CAE 463/524
Building Enclosure Design
Spring 2015

Lecture 8: March 10, 2015
Campus project presentations
Finish air movements + blower door testing

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Campus projects due

Building	Team members
Alumni	Maria, Yin Ling, Whitney, Liz
Crown	Henry, Yun Joon, Jose, Oleg
E1 - Rettaliata	Jinzhe, Julie, Roger, Rebecca
Hermann	Dilip, Allan, Dhaval
SSV	Thomas, Kim, Larry, Michelle

Last time

- Finished moisture movements (ventilated cavities)
- Introduce air movements
  - Infiltration/exfiltration (stack effect, wind)
  - Ventilation
  - Blower door airtightness testing
  - Air exchange rate testing

Measuring actual air exchange rates

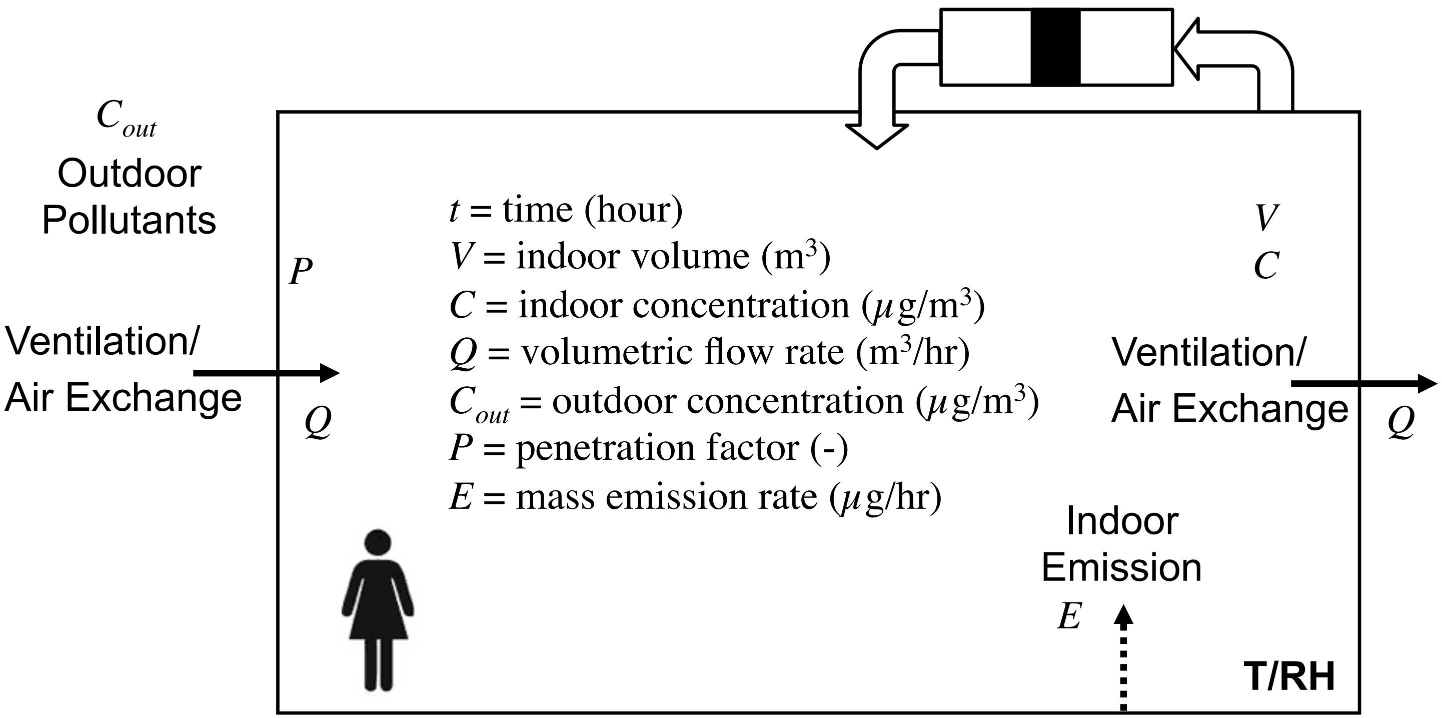
- Two general strategies to get air exchange rate
  - AER, ACH, and λ all used interchangeable for AER

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

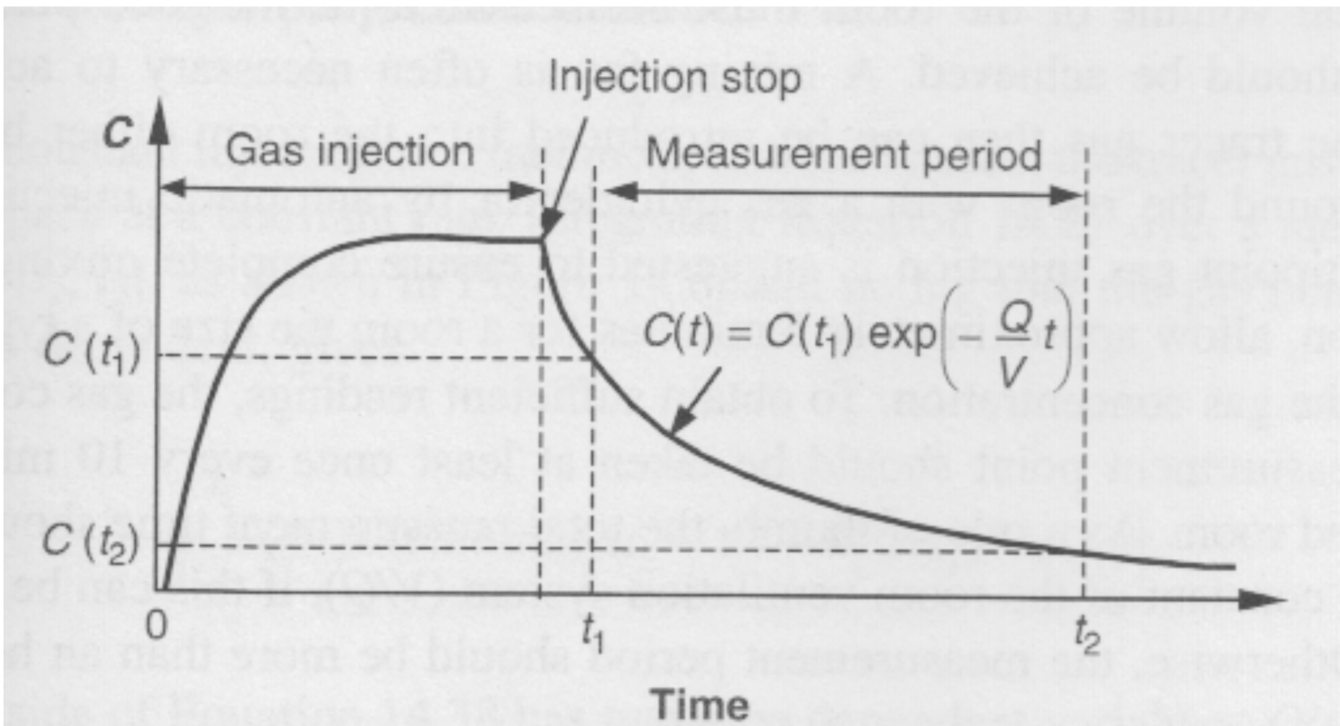


$$C_{ss} = PC_{out} + \frac{E}{\lambda V}$$

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

How do we measure λ?

- Tracer gas testing: Inject an inert tracer gas, and measure the decay from C(t=0) after time t=0



How do we measure λ?

- In this case, E = 0
- Assume P = 0 (reasonable for inert gas)

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

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

0

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

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

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

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:

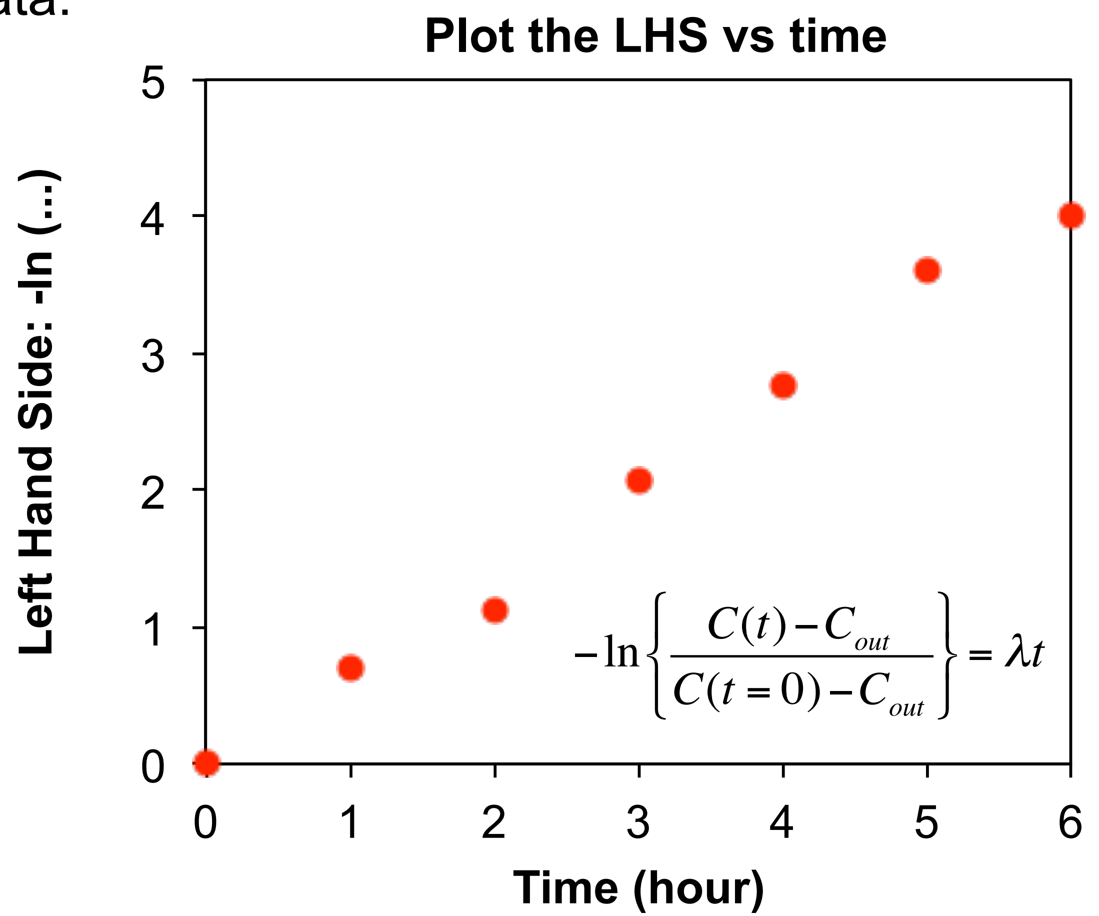
$$-\ln\left\{\frac{C(t) - C_{out}}{C(t=0) - C_{out}}\right\} = \lambda t$$

- 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



How do we measure λ?

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Time (hr)	C(t) (ppm)
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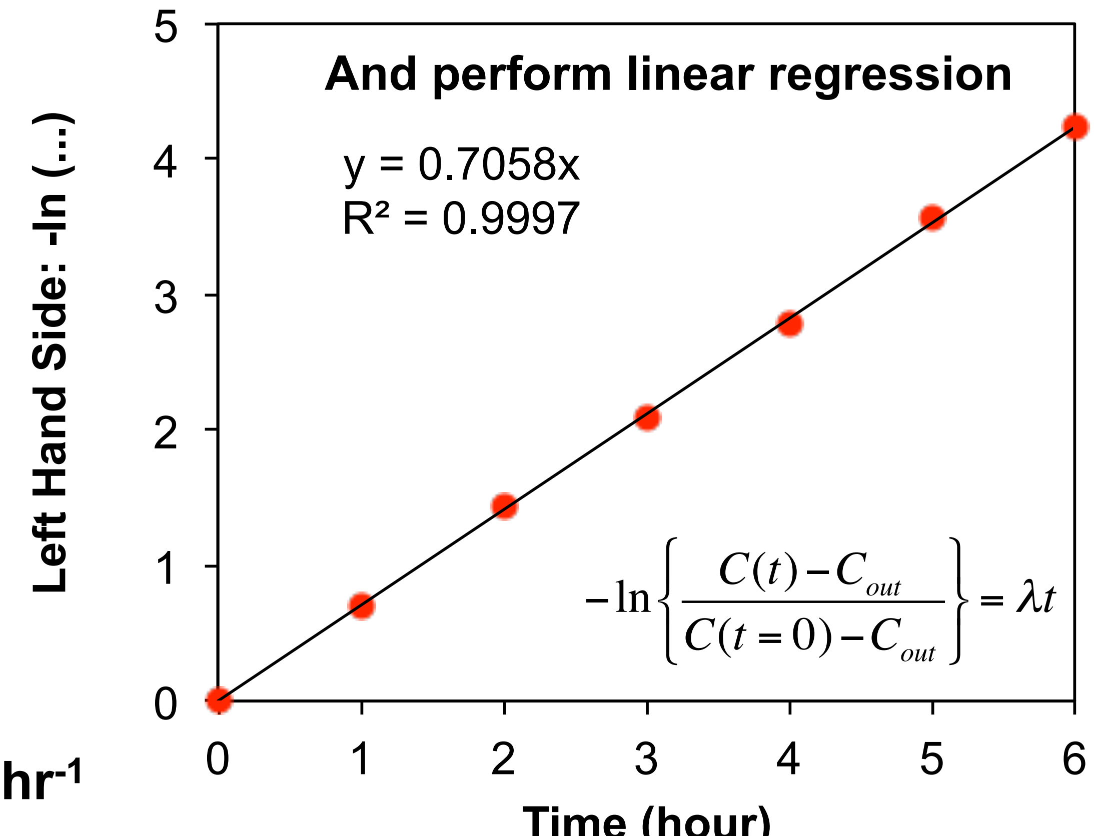
Plot the LHS vs time



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

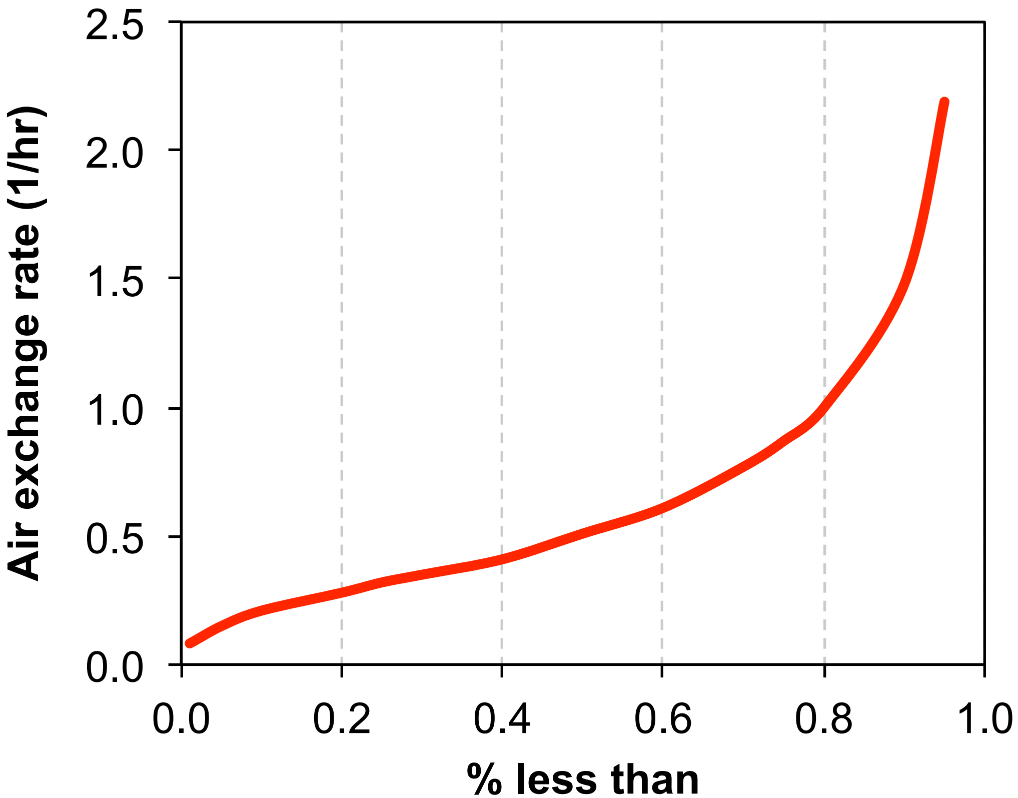
AER = λ = slope = 0.71 hr^{-1}

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

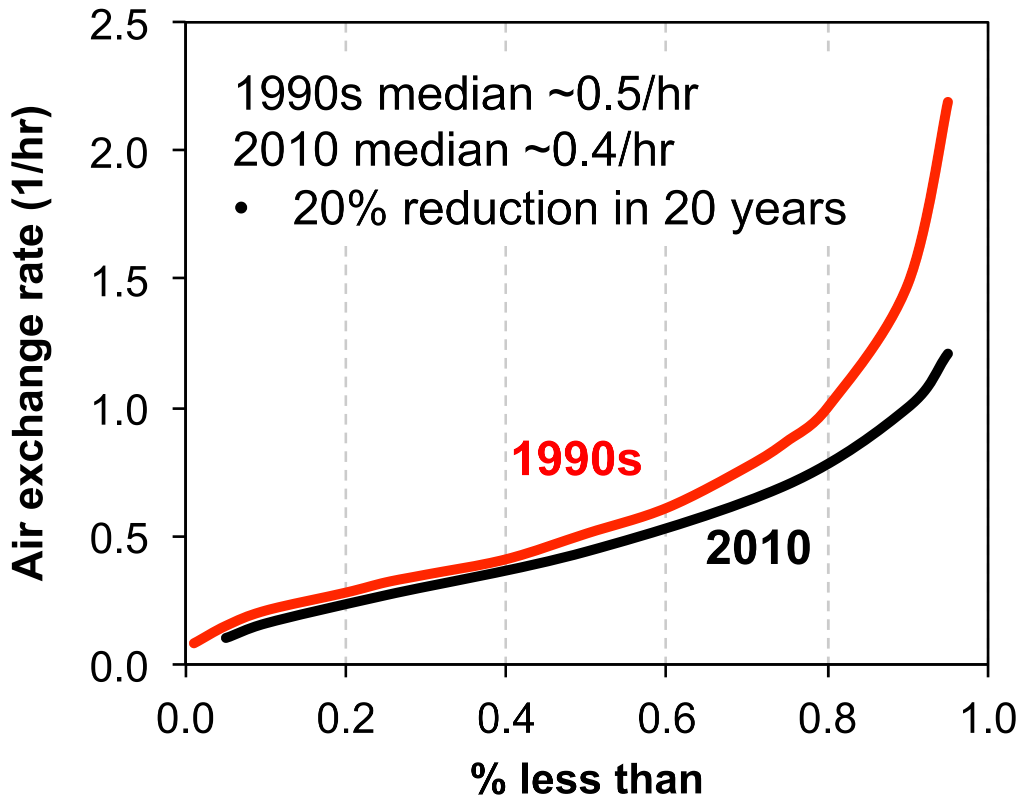


- What do you think this curve looks like now?

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)

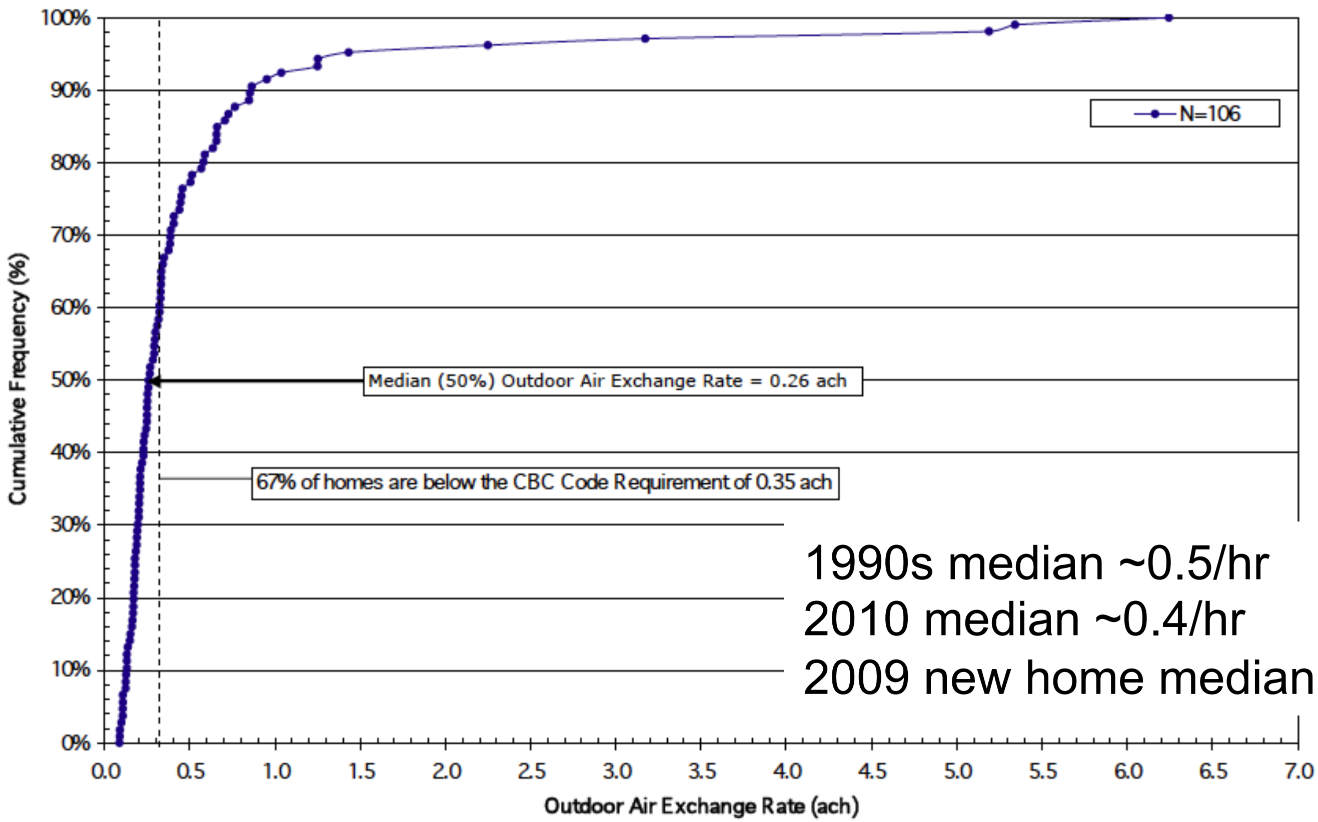


- What about new homes?

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)



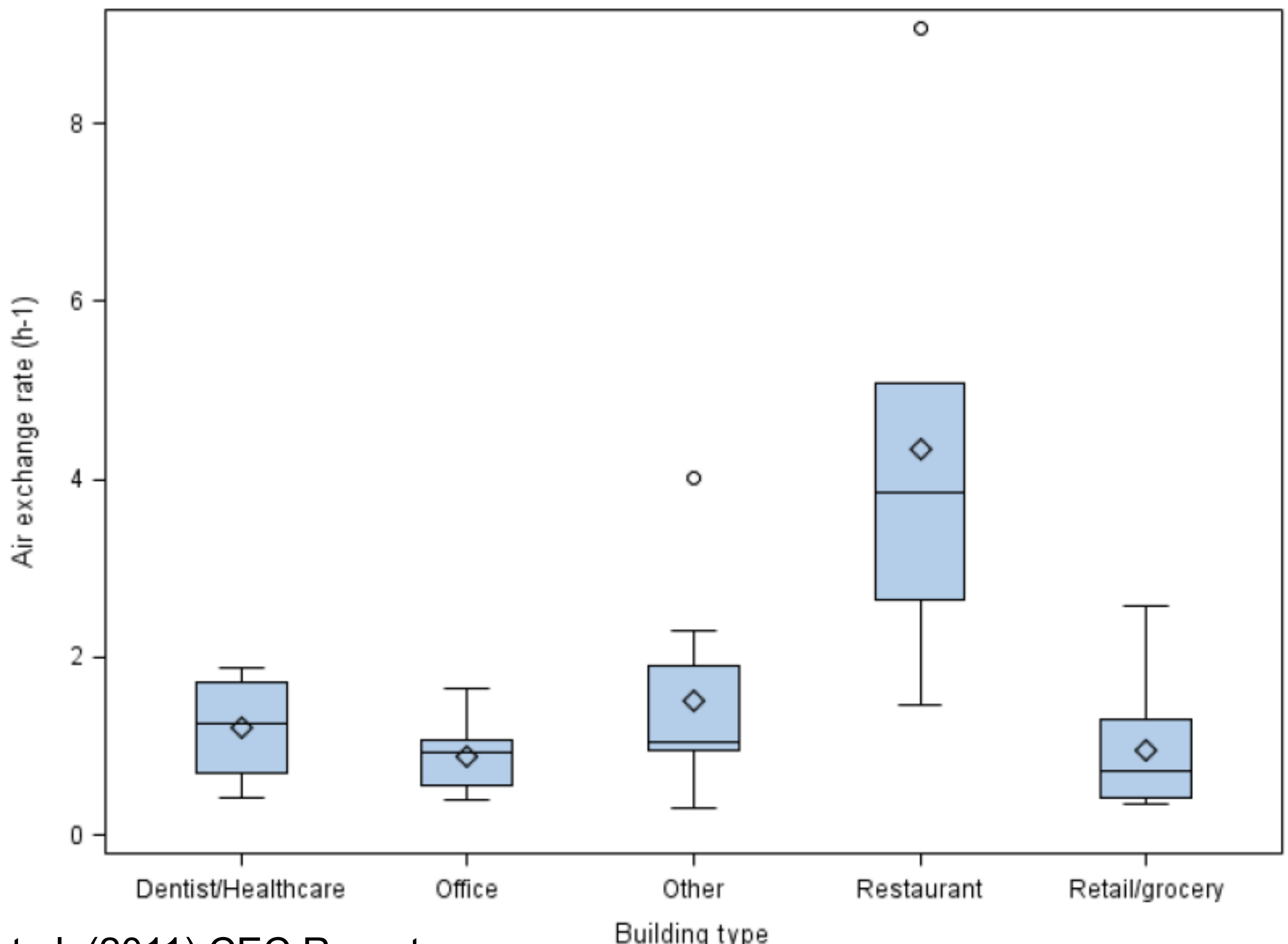
1990s median ~0.5/hr
2010 median ~0.4/hr
2009 new home median ~0.26/hr

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

Offermann et al. 2009 CEC PIER Report

Measured air exchange rates: Commercial buildings

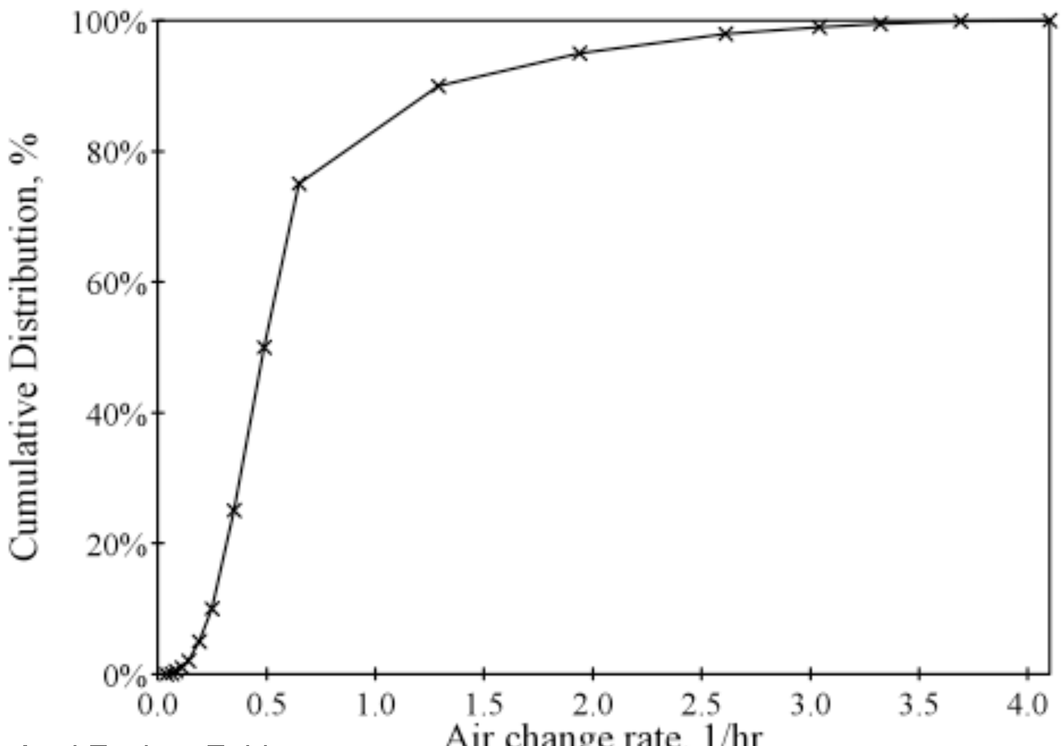
- Recent study of ~40 commercial buildings in CA



Bennett et al. (2011) CEC Report

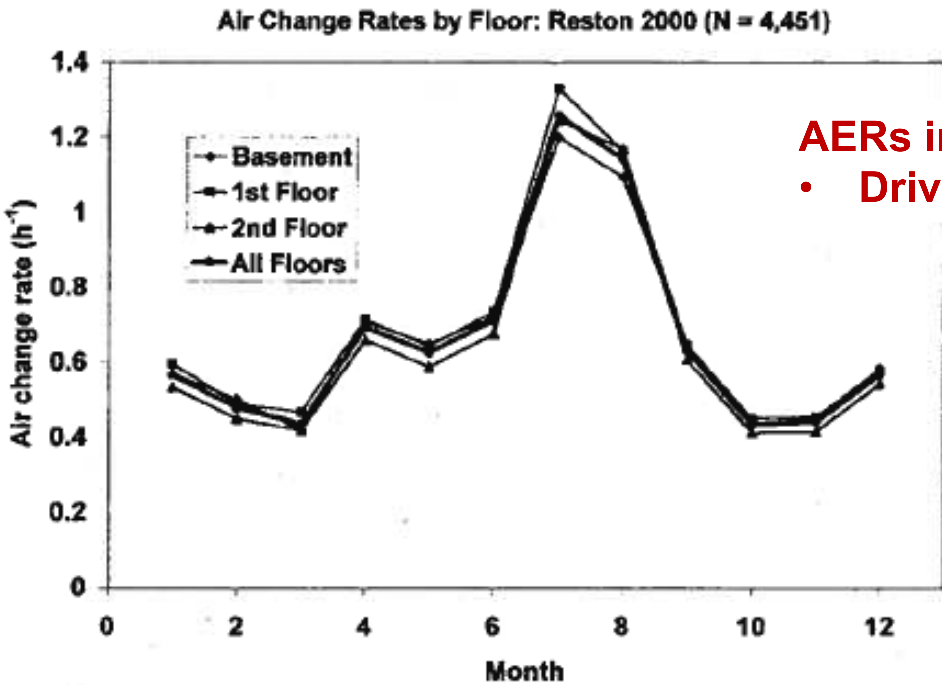
Variations in AER in individual buildings

- 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*

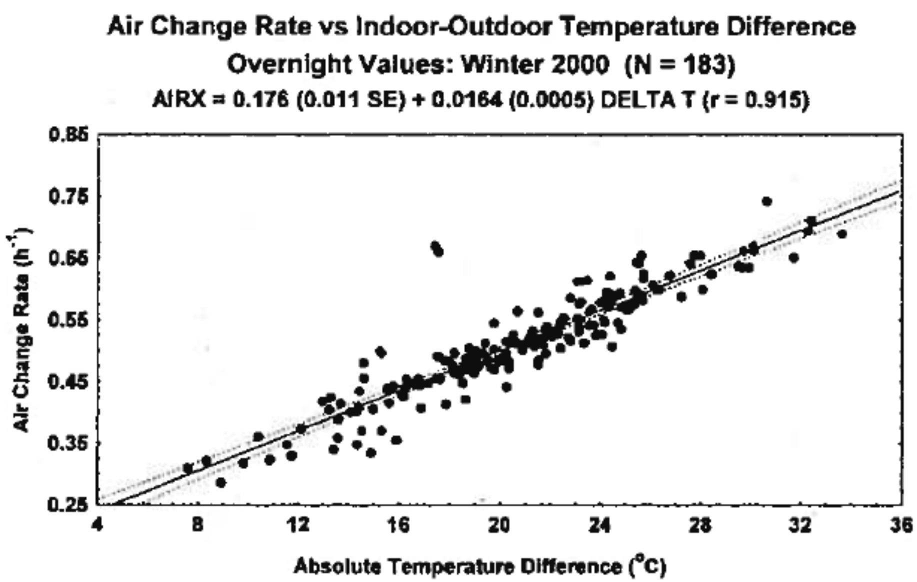
Variation in AER in individual buildings



AERs in individual buildings can vary by season

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

AERs can vary by I/O temperature within seasons

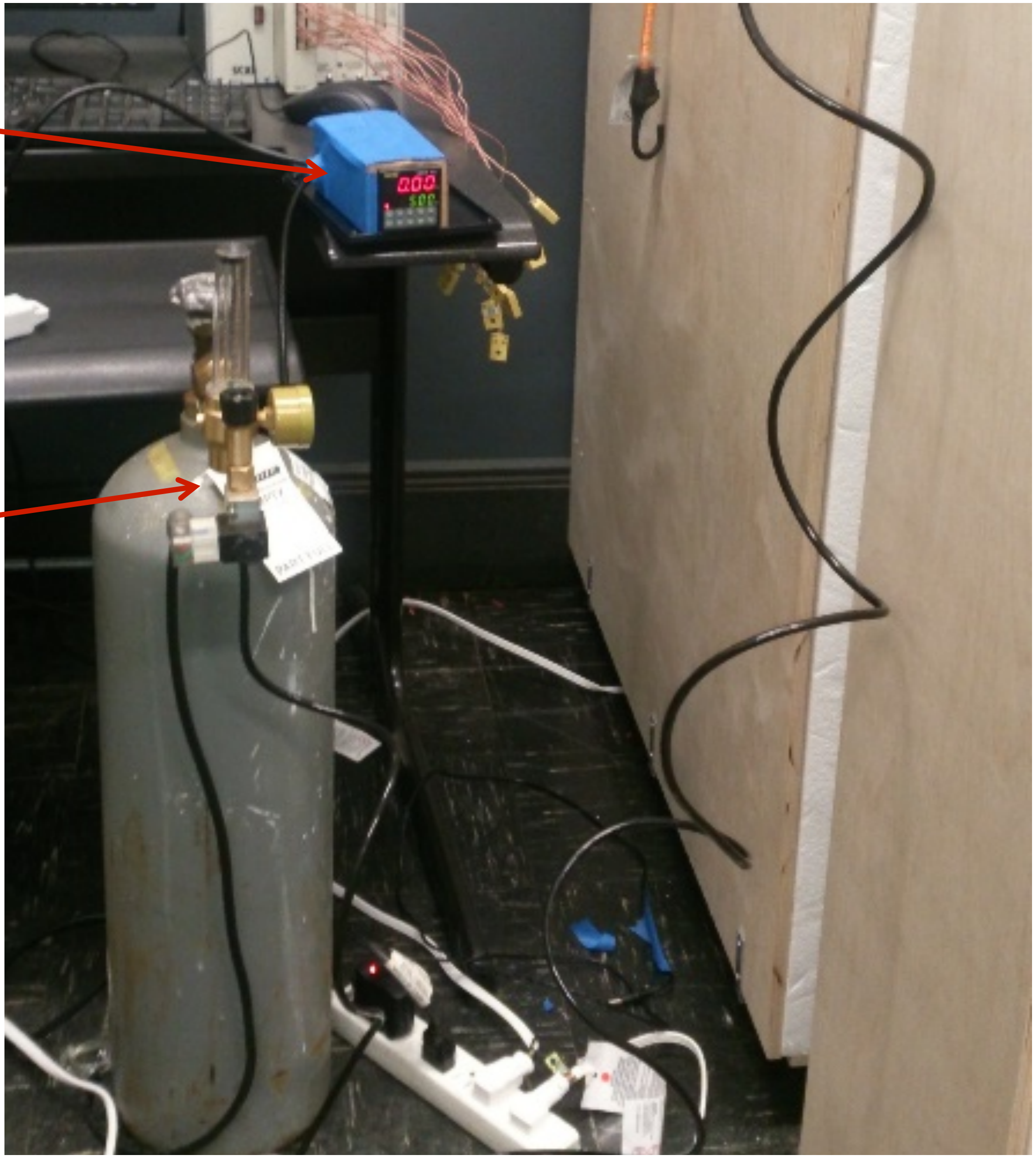


Wallace et al. 2002 *J Expo Anal Environ Epidem*

Variation in AER in individual buildings

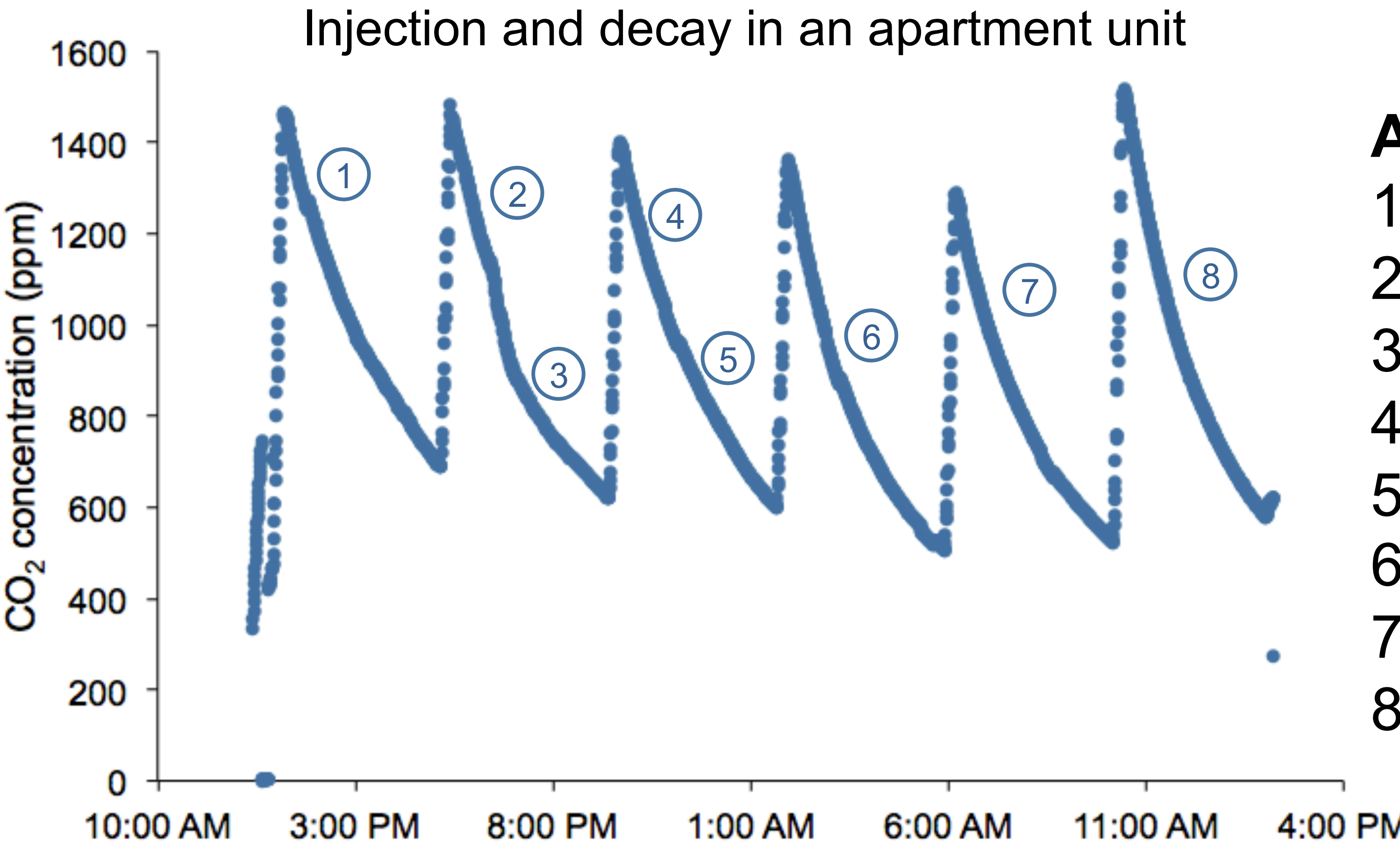
Sestos timer

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 infiltration models and blower door 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

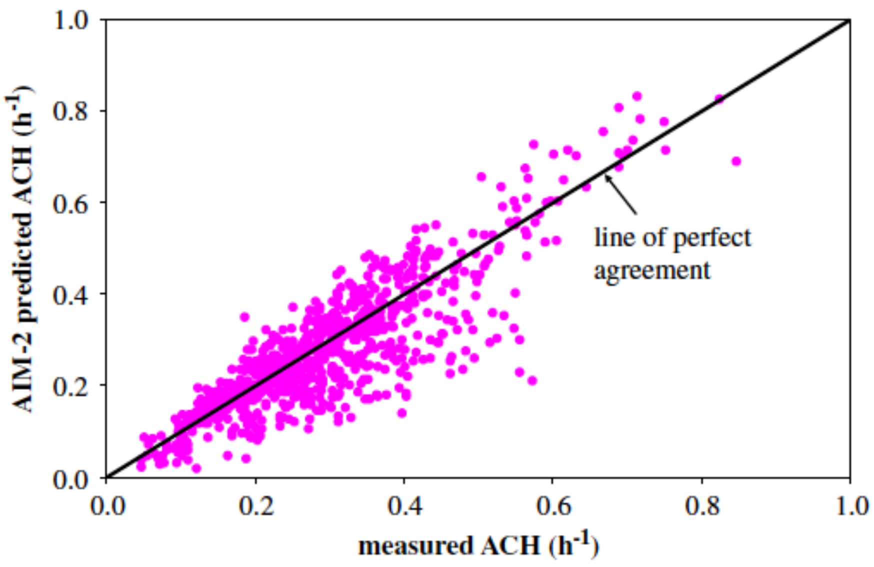
- Alberta air infiltration model (AIM-2)

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

where β is an empirical constant equal to -0.33.

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

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



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

$$Q_{\mathrm{inf}} = A_{\mathrm{inf}}\sqrt{k_{\mathrm{s}}|T_{\mathrm{in}} - T_{\mathrm{out}}| + k_{\mathrm{w}}U^2}$$

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

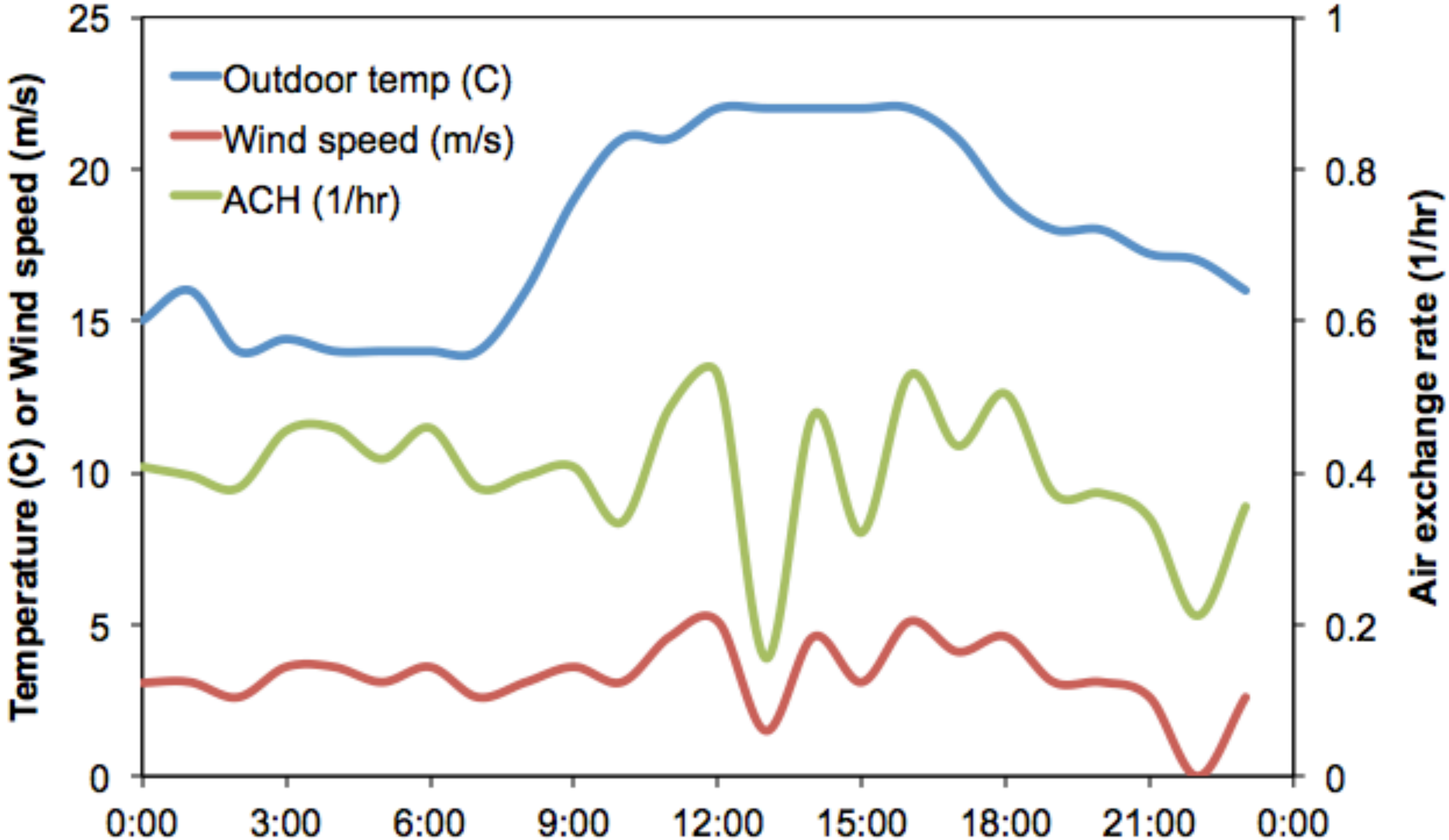
Table S3. Local sheltering

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



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

BLOWER DOOR DEMONSTRATION

Procedure for modern blower door test

1. Install calibrated fan (i.e., “blower door”)

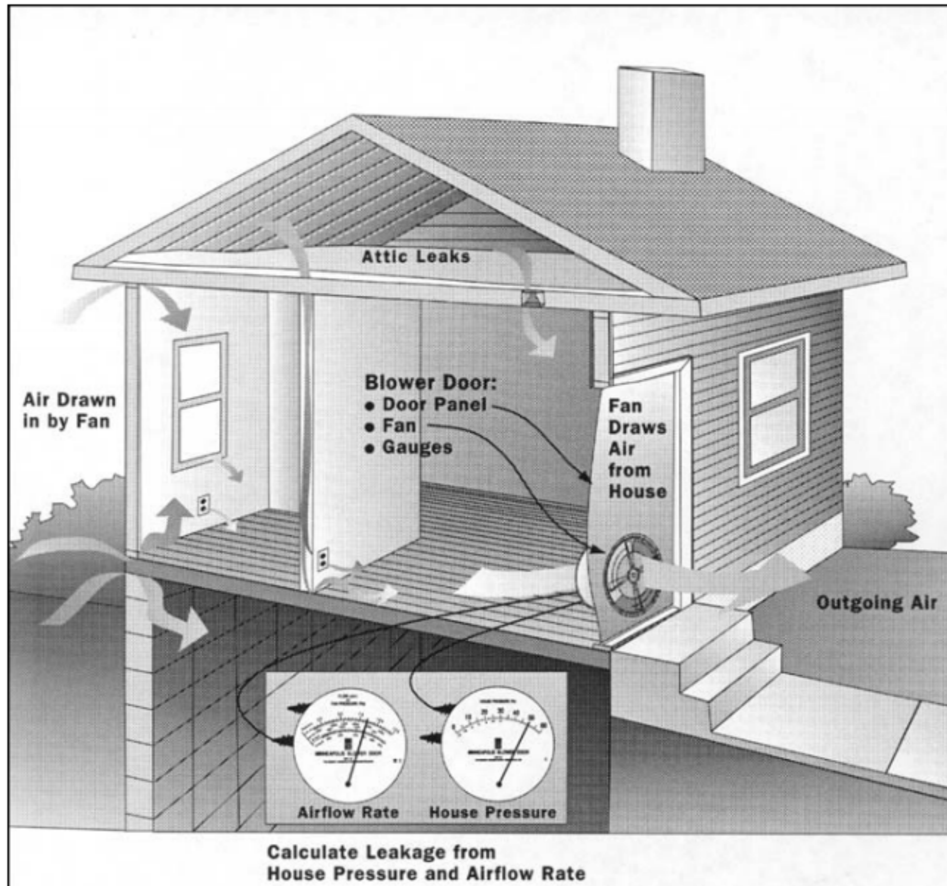
2. Use fan to create artificial pressure difference between inside and outside

3. Measure flow at several inside-outside pressure differences

4. Find n and C, which help determine relationship between flow (Q) and pressure (ΔP)

Blower doors: theory of operation

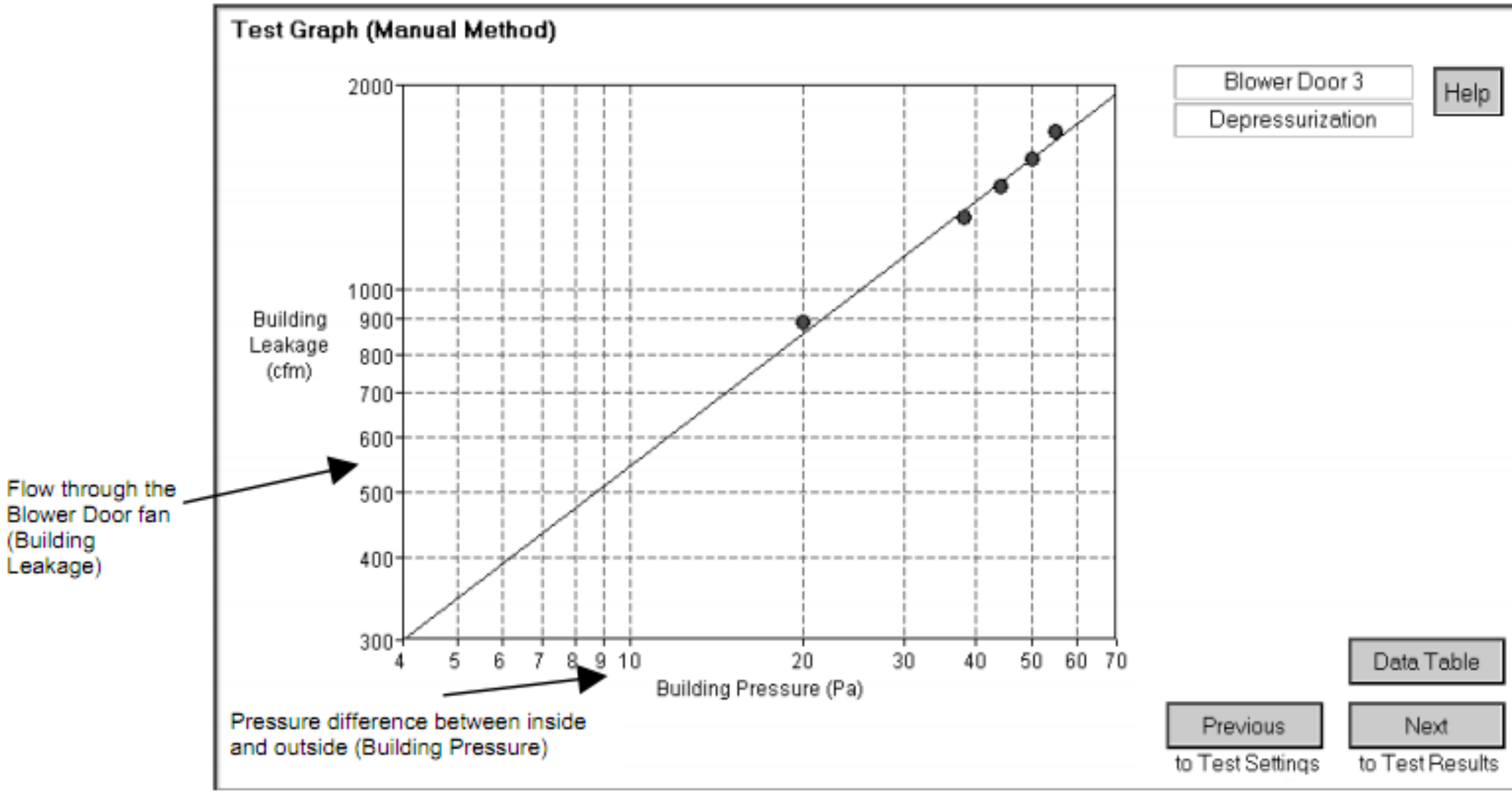
- Used to measure air-tightness in buildings worldwide



Source: Energy Conservatory Blower Door Manual

Blower doors: theory of operation

- Record flow through blower door (and thus through leaks) at each measured I/O pressure difference



Blower doors: theory of operation

- Perform test across a range of pressures and flows
- Develop relationship:

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

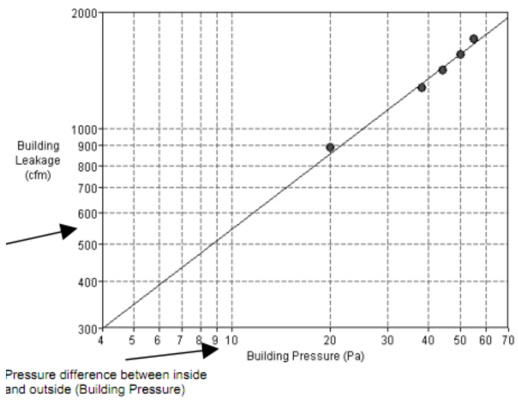
- To solve for C & n from measurements of Q and ΔP,
  - Log transform equation:

$$\ln Q = \ln C + n \ln \Delta P$$

Y = b + mx

Slope = n
Intercept = lnC, therefore C = $\exp^{\text{intercept}}$

Blower door tests: resulting parameters



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

- Airflow ($m^3\ s^{-1}$)
- Leakage Coefficient ($m^3\ s^{-1}\ Pa^{-n}$)
- I/O Pressure Difference (Pa)
- Leakage Exponent (dimensionless)

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

Estimated Leakage Area (cm^2)

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

Normalized Leakage, NL (dimensionless)

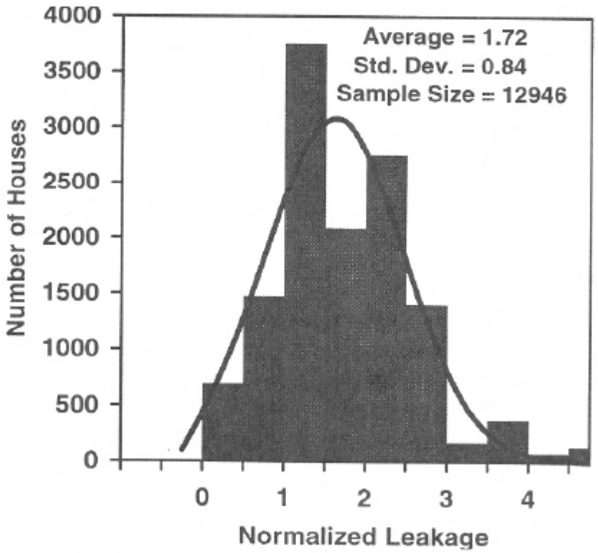
$$ACH_{50} = \frac{Q_{50\ Pa}}{V}$$

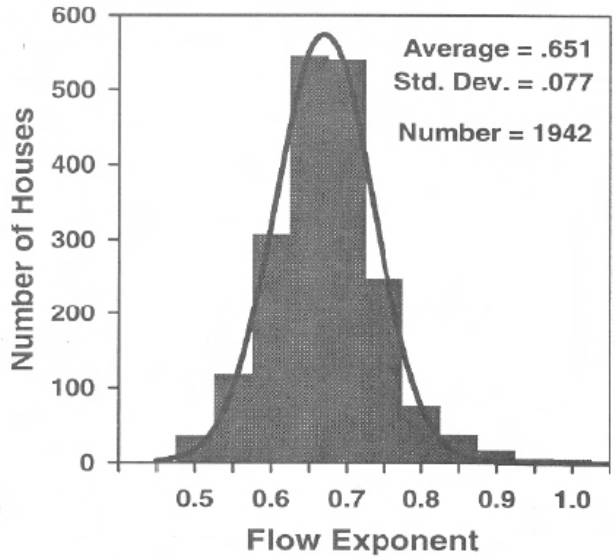
Air Changes per Hour @ 50 Pa (hr^{-1})

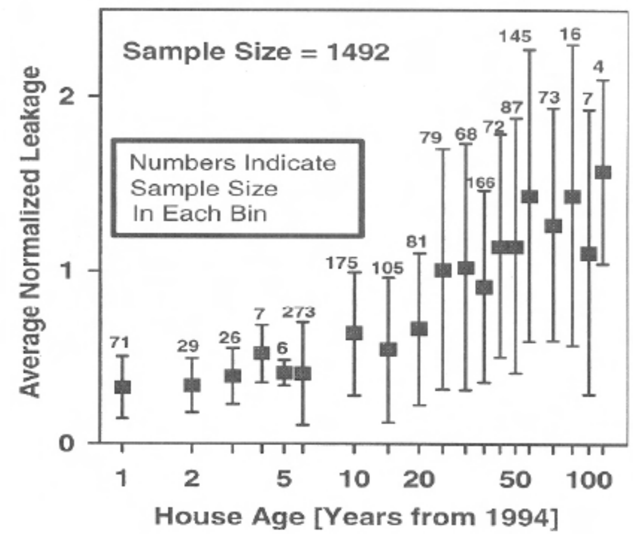
Source: ASTM E 779 and ASHRAE Standard 119

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

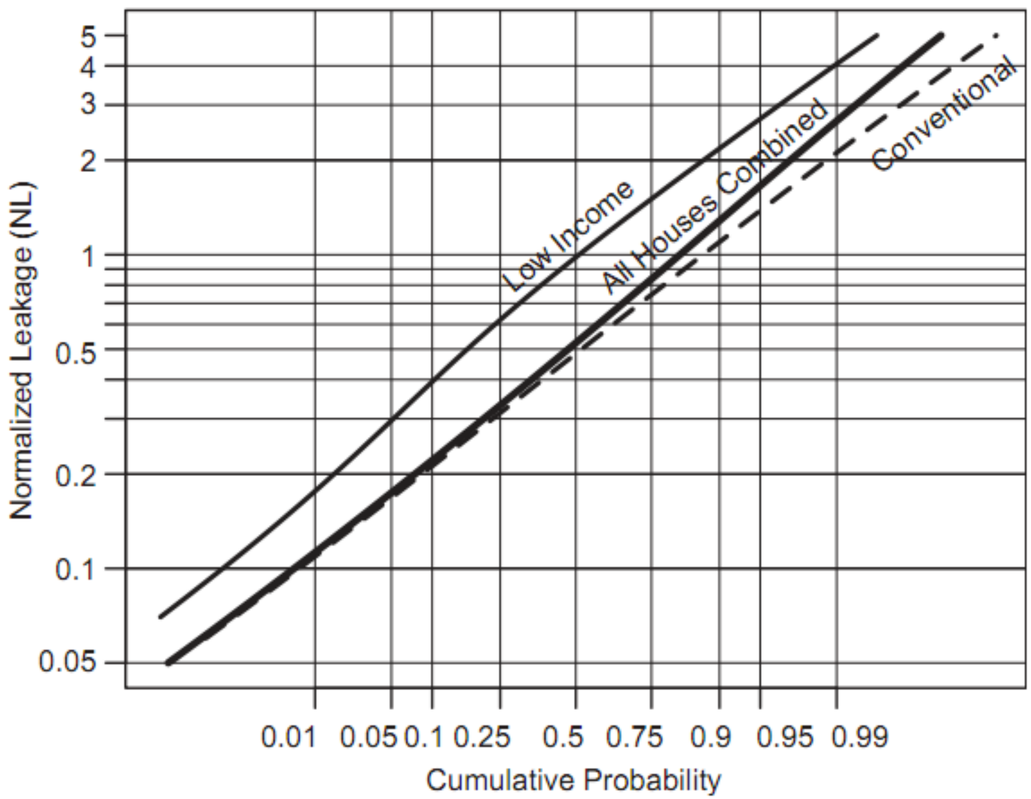
- LBNL continues to maintain a database of blower door data
  - http://resdb.lbl.gov/
  - Almost 150000 homes characterized as of 2012

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

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

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

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



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

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

ENERGY IMPACTS

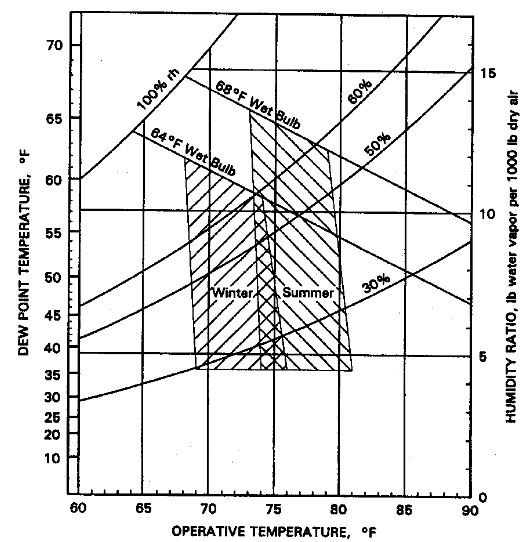
of air leakage

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

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

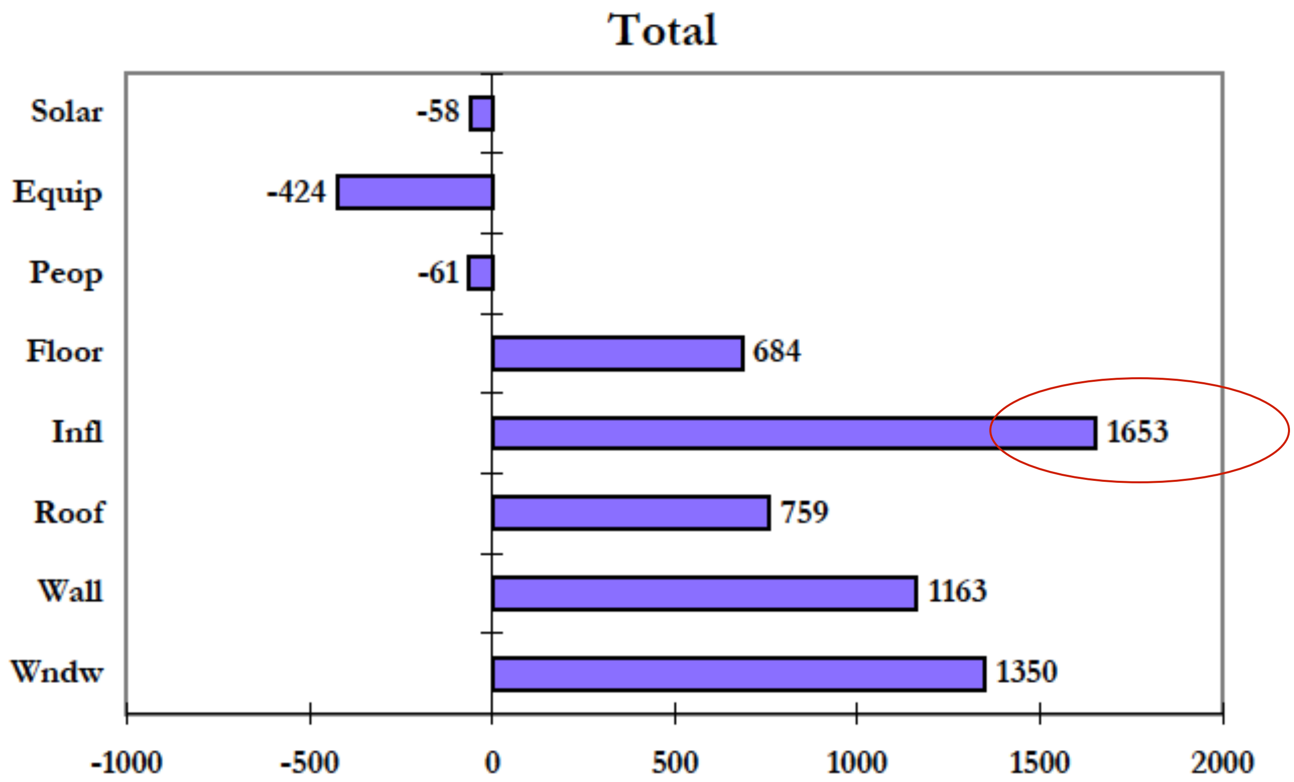
$$\dot{m} = \dot{V}_{leaks} \rho_{air}$$



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

Just how important are building envelopes for energy use?

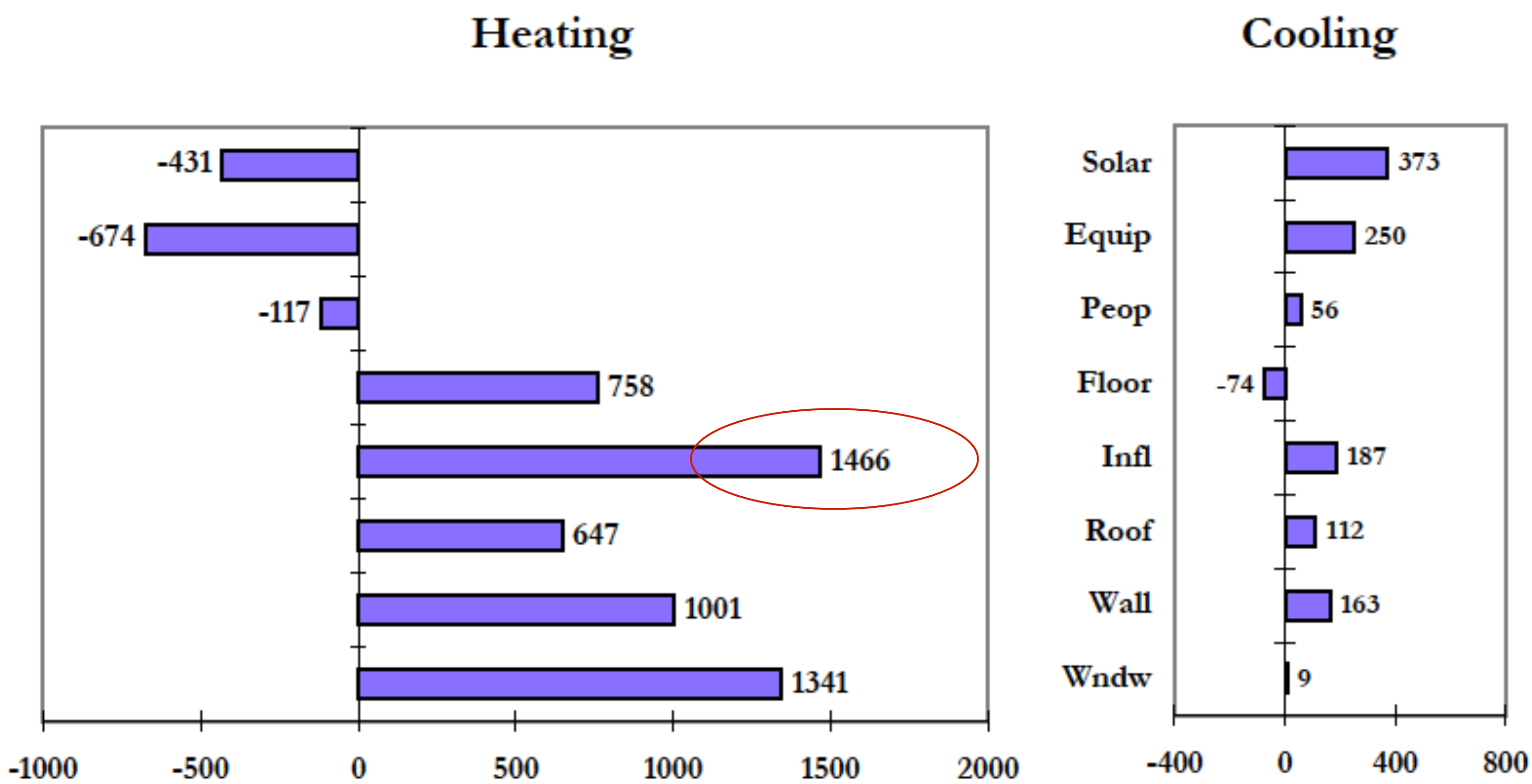
- 1999 study by Lawrence Berkeley National Laboratory
  - *Residential Heating and Cooling Loads Component Analysis*
  - Air infiltration is the single greatest contributor to energy use in U.S. homes



Aggregate component loads for all residential buildings (trillion BTUs)

Just how important are building envelopes for energy use?

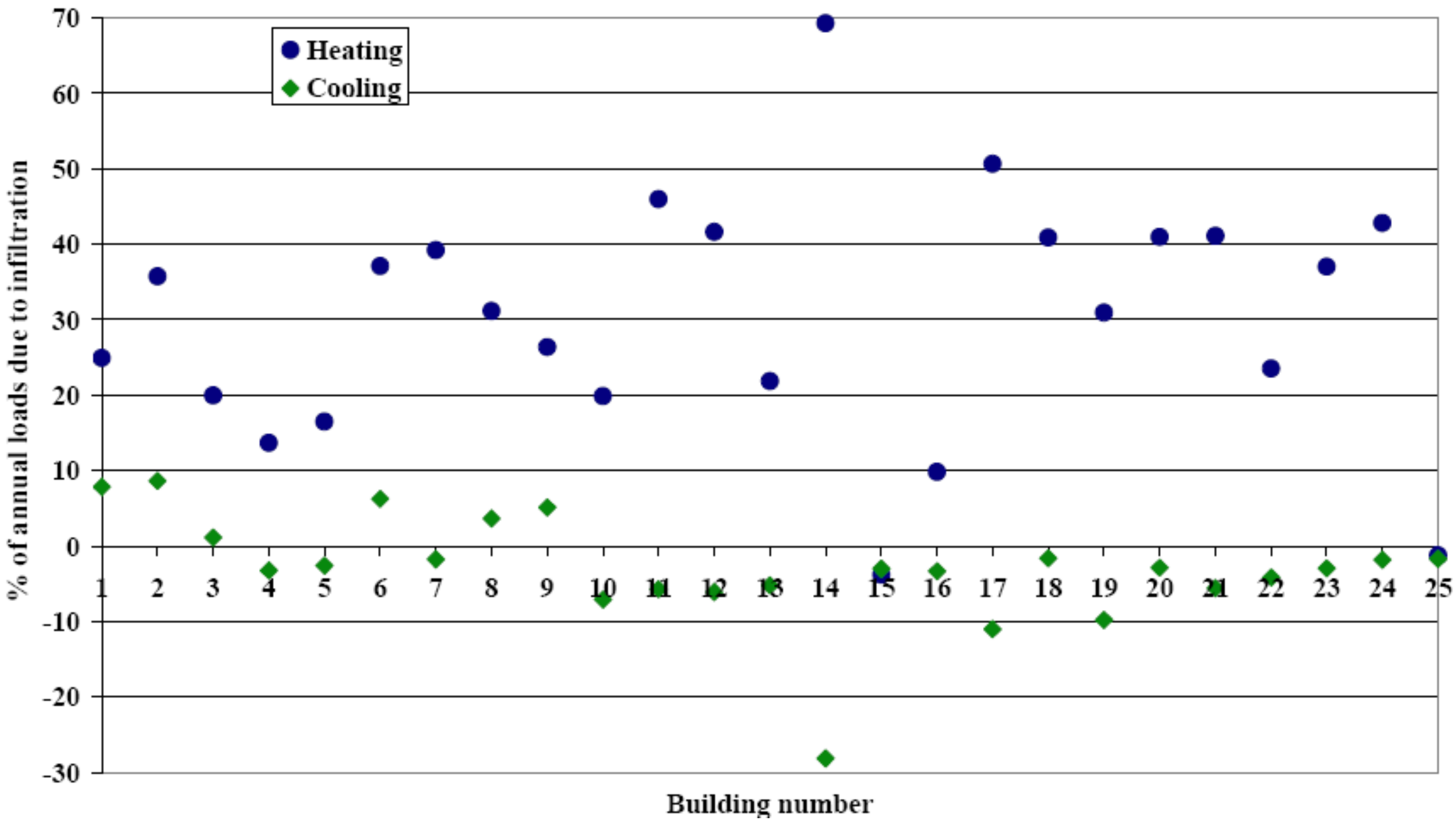
- 1999 study by Lawrence Berkeley National Laboratory
  - *Residential Heating and Cooling Loads Component Analysis*
  - Infiltration particularly important for heating loads



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 m^2 in floor space



Infiltration in commercial buildings

- Results show that infiltration accounts for 33% of heating loads in commercial buildings, on average
  - Huge!

- Cooling load effects vary by climate and are smaller
  - Infiltration actually accounted for a net negative cooling load of about 3.3% on average
  - Means that commercial buildings were probably dominated by internal loads and cold infiltrated air actually reduced need for cooling

CONTROLLING LEAKAGE

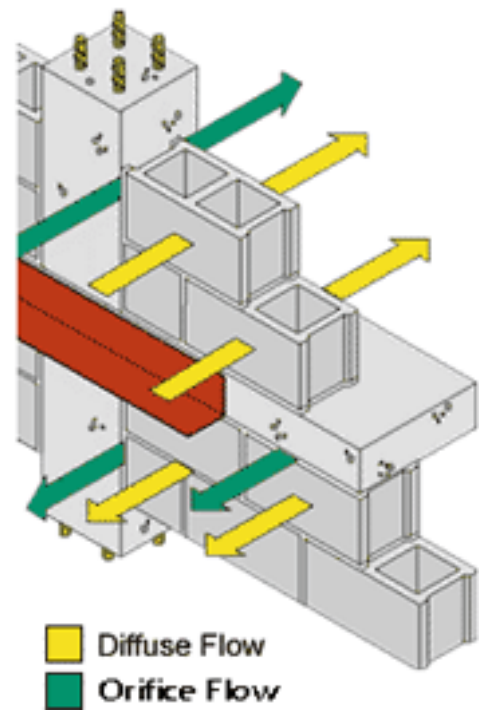
in enclosure design and construction

Controlling air leakage

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



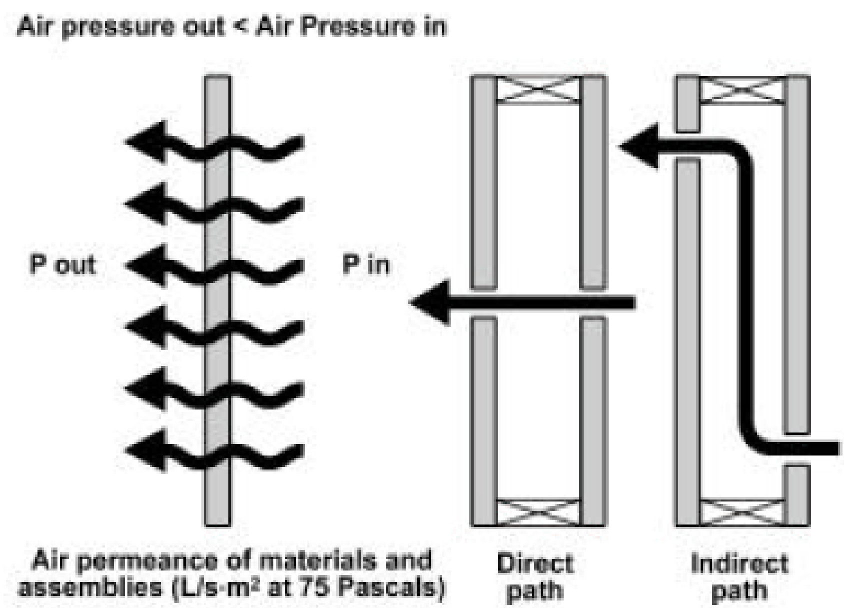
A tale of three barriers …

- 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
  - 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

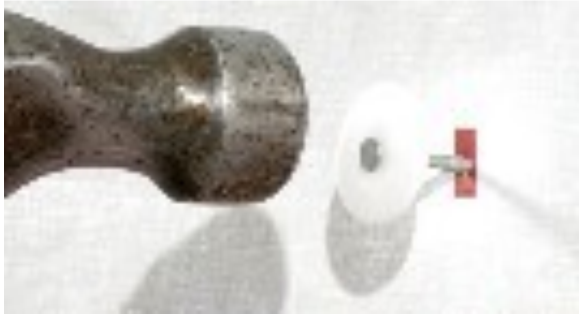
Air Permeance of Building Materials

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

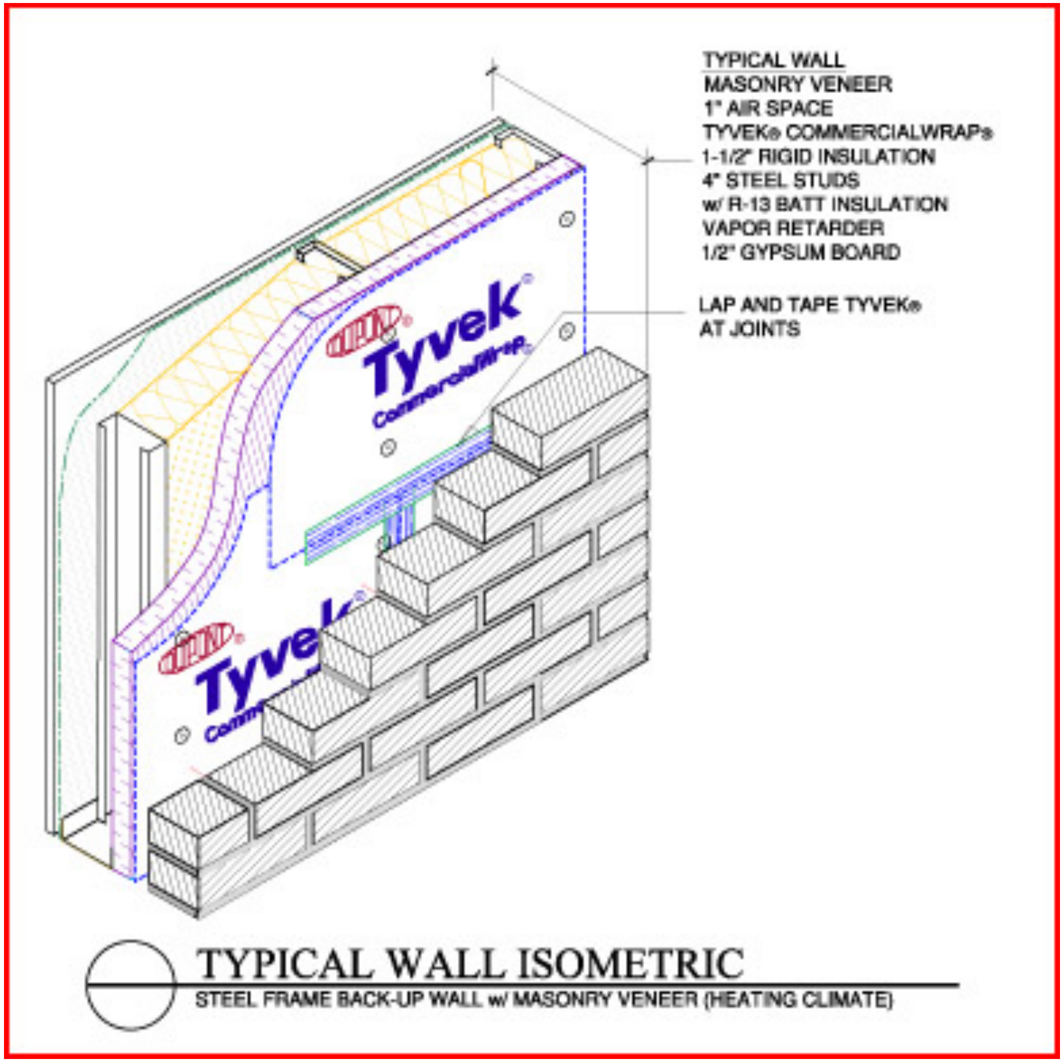


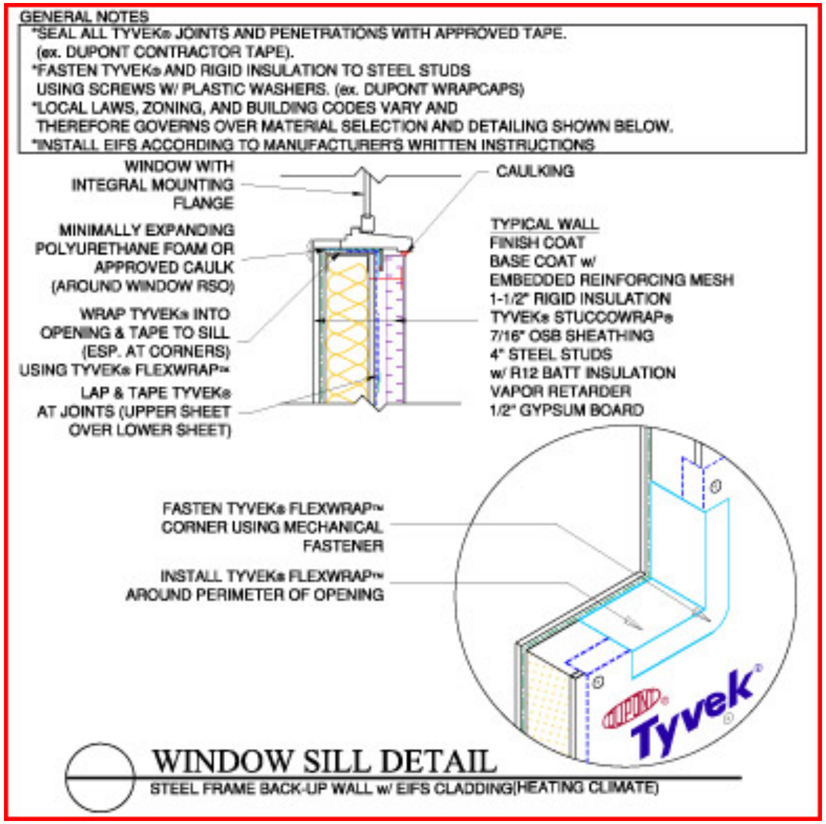
Building wraps: exterior air barrier

Building wraps: exterior air barrier

Photograph 2 – Exterior Air Barrier Using Adhered Membrane

Building wraps: detail drawings





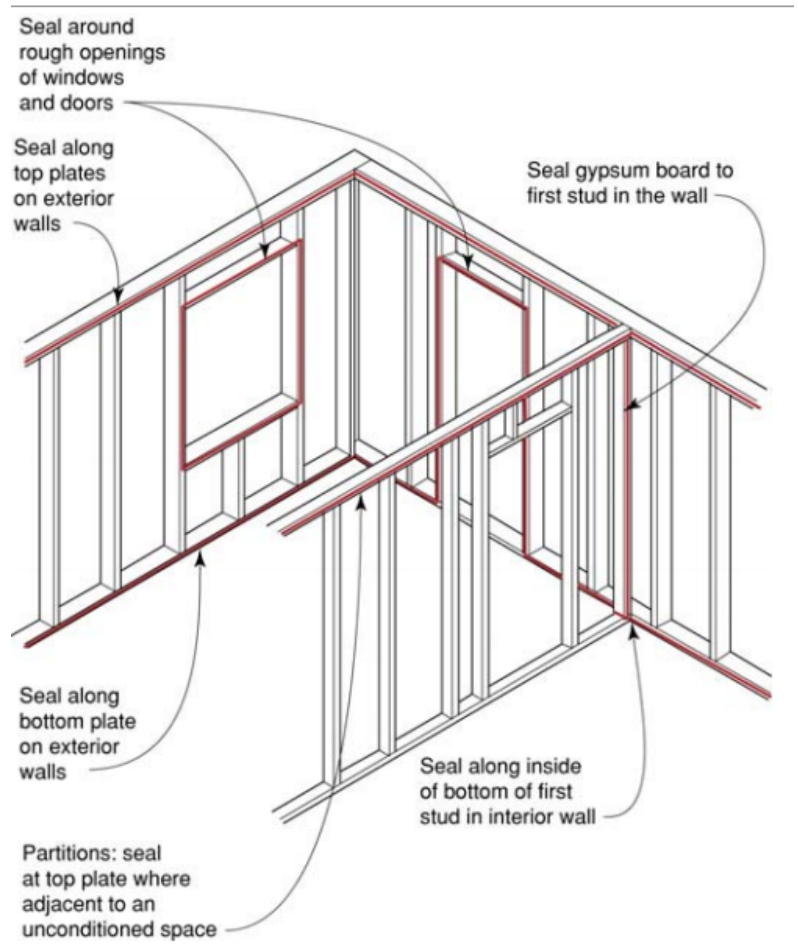
Air barriers also require sealants

- 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

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

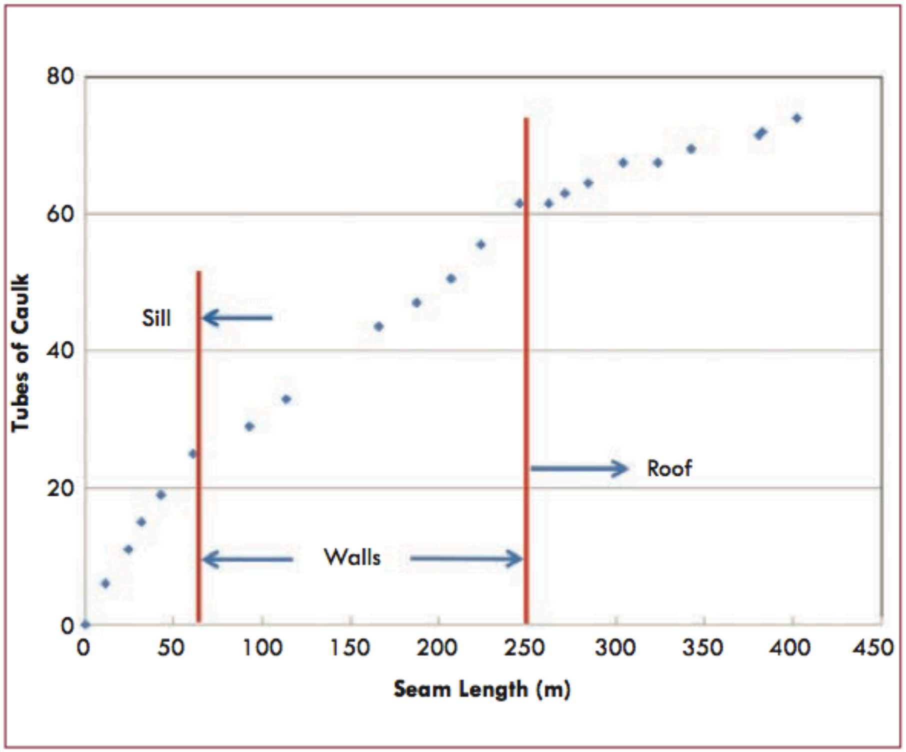
“Supersealing a house” during new construction

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

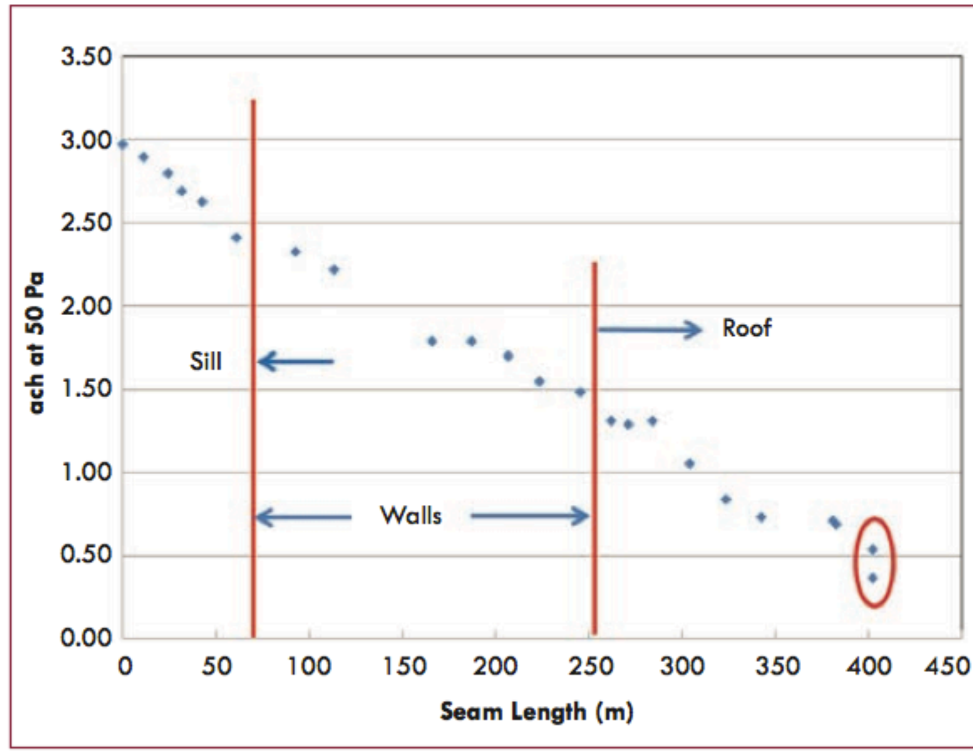
Newell and Newell (2011) *ASHRAE Journal*

“Supersealing a house” during new construction

Cumulative length of caulking



Reductions in ACH50 (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

- Case study at NIST test 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

- Case study at NIST test house
- 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

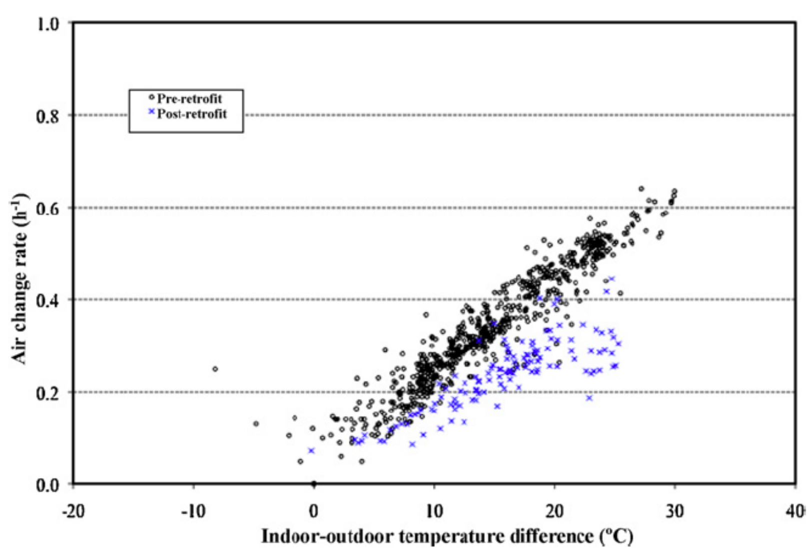


Fig. 6. Pre- and post-retrofit measured air change rates as a function of temperature difference (low wind speed): forced-air fan off (Condition 0).

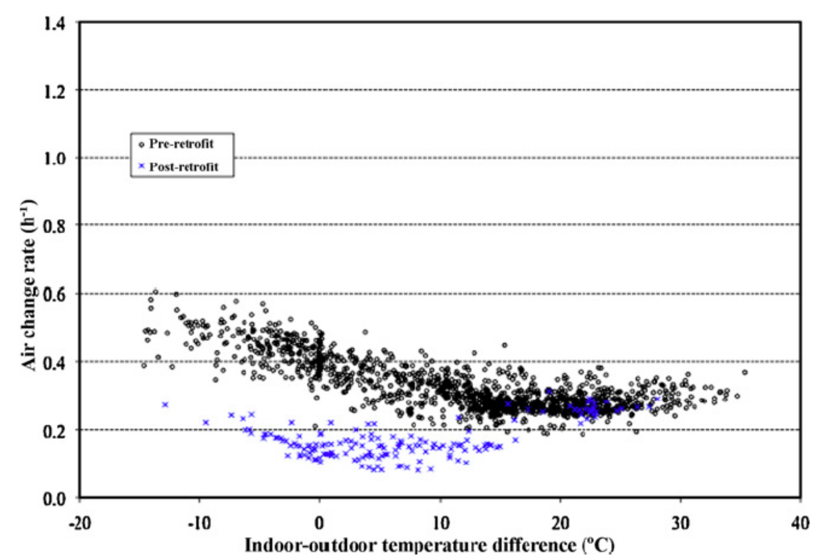
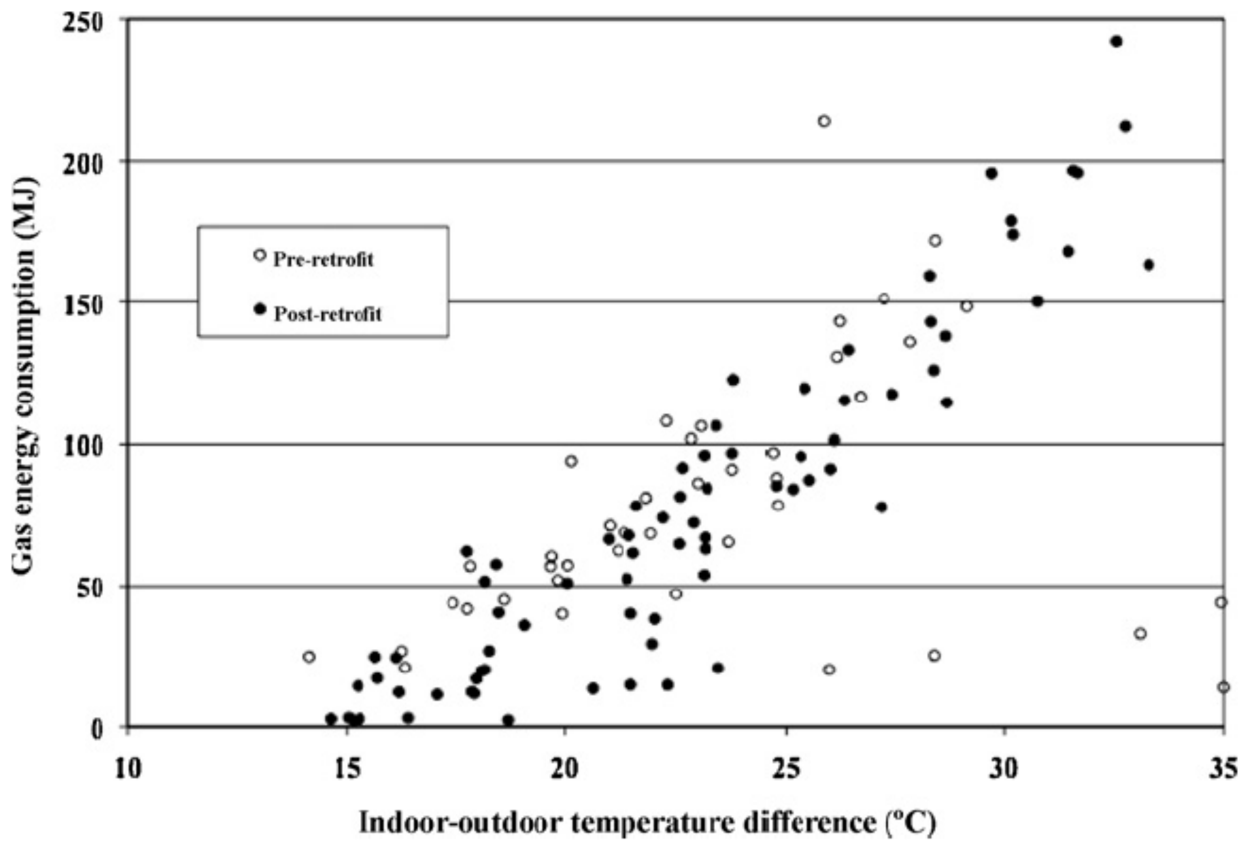


Fig. 8. Pre- and post-retrofit measured air change rates as a function of temperature difference (low wind speed): forced-air fan on, outdoor air intake sealed (Condition 1a).

Nabinger and Persily (2011) *Energy and Buildings*

Air sealing during retrofits

- Case study at NIST test house
- Measured changes in heating energy use
  - A lot of scatter (many influencing factors)
  - General trend was ~8% reduction in heating energy use



Nabinger and Persily (2011) *Energy and Buildings*