

CAE 463/524

Building Enclosure Design

Spring 2015

Lecture 9: March 24, 2015

Introduce final project expectations

Finish air leakage in enclosures

Windows, daylighting, and enclosures

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Research

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sustainability research within the built environment*

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Course catch-up

- **2 and 3 weeks ago:**
 - Air movements / air leakage
 - Campus project presentations
 - Blower door test demonstration
- **Today:**
 - Take-home exam released today
 - Due 1 week from today (Tuesday March 31 by 5 pm)
 - Introduce final project expectations
 - Finish air leakage
 - Windows and daylighting in enclosure design

Project 2: High performance enclosure research

- Objective
 - Extend what you will learn about HAM and building enclosures and research a relatively “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

- Deliverable
 - Final report of findings, similar to a conference proceeding
 - ~~Final presentation of findings (?)~~
 - Since we have 19 people in the course and you already had a group presentation, would you prefer to:
 1. Do individual projects and no presentation? or
 2. Do group projects with a presentation on April 28?
- Expectations
 - Assignment/expectations document will be uploaded to Blackboard today
 - Two example reports will also be provided 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

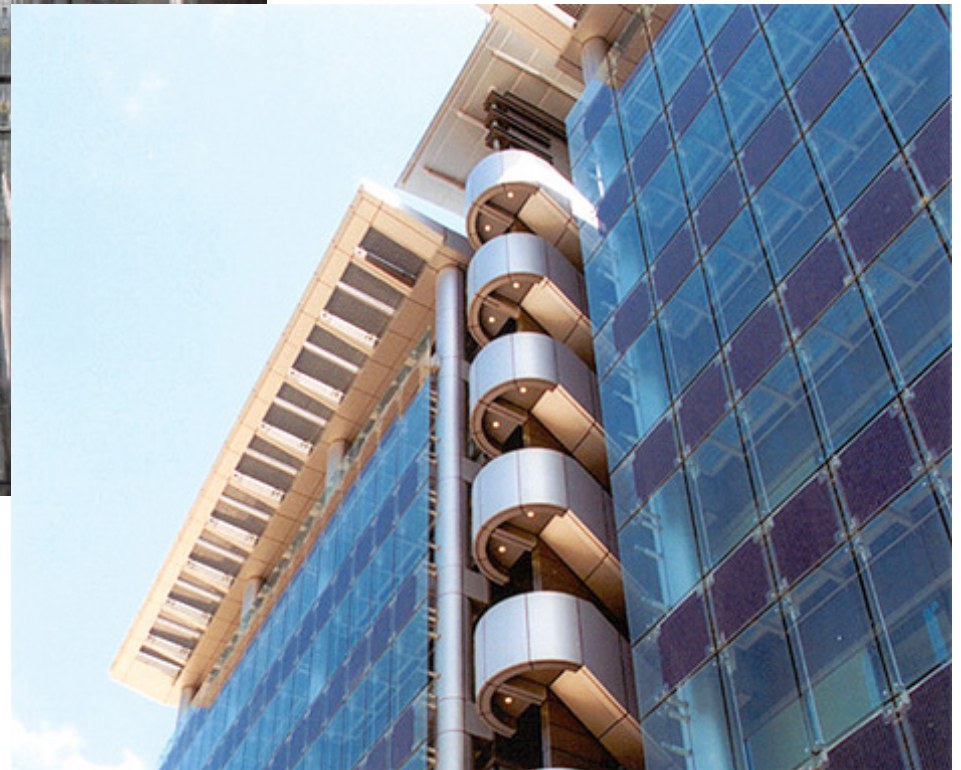


Green
walls

Project 2: High performance enclosure research



Double skin facades

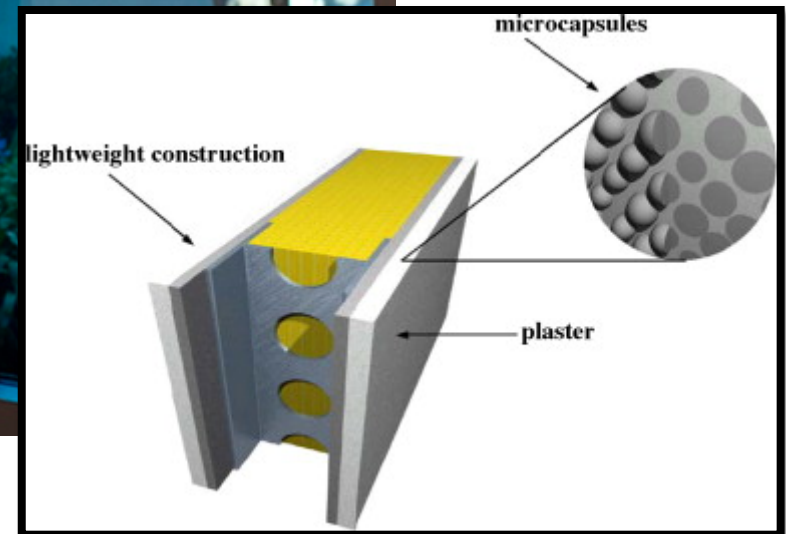


Building integrated photovoltaics

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

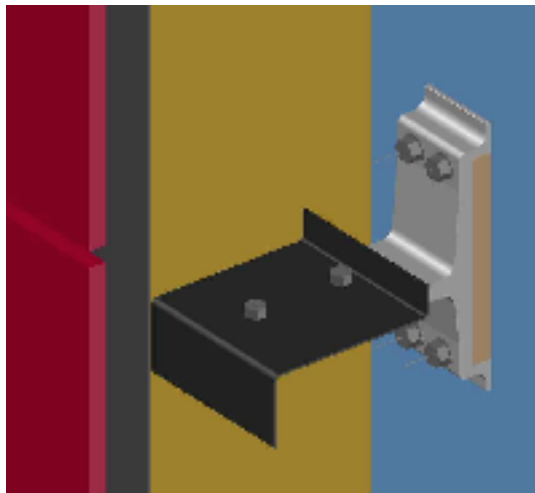
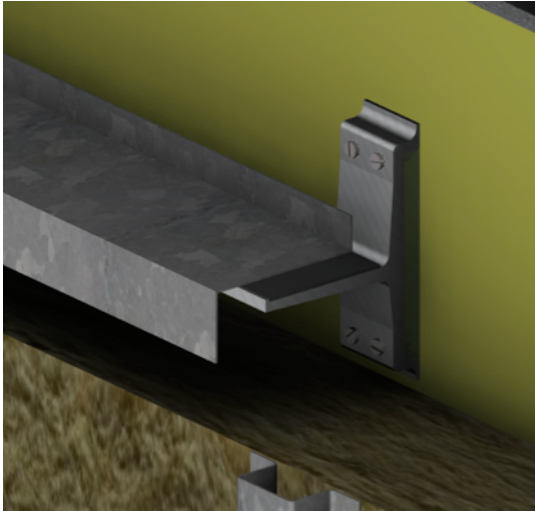


“Cool” roofs (e.g., white roofs)

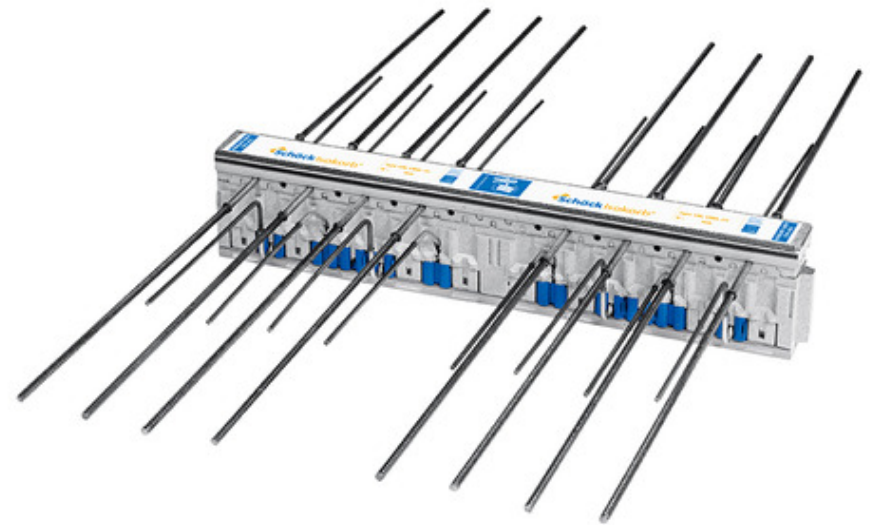
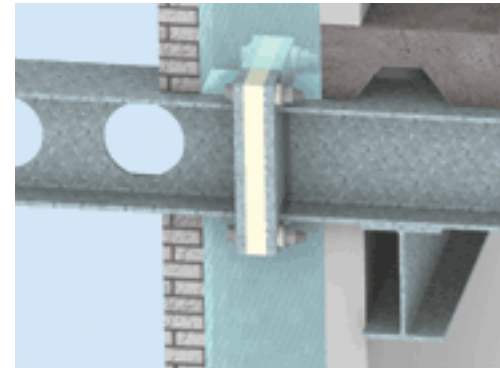


Straw bale construction

Project 2: High performance enclosure research

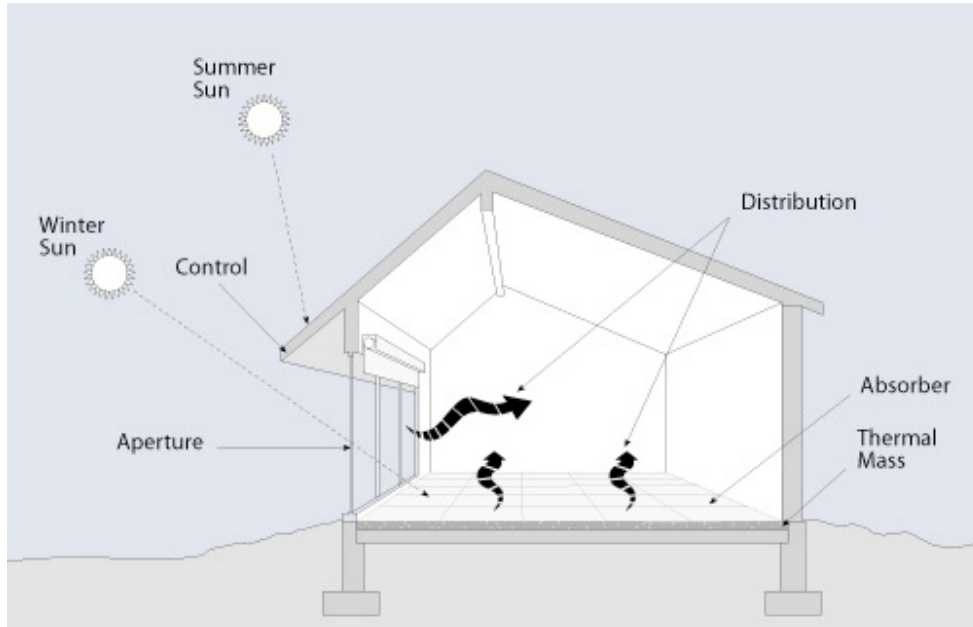


Thermal break systems for cladding



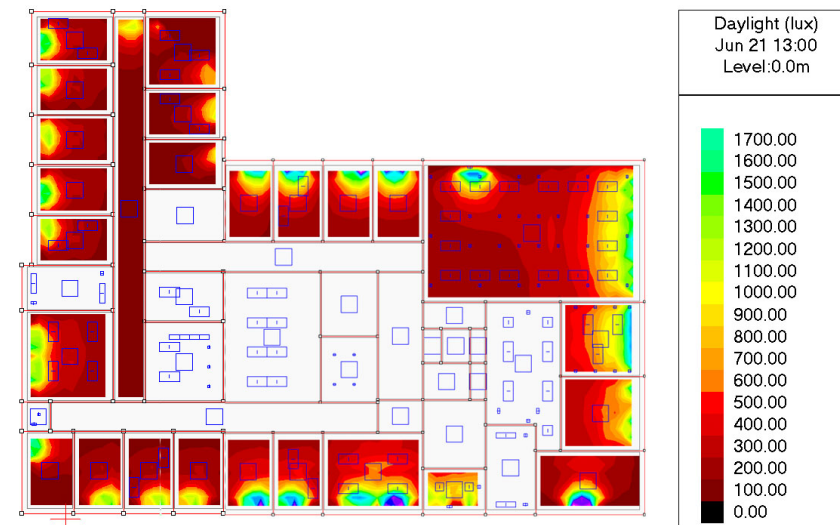
Thermal break systems for balconies

Project 2: High performance enclosure research



Passive solar and thermal mass

Daylighting and energy trade-offs



Project 2: Topic selection

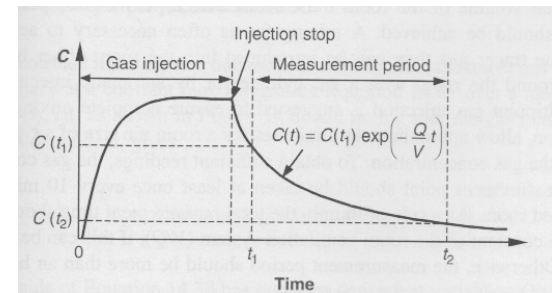
- **Email me** your topics by **Friday April 3, 2015**

Name	Project topic
Behrens, Maria C.	
Geoghegan, Thomas	
Irazabal, Carlos H.	
Jung, Yun Joon	
Lis, Kimberly A.	
Ng, Yin Ling	
Theisen, Whitney A.	
Carrillo Garcia, Jose	
Dorn, Lawrence E.	
Erukulla, Dilip Kumar	
Liang, Jinzhe	
Mullin, Elizabeth M.	
Tuz, Oleg	
Chandler, Julie A.	
Chung, Allan	
Fortune, Roger G.	Brooklyn Trust building
Gadani, Dhaval S.	
Jarosz, Michelle M.	
Linn, Rebecca C.	

FINISHING AIR LEAKAGE

Summary of air leakage measurements

- Blower door
 - Easy to perform
 - Spot measurements
 - Compare building to building
 - *Can* be used to link to actual AER
 - Difficult to get accurate predictions
- AER testing with tracer gas
 - Harder to perform
 - More time consuming (and expensive)
 - Real-life accurate measurements
 - Providing assumptions are met
- In enclosure design
 - Best to target tight envelope
 - Use blower door during construction

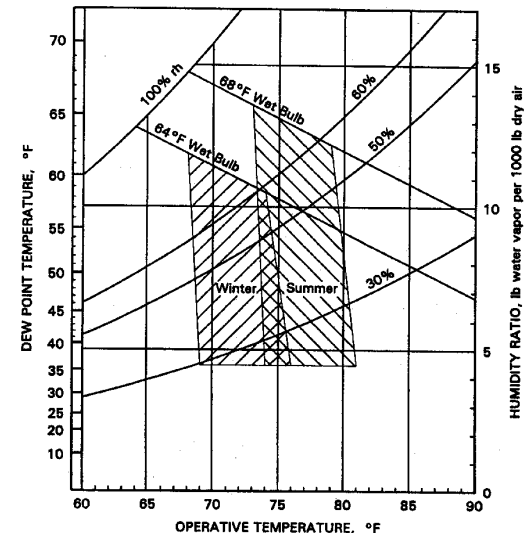


Air infiltration and energy use

- Infiltration is estimated to account for 25-50% of heating loads in both residential and commercial buildings
 - What factors does this depend on?
 - Outdoor climate
 - Indoor climate
 - Airtightness of building
 - Driving forces

$$Q_{\text{inf}} = \dot{m} C_p (T_{\text{in}} - T_{\text{out}})$$

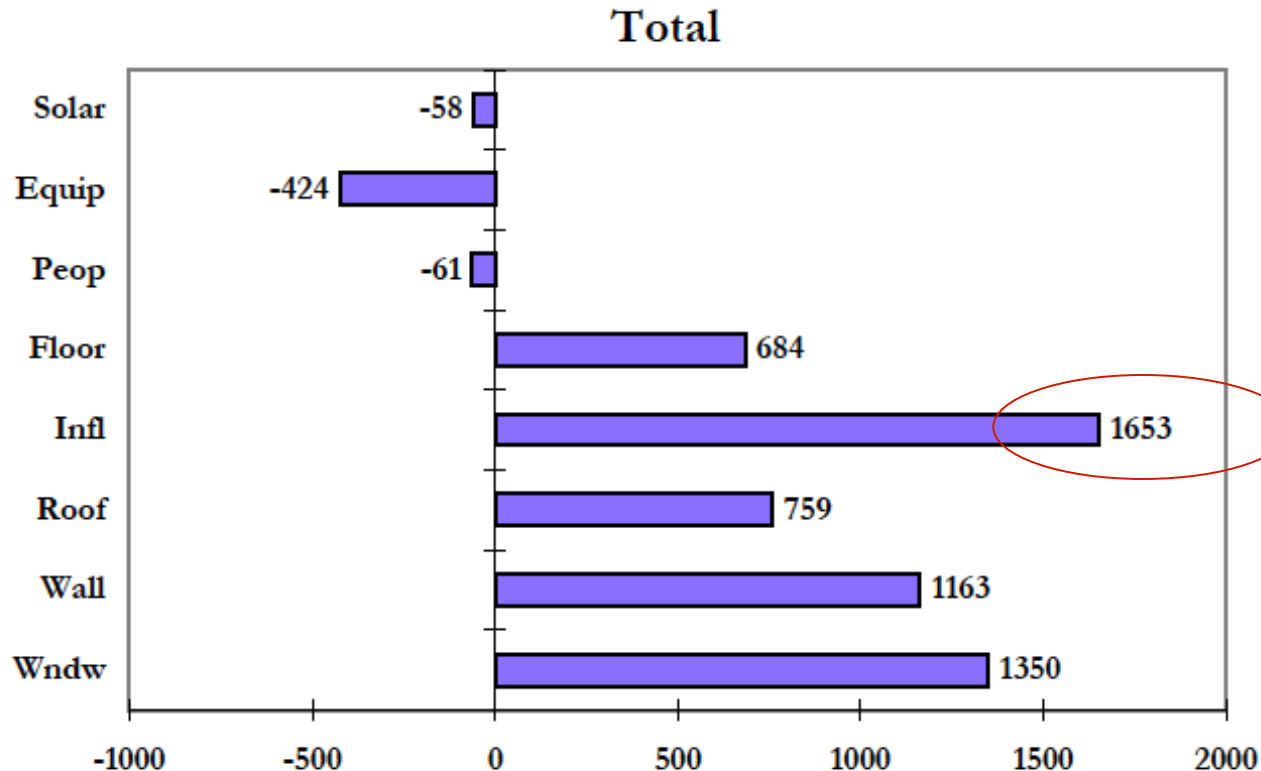
$$\dot{m} = \dot{V}_{\text{leaks}} \rho_{\text{air}}$$



As we keep T_{in} in the thermal comfort zone

Just how important are building envelopes for energy use?

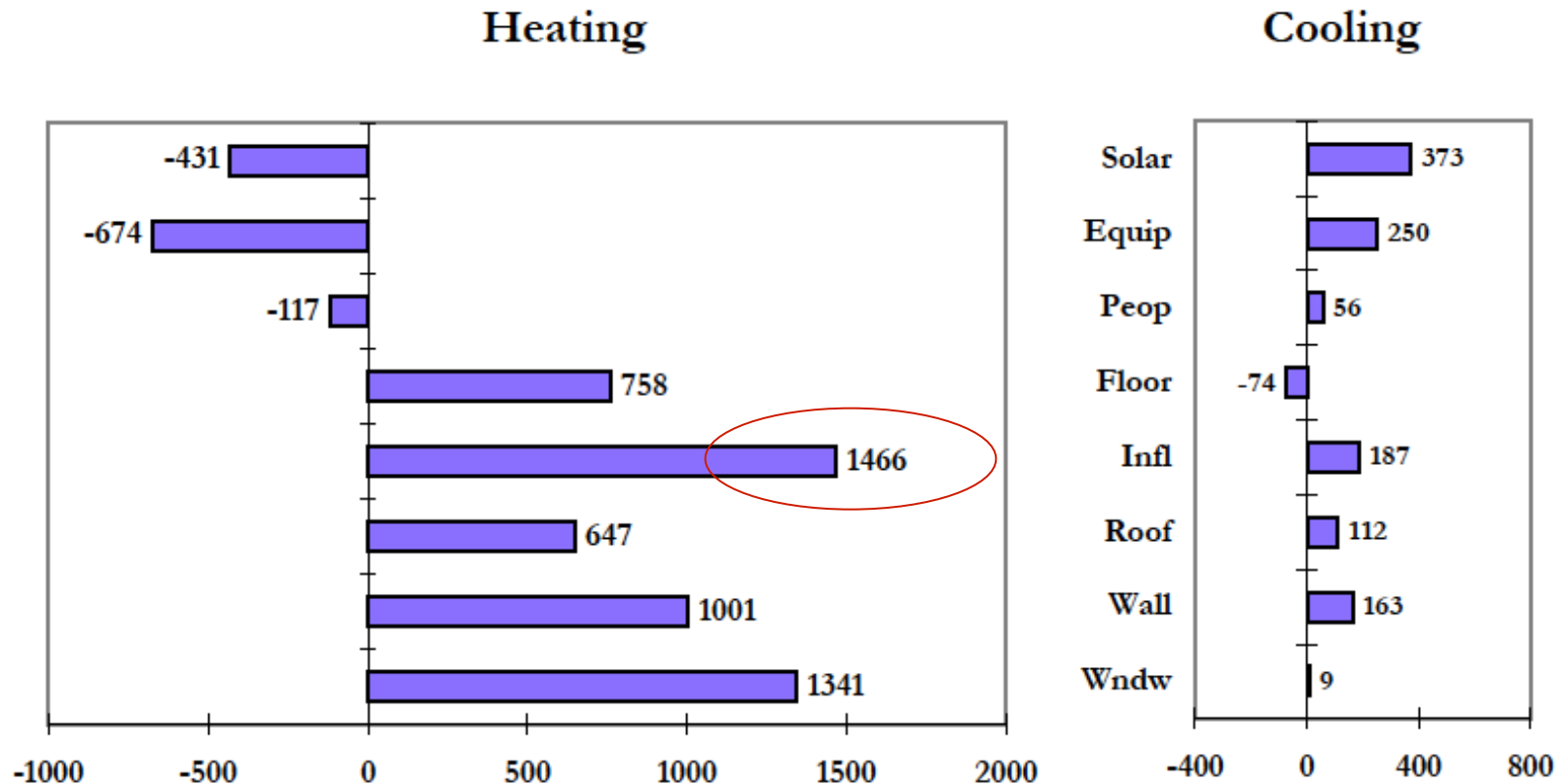
- 1999 study by Lawrence Berkeley National Laboratory
 - *Residential Heating and Cooling Loads Component Analysis*
 - Air infiltration is the **single greatest contributor** to energy use in U.S. homes



Aggregate component loads for all residential buildings (trillion BTUs)

Just how important are building envelopes for energy use?

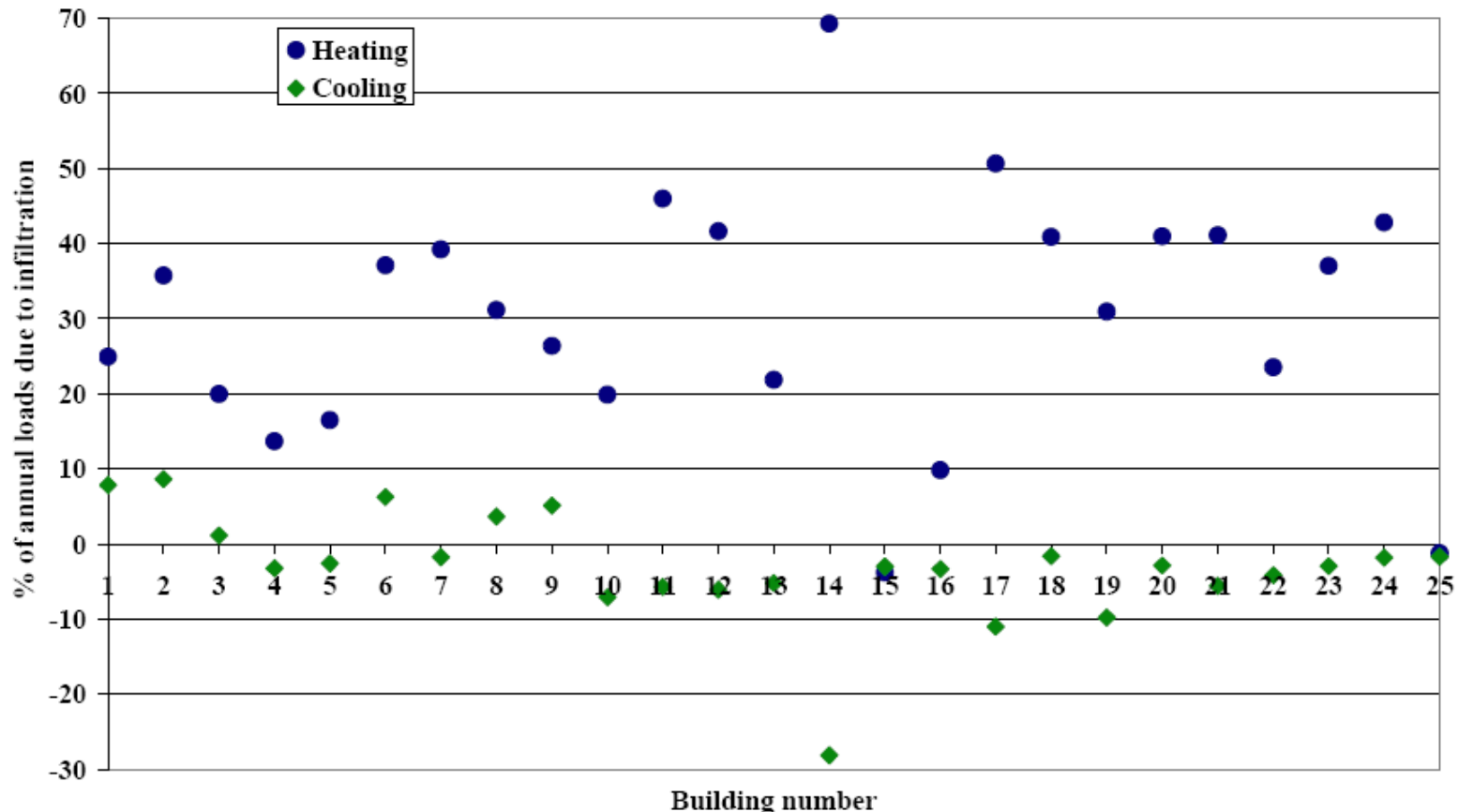
- 1999 study by Lawrence Berkeley National Laboratory
 - *Residential Heating and Cooling Loads Component Analysis*
 - Infiltration particularly important for **heating** loads



Aggregate component loads for all residential buildings (trillion BTUs)

Infiltration in commercial buildings

- A 2005 NIST study on the effect of infiltration on heating and cooling loads in commercial buildings:
 - Buildings ranged in size from 1 to 45 floors, located all over the US
 - 576 to 230000 m² in floor space



Infiltration in commercial buildings

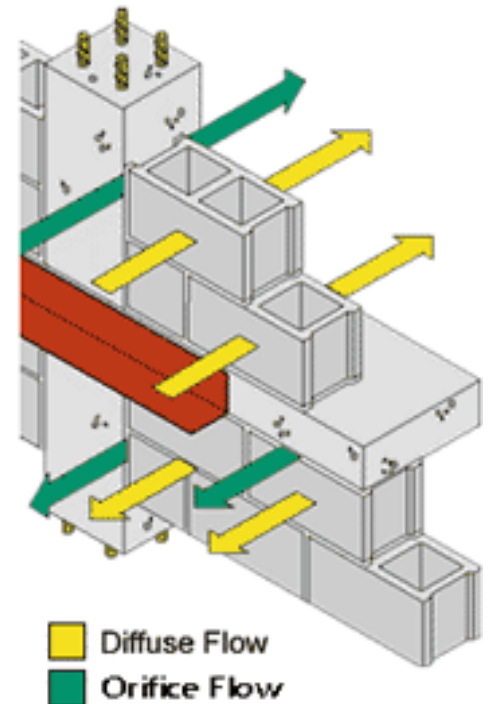
- Results show that air infiltration accounts for 33% of **heating loads** in commercial buildings, on average
 - Huge!
- **Cooling load** effects vary by climate and are smaller
 - Air infiltration actually accounted for a net *negative* cooling load of about 3.3% on average
- Why?
 - Commercial buildings were probably dominated by internal loads and cold infiltrated air actually helped reduce the need for cooling

CONTROLLING AIR LEAKAGE

in enclosure design and construction

Controlling air leakage

- We can control air leakage primarily through good construction
 - No sloppy joints
 - Proper air sealing/caulking
 - Controls “orifice flow”
- Even with good construction, air can diffuse through porous materials
 - Proper use of air barrier materials controls “diffuse flow”
- Let’s learn a little more about **air barriers** and how they relate to water and vapor barriers

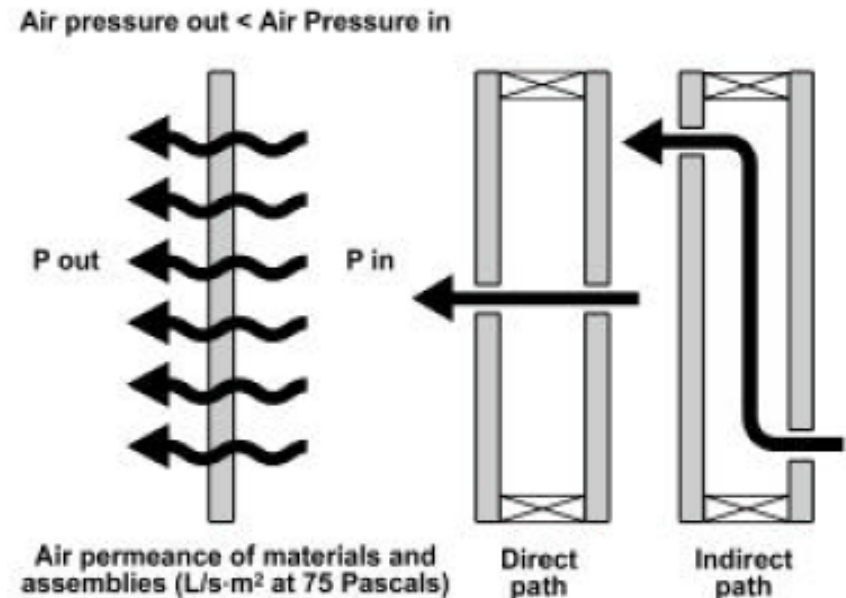


Three types of barriers ...

- We have encountered three terms that are often interchanged and confused:
 - Air barrier
 - Water barrier
 - Vapor barrier
- They are three different terms with three different meanings:
 - An **air barrier** resists or blocks the movement of air
 - It does not necessarily stop vapor diffusion
 - A **water barrier** blocks the transmission of liquid water
 - Does not necessarily stop vapor diffusion or air movement
 - A **vapor barrier** blocks vapor diffusion
 - Does not necessarily stop air movement

Air barrier systems

- **Air barrier systems** are designed to control the movement of air between the inside and outside of the building through all paths
 - Air diffusion
 - Direct leaks
 - Indirect leaks
- An air barrier **material** resists diffusion and direct transport of air
 - Most air barriers are also water barriers
 - But not all are vapor barriers



Air barrier materials

- An air barrier is a material with an air **permeance** of less than $0.02 \text{ L/s/m}^2 @ 75 \text{ Pa}$
 - $0.004 \text{ cfm/ft}^2 @ 0.3 \text{ in H}_2\text{O}$
- Air barrier materials only work properly if there are no other air leaks that allow airflow to bypass the materials
- This is tested using ASTM E 2178 and is regulated by the Air Barrier Association of America (ABAA)
- Information on material testing:
http://www.airbarrier.org/materials/index_e.php



Air permeance of materials (@ 75 Pa)

Air barriers

Material	Leakage $L/(s \cdot m^2)$
Roofing Membrane	0
Aluminum Foil	0
Mod. Bitum Roof	0
Plywood (3/8")	0
Extruded Poly (38mm)	0
Foil Back Urethane (1")	0
Cement Board	0
Foil Backed Gypsum	0
Plywood (1/4")	0.0067
OSB (1/2")	0.019

Not air barriers

Material	Leakage $L/(s \cdot m^2)$
Gypsum (1/2")	0.020
Particle Board (5/8")	0.026
Expanded Poly	0.19
Roofing Felt (30lb)	0.19
Asphalt Felt (15lb)	0.40
Fiberboard (1/2")	0.082
Olefin Film	0.953
Glasswool Insulation	36.7

From CMHC Study 98-109

Air Permeance of Building Materials

Air permeance and permeability

2013 ASHRAE Handbook Chapter 26

Table 4 Air Permeability of Different Materials

Material	Mean Air Permeability, kg/(Pa·s·m)
Cement board, 12.5 mm, 1140 kg/m ³	3×10^{-8}
Fiber cement board, 6.3 mm, 1380 kg/m ³	3×10^{-12}
Gypsum wall board, 12.5 mm, 625 kg/m ³	4.2×10^{-9}
with one coat primer	2.2×10^{-8}
with one coat primer/two coats latex paint	2.5×10^{-9}
Hardboard siding, 9.5 mm, 740 kg/m ³	4.5×10^{-9}
Oriented strand board (OSB), 1140 kg/m ³ , 9.5 mm	1×10^{-9}
11 mm	2×10^{-9}
12.5 mm	1×10^{-9}
Douglas fir plywood, 12.5 mm, 455 kg/m ³	4×10^{-11}
16 mm, 545 kg/m ³	1×10^{-9}
Canadian softwood plywood, 19 mm, 450 kg/m ³	2×10^{-11}
Wood fiber board, 9.5 mm, 320 kg/m ³	2.5×10^{-7}

*Units similar to water vapor permeability

Masonry Materials

Aerated concrete, 460 kg/m ³	5×10^{-9}
Cement mortar, 1600 kg/m ³	1.5×10^{-9}
Clay brick, 100 by 100 by 200 mm, 1990 kg/m ³	$2 \text{ to } 5 \times 10^{-10}$
Limestone, 2500 kg/m ³	negligible
Portland stucco mix, 1990 kg/m ³	1×10^{-11}
Eastern white cedar, (transverse) 19 mm, 465 kg/m ³	negligible
Eastern white pine, (transverse) 19 mm, 465 kg/m ³	1×10^{-12}
Southern yellow pine, (transverse) 19 mm, 500 kg/m ³	3×10^{-11}
Spruce, (transverse) 19 mm, 400 kg/m ³	5×10^{-11}
Western red cedar, (transverse) 19 mm, 350 kg/m ³	$< 1 \times 10^{-12}$
Cellulose insulation, dry blown, 32 kg/m ³	2.9×10^{-4}
Glass fiber batt, 16 kg/m ³	2.5×10^{-4}
Polystyrene expanded, 16 kg/m ³	1.1×10^{-8}
sprayed foam, 38 kg/m ³	1×10^{-11}
6.5 to 19 kg/m ³	4.2×10^{-9}
Polyisocyanurate insulation, 26.5 kg/m ³	negligible
Bituminous paper (#15 felt), (transverse) 0.7 mm, 865 kg/m ³	2.5×10^{-6}
Asphalt-impregnated paper	1.1×10^{-6}
#10, (transverse) 0.13 mm, 95 kg/m ³	
#30, (transverse) 0.15 mm, 130 kg/m ³	6.6×10^{-6}
#60, (transverse) 0.23 mm, 260 kg/m ³	7.1×10^{-6}
Spun bonded polyolefin (SBPO) (transverse) 0.1 mm, 14 kg/m ³	4.6×10^{-7}
with crinkled surface, (transverse) 0.075-0.1 mm, 15 kg/m ³	3×10^{-7}
Wallpaper, vinyl, (transverse) 0.13 mm, 94 kg/m ³	5×10^{-9}
Exterior insulated finish system (EIFS), 1 mm, 1140 kg/m ³	0

Source: Kumaran (2002).

Tyvek building wrap

- Tyvek and other building wrap materials are both **air** and **water** barriers
 - But NOT **vapor** barriers
 - You can install them on the exterior of the building without regards to condensation caused by vapor diffusion
 - A material that is also a vapor barrier can be added for climates where vapor barriers should be installed toward the outside
- Tyvek must be installed with care to ensure proper sealing and flashing and to minimize penetrations through the material



Tyvek building wrap



Building wrap components



Building wraps: exterior air barrier

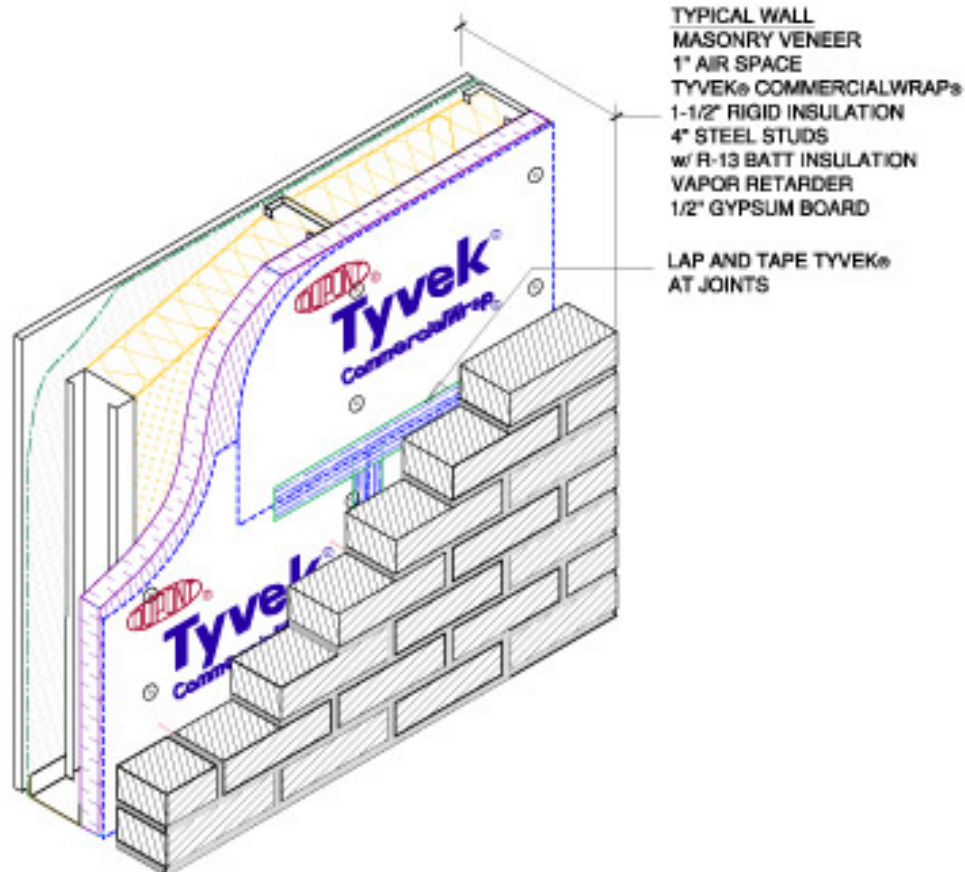


Photograph 2 – Exterior Air Barrier Using Adhered Membrane

Building wraps: exterior air barrier



Building wraps: detail drawings

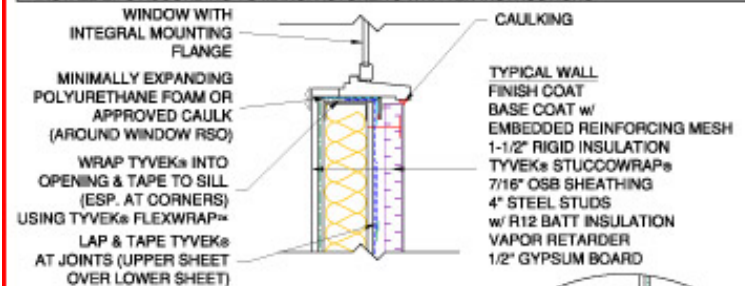


TYPICAL WALL ISOMETRIC

STEEL FRAME BACK-UP WALL w/ MASONRY VENEER (HEATING CLIMATE)

GENERAL NOTES

- *SEAL ALL TYVEK® JOINTS AND PENETRATIONS WITH APPROVED TAPE.
(ex. DUPONT CONTRACTOR TAPE).
- *FASTEN TYVEK® AND RIGID INSULATION TO STEEL STUDS
USING SCREWS w/ PLASTIC WASHERS. (ex. DUPONT WRAPCAPS)
- *LOCAL LAWS, ZONING, AND BUILDING CODES VARY AND
THEREFORE GOVERNS OVER MATERIAL SELECTION AND DETAILING SHOWN BELOW.
- *INSTALL EIFS ACCORDING TO MANUFACTURER'S WRITTEN INSTRUCTIONS



- FASTEN TYVEK® FLEXWRAP™
CORNER USING MECHANICAL
FASTENER
- INSTALL TYVEK® FLEXWRAP™
AROUND PERIMETER OF OPENING



WINDOW SILL DETAIL

STEEL FRAME BACK-UP WALL w/ EIFS CLADDING (HEATING CLIMATE)

Air barriers also require sealants

- To ensure the air barrier system really stops air, the overlap of air barriers must be considered
 - Proper adhesives and sealants must be used
 - **Tapes** are used to seal all overlaps on building wraps
 - **Caulks** are used to seal around joints between framing members, sill plates, sheathing, joists, etc.
 - If proper sealing is not done, air transport will occur
- Consult with manufacturers for instructions
 - And do as they say

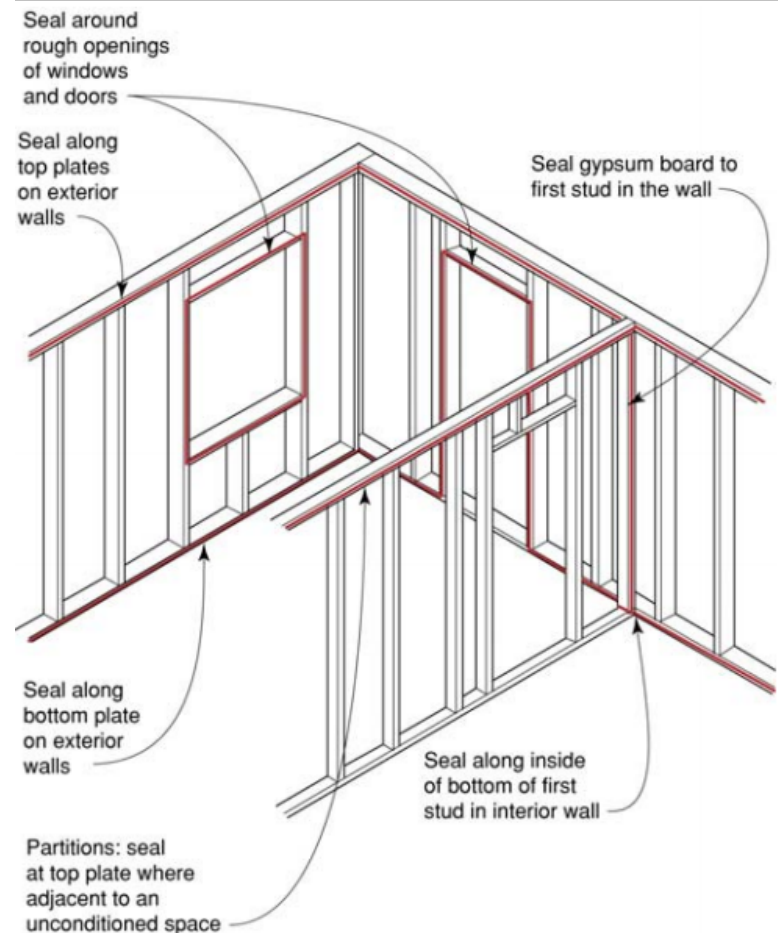
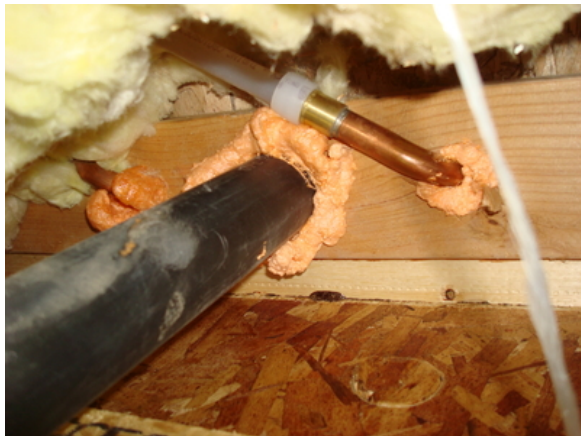


Some visual evidence of air leakage



Air sealing

- Air sealing around framing members, sill plates, sheathing, joists, plumbing penetrations, and many other places is one of the easiest and cheapest ways to reduce air leakage during construction
 - “Great Stuff” lives up to its name



Air sealing at construction



Air sealing during retrofits



Before chimney sealing



After chimney sealing

Air sealing during retrofits



Before band joist sealing



After band joist sealing

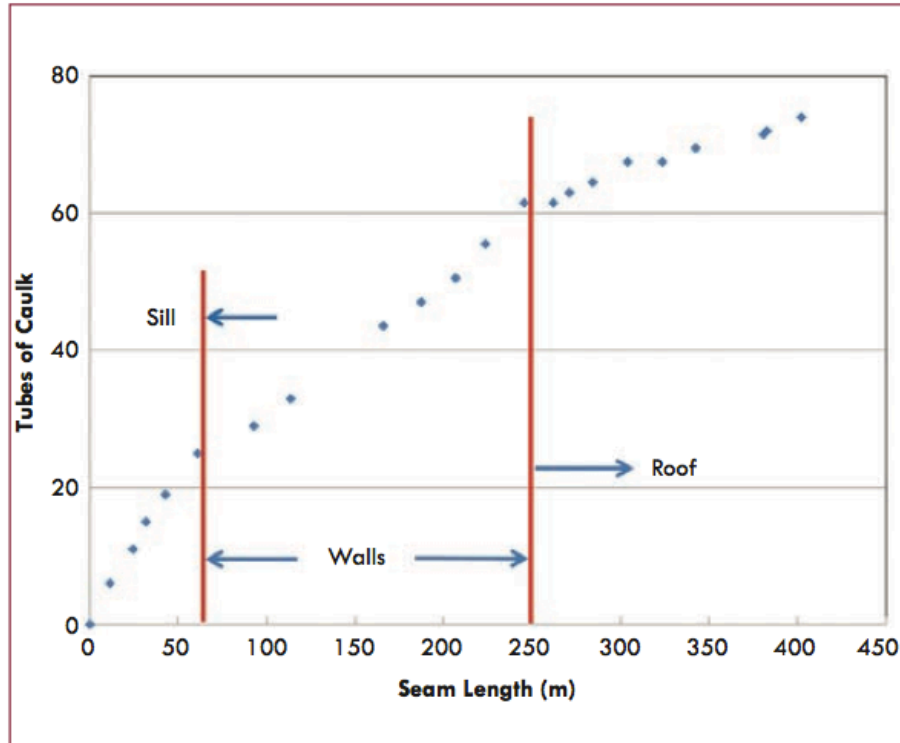
“Supersealing a house” during new construction

- Father and son team recently built a net zero energy capable home in Illinois
 - They performed blower door testing as they air sealed

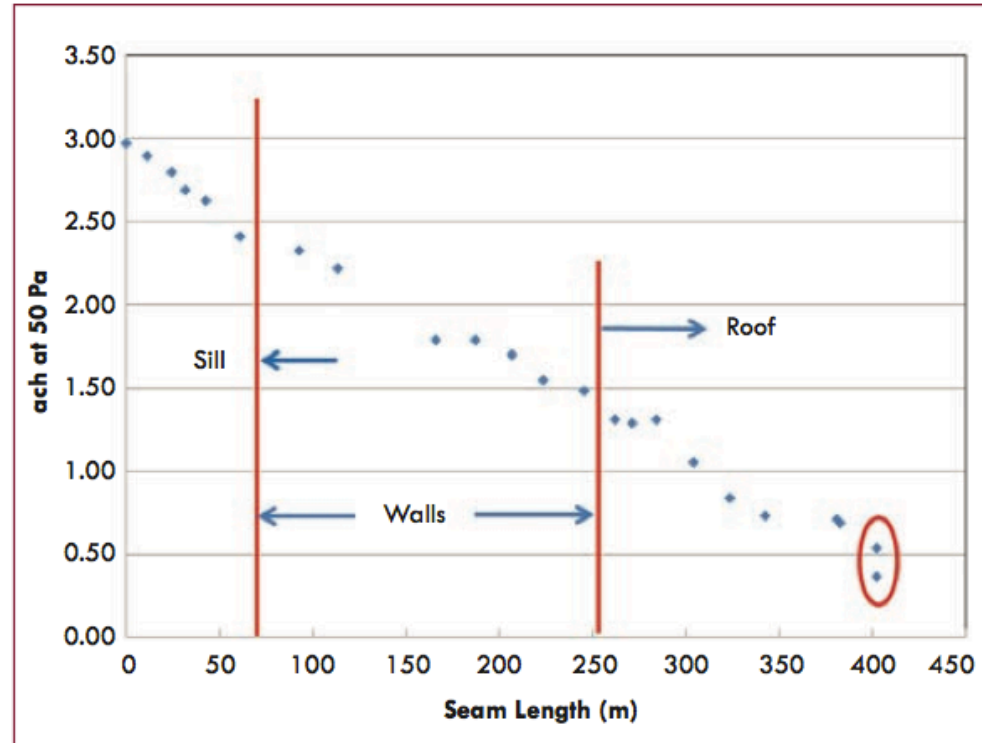


“Supersealing a house” during new construction

Cumulative length of caulking



Reductions in ACH₅₀ (blower door)



Air sealing during retrofits

- Case study at NIST test house
 - Manufactured test house in Gaithersburg, MD



- Performed retrofits
 - Increased envelope and HVAC ductwork airtightness
 - Installing house wrap and air sealing penetrations

Air sealing during retrofits

- Images of air sealing NIST house



Drain line in floor (from below), leakage associated with large hole in floor relative to pipe diameter



Drain and water lines after sealing

Air sealing during retrofits

- Blower door tests
 - Pre-retrofit: $ACH_{50} = 11.8 \text{ hr}^{-1}$
 - Post-retrofit: $ACH_{50} = 9.0 \text{ hr}^{-1}$
- Measured air exchange rates
 - 4% to 51% reduction in AERs after house wrap and air sealing retrofits
 - Depending on HVAC and climate conditions

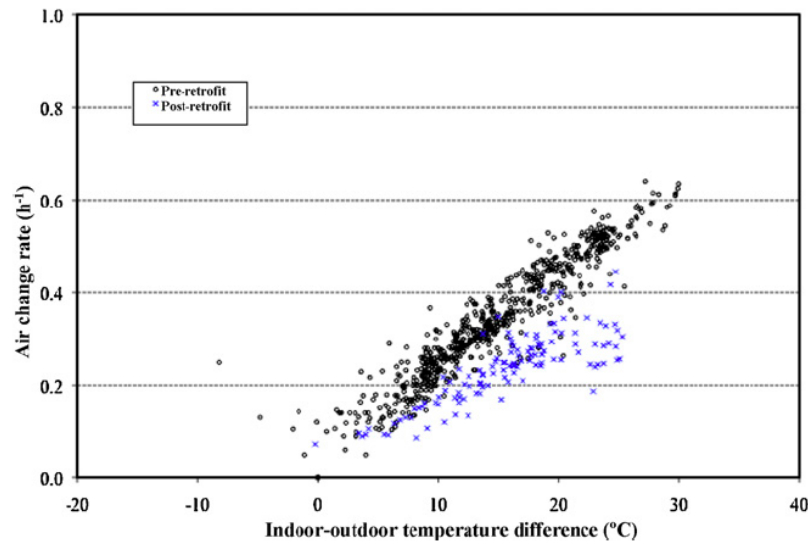


Fig. 6. Pre- and post-retrofit measured air change rates as a function of temperature difference (low wind speed): forced-air fan off (Condition 0).

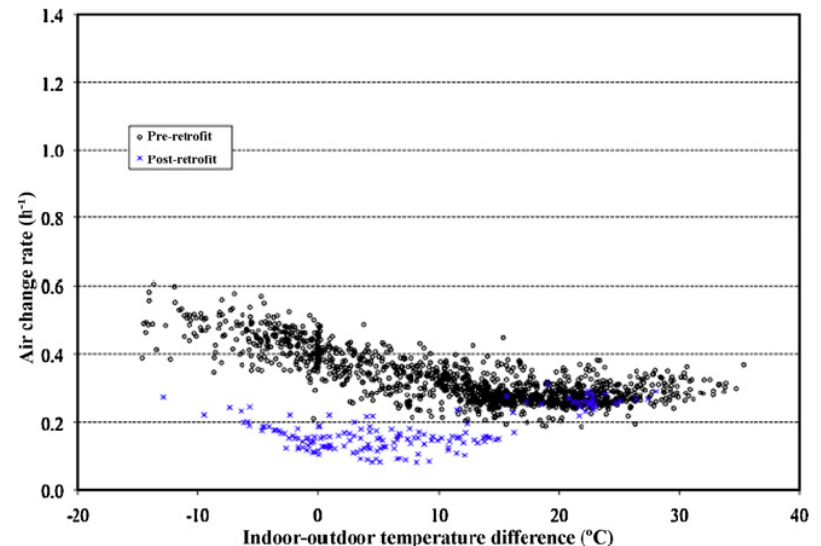
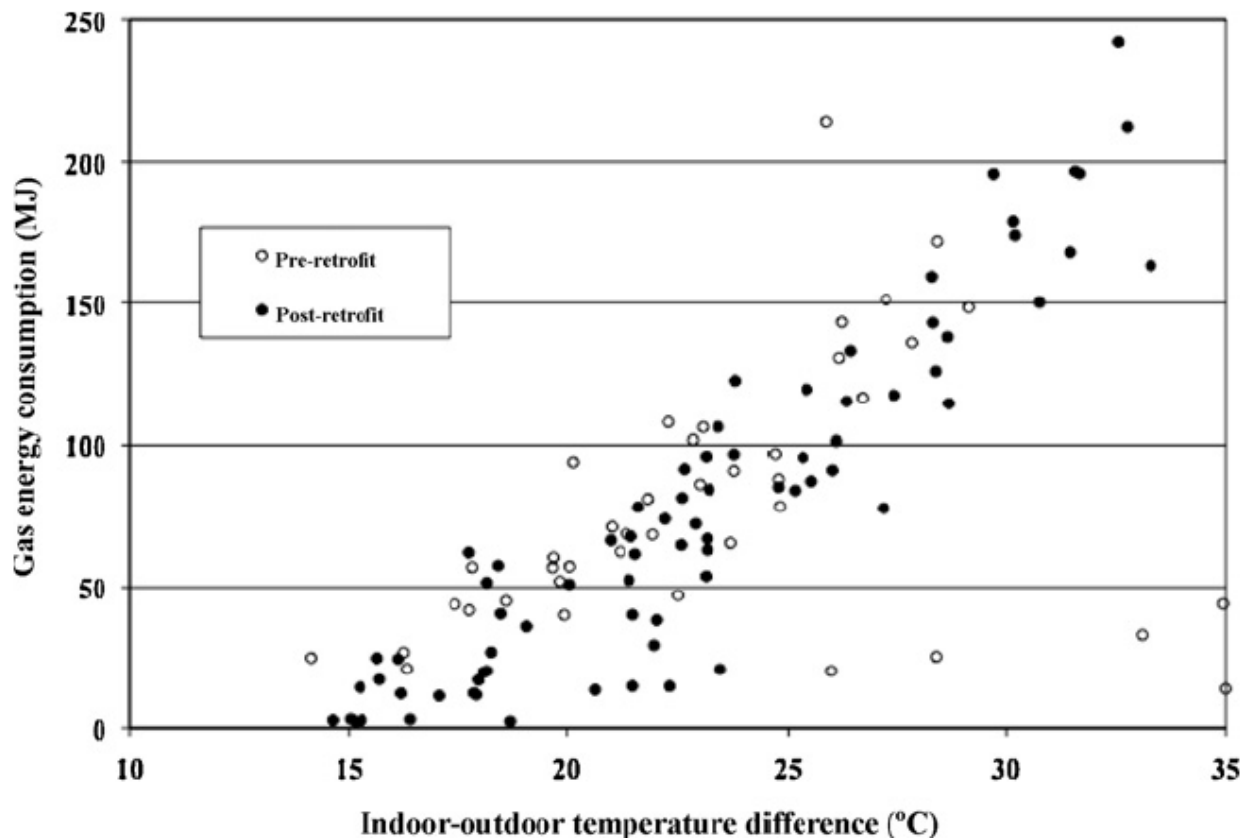


Fig. 8. Pre- and post-retrofit measured air change rates as a function of temperature difference (low wind speed): forced-air fan on, outdoor air intake sealed (Condition 1a).

Air sealing during retrofits

- Measured changes in heating energy use
 - A lot of scatter (many influencing factors)
 - General trend, however, was ~8% reduction in heating energy use



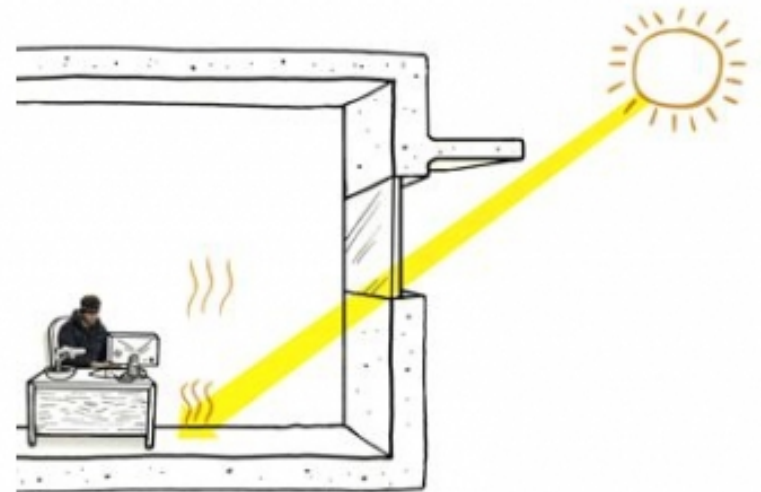
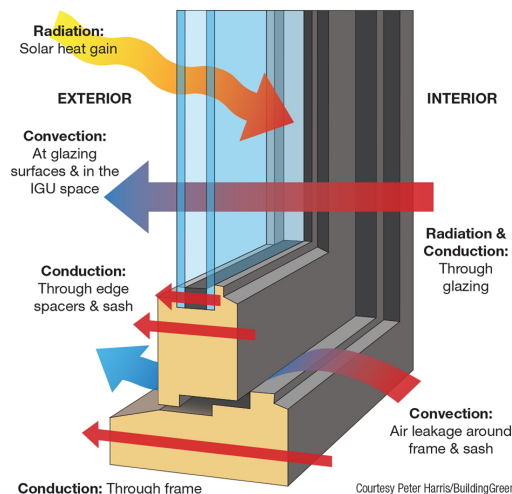
Summary of air movements

- Categories
 - Infiltration/exfiltration
 - Ventilation (natural or forced)
- Driving forces
 - Stack effect
 - Temperature and height differences
 - Leakage distributions
 - Wind effects
 - Wind direction
 - Wind speed
 - Leakage distributions
- Air tightness vs. actual air exchange rates
- Air permeance, air sealing, and air barriers

WINDOWS AND DAYLIGHTING

Lecture objectives

- Refresh our memory on the the basic components of fenestration/windows
 - Review from CAE 331/513 Building Science
- Understand building envelope design guidelines for fenestration systems
- Understand basics of daylighting and energy trade-offs



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 (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 (solar heat gain – utilize in cold climates; restrict in warm climates)
 - Use appropriate materials/assemblies to minimize heat transfer
 - 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

Fenestration and **total heat gains**

- The total heat gain of fenestration is the sum of two terms:
 - The heat gain from transmitted solar radiation
 - The combined conductive/convective/LWR thermal heat gain from the temperature difference between the interior and exterior
- In the summer, both terms are positive towards the interior and add to **heat gains** and increase the need for cooling
- In the winter, solar is positive inwards (**gain**) but thermal is negative towards the exterior (**loss**)
 - Net heat gain may be in either direction depending on magnitude

Fenestration and **total heat gains**

- Calculating the **conductive** heat gain/loss through fenestration is easy:

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

- 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):

$$Q_{solar} = (I_{solar} A) SHGC$$

Single glaze U-value

- U-value for a **single pane** of glass:

$$U = \left(\frac{1}{h_{int}} + \frac{L_{glass}}{k_{glass}} + \frac{1}{h_{ext}} \right)^{-1}$$

$$k_{glass} = \sim 1 \text{ W/mK}$$

$$L_{glass} = \sim 3 \text{ mm (0.003 m)}$$

$$^*R_{glass} \text{ is negligible } (\sim 0.005 \text{ m}^2\text{K/W})$$

$$h_{ext} = 29 \text{ W/m}^2\text{K is typical}$$

Table 2 Indoor Surface Heat Transfer Coefficient h_i in $\text{W}/(\text{m}^2 \cdot \text{K})$, Vertical Orientation (Still Air Conditions)

Glazing ID	Glazing Type	Glazing Height m	Winter Conditions			Summer Conditions		
			Glass Temp. °C	Temp. Diff. °C	h_i $\text{W}/(\text{m}^2 \cdot \text{K})$	Glass Temp. °C	Temp. Diff. °C	h_i $\text{W}/(\text{m}^2 \cdot \text{K})$
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 $t_i = 21^\circ\text{C}$, outdoor air temperature $t_o = -18^\circ\text{C}$, no solar radiation

Summer conditions: room air temperature $t_i = 24^\circ\text{C}$, outdoor air temperature $t_o = 32^\circ\text{C}$, direct solar irradiance $E_D = 748 \text{ W/m}^2$

$h_i = h_{ic} + h_{iR} = 1.46(\Delta T/L)^{0.25} + e\Gamma(T_g^4 - T_i^4)/\Delta T$

where $\Delta T = T_g - T_i$, K; L = glazing height, m; T_g = glass temperature, K

Computing U for a single glaze

$$U = \left(\frac{1}{h_{int}} + \frac{L_{glass}}{k_{glass}} + \frac{1}{h_{ext}} \right)^{-1}$$

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

Q: What contributes most to heat transfer resistance?

A: Not the glass! Actually the interior convection

What about multiple 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

Double- and triple-glazed glazing units

- 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

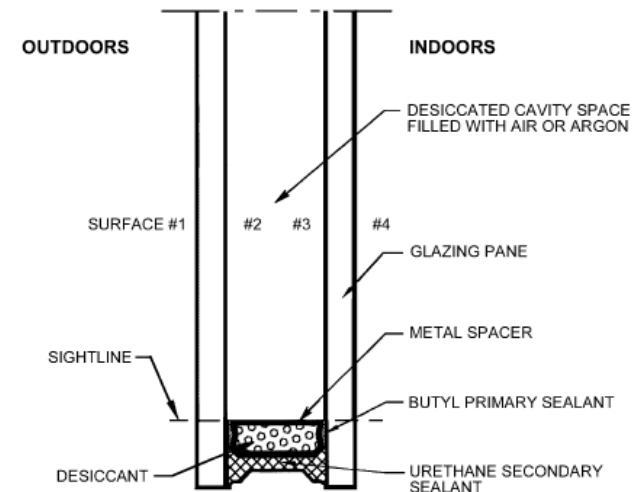


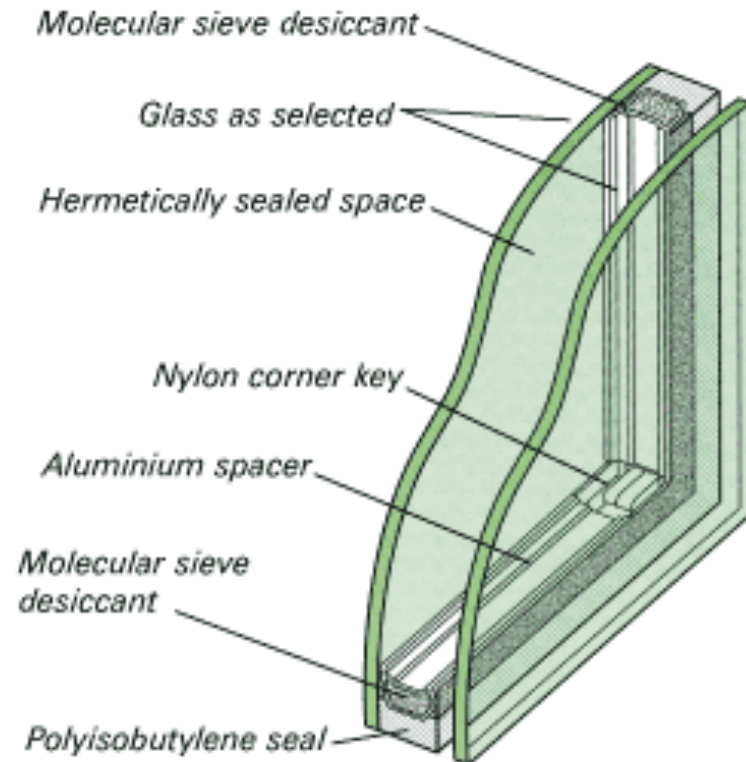
Fig. 1 Insulating Glazing Unit (IGU) Construction Detail

Insulated Glazing Units



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



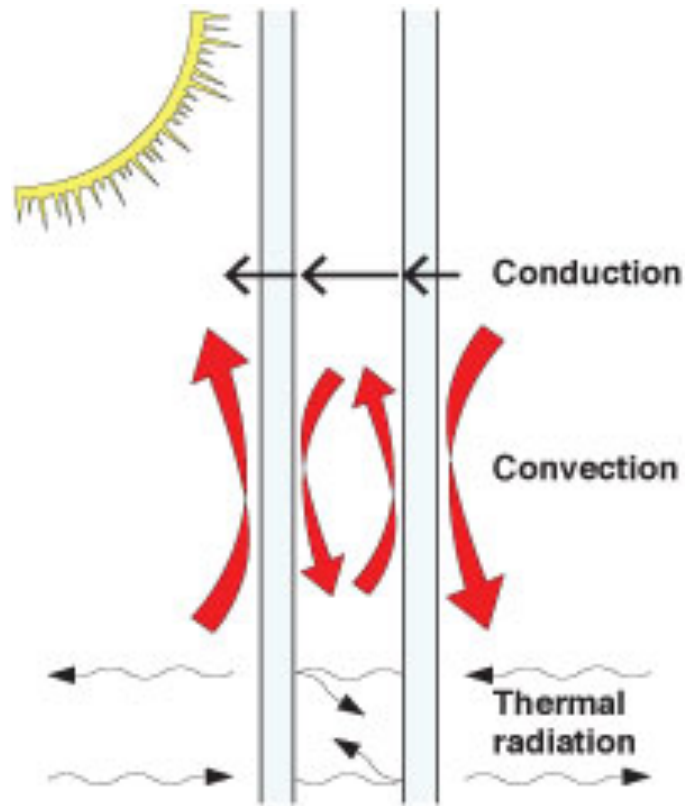
U-values for IGUs

- 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* can be estimated with a program called WINDOW
 - A companion to THERM
 - This is really the most cost-effective method to get accurate *U*
- Decent estimates of *U* 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

Separation distance

- U 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

U-values and multiple layers of glazing

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

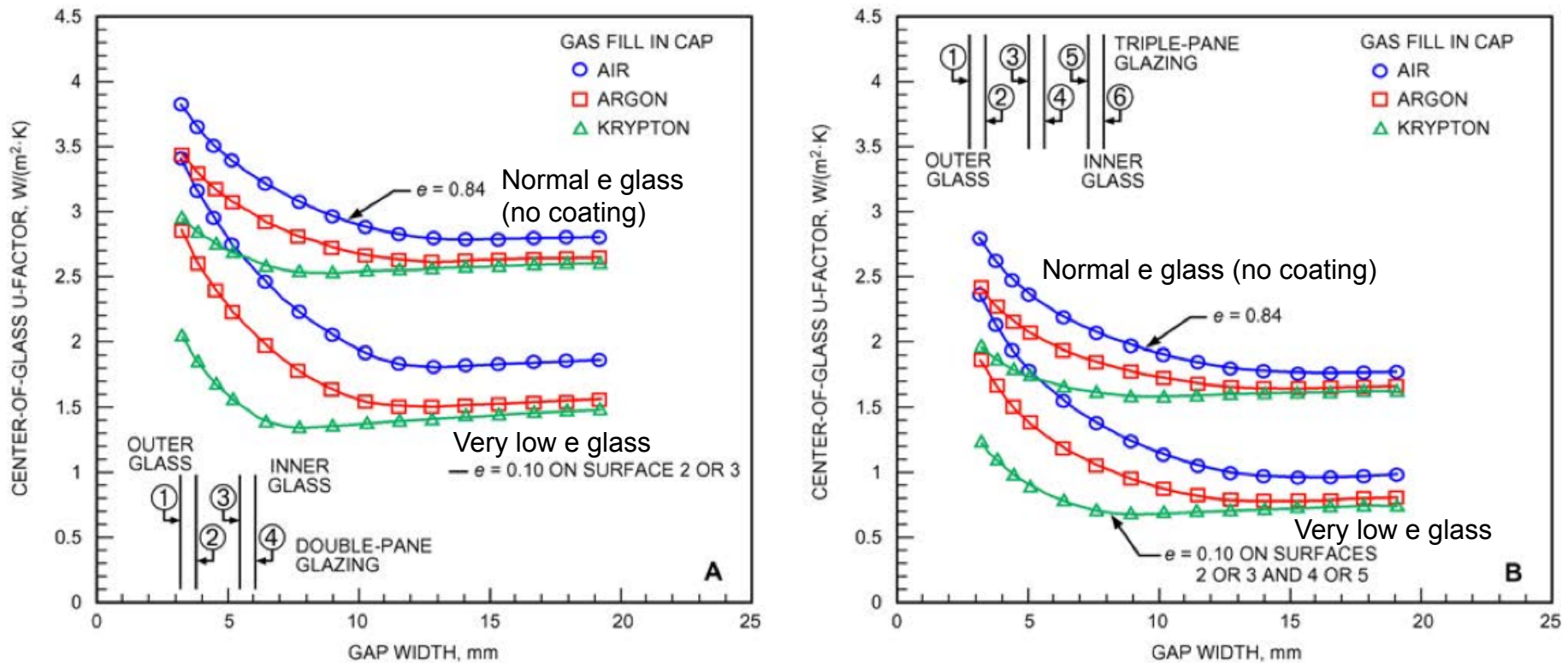


Fig. 3 Center-of-Glass U-Factor for Vertical Double- and Triple-Pane Glazing Units

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

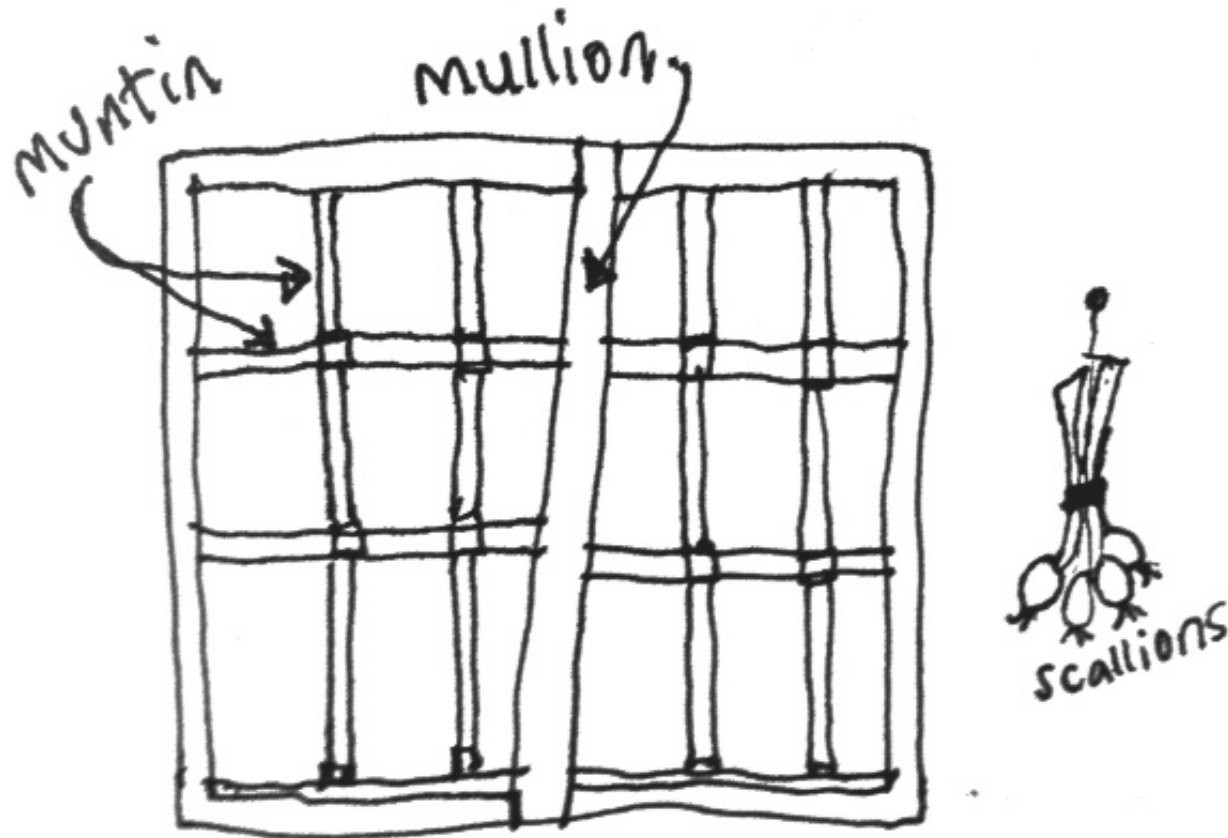
$$k_{air} = 0.025 \text{ W/mK}$$

$$k_{argon} = 0.016 \text{ W/mK}$$

$$k_{krypton} = 0.0088 \text{ W/mK}$$

What about full window/fenestration assemblies?

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



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:

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

Where:

U = overall coefficient of heat transfer (U-factor), W/m²K

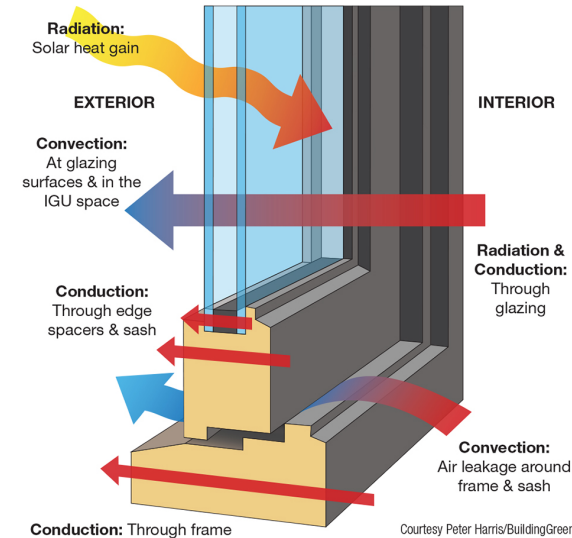
A_{pf} = total *projected* area of fenestration, m²

T_{in} = indoor air temperature, K

T_{out} = outdoor air temperature, K

SHGC = solar heat gain coefficient, -

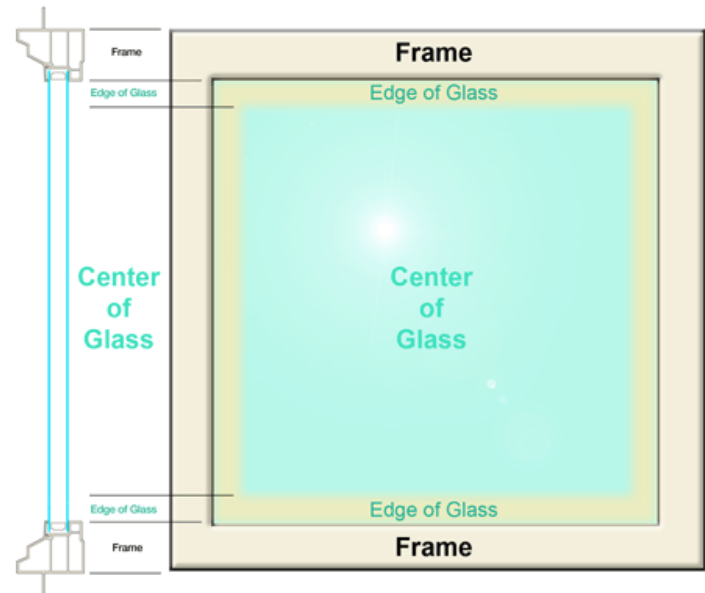
I_{solar} = incident total irradiance, W/m²



Window U-factors

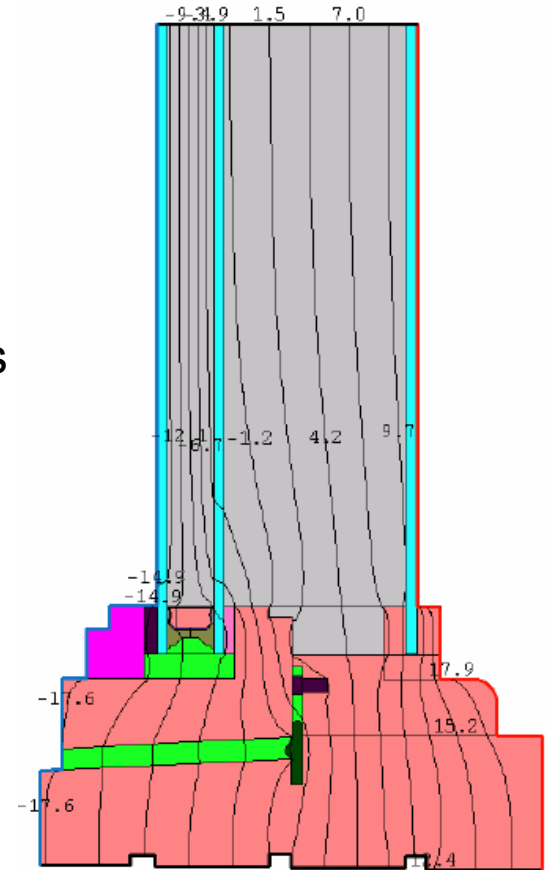
- U-values (or U-factors) for windows include all of the elements of the fenestration system
 - Center of glass properties (cg)
 - Edge of glass properties (eg)
 - Frame properties (f)
- The overall U-factor is estimated using area-weighted U-factors for each:

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



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 $W/(m^2 \cdot K)$, 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.

^aDepends strongly on width of thermal break. Value given is for 9.5 mm.

^bSingle glazing corresponds to individual glazing unit thickness of 3 mm. (nominal).

^cDouble glazing corresponds to individual glazing unit thickness of 19 mm. (nominal).

^dTriple glazing corresponds to individual glazing unit thickness of 34.9 mm. (nominal).

^eGlass thickness in curtainwall and sloped/overhead glazing is 6.4 mm.

^fSingle glazing corresponds to individual glazing unit thickness of 6.4 mm. (nominal).

^gDouble glazing corresponds to individual glazing unit thickness of 25.4 mm. (nominal).

^hTriple glazing corresponds to individual glazing unit thickness of 44.4 mm. (nominal).

n/a Not applicable

U_{cg} , U_{eg} , and U_f combine to yield **assembly U factors**

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

Product Type			Vertical Installation										
			Glass Only		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 3.2 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

Low-emissivity (“low-e”) glass

- Improves thermal performance
 - Very 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 emissivity < 0.4 is typical
 - Standard glass is ~ 0.8
 - Result:
 - Reduced U-value for double glaze windows

U_{cg} , U_{eg} , and U_f combine to yield **assembly U factors**

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												
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

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

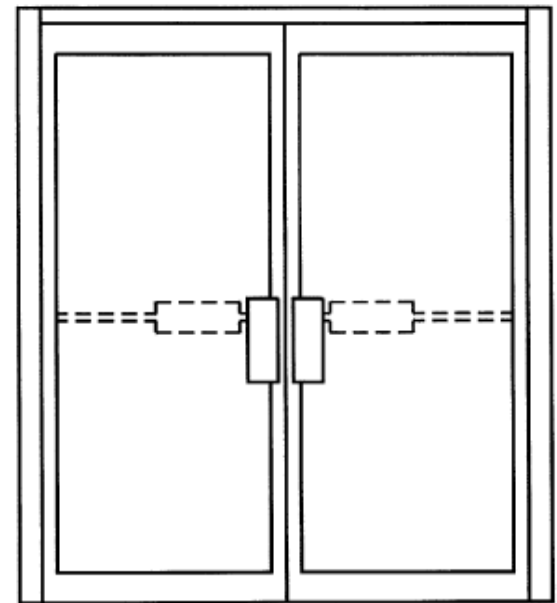


Fig. 5 Details of Stile-and-Rail Door

Doors

- U-values for typical doors

Table 6 U-Factors of Doors in $W/(m^2 \cdot K)$

Door Type	No Glazing	Single Glazing	Double Glazing with 12.7 mm Airspace	Double Glazing with 12.7 mm Argon, $e = 0.10$
SWINGING DOORS (Rough Opening, 970 × 2080 mm)				
<i>Slab Doors</i>				
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			
<i>Style and Rail Doors</i>				
Sliding glass doors/ French doors		Use Table 4 (operable)		

Table 6 U-Factors of Doors in $W/(m^2 \cdot K)$

Door Type	No Glazing	Single Glazing	Double Glazing with 12.7 mm Airspace	Double Glazing with 12.7 mm Argon, $e = 0.10$
<i>Site-Assembled Style and Rail Doors</i>				
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 $W/(m^2 \cdot K)$ for non-thermally broken sill)

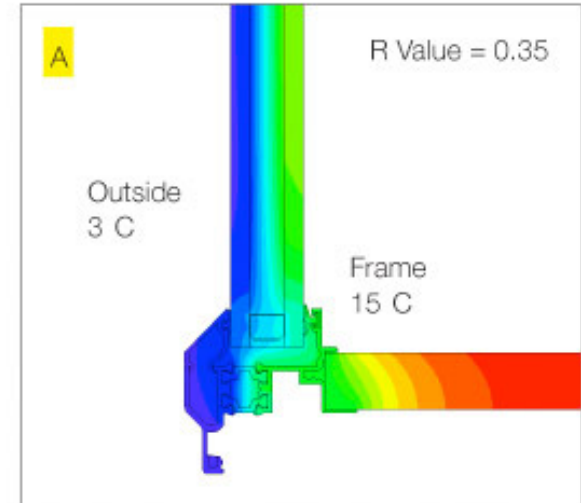
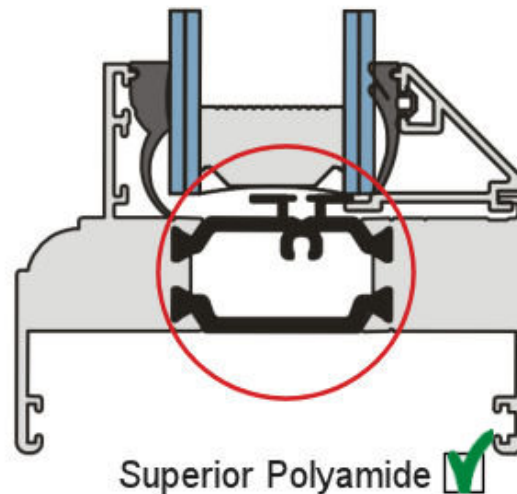
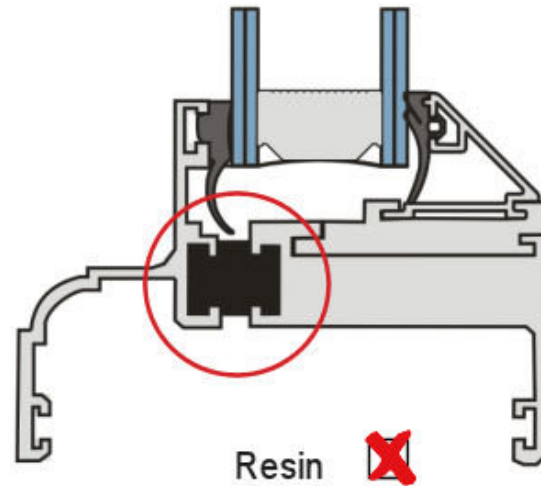
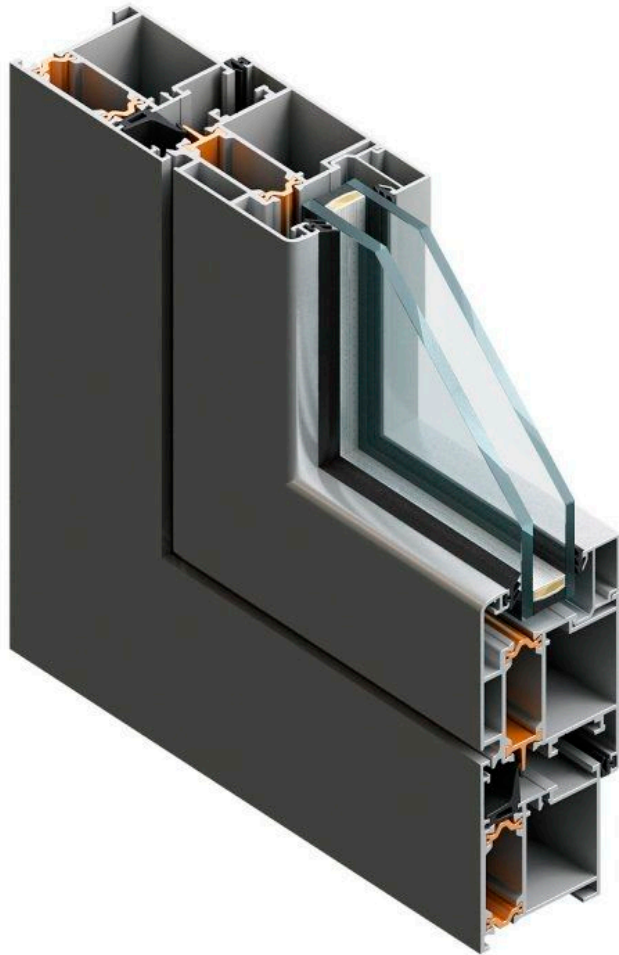
^b non-thermally broken sill

^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.

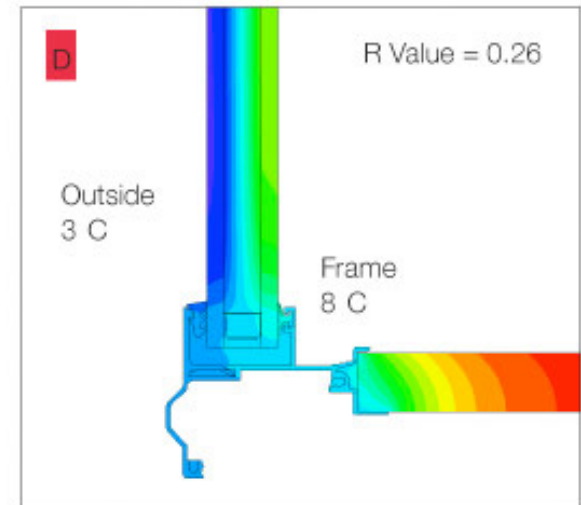
Ways to achieve low U-values in fenestration

- Heavy gas fill
 - Air has a lower thermal conductivity than glass
 - 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
- Optimize air spaces
 - 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 U-values further
 - Downsides: higher costs and typically reduced optical transmission
- 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

Thermally-broken window frames



Thermal Heart™ with clear double glazing



Non-thermally broken with clear double glazing

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
- The same general rules as windows apply for thermal and moisture performance

Curtain walls



- Walls of Glass, PBS NOVA on One World Trade Center
 - <http://www.pbs.org/wgbh/nova/tech/walls-glass.html>

One World Trade Center curtain wall install



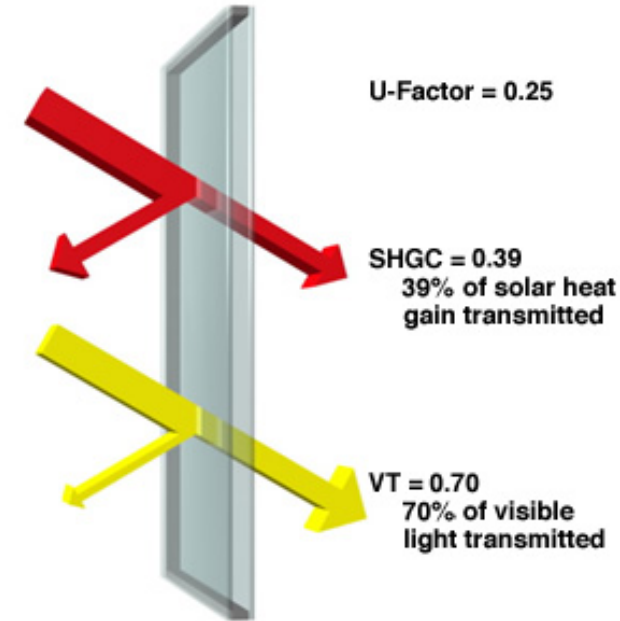
One World Trade Center curtain walls

- What were those magic properties that let light in but keep heat out?



Two other fenestration terms: SHGC and VT

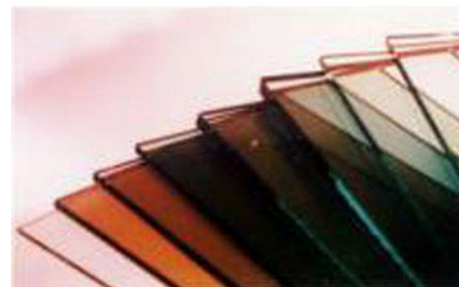
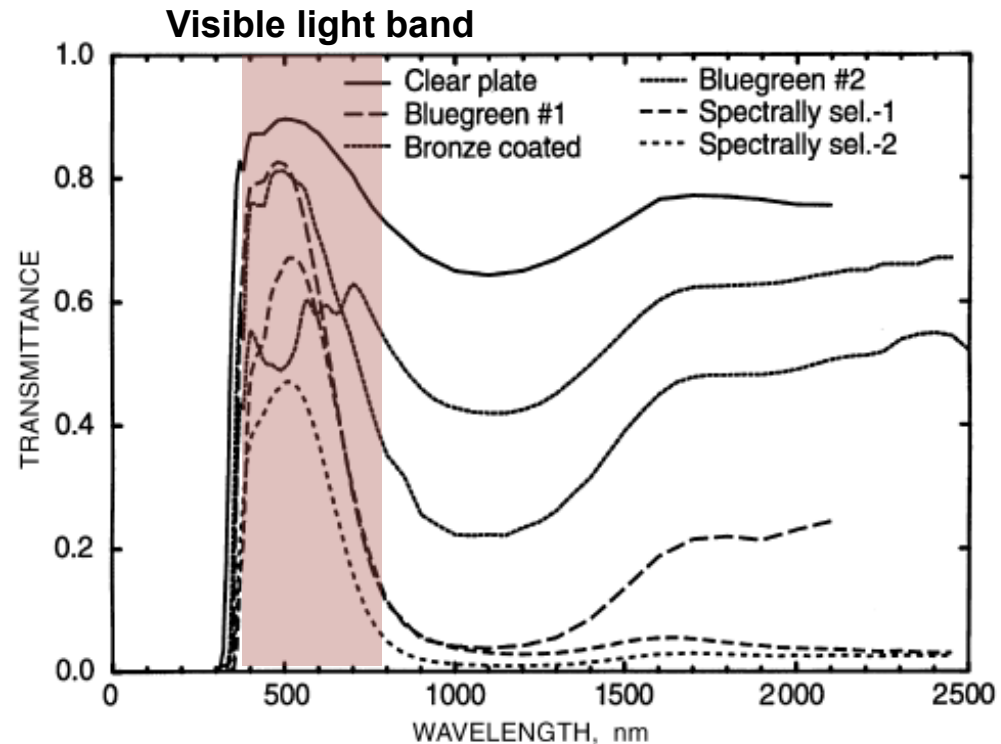
- So far we've only discussed thermal transfer
 - U-value or U-factor
- Fenestration also allows for solar heat transfer and transfer of visible light
 - **SHGC**: Solar Heat Gain Coefficient
 - Energy transfer coefficient for all wavelengths of solar thermal radiation
 - **VT**: Visible Transmission Coefficient
 - Transmission coefficient for visible wavelength solar radiation



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

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



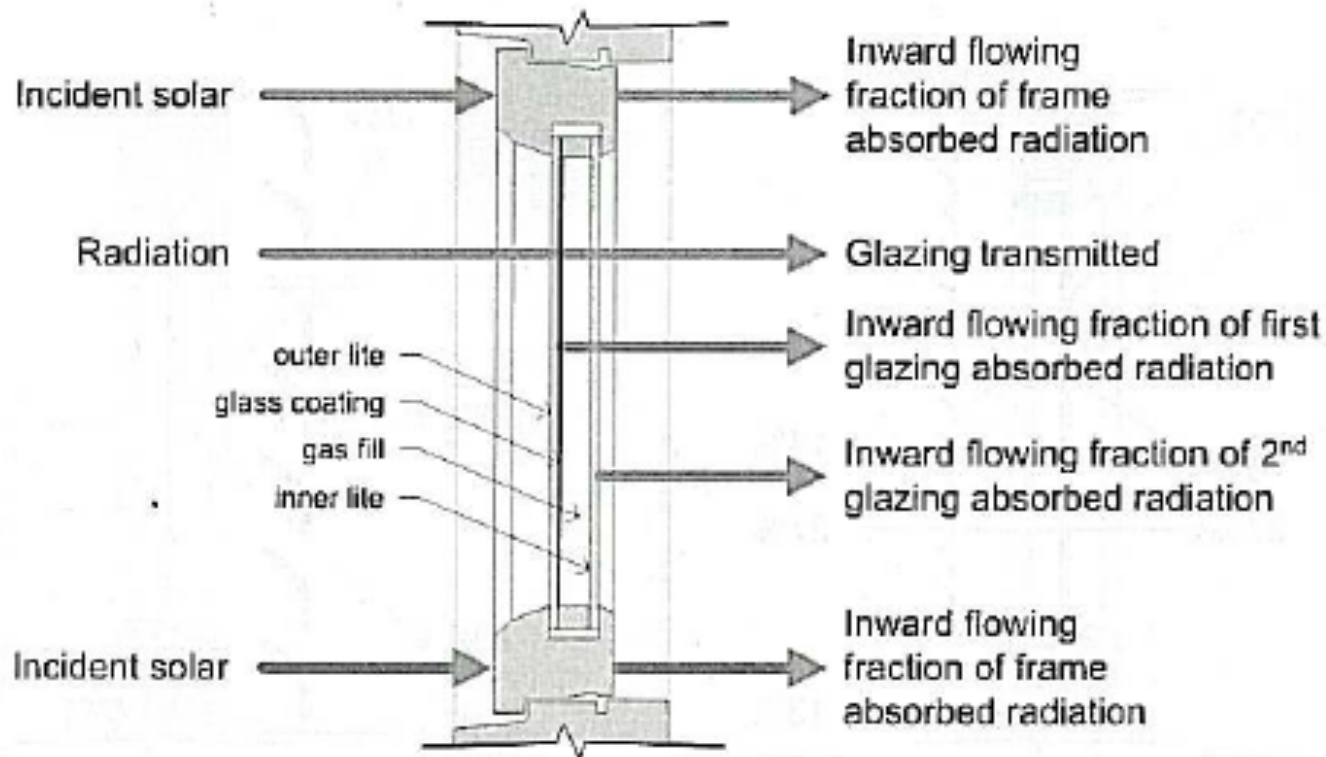
Tinted glass



Reflective glass

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



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

SHGC and energy use

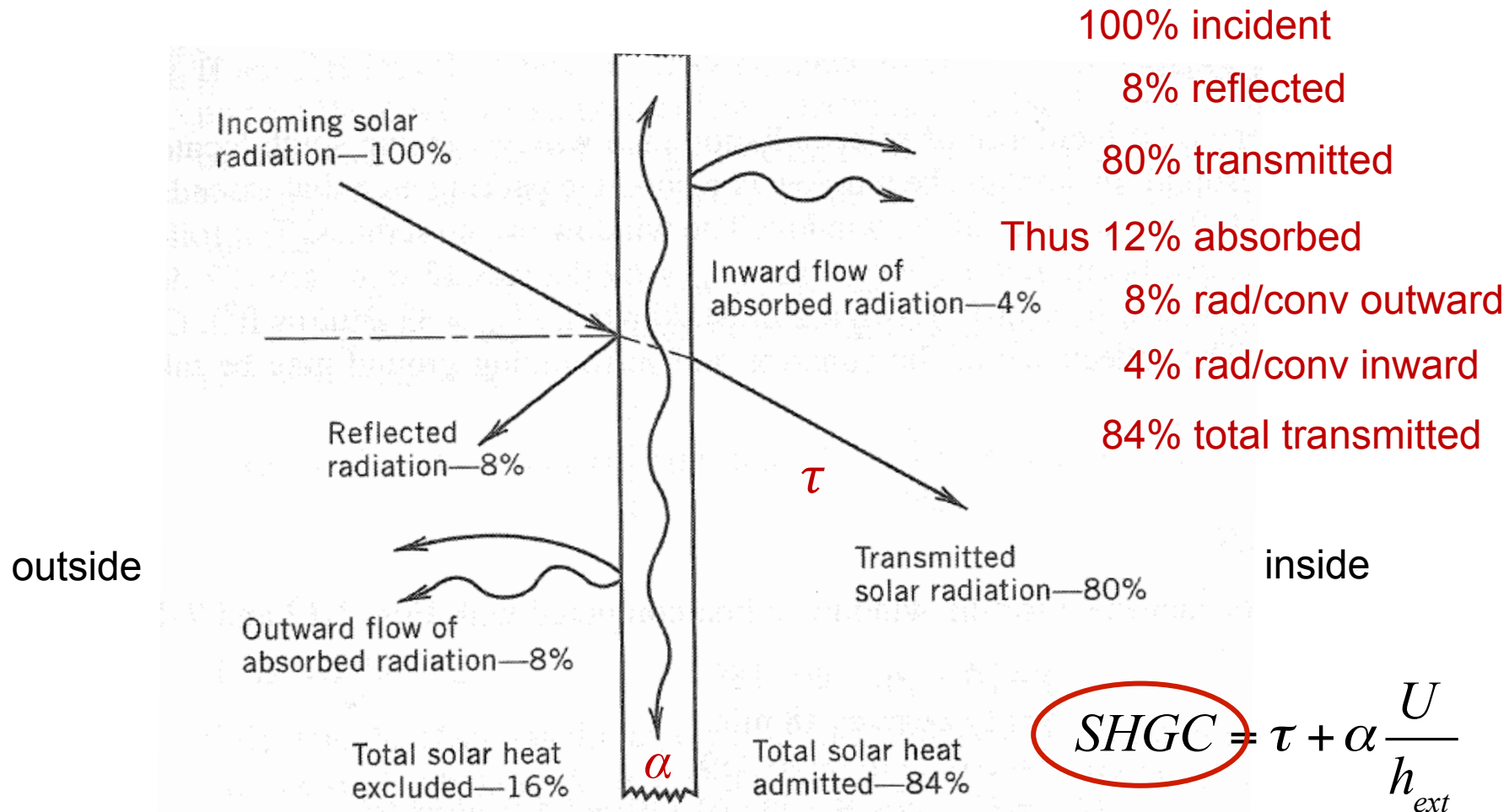
- Importance of dominant loads
- If we are dominated by the need for heating energy
 - We want to make use of solar energy to help heat our space
 - We want a higher SHGC
 - We would then use shading to reduce SHGC in summer
- If we are dominated by the need for cooling energy
 - We want a low SHGC to reduce solar heating
 - Can still use shading to help even more in the summer

Solar heat gain coefficient, SHGC

- Bounds: $0 < \text{SHGC} < 1$
- 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 stock data for directional and spectral variations

Solar heat gain coefficient, SHGC

- For a **single pane** of glass:



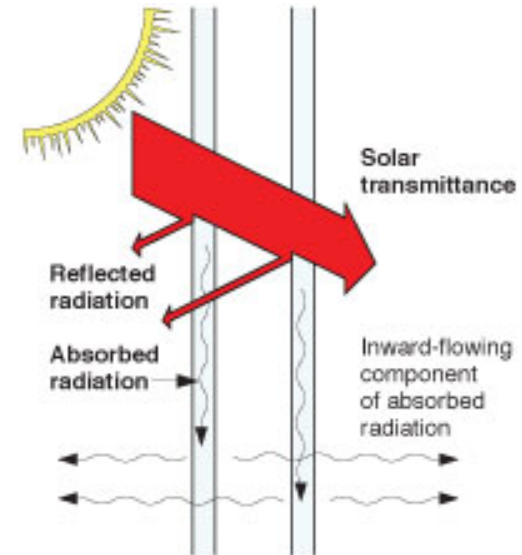
Solar heat gain coefficient, SHGC, for double glaze

- For **double glazing** with a small air space:

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

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

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



- This ends up being a complex problem...

Using tinted glass to vary SHGC and VT

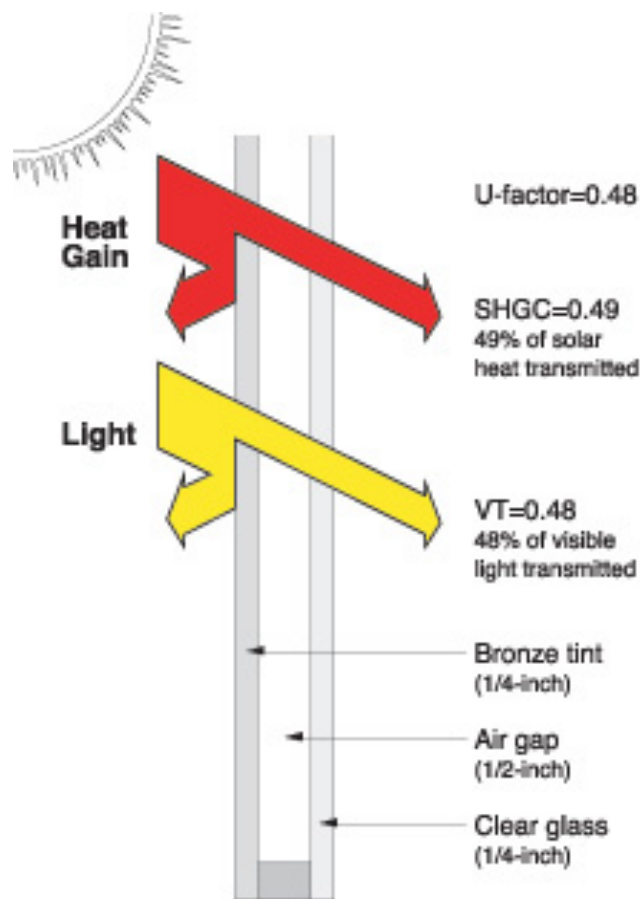


Figure 3-14. Double glazing with bronze-tinted glass on the outside layer

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

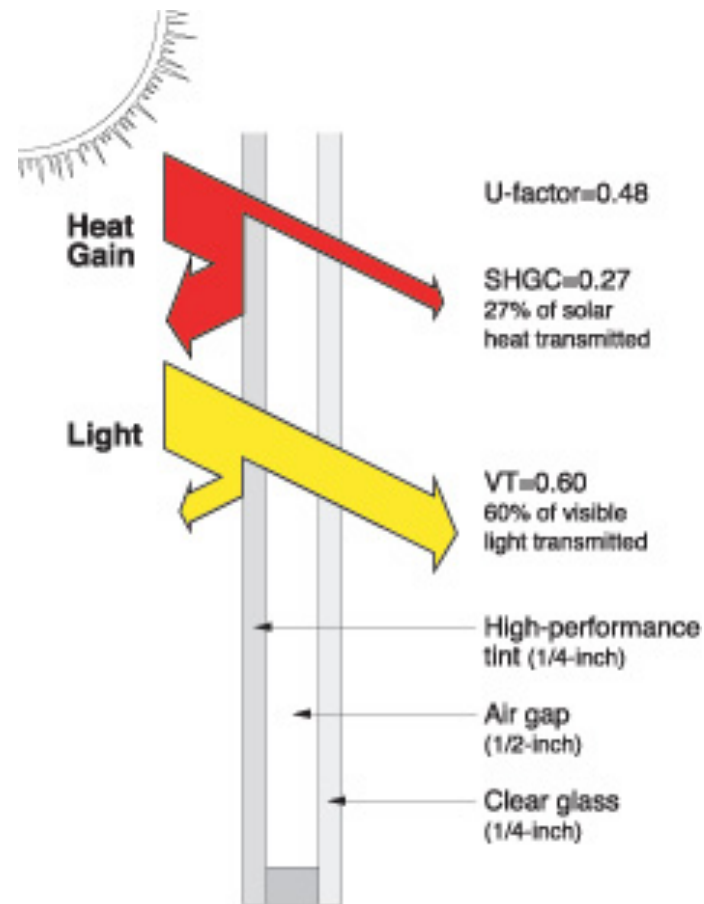


Figure 3-15. Double glazing with high-performance tint on the outside layer

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

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

Finding VT and SHGC data from ASHRAE

- If the manufacturer does not provide more detailed data, you can get prototypical data from ASHRAE Handbook
 - SHGC, solar transmittance, reflectance, and absorptance properties for glazing all vary with **incidence angles of solar radiation**

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			
												Aluminum		Other Frames		Aluminum		Other Frames	
												Operable	Fixed	Operable	Fixed	Operable	Fixed	Operable	Fixed
ID	Glass Thick., mm	Center Glazing T_v		Normal 0.00	40.00	50.00	60.00	70.00	80.00	Hemis., Diffuse									
<i>Uncoated Single Glazing</i>																			
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 (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 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}_1^f	0.10	0.11	0.11	0.12	0.13	0.13	0.11									
				\mathcal{A}_2^f	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}_1^f	0.17	0.18	0.19	0.20	0.21	0.20	0.19									
				\mathcal{A}_2^f	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}_1^f	0.30	0.33	0.34	0.36	0.37	0.34	0.33									
				\mathcal{A}_2^f	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}_1^f	0.48	0.51	0.52	0.53	0.53	0.45	0.50									
				\mathcal{A}_2^f	0.07	0.07	0.07	0.07	0.06	0.04	0.07									

VT and SHGC data from ASHRAE HOF

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 (*Continued*)

Glazing System				Center-of-Glazing Properties								Total Window SHGC at Normal Incidence				Total Window T_v at Normal Incidence			
												Aluminum		Other Frames		Aluminum		Other Frames	
												Operable	Fixed	Operable	Fixed	Operable	Fixed	Operable	Fixed
ID	Glass Thick., mm		Center Glazing T_v		Normal 0.00	40.00	50.00	60.00	70.00	80.00	Hemis., Diffuse								
<i>Low-e Double Glazing, $e = 0.2$ on surface 2</i>																			
17a	3	LE CLR	0.76	SHGC	0.65	0.64	0.61	0.56	0.43	0.23	0.57	0.59	0.60	0.53	0.58	0.68	0.68	0.61	0.67
				T	0.59	0.56	0.54	0.48	0.36	0.18	0.50								
				R^f	0.15	0.16	0.18	0.24	0.37	0.61	0.22								
				R^b	0.17	0.18	0.20	0.26	0.38	0.61	0.24								
				\mathcal{A}_1^f	0.20	0.21	0.21	0.21	0.20	0.16	0.20								
				\mathcal{A}_2^f	0.07	0.07	0.08	0.08	0.07	0.05	0.07								
17b	6	LE CLR	0.73	SHGC	0.60	0.59	0.57	0.51	0.40	0.21	0.53	0.55	0.55	0.49	0.53	0.65	0.66	0.58	0.64
				T	0.51	0.48	0.46	0.41	0.30	0.14	0.43								
				R^f	0.14	0.15	0.17	0.22	0.35	0.59	0.21								
				R^b	0.15	0.16	0.18	0.23	0.35	0.57	0.22								
				\mathcal{A}_1^f	0.26	0.26	0.26	0.26	0.25	0.19	0.25								
				\mathcal{A}_2^f	0.10	0.11	0.11	0.11	0.10	0.07	0.10								

Using $SHGC_N$

- If we are not worried about great accuracy, we can just 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 incidence 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 (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	
					Normal	40.00	50.00	60.00	70.00	80.00	Hemis., Diffuse	Operable	Fixed	Operable	Fixed	Operable	Fixed	Operable	Fixed
ID	Glass Thick., mm	Center Glazing T_V			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}_1^f	0.10	0.11	0.11	0.12	0.13	0.13	0.11								
				\mathcal{A}_2^f	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	0.67	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}_1^f	0.17	0.18	0.19	0.20	0.21	0.20	0.19								
				\mathcal{A}_2^f	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}_1^f	0.30	0.33	0.34	0.36	0.37	0.34	0.33								
				\mathcal{A}_2^f	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}_1^f	0.48	0.51	0.52	0.53	0.53	0.45	0.50								
				\mathcal{A}_2^f	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/m² at an angle of incidence of 60° and the diffuse + reflected incident radiation is 70 W/m², what is the instantaneous solar heat gain?
 - SHGC_N = 0.63

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

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

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

Finding SHGC, U, VT, and air leakage data

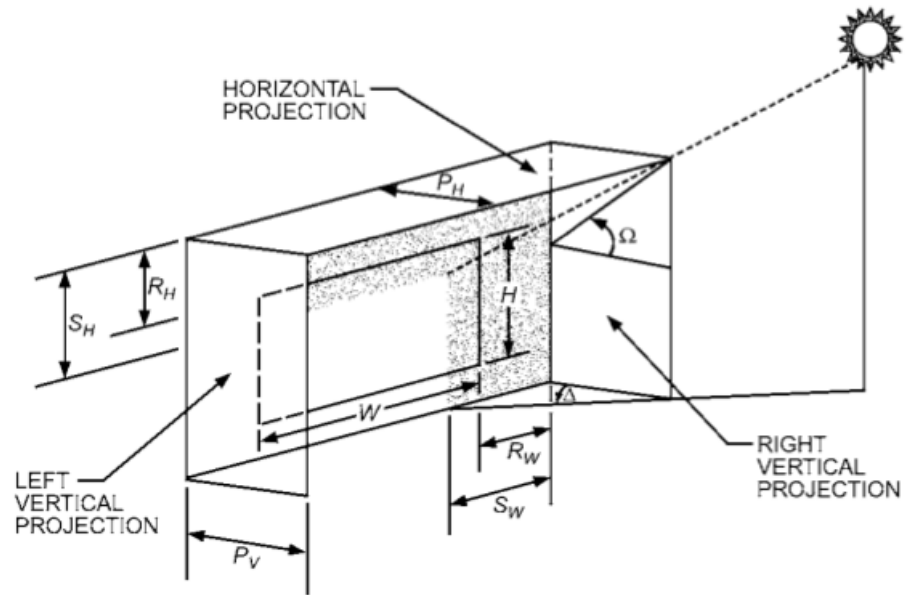
- Another place to get SHGC, U, VT, and air leakage data is from the manufacturer label
 - The SHGC given on the NFRC label is the normal incident and total assembly SHGC

 World's Best Window Co. Millennium 2000+ Vinyl-Clad Wood Frame Double Glazing • Argon Fill • Low E Product Type: Vertical Slider	
ENERGY PERFORMANCE RATINGS	
U-Factor (U.S./I-P) 0.35	Solar Heat Gain Coefficient 0.32
ADDITIONAL PERFORMANCE RATINGS	
Visible Transmittance 0.51	Air Leakage (U.S./I-P) 0.2
<small>Manufacturer stipulates that these ratings conform to applicable NFRC procedures for determining whole product performance. NFRC ratings are determined for a fixed set of environmental conditions and a specific product size. Consult manufacturer's literature for other product performance information. www.nfrc.org</small>	

 World's Best Window Co. Millennium 2000+ Vinyl-Clad Wood Frame Double Glazing • Dynamic Glazing • Argon Fill • Low E Product Type: Vertical Slider	
ENERGY PERFORMANCE RATINGS	
U-Factor (U.S./I-P) 0.30 <small>Variable</small> 0.40 <small>Off/Closed On/Open</small>	Solar Heat Gain Coefficient 0.10 <small>Variable</small> 0.50 <small>Off/Closed On/Open</small>
ADDITIONAL PERFORMANCE RATINGS	
Visible Transmittance 0.03 <small>Variable</small> 0.65 <small>Off/Closed On/Open</small>	Air Leakage (U.S./I-P) 0.2
<small>Manufacturer stipulates that these ratings conform to applicable NFRC procedures for determining whole product performance. NFRC ratings are determined for a fixed set of environmental conditions and a specific product size. NFRC does not recommend any product and does not warrant the suitability of any product for any specific use. Consult manufacturer's literature for other product performance information. www.nfrc.org</small>	

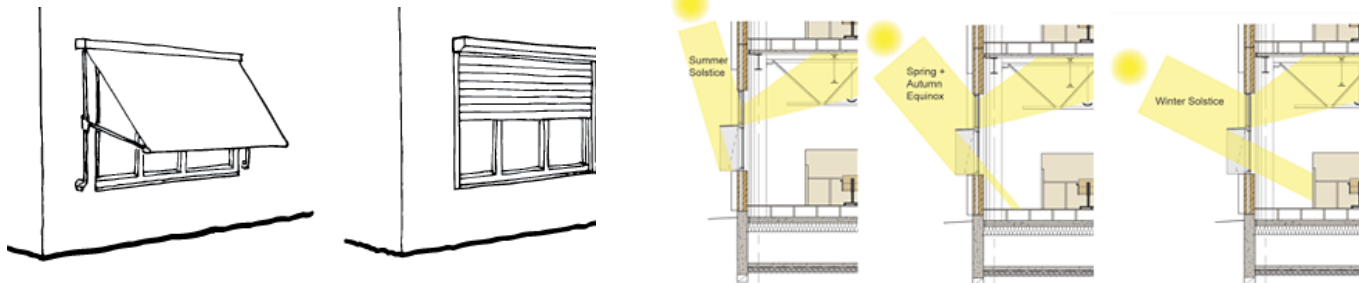
What about shading?

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

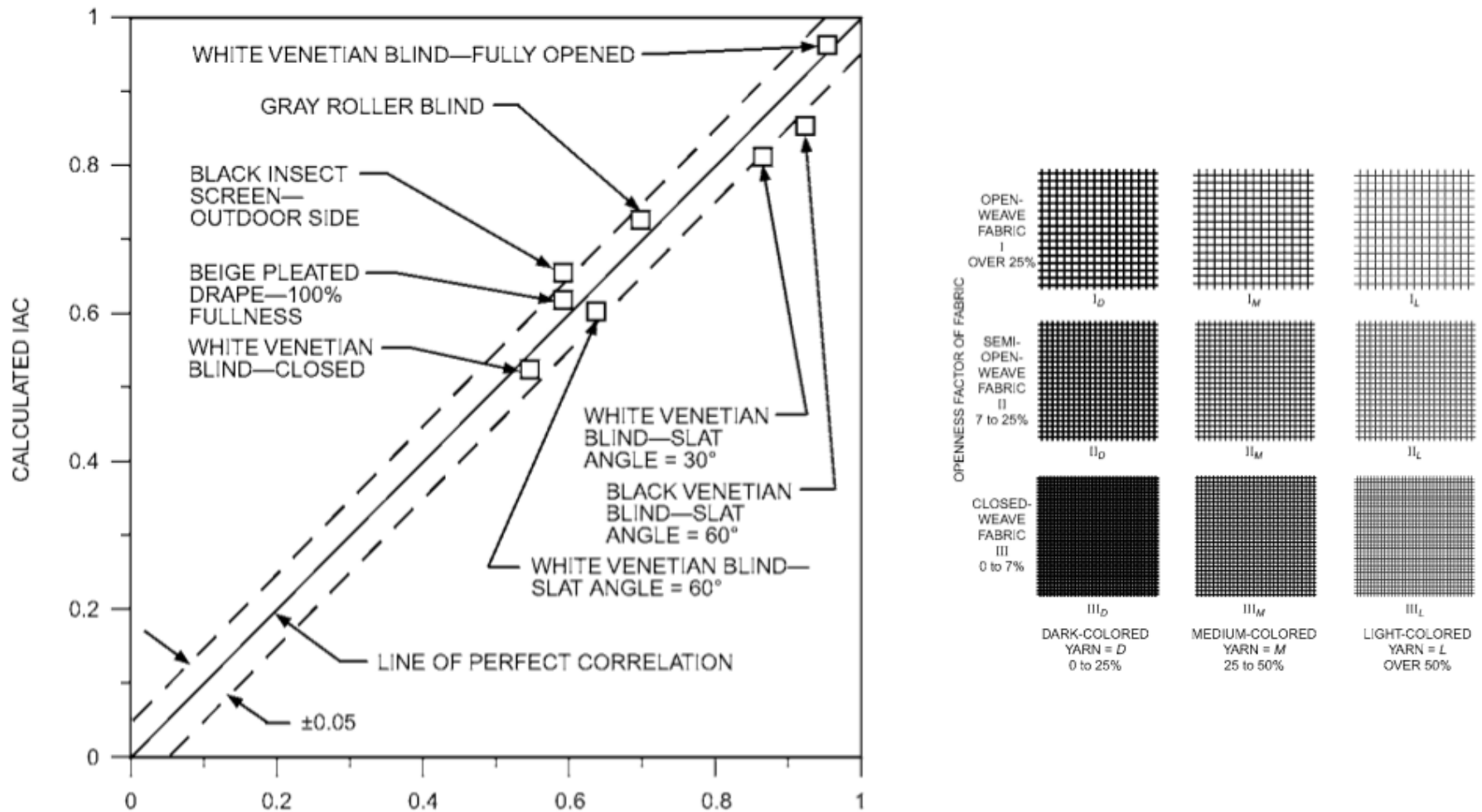


$$Q_{\text{window}} = UA_{pf}(T_{\text{out}} - T_{\text{in}}) + I_{\text{direct}} A_{pf} SHGC(\theta) IAC(\theta, \Omega) + (I_{\text{diffuse+reflected}}) A_{pf} SHGC_{\text{diffuse+reflected}} IAC_{\text{diffuse+reflected}}$$

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



IAC for blinds and drapes: ASHRAE HOF 2013



Other fenestration topics: 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**



One World Trade Center curtain walls

- What were those magic properties that let light in but keep heat out?

BENSON

Curtain wall supplier



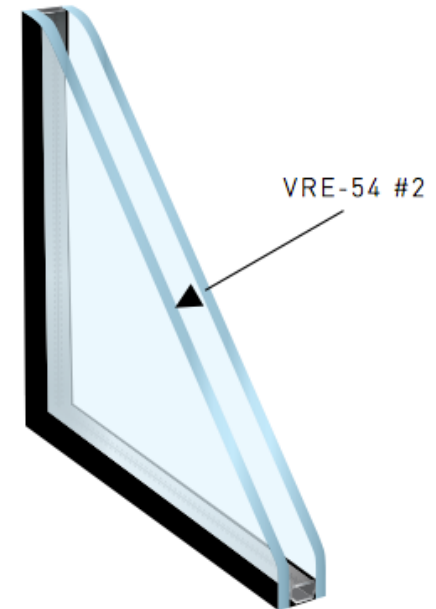
Glass supplier

Using "Viracon's VRE-54 coating on highly transparent low-iron glass" with "neutral tint" and "high light transmission"



1" VRE1-54 INSULATING

1/4" [6mm] clear with VRE-54 #2
1/2" [13.2mm] airspace
1/4" [6mm] clear



VLT	47%
Winter u-value	0.30
Summer u-value	0.27
SHGC	0.31

GLAZING: DESIGN CONSIDERATIONS

Why or 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 key design considerations:
 - Limits occupant privacy
 - Lower resistance to thermal transmission
 - Entry of sunlight adds to cooling loads
 - High initial costs and ongoing maintenance costs
 - High embedded energy (from manufacturing)

Can highly glazed building facades be 'green'?



- What do you see?
 - Energy hogs?
 - Energy efficient buildings?



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
 - Lower U, lower SHGC, greater VT
 - Are the gains good enough to warrant large amounts of glazing?
 - Floor-to-ceiling?
 - Biggest arguments for high-glazing
 - Increased daylighting
 - Occupant satisfaction
 - Aesthetics

Can highly glazed building facades be 'green'?

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

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

Can highly glazed building facades be 'green'?

- One argument: daylighting
 - Glazing lets light in
- Daylighting can offset the need for electric lighting
 - Can 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

Can highly glazed building facades be 'green'?



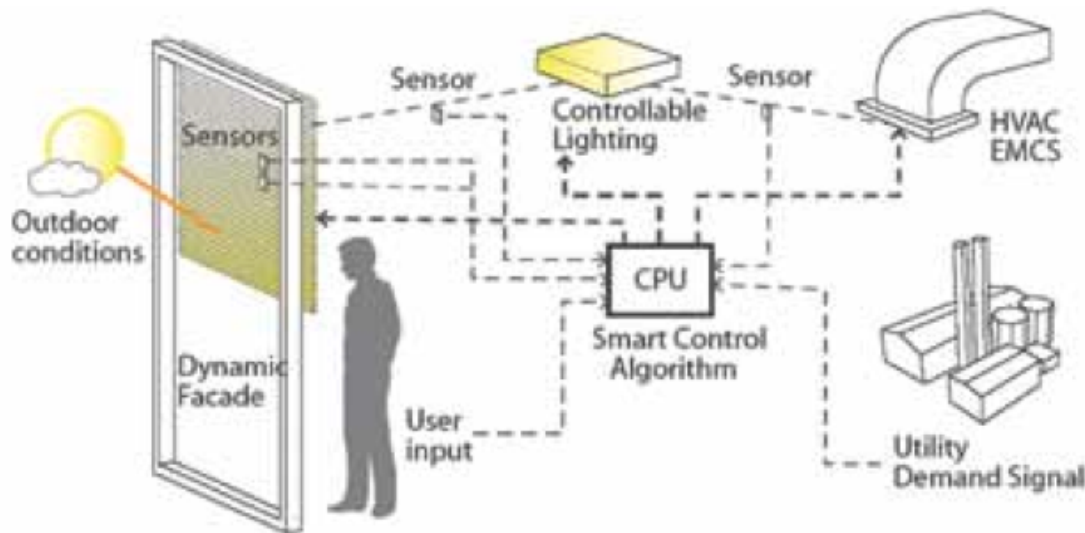
- So which one of these do you choose?



Designing with glass for daylighting: Controls



Systems need to be used with **dimming ballasts** or other advanced **lighting controls**



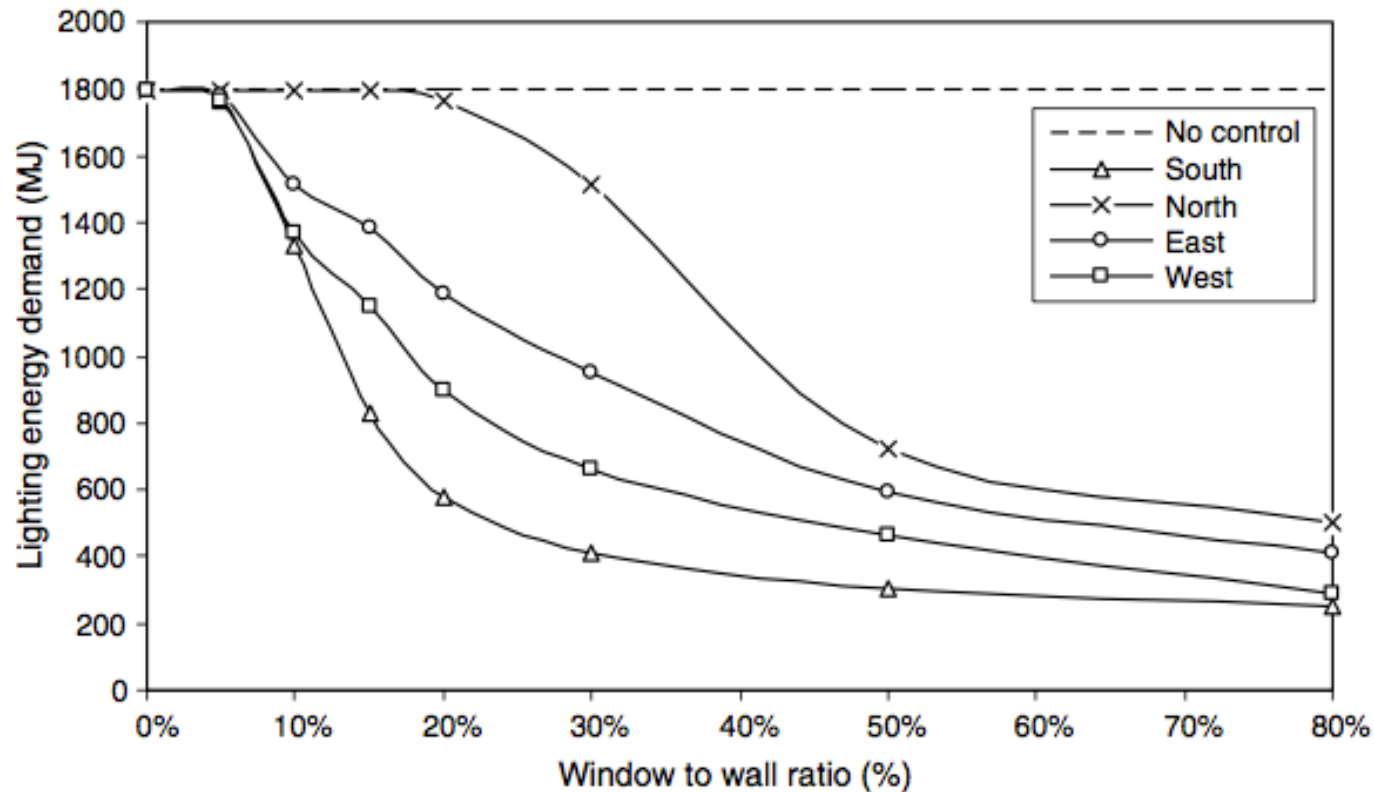
Selkowitz 2011 *Journal of Building Enclosure Design*



Lee and Selkowitz 2006 *Energy and Buildings*

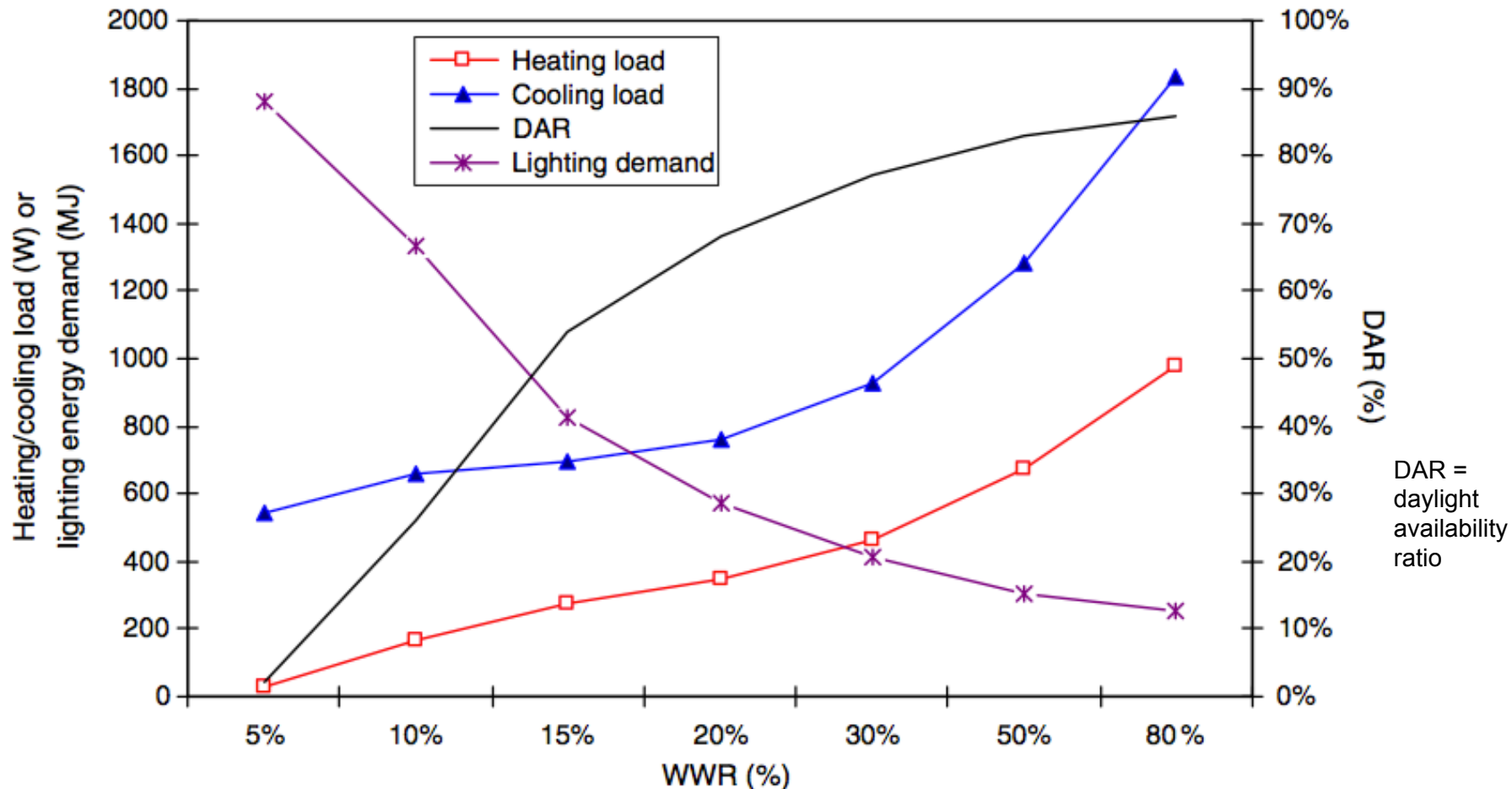
Energy impacts of glazing

Increased daylighting can save **lighting energy** depending on WWR and orientation:



Energy impacts of glazing

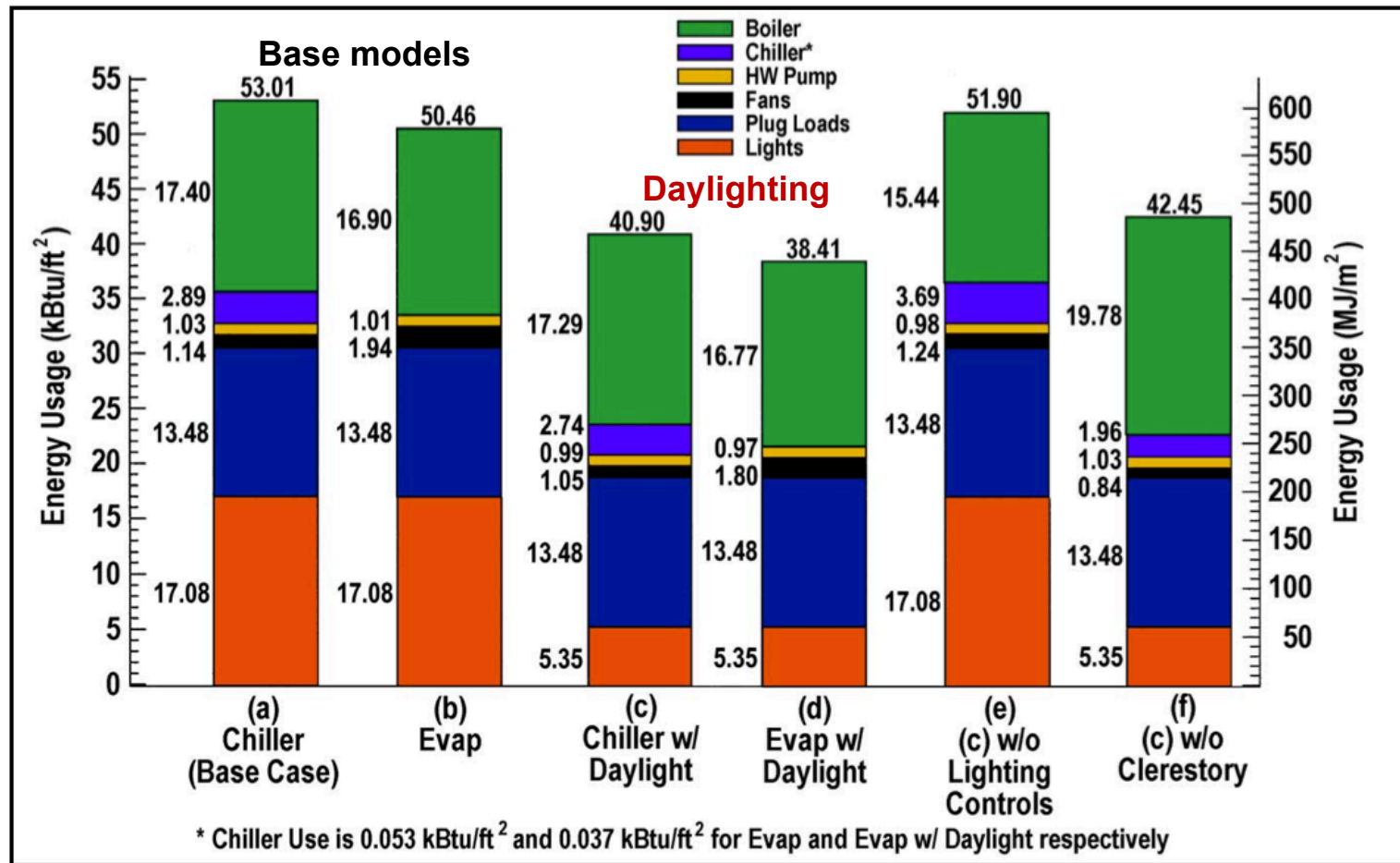
But daylighting also affects **heating and cooling loads**...



...so how do we find the right balance?

Energy impacts of glazing

- Example project: **Energy modeling w/ daylighting** in Colorado:



What about in a warmer climate?

Need to perform whole building energy modeling

Other methods of achieving daylighting efficiently

- Skylights
- Light pipes and fiber optic daylighting systems
- Light shelves
- Still need to be used with dimming ballasts or other advanced lighting controls

Skylights

- Typically limited to low-rise structures



Solar tubes



Daylighting Technology



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

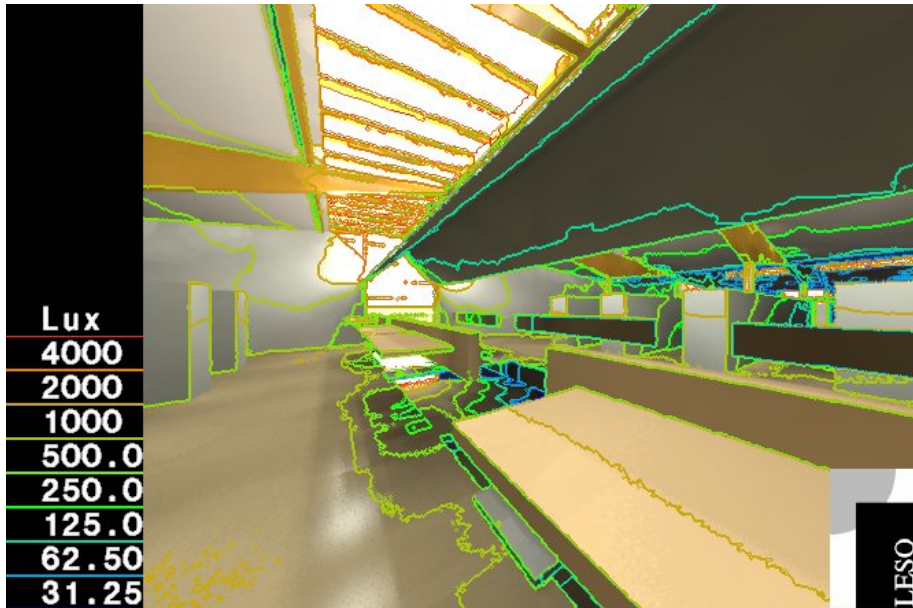


* Specular reflectance greater than 99% with wavelength specific reflectance up to 99.7% for the visible spectrum.

Light shelves

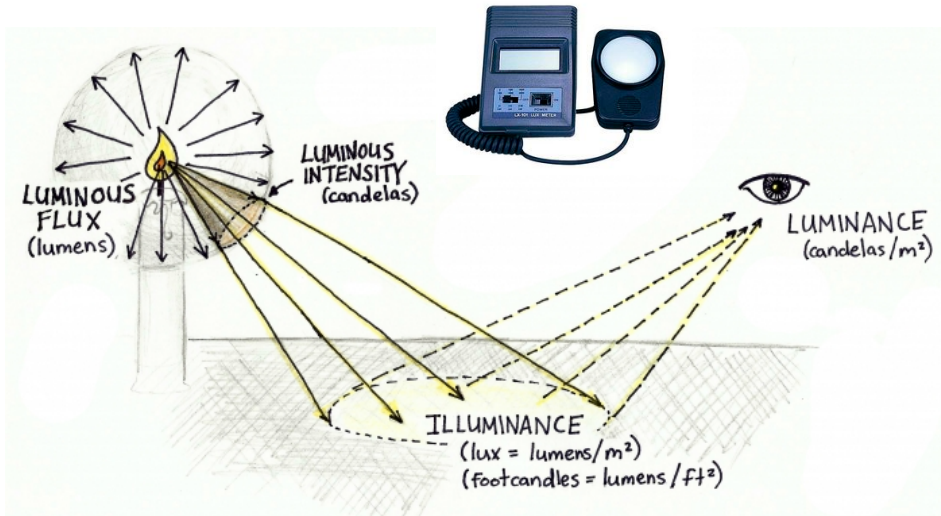


Combining software and hardware for investigating daylighting

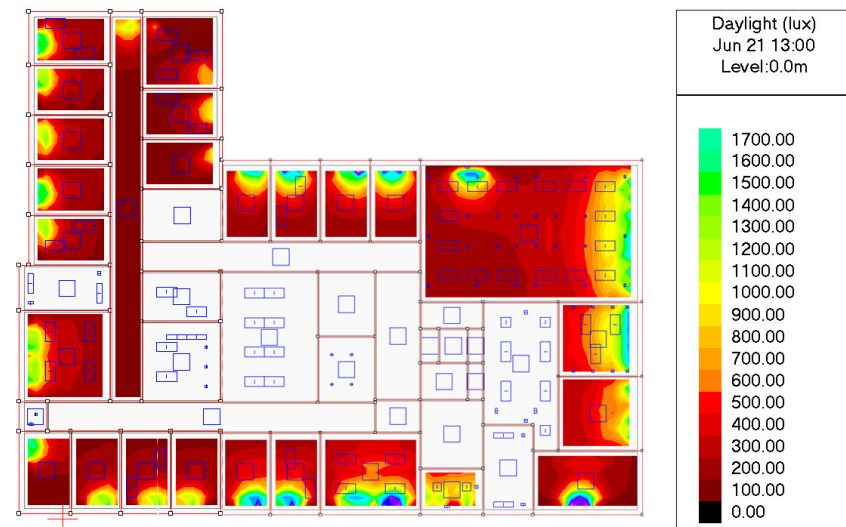


Software: Radiance

<http://floyd.lbl.gov/deskrad/download.htm>



Hardware: Light sensors



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

New technologies are pushing the boundaries on thermal performance of fenestration

- Building integrated photovoltaics (BIPV)
 - Photovoltaic (PV) cells provide shading and generate electricity
- 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



Next week

- Turn in your take-home exams on March 31 in class
- Select your final project topic by April 3
- Next lecture: Energy simulation in enclosure design