“Building Energy Analysis” Course Notes – Fall 2021
Prepared by D. Mather

BE1: BUILDING ENVELOPE

Module Overview

This module provides a brief summary of certain aspects related to the energy analysis of building envelope components. The material focuses on two typical "weak points" in building envelopes: "thermal bridges" and windows.

Note: The material in this module is somewhat more qualitative rather than quantitative.

Relevant Course Intended Learning Outcomes:

- Apply basic energy calculations to a variety of components and systems impacting building energy use.
- Recognize the interactive effects between different building components and systems as related to energy use.

1. Introduction

The building envelope provides separation between the indoor and outdoor environments. Its components include walls, windows, roofs, and some others. The energy flows across the envelope can have important impacts on building energy use. In fact, these flows are often the dominant factor in building energy use—especially in locations where large differentials occur between the desired indoor and outdoor conditions (e.g. hot or cold climates).

Important modes of energy transfer across the building envelope include:

- thermal transmission (e.g. through solid surfaces; U-value)
- solar energy transmission
- air movement ("ventilation")

The two *transmission* paths mentioned above involve energy flow without mass flow and occur as one or more forms of heat flow through solid surfaces. It is typical to split solid surfaces into two categories:

- opaque components (or assemblies): the ability of shortwave radiation (e.g. solar energy) to pass directly through the surface is negligible; the radiation might be reflected and/or absorbed.

- glazing components (or assemblies): transparent/translucent (e.g. windows, skylights); allows direct passage of some of the shortwave radiation striking it.

For an opaque component—provided that the component is effectively "air-tight"—the key characteristic relevant to energy performance is generally the **effective U-value**. Moreover, we might say that it's the size of the component in combination with its U-value—i.e. the "**UA product"**—that really determine its importance. However, some other characteristics can be important with respect to energy performance, such as its "thermal capacitance" (i.e. ability to store thermal energy).

For a glazing component—provided that it is effectively "air-tight"—we typically view the important characteristics to be the **Effective U-value** and **Solar Heat Gain Coefficient (SHGC)**. The SHGC indicates the ability of the component to allow solar energy striking one side to pass through and become a heat gain to the environment on the other side. These characteristics—along with the size of the component—will generally determine the importance of the component.

READING:

Read the following brief article (12 pages) by Prof. John Straube, UW CEE. A copy will be provided in LEARN.

"BSD-011: Thermal Control in Buildings" John Straube, Dec. 2011.

2. U-Value and R-Value: Metric vs IP Units

Our simple thermal transmittance equation is:

$$\dot{Q} = U \cdot A \cdot (T_H - T_C) = \frac{A}{R} \cdot (T_H - T_C)$$

The units of the terms in the equation would generally be as indicated below, depending on whether the calculations are performed in Metric (SI) or Inch-Pound (IP) units:

Term	Metric	IP
$\dot{Q}$	W	btu/hr
A	m^2	ft^2
T_H, T_C	°C	°F
U	$W/m^2 \cdot$ °C	$btu/hr \cdot ft^2 \cdot$ °F
R	$m^2 \cdot$ °C$/W$	$hr \cdot ft^2 \cdot$ °F$/btu$

In North America, both unit systems are frequently encountered, and therefore, it is useful to be able to work in both and convert between the two. North American industry often uses the following convention:

Term	Inferred Units
"U" or "U-value"	$btu/hr \cdot ft^2 \cdot$ °F
"USI" or "USI-value"	$W/m^2 \cdot$ °C
"R" or "R-value"	$hr \cdot ft^2 \cdot$ °F$/btu$
"RSI" or "RSI-value"	$m^2 \cdot$ °C$/W$

Conversion factors:

U-value × **5.678** = USI-value

R-value ÷ **5.678** = RSI-value

Example:

<u>Extruded Polystyrene Insulation (XPS)</u>

Typically “R-5 per inch” (at “room temperature”)

A 2-inch thick piece is rated **“R-10”**

RSI-value = R-value ÷ 5.678 = 10 ÷ 5.678 ≈ **1.76**

Note: The U-value for a 2-inch layer of this insulation:

U = 1/R = 1/10 = **0.1** $(btu/hr \cdot ft^2 \cdot °F)$

USI = 1 / RSI = 1/ 1.76 ≈ **0.568** $(W/m^2 \cdot °C)$

or

USI = U × 5.678 = 0.1 × 5.678 ≈ 0.568 $(W/m^2 \cdot °C)$

3. Nominal R-Values of Selected Insulation Types

For properly installed, uncompressed, undamaged insulation—and in the absence of air-movement through the insulation—the following are approximate R-values (LTTR*) typically attributed to different types of insulation (when at approx. room temperature):

Type	R-value per inch
1. Fibreglass batt	**≈ 3.3**
2. Mineral wool batt	**≈ 4.3**
3. Expanded Polystyrene sheet (EPS)	**≈ 4**
4. Extruded Polystyrene sheet (XPS)	**≈ 5**
5. Polyisocyanurate sheet (“polyiso”)	**≈ 6**

* LTTR = long-term thermal-resistance = “aged R-value”

Actual R-values will depend on installation and operating conditions. (For example: See Building Science Corporation “[Info-502: Temperature Dependence of R-values in Polyisocyanurate Roof Insulation”](), April 12, 2013. Please note that reference to this document is provided for information only, i.e. reviewing it is optional—it’s not going to be used on a test/quiz/exam.)

4. Thermal Bridging

Thermal bridging can have an important impact on the thermal performance of an assembly. This occurs when non-insulating components provide thermal paths that allow heat to bypass the insulating components, increasing the overall U-value.

Depending on the situation, thermal bridging effects can range from “modest” (e.g. wood studs in residential construction) to “very significant” (e.g. aluminum components in curtain-wall/window-wall systems).

Building Envelope Thermal Bridging Guide (BETBG) version 1.6 (2021)

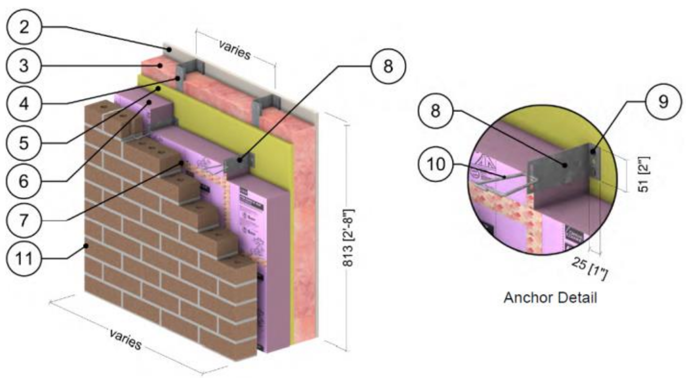
https://www.bchousing.org/research-centre/library/residential-design-construction/building-envelope-thermal-bridging-guide

- Provides guidance on calculating effective U-values for assemblies to account for the impacts of thermal bridging. It includes many common modern assemblies.

Appendix A: Catalogue Material Data Sheets BUILDING ENVELOPE THERMAL BRIDGING GUIDE v1.6

Detail 5.1.60

Exterior and Interior Insulated 6” x 1 5/8” Steel Stud (16” o.c. and 24” o.c.) Wall Assembly with Steel Brick Anchors Supporting Brick Veneer and Owens Corning R-20 Batt Insulation in Stud Cavity – Clear Wall



ID	Component	Thickness Inches (mm)	Conductivity Btu·in / ft²·hr·°F (W/m K)	Nominal Resistance hr·ft²·°F/Btu (m²K/W)	Density lb/ft³ (kg/m³)	Specific Heat Btu/lb·°F (J/kg K)
1	Interior Films[1]	-	-	R-0.7 (0.12 RSI)	-	-
2	Gypsum Board	1/2" (13)	1.1 (0.16)	R-0.5 (0.08 RSI)	50 (800)	0.26 (1090)
3	Ecotouch Pink Fiberglass Batt	6" (152)	0.30 (0.043)	R-20 (3.5 RSI)	0.55 (8.8)	0.17 (710)
4	6" x 1 5/8" Steel Studs	18 Gauge	430 (62)	-	489 (7830)	0.12 (500)
5	Exterior Sheathing	5/8" (16)	1.1 (0.16)	R-0.6 (0.10 RSI)	50 (800)	0.26 (1090)
6	Foamular CodeBord/C-200 Extruded Polystyrene Rigid Insulation (XPS) Type 3	Varies	0.20 (0.029)	R-5 to R-15 (0.88 to 2.64 RSI)	Varies	0.29 (1220)
7	Vented Air Cavity	1 1/2" (38)	-	R-0.4 (0.07 RSI)	0.075 (1.2)	0.24 (1000)
8	Galvanized Steel Veneer Anchor	Varies	430 (62)	-	489 (7830)	0.12 (500)
9	Galvanized Steel Fasteners	0.28" (7) Ø	430 (62)	-	489 (7830)	0.12 (500)
10	Galvanized Steel Wire Pintle	-	430 (62)	-	489 (7830)	0.12 (500)
11	Brick Veneer	3 5/8" (92)	5.4 (0.78)	-	120 (1920)	0.19 (720)
12	Exterior Film[1]	-	-	R-0.2 (0.03 RSI)	-	-

[1] Value selected from table 1, p. 26.1 of 2009 ASHRAE Handbook – Fundamentals depending on surface orientation

A.5.60

VIDEO + READING:

1. Watch [“Video 1 – Introduction to the Building Envelope Thermal Bridging Guide”] (11 mins)

2. <u>Skim</u> the content in the **main body (Sections 1-6, pgs. 1-31)** of the BETBG. Review the content until you feel you have a reasonable understanding of the terms in the effective thermal transmittance equation:

$$U_T = U_o + \underbrace{\frac{\sum(\psi \cdot L) + \sum(\chi)}{A_{total}}}_{\text{linear and point ‘anomalies’}}$$

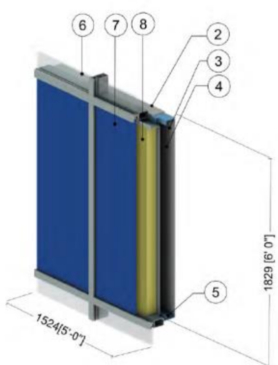
$\psi = psi$
$\chi = chi$

clear field

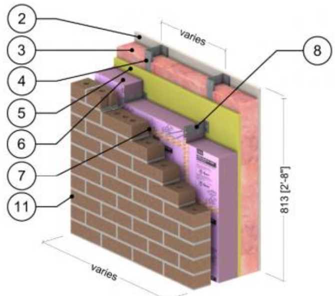
total effective assembly thermal transmittance

3. Review and attempt to understand the BETBG Appendix A & Appendix B information sheets for the **three** construction details listed below. Compare the clear-field values of the three types. (Note: Copies of these sheets are provided in the appendix of this set of notes.)

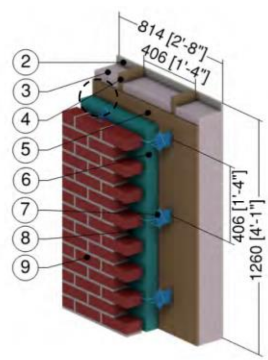
Detail 4.1.1



Detail 5.1.60



Detail 8.1.19



5. Energy Flow through Windows

Energy can move across the building envelope through windows (and other glazings) by thermal transmission, solar transmission, and air movement. For many buildings, the energy flow through windows are the dominant energy flows across the envelope and will have a significant impacts on heating and cooling energy requirements.

Transmission of visible daylight through glazings can provide useful illumination, but can sometimes cause issues of visual or thermal discomfort (e.g. when direct sunlight passes through a window).

"Fenestration" — In architecture and building engineering, this is a general term referring to the windows, skylights, and doors of a building (i.e. "openings").

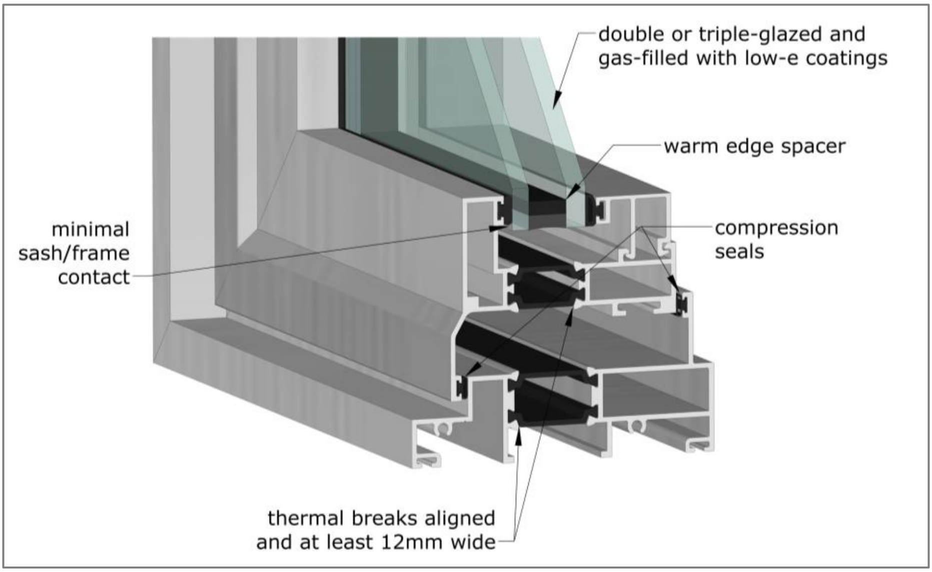
Key Performance Metrics

The following are key performance metrics of concern for our purposes:

- U-value — Effective Thermal Transmittance
- SHGC — Solar Heat Gain Coefficient
- VLT (or VT) — Visible Light Transmittance (Visible Transmittance)

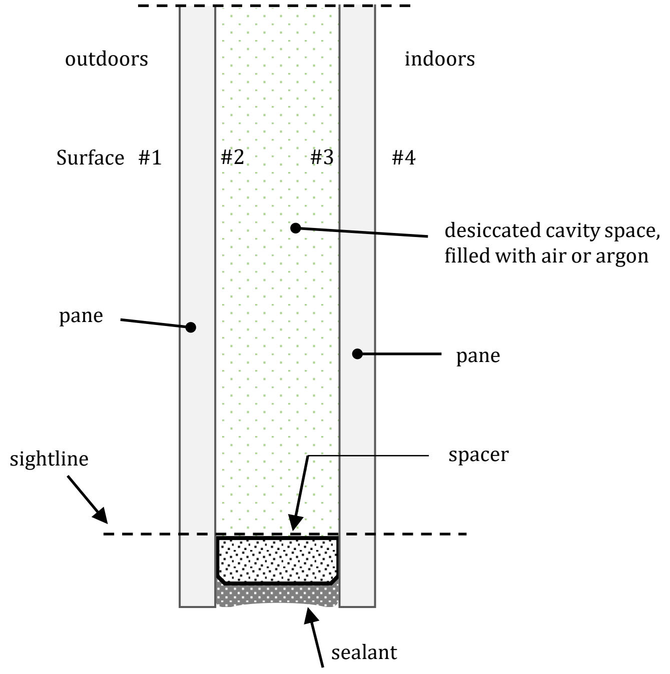
Window Components

When discussing window technology, we often categorize a component as being part of the insulated glazing unit (IGU) or the frame. The primary components of an IGU are the glass panes and edge spacer(s).



Typical Details of a Double-Glazed IGU

(Adapted from ASHRAE Handbook of Fundamental 2009 SI)



READING & VIDEO:

- Read the 1-page [“Technology Primer”]() by Natural Resources Canada (NRCan).

- Watch the following video for an overview of the key components of a window. The manufacturing process shown is for a residential window manufacturer. Please note that the video is informative, but it’s also a long commercial for the manufacturer, so please apply appropriate critical judgment as you watch.

“Behind-the-Scenes: Simonton Windows Plant Tour” 2013
https://youtu.be/BZY5-T_E5MA **(19 mins)**

6. Window U-Values

“Center-of-Glass” vs “Overall” Performance

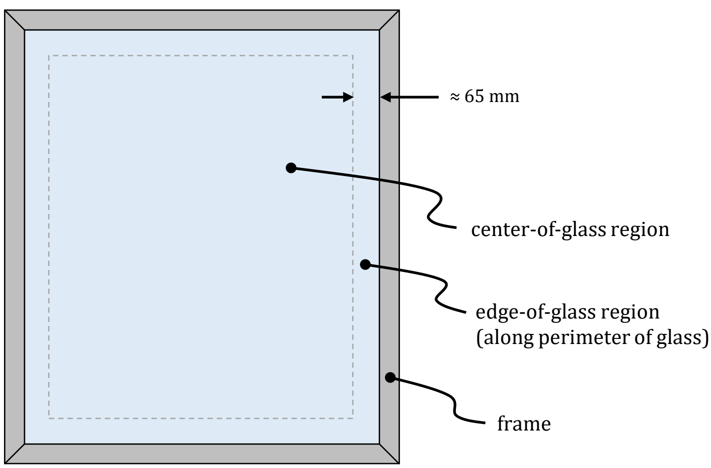
When discussing window performance, metrics may be stated for the “center-of-glass” region or the overall window unit (i.e. including spacer and frame).

In the center-of-glass region, energy flows are treated as one-dimensional (i.e. along the direction normal to the glass panes). In the edge-of-glass and frame regions, the energy flows are more complex, i.e. two- or three-dimensional. (Note: The edge-of-glass region is usually treated as extending ≈65 mm from the “sightline”.)

In general we might say that the unit’s overall U-value depends on the performance of the center-of-glass, edge-of-glass, and frame portions:

$$U_o = \frac{U_{cg}A_{cg} + U_{eg}A_{eg} + U_f A_f}{A_o}$$

For this course, it’s sufficient to be aware of the basic difference in the meanings of “center-of-glass” versus “overall” performance.



The table below shows center-of-glass and overall window U-values for selected glazing and frame systems. The key variations in the glazing and frame types include:

- Number of panes (single, double, triple)
- Use of low-emissivity (“low-e”) coating
- Air- vs argon-filled cavities (for double- and triple-pane windows)
- Type of frame material (affecting frame thermal conductivity)

Approximate Effective Thermal Transmittance (W/m^2-°C) for Selected Fenestration Products

(For “Fixed Windows”; from ASHRAE Handbook of Fundamentals 2009)

Glazing Type	Row #	Fill Gas	IGU Only	Overall Window	
			Center-of-glass	Alum. Frame (with thermal break)	Fiberglass or Vinyl Frame
Single Glazed	1	n/a	5.91	6.06	5.40
Double Glazed	2	air	2.73	3.18	2.72
	3	argon	2.56	3.04	2.58
Double Glazed + low-e e = 0.20 (surface 2 or 3)	4	air	1.99	2.55 *	2.12
	5	argon	1.70	2.30 *	1.88
Double Glazed + low-e e = 0.05 (surface 2 or 3)	6	air	1.70	2.30 *	1.88
	7	argon	1.42	2.06 *	1.65
Triple Glazed	8	air	1.76	2.34	1.92
	9	argon	1.65	2.24	1.83
Triple Glazed + two low-e coatings e = 0.20 (surface 2/3 & 4/5)	10	air	1.14	1.80	1.40
	11	argon	0.97	1.65	1.26

Notes:

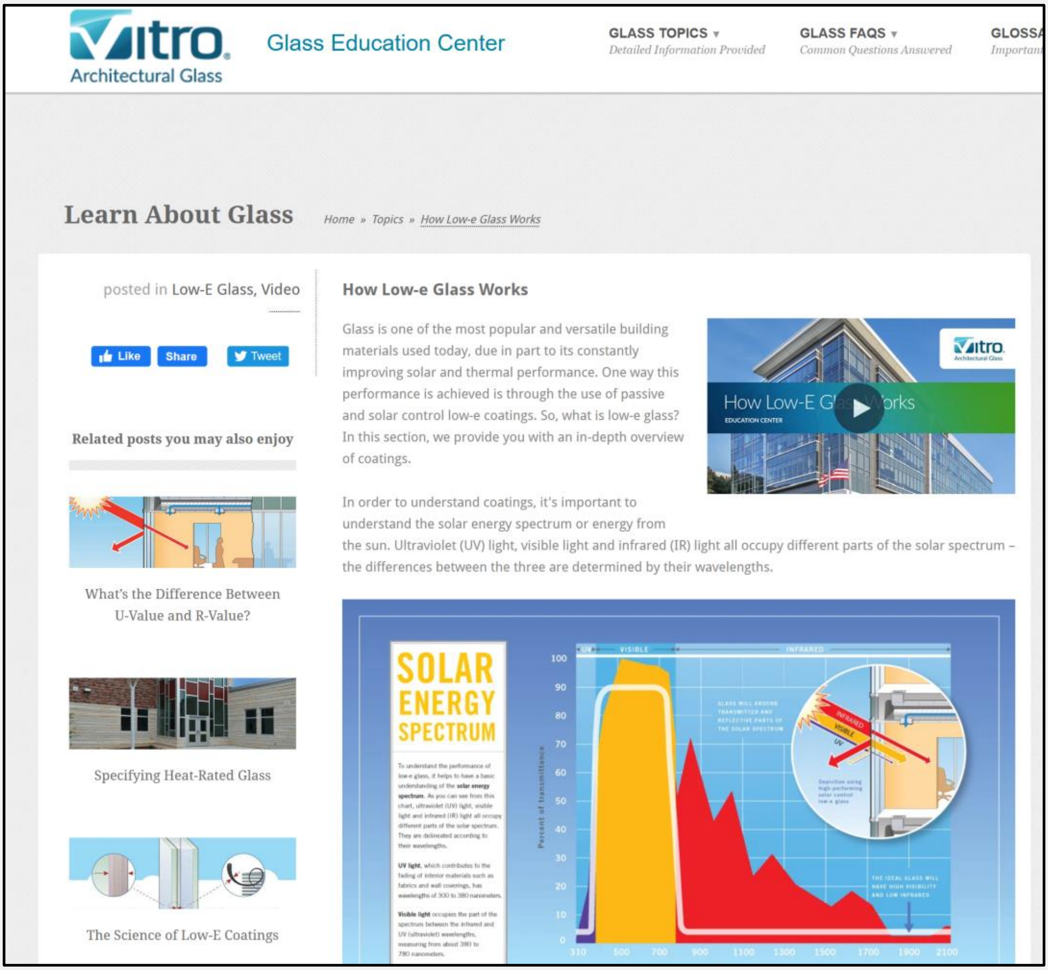
- Vertical installation
- Aluminum spacer
- Overall dimensions: 1.5m (h) x 1.2 m (w)
- Frame width: aluminum = 33mm, fiberglass/vinyl = 46 mm

* Typical for commercial new construction in Ontario

READING:

"How Low-e Glass Works"
http://glassed.vitroglazings.com/topics/how-low-e-glass-works

Please review the information on the website indicated. Try to develop a general understanding of the meaning of "low-e" (low emissivity). Note that a video on the website covers the same material that is provided by text.

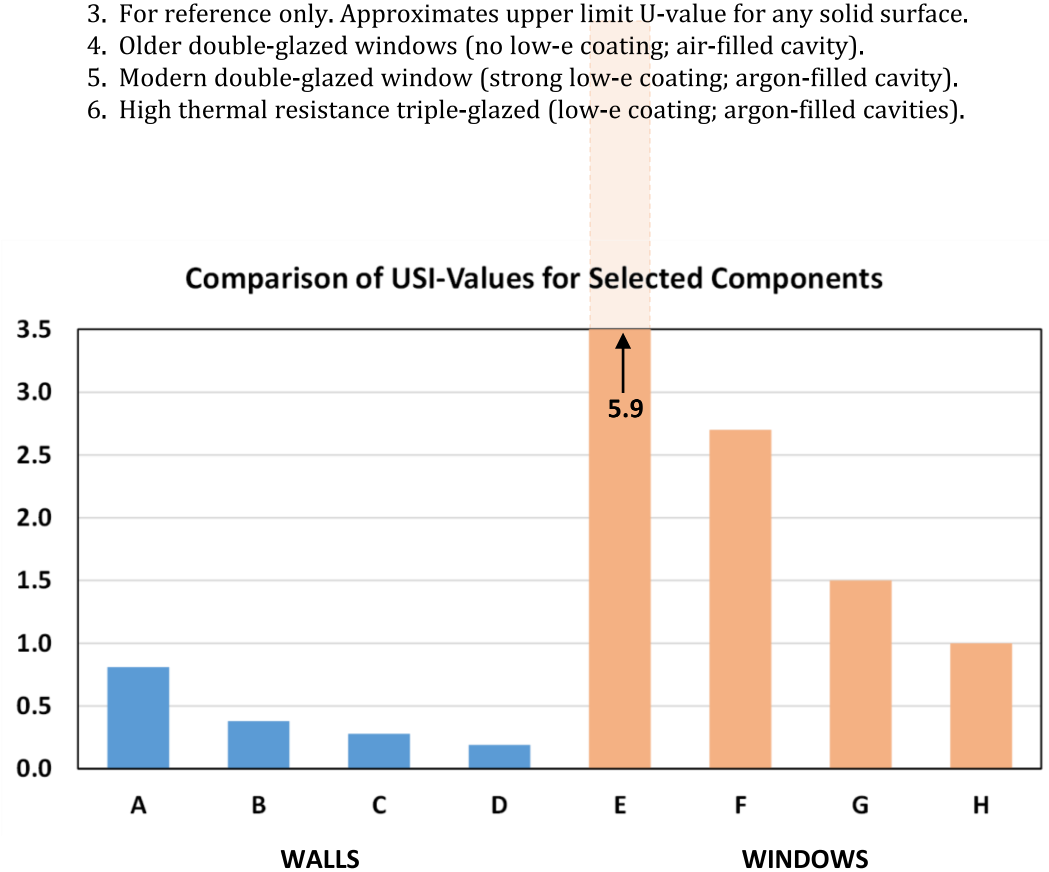


7. “Order of Magnitude” U-Values

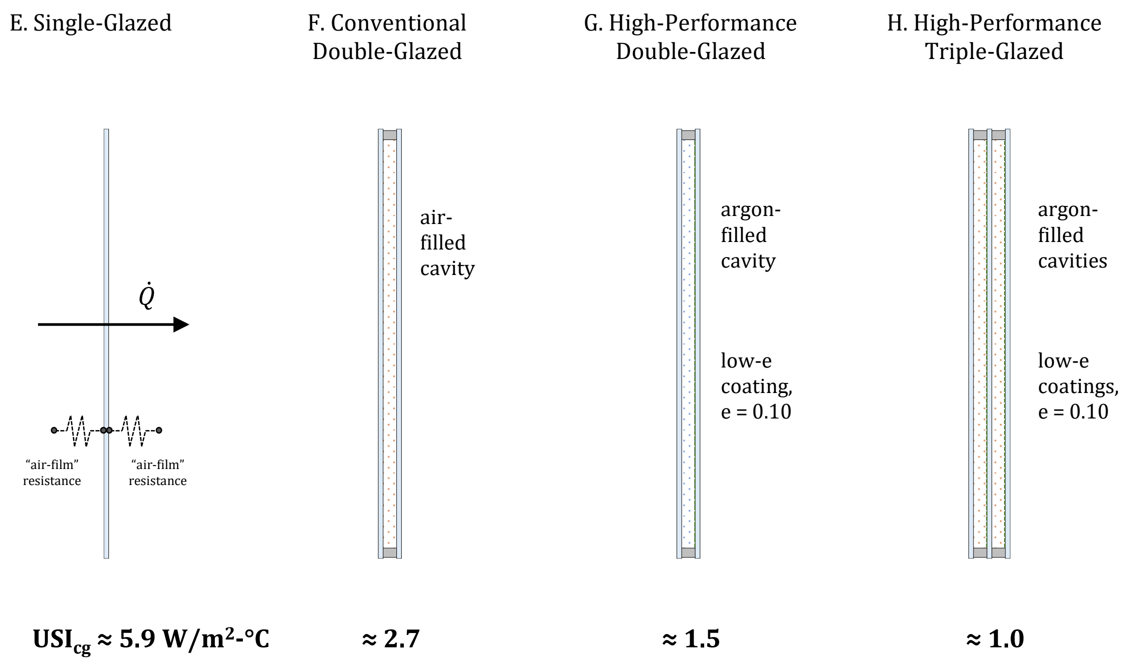
For some discussions, it is helpful to have some idea of the range of typical U-values that we may expect to see in building construction. Let’s compare several wall assemblies and the center-of-glass performance for several windows.

Type	Description	U $(W/m^2 \cdot °C)$	Equivalent R-value
Walls	A. Low Thermal Resistance [1]	0.81	R-7
	B. Typical “Code Compliant” [2]	0.38	R-15
	C. “Better than Code”	0.28	R-20
	D. High Performance	0.19	R-30
Windows	E. Single Glazed [3]	5.9	R-1.0
	F. “Conventional” Double-Glazed [4]	2.7	R-2.1
	G. High Performance Double-Glazed [5]	1.5	R-3.8
	H. High Performance Triple-Glazed [6]	1.0	R-5.7

Notes:
1. For example, spandrel panel in aluminum-framed curtainwall.
2. Based on Ontario Building Code.
3. For reference only. Approximates upper limit U-value for any solid surface.
4. Older double-glazed windows (no low-e coating; air-filled cavity).
5. Modern double-glazed window (strong low-e coating; argon-filled cavity).
6. High thermal resistance triple-glazed (low-e coating; argon-filled cavities).

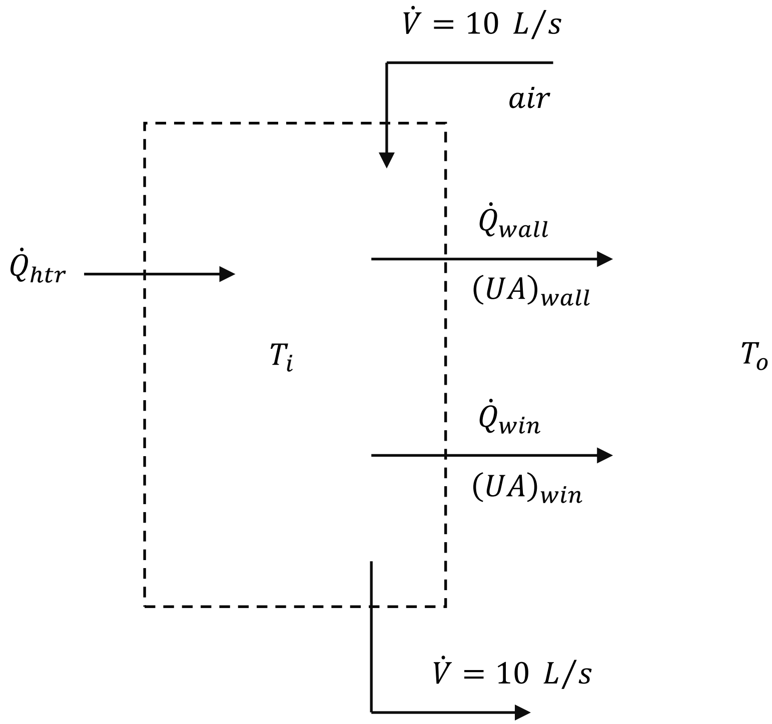


Representative Performance of Selected Glazing Systems



8. The Problem of Parallel Energy Flows

Consider the previous discussion (EA3, Section 5) of a room to be kept at T_i despite heat loss through several parallel paths.

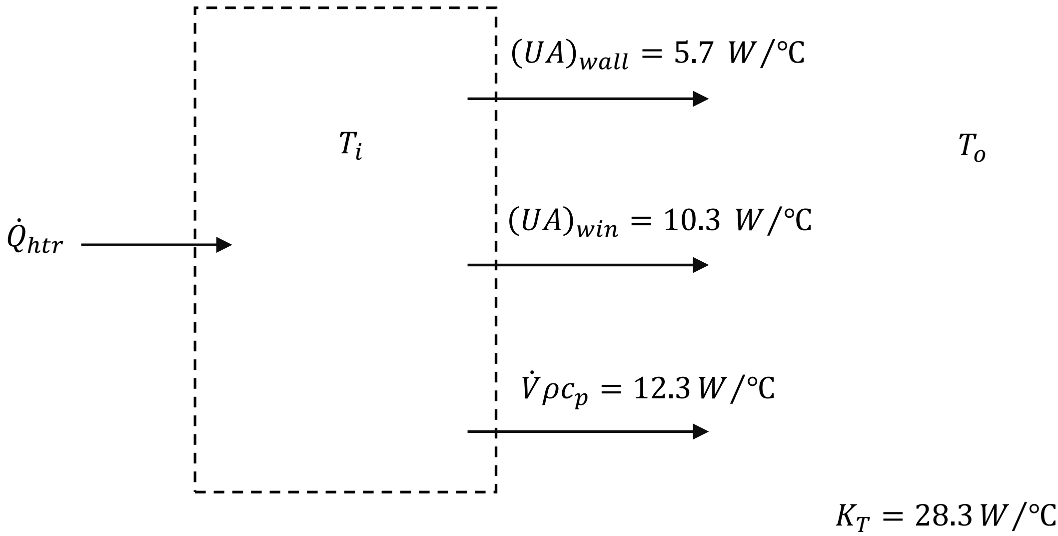


Say the heat loss factors are:

Walls:	$U = 0.38\ W/m^2 \cdot ℃, A = 15\ m^2,\ UA = 5.7\ W/℃$
Windows*:	$U = 2.06\ W/m^2 \cdot ℃, A = 5\ m^2,\ UA = 10.3\ W/℃$
Ventilation:	$\dot{V}\rho c_p = 12.3\ W/℃$
Total:	$28.3\ W/℃$

* Note: The U-value here is similar to that for a “high-performance” double-glazing in a thermally-broken aluminum frame.

An alternate representation of the heat loss paths:



If the heating rate is to match the heat loss rate, then:

$$\dot{Q}_{htr} = \left[\dot{V}\rho c_p + (UA)_{wall} + (UA)_{win}\right] \cdot (T_i - T_o) = K_T \cdot (T_i - T_o)$$

e.g. If $T_i = 20°C, and\ T_o = 0°C,$ then $\dot{Q}_{htr} = 566\, W$

Suppose the parameters as listed above (U, A, etc.) represent the initial design for a building and the interest of the design team now is to evaluate options for improving the building's performance. A reduction in heat loss is desired to help accomplish this.

The team discusses the situation and notices that the wall U-values are "just barely" code compliant (i.e. minimum insulation needed to meet code). Further, they note that the window area seems "modest" relative to the size of the walls and high-performance double-glazed windows are already specified, so perhaps the windows are already "OK". Also, some ventilation is required to maintain reasonable indoor air quality, and 10 L/s is seen as a "reasonable" rate for the space.

As the discussion continues, a member of the design team mentions that they've heard that "green buildings" use "super-insulated" walls. So the best solution is probably to make the wall insulation much better, as that will provide a significant improvement—right?

The team the proceeds to evaluate a design where the wall thermal resistance is doubled. They are disappointed when the calculations indicate that this only reduces the overall heat loss by about 10%.

Perhaps doubling the insulation value wasn't enough? So, they try doubling it again, but find that the overall reduction has increased to only 15% (vs the initial design). That isn't enough, so double it again….?

Question:

What is the maximum % reduction in the overall heat loss (vs the initial design) that the design team could expect to achieve with wall insulation?

As more and more insulation is added to the walls, the heat loss through the walls will approach zero.

$$\left.\begin{array}{l} \xrightarrow{5.7\ W/{}^\circ\mathrm{C}} \\[2em] \xrightarrow{10.3\ W/{}^\circ\mathrm{C}} \\[2em] \xrightarrow{12.3\ W/{}^\circ\mathrm{C}} \end{array}\right\} 28.3\, W/{}^\circ\mathrm{C} \qquad\qquad \left.\begin{array}{l} \xrightarrow{\to \mathbf{0}\ \boldsymbol{W}/{}^\circ\mathrm{C}} \\[2em] \xrightarrow{10.3\ W/{}^\circ\mathrm{C}} \\[2em] \xrightarrow{12.3\ W/{}^\circ\mathrm{C}} \end{array}\right\} 22.6\, W/{}^\circ\mathrm{C}$$

At some point there would be sufficient insulation in the walls that the heat loss through that path seems negligible (i.e. tiny) compared to the other paths. At that point we *could* keep buying more insulation and adding it to the walls, but it would have an insignificant impact on the overall heat loss.

We can see the limits in the potential benefit of working on any one path in the initial analysis—the lowest possible heat loss is zero.

$5.7\ W/{}^\circ\mathrm{C}$	$(\mathbf{20.1}\%)$
$10.3\ W/{}^\circ\mathrm{C}$	$(\mathbf{36.4}\%)$
$12.3\, W/{}^\circ\mathrm{C}$	$(\mathbf{43.5}\%)$
$28.3\, W/{}^\circ\mathrm{C}$	$(\mathbf{100}\%)$

When energy flows occur in parallel and improving one path has no impact on the other paths, we need to be careful to work on the <u>significant paths</u> if we want to achieve a <u>significant</u> overall improvement.

There are many situations in which "loads" (e.g. on HVAC equipment) are created due to parallel energy flows. This is not restricted to heat loss situations—they also occur in heat gain (i.e. cooling load) situations.

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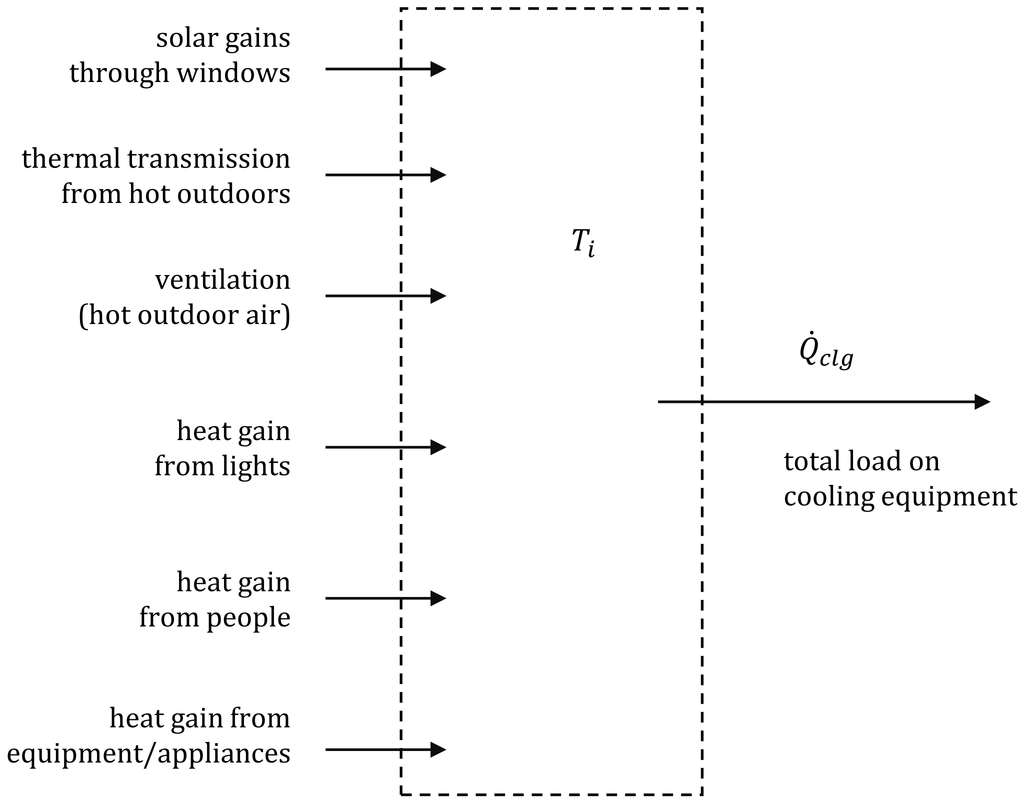
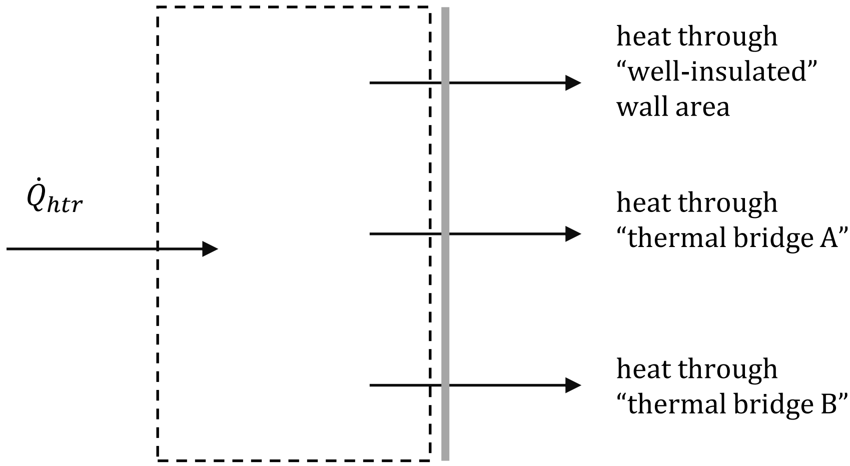


Thermal bridges are a version of the parallel flow problem. If the thermal bridge is not corrected, there may be very little benefit to upgrading insulation in the “well-insulated” section.

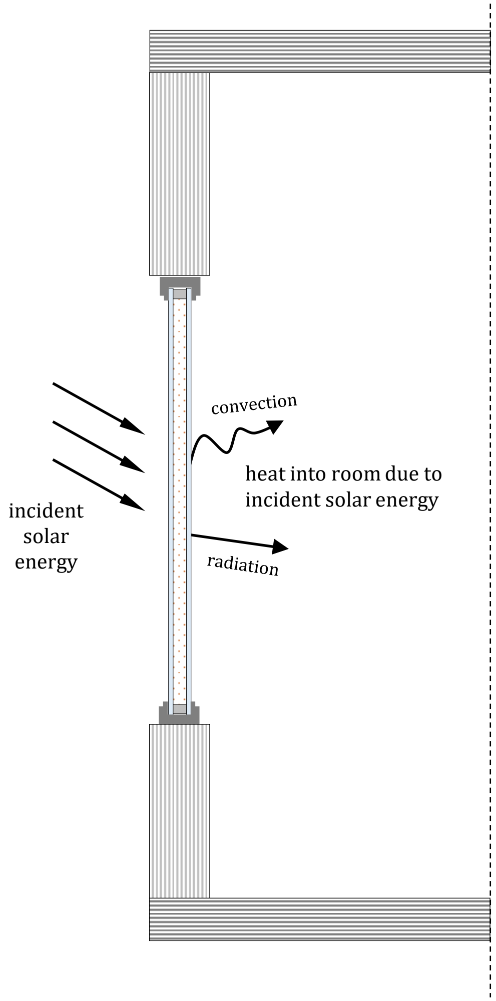


9. Solar Heat Gain Coefficient

Solar Heat Gain Coefficient (SHGC) =

Fraction of solar heat gain through a window relative to the amount of solar energy striking the window (including visible and invisible wavelengths).

$$SHGC = \frac{solar\ heat\ gain\ through\ window}{solar\ energy\ striking\ the\ window}$$



Note: SHGC accounts for both visible and invisible solar energy (heat gain). VLT considers only visible light (incident and transmission).

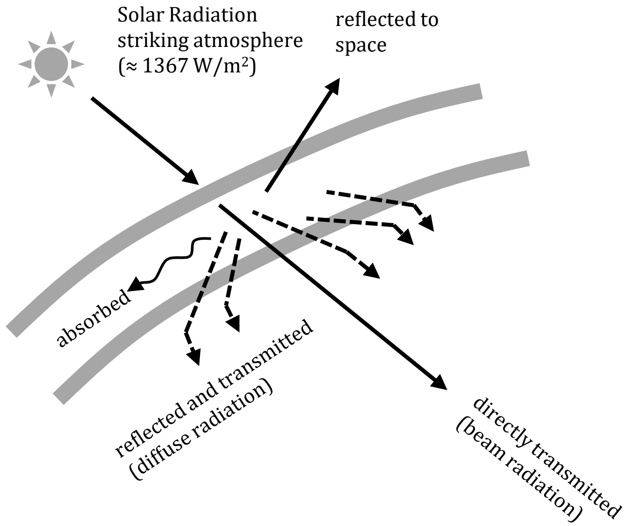
Note that solar energy strikes the window at many angles simultaneously. Some of the energy may be "direct" from the sun and some may be "diffuse" (and/or reflected).

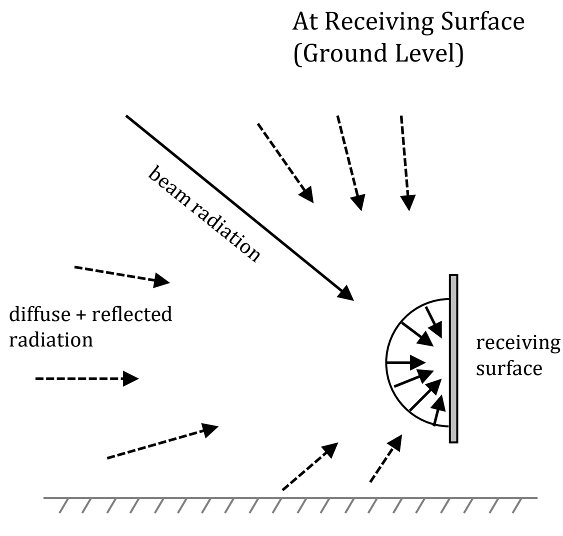
The "angle of incidence" has an important impact on what happens to a solar photon as it strikes the window, so we'll generally separately assess the heat gains from the direct and diffuse solar energy striking the window.

Effect of Atmosphere on Solar Radiation

Some of solar radiation that reaches Earth's atmosphere may pass directly through to the receiving surface. We call this the "direct" (or beam) radiation.

Some solar radiation interacts with the atmosphere, e.g. reflection, absorption. (The "sky" we see during daylight hours is solar radiation reflected by particles in the atmosphere.) The radiation arriving at the receiving surface which is not "direct" is called "diffuse".



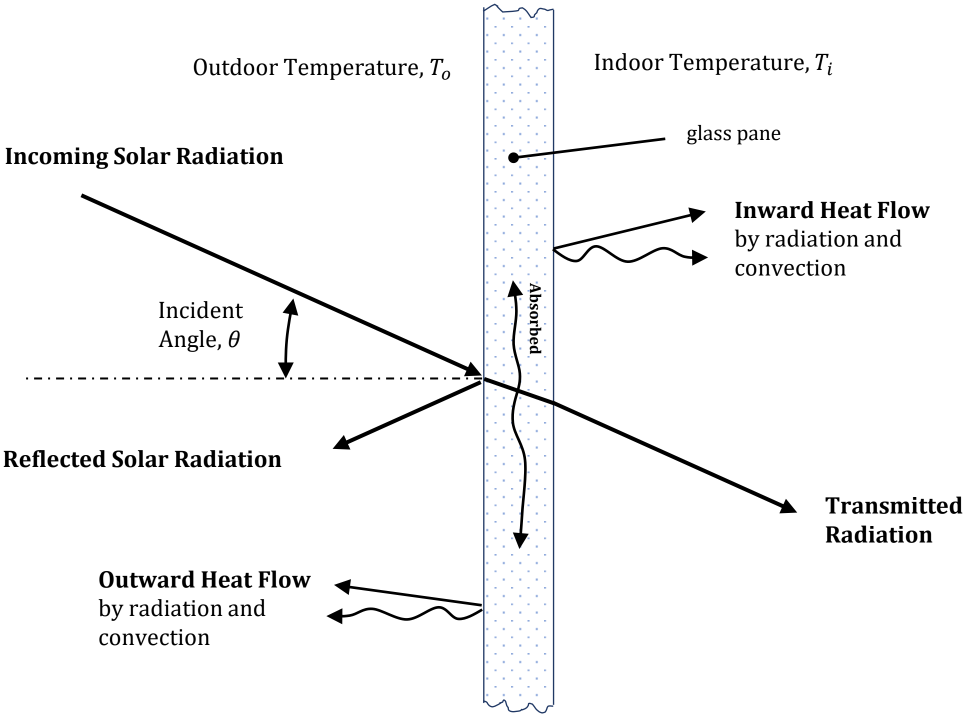


- Position of sun moves across sky—direction of **beam radiation** changes during the day (and over the course of a year).

- Most windows receive **diffuse and reflected radiation** for much of the day.

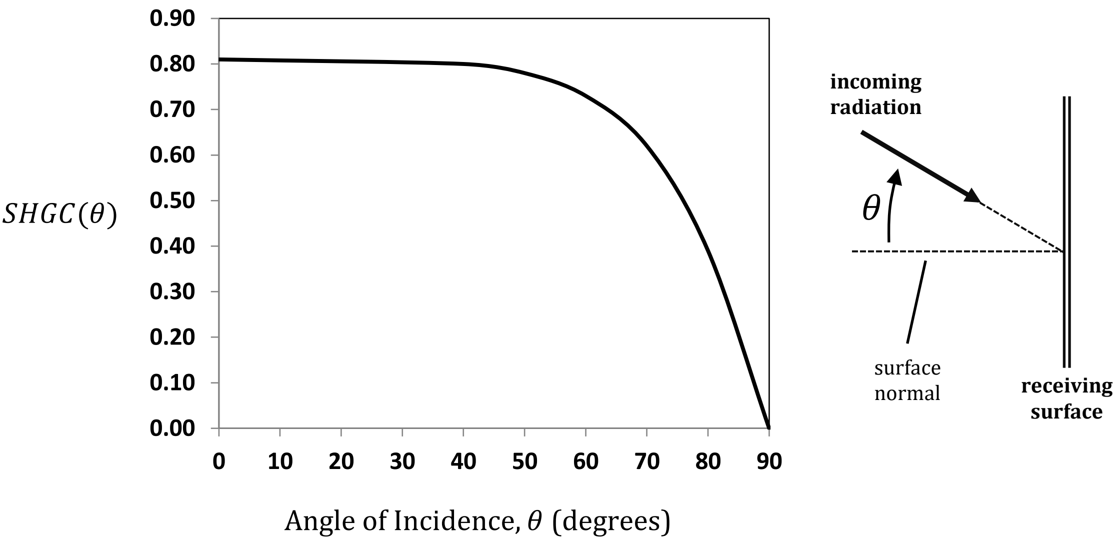
Instantaneous Heat Balance for Sunlit Glazing Material

(Adapted from ASHRAE Handbook of Fundamentals SI 2009, Chapter 15.)



Approximate Impact of "Angle of Incidence" on SHGC

Single Sheet of Clear Architectural Glass (6 mm thickness)



Approximate Properties of Select Generic Glazings

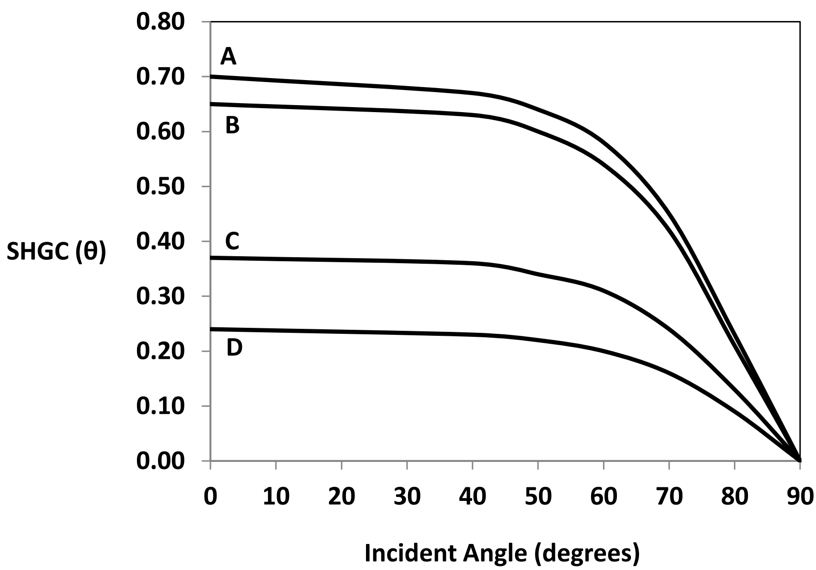
(Based on ASHRAE Handbook of Fundamentals 2009 SI, Chapter 15.)

Glazing System	Description
A	Double glazed, clear glass, 12.7 mm air space
B	Double glazed, clear glass, low-e = 0.2 on surface 3, 12.7 mm argon space
C	Double glazed, clear glass, low-e = 0.05 on surface 2, 12.7 mm argon space
D	Double glazed, gray tint outer pane, low-e = 0.05 on surface 2, 12.7 mm argon space

Glazing System	CoG U-value W/m^2-°C	CoG Visible Transmitt.	CoG SHGC							
			Incidence Angle - Beam Radiation							Hemis.
			0°	40°	50°	60°	70°	80°	90°	Diffuse
A	2.7	0.78	0.70	0.67	0.64	0.58	0.45	0.23	0.00	0.60
B	1.7	0.73	0.65	0.63	0.60	0.54	0.42	0.21	0.00	0.56
C	1.4	0.70	0.37	0.36	0.34	0.31	0.24	0.13	0.00	0.32
D	1.4	0.35	0.24	0.23	0.22	0.20	0.16	0.09	0.00	0.21

Beam radiation at a specific angle of incidence

For diffuse radiation, at uniform intensity over the hemisphere viewed by the surface



Glazing Solar Energy Flux due to Direct Beam Radiation

$$Q_B" \quad = \quad E_{B,N}" \cdot \cos\theta \cdot SHGC_\theta$$

$Q_B"\ (W/m^2) =$

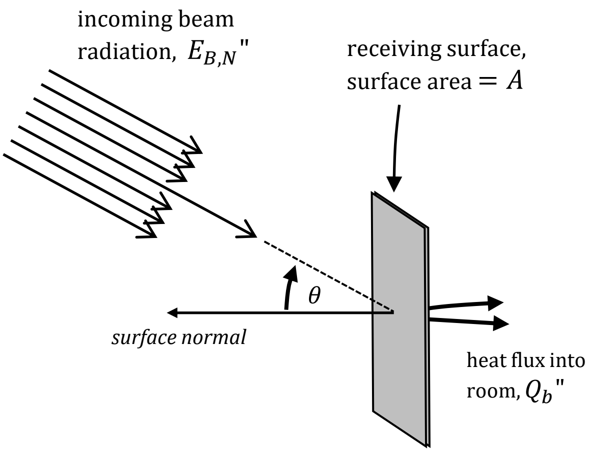
W of heat entering the room (due to beam radiation), per unit surface area of glazing

$E_{B,N}"\ (W/m^2) =$

incoming flux of beam radiation measured perpendicular to the direction of travel

$\theta =$

"incident angle" (between surface normal and direction of beam radiation)



Glazing Solar Energy Flux due to Diffuse & Reflected Radiation

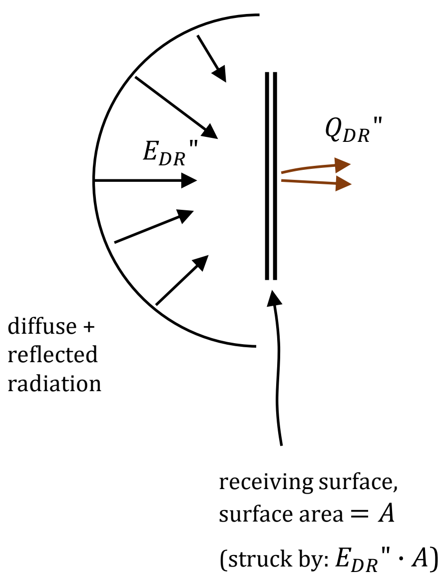
$$Q_{DR}" = E_{DR}" \cdot SHGC_{DR}$$

$Q_{DR}"\ (W/m^2) =$

watts of heat entering the room (due to D & R radiation), per unit surface area of the glazing

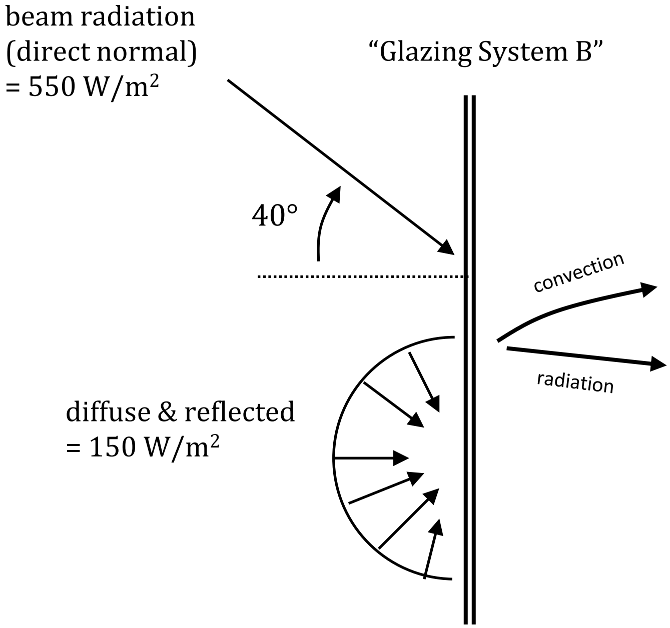
$E_{DR}"\ (W/m^2) =$

watts of diffuse and reflected radiation striking the glazing, per unit surface area of the glazing



Example Calculation

Estimate the center-of-glass total solar heat flux for the situation indicated below.



$Q_T" = Q_B" + Q_{DR}"$

Solution:

$SHGC_{\theta=40°} = 0.63$

$SHGC_{DR} = 0.56$

$Q_B" = E_{B,N}" \cdot \cos\theta \cdot SHGC_\theta$

$= (550 \text{ W/m}^2) \cdot (\cos 40°) \cdot (0.63)$

$= (550 \text{ W/m}^2) \cdot (0.766) \cdot (0.63)$

$= 421 \text{ W/m}^2 (0.63)$

$= 265 \text{ W/m}^2$

$Q_{DR}" = E_{DR}" \cdot SHGC_{DR}$

$= (150 \text{ W/m}^2) \cdot (0.56)$

$= 84 \text{ W/m}^2$

$Q_T" = Q_B" + Q_{DR}" = 265 + 84 = \mathbf{349\ W/m^2}$