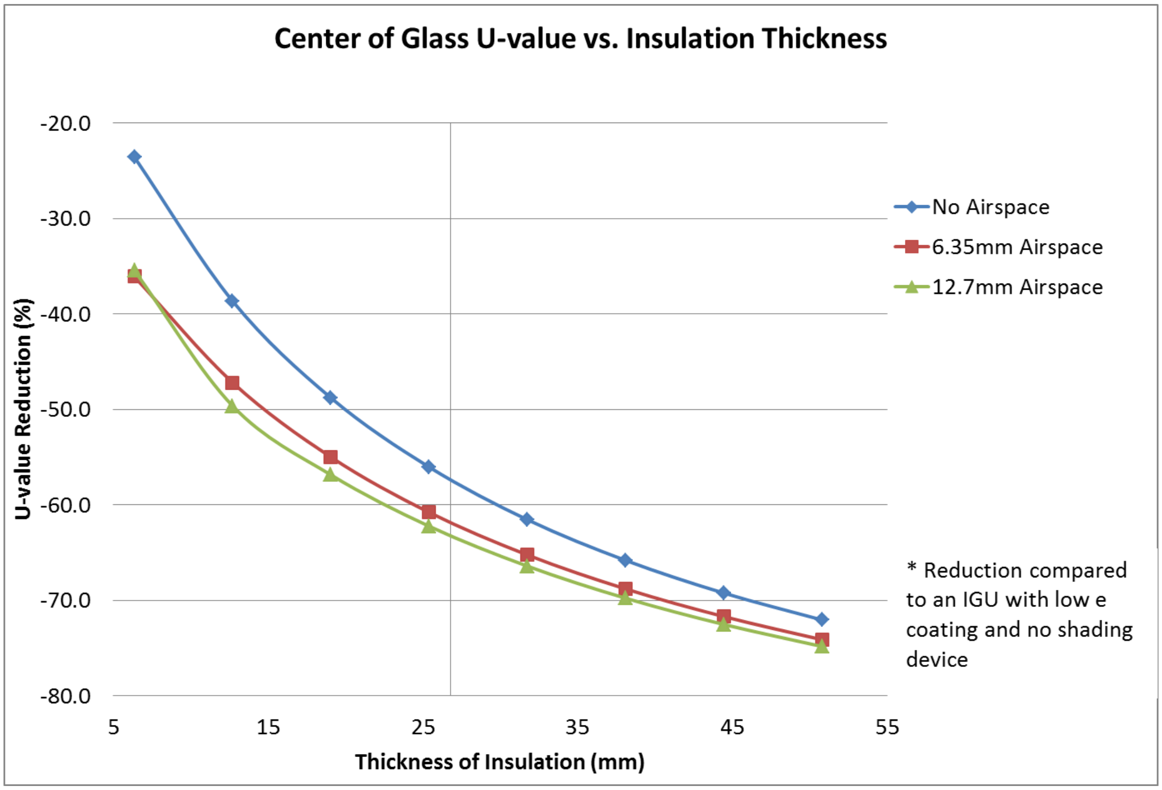


Figure 97: Center of glass U-value vs. insulation thickness for several insulation methods.

The edge-of-glass and frame region were examined next. A simple wood frame was used, with properties taken from the sample THERM tutorial. In these models, the film coefficients are specified based on the surface they are applied on. In general, different coefficients are specified for framing and glazing elements. U-value "tags" are applied to surfaces at this stage as well. The U-value tags are applied to interior surfaces. THERM uses these surface tags to determine the area over which the U-value results will be integrated. Figure 98 shows the model and infrared results for the base IGU and frame. Edge-of-glass and Frame U-values were defined by integrating the heat flux through their respective interior exposed surface areas.

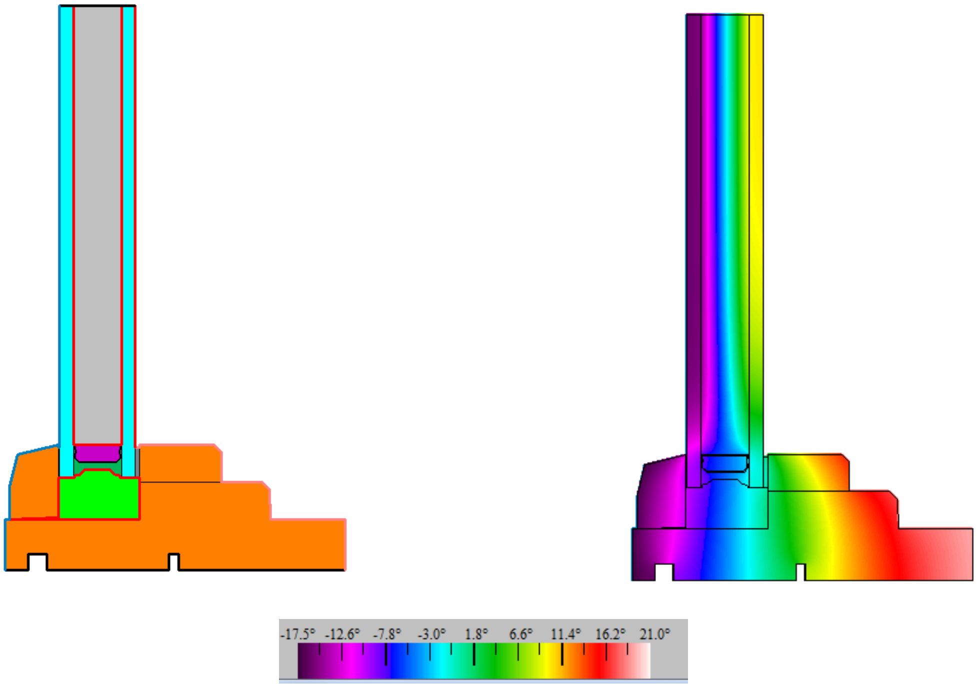


Figure 98: Model of IGU with standard wood frame (left) and infrared analysis (right) obtained using THERM. The temperatures are given in Celsius.

Figure 99 demonstrates that the behavior of each installation method was similar. In this stage of the analysis, it was assumed that the frame would be "slightly ventilated". During the region where the insulation is within the jamb cavity, the installation method had the most significant effect, resulting in as much as 10% of a variance in performance. The system with the 12.7mm airspace performed the best in this region, and nearly the best for thicker insulation thickness. When the insulation thickness was greater than the jamb thickness, the 6.35mm insulation method performed slightly better.

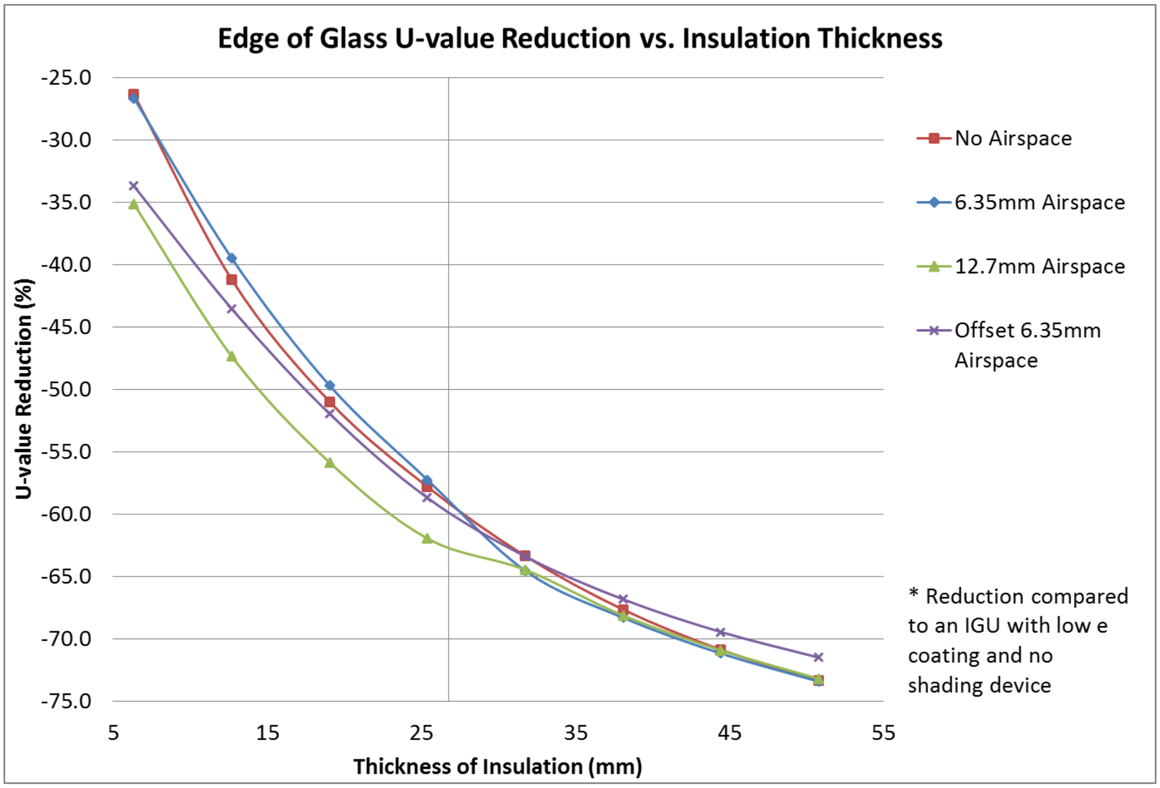


Figure 99: Edge of glass U-value reduction vs. insulation thickness for various installation methods with ventilated cavities.

Figure 100 shows the frame U-values for each installation method assuming slightly ventilated cavities. Although there was a significant amount of irregularity for systems in this region, one common trend was that the system performance plateaus after a thickness of insulation in excess of the jamb cavity was achieved. In fact, when the data is shifted to reflect the distance from the interior glazing surface to the interior face of the insulation, the results, shown in Figure 101 and Figure 102, make much more sense.

It is speculated that some of the irregularities were caused by the changing exposed surface area of the frame material due to the thickness of insulation. Systems in which the insulation is offset from the jamb surface had the least variance in performance based on additional insulation (~3%). When no airspace was used, additional insulation thickness improved the performance of the system. For systems with an airspace, additional insulation thickness actually reduced performance. One possible explanation for this phenomena is that the thicker insulation systems have more exposed surface area to absorb heat and transfer it to the frame through the thermal bridge where the frame and insulation contact.

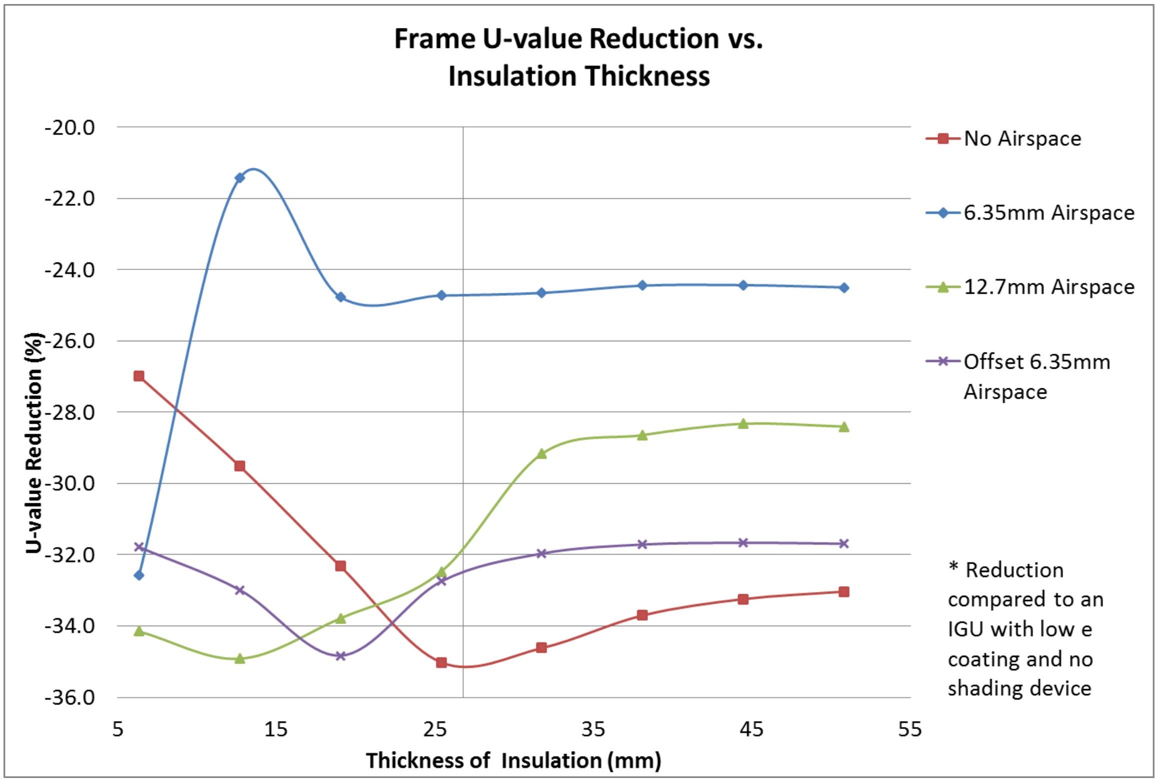


Figure 100: Reduction in frame U-value vs. insulation thickness for various insulation thicknesses with ventilated cavities

Infrared schematics are shown in Figure 103, Figure 104, and Figure 105 for 6.35mm insulation thickness, 50.8mm insulation thickness, and the offset insulation method, respectively. Note how the glazing surface is significantly colder when 50.8mm insulation (Figure 103) is used as compared to 6.35mm insulation (Figure 104). Condensation is likely to be a problem if the insulation cavity cannot be sealed from the warm, moist interior air.

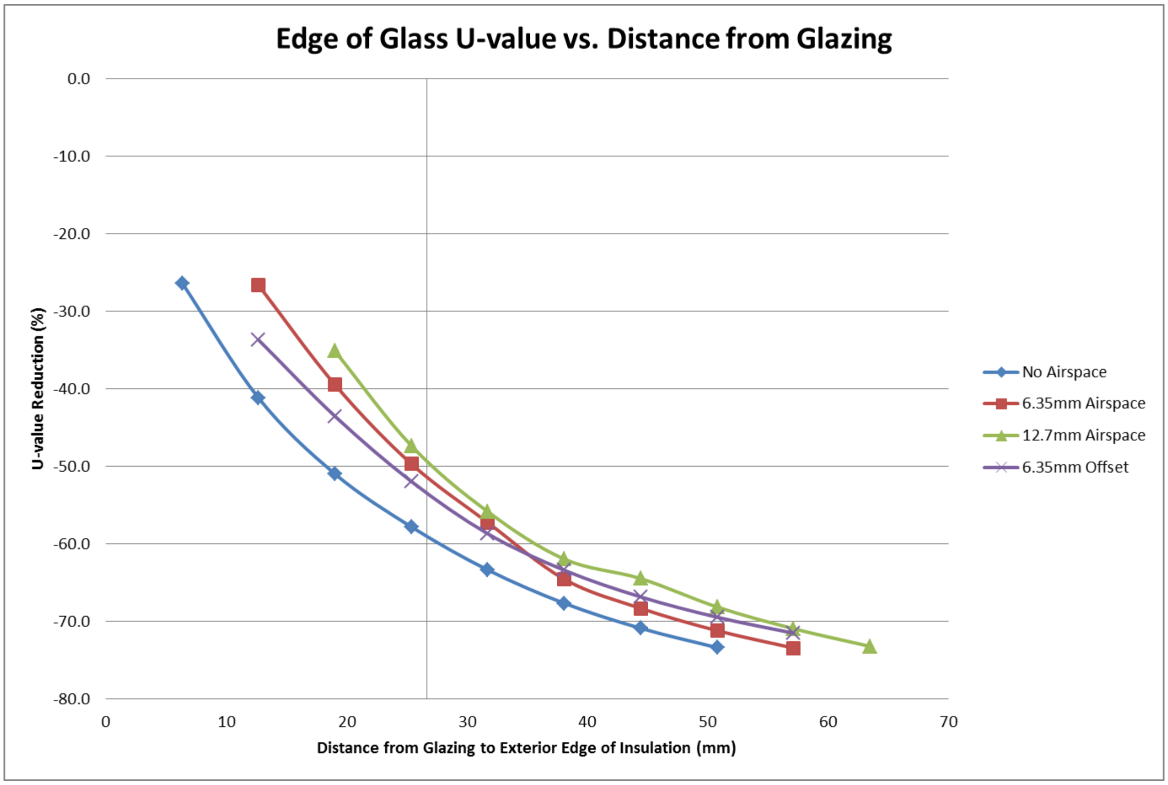


Figure 101: Edge-of-glass U-value reduction vs. distance from glazing surface

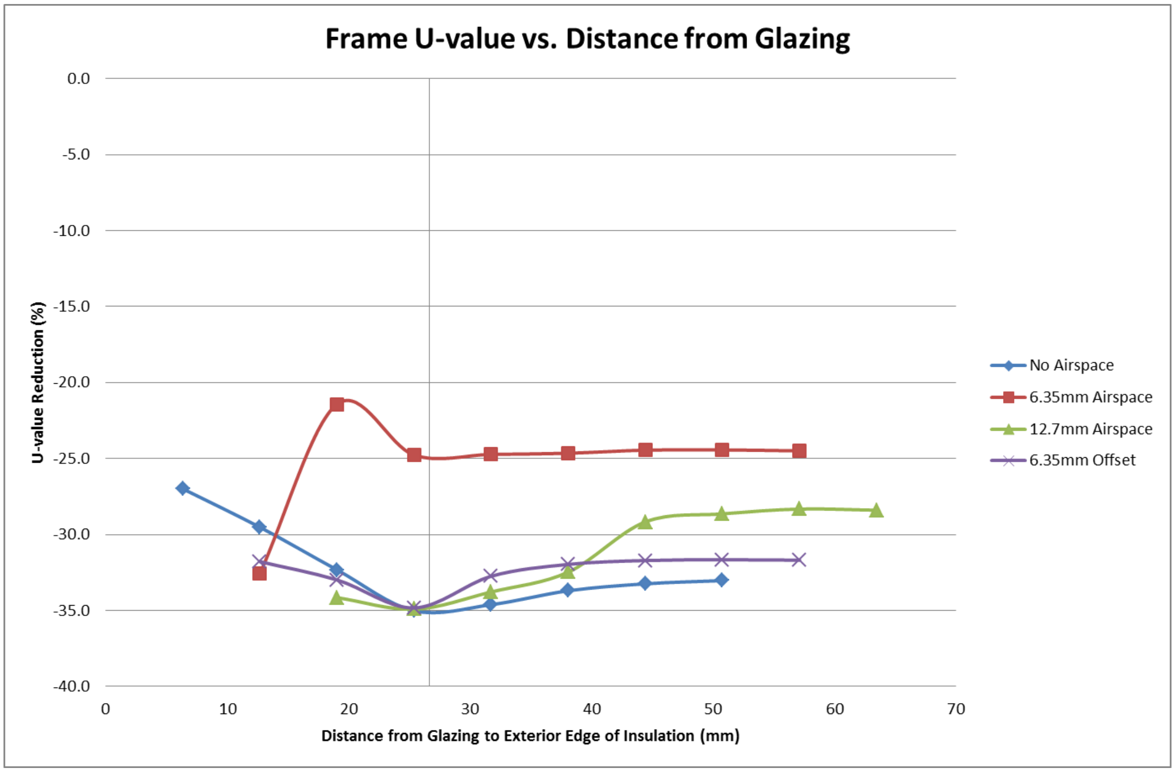


Figure 102: Frame U-value reduction vs. distance from glazing surface.

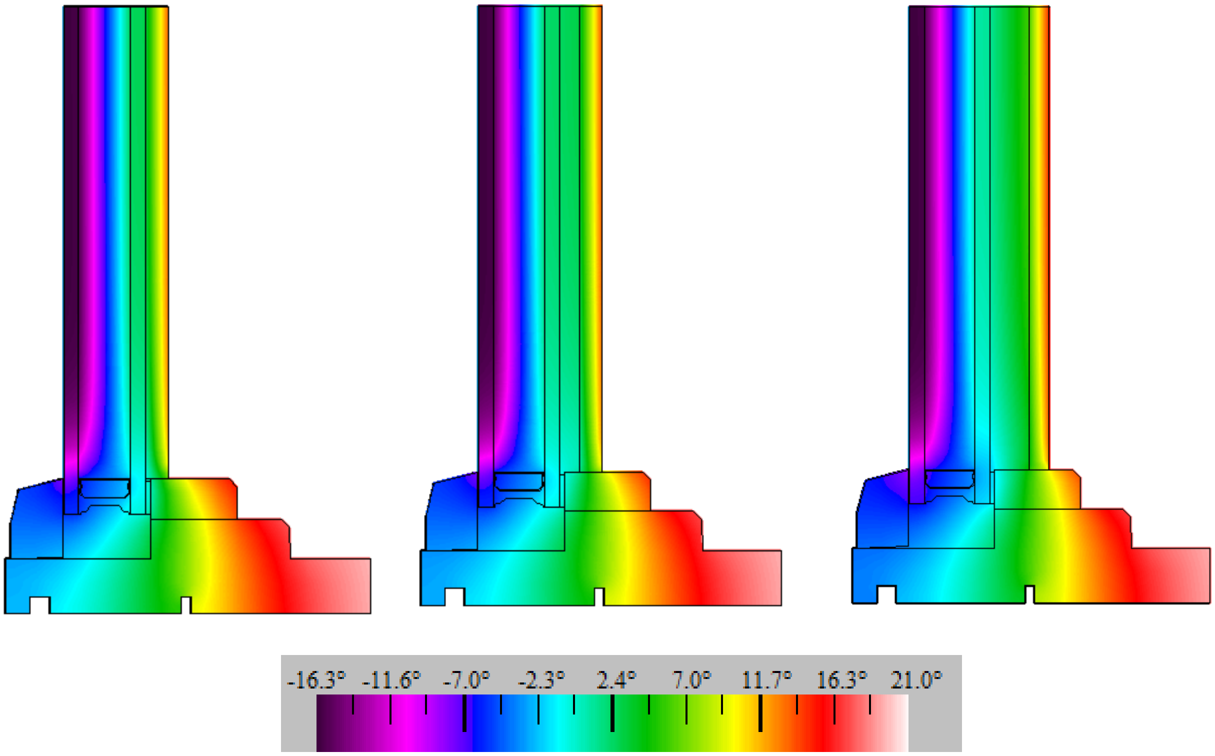


Figure 103: Comparison of infrared energy through glazing system with 1/4” insulation with no airspace (left), 6.35mm airspace (middle) and 12.7mm airspace (right). The temperatures are given in Celsius.

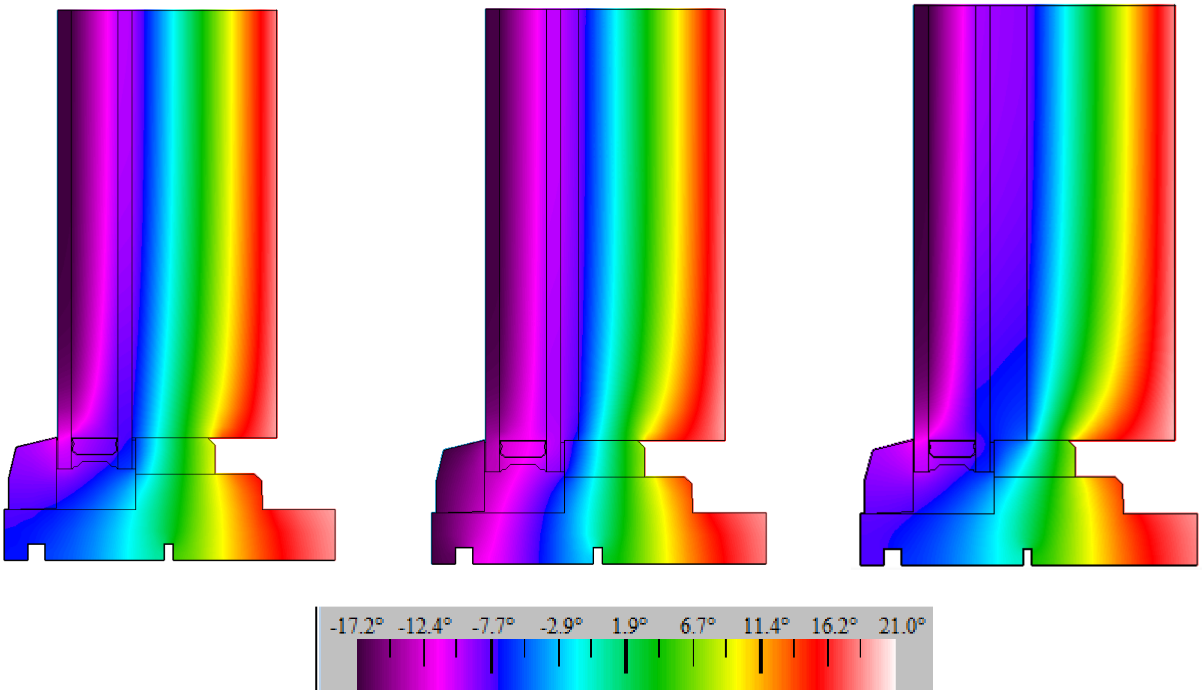


Figure 104: Comparison of infrared energy through glazing system with 2” insulation with no airspace (left), 6.35mm airspace (middle) and 12.7mm airspace (right). The temperatures are given in Celcius.

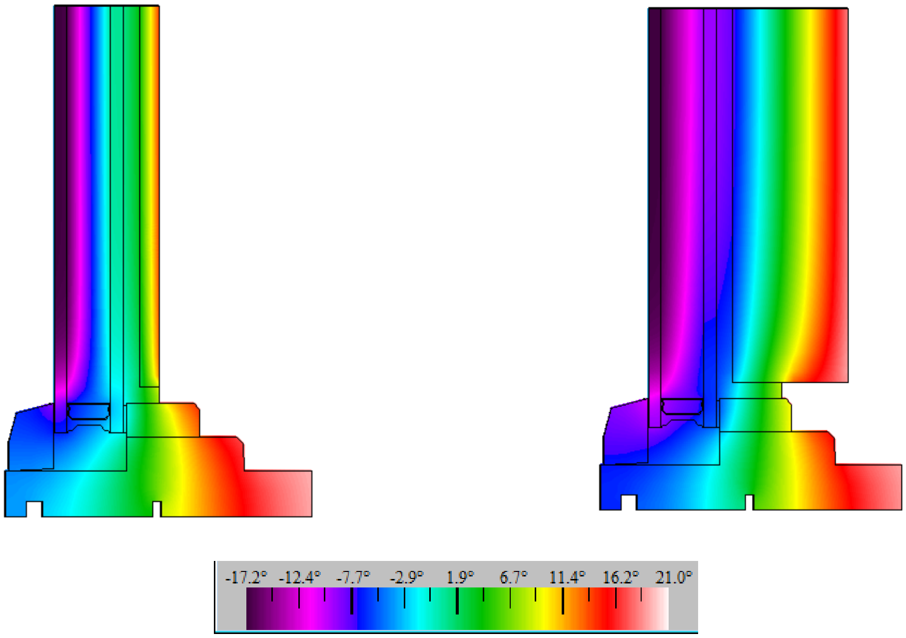


Figure 105: Infrared diagrams for IGU with insulation offset from frame for system with 6.35mm insulation (left) and 50.8mm (right) insulation. The temperatures are given in Celcius.

It was desired to investigate the effect of modeling the insulation cavity as slightly ventilated or non-ventilated. Figure 106 and Figure 107 show, respectively, the edge-of-glass and frame U-value reduction as a function of insulation thickness for a 6.35mm insulation cavity. Both figures indicate that the modeling method makes little difference (<1%) as long as the insulation thickness has not exceeded the frame cavity.

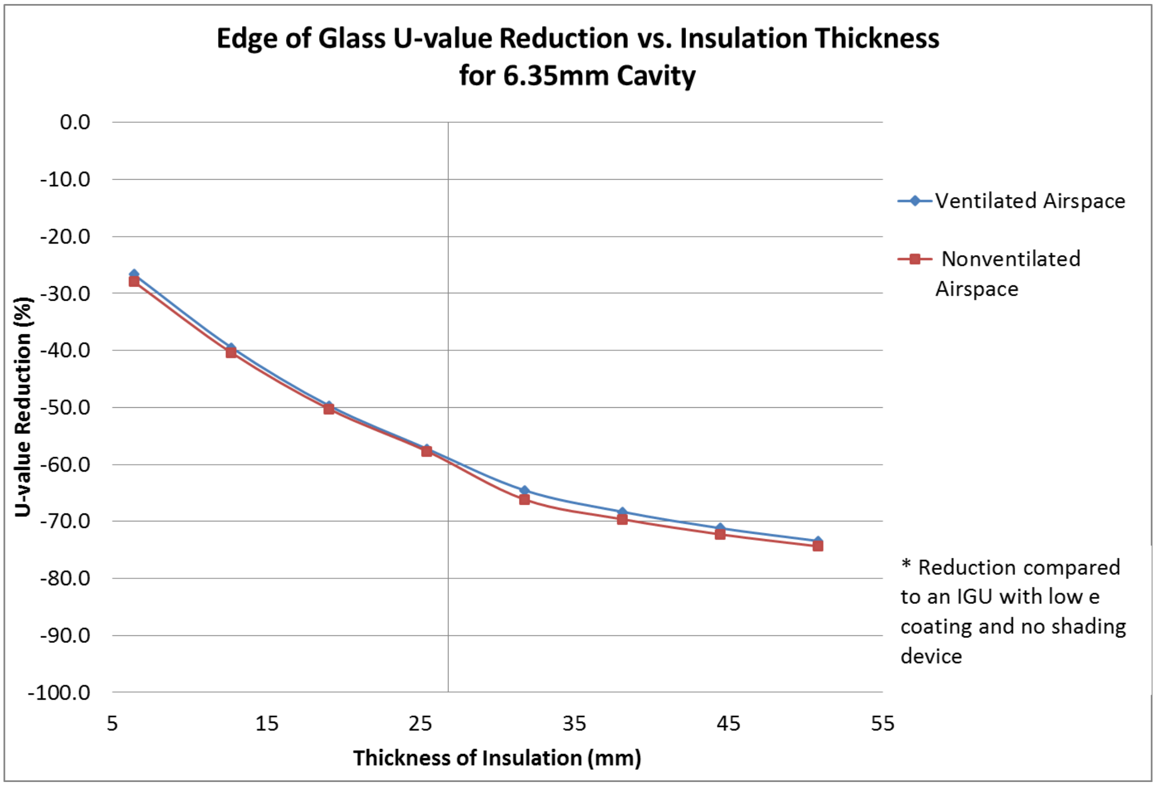


Figure 106: Edge-of-glass U-value reduction vs. insulation thickness for 6.35mm ventilated and non-ventilated cavities

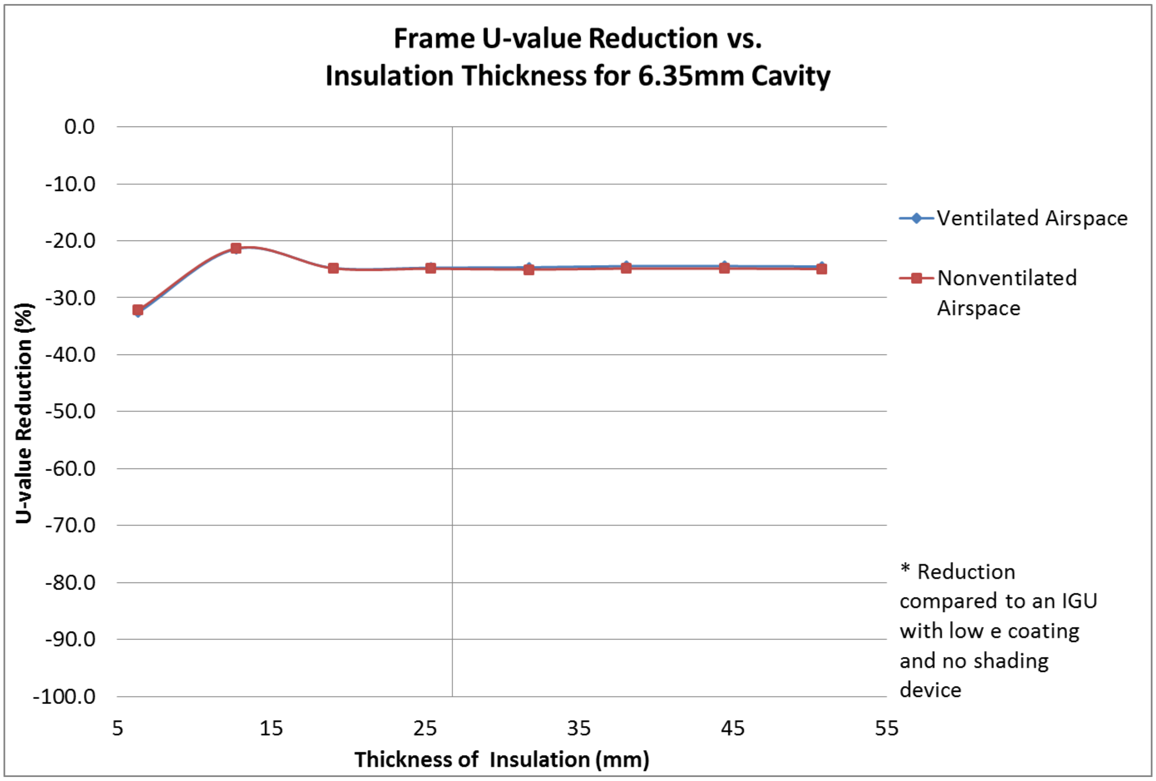


Figure 107: Frame U-value reduction vs. insulation thickness for 6.35mm ventilated and non-ventilated cavities.

Figure 108 and Figure 109 show, respectively, the edge-of-glass and frame U-value reduction as a function of insulation thickness for a 12.7mm insulation cavity. For the edge-of-glass region, non-ventilated airspaces perform 5-10% better than a similar system with a slightly ventilated cavity when the insulation is within the jamb cavity. However, there is little difference in performance for insulation thicknesses in excess of the jamb cavity.

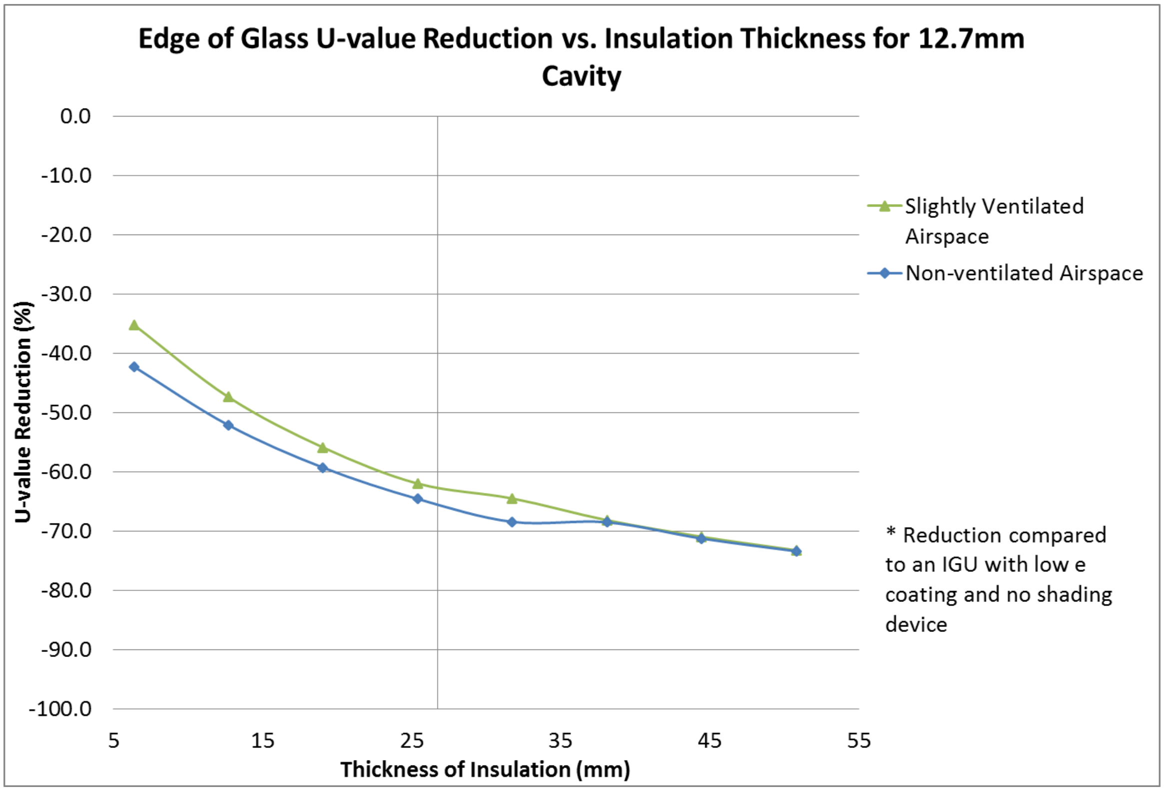


Figure 108: Edge-of-glass U-value reduction vs. insulation thickness for ventilated and non-ventilated, 12.7mm cavities.

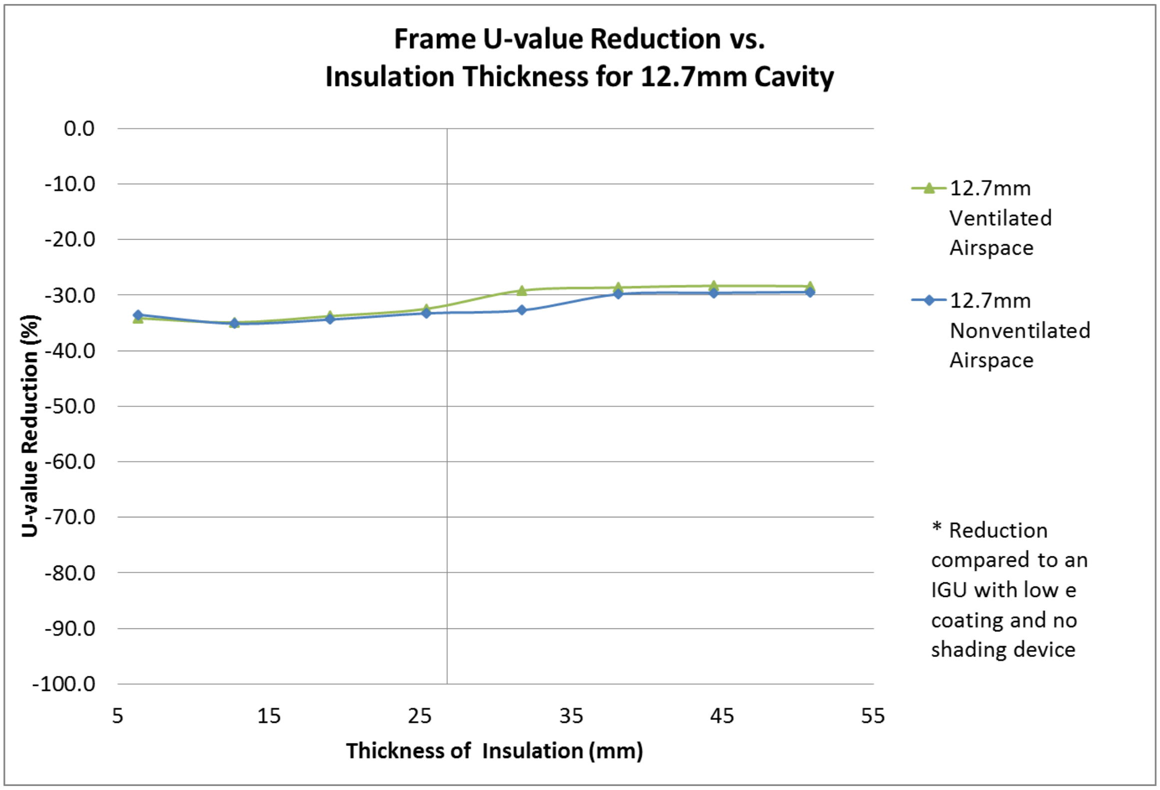


Figure 109: Frame U-value reduction vs. insulation thickness for ventilated and unventilated, 12.7mm cavities.

7.4 Insulated Layer Summary

The performance study for insulated layers was completed assuming various thicknesses of expanded polystyrene (EPS) were added to glazing systems using several different installation methods. The installation methods examined include mounting the insulation flush with the jamb. In addition, the effect of modeling the cavity formed between the insulation and the glazing as slightly ventilated or non-ventilated was examined. A summary of the results is shown in Table 16. Installation methods that create a wider airspace between the glazing and the insulation performed better than the others, although the variance in performance between installation methods decreased with increasing insulation thickness. In addition, the effectiveness of using increased thicknesses of insulation was decreased as the insulation extends beyond the thickness of the sill.

Table 16: Summary of center of glass (top), edge of glass (middle) and frame (bottom) U-value reductions for insulated layer analysis

Criteria Explored	Range of Center of Glass U-value Reduction (%)	Reference Figure
Insulation Thickness Installation Method	23 - 75	Figure 97

Criteria Explored	Range of Edge of Glass U-value Reduction (%)	Reference Figure
Insulation Thickness Installation Method	26 - 74	Figure 99, Figure 101
Cavity Type (6.35mm)	27.5 - 74	Figure 106
Cavity Type (12.7mm)	35 - 74	Figure 108

Criteria Explored	Range of Frame U-value Reduction (%)	Reference Figure
Insulation Thickness Installation Method	21 - 35	Figure 100,Figure 102
Cavity Type (6.35 mm)	21 - 35	Figure 107
Cavity Type (12.7mm)	28.5 - 35	Figure 109

8. Perforated Screen Style Attachments

8.1 Insect Screens

Insect screens are a common component of most residential window systems. These screens provide some shading effect; however, their presence is not taken into account with performance values for most window systems. Therefore, their impact should be evaluated. For improved shading potential, retractable screen can also be used (see Section 5.1: Interior Curtains and Draperies).

Figure 110: Insect screens, with their fine mesh, provide shading on the window. Image Source: Screen Mobile, 2013

Thermal Improvement

Window screens can be an effective means of reducing the solar heat gain through glazing. When the screens are located on the exterior of the window, they reduce the SHGC by 46%. When they are located on the inside of the window, a 15% reduction in SHGC occurs (Brunger et al., 1999).

Although insect screens do not add any insulation value to the window, they do slow the convective heat flow away from the surface of the window. When insect screens are in the typical location (on the exterior of the glazing), the U-value is reduced by 7%. However, if the screens are placed on the interior side of the glazing, a 14% reduction in U-value occurs. This improvement of the performance of the screens on the inside of the window occurs because the forced convective flow that occurs outside is much more powerful than the natural convective flow that occurs inside (Brunger et al., 1999).

Comfort

Use of an insect screen will have a slight impact on the thermal comfort of the space. Since the screen does have an impact on the U-value of the window, the interior surface of the glazing, or the screen itself (depending on the configuration), will be warmer than a configuration that includes only the glazing. This will result in a more comfortable interior environment.

Condensation Potential

Since the glazing surface will be warmer when insect screens are placed on the exterior side of the glazing, there will be a lower likelihood of condensation development.

Impact on Daylighting

The fine mesh used for insect screens results in a slight reduction in daylighting potential. For now, it will be assumed that the reduction in visual transmittance of mesh screens is similar to the reduction of solar heat gain, 46% and 15% for the exterior and interior, respectively.

Air Leakage
Although there will be a slight reduction in the air leakage through the window sashes due to the window screens fine mesh, the impact will likely be marginal.

Cost
Insect screens are usually a fiberglass mesh product. A 60”x25’ roll of Phifer Fiberglass Screen Wire costs $27.98. Screens for (10) 30”x60” windows can be cut from this roll, resulting in a cost of $2.80 per window. 1”x2”x8’ spruce pine furring strips cost $1.12 each. This translates to $2.24 for a single window. Total cost, therefore, is $5.04 to create a screen for a window (Lowe’s, 2013).

Ease of Operation
Insect screens are typically left in place throughout the year, although they can be easily removed if desired.

Privacy
Screens are not an effective means of creating privacy.

Aesthetics
Although window screens do affect the clarity of the window, they are so common that most users do not notice their presence.

Figure 111 shows the at-a-glance performance diagram for insect screens.

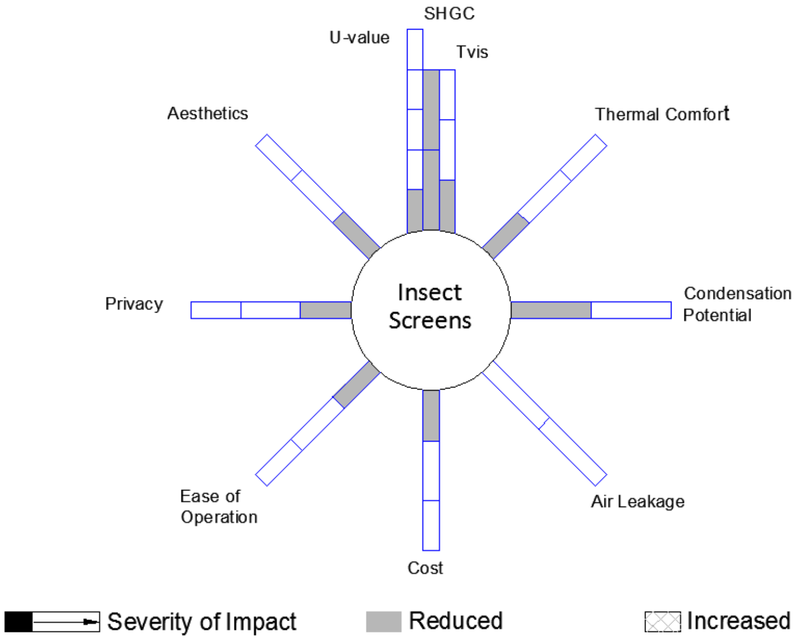


Figure 111: At-a-glance performance diagram for insect screens

8.2 Perforated Screen Analysis

The first portion of the analysis was the investigation of the effect of the spacing, denoted by Sx and Sy in Figure 112, between perforations for both interior and exterior systems. The motivation for using this criterion is to determine the effect of frequency of perforations (the number of perforations per unit area) on shade performance. The size of the perforations was kept constant at 6.35mm for the diameter, width/height, and width, respectively, for circular, square, or rectangular perforations.

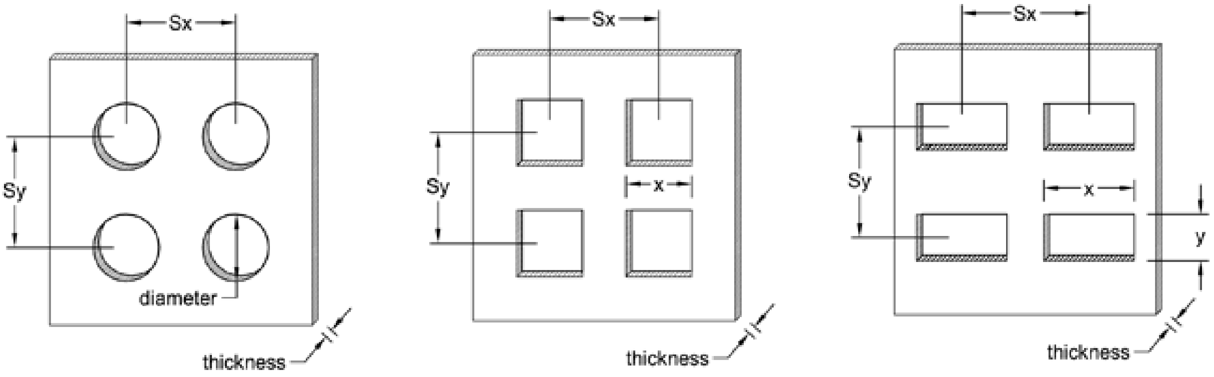


Figure 112: Schematic for circular (left), square (middle), and rectangular (right) perforated screens. Image Source: LBNL, 2013a

The results of this analysis revealed several conclusions. The first was that all of the shades provided an identical reduction in U-value of 13.6% and 26.1% for interior and exterior blinds, respectively. The screens are effective at disrupting the convective heat flow on either side of the glazing system. However, it is interesting to note that Bruger et al. (1999) noted that the screens were more effective on the interior side of the glazing then the exterior side.

While the spacing between the perforations did not have a significant effect on the screens ability to reduce the U-value, they had a significant effect on SHGC reduction (Figure 113). As the distance between perforations reaches ~20mm, the shades reach their maximum shading capability, reducing the SHGC by 45% and 85% for interior and exterior shades, respectively.

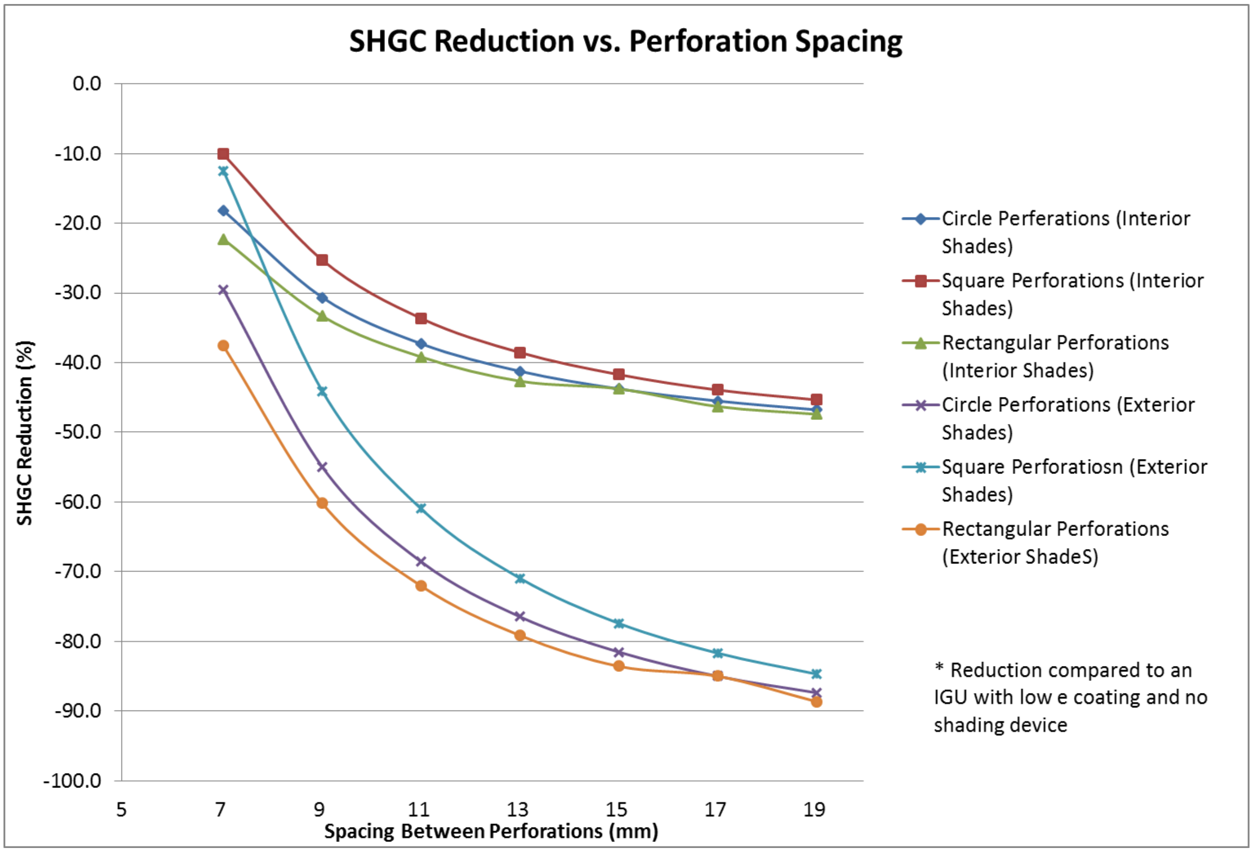


Figure 113: Reduction in SHGC as a function of perforation spacing for interior and exterior shades.

The next criterion was the effect of the distance between the screen and the glazing system on the system. While the SHGC only marginally affected the location of the screen, the effect on the U-value was much greater (Figure 114). The screens are capable of reducing the U-value by as much as 26% and 18% for exterior and interior shades, respectively. Additionally, the proximity to the glazing does not necessarily correspond to improvement in behavior. For interior screens, the maximum reduction in U-value occurs at a distance of ~7mm. Distances greater or less than this value will not experience as great of a U-value reduction.

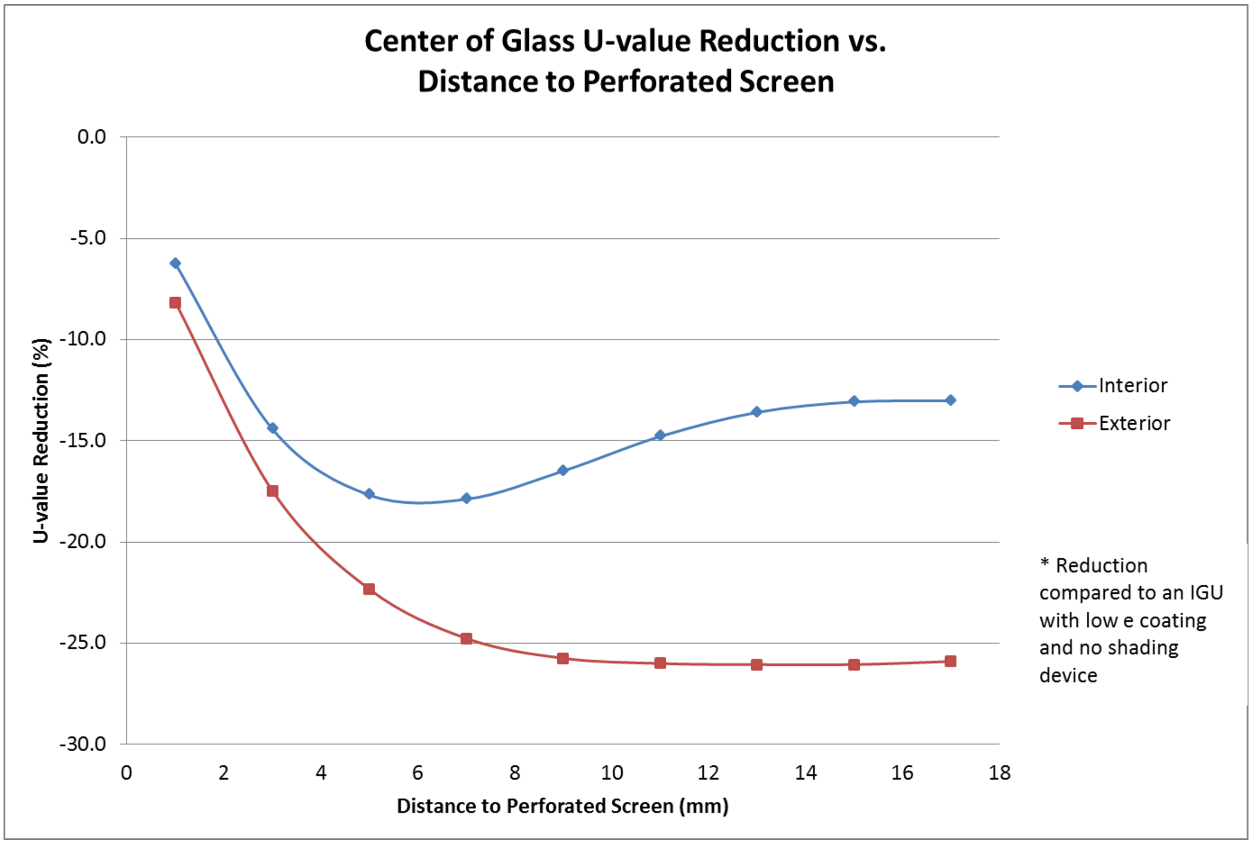


Figure 114: Reduction in U-value as a function of the distance between the glazing and the perforated screens for interior and exterior shades.

8.3 Perforated Screen Summary

The effect of the shape of perforations as well as their placement was investigated for interior and exterior shades. Perforated screens are most useful for reducing solar heat gain. Interior screens reduce the SHGC by as much as 46%, while exterior shade can reduce the U-value by 88%. Rectangular shaped perforations performed the best, while circular perforations performed the worst. The shape of perforations had no effect on the U-value. Rather, the primary variable affecting performance was the width of the cavity between the screen and the glazing. Exterior shades spaced at a minimum of 9mm from the glazing surface reduce the U-value by 26%, while interior shades perform best when spaced at ~6mm, resulting in a 17.5% reduction. A summary of this analysis is shown in Table 17.

Table 17: Summary of center-of-glass U-value (top) and SHGC (bottom) reductions for perforated screens

Criteria Explored	Range of Center of Glass U-value Reduction (%)	Reference Figure
Shading Cavity Thickness (Interior)	7-17.5	Figure 114
Shading Cavity Thickness (Exterior)	8-26	Figure 114

Criteria Explored	Range of SHGC Reduction (%)	Reference Figure
Perforation Shape Perforation Spacing (Interior)	10-46	Figure 113
Perforation Shape Perforation Spacing (Exterior)	12-88	Figure 113

9. Cellular Shade Style Attachments

9.1 Cellular Shades

This system uses a dual cell design that creates an air gap, which provides additional insulation. There are many varieties of insulated blinds on the market. Some varieties have cells that can be "compressed' to essentially act as conventional blinds while others are permanently in their expanded view. In addition, these blinds are typically designed to be adjustable from the top as well as the bottom (see Figure 115.)

Figure 115: Insulated cellular blinds provide shading, light diffusion, as well as additional insulation. Image source: Levolor, 2013.

Thermal Improvement

The most basic designs serve primarily to create a layer of insulation on the inside of the window. Some more advanced models have edge tracks that help to limit the air movement around the blinds. The creation of a sealed "air gap" will boost the performance of the system. Other designs have a reflective polyester layer on the side of the blind facing the window. This serves as a radiant barrier, which can help reduce heat further.

The degree of thermal improvement will vary based on the exact system used. One manufacturer, Levolor, produces 4 basic categories of cellular shades, which are appropriate for improving thermal efficiency.

- **Shear with Energy Shield Backing** – These are the most transparent of the cellular blinds produced by Levolor. The quality of the fabrics used is also rated as the highest. They have a SHGC of 0.44, and an effective R-value of 3.33 (a U-value of 0.3). When paired with a single-glazed window with a U-value of 1.12, the U-value for the combined system is 0.23. This is a 79.5% improvement.
- **Woven Fabrics with Energy Shield Backing** – These fabrics typically have more complicated designs. Their SHGC is 0.25 and the R-value ranges between 3.45-3.62 based on the exact fabric used. An average R value of 3.53 will be used. This corresponds to a total U-value (when paired with single glazing) of 0.226 (a 79.8% improvement).
- **Non-Woven Fabrics with Energy Shield Backing** – These shades have an SHGC of 0.23 and an R-value ranging from 3.45-3.57 depending on the specific fabric used. An average R-value of 3.51

will be used. This corresponds to a total U-value (when paired with single glazing) of 0.227 (a 79.7% improvement).

- **Double Cell** – These systems have dual cells instead of the single cells for the systems listed above. No Energy Shield Backing is used for these systems, probably due to the added insulation value given by the dual cells. They feature an SHGC of 0.19 and an R-value of 3.85, corresponding to a total U-value of 0.21 (81% improvement).

There are several important issues to note regarding these values. First, the actual performance of the combined window and shade system will likely not be as good as that predicted in the above figures. This is because the method of using a U-value that is based on the reciprocal of the combined R-value assumes that conduction is the only mode of heat transfer taking place. In reality, convective heat flow will pull air from between the interstitial space between the glass and the shade around into the room unless the shades are thoroughly sealed. In addition, the positive air space between the glazing and the shade is not taken into account.

One other issue is that the relative improvement between each of these systems is quite small. This indicates that the choice between each will wind up being more a factor of the owners aesthetic preferences than the performance of each system.

The Cold Climate Housing Research Center also investigated the performance of cellular blinds. When they performed computer analysis of double cellular shades on a double glazed window, they found that a 15% improvement could be achieved. When they measured this performance in the field, they found that a 60% improvement could be achieved. It was noted in the study that the window that was investigated was very large, which could partially account for the variation between the computer and physical analysis. For this study, the 60% improvement will be used since it lies in between the CCHRC computer analysis and manufacturer data listed above.

Comfort

These blinds will radiate significantly less cold than the glass itself. This means that the thermal comfort of the space will be significantly improved.

Condensation Potential

Since this method reduces the temperature of the glazing but does not prevent transport of water vapor to the inside surface of the glass, condensation will likely be an issue, particularly in colder climates.

Air Leakage

Although these shades are air permeable, they will reduce the amount of air leakage through the window sash.

Cost

The cost of this system will vary based on the type used. For the Levolor systems described above, the price for a single 30”x60” window are as follows (Lowe’s, 2013).

- **Shear with Energy Shield**: $221
- **Woven Fabrics with Energy Shield Backing** - $141 base price plus Energy Shield Backing surchage = $177
- **Non-Woven Fabrics with Energy Shield Backing** - $106 base price plus Energy Shield Backing surcharge = $142.

- **Double Cell** - $110.

Ease of Operation
After initial installation, these units require very little work on the part of the user. The blinds can be easily adjusted using pull cords. In addition, many of these systems offer additional utility of allowing you to adjust the level of the shades from the top as well as the bottom. This allows the user to allow for light and or view according to their preferences.

Privacy
The type of material used for the shades will have a significant impact on how well they provide privacy. While nearly all cellular shades will block a direct view into the building, silhouettes will still be visible through sheer fabrics.

Impact on Daylighting
These systems are usually made of an opaque fabric which blocks view to the outside. Some units are comprised of a light diffusing material that can actually help transmit light further into the interior of the building while blocking glare, while others are completely opaque and will completely block light. Most models can be retracted to allow for complete views when not needed, and others have cells that can be compressed, functioning in the same way as conventional blinds.

Aesthetics
This system will have a substantial effect on the space, albeit one that most would consider positive. The shades come in a variety of different colors that can be used to meet the needs of any space.

Figure 116 shows the at-a-glance performance diagram for cellular shades.

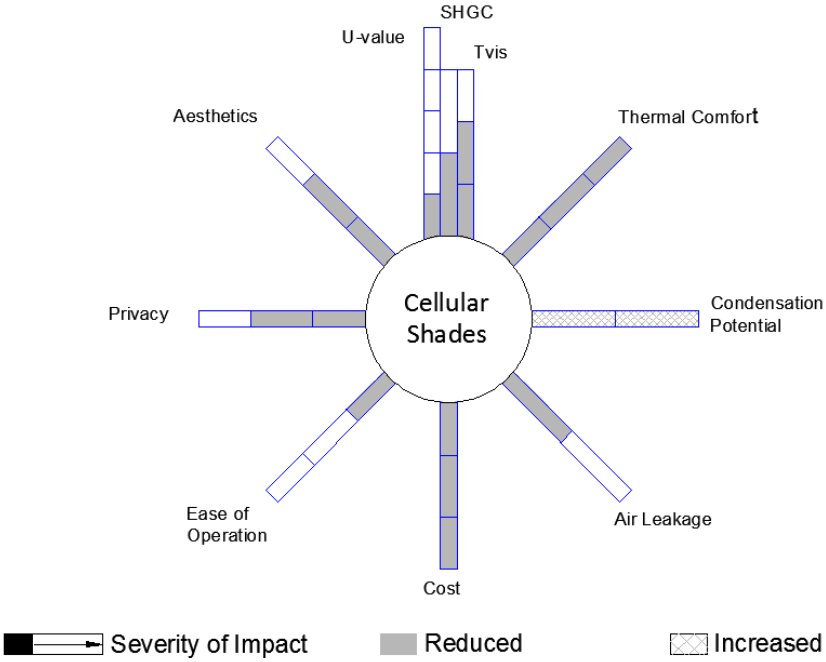
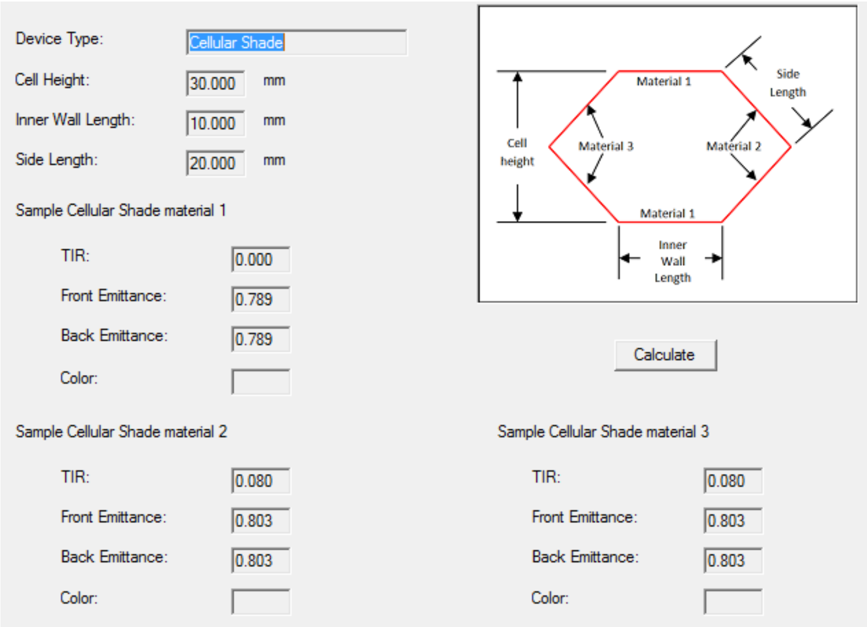


Figure 116: At-a-glance performance diagram for cellular shades.

9.2 Cellular Shades Analysis

The latest version of WINDOW (LBNLa., 2013) currently allows for the inclusion of cellular shades in a glazing system. The parameters that are important for defining the cellular shades are geometric properties including the cell height, inner wall length, and side wall lengths as well as material properties such as infrared transmittance (T_{IR}) and front and back emmisivity for each material used in the shade. WINDOW then uses a Bi-Directional Scattering Distribution Function (BDSF) to calculate the performance properties for the shade. The key parameters for cellular shades are shown in Figure 117.



Device Type: Cellular Shade

Cell Height: 30.000 mm

Inner Wall Length: 10.000 mm

Side Length: 20.000 mm

Sample Cellular Shade material 1

TIR: 0.000

Front Emittance: 0.789

Back Emittance: 0.789

Color:

Sample Cellular Shade material 2

TIR: 0.080

Front Emittance: 0.803

Back Emittance: 0.803

Color:

Sample Cellular Shade material 3

TIR: 0.080

Front Emittance: 0.803

Back Emittance: 0.803

Color:

Figure 117: Screenshot from LBNL WINDOW showing cellular shade parameters for cellular blinds

The inclusion of cellular shade properties is still a new feature for WINDOW. Therefore, there is no ability to create or edit cellular shades "in-program" apart from those pre-defined by the program. The properties of the eight pre-defined cellular shades are shown in Table 18.

Table 18: Properties of pre-defined cellular shades in WINDOW. Data source: LBNL, 2013a

	Geometric Properties			Material 1			Material 2	Material 3
	Cell Height (mm)	Interior Wall Length (mm)	Side Length (mm)	T_{IR}	Front Emittance	Back Emittance	T_{IR}	T_{IR}
Dark, Opaque	30	10	20	0	0.789	0.789	0.080	0.080
Medium, Opaque	30	10	20	0	0.789	0.789	0.189	0.189
Light, Opaque	30	10	20	0.031	0.776	0.776	0.065	0.065
Sheer, Dark	30	7	20	0.234	0.697	0.697	0.495	0.495
Sheer, Medium	30	7	20	0.127	0.771	0.771	0.270	0.270
Shear, Light	30	7	20	0.294	0.631	0.631	0.517	0.517
Opaque, White Inside, Dark Interior	30	10	20	0	0.789	0.789	0.821	0.803
Opaque, White Inside, Medium Interior	30	10	20	0	0.789	0.789	0.821	0.691

Figure 118 shows the percent reduction in U-value and SHGC obtained by using each of the predefined cellular shades. As would be expected, the opaque shades were much more effective at reducing solar heat gain than their sheer counterparts. However, all of the shades were similarly effective at reducing the U-value.

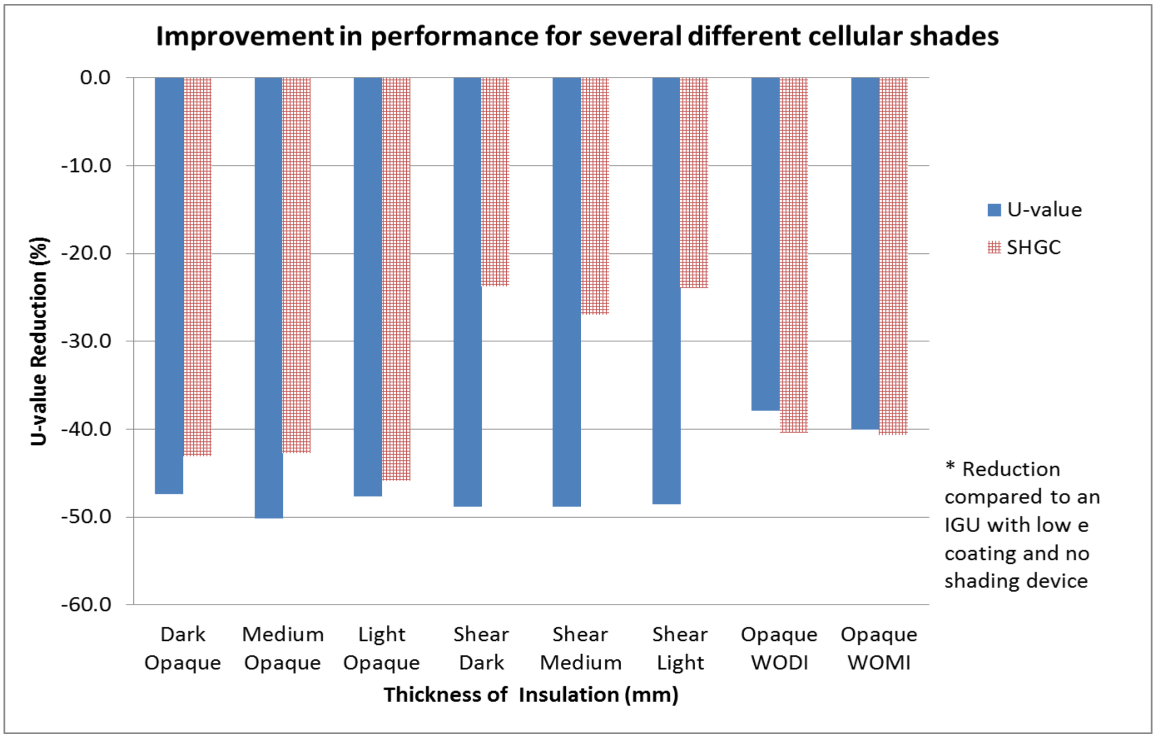


Figure 118: Comparison of U-value performance for pre-defined cellular shading systems.

The pre-defined shades can be edited by modifying the XML text files outside of the program. However, this is an extremely cumbersome process, as the BDSF must be re-calculated to obtain results that WINDOW can use, a process that takes 1-2 hours per file that is augmented. This process was undertaken to establish the effect of using cellular shades with varying cell heights.

The results demonstrate that a lower U-value can be achieved as the shade moves farther from the glazing surface, with a total variance in performance of ~6% over the range of values investigated (Figure 119). It should be noted that this is the opposite of what was seen for venetian blinds.

The results for the SHGC are as would be expected. Smaller cells are more effective in limiting solar heat gain as there are more horizontal segments to reflect light (Figure 120).

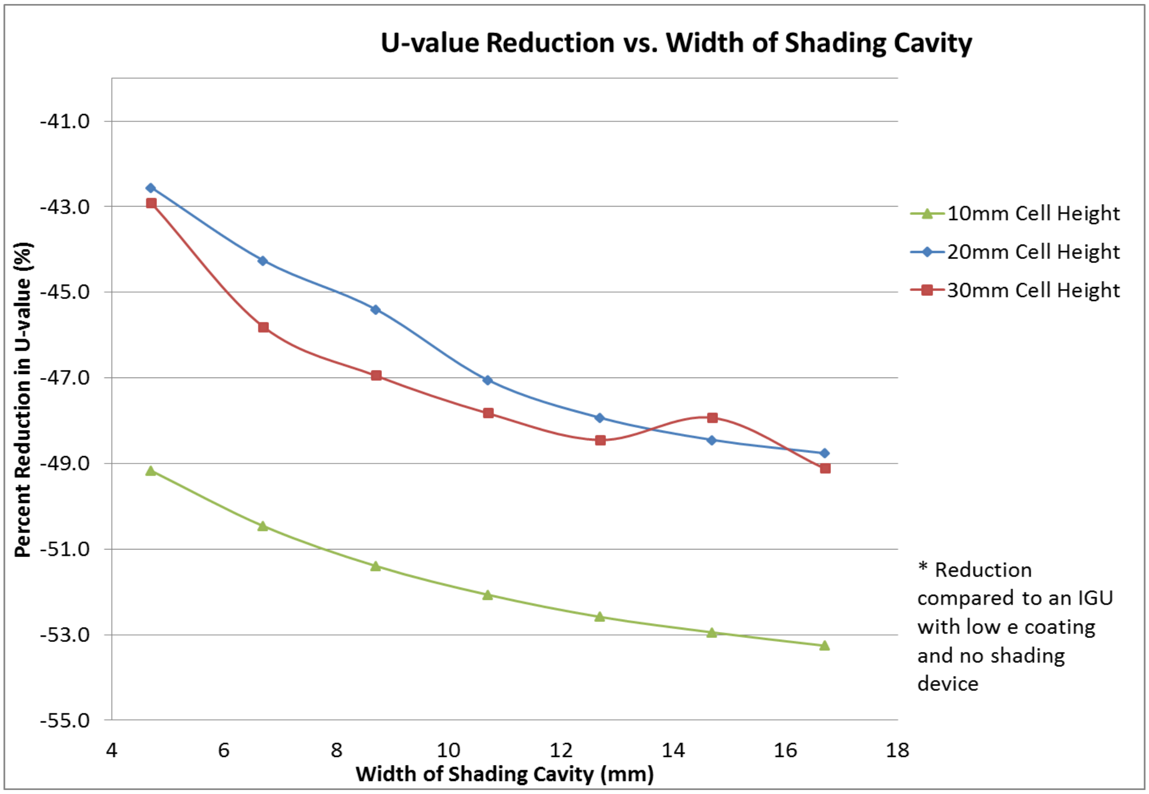


Figure 119: U-value reduction vs. width of shading cavity for several different cell heights.

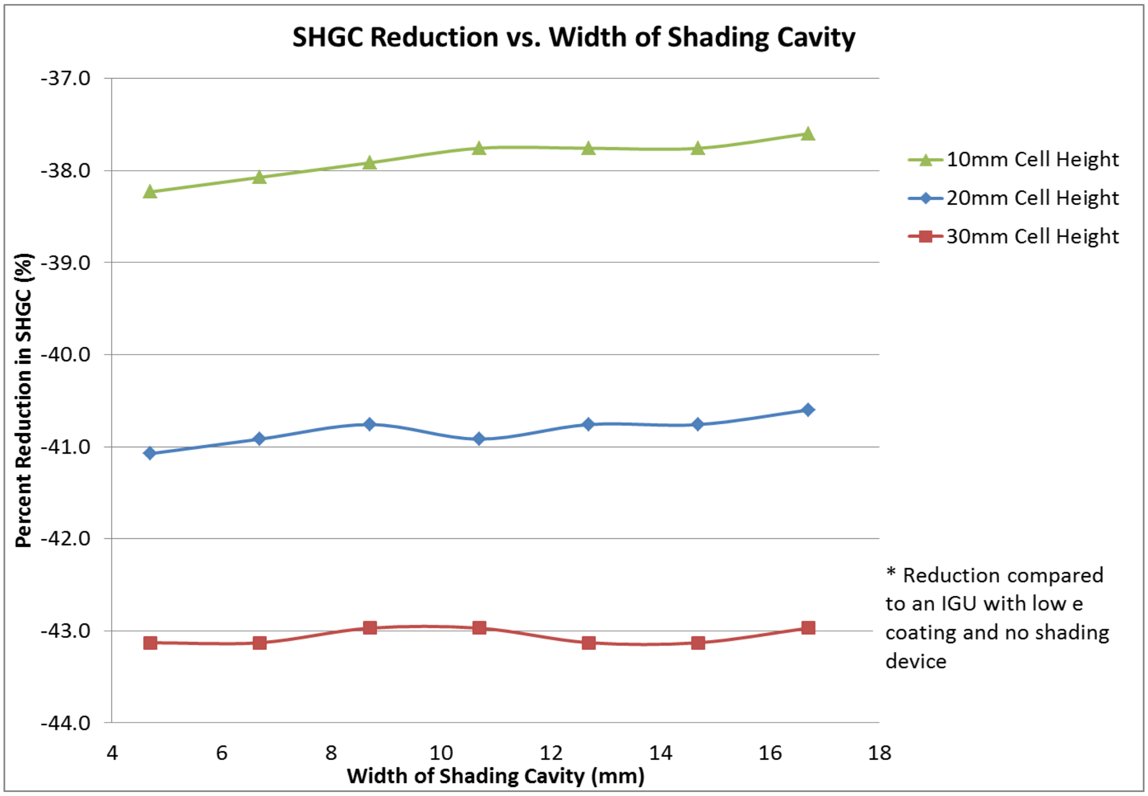


Figure 120: SHGC reduction vs. width of shading cavity for several different cell heights.

9.3 Cellular Shade Summary

As was previously discussed, WINDOW offers limited potential for the investigation of cellular shades. The criteria investigated were cell height as well as shading cavity width. In addition, the performance of several predefined cellular structures was investigated. From an insulative standpoint, it was found that the shades performed similarly, reducing the U-value between 39-53% regardless of the type of material used. In general, reducing the cell height resulted in smaller U-values, but higher SHGCs. In addition, larger shading cavities reduced the U-values, but had little effect on SHGC's. A summary of the results from this study can be seen in Table 19.

Table 19: Summary of center of glass U-value (top) and SHGC (bottom) reductions for cellular shades.

Criteria Explored	Range of center of glass U-value Reduction	Reference Figure
Predefined Shades	38-50	Figure 118
Shading Cavity Width Cell Height	39-53.5	Figure 119

Criteria Explored	Range of SHGC Reduction	Reference Figure
Predefined Shades	39-53	Figure 118
Shading Cavity Width Cell Height	37.5-43	Figure 120

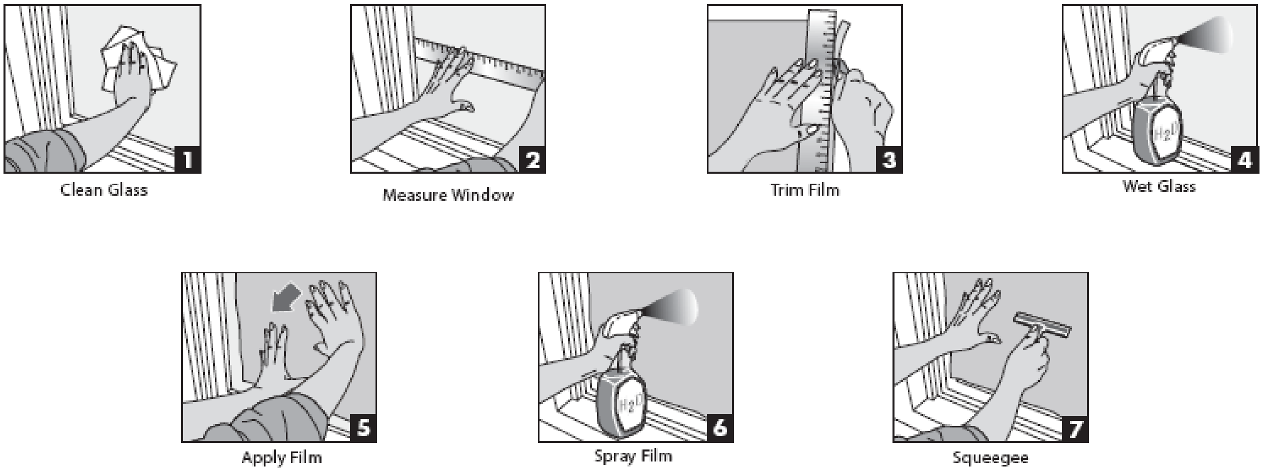
10. Other Methods of Window Retrofits

10.1 Low-Emissivity Films

Low-emissivity coatings are usually applied to glass at the manufacturing stage. While coated windows have become more common, many older homes still use uncoated glass. In these cases, a low-emissivity film can be applied to the existing glass. As is shown in Figure 121, the installation of this film can generally be performed easily without the need for skilled labor.

Figure 121: Low-E film on interior glazing. Image Source: Vista Window Film, 2013

Figure 122 shows the general steps involved with the process in pictograph form. The film is measured and cut to fit the exact size of the glass. Once the film has been cut, it is applied to a damp, clean window surface. The film is then sprayed with water again, at which point it is squeegeed to remove any air bubbles.



Clean Glass
Measure Window
Trim Film
Wet Glass
Apply Film
Spray Film
Squeegee

Figure 122: DIY installation instructions for low-e film. Image source: Energy-Film, 2013.

Thermal Improvement

While these films do not add an additional insulating capacity to the window, they will help reduce the extent to which heat that is absorbed by the window from being radiated to the next layer of glass or into the room. When applied to the inside surface of a window, they will also help to reduce the extent to which infrared heat from inside the building is able transfer through the system in the winter. This is beneficial for passive solar heating.

A low-e film manufactured by GILA (Product LES361) was chosen for use in this study. This film has a Total Solar Energy Rejection value of 70, meaning that 70% of the total solar energy is prevented from being transmitted through the film. This product has a T_{vis} of 0.3, and an emissivity of 0.44.

Thermal Comfort

Low-emissivity films applied to the window interior will reduce the radiation coming off of the window, thus improving the thermal comfort of the space.

Condensation Potential

Low-emissivity films will not affect the temperature of the glass. Therefore, the risk of condensation will stay the same.

Impact on Daylighting

The effect of window films on the visual transmittance of the window will vary from a film to film basis. The GILA product being investigated in this study has a T_{vis} of 0.3, meaning 30% of visible light is allowed to pass through the window.

Air Leakage

These films are applied directly to the surface of the window. As such, they will have no effect on the air leakage through either the sash or the frame.

Cost

A 36”x180” GILA window film costs $37.80. This will be large enough to cover three 30”x60” windows, resulting in a cost of $12.60 per window (Lowe’s, 2013).

Ease of Operation

Once these films are installed, they require no additional effort to operate throughout their lifetime.

Aesthetics

Low-emissivity films can come in a variety of colors and tints. Some of these will look noticeably darker than standard glass, while others are virtually undetectable. Figure 123 demonstrates the difference between a window with and without the inclusion of a film. Many of these films are acceptable for use on historic homes.

Figure 123: Comparison of a window with no film (left) and a GILA heat-control window film (right). Image source: Lowes, 2013.

10.2 Draft Snakes

“Draft Snakes” are essentially a fabric tube filled with rice or a similar fill. When placed along a window sill, they serve to block any drafts that are entering the space. Draft snakes are commonly used for doors as well.

Figure 124: Draft Snake on window sill. Image Source: This Old House, 2013.

As can be seen in Figure 124, draft snakes are not intended to block the entire window assembly. They are only intended to prevent drafts that occur along the base of the window. Therefore, other criteria such as thermal improvement, comfort, condensation potential, and daylighting are not applicable to this attachment.

Air Leakage
Draft snakes are only useful for leaky windows. Although they will not impact the sides of the sashes, they can effectively stop air leakage through the top or bottom sash of double-hung window. They will not have a substantial effect on newer, more airtight windows.

Cost
Draft snakes are available in a variety of models and trade names. They can also be easily created in a DIY fashion to fit any size window at a low cost. Frost-King produces a product called a “Draft Stop”, which can be used for either windows or doors. This product costs $6.97 and can be used for up to a 36” wide window or door (Lowe’s, 2013).

11. Summary and Conclusions

Numerous window retrofit solutions were compared using a variety of criteria. These include quantitative criteria such as reductions in U-value and SHGC obtained through literature as well as computer analysis using the software WINDOW and THERM. Additional criteria including daylighting impact, thermal comfort, condensation potential, air leakage, cost, ease of operation, privacy, and aesthetics were examined. The information obtained through literature review is summarized in Table 20 while that developed using WINDOW and THERM analysis is found in

Table 21.

There were several general conclusions that can be reached from the analytical portion of this study.

- Window retrofit solutions generally function by reducing convective and radiative heat loss. Conduction has a small role, if any, in their function.
- Exterior shades are generally more effective at reducing U-value and dramatically more effective at reducing SHGC than those placed on the interior.

In addition, several specific conclusions regarding specific features of different retrofit solutions were obtained.

Venetian Blinds

- In general, systems with shiny metallic surfaces will perform better than those matt finishes.
- Blinds should be installed as close to the glazing surface as possible within the frame to limit the flow of convection along the glazing surface.
- Venetian blinds capable of limiting airflow when in the closed (±90°) position can potentially significantly reduce thermal transmittance of the system.
- Blinds in the 0° position will reduce the U-value without substantially reducing the SHGC. This can be beneficial for passive solar heating.

Fabric Shades

- The use of air impermeable materials will be most effective at reducing the U-value as well as solar heat gain.
- Fabric shades should be mounted as close to the glazing surface as possible.

Glazing Layers

- Not all materials in the glazing layer category that appear to be optically clear perform equally. The specific optical characteristics of the material have a potentially significant impact on performance.
- Low-emissivity coatings installed on the interior of the glazing will reduce the U-value while having a smaller impact on reducing solar heat gain.

Insulated Layers

- Insulating layers will perform better with airspace between the insulation and the glazing. In general, performance will improve as the width of the airspace increases.

Perforated Screens

- Perforated screens are substantially more effective at reducing solar heat gain than thermal transmittance. Therefore, if passive solar heating is desired, the window assembly will perform better if the screens are removed.

Cellular Shades

- The color of cellular shades will not drive the performance of the system. However, the opacity of the material will. More opaque materials are more effective at limiting solar heat gain.
- Systems with smaller cell heights will perform better for passive solar heating applications.

Several recommendations could be developed based on the results of this study for the selection of interior and exterior retrofit systems when energy efficiency is the primary concern.

For interior systems:

- Fabric Shades and Perforated Screens will likely not be effective options for reducing the thermal transmittance of the window assembly.
- The best retrofit option for reducing the thermal transmittance of the system is utilization of insulating layers. Cellular shades and venetian blinds can also be effective options for U-value reduction.
- The best retrofit option for reducing solar heat gain is installation of additional glazing layers (including thin films) with spectrally selective coatings. Venetian blinds and cellular shades are also effective options for reducing the SHGC.
- In mixed climates, venetian blinds and cellular shades are systems that are effective at reducing both the U-value and the SHGC to varying degrees based on how they are operated.

For exterior systems

- The best retrofit option for reducing thermal transmittance is installation of additional glazing layers incorporating low-emissivity coatings. Insulating layers are also likely to be an effective option, although this particular criteria was not directly analyzed in this study.
- The best retrofit option for reducing solar heat gain are utilizing venetian blind type systems (including shutters with operable louvers).

The effectiveness of the LBNL software WINDOW and THERM of obtaining results for window retrofit performance was found to vary based on the type of systems. The process of obtaining results was found to be very simple for venetian blinds, glazing layers, and perforated screens. A layman would most likely be able to undertake this process. The process for fabric shades, while still simple, involves definitions and variables that are difficult to define in a meaningful way (e.g., thread spacing). Therefore, it is unlikely the layman would be able to obtain meaningful results using the software. The process of calculating results for insulated layers requires the use of the more complicated software of the two, THERM. That being said, anyone with experience utilizing drafting software could utilize the software without trouble. Lastly, the software was found to only have limited potential for use with cellular shades. The user is currently limited to analyzing predefined systems without taking modifying the program files, which is probably beyond the scope of the average user. This shortcoming was expected, however, as the cellular shades feature is still only available in the beta version of the software.

Table 20: Summary of window retrofit criteria based on literature review.

	Thermal Improvement	Comfort	Condensation Risk	Retrofit Cost for 30"x60" Window	Impact on Daylighting	Air Leakage	Ease of Operation	Aesthetic Impact
Shutters	up to 532% for custom designs[1]	Improved	Reduced	$100 [2]	Significant	Potentially reduced	Significant work required	Substantial
Venetian Blinds	20%, more effective for SHG reduction	Improved	Increased	$43-$151 [5]	Significant depending on use	Ineffective	Potentially significant work required	Substantial
Interior Shutters	up to 696% for custom designs[1]	Significant Improvement	Potentially Significant Increase	$21.29 (DIY) - $478 (High end wood shutters)[5]	Significant based on use and design	Reduced	Some work required	Substantial
Curtains and Draperies	38%[1]	Improved	Potentiall Significant Increase	$29.98 [5]	Significant based on use and design	Potentially reduced	Some work required	Substantial
Roller Shades	Used for SHG reduction	Improved	Increased	$128-$278[5]	Significant based on use and design	Ineffective	Some work required	Substantial
Storm Windows	121%[1]	Improved	Reduced	$108.74 [5]	No Impact	Reduced by 5.7-8.6%[6]	Minimal work required	Substantial
Plastic Wrap on Window Screens	20%	Improved	Reduced	$1.99 [5]	No	Potentially reduced	Requires work for yearly installation	Minimal
Plastic Wrap on Window Frames	24% [1]	Improved	No effect	$1.99 [5]	No	Signficantly reduced	Some work for yearly installation	Minimal
Roller Shutters	28%[3]	Improved	Reduced	$600 [4]	Significant	Reduced	Potentially significant work required	Substantial
Insulating Blinds	60%[1]	Improved	Increased	$110 [5]	Significant depending on use	Potentially reduced	Some work required	Substantial
Window Screens	7%[7]	Slight Improvement	Marginally Reduced	$5.04 [5]	Minimal	Ineffective	Minimal work required	Minimal
Low Emissivity Films	Used for SHG reduction	Improved	No effect	$12.60 [5]	Minimal	Ineffective	Some work for initial installation	Potentially substantial based on film
Draft Snakes	N/A	N/A	N/A	$6.97 [5]	N/A	Signficantly reduced	Minimal work required	Minimal

[1] Craven et al., 2011

[2] http://architecturaldepot.com/

[3] ATi, 2009

[4] Personal Correspondance with Stefan Poetsch (Rollac)

[5] Lowes

[6] Drumeller et al., 2007

[7] Brunger et al., 1999

Table 21: Summary of WINDOW and THERM performance analysis for retrofit systems*

	Center of Glass Reduction in U-value (%)		Center of Glass Reduction in SHGC (%)	
	Min	Max	Min	Max
Venetian Blinds				
Interior	4	60	-15	50
Exterior	11	26	-5	95
Fabric Shades				
Interior	6	14	5	33
Exterior	24	25.5	25	85
Glazing Layers				
Interior	28.75	47	8.5	67.5
Exterior	32	51.5	3	85
Insulating Layers				
Interior	23	75		
Exterior				
Perforated Screens				
Interior	7	17.5	10	46
Exterior	8	26	12	88
Cellular Shades				
Interior	38	53.5	37.5	53
Exterior				

Reductions in U-value and SHGC are taken as a reference to those for an IGU with a low-emissivity coating. Single-glazed systems will experience greater reductions, while those for triple-glazed systems will be lower. It is important to note that a positive percent reduction translates to improved thermal performance and reduced solar heat gain, while negative values translate to decreased thermal performance and increased solar heat gain.

12. Further Research

There are several shortcomings to this study that could be resolved through further research. These stem mainly from the inability of computer testing (using existing software) to properly evaluate the performance of window/window retrofit assemblies. As discussed in Section 2.7, the thermal transmittance of the complete assembly is based largely on the role of convection heat transfer through the window retrofit. While WINDOW has developed algorithms to account for this, the variability of real systems and mounting methods can potentially significantly alter this behavior. Therefore, physical testing is needed for several reasons.

First, physical testing would allow for the validation of the WINDOW analysis. Secondly, physical testing would allow for the determination of surface temperatures at several locations on the assembly. With sufficient physical testing, a set of isotherms could be determined. Condensation potential could then be evaluated by determining the location of the dew point on the window/window attachment assembly. If the dew point is located within the assembly itself, there will be potential for condensation. If the dew point lies on the exterior of the window assembly, there is no risk of condensation.

Another shortcoming of the WINDOW analysis is a lack of detailed spectral data (interior and exterior reflectance, transmittance, and absorptance) for shading systems. Without detailed spectral data, the SHGC and T_{vis} could vary significantly. Physical testing of specimens could not only generate this spectral data, but could also be used to validate WINDOW modeling. Such data could also be used for energy analysis, thus allowing for a measurement of return on investment.

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