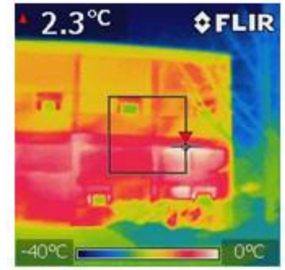
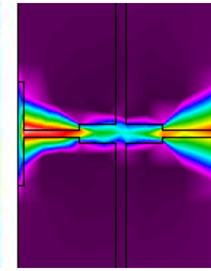
CAE 331/513
Building Science
Fall 2019





September 12, 2019
Fenestration (doors and windows)

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Last time and this time

- Combined mode heat transfer and energy balances
  - Multiple modes of heat transfer in parallel to calculate combined R-values and U-values
  - Energy balances and solving for unknown parameters

- HW #2 is due now

Simplifying radiation (correction)

- We can also define a <u>radiation heat transfer coefficient</u> that is analogous to other heat transfer coefficients

$$Q_{rad,1\rightarrow 2} = \boxed{h_{rad}} A_1\left(T_1 - T_2\right) = \frac{1}{R_{rad}} A_1\left(T_1 - T_2\right)$$

- When $A_1 = A_2$, and T_1 and T_2 are within ~50°F of each other, we can approximate h_{rad} with a simpler equation:

$$\cancel{h_{rad} = \frac{4\sigma T_{avg}^3}{\frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 1}}$$

where

$$T_{avg} = \frac{T_1 + T_2}{2}$$

Simplifying radiation (correction)

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$$Q_{rad,1\rightarrow 2} = \boxed{h_{rad}} A_1\left(T_1 - T_2\right) = \frac{1}{R_{rad}} A_1\left(T_1 - T_2\right)$$

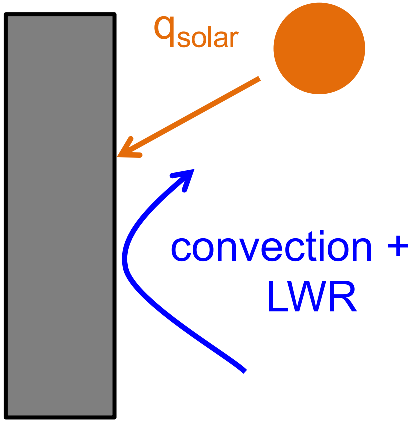
- When $A_1 = A_2$, and T_1 and T_2 are within ~50°F of each other, we can approximate h_{rad} with a simpler equation:

$$\boxed{h_{rad} = \frac{4\sigma T_{avg}^3}{\frac{1-\varepsilon_1}{\varepsilon_1} + \frac{A_1}{A_2}\frac{1-\varepsilon_2}{\varepsilon_2} + \frac{1}{F_{1-2}}}}$$

where

$$T_{avg} = \frac{T_1 + T_2}{2}$$

Correction!



SURFACE ENERGY BALANCES

Surface energy balances

- We know that multiple modes of heat transfer are typically acting at the same time at multiple points point within a building…

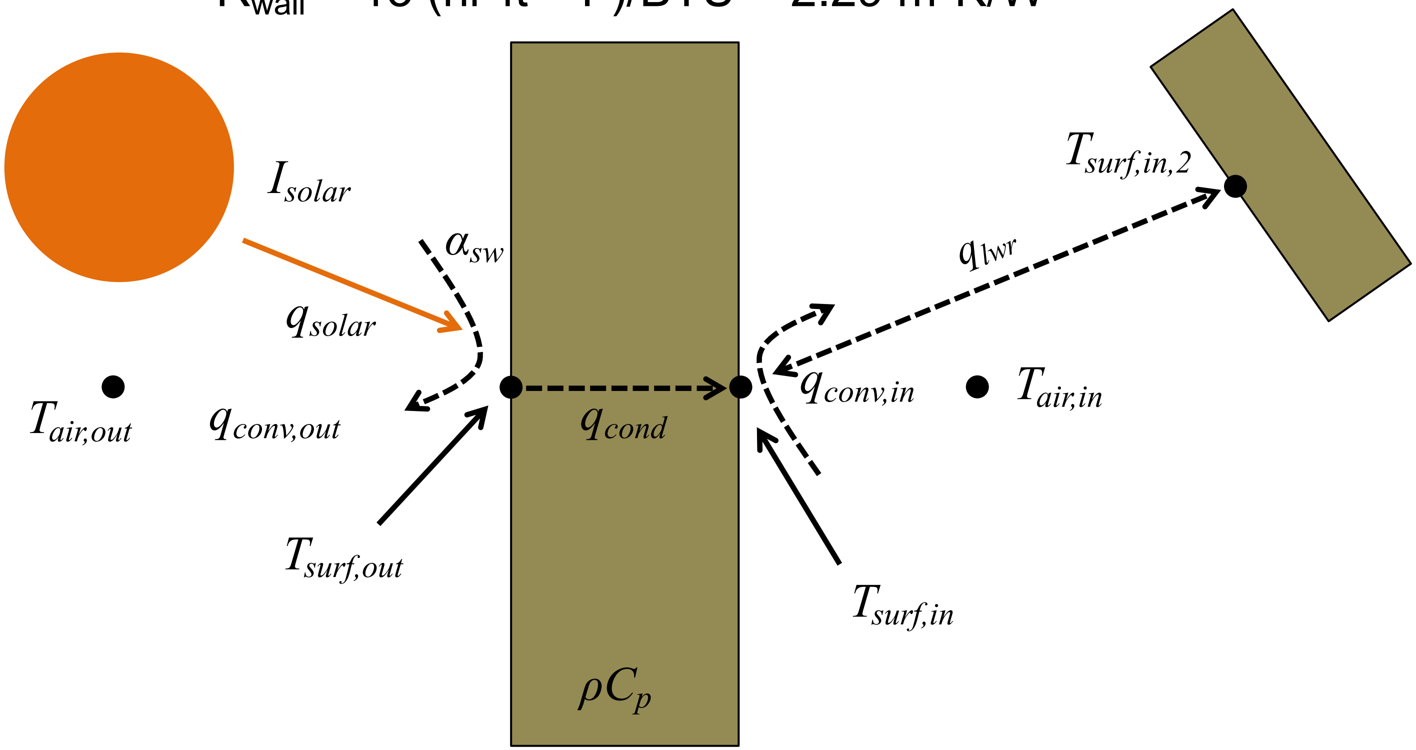
  … So we can also write expressions to quantify heat flow/ flux to/from these various points simultaneously by accounting for all relevant modes of heat transfer

  – Writing “building energy balances”
  – Solving systems of equations

Surface energy balances: Simplified

Imagine an external wall of a building:

R_{wall} = 13 (hr-ft^2-°F)/BTU = 2.29 m^{2}K/W



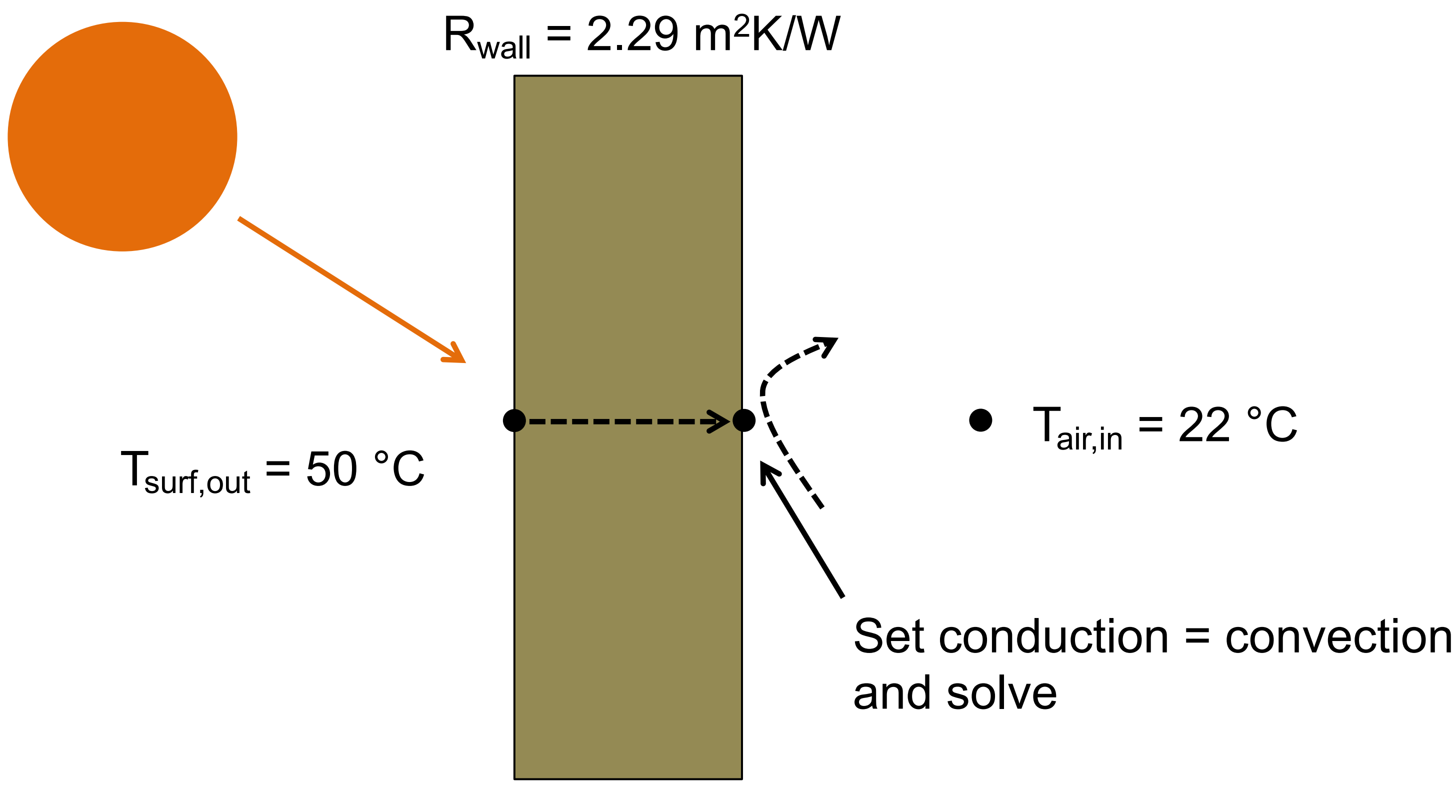
How is this helpful to us?

- Imagine the classroom wall behind me is being heated by the sun on the other side
- The exterior surface temperature is 122°F (50°C)
- The interior air temperature is 72°F (22°C)
- The R-value of the wall is R-13 (IP) (2.29 m^2K/W)
- What is the <u>interior surface temperature</u> of the wall?

- This interior surface temperature impacts the heat flux to indoor air, as well as the surrounding surface temperatures (via radiation), which all impact the building's <u>energy balance</u>

Surface energy balance example

- Estimate the surface temperature of an interior wall whose exterior side is being warmed by the sun
  - Assume that LWR can be ignored and assume steady-state



Typical convective "film resistances"

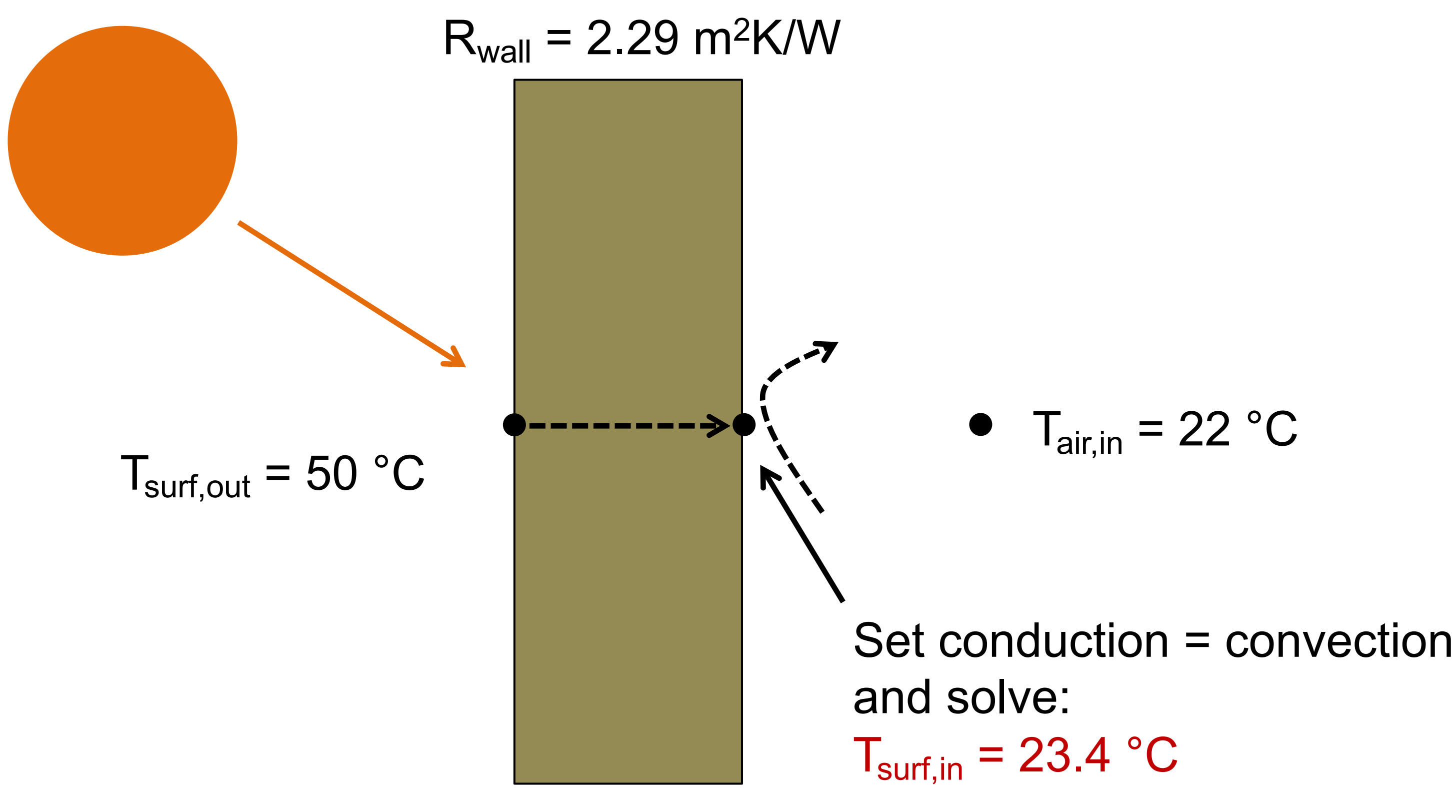
- We often use the values given below for most conditions
  - Especially when we lack other information

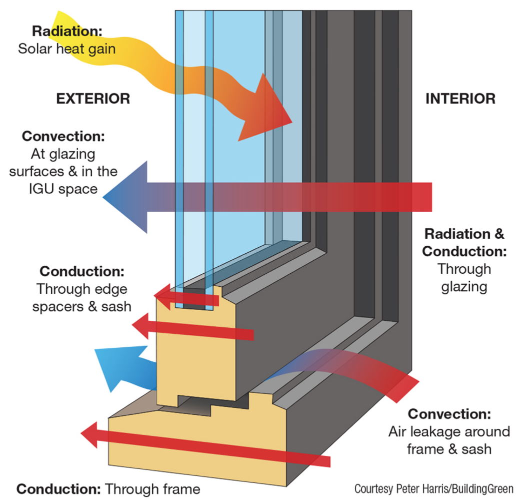
Surface Conditions	Horizontal Heat Flow	Upwards Heat Flow	Downwards Heat Flow
Indoors: R_{in}	0.12 m^2K/W (SI) 0.68 $h \cdot ft^2 \cdot {}^\circ F/Btu$ (IP)	0.11 m^2K/W (SI) 0.62 $h \cdot ft^2 \cdot {}^\circ F/Btu$ (IP)	0.16 m^2K/W (SI) 0.91 $h \cdot ft^2 \cdot {}^\circ F/Btu$ (IP)
R_{out}: 6.7 m/s wind (Winter)		0.030 m^2K/W (SI) 0.17 $h \cdot ft^2 \cdot {}^\circ F/Btu$ (IP)	
R_{out}: 3.4 m/s wind (Summer)		0.044 m^2K/W (SI) 0.25 $h \cdot ft^2 \cdot {}^\circ F/Btu$ (IP)	

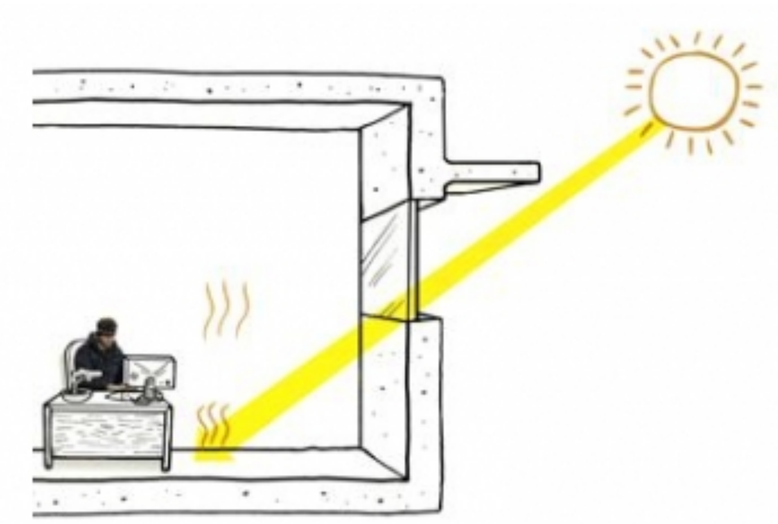
We can still sum resistances in series, even if it involves different modes of heat transfer

Surface energy balance example

- Estimate the surface temperature of an interior wall whose exterior side is being warmed by the sun
  - Assume that LWR can be ignored and assume steady-state







HEAT TRANSFER THROUGH <u>FENESTRATION</u>

Definition: Fenestration

- **“Fenestration”**
  - Technically: Areas of the building 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 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 (for better or worse)

Fenestration and energy use

- Fenestration impacts building energy use by:
  - Heat transfer
    - Conduction, convection, long-wave radiation, and short-wave radiation
    - Example: we should utilize solar heat gain in cold climates and restrict it in warm climates
    - We should also use appropriate materials/assemblies to minimize heat transfer
  - Air leakage
    - Penetrations in walls and roofs for fenestration can be problematic for creating pathways for air leaks (advection)
  - 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

Fenestration and total heat gain

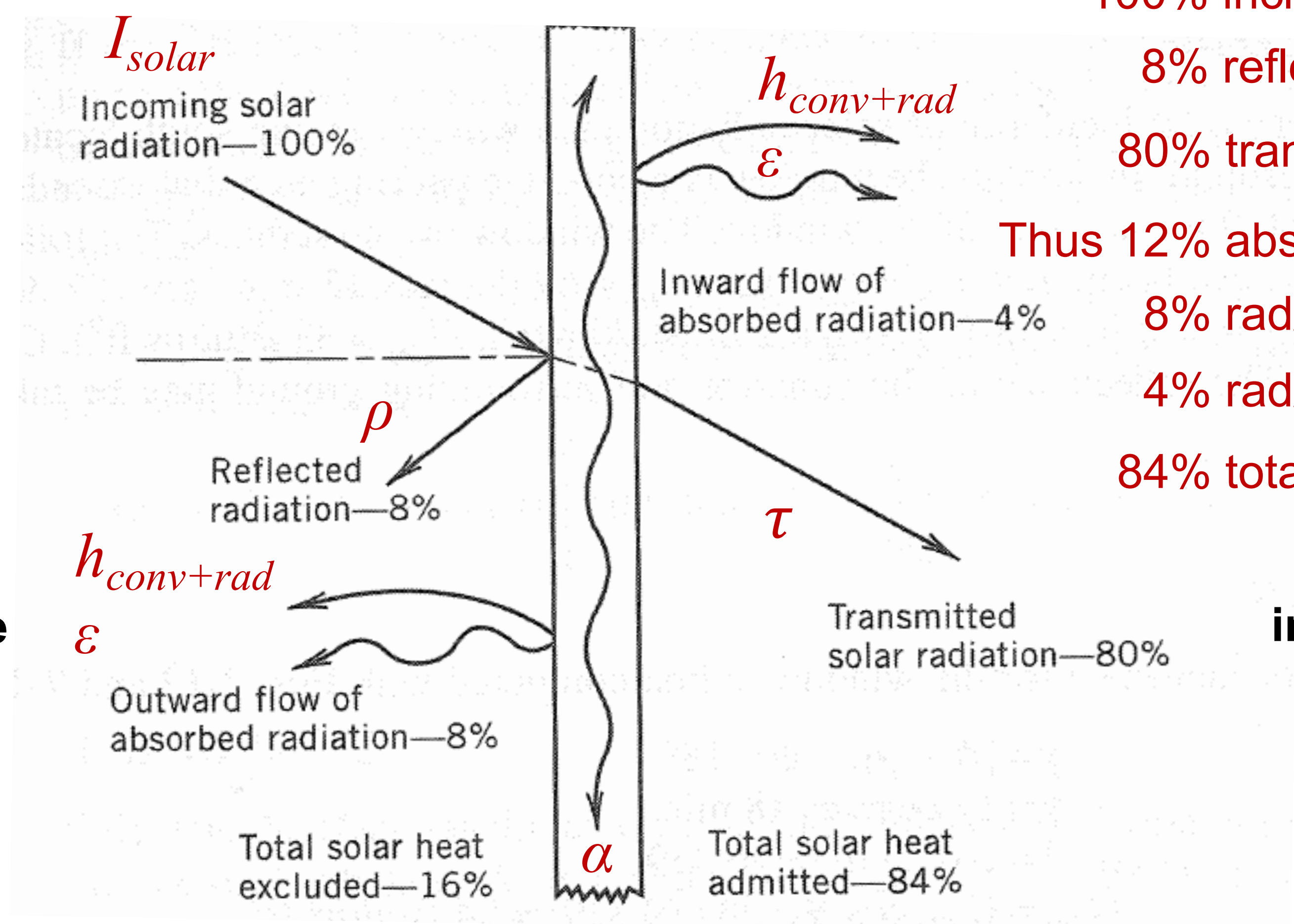
- The total heat gain of fenestration is the <u>sum of two terms</u>:
  - The amount of heat gain from solar radiation passing through
  - Combined conductive/convective/LWR thermal heat gain or loss from the temperature difference between the interior and exterior

- In the summer, both terms are positive towards the interior and add to heat gains

- In the winter, solar is positive inwards (gain) but conduction/convection/LWR is negative towards the exterior (loss)
  - Net heat gain may be in either direction

Solar radiation and fenestration

- Solar radiation through a single window pane



outside

inside

100% incident

8% reflected

80% transmitted

Thus 12% absorbed

8% rad/conv outward

4% rad/conv inward

84% total transmitted

Total heat gain through windows

- Calculating the heat gain/loss through a window based on indoor/outdoor temperature differences is relatively easy:

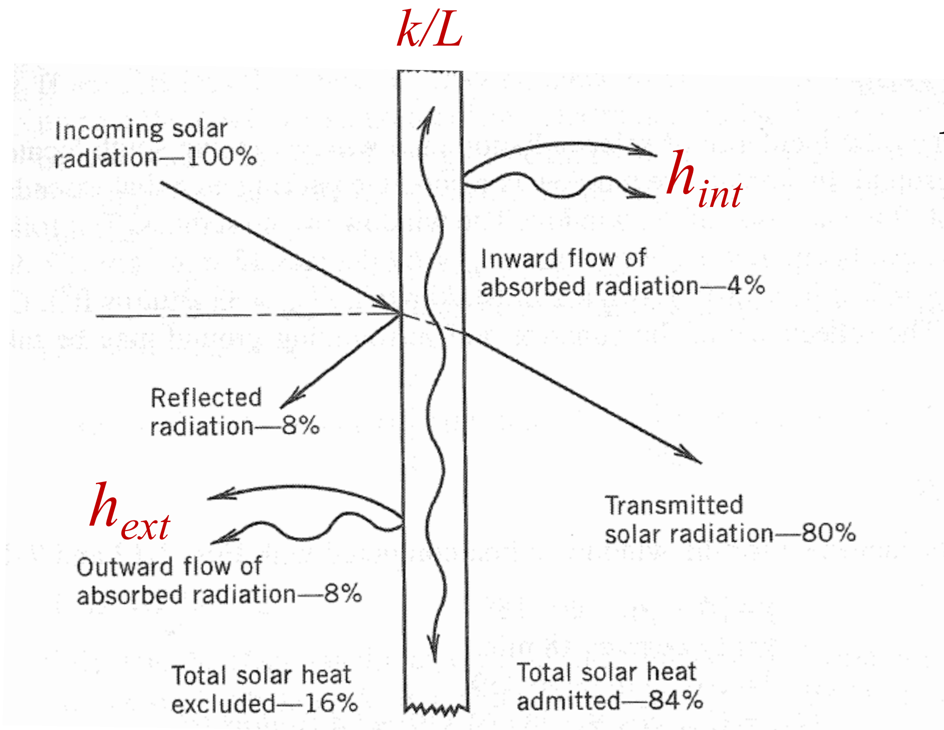
$$Q = UA(T_{in} - T_{out}) = UA\Delta T$$

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

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

Glazing U-values

- U-values include the thermal resistance of the glass (or glazing assembly), as well as the interior and exterior “film” thermal resistance



$$R = \frac{1}{U} = \frac{1}{h_{int}} + \frac{L_{glass}}{k_{glass}} + \frac{1}{h_{ext}}$$

k_{glass} = ~1 W/mK
L_{glass} = ~5 mm (~0.2 inches)

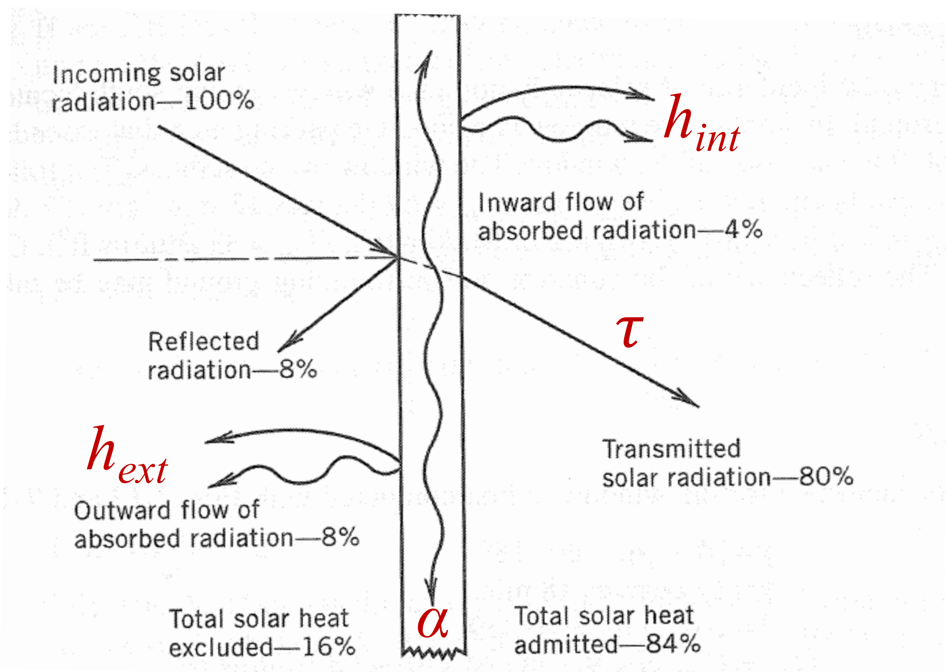
Typical R_{int} = 0.12 m^2K/W
Typical R_{ext} = 0.04 m^2K/W

Solar heat gain coefficient, SHGC

- For a single pane of glass:

$$SHGC = \tau + \alpha \frac{U}{h_{ext}}$$

$U=k/L$



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

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

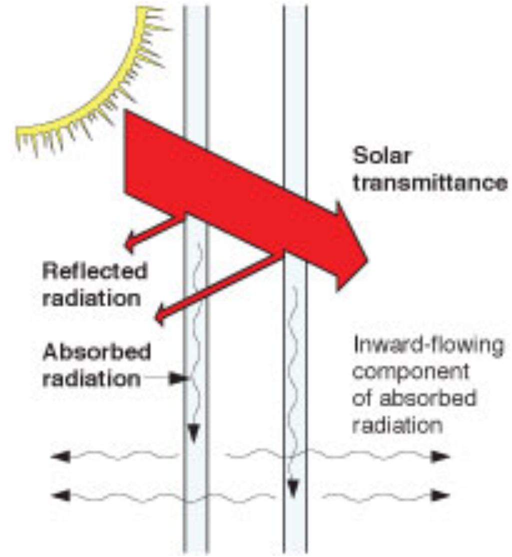
Solar heat gain coefficient, SHGC

- For double glazing with a small still air gap:

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

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

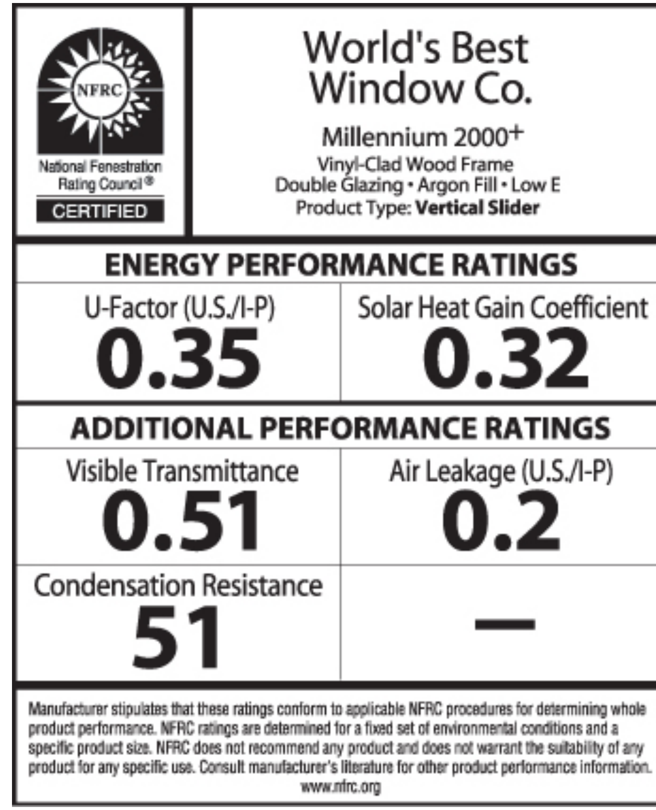
$^{*}R_{outer\ pane}$ and $R_{inner\ pane}$ are negligible



It gets complicated quickly!

Manufacturer supplied SHGC

- Glazing manufacturers will measure and report SHGC values 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)



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

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

Complex SHGC

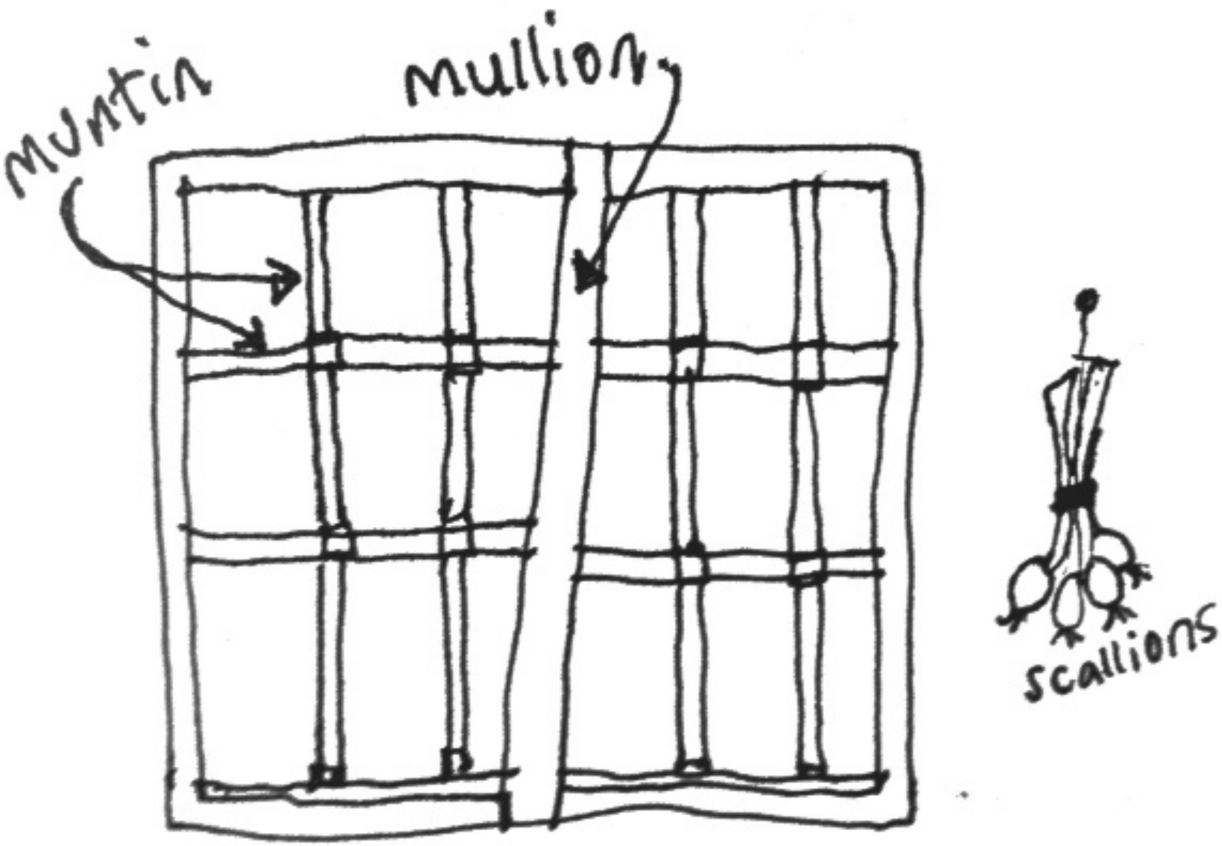
- SHGC, solar transmittance, reflectance, and absorptance properties for glazing all vary with incidence angles of solar radiation (θ)
- The ASHRAE Handbook of Fundamentals **Chapter 15** provides data for a large variety of glazing types

Table 10 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

					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 Single Glazing																			
1a	3	CLR	0.90	SHGC	0.86	0.84	0.82	0.78	0.67	0.42	0.78	0.78	0.79	0.70	0.76	0.80	0.81	0.72	0.79
				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	0.74	0.74	0.66	0.72	0.78	0.79	0.70	0.77
				T	0.77	0.75	0.73	0.68	0.58	0.35	0.69								
				R^f	0.07	0.08	0.09	0.13	0.24	0.48	0.13								
				R^b	0.07	0.08	0.09	0.13	0.24	0.48	0.13								
				$\mathcal{A}_1^f$	0.16	0.17	0.18	0.19	0.19	0.17	0.17								

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**



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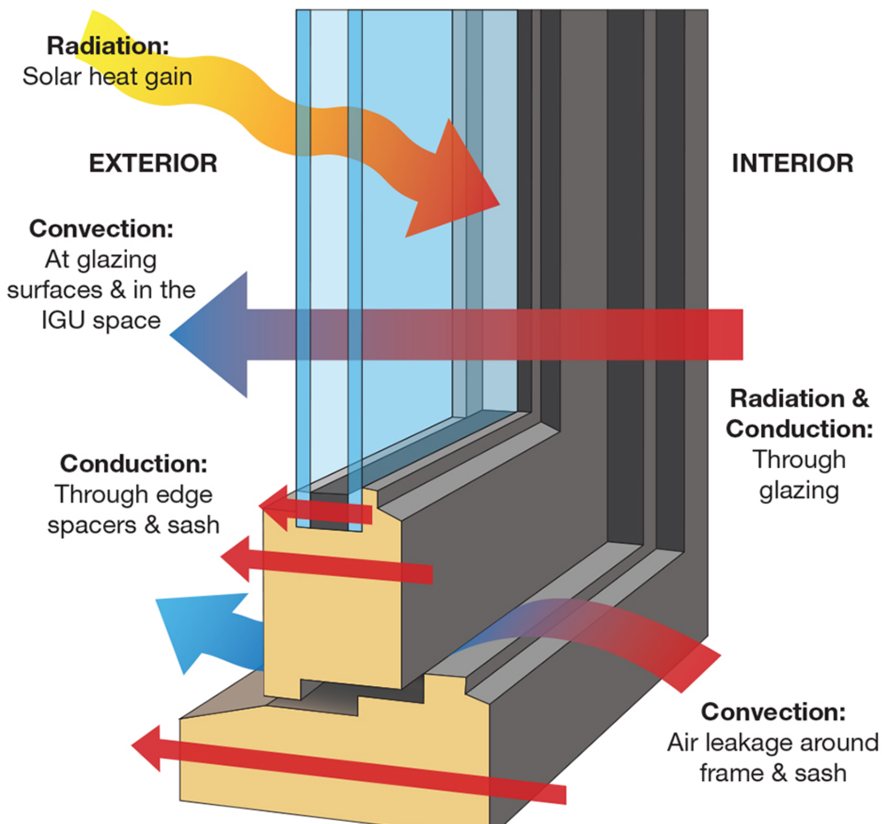


Courtesy Peter Harris/BuildingGreen

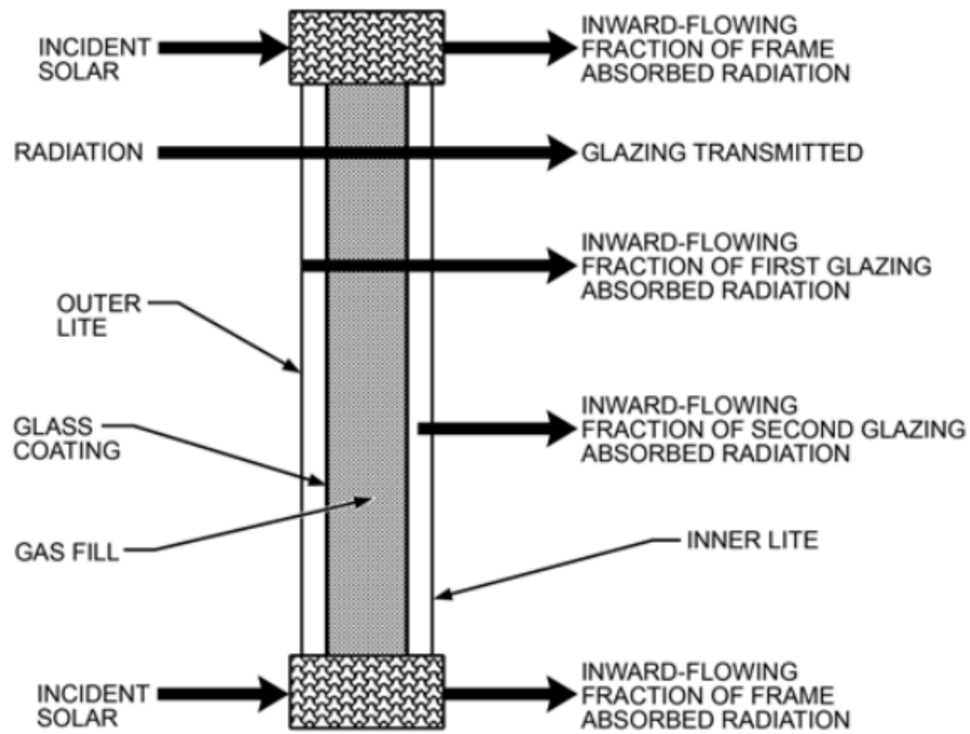


Fig. 13 Components of Solar Radiant Heat Gain with Double-Pane Fenestration, Including Both Frame and Glazing Contributions

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 or Btu/ft^2hF

A_{pf} = total projected area of fenestration, m^2 or ft^2

T_{in} = indoor air temperature, K or F

T_{out} = outdoor air temperature, K or F

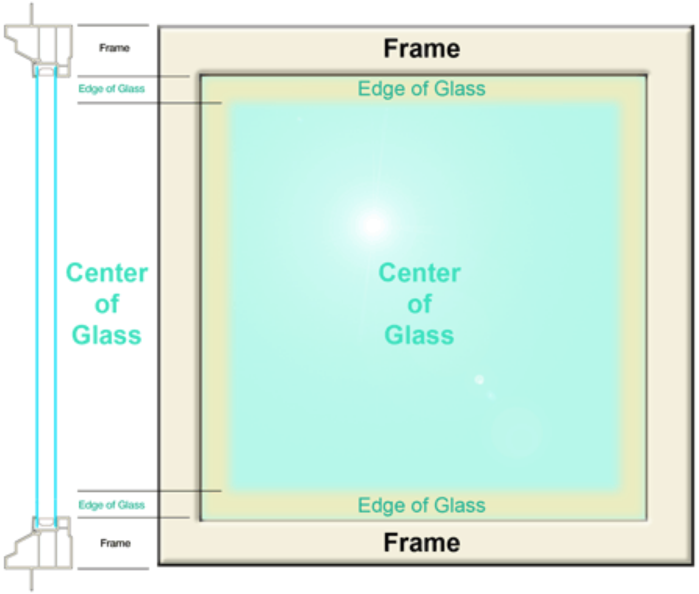
$SHGC$ = solar heat gain coefficient, -

I_{solar} = incident total irradiance, W/m^2 or Btu/ft^2hF

Window assembly U-values

- U-values (or U-factors) for windows include all of the elements of the fenestration system
  - Center of glass properties (*cg*)
  - Edge of glass properties (*eg*)
  - Frame properties (*f*)
- The overall U-factor is estimated using area-weighted U-factors for each:

$$U = \frac{U_{cg}A_{cg} + U_{eg}A_{eg} + U_f A_f}{A_{pf}}$$



Edge of glass is typically ~2.5 inches wide

Assembly U-value data: ASHRAE HOF Ch. 15 (SI)

Table 4 U-Factors for Various Fenestration Products in $W/(m^2 \cdot K)$

Product Type		Glass Only		Vertical Installation									
				Operable (including sliding and swinging glass doors)					Fixed				
Frame 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
ID	Glazing Type												
	Single Glazing												
1	3 mm glass	*5.91*	*5.91*	7.01	6.08	5.27	5.20	4.83	6.38	6.06	5.58	5.58	5.40
2	6 mm acrylic/polycarb	*5.00*	*5.00*	6.23	5.35	4.59	4.52	4.18	5.55	5.23	4.77	4.77	4.61
3	3.2 mm acrylic/polycarb	*5.45*	*5.45*	6.62	5.72	4.93	4.86	4.51	5.96	5.64	5.18	5.18	5.01
	Double Glazing												
4	6 mm airspace	*3.12*	*3.63*	4.62	3.61	3.24	3.14	2.84	3.88	3.52	3.18	3.16	3.04
5	13 mm airspace	*2.73*	*3.36*	4.30	3.31	2.96	2.86	2.58	3.54	3.18	2.85	2.83	2.72
6	6 mm argon space	*2.90*	*3.48*	4.43	3.44	3.08	2.98	2.69	3.68	3.33	3.00	2.98	2.86
7	13 mm argon space	*2.56*	*3.24*	4.16	3.18	2.84	2.74	2.46	3.39	3.04	2.71	2.69	2.58
	Double Glazing, e = 0.60 on surface 2 or 3												
8	6 mm airspace	*2.95*	*3.52*	4.48	3.48	3.12	3.02	2.73	3.73	3.38	3.04	3.02	2.90
9	13 mm airspace	*2.50*	*3.20*	4.11	3.14	2.80	2.70	2.42	3.34	2.99	2.67	2.65	2.53
10	6 mm argon space	*2.67*	*3.32*	4.25	3.27	2.92	2.82	2.54	3.49	3.13	2.81	2.79	2.67
11	13 mm argon space	*2.33*	*3.08*	3.98	3.01	2.68	2.58	2.31	3.20	2.84	2.52	2.50	2.39
	Double Glazing, e = 0.40 on surface 2 or 3												
12	6 mm airspace	*2.78*	*3.40*	4.34	3.35	3.00	2.90	2.61	3.59	3.23	2.90	2.88	2.77
13	13 mm airspace	*2.27*	*3.04*	3.93	2.96	2.64	2.54	2.27	3.15	2.79	2.48	2.46	2.35
14	6 mm argon space	*2.44*	*3.16*	4.07	3.09	2.76	2.66	2.38	3.30	2.94	2.62	2.60	2.49
15	13 mm argon space	*2.04*	*2.88*	3.75	2.79	2.48	2.38	2.11	2.95	2.60	2.29	2.27	2.16
	Double Glazing, e = 0.20 on surface 2 or 3												
16	6 mm airspace	*2.56*	*3.24*	4.16	3.18	2.84	2.74	2.46	3.39	3.04	2.71	2.69	2.58
17	13 mm airspace	*1.99*	*2.83*	3.70	2.75	2.44	2.34	2.07	2.91	2.55	2.24	2.22	2.12
18	6 mm argon space	*2.16*	*2.96*	3.84	2.88	2.56	2.46	2.19	3.05	2.70	2.38	2.36	2.26
19	13 mm argon space	*1.70*	*2.62*	3.47	2.53	2.24	2.14	1.88	2.66	2.30	2.00	1.98	1.88
	Double Glazing, e = 0.10 on surface 2 or 3												
20	6 mm airspace	*2.39*	*3.12*	4.02	3.05	2.72	2.62	2.34	3.25	2.89	2.57	2.55	2.44
21	13 mm airspace	*1.82*	*2.71*	3.56	2.62	2.32	2.22	1.96	2.76	2.40	2.10	2.08	1.98
22	6 mm argon space	*1.99*	*2.83*	3.70	2.75	2.44	2.34	2.07	2.91	2.55	2.24	2.22	2.12
23	13 mm argon space	*1.53*	*2.49*	3.33	2.40	2.12	2.02	1.76	2.51	2.16	1.86	1.84	1.74

Assembly U-value data: ASHRAE HOF Ch. 15 (IP)

Table 4 U-Factors for Various Fenestration Products in Btu/h·ft^2·°F

Product Type		Glass Only		Vertical Installation									
				Operable (including sliding and swinging glass doors)					Fixed				
Frame 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
ID	Glazing Type												
	Single Glazing												
1	1/8 in. glass	1.04	1.04	1.23	1.07	0.93	0.91	0.85	1.12	1.07	0.98	0.98	1.04
2	1/4 in. acrylic/polycarbonate	0.88	0.88	1.10	0.94	0.81	0.80	0.74	0.98	0.92	0.84	0.84	0.88
3	1/8 in. acrylic/polycarbonate	0.96	0.96	1.17	1.01	0.87	0.86	0.79	1.05	0.99	0.91	0.91	0.96
	Double Glazing												
4	1/4 in. air space	0.55	0.64	0.81	0.64	0.57	0.55	0.50	0.68	0.62	0.56	0.56	0.55
5	1/2 in. air space	0.48	0.59	0.76	0.58	0.52	0.50	0.45	0.62	0.56	0.50	0.50	0.48
6	1/4 in. argon space	0.51	0.61	0.78	0.61	0.54	0.52	0.47	0.65	0.59	0.53	0.52	0.51
7	1/2 in. argon space	0.45	0.57	0.73	0.56	0.50	0.48	0.43	0.60	0.53	0.48	0.47	0.45
	Double Glazing, e = 0.60 on surface 2 or 3												
8	1/4 in. air space	0.52	0.62	0.79	0.61	0.55	0.53	0.48	0.66	0.59	0.54	0.53	0.52
9	1/2 in. air space	0.44	0.56	0.72	0.55	0.49	0.48	0.43	0.59	0.53	0.47	0.47	0.44
10	1/4 in. argon space	0.47	0.58	0.75	0.57	0.51	0.50	0.45	0.61	0.55	0.49	0.49	0.47
11	1/2 in. argon space	0.41	0.54	0.70	0.53	0.47	0.45	0.41	0.56	0.50	0.44	0.44	0.41
	Double Glazing, e = 0.40 on surface 2 or 3												
12	1/4 in. air space	0.49	0.60	0.76	0.59	0.53	0.51	0.46	0.63	0.57	0.51	0.51	0.49
13	1/2 in. air space	0.40	0.54	0.69	0.52	0.47	0.45	0.40	0.55	0.49	0.44	0.43	0.40
14	1/4 in. argon space	0.43	0.56	0.72	0.54	0.49	0.47	0.42	0.58	0.52	0.46	0.46	0.43
15	1/2 in. argon space	0.36	0.51	0.66	0.49	0.44	0.42	0.37	0.52	0.46	0.40	0.40	0.36
	Double Glazing, e = 0.20 on surface 2 or 3												
16	1/4 in. air space	0.45	0.57	0.73	0.56	0.50	0.48	0.43	0.60	0.53	0.48	0.47	0.45
17	1/2 in. air space	0.35	0.50	0.65	0.48	0.43	0.41	0.37	0.51	0.45	0.39	0.39	0.35
18	1/4 in. argon space	0.38	0.52	0.68	0.51	0.45	0.43	0.39	0.54	0.47	0.42	0.42	0.38
19	1/2 in. argon space	0.30	0.46	0.61	0.45	0.39	0.38	0.33	0.47	0.41	0.35	0.35	0.30

Assembly U-value data: ASHRAE HOF Ch. 15 (IP)

Notes:

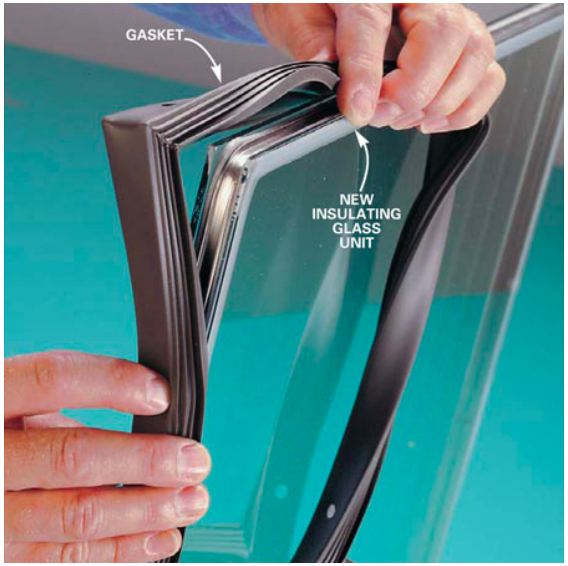
1. All heat transmission coefficients in this table include film resistances and are based on winter conditions of 0°F outdoor air temperature and 70°F indoor air temperature, with 15 mph outdoor air velocity and zero solar flux. Except for single glazing, small changes in indoor and outdoor temperatures do not significantly affect overall U-factors. Coefficients are for vertical position except skylight values, which are for 20° from horizontal with heat flow up.

Table 5 Glazing U-Factors for Various Wind Speeds in Btu/h·ft²·°F

Wind Speed, mph		
15	**7.5**	**0**
0.10	0.10	0.10
0.20	0.20	0.19
0.30	0.29	0.28
0.40	0.38	0.37
0.50	0.47	0.45
0.60	0.56	0.53
0.70	0.65	0.61
0.80	0.74	0.69
0.90	0.83	0.78
1.00	0.92	0.86
1.10	1.01	0.94
1.20	1.10	1.02
1.30	1.19	1.10

Assembly U-values and multiple layers of glazing

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



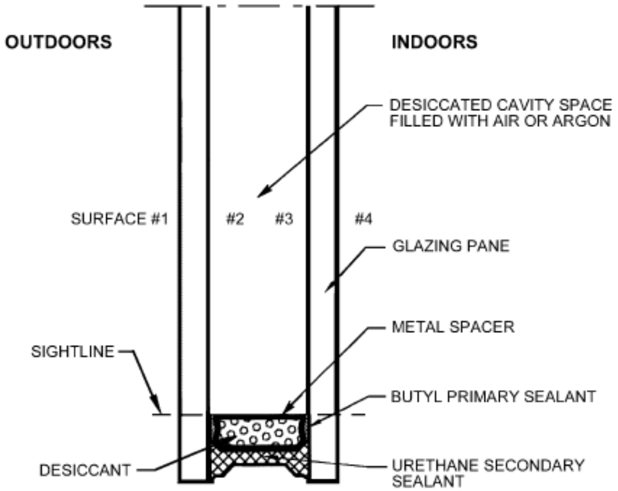
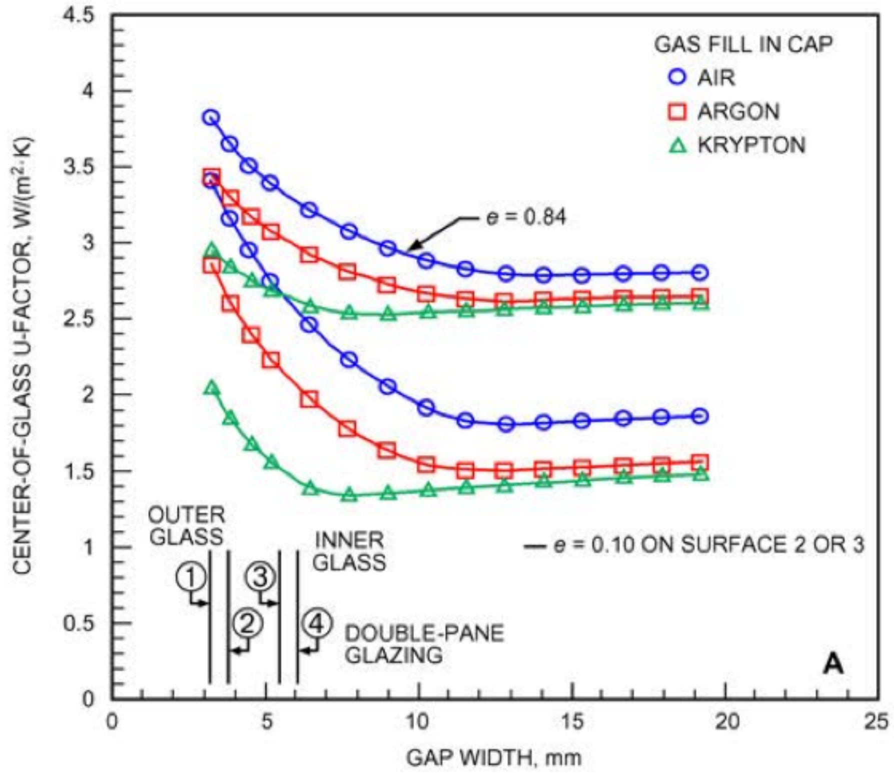


Fig. 1 Insulating Glazing Unit (IGU) Construction Detail

U-values and multiple layers of glazing

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

Center of glass U-values for double pane glazing



Q: Why does argon filled have lower U value than air filled?

k_{air} = 0.025 W/mK

k_{argon} = 0.016 W/mK

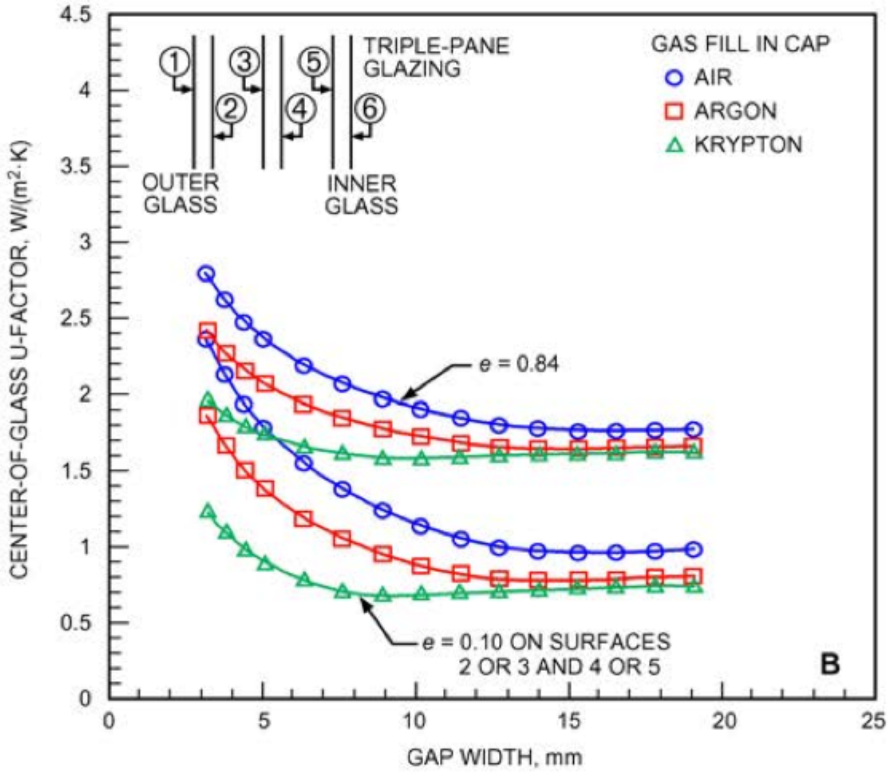
$k_{krypton}$ = 0.0088 W/mK

ASHRAE Handbook of Fundamentals: Chapter 15

U-values and multiple layers of glazing

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

Center of glass U-values for triple pane glazing



How are window U and SHGC values determined?

- Measurements
  - NFRC 102, 201, 202, etc.

- Models
  - LBNL THERM and WINDOW software

http://www.intertek.com/building/standards/

Window U-value measurements

NFRC 102

Standard: NFRC 102 – Procedure for Measuring the Steady-State Thermal Transmittance of Fenestration Systems

Scope: This test is applicable to both residential and commercial fenestration products.

Applicable Products: Windows, Doors, Skylights, Curtain Walls

Test Procedure: The test utilizes an apparatus known as a guarded hot box. The guarded hot box consists of a cold room and a warm room. The cold room contains refrigeration coils to maintain temperatures as low as -22°F (-30°C) and fans to replicate wind speeds of 15 mph (24 kph). The warm room contains electric heating elements to maintain temperatures up to 100°F (38°C). The warm room is enclosed within a second room, known as the guard room, with the same heating capabilities.

In the NFRC 102 test, the product is placed in a wall between the warm and cold rooms. Temperatures of 70°F (21°C) and 0°F (-18°C) and a wind speed of 15 mph (24 kph) are maintained in the two rooms until steady-state conditions have been met for temperature on both sides and energy input to the warm side. The heat flow through the product is measured to determine the U-Factor of the product.

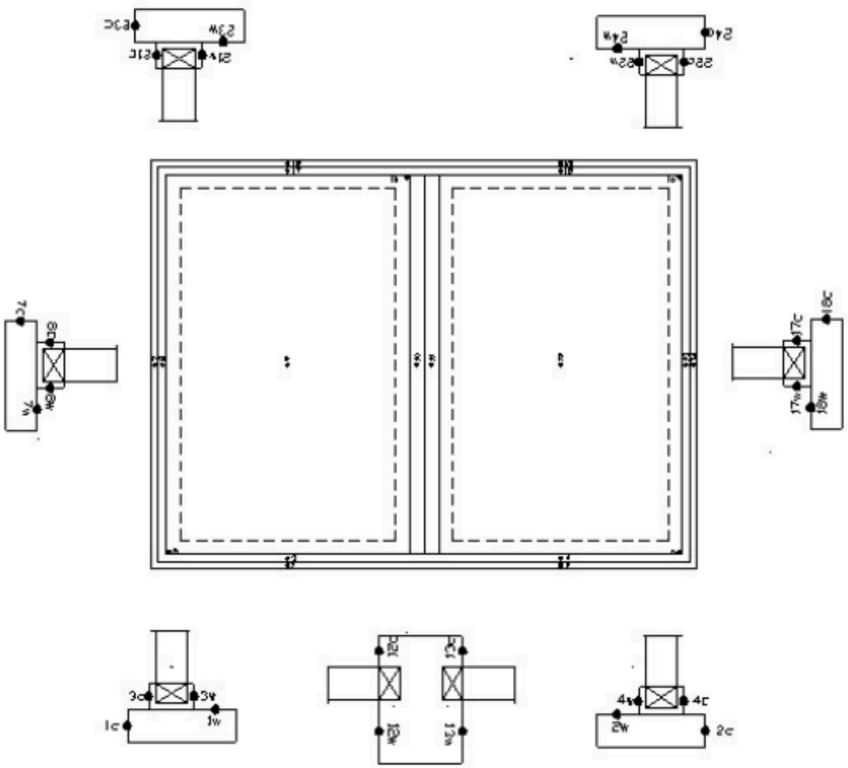
End Result: The thermal transmittance (U-Factor) of the product is determined. The U-Factor can be used to determine energy losses through products. This test is used in conjunction with the NFRC 100 simulation methods to prove the validity of the simulation results for the product. This typically is used to certify windows, doors, skylights and curtain walls for U-Factor.

Special Notes: Alternative U-Factor methods which may be appropriate are NFRC 100, AAMA 1503, CSA A440.2, ASTM C1199, and ASTM C1363.

http://www.intertek.com/building/standards/nfrc-102/

Window U-value measurements

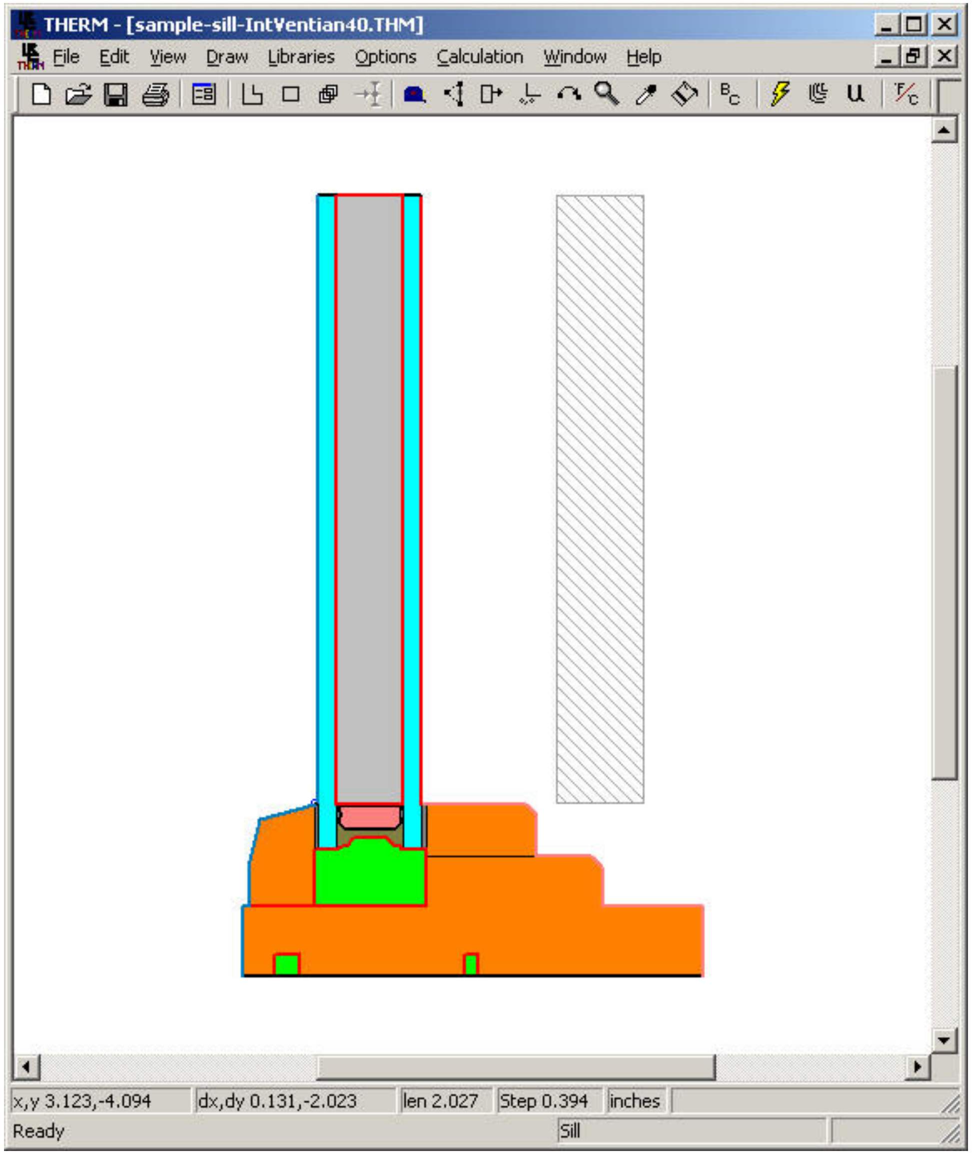
NFRC 102 test procedure



http://ftl-incinfo.com/images/thermal_chamber.jpg

Window U-value models

NFRC 100 model (software)

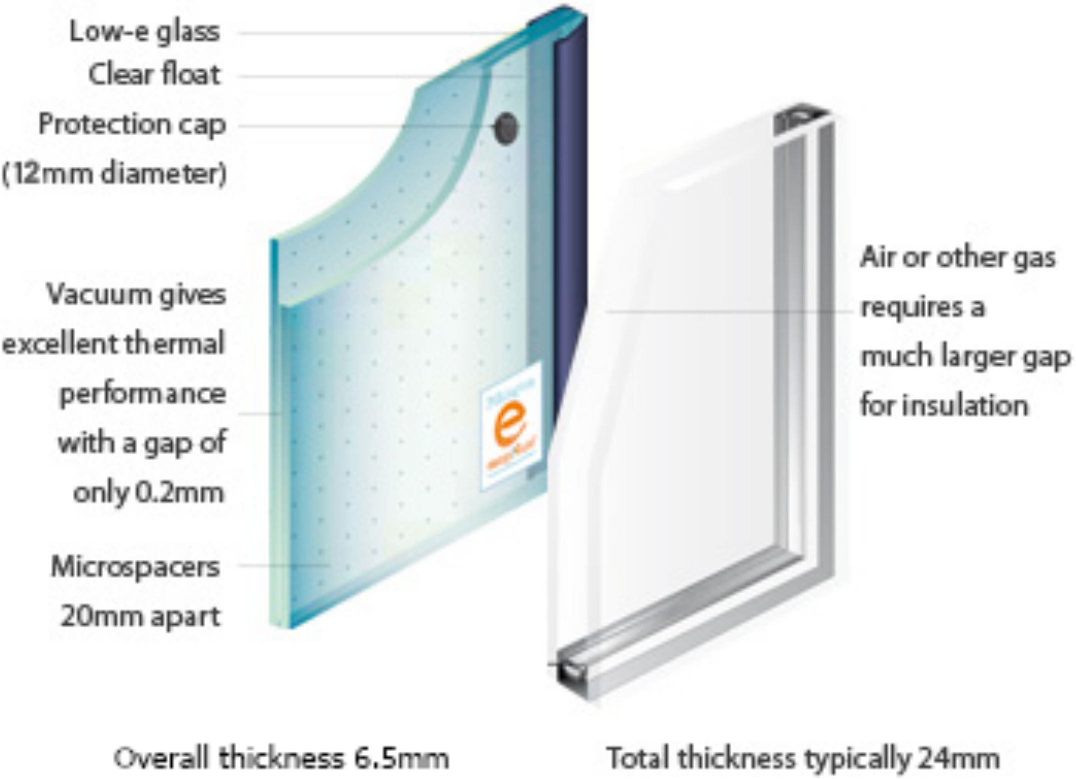


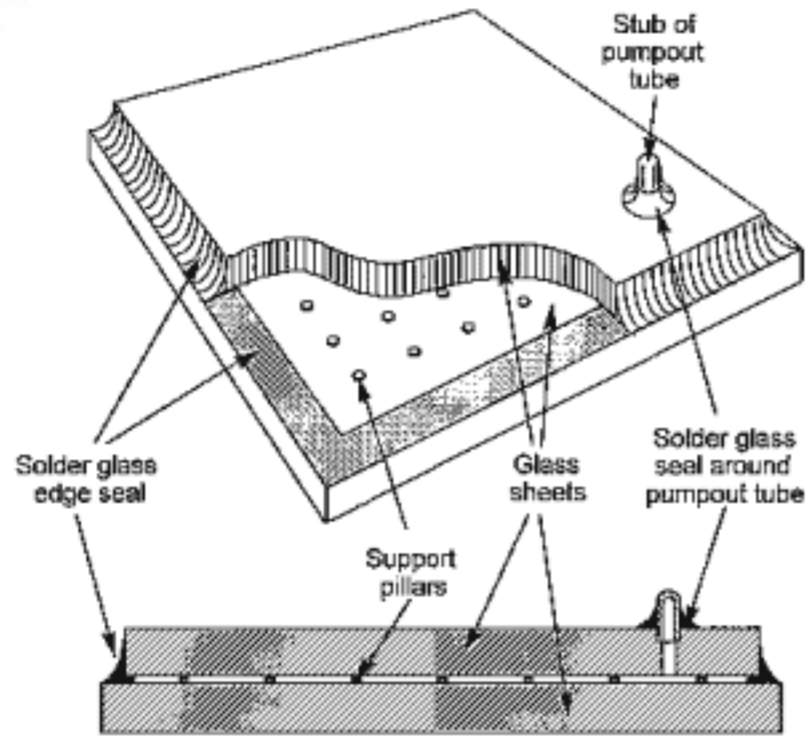
https://windows.lbl.gov/software/therm/6/THERM63_Features.html

Multiple layers of glazing under a vacuum

New window on the north side of Alumni Hall

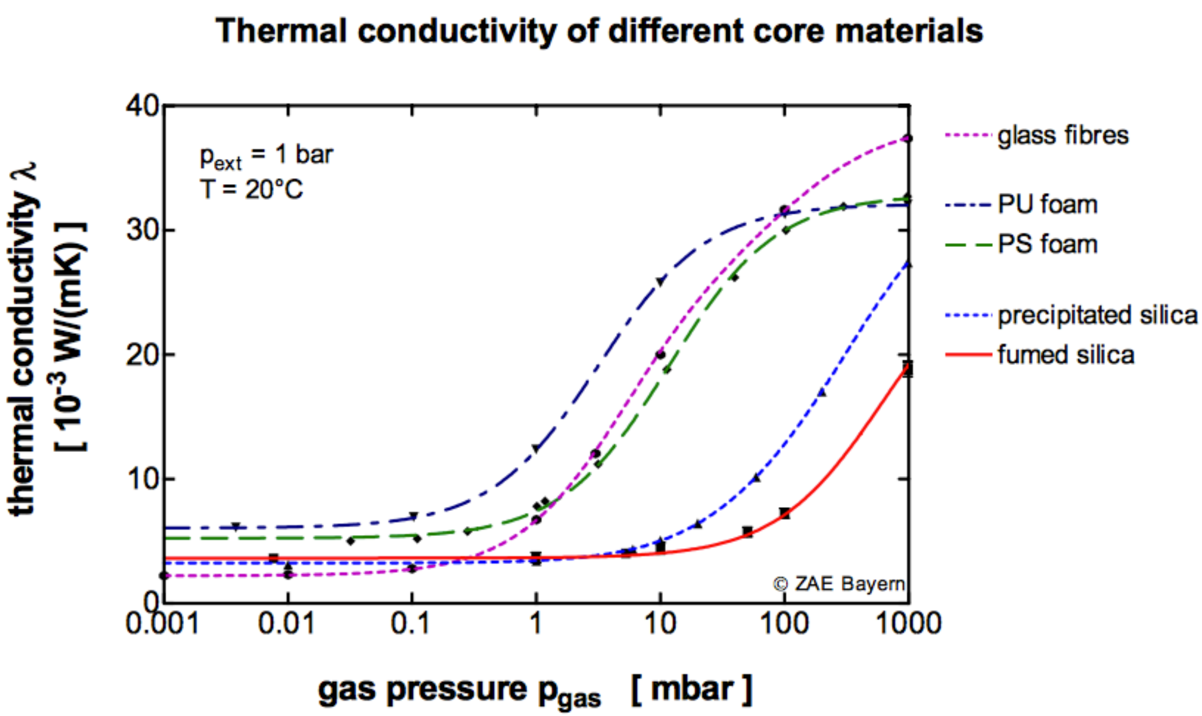
Multiple layers of glazing under a vacuum





Multiple layers of glazing under a vacuum

- In addition to replacing the fill gas with a lower conductivity gas, you can also attempt to evacuate an insulated cavity by placing it **under a vacuum**
  - Eliminates any chance of convection (no air)
  - Can reduce the thermal conductivity of the gas left in the cavity



http://www.iea-ebc.org/fileadmin/user_upload/docs/EBC_Annex_39_Report_Subtask-A.pdf

Multiple layers of glazing under a vacuum

	Thickness (mm)	Visible Light[2]		Solar Energy[2]		U-Factor[5]		Solar Heat Gain Coefficient[7]
		Transmittance[3] %	Reflectance[4] %	Transmittance[3] %	Reflectance[4] %	Europe (W/sq m K)	U.S. Winter (Btu/hr.sq ft. °F)	
Pilkington **Spacia™**	6.2	76	16	61	15	1.4	0.25	0.66
Pilkington **Spacia™** Cool	6.2	70	23	46	36	1.0	0.18	0.49
Pilkington **Spacia™** Shizuka	9.2	73	15	56	13	1.4	0.25	0.61
Pilkington **Spacia™** Cool Shizuka	9.2	68	22	42	29	1.0	0.18	0.46
Pilkington **Spacia™** 21 Thermal Control	18.2	64	22	47	19	0.9	0.16	0.58
Pilkington **Spacia™** 21 Thermal Control	21.2	64	22	47	19	0.8	0.14	0.58
Pilkington **Spacia™** 21 Solar Control	18.2	59	25	37	27	0.7	0.15	0.46
Pilkington **Spacia™** 21 Solar Control	21.2	59	25	37	27	0.7	0.14	0.46
Pilkington **Spacia™** 21 Solar Control Green	18.2	58	19	29	40	0.8	0.14	0.34

*U.S. U-Factor (Btu/hr.sq ft. °F) is based on NFRC/ASTM standards - All performance values are center-of-glass values calculated by the LBNL Window 6.3 program

**See Pilkington Architectural Product Guide for explanation of superscript references-[1, 10] ***All products are available in thicker forms if additional glass strength is required.

https://www.pilkington.com/en/us/products/product-categories/thermal-insulation/pilkington-spacia#brochures

Doors

- Doors usually 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

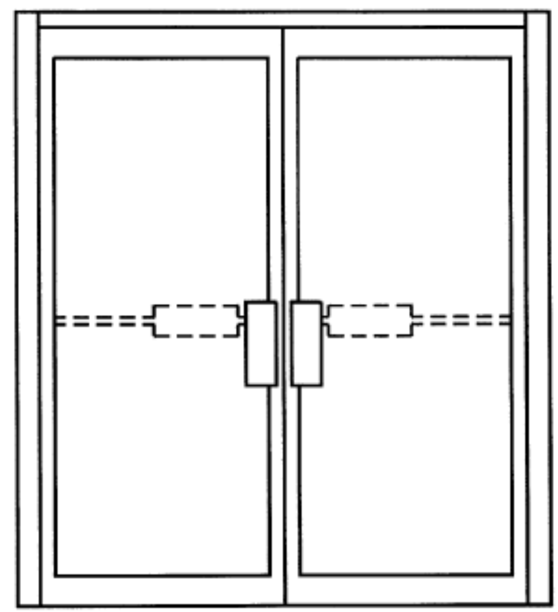


Fig. 5 Details of Stile-and-Rail Door

Doors: Typical U-values

Table 6 Design U-Factors of Swinging Doors in Btu/h·ft²·°F

Door Type (Rough Opening = 38 × 82 in.)	No Glazing	Single Glazing	Double Glazing with 1/2 in. Air Space	Double Glazing with $e = 0.10$, 1/2 in. Argon
Slab Doors				
Wood slab in wood frame[a]	0.46			
6% glazing (22 × 8 in. lite)	—	0.48	0.46	0.44
25% glazing (22 × 36 in. lite)	—	0.58	0.46	0.42
45% glazing (22 × 64 in. lite)	—	0.69	0.46	0.39
More than 50% glazing		Use Table 4 (operable)		
Insulated steel slab with wood edge in wood frame[b]	0.16			
6% glazing (22 × 8 in. lite)	—	0.21	0.19	0.18
25% glazing (22 × 36 in. lite)	—	0.39	0.26	0.23
45% glazing (22 × 64 in. lite)	—	0.58	0.35	0.26
More than 50% glazing		Use Table 4 (operable)		
Foam insulated steel slab with metal edge in steel frame[c]	0.37			
6% glazing (22 × 8 in. lite)	—	0.44	0.41	0.39
25% glazing (22 × 36 in. lite)	—	0.55	0.48	0.44
45% glazing (22 × 64 in. lite)	—	0.71	0.56	0.48
More than 50% glazing		Use Table 4 (operable)		
Cardboard honeycomb slab with metal edge in steel frame	0.61			
Stile-and-Rail Doors				
Sliding glass doors/French doors		Use Table 4 (operable)		
Site-Assembled Stile-and-Rail Doors				
Aluminum in aluminum frame	—	1.32	0.93	0.79
Aluminum in aluminum frame with thermal break	—	1.13	0.74	0.63

Notes:
[a]Thermally broken sill [add 0.03 Btu/h·ft²·°F for non-thermally broken sill]
[b]Non-thermally broken sill
[c]Nominal U-factors are through center of insulated panel before consideration of thermal bridges around edges of door sections and because of frame.

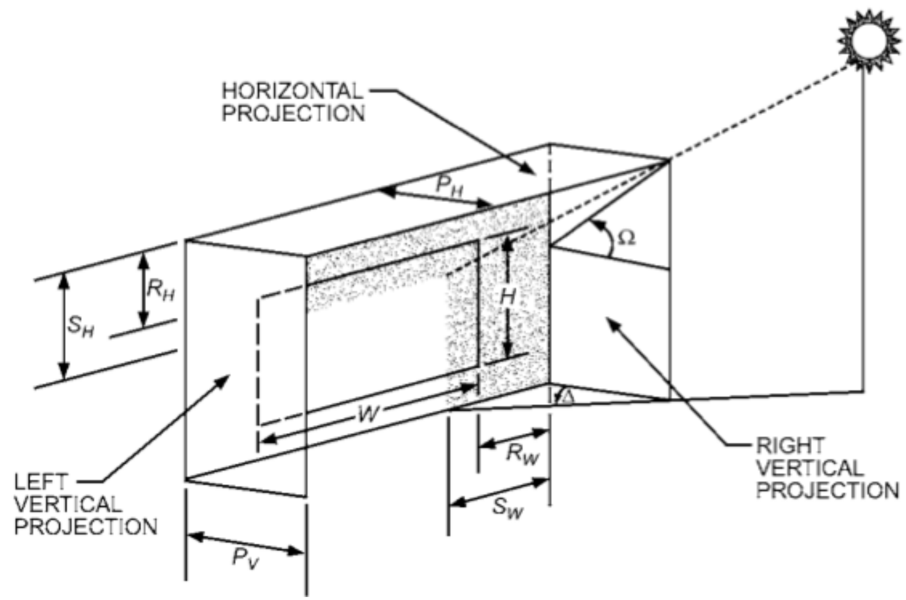
Table 7 Design U-Factors for Revolving Doors in Btu/h·ft²·°F

Type	Size (Width × Height)	U-Factor
3-wing	8 × 7 ft	0.79
	10 × 8 ft	0.80
4-wing	7 × 6.5 ft	0.63
	7 × 7.5 ft	0.64
Open*	82 × 84 in.	1.32

*U-factor of Open door determined using NFRC *Technical Document* 100-91. It has not been updated to current rating methodology in NFRC *Technical Document* 100-2010.

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:



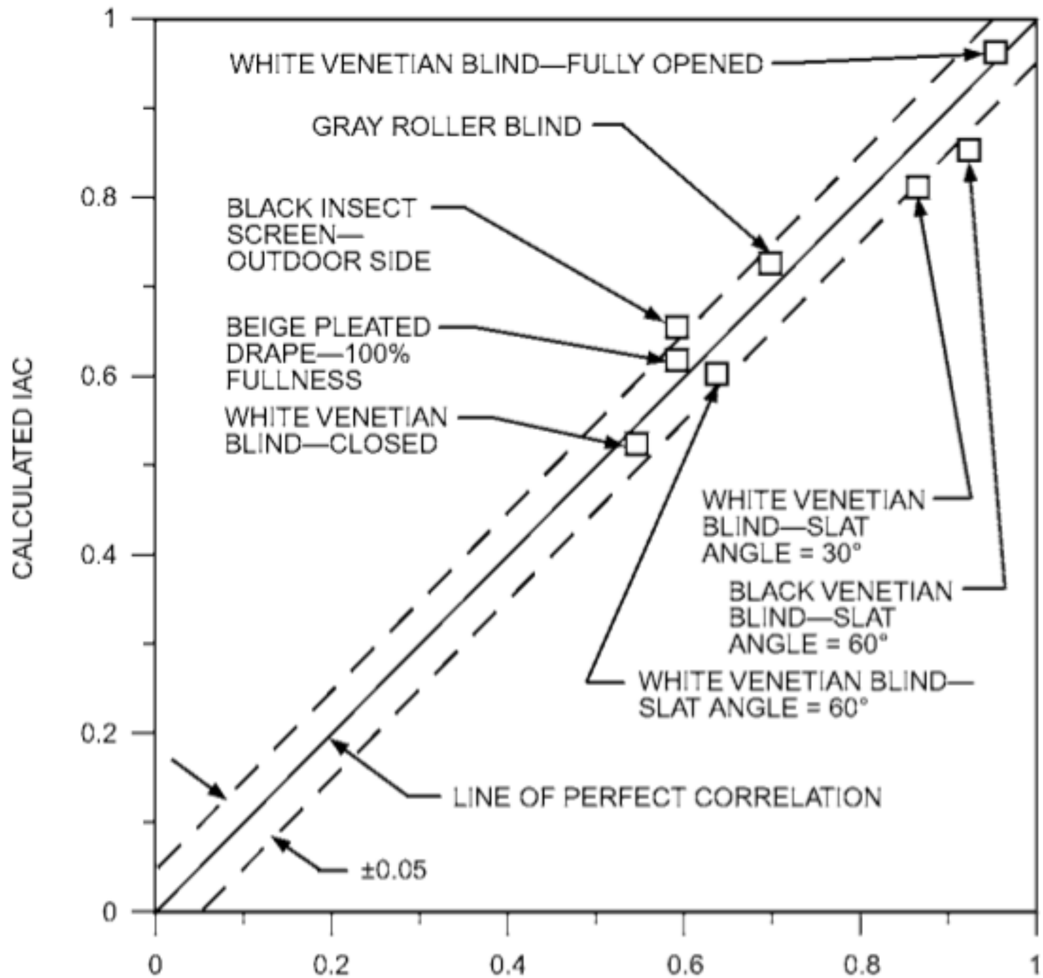
$$Q_{window} = UA_{pf}\left(T_{out} - T_{in}\right) + I_{direct}A_{pf}SHGC(\theta)IAC(\theta,\Omega) + (I_{diffuse+reflected})A_{pf}SHGC_{diffuse+reflected}IAC_{diffuse+reflected}$$

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

Or more simply: $$Q_{window} = UA_{pf}\left(T_{out} - T_{in}\right) + I_{solar}A_{pf}SHGC \cdot IAC$$

(ignoring incidence angle effects)

IAC for blinds and drapes: ASHRAE HOF 2013



Example fenestration problem

- Estimate the design U-factor for a manufactured fixed fenestration product with a reinforced vinyl frame and 1/8 inch clear double-glazing with a low-e coating (e = 0.1) on one surface
  - The gap is 0.5 inches wide and argon-filled
  - The spacer is metal
  - Outdoor wind speed is 7.5 mph
  - The window dimensions are 2 ft x 4 ft

- If it is 10°F outside and 70°F inside, what is the heat gain/loss through the window? (ignoring solar radiation)

- If 100 BTU/hr-ft^2 of solar radiation strikes the window, what is the total heat gain?

Example fenestration problem

- Step 1: Locate the glazing system type in Table 4 (ID = 23)

Table 4 U-Factors for Various Fenestration Products in Btu/h· ft^2 · °F

Product Type		Glass Only		Vertical Installation									
				Operable (including sliding and swinging glass doors)					Fixed				
Frame 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
ID	Glazing Type												
	Double Glazing, *e* = 0.10 on surface 2 or 3												
20	1/4 in. air space	0.42	0.55	0.71	0.54	0.48	0.46	0.41	0.57	0.51	0.45	0.45	0.42
21	1/2 in. air space	0.32	0.48	0.63	0.46	0.41	0.39	0.34	0.49	0.42	0.37	0.37	0.32
22	1/4 in. argon space	0.35	0.50	0.65	0.48	0.43	0.41	0.37	0.51	0.45	0.39	0.39	0.35
23	1/2 in. argon space	0.27	0.44	0.59	0.42	0.37	0.36	0.31	0.44	0.38	0.33	0.32	0.27
	Double Glazing, *e* = 0.05 on surface 2 or 3												

- Step 2: Adjust for wind speed
  - Table 5 in Chapter 15 of the ASHRAE HoF

Example fenestration problem

Notes:
1. All heat transmission coefficients in this table include film resistances and are based on winter conditions of 0°F outdoor air temperature and 70°F indoor air temperature, with 15 mph outdoor air velocity and zero solar flux. Except for single glazing, small changes in indoor and outdoor temperatures do not significantly affect overall U-factors. Coefficients are for vertical position except skylight values, which are for 20° from horizontal with heat flow up.

Table 5 Glazing U-Factors for Various Wind Speeds in Btu/h·ft²·°F

Wind Speed, mph		
15	**7.5**	**0**
0.10	0.10	0.10
0.20	0.20	0.19
0.30	0.29	0.28
0.40	0.38	0.37
0.50	0.47	0.45
0.60	0.56	0.53
0.70	0.65	0.61
0.80	0.74	0.69
0.90	0.83	0.78
1.00	0.92	0.86
1.10	1.01	0.94
1.20	1.10	1.02
1.30	1.19	1.10

$$\frac{0.33-0.30}{0.40-0.30} = \frac{U_{7.5\ \mathrm{mph}}-0.29}{0.38-0.29}$$

$$\boxed{U_{7.5\ \mathrm{mph}} = 0.32\ \mathrm{Btu/h\cdot ft^2\cdot °F}}$$

Example fenestration problem

- Step 3: Calculate heat loss/gain through window

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

- Step 4: Find SHGC and calculate heat gain through window

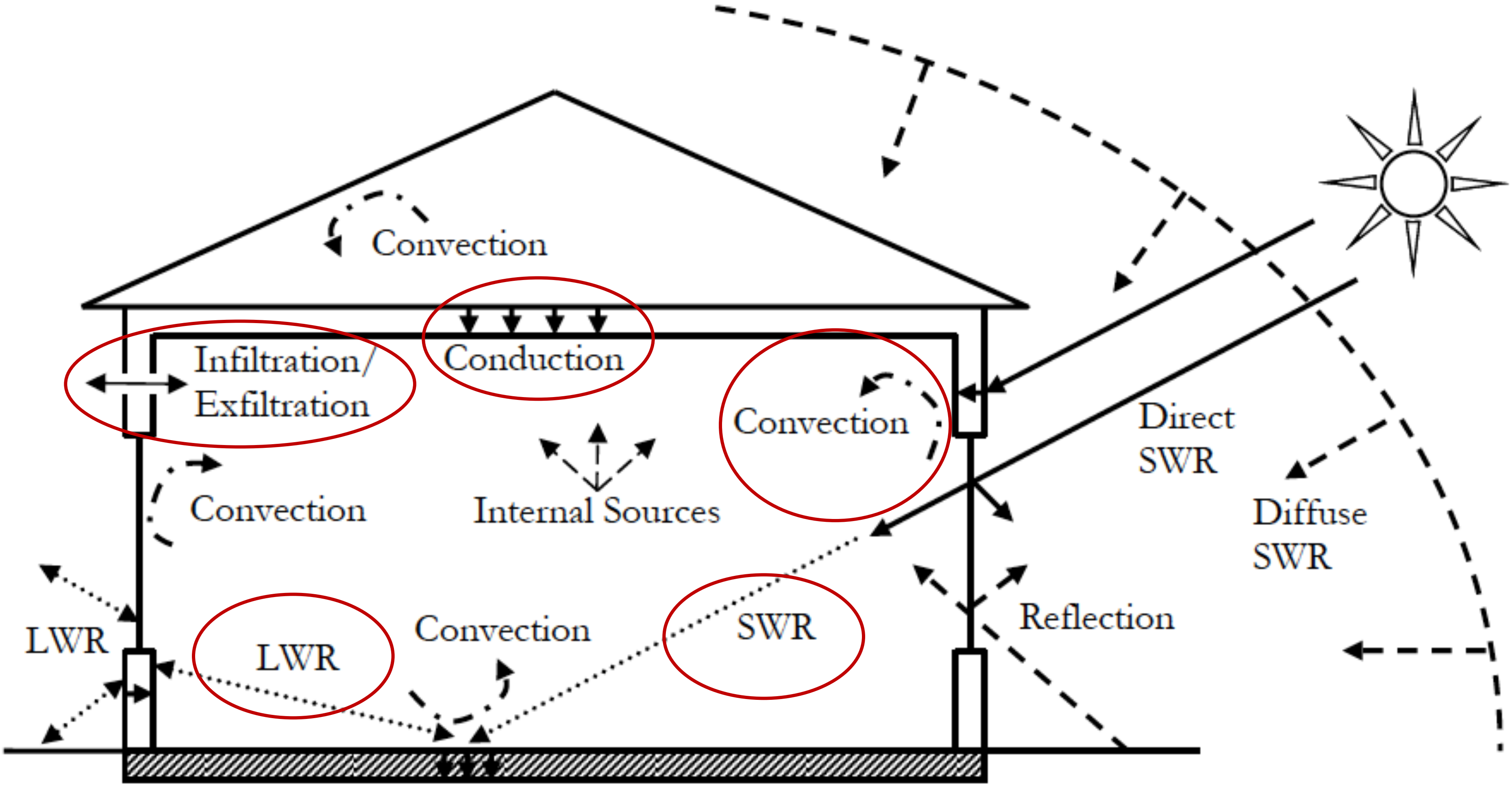
$$Q_{window} = UA_{pf}\left(T_{out} - T_{in}\right) + \underline{I_{solar}A_{pf}SHGC}$$

Example fenestration problem

Table 10 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., in.		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
Low-e Double Glazing, e = 0.1 on surface 3																			
21c	1/8	CLR LE	0.75	SHGC	0.60	0.58	0.56	0.51	0.40	0.22	0.52	0.55	0.55	0.49	0.53	0.67	0.68	0.60	0.66
				T	0.48	0.45	0.43	0.37	0.27	0.13	0.40								
				R^f	0.26	0.27	0.28	0.32	0.42	0.62	0.31								
				R^b	0.24	0.24	0.26	0.29	0.38	0.58	0.28								
				$\mathcal{A}_1^f$	0.12	0.13	0.14	0.14	0.15	0.15	0.13								
				$\mathcal{A}_2^f$	0.14	0.15	0.15	0.16	0.16	0.10	0.15								

Summary: Modes of heat transfer in a building



Summary to date: Modes of heat transfer in a building

Conduction

$$q = \frac{k}{L}\left(T_{surf,1} - T_{surf,2}\right)$$

$$\frac{k}{L} = U = \frac{1}{R}$$

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

$$R_{total} = R_1 + R_2 + R_3 + \ldots$$

For thermal bridges and combined elements:

$$U_{total} = \frac{A_1}{A_{total}}U_1 + \frac{A_2}{A_{total}}U_2 + \ldots$$

Window (combined modes)

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

Convection

$$q_{conv} = h_{conv}\left(T_{fluid} - T_{surf}\right)$$

$$R_{conv} = \frac{1}{h_{conv}}$$

Advection

$$Q_{bulk} = \dot{m}C_p\Delta T$$

Radiation

Long-wave

$$q_{1\to2} = \frac{\sigma\left(T^4_{surf,1} - T^4_{surf,2}\right)}{\frac{1-\varepsilon_1}{\varepsilon_1} + \frac{A_1}{A_2}\frac{1-\varepsilon_2}{\varepsilon_2} + \frac{1}{F_{12}}}$$

$$q_{rad,1\to2} = h_{rad}\left(T_{surf,1} - T_{surf,2}\right)$$

$$h_{rad} = \frac{4\sigma T^3_{avg}}{\frac{1-\varepsilon_1}{\varepsilon_1} + \frac{A_1}{A_2}\frac{1-\varepsilon_2}{\varepsilon_2} + \frac{1}{F_{1-2}}}$$

$$q_{1\to2} = \varepsilon_{surf}\sigma F_{12}\left(T^4_{surf,1} - T^4_{surf,2}\right)$$

Solar radiation: (opaque surface) $q_{solar} = \alpha I_{solar}$

Transmitted solar radiation: (transparent surface) $q_{solar} = \tau I_{solar}$