CAE 463/524
Building Enclosure Design
Spring 2014

Lecture 9: March 25, 2014
Windows and daylighting

Built
Environment
Research
@ IIT

Advancing energy, environmental, and sustainability research within the built environment

www.built-envi.com

Twitter: @built_envi

Dr. Brent Stephens, Ph.D.
Civil, Architectural and Environmental Engineering
Illinois Institute of Technology
brent@iit.edu

Course catch-up

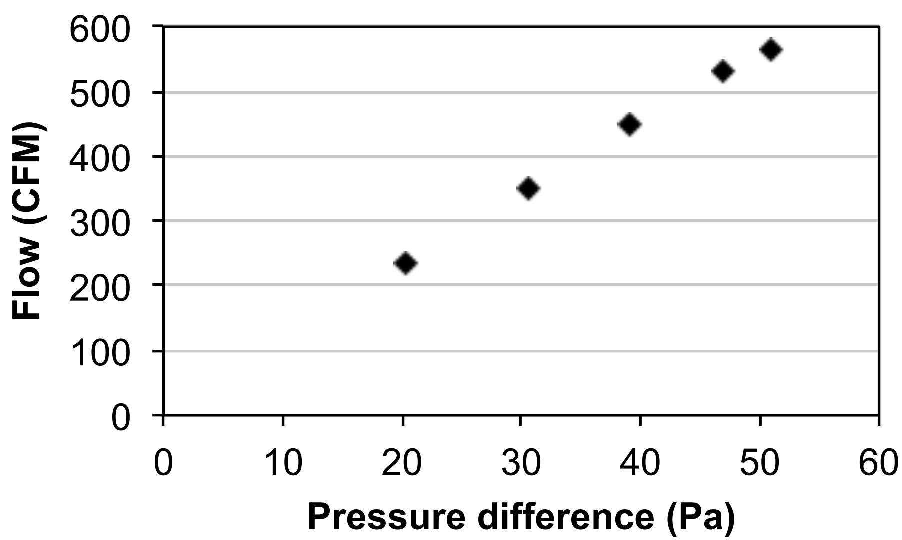
- Two weeks ago: Blower door test demonstration

- Today:
  - Take-home exam assigned (actually released 1 wk ago)
    - Due 1 week from today
  - Introduce final project expectations
  - Windows and daylighting in enclosure design

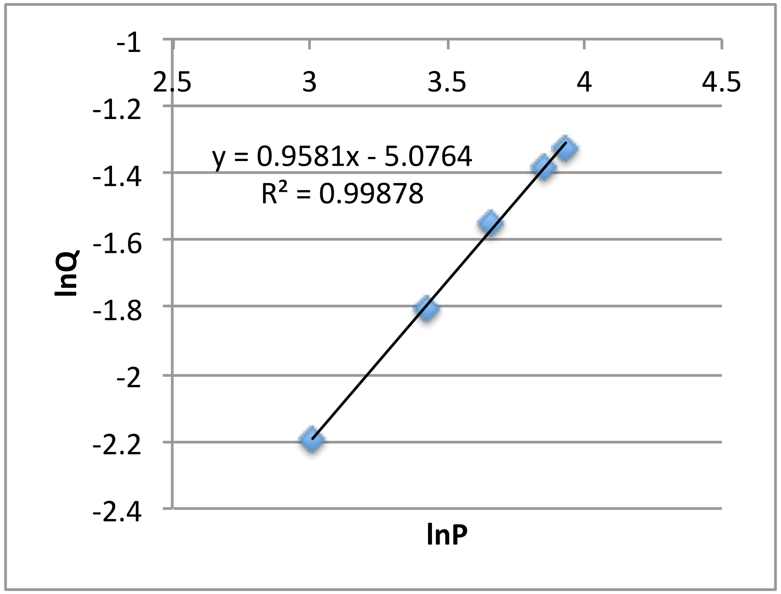
Blower door data from 2 weeks ago

- Two weeks ago we demonstrated use of the blower door for measuring airtightness in an apartment unit in Carman Hall
- We recorded the following data in depressurization mode

dP (Pa)	Flow (CFM)	Flow (m3/s)
20.3	236	0.111
30.7	350	0.165
39	451	0.213
47	531	0.251
51	564	0.266



Blower door data from 2 weeks ago



n = 0.96
C = 0.00623 CFM/Pa^n
ELA = 89 cm^2
A_{floor} = 72 m^2
H = 2.5 m
NL = 0.12
V = 180 m^3
ACH50 = 5.3 1/hr

$$Q = C\Delta P^n$$

Leakage Exponent (dimensionless)

Airflow ($m^3\ s^{-1}$)

Leakage Coefficient ($m^3\ s^{-1}\ Pa^{-n}$)

I/O Pressure Difference (Pa)

$$ELA = C\Delta P_{ref}^{n-0.5}\sqrt{\frac{\rho}{2}}$$

Estimated Leal (m^2) rea (cm^2)

$$NL = 1000\frac{ELA}{Af}\left(\frac{H}{2.5m}\right)^{0.3}$$

Normalized Leakage, NL (dimensionless)

$$ACH_{50} = \frac{Q_{50\ Pa}}{V}$$

Air Changes per Hour @ 50 Pa (hr^{-1})

50

Project 2: High performance enclosure research

- Objective
  - Extend what you will learn about HAM and building enclosures and research a “high performance” enclosure construction
    - Literature review, product review, and examples
    - Advantages and disadvantages
    - HAM analysis
    - Energy analysis
    - Cost considerations
    - Practical design considerations
    - Environmental and sustainability impacts

Project 2: High performance enclosure research

- Deliverables
  - Final report of findings (approx. 8-10 pages)
    - Similar to a conference proceeding
  - Final presentation of findings
    - Similar to a conference presentation

- Expectations
  - Assignment/expectations document on BB
  - Two example reports on BB

Project 2: High performance enclosure research

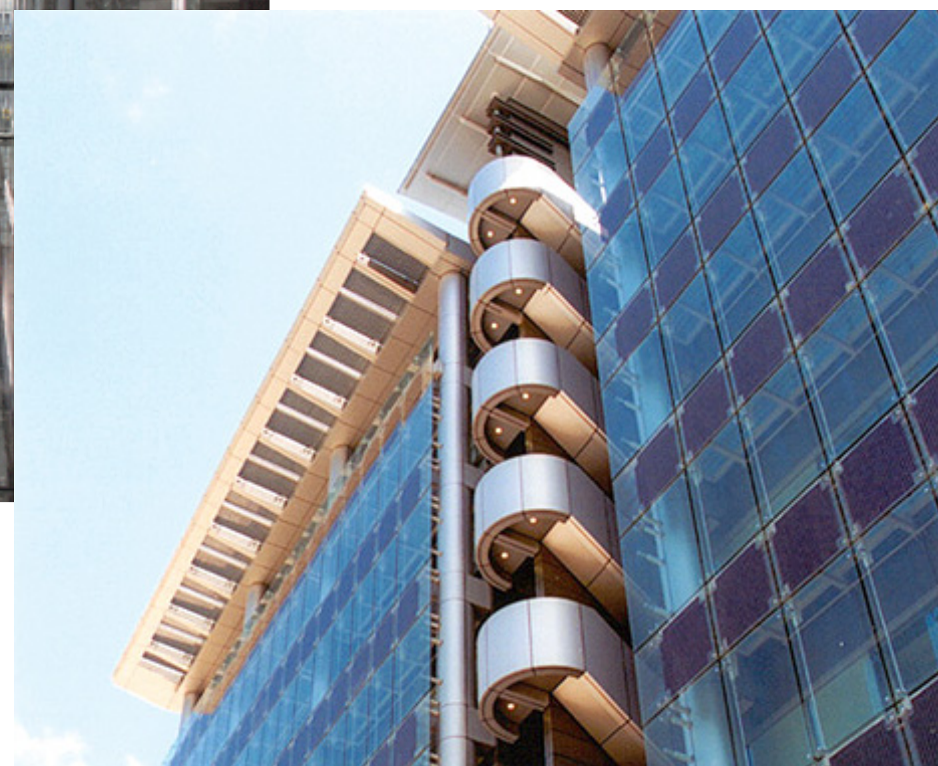
- Many new enclosure products/technologies/designs exist
  - How do they actually perform?
  - What are their advantages/disadvantages?

Green roofs

Green walls

Project 2: High performance enclosure research

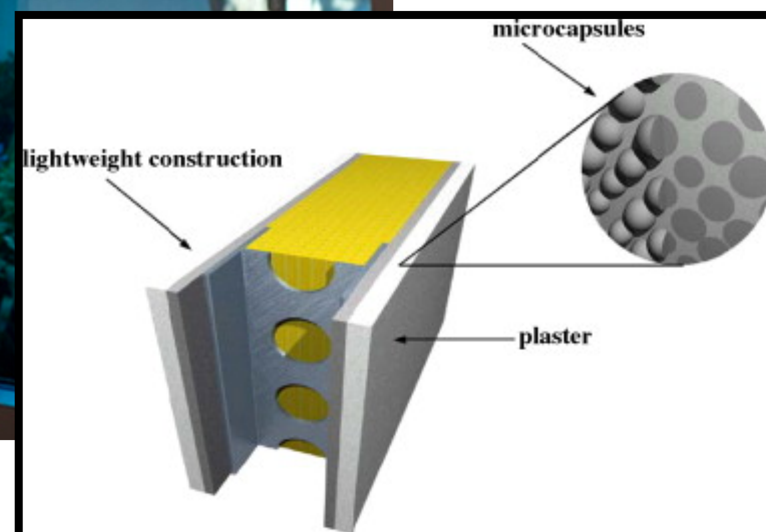
Double skin facades



Building integrated photovoltaics

Project 2: High performance enclosure research

Electrochromic windows ("smart glass")



Phase change insulation materials

Project 2: High performance enclosure research

Bio-based insulation materials (mushrooms)

Structural insulated panels (SIPS)

Project 2: High performance enclosure research

“Cool” roofs (e.g., white roofs)

Straw bale construction

Project 2: Topic selection

- Email me your topics by April 1, 2014

Name	**Final project topic**
Johnson, Ajay T.	
Lizama Velazquez, Sara	
Nicolau De Souza, Bruna Franciele	Green roofs
Fan, YiYun	
Jose, Ivan A.	
Azimi, Parham	
Fazli, Torkan	
Hoover, Kyleen	
Hubert, Janis M.	
Khan, Imran A.	
Mele, Andi	
Pinzon Latorre, Andres A.	
Toonen-Talamo, Allison R.	

WINDOWS AND DAYLIGHTING

Lecture objectives

- Understand basic components of fenestration
- Understand various ways of representing heat transfer through fenestration
- Understand basic calculations for U values
- Understand basic calculations of SHGC
- Understand building envelope design guidelines for fenestration systems
- Understand daylighting

Fenestration

- "Fenestration"
  - Areas of the enclosure that let visible light through
  - Also the term used for windows, doors, and skylights
  - Fenestration concerns the units themselves, as well as placement and shading
    - Two buildings with the same windows that are located in different positions are considered to have different fenestration

- Placement is important both visually and for building physics
  - By changing the locations of windows and shading devices, the use of electric lighting and overall building energy use can be drastically altered

Fenestration: energy use and thermal comfort

- Fenestration impacts building energy use by:
  - Thermal heat transfer
    - Conduction, convection, long-wave radiation, and Short-wave radiation (solar heat gain)
    - Use appropriate materials/assemblies to minimize heat transfer
  - Solar heat gain
    - Utilize in cold climates; restrict in warm climates
  - Air leakage
    - Penetrations in walls and roofs for fenestration can be problematic
  - Daylighting
    - Utilize to reduce lighting requirements

Fenestration components

Fenestration consists of three main components:

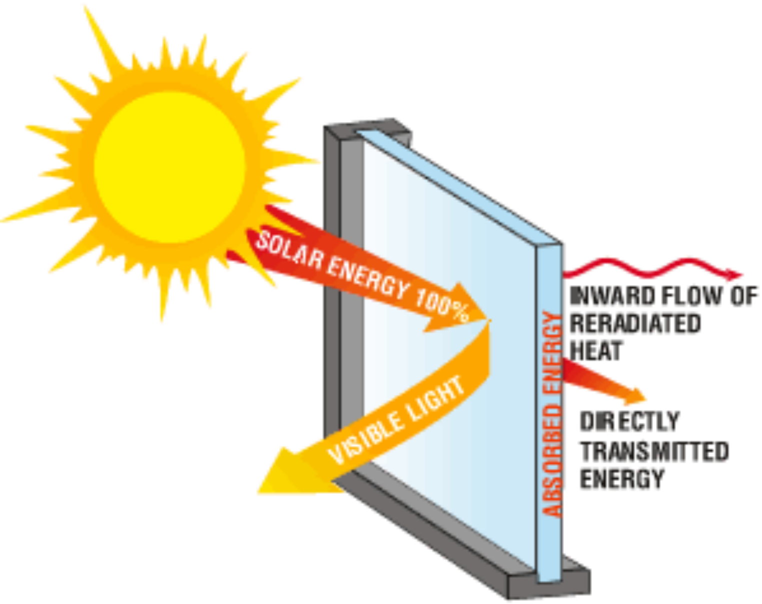
1. Glazing
   - The main part of fenestration that lets the light through
   - Usually glass
     - Occasionally plastic
   - A layer is called a *glaze* or a *pane* or a *lite*
2. Framing
   - The material that holds the glazing in place
     - Attaches it to the rest of the enclosure
   - Usually wood, metal, plastic or fiberglass
3. Shading devices and/or screens
   - A unit may or may not have shading
   - Either from other building components or shading devices that may or may not be an integral part of the overall assembly

Glazing units

- In some climates, single glazes of glass are used in windows or curtain wall assemblies
  - Single glazes have high U values (low R values)
    - Poor insulators
  - Single glazes must be quite thick for large sizes to handle wind loads
    - Thick glazes can have color and visibility distortions

- Throughout most of the U.S., a multiple glaze unit or insulated window assembly should be used
  - Also called an insulated glazing unit (IGU)
  - Much of IIT has single glaze windows
    - Mies van der Rohe used them before IGUs were available

Heat gain through fenestration

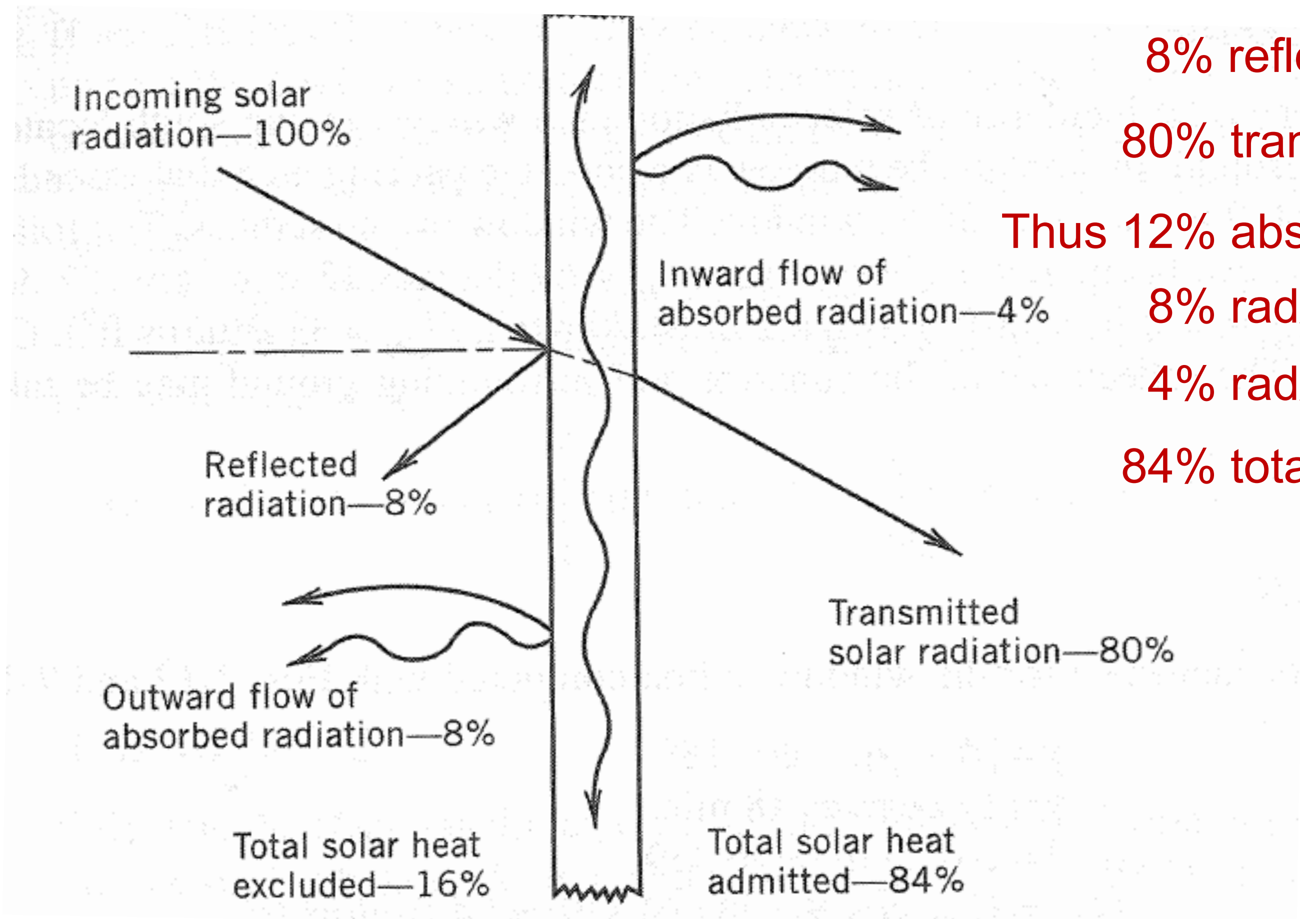


Energy flows through fenestration via:

- Conductive and convective heat transfer caused by I/O temperature difference and wind
- Net long-wave radiation (> 2.5 μm wavelength) radiative exchange between fenestration and its surroundings
  - Also between glazing layers
- Short-wave (< 2.5 μm) solar radiation incident on the fenestration product
  - Part of the incident solar energy is **transmitted** and eventually absorbed by the room surfaces
    - That energy adds to heat gain
  - Part of the incident solar energy is **absorbed** by the fenestration and reradiated as thermal energy toward the inside

Solar radiation and **windows** (i.e., **fenestration**)

- Solar radiation through a single glaze



100% incident

8% reflected

80% transmitted

Thus 12% absorbed

8% rad/conv outward

4% rad/conv inward

84% total transmitted

Total heat transfer

The heat gain through fenestration consists of two main components:

- $Q_{thermal}$ = heat transfer between indoor and outdoor air
  - This is positive or negative depending on temperature

- Q_{solar} = heat transfer from solar radiation
  - This is always a positive number during daytime

The total heat transfer through fenestration will then be:

$$Q_{total} = Q_{thermal} + Q_{solar}$$

Heat gain through windows

- Calculating the **thermal** heat gain through a window is easy

$$Q_{thermal} = UA\Delta T$$

- Accounting for **solar** heat gain is more complicated
  - Need to include spectral and angular characteristics of radiation and glazing
  - Need to include absorption of solar energy and re-radiation of thermal energy
- We can do this with a simplified metric
  - The solar heat gain coefficient (SHGC):

$$Q_{solar,window} = \left(I_{solar}A\right)SHGC$$

What about window assemblies?

- In addition to glazing material, windows also include framing, mullions, muntin bars, dividers, and shading devices
  - These all combine to make **fenestration systems**

- Total heat transfer through an assembly:

$$Q_{window} = UA_{pf}\left(T_{out} - T_{in}\right) + I_{solar}A_{pf}SHGC$$

Where:
U = overall coefficient of heat transfer (U-factor), W/m^2K
A_{pf} = total *projected* area of fenestration, m^2
T_{in} = indoor air temperature, K
T_{out} = outdoor air temperature, K
SHGC = solar heat gain coefficient, -
I_{solar} = incident total irradiance, W/m^2

Basic steady-state solution

- If we assume steady state conditions, we can write the thermal and solar heat gains in terms of temperature differences and incident radiation as:

$$Q_{total} = U_{total} A_{proj} (T_{out} - T_{in}) + (SHGC) A_{proj} I_{total}$$

where

- U_{total} is the overall U factor for the assembly (W/m^{2}K)
- A_{proj} = total projected area of assembly (m^2)
- $SHGC$ = solar heat gain coefficient (dimensionless)
- I_{total} = total incident solar irradiance (W/m^2)

Another breakdown

- The previous equation is useful for bulk estimates of heat transfer through fenestration

- For more complete building heating and cooling models (heat balance, radiant time series, etc.), we need to break the solar term down further into:
  - Transmitted solar
  - Absorbed and reradiated thermal
  - Absorbed and conducted thermal

- So SHGC alone is not enough for detailed calculations
  - But good for overall estimate
  - More on SHGC later

FENESTRATION:
THERMAL HEAT TRANSFER

Let's begin with U Values

- Since fenestration has both a frame and glazing, we must consider heat transfer through both
  - Need to know both areas A_{frame} and A_{glass}
- Because there is complex 2-D heat transfer around the frame/glazing interface, we break the glazing into:
  - (1) Frame area
  - (2) Center area
  - (3) Glazing area around the frame (i.e., "edge of glass")
    - This is the ~2.5 inches (63 mm) of glazing adjacent to the frame
    - The center of glass area then is $A_{center} = A_{glass} - A_{edge\ of\ glass}$
- Each region has its own U value
- Total area:

$$A_{proj} = A_{frame} + A_{glass} = A_{frame} + A_{center} + A_{edge\ of\ glass}$$

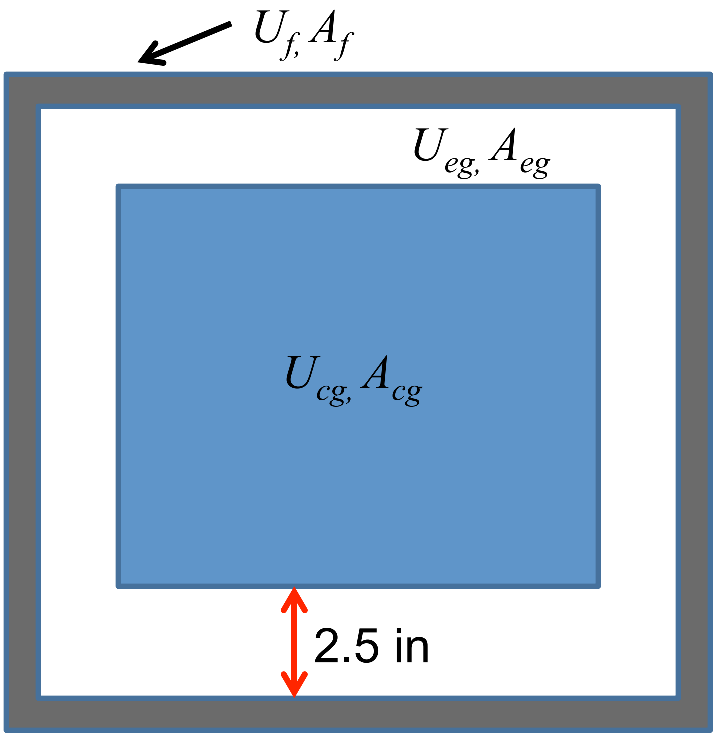
Computing the overall U Value

- The overall U value is therefore:

$$U_{tot} = \frac{U_{cg}A_{cg} + U_{eg}A_{eg} + U_f A_f}{A_{proj}}$$

where

- U_{cg} = center of glass U value
- U_{eg} = edge of glass U value
- U_f = U value of frame
- A_{cg} = center of glass area
- A_{eg} = edge of glass area
- A_f = frame area



A_{eg} is a 2.5 inch (6.4 cm) strip next to the frame

Computing U_{cg} for a single glaze

For a clear single glaze the computation can use simple conduction + convection

$$U_{cg} = \left(\frac{1}{h_{out}} + \frac{1}{h_{in}} + \frac{L}{k} \right)^{-1}$$

– h_{out}, h_{in} are the exterior and interior convection coefficients, L is the thickness, and k the glass conductivity

– Thermal conductivity of pure glass is ~1 W/mK

h_{out} and h_{in}

- h_{out} depends upon outside temperature and wind speed
  - For typical winter conditions:
    - h_{out} = 29 W/(m^{2}K) is typically used
- h_{in} from natural convection depends upon window size and temperature differences
  - h_{in} =8.3 W/(m^{2}K) is typically used
  - ASHRAE HOF 2005 gives values for better accuracy

Table 2 Indoor Surface Heat Transfer Coefficient h_i in W/(m^2·K), Vertical Orientation (Still Air Conditions)

Glazing ID	Glazing Type	Glazing Height m	Winter Conditions: Glass Temp. °C	Winter Conditions: Temp. Diff. °C	Winter Conditions: h_i W/(m^2·K)	Summer Conditions: Glass Temp. °C	Summer Conditions: Temp. Diff. °C	Summer Conditions: h_i W/(m^2·K)
1	Single glazing	0.6	–9	30	8.04	33	9	4.12
		1.2	–9	30	7.42	33	9	3.66
		1.8	–9	30	7.10	33	9	3.43
5	Double glazing with 12.7 mm airspace	0.6	7	14	7.72	35	11	4.28
		1.2	7	14	7.21	35	11	3.80
		1.8	7	14	6.95	35	11	3.55
23	Double glazing with $e = 0.1$ on surface 2 and 12.7 mm argon space	0.6	13	8	7.44	34	10	4.20
		1.2	13	8	7.00	34	10	3.73
		1.8	13	8	6.77	34	10	3.49
43	Triple Glazing with $e = 0.1$ on surfaces 2 and 5 and 12.7 mm argon spaces	0.6	17	4	7.09	40	16	4.61
		1.2	17	4	6.72	40	16	4.08
		1.8	17	4	6.53	40	16	3.81

Notes:
Glazing ID refers to fenestration assemblies in Table 4.
Winter conditions: room air temperature $t_i = 21$°C, outdoor air temperature $t_o = -18$°C, no solar radiation
Summer conditions: room air temperature $t_i = 24$°C, outdoor air temperature $t_o = 32$°C, direct solar irradiance $E_D = 748$ W/m^2
$h_i = h_{ic} + h_{iR} = 1.46(\Delta T/L)^{0.25} + e\Gamma(T_g^4 - T_i^4)/\Delta T$
where $\Delta T = T_g - T_i$, K; L = glazing height, m; T_g = glass temperature, K

Computing U_{cg} for a single glaze

$$U_{cg} = \left(\frac{1}{h_{out}} + \frac{1}{h_{in}} + \frac{L}{k} \right)^{-1}$$

$$U_{cg} = \left(\frac{1}{29 \frac{\mathrm{W}}{\mathrm{m^2K}}} + \frac{1}{8 \frac{\mathrm{W}}{\mathrm{m^2K}}} + \frac{0.003\ \mathrm{m}}{1\ \frac{\mathrm{W}}{\mathrm{mK}}} \right)^{-1} \approx 6 \frac{\mathrm{W}}{\mathrm{m^2K}}$$

Q: What contributes most to heat transfer resistance?

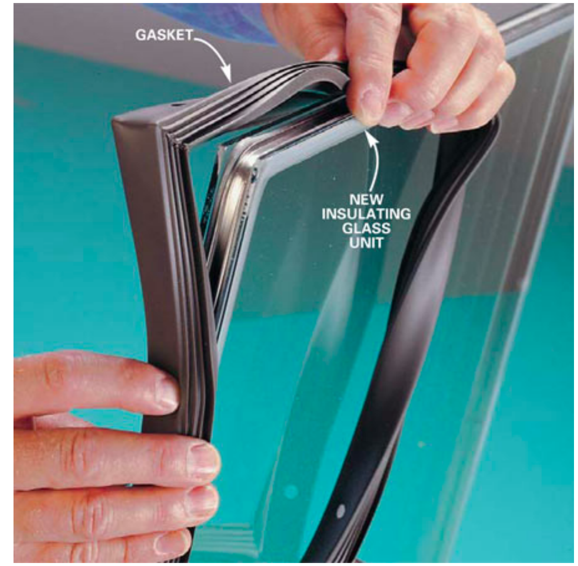
A: Not the glass! Actually the interior convection

What about double- and triple-glazed windows?

- Insulated glazing units (IGUs)
  - 2 or more glazes of glass
    - Separated with a spacer
  - Double glazing: 2 sheets
  - Triple glazing: 3 sheets
    - Much less common (expensive)

- Primary purpose: thermal control
  - 2 glazes cuts heat loss nearly in half
  - 3 glazes cuts heat loss by about 2/3

- Higher initial costs but …
  - Reduces operating costs
  - Increases comfort
  - Provides additional architectural options



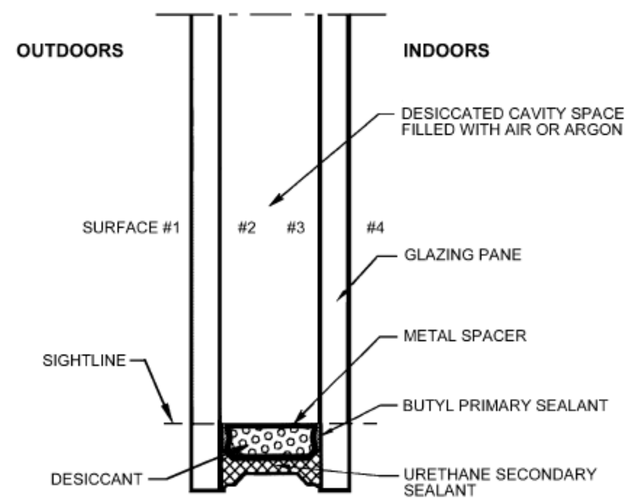
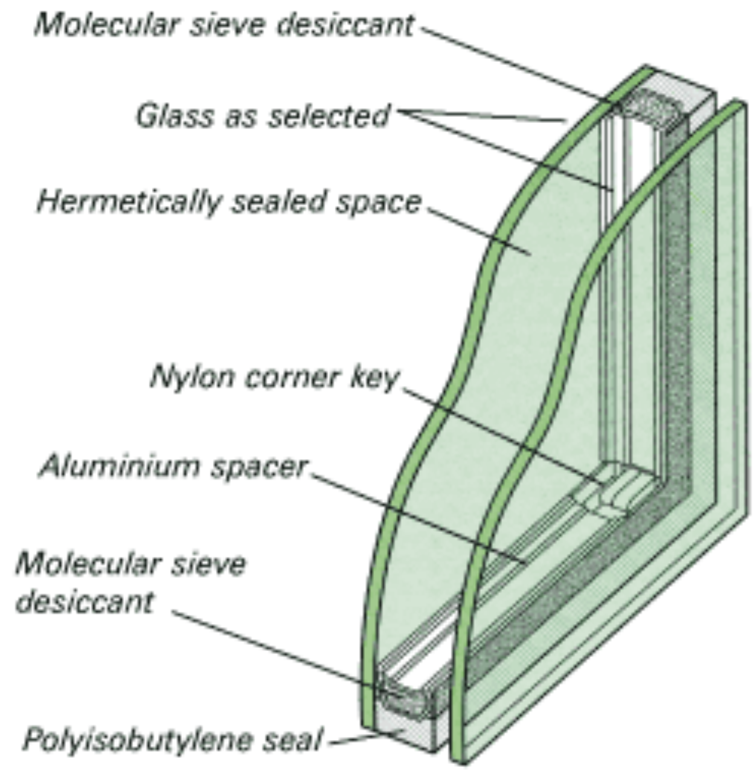


Fig. 1 Insulating Glazing Unit (IGU) Construction Detail

Components of insulated glazing units (IGU)

- Glass
  - Annealed, tempered, laminated
  - Clear, tinted, or reflective film
- Spacer
  - Separates the glazes
  - Metallic spacers act as thermal bridges but are commonly used
    - Insulating spacers can also be used
- Air space
  - Dry air or inert gas (Ar, Kr)
  - Desiccants added to absorb moisture and reduce fogging
- Sealant
  - Hermetically seals unit to prevent air escape & moisture penetration



Insulated Glazing Units

Computing U_{cg} for a double glaze with air cavity

- Start with single-glaze equation:

$$U_{cg} = \left(\frac{1}{h_{out}} + \frac{1}{h_{in}} + \frac{L}{k} \right)^{-1}$$

- Add terms for:
  - Conduction through the second glass pane
  - Conduction through the still air space ($k_{\text{still air}}$ = 0.025 W/mK)
  - Convection (if any) in air space (try to minimize)
  - Radiation within air space (long-wave)
- This ends up being a complex problem…

U_{cg} for IGUs

- For an insulated glass unit, there is an air space between the glazes
  - The cavity transmits heat by conduction (if still air), natural convection, and radiation
- U_{cg} can be estimated with a program called WINDOW
  - Companion to THERM
  - This is the preferred method to get U_{cg}
- Decent estimates of U_{cg} can also be obtained using ASHRAE HOF for similar window constructions

Product Type	Glass Only	
Frame Type ID Glazing Type	Center of Glass	Edge of Glass
Single Glazing		
1 3.2 mm glass	*5.91*	*5.91*
2 6.4 mm acrylic/polycarb	*5.00*	*5.00*
3 3.2 mm acrylic/polycarb	*5.45*	*5.45*
Double Glazing		
4 6.4 mm airspace	*3.12*	*3.63*
5 12.7 mm airspace	*2.73*	*3.36*
6 6.4 mm argon space	*2.90*	*3.48*
7 12.7 mm argon space	*2.56*	*3.24*
Double Glazing, e = 0.60 on surface 2 or 3		
8 6.4 mm airspace	*2.95*	*3.52*
9 12.7 mm airspace	*2.50*	*3.20*
10 6.4 mm argon space	*2.67*	*3.32*
11 12.7 mm argon space	*2.33*	*3.08*

Typical U_{cg} plots: Function of spacing

- We can separate glass panes with air-tight layers of air or other gases

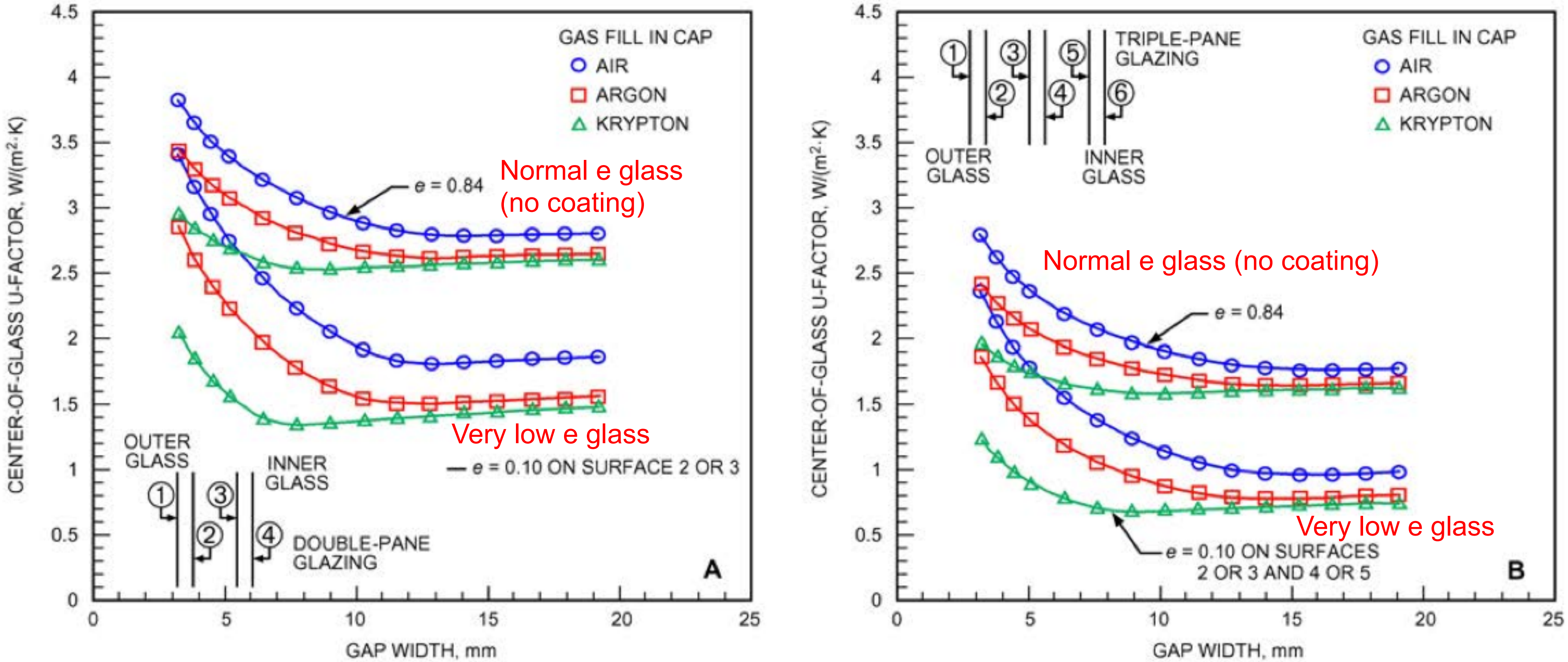


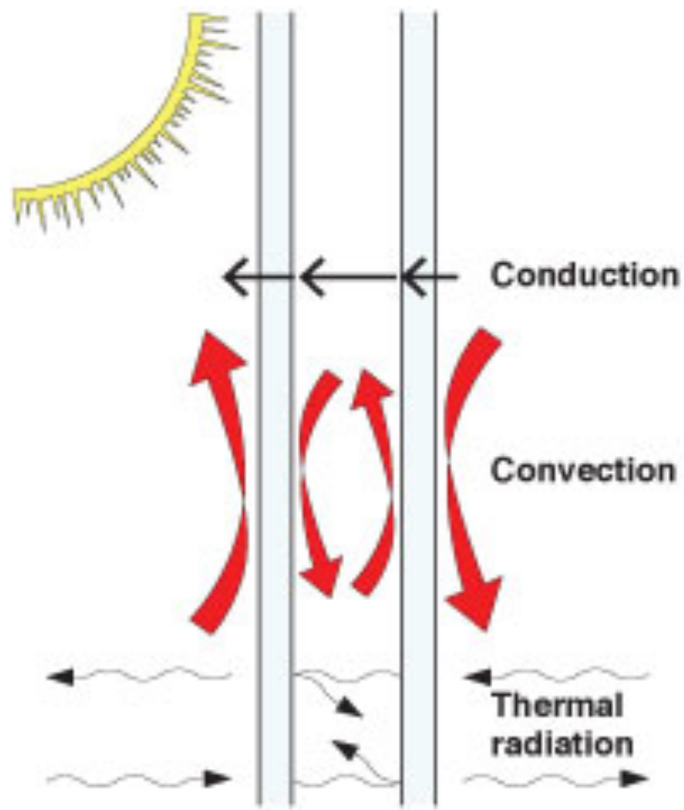
Fig. 3 Center-of-Glass U-Factor for Vertical Double- and Triple-Pane Glazing Units

Thermal conductivities:
Air 0.025 W/mK
Argon 0.017 W/mK
Krypton 0.009 W/mK

2013 ASHRAE Handbook of Fundamentals: Chapter 15

Separation distance

- U_{cg} first decreases with separation distance and but then rises
  - Why would that happen?



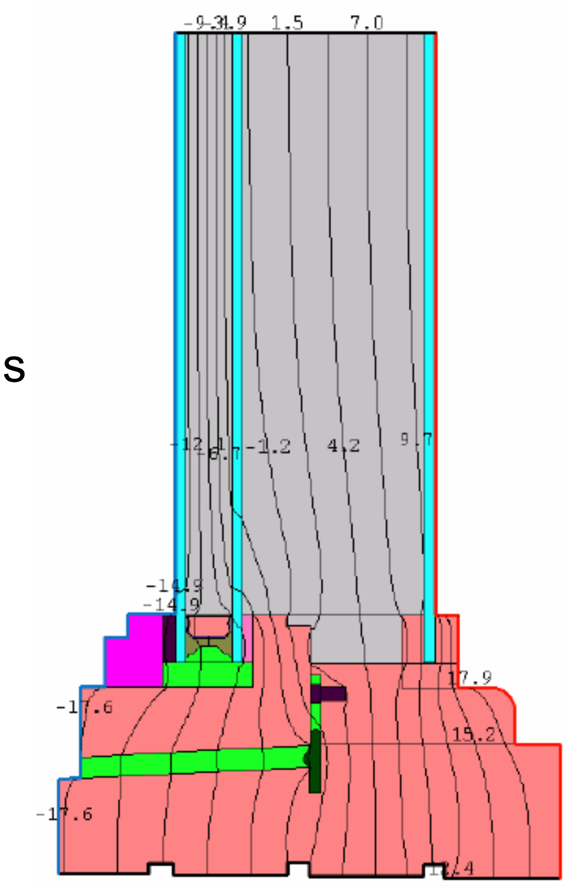
Separation distance

- At first, the separation distance reduces conductive heat transfer through the gas
  - Spacing too low → conduction occurs easily
    - k/L is too high
- But with larger spacing, more convection can occur and the heat transfer actually improves
  - Spacing too high → convective currents
- There is no real change in radiation transfer with spacing
- Optimal spacing typically 15-20 mm
  - This is not an issue in vacuum insulated glass

Finding U_{eg} and U_f

- U_{eg} and U_f are usually determined experimentally or using computer software
  - THERM
  - WINDOW
    - Another free 2-D thermal finite element analysis program specially designed for computing window system heat transfer

- The frame shape and materials play a large role in determining both U_{eg} and U_f



Estimating U_f and U_{eg}

- If you need to get a U_f or a U_{eg} and do not have access to software (or don't have hours to kill)
  - You can look up prototypical numbers in the ASHRAE HOF

Table 1 Representative Fenestration Frame U-Factors in W/(m^2·K), Vertical Orientation

Frame Material	Type of Spacer	Product Type/Number of Glazing Layers																		
		Operable			Fixed			Garden Window		Plant-Assembled Skylight			Curtainwall[e]			Sloped/Overhead Glazing[e]				
		Single[b]	Double[c]	Triple[d]	Single[b]	Double[c]	Triple[d]	Single[b]	Double[c]	Single[b]	Double[c]	Triple[d]	Single[f]	Double[g]	Triple[h]	Single[f]	Double[g]	Triple[h]
Aluminum without thermal break	All	13.51	12.89	12.49	10.90	10.22	9.88	10.67	10.39	44.57	39.86	39.01	17.09	16.81	16.07	17.32	17.03	16.30
Aluminum with thermal break[a]	Metal	6.81	5.22	4.71	7.49	6.42	6.30			39.46	28.67	26.01	10.22	9.94	9.37	10.33	9.99	9.43
	Insulated	n/a	5.00	4.37	n/a	5.91	5.79			n/a	26.97	23.39	n/a	9.26	8.57	n/a	9.31	8.63
Aluminum-clad wood/ reinforced vinyl	Metal	3.41	3.29	2.90	3.12	2.90	2.73			27.60	22.31	20.78						
	Insulated	n/a	3.12	2.73	n/a	2.73	2.50			n/a	21.29	19.48						
Wood /vinyl	Metal	3.12	2.90	2.73	3.12	2.73	2.38	5.11	4.83	14.20	11.81	10.11						
	Insulated	n/a	2.78	2.27	n/a	2.38	1.99	n/a	4.71	n/a	11.47	9.71						
Insulated fiberglass/ vinyl	Metal	2.10	1.87	1.82	2.10	1.87	1.82											
	Insulated	n/a	1.82	1.48	n/a	1.82	1.48											
Structural glazing	Metal												10.22	7.21	5.91	10.33	7.27	5.96
	Insulated												n/a	5.79	4.26	n/a	5.79	4.26

Note: This table should only be used as an estimating tool for early phases of design.
[a]Depends strongly on width of thermal break. Value given is for 9.5 mm.
[b]Single glazing corresponds to individual glazing unit thickness of 3 mm. (nominal).
[c]Double glazing corresponds to individual glazing unit thickness of 19 mm. (nominal).
[d]Triple glazing corresponds to individual glazing unit thickness of 34.9 mm. (nominal).
[e]Glass thickness in curtainwall and sloped/overhead glazing is 6.4 mm.
[f]Single glazing corresponds to individual glazing unit thickness of 6.4 mm. (nominal).
[g]Double glazing corresponds to individual glazing unit thickness of 25.4 mm. (nominal).
[h]Triple glazing corresponds to individual glazing unit thickness of 44.4 mm. (nominal).
n/a Not applicable

U_{cg}, U_{eg} and overall U factors

Table 4 U-Factors for Various Fenestration Products in W/(m²·K)

Product Type	Glass Only		Vertical Installation									
			Operable (including sliding and swinging glass doors)					Fixed				
Frame Type ID Glazing Type	Center of Glass	Edge of Glass	Aluminum without Thermal Break	Aluminum with Thermal Break	Reinforced Vinyl/ Aluminum Clad Wood	Wood/ Vinyl	Insulated Fiberglass/ Vinyl	Aluminum without Thermal Break	Aluminum with Thermal Break	Reinforced Vinyl/ Aluminum Clad Wood	Wood/ Vinyl	Insulated Fiberglass/ Vinyl
Single Glazing												
1 3.2 mm glass	*5.91*	*5.91*	7.24	6.12	5.14	5.05	4.61	6.42	6.07	5.55	5.55	5.35
2 6.4 mm acrylic/polycarb	*5.00*	*5.00*	6.49	5.43	4.51	4.42	4.01	5.60	5.25	4.75	4.75	4.58
3 3.2 mm acrylic/polycarb	*5.45*	*5.45*	6.87	5.77	4.82	4.73	4.31	6.01	5.66	5.15	5.15	4.97
Double Glazing												
4 6.4 mm airspace	*3.12*	*3.63*	4.93	3.70	3.25	3.13	2.77	3.94	3.56	3.19	3.17	3.04
5 12.7 mm airspace	*2.73*	*3.36*	4.62	3.42	3.00	2.87	2.53	3.61	3.22	2.86	2.84	2.72
6 6.4 mm argon space	*2.90*	*3.48*	4.75	3.54	3.11	2.98	2.63	3.75	3.37	3.00	2.98	2.85
7 12.7 mm argon space	*2.56*	*3.24*	4.49	3.30	2.89	2.76	2.42	3.47	3.08	2.73	2.70	2.58
Double Glazing, e = 0.60 on surface 2 or 3												
8 6.4 mm airspace	*2.95*	*3.52*	4.80	3.58	3.14	3.02	2.67	3.80	3.41	3.05	3.03	2.90
9 12.7 mm airspace	*2.50*	*3.20*	4.45	3.26	2.85	2.73	2.39	3.42	3.03	2.68	2.66	2.54
10 6.4 mm argon space	*2.67*	*3.32*	4.58	3.38	2.96	2.84	2.49	3.56	3.17	2.82	2.80	2.67
11 12.7 mm argon space	*2.33*	*3.08*	4.31	3.13	2.74	2.62	2.28	3.28	2.89	2.54	2.52	2.40
Double Glazing, e = 0.40 on surface 2 or 3												
12 6.4 mm airspace	*2.78*	*3.40*	4.66	3.46	3.03	2.91	2.56	3.66	3.27	2.91	2.89	2.76
13 12.7 mm airspace	*2.27*	*3.04*	4.27	3.09	2.70	2.58	2.25	3.23	2.84	2.49	2.47	2.35
14 6.4 mm argon space	*2.44*	*3.16*	4.40	3.21	2.81	2.69	2.35	3.37	2.98	2.63	2.61	2.49
15 12.7 mm argon space	*2.04*	*2.88*	4.09	2.93	2.55	2.43	2.10	3.04	2.65	2.31	2.29	2.17
Double Glazing, e = 0.20 on surface 2 or 3												
16 6.4 mm airspace	*2.56*	*3.24*	4.49	3.30	2.89	2.76	2.42	3.47	3.08	2.73	2.70	2.58
17 12.7 mm airspace	*1.99*	*2.83*	4.05	2.89	2.52	2.39	2.07	2.99	2.60	2.26	2.24	2.13
18 6.4 mm argon space	*2.16*	*2.96*	4.18	3.01	2.63	2.51	2.17	3.13	2.74	2.40	2.38	2.26
19 12.7 mm argon space	*1.70*	*2.62*	3.83	2.68	2.33	2.21	1.89	2.75	2.36	2.03	2.01	1.90

- U factors shown for winter conditions with 24 km/h (15 mph) winds

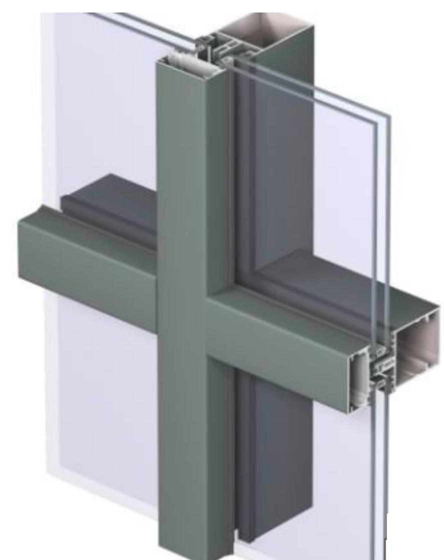
U_{cg}, U_{eg} and overall U factors

Table 4 U-Factors for Various Fenestration Products in W/(m²·K)

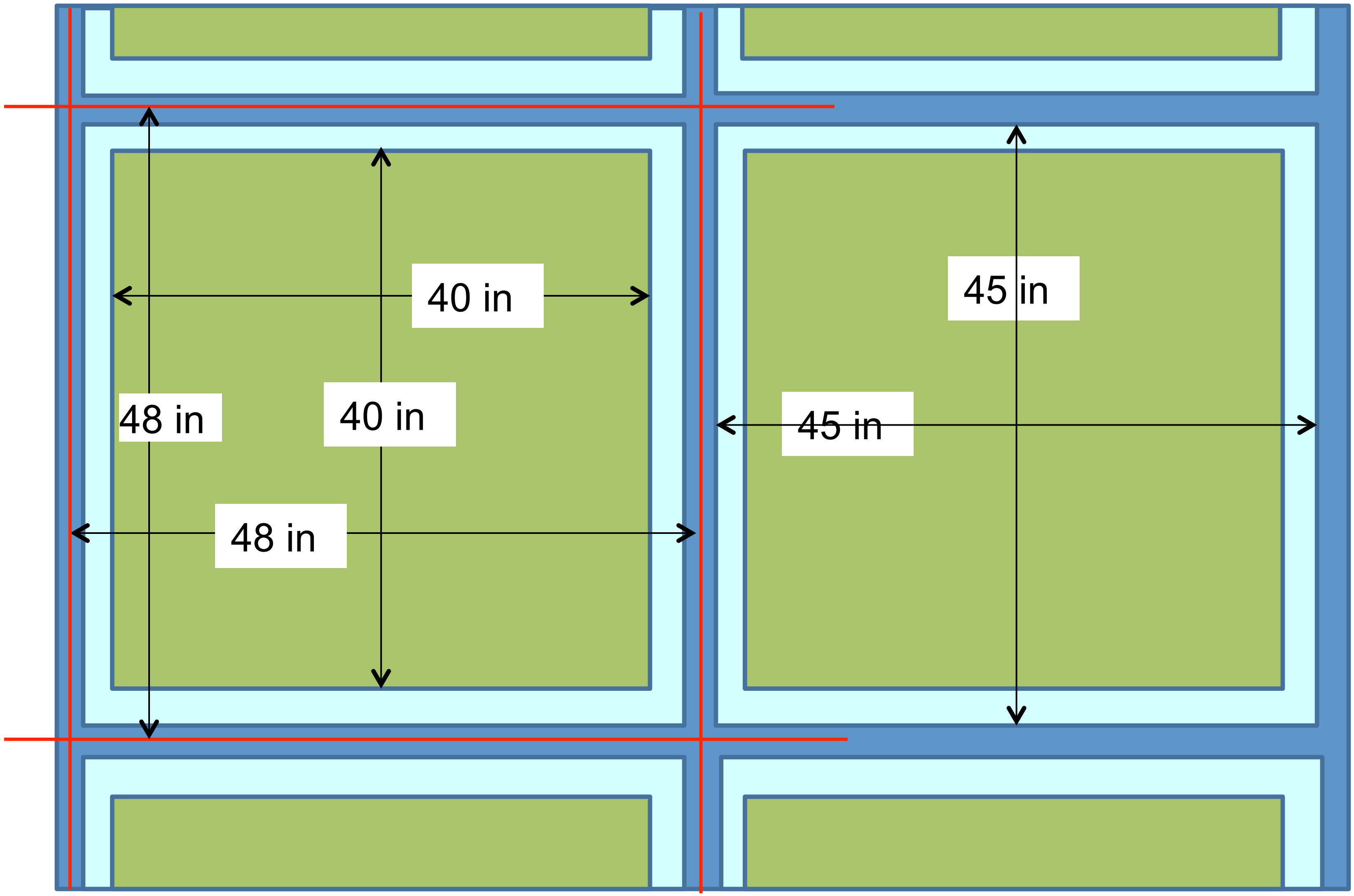
Product Type	Glass Only		Vertical Installation									
			Operable (including sliding and swinging glass doors)					Fixed				
Frame Type / ID Glazing Type	Center of Glass	Edge of Glass	Aluminum without Thermal Break	Aluminum with Thermal Break	Reinforced Vinyl/ Aluminum Clad Wood	Wood/ Vinyl	Insulated Fiberglass/ Vinyl	Aluminum without Thermal Break	Aluminum with Thermal Break	Reinforced Vinyl/ Aluminum Clad Wood	Wood/ Vinyl	Insulated Fiberglass/ Vinyl
Double Glazing, *e* = 0.10 on surface 2 or 3												
20 6.4 mm airspace	*2.39*	*3.12*	4.36	3.17	2.78	2.65	2.32	3.32	2.93	2.59	2.56	2.45
21 12.7 mm airspace	*1.82*	*2.71*	3.92	2.77	2.41	2.28	1.96	2.84	2.45	2.12	2.10	1.99
22 6.4 mm argon space	*1.99*	*2.83*	4.05	2.89	2.52	2.39	2.07	2.99	2.60	2.26	2.24	2.13
23 12.7 mm argon space	*1.53*	*2.49*	3.70	2.56	2.22	2.10	1.79	2.60	2.21	1.89	1.86	1.76
Double Glazing, *e* = 0.05 on surface 2 or 3												
24 6.4 mm airspace	*2.33*	*3.08*	4.31	3.13	2.74	2.62	2.28	3.28	2.89	2.54	2.52	2.40
25 12.7 mm airspace	*1.70*	*2.62*	3.83	2.68	2.33	2.21	1.89	2.75	2.36	2.03	2.01	1.90
26 6.4 mm argon space	*1.87*	*2.75*	3.96	2.81	2.44	2.32	2.00	2.89	2.50	2.17	2.15	2.03
27 12.7 mm argon space	*1.42*	*2.41*	3.61	2.48	2.15	2.02	1.71	2.50	2.11	1.79	1.77	1.67
Triple Glazing												
28 6.4 mm airspace	*2.16*	*2.96*	4.11	2.89	2.51	2.45	2.16	3.10	2.73	2.38	2.33	2.25
29 12.7 mm airspace	*1.76*	*2.67*	3.80	2.60	2.25	2.19	1.91	2.76	2.39	2.05	2.01	1.93
30 6.4 mm argon space	*1.93*	*2.79*	3.94	2.73	2.36	2.30	2.01	2.90	2.54	2.19	2.15	2.07
31 12.7 mm argon space	*1.65*	*2.58*	3.71	2.52	2.17	2.12	1.84	2.66	2.30	1.96	1.91	1.84
Triple Glazing, *e* = 0.20 on surface 2,3,4, or 5												
32 6.4 mm airspace	*1.87*	*2.75*	3.89	2.69	2.32	2.27	1.98	2.86	2.49	2.15	2.10	2.03
33 12.7 mm airspace	*1.42*	*2.41*	3.54	2.36	2.02	1.97	1.70	2.47	2.10	1.77	1.73	1.66
34 6.4 mm argon space	*1.59*	*2.54*	3.67	2.48	2.13	2.08	1.80	2.61	2.25	1.91	1.87	1.80
35 12.7 mm argon space	*1.25*	*2.28*	3.40	2.23	1.91	1.86	1.59	2.32	1.96	1.63	1.59	1.52
Triple Glazing, *e* = 0.20 on surfaces 2 or 3 and 4 or 5												
36 6.4 mm airspace	*1.65*	*2.58*	3.71	2.52	2.17	2.12	1.84	2.66	2.30	1.96	1.91	1.84
37 12.7 mm airspace	*1.14*	*2.19*	3.31	2.15	1.84	1.78	1.52	2.23	1.86	1.54	1.49	1.43
38 6.4 mm argon space	*1.31*	*2.32*	3.45	2.27	1.95	1.90	1.62	2.37	2.01	1.68	1.63	1.56
39 12.7 mm argon space	*0.97*	*2.05*	3.18	2.03	1.72	1.67	1.41	2.08	1.71	1.39	1.35	1.29
Triple Glazing, *e* = 0.10 on surfaces 2 or 3 and 4 or 5												
40 6.4 mm airspace	*1.53*	*2.49*	3.63	2.44	2.10	2.05	1.77	2.57	2.20	1.86	1.82	1.75
41 12.7 mm airspace	*1.02*	*2.10*	3.22	2.07	1.76	1.71	1.45	2.13	1.76	1.44	1.40	1.33
42 6.4 mm argon space	*1.19*	*2.23*	3.36	2.19	1.87	1.82	1.55	2.27	1.91	1.58	1.54	1.47
43 12.7 mm argon space	*0.80*	*1.92*	3.05	1.90	1.61	1.56	1.30	1.93	1.57	1.25	1.21	1.15

Example problem

- Estimate the U factor for the 4 ft x 4 ft vision glass section of a curtain wall
  - The vision IGU has low e glass (emissivity of 0.40)
  - ½” (12 mm) air space and metal spacer
- The aluminum mullions are 3 inches (76 mm) wide and have a thermal break
  - In a curtain wall, half the mullion is associated with one IGU and half with the other so we have 1.5 inch of mullion



Example problem: schematic



Example problem

- With a 3 inch mullion, there will be 1.5 inches of frame on each edge
  - The total glass dimension is 48 in – 1.5 in – 1.5 in = 45 in

- Edge-of-glass width is 2.5 inch
  - So center of glass dimension is is 45 - 5 = 40 inches

A_{cg} = (40)x(40)=1600 in^2

A_{eg} = (45x45) - A_{cg} = 425 in^2

A_f = (48x48)-(45x45) = 279 in^2

Example problem

- Find U_f

Table 1 Representative Fenestration Frame U-Factors in W/(m²·K), Vertical Orientation

		Product Type/Number of Glazing Layers																
		Operable			Fixed			Garden Window		Plant-Assembled Skylight			Curtainwall[e]			Sloped/Overhead Glazing[e]		
Frame Material	Type of Spacer	Single[b]	Double[c]	Triple[d]	Single[b]	Double[c]	Triple[d]	Single[b]	Double[c]	Single[b]	Double[c]	Triple[d]	Single[f]	Double[g]	Triple[h]	Single[f]	Double[g]	Triple[h]
Aluminum without thermal break	All	13.51	12.89	12.49	10.90	10.22	9.88	10.67	10.39	44.57	39.86	39.01	17.09	16.81	16.07	17.32	17.03	16.30
Aluminum with thermal break[a]	Metal	6.81	5.22	4.71	7.49	6.42	6.30			39.46	28.67	26.01	10.22	9.94	9.37	10.33	9.99	9.43
	Insulated	n/a	5.00	4.37	n/a	5.91	5.79			n/a	26.97	23.39	n/a	9.26	8.57	n/a	9.31	8.63
Aluminum-clad wood/ reinforced vinyl	Metal	3.41	3.29	2.90	3.12	2.90	2.73			27.60	22.31	20.78						
	Insulated	n/a	3.12	2.73	n/a	2.73	2.50			n/a	21.29	19.48						
Wood /vinyl	Metal	3.12	2.90	2.73	3.12	2.73	2.38	5.11	4.83	14.20	11.81	10.11						
	Insulated	n/a	2.78	2.27	n/a	2.38	1.99	n/a	4.71	n/a	11.47	9.71						
Insulated fiberglass/ vinyl	Metal	2.10	1.87	1.82	2.10	1.87	1.82											
	Insulated	n/a	1.82	1.48	n/a	1.82	1.48											
Structural glazing	Metal												10.22	7.21	5.91	10.33	7.27	5.96
	Insulated												n/a	5.79	4.26	n/a	5.79	4.26

Note: This table should only be used as an estimating tool for early phases of design.
[a]Depends strongly on width of thermal break. Value given is for 9.5 mm.
[b]Single glazing corresponds to individual glazing unit thickness of 3 mm. (nominal).
[c]Double glazing corresponds to individual glazing unit thickness of 19 mm. (nominal).
[d]Triple glazing corresponds to individual glazing unit thickness of 34.9 mm. (nominal).
[e]Glass thickness in curtainwall and sloped/overhead glazing is 6.4 mm.
[f]Single glazing corresponds to individual glazing unit thickness of 6.4 mm. (nominal).
[g]Double glazing corresponds to individual glazing unit thickness of 25.4 mm. (nominal).
[h]Triple glazing corresponds to individual glazing unit thickness of 44.4 mm. (nominal).
n/a Not applicable

U_f = 9.94 W/(m²K)

Example problem

- Find U_{cg} and U_{eg}

Table 4 U-Factors for Various Fenestration Products in W/(m²·K)

Product Type	Glass Only		Vertical Installation									
			Operable (including sliding and swinging glass doors)					Fixed				
Frame Type ID Glazing Type	Center of Glass	Edge of Glass	Aluminum without Thermal Break	Aluminum with Thermal Break	Reinforced Vinyl/ Aluminum Clad Wood	Wood/ Vinyl	Insulated Fiberglass/ Vinyl	Aluminum without Thermal Break	Aluminum with Thermal Break	Reinforced Vinyl/ Aluminum Clad Wood	Wood/ Vinyl	Insulated Fiberglass/ Vinyl
Single Glazing												
1 3.2 mm glass	*5.91*	*5.91*	7.24	6.12	5.14	5.05	4.61	6.42	6.07	5.55	5.55	5.35
2 6.4 mm acrylic/polycarb	*5.00*	*5.00*	6.49	5.43	4.51	4.42	4.01	5.60	5.25	4.75	4.75	4.58
3 3.2 mm acrylic/polycarb	*5.45*	*5.45*	6.87	5.77	4.82	4.73	4.31	6.01	5.66	5.15	5.15	4.97
Double Glazing												
4 6.4 mm airspace	*3.12*	*3.63*	4.93	3.70	3.25	3.13	2.77	3.94	3.56	3.19	3.17	3.04
5 12.7 mm airspace	*2.73*	*3.36*	4.62	3.42	3.00	2.87	2.53	3.61	3.22	2.86	2.84	2.72
6 6.4 mm argon space	*2.90*	*3.48*	4.75	3.54	3.11	2.98	2.63	3.75	3.37	3.00	2.98	2.85
7 12.7 mm argon space	*2.56*	*3.24*	4.49	3.30	2.89	2.76	2.42	3.47	3.08	2.73	2.70	2.58
Double Glazing, $e = 0.60$ on surface 2 or 3												
8 6.4 mm airspace	*2.95*	*3.52*	4.80	3.58	3.14	3.02	2.67	3.80	3.41	3.05	3.03	2.90
9 12.7 mm airspace	*2.50*	*3.20*	4.45	3.26	2.85	2.73	2.39	3.42	3.03	2.68	2.66	2.54
10 6.4 mm argon space	*2.67*	*3.32*	4.58	3.38	2.96	2.84	2.49	3.56	3.17	2.82	2.80	2.67
11 12.7 mm argon space	*2.33*	*3.08*	4.31	3.13	2.74	2.62	2.28	3.28	2.89	2.54	2.52	2.40
Double Glazing, $e = 0.40$ on surface 2 or 3												
12 6.4 mm airspace	*2.78*	*3.40*	4.66	3.46	3.03	2.91	2.56	3.66	3.27	2.91	2.89	2.76
13 12.7 mm airspace	*2.27*	*3.04*	4.27	3.09	2.70	2.58	2.25	3.23	2.84	2.49	2.47	2.35
14 6.4 mm argon space	*2.44*	*3.16*	4.40	3.21	2.81	2.69	2.35	3.37	2.98	2.63	2.61	2.49
15 12.7 mm argon space	*2.04*	*2.88*	4.09	2.93	2.55	2.43	2.10	3.04	2.65	2.31	2.29	2.17
Double Glazing, $e = 0.20$ on surface 2 or 3												
16 6.4 mm airspace	*2.56*	*3.24*	4.49	3.30	2.89	2.76	2.42	3.47	3.08	2.73	2.70	2.58
17 12.7 mm airspace	*1.99*	*2.83*	4.05	2.89	2.52	2.39	2.07	2.99	2.60	2.26	2.24	2.13
18 6.4 mm argon space	*2.16*	*2.96*	4.18	3.01	2.63	2.51	2.17	3.13	2.74	2.40	2.38	2.26
19 12.7 mm argon space	*1.70*	*2.62*	3.83	2.68	2.33	2.21	1.89	2.75	2.36	2.03	2.01	1.90

U_{cg} = 2.27 W/(m²K) and U_{eg} = 3.04 W/(m²K)

Example problem

- So, our info is:

A_{cg} = 1600 in^2, U_{cg}=2.27 W/(m^{2}K)

A_{eg} = 425 in^2, U_{eg}=3.04 W/(m^{2}K)

A_f = = 279 in^2, U_f= 9.94 W/(m^{2}K)

And thus the total U factor for the section is:

$$U = \frac{2.27 \times 1600 + 3.04 \times 425 + 9.94 \times 279}{48 \times 48} = 3.34 \text{ W/(m}^2\text{K)}$$

$$R = \frac{1}{3.34} = 0.30 \text{ (m}^2\text{K)/W (SI)} = \text{R-1.7 (IP)}$$

Doors

- Doors are often overlooked in terms of thermal integrity of the envelope in many buildings
  - Represent a small area fraction of the shell
    - But U value is usually quite large
    - Net impact is usually larger than the area fraction
- Doors are much bigger issues for some industrial buildings
  - Overhead loading bay doors
- Issue for air leakage too

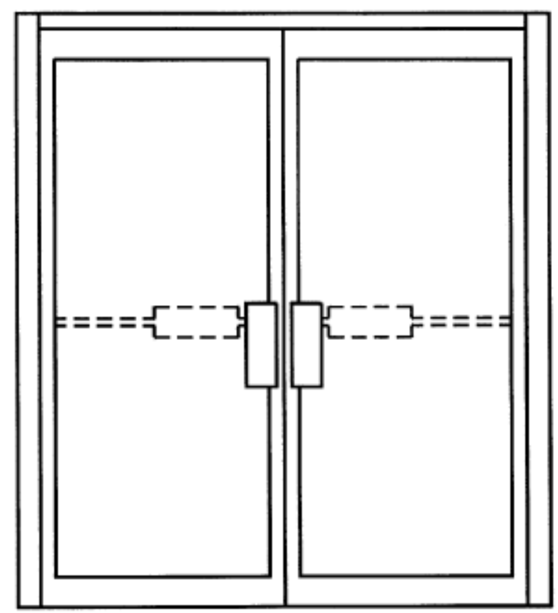


Fig. 5 Details of Stile-and-Rail Door

Doors

- U values for typical doors

Table 6 U-Factors of Doors in W/(m²·K)

Door Type	No Glazing	Single Glazing	Double Glazing with 12.7 mm Airspace	Double Glazing with $e = 0.10$, 12.7 mm Argon
SWINGING DOORS (Rough Opening, 970 × 2080 mm)				
Slab Doors				
Wood slab in wood frame[a]	2.61			
6% glazing (560 × 200 lite)	—	2.73	2.61	2.50
25% glazing (560 × 910 lite)	—	3.29	2.61	2.38
45% glazing (560 × 1620 lite)	—	3.92	2.61	2.21
More than 50% glazing		Use Table 4 (operable)		
Insulated steel slab with wood edge in wood frame[a]	0.91			
6% glazing (560 × 200 lite)	—	1.19	1.08	1.02
25% glazing (560 × 910 lite)	—	2.21	1.48	1.31
45% glazing (560 × 1630 lite)	—	3.29	1.99	1.48
More than 50% glazing		Use Table 4 (operable)		
Foam insulated steel slab with metal edge in steel frame[b]	2.10			
6% glazing (560 × 200 lite)	—	2.50	2.33	2.21
25% glazing (560 × 910 lite)	—	3.12	2.73	2.50
45% glazing (560 × 1630 lite)	—	4.03	3.18	2.73
More than 50% glazing		Use Table 4 (operable)		
Cardboard honeycomb slab with metal edge in steel frame	3.46			
Style and Rail Doors				
Sliding glass doors/ French doors		Use Table 4 (operable)		
Site-Assembled Style and Rail Doors				
Aluminum in Aluminum Frame	—	7.49	5.28	4.49
Aluminum in Aluminum Frame with Thermal Break	—	6.42	4.20	3.58
REVOLVING DOORS (Rough Opening, 2080 × 2130 mm)				
Aluminum in aluminum frame				
Open	—	7.49	—	—
Closed	—	3.69	—	—
SECTIONAL OVERHEAD DOORS (Nominal, 3050 × 3050 mm)				
Uninsulated steel (nominal $U = 6.53$)[c]	6.53	—	—	—
Insulated steel (nominal $U = 0.62$)[c]	1.36	—	—	—
Insulated steel with thermal break (nominal $U = 0.45$)[c]	0.74	—	—	—

Note: All dimensions are in millimetres.
[a] thermally broken sill (add 0.17 W/(m²·K) for non-thermally broken sill)
[b] non-thermally broken sill
[c] Nominal U-factors are through the center of the insulated panel before consideration of thermal bridges around the edges of the door sections and due to the frame.

Spandrel glass

- In some constructions, opaque glass is used for architectural purposes
  - "Spandrel glass"
- Spandrel glass should have insulation added to the inside improve the thermal performance
  - But the insulation will not reduce heat transfer through the **frame**

Ways to achieve low U values

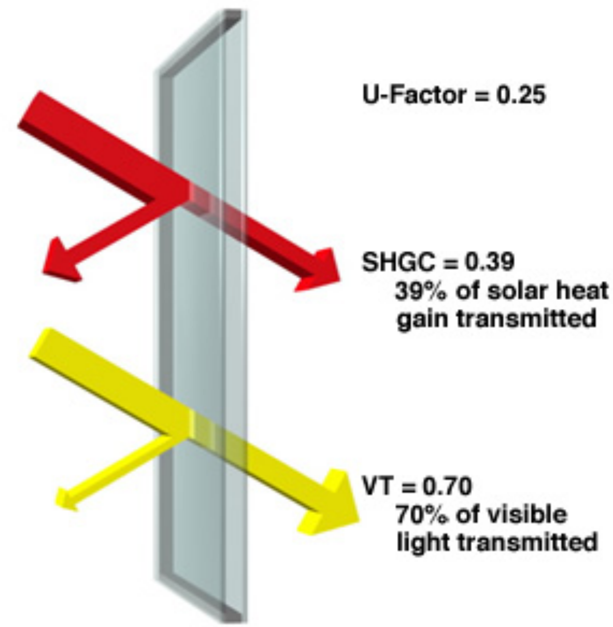
- Optimize air spaces
  - Air has a lower thermal conductivity than glass
  - Effectiveness is limited by convective heat transfer between glazes
    - So about 12 mm for Air or Argon fill
    - About 6 mm for Krypton fill
  - Triple panes can reduce convection at the expense of higher cost
    - Harder sealing and reduced optical transmission
- Heavy gas fill
  - Heavy gases like Argon or Krypton have lower conductivity than air
    - This is good for acoustics too
  - A vacuum between glazes is a great idea
    - But sealing is more difficult than for gas infill
- Low conductivity frames
  - Much heat is gained/lost through frames, especially in larger curtain walls
  - Good frames have thermal breaks of plastic or fiberglass
  - Thermal breaks need to have similar thermal expansion coefficients as other components to ensure seals can be maintained

WINDOW RATINGS: SHGC AND VISIBLE TRANSMITTANCE

Fenestration transmission terms

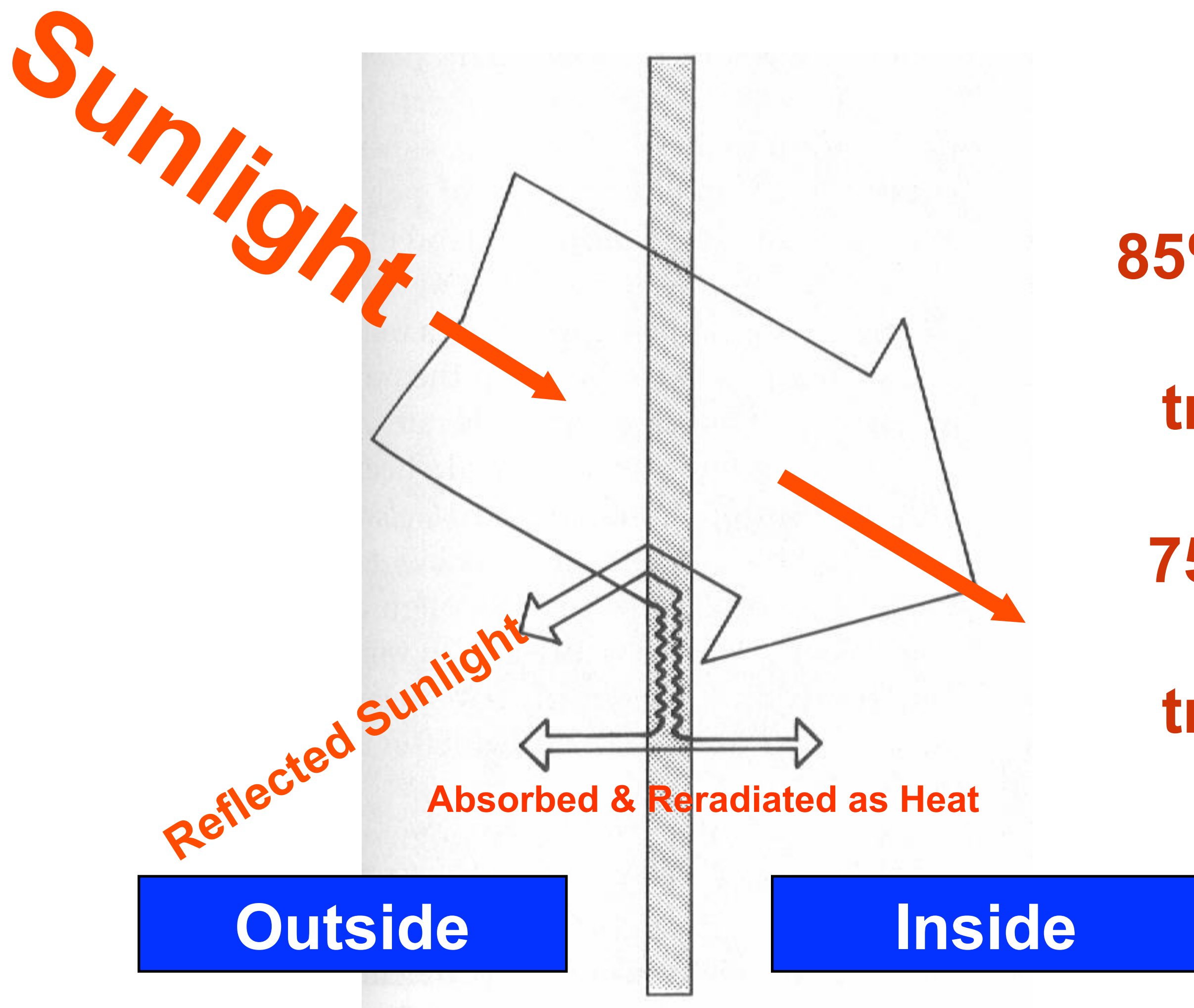
- So far we've only discussed thermal heat transfer
  - U value

- Fenestration also allows for solar heat transfer and transfer of visible light
  - **SHGC**: Solar Heat Gain Coefficient
    - Energy transfer coefficient for all wavelengths of solar thermal radiation
  - **VT**: Visible Transmission Coefficient
    - Transmission coefficient for visible wavelength solar radiation



U, SHGC, and VT for a window with a bronze reflective film

VT and SHGC concepts: clear glass example

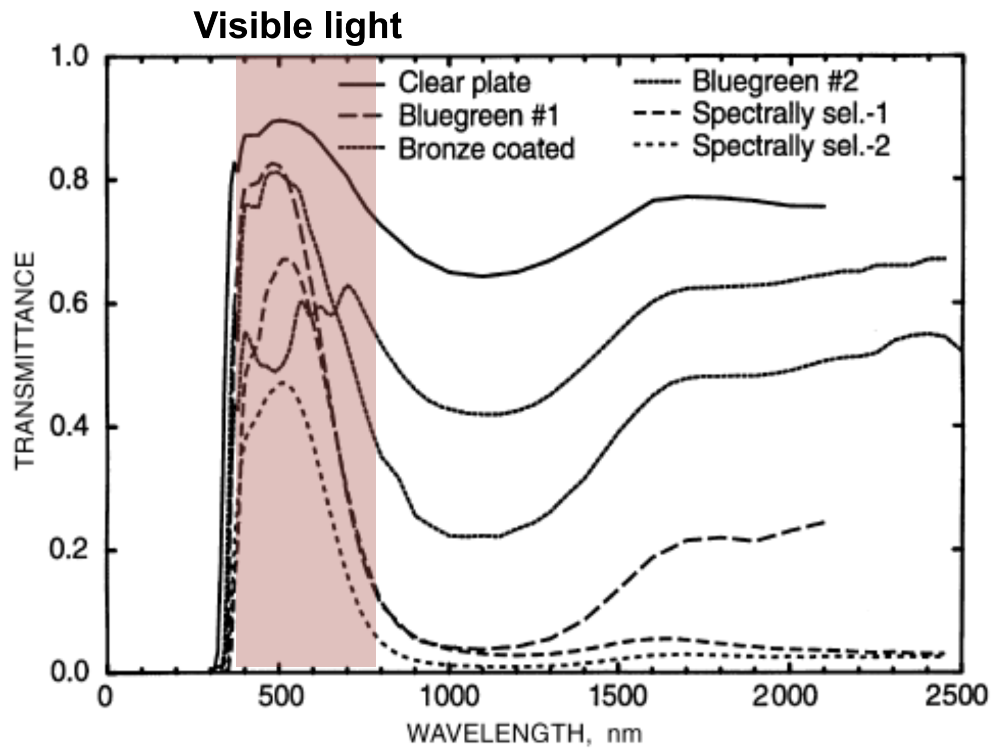


85% of visible energy transmitted

75% of total energy transmitted

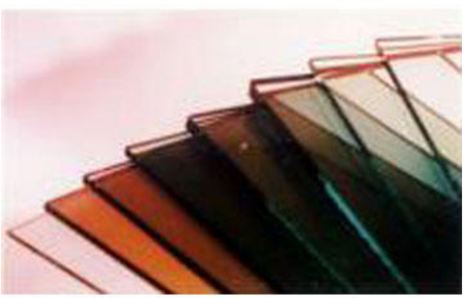
Transmission of visible light: VT of glazing units

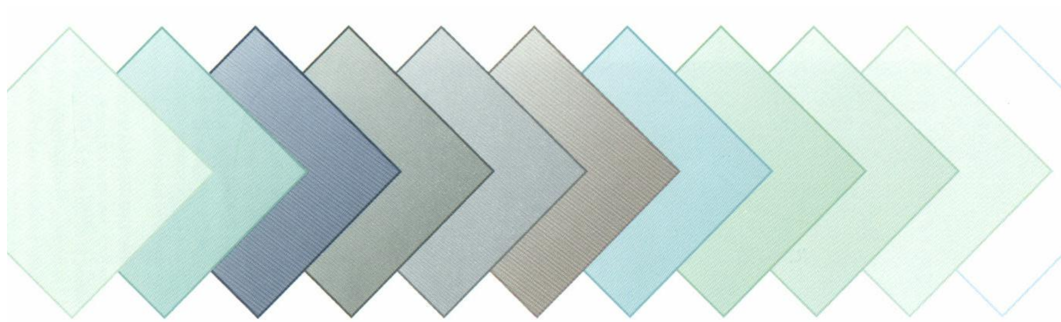
- Clear glass
  - Transmits 75% of incident solar radiation or more
    - Infrared (larger wavelength)
  - Transmits 85% of visible light
- Tinted glass
  - Available in many colors
  - Applied as coatings
  - Differ in solar radiation and visible light transmission
    - Typical range 40% to 80%
- Reflective glass
  - 5-40% VT



Tinted glass

- Glass with added chemical or metal particle additives
  - Iron oxides produce green tints
  - Selenium oxides produce bronze tints
  - Cobalt oxides produce blue tints

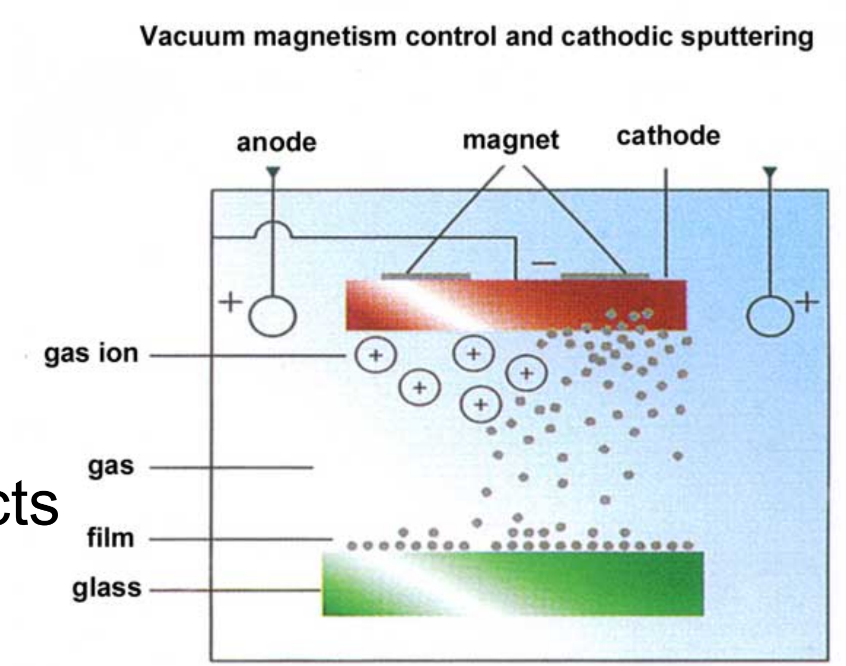




Tinted glass examples

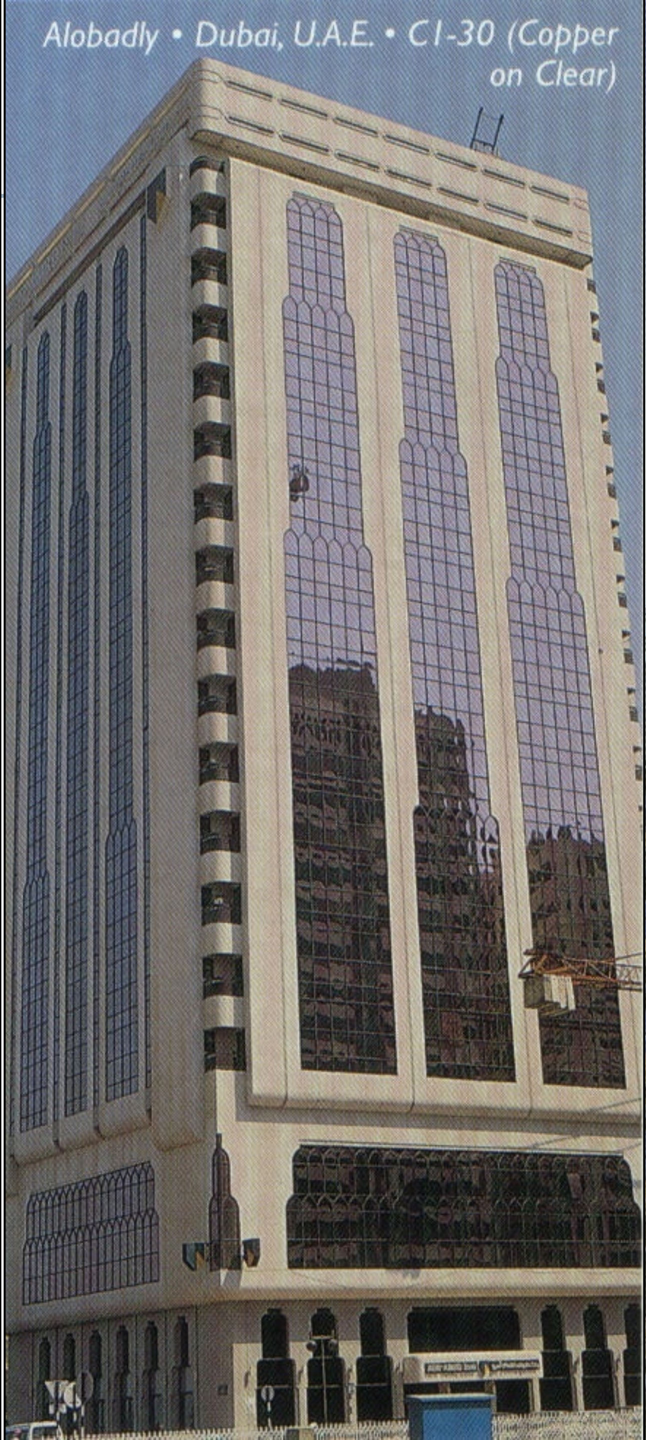
Reflective glass

- Glass with a film oxide coating applied to surface
  - Appears much like tinted glass
- Metal films allow for mirror effects as well as colors

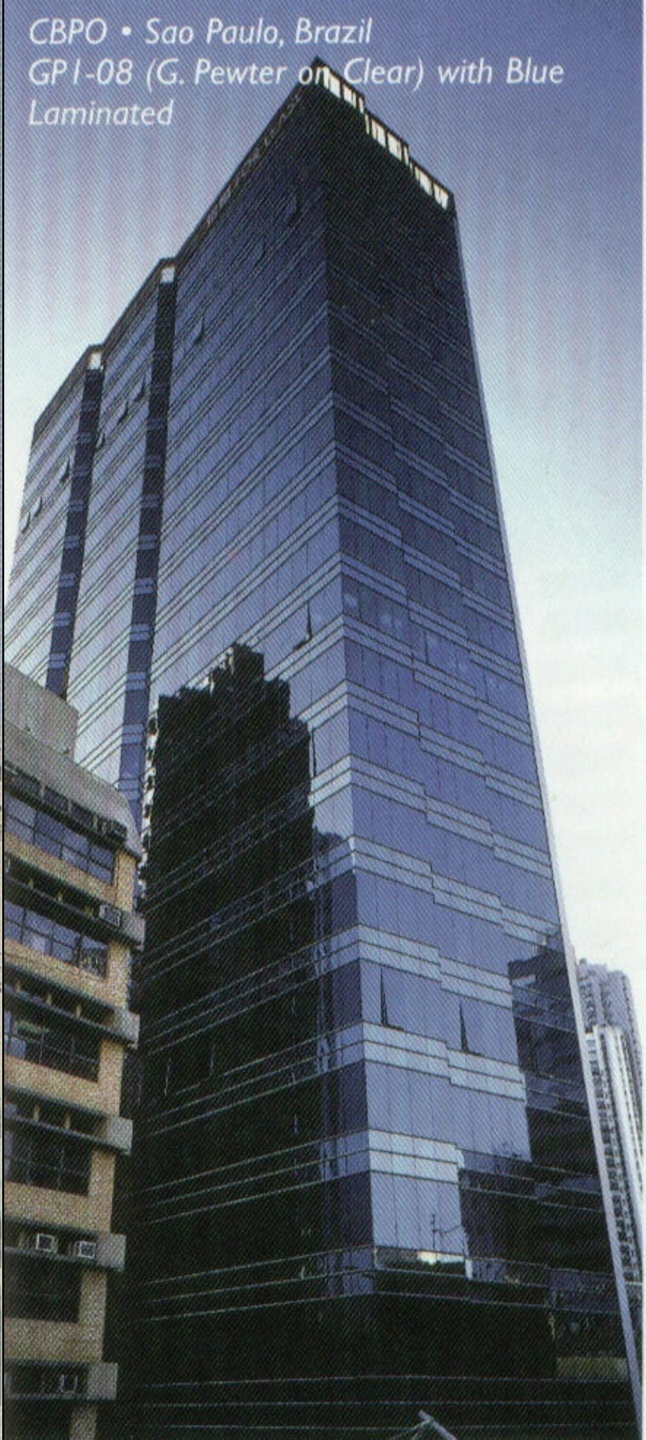


Reflective Glass

Guangdong
Hong Kong
S6-08 (Silver on Blue Green)



Alobadly • Dubai, U.A.E. • C1-30 (Copper on Clear)



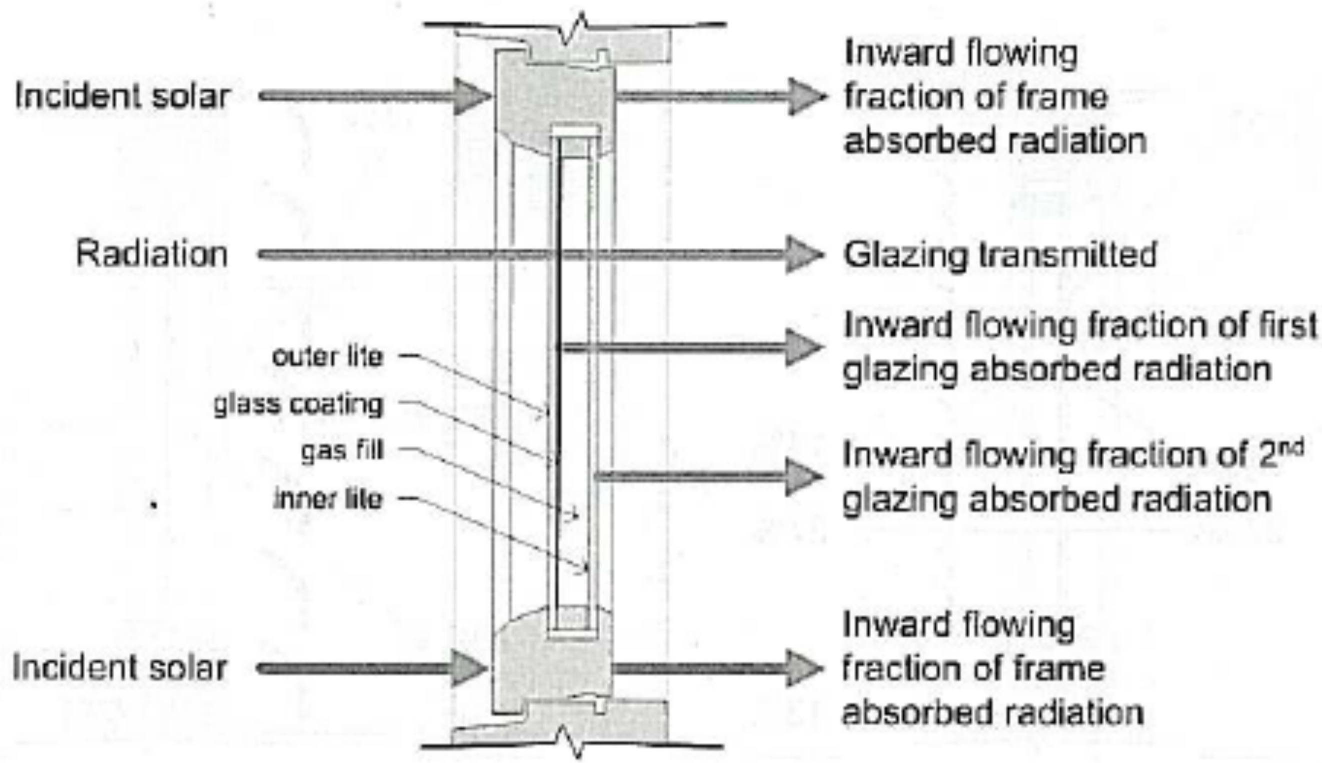
CBPO • Sao Paulo, Brazil
GP1-08 (G. Pewter on Clear) with Blue Laminated

Typical VT for different glazing types

Glazing	Visible T_v
Reflective blue-green	0.33
Film on clear glass	0.19
Green tinted, medium	0.75
Green low-e	0.71
Sun-control low-e + green	0.36
Super low-e + clear	0.71
Super low-e + green	0.60

Solar Heat Gain Coefficient (SHGC)

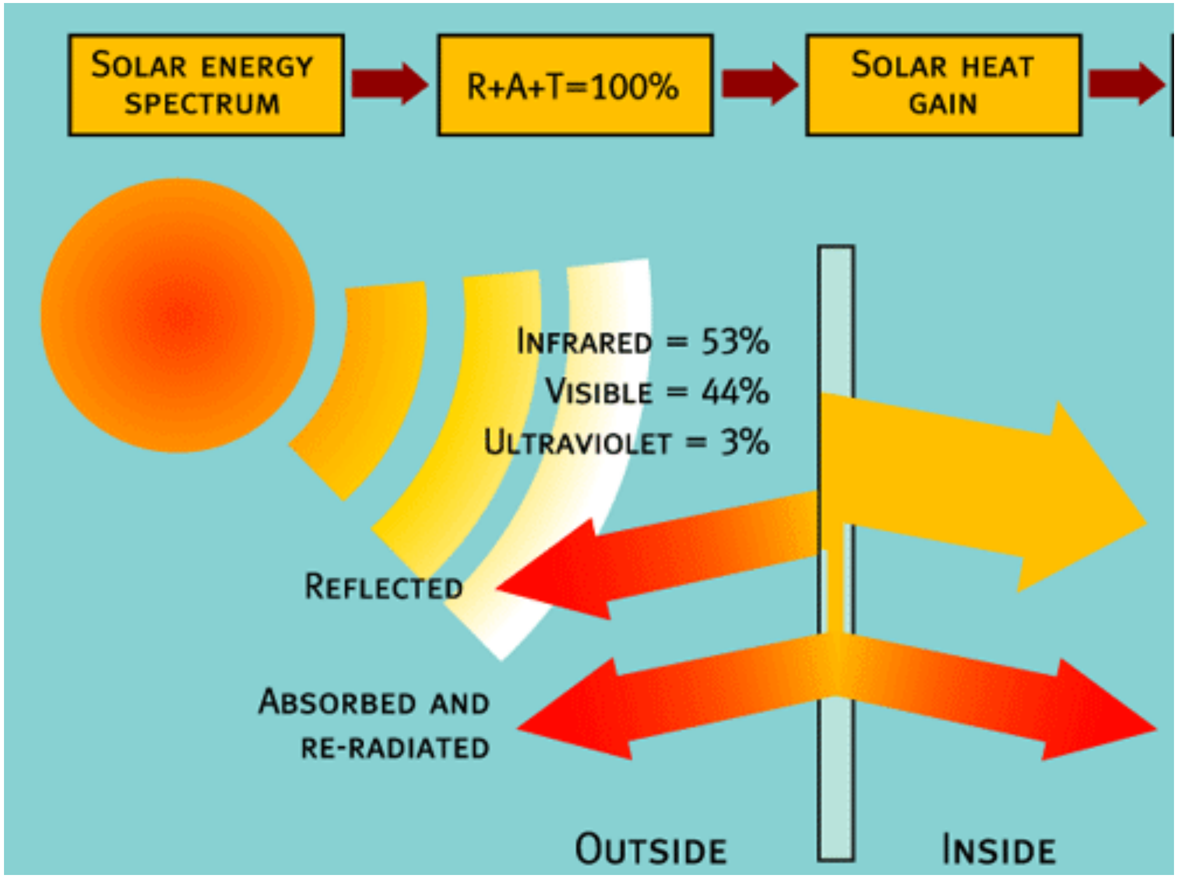
- The SHGC is the fraction of incident solar radiation that is transmitted through a window and becomes part of the heat gain for the interior



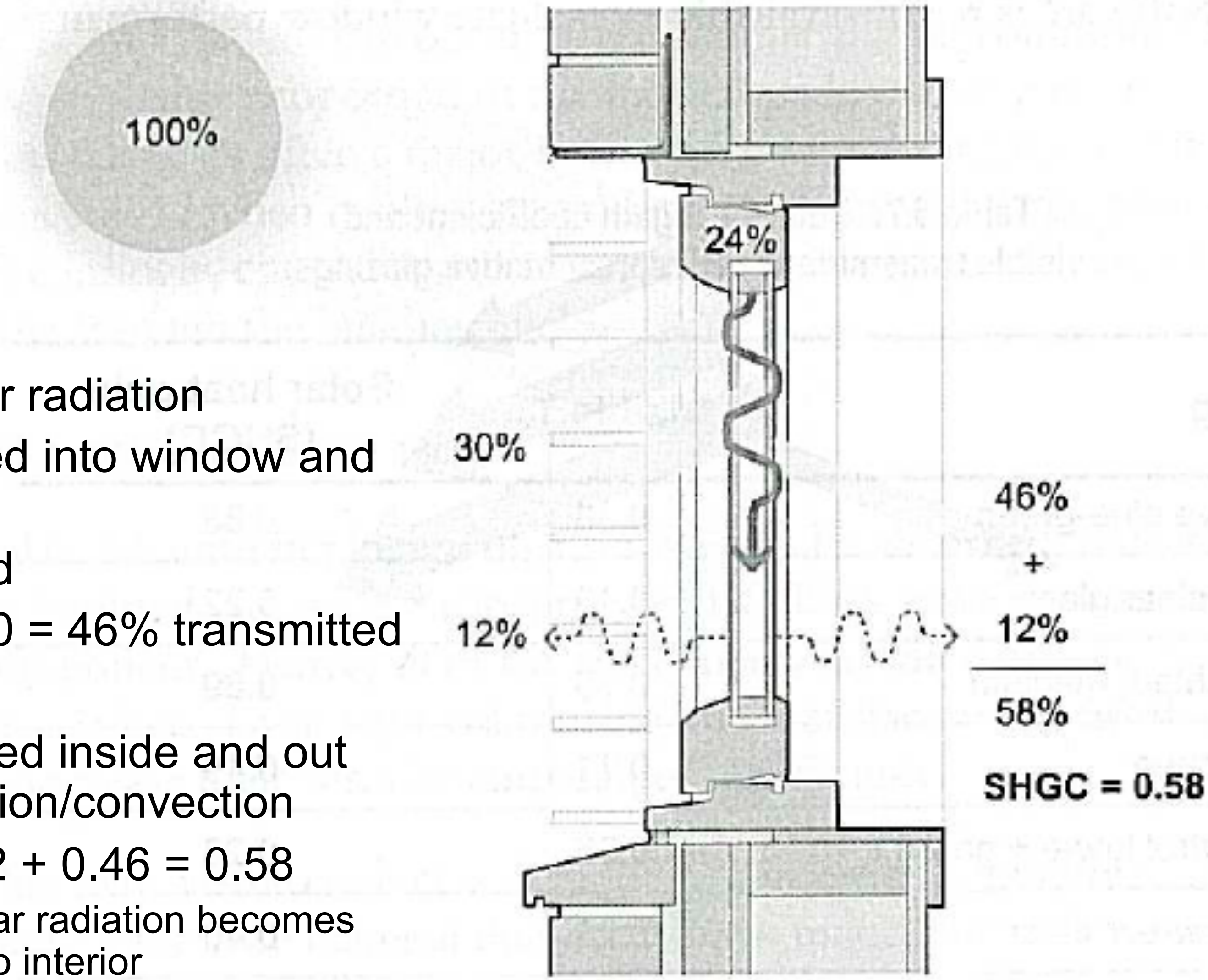
$$Q_{total} = U_{total}A_{proj}(T_{out} - T_{in}) + (SHGC)A_{proj}I_{total}$$

Solar Heat Gain Coefficient (SHGC)

- The SHGC is the fraction of incident solar radiation that is transmitted through a window and becomes part of the heat gain for the interior



Solar Heat Gain Coefficient (SHGC)



- In this case:
  - 100% of solar radiation
  - 24% absorbed into window and frame
  - 30% reflected
  - 100 – 24 – 30 = 46% transmitted
  - 12% reradiated inside and out after conduction/convection
  - SHGC = 0.12 + 0.46 = 0.58
    - 58% of solar radiation becomes heat gain to interior

Solar heat gain coefficient, SHGC

$$Q_{solar,window} = \left(I_{solar} A\right) SHGC$$

- For a single pane of glass:

$$SHGC = \tau + \alpha \frac{U}{h_{ext}} \qquad \frac{1}{U} = \frac{1}{h_{int}} + \frac{1}{R_{glass}} + \frac{1}{h_{ext}}$$

$^*R_{glass}$ is negligible

- For double glazing with a small air space:

$$SHGC = \tau + \alpha_{outer\ pane} \frac{U}{h_{ext}} + \alpha_{inner\ pane} U \left(\frac{1}{h_{ext}} + \frac{1}{h_{airspace}} \right)$$

$$\frac{1}{U} = \frac{1}{h_{int}} + \frac{1}{R_{outer\ pane}} + \frac{1}{h_{airspace}} + \frac{1}{R_{inner\ pane}} + \frac{1}{h_{ext}}$$

$^*R_{outer\ pane}$ and $R_{inner\ pane}$ are negligible

Solar Heat Gain Coefficient (SHGC)

- The SHGC is the fraction of incident solar radiation that is transmitted through a window and becomes part of the heat gain for the interior

  Bounds:

  $0 < SHGC < 1$

- In general, SHGC is a function of both radiation wavelength and solar incident angle
- If only a single number is given, it will be normal incidence and averaged over all wavelengths
  - ASHRAE has some very complicated calculations for directional and spectral variations
    - We are not going to cover these

SHGC and energy use

- SHGC is directly related to building heating from the sun

- If we are dominated by the need for heating energy
  - We want to make use of solar energy to help heat our space
  - We want a higher SHGC
  - We would then use shading to reduce SHGC in summer

- If we are dominated by the need for cooling energy
  - We want a low SHGC to reduce solar heating
  - Can still use shading to help even more in the summer

- Note importance of dominant loads
  - Will explore in more detail in a future lecture

Typical VT and SHGC for different glazing types

Table 5.7: Solar heat gain coefficient and visible transmittance of representative glazings

Glazing	Visible T_v	Solar heat gain (SHGC)
Reflective blue-green	0.33	0.38
Film on clear glass	0.19	0.22
Green tinted, medium	0.75	0.69
Green low-e	0.71	0.49
Sun-control low-e + green	0.36	0.23
Super low-e + clear	0.71	0.40
Super low-e + green	0.60	0.30

Tinted glass heat gain

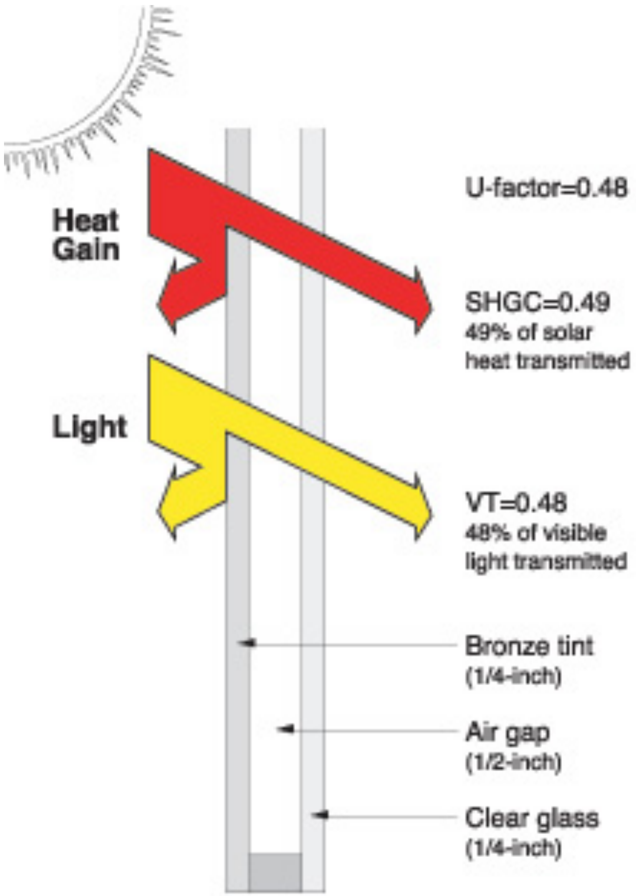


Figure 3-14. Double glazing with bronze-tinted glass on the outside layer

All values are for the glazing alone (center-of-glass).
Values for the total window will vary with frame type.
U-factor is in Btu/hr-sf-°F
SHGC=solar heat gain coefficient
VT=visible transmittance

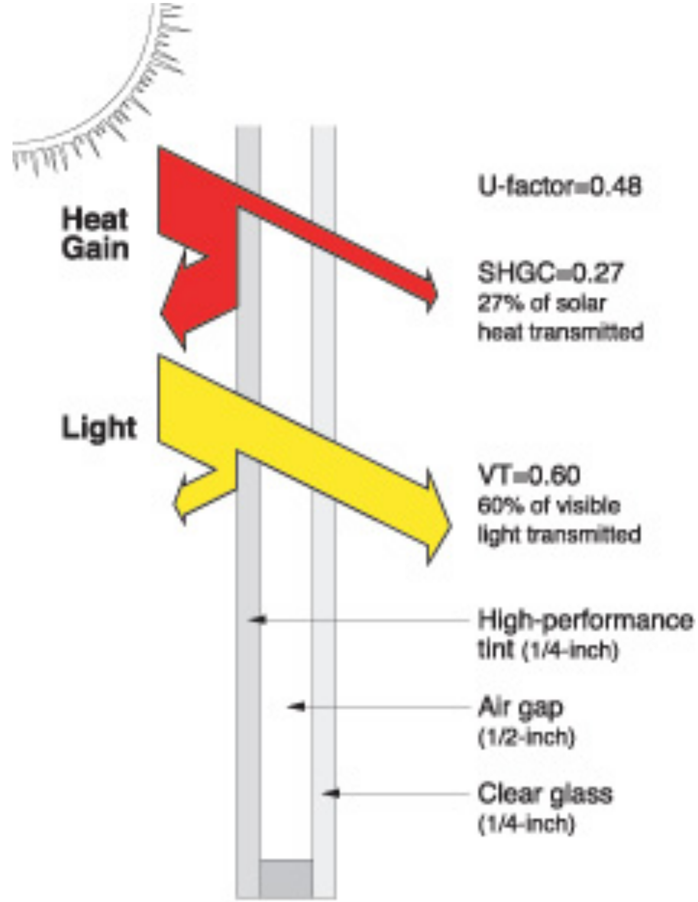


Figure 3-15. Double glazing with high-performance tint on the outside layer

All values are for the glazing alone (center-of-glass).
Values for the total window will vary with frame type.
U-factor is in Btu/hr-sf-°F
SHGC=solar heat gain coefficient
VT=visible transmittance

Low-emissivity (“low-e”) glass

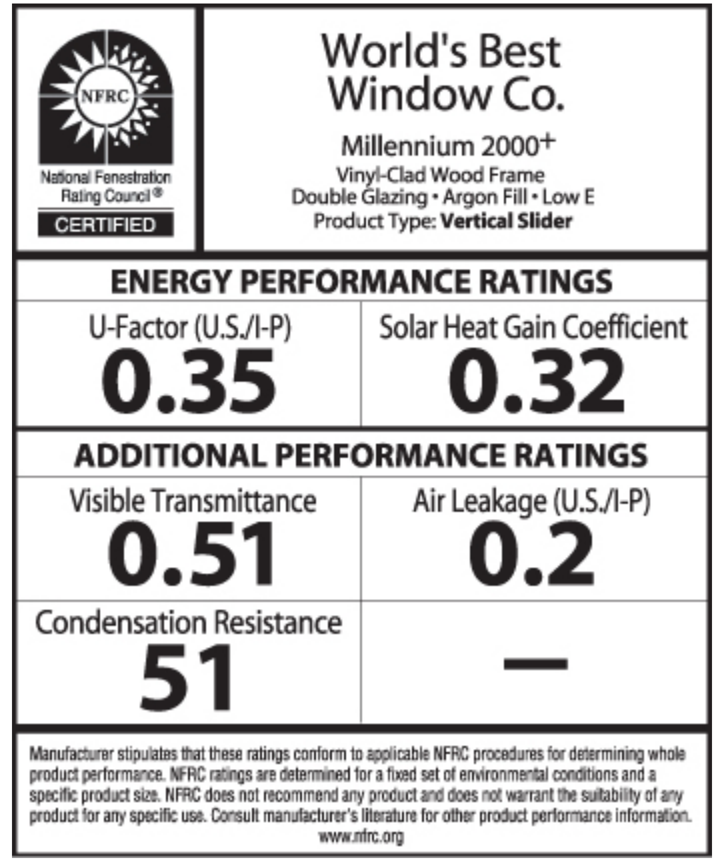
- Improves thermal performance
  - Ultra-thin, transparent, metallic coating
  - Generally placed on glazing surfaces inside air space
    - Never on the exterior; condensation can increase emissivity
  - Reflects long wavelength IR radiation
    - Transmits most short-wave (sunlight)
      - Keeps thermal heat inside in winter
      - Keeps thermal heat outside in summer
  - Long wavelength emittance < 0.4 is typical
    - Standard glass is ~0.8
  - Result:
    - Reduced SHGC and U value for double glaze windows with under 10% reduction in visible light transmission

Finding SHGC, U, VT, and air leakage

- One place to start getting SHGC info is from the manufacturer label
- The SHGC given on the NFRC label is the <u>normal incident</u> and total assembly SHGC

Manufacturer supplied SHGC

- Glazing manufacturers will measure and present SHGC for normal incidence according to the methods of NFRC 200
  - National Fenestration Rating Council has developed methods for rating and labeling SHGC, U factors, air leakage, visible transmittance and condensation resistance of fenestration products
- In reality, SHGC is a function of incidence angle (θ)



$$Q_{solar,window} = I_{direct} SHGC(\theta) A + (I_{diffuse+reflected}) SHGC_{diffuse+reflected} A$$

Finding VT and SHGC data

- If the manufacturer does not provide more detailed data, you can get prototypical data from ASHRAE HOF

Table 13 Visible Transmittance (T_v), Solar Heat Gain Coefficient (SHGC), Solar Transmittance (T), Front Reflectance (R^f), Back Reflectance (R^b), and Layer Absorptance ($\mathcal{A}_n^f$) for Glazing and Window Systems

	Glazing System				Center-of-Glazing Properties							Total Window SHGC at Normal Incidence				Total Window T_V at Normal Incidence			
					Incidence Angles							Aluminum		Other Frames		Aluminum		Other Frames	
ID	Glass Thick., mm		Center Glazing T_V		Normal 0.00	40.00	50.00	60.00	70.00	80.00	Hemis., Diffuse	Operable	Fixed	Operable	Fixed	Operable	Fixed	Operable	Fixed
Uncoated Single Glazing																			
1a	3	CLR	0.90	SHGC	0.86	0.84	0.82	0.78	0.67	0.42	0.78	0.75	0.78	0.64	0.75	0.77	0.80	0.66	0.78
				T	0.83	0.82	0.80	0.75	0.64	0.39	0.75								
				R^f	0.08	0.08	0.10	0.14	0.25	0.51	0.14								
				R^b	0.08	0.08	0.10	0.14	0.25	0.51	0.14								
				$\mathcal{A}_1^f$	0.09	0.10	0.10	0.11	0.11	0.11	0.10								
1b	6	CLR	0.88	SHGC	0.81	0.80	0.78	0.73	0.62	0.39	0.73	0.71	0.74	0.60	0.71	0.75	0.79	0.64	0.77
				T	0.88	0.87	0.85	0.80	0.69	0.43	0.80								
				R^f	0.08	0.09	0.11	0.15	0.27	0.53	0.14								
				R^b	0.08	0.09	0.11	0.15	0.27	0.53	0.14								
				$\mathcal{A}_1^f$	0.16	0.17	0.18	0.19	0.19	0.17	0.17								

VT and SHGC data from ASHRAE HOF

Table 13 Visible Transmittance (T_v), Solar Heat Gain Coefficient (SHGC), Solar Transmittance (T), Front Reflectance (R^f), Back Reflectance (R^b), and Layer Absorptance ($\mathcal{A}^f_n$) for Glazing and Window Systems

					Center-of-Glazing Properties							Total Window SHGC at Normal Incidence				Total Window T_V at Normal Incidence			
	Glazing System				Incidence Angles							Aluminum		Other Frames		Aluminum		Other Frames	
ID	Glass Thick., mm		Center Glazing T_V		Normal 0.00	40.00	50.00	60.00	70.00	80.00	Hemis., Diffuse	Operable	Fixed	Operable	Fixed	Operable	Fixed	Operable	Fixed
Uncoated Double Glazing																			
5a	3	CLR CLR	0.81	SHGC	0.76	0.74	0.71	0.64	0.50	0.26	0.66	0.67	0.69	0.56	0.66	0.69	0.72	0.59	0.70
				T	0.70	0.68	0.65	0.58	0.44	0.21	0.60								
				R^f	0.13	0.14	0.16	0.23	0.36	0.61	0.21								
				R^b	0.13	0.14	0.16	0.23	0.36	0.61	0.21								
				$\mathcal{A}^f_1$	0.10	0.11	0.11	0.12	0.13	0.13	0.11								
				$\mathcal{A}^f_2$	0.07	0.08	0.08	0.08	0.07	0.05	0.07								
5b	6	CLR CLR	0.78	SHGC	0.70	0.67	0.64	0.58	0.45	0.23	0.60	0.61	0.63	0.52	0.61	0.66	0.69	0.57	0.68
				T	0.61	0.58	0.55	0.48	0.36	0.17	0.51								
				R^f	0.11	0.12	0.15	0.20	0.33	0.57	0.18								
				R^b	0.11	0.12	0.15	0.20	0.33	0.57	0.18								
				$\mathcal{A}^f_1$	0.17	0.18	0.19	0.20	0.21	0.20	0.19								
				$\mathcal{A}^f_2$	0.11	0.12	0.12	0.12	0.10	0.07	0.11								
5c	3	BRZ CLR	0.62	SHGC	0.62	0.60	0.57	0.51	0.39	0.20	0.53	0.55	0.57	0.46	0.54	0.53	0.55	0.45	0.54
				T	0.55	0.51	0.48	0.42	0.31	0.14	0.45								
				R^f	0.09	0.10	0.12	0.16	0.27	0.49	0.15								
				R^b	0.12	0.13	0.15	0.21	0.35	0.59	0.19								
				$\mathcal{A}^f_1$	0.30	0.33	0.34	0.36	0.37	0.34	0.33								
				$\mathcal{A}^f_2$	0.06	0.06	0.06	0.06	0.05	0.03	0.06								
5d	6	BRZ CLR	0.47	SHGC	0.49	0.46	0.44	0.39	0.31	0.17	0.41	0.44	0.46	0.37	0.43	0.40	0.42	0.35	0.41
				T	0.38	0.35	0.32	0.27	0.20	0.08	0.30								
				R^f	0.07	0.08	0.09	0.13	0.22	0.44	0.12								
				R^b	0.10	0.11	0.13	0.19	0.31	0.55	0.17								
				$\mathcal{A}^f_1$	0.48	0.51	0.52	0.53	0.53	0.45	0.50								
				$\mathcal{A}^f_2$	0.07	0.07	0.07	0.07	0.06	0.04	0.07								

Using $SHGC_N$

- If we are not worried about great accuracy, we can use the total window $SHGC_N$ with the overall incident solar radiation to find instantaneous solar heat gain q_{solar}

$$q_{solar} = SHGC_N I_{total}$$

where

$SHGC_N$ = total window SHGC at normal incidence

$I_{total} = I_{DN} \cos\theta + I_d + I_R =$ total solar irradiance

SHGC Example

- A fixed fenestration system has aluminum frames supporting a double glazed clear window (with VT of 78%)
  - If the direct normal incident solar radiation is 700 W/m^2 at an angle of 60° and the diffuse + reflected incident radiation is 70 W/m^2, what is the instantaneous solar heat gain?

Finding VT and SHGC data

Table 13 Visible Transmittance (T_v), Solar Heat Gain Coefficient (SHGC), Solar Transmittance (T), Front Reflectance (R^f), Back Reflectance (R^b), and Layer Absorptance ($\mathcal{A}^f_n$) for Glazing and Window Systems

	Glazing System				Center-of-Glazing Properties							Total Window SHGC at Normal Incidence				Total Window T_V at Normal Incidence			
					Incidence Angles							Aluminum		Other Frames		Aluminum		Other Frames	
ID	Glass Thick., mm		Center Glazing T_V		Normal 0.00	40.00	50.00	60.00	70.00	80.00	Hemis., Diffuse	Operable	Fixed	Operable	Fixed	Operable	Fixed	Operable	Fixed
Uncoated Double Glazing																			
5a	3	CLR CLR	0.81	SHGC	0.76	0.74	0.71	0.64	0.50	0.26	0.66	0.67	0.69	0.56	0.66	0.69	0.72	0.59	0.70
				T	0.70	0.68	0.65	0.58	0.44	0.21	0.60								
				R^f	0.13	0.14	0.16	0.23	0.36	0.61	0.21								
				R^b	0.13	0.14	0.16	0.23	0.36	0.61	0.21								
				$\mathcal{A}^f_1$	0.10	0.11	0.11	0.12	0.13	0.13	0.11								
				$\mathcal{A}^f_2$	0.07	0.08	0.08	0.08	0.07	0.05	0.07								
5b	6	CLR CLR	0.78	SHGC	0.70	0.67	0.64	0.58	0.45	0.23	0.60	0.61	0.63	0.52	0.61	0.66	0.69	0.57	0.68
				T	0.61	0.58	0.55	0.48	0.36	0.17	0.51								
				R^f	0.11	0.12	0.15	0.20	0.33	0.57	0.18								
				R^b	0.11	0.12	0.15	0.20	0.33	0.57	0.18								
				$\mathcal{A}^f_1$	0.17	0.18	0.19	0.20	0.21	0.20	0.19								
				$\mathcal{A}^f_2$	0.11	0.12	0.12	0.12	0.10	0.07	0.11								
5c	3	BRZ CLR	0.62	SHGC	0.62	0.60	0.57	0.51	0.39	0.20	0.53	0.55	0.57	0.46	0.54	0.53	0.55	0.45	0.54
				T	0.55	0.51	0.48	0.42	0.31	0.14	0.45								
				R^f	0.09	0.10	0.12	0.16	0.27	0.49	0.15								
				R^b	0.12	0.13	0.15	0.21	0.35	0.59	0.19								
				$\mathcal{A}^f_1$	0.30	0.33	0.34	0.36	0.37	0.34	0.33								
				$\mathcal{A}^f_2$	0.06	0.06	0.06	0.06	0.05	0.03	0.06								
5d	6	BRZ CLR	0.47	SHGC	0.49	0.46	0.44	0.39	0.31	0.17	0.41	0.44	0.46	0.37	0.43	0.40	0.42	0.35	0.41
				T	0.38	0.35	0.32	0.27	0.20	0.08	0.30								
				R^f	0.07	0.08	0.09	0.13	0.22	0.44	0.12								
				R^b	0.10	0.11	0.13	0.19	0.31	0.55	0.17								
				$\mathcal{A}^f_1$	0.48	0.51	0.52	0.53	0.53	0.45	0.50								
				$\mathcal{A}^f_2$	0.07	0.07	0.07	0.07	0.06	0.04	0.07								

SHGC example

- A fixed fenestration system has aluminum frames supporting a double glazed clear window (with VT of 78%)
  - If the direct normal incident solar radiation is 700 W/m^2 at an angle of 60° and the diffuse + reflected incident radiation is 70 W/m^2, what is the instantaneous solar heat gain?
  - $SHGC_N = 0.63$

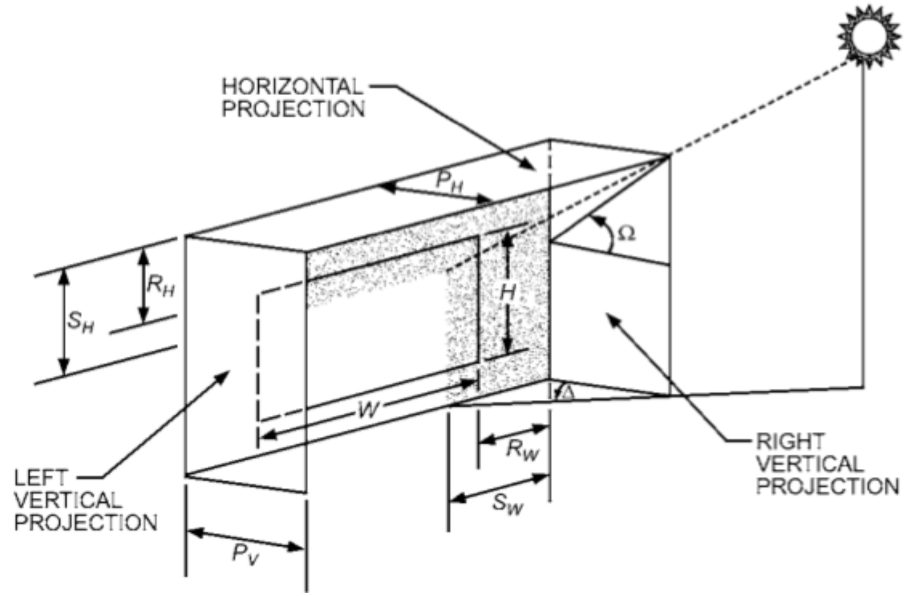
$$I_t = I_{DN} \cos\theta + I_d + I_R$$

$$I_t = 700 \cos 60° + 70 = 350 + 70 = 420 \ \frac{\text{W}}{\text{m}^2}$$

$$q_s = SHGC_N \cdot I_t = 0.63 \cdot 420 = 265 \ \frac{\text{W}}{\text{m}^2}$$

What about shading?

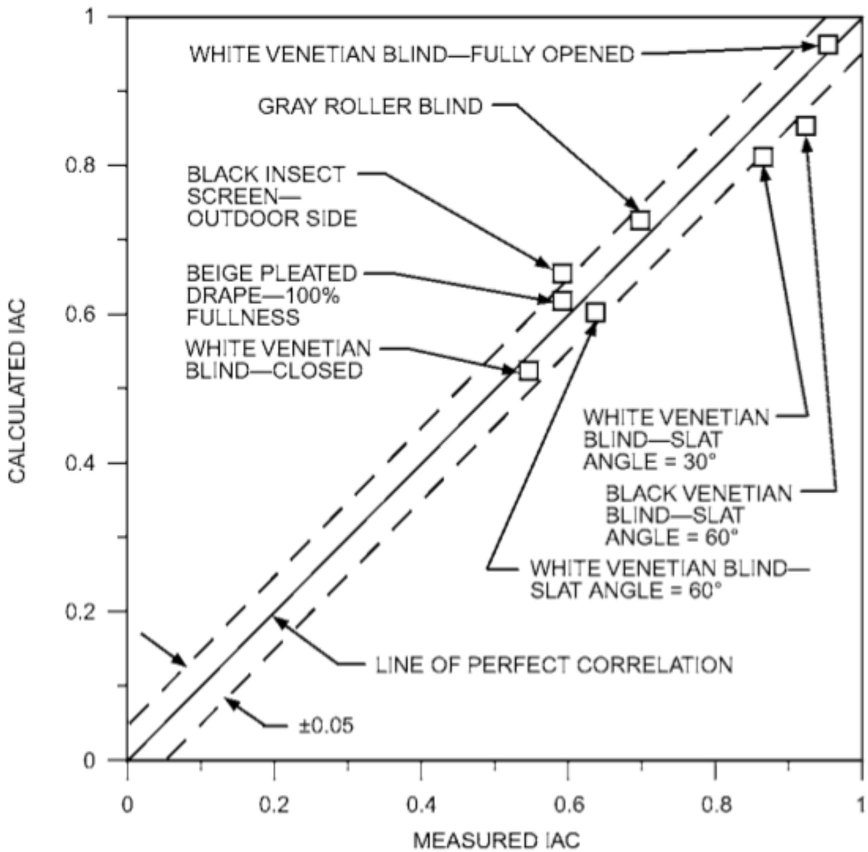
- Shading devices, including drapes and blinds, can mitigate some solar heat gain
- We can attempt to describe this with an **indoor solar attenuation coefficient (IAC)**
- Heat gain through a window can be modified as follows:

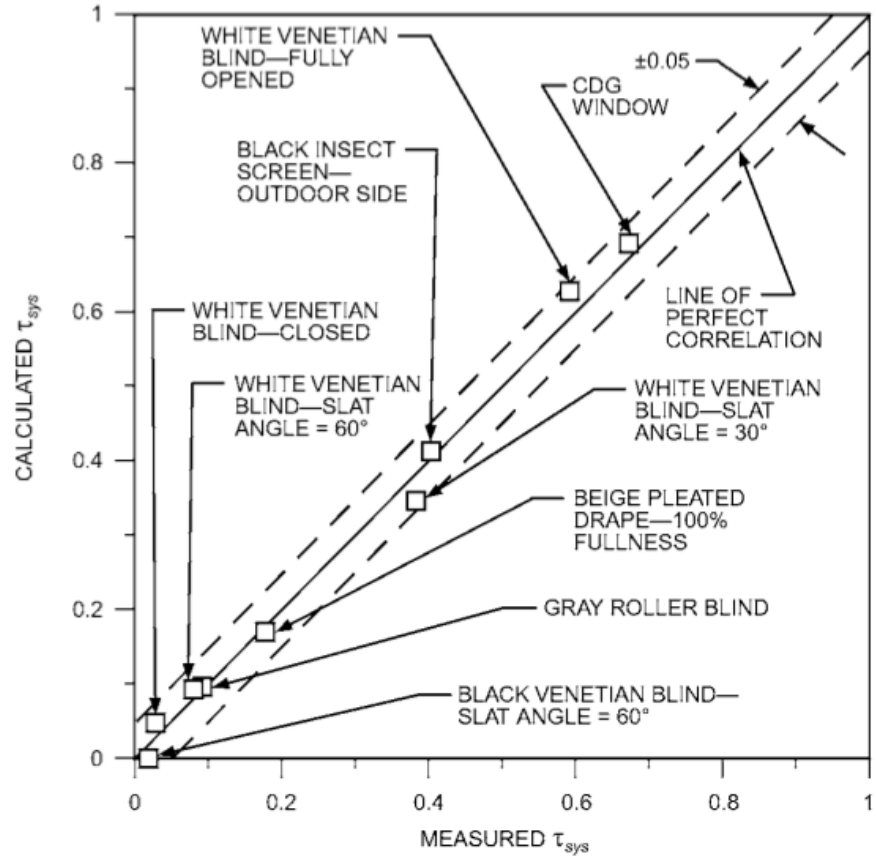


$$Q_{window} = UA_{pf}\left(T_{out} - T_{in}\right) + I_{direct}A_{pf}SHGC(\theta)IAC(\theta,\Omega) + (I_{diffuse+reflected})A_{pf}SHGC_{diffuse+reflected}IAC_{diffuse+reflected}$$

IAC is a function of incidence angle, θ, and the angle created by a shading device

Blinds and drapes: ASHRAE Handbook





GLAZING: DESIGN CONSIDERATIONS

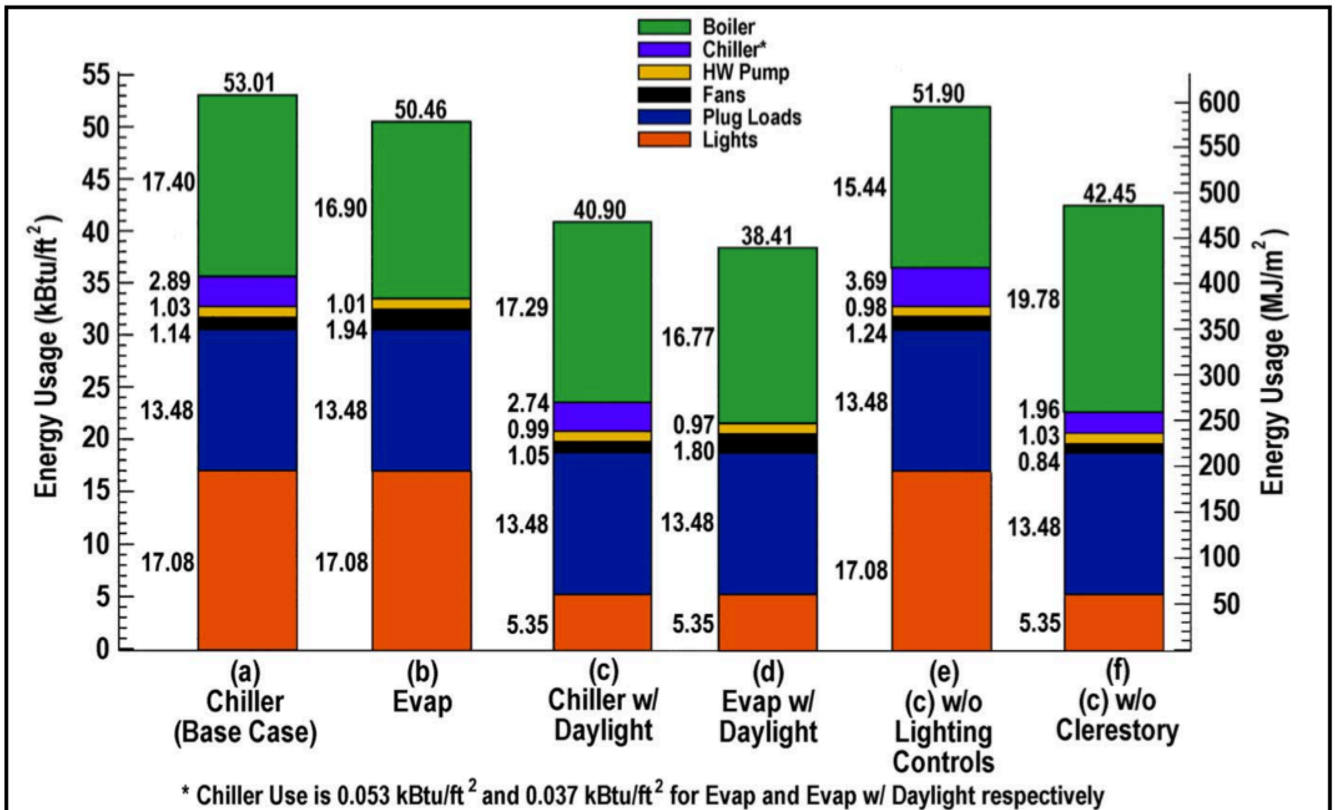
Why/why not design with glass?

- Benefits of using glass
  - Allows entry of high quality natural light
    - Proper use of daylight can reduce lighting energy costs
  - Entry of sunlight provides warmth
    - Passive solar heating can reduce heating costs
  - Provide views of exterior environment
    - Reduces stress of occupants and may increase productivity

- Disadvantages and design considerations
  - Limits occupant's privacy
  - Lower resistance to thermal transmission
  - Entry of sunlight adds to cooling load
  - High initial costs and ongoing maintenance costs
  - High embedded energy (from manufacturing)

Energy impacts of glazing

- Although windows are typically a thermal weakness on the envelope, they can also be used to save lighting energy
  - Particular advanced windows (e.g. R-5 IP or higher)
- Example project: Daylighting in Colorado



McHugh et al. 1998 *ASHRAE Journal*

Methods of achieving daylighting efficiently

- Skylights
- Light pipes and fiber optic daylighting systems
- Light shelves

- Need to be used with dimming ballasts or other advanced lighting controls

Skylights

- Typically limited to low-rise structures

Solar tubes


Daylighting Technology
ENERGY STAR
Capture
Raybender® 3000 Technology
A patented daylight-capturing dome lens that:
• Redirects low-angle sunlight for maximum light capture
• Rejects overpowering midday summer sunlight
• Provides consistent daylighting throughout the day
LightTracker™ Reflector
An innovative in-dome reflector that:
• Redirects low-angle winter sunlight for maximum light capture
• Increases light input for greater light output
• Delivers unsurpassed year-round performance
Transfer
Spectralight® Infinity Tubing
Tubing made of the world's most reflective material that:
• Delivers 99.7% * specular reflectivity for maximum sunlight transfer
• Provides the purest color rendition possible so colors are truer, brighter
• Allows for run lengths over 30 feet to deliver sunlight to lower floors
Deliver
Stylish Daylight Delivery
Form and function combine for optimal daylight diffusion with:
• Solatube Decorative Fixtures
• Warming and Softening Effect Lenses
• Ventilation, dimmer and nighttime lighting options
* Specular reflectance greater than 99% with wavelength specific reflectance up to 99.7% for the visible spectrum.

Light shelves

Can highly glazed building facades be 'green'?

- What do you see?
  - Energy hog?
  - Energy efficiency?

Can highly glazed building facades be ‘green’?

- In the past, windows did little to control heat loss and solar gain
  - Many older buildings had restricted window-to-wall areas

- Tremendous gains in glazing performance have been made in recent years
  - Are the gains good enough to warrant large amounts of glazing?
    - Floor-to-ceiling?
  - Biggest arguments *for* high-glazing
    - Increased daylighting
    - Occupant satisfaction
    - Aesthetics

Straube, 2008. *Building Science Insights* 006

Can highly glazed building facades be 'green'?

- Let's pick U values from our tables
  - Poor performing single-glazed window
    - U ~5 W/(m^{2}K) installed
    - R ~0.2 (m^{2}K)/W → R-1 (IP)
  - High performing triple glazed low-e argon window
    - U ~1 W/(m^{2}K) installed
    - R ~1 (m^{2}K)/W → R-5 (IP)
  - 1 inch (2.5 cm) of rigid insulation
    - R ~1 (m^{2}K)/W → R-5 (IP)
  - The best performing windows have worse thermal performance than the simplest lowest-cost wall with rigid insulation

Straube, 2008. *Building Science Insights* 006

Can highly glazed building facades be ‘green’?

- On a cold winter day, offices exposed to sun require cooling
  - Those in the shade still need heat
  - Many will be uncomfortable

- Poor thermal performance of highly glazed facades
  - The solar heat gain resulting from large amounts of glazing often drives the size of a building’s air-conditioning plant
  - Low-e coatings and other materials that let in visible light but block infrared heat radiation are miraculous
    - But we squander their potential by increasing window areas

Straube, 2008. *Building Science Insights* 006

Can highly glazed building facades be 'green'?

- One argument: daylighting
  - Glazing let's light in
- Daylighting can certainly offset the need for electric lighting
  - Also improve psychological attitude about a space
- But you don't need floor-to-ceiling windows to achieve adequate daylighting
  - Very little benefit to vision glass installed at the floor
    - Unless you spend a lot of time lying on the floor
  - Typically no daylighting or energy benefits with window-to-wall ratios over 60%
    - 25-40% is usually optimum for achieving daylighting + energy conservation
    - Glazing should still be high performance

Straube, 2008. *Building Science Insights* 006

Can highly glazed building facades be 'green'?

- So which one of these do you choose?

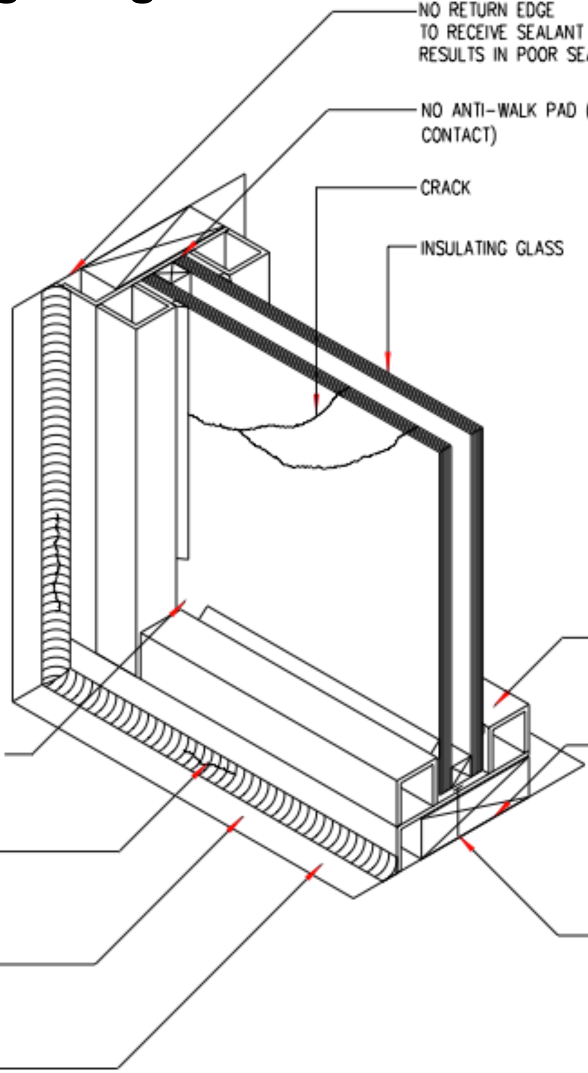
Straube, 2008. *Building Science Insights* 006

Thermal design with glass

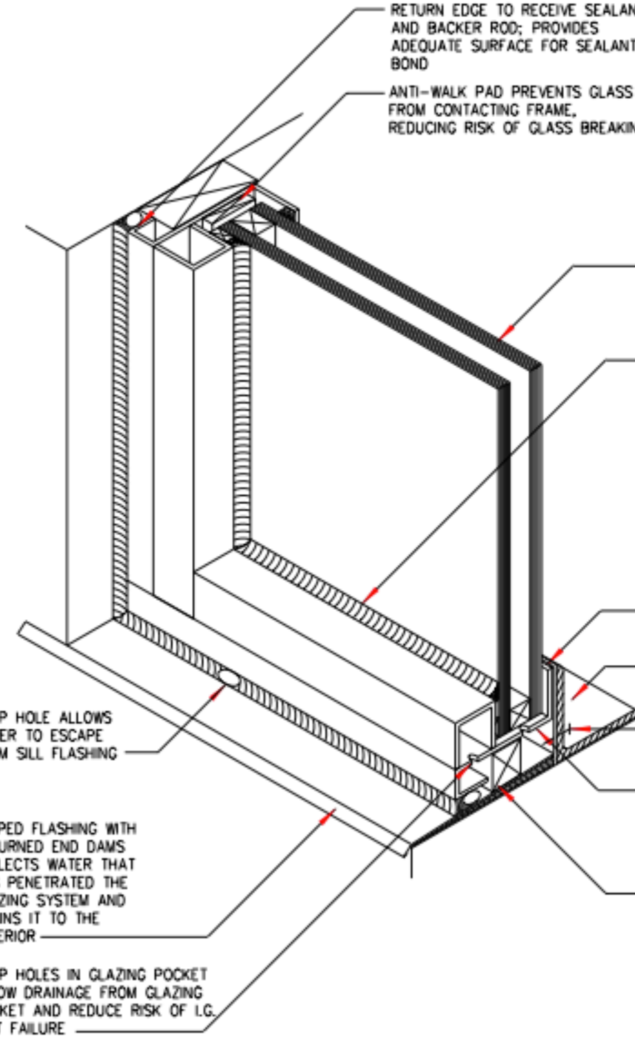
- There are many methods used to compensate for its poor thermal properties
  - Insulated windows with double & triple glazing
  - Low E coatings
  - Low conductivity gas fills
  - Tinting
  - Reflective coatings
  - Curtains and shutters
  - Window sizing & orientation on the building
  - Shading or overhangs

Design details for glazing

Poor glazing detail



Better glazing detail



http://www.wbdg.org/pdfs/edg/fen_2003_3446_312.pdf

Curtain walls

- Curtain walls are thin, usually aluminum-framed, walls containing in-fills of glass, metal panels, or thin stone
  - The framing is attached to the building structure and does not carry the floor or roof loads of the building
  - The wind and gravity loads are transferred to the building structure, typically at the floor line

- Stick systems
  - The frame (mullions) and glass/panels are installed and connected piece by piece
- Unitized (modular) systems
  - The wall is composed of large units that are assembled and glazed in the factory and shipped to the site

- Same general rules as windows apply for thermal and moisture performance

Curtain walls

- Walls of Glass, PBS NOVA
  - http://www.pbs.org/wgbh/nova/tech/walls-glass.html
- One World Trade curtain wall install
  - https://www.youtube.com/watch?v=PtNyBoyLdSc#t=69

New technologies are pushing the boundaries on thermal performance

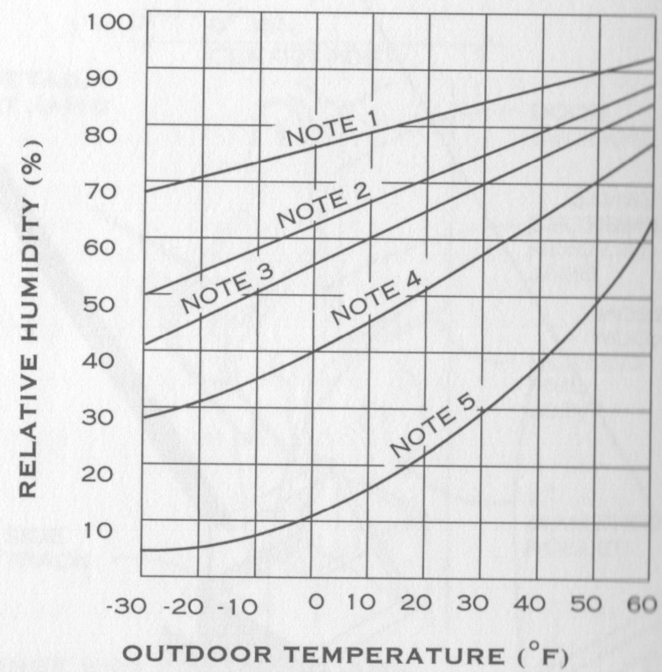
- Building Integrated Photovoltaic (BIPV)
  - Photovoltaic (PV) cells provide shading and generate electricity
  - Will have a project on BIPV

- Vacuum insulated windows
  - Removing air eliminates conduction and convection
    - Effective but expensive to manufacturer

- Aerogel
  - Transparent silica gel with a very low density
  - Very high insulating properties
  - Very good sound absorption properties

Importance of heat transfer for condensation

- Heat transfer through fenestration is not only important for energy performance
  - Also for moisture performance
  - At low outdoor temperatures
    - Condensation will occur on the cold indoor surfaces of poorly insulated windows
    - Even at low indoor humidities



NOTES

1. Triple-glazed windows with two low-E coatings and argon gas fill.
2. Double-glazed windows with a low-E coating and argon gas fill.
3. Double-glazed windows with a low-E coating.
4. Double-glazed windows.
5. Single-glazed windows.

CONDITIONS THAT LEAD TO CONDENSATION ON WINDOWS

Importance of fenestration for practical concerns

- Selection of window frame materials
  - Design for energy, maintenance, and moisture concerns

WINDOW FRAME DETAILS

WINDOW FRAME TYPES

FRAME TYPE	CHARACTERISTICS	MAINTENANCE	FINISHES	HEAT TRANSFERENCE	SUSTAINABILITY	NOTES
Wood	Solid members; ease of milling into complex shapes; attractive and traditional appearance U-factor: 0.3–0.5	Rot prevention: refinish in 5 to 10-year cycle or permanent finish	Oil or latex paint, stains, oils, or varnishes; preservatives; polyurethane resin coatings; prefinished or site finished	Low	Renewable resource; requires high-quality solid stock	Traditional and typical material; variety of species available; easy repair
Wood with cladding	Metal- or plastic-clad wood U-factor for vinyl clad: 0.3–0.5; for metal clad: 0.4–0.6	Minimal	See metal and plastic frames	Low with vinyl cladding, slightly higher with metal	Use of less desirable wood materials; salvageable cladding	Wood for stability/ strength, cladding for maintenance
Hybrids	Wood interior, metal or plastic exterior U-factor for vinyl/wood: 0.3–0.5; for metal/wood: 0.4–0.6	See wood, metal, and plastic categories	See other categories	Low with vinyl/wood hybrid, slightly higher with metal/wood hybrid	Use of lower quantities of any one material	Good interior look with good exterior performance and low maintenance
Steel	Thin bar/ angle steel profiles; cast, extruded, forged U-factor: similar to that of aluminum	Rust prevention: refinish in 5 to 10-year cycle or permanent finish	Galvanizing, zinc-phosphate coatings; primed; painted; factory finishes: baked enamel, fluoropolymer, polyurethane coatings	High, unless thermal break is installed	Non-renewable, salvageable	High strength/smallest frame profiles of all types; stainless steel available but expensive
Aluminum	Box profiles; extrusions; lightweight U-factor: 1.0 (with thermal break), 1.9–2.2 (without thermal break)	Minimal	Natural; factory-applied: baked enamel, epoxy, anodized, electrostatic (powder), fluoropolymer coatings	High unless thermal break is installed	Non-renewable, salvageable	High strength, no maintenance
Vinyl (PVC)	High impact resistance; box profiles; multi-chambered extrusions U-factor for hollow: 0.3–0.5; for insulated: 0.2–0.4	Minimal	Integral when fabricated (limited colors)	Low	Non-renewable, petroleum-based	UV/sun protection from discoloration may be required; salt air and acid resistant
Fiberglass	Box profiles, polymer-based thermoplastic; dimensionally stable U-factor for hollow: 0.3–0.5; for insulated: 0.2–0.4	Minimal	Integral when fabricated	Low	Spun glass in resin binders	More expensive but more structurally stable than vinyl

John Carmody, University of Minnesota; Minneapolis, Minnesota
Stephen Selkowitz, Lawrence Berkeley National Laboratory; Berkeley, California

Next week

- Turn in your take-home exams
- Energy simulation in enclosure design