CAE 463/524
Building Enclosure Design
Spring 2015

Lecture 7: March 3, 2015
Air movements in enclosures

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Dr. Brent Stephens, Ph.D.
Civil, Architectural and Environmental Engineering
Illinois Institute of Technology
brent@iit.edu

Last time

- Hygrothermal analysis
  - Use of WUFI
  - HW 3 assigned (due today)

- Moisture management and building enclosures

Where are we now?

- Building science and psychrometrics review
- Modes of heat transfer
- Surface energy balances
- Complex conduction
  - 2-D conduction with THERM
- Moisture/water vapor transport
  - 1-D moisture modeling (WUFI)
- Moisture/water vapor control
- Air movements and infiltration
- Windows/daylighting
- Energy simulation and enclosure design
- Thermal mass
- Codes/standards/applications

Next time: Campus projects due

- Presentations and reports due March 10 (1 week from today)
  - Presentations in class
    - Try to share presentation load among members
    - But it's OK if that's not possible
  - Aim for 10-15 minute presentations
    - Will learn blower door techniques afterwards

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

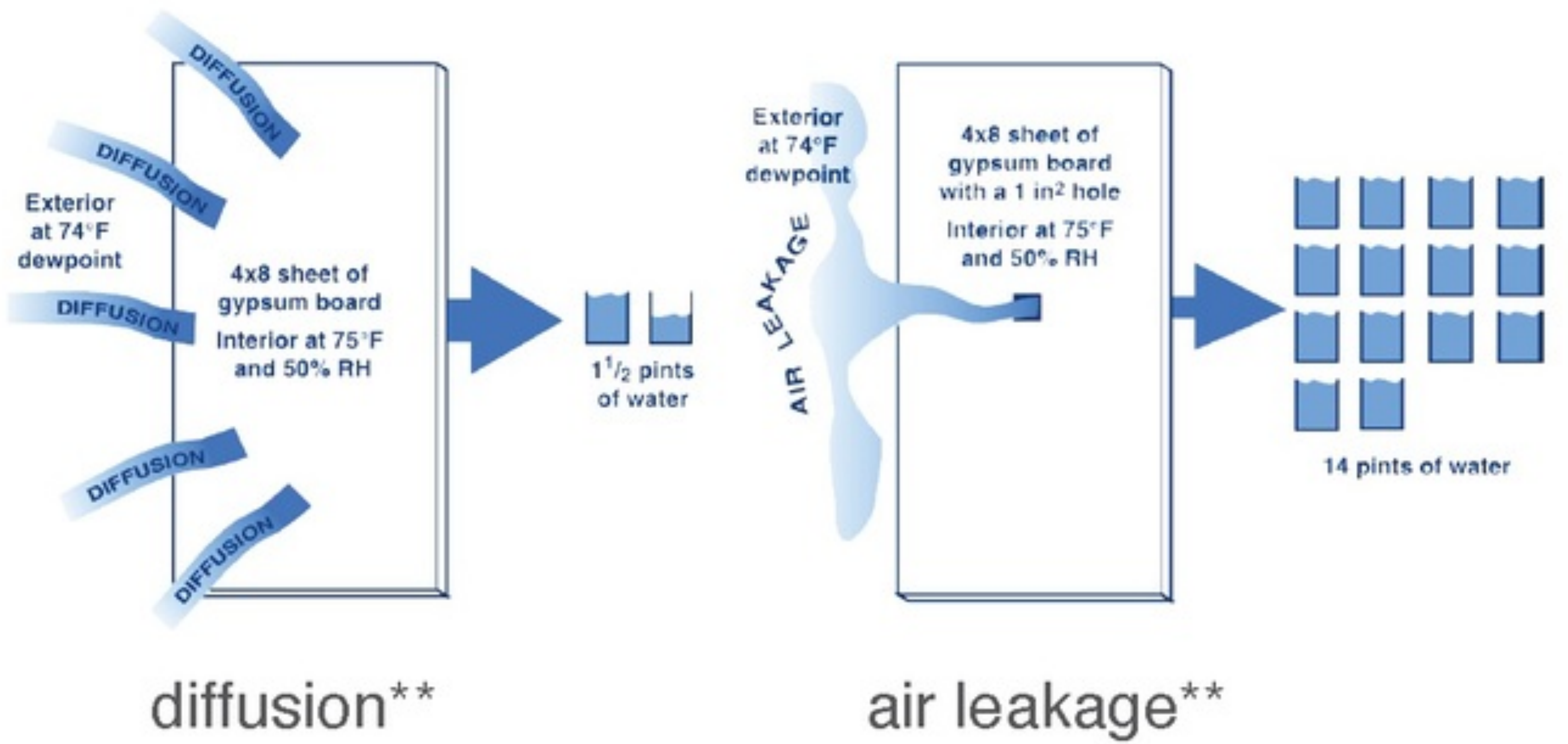
This time

- Finish moisture management and control
- Airflows in enclosures
  - Fundamentals
  - Governing equations
  - Measurement techniques
  - Energy implications
  - Control strategies and applications

First…

AIR CAVITIES FOR MOISTURE MANAGEMENT

Bulk vapor transport vs. vapor diffusion



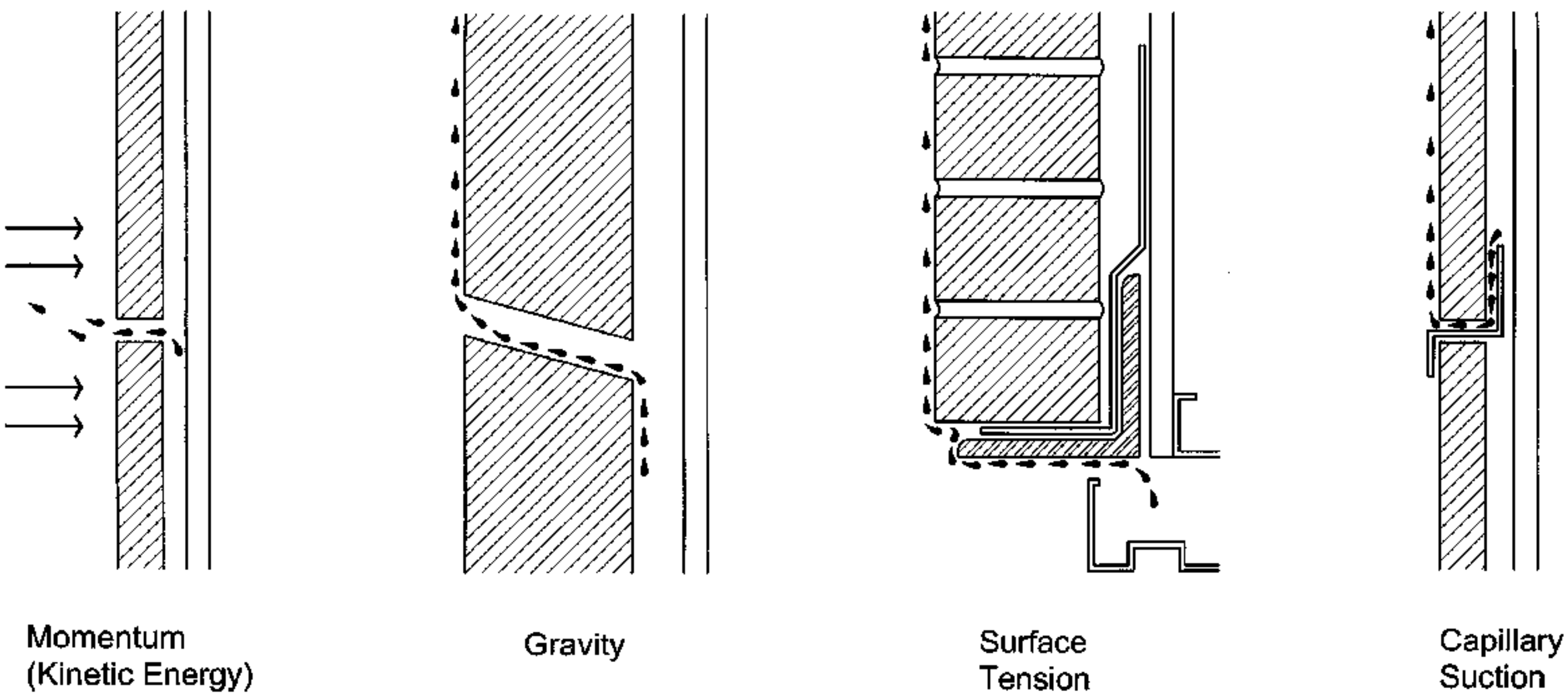
Materials: Vapor barriers and vapor retarders

- Vapor barriers are used in certain climates when condensation would be a regular occurrence
  - Hot-humid climates and very cold climates
- Vapor retarders are useful in many more climates
  - Cold and mixed climates
  - Sealing is not as important with a pure vapor barrier

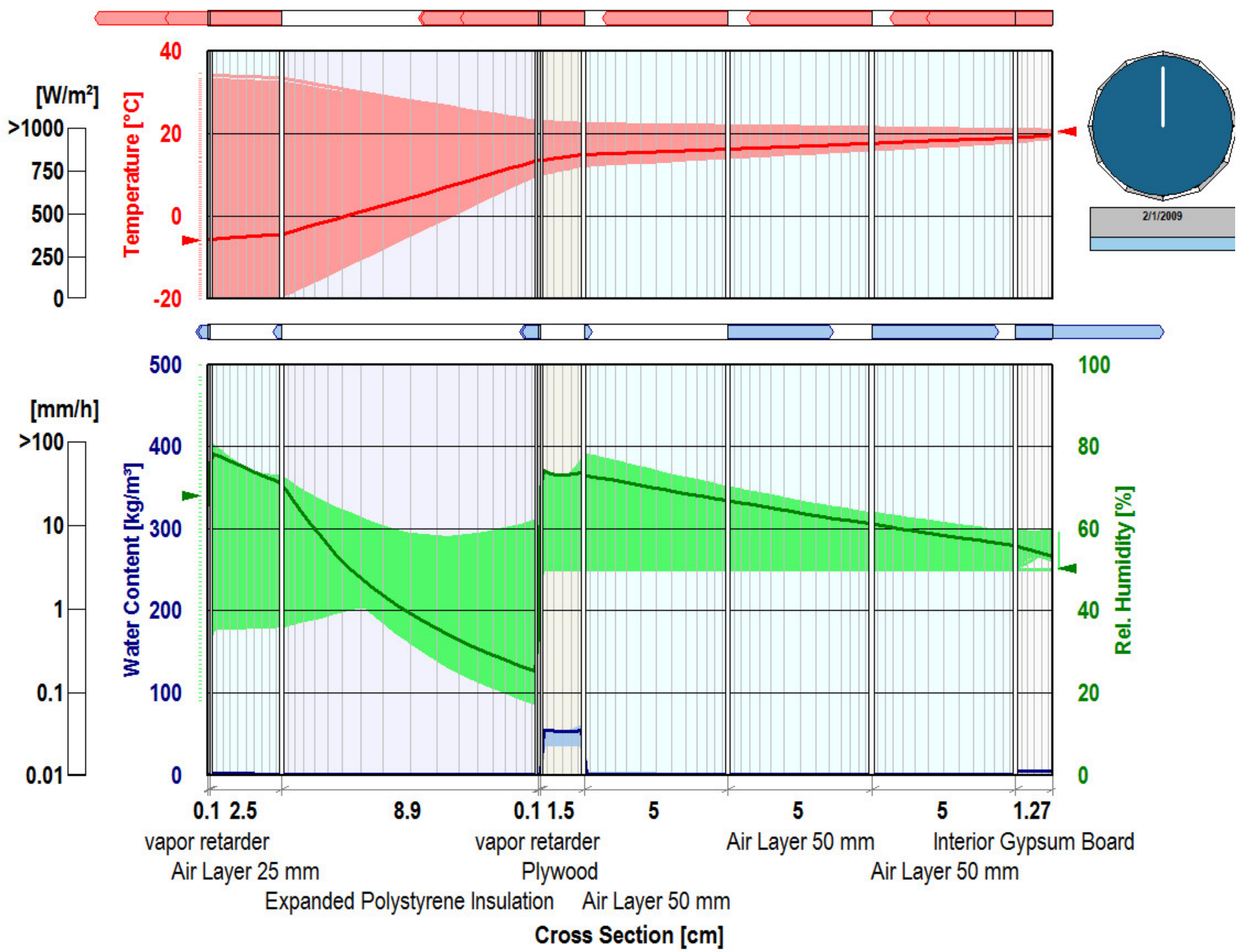
Type	Perms (IP units) [grains/(hr ft^2 inHg)]	SI units [ng/(s m^2 Pa)]	Example
Class I vapor retarder Vapor barrier Vapor impermeable	0.1 or less	5.7	Foil Polyethylene
Class II vapor retarder Vapor semi-impermeable	0.1-1	5.7-57	Brick XPS
Class III vapor retarder Vapor semi-permeable	1-10	57-570	Poly-iso EPS
Vapor permeable NOT a vapor retarder	10+	570+	Gypsum board

Condensed water (liquid) transport

- There are 4 main mechanisms for condensed moisture or rain to enter into wall cavities or directly inside buildings
  - These can be stopped fairly easily with simple design ideas

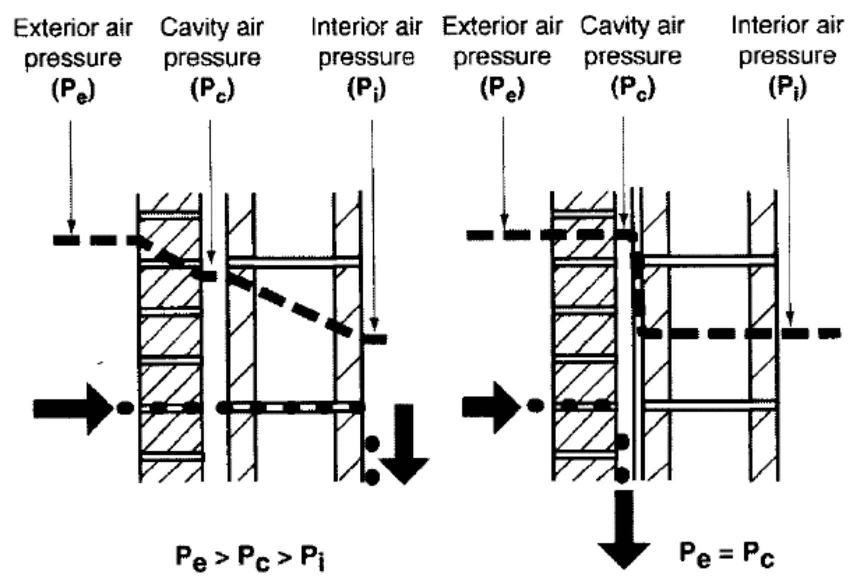


WUFI: Hygrothermal analysis tool



Use of air cavities in moisture management

- Air cavities can provide beneficial breaks to:
  - Stop capillary suction and reduce momentum driven rain entry
  - Allow flashings to direct gravity flow to exterior
  - Allow for pressure equalization to force rain back to exterior
- Intentional “**drain-screen**” walls and “**rain screen**” walls



Driven by air pressure differences, rain droplets are drawn through wall openings from the exterior to the interior

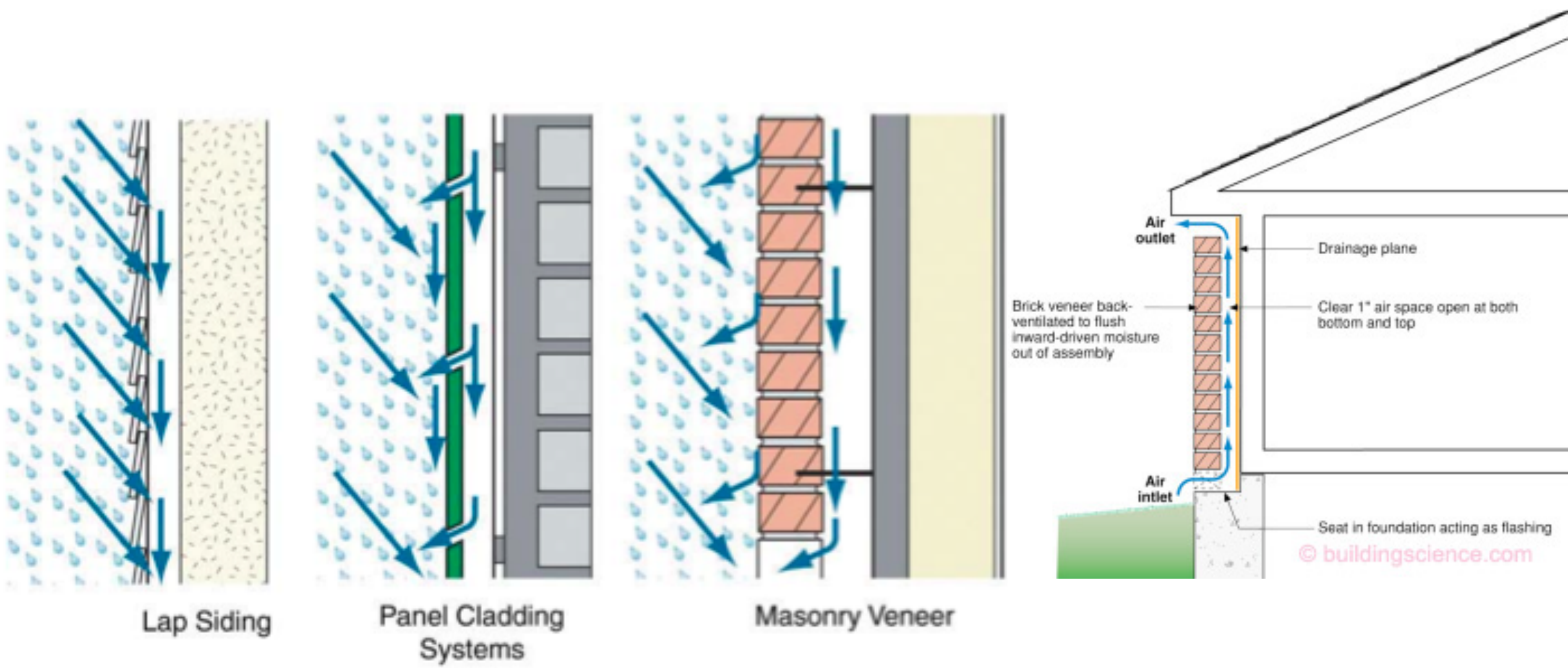
By creating pressure equalization between the exterior and cavity air, air pressure is diminished as a driving force for rain entry.

Pressure equalization: Cavity ventilation

Drain-screen walls

- A **drain-screen** wall allows some water to penetrate the outer layer of a wall assembly
  - But uses the air cavity to break most water transport and provide drainage
    - Air space should be at least 5 mm (~1/4”) wide, although 10 mm (~3/8”) is a better minimum to allow for normal construction tolerances
- The “screen-drained” wall then uses properly designed and installed flashing to redirect water from the drainage plane back outside the cavity
- Examples include cavity walls, brick and stone veneer, vinyl siding, and drained EIFS (synthetic stucco)

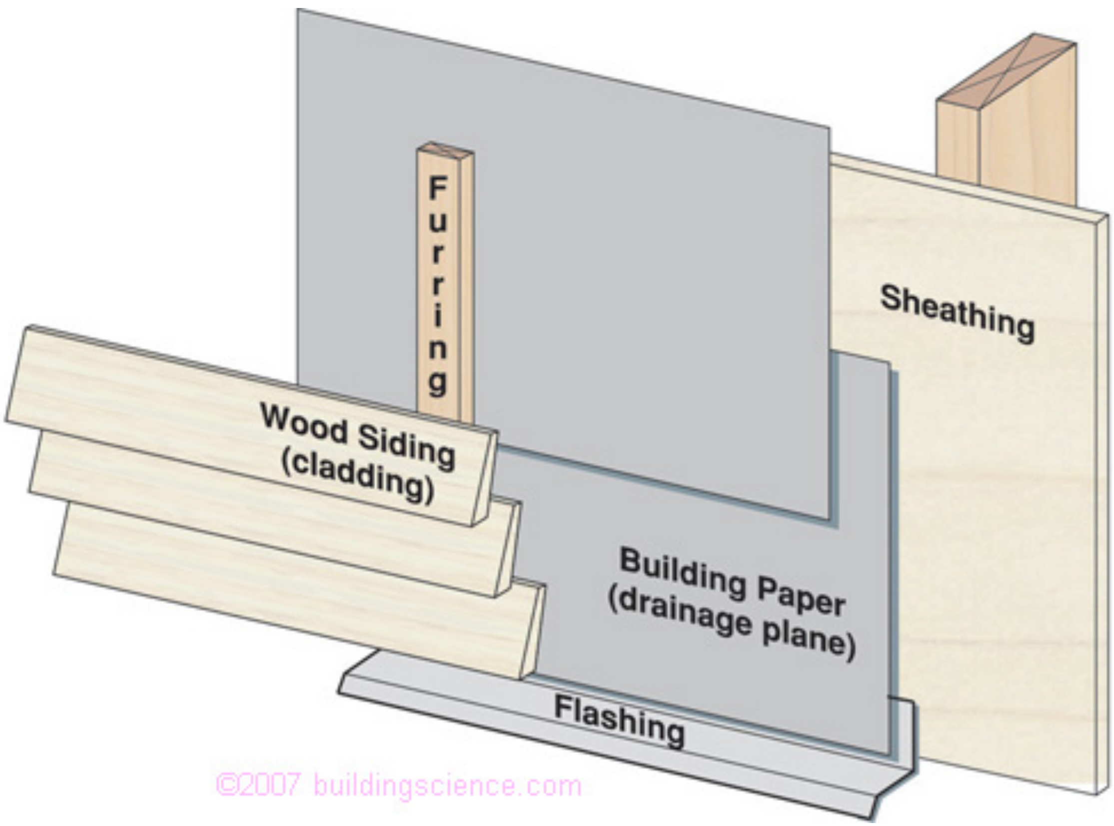
Drain-screen walls: Cavity ventilation



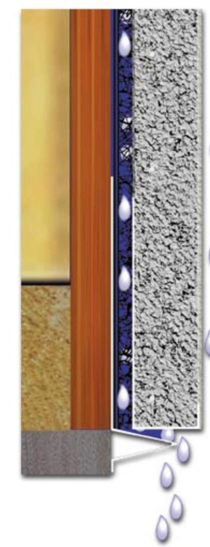
Each requires: (1) screen or cladding; (2) drainage gap; (3) drainage plane; (4) flashing at the base to direct water outwards; and (5) drain holes or weep holes to allow water out

Straube 2006

Drain-screen walls: Cavity ventilation



Furring and cavity ventilation



Drainage mats

Rain screen walls

- If we are a little more careful in the design of the air cavity between the outer layer and inner layers we can improve performance

- If the cavity has holes to the outside and the inside layer has an air barrier, the cavity will actually be pressurized to a pressure similar to outside
  - This will keep water from being driven into the cavity with by the pressure difference
  - We call this design a **rain screen** wall

Rain screen wall: Prevent momentum driven rain

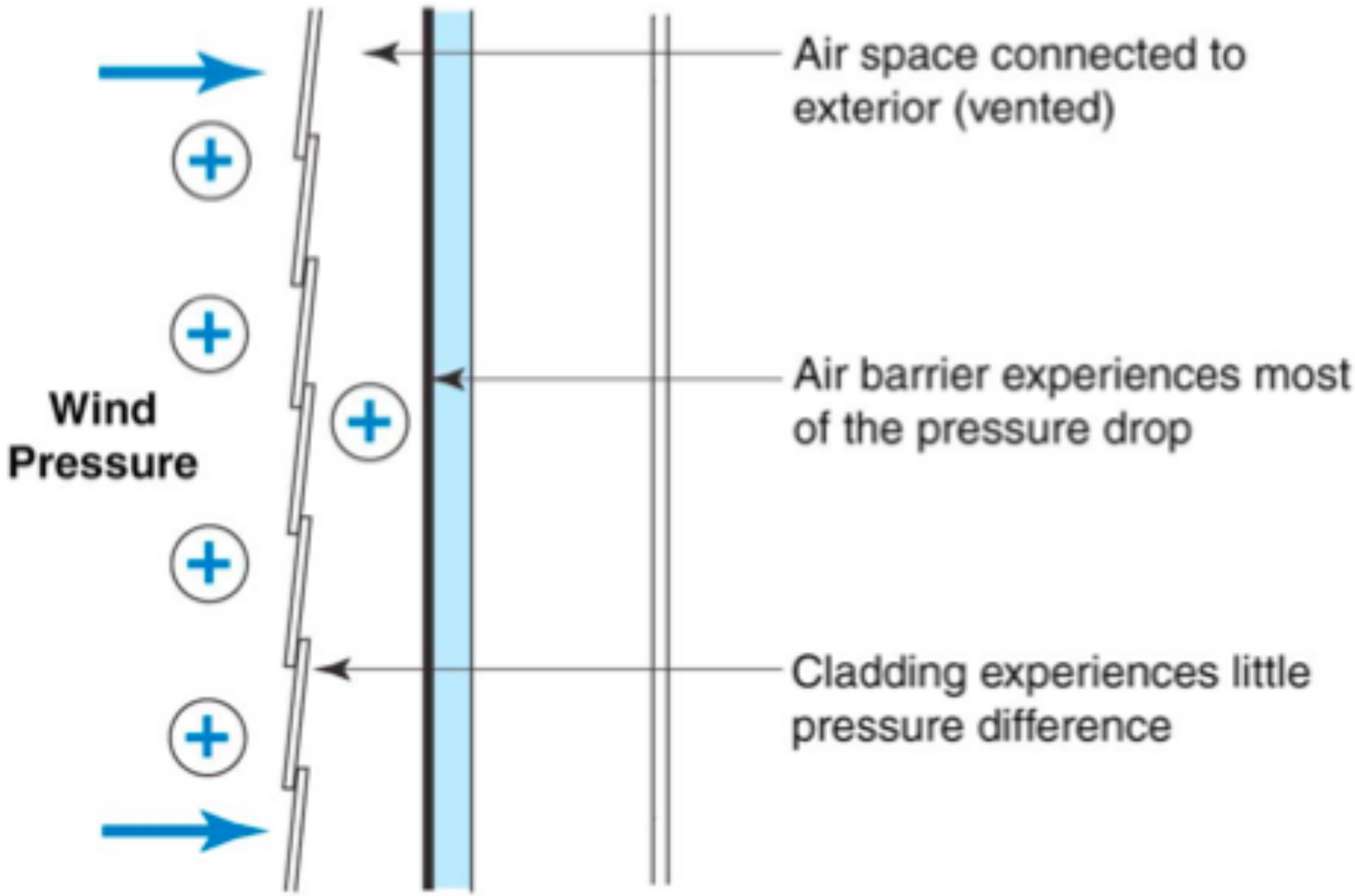
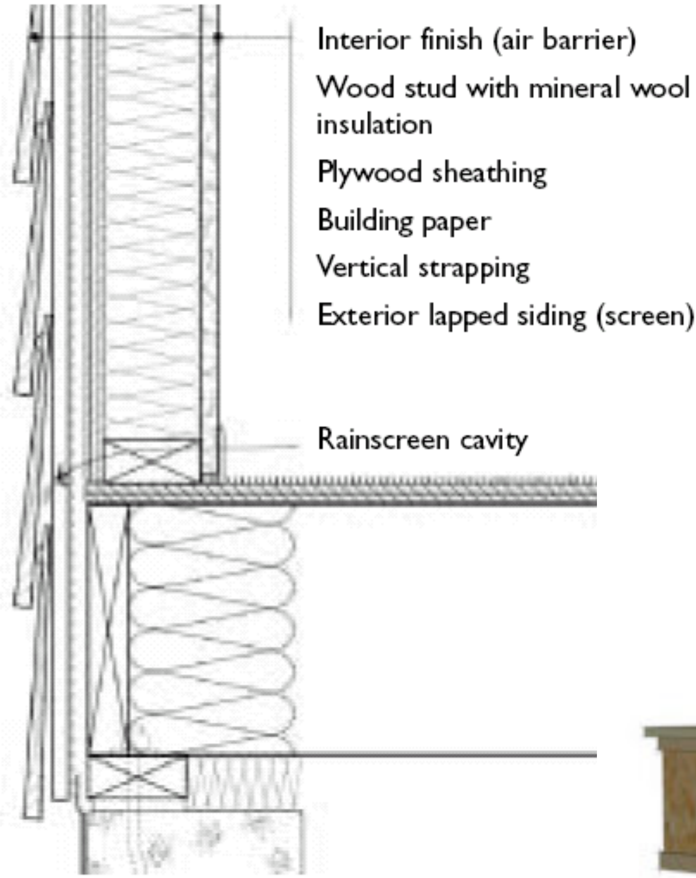


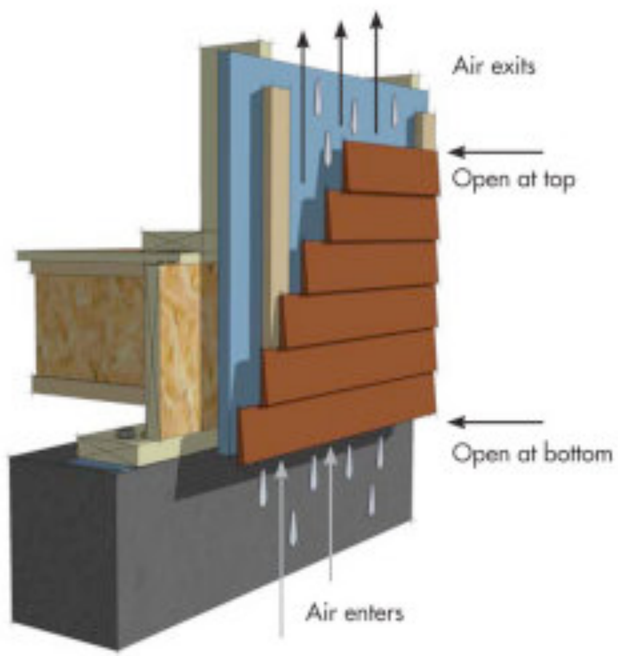
Figure 7: Pressure Moderated Air Space

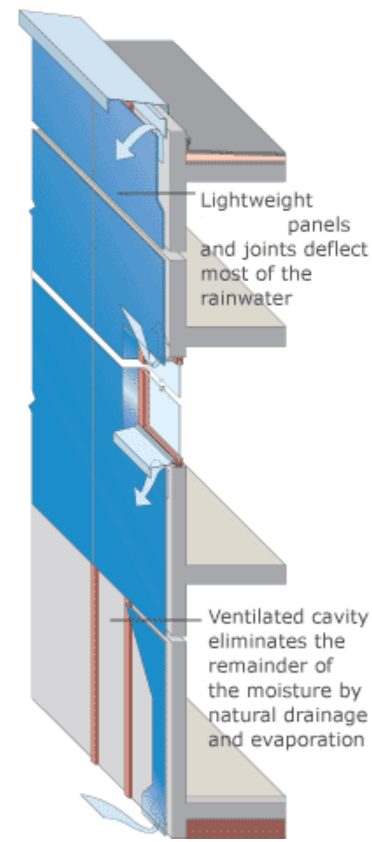
Straube 2006

Open (ventilated) rain screen



- A wall with siding will have natural air gaps
- Siding gaps act as a vent opening for drainage and drying
- Must have an **air barrier** somewhere on interior wall





Open rain screen video

https://www.youtube.com/watch?v=78KKx2Nx2m4

Pressure equalized rain screen (PER)

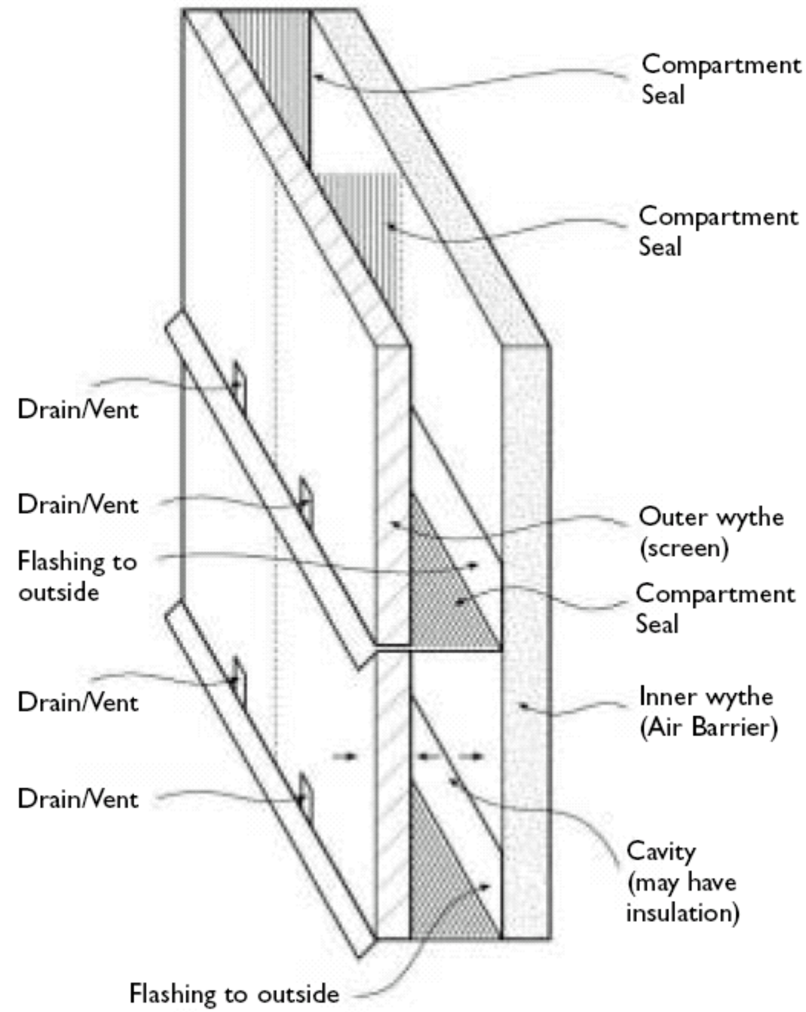
- Another type of rain screen is **pressure equalized**
  - Used more for tall buildings

- Allows compartmentalization of façade into chambers
  - Makes the pressure in the air cavity track outside air pressure
  - Stops the rain from even entering the cavity (if driven by pressure difference)

- PER screens are useful in high rain areas but are usually too expensive for general wall design

Basic PER design

- Flashing
  - Directs dripping water to the exterior drains
- Drain/Vents
  - Act as openings for pressure equalization
  - Allow rain that enters cavity to drain out
- Compartmental Seals
  - Breaks the interior cavity into smaller sections



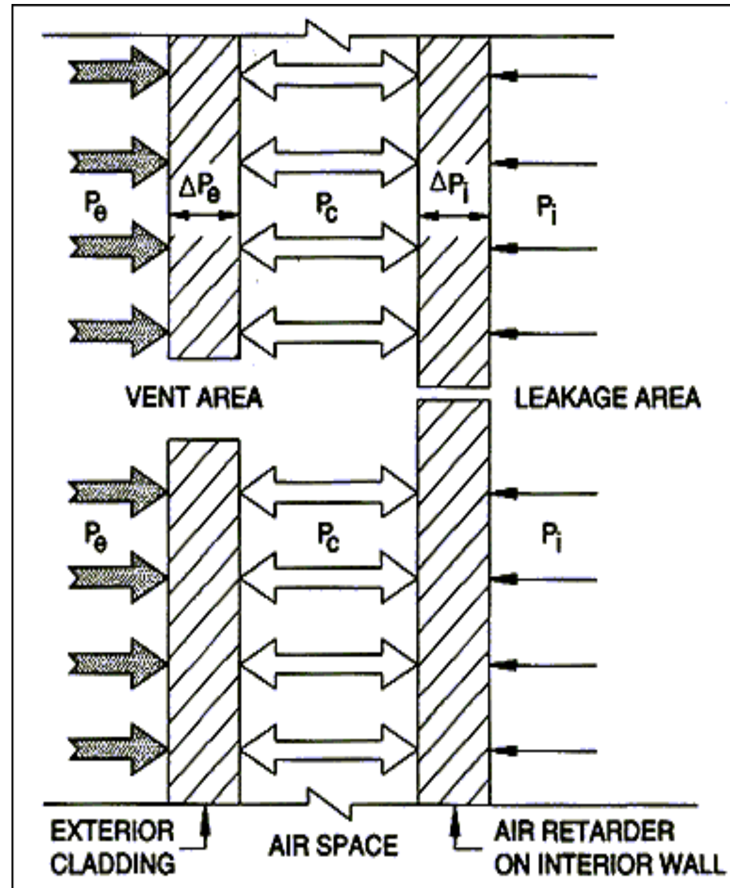
Pressure Equalized Rain Screen (PER)

- Large opening in exterior cladding increases cavity pressure equal to that of exterior so rain doesn't enter

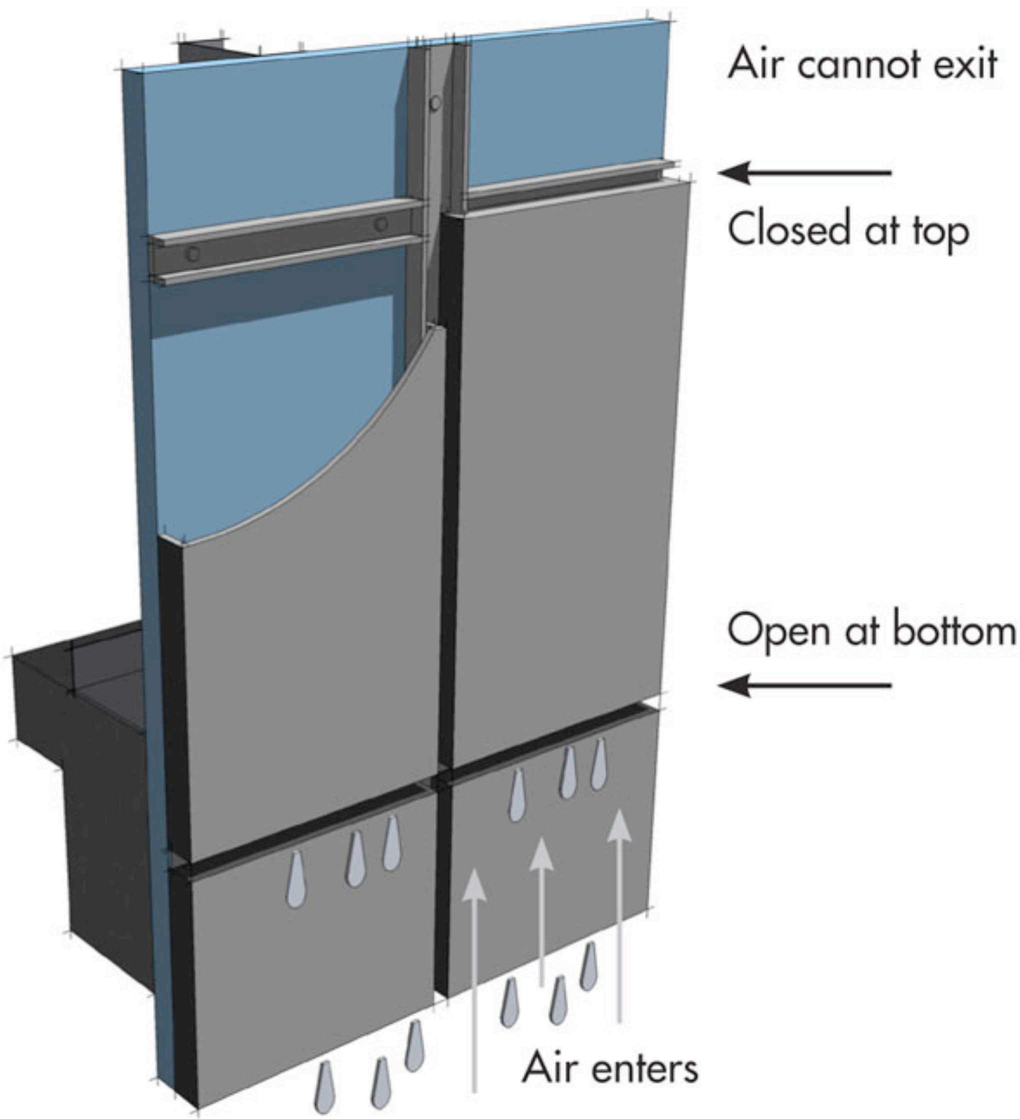
$$P_c \approx P_e,\ \Delta P_e \rightarrow 0$$

- Interior wall must have an air barrier to ensure that high cavity pressure is maintained

$$P_c > P_i\ ,\ \Delta P_i > 0$$



PER detail



MOISTURE MANAGEMENT AND CONTROL: SUMMARY

Moisture management rules

- Remember:
  - For a moisture problem to occur
    - There must a source
    - There must be a route
    - There must be a driving force
    - The materials involved must be susceptible
  - Eliminate any one will avoid a problem, in theory
  - In practice, difficult to:
    - Remove all moisture sources
    - Build walls with no imperfections
    - Remove all driving forces for moisture movement
    - So, if you can address two of these
      - You will reduce the likelihood of having a problem

Susceptibility and vulnerability

- As we’ve seen, different materials and assemblies vary in their susceptibility to moisture-related damage
- Standards, codes, and industry criteria help assess susceptibility of materials
- Susceptible materials are susceptible only in a vulnerable environment
  - Responsibility of designers and builders to ensure that a material or assembly are used in appropriate manners
  - Location is a primary determinant of exposure
    - The location of the relevant portion of material on the wall
      - The wall on the building
        - The building on the site
          - And of the geographical region of the site

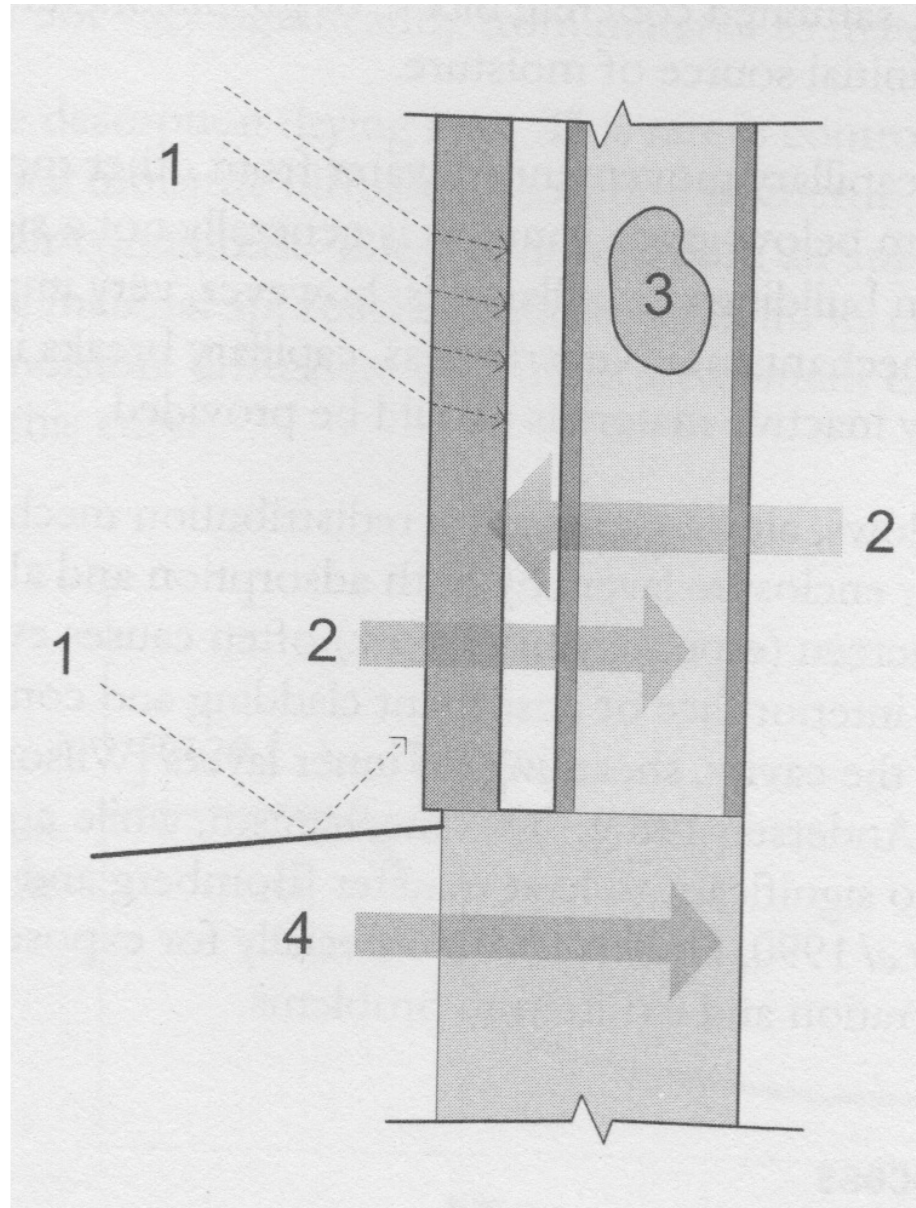
Moisture control

- If a balance between wetting and drying is maintained
  - Moisture will not accumulate over time
    - Moisture problems would then be unlikely

- Need to be cognizant of:
  - Moisture sources
  - Moisture removal mechanisms
  - Moisture storage

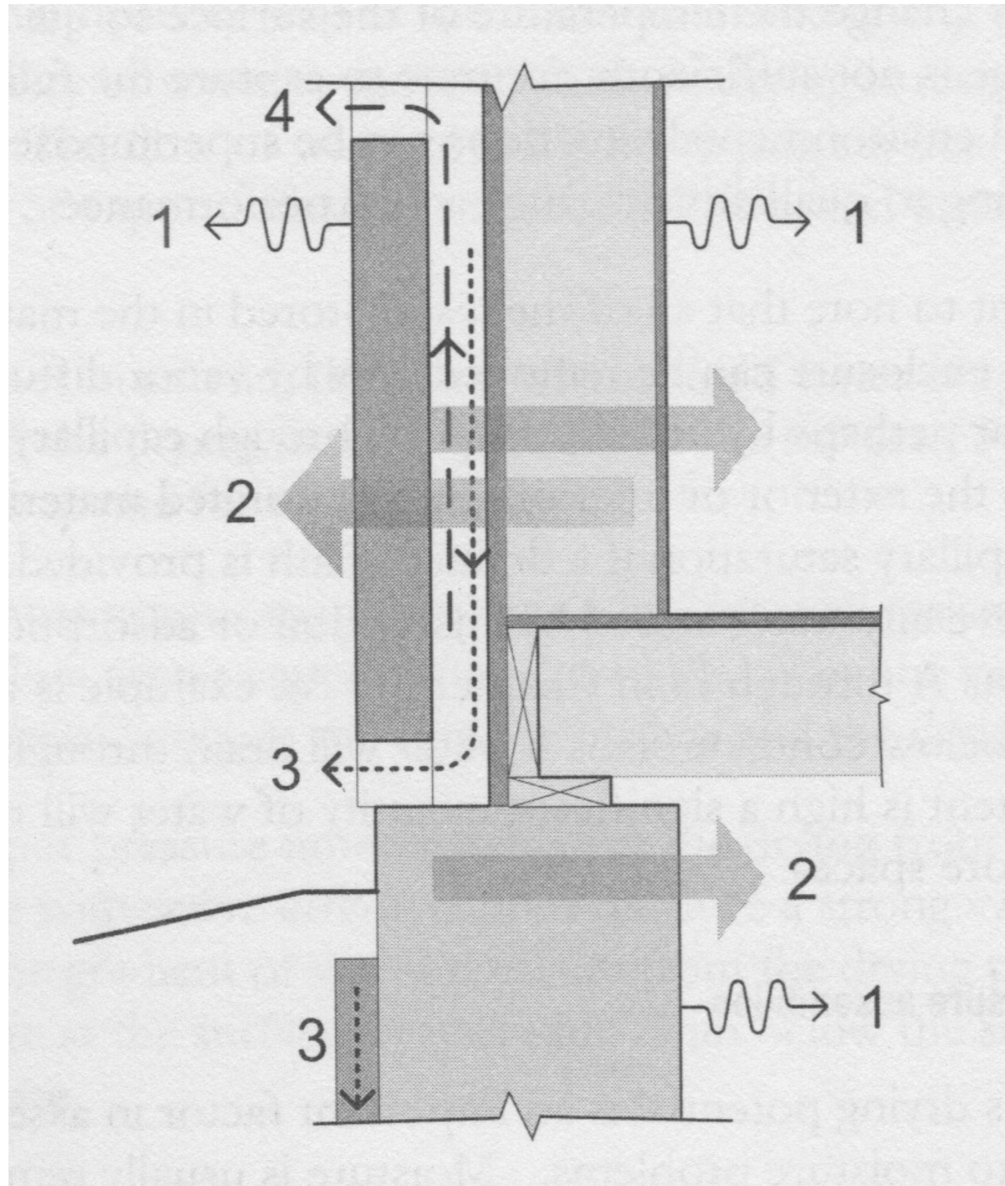
Wetting process (sources)

1. Precipitation
   - Driving rain
2. Water vapor transport
   - Diffusion
   - Air leakage
3. Built-in and stored moisture
   - During construction
4. Ground water



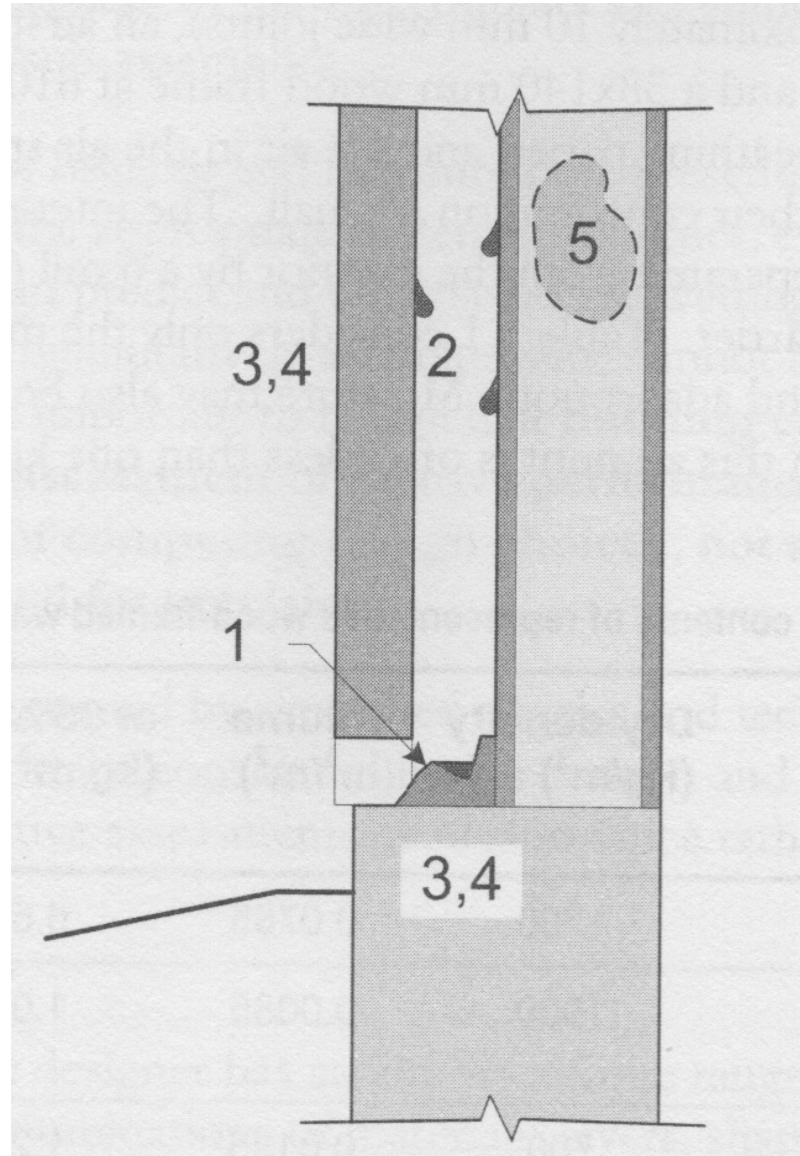
Drying mechanisms

1. Evaporation
2. Vapor transport
   - Diffusion
   - Air leakage
   - Outward or inward
3. Drainage
   - Driven by gravity
4. Ventilation drying



Moisture storage

1. Trapped in small depressions
   – Poorly drained portions of assemblies
2. Adhered by surface tension to materials
   – Droplets
   – Or even frost or ice
3. Adsorbed in or on hygroscopic building materials
   – Brick, wood, fibrous insulation, paper
4. Retained by capillarity (absorbed) in porous material
5. Stored in the air as vapor



Condensation control

- Two types that must be considered
  - Interior surface condensation
  - Interstitial (within enclosure) condensation
    - Just as important in hot-humid climates as in cold climates

- Like we’ve discussed, condensation on building surfaces is undesirable
  - On interior surfaces:
    - Moisture will damage moisture-sensitive finishes (wallpaper, paint, wood, gypsum wallboard)
    - Provides moisture for mold growth

Condensation control

- Surface condensation is often the result of dynamic/short-term variations in temperature or absolute humidity
  - Cold windy night
  - Cool morning
  - After a shower
  - During cooking

  - Need to consider these events

Condensation control

- Most modern enclosure walls and roofs are well insulated such that interior surface condensation in winter shouldn't be a problem
  - In winter, interior surface temperature is high enough to not be below indoor air dew point

- Surface condensation becomes a problem when:
  - Thermal resistance of the enclosure is low (i.e., at thermal bridges)
  - Surface film has an unusually high value
  - Interior humidity is very high

Designing enclosures for moisture control

- Building enclosure design usually involves the assessment of relative performance, pass-fail assessments, or the ranking of competing design choices
  - Not absolute values
  - Rarely a need for absolute precision

- Results generated by the simplified physics and solution techniques so far should be considered
  - Applied to arrive at reliable relative assessments
    - Rather than precise quantities

Designing enclosures for moisture control

- Material choices
  - You have an almost infinite range of choices considering possible combinations of
    - Materials
    - Layers
    - Shape
    - Orientation
  - There are no universally “good” materials

Refer to Building Science Corp's website for more info

- "Enclosures that work"
  - http://www.buildingscience.com/doctypes/enclosures-that-work

- "Designs that work"
  - http://www.buildingscience.com/doctypes/designs-that-work

- "Understanding vapor barriers"
  - http://www.buildingscience.com/documents/digests/bsd-106-understanding-vapor-barriers

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

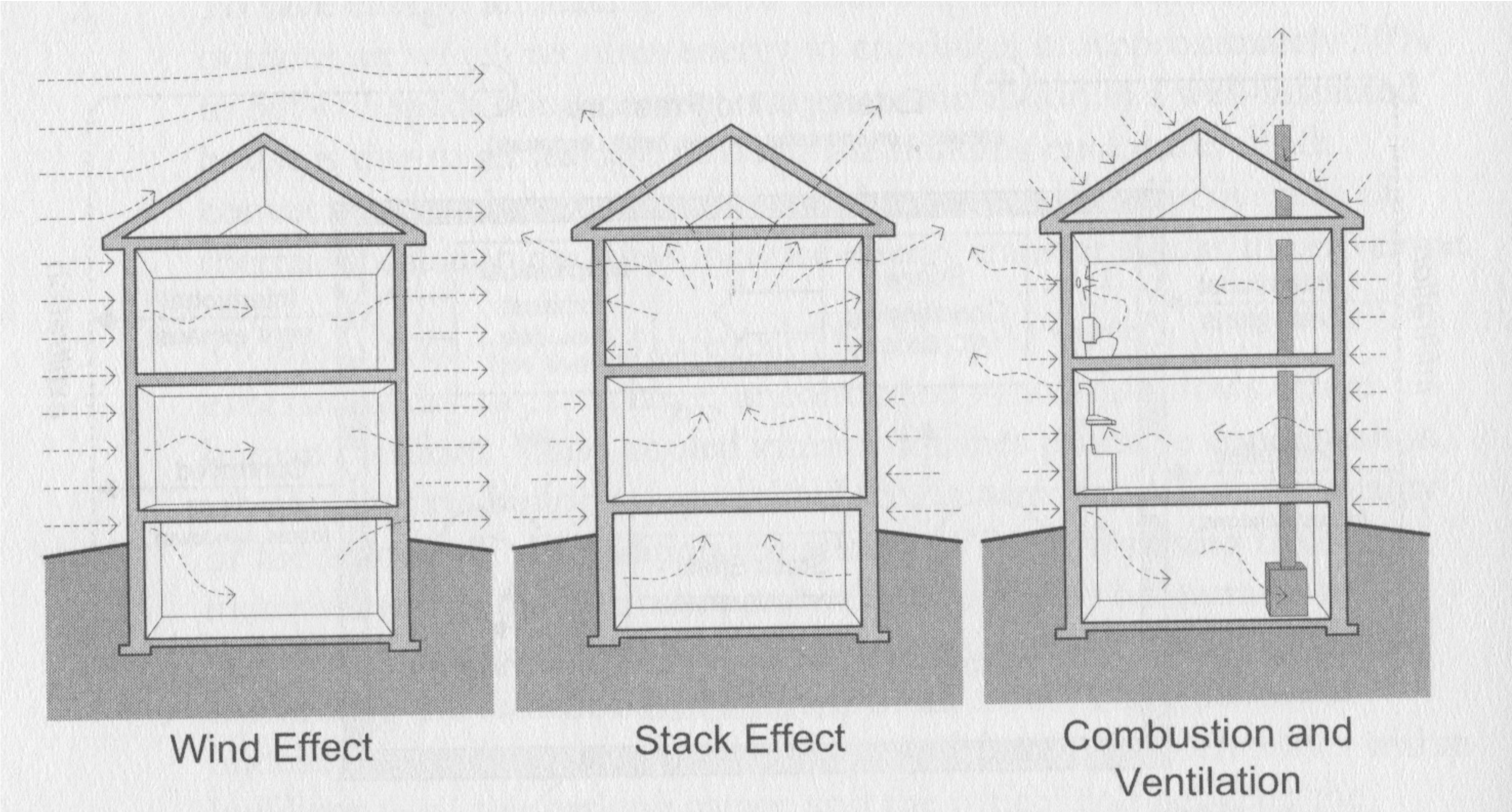
- Outdoor air flowing into a building
  - Can dilute indoor contaminants (good)
  - Can lead to excess energy use (bad)
  - Can lead to moisture transport (good or bad)

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

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., 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)

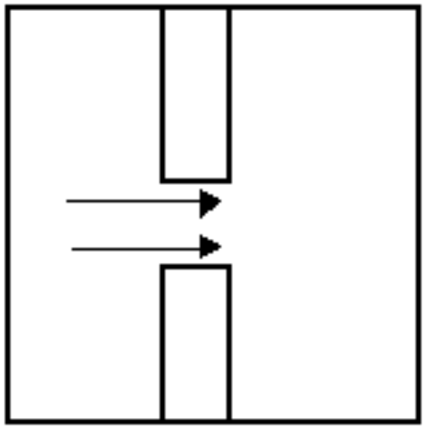
Basic fluid mechanics: flow through a crack

- 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:

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

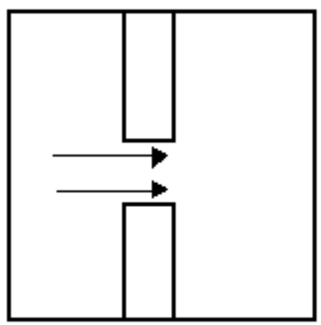


  - Rearranging:

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

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:



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

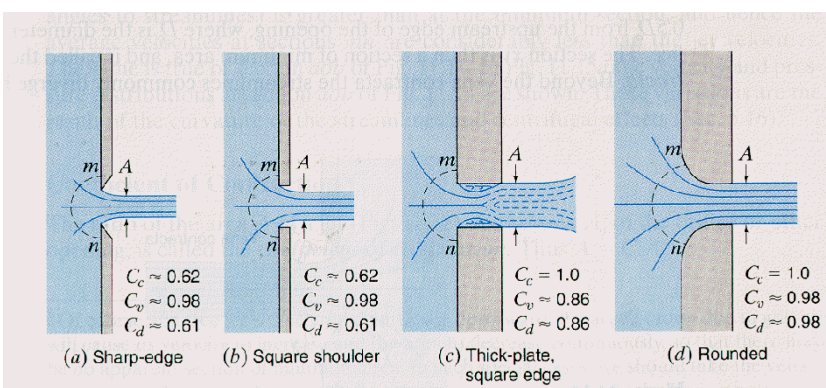
where ΔP is the pressure difference across the opening

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



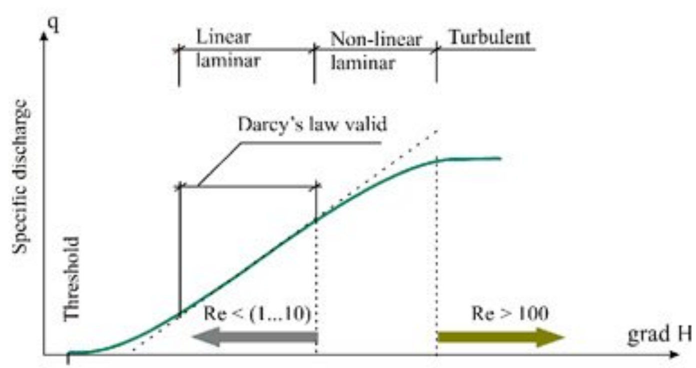
$$Q = C_d A\sqrt{\frac{2\Delta P}{\rho}}$$

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]

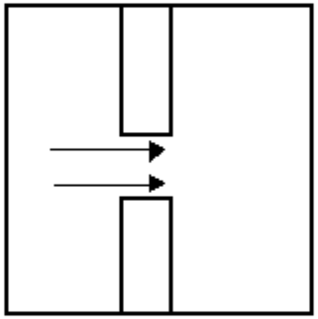
Material	K (x 10^6)	n
200 mm concrete block	150	0.990
12.7 mm drywall, unfinished	0.266	0.995
12.7 mm interior moisture-resistant drywall	0.120	1.000
12.7 mm sheathing grade gypsum & taped joints	0.200	1.000
11 mm asphalt-impregnated fibreboard	11.27	0.995
11 mm fibreboard	11.47	0.990
8 mm plywood sheathing	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:

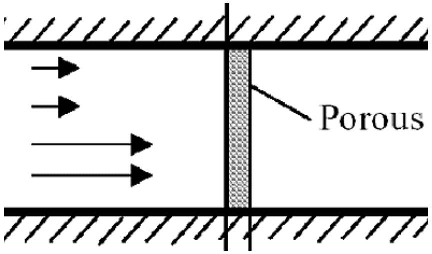
1. Some materials with no measurable leakage, i.e. $K < 8 \times 10^{-8}$ m /(Pa·s), 38 mm Type IV extruded polystyrene, 9.5 mm plywood sheathing, foil-faced foam insulations, foil-backed drywall, taped and finished gypsum drywall w/ 2 coats of latex paint and, of course, roofing membranes, steel sheeting, etc.
2. Materials with a permeance of more than about 1.5×10^{-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 25×10^{-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

- 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

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

  - *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

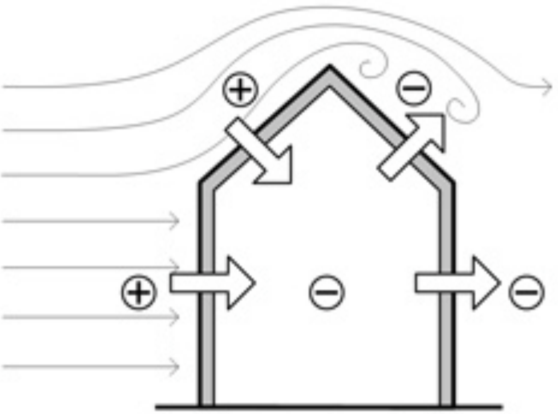
- Power law relationship for any tested assembly
  - Valid for single objects and/or entire enclosures

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

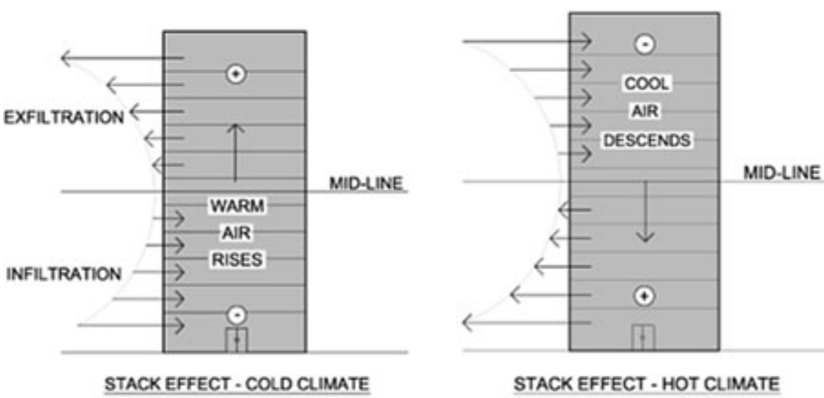
  - Will come back to this relationship later in the lecture
  - For now, we will learn about the major driving force:
    - ΔP (pressure difference)
    - Questions:
      - What drives ΔP?
      - How do we estimate ΔP?
        - » What are typical magnitudes?

Infiltration driving forces

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

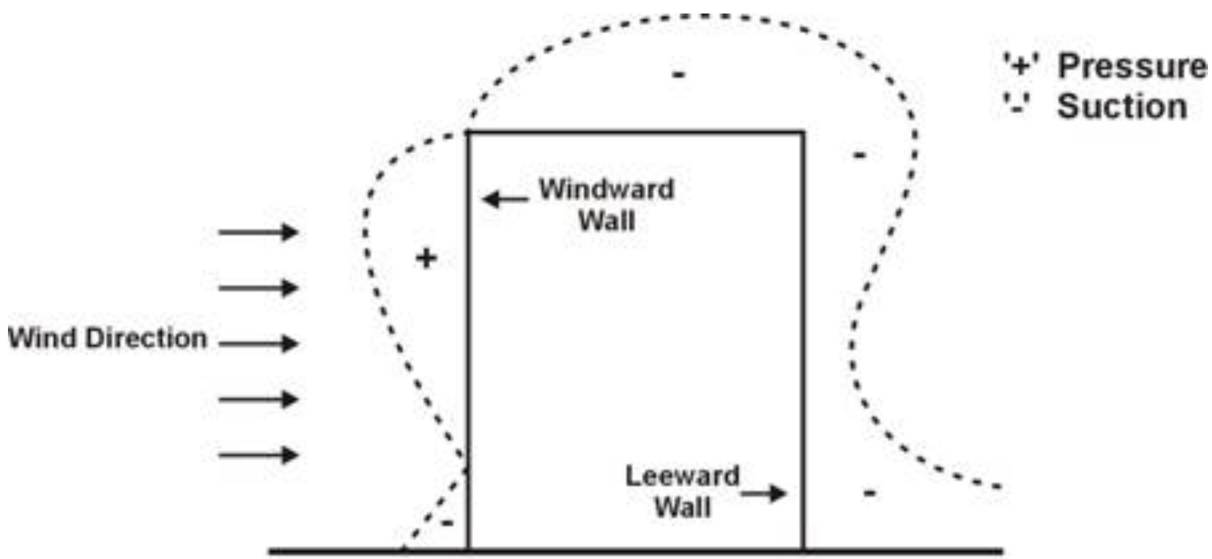


  - Driven by **stack pressure/stack effect**
    - Building height
    - Indoor and outdoor temperatures



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:

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

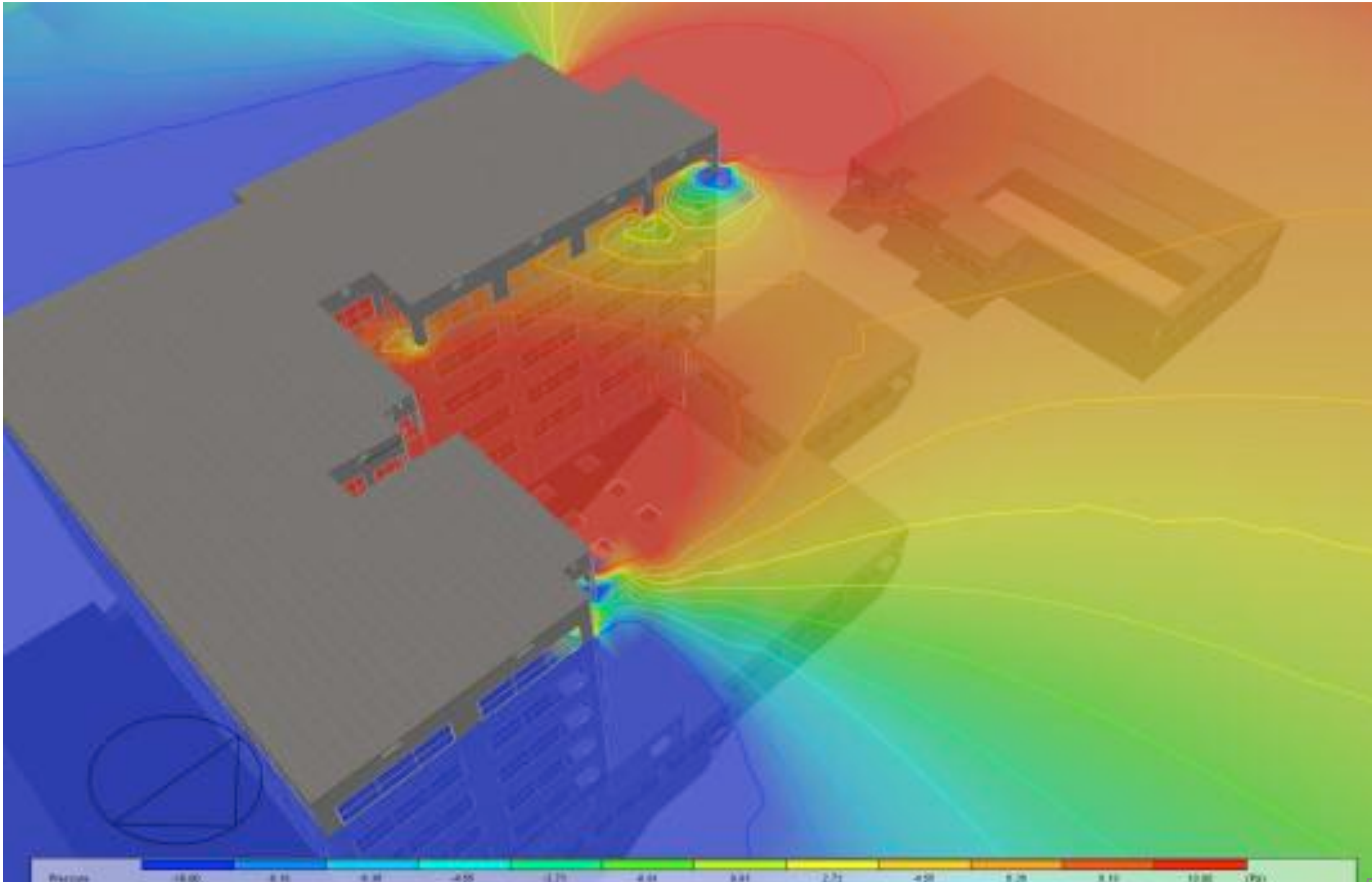
$P_{velocity}$ = wind velocity pressure; U_h = air velocity at building height, h; ρ_{air} = air density

- 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:

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

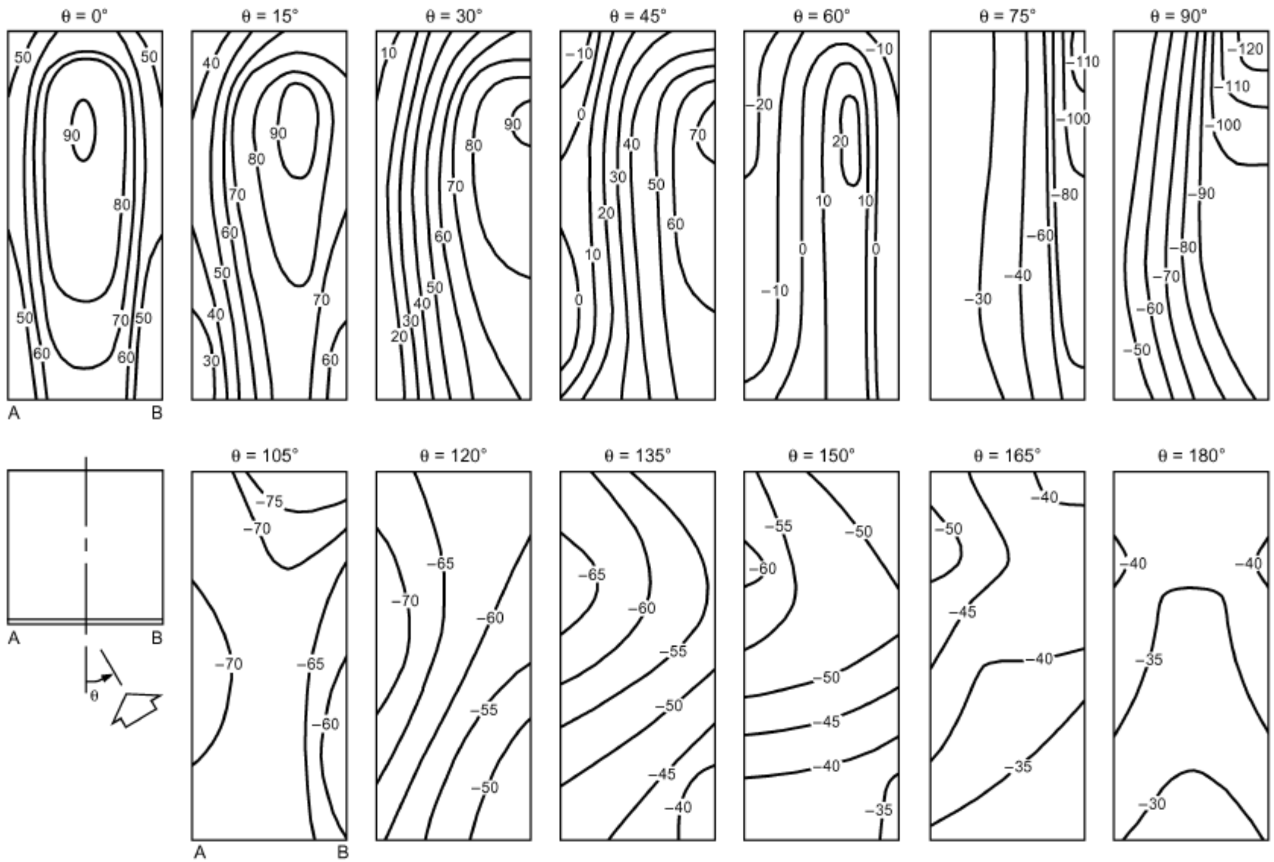


Fig. 4 Local Pressure Coefficients ($C_p \times 100$) for Tall Building with Varying Wind Direction
(Davenport and Hui 1982)

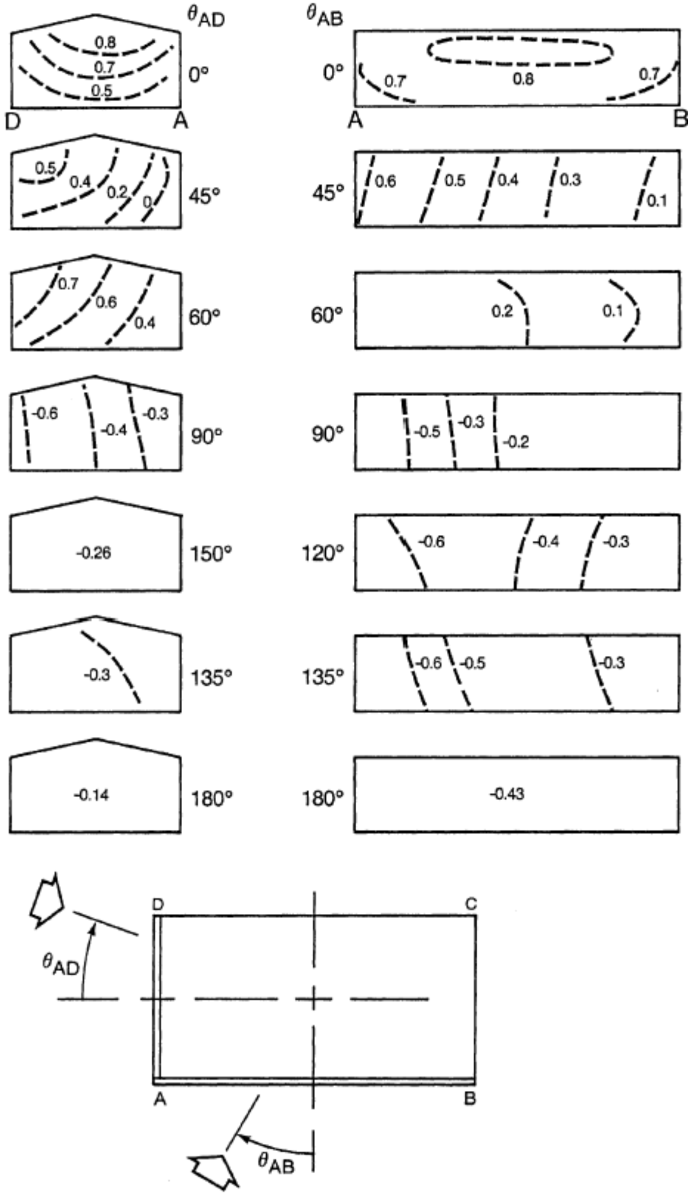
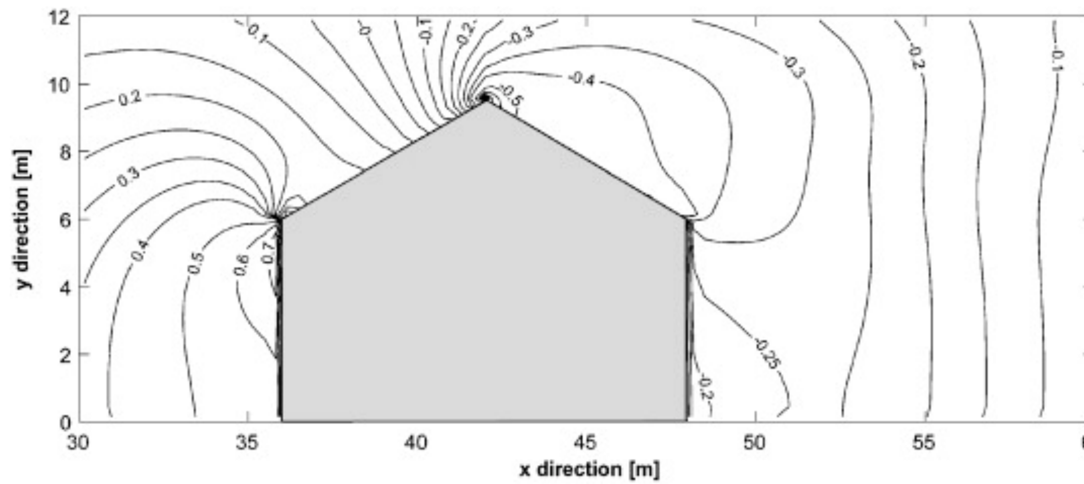


Fig. 5 Local Pressure Coefficients for Walls of Low-Rise Building with Varying Wind Direction
(Holmes 1986)



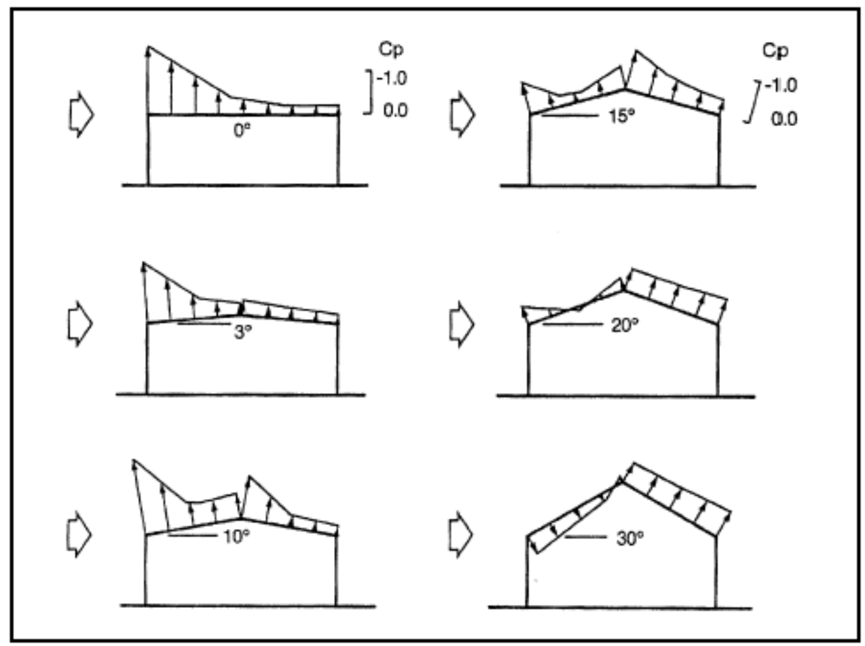


Fig. 8 Local Roof Pressure Coefficients for Roof of Low-Rise Buildings
(Holmes 1986)

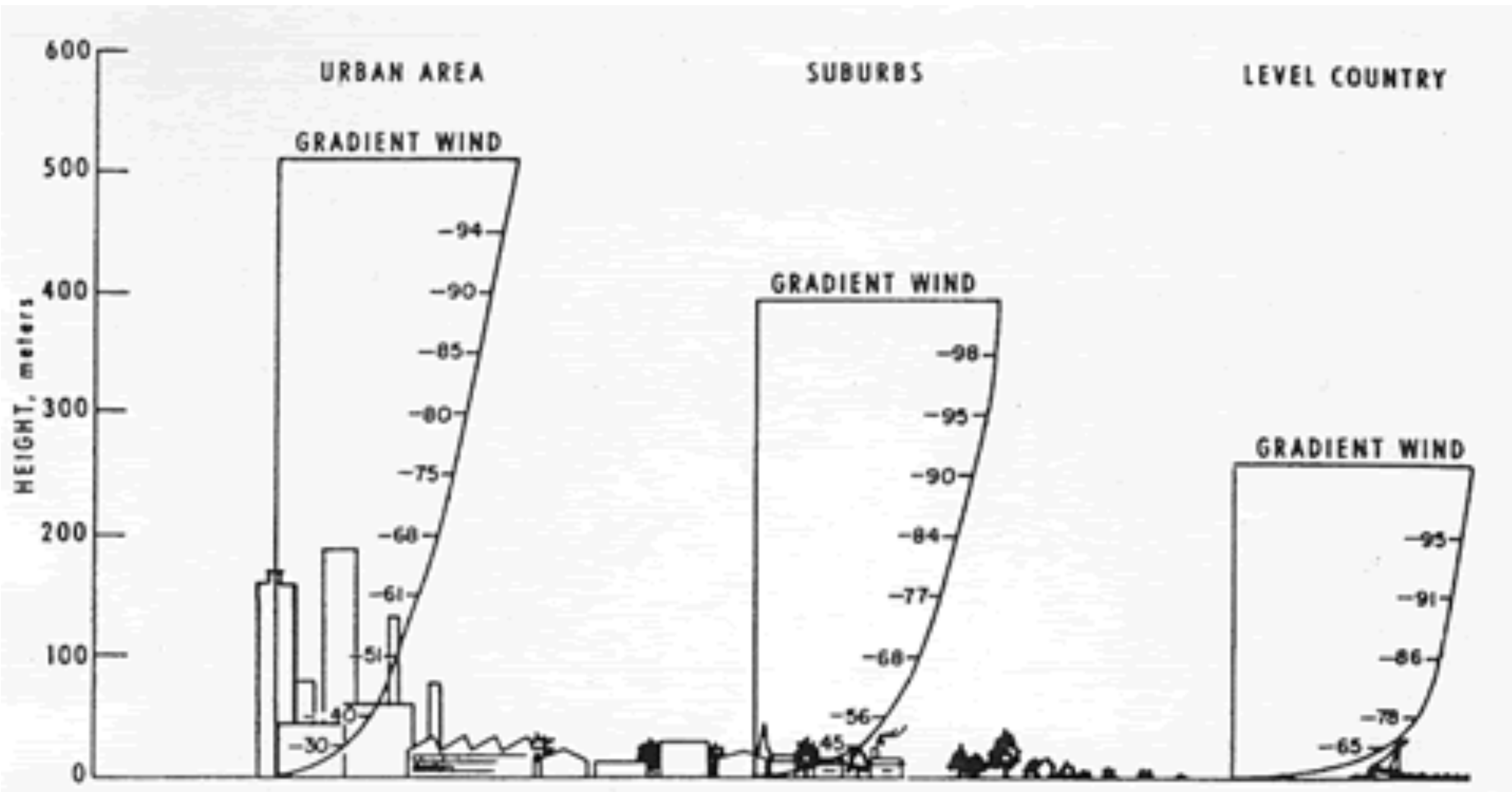
Wind speed

- 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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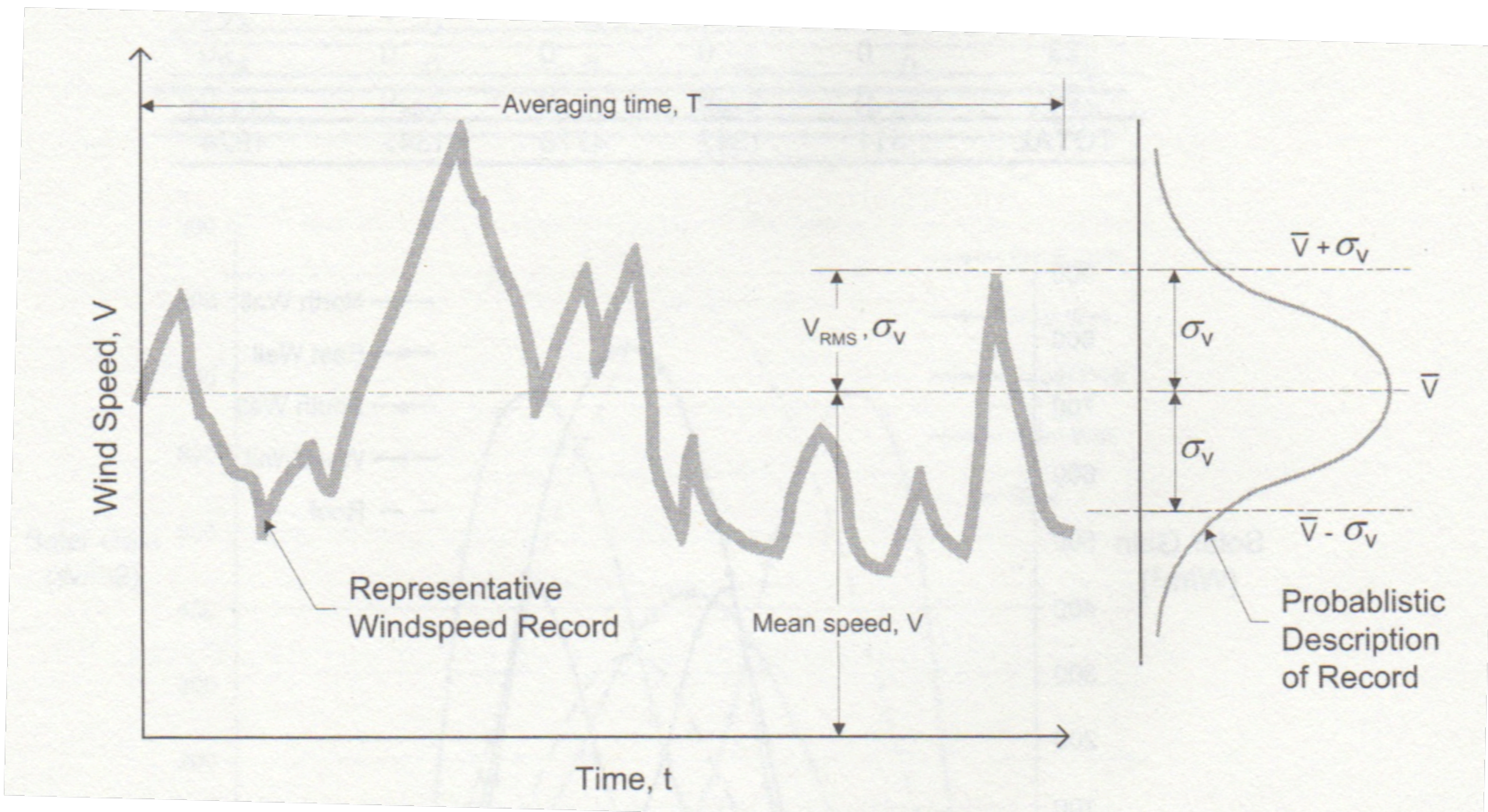
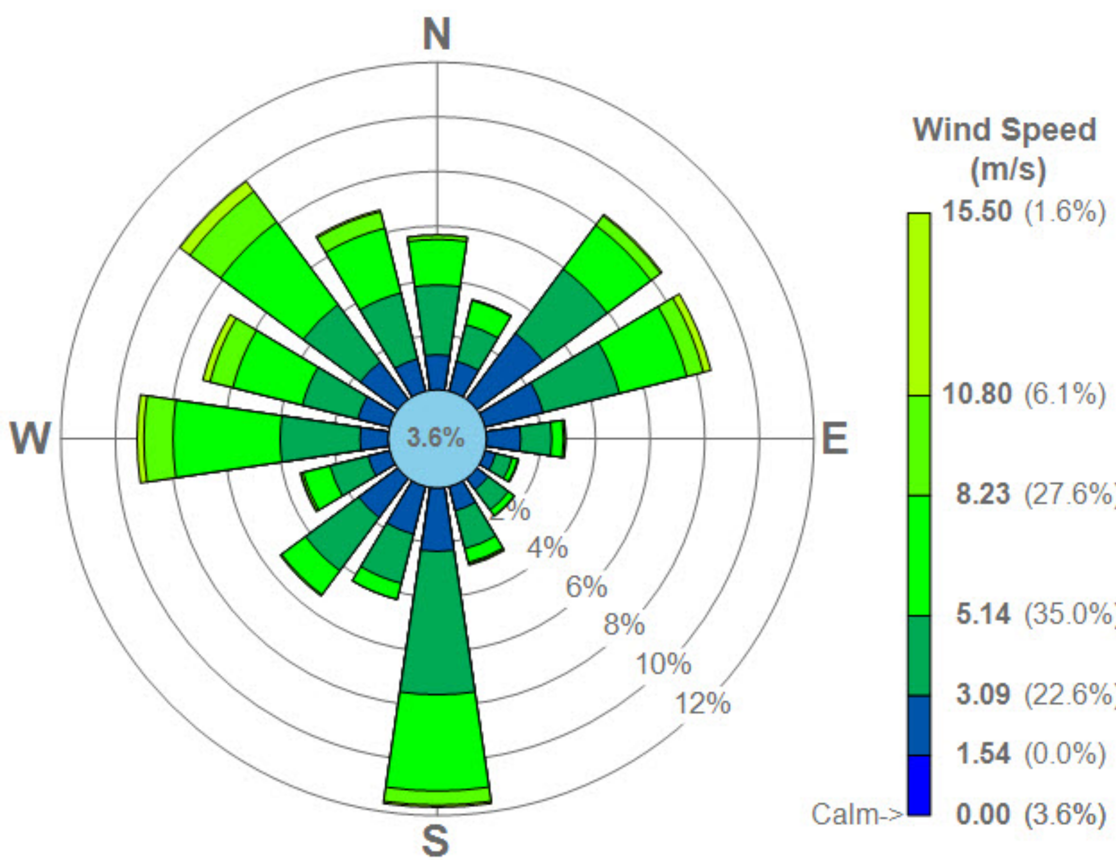
Temporal wind speed variations

- 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

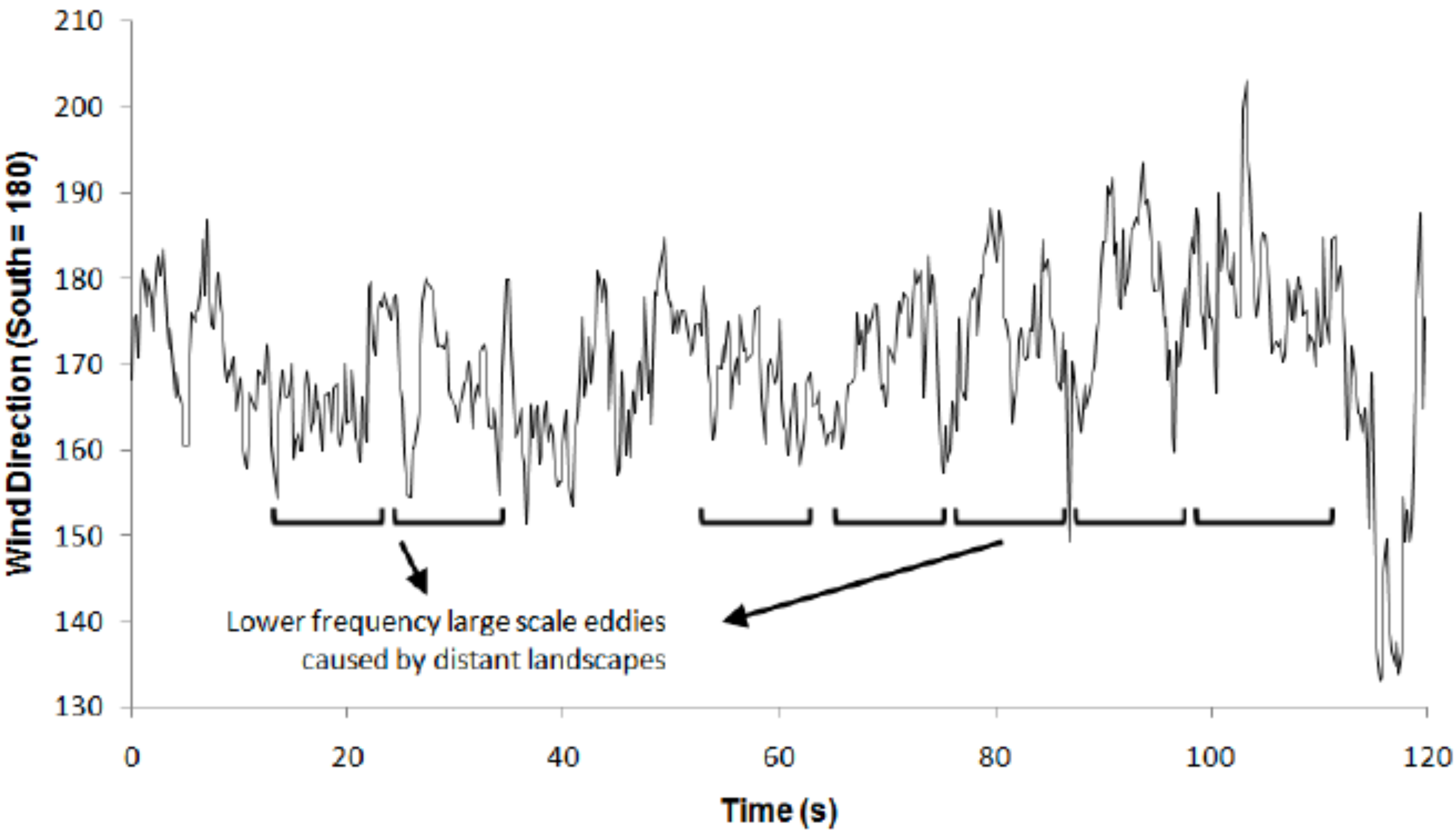


Wind speed and direction data

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



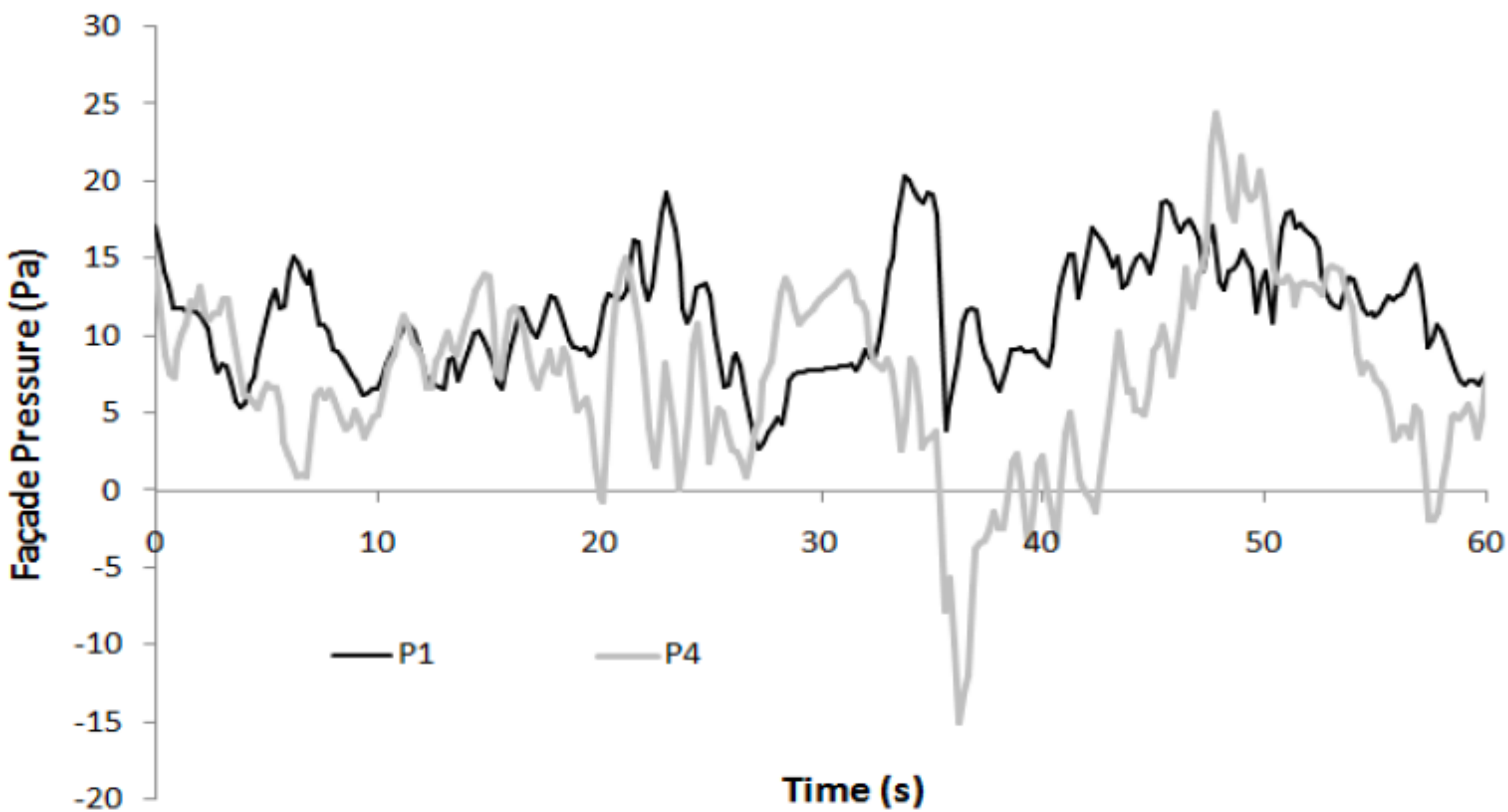
Real measured wind data: instantaneous direction changes



Courtesy of Dr. James Lo, Dissertation 2012

Real measured wind data: instantaneous façade pressures

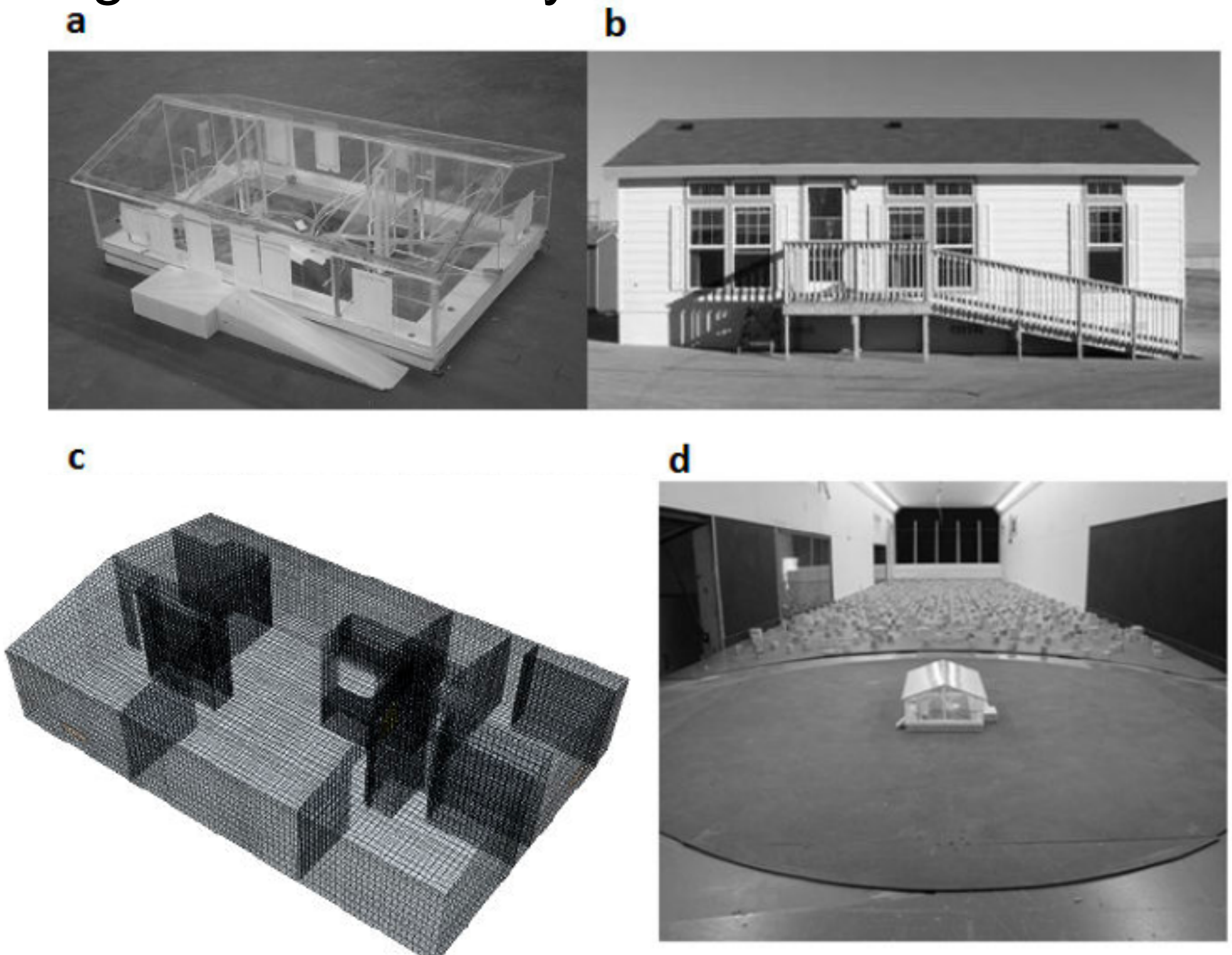
- Surface pressures measured on two different facades



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:

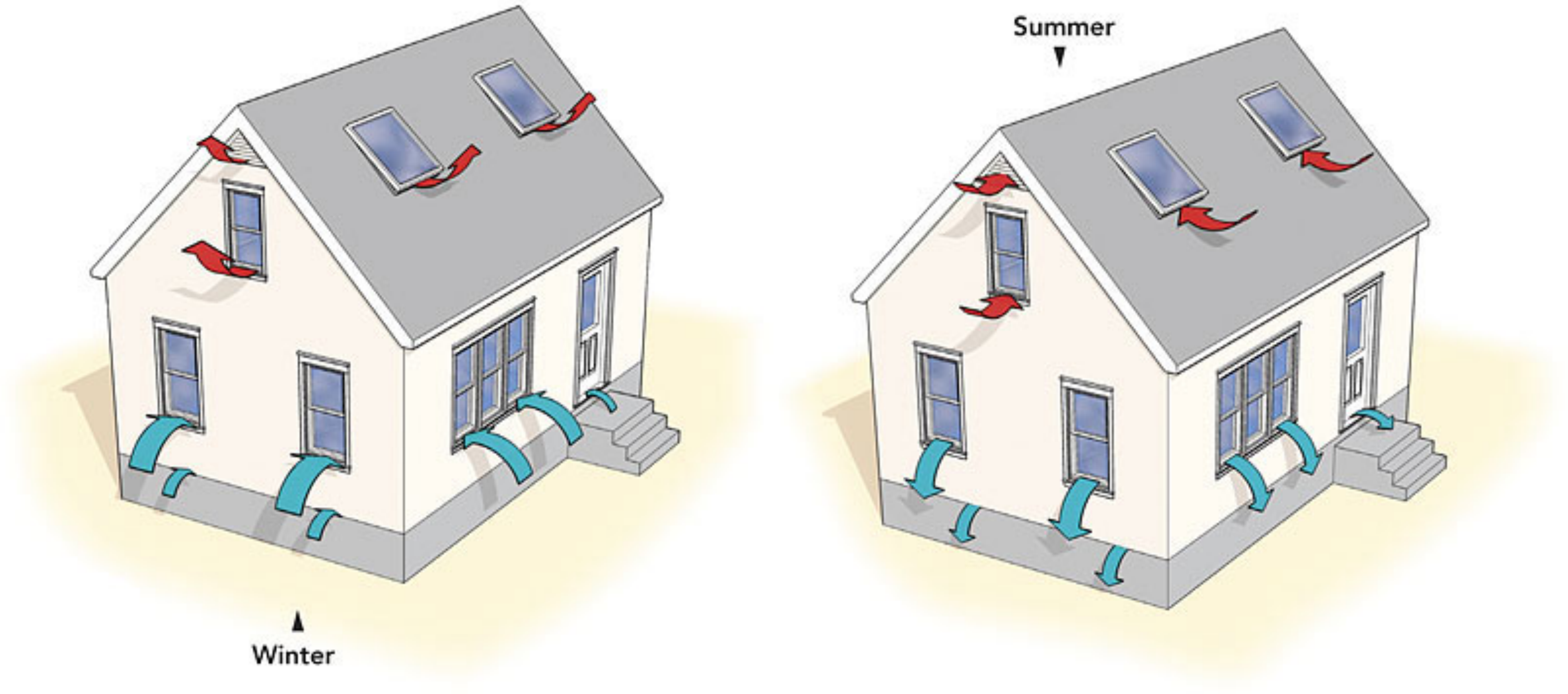
$$P = \rho g h$$

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)

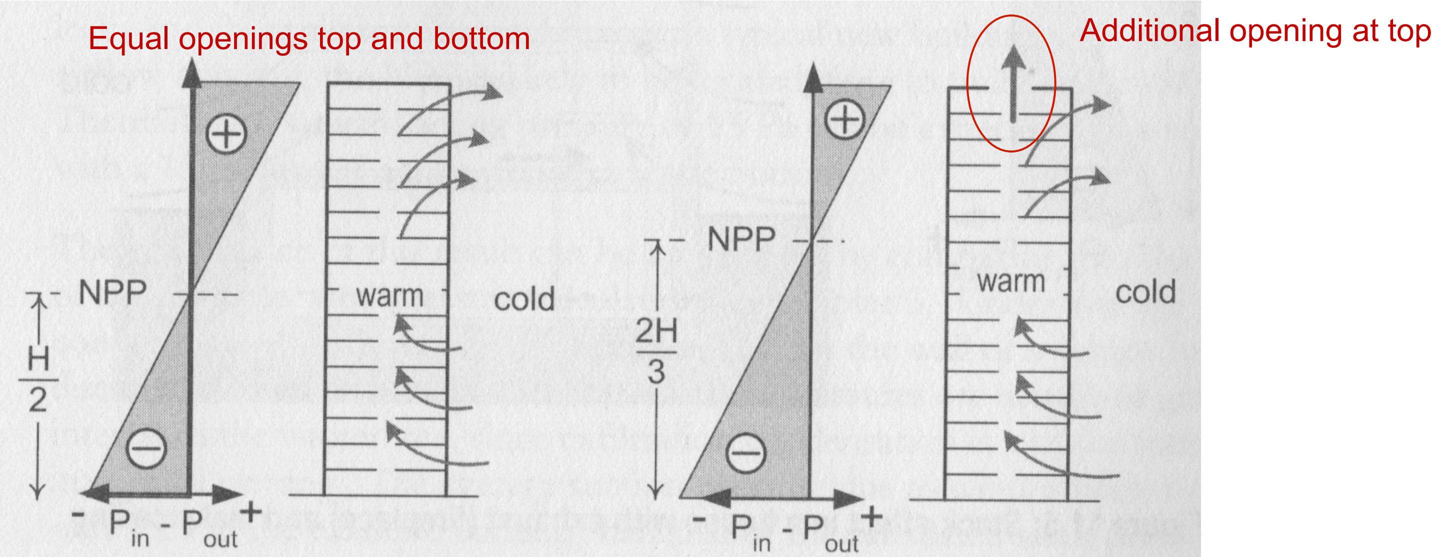


Figure 11.4: Stack-effect driven airflow through typical multi-story building

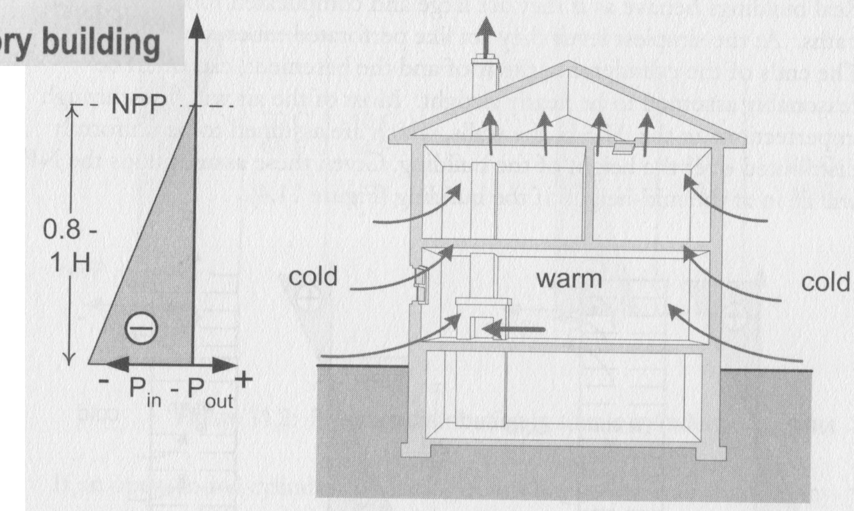
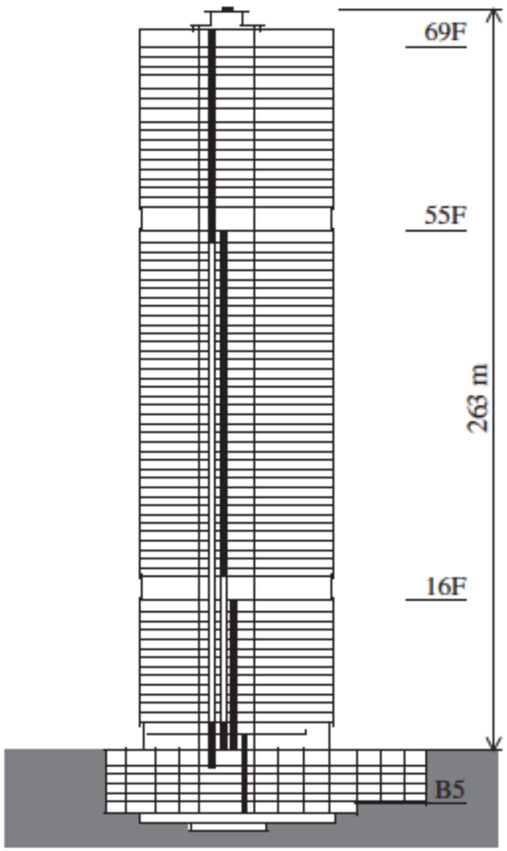
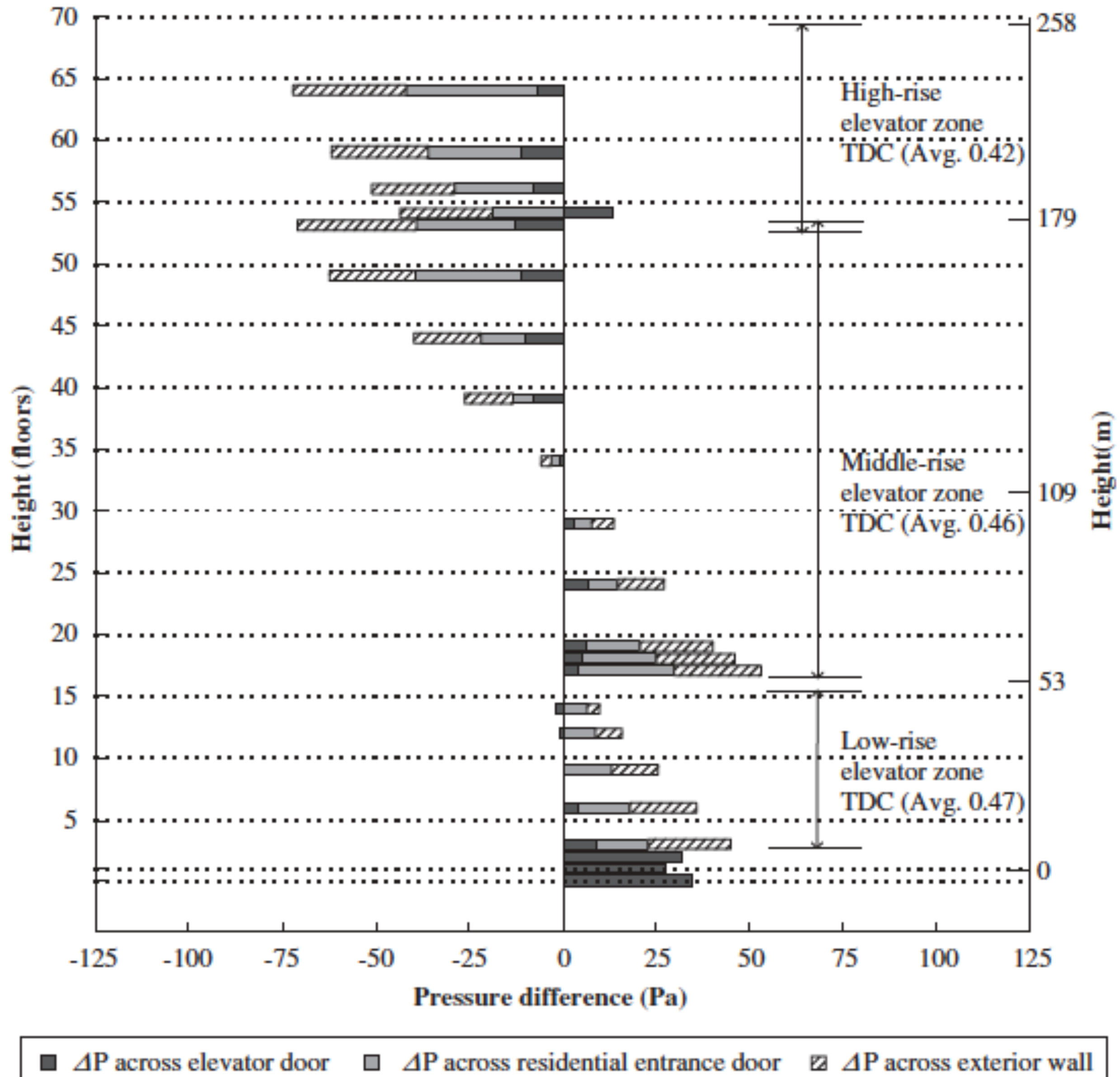


Figure 11.5: Stack effect in a house with exhaust (fireplace) and leaky ceiling

Real field measurements of stack effect

~70 story building in Korea

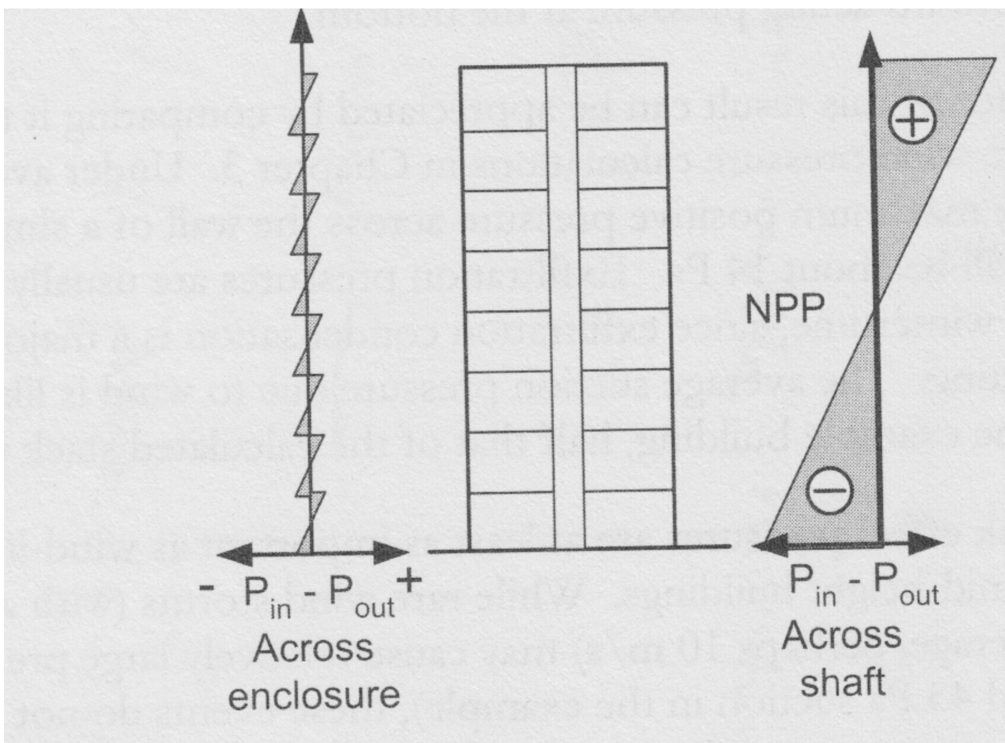




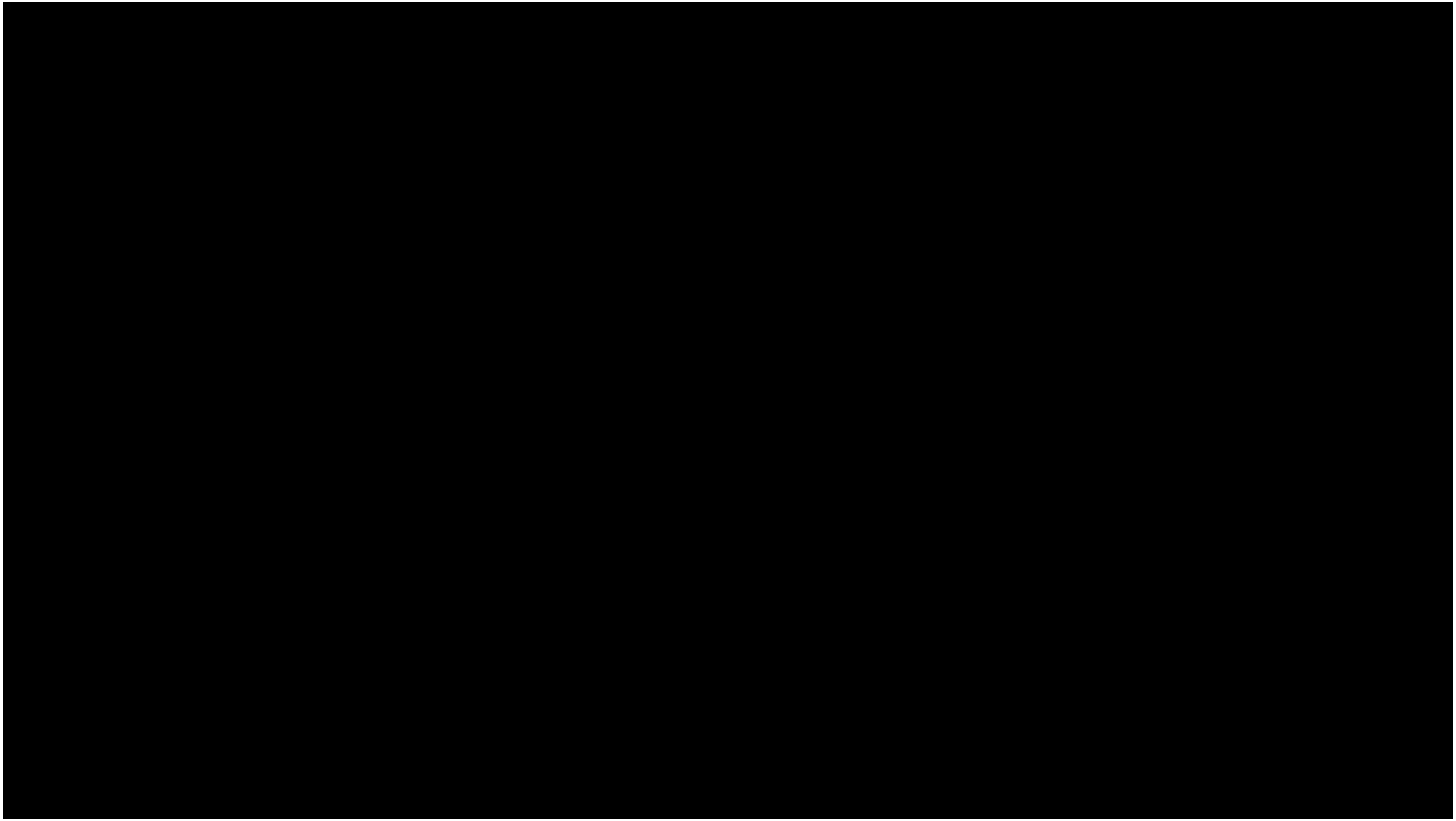
Jo et al. **2007** *Building and Environment* 42:263–277

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

Procedure for modern **blower door** test

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

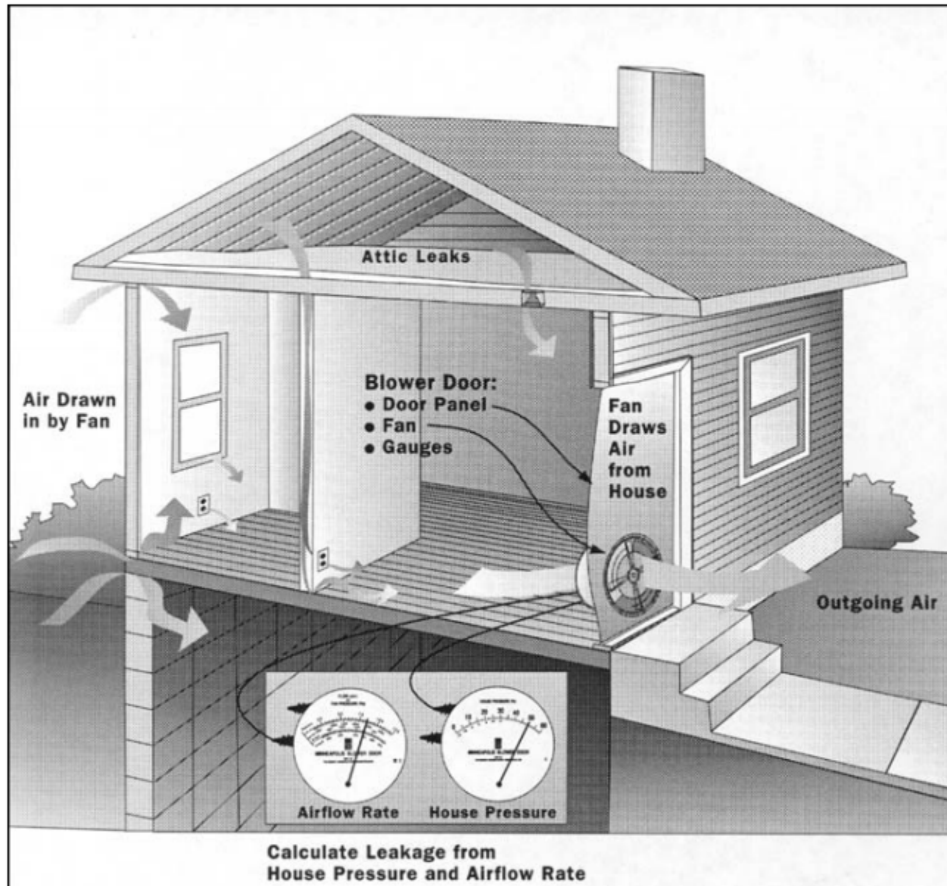
2. Use fan to create artificial pressure difference between inside and outside

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

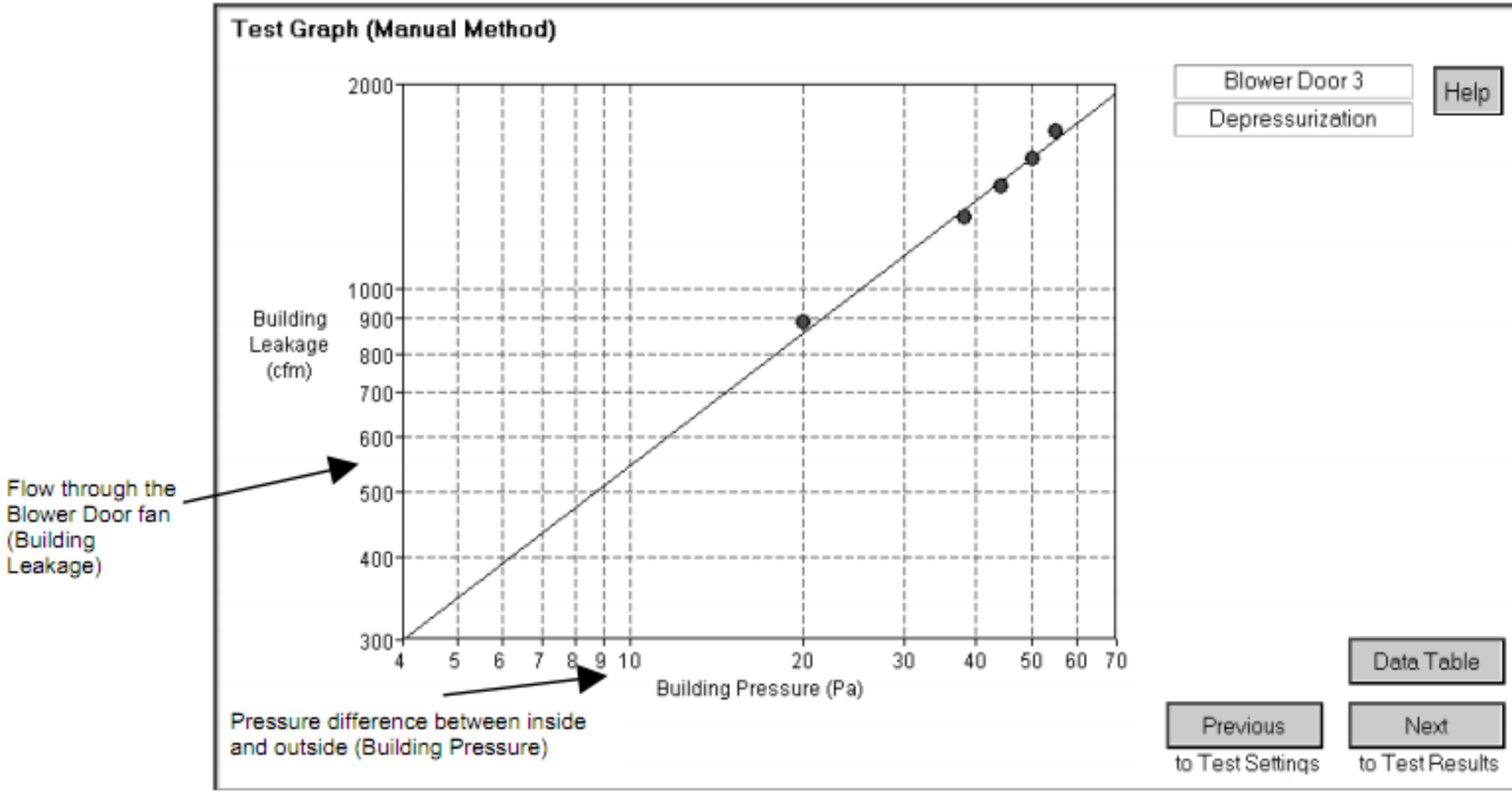
- Used to measure air-tightness in buildings worldwide



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:

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

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

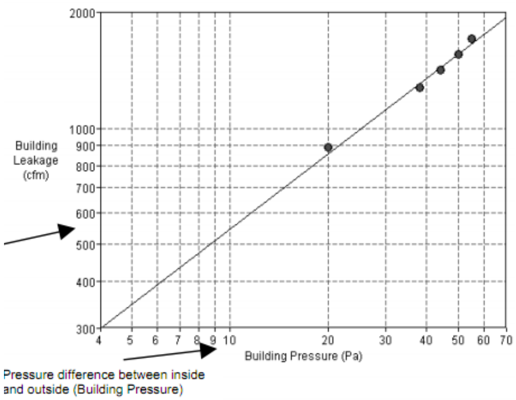
$$\ln Q = \ln C + n \ln \Delta \mathrm{P}$$

$$\mathrm{Y} \quad = \quad \mathrm{b} \; + \; \mathrm{mx}$$

Slope = n

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

Blower door tests: Resulting parameters



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

Leakage Exponent (dimensionless)

Airflow ($m^3\ s^{-1}$)

Leakage Coefficient ($m^3\ s^{-1}\ Pa^{-n}$)

I/O Pressure Difference (Pa)

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

Estimated Leakage Area (cm^2)

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

Normalized Leakage, NL (dimensionless)

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

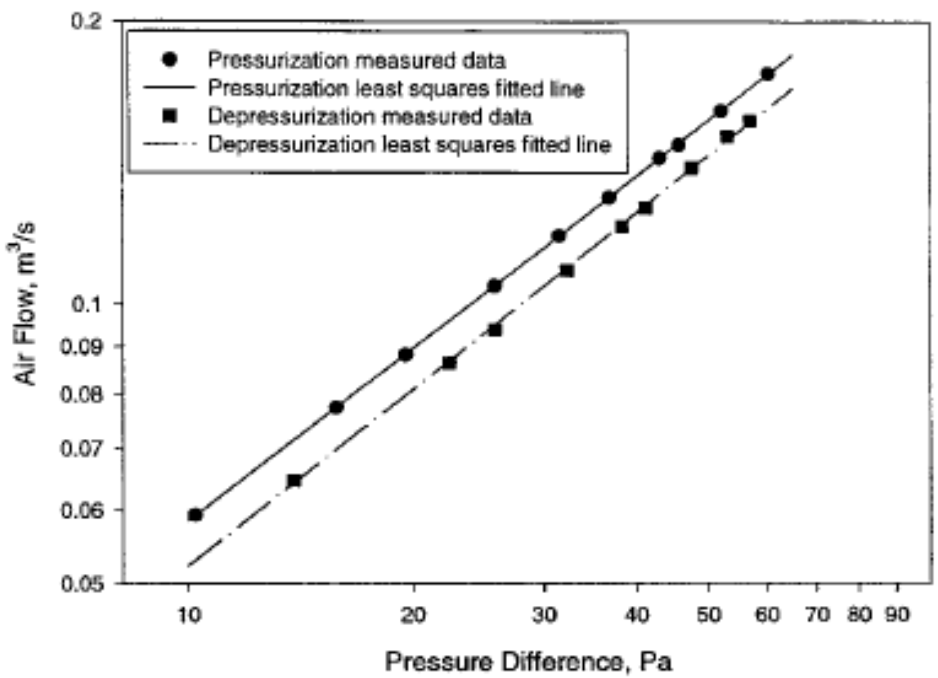
Air Changes per Hour @ 50 Pa (hr^{-1})

Source: ASTM E 779 and ASHRAE Standard 119

Blower door test standard: ASTM E 779

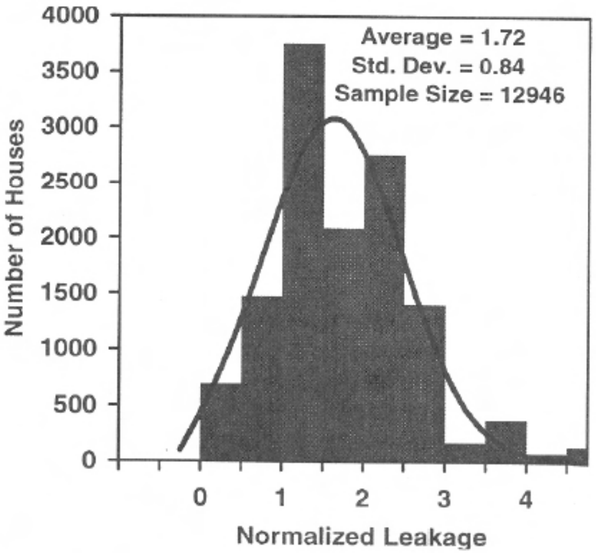
- In ASTM E 779, the leakage rate, Q, is measured at several pressures from ~10 Pa to ~60 Pa in increments of 5-10 Pa
  - Test is performed once during pressurization mode
    - Air blowing into the building
  - Then performed again in depressurization mode
    - Air blowing out of the building
  - Can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

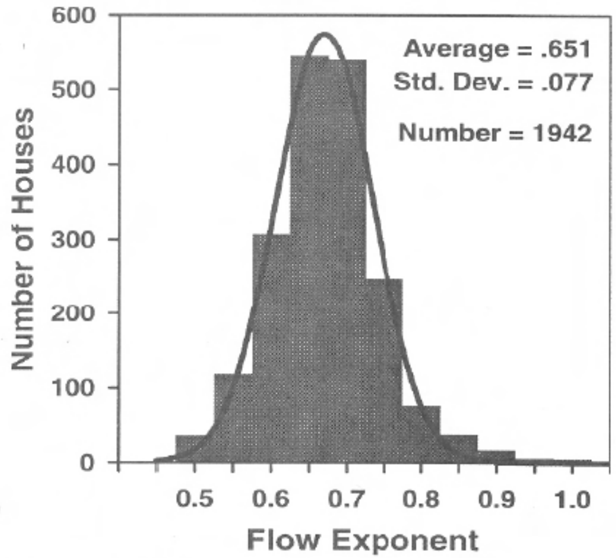
Question:
Why would pressurization and depressurization tests yield different results in a single building?

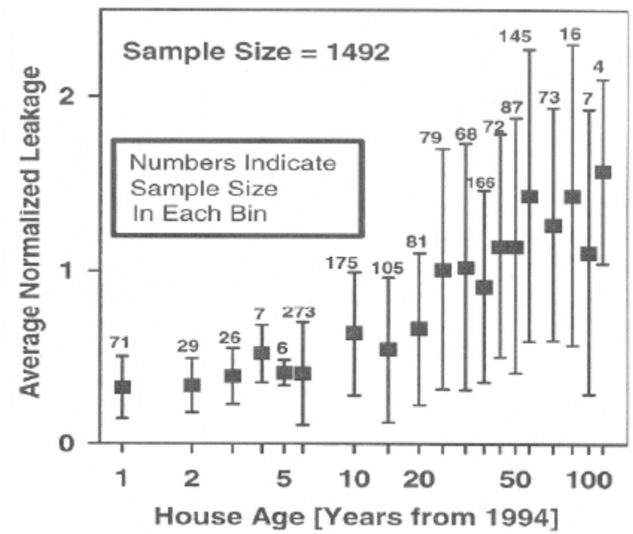


Blower door results: US homes

- 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

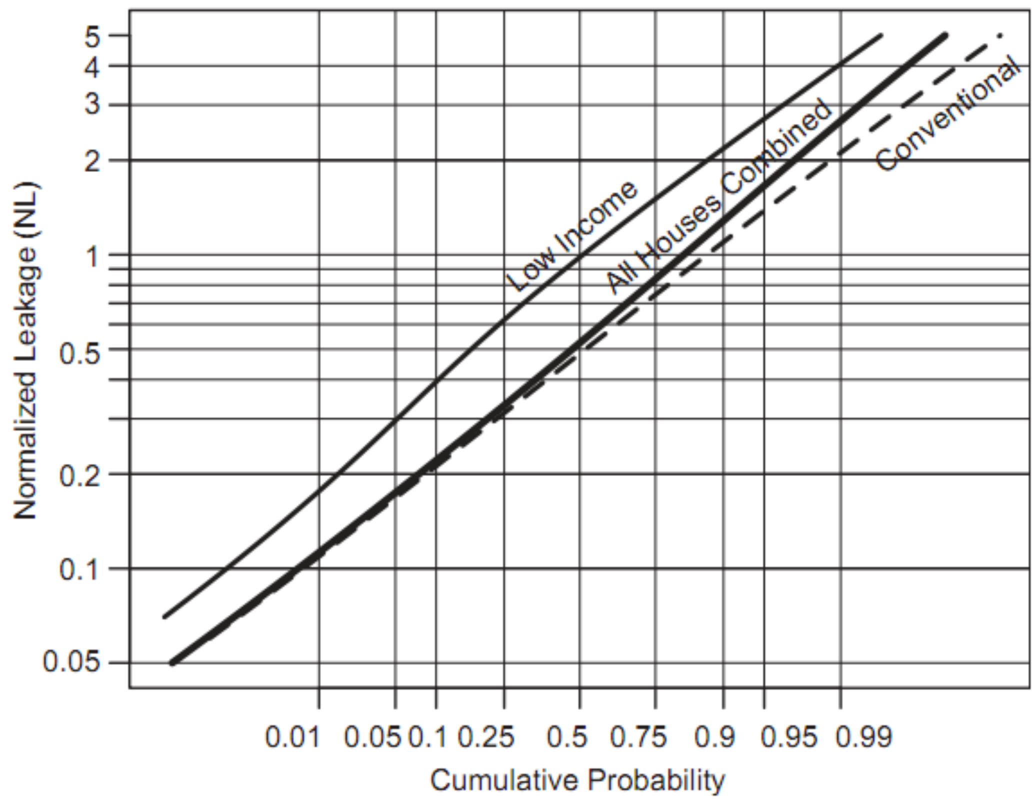
- LBNL continues to maintain a database of blower door data
  - http://resdb.lbl.gov/
  - Almost 150,000 homes characterized

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

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

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

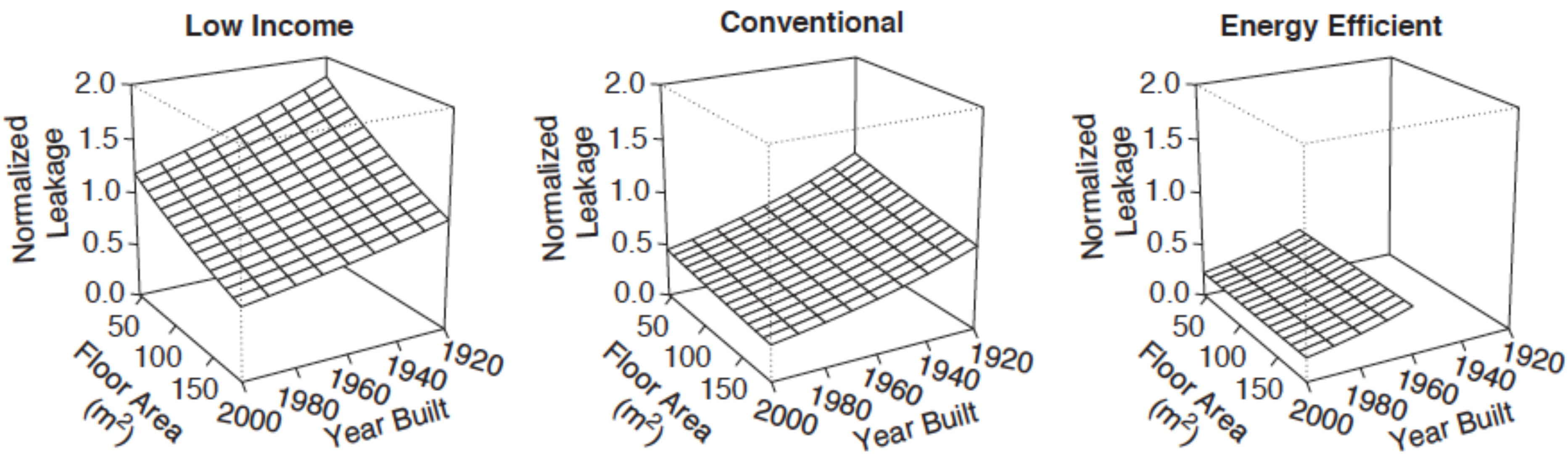
$$ACH_{50} = \frac{Q_{50\ Pa}}{V}$$



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

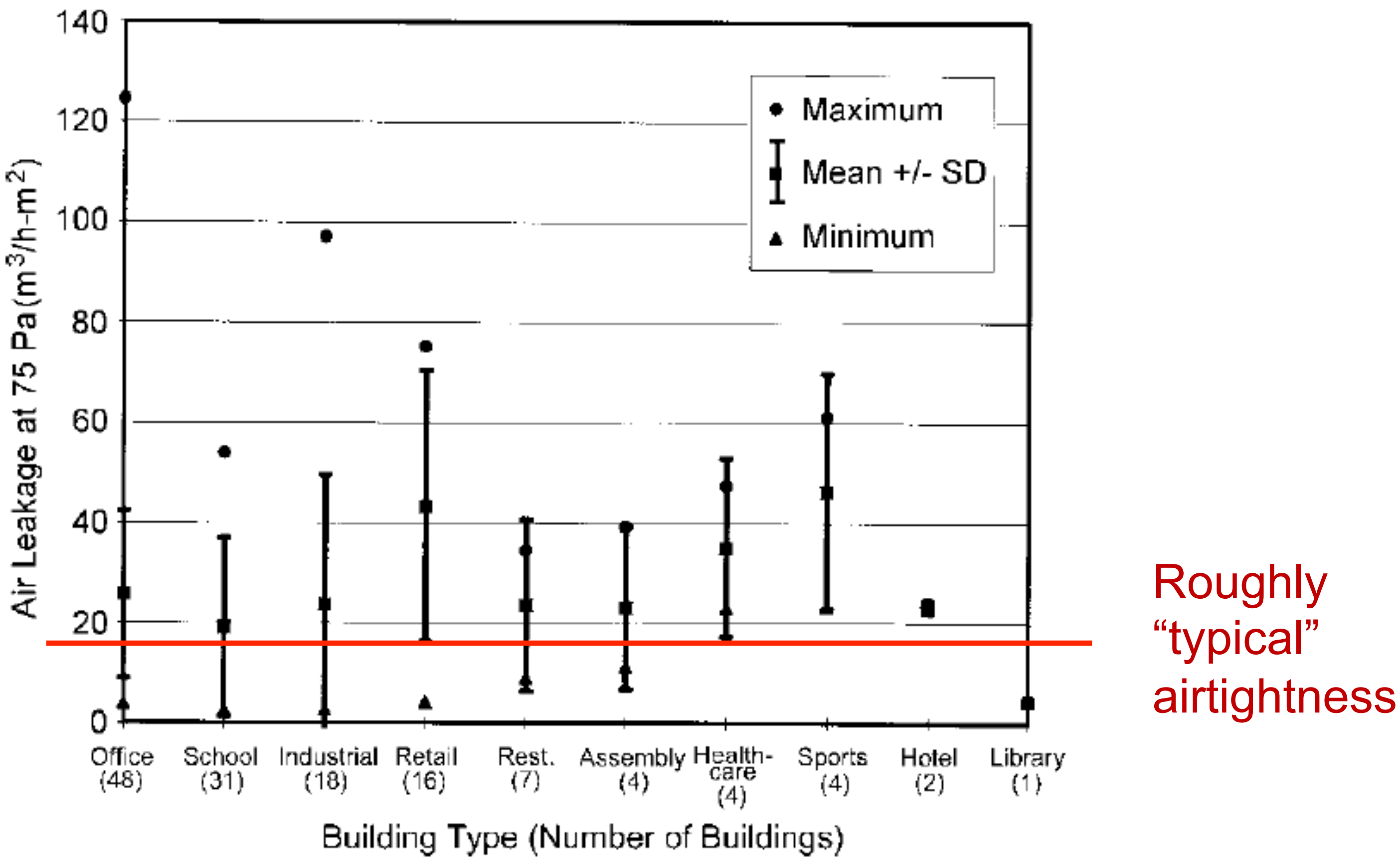


$$NL = 1000\frac{ELA}{Af}\left(\frac{H}{2.5m}\right)^{0.3}$$

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

Commercial building air leakage

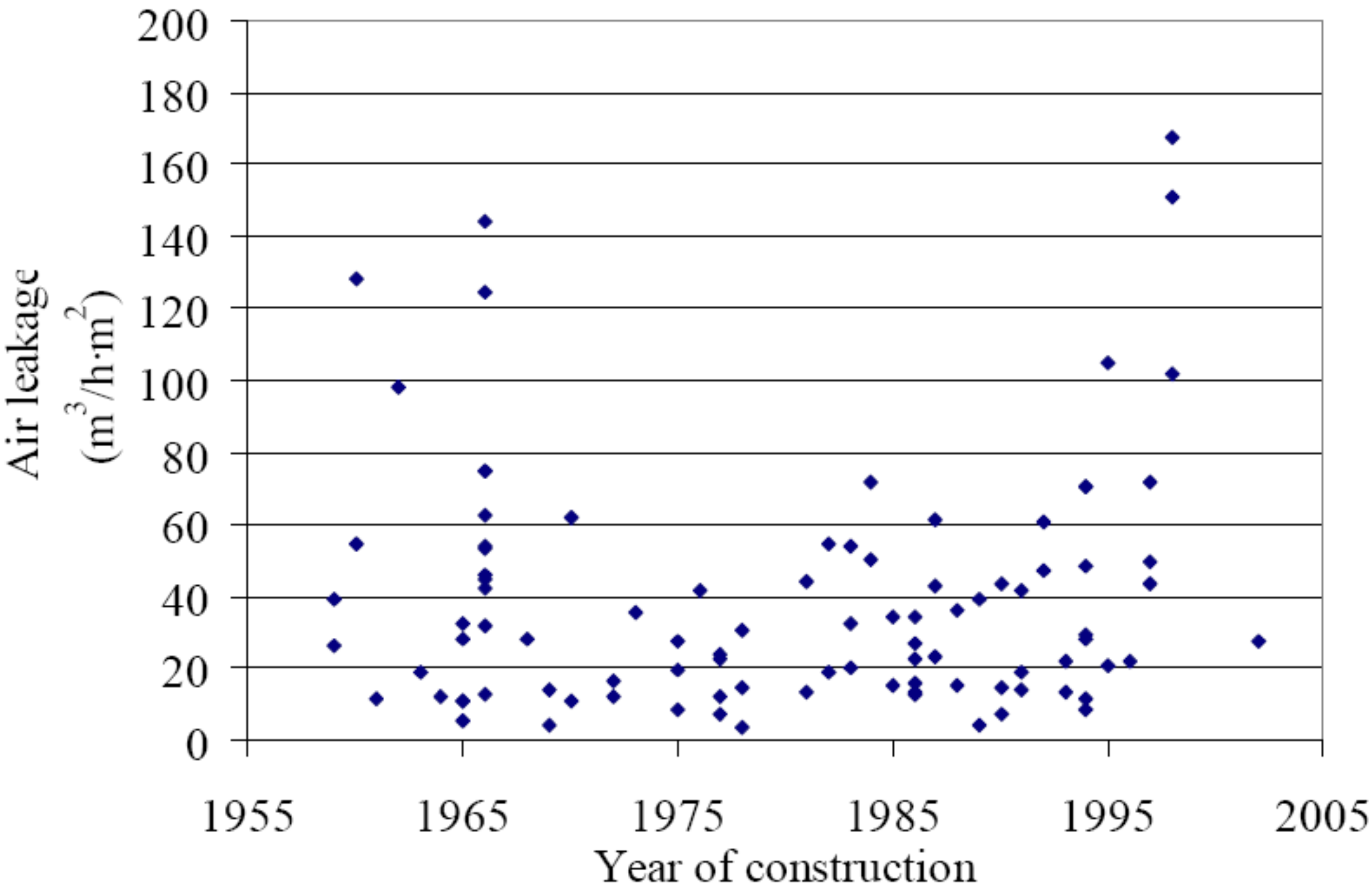
- Traditionally assumed that commercial and institutional buildings were built to be airtight
  - Turns out that's not always the case



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

Commercial building air leakage vs. age

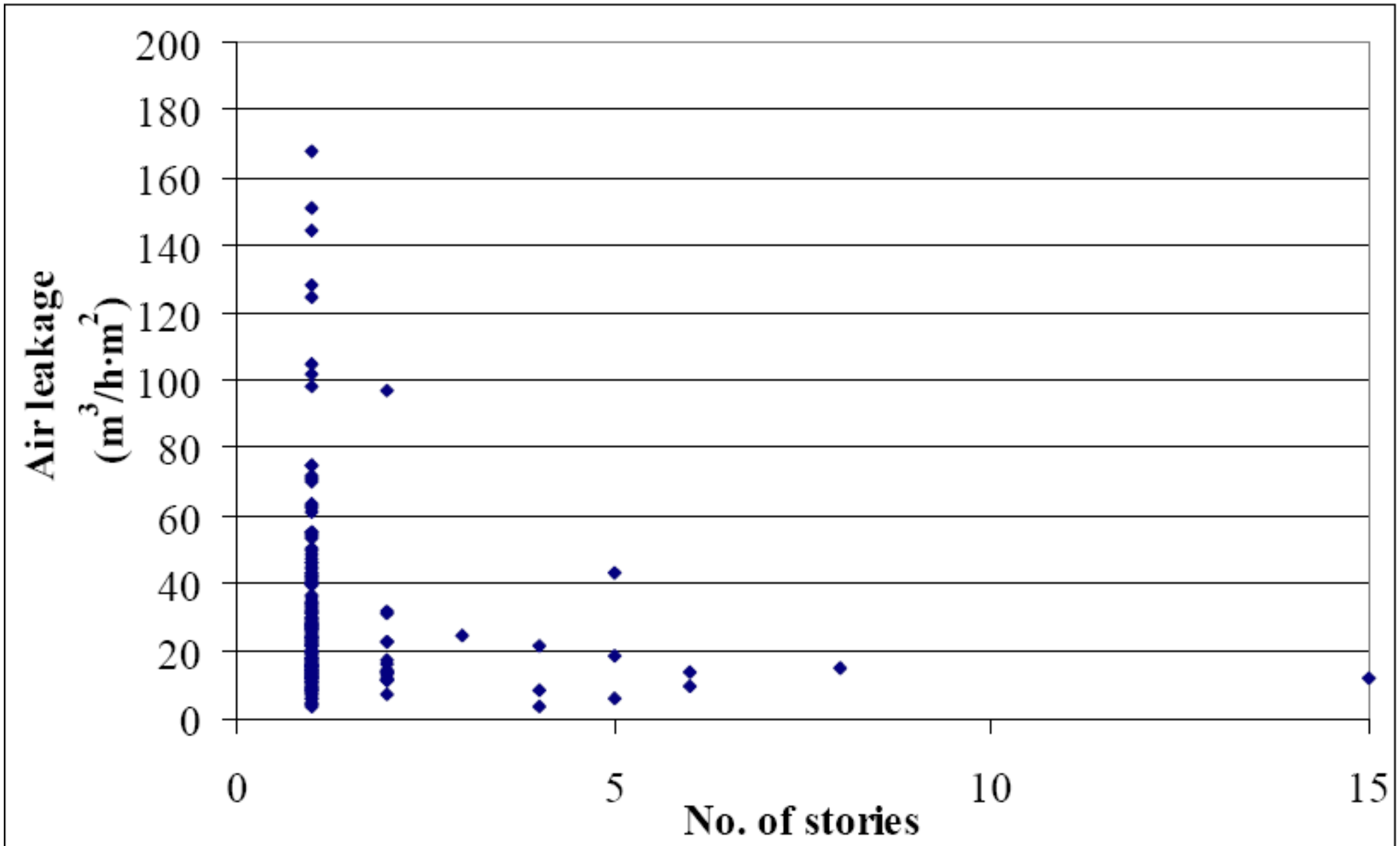
- Less correlation with age than other factors
  - Note small range of age



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

Commercial building air leakage vs. height

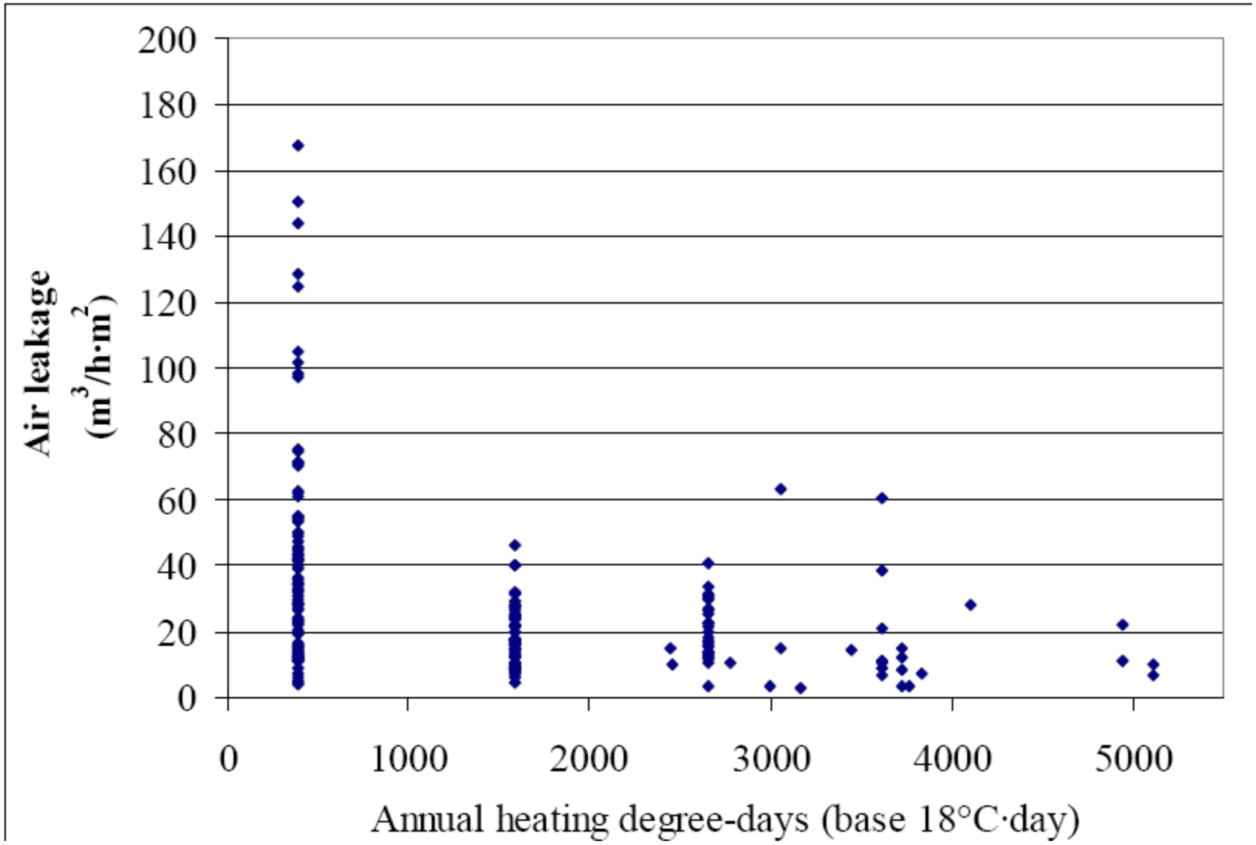
- Taller buildings were tighter
  - Stronger construction standards?



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

Commercial building air leakage vs. climate zone

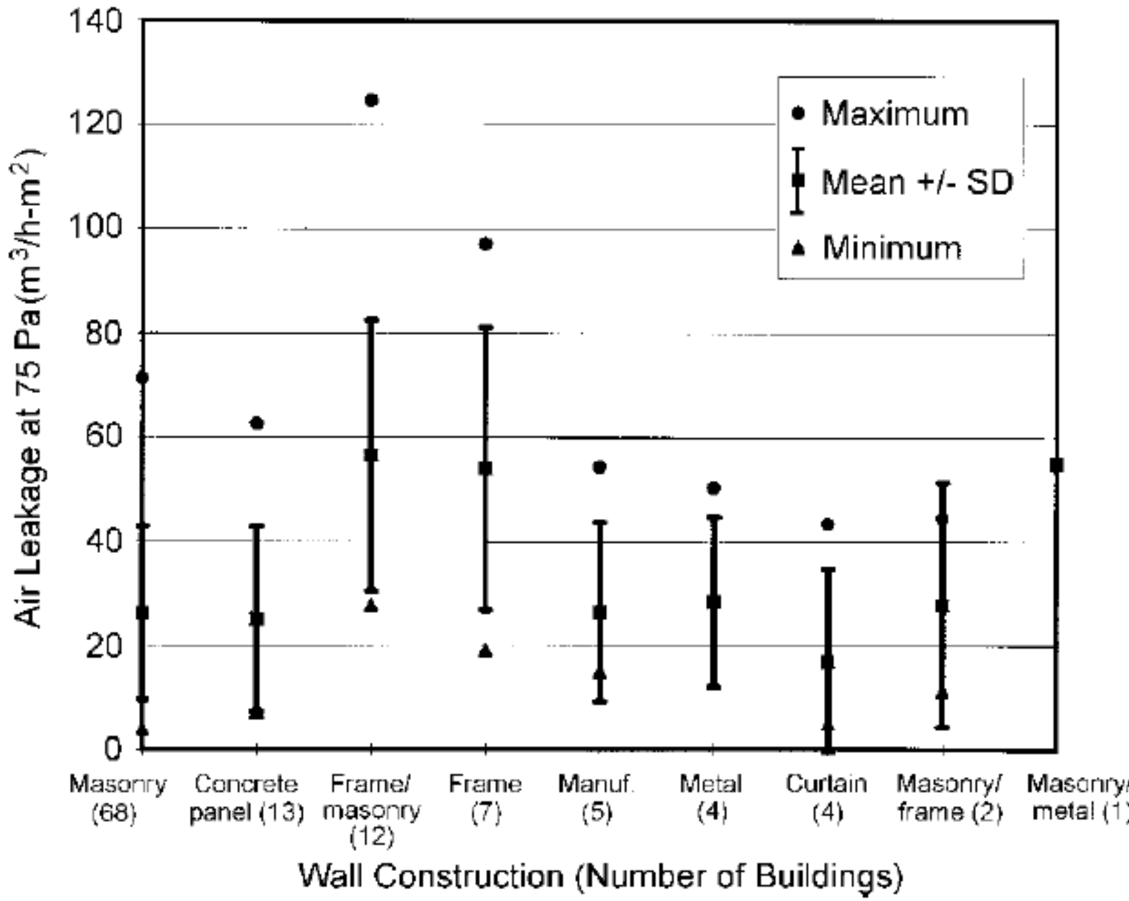
- Buildings were tighter in colder climates
  - Necessity?
  - Stricter building codes?



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

Commercial building air leakage vs. wall type

- Leakage varied by wall construction type
  - 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

Some recommended whole-envelope leakage rates

Air Leakage Index ($m^3/hr/ m^2$ @ 50Pa)		
Building Type	**Best Practice**	**Normal**
Offices (naturally ventilated)	3.0	7.0
Offices (mixed mode)	2.5	5.0
Offices (air conditioned/low energy)	2.0	5.0
Factories/Warehouses	2.0	6.0
Superstores	1.0	5.0
Schools	3.0	9.0
Hospitals	5.0	9.0
Museums and Archival Stores	1.0	1.5
Cold Stores	0.2	0.35
Dwellings (naturally ventilated)	3.0	9.0
Dwellings (mechanically ventilated)	3.0	5.0

From UK CIBSE-T23 Building Standard

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

Measuring actual air exchange rates

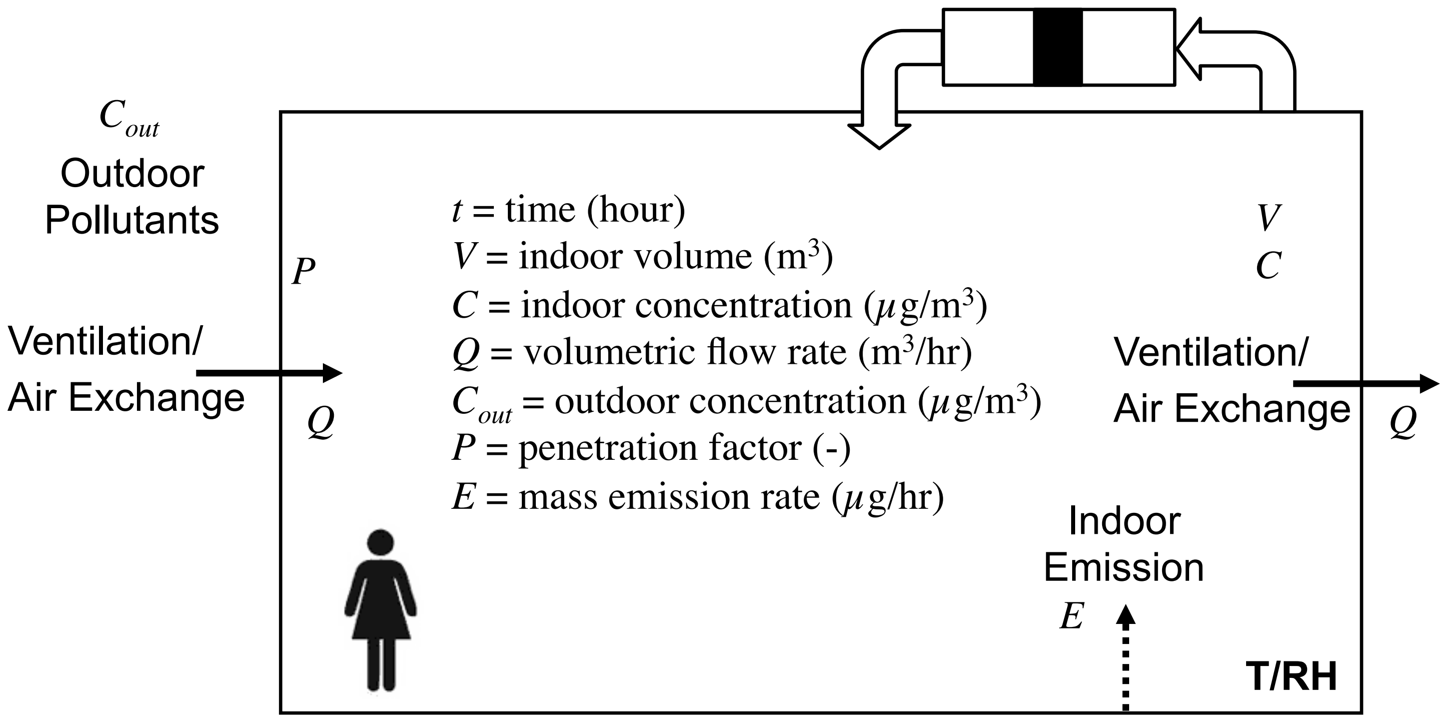
- Two general strategies to get air exchange rate
  - AER, ACH, and λ all used interchangeable for AER

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



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

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

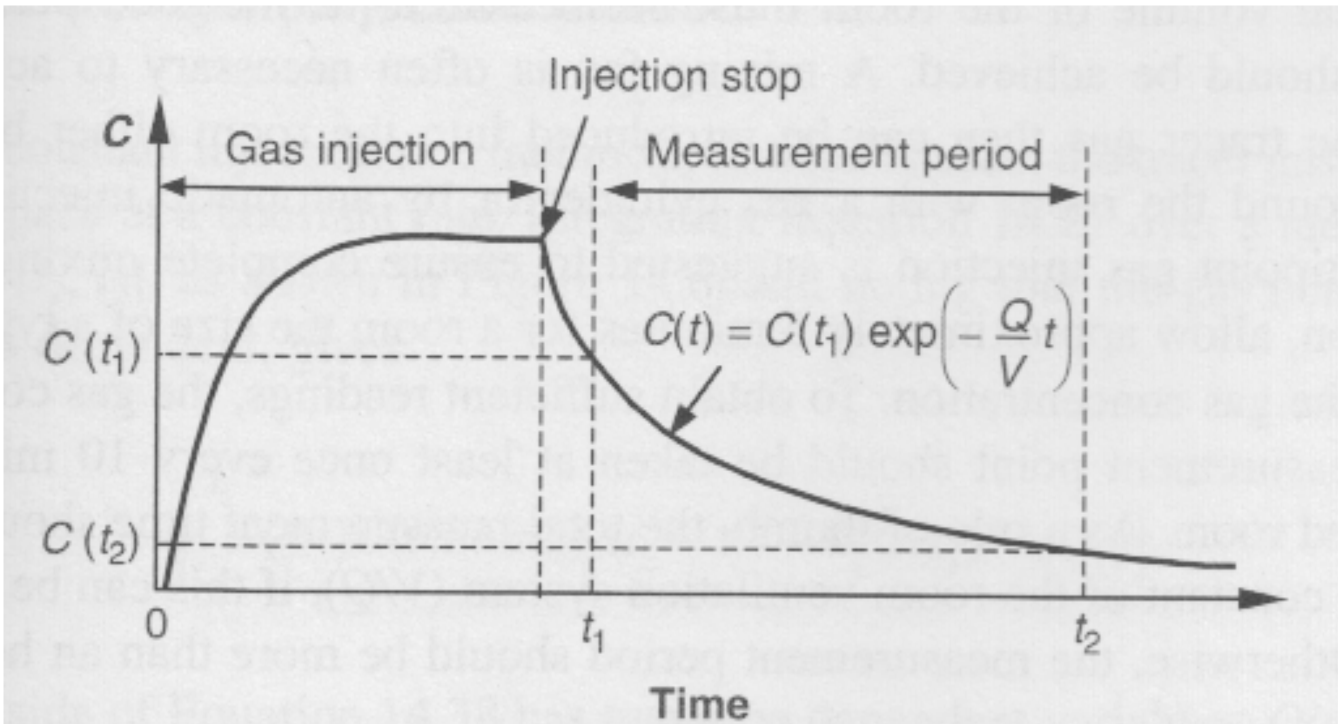
Common tracer gases

- SF_6
  - ppm with IR absorption
  - ppb with GC/ECD
- CO_2
- Nitrous oxide
- Freon
- Helium

- Really no “perfect” tracer yet
  - Some are too expensive
  - Humans are sources of some
  - Some have human health and/or climate impacts of others

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)

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

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

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

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

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

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:

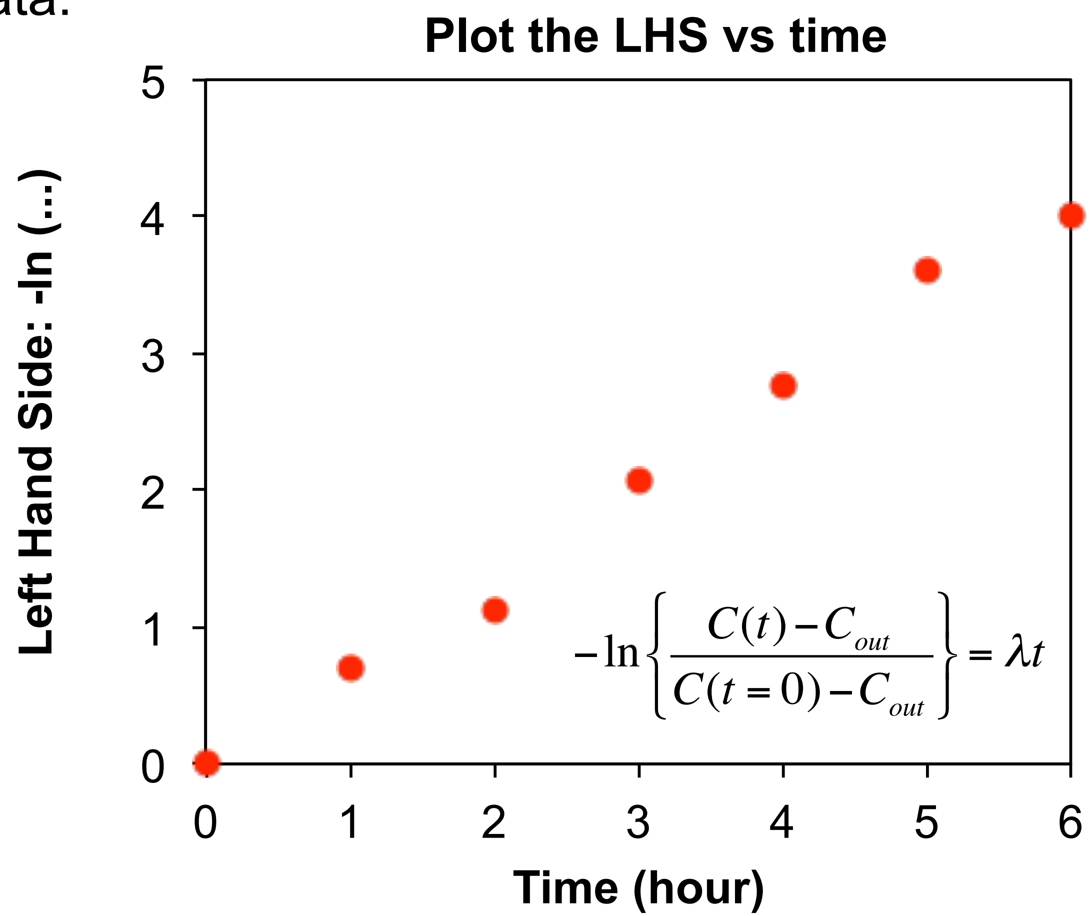
$$-\ln\left\{ \frac{C(t) - C_{out}}{C(t=0) - C_{out}} \right\} = \lambda t$$

- 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?

- **Example:** You perform a tracer test with CO_2
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Time (hr)	C(t) (ppm)
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1	1450
2	900
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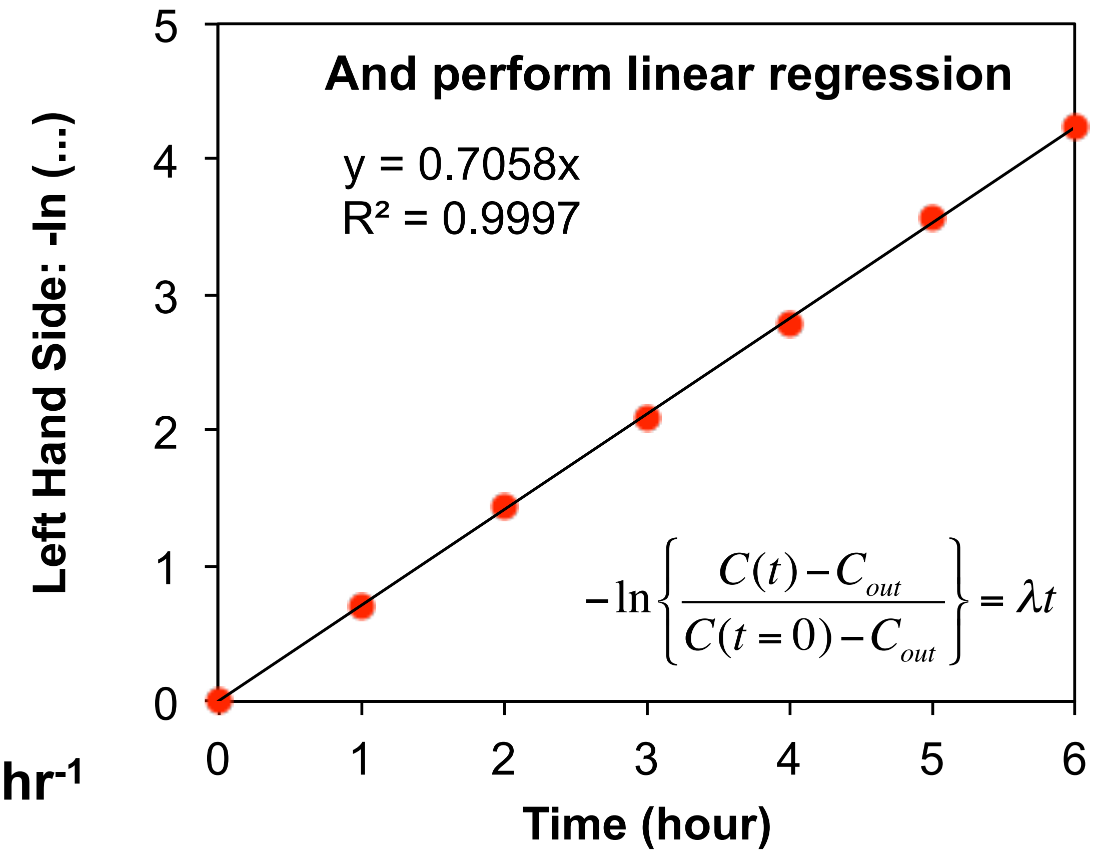
6	430

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}

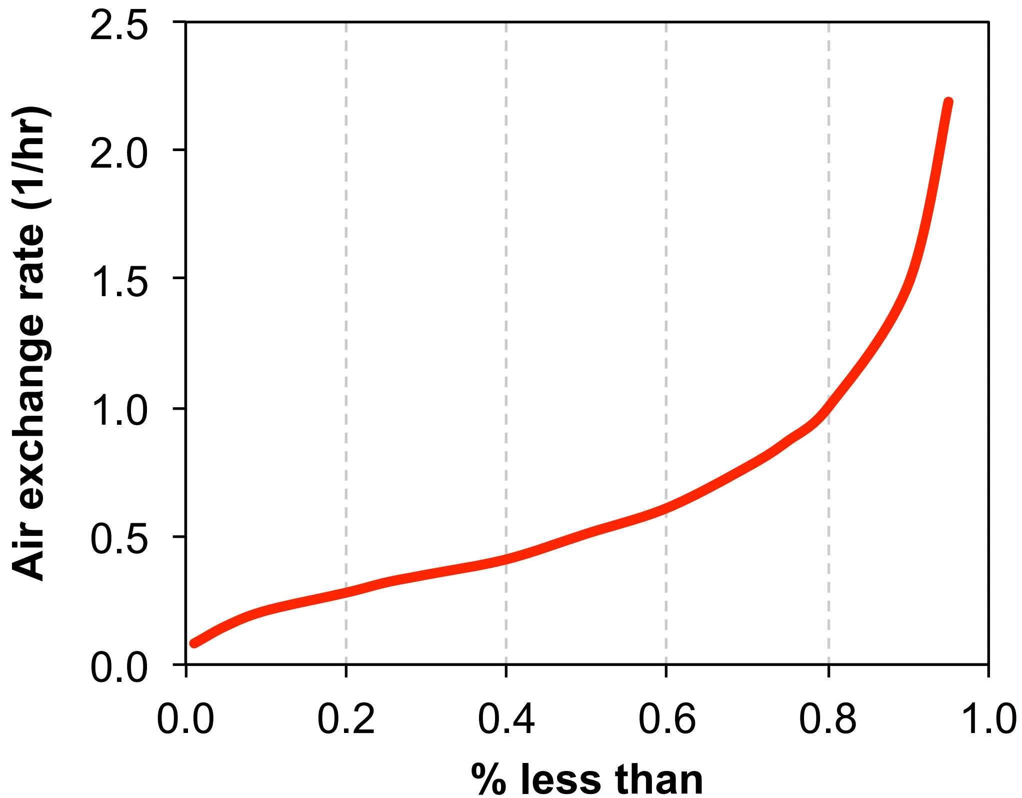
Decay test for AER

- 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

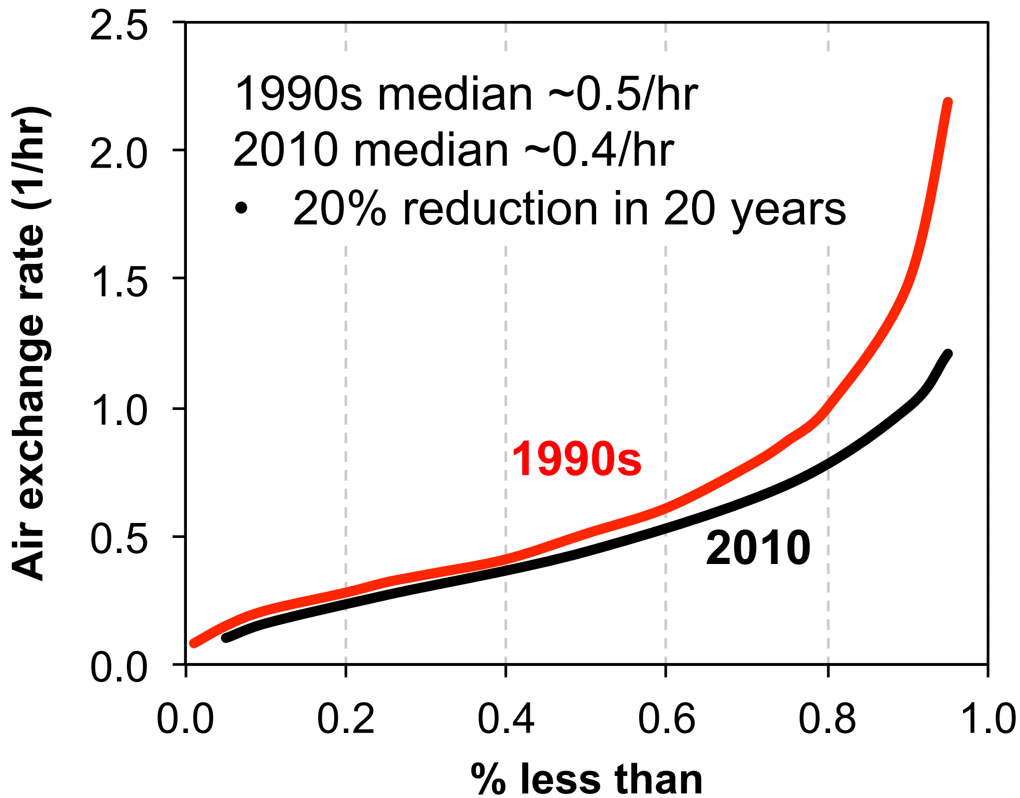


- What do you think this curve looks like now?

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)

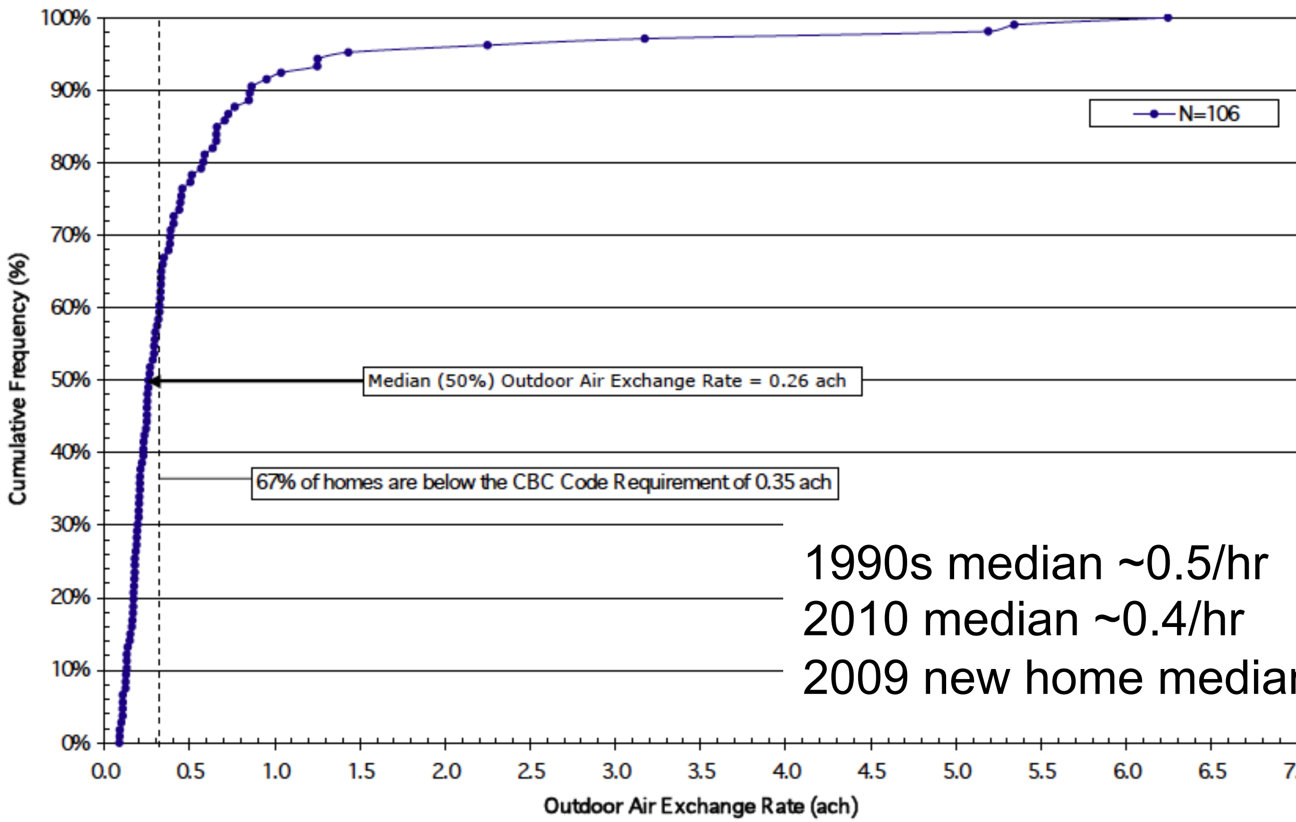


- What about new homes?

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)



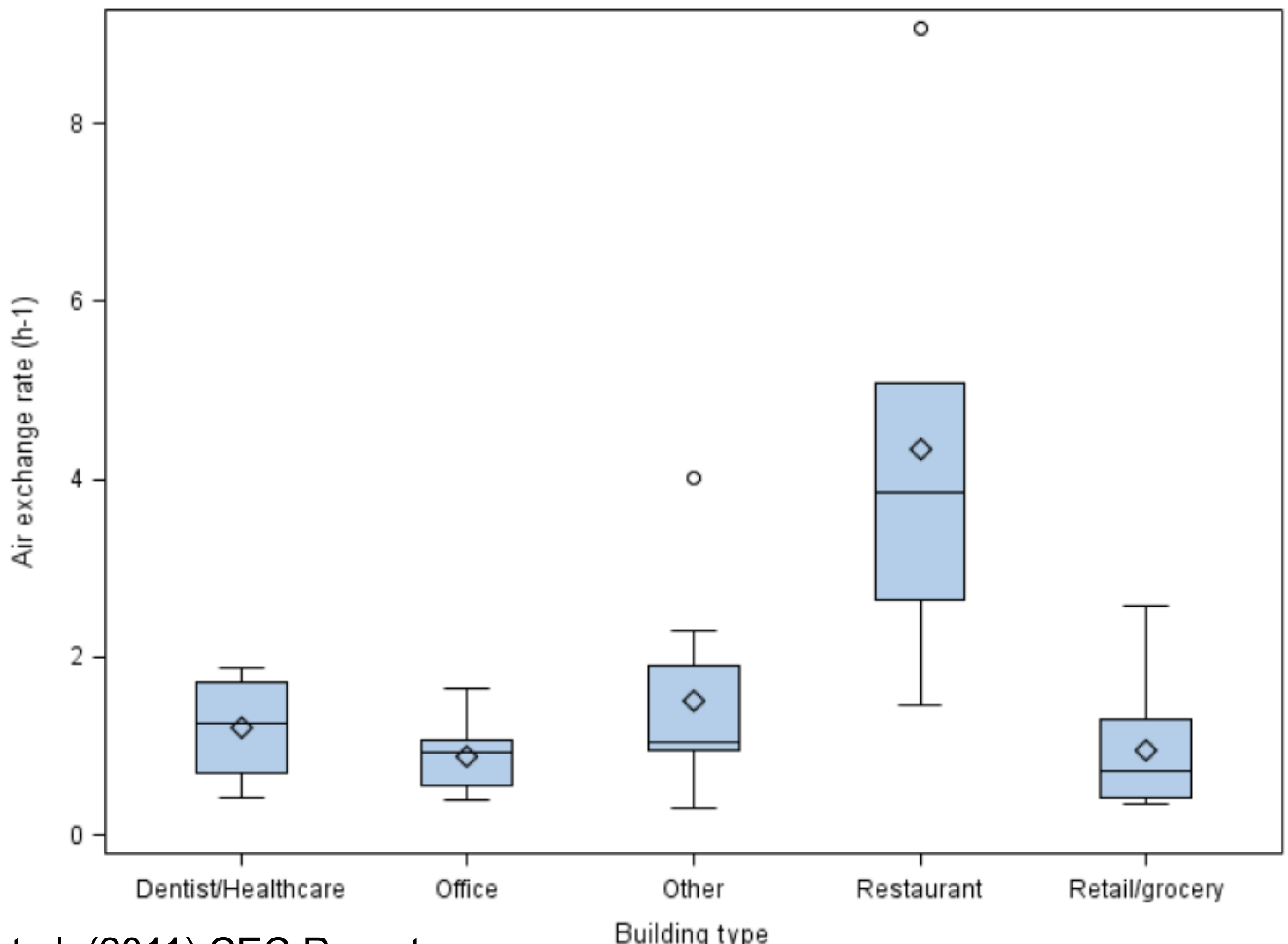
1990s median ~0.5/hr
2010 median ~0.4/hr
2009 new home median ~0.26/hr

- 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

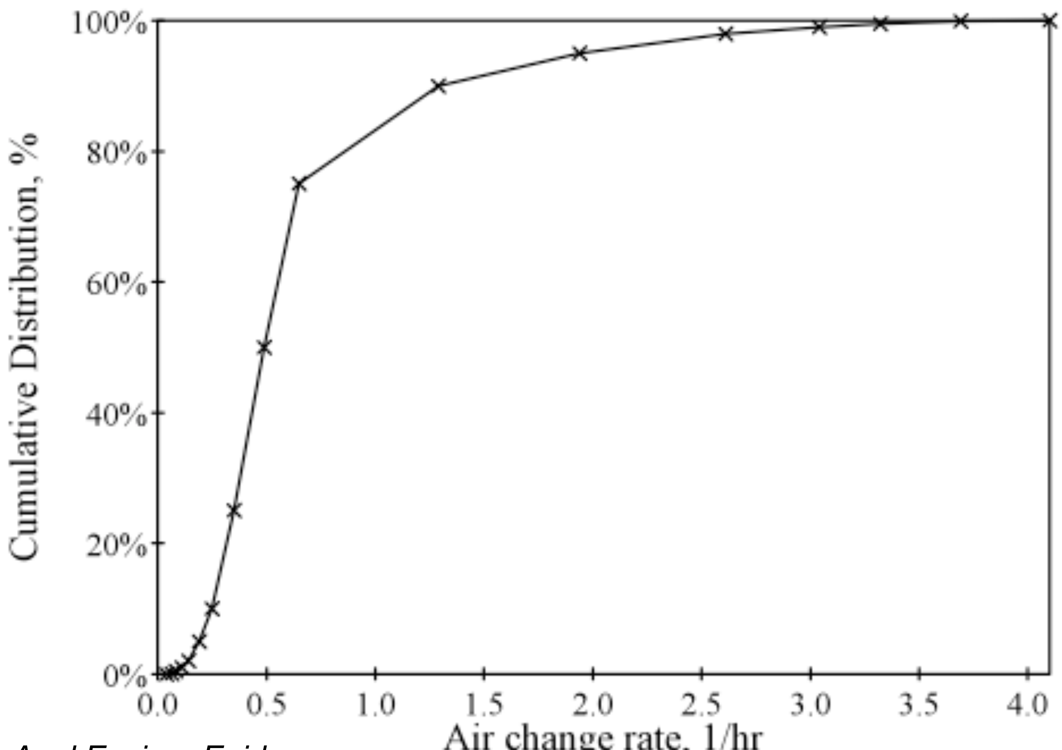
- Recent study of ~40 commercial buildings in CA



Bennett et al. (2011) CEC Report

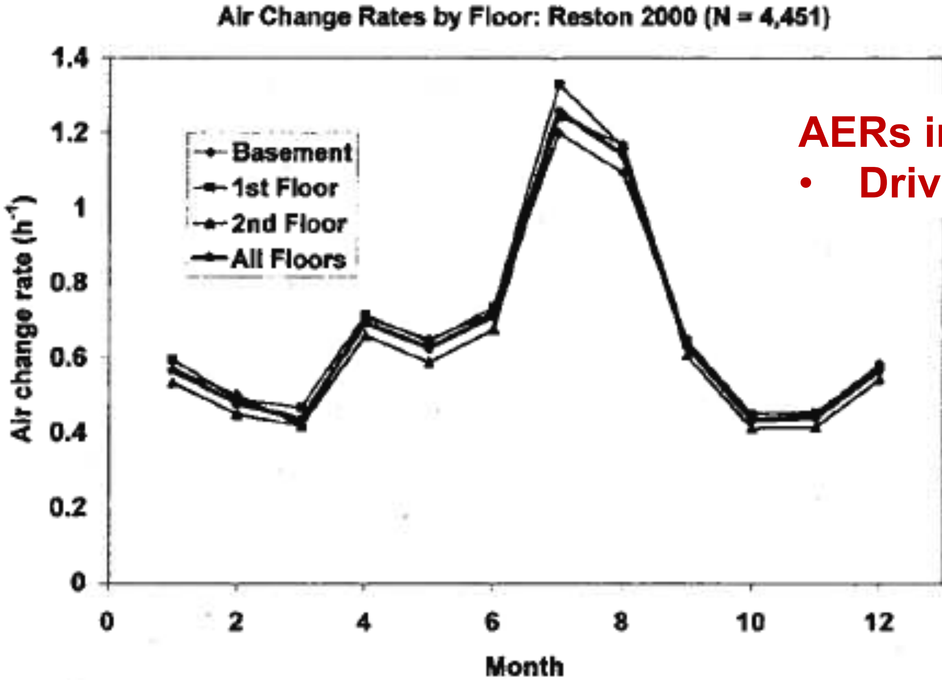
Variations in AER in individual buildings

- 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



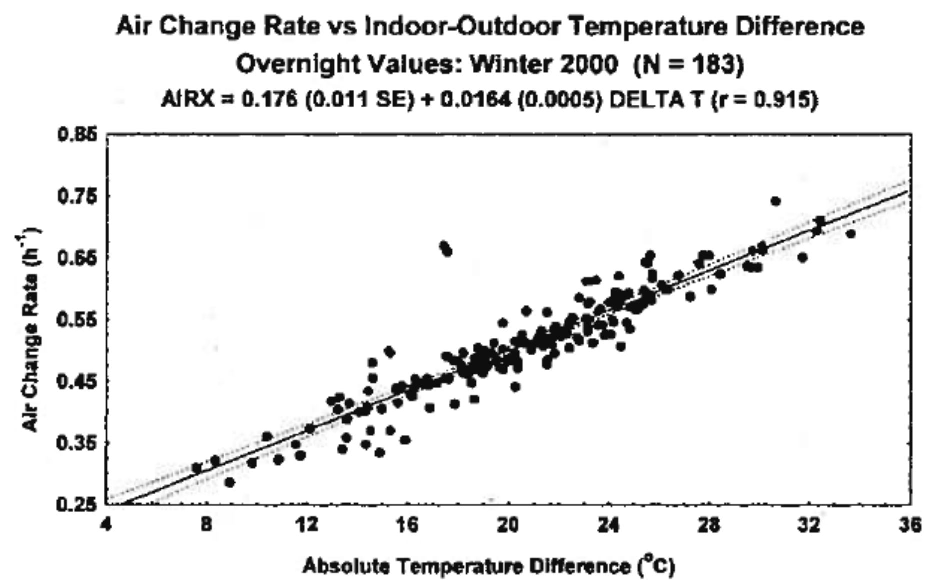
Wallace et al. 2002 *J Expo Anal Environ Epidem*

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*

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 models and blower door data to predict AER with reasonable accuracy
  - 2013 ASHRAE Handbook of Fundamentals Chapter 16
  - 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

- LBL model

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

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

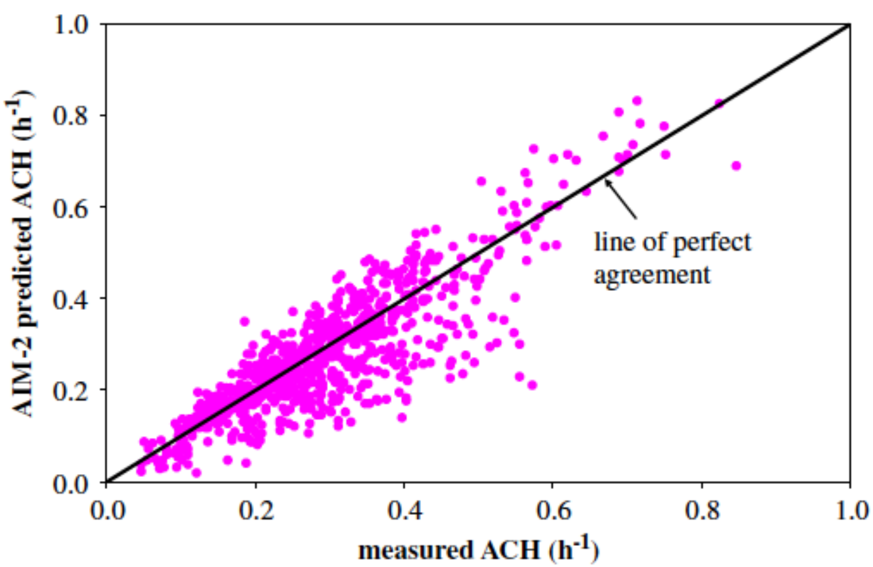
- Alberta air infiltration model (AIM-2)

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

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

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

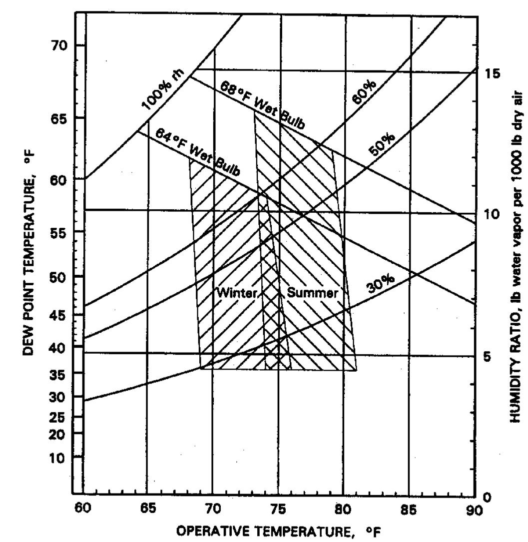
of air leakage

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

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

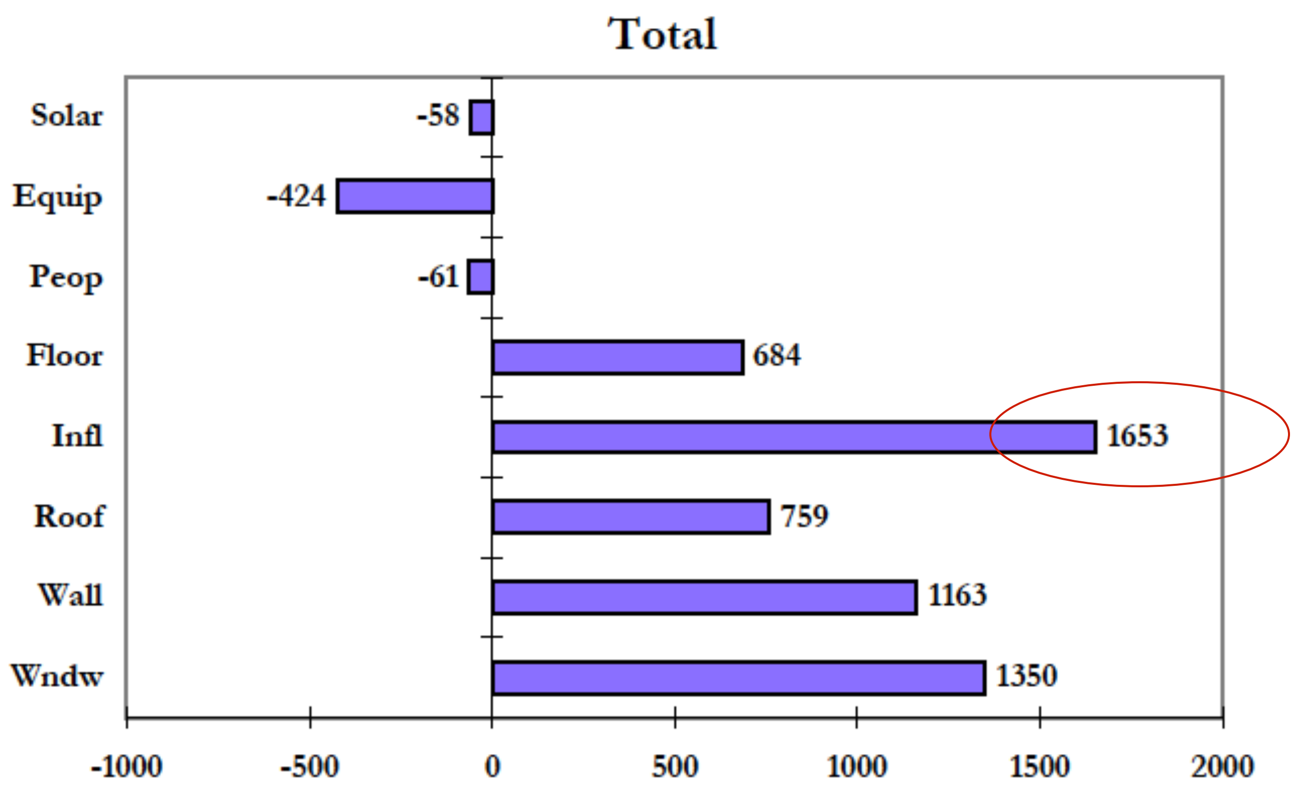
$$\dot{m} = \dot{V}_{leaks} \rho_{air}$$



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

Just how important are building envelopes for energy use?

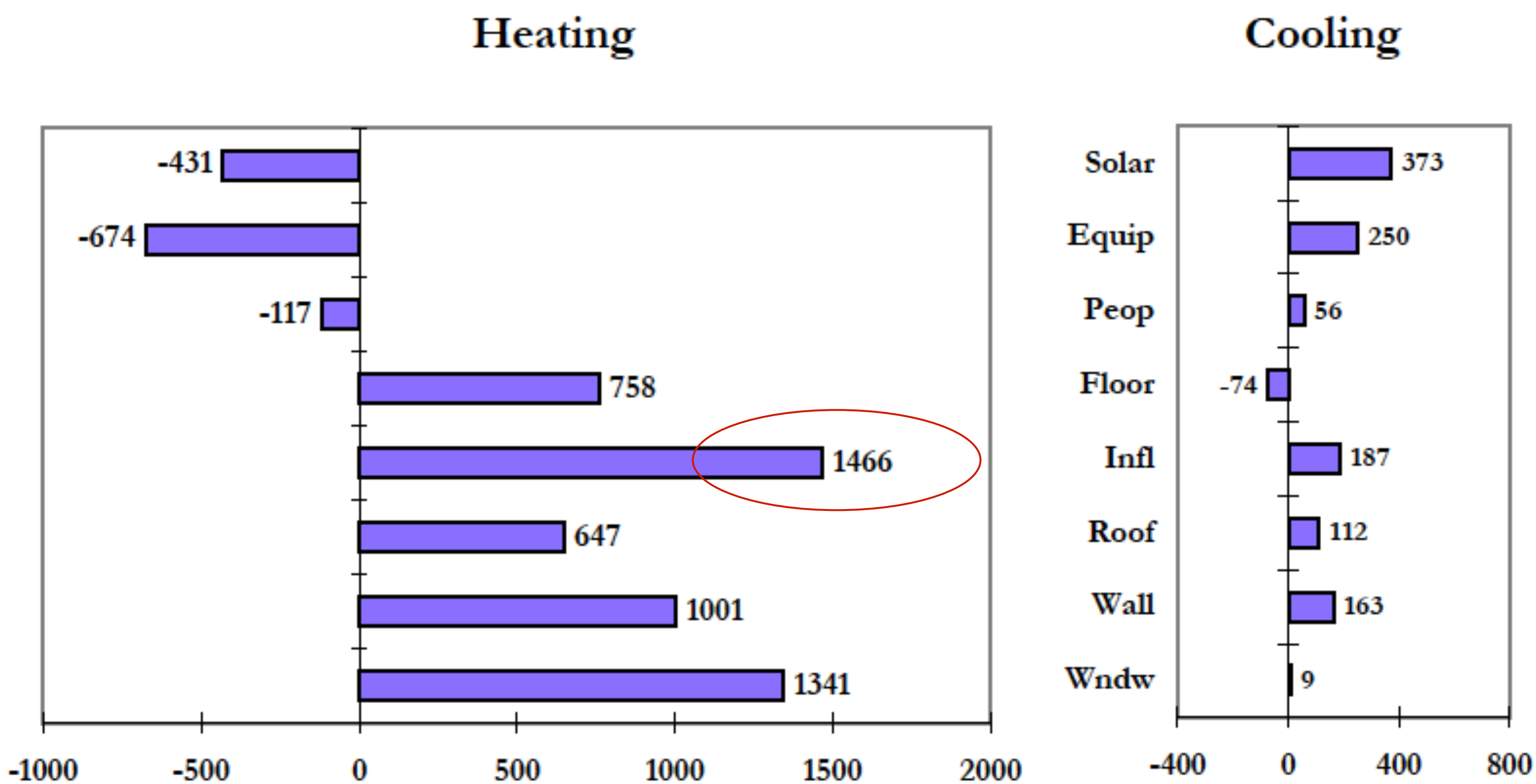
- 1999 study by Lawrence Berkeley National Laboratory
  - *Residential Heating and Cooling Loads Component Analysis*
  - Air infiltration is the single greatest contributor to energy use in U.S. homes



Aggregate component loads for all residential buildings (trillion BTUs)

Just how important are building envelopes for energy use?

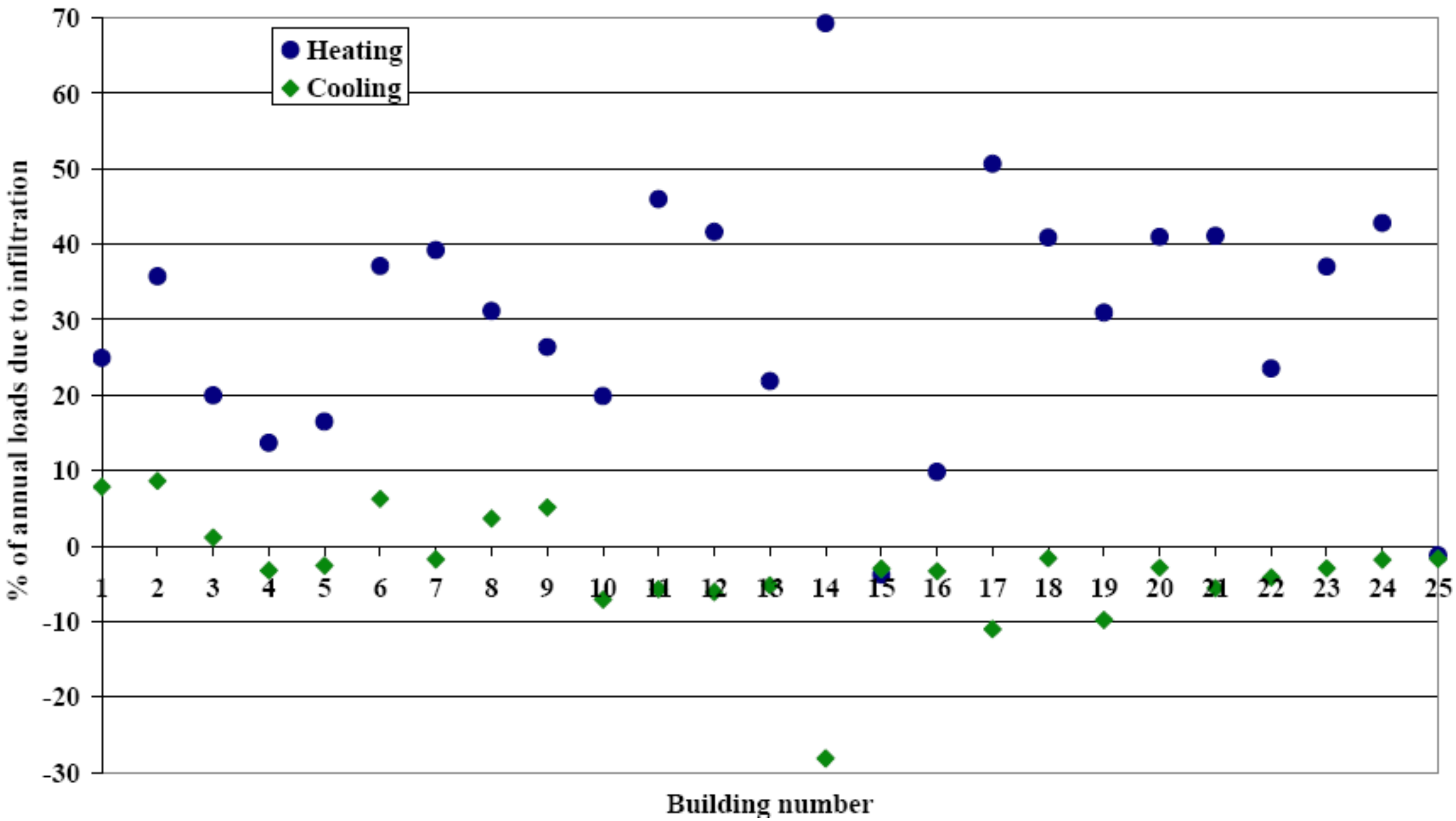
- 1999 study by Lawrence Berkeley National Laboratory
  - *Residential Heating and Cooling Loads Component Analysis*
  - Infiltration particularly important for heating loads



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

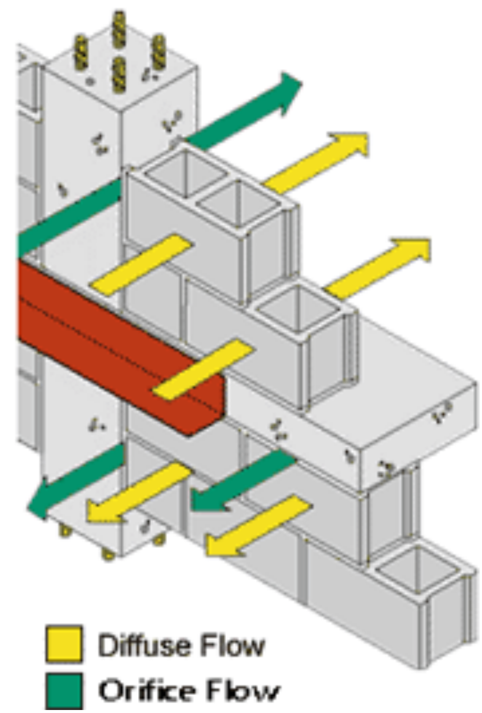
in enclosure design and construction

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



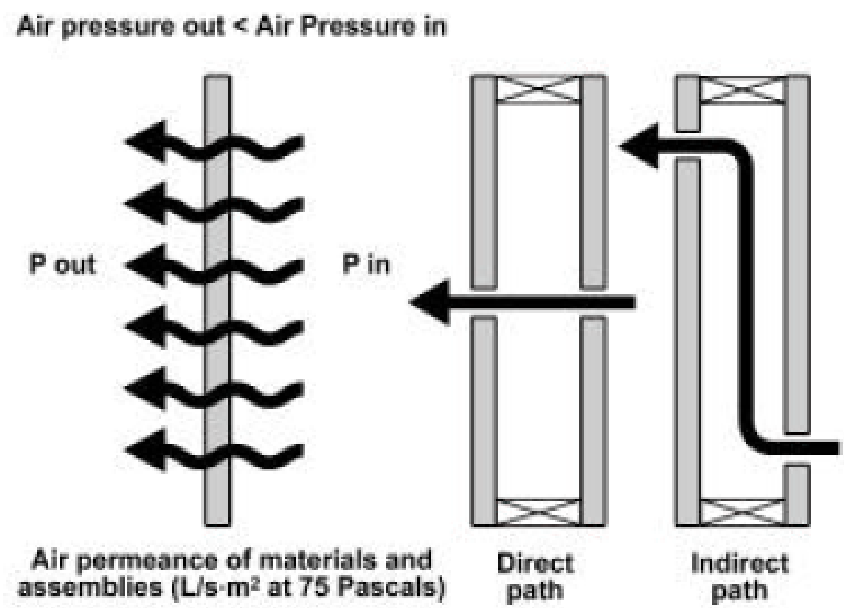
A tale of three barriers …

- 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 $L/(s \cdot m^2)$
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

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

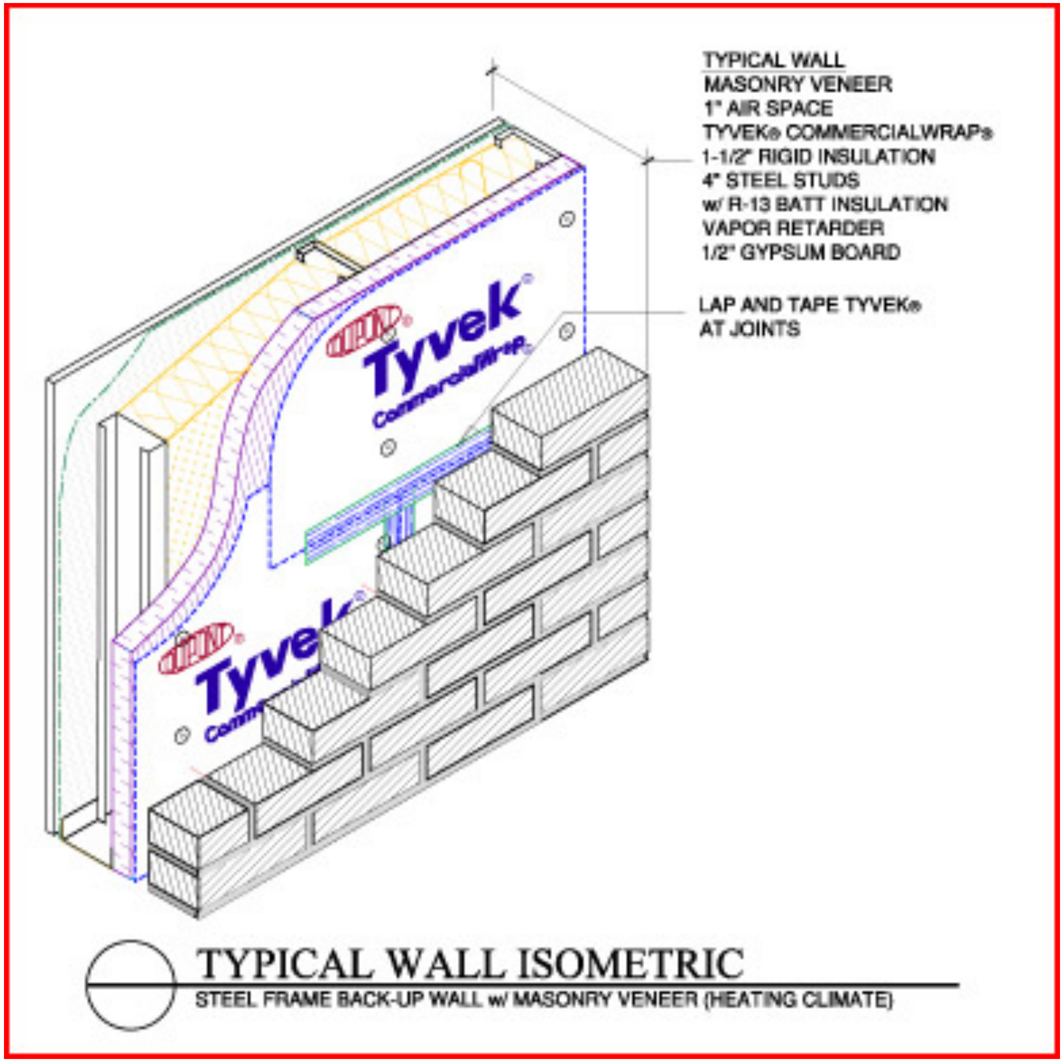
Building wrap components

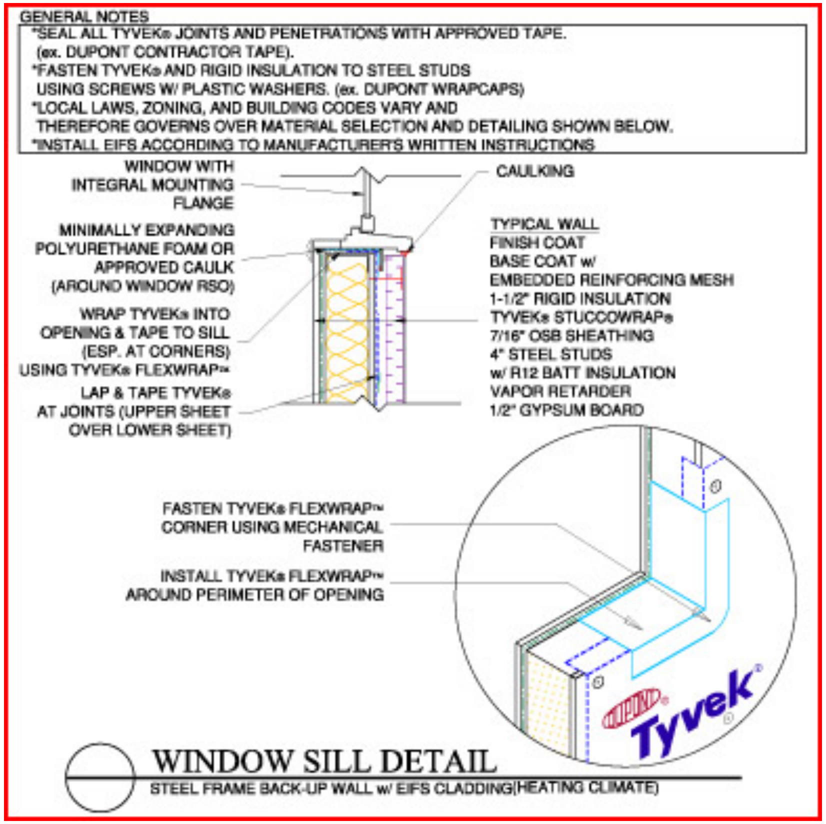
Building wraps: exterior air barrier

Building wraps: exterior air barrier

Photograph 2 – Exterior Air Barrier Using Adhered Membrane

Building wraps: detail drawings





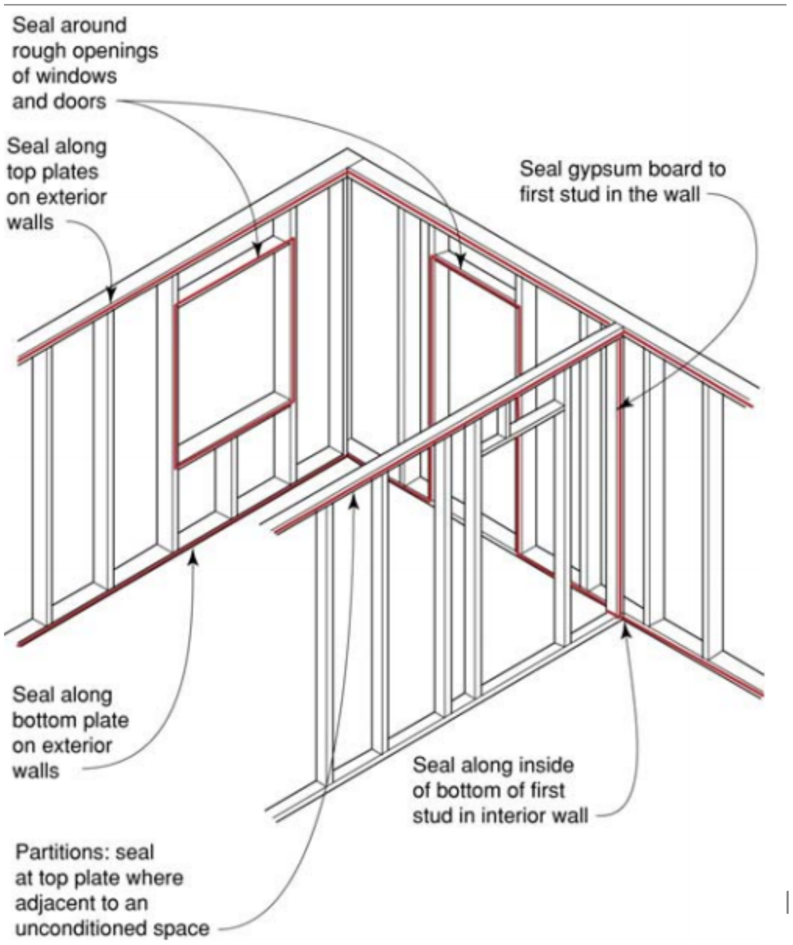
Air barriers also require sealants

- 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

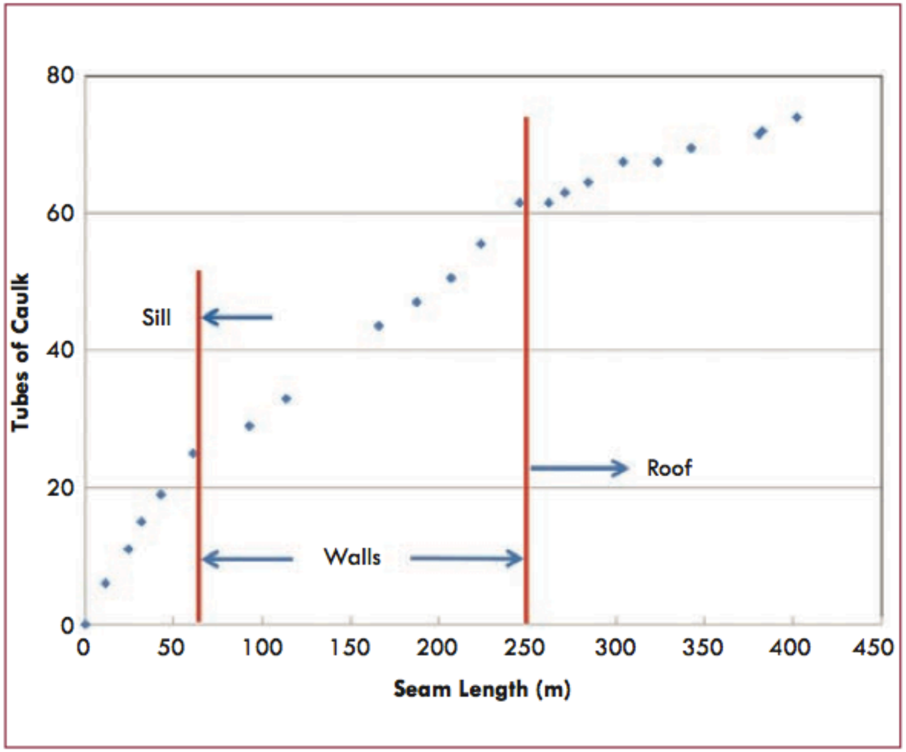
"Supersealing a house" during new construction

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

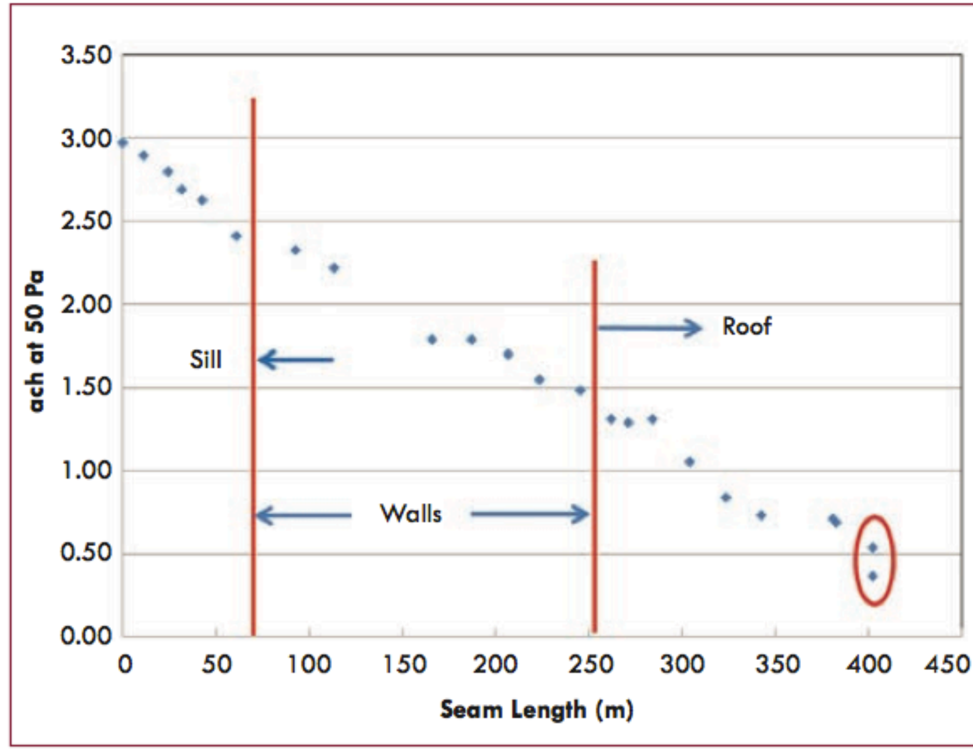
Newell and Newell (2011) *ASHRAE Journal*

"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

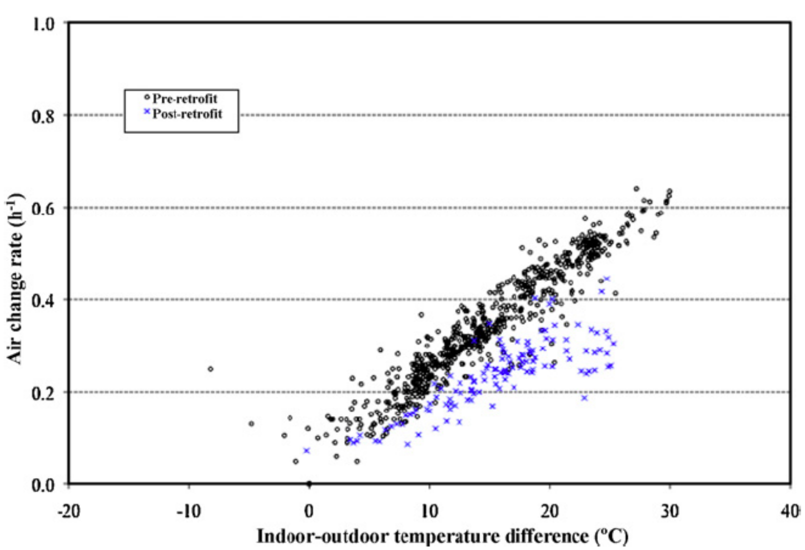


Fig. 6. Pre- and post-retrofit measured air change rates as a function of temperature difference (low wind speed): forced-air fan off (Condition 0).

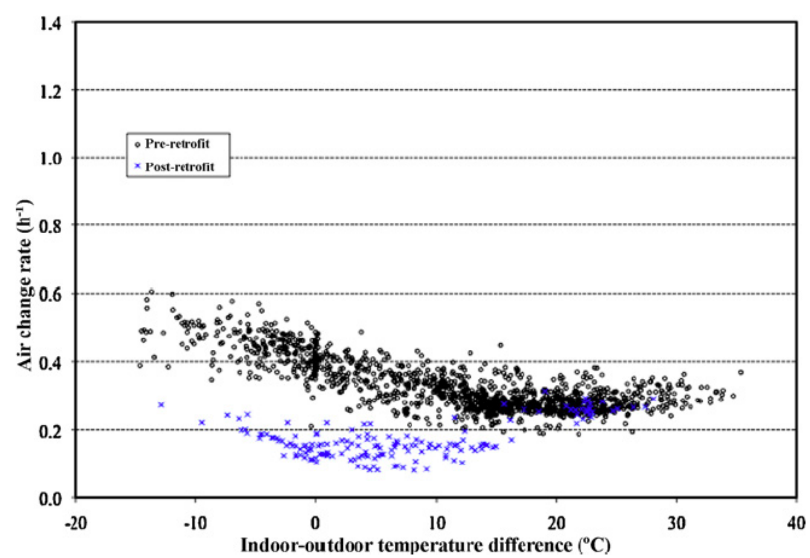
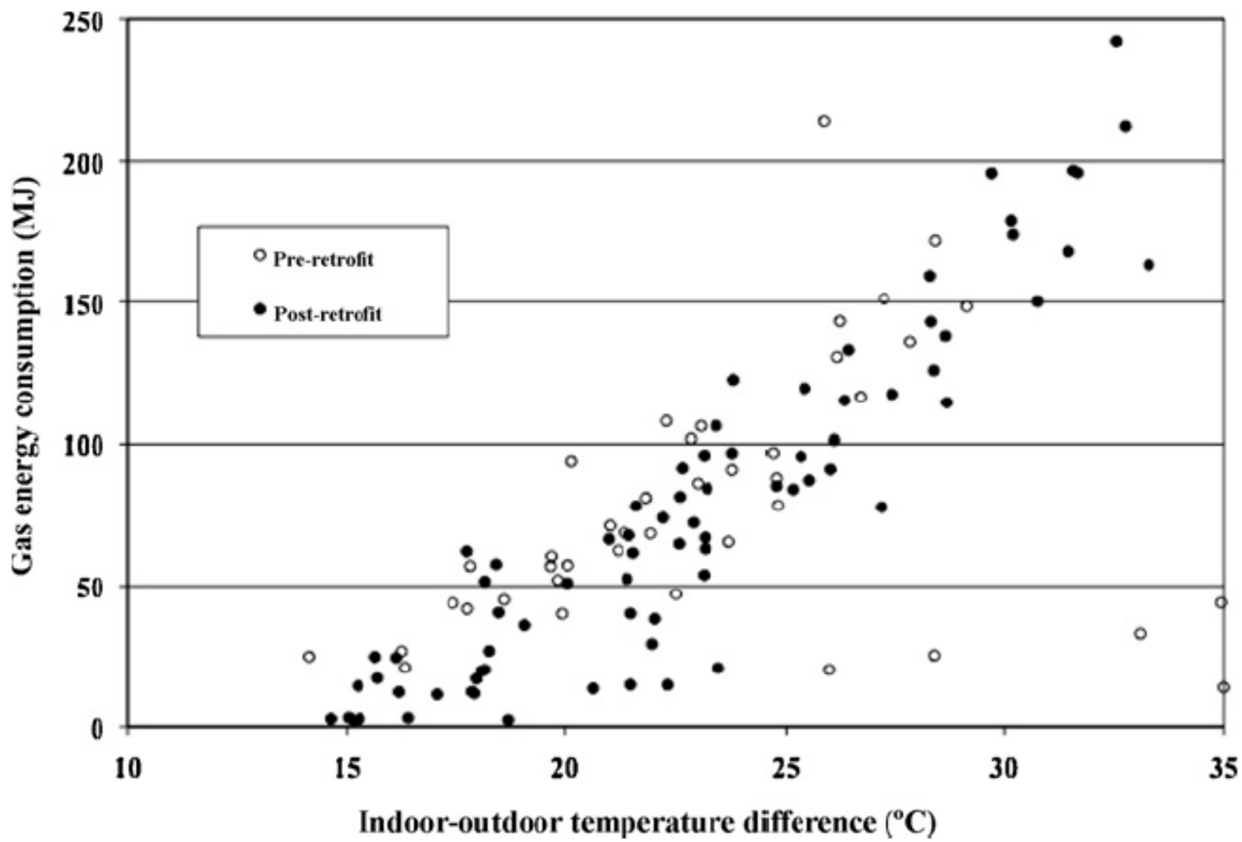


Fig. 8. Pre- and post-retrofit measured air change rates as a function of temperature difference (low wind speed): forced-air fan on, outdoor air intake sealed (Condition 1a).

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*

Next week (March 10)

- First: Campus project presentations in class
- Then: Blower door testing in classroom (not Carman Hall)