CAE 463/524
Building Enclosure Design
Spring 2016

Week 9: March 8, 2016

Air movements in enclosures

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Last time

- Moisture management and building enclosures
  - Fundamentals of liquid water transport
  - Understanding vapor barriers
  - Practical guidance and detail drawings for preventing water problems

Where are we now?

- Building science and psychrometrics review
- Surface energy balances
- Solar radiation
- Complex conduction
  - 2-D conduction with THERM
- Moisture/water vapor transport
  - 1-D moisture modeling (WUFI)
- Moisture/water vapor control
- Air movements and infiltration
- Fenestration and roofing
- Campus project presentations (March 29)
- Energy simulation and enclosure design (2 weeks)
- Codes/standards/applications
- Guest lecture (April 26)

Today's objectives

- Airflows in enclosures
  - Fundamentals
  - Governing equations
  - Measurement techniques
    - Blower door tests
  - Energy implications
  - Control strategies and applications

AIRFLOWS IN ENCLOSURES

Heat, air, and moisture: HAM

- Thus far in class, we've spent a lot of time on:
  - **Heat** transfer and **moisture** transport

- We've only briefly touched on:
  - **Air** transport

- Air movement is crucial to both heat and moisture transport
  - Air transport accounts for large portion of energy use
  - Air transport also a major source of water vapor that can lead to condensation
    - Indoor-to-outdoor flows in cold climates
    - Outdoor-to-indoor flows in warm, humid climates

Airflows in building enclosures

- Outdoor air flowing into a building
  - Can dilute indoor contaminants (good)
  - Can lead to excess energy use (bad)
  - Can lead to moisture transport (good or bad)

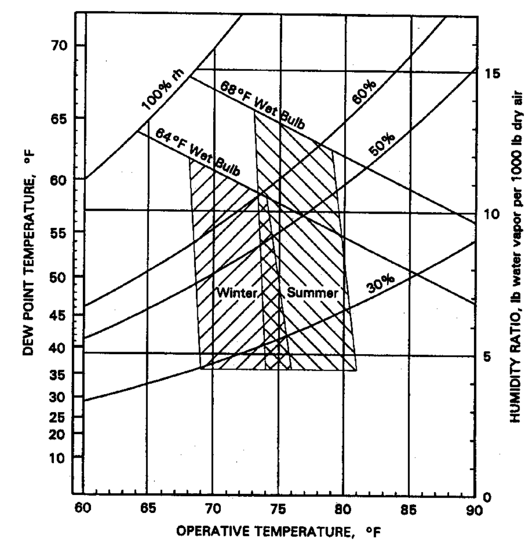
- Two primary categories of air movement:
  - **Ventilation**
    - Usually intentional
  - **Infiltration/exfiltration**
    - Usually unintentional

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

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

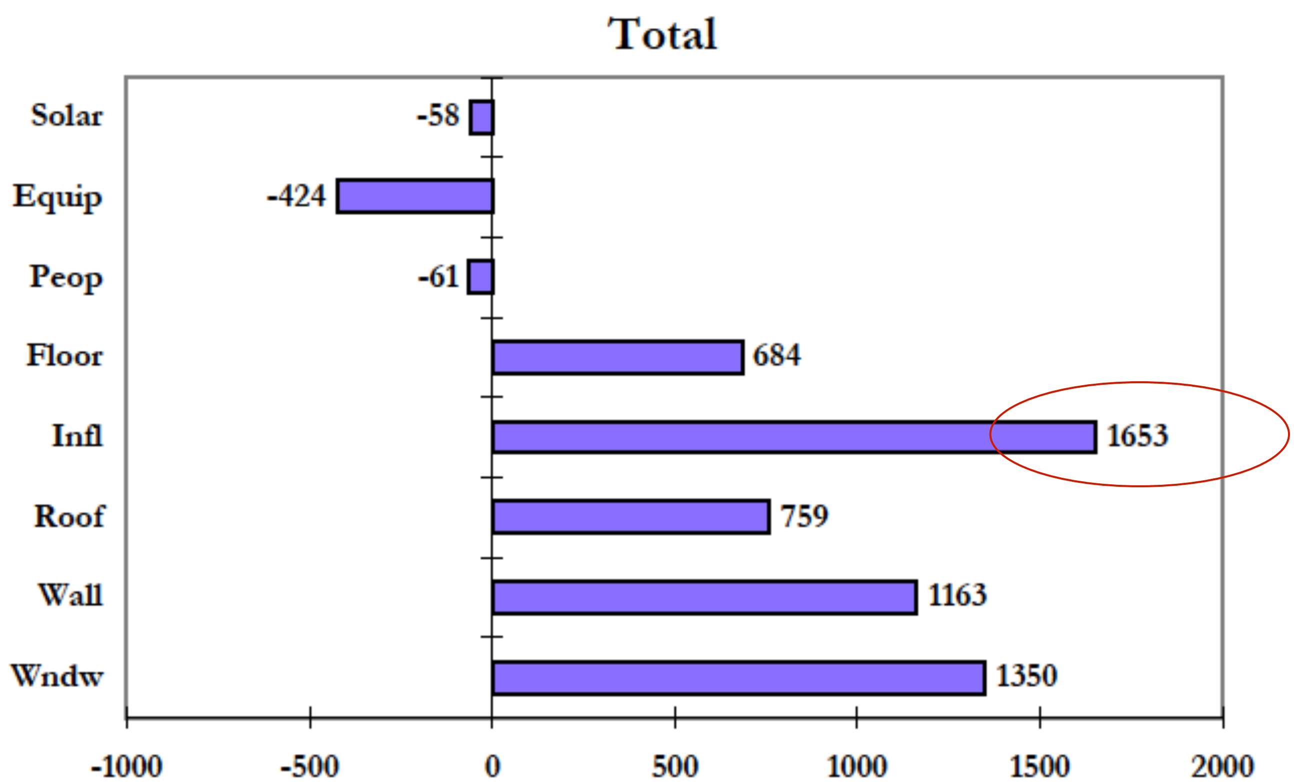
$$\dot{m} = \dot{V}_{leaks} \rho_{air}$$



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

Just how important are building envelopes for energy use?

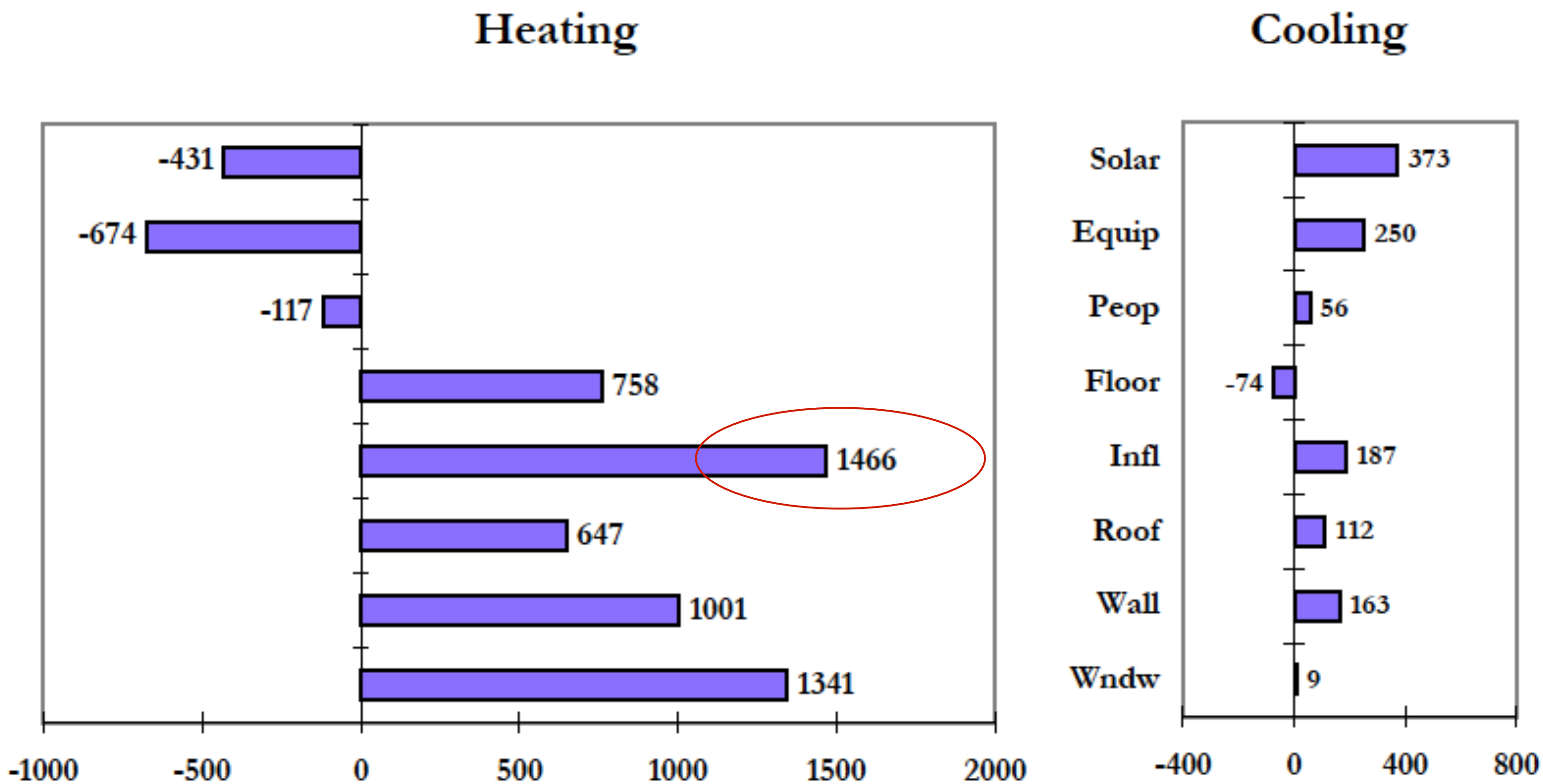
- 1999 study by Lawrence Berkeley National Laboratory
  - *Residential Heating and Cooling Loads Component Analysis*
  - Air infiltration is the single greatest contributor to energy use in U.S. homes



Aggregate component loads for all residential buildings (trillion BTUs)

Just how important are building envelopes for energy use?

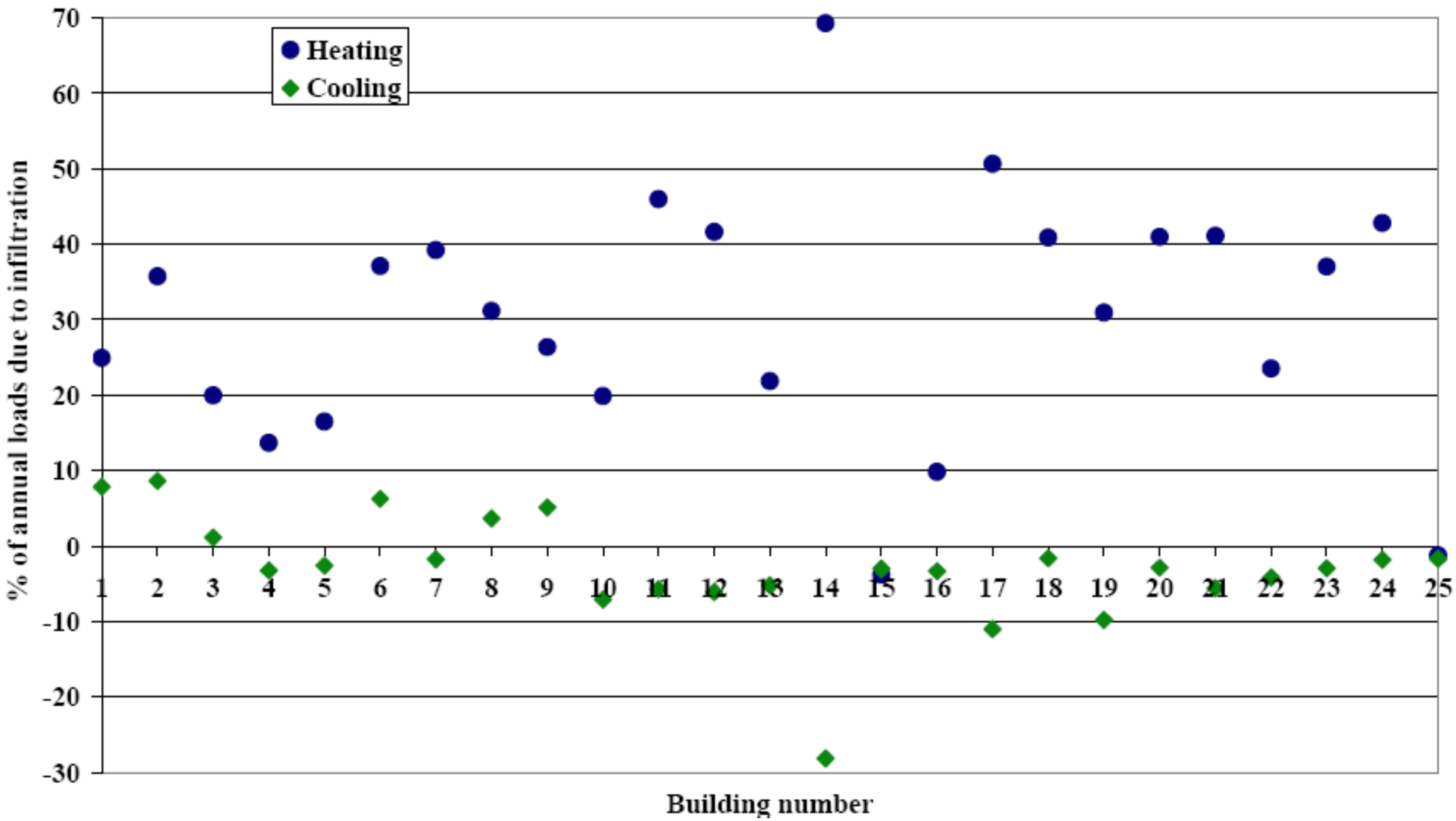
- 1999 study by Lawrence Berkeley National Laboratory
  - *Residential Heating and Cooling Loads Component Analysis*
  - Infiltration particularly important for heating loads



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! (and bigger than expected)

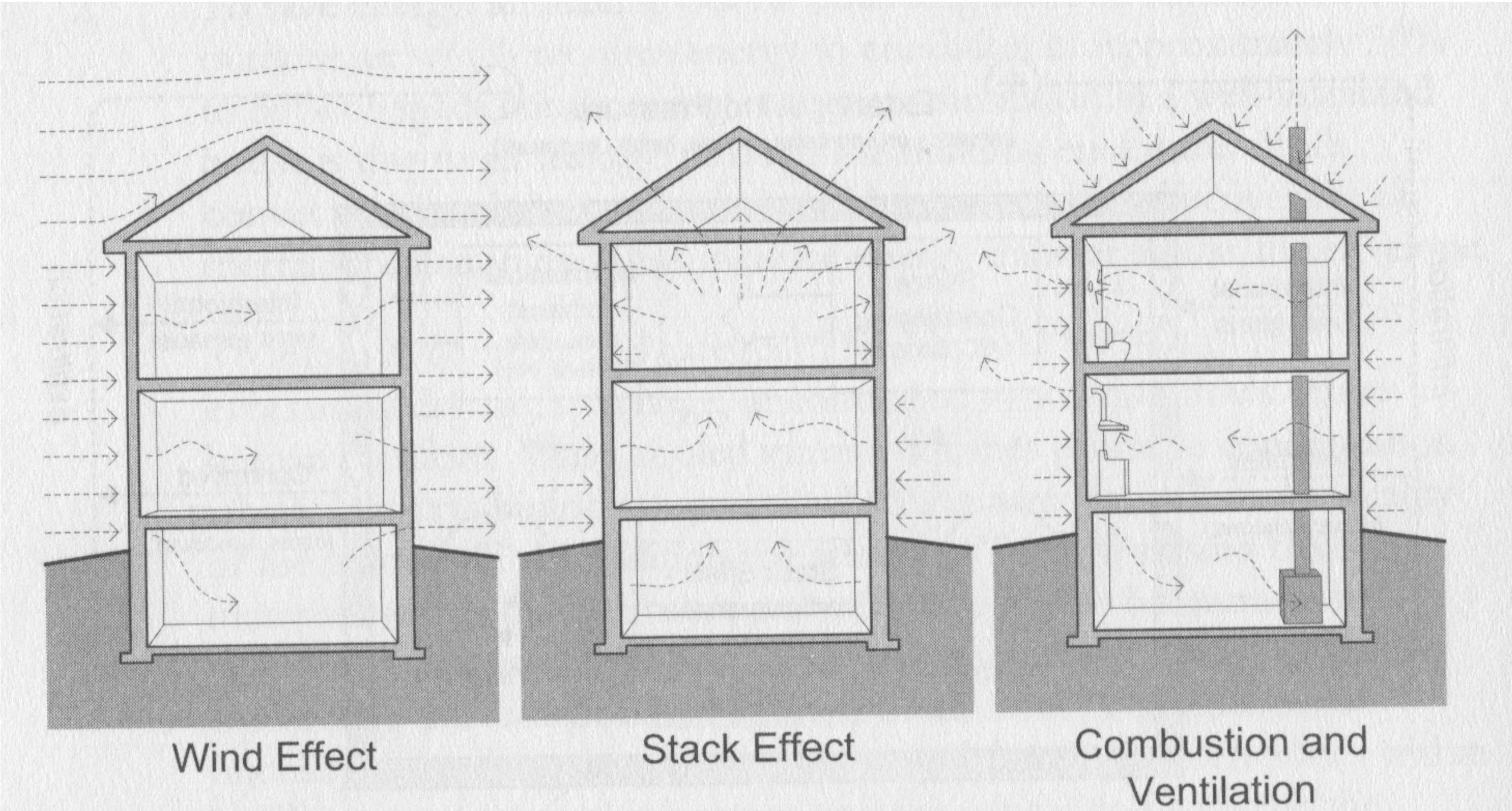
- Cooling load effects vary by climate and are smaller
  - Infiltration actually accounted for a net negative cooling load of about 3.3% on average
  - Means that commercial buildings were probably dominated by internal loads and cold infiltrated air actually reduced the need for cooling

Airflow in enclosures

- For airflow to occur:
  - There must be a flow path (opening)
  - There must be an air pressure difference (driving force)

- Three primary mechanisms generate pressure differences (driving forces)
  - Wind
  - Stack effect (natural buoyancy)
  - Mechanical air handling equipment

Driving forces



Infiltration/exfiltration

Ventilation

Infiltration and exfiltration

- **Infiltration** is the flow of outdoor air **into** a building through leaks, cracks, and other unintentional paths
  - Typically unintentional
- **Exfiltration** is the flow of indoor air **out of** the building through those same paths
- Both mechanisms transport air and moisture
  - Affect heating and cooling loads of a building
  - Also affect indoor air quality

Infiltration

- Outside airflow into a building is driven chiefly by pressure differences caused by:
  - Winds
  - Temperature differences
    - Stack effect

- In smaller (< 3 story) residences
  - Pressure gradient on the façade resulting from gusting wind is often the dominant driving force for infiltration

- In larger buildings (e.g., mid and high rises)
  - Driving force is typically stack effect
  - Differences in temperature + height → large buoyancy differences

Basic fluid mechanics

- Consider mass of air flow into an enclosure element
  - Must equal the mass of air flow out
    - Although water vapor and heat energy can be gained or lost
  - Treat air as incompressible ideal gas
    - Bernoulli's equation
    - Relates velocity, pressure, and location

$$\mathrm{p}_1 + \frac{1}{2}\rho_1 v_1^2 + \rho_1 g h_1 = \mathrm{p}_2 + \frac{1}{2}\rho_2 v_2^2 + \rho_2 g h_2$$

Static pressure	Velocity pressure (kinetic)	Pressure head (potential)

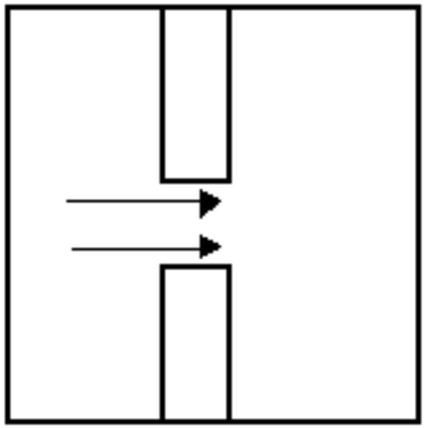
Basic fluid mechanics: flow through a crack

- Given a crack, orifice, or opening in enclosure (channel flow)
  - Assume no height difference ($h_1 = h_2$), constant density ($\rho_1 = \rho_2$), and that v_1 is negligible (very far from the crack)

$$\mathrm{p}_1 + \frac{1}{2}\rho_1 v_1^2 + \rho_1 g h_1 = \mathrm{p}_2 + \frac{1}{2}\rho_2 v_2^2 + \rho_2 g h_2$$

- Becomes:

$$\mathrm{p}_1 = \mathrm{p}_2 + \frac{1}{2}\rho_2 v_2^2$$

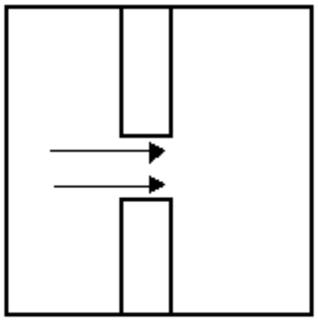


- Rearranging:

$$\frac{2\left(\mathrm{p}_1 - \mathrm{p}_2\right)}{\rho} = v^2$$

Basic fluid mechanics: flow through a crack

- Given a crack, orifice, or opening in enclosure (channel flow)
  - Assume no height difference ($h_1 = h_2$), constant density ($\rho_1 = \rho_2$), and that v_1 is negligible (very far from the crack)
  - Velocity through crack can be expressed as:



$$v = \sqrt{\frac{2\Delta P}{\rho}}$$

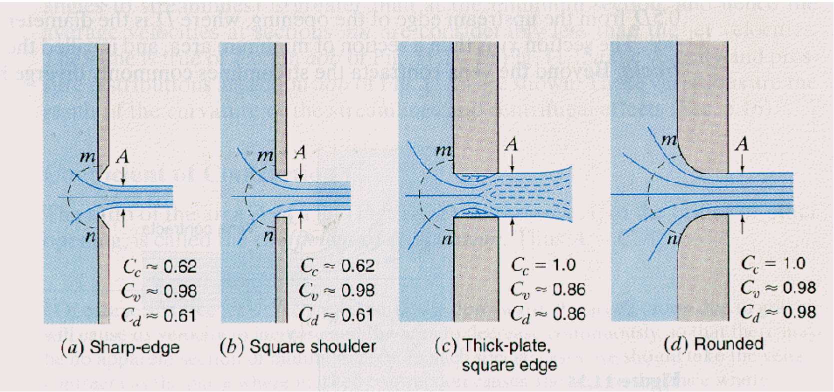
where ΔP is the pressure difference across the opening

Basic fluid mechanics: flow through a crack

- Given an area, A, of the opening/crack/orifice, the airflow rate, Q, will be:

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

  – But only under *ideal* conditions
  – Measurements would deviate from this calculation
    - Ignores losses due to friction and turbulence
    - Enter: the discharge coefficient, C_d
      – Accounts for fluid contraction and friction
      – Typical C_d for sharp-edge orifice is 0.61



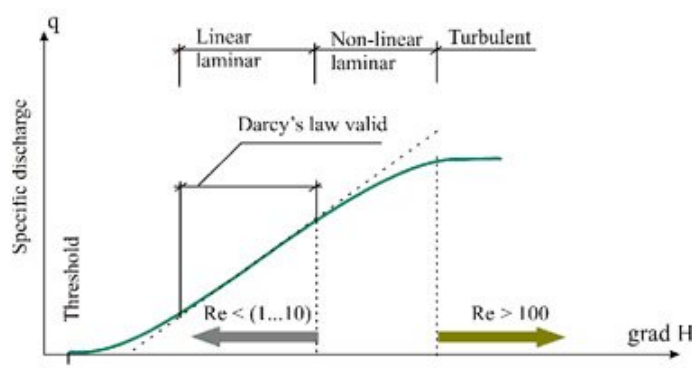
$$Q = C_d A\sqrt{\frac{2\Delta P}{\rho}}$$

Basic fluid mechanics: laminar flow through porous media

- Laminar flow through a crack or porous medium can be described by **Darcy's** equation
  - Airflow related linearly to driving air pressure difference

$$Q = KA\Delta \mathrm{P}$$

    - K is a proportionality constant (m/Pa-s)
    - Also referred to as air permeance
      - Used much in the same way as vapor permeance



  - Remember that channel flow was just related to the square root of ΔP

Air permeance of materials

- Our book lists materials and their air permeance
  - Data can be difficult to find
  - Note that the values in this table should be multiplied by 10^{-6} to get actual value
  - Example:
    - K for 200 mm of concrete brick is not 150 m/(Pa-s)
    - K is actually 150 x 10^{-6} m/(Pa-s)
  - Also: values of n near 1.0 show the approximately linear relationship between flow and pressure (will explore later)

Table 7.1: Air permeance of common building materials ($Q = k\,\Delta P^n$) [Bumbaru *et al* 1988]

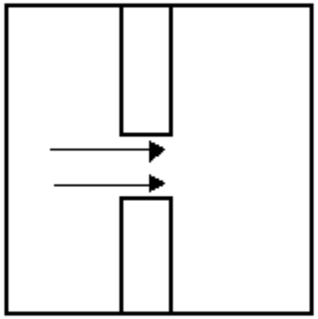
Material	K (x 10^6)	n
200 mm concrete block	150	0.990
12.7 mm drywall, unfinished	0.266	0.995
12.7 mm interior moisture-resistant drywall	0.120	1.000
12.7 mm sheathing grade gypsum & taped joints	0.200	1.000
11 mm asphalt-impregnated fibreboard	11.27	0.995
11 mm fibreboard	11.47	0.990
8 mm plywood sheathing	0.11	0.944
16 mm waferboard	0.101	0.979
12.7 mm particle board	0.210	0.996
15 x 127 m tongue & groove boards (8 joints / m)	1670	0.564
30 lb roofing felt	2.535	0.996
15 lb unperforated asphalt building paper	3.607	1.000
15 lb. perforated asphalt sheathing paper	6.629	0.947
Tyvek on 25 mm fibreglass (Glasclad™)	6.877	0.987
Tyvek™ on 11 mm fibreboard	6.5	1.000
38 Sprayed in-place cellulose	1320	0.970
75 mm loose-fill vermiculite	1030	0.979
152 mm fibreglass batt insulation	610	0.949
25.4 mm Type I expanded polystyrene	250	0.900
25.4 mm Type II expanded polystyrene	1.63	0.993

Notes:

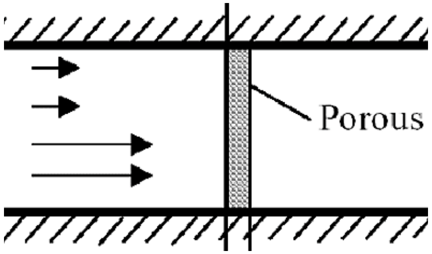
1. Some materials with no measurable leakage, i.e. K < 8 x 10^{-8} m /(Pa·s), 38 mm Type IV extruded polystyrene, 9.5 mm plywood sheathing, foil-faced foam insulations, foil-backed drywall, taped and finished gypsum drywall w/ 2 coats of latex paint and, of course, roofing membranes, steel sheeting, etc.
2. Materials with a permeance of more than about 1.5 x 10^{-6} m/(Pa·s) are generally inadequate for use as part of an air barrier system. However, materials with a permeance of less than about 25 x 10^{-6} m/(Pa·s) can be used as secondary layers of airflow resistance to control convective heat and moisture flows, wind washing, etc.

Basic fluid mechanics: flow through real cracks

- Two primary flow regimes in **real building cracks**:
  1. Channel flow (mostly turbulent; Bernoulli)
     - Fluid flow behavior is dominated by fluid inertia
       – More chaotic behavior
     - Airflow through larger openings and with higher ΔP

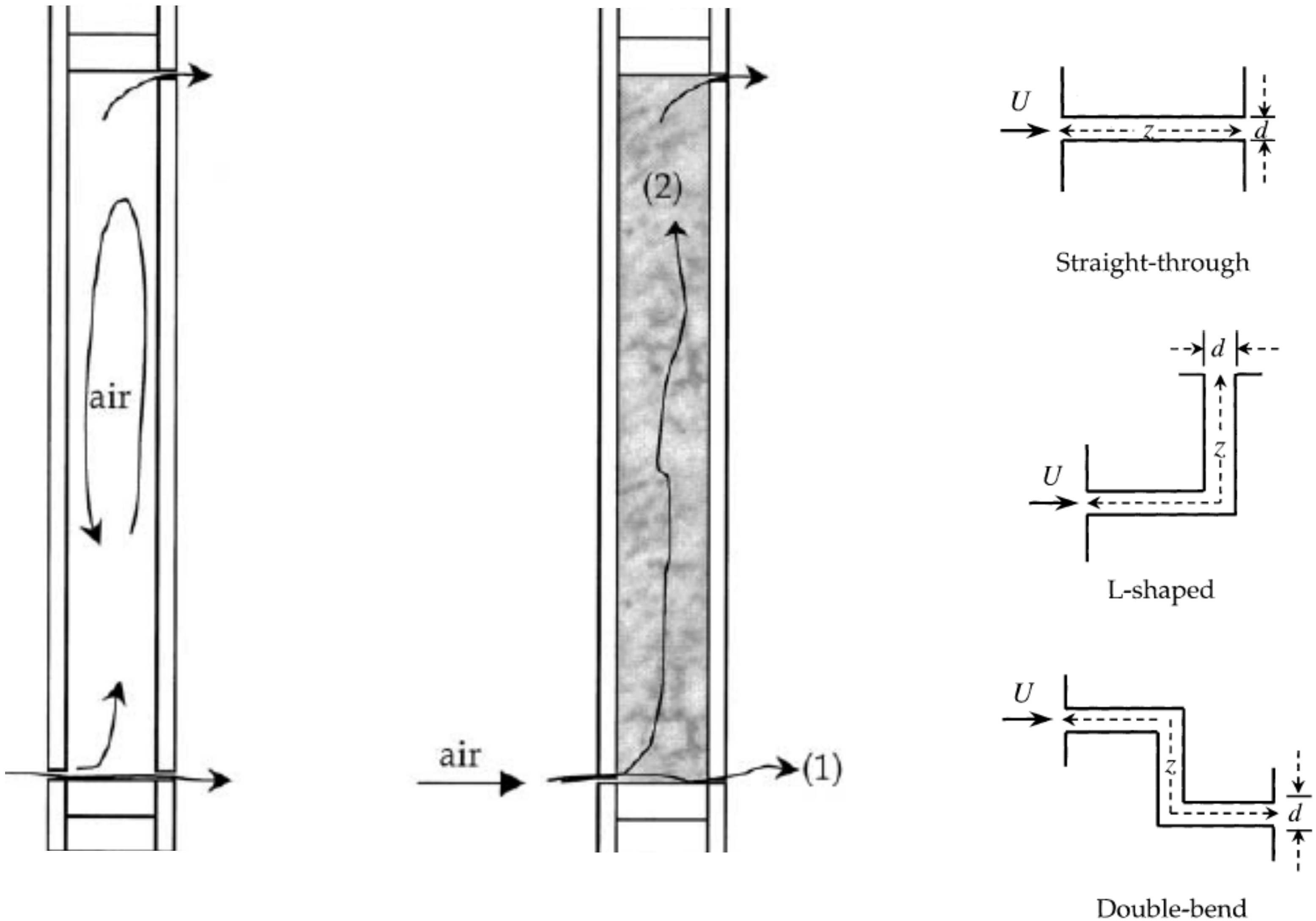


  2. Porous media flow (laminar; Darcy)
     - Fluid flow is dominated by viscosity of the fluid
       – Streamline flow; no disruption between layers
     - Airflow through smaller cracks and pores
       – Under smaller pressure differences



- What do actual flows look like?

Fluid mechanics: Actual flows in enclosures



Liu and Nazaroff, **2001** *Atmos Environ*

Fluid mechanics: Actual flows in enclosures

- In reality, air flows in building enclosures may include a mixture of laminar, turbulent, and transitional flows

  Instead of flow through:

  – Single cracks/openings/orifices (turbulent)

  – Single materials with some air permeance (laminar)

  Actual flows include: a number of series or parallel cracks, orifices, and permeable materials

  – It is very difficult (impossible, really) to accurately determine the number, size, and location of cracks/orifices/leaks in a building envelope

    - Impossible to specifically design for this as well

- We often rely on a general **power law** relationship between airflow and pressure difference

Fluid mechanics: Actual flows in enclosures

- Power law relationship for any tested assembly
  - Valid for single objects and/or entire enclosures

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

  - *C* is a flow coefficient
    - An empirical measure that accounts for opening area, the flow path, the flow regime, and frictional effects
    - *Strange units* for *C*: $m^3/(s\text{-}Pa^n)$
  - n is a flow exponent
    - Bounded by 0.5 (channel flow) and 1.0 (porous flow)
    - Often equals ~0.65 in practice

  - This relationship is not fully grounded in theory
    - Tends to just work!

Fluid mechanics: Actual flows in enclosures

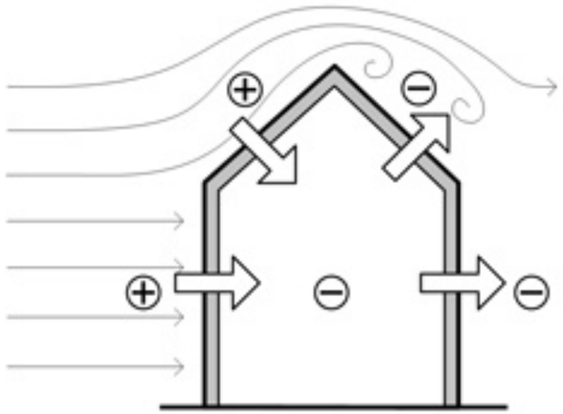
- Power law relationship for any tested assembly
  - Valid for single objects and/or entire enclosures

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

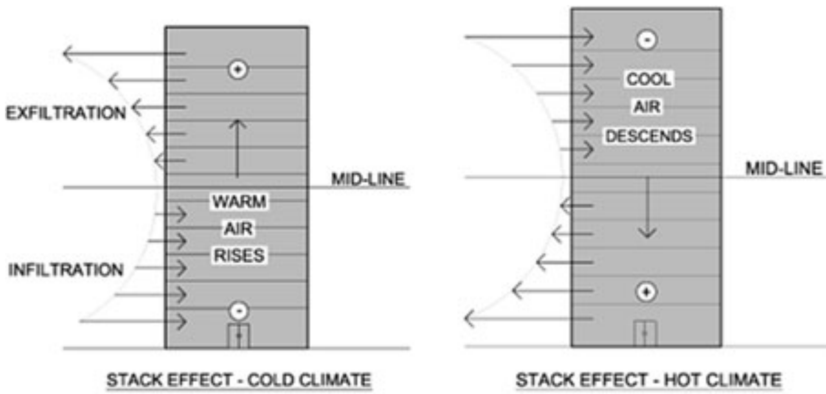
  - Will come back to this relationship later in the lecture
  - For now, we will learn about the major driving force:
    - ΔP (pressure difference)
    - Questions:
      - What drives ΔP?
      - How do we estimate ΔP?
        - » What are typical magnitudes?

Infiltration driving forces

- Pressure gradient across envelope
  - Driven by **wind pressure**
    - Wind velocity
    - Wind direction
    - Local terrain
    - Building shape

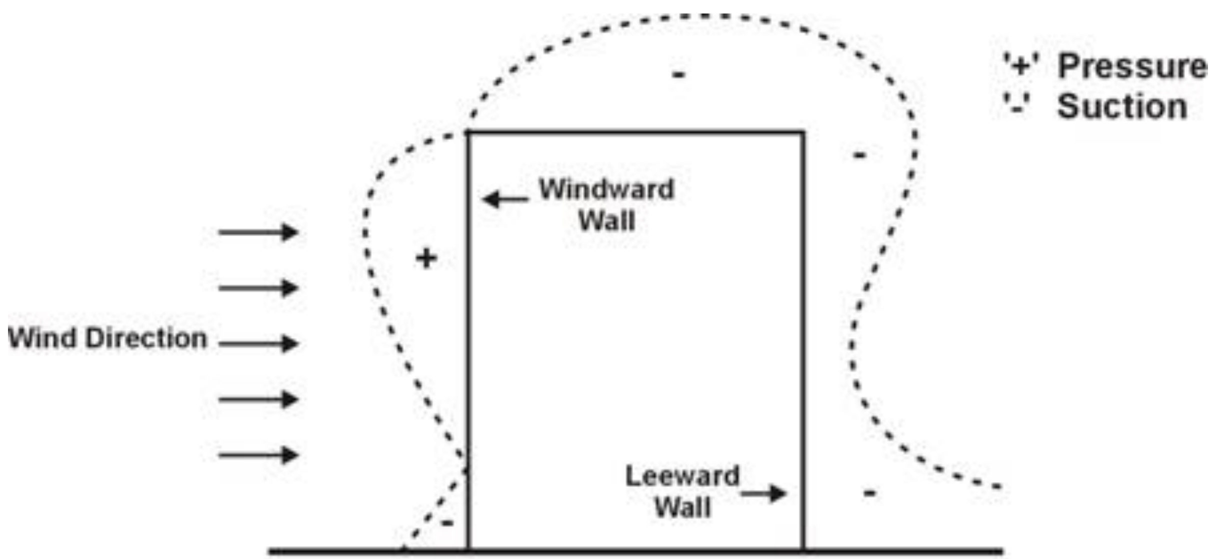


  - Driven by **stack pressure/stack effect**
    - Building height
    - Indoor and outdoor temperatures



Wind pressure

- Wind induces a pressure on a building's exterior surface
  - Depends on wind direction, wind speed, air density, surface orientation, and surrounding conditions
  - Generally positive pressure on the windward side
  - Generally negative or positive on the leeward sides
    - Depending on wind angle and building shape



Wind pressure

- From velocity component of Bernoulli Equation:

$$P_{velocity} = \frac{1}{2}\rho_{air}U_h^2$$

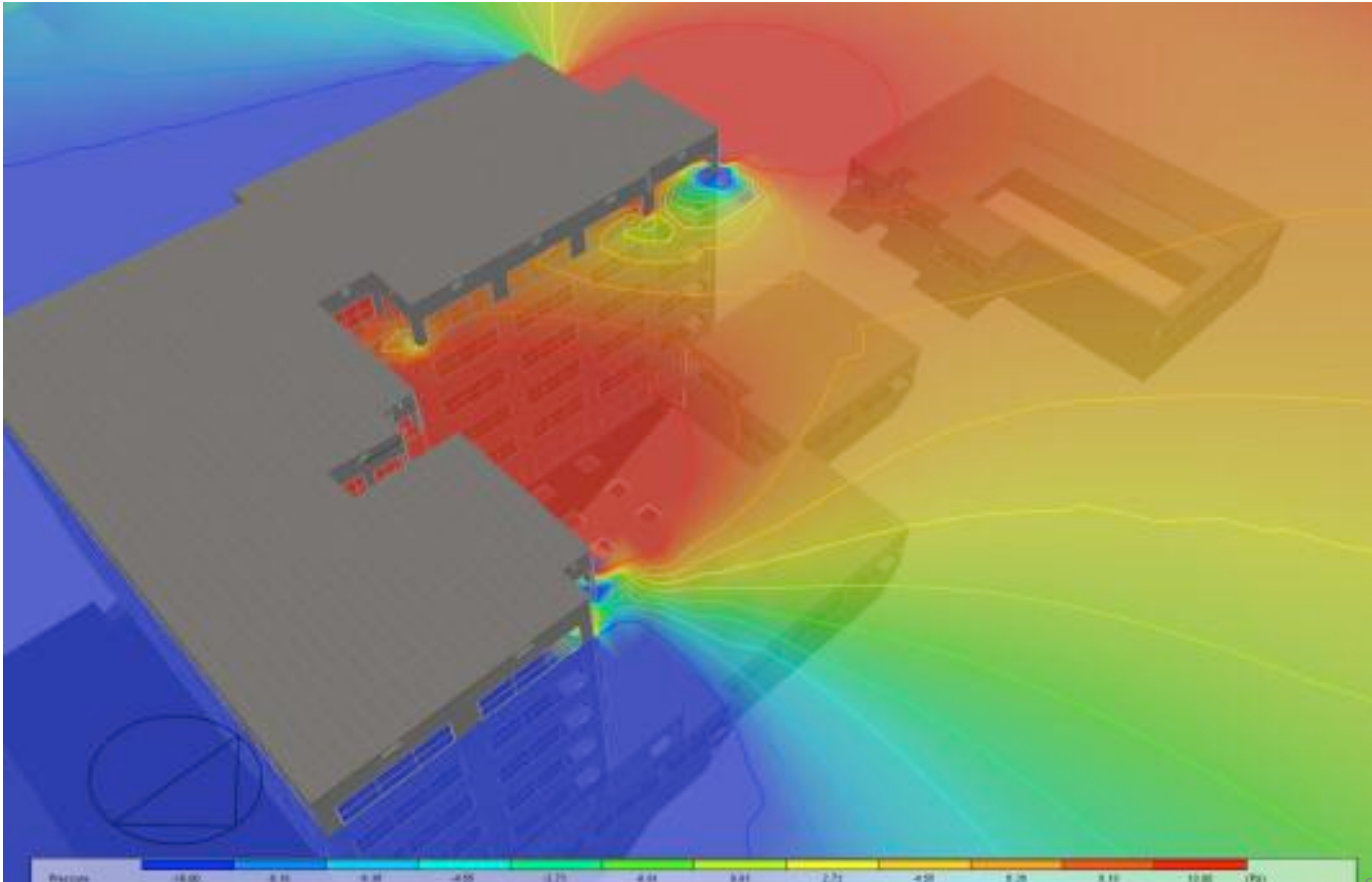
$P_{velocity}$ = wind velocity pressure; U_h = air velocity at building height, h; ρ_{air} = air density

- To convert velocity pressure to the difference between surface pressure and local atmospheric pressure:
  - Multiply by local wind pressure coefficient, C_p

$$P_{surface} = \Delta P = C_p P_{velocity} = \frac{1}{2} C_P \rho U_h^2$$

  - Get C_p from measurements or from 2013 ASHRAE Fundamentals Chapter 24

Wind pressure coefficients (C_p)



Wind pressure coefficients (C_p)

- Difference between pressure on a building surface and the local outdoor atmospheric pressure at the same height, P_s:

$$P_{surface} = \Delta P = C_p P_{velocity} = \frac{1}{2} C_p \rho U_h^2$$

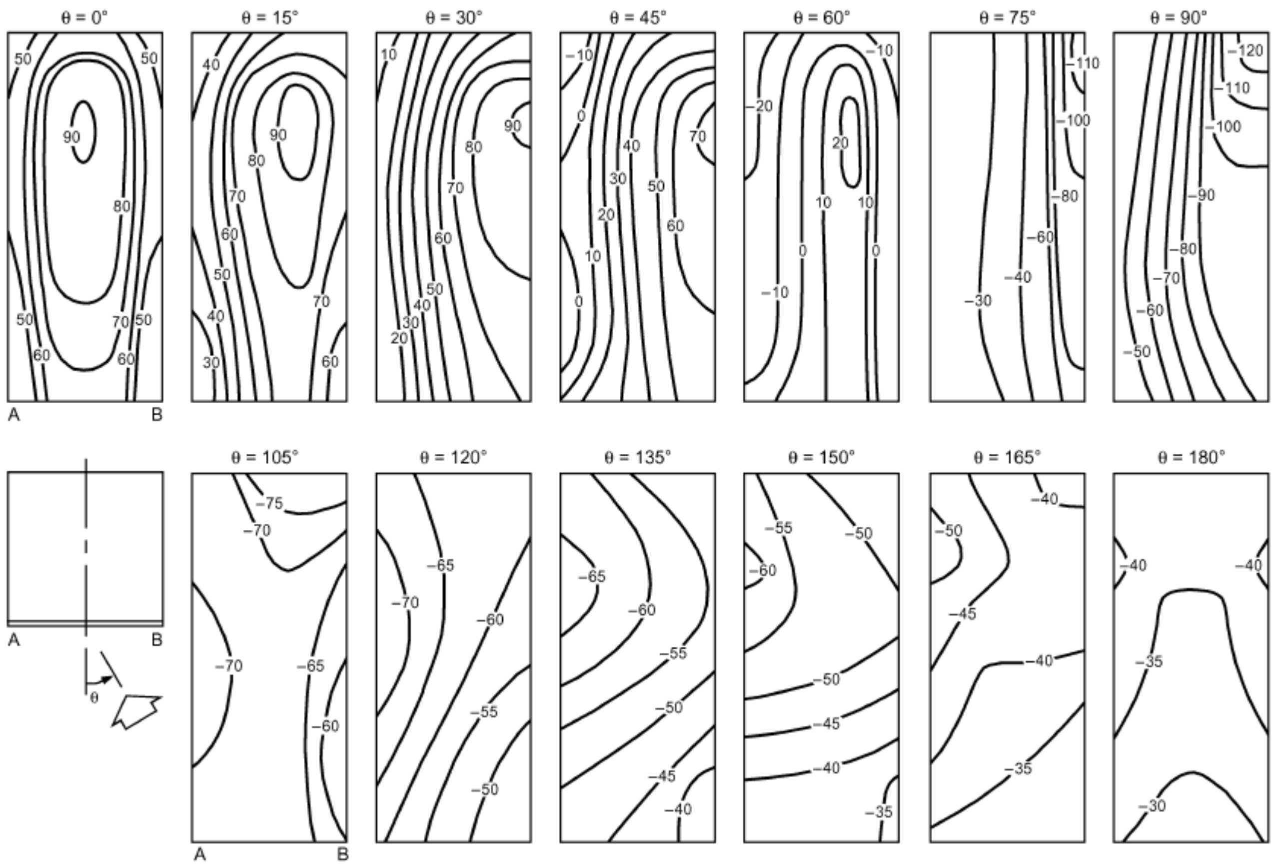


Fig. 4 Local Pressure Coefficients ($C_p \times 100$) for Tall Building with Varying Wind Direction
(Davenport and Hui 1982)

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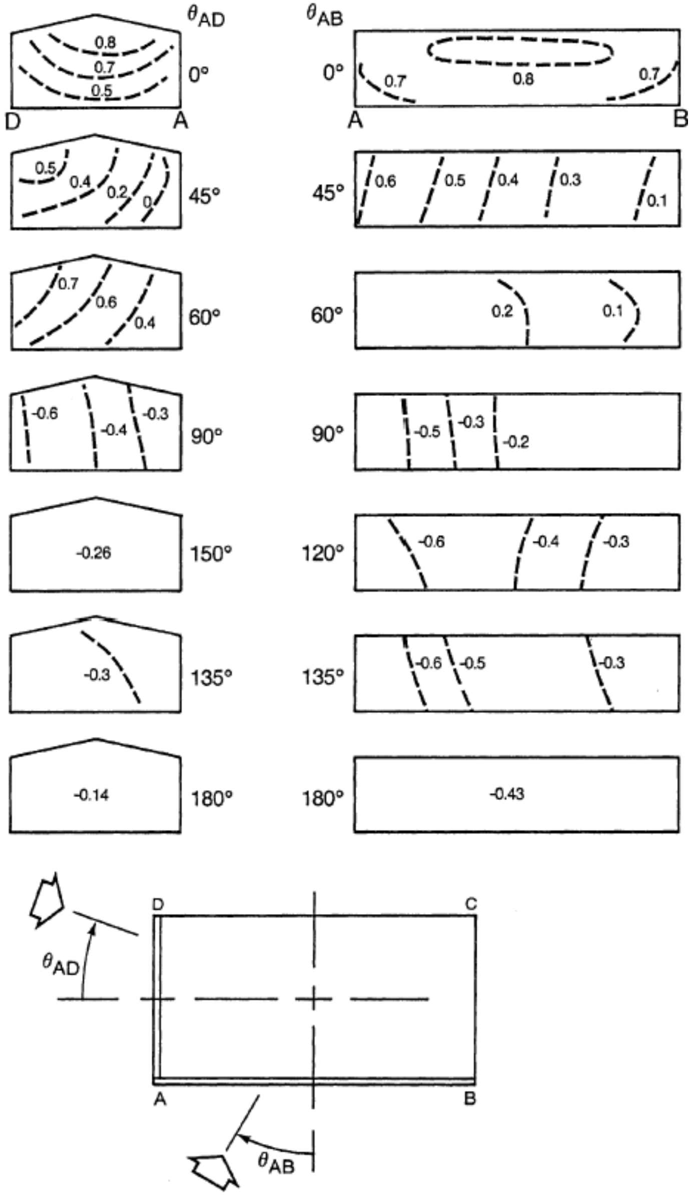
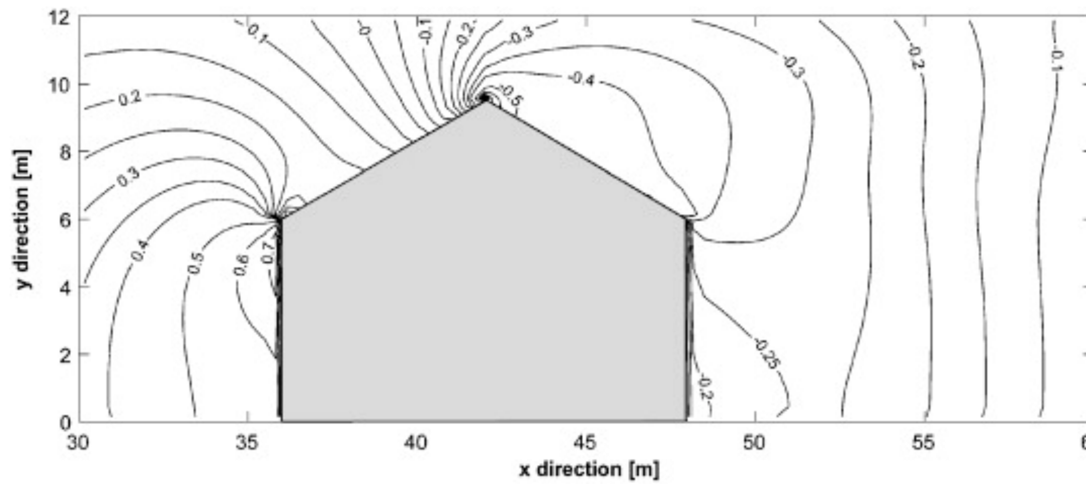


Fig. 5 Local Pressure Coefficients for Walls of Low-Rise Building with Varying Wind Direction
(Holmes 1986)



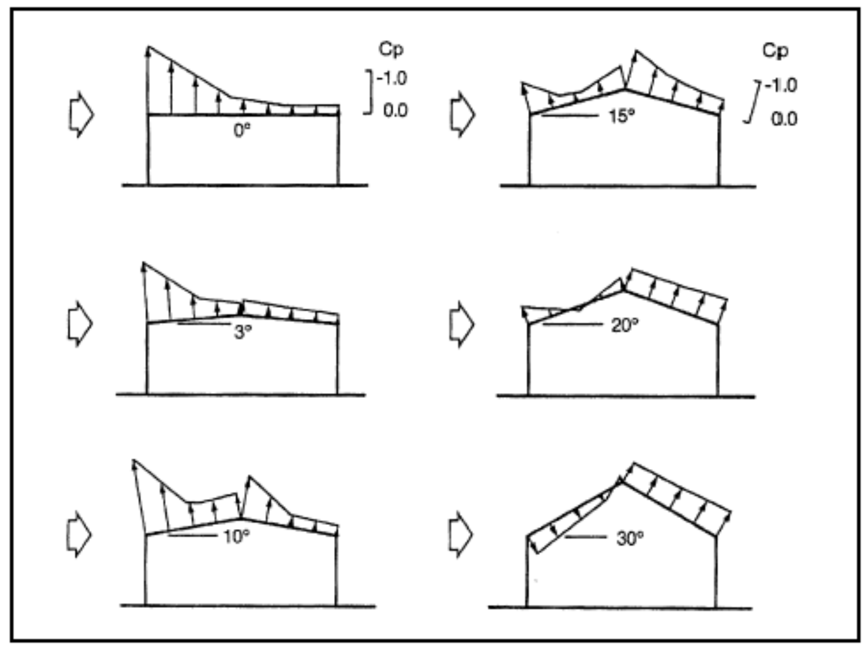


Fig. 8 Local Roof Pressure Coefficients for Roof of Low-Rise Buildings
(Holmes 1986)

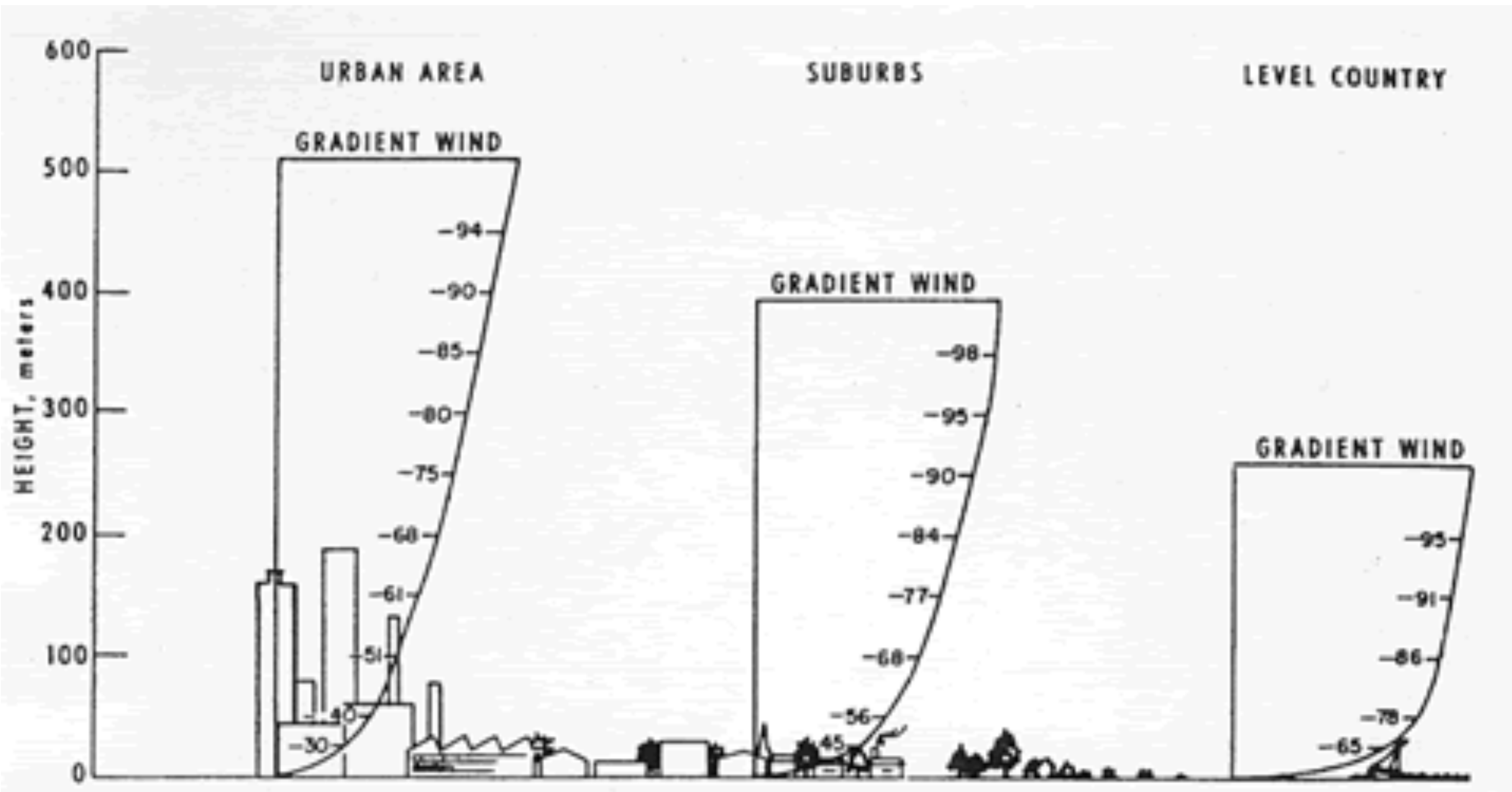
Wind speed

- Wind pressure is obviously driven not just by wind direction and how that relates to the building
  - But also wind speed
  - Particularly ***local*** wind speed
    - Local to the building location
    - Local to specific location on the building

- Wind speed varies drastically in space and time
  - Vertically
  - Horizontally

Vertical wind speed gradients

- Mean velocity of the wind (and thus the wind pressure) varies with height and terrain



Vertical wind speed gradients

- Local wind speed at height H can be estimated by applying height and terrain corrections

$$U_H = U_{met}\left(\frac{\delta_{met}}{H_{met}}\right)^{a_{met}}\left(\frac{H}{\delta}\right)^{a}$$

"Met" refers to local meteorological station

Table 1 Atmospheric Boundary Layer Parameters

Terrain Category	Description	Exponent a	Layer Thickness δ, m
1	Large city centers, in which at least 50% of buildings are higher than 21.3 m, over a distance of at least 0.8 km or 10 times the height of the structure upwind, whichever is greater	0.33	460
2	Urban and suburban areas, wooded areas, or other terrain with numerous closely spaced obstructions having the size of single-family dwellings or larger, over a distance of at least 460 m or 10 times the height of the structure upwind, whichever is greater	0.22	370
3	Open terrain with scattered obstructions having heights generally less than 9.1 m, including flat open country typical of meteorological station surroundings	0.14	270
4	Flat, unobstructed areas exposed to wind flowing over water for at least 1.6 km, over a distance of 460 m or 10 times the height of the structure inland, whichever is greater	0.10	210

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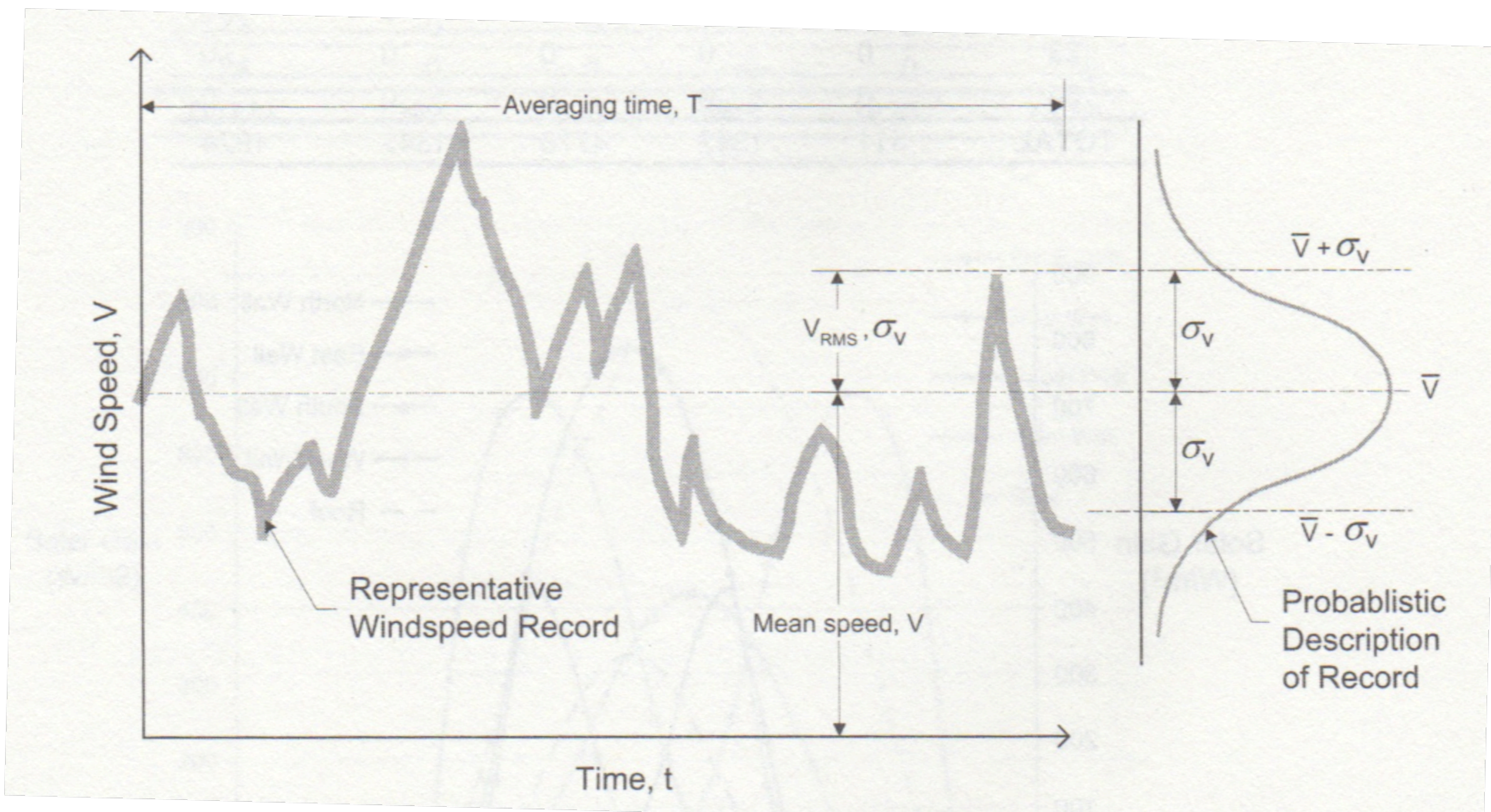
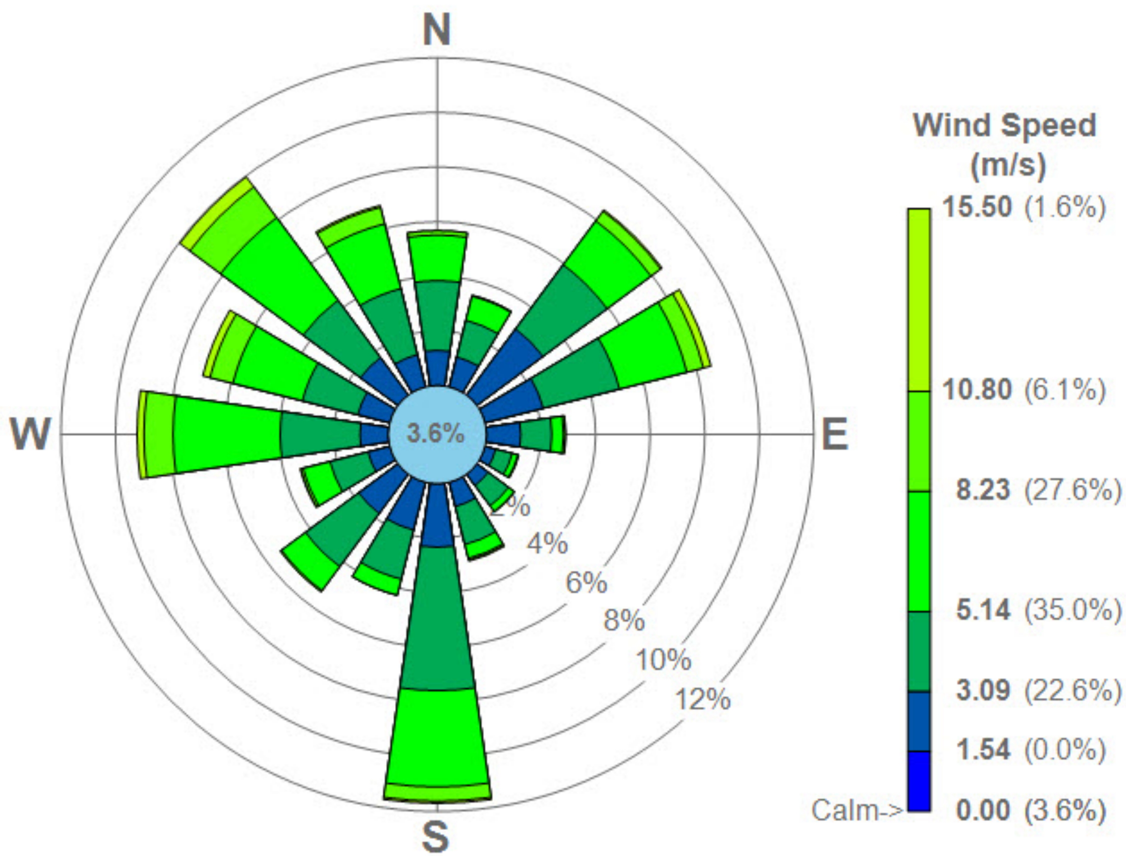
Temporal wind speed variations

- Wind speed and direction changes often and quickly
  - Sub-one-second velocities are required for detailed analysis
  - Very difficult to do accurately in design phase
    - Requires extensive modeling and/or wind tunnel studies
  - Approximate design can be done with means and distributions

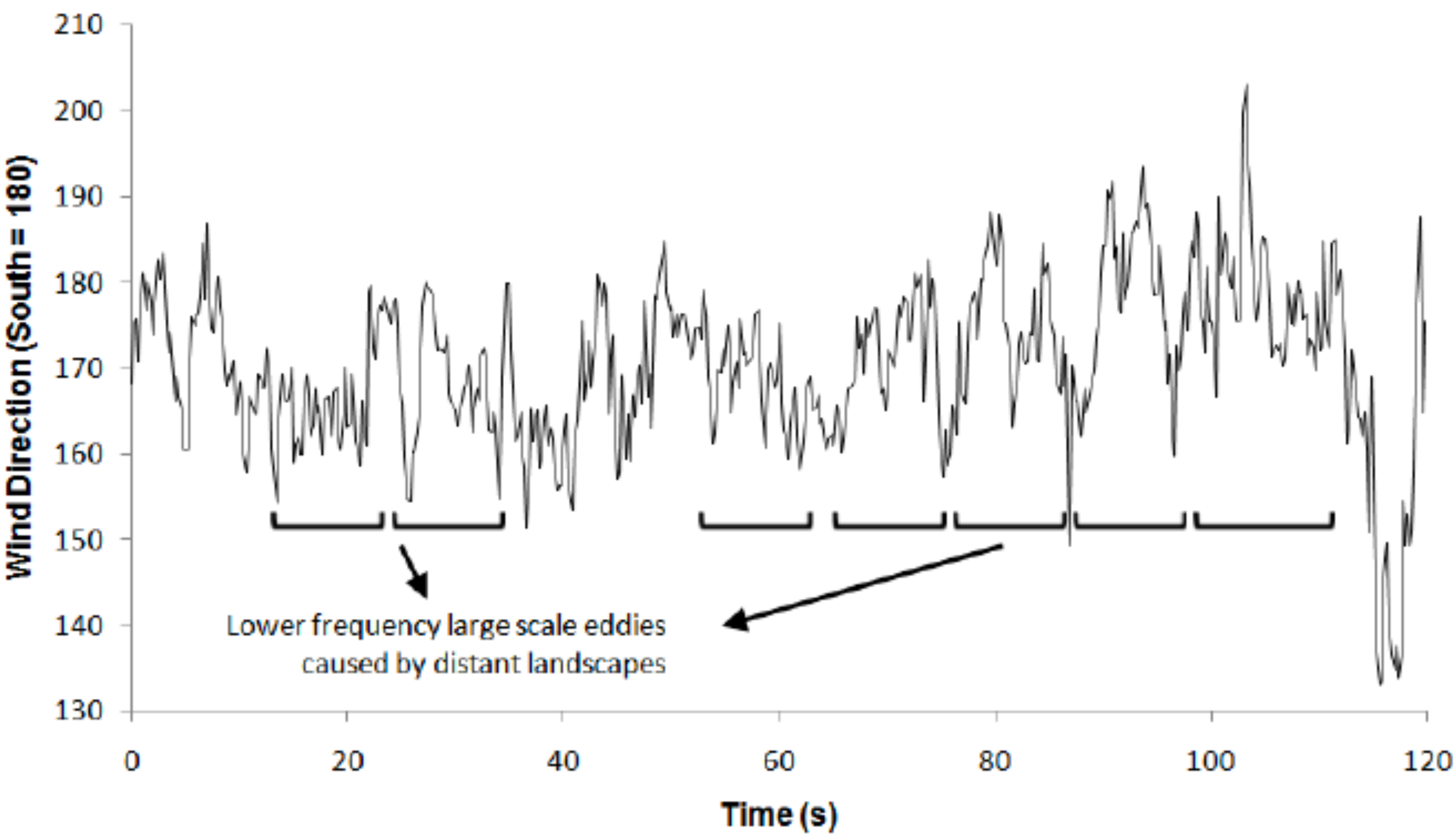


Wind speed and direction data

- Can get hourly values from NOAA's National Climatic Data Center
  - Just like TMY weather data for heat transfer simulations



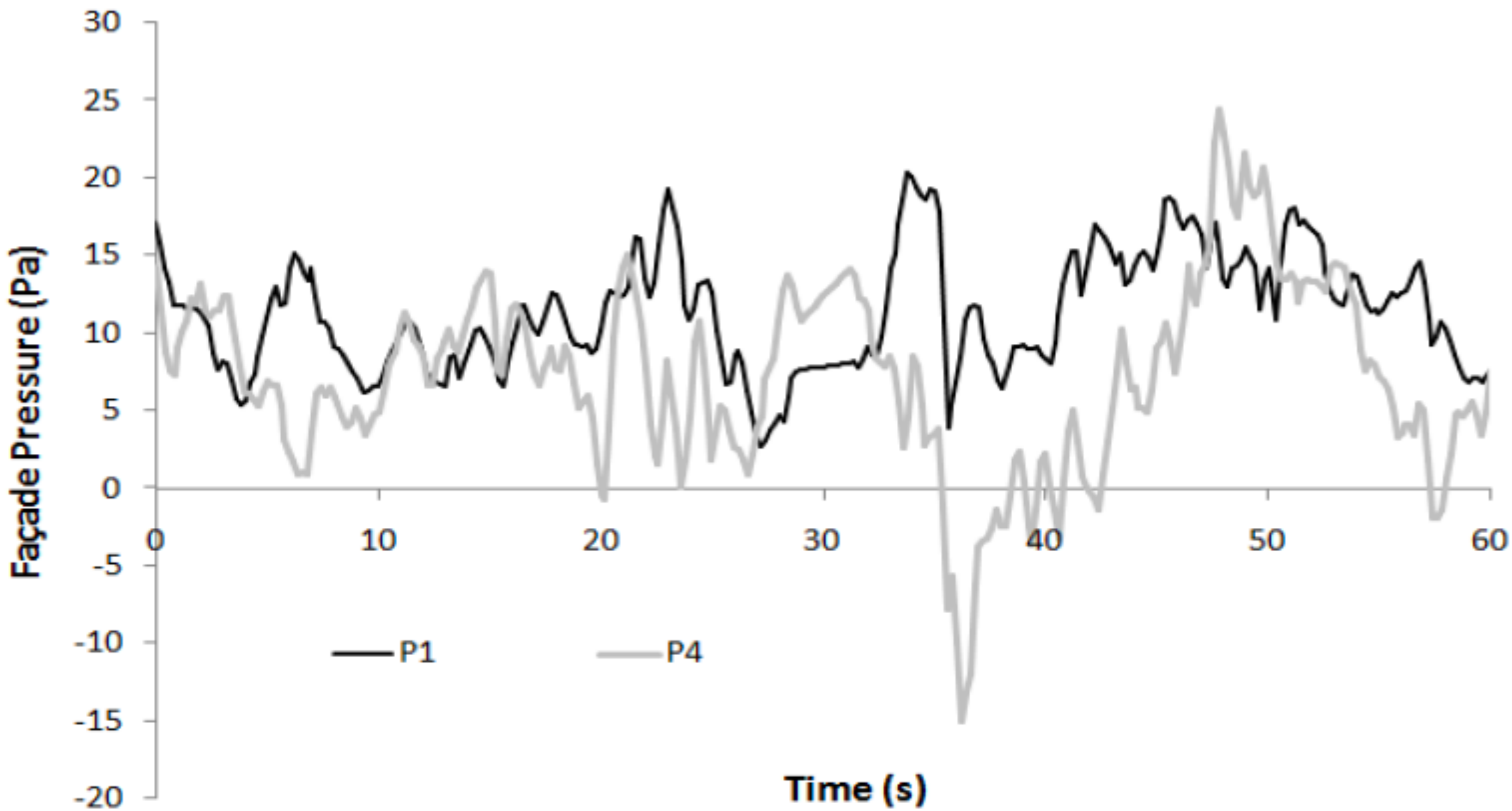
Real measured wind data: instantaneous direction changes



Courtesy of Dr. James Lo, Dissertation 2012

Real measured wind data: instantaneous façade pressures

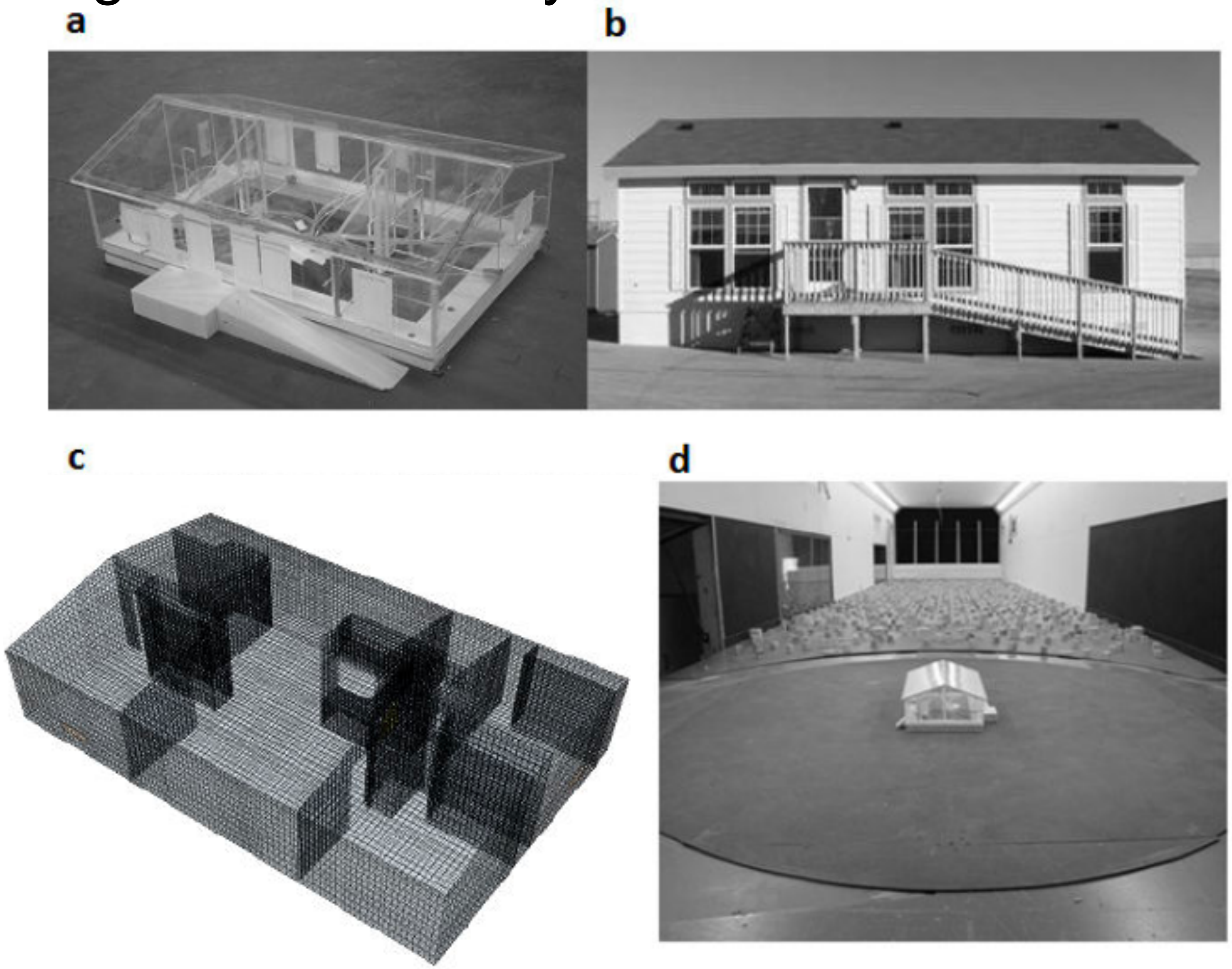
- Surface pressures measured on two different facades



Courtesy of Dr. James Lo, Dissertation 2012

Detailed wind analysis in design phase

- Designing for natural ventilation can be costly and time-consuming to do accurately!



Courtesy of Dr. James Lo, Dissertation 2012

Stack effect

- Next up: stack effect
  - Driven by temperature differences across envelope
  - Remember the ideal gas law?
  - Air temperature difference yields air density difference

$$\rho = \frac{P}{RT}$$

  - Density difference drives buoyancy
  - Stack pressure:

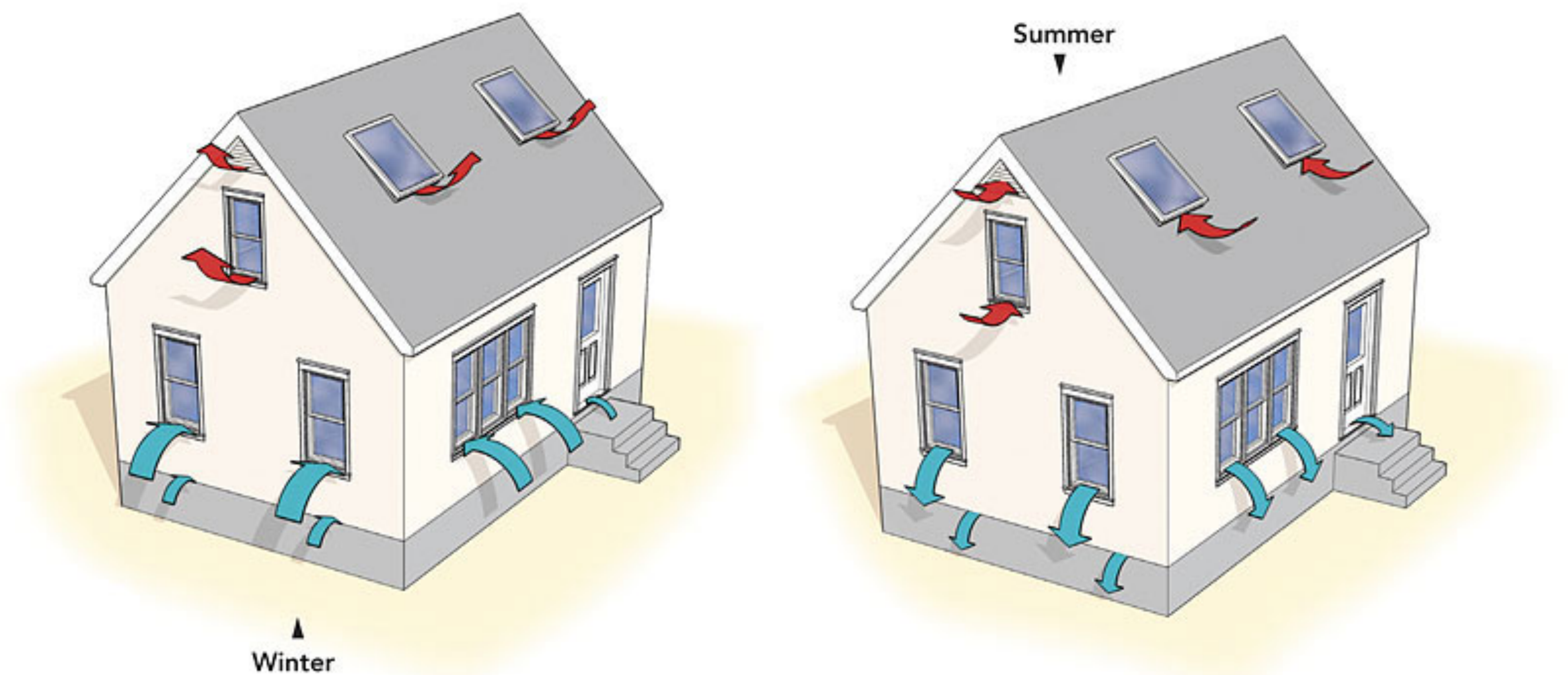
$$P = \rho g h$$

Stack effect

- In wintertime
  - Air within a building acts like a bubble of hot air in a sea of cold air
  - Rises to the top
  - Draws **outdoor air in from** cracks/gaps/openings in the **bottom**
  - Indoor air out through top

- In summertime
  - Air within a building acts like a bubble of cold air in a sea of hot air
  - Falls to the bottom
  - Drives **indoor air out through** cracks/gaps/openings in **bottom**
  - Outdoor air in through top
    - Temperature differences usually lower in the summer time so amount of flow is smaller

Stack effect: winter vs. summer



http://www.greenbuildingadvisor.com/stack-effect-when-buildings-act-chimneys

Stack effect

- The greater the height of the building
  - The greater the potential difference in stack pressure

- Stack pressure difference:

$$\Delta P_{stack} = \left(\rho_{out} - \rho_{in}\right) g \left(H_{NPL} - H\right)$$

$$\Delta P_{stack} = \rho_{out} \left(\frac{T_{out} - T_{in}}{T_{in}}\right) g \left(H_{NPL} - H\right)$$

  - Where H_{NPL} is the height of neutral pressure level above a reference plane without any other driving forces
    - Sign convention: P_{stack} positive → flow driven outward

Stack effect

- Neutral pressure level (NPL)
  - Vertical location where there is no pressure difference
    - Influenced by the **enclosure leakage distribution** over the exterior and by interior compartmentalization
  - It is not necessarily located at the mid-height of a building
    - If there are more openings at the top of a building (e.g., big roof penetrations) than on the bottom, the NPL will be moved closer to the larger top openings
    - It is a moving target (can be difficult to predict accurately)

Neutral pressure level (NPL or NPP)

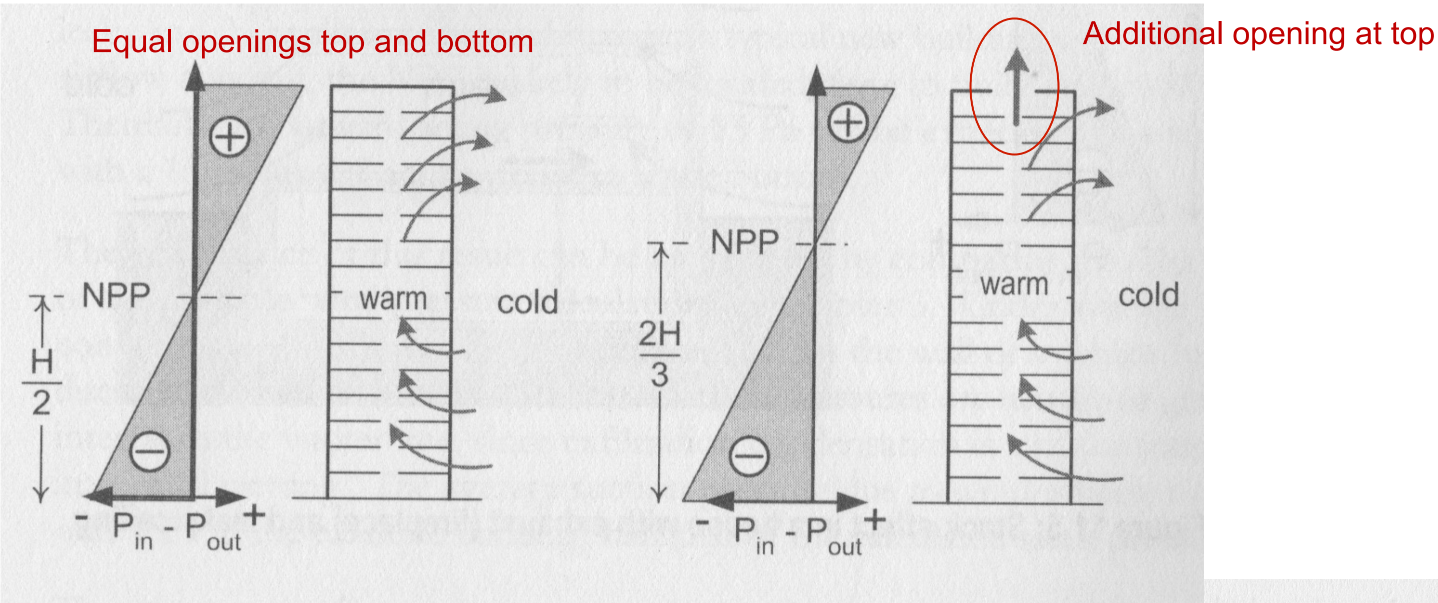


Figure 11.4: Stack-effect driven airflow through typical multi-story building

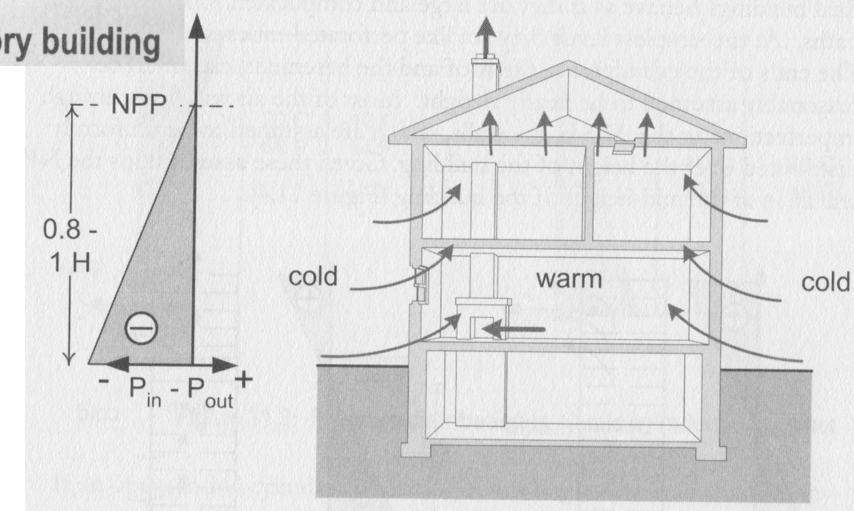
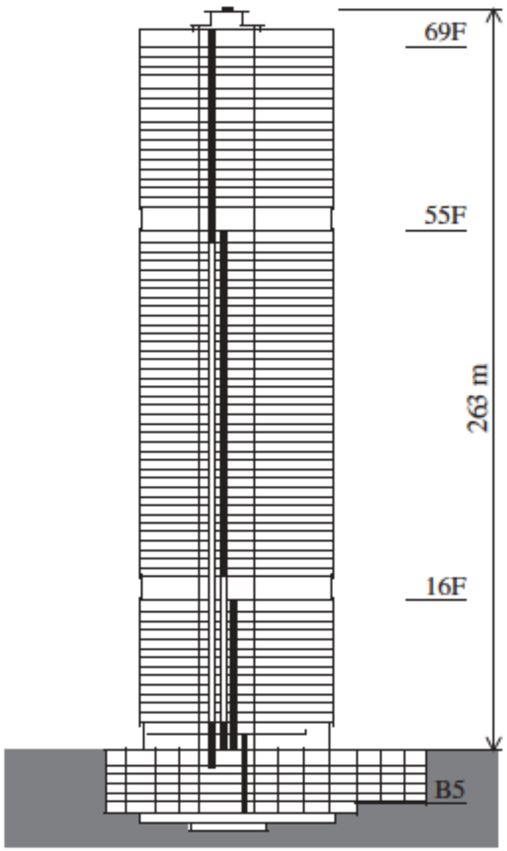
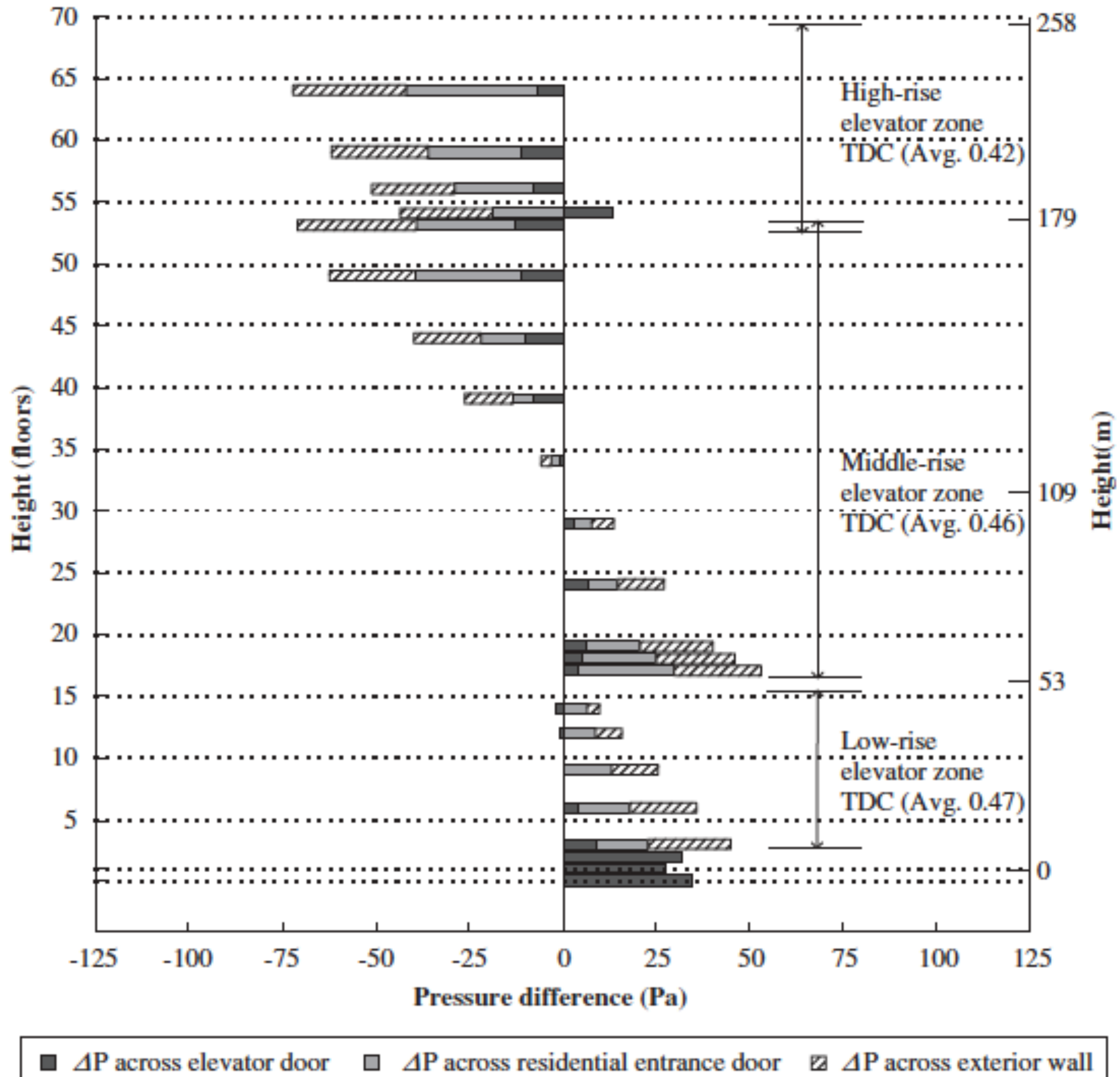


Figure 11.5: Stack effect in a house with exhaust (fireplace) and leaky ceiling

Real field measurements of stack effect

~70 story building in Korea

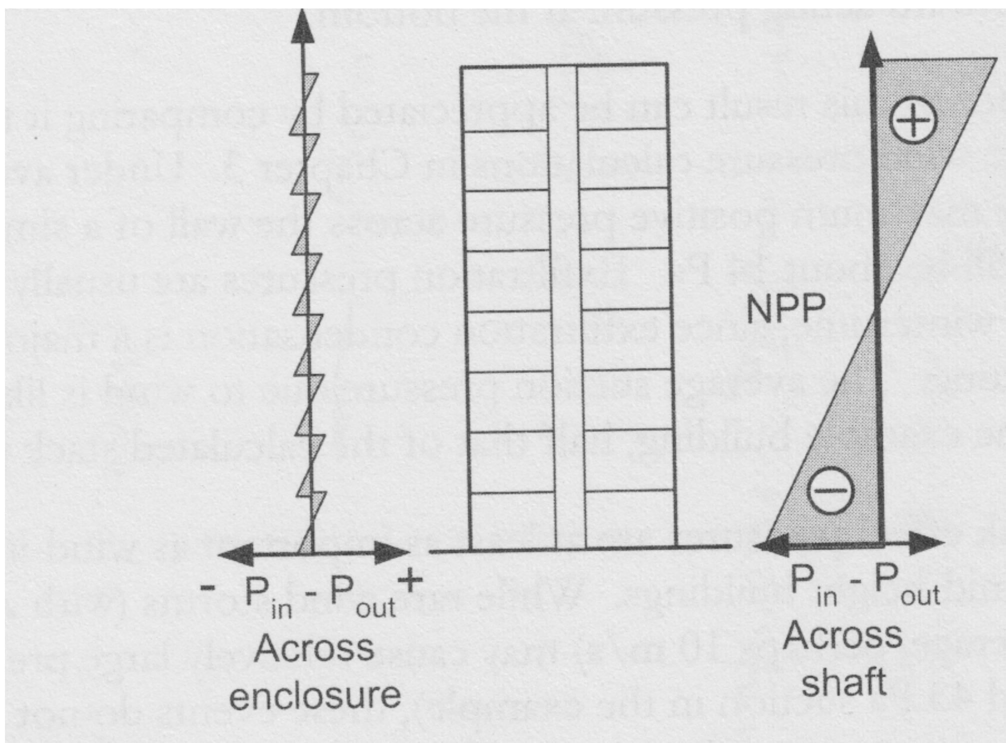




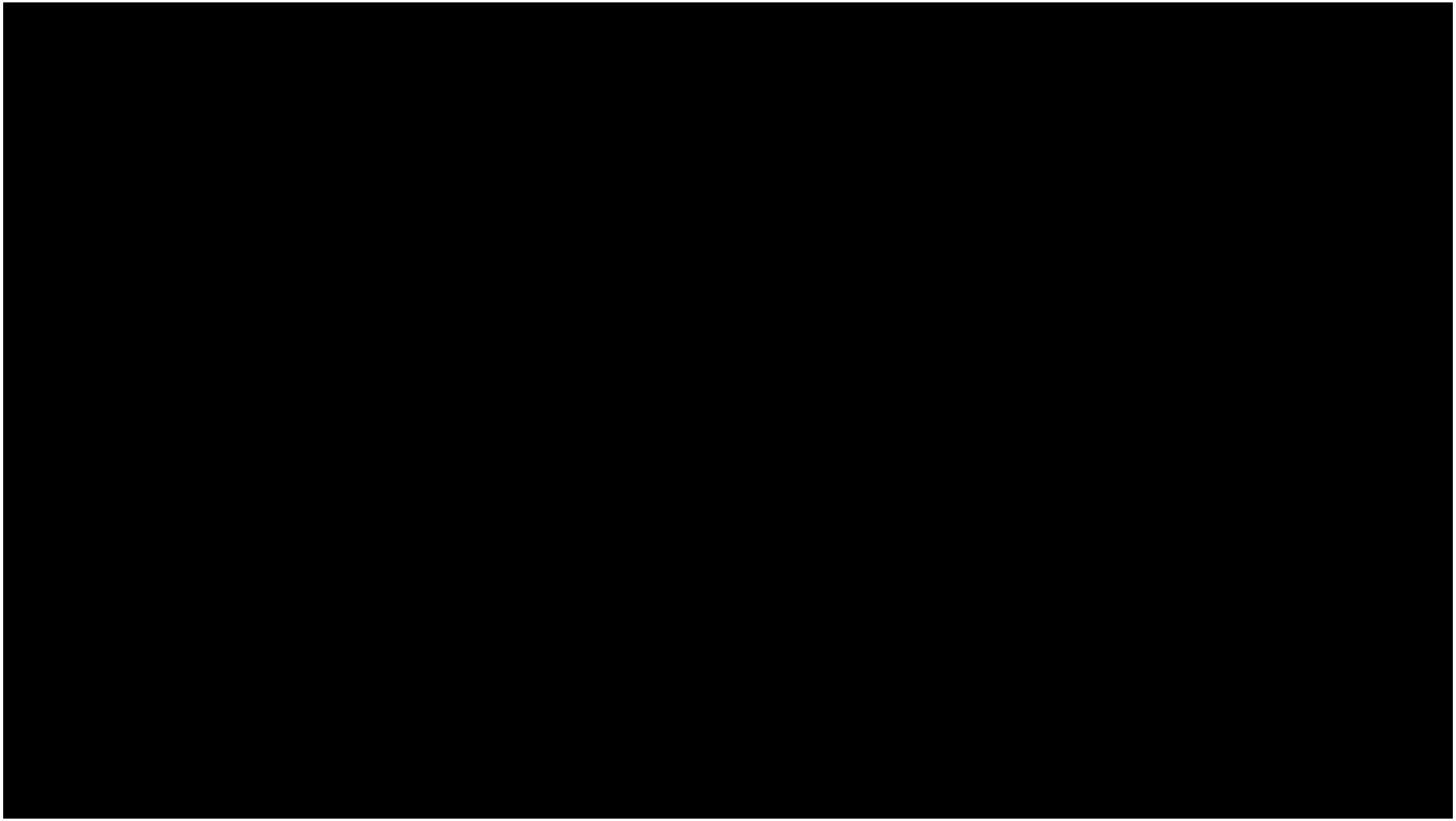
Jo et al. **2007** *Building and Environment* 42:263–277

Designing for stack effect

- One way to design for stack effect is to provide a physical air barrier between floors
  - Break the path of airflow
    - Works well for occupied floors
    - Vertical shafts (stair wells and elevator shafts) can't be sealed vertically
      - But can be sealed from each floor with a foyer



Designing for stack effect in tall buildings



https://www.youtube.com/watch?v=jz1HqL4PHVQ http://www.dougking.co.uk/videos/

Combining driving forces

- We've covered stack pressures and wind pressures
- We've also discussed an empirical relationship between flow and pressure difference:

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

- To get total ΔP across a leak, simply add stack- and wind-induced ΔP (as well as any ΔP due to mechanical systems)

$$\Delta P_{total} = \Delta P_{stack} + \Delta P_{wind} + \Delta P_{HVAC}$$

$$\Delta P_{total} = \rho_{out}\left(\frac{T_{out} - T_{in}}{T_{in}}\right)g\left(H_{NPL} - H\right) + \frac{1}{2}C_P \rho U_h^2 + \Delta P_{HVAC}$$

Air leakage coefficient

- We have spent a lot of time trying to find ΔP
  - Now we will try to find the leakage coefficient, C, in order to establish flow, Q, across a leak

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

  - Once the flow is known:
    - Energy and indoor air quality impacts can be estimated
  - One of the best ways to do this is with fan pressurization techniques
    - i.e. **blower door** tests

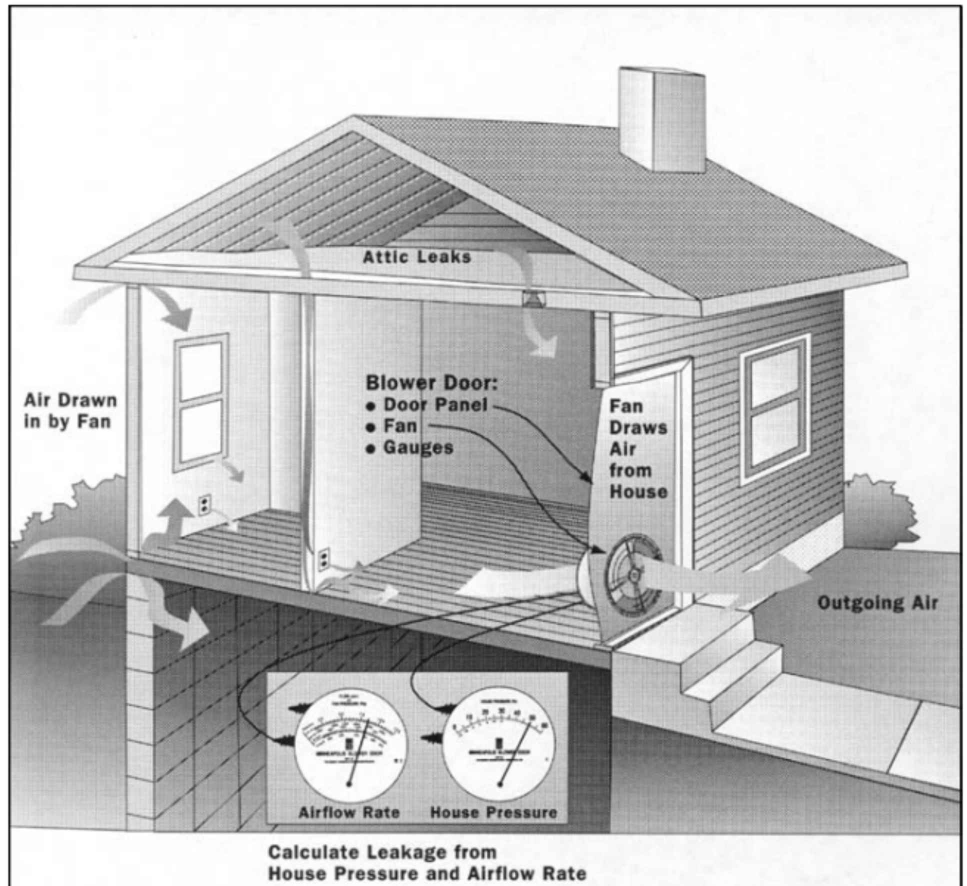
BLOWER DOOR TESTS

Procedure for a blower door test

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

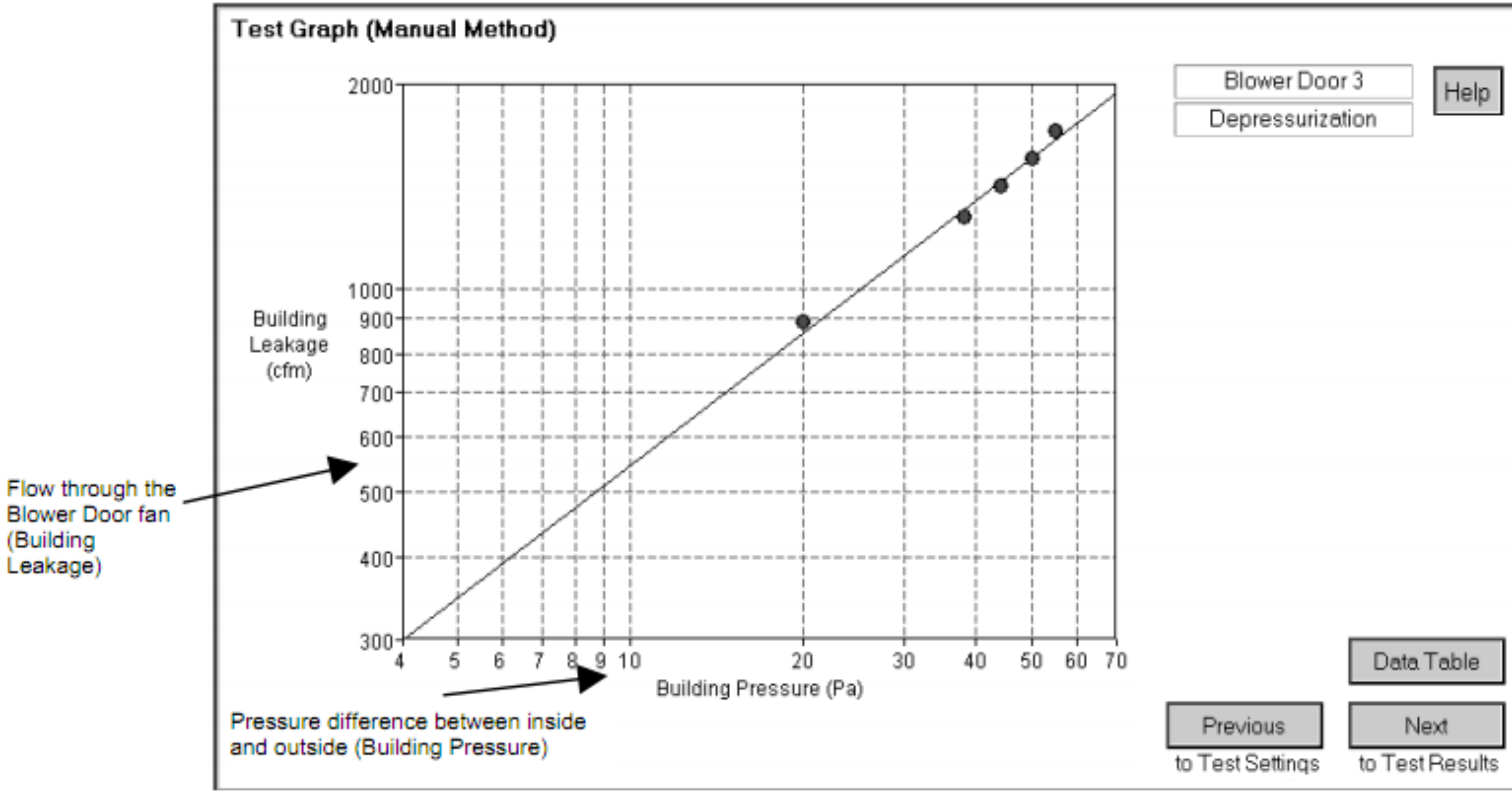
- Used to measure air-tightness in buildings worldwide



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:

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

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

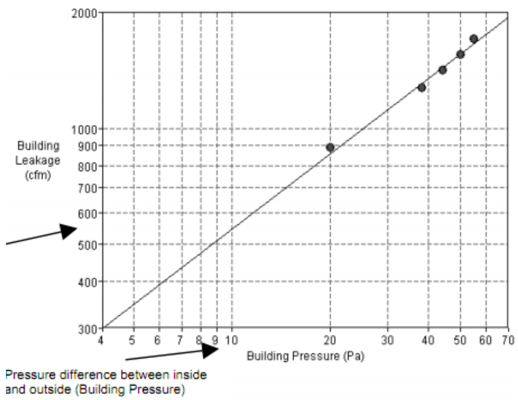
$$\ln Q = \ln C + n \ln \Delta\mathrm{P}$$

$$Y \quad = \quad b \; + \; mx$$

Slope = n

Intercept = lnC, therefore C = $e^{\text{intercept}}$

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)

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

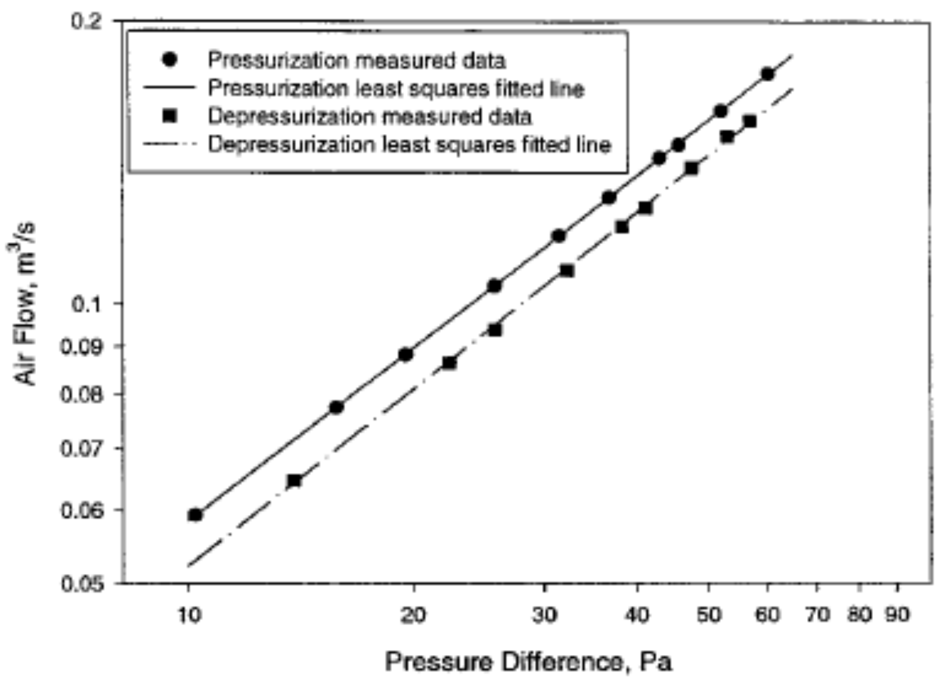
Air Changes per Hour @ 50 Pa (hr^{-1})

Source: ASTM E 779 and ASHRAE Standard 119

Blower door test standard: ASTM E 779

- In ASTM E 779, the leakage rate, Q, is measured at several pressures from ~10 Pa to ~60 Pa in increments of 5-10 Pa
  - Test is performed once during pressurization mode
    - Air blowing into the building
  - Then performed again in depressurization mode
    - Air blowing out of the building
  - Can do these during and after construction to verify design

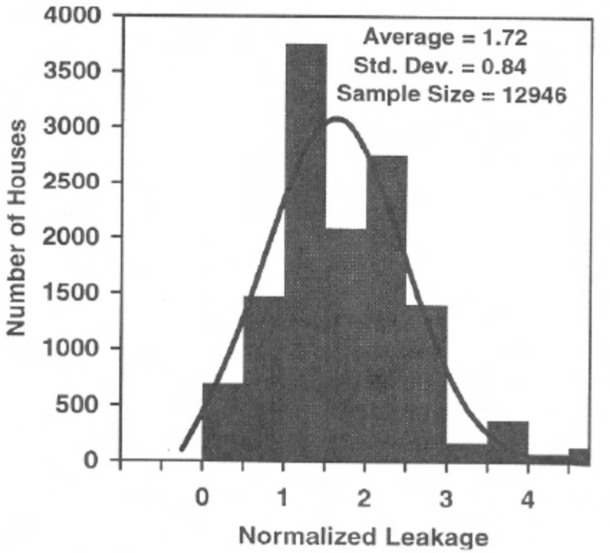
Question:
Why would pressurization and depressurization tests yield different results in a single building?

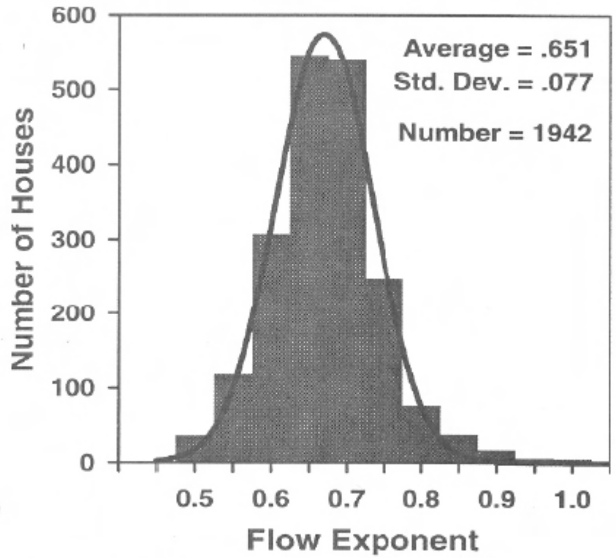


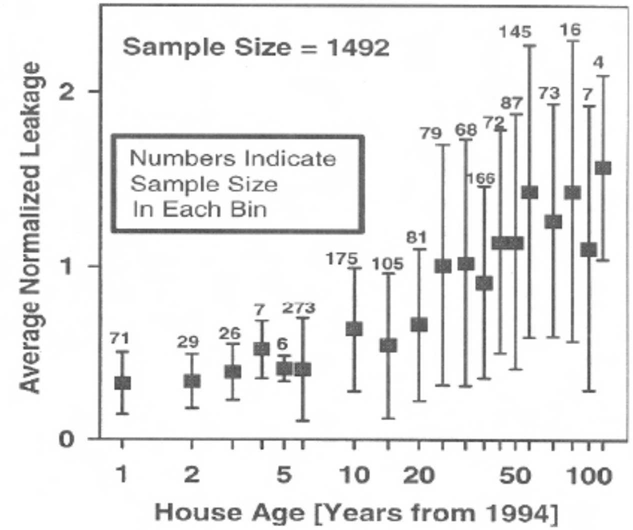
BLOWER DOOR DEMONSTRATION

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

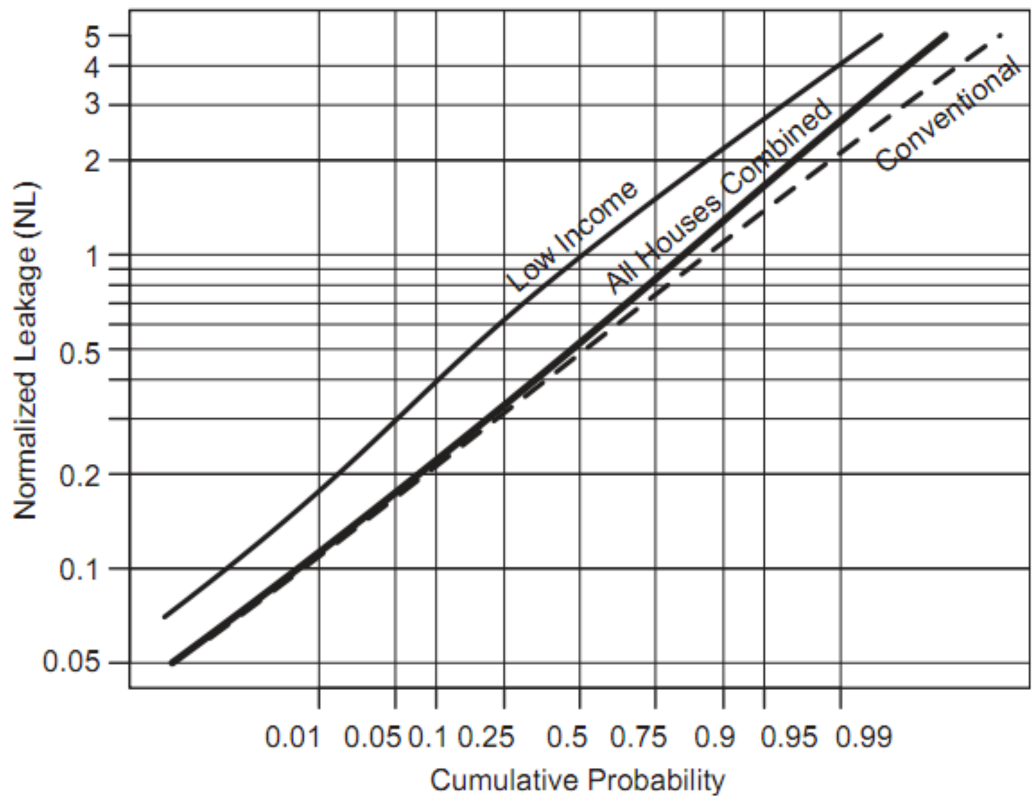
- LBNL continues to maintain a database of blower door data
  - http://resdb.lbl.gov/
  - Almost 150,000 homes characterized

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

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

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

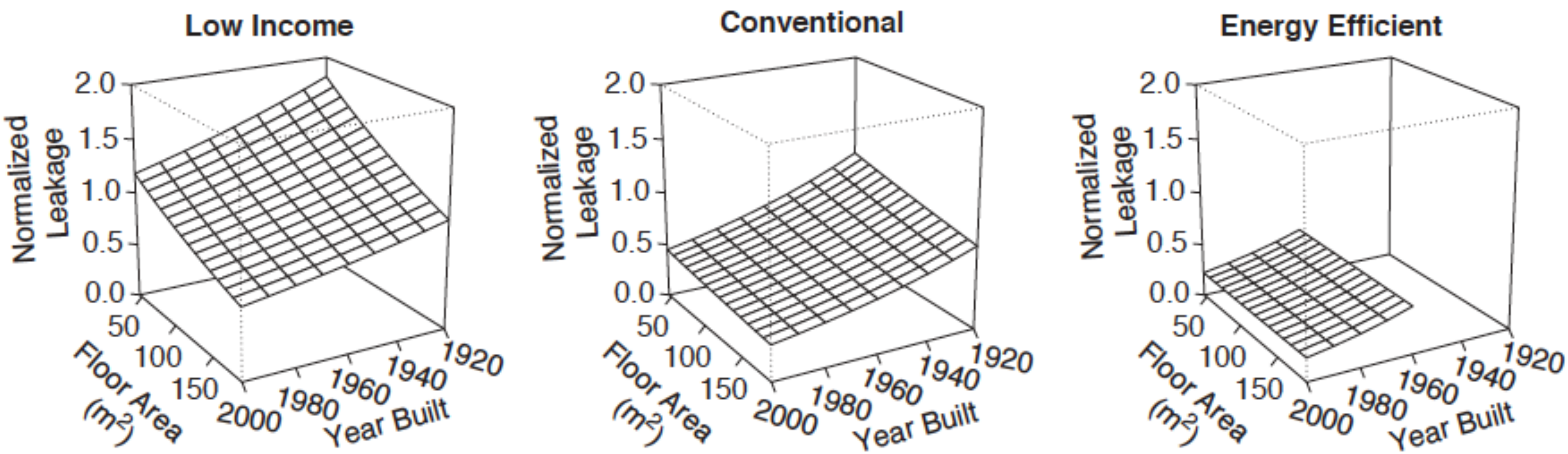
$$ACH_{50} = \frac{Q_{50\ Pa}}{V}$$



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

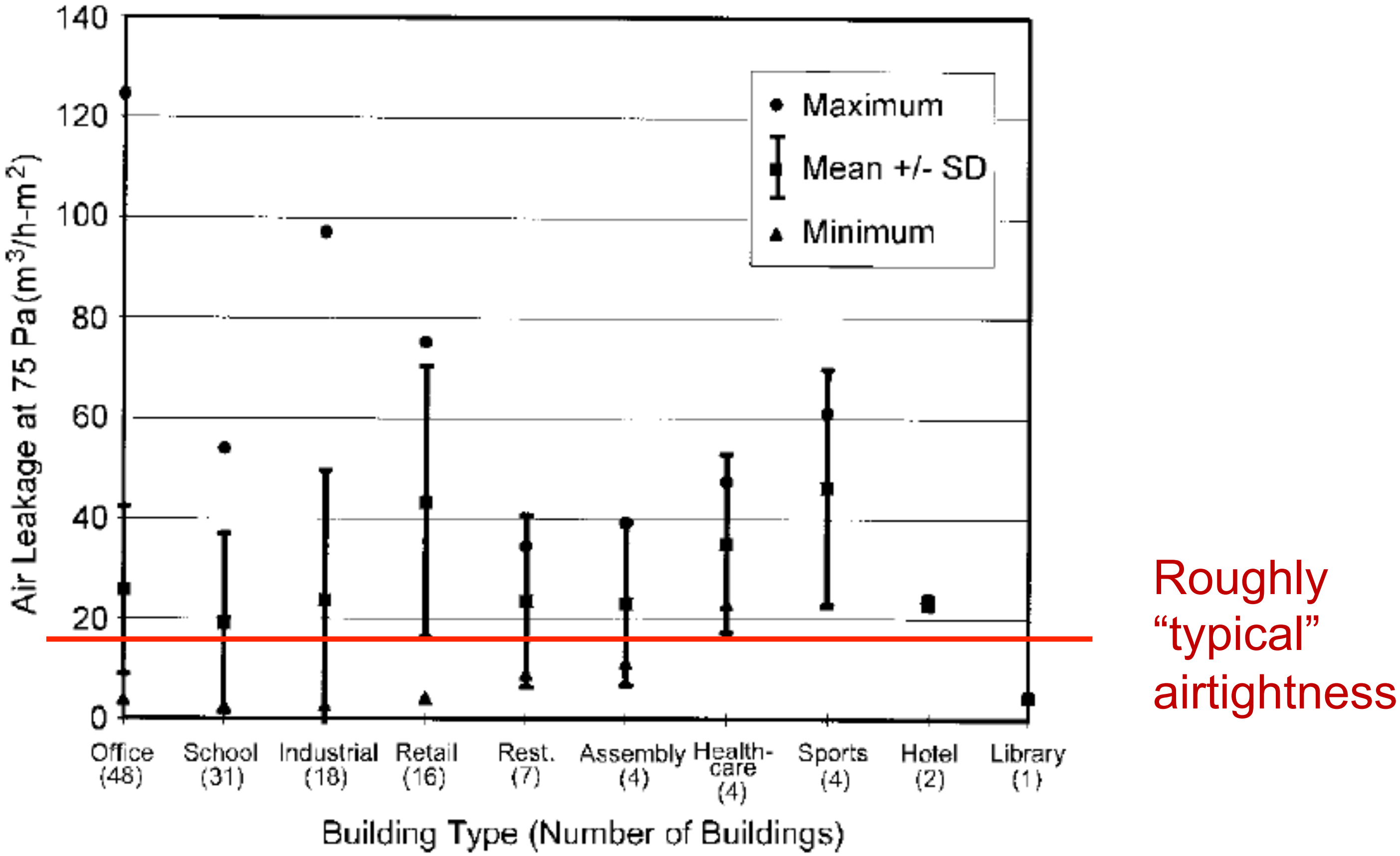


$$NL = 1000\frac{ELA}{Af}\left(\frac{H}{2.5m}\right)^{0.3}$$

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

Commercial building air leakage

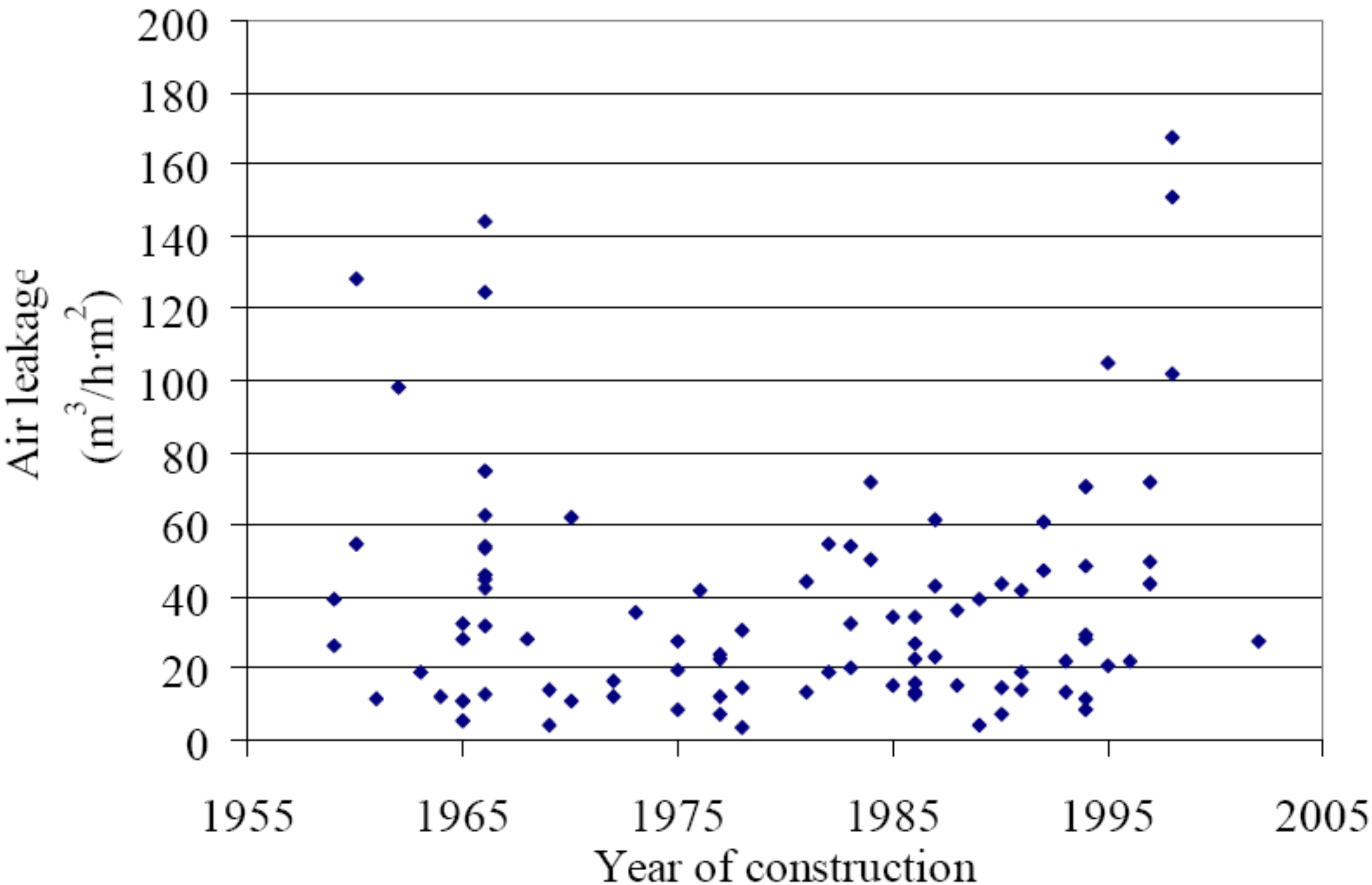
- Traditionally assumed that commercial and institutional buildings were built to be airtight
  - Turns out that's not always the case



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

Commercial building air leakage vs. age

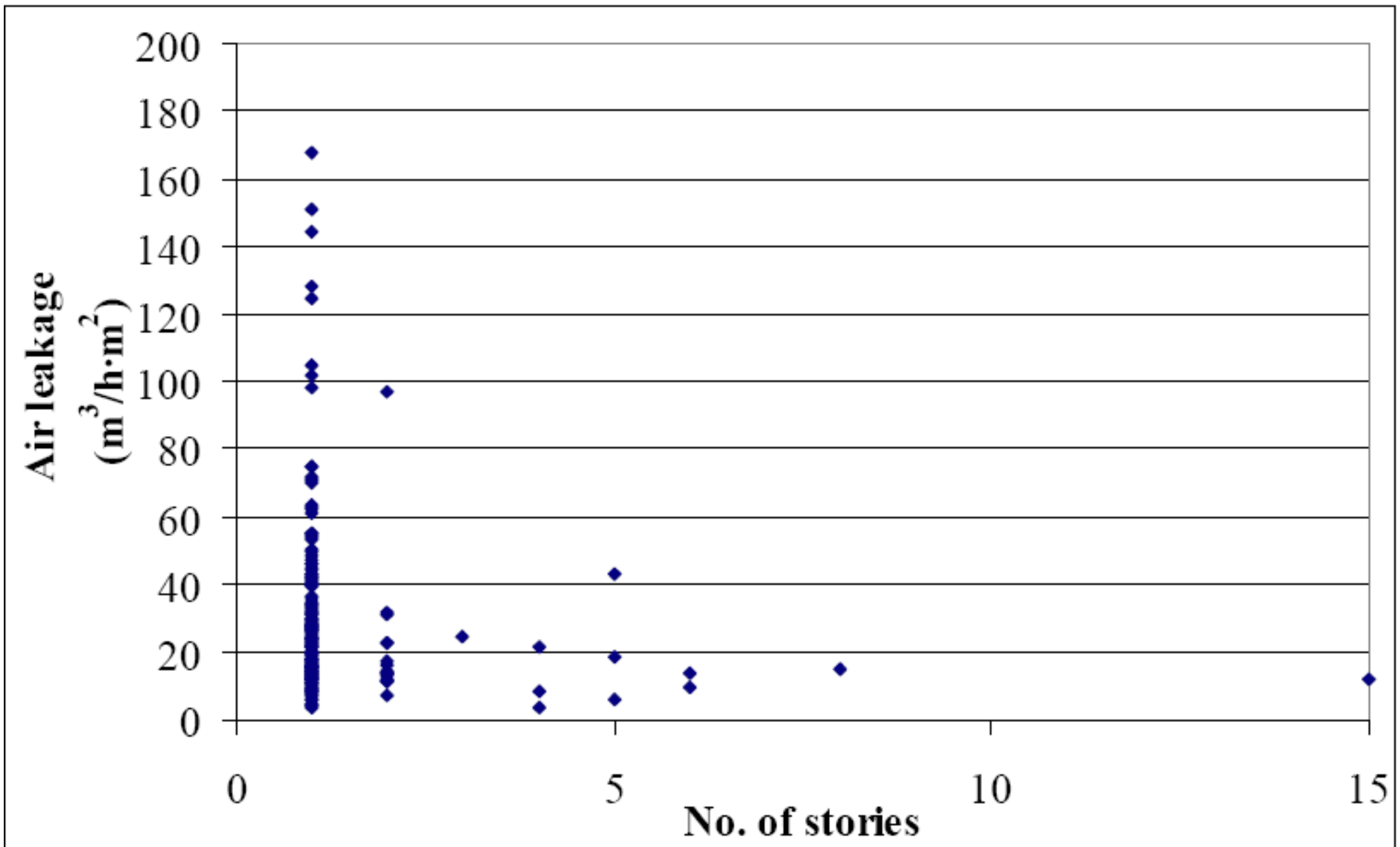
- Less correlation with age than other factors
  - Note small range of age



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

Commercial building air leakage vs. height

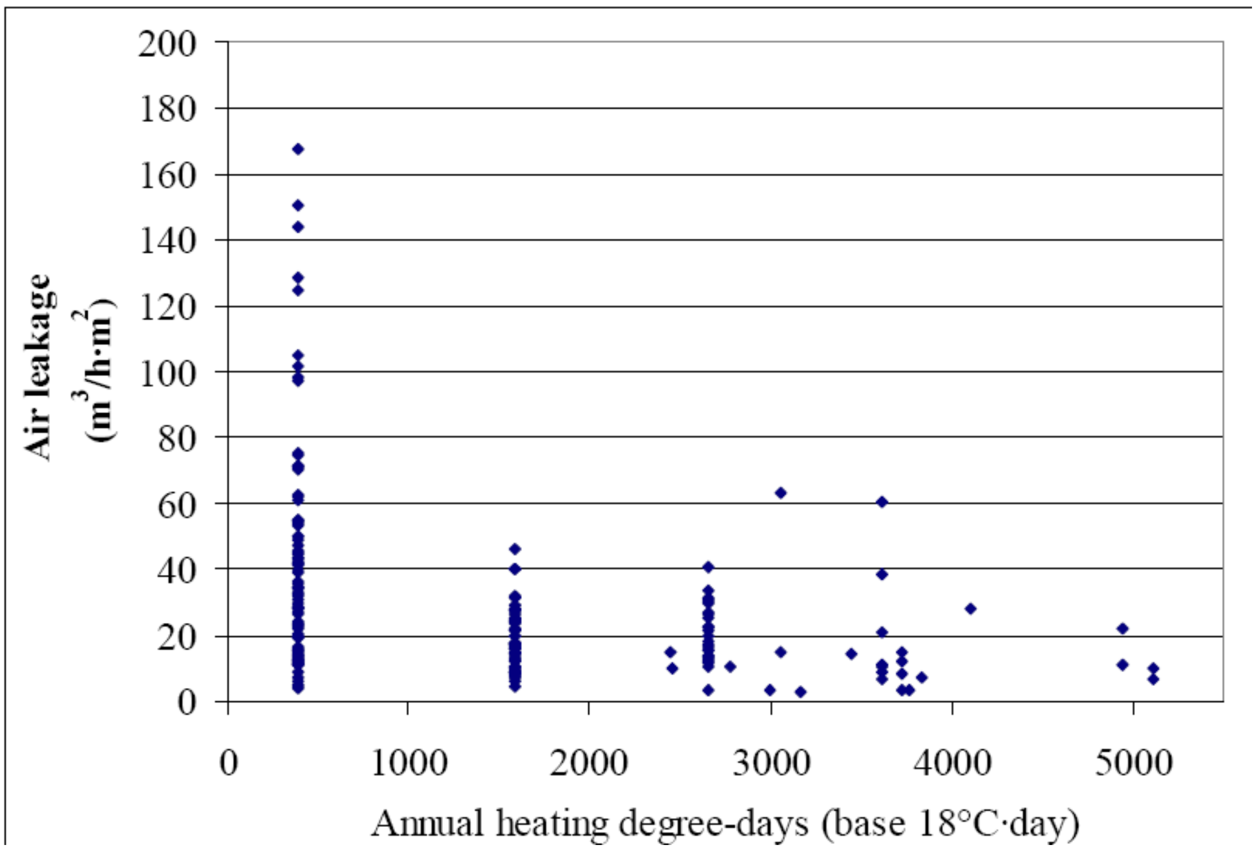
- Taller buildings were tighter
  - Stronger construction standards?



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

Commercial building air leakage vs. climate zone

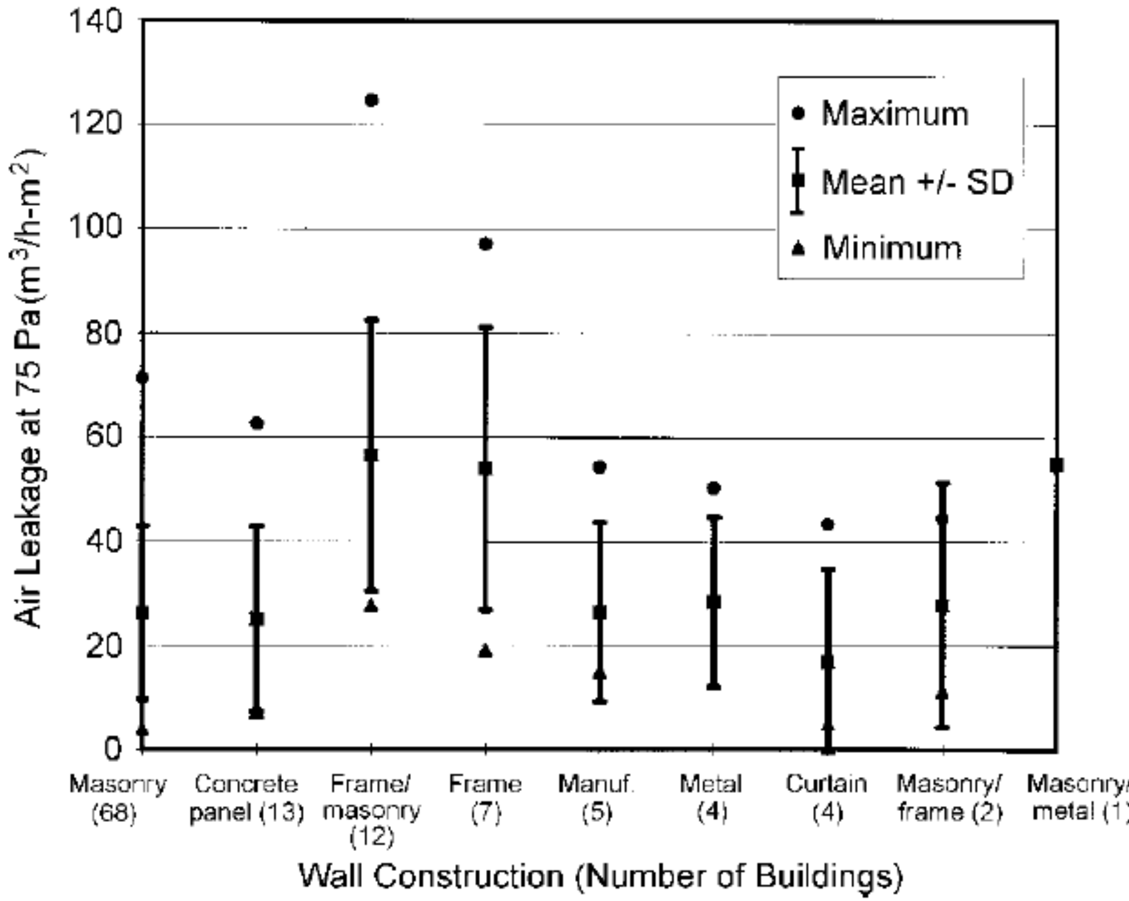
- Buildings were tighter in <u>colder</u> climates
  - Necessity?
  - Stricter building codes?



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”

Residential component leakage

Component	Range	Average
Walls	18-50%	35%
Ceilings	3-30%	13%
Windows/Doors	6-22%	15%
Fireplaces	0-30%	12%
HVAC	3-28%	18%
Other Vents	2-12%	5%

- Surprisingly little information on this topic

ASHRAE HOF 2005

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

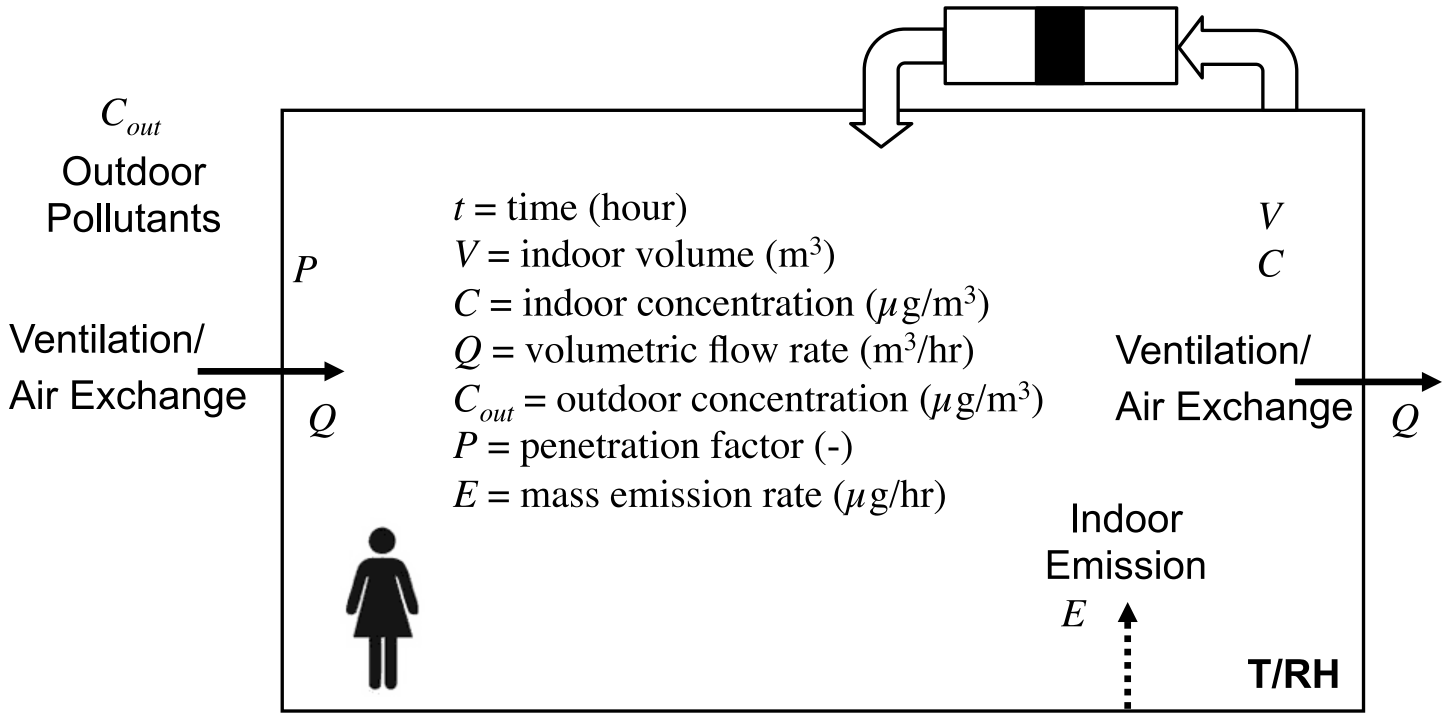
- Two general strategies to get air exchange rate
  - AER, ACH, and λ all used interchangeable for AER

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

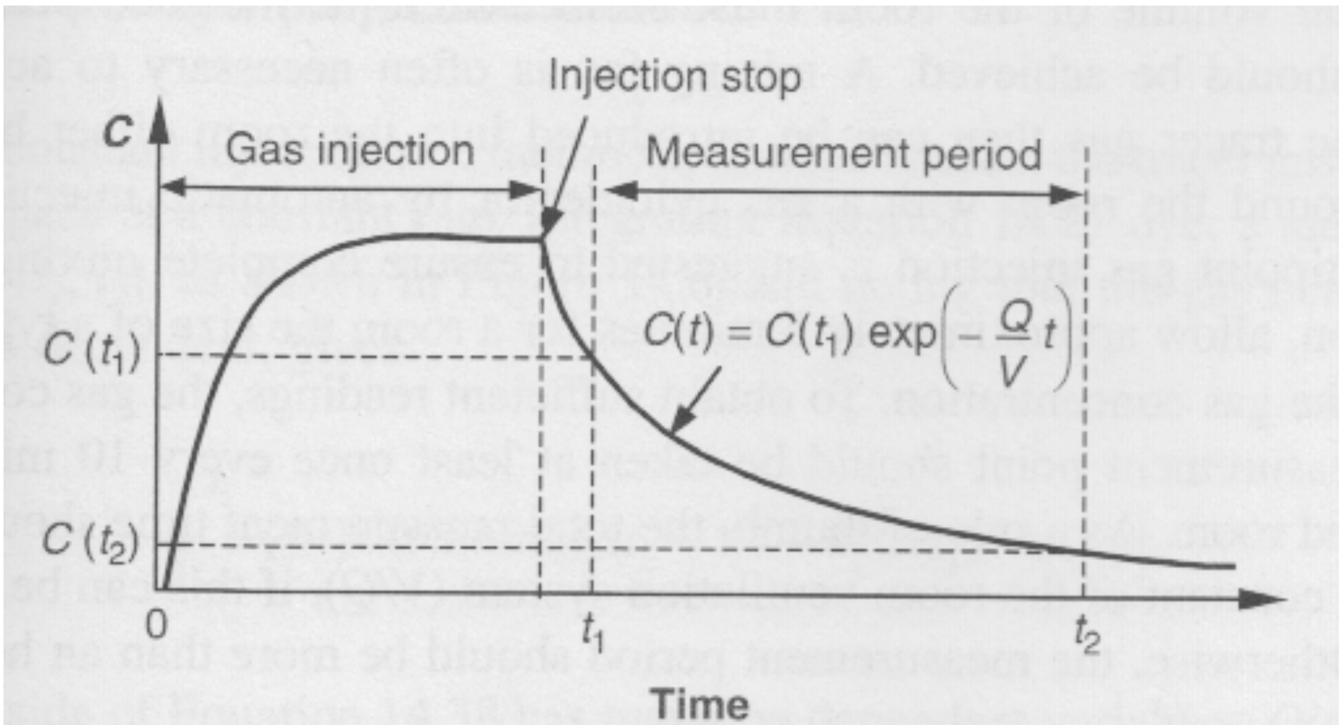


$$\boxed{C_{ss} = PC_{out} + \frac{E}{\lambda V}}$$

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

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)

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

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

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

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

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

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:

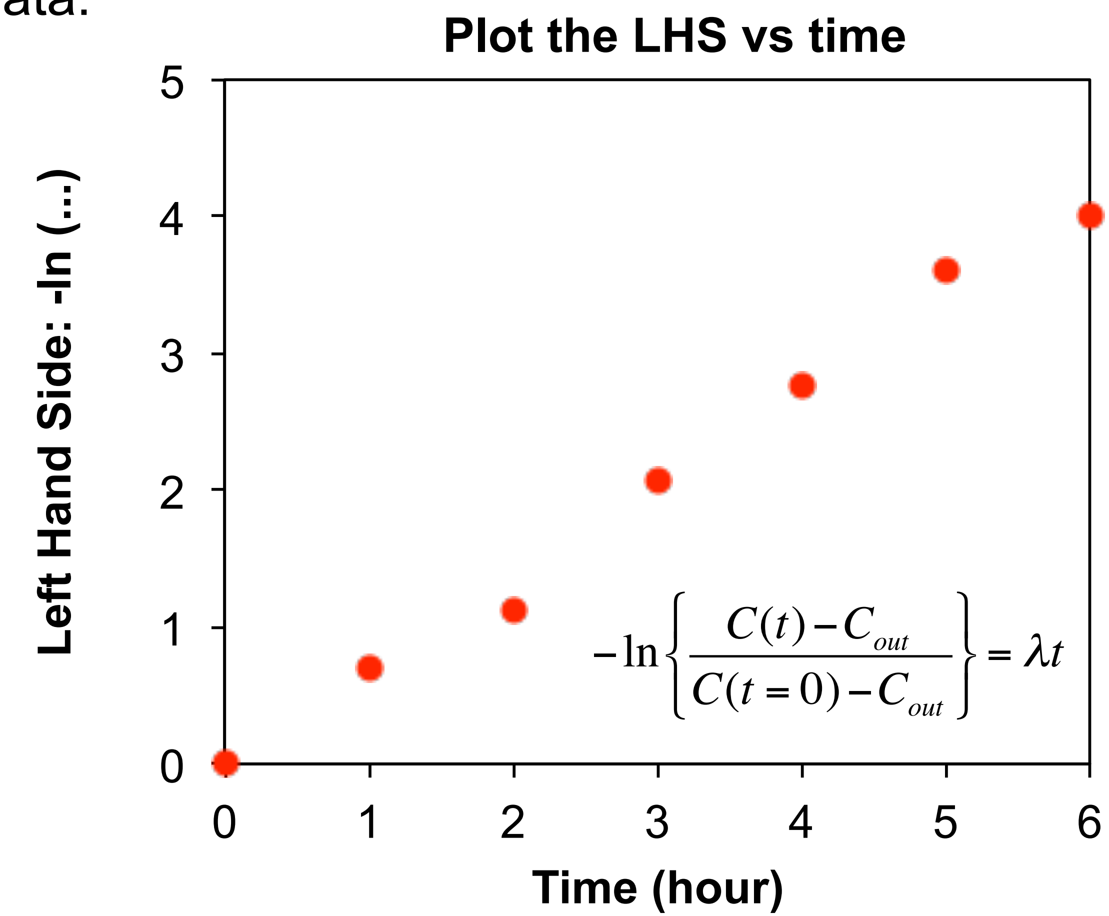
$$-\ln \left\{ \frac{C(t) - C_{out}}{C(t=0) - C_{out}} \right\} = \lambda t$$

- 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



How do we measure λ?

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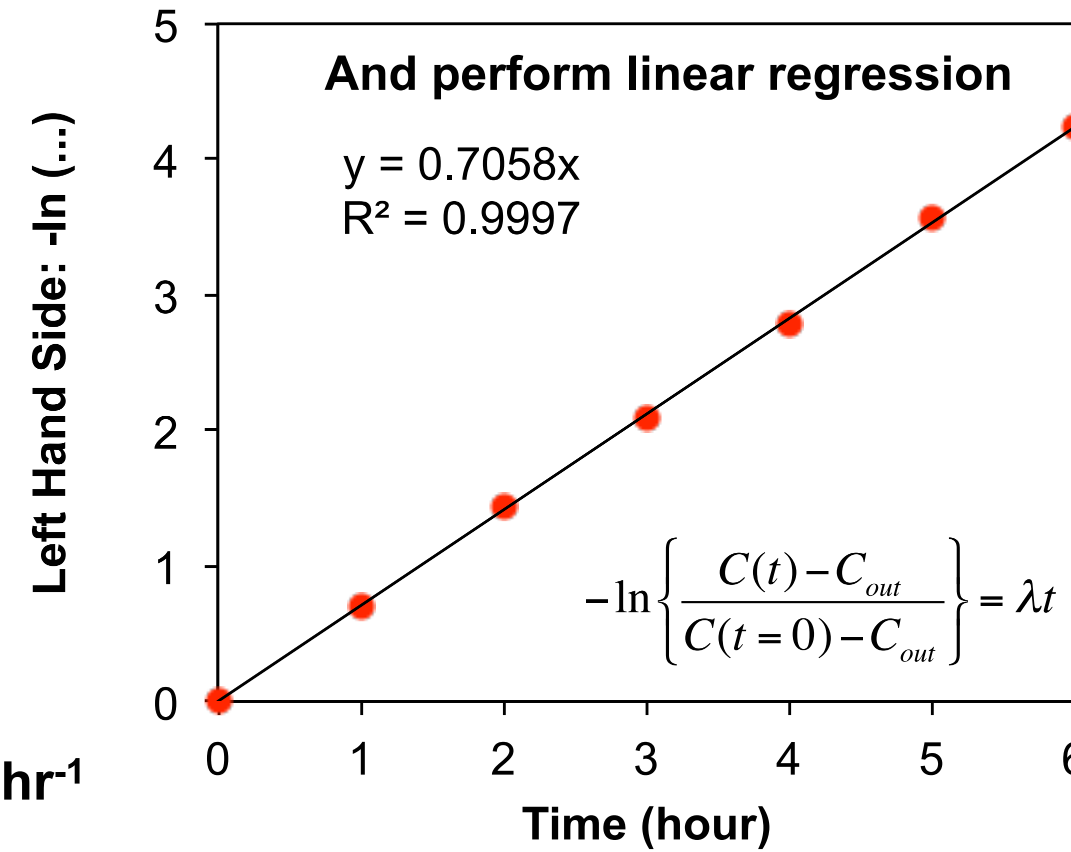
  - You record these data:

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

Plot the LHS vs time



AER = λ = slope = 0.71 hr^{-1}

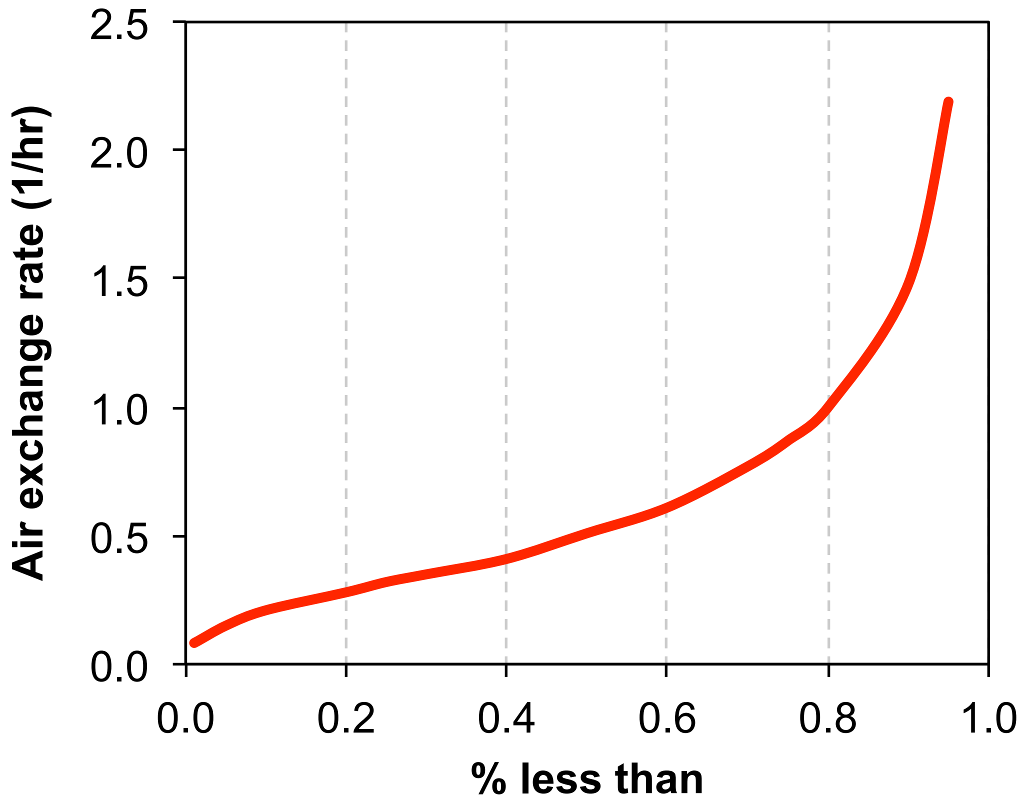
Decay test for AER

- 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

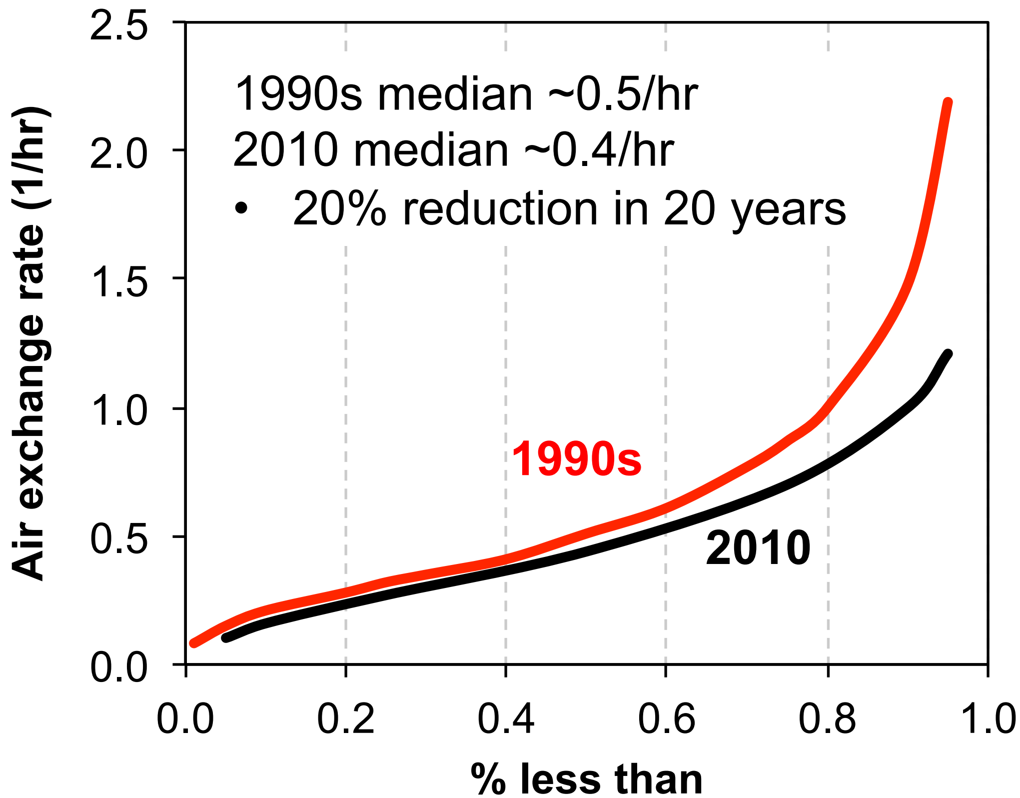


- What do you think this curve looks like now?

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)

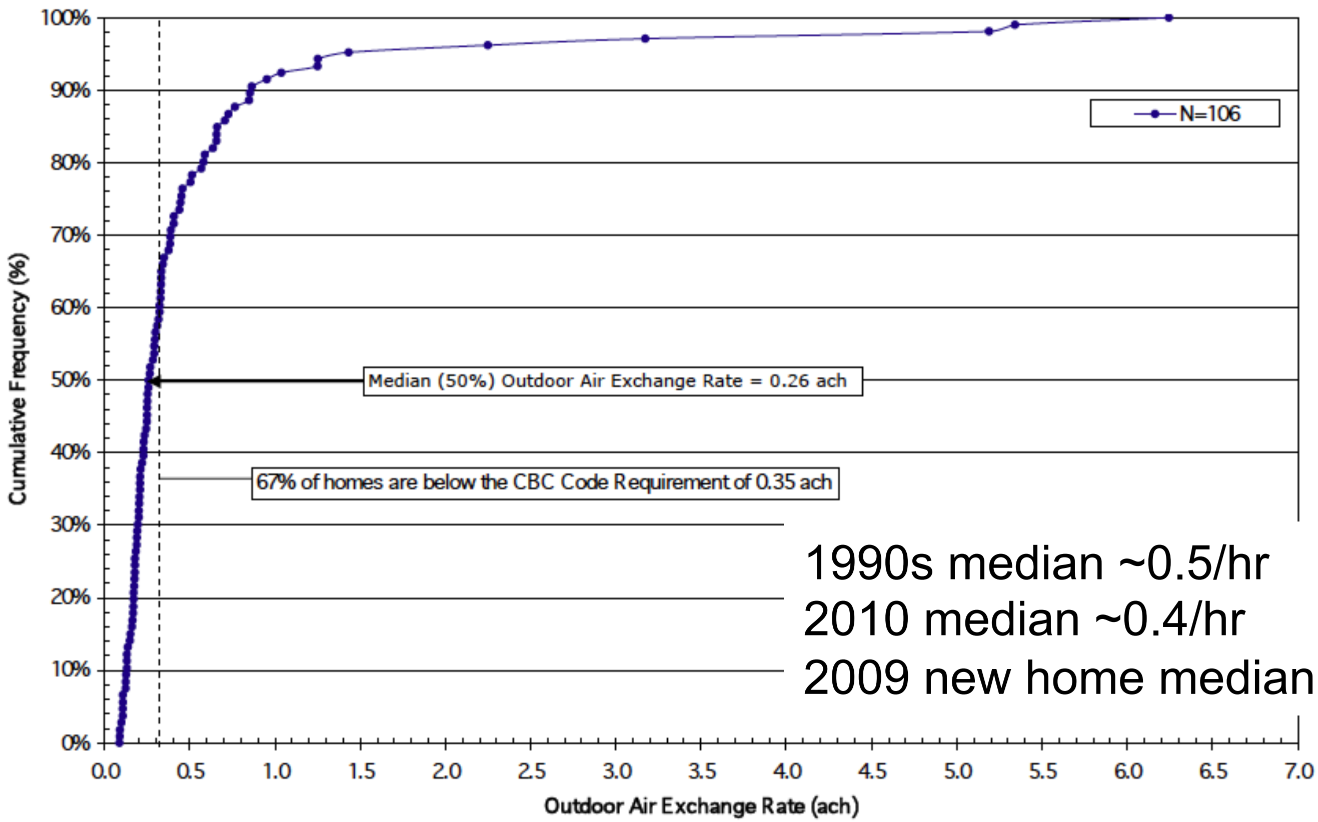


- What about new homes?

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)



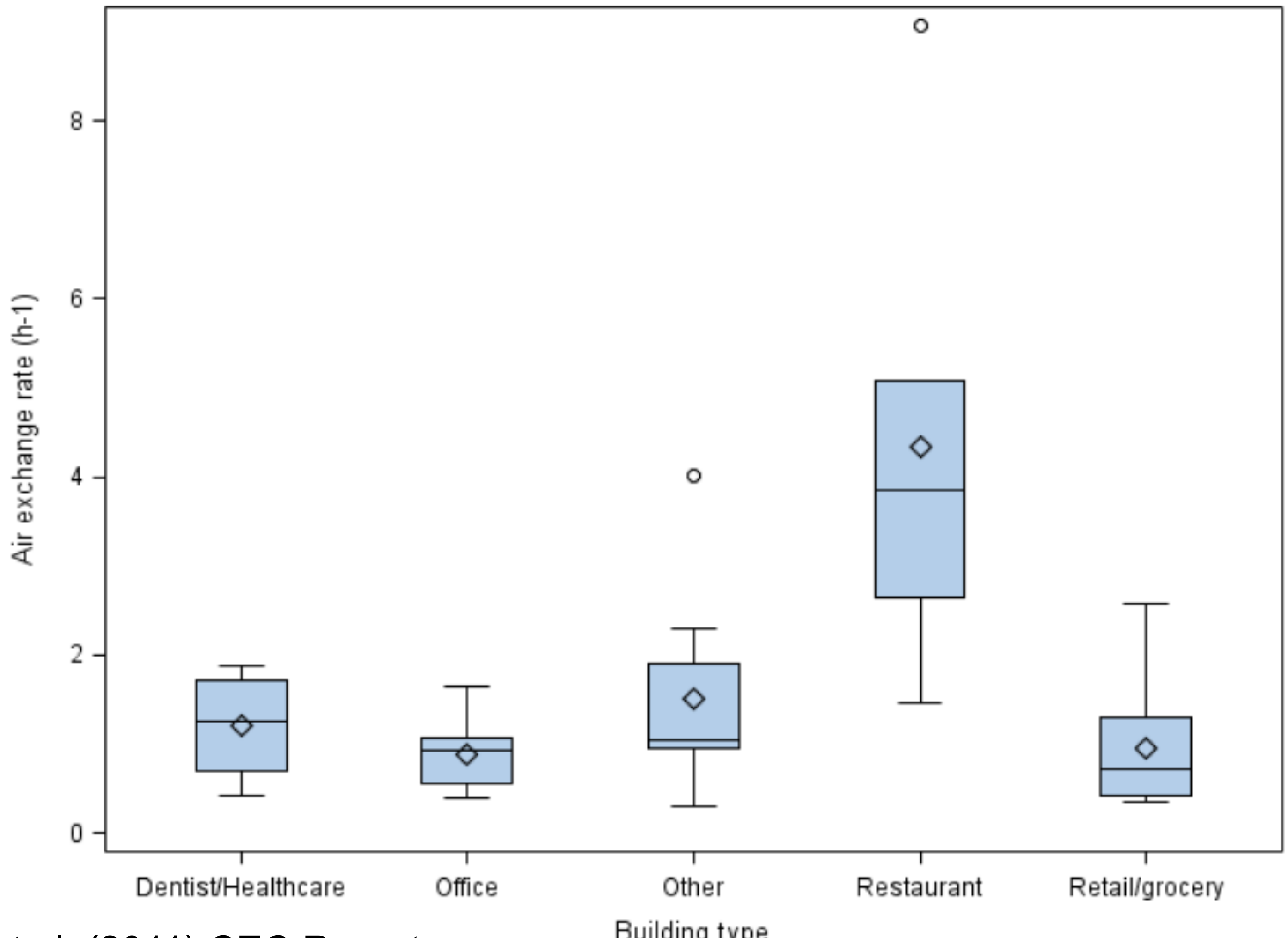
1990s median ~0.5/hr
2010 median ~0.4/hr
2009 new home median ~0.26/hr

- 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

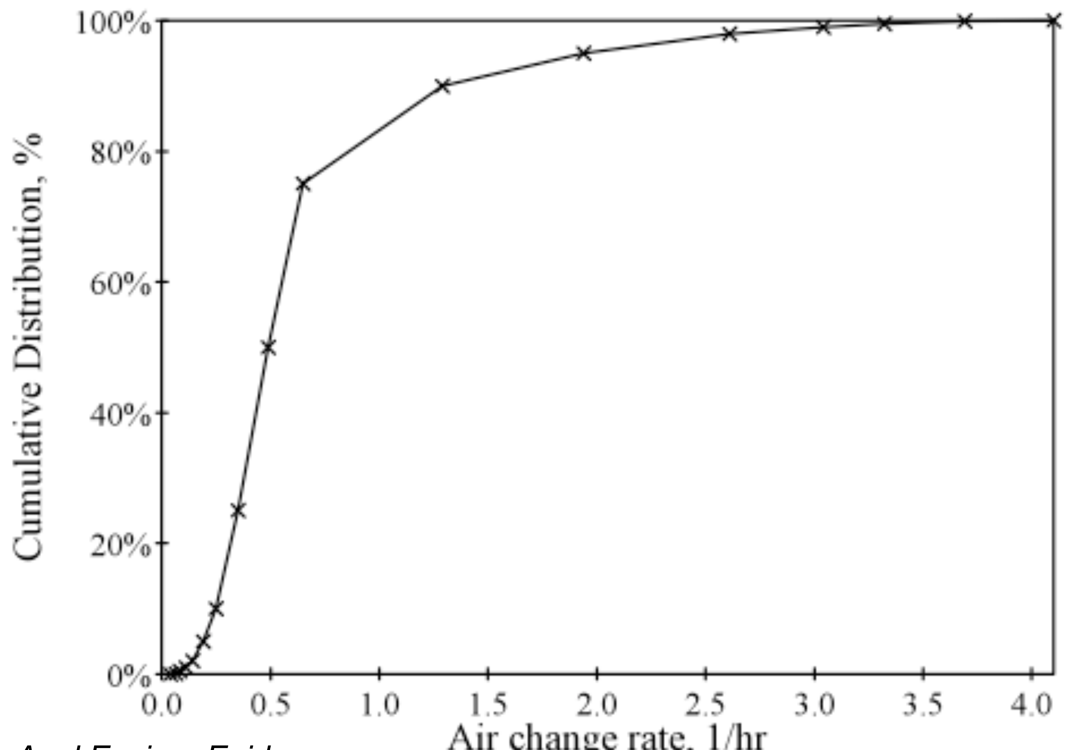
- Recent study of ~40 commercial buildings in CA



Bennett et al. (2011) CEC Report

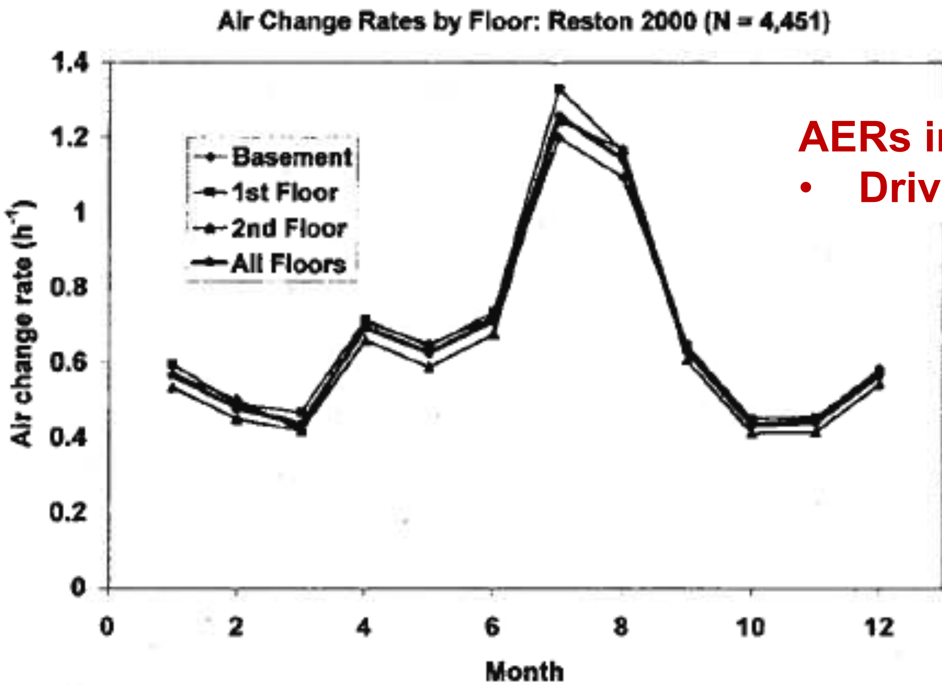
Variations in AER in individual buildings

- 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



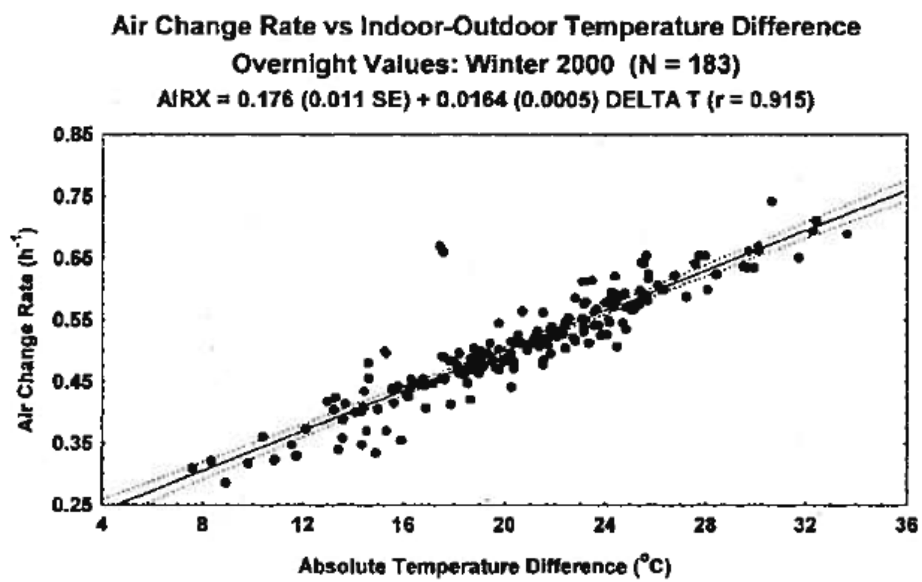
Wallace et al. 2002 *J Expo Anal Environ Epidem*

Variation in AER in individual buildings



AERs in individual buildings can vary by season

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



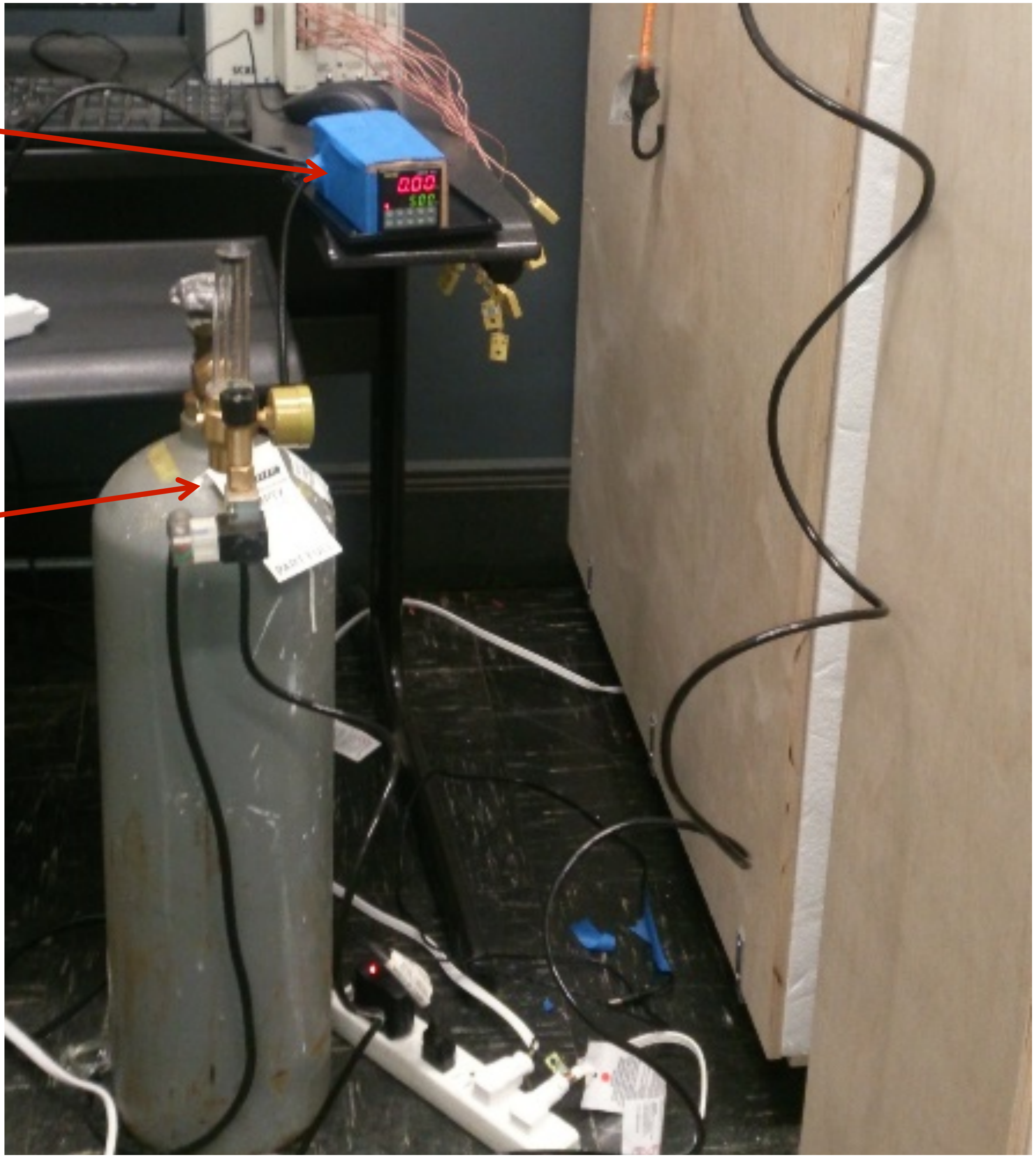
AERs can vary by I/O temperature within seasons

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

Variation in AER in individual buildings

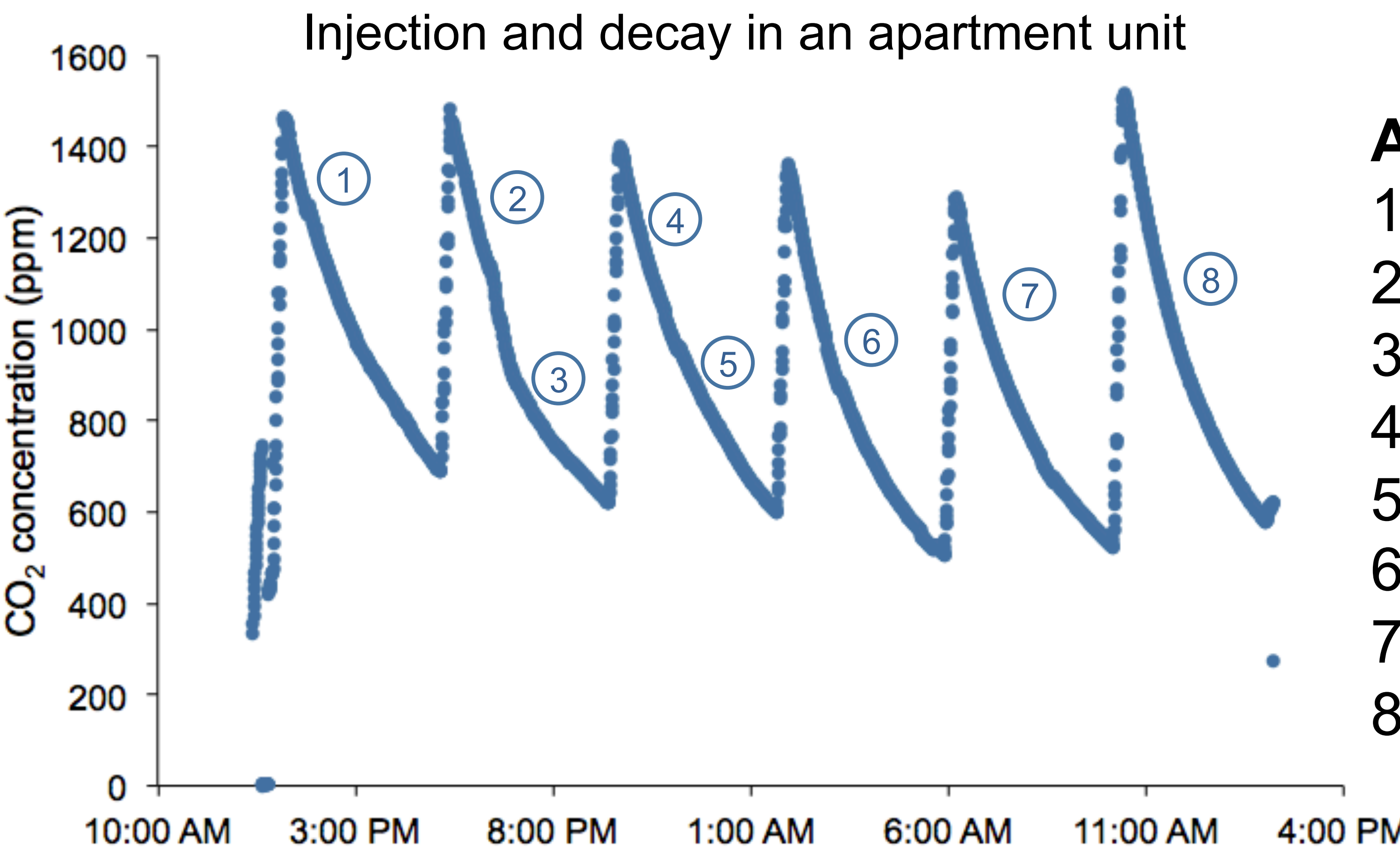
Sestos timer

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: $\mathrm{ACH} \approx \frac{\mathrm{ACH}_{50}}{F}$
    - 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

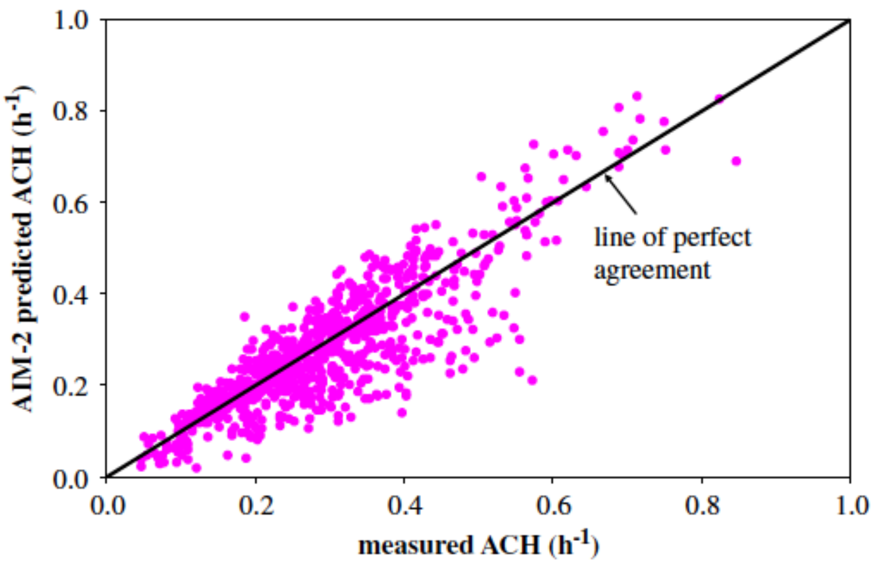
- Alberta air infiltration model (AIM-2)

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

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

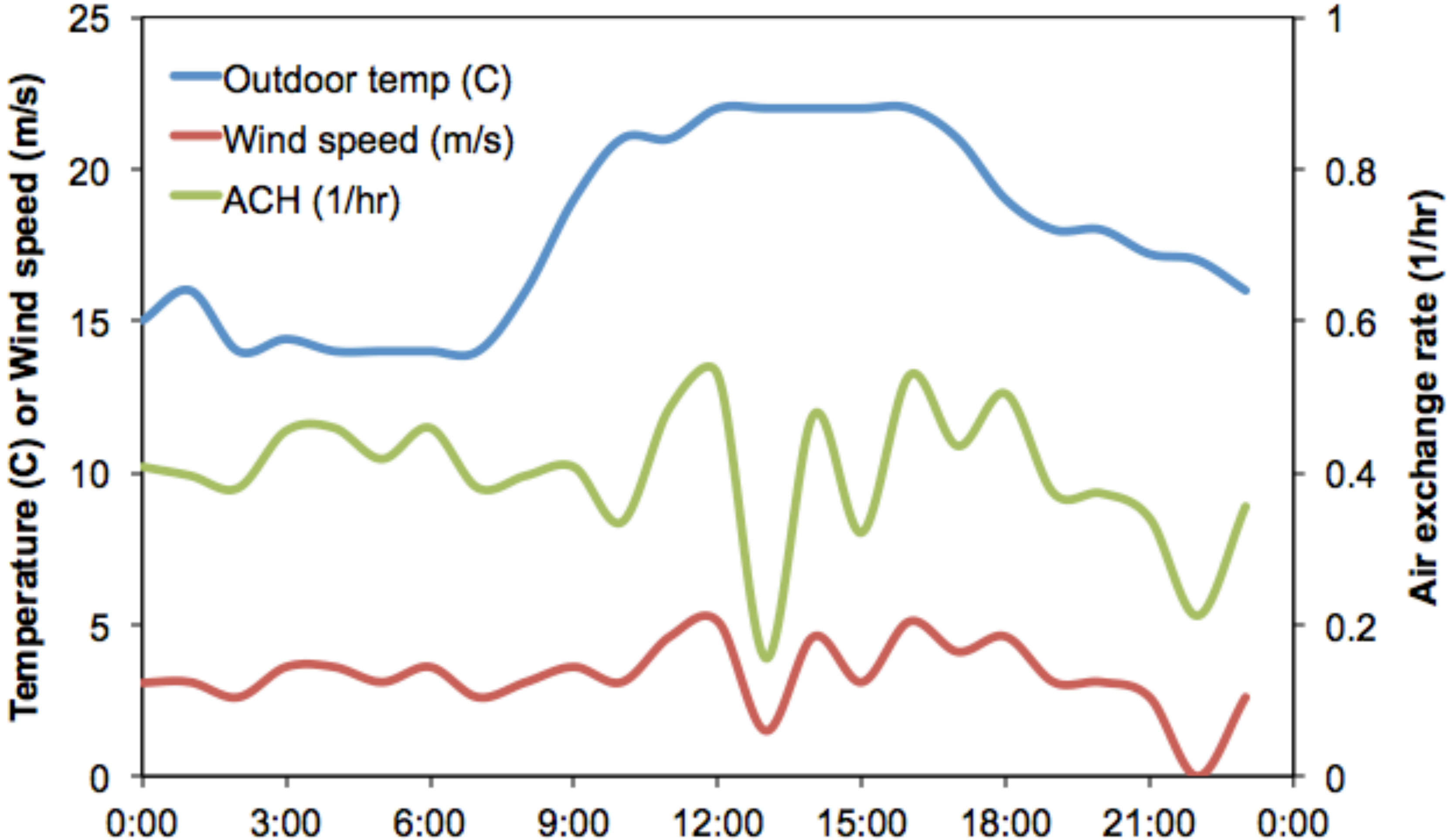
Table S3. Local sheltering

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

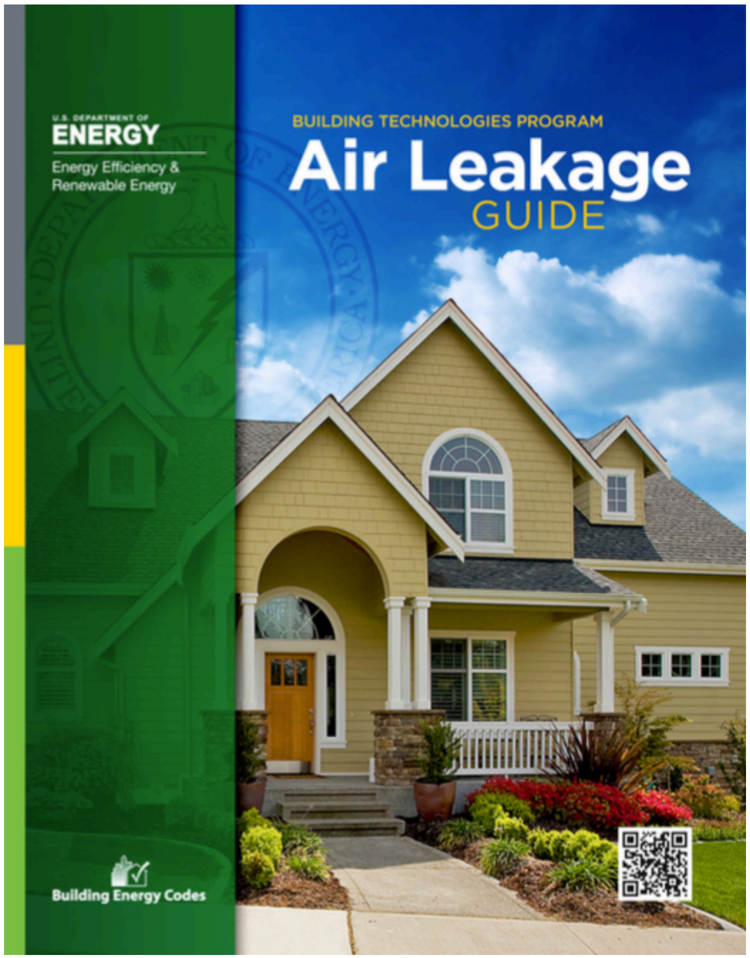


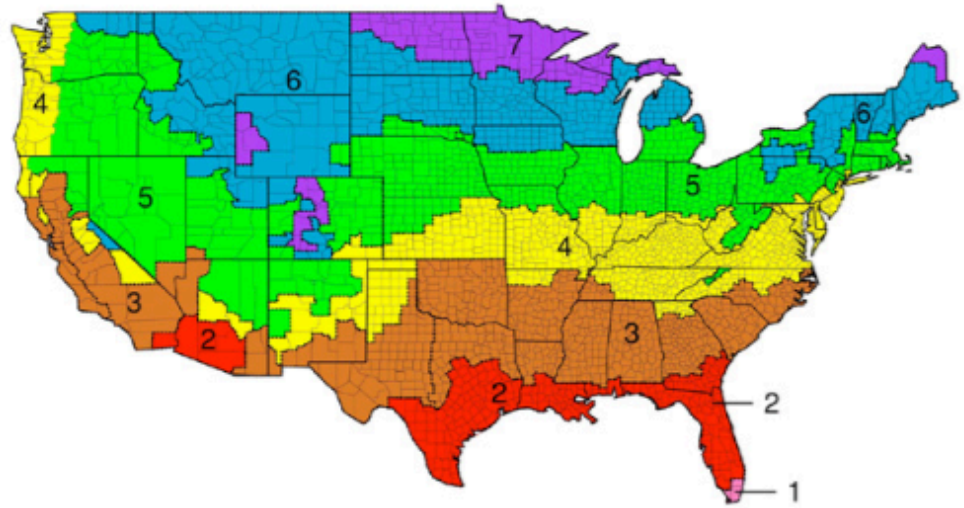
$$Q_{\text{inf}} = A_{\text{inf}}\sqrt{k_s|T_{\text{in}} - T_{\text{out}}| + k_w U^2}$$

CONTROLLING LEAKAGE

in enclosure design and construction

Some recommended whole-envelope leakage values





All of Alaska in Zone 7
except for the following buroughs in Zone 8:

- Bethel
- Dellingham
- Fairbanks N.Star
- Nome
- North Slope
- Northwest Arctic
- Southeast Fairbanks
- Wade Hampton
- Yukon-Koyukuk

Zone 1 includes:

- Hawaii
- Guam
- Puerto Rico
- Virgin Islands

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

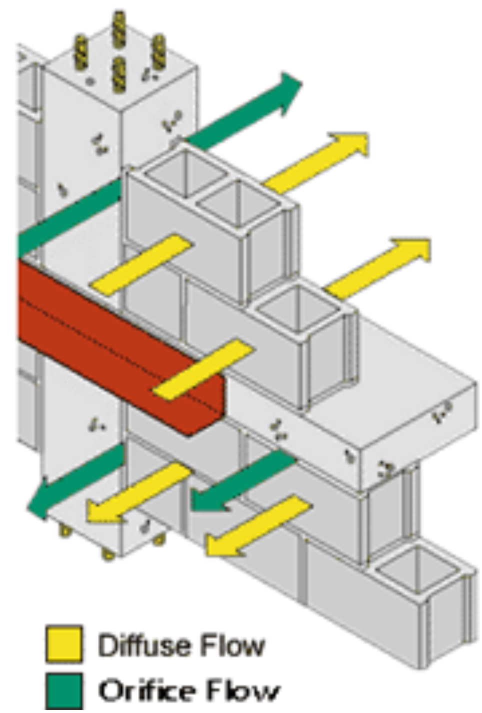
Table 1: 2009 vs. 2012 IECC Comparisons

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



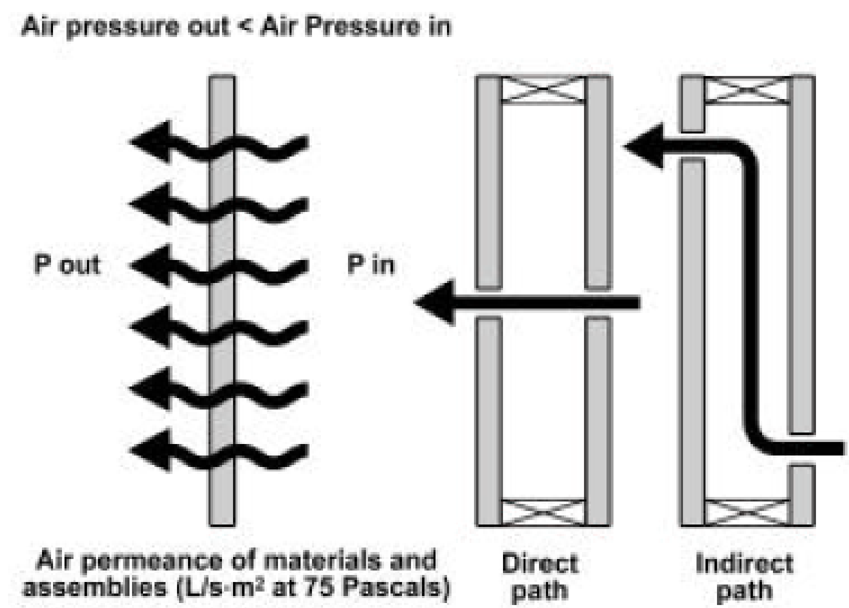
A tale of three barriers …

- 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 $L/(s \cdot m^2)$
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 $L/(s \cdot m^2)$
Gypsum (1/2”)	0.020
Particle Board (5/8”)	0.026
Expanded Poly	0.19
Roofing Felt (30lb)	0.19
Asphalt Felt (15lb)	0.40
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).

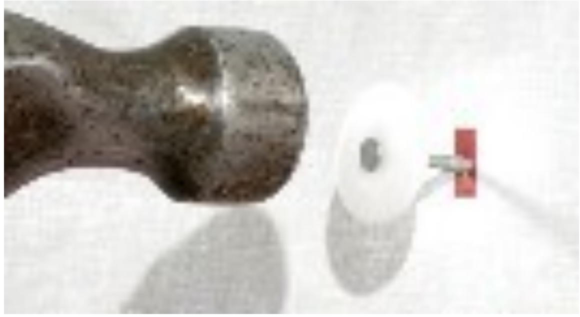
*Units similar to water vapor permeability

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

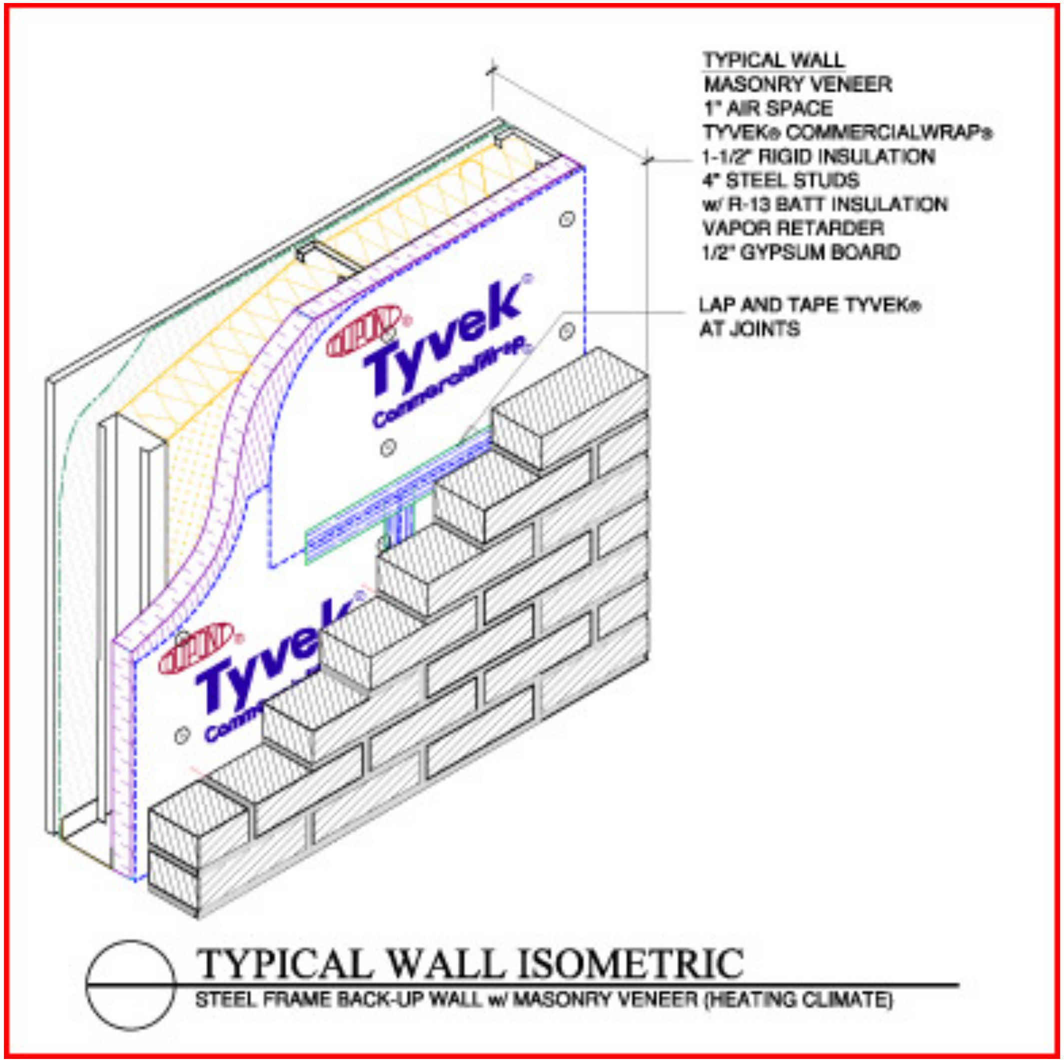


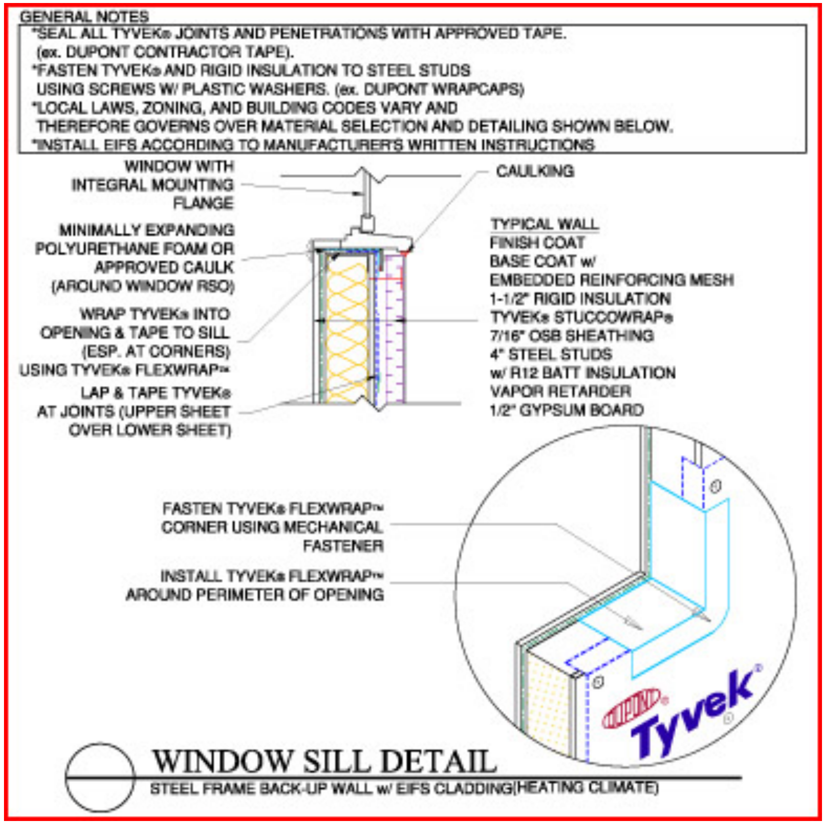
Building wraps: exterior air barrier

Building wraps: exterior air barrier

Photograph 2 – Exterior Air Barrier Using Adhered Membrane

Building wraps: detail drawings

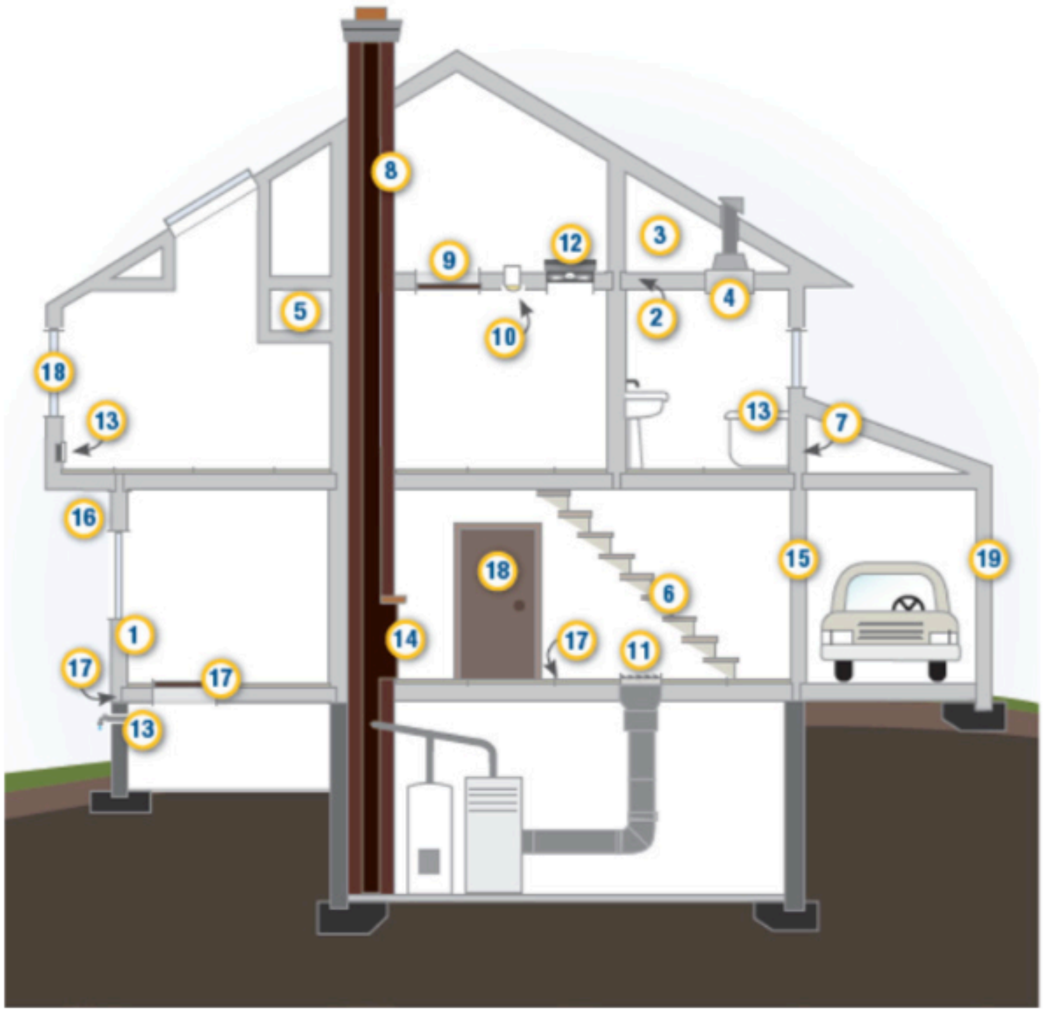




Air barriers also require sealants

- 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



Air Sealing Trouble Spots

1. Air Barrier and Thermal Barrier Alignment
2. Attic Air Sealing
3. Attic Kneewalls
4. Shaft for Piping or Ducts
5. Dropped Ceiling/Soffit
6. Staircase Framing at Exterior Wall
7. Porch Roof
8. Flue or Chimney Shaft
9. Attic Access
10. Recessed Lighting
11. Ducts
12. Whole-House Fan
13. Exterior Wall Penetrations
14. Fireplace Wall
15. Garage/Living Space Walls
16. Cantilevered Floor
17. Rim Joists, Sill Plate, Foundation, Floor
18. Windows & Doors
19. Common Walls Between Attached Dwelling Units

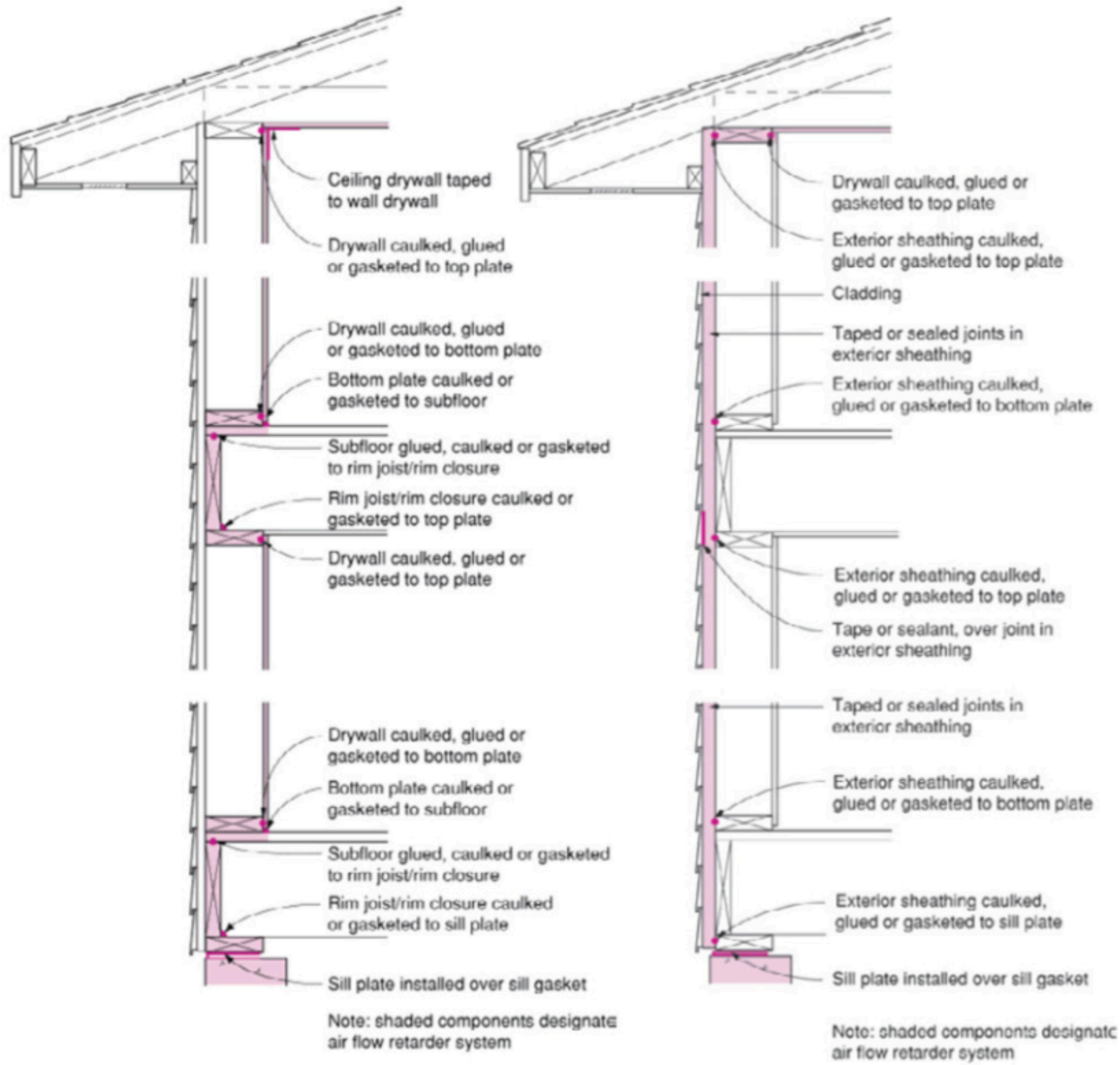
Figure 4: Building America—air sealing trouble spots

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

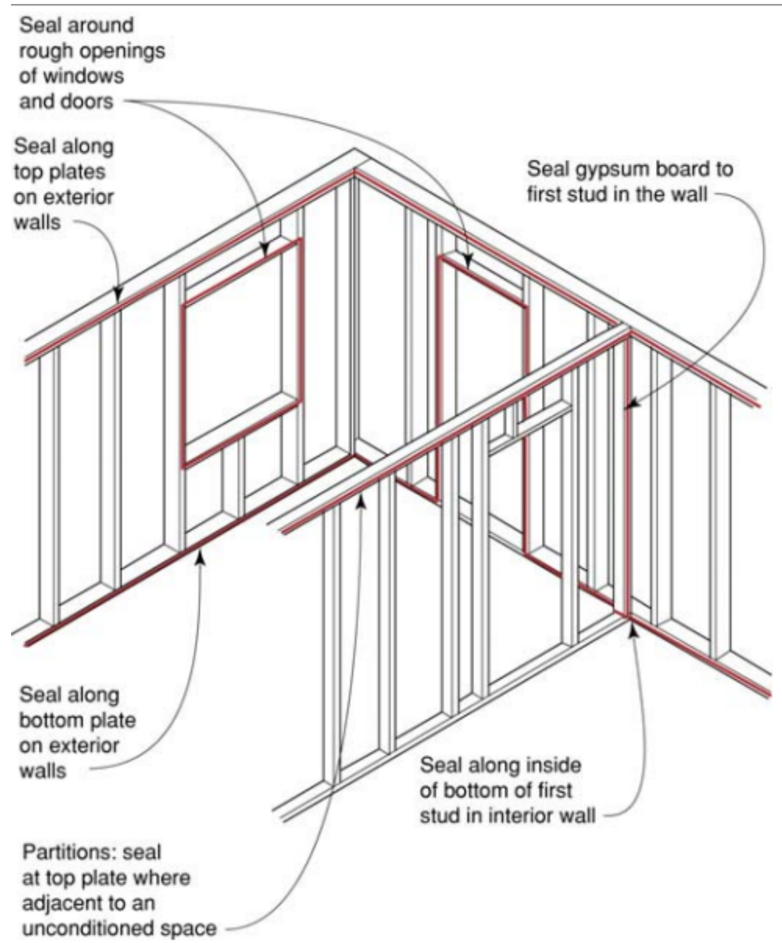


Source: Building Science Corporation

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

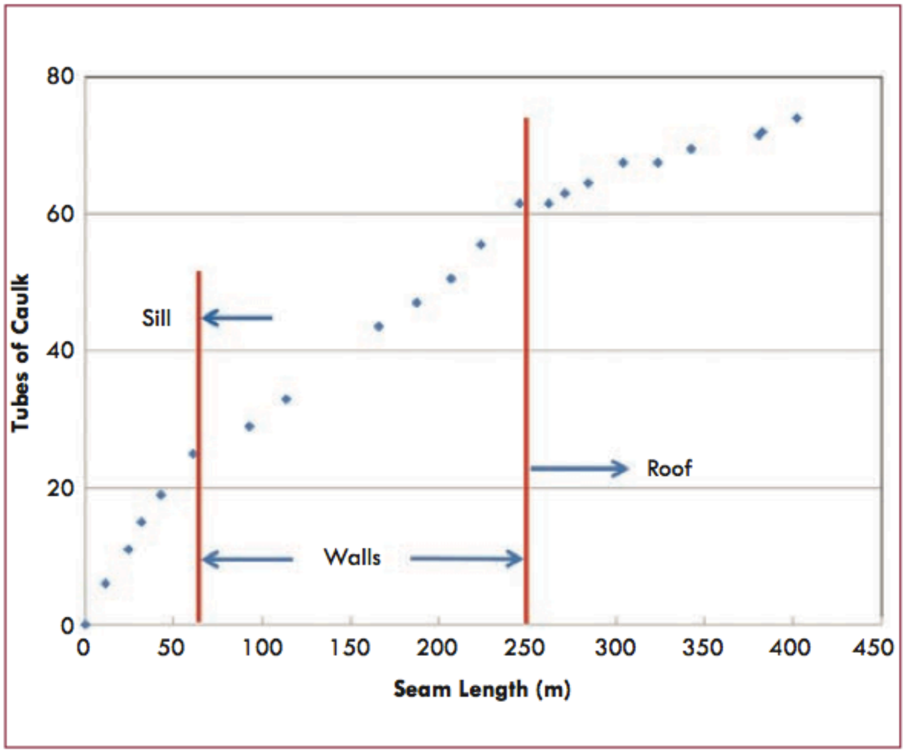
“Supersealing a house” during new construction

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

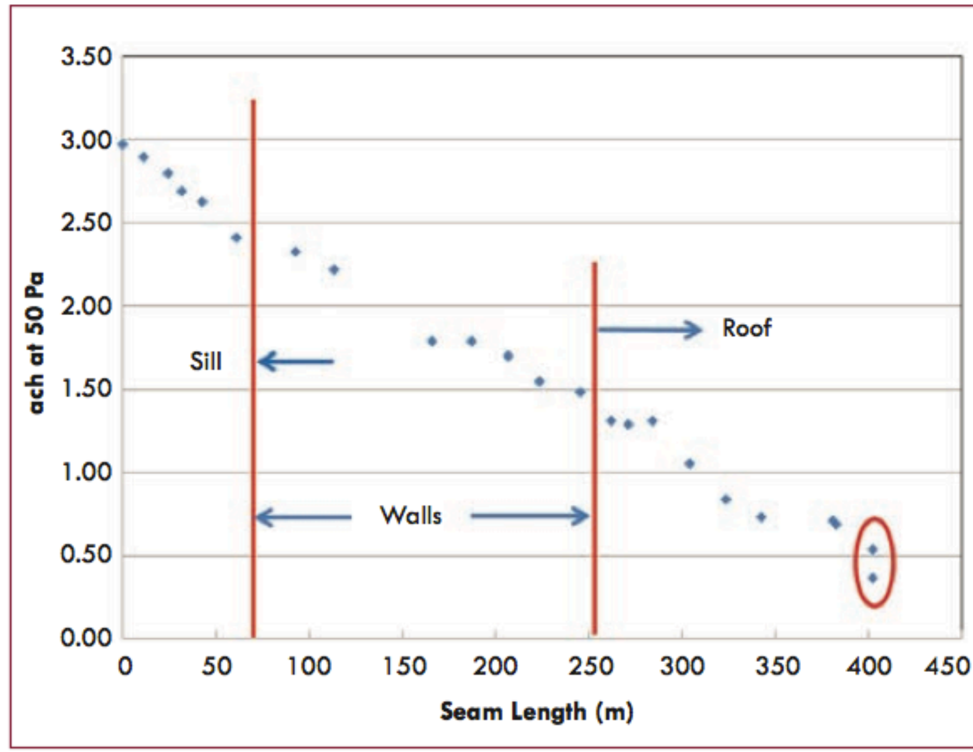
Newell and Newell (2011) *ASHRAE Journal*

“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

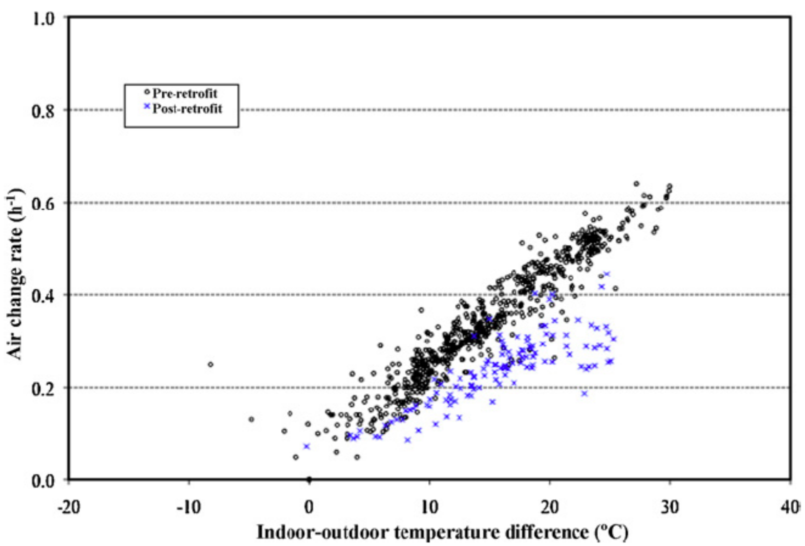


Fig. 6. Pre- and post-retrofit measured air change rates as a function of temperature difference (low wind speed): forced-air fan off (Condition 0).

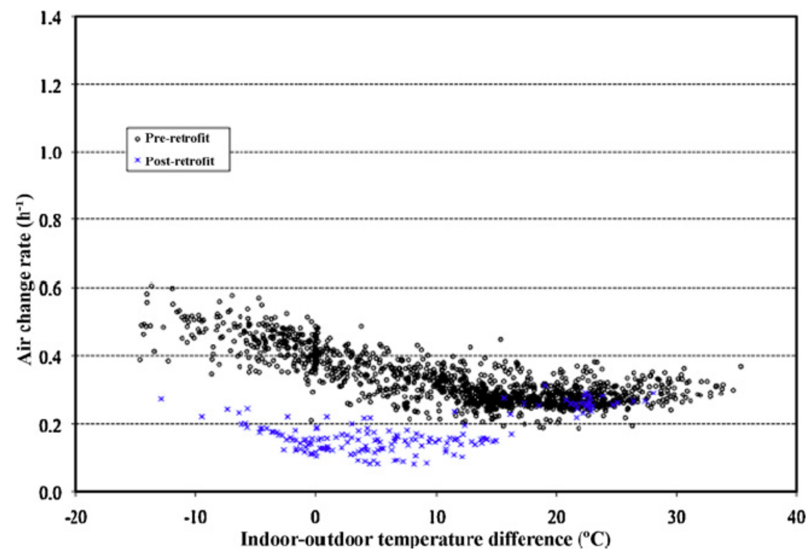
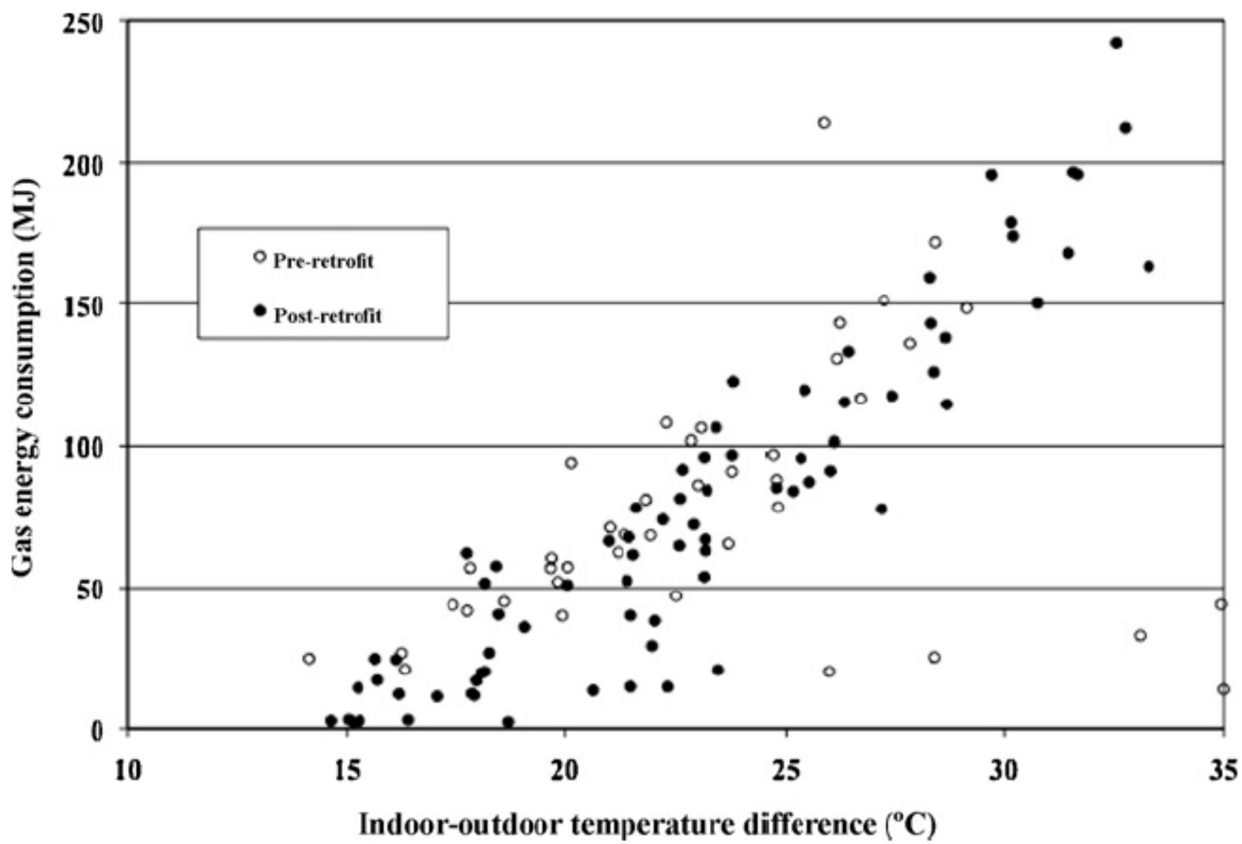


Fig. 8. Pre- and post-retrofit measured air change rates as a function of temperature difference (low wind speed): forced-air fan on, outdoor air intake sealed (Condition 1a).

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

- 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