CAE 463/524
Building Enclosure Design
Spring 2016

Week 11: March 22, 2016
Finishing air movements in enclosures
Fenestration and glazing design

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Next time: Campus projects due

- Presentations and reports are due March 29
  - 1 week from today
  - Email me PDF of your reports
  - Presentations in class March 29
    - Try to share presentation responsibilities among members
      - (But it's OK if that's not possible due to scheduling constraints)
    - Send me PowerPoint or PDF file a few minutes before class
  - Aim for 15-20 minute presentations per group

Team #	Members	Building
1	Naveen, Julia, Xu, Luanzhizi, Steve	Alumni
2	Bianca, Al, Taylor, David	SSV
3	Nina, Dina, Lindsey, Salvatore, JiWan	Vandercook
4	Andrea, Ben, Keonho, Kevin	Crown
5	Afshin, Ali, Mehdi, Jose, Kamal	Siegel

Course catch-up

- **2 weeks ago:**
  - Air movements / air leakage
  - Blower door test demonstration

- **Today:**
  - Finish air movements / air leakage in enclosures
  - Fenestration
    - Windows and daylighting in enclosure design

AIRFLOWS IN ENCLOSURES

Summary of air movements in enclosures

- Air infiltration is the single greatest contributor to energy use in U.S. homes
  - Can be substantial in commercial buildings too
- Driving forces
  - Wind and stack pressures
- Flow through cracks and porous materials

$$Q = C_d A \sqrt{\frac{2\Delta P}{\rho}}$$

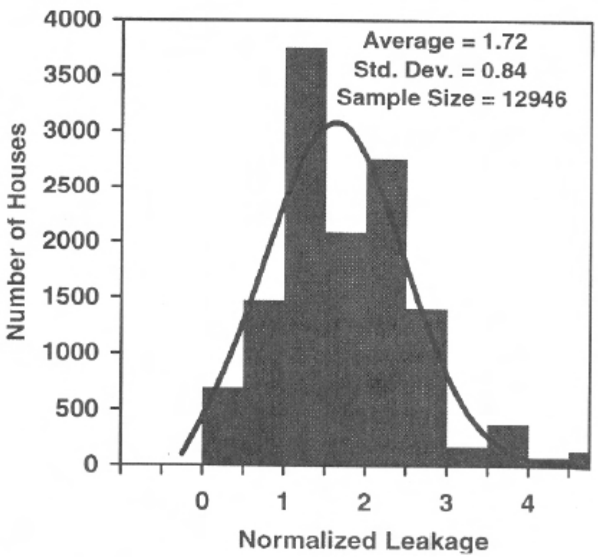
$$Q = KA\Delta P$$

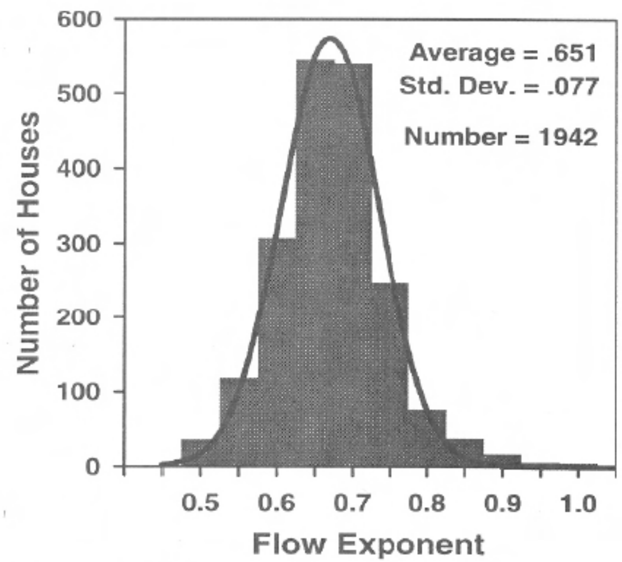
- Blower door tests
  - Estimated leakage area
  - Normalized leakage
  - ACH_{50}

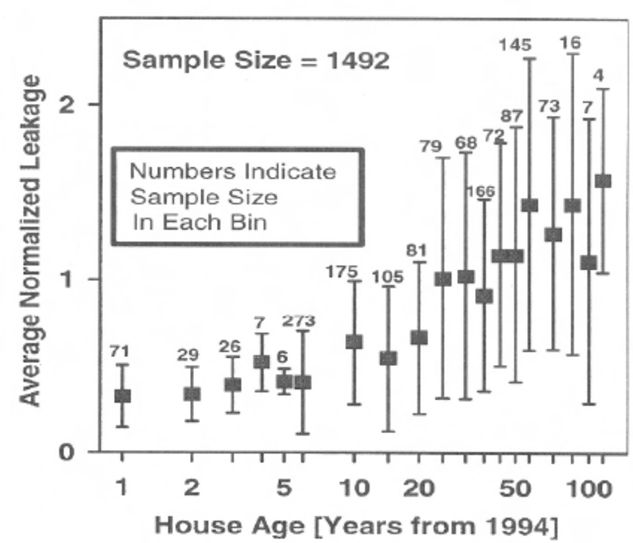
$$Q = C\Delta P^{n}$$

Blower door results: US homes

- From a big database of blower door tests





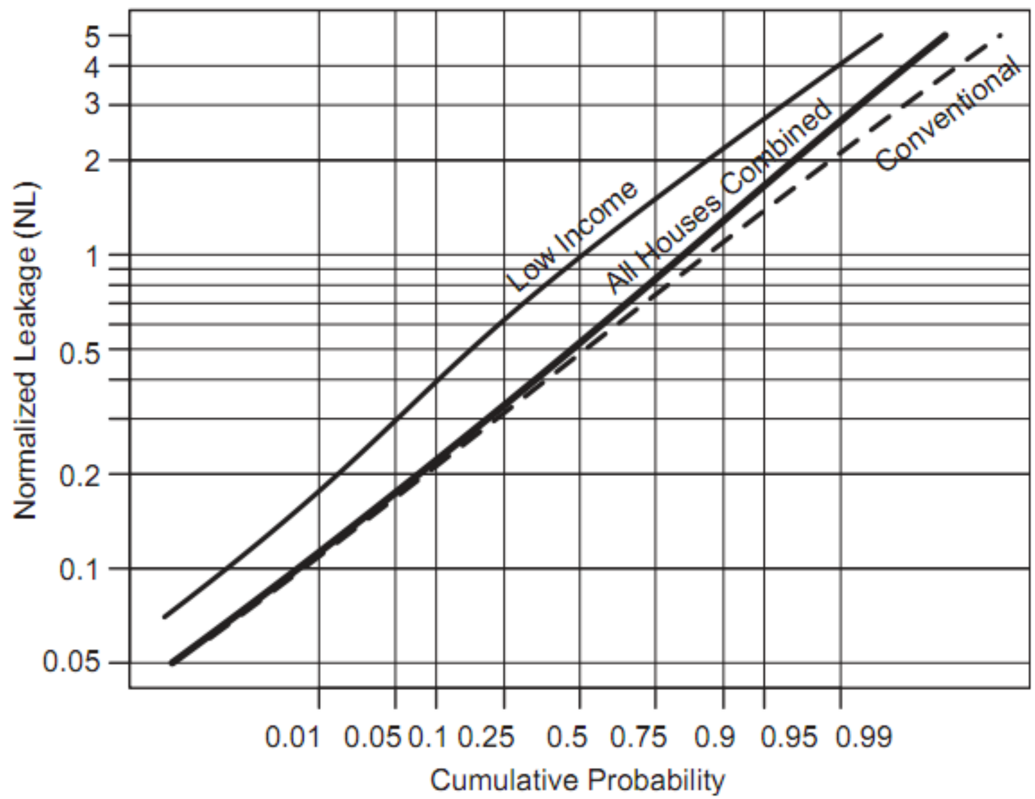


	Mean	Std Dev.	Number of Houses
Year Built	1965	24.2	1492
Floor Area [m^2]	156.4	66.7	12946
Normalized Leakage	1.72	0.84	12946
ACH_{50}	29.7	14.5	12902
Exponent	0.649	0.084	2224

Sherman and Dickerhoff 1998 *ASHRAE Transactions*

Residential blower door data

- LBNL continues to maintain a database of blower door data
  - http://resdb.lbl.gov/
  - Almost 150,000 homes characterized



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

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

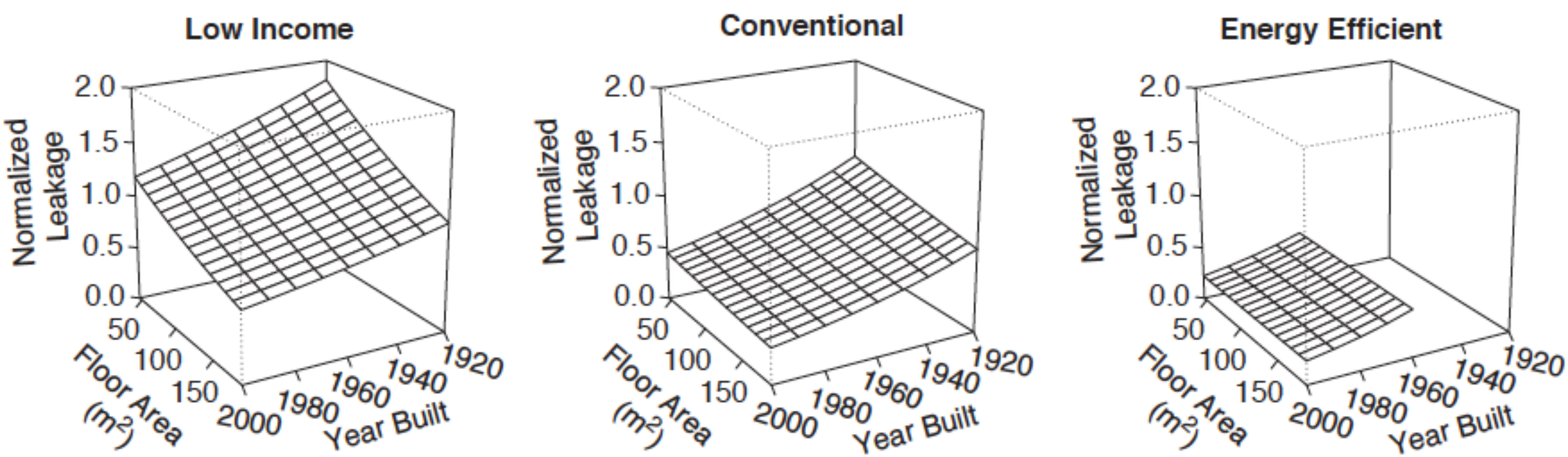
$$NL = 1000\frac{ELA}{Af}\left(\frac{H}{2.5m}\right)^{0.3}$$

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

Source: Chan et al., 2005 *Atmos Environ*
>70000 air leakage measurements in U.S.

Residential blower door data

- Residential air leakage is a function of:
  - Building age
  - Building size (floor area)
  - Status/existence of efficiency retrofits
  - Socioeconomic status of occupants

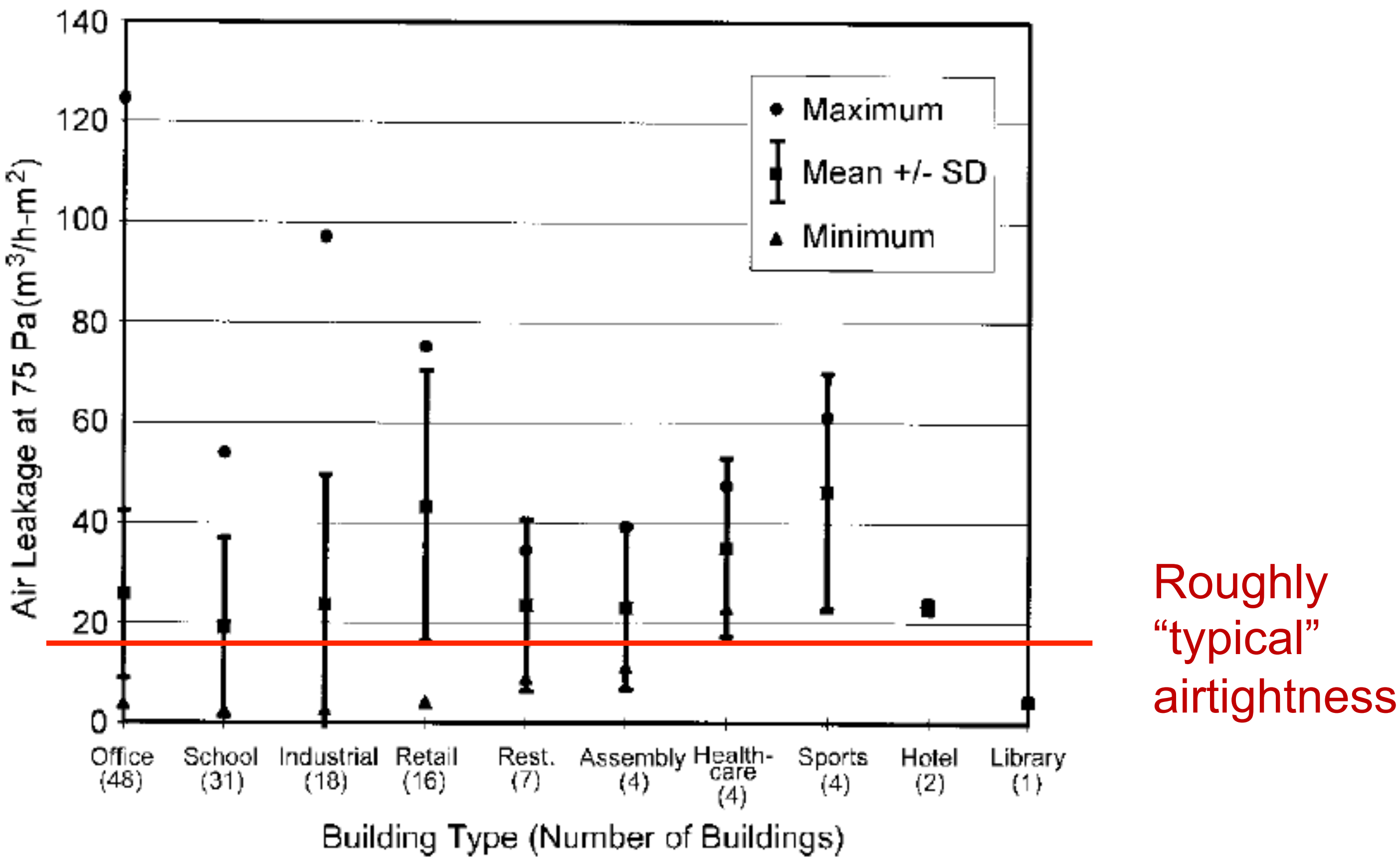


$$NL = 1000\frac{ELA}{Af}\left(\frac{H}{2.5m}\right)^{0.3}$$

Source: Chan et al., 2005 *Atmos Environ*
>70000 air leakage measurements in U.S.

Commercial building air leakage

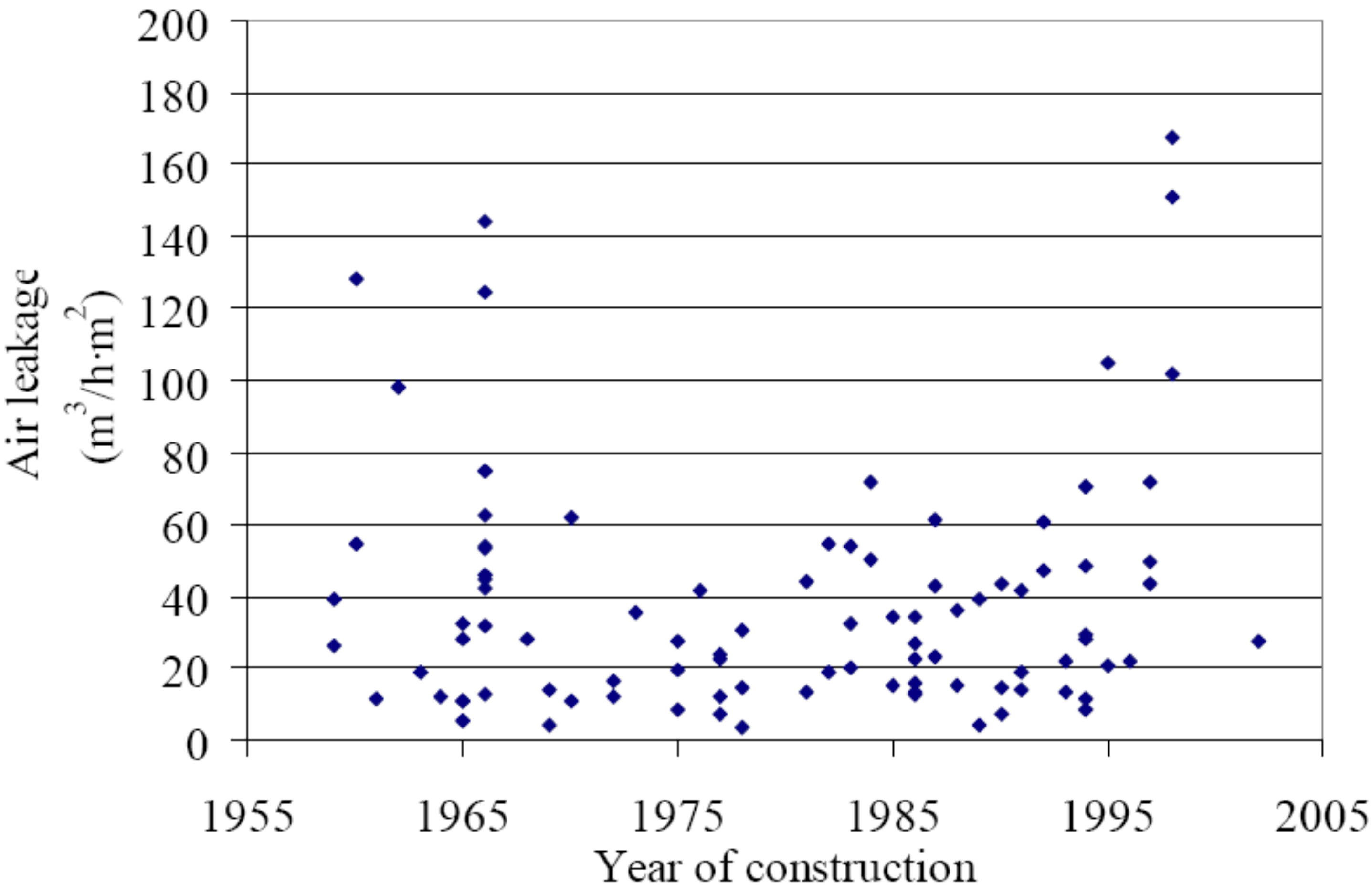
- Traditionally assumed that commercial and institutional buildings were built to be airtight
  - Turns out that's not always the case



Persily, 1999 *ASHRAE Journal,* "Myths about building envelopes"

Commercial building air leakage vs. age

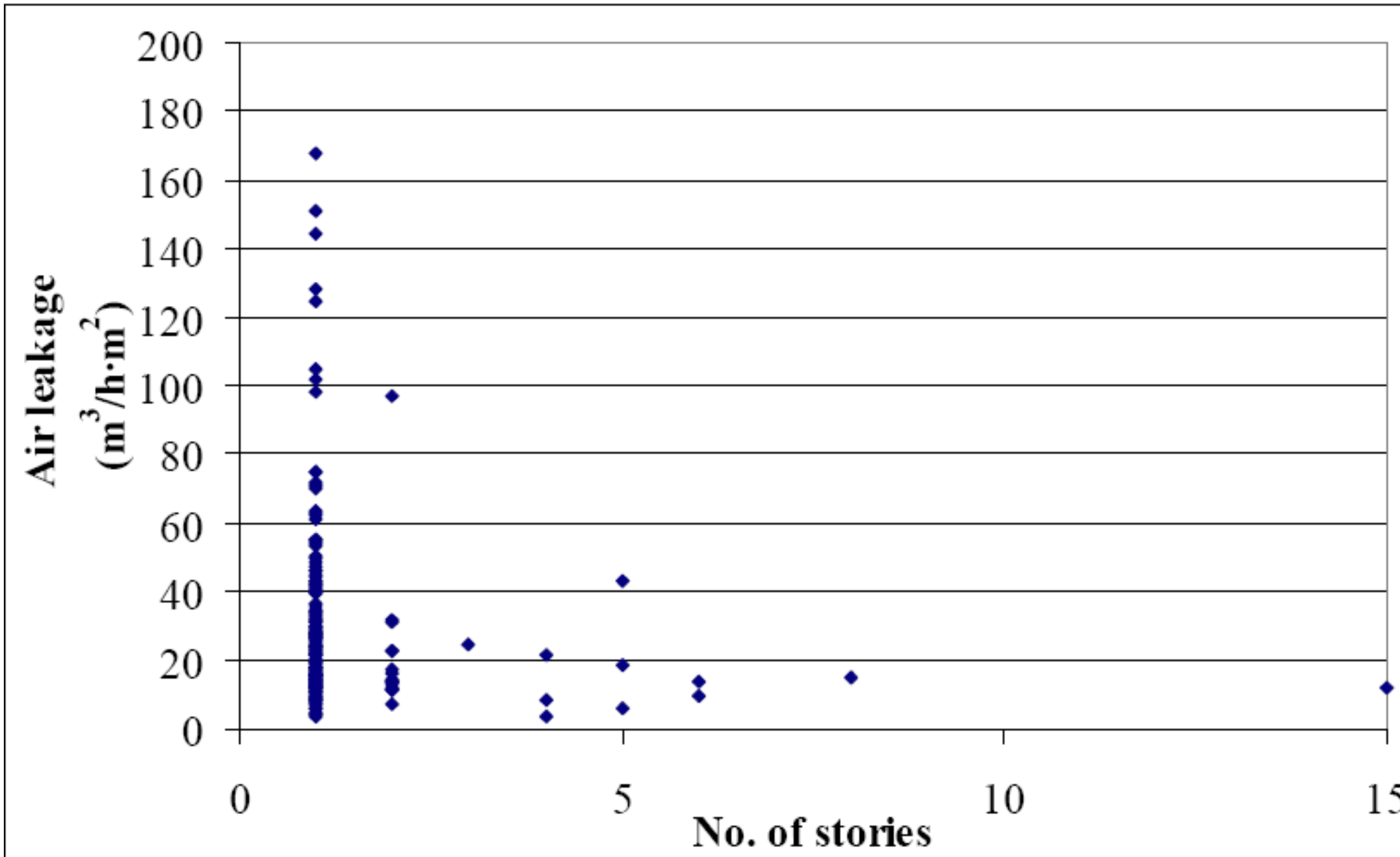
- Less correlation with age than other factors
  - Note small range of age



Persily, 1999 *ASHRAE Journal,* “Myths about building envelopes”

Commercial building air leakage vs. height

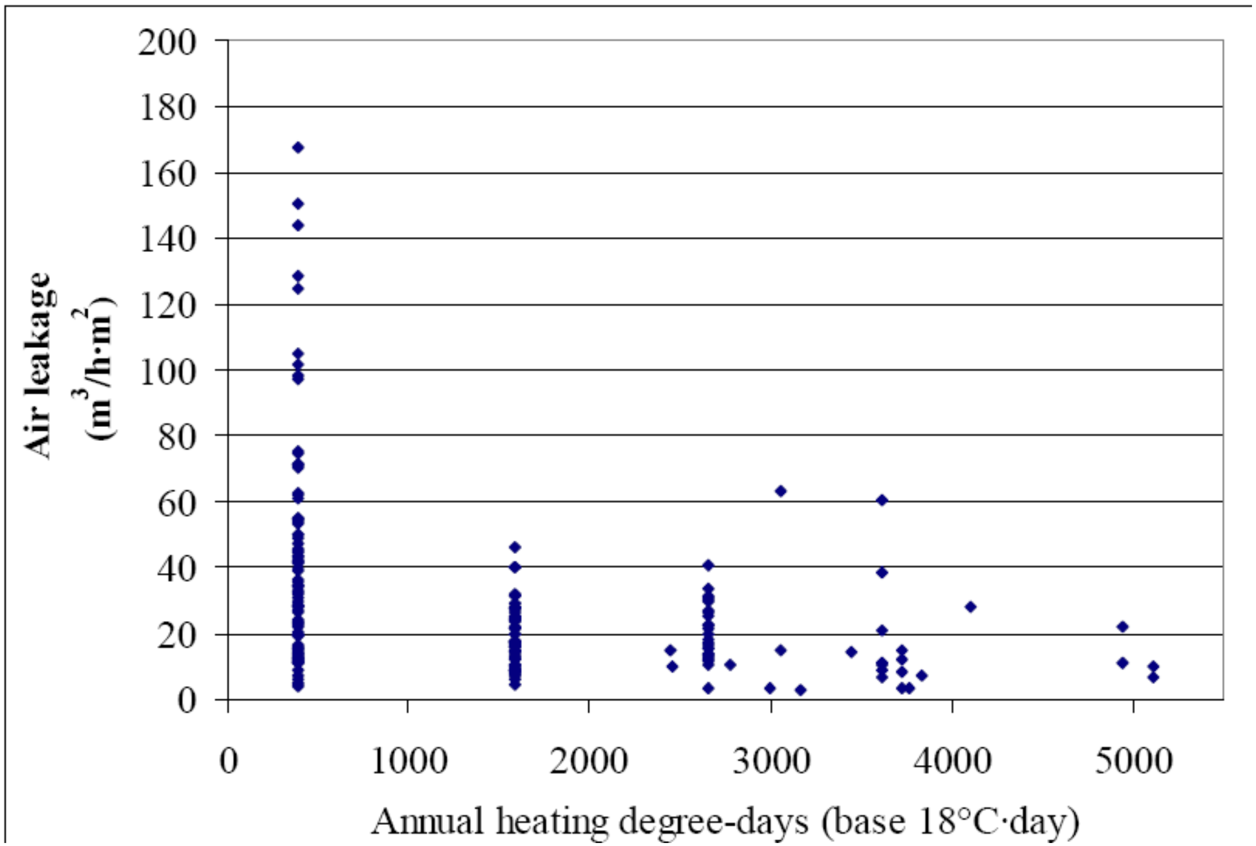
- Taller buildings were tighter
  - Stronger construction standards?



Persily, 1999 *ASHRAE Journal,* "Myths about building envelopes"

Commercial building air leakage vs. climate zone

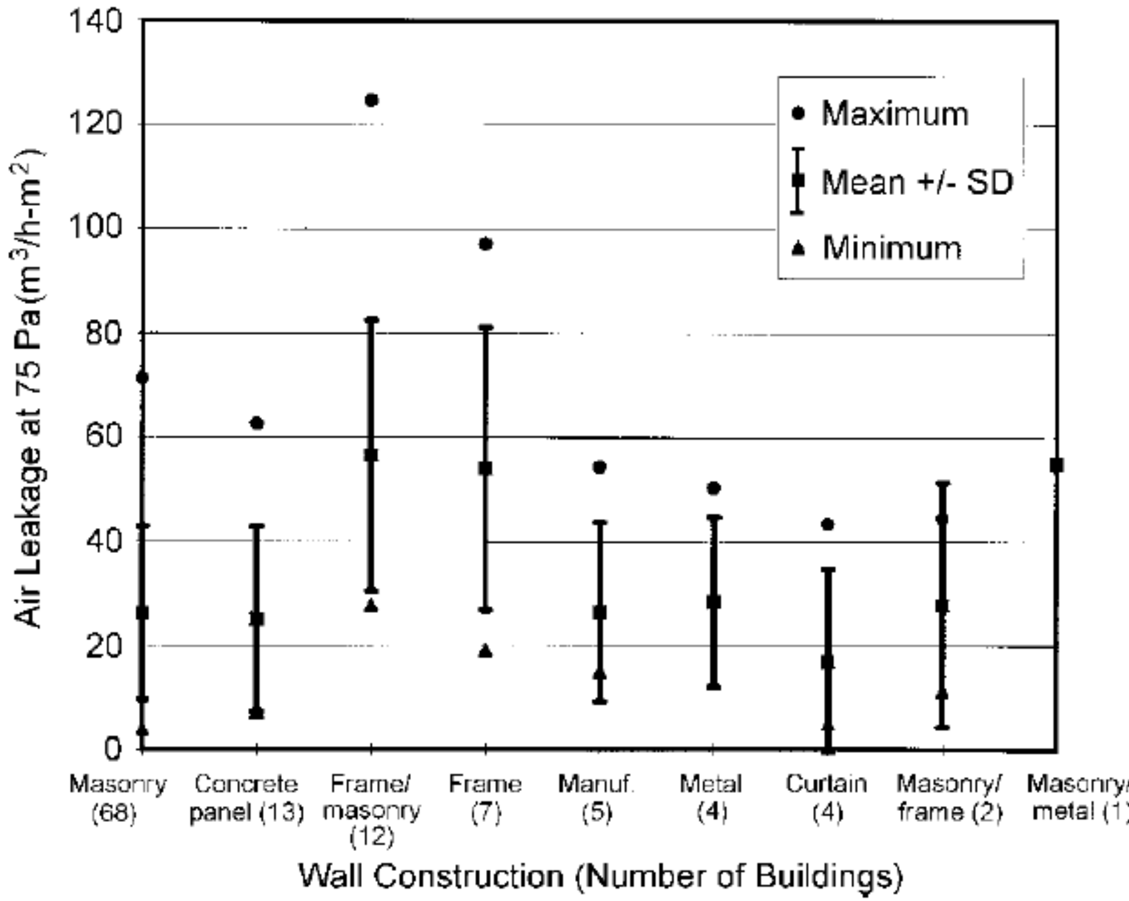
- Buildings were tighter in colder climates
  - Necessity?
  - Stricter building codes?



Persily, 1999 *ASHRAE Journal,* "Myths about building envelopes"

Commercial building air leakage vs. wall type

- Leakage varied by <u>wall construction type</u>
  - Frame construction leakier than masonry, metal or curtain walls



Persily, 1999 *ASHRAE Journal,* “Myths about building envelopes”

Limitations to blower door tests

- Sufficient flow rates are difficult to obtain in large and/or leaky buildings
  - Can use multiple fans
- Not good for complex leakage paths
  - Multizone buildings
- ***Does not give you actual air exchange rate (AER)***
  - AER is the rate of replacement of indoor air with outdoor air (units of inverse time, e.g., 1/hour)
  - AER is dependent on wind, ΔT, time
    - Blower door tests are not
- Most useful for comparing building to building airtightness

Measuring actual air exchange rates

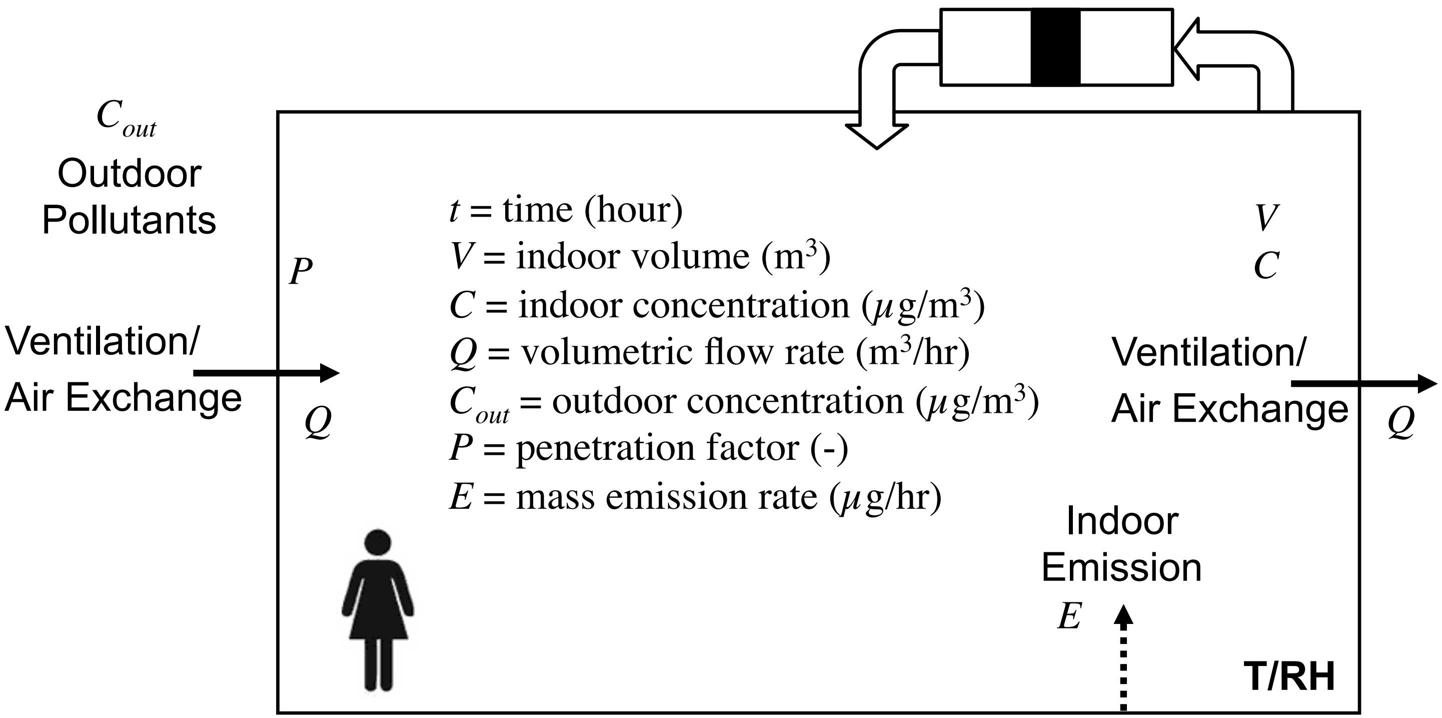
- Two general strategies to measure or estimate the instantaneous air exchange rate
  - "AER," "ACH," and "λ" all used interchangeably

1. Direct measurement
   - Tracer gas (constant injection or decay)
     - Apply well-mixed reactor model to fit data

2. Indirect measurement and model
   - Perform blower door tests to characterize envelope leakage
   - Apply infiltration model to predict AER based on driving forces

Tracer gas testing

- Release gas and measure concentration
- Use well-mixed model to estimate AER from decay



$$\boxed{C_{ss} = PC_{out} + \frac{E}{\lambda V}}$$

$$V\frac{dC}{dt} = PQC_{out} - QC + E$$

Dynamic solution to mass balance

- Start with basic mass balance:

$$\frac{dC}{dt} = P\lambda C_{out} - \lambda C + \frac{E}{V}$$

- Rearrange:

$$\frac{1}{P\lambda C_{out} - \lambda C + \frac{E}{V}} dC = dt$$

- Factor out (-1):

$$\frac{1}{\lambda C - P\lambda C_{out} - \frac{E}{V}} dC = -dt$$

- Substitute: $\text{Let } x = \text{denominator} = \lambda C - P\lambda C_{out} - \frac{E}{V}$
  - So that: $\frac{dx}{dC} = \lambda \longrightarrow dC = \frac{1}{\lambda} dx$

Dynamic solution to mass balance

Letting $x = \lambda C - P\lambda C_{out} - \frac{E}{V}$ and thus $\frac{dx}{dC} = \lambda$ transforms:

$$\frac{1}{\lambda C - P\lambda C_{out} - \frac{E}{V}} dC = -dt \xrightarrow{\text{into}} \frac{1}{\lambda}\left(\frac{1}{x}\right) dx = -dt$$

- We can now solve this simpler equation

Rearrange:

$$\left(\frac{1}{x}\right) dx = -\lambda dt$$

Integrate both sides:

$$\int_{x_0}^{x} \frac{1}{x} dx = -\lambda \int_0^t dt$$

Solution with x:

$$\ln(x)\Big|_{x_0}^{x} = -\lambda t$$

Substitute back in for x:

$$\ln\left\{\frac{\lambda C - P\lambda C_{out} - \frac{E}{V}}{\lambda C(t=0) - P\lambda C_{out} - \frac{E}{V}}\right\} = -\lambda t$$

Dynamic solution to mass balance

$$\ln\left\{\frac{\lambda C - P\lambda C_{out} - \frac{E}{V}}{\lambda C(t=0) - P\lambda C_{out} - \frac{E}{V}}\right\} = -\lambda t$$

- Raise *e* to both sides:

$$\frac{\lambda C - P\lambda C_{out} - \frac{E}{V}}{\lambda C(t=0) - P\lambda C_{out} - \frac{E}{V}} = e^{-\lambda t}$$

- Rearrange:

$$\lambda C - P\lambda C_{out} - \frac{E}{V} = \left\{\lambda C(t=0) - P\lambda C_{out} - \frac{E}{V}\right\} e^{-\lambda t}$$

Dynamic solution to mass balance

- Solve for C:
  - Which is *C* at time *t*, or *C(t)*

$$\lambda C - P\lambda C_{out} - \frac{E}{V} = \left\{ \lambda C(t=0) - P\lambda C_{out} - \frac{E}{V} \right\} e^{-\lambda t}$$

$$\boxed{C(t) = C(t=0)\cancelto{0}{e^{-\lambda t}} + \left(PC_{out} + \frac{E}{\lambda V} \right)\left(1 - \cancelto{0}{e^{-\lambda t}} \right)}$$

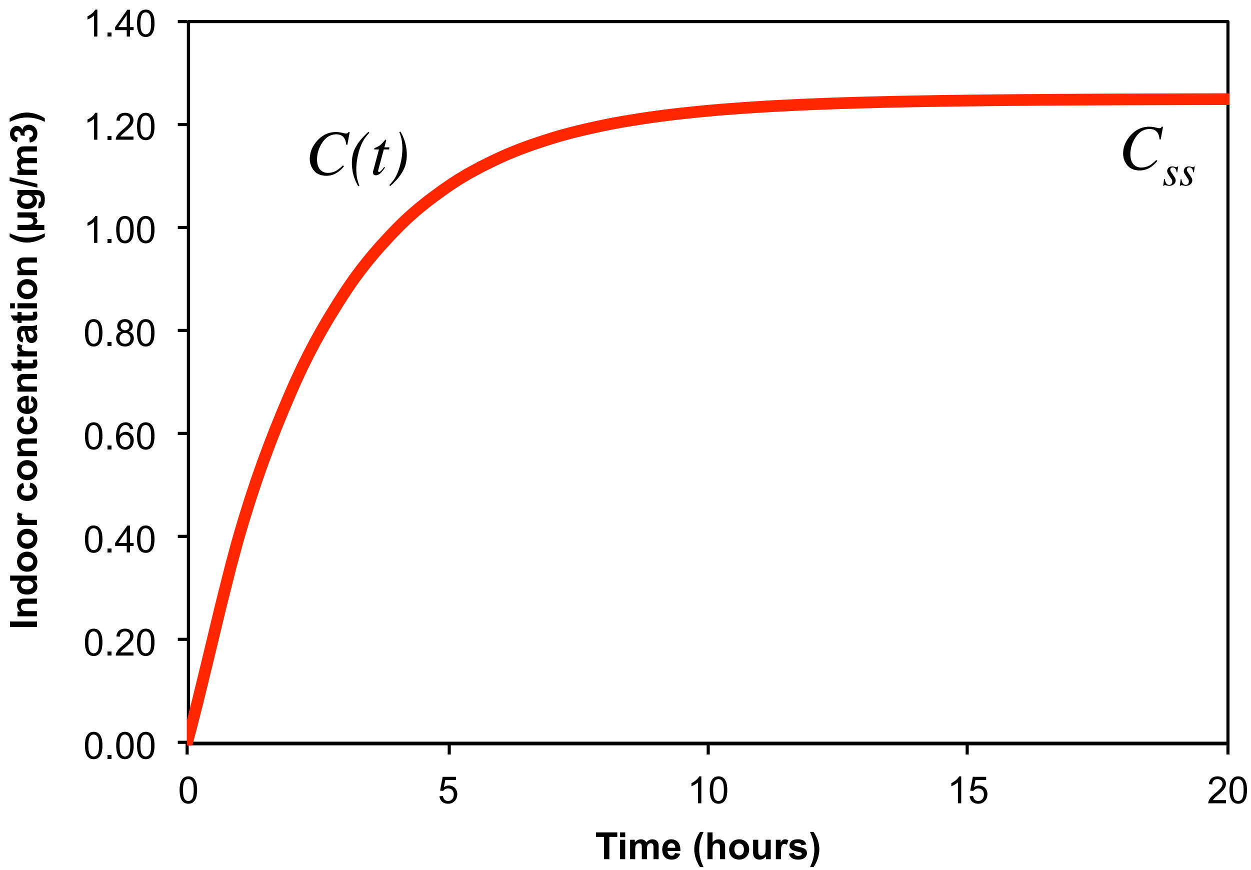
- What do these two terms represent?

- What happens as t $\rightarrow \infty$?

$$\boxed{C(t \rightarrow \infty) = PC_{out} + \frac{E}{\lambda V} = \text{our steady state solution}}$$

Dynamic solution to mass balance

- Example concentration profile
  - V = 200 m^3, E = 100 µg/hr, λ = 0.4/hr, C_{out} = 0, P = 1



Time to reach steady state

$$C(t) = C(t=0)e^{-\lambda t} + \left(PC_{out} + \frac{E}{\lambda V}\right)\left(1 - e^{-\lambda t}\right)$$

- If we assume an inert pollutant emitted indoors with an initial concentration of zero, how long would it take to achieve 95% of steady state?
- 95% of steady-state is reached when:

$$\left(1 - e^{-\lambda t}\right) = 0.95 \longrightarrow e^{-\lambda t} = 1 - 0.95 = 0.05$$

$$-\lambda t = \ln(0.05) \longrightarrow \lambda t = -\ln(0.05) = 3$$

$$\boxed{t = \frac{3}{\lambda}}$$

Consider λ = 0.1 hr^{-1}

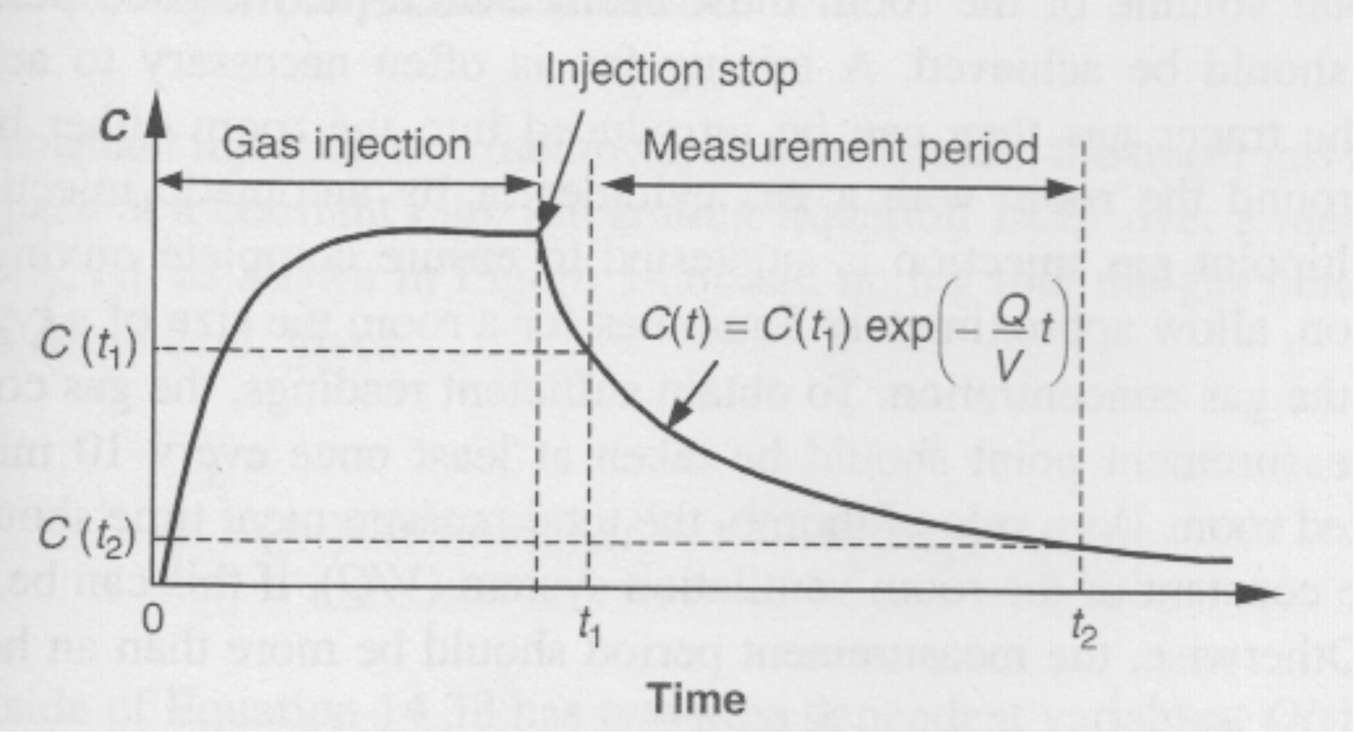
t to 95% steady state = 30 hours

Consider λ = 1 hr^{-1}

t to 95% steady state = 3 hours

How do we measure λ?

- One method is to inject an inert tracer gas, and measure the decay from C(t=0) after time t=0



How do we measure λ?

- One method is to inject an inert tracer gas, and measure the decay from C(t=0) after time t=0
  - In this case, E = 0
  - Assume P = 1 (reasonable for inert gas)

$$C(t) = C(t=0)e^{-\lambda t} + \left(PC_{out} + \cancel{\frac{E}{\lambda V}}_{0}\right)\left(1 - e^{-\lambda t}\right)$$

$$C(t) = C(t=0)e^{-\lambda t} + C_{out}\left(1 - e^{-\lambda t}\right)$$

$$C(t) = C(t=0)e^{-\lambda t} + C_{out} - C_{out}e^{-\lambda t}$$

$$C(t) - C_{out} = \left\{C(t=0) - C_{out}\right\}e^{-\lambda t}$$

How do we measure λ?

$$C(t) - C_{out} = \left\{ C(t=0) - C_{out} \right\} e^{-\lambda t}$$

$$\frac{C(t) - C_{out}}{C(t=0) - C_{out}} = e^{-\lambda t}$$

- Take the natural log of both sides:

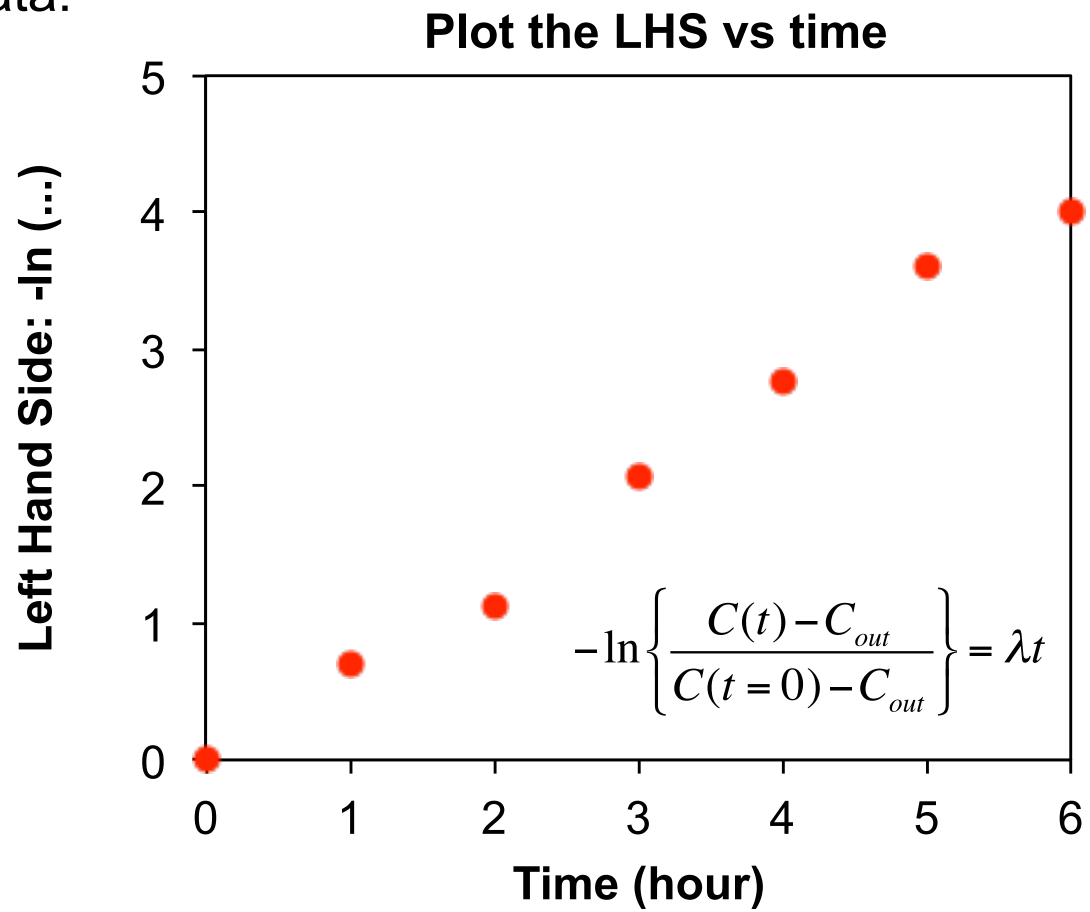
$$-\ln\left\{ \frac{C(t) - C_{out}}{C(t=0) - C_{out}} \right\} = \lambda t$$

- To find λ, plot left hand side versus right hand side
  - Slope of that line is λ

How do we measure λ?

- **Example:** You perform a tracer test with CO_2
  - You measure a constant outdoor concentration of 400 ppm
  - You elevate indoors to 2000 ppm, then leave for 6 hours
  - You record these data:

Time (hr)	C(t) (ppm)
0	2500
1	1450
2	900
3	660
4	530
5	460
6	430



$$-\ln\left\{\frac{C(t)-C_{out}}{C(t=0)-C_{out}}\right\}=\lambda t$$

How do we measure λ?

- **Example:** You perform a tracer test with CO_2
  - You measure a constant outdoor concentration of 400 ppm
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Time (hr)	C(t) (ppm)
0	2500
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4	530
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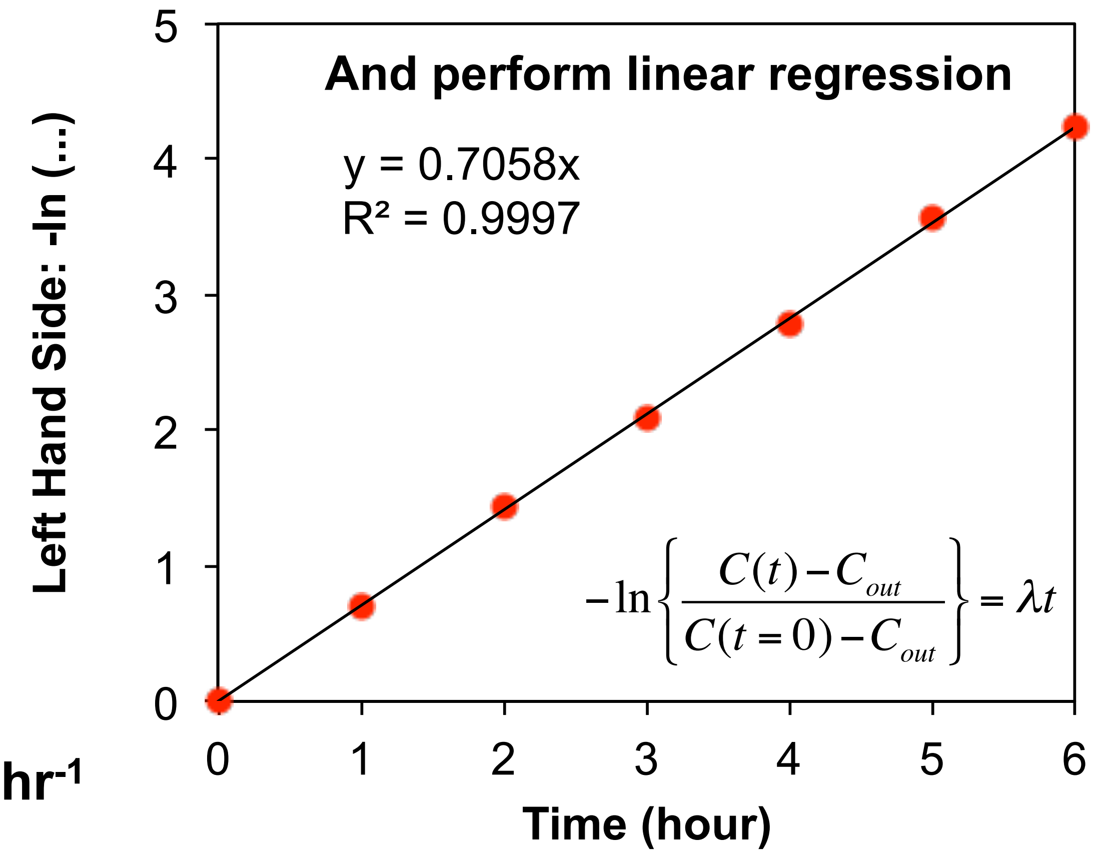
Plot the LHS vs time



$$-\ln\left\{\frac{C(t)-C_{out}}{C(t=0)-C_{out}}\right\}=\lambda t$$

AER = λ = slope = 0.71 hr^{-1}

What makes a good tracer gas?

Characteristics

- Non-reactive (inert)
- Non-toxic
- Colorless
- Odorless
- Cheap
  - Gas
  - Sensor
- Low detection limits
- Portable

Commonly used gases

- Carbon dioxide (CO_2)
  - People are a source
  - Need to account for E/V
- Nitrous oxide (N_2O)
  - Laughing gas
  - Toxic at high levels
- Freon (CFC)
  - Global warming potential
- Helium (He)
  - Costs
- Sulfur hexafluoride (SF_6)
  - Global warming potential

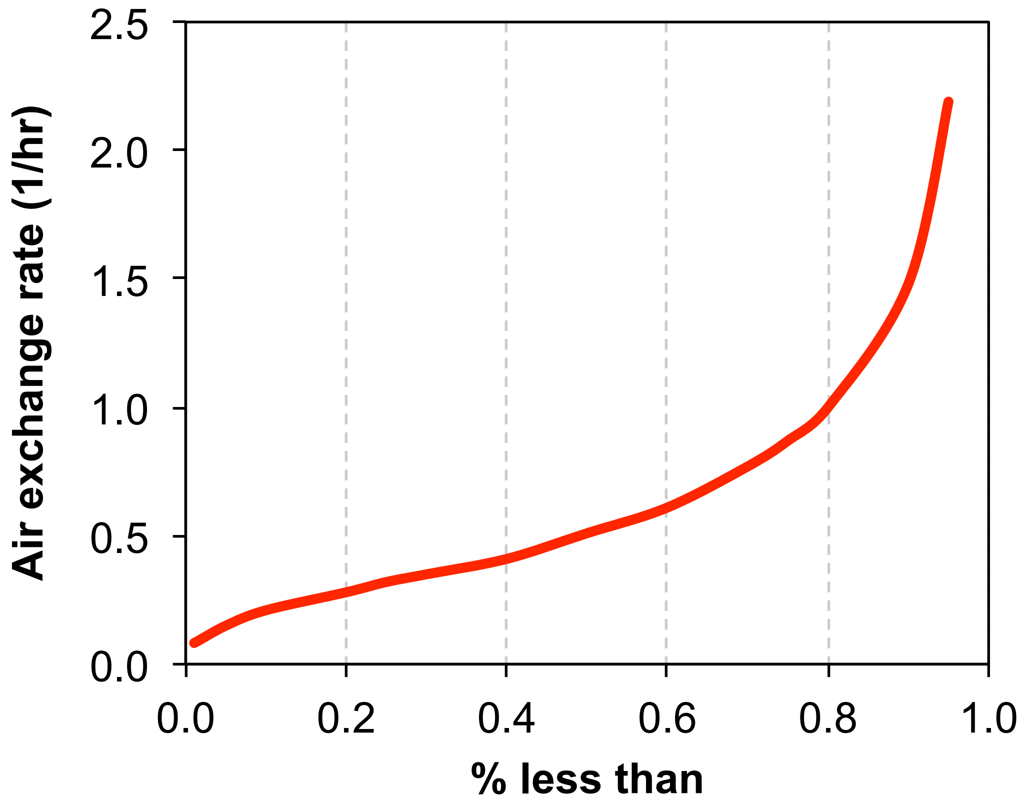
Decay test for AER

- Advantages
  - Don’t need to release precise amount
  - Don’t need to measure volume (if you just want air exchange rate)

- Disadvantages
  - Need to keep building well-mixed
  - Recontamination from buffer spaces
  - House needs to stay in one condition for entire test

What are typical values of λ (AER)?

- Distribution of AERs in ~2800 homes in the U.S.
  - Measured using PFT (perfluorocarbon tracer) in the early 1990s

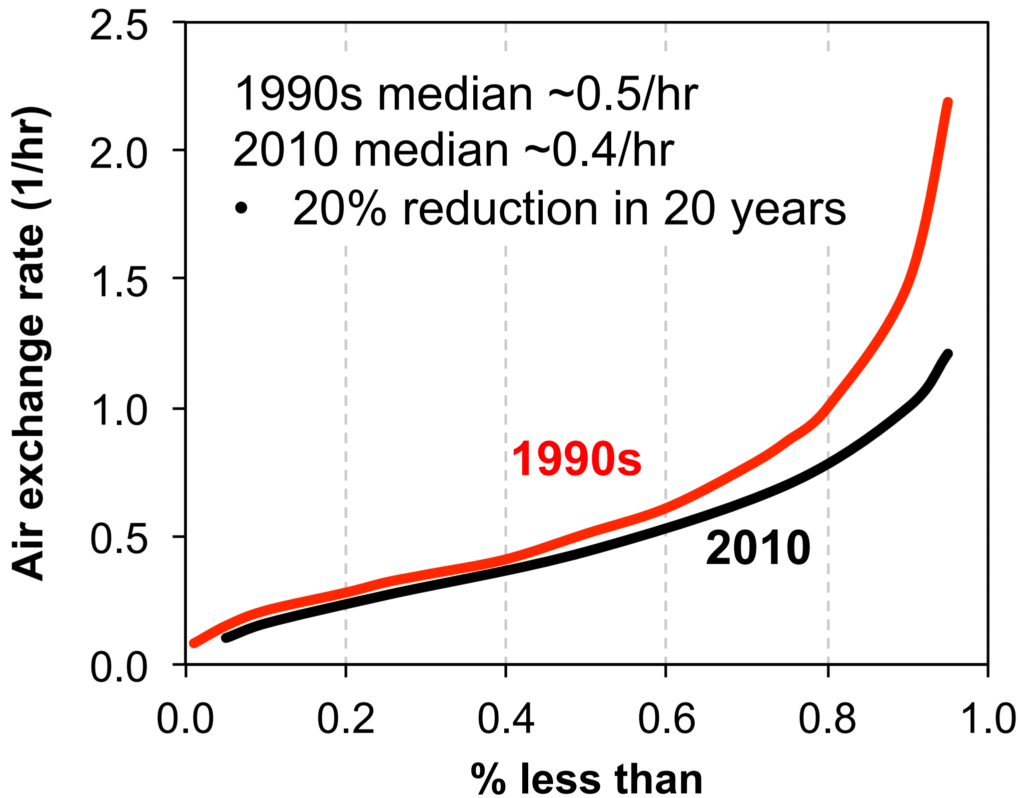


- What do you think this curve looks like now?

Murray and Burmaster, 1995 *Risk Analysis*

What are typical values of λ (AER)?

- Distribution of AERs U.S. homes
  - Early 1990s and revisited in 2010 (Persily et al. 2010)

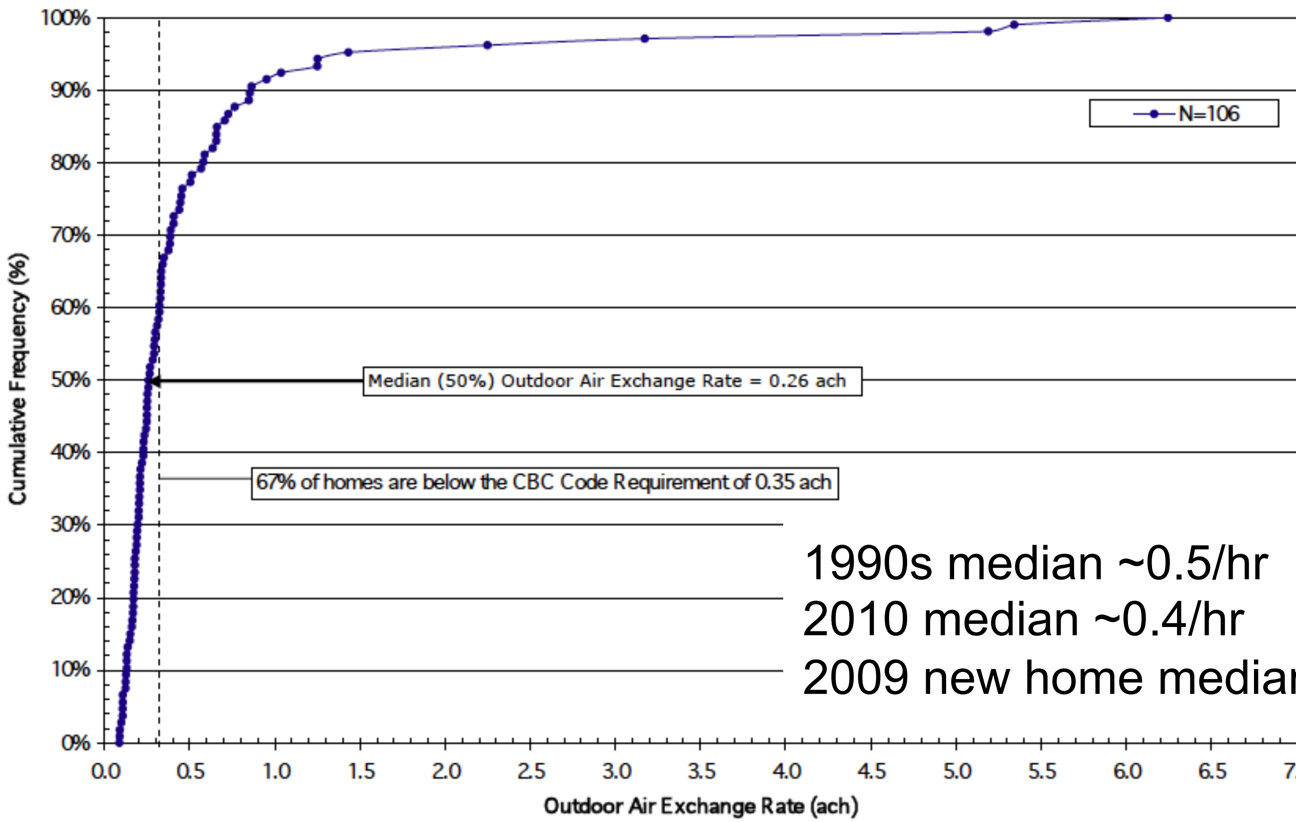


- What about new homes?

Murray and Burmaster, 1995 *Risk Analysis*; Persily et al. 2010 *Indoor Air*

What are typical values of λ (AER)?

- Distribution of AERs U.S. homes
  - Addition of 106 new homes (Offermann et al., 2009)



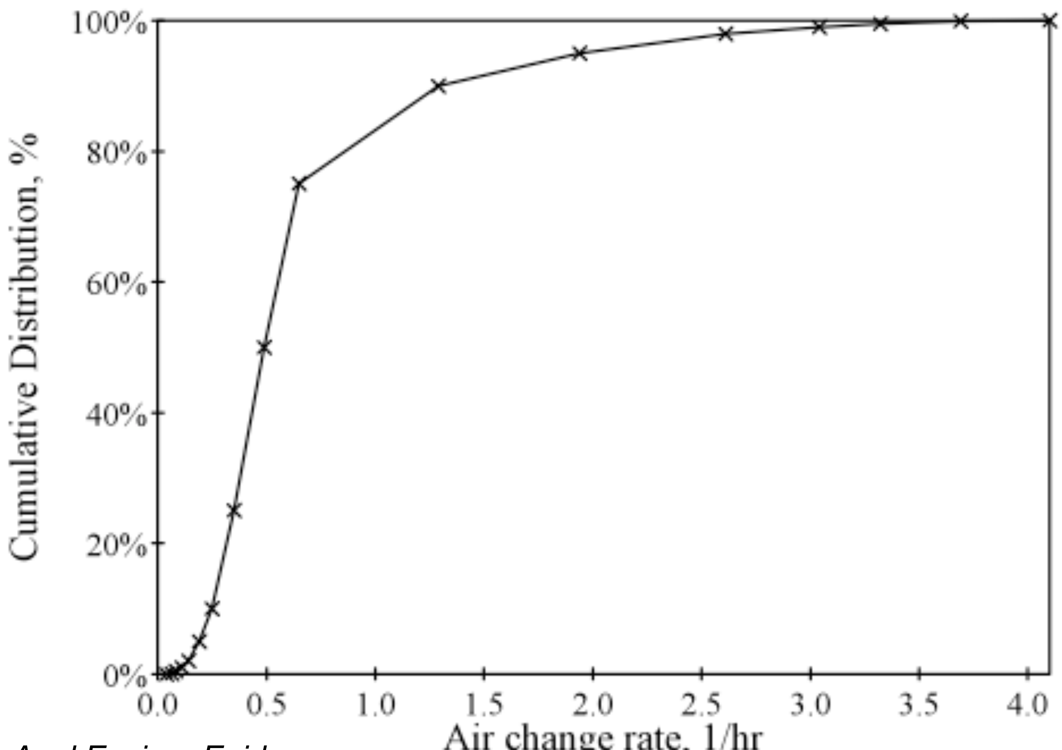
1990s median ~0.5/hr
2010 median ~0.4/hr
2009 new home median ~0.26/hr

- Not uncommon for new homes to have AER = 0.05-0.20 per hour

Offermann et al. 2009 CEC PIER Report

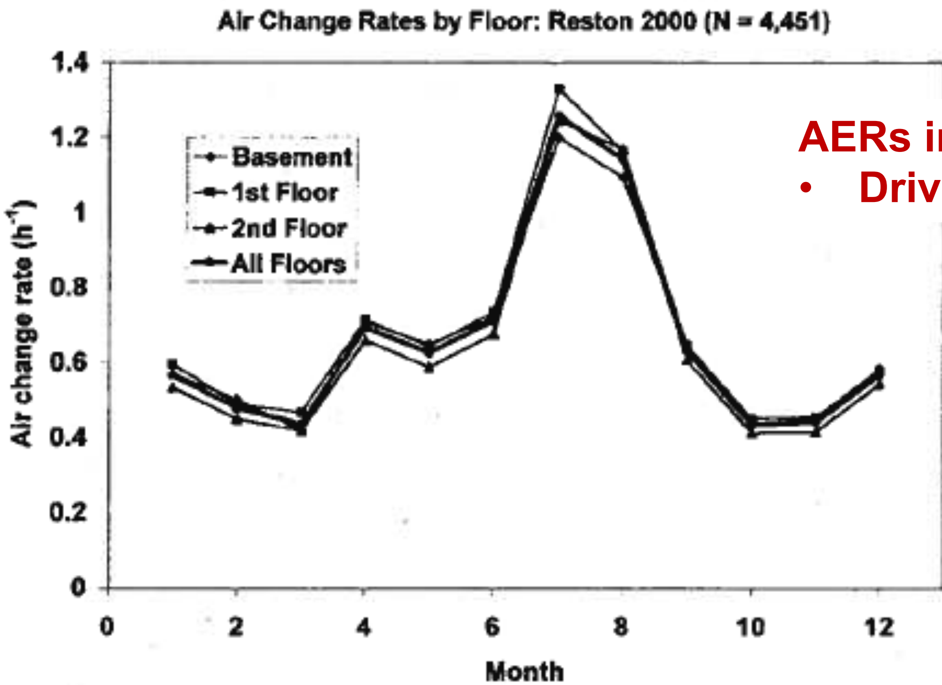
Variations in AER in individual buildings

- Air exchange rates differ within the same building over time
  - Differences vary by driving forces and building characteristics
- Example research: "Continuous measurements of air change rates in an occupied house for 1 year: the effect of temperature, wind, fans, and windows"
  - 4600 AERs measured by automated SF_6 system in one house for 2 years



Wallace et al. 2002 *J Expo Anal Environ Epidem*

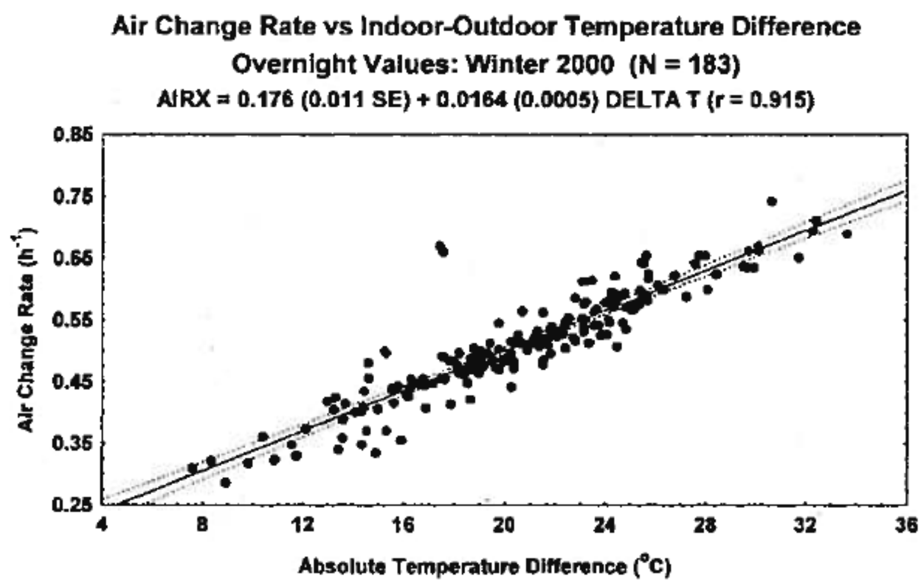
Variations in AER in individual buildings



AERs in individual buildings can vary by season

- **Driving forces: temperature, wind speed**

AERs can vary by I/O temperature within seasons

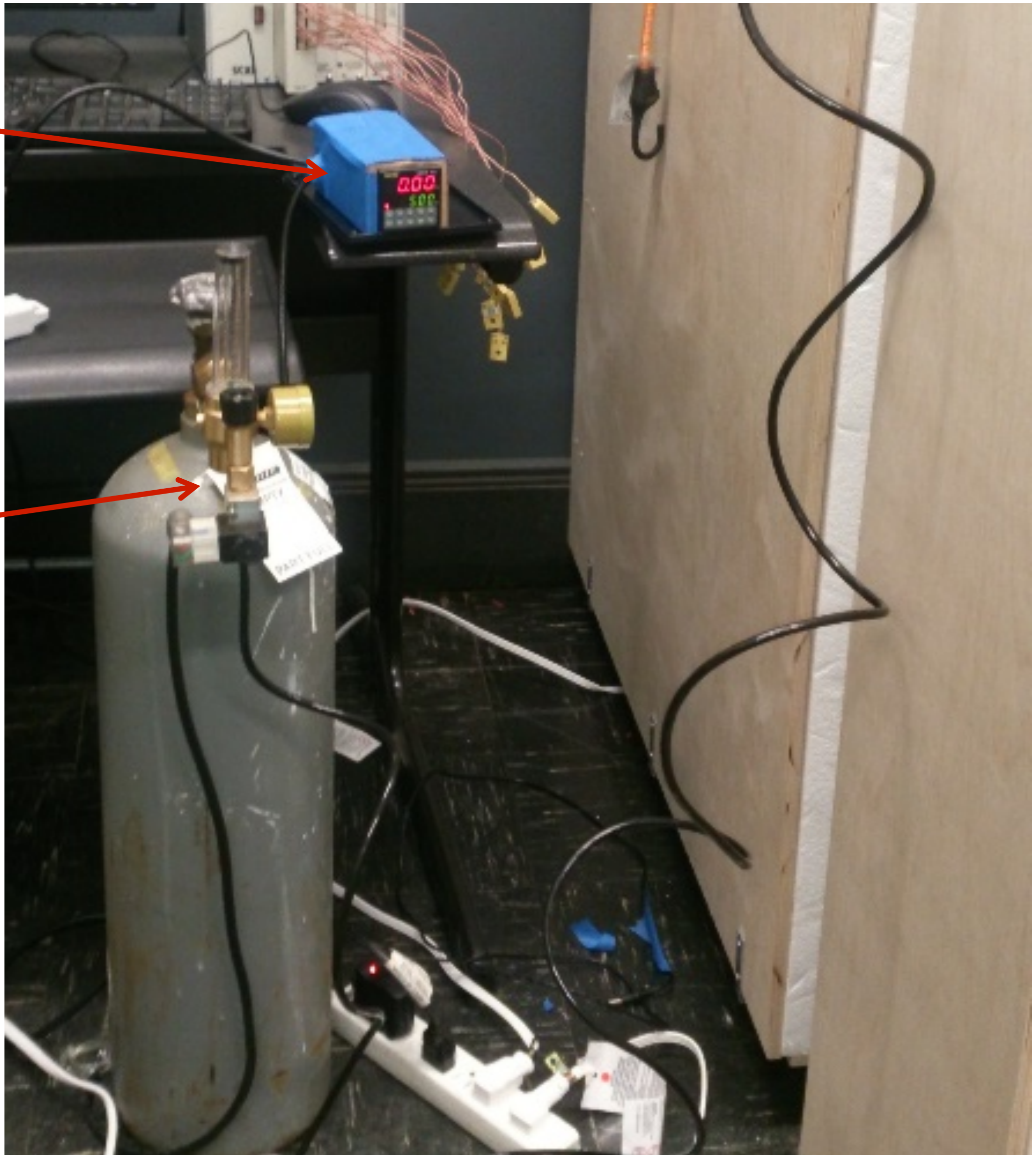


Wallace et al. 2002 *J Expo Anal Environ Epidem*

Variation in AER in individual buildings

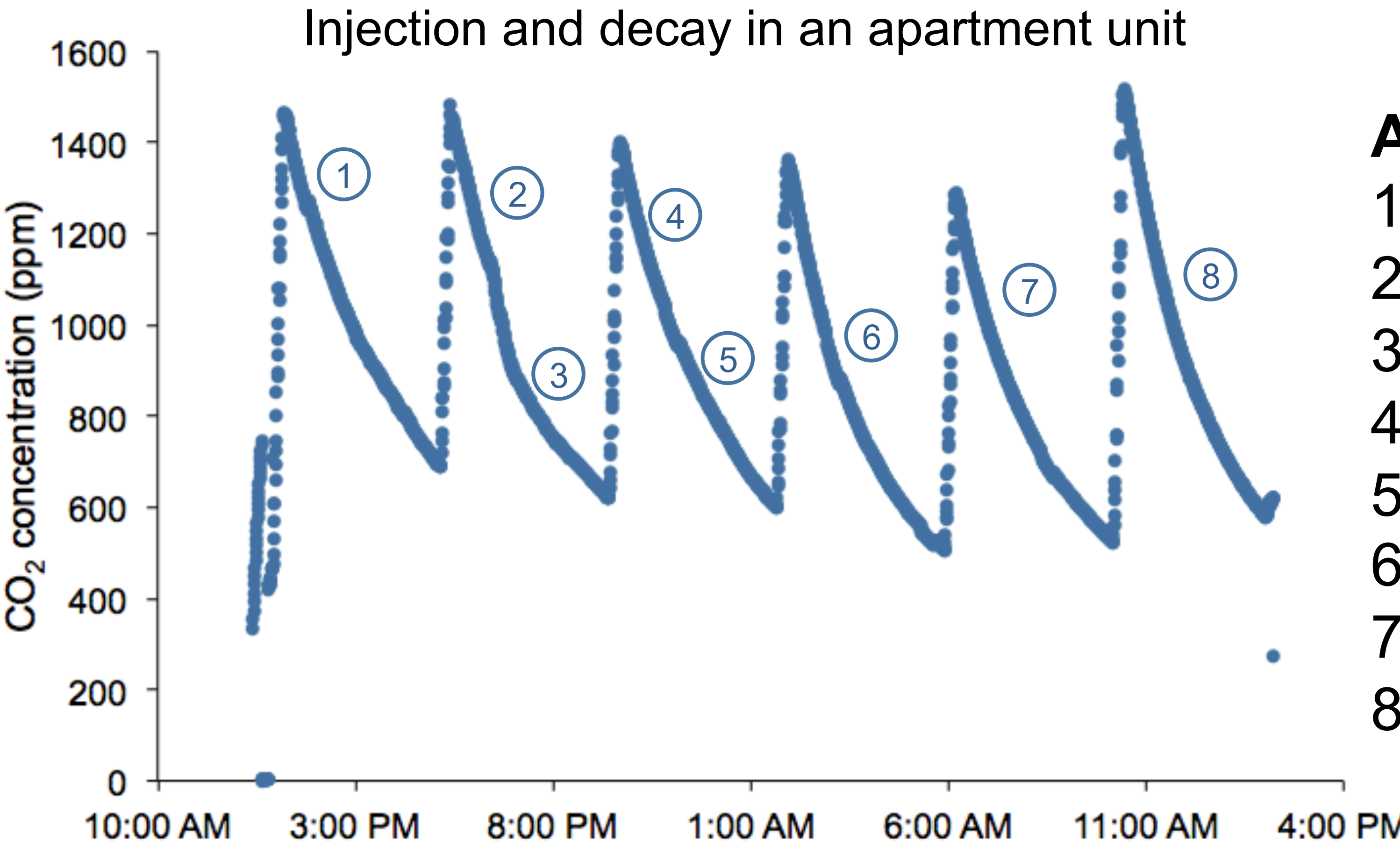
Sestos timer

Regulator



Measurements in Carman Hall apartment unit

Variation in AER in individual buildings



ACH
1) 0.28/hr
2) 0.37/hr
3) 0.52/hr
4) 0.28/hr
5) 0.36/hr
6) 0.46/hr
7) 0.40/hr
8) 0.43/hr

CO_2 measured w/ PP Systems SBA-5

Where does that leave us?

- Some have tried to correlate blower door leakage parameters to actual AER
  - One way is to simply divide ACH_{50} by a factor, F: $$ACH \approx \frac{ACH_{50}}{F}$$
    - F = 16 has been shown to provide accurate enough descriptions across a large dataset
    - But not sufficient for *instantaneous* AER predictions in a real building
  - We can use <u>air infiltration models</u> and blower door test data to predict AER with reasonable accuracy
    - 2013 ASHRAE Handbook of Fundamentals Chapter 16
    - LBL, LBLX, AIM-2, and others
    - Typically requires some inputs that are potentially difficult to obtain
      - More advanced forms of models require distribution of leakage sites (really just impossible to get)

Air infiltration models

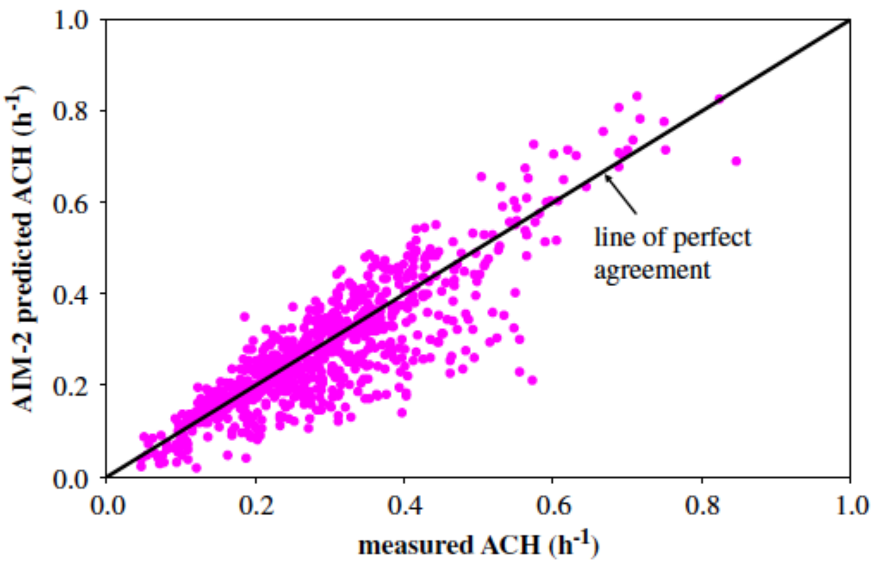
- Alberta air infiltration model (AIM-2)

$$Q = [Q_s^{1/n} + Q_w^{1/n} + \beta(Q_s Q_w)^{1/2n}]^n$$

where β is an empirical constant equal to -0.33.

$$Q_s = Cf_s(\Delta P_s)^n = Cf_s \left[\rho_{out} g H \frac{|T_{in} - T_{out}|}{T_{in}} \right]^n$$

$$Q_w = Cf_w(\Delta P_w)^n = Cf_w \left[\frac{\rho_{out}(S_w U)^2}{2} \right]^n$$



Wang et al. (2009) *Building and Environment*

These factors f_s, f_w, and S_w take several parameters into account, including leakage distribution sites and shielding by other buildings

- Empirical
- Difficult to get

Air infiltration models

- LBL model

$$Q_{\text{inf}} = A_{\text{inf}}\sqrt{k_s |T_{\text{in}} - T_{\text{out}}| + k_w U^2}$$

From blower door test

Table S1. Stack coefficient $k_s\left[(\mathrm{L/s})^2/(\mathrm{cm}^4\cdot\mathrm{K})\right]$

	House height (stories)		
	One	Two	Three
Stack coefficient	0.000145	0.000290	0.000435

Table S2. Wind coefficient $k_w\left[(\mathrm{L/s})^2/(\mathrm{cm}^4\cdot(\mathrm{m/s})^2)\right]$

	House height (stories)		
Shelter class	One	Two	Three
1	0.000319	0.000420	0.000494
2	0.000246	0.000325	0.000382
3	0.000174	0.000231	0.000271
4	0.000104	0.000137	0.000161
5	0.000032	0.000042	0.000049

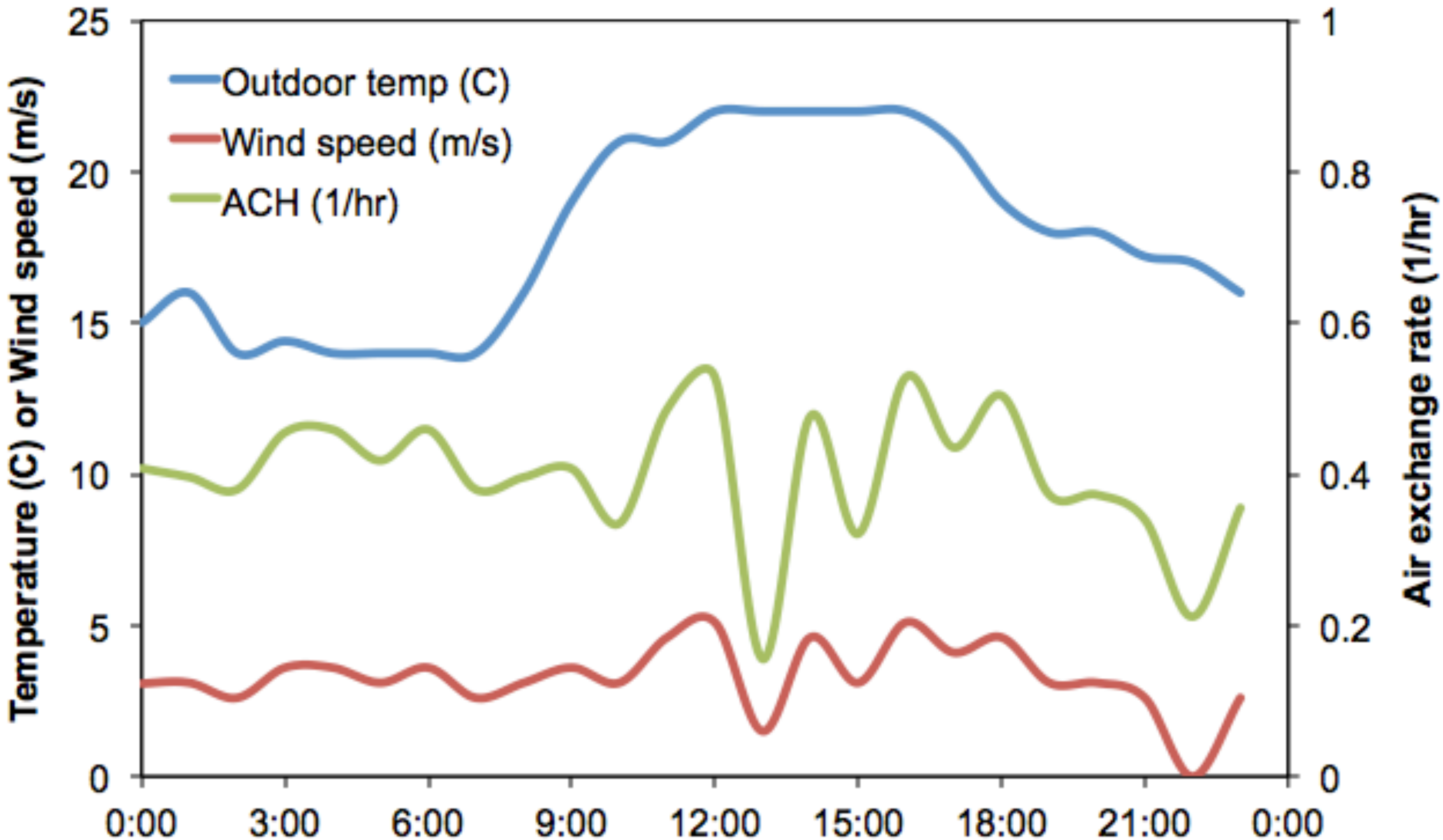
Table S3. Local sheltering

Shelter class for LBL and LBLX models[1]	Shelter class for SF model[2]	Description[1]
1	Exposed	No obstructions or local shielding
2	Normal	Typical shelter for an isolated rural house
3	Normal	Typical shelter caused by other buildings across street from building under study
4	Normal	Typical shelter for urban buildings on larger lots where sheltering obstacles are more than one building height away
5	Well-shielded	Typical shelter produced by buildings or other structures immediately adjacent (closer than one building height): e.g., neighboring houses on same side of street, trees, bushes, etc.

Breen et al. (2010) *Environ Sci Technol*

Air infiltration models

Combining outdoor temperature, indoor temperature, and wind speed data to model instantaneous AER

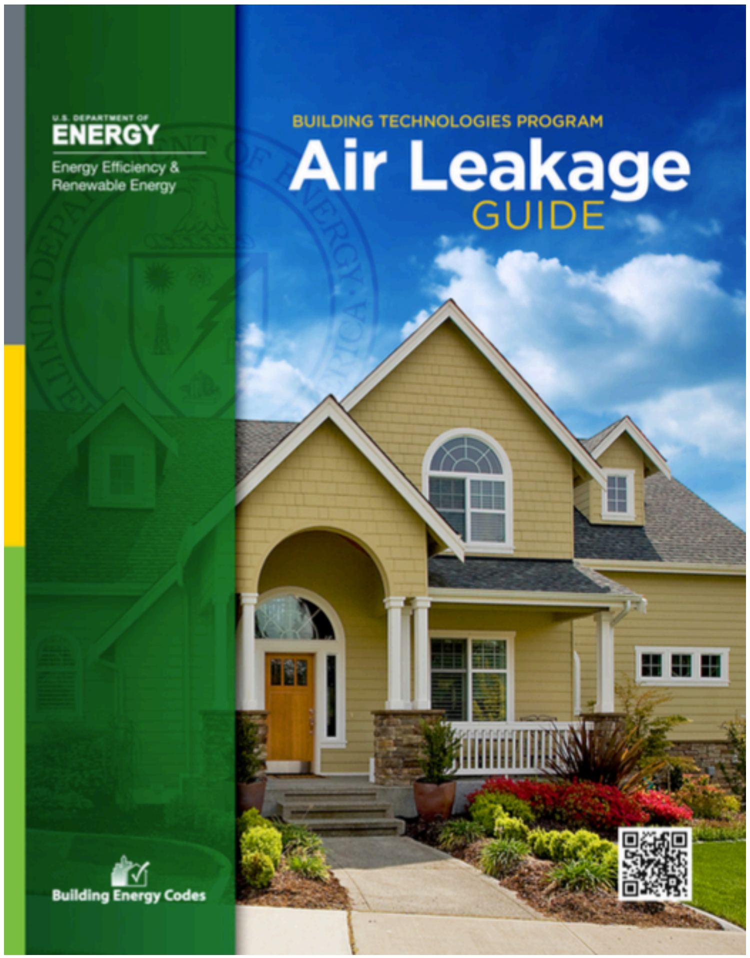


$$Q_{\text{inf}} = A_{\text{inf}}\sqrt{k_s|T_{\text{in}} - T_{\text{out}}| + k_w U^2}$$

CONTROLLING LEAKAGE

in enclosure design and construction

Some recommended whole-envelope leakage values



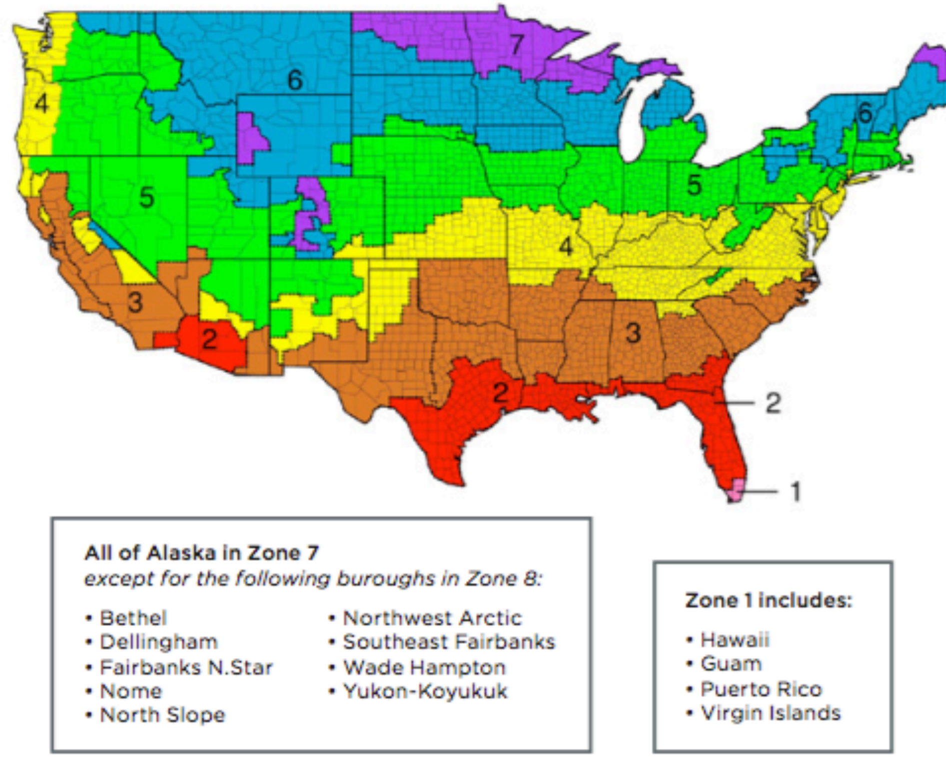


Figure 2: Climate zones (by county) for the 2012 IECC

Climate Zone	2009 IECC	2012 IECC
1 - 2	< 7 ACH	≤ 5 ACH @ 50 pascals
3 - 8	< 7 ACH @ 50 pascals	≤ 3 ACH @ 50 pascals

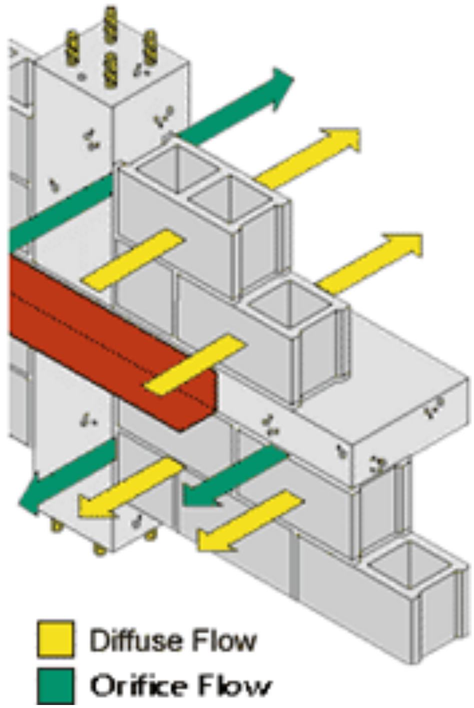
Table 1: 2009 vs. 2012 IECC Comparisons

Controlling air leakage

- We can control air leakage primarily through good construction
  - No sloppy joints
  - Proper air sealing/caulking
  - Proper use of air barriers

- Even with good construction, air can diffuse through porous materials

- Let's learn a little more about air barriers and the related water and vapor barriers



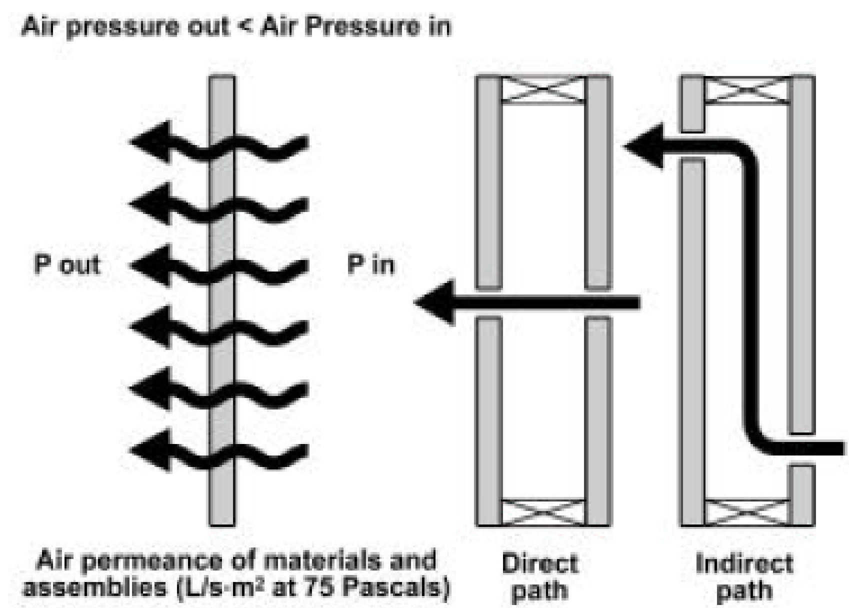
Three barriers …

- 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 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
  - Low air permeance
  - 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 no more than 0.02 L/s/m^2 @ 75 Pa
  - 0.004 cfm/ft^2 @ 0.3 in H_2O
- 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)
- Here is some information on material testing:
  http://www.airbarrier.org/materials/index_e.php

Air permeance of materials

Air barriers

Material	Leakage L/(s·m²)
Roofing Membrane	0
Aluminum Foil	0
Mod. Bitum Roof	0
Plywood (3/8”)	0
Extruded Poly (38mm)	0
Foil Back Uretheane (1”)	0
Cement Board	0
Foil Backed Gysum	0
Plywood (1/4”)	0.0067
OSB (1/2”)	0.019

Not air barriers

Material	Leakage L/(s·m²)
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
Fibreboard (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}
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 to 5×10^{-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).

*Units similar to water vapor permeability

Tyvek building wrap

- Tyvek and other building wrap materials are **air** and **water** barriers
  - But NOT **vapor** barriers
  - 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

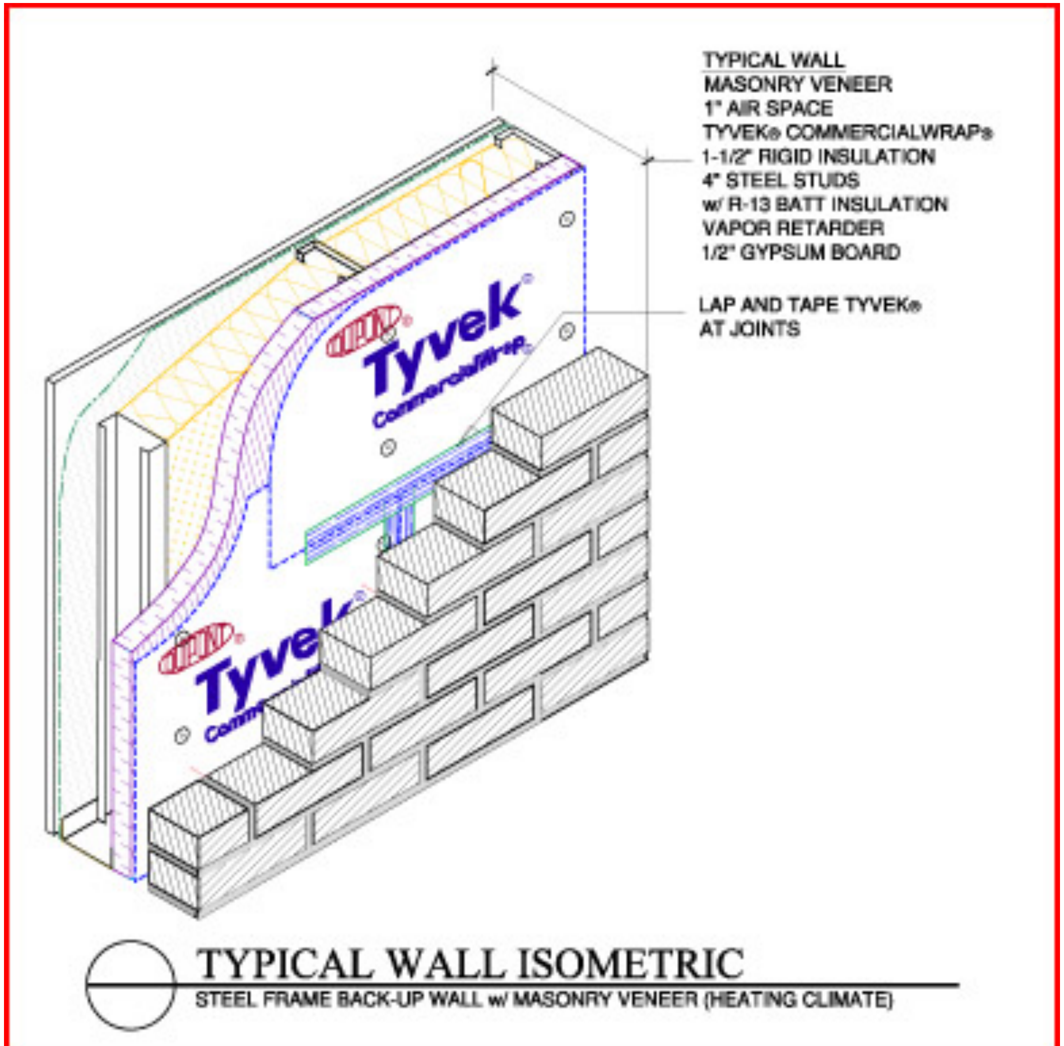
Building wrap components

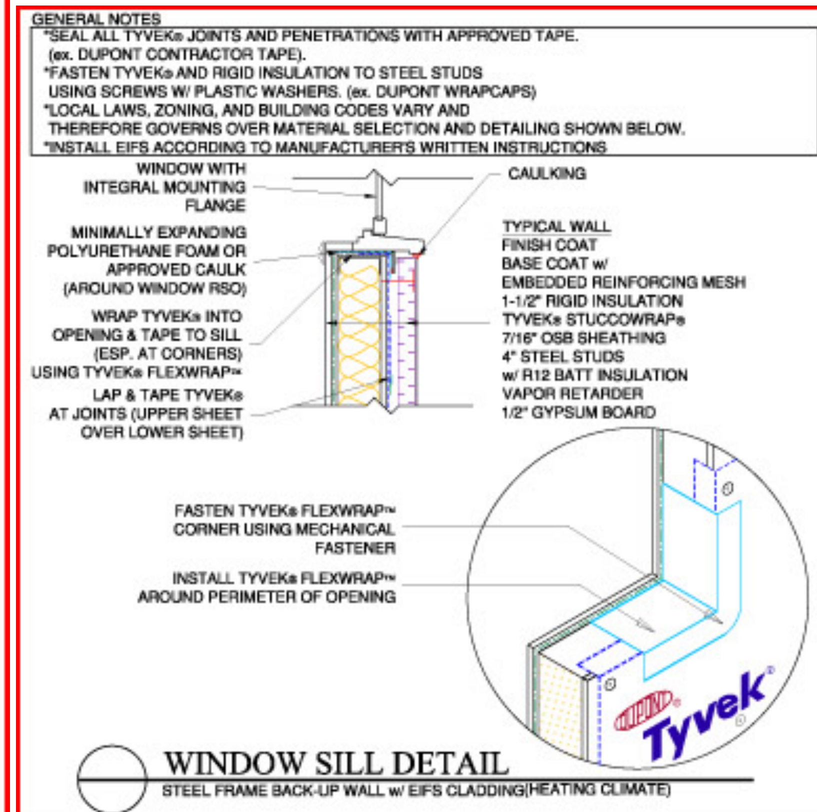
Building wraps: exterior air barrier

Building wraps: exterior air barrier

Photograph 2 – Exterior Air Barrier Using Adhered Membrane

Building wraps: detail drawings





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

Typical sites in need of air sealing

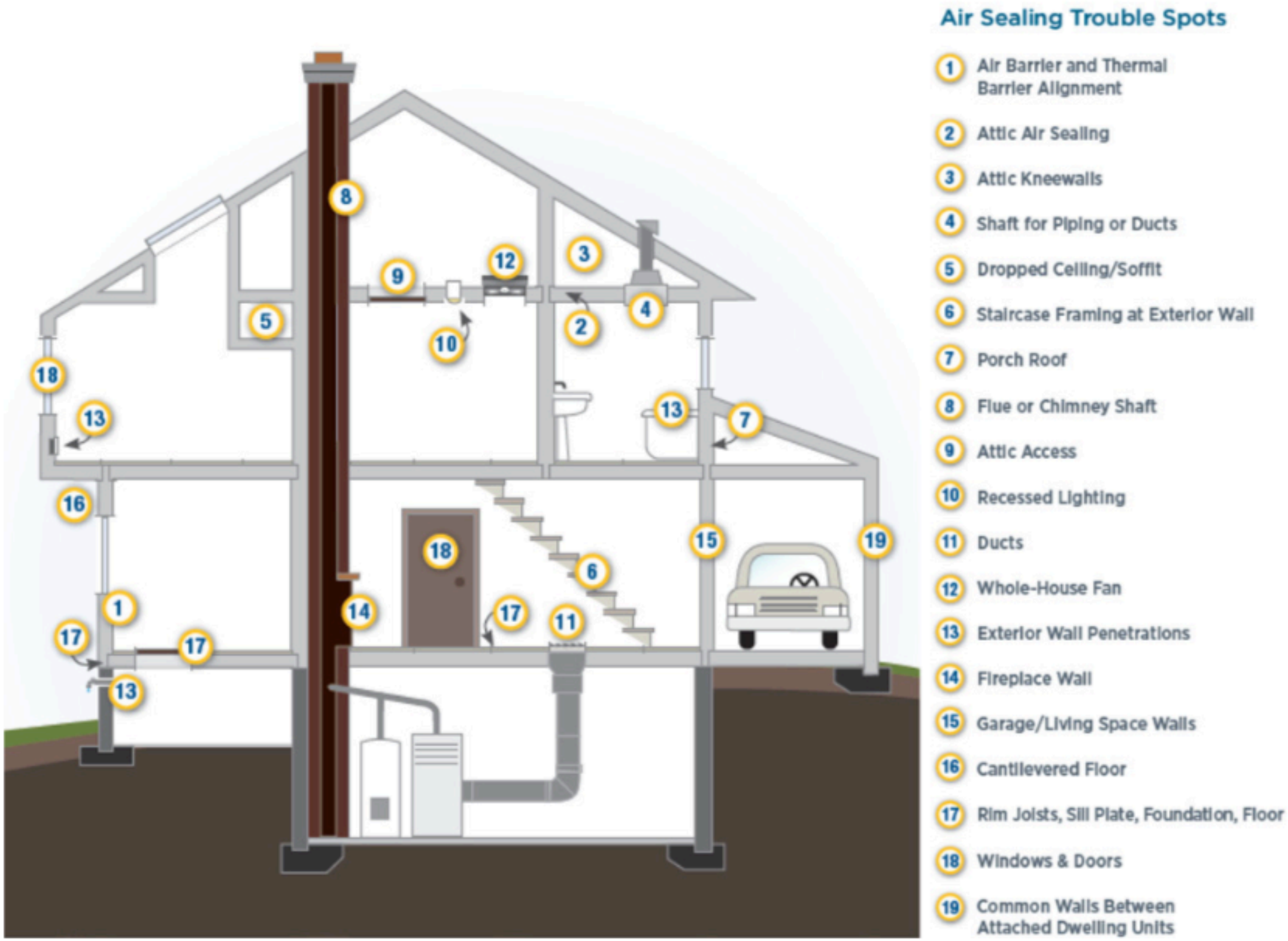


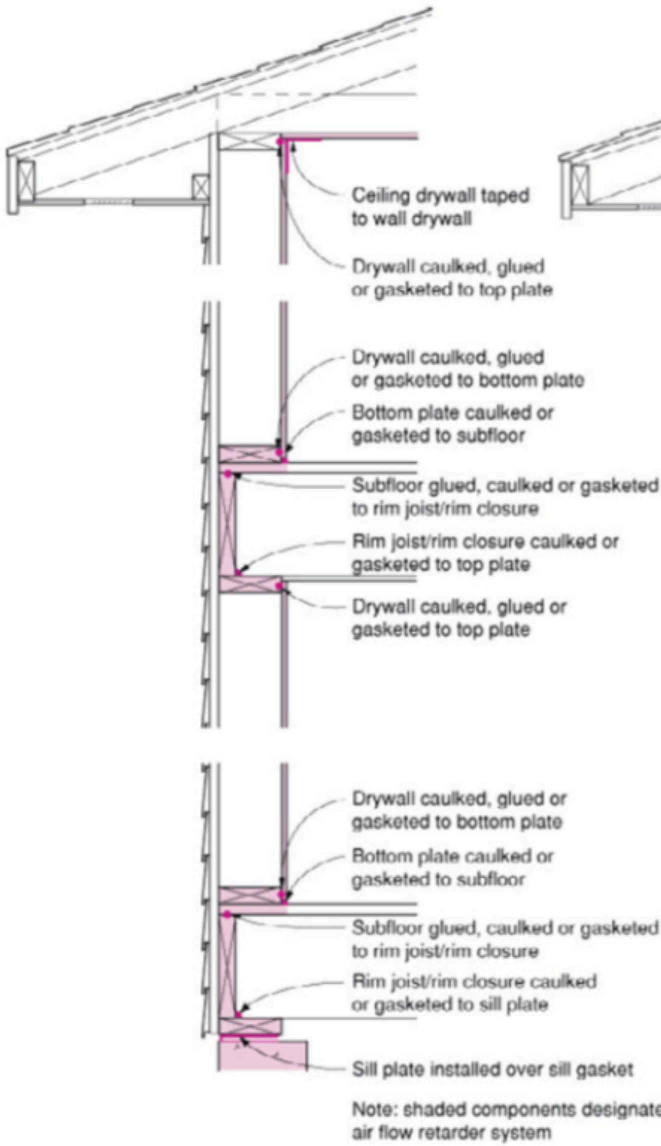
Figure 4: Building America—air sealing trouble spots

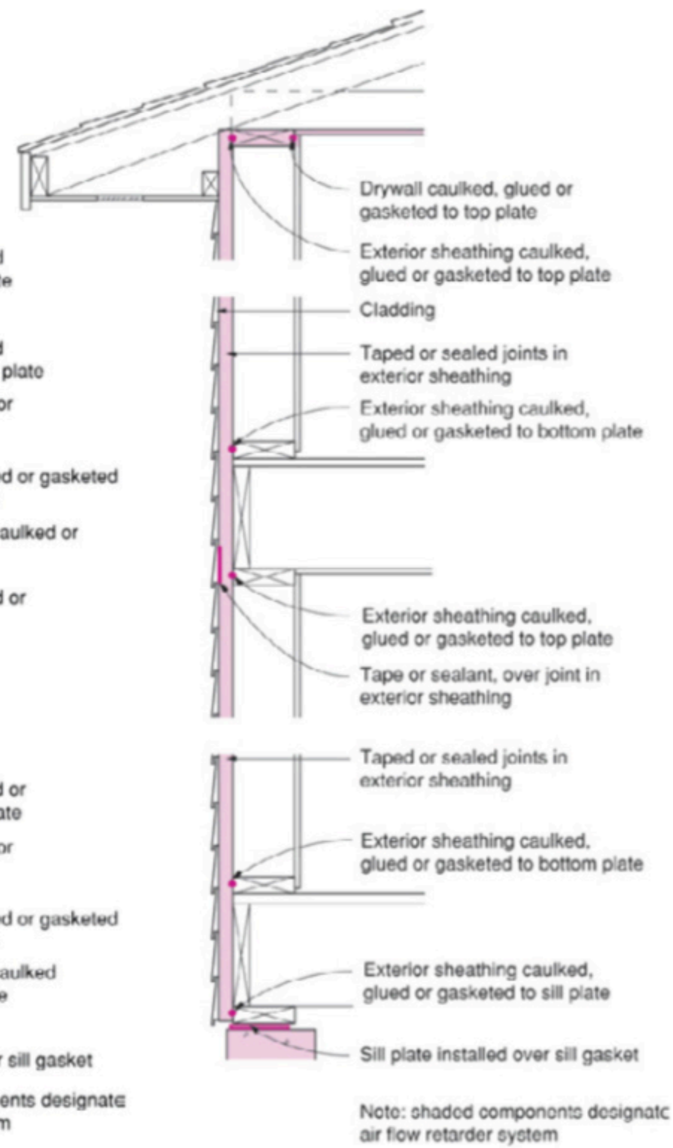
Typical sites in need of air sealing

COMPONENT	CRITERIA*
Air barrier and thermal barrier	A continuous air barrier shall be installed in the building envelope. Exterior thermal envelope contains a continuous air barrier. Breaks or joints in the air barrier shall be sealed. Air-permeable insulation shall not be used as a sealing material.
Ceiling/attic	The air barrier in any dropped ceiling/soffit shall be aligned with the insulation and any gaps in the air barrier sealed. Access openings, drop down stair or knee wall doors to unconditioned attic spaces shall be sealed.
Walls	Corners and headers shall be insulated and the junction of the foundation and sill plate shall be sealed. The junction of the top plate and top of exterior walls shall be sealed. Exterior thermal envelope insulation for framed walls shall be installed in substantial contact and continuous alignment with the air barrier. Knee walls shall be sealed.
Windows, skylights and doors	The space between window/door jambs and framing and skylights and framing shall be sealed.
Rim joists	Rim joists shall be insulated and include the air barrier.
Floors (including above-garage and cantilevered floors)	Insulation shall be installed to maintain permanent contact with underside of subfloor decking. The air barrier shall be installed at any exposed edge of insulation.
Crawl space walls	Where provided in lieu of floor insulation, insulation shall be permanently attached to the crawl space walls. Exposed earth in unvented crawl spaces shall be covered with a Class I vapor retarder with overlapping joints taped.
Shafts, penetration	Duct shafts, utility penetrations and flue shafts opening to exterior or unconditioned space shall be sealed.
Narrow cavities	Batts in narrow cavities shall be cut to fit, or narrow cavities shall be filled by insulation that on installation readily conforms to the available cavity space.
Garage separation	Air sealing shall be provided between the garage and conditioned spaces.
Recessed lighting	Recessed light fixtures installed in the building thermal envelope shall be air tight, IC rated, and sealed to the drywall.
Plumbing and wiring	Batt insulation shall be cut neatly to fit around wiring and plumbing in exterior walls, or insulation that on installation readily conforms to available space shall extend behind piping and wiring.
Shower/tub on exterior wall	Exterior walls adjacent to showers and tubs shall be insulated and the air barrier installed separating them from the showers and tubs.
Electrical/phone box on exterior walls	The air barrier shall be installed behind electrical or communication boxes or air sealed boxes shall be installed.
HVAC register boots	HVAC register boots that penetrate building thermal envelope shall be sealed to the subfloor or drywall.
Fireplace	An air barrier shall be installed on fireplace walls. Fireplaces shall have gasketed doors.

*In addition, inspection of log walls shall be in accordance with the provisions of ICC-400.

Air sealing details



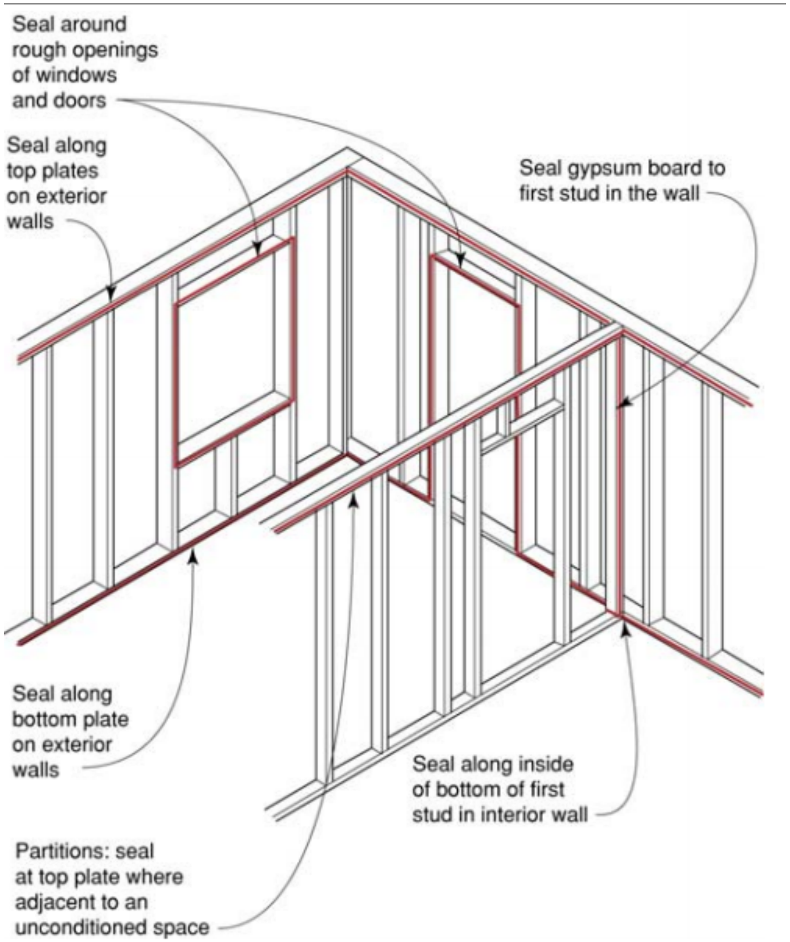


Source: Building Science Corporation

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

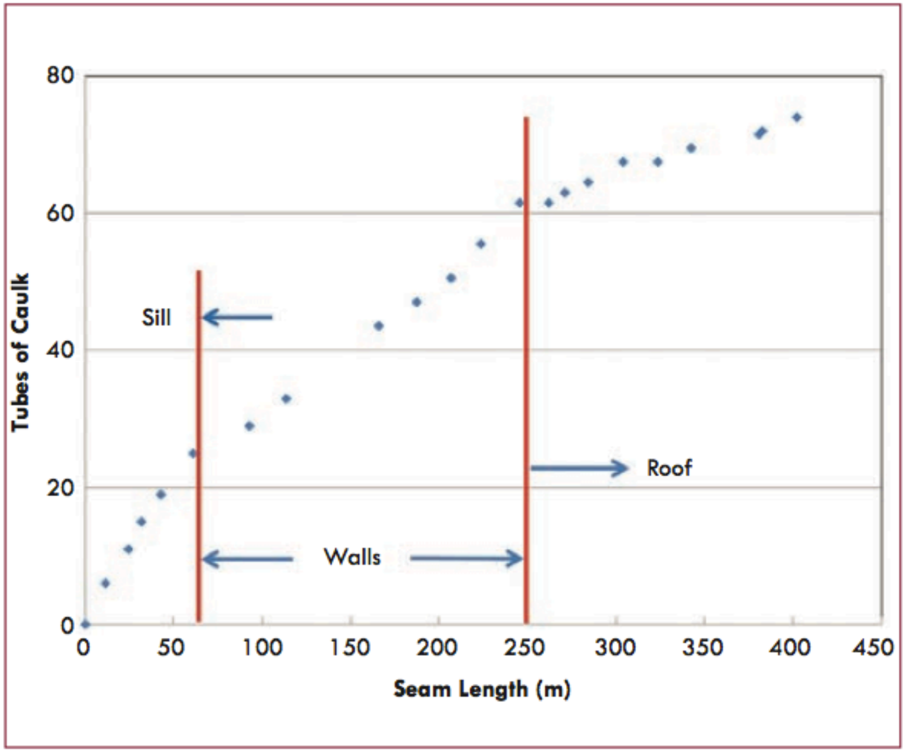
“Supersealing a house” during new construction

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

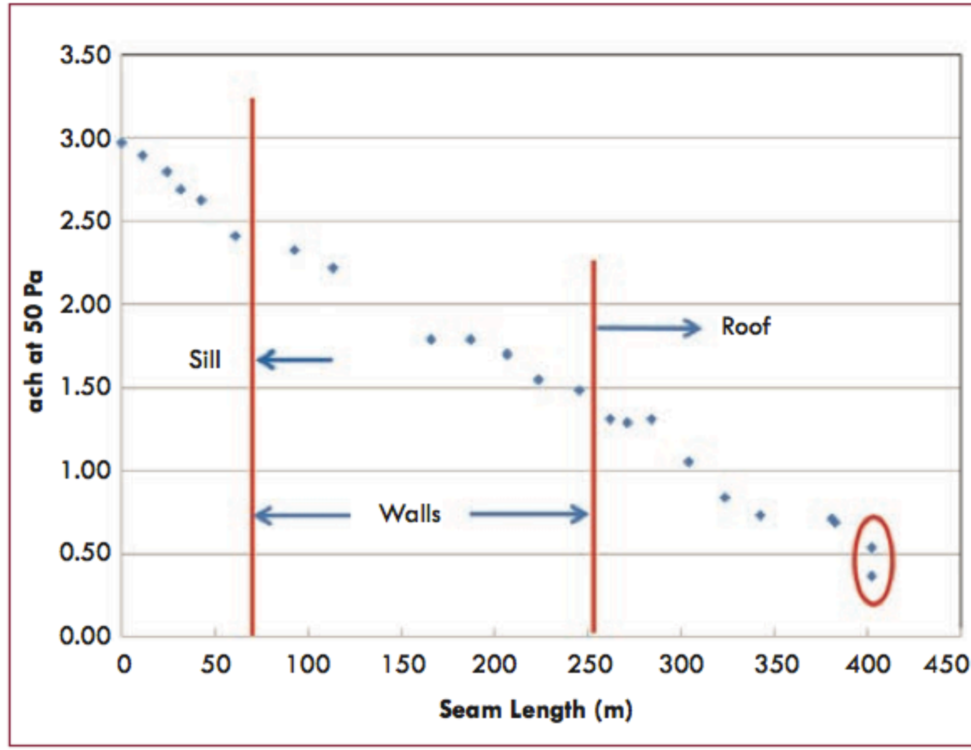
Newell and Newell (2011) *ASHRAE Journal*

“Supersealing a house” during new construction

Cumulative length of caulking



Reductions in ACH_{50} (blower door)



Newell and Newell (2011) *ASHRAE Journal*

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

Nabinger and Persily (2011) *Energy and Buildings*

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

Nabinger and Persily (2011) *Energy and Buildings*

Air sealing during retrofits

- Blower door tests
  - Pre-retrofit: ACH_{50} = 11.8 hr^{-1}
  - Post-retrofit: ACH_{50} = 9.0 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

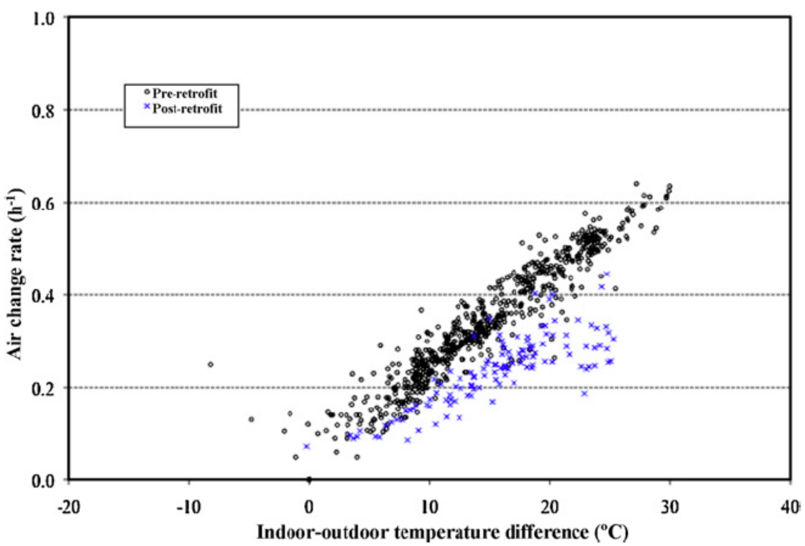


Fig. 6. Pre- and post-retrofit measured air change rates as a function of temperature difference (low wind speed): forced-air fan off (Condition 0).

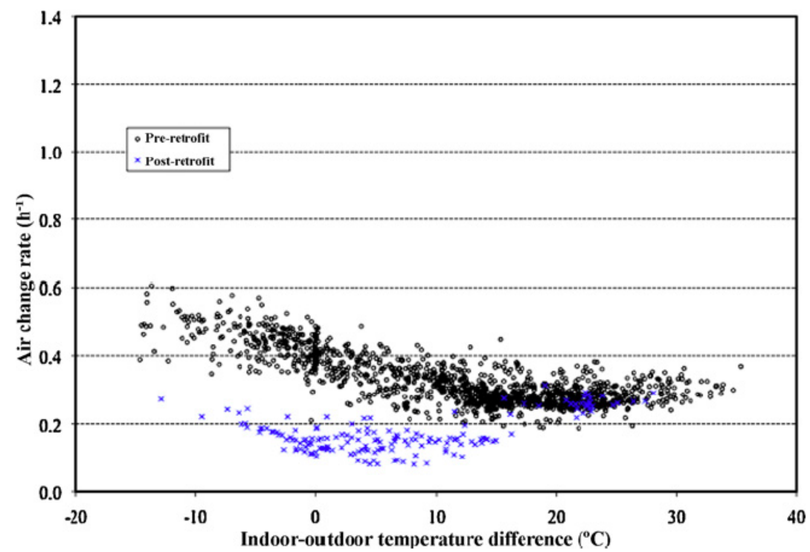
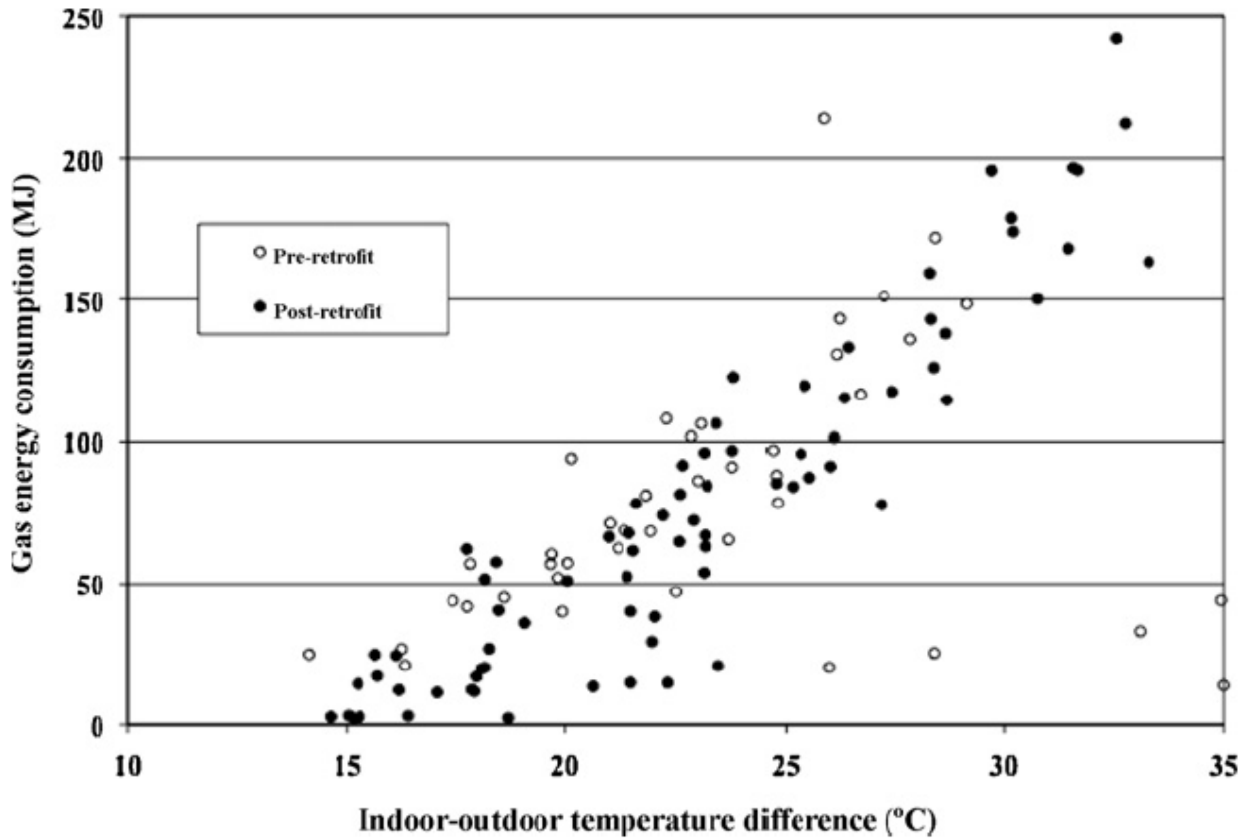


Fig. 8. Pre- and post-retrofit measured air change rates as a function of temperature difference (low wind speed): forced-air fan on, outdoor air intake sealed (Condition 1a).

Nabinger and Persily (2011) *Energy and Buildings*

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



Nabinger and Persily (2011) *Energy and Buildings*

Summary of air movements in enclosures

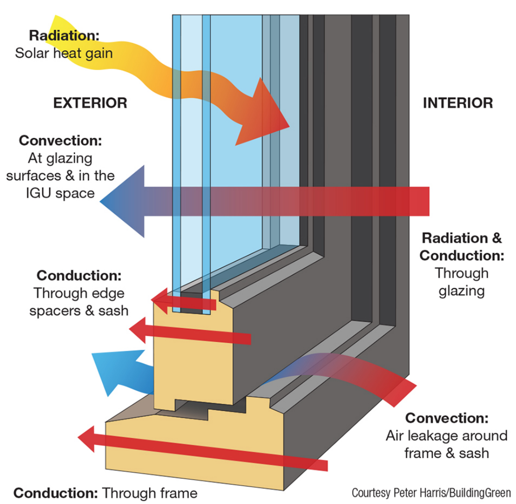
- Categories
  - Infiltration/exfiltration
  - Ventilation (natural or forced)
- Driving forces
  - Stack effect
    - Temperature and height differences
    - Leakage distributions
  - Wind effects
    - Wind direction
    - Wind speed
    - Leakage distributions
- Air tightness vs. actual air exchange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

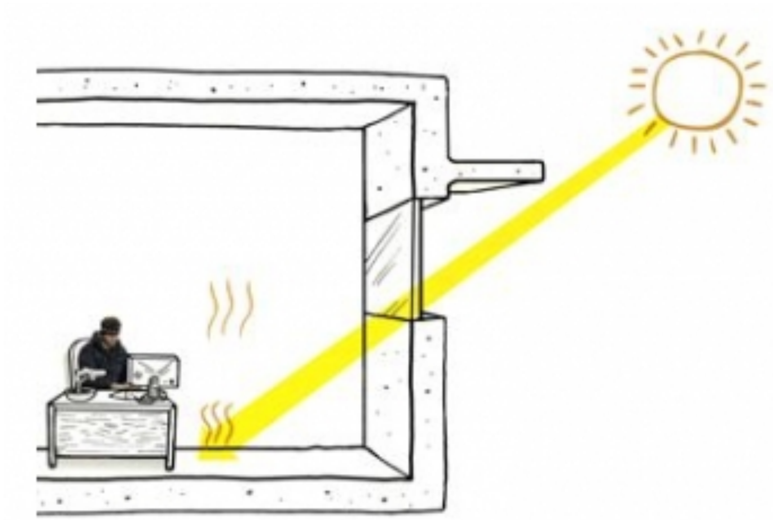
FENESTRATION

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):

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

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
  - Much of IIT has single glaze windows
    - Mies van der Rohe used them before IGUs were available

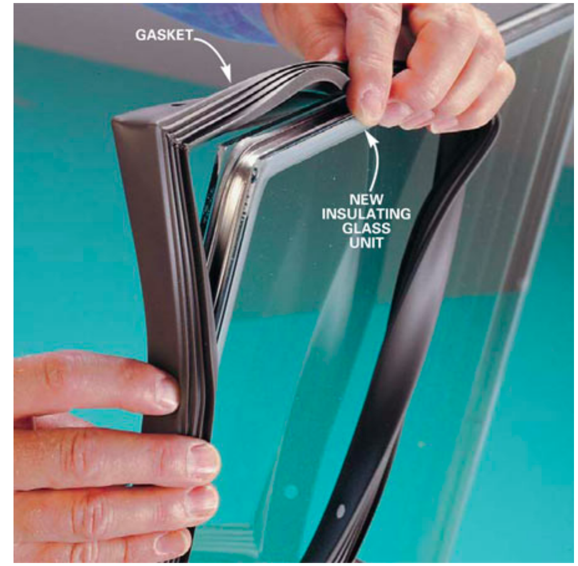
- Throughout most of the U.S., a multiple glaze unit or insulated window assembly should be used
  - Also called an insulated glazing unit (IGU)

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



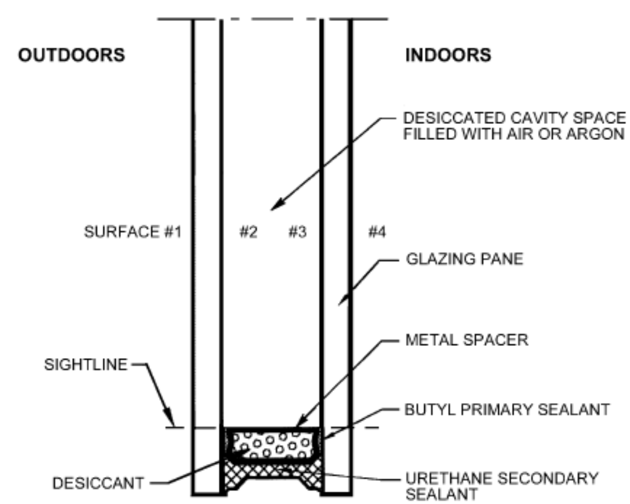
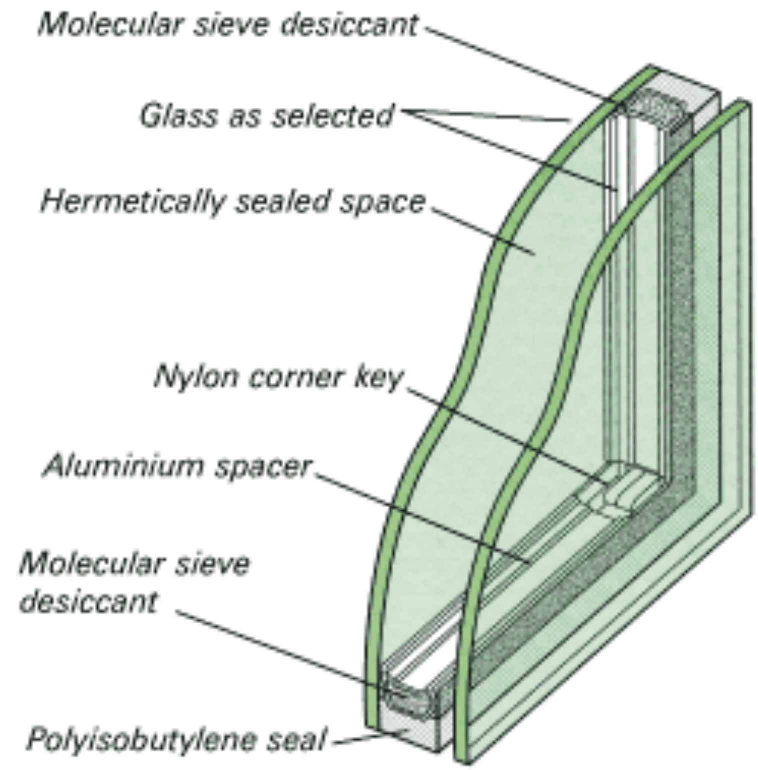


Fig. 1 **Insulating Glazing Unit (IGU) Construction Detail**

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*

U-values and multiple layers of glazing

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

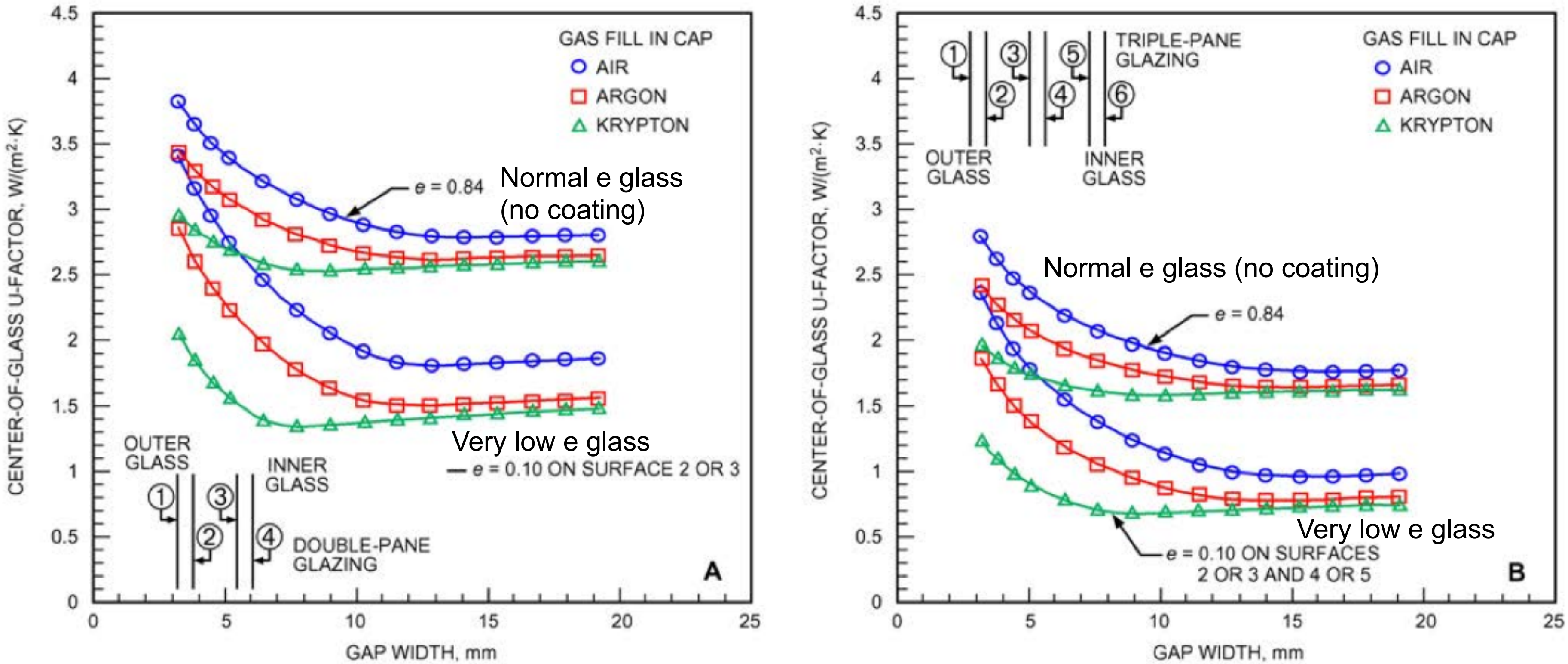


Fig. 3 Center-of-Glass U-Factor for Vertical Double- and Triple-Pane Glazing Units

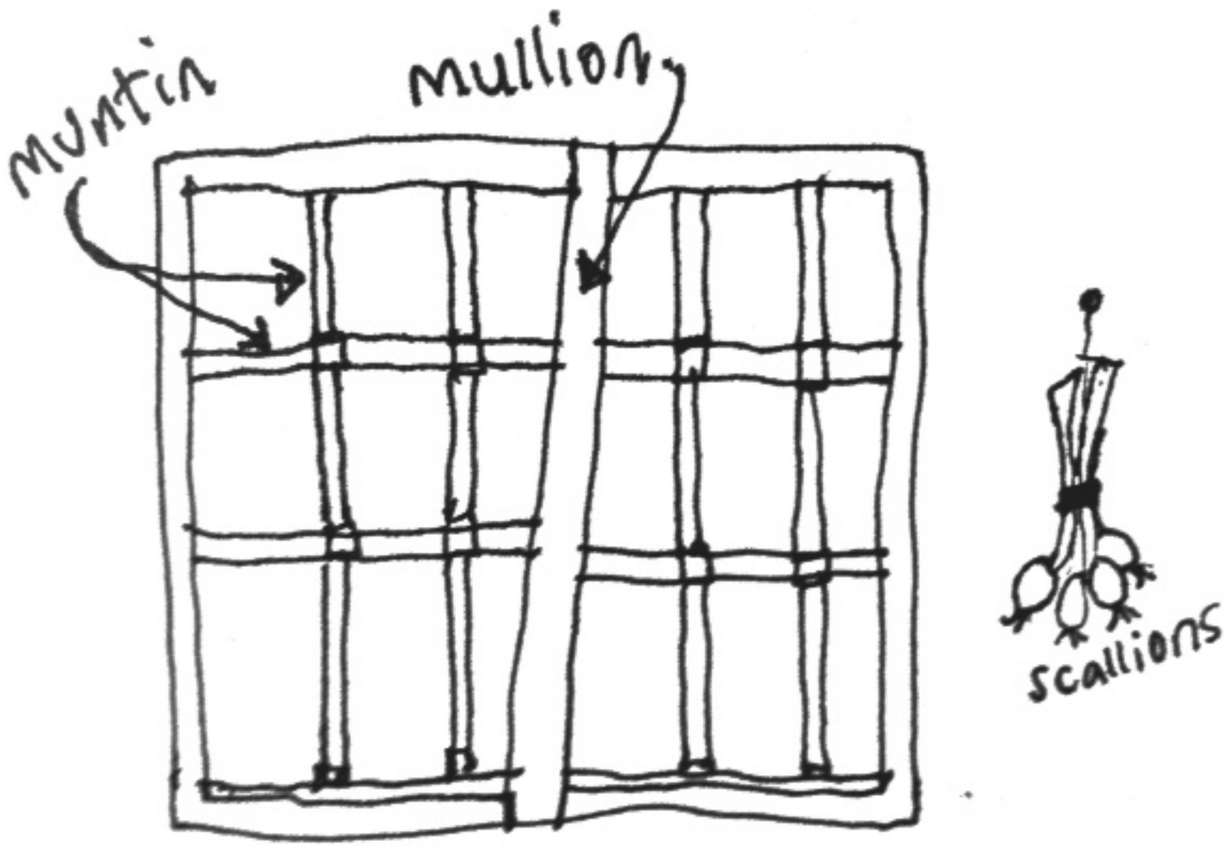
Q: Why does argon have lower U value than air?

k_{air} = 0.025 W/mK
k_{argon} = 0.016 W/mK
$k_{krypton}$ = 0.0088 W/mK

2013 ASHRAE Handbook of Fundamentals: Chapter 15

What about full window/fenestration assemblies?

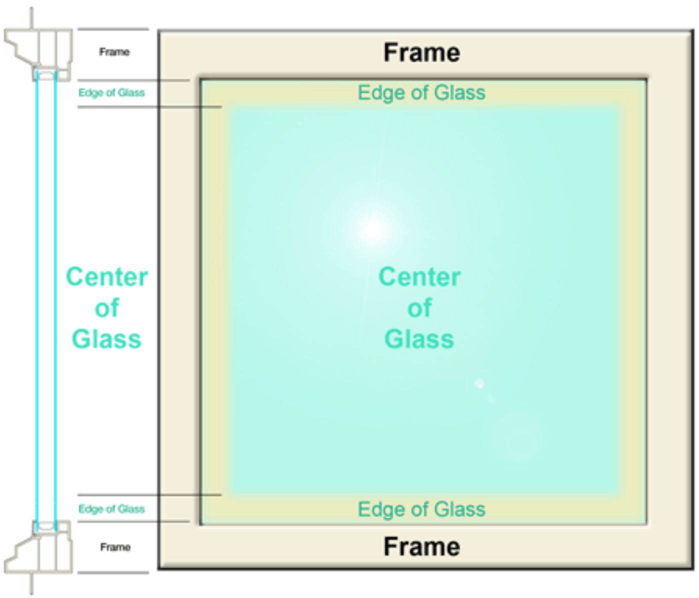
- In addition to glazing material, windows also include framing, mullions, muntin bars, dividers, and shading devices
  - These all combine to make **fenestration systems**



Window assembly U-factors

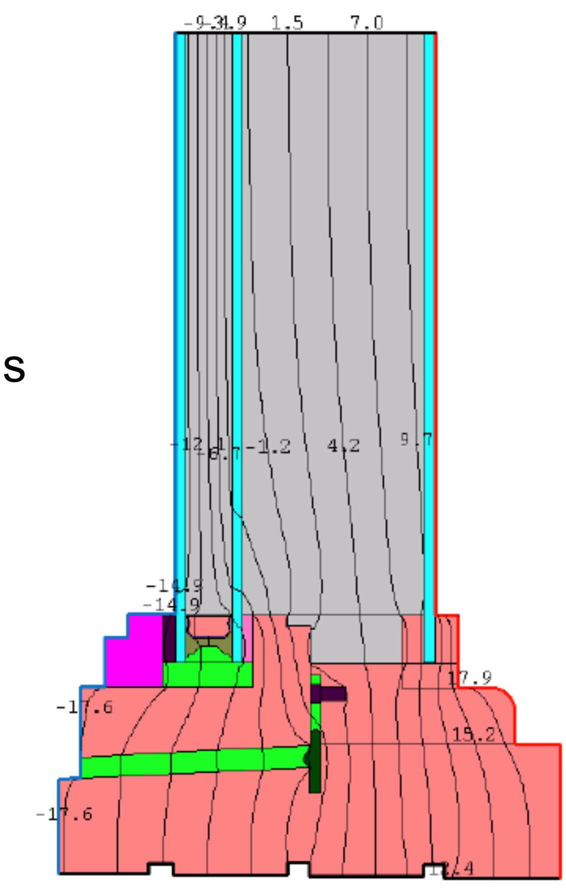
- U-values (or U-factors) for windows include all of the elements of the fenestration system
  - Center of glass properties (*cg*)
  - Edge of glass properties (*eg*)
  - Frame properties (*f*)
- The overall U-factor is estimated using area-weighted U-factors for each:

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



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 spend)
  - You can look up prototypical numbers in the ASHRAE HOF

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

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

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

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

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

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

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

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

Doors

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

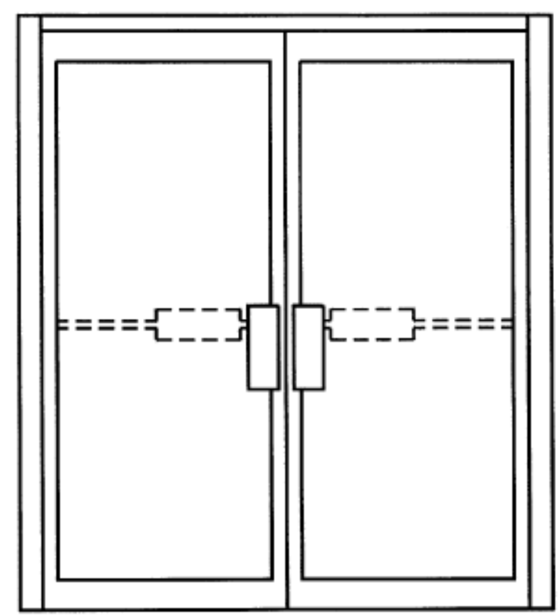


Fig. 5 Details of Stile-and-Rail Door

Doors

- U-values for typical doors

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

Door Type	No Glazing	Single Glazing	Double Glazing with 12.7 mm Airspace	Double Glazing with $e = 0.10$, 12.7 mm Argon
SWINGING DOORS (Rough Opening, 970 × 2080 mm)				
Slab Doors				
Wood slab in wood frame[a]	2.61			
6% glazing (560 × 200 lite)	—	2.73	2.61	2.50
25% glazing (560 × 910 lite)	—	3.29	2.61	2.38
45% glazing (560 × 1620 lite)	—	3.92	2.61	2.21
More than 50% glazing		Use Table 4 (operable)		
Insulated steel slab with wood edge in wood frame[a]	0.91			
6% glazing (560 × 200 lite)	—	1.19	1.08	1.02
25% glazing (560 × 910 lite)	—	2.21	1.48	1.31
45% glazing (560 × 1630 lite)	—	3.29	1.99	1.48
More than 50% glazing		Use Table 4 (operable)		
Foam insulated steel slab with metal edge in steel frame[b]	2.10			
6% glazing (560 × 200 lite)	—	2.50	2.33	2.21
25% glazing (560 × 910 lite)	—	3.12	2.73	2.50
45% glazing (560 × 1630 lite)	—	4.03	3.18	2.73
More than 50% glazing		Use Table 4 (operable)		
Cardboard honeycomb slab with metal edge in steel frame	3.46			
Style and Rail Doors				
Sliding glass doors/ French doors		Use Table 4 (operable)		

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

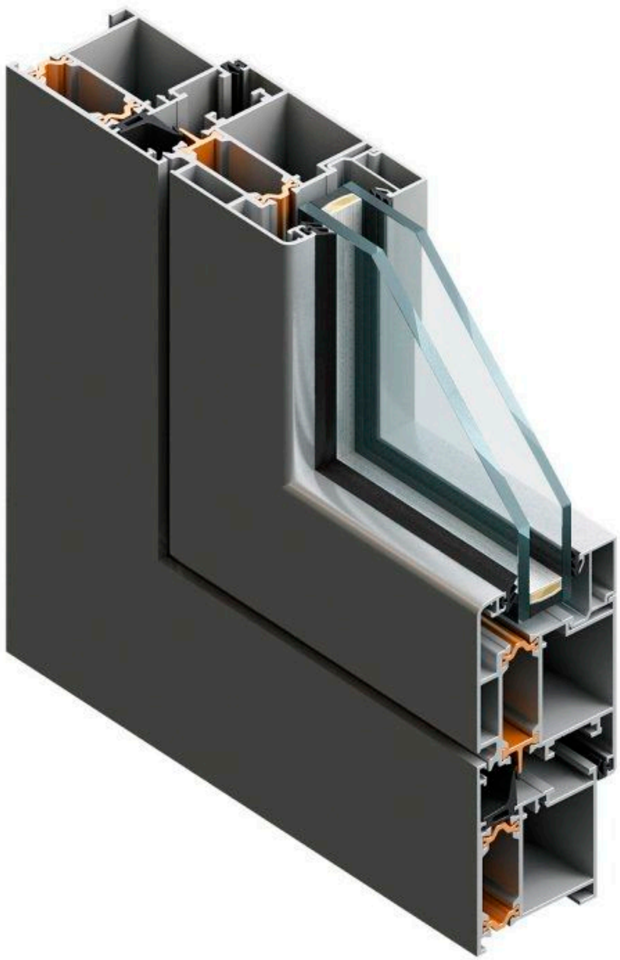
Door Type	No Glazing	Single Glazing	Double Glazing with 12.7 mm Airspace	Double Glazing with $e = 0.10$, 12.7 mm Argon
Site-Assembled Style and Rail Doors				
Aluminum in Aluminum Frame	—	7.49	5.28	4.49
Aluminum in Aluminum Frame with Thermal Break	—	6.42	4.20	3.58
REVOLVING DOORS (Rough Opening, 2080 × 2130 mm)				
Aluminum in aluminum frame				
Open	—	7.49	—	—
Closed	—	3.69	—	—
SECTIONAL OVERHEAD DOORS (Nominal, 3050 × 3050 mm)				
Uninsulated steel (nominal $U = 6.53$)[c]	6.53	—	—	—
Insulated steel (nominal $U = 0.62$)[c]	1.36	—	—	—
Insulated steel with thermal break (nominal $U = 0.45$)[c]	0.74	—	—	—

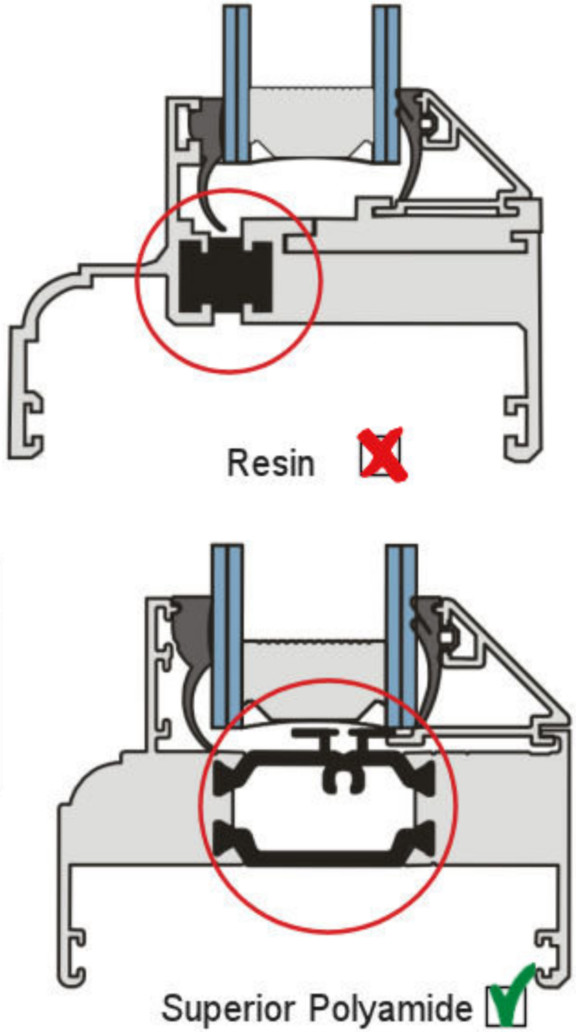
Note: All dimensions are in millimetres.
[a] thermally broken sill (add 0.17 W/(m²·K) for non-thermally broken sill)
[b] non-thermally broken sill
[c] Nominal U-factors are through the center of the insulated panel before consideration of thermal bridges around the edges of the door sections and due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

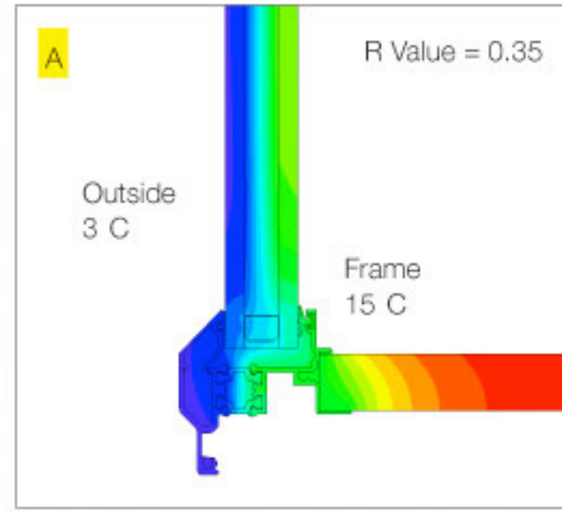
Ways to achieve low U-values in fenestration

- 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

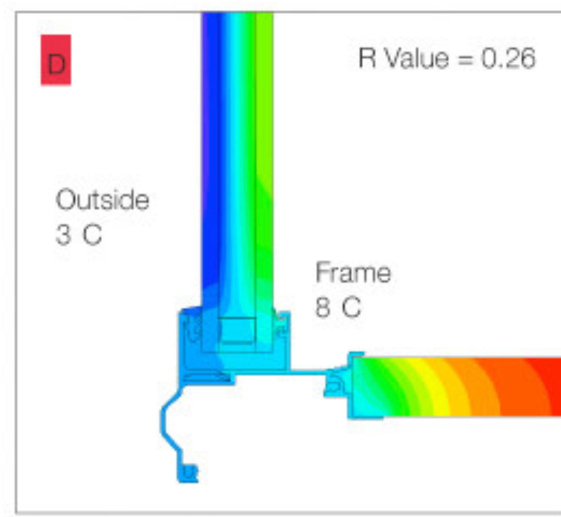
Thermally-broken window frames







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

One World Trade Center curtain wall install

https://www.youtube.com/watch?v=2y2x_2OaNrI

One World Trade Center curtain wall install

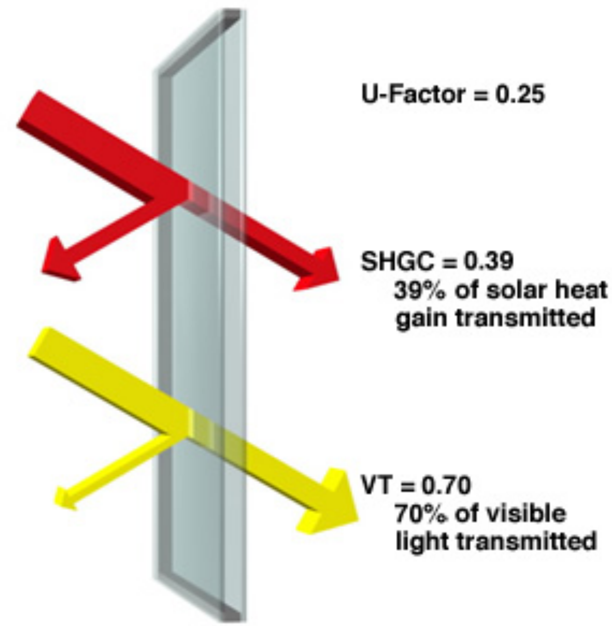
- Walls of Glass, PBS NOVA on One World Trade Center
  - http://www.pbs.org/wgbh/nova/tech/walls-glass.html

One World Trade Center curtain walls

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

Two other fenestration terms: SHGC and VT

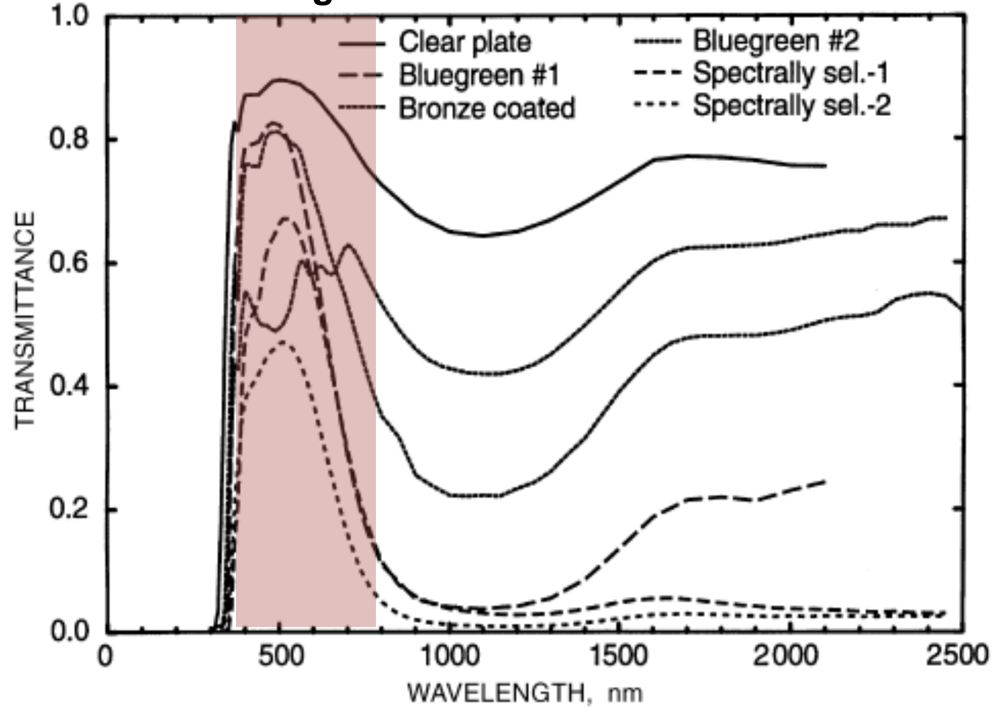
- Fenestration also allows for solar heat transfer and transfer of visible light
  - **SHGC**: Solar Heat Gain Coefficient
    - Energy transfer coefficient for all wavelengths of solar thermal radiation
  - **VT**: Visible Transmission Coefficient
    - Transmission coefficient for visible wavelength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

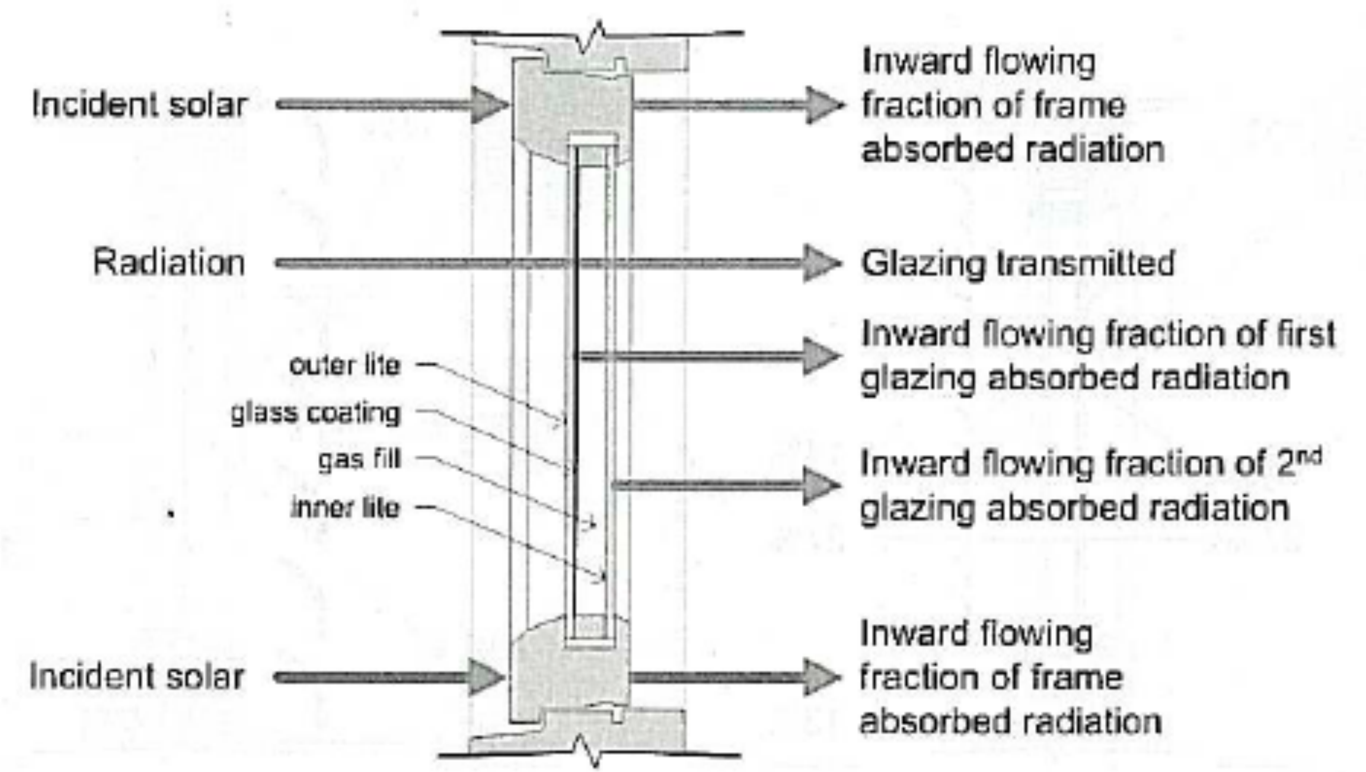


Tinted glass

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



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

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: $0 < SHGC < 1$

- 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

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 ($\mathcal{A}^f_n$) for Glazing and Window Systems

ID	Glazing System: Glass Thick., mm	Glazing System	Center Glazing T_V		Center-of-Glazing Properties, Incidence Angles: Normal 0.00	40.00	50.00	60.00	70.00	80.00	Hemis., Diffuse	Total Window SHGC at Normal Incidence, Aluminum: Operable	Aluminum: Fixed	Other Frames: Operable	Other Frames: Fixed	Total Window T_V at Normal Incidence, Aluminum: Operable	Aluminum: Fixed	Other Frames: Operable	Other Frames: Fixed
Uncoated Single Glazing																			
1a	3	CLR	0.90	SHGC	0.86	0.84	0.82	0.78	0.67	0.42	0.78	0.75	0.78	0.64	0.75	0.77	0.80	0.66	0.78
				T	0.83	0.82	0.80	0.75	0.64	0.39	0.75								
				R^f	0.08	0.08	0.10	0.14	0.25	0.51	0.14								
				R^b	0.08	0.08	0.10	0.14	0.25	0.51	0.14								
				$\mathcal{A}^f_1$	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								
				$\mathcal{A}^f_1$	0.16	0.17	0.18	0.19	0.19	0.17	0.17								

VT and SHGC data from ASHRAE HOF

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

	Glazing System				Center-of-Glazing Properties							Total Window SHGC at Normal Incidence				Total Window T_V at Normal Incidence			
					Incidence Angles							Aluminum		Other Frames		Aluminum		Other Frames	
ID	Glass Thick., mm		Center Glazing T_V		Normal 0.00	40.00	50.00	60.00	70.00	80.00	Hemis., Diffuse	Operable	Fixed	Operable	Fixed	Operable	Fixed	Operable	Fixed
Uncoated 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: Incidence Angles							Total Window SHGC at Normal Incidence: Aluminum		Total Window SHGC at Normal Incidence: Other Frames		Total Window T_v at Normal Incidence: Aluminum		Total Window T_v at Normal Incidence: 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
Low-e Double Glazing, e = 0.2 on surface 2																			
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 ($\mathcal{A}_n^f$) for Glazing and Window Systems

	Glazing System				Center-of-Glazing Properties							Total Window SHGC at Normal Incidence				Total Window T_V at Normal Incidence			
					Incidence Angles							Aluminum		Other Frames		Aluminum		Other Frames	
ID	Glass Thick., mm		Center Glazing T_V		Normal 0.00	40.00	50.00	60.00	70.00	80.00	Hemis., Diffuse	Operable	Fixed	Operable	Fixed	Operable	Fixed	Operable	Fixed
Uncoated 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								

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?
  - $SHGC_N = 0.63$

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

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

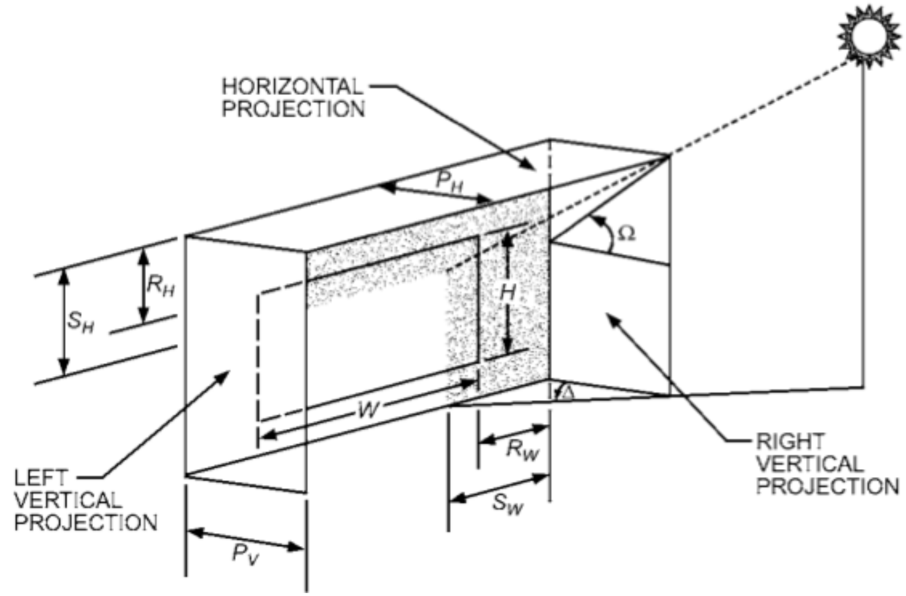
$$q_s = SHGC_N \cdot I_t = 0.63 \cdot 420 = 265 \, \frac{\mathrm{W}}{\mathrm{m}^2}$$

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 <u>normal incident</u> and total assembly SHGC

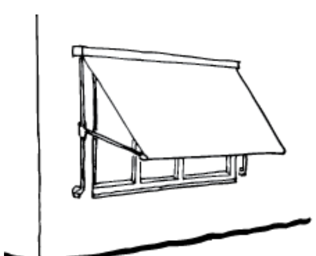
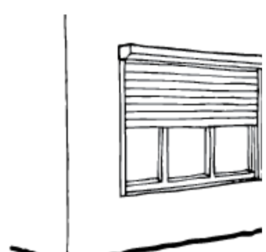
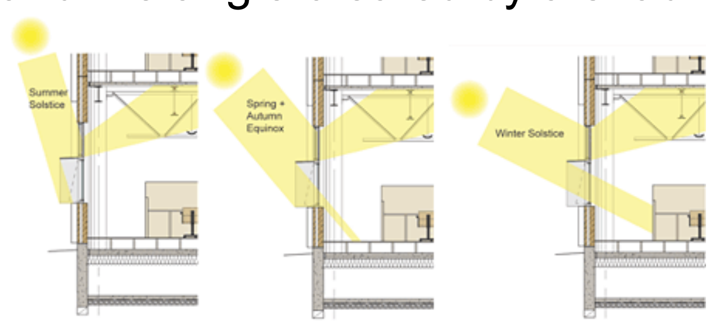
What about shading?

- 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:

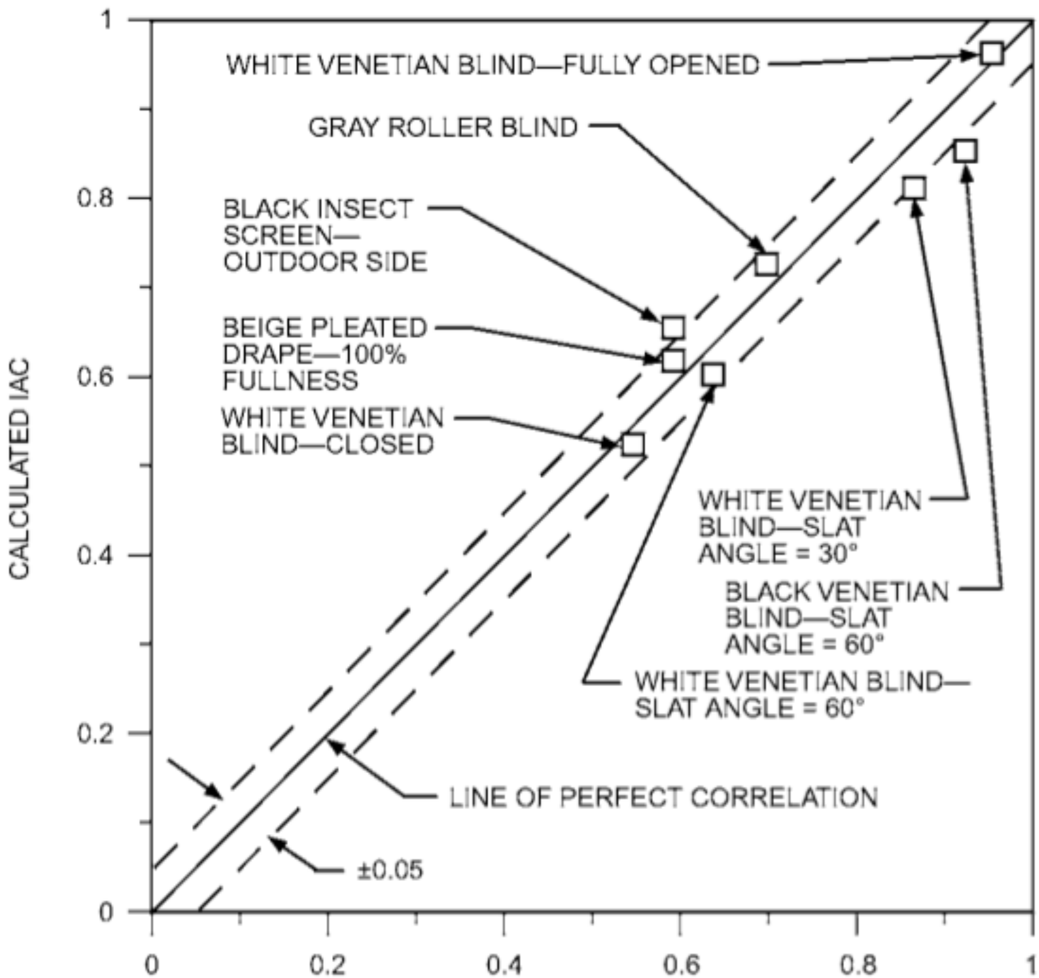


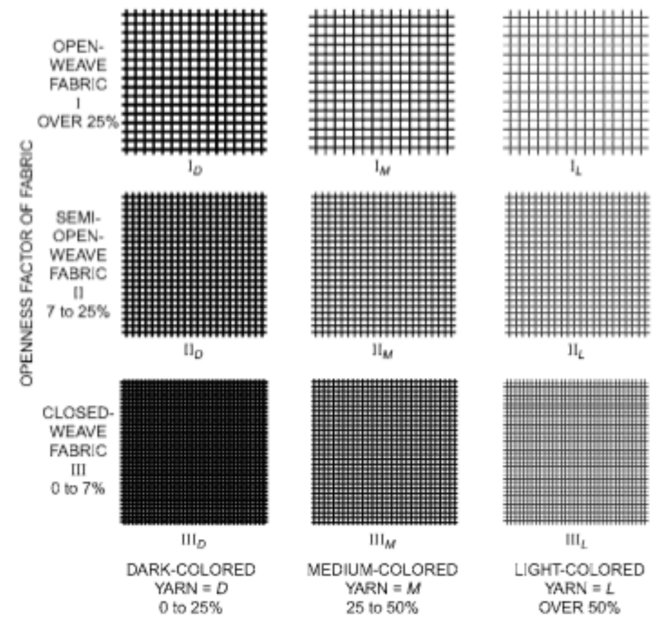
$$Q_{window} = UA_{pf}\left(T_{out} - T_{in}\right) + I_{direct} A_{pf} SHGC(\theta) IAC(\theta,\Omega) + (I_{diffuse+reflected}) A_{pf} SHGC_{diffuse+reflected} IAC_{diffuse+reflected}$$

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

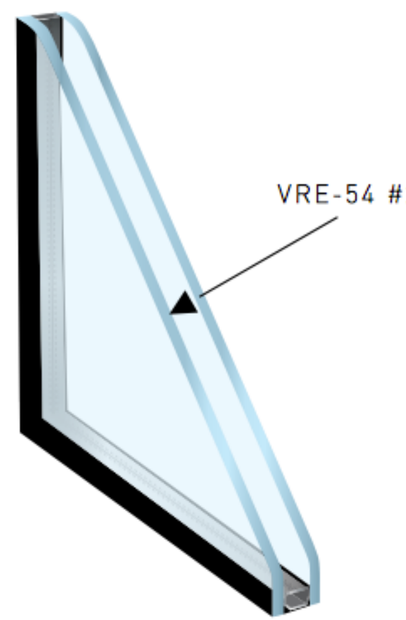
VIRACON®
GLASS IS EVERYTHING™

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

http://glassmagazine.com/article/commercial/cladding-icon-1311598

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

Straube, **2008** *Building Science Insights* 006

Can highly glazed building facades be 'green'?

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

Straube, **2008** *Building Science Insights* 006

Can highly glazed building facades be ‘green’?

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

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

Straube, **2008** *Building Science Insights* 006

Can highly glazed building facades be ‘green’?

- One argument: daylighting
  - Glazing 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

Straube, **2008** *Building Science Insights* 006

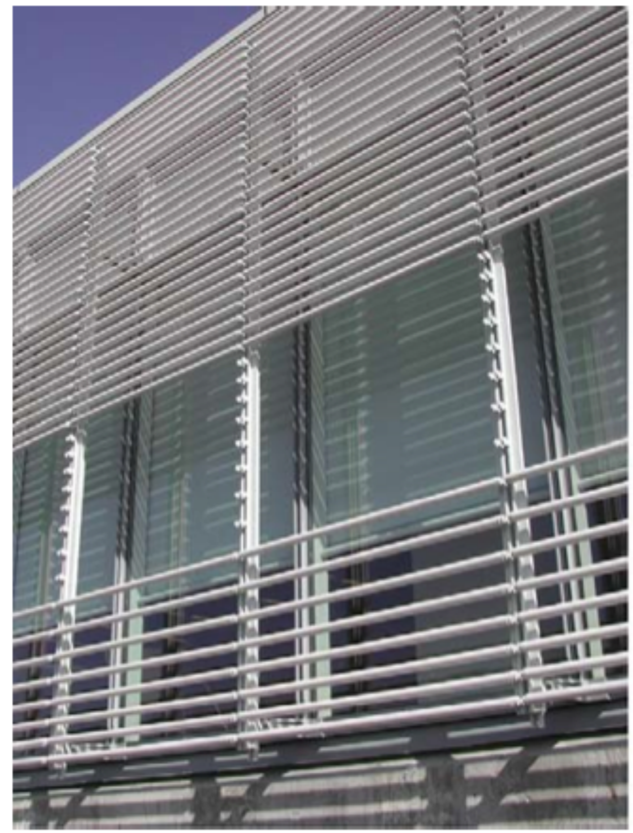
Can highly glazed building facades be 'green'?

- So which one of these do you choose?

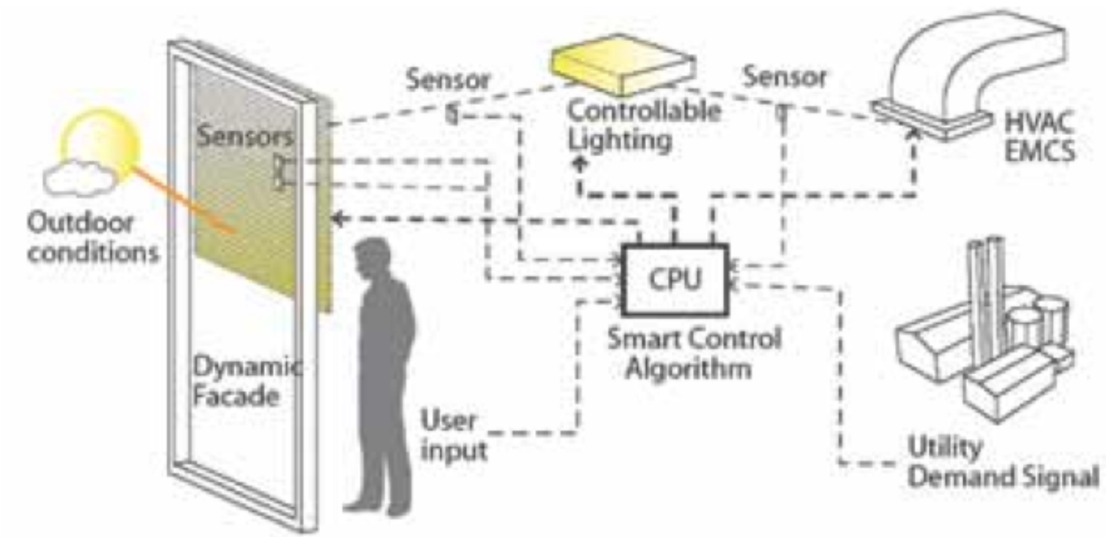
Straube, **2008** *Building Science Insights* 006

Designing with glass for daylighting: Controls

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



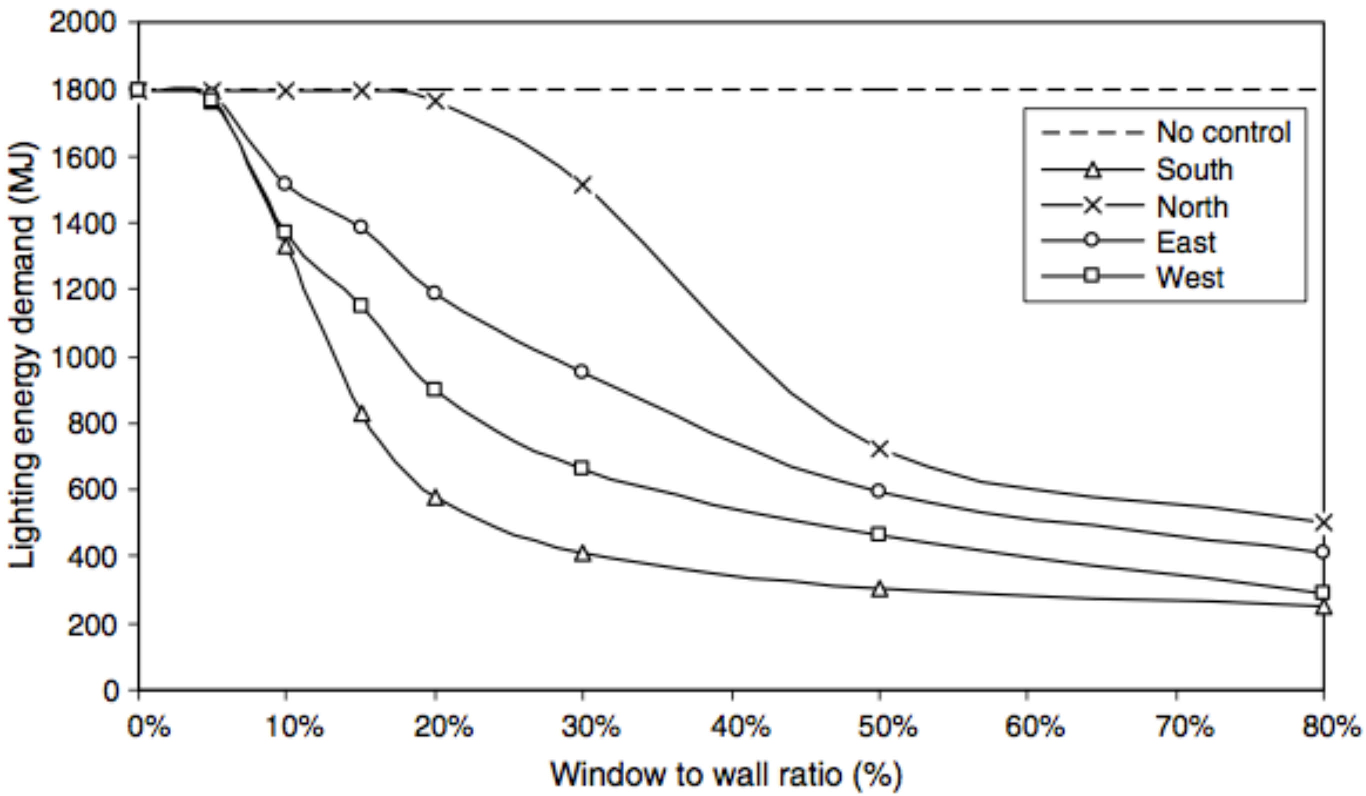
Lee and Selkowitz **2006** *Energy and Buildings*



Selkowitz **2011** *Journal of Building Enclosure Design*

Energy impacts of glazing

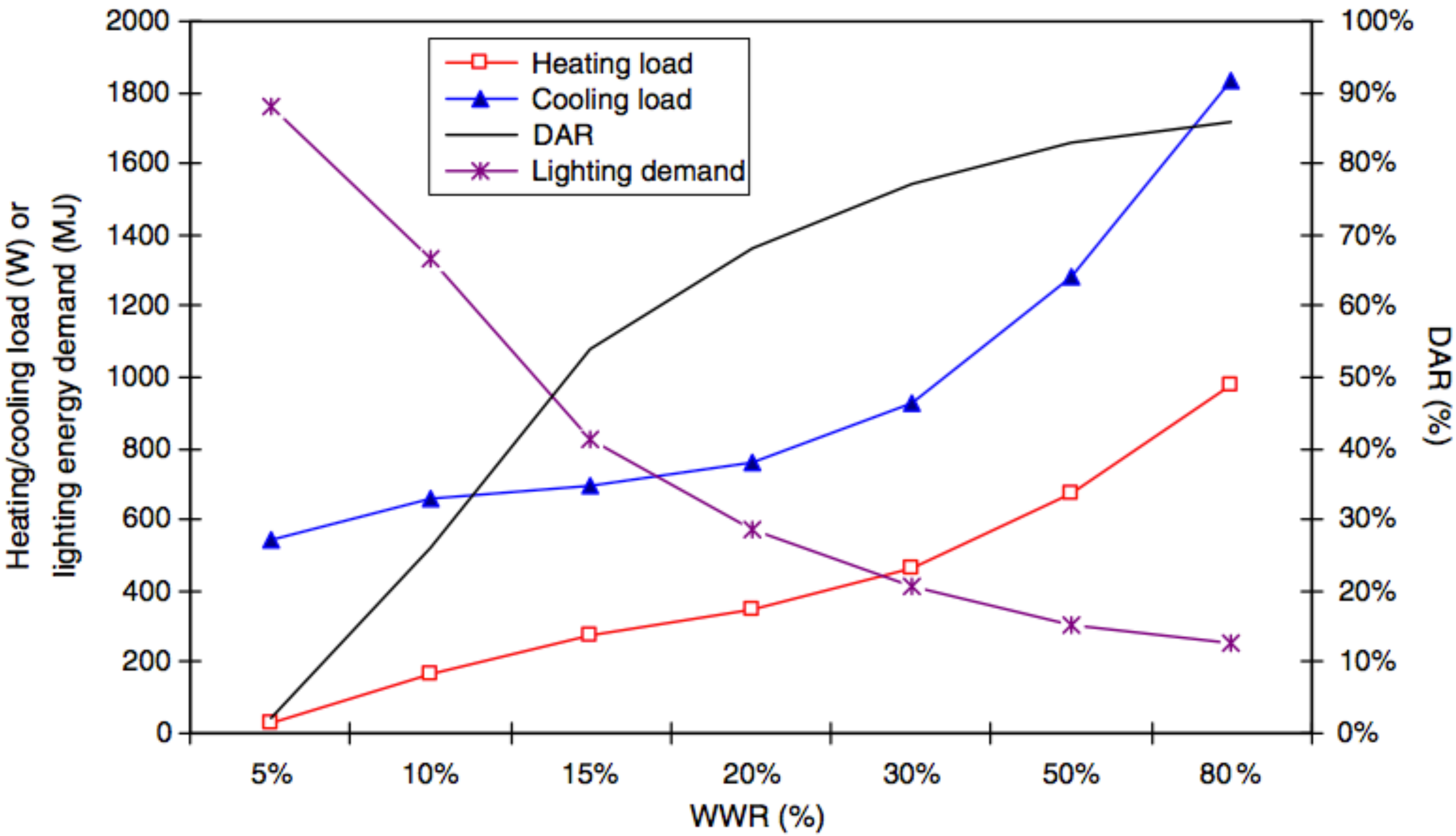
Increased daylighting can save **lighting energy** depending on WWR and orientation:



Tzempelikos and Athienitis **2007** *Solar Energy*

Energy impacts of glazing

But daylighting also affects heating and cooling loads…



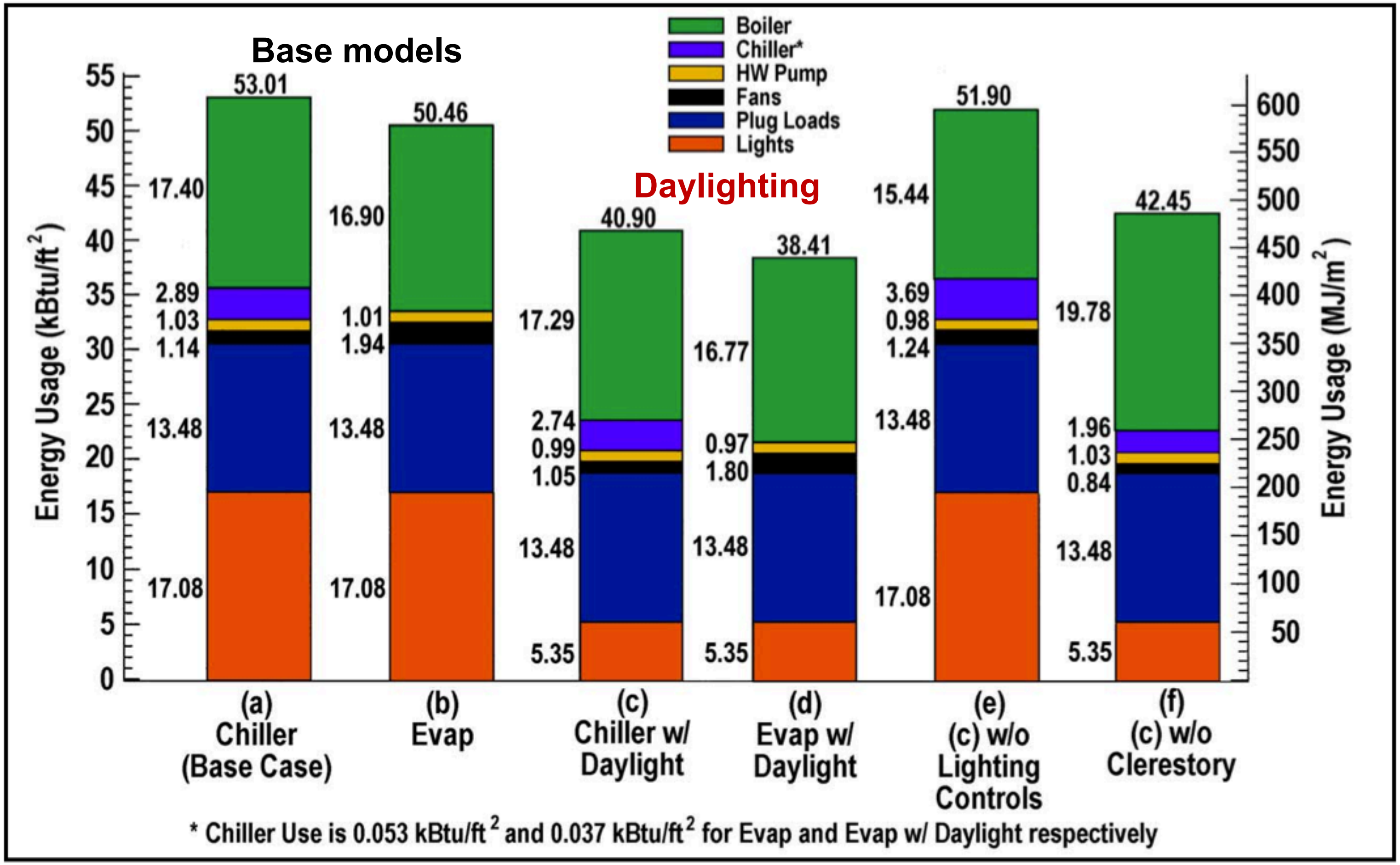
DAR = daylight availability ratio

…so how do we find the right balance?

Tzempelikos and Athienitis **2007** *Solar Energy*

Energy impacts of glazing

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



McHugh et al. **1998** *ASHRAE Journal*

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

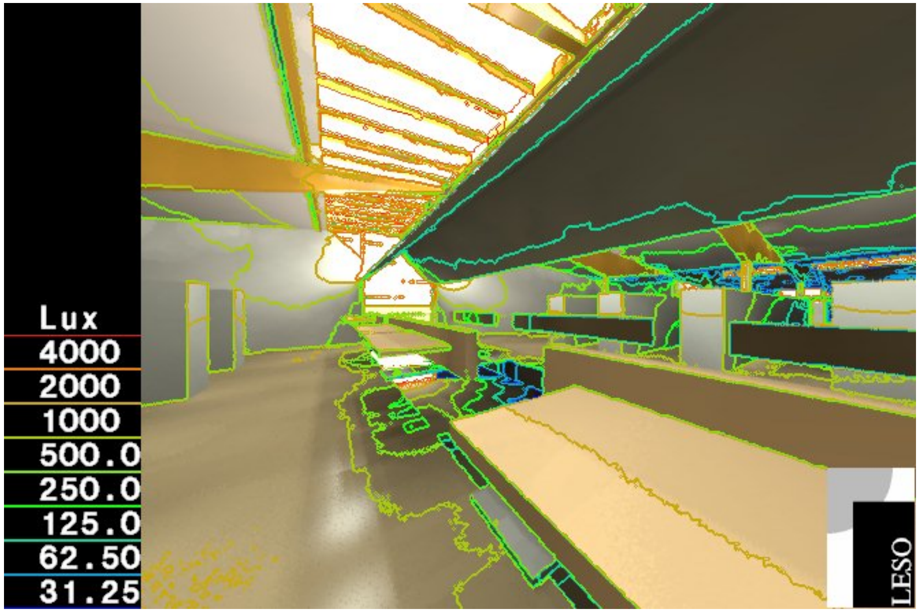
- Typically limited to low-rise structures

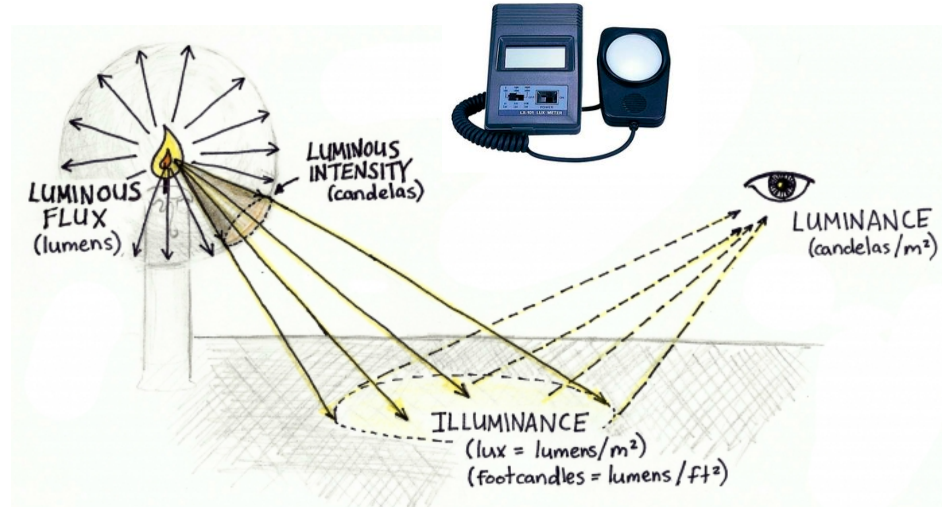
Solar tubes

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

Light shelves

Combining software and hardware for investigating daylighting

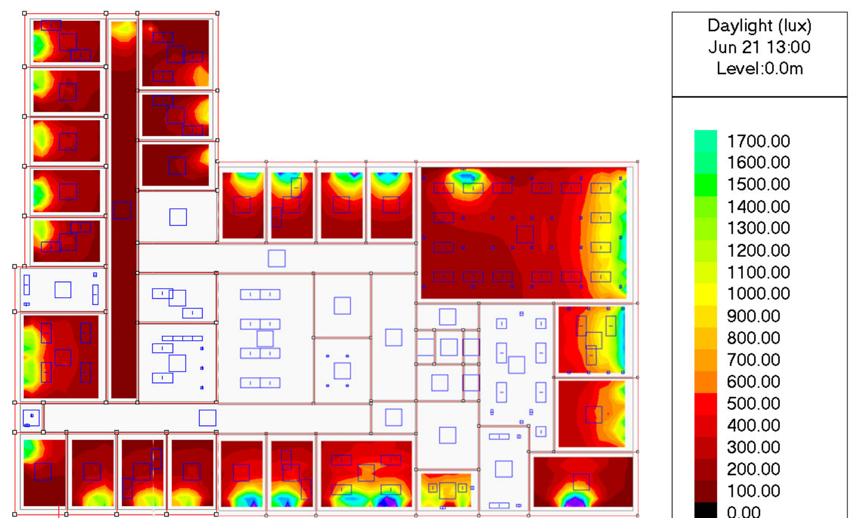




Hardware: Light sensors

Software: Radiance

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



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