Advanced Building Science

- Air Exchange in Buildings
  - Calculating airflows
  - Superposition
    - wind & stack
    - balanced and unbalanced
  - Simplified air exchange models

- Readings
  - HF: Chapter 16.1 – 16.25
  - HF: Chapter 24 => OK to "review" modeling

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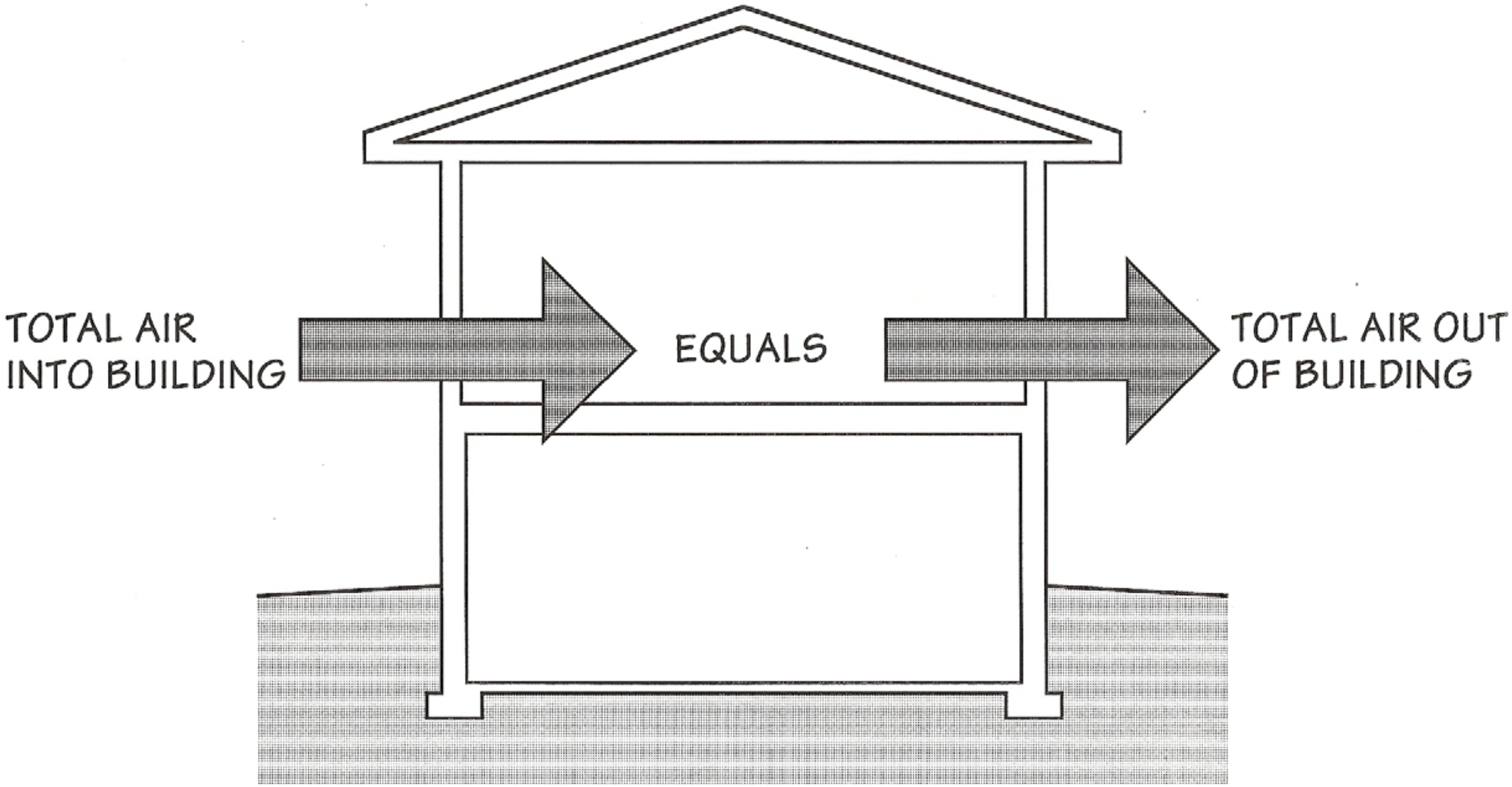
Air Exchange in Buildings

The Air Balance



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Air Exchange in Buildings

To Have Airflow, You Must Have:

- Hole or path
  - random (leaks)
    - direct
    - indirect
  - intentional openings
- Pressure difference
  - outside pressures
    - airflow around buildings
    - temperatures (stack effect)
  - interior pressures
    - chimneys
    - mechanical systems

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Air Exchange in Buildings

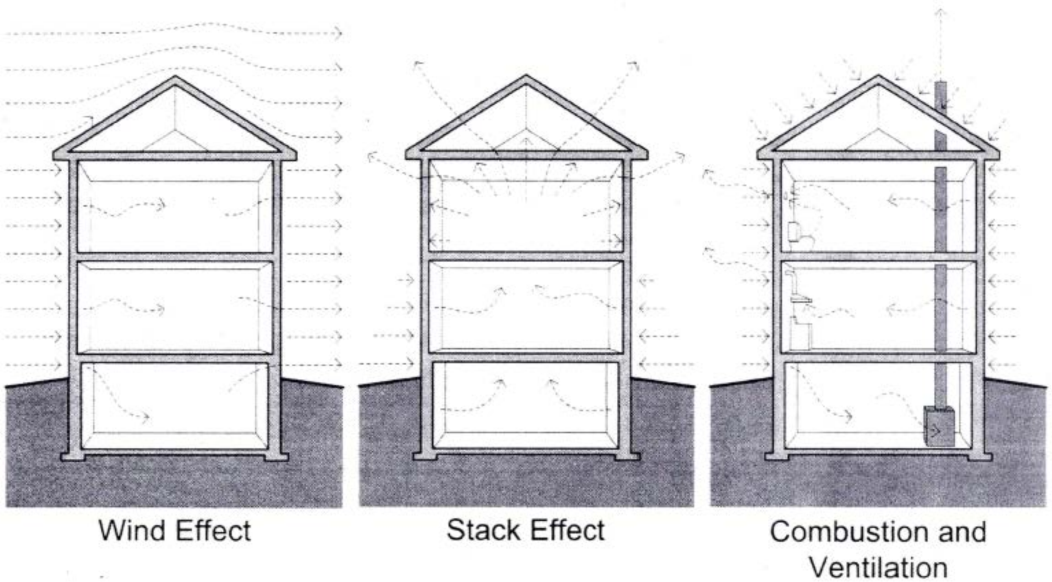

Figure 7.2: Forces driving air flow through building enclosures

7.2 Basic physics

Source: Straube & Burnett, Building Science for Building Enclosures, Chapter 7)

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Types of Air Exchange in Buildings

1. Air Infiltration and Exfiltration
   - Random leaks
   - Natural driving forces (wind/temperature)
2. Natural Ventilation
   - Intentional openings (windows)
   - Natural driving forces (wind/temperature)
3. Chimneys
   - Intentional openings (flue)
   - Thermally (or mechanically) driven
4. Exhaust Devices
   - Intentional openings (vents)
   - Mechanically driven (fans, etc.)
5. Mechanical Ventilation
   - Intentional openings (vents or grills)
   - Mechanically driven (fans, etc.)

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Physics of Airflow in Buildings

General Power Law

$Q = c \times (\Delta P)^n$ *(HF 16.14)*

- c = flow coefficient (related to hole size)
- n = flow exponent (related to hole type)

– For a square edge orifice:

$$\mathbf{cfm = 1.07 \times A \times \sqrt{\Delta P}}$$

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Physics of Airflow in Buildings

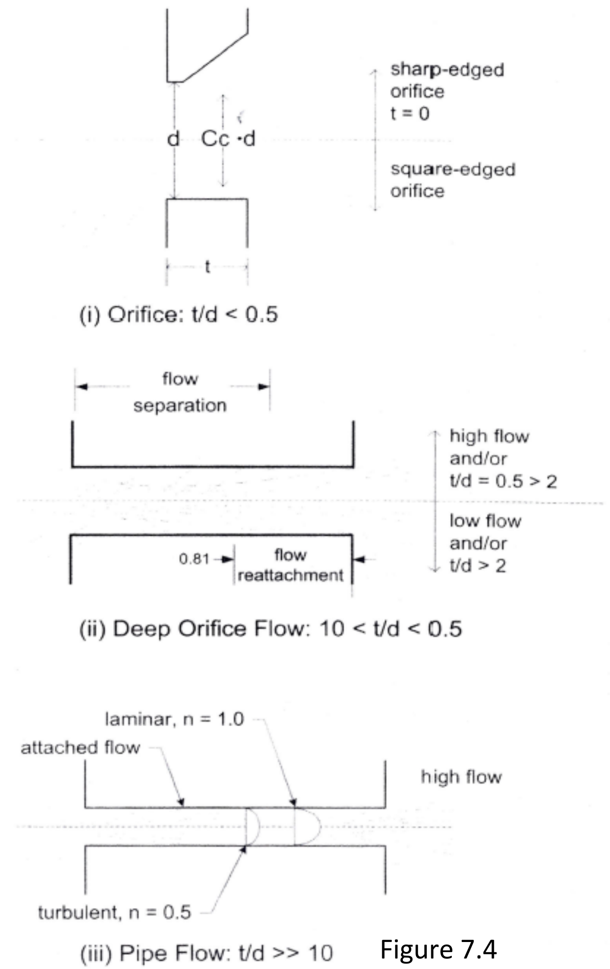

Figure 7.4

Source: Straube & Burnett, Building Science for Building Enclosures, Chapter 7

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Physics of Airflow in Buildings

Calculating Pressures -- Wind

$$p_w = 0.0129 \times C_P \times \rho \times \frac{U^2}{2}$$ *(see HF 16.7)*

- p_w = wind surface pressure (inches of water)
- C_P = wind surface pressure coefficient
- ρ = outside air density (about 0.075)

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Physics of Airflow in Buildings

Calculating Pressures -- Stack

$$p_s = p_r - (0.00598 \times \rho \times g \times H)$$ *(see HF 16.7)*

- p_s = stack pressure (inches of water)
- p_r = stack pressure at reference height
- g = gravitational constant (32.2 ft/s^2)

– For pressure at a horizontal leak:

$$\Delta p_s = 0.00598 \times \rho_o \times ((T_i - T_o) / T_i)) \times g \times (H_{npl} - H)$$

- T in and out (in ° Rankin)

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Air Leakage

Residential Air Leakage

– Envelope leakage measurement

– Airtightness ratings

– Air leakage of building components

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Air Leakage

Leakage Distribution	Range	Average
– Walls	18 to 50%	35%
– Ceilings	3 to 30%	18%
– Forced air systems	3 to 28%	18%
– Windows and doors	6 to 22%	15%
– Fireplaces	0 to 30%	12%
– Vents	2 to 12%	5%

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Air Leakage

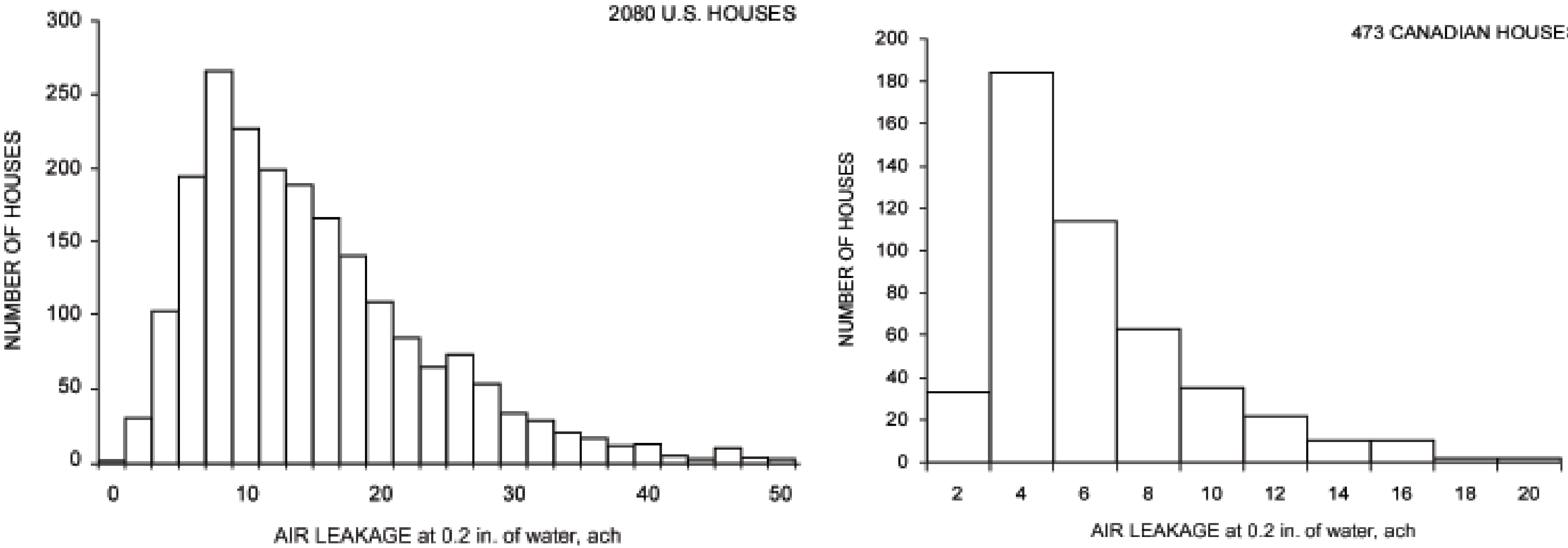

Fig. 10 Envelope Leakage Measurements

Source: ASHRAE Handbook Fundamentals 2009, Chapter 16

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Air Leakage

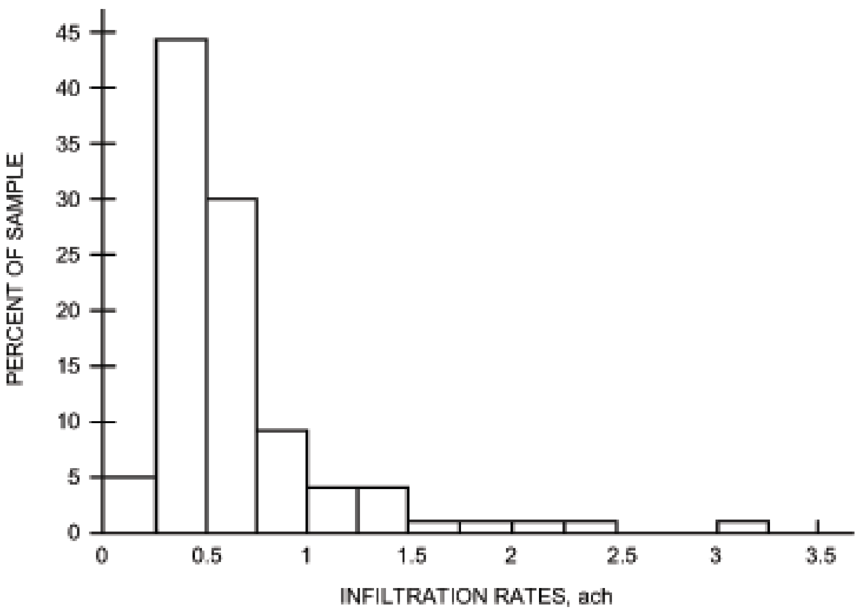

Fig. 11 Histogram of Infiltration Values for Then-New Construction

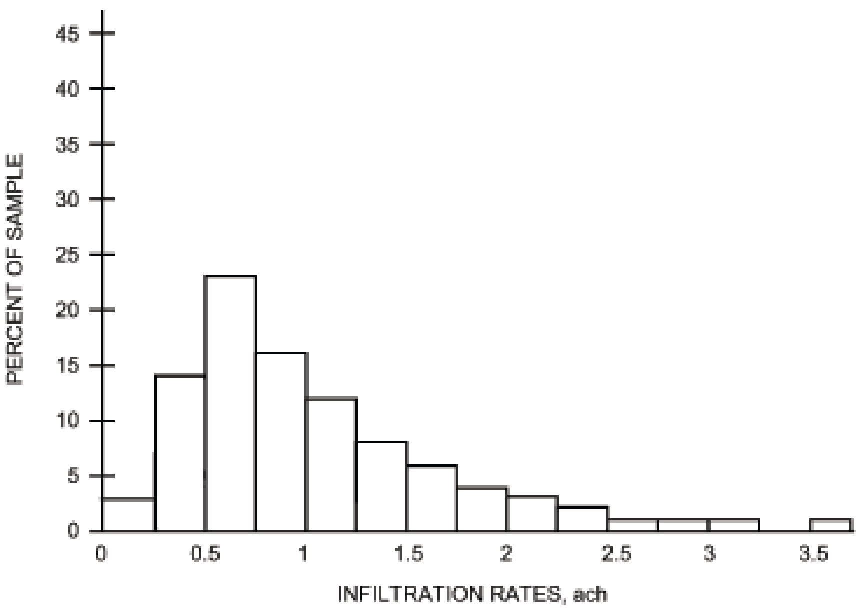

Fig. 12 Histogram of Infiltration Values for Low-Income Housing

Source: ASHRAE Handbook Fundamentals 2013, Chapter 16

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Air Leakage

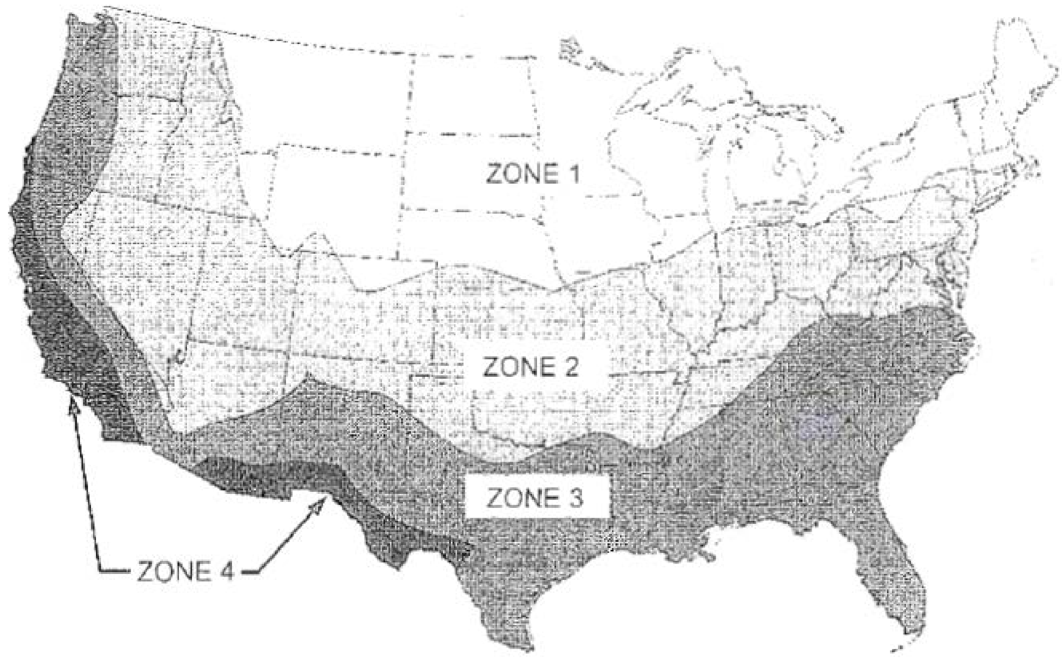

Fig. 13 Airtightness Zones for Residences in the United States (Sherman 1995)

Source: ASHRAE Handbook Fundamentals 2013, Chapter 16

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Air Exchange

- Simplified Air Exchange Models
  - Single zone vs. Multi zone

- Superposition
  - When adding stack and wind (using quadrature)
  - When adding air infiltration and unbalanced mechanical

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Air Exchange

Quadrature

- Stack and wind interact with each other
- Therefore, they are not simply additive

$$Q = \sqrt{(Q_s^2 + Q_w^2)}$$ *(see HF 16.23)*

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Air Exchange

- Basic Model (LBNL by Sherman & Grimsrud)

$$\mathbf{Q = A_L \times \sqrt{(C_s \times \Delta T) + (C_w \times U^2)}}$$

(see HF 16.23)

- Q = airflow rate in cfm
- A_L = effective air leakage area in in^2
- C_s = stack coefficient
- ΔT = temperature difference in ^oF
- C_w = wind coefficient
- U = wind speed in mph

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Table 5-3 Effective Leakage Area of Building Components (0.016 in. of water pressure difference)
(Table 3, Chapter 25, 1997 *ASHRAE Handbook—Fundamentals*)

	Units (see note)	Best Estimate	Minimum	Maximum
Ceiling				
General	in^2/ft^2	0.026	0.011	0.04
Drop	in^2/ft^2	0.0027	0.00066	0.003
Ceiling penetrations				
Whole-house fans	in^2 ea	3.1	0.25	3.3
Recessed lights	in^2 ea	1.6	0.23	3.3
Ceiling/Flue vent	in^2 ea	4.8	4.3	4.8
Surface-mounted lights	in^2 ea	0.13		
Chimney	in^2 ea	4.5	3.3	5.6
Crawl space				
General (area for exposed wall)	in^2/ft^2	0.144	0.1	0.24
8 in. by 16 in. vents	in^2 ea	20		
Door frame				
General	in^2 ea	1.9	0.37	3.9
Masonry, not caulked	in^2/ft^2	0.07	0.024	0.07
Masonry, caulked	in^2/ft^2	0.014	0.004	0.014
Wood, not caulked	in^2/ft^2	0.024	0.009	0.024
Wood, caulked	in^2/ft^2	0.004	0.001	0.004
Trim	in^2/lfc	0.05		
Jamb	in^2/lfc	0.4	0.3	0.5
Threshold	in^2/lfc	0.1	0.06	1.1
Doors				
Attic/crawl space, not weatherstripped	in^2 ea	4.6	1.6	5.7
Attic/crawl space, weatherstripped	in^2 ea	2.8	1.2	2.9
Attic fold down, not weatherstripped	in^2 ea	6.8	3.6	13
Attic fold down, weatherstripped	in^2 ea	3.4	2.2	6.7
Attic fold down, with insulated box	in^2 ea	0.6		
Attic from unconditioned garage	in^2 ea	0	0	0
Double, not weatherstripped	in^2/ft^2	0.16	0.1	0.32
Double, weatherstripped	in^2/ft^2	0.12	0.04	0.33
Elevator (passenger)	in^2 ea	0.04	0.022	0.054
General, average	in^2/lfc	0.015	0.011	0.021
Interior (pocket, on top floor)	in^2 ea	2.2		
Interior (stairs)	in^2/lfc	0.04	0.012	0.070
Mail slot	in^2/lfc	0.2		
Sliding exterior glass patio	in^2 ea	3.4	0.46	9.3
Sliding exterior glass patio	in^2/ft^2	0.079	0.009	0.22
Storm (difference between with and without)	in^2 ea	0.9	0.46	0.96
Single, not weatherstripped	in^2 ea	3.3	1.9	8.2
Single, weatherstripped	in^2 ea	1.9	0.6	4.2
Vestibule (subtract per each location)	in^2 ea	1.6		
Electrical outlets/Switches				
No gaskets	in^2 ea	0.38	0.08	0.96
With gaskets	in^2 ea	0.023	0.012	0.54
Furnace				
Sealed (or no) combustion	in^2 ea	0	0	0
Retention head or stack damper	in^2 ea	4.6	3.1	4.6
Retention head and stack damper	in^2 ea	3.7	2.8	4.6
Floors over crawl spaces				
General	in^2/ft^2	0.032	0.006	0.071
Without ductwork in crawl space	in^2/ft^2	0.0285		
With ductwork in crawl space	in^2/ft^2	0.0324		
Fireplace				
With damper closed	in^2/ft^2	0.62	0.14	1.3
With damper open	in^2/ft^2	5.04	2.09	5.47
With glass doors	in^2/ft^2	0.58	0.06	0.58
With insert and damper closed	in^2/ft^2	0.52	0.37	0.66
With insert and damper open	in^2/ft^2	0.94	0.58	1.3
Gas water heater	in^2 ea	3.1	2.3	3.9
Joints				
Ceiling-wall	in^2/lfc	0.070	0.0075	0.12
Sole plate, floor/wall, uncaulked	in^2/lfc	0.2	0.018	0.26
Sole plate, floor/wall, caulked	in^2/lfc	0.04	0.0035	0.056
Top plate, band joist	in^2/lfc	0.005	0.0035	0.018
Piping/Plumbing/Wiring penetrations				
Uncaulked	in^2 ea	0.9	0.31	3.7
Caulked	in^2 ea	0.3	0.16	0.3
Vents				
Bathroom with damper closed	in^2 ea	1.6	0.39	3.1
Bathroom with damper open	in^2 ea	3.1	0.95	3.4
Dryer with damper	in^2 ea	0.46	0.45	1.1
Dryer without damper	in^2 ea	2.3	1.9	5.3
Kitchen with damper open	in^2 ea	6.2	2.2	11
Kitchen with damper closed	in^2 ea	0.8	0.16	1.1
Kitchen with tight gasket	in^2 ea	0.16		
Walls (exterior)				
Cast-in-place concrete	in^2/ft^2	0.007	0.0007	0.026
Clay brick cavity wall, finished	in^2/ft^2	0.0098	0.0007	0.033
Precast concrete panel	in^2/ft^2	0.017	0.0004	0.024
Lightweight concrete block, unfinished	in^2/ft^2	0.05	0.019	0.058
Lightweight concrete block, painted or stucco	in^2/ft^2	0.016	0.0075	0.016
Heavyweight concrete block, unfinished	in^2/ft^2	0.0036		
Continuous air infiltration barrier	in^2/ft^2	0.0022	0.0008	0.003
Rigid sheathing	in^2/ft^2	0.005	0.0042	0.006
Window framing				
Masonry, uncaulked	in^2/ft^2	0.094	0.082	0.148
Masonry, caulked	in^2/ft^2	0.019	0.016	0.03
Wood, uncaulked	in^2/ft^2	0.025	0.022	0.039
Wood, caulked	in^2/ft^2	0.004	0.004	0.007
Windows				
Awning, not weatherstripped	in^2/ft^2	0.023	0.011	0.035
Awning, weatherstripped	in^2/ft^2	0.012	0.006	0.017
Casement, weatherstripped	in^2/lfc	0.011	0.005	0.14
Casement, not weatherstripped	in^2/lfc	0.013		
Double horizontal slider, not weatherstripped	in^2/lfc	0.052	0.0009	0.16
Double horizontal slider, wood, weatherstripped	in^2/lfc	0.026	0.0070	0.081
Double horizontal slider, aluminum, weatherstripped	in^2/lfc	0.034	0.027	0.038
Double-hung, not weatherstripped	in^2/lfc	0.12	0.040	0.29
Double-hung, weatherstripped	in^2/lfc	0.031	0.009	0.089
Double-hung with storm, not weatherstripped	in^2/lfc	0.046	0.023	0.080
Double-hung with storm, weatherstripped	in^2/lfc	0.037	0.021	0.05
Double-hung with pressurized track, weatherstripped	in^2/lfc	0.023	0.018	0.026
Jalousie	in^2/louver	0.524		
Lumped	in^2/lfs	0.022	0.00042	0.097
Single horizontal slider, weatherstripped	in^2/lfs	0.031	0.009	0.097
Single horizontal slider, aluminum	in^2/lfs	0.04	0.013	0.097
Single horizontal slider, wood	in^2/lfs	0.021	0.013	0.047
Single horizontal slider, wood clad	in^2/lfs	0.030	0.025	0.038
Single-hung, weatherstripped	in^2/lfs	0.041	0.029	0.058
Sill	in^2/lfc	0.0099	0.0065	0.010
Storm inside, heat shrink	in^2/lfs	0.00085	0.00042	0.00085
Storm inside, rigid sheet with magnetic seal	in^2/lfs	0.0056	0.00085	0.011
Storm inside, flexible sheet with mechanical seal	in^2/lfs	0.0072	0.00085	0.039
Storm inside, rigid sheet with mechanical seal	in^2/lfs	0.019	0.0021	0.039
Storm outside, pressurized track	in^2/lfc	0.025		
Storm outside, 2-track	in^2/lfc	0.058		
Storm outside, 3-track	in^2/lfc	0.116		

Note: Air leakage areas are based on values found in the literature. The effective air leakage area (in square inches) is based on a pressure difference of 0.016 in. of water and $C_D = 1$.

Abbreviations: ft^2 = gross area in square feet; ea = each; lfc = linear foot of crack; lfs = linear foot of sash

Howell, Sauer, Goad 1998, Principles of Heating, Ventilating, and Air Conditioning

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Air Exchange

Table 4 Basic Model Stack Coefficient C_s

	House Height (Stories)		
	One	Two	Three
Stack coefficient	0.0150	0.0299	0.0449

Source: ASHRAE Handbook Fundamentals 2013, Chapter 16

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Infiltration

Table 5 Local Shelter Classes

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

Source: ASHRAE Handbook Fundamentals 2013. Chapter 16

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Infiltration

Table 6 Basic Model Wind Coefficient C_w

Shelter Class	House Height (Stories)		
	One	Two	Three
1	0.0119	0.0157	0.0184
2	0.0092	0.0121	0.0143
3	0.0065	0.0086	0.0101
4	0.0039	0.0051	0.0060
5	0.0012	0.0016	0.0018

Source: ASHRAE Handbook Fundamentals 2013, Chapter 16

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Air Exchange

- Enhanced Model (AIM-2 by Walker & Wilson)

$$Q_s = c \times C_s \times \Delta T^n$$ *(see HF 16.23)*

$$Q_w = c \times C_w \times (s \times U)^{2n}$$ *(see HF 16.23)*

  - **c = flow coefficient**
  - **C_s = stack coefficient**
  - **C_w = wind coefficient**
  - **s = shelter factor**
  - **$U = G \times U_{met}$**

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Air Exchange

Table 7 Enhanced Model Wind Speed Multiplier *G*

	House Height (Stories)		
	One	Two	Three
Wind speed multiplier *G*	0.48	0.59	0.67

Source: ASHRAE Handbook Fundamentals. 2013, Chapter 16

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Air Exchange

Table 8 Enhanced Model Stack and Wind Coefficients

	One Story		Two Story		Three Story	
	No Flue	With Flue	No Flue	With Flue	No Flue	With Flue
C_s	1.46	1.87	2.13	2.41	2.68	2.92
C_w for basement slab	2.14	1.95	2.34	2.14	2.34	2.29
C_w for crawlspace	1.75	1.75	1.95	1.95	2.07	2.11

Source: ASHRAE Handbook Fundamentals 2013. Chapter 16

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Air Exchange

Table 9 Enhanced Model Shelter Factor *s*

Shelter Class	No Flue	One Story with Flue	Two Story with Flue	Three Story with Flue
1	1.00	1.10	1.07	1.06
2	0.90	1.02	0.98	0.97
3	0.70	0.86	0.81	0.79
4	0.50	0.70	0.64	0.61
5	0.30	0.54	0.47	0.43

Source: ASHRAE Handbook Fundamentals 2013, Chapter 16

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Physics of Airflow in Buildings

Calculating Airflows Stack

- Stack + Fan

Source: Gary Nelson, Energy Conservatory

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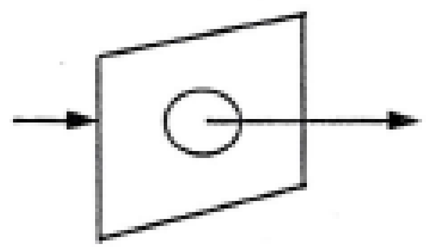
Physics of Airflow in Buildings

ORIFICE FLOW

- Hole in a thin flat material (special case).
- Dimensions of the hole should be less than 1/2 the dimensions of the flat material.
- Near sea level: $CFM = 1.07 \times A \times \sqrt{(\Delta P)}$

where: A = area of the hole in sq. inches
Δ P = pressure drop across the hole (Pa)



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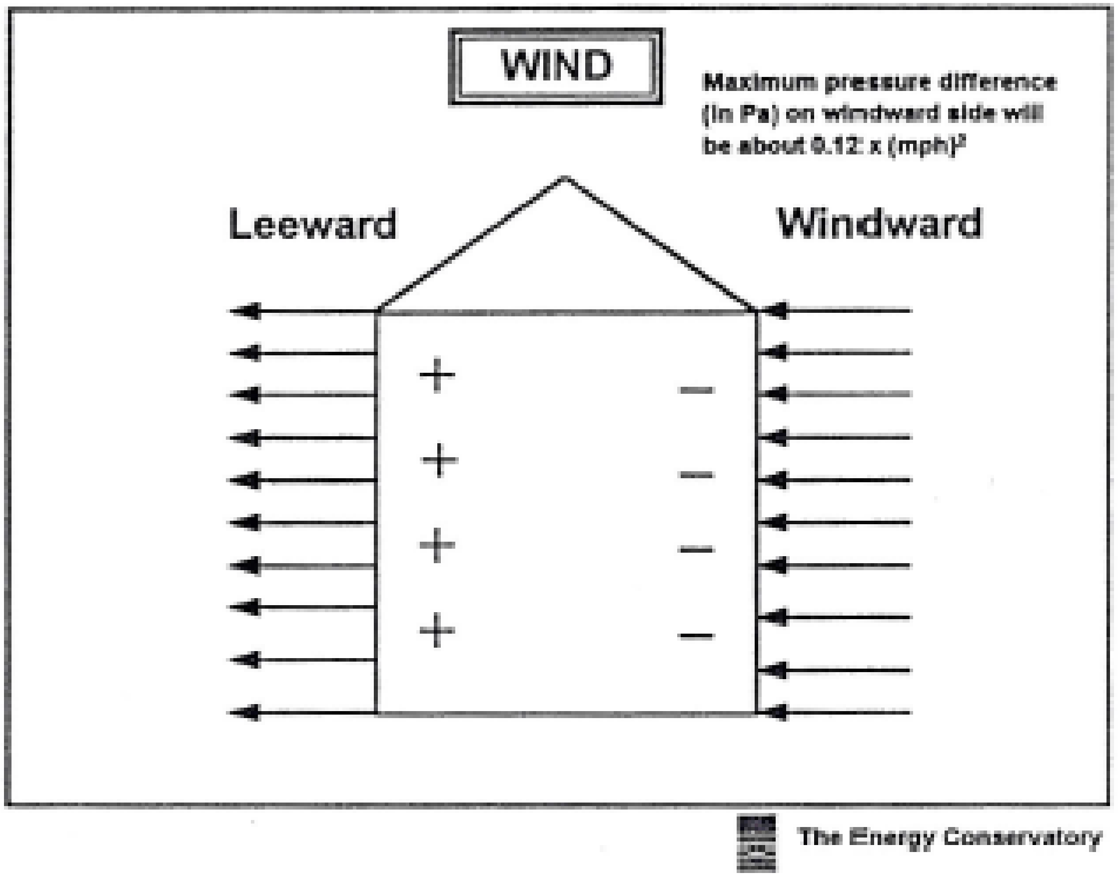
Infiltration (Wind)



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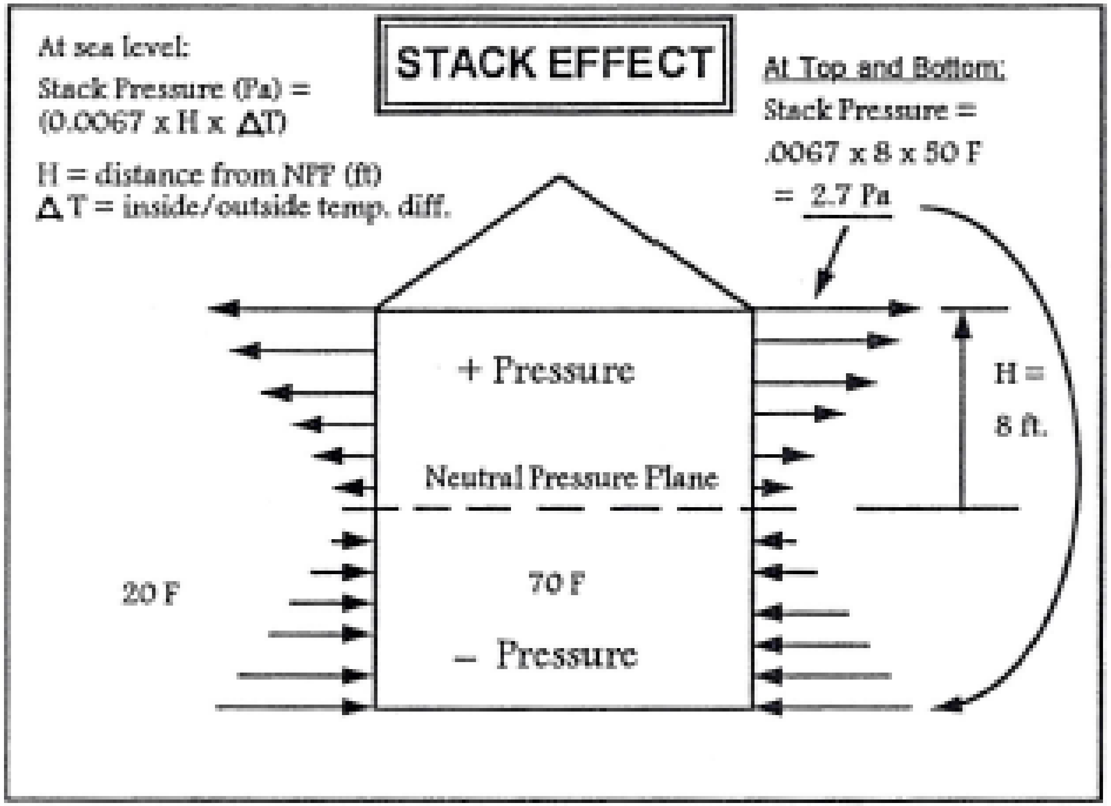
Infiltration (Stack)



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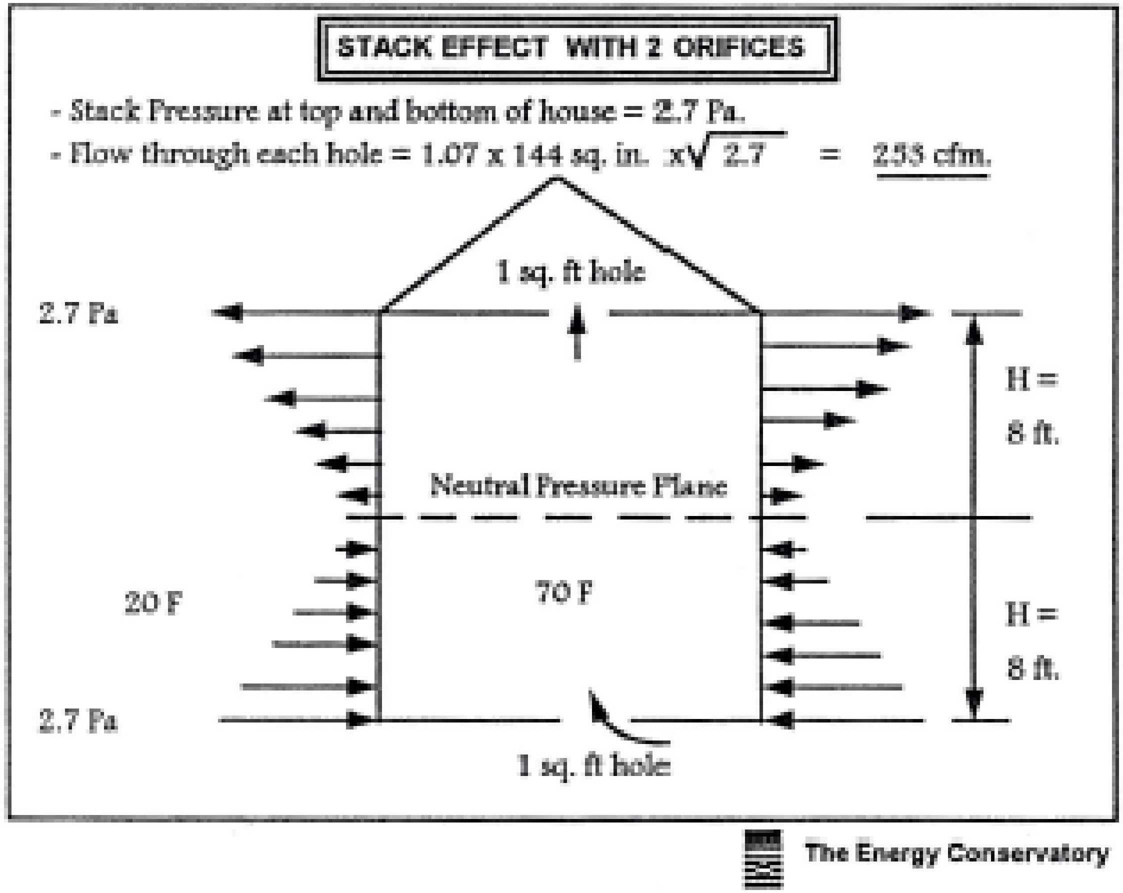
Infiltration (Stack Only)



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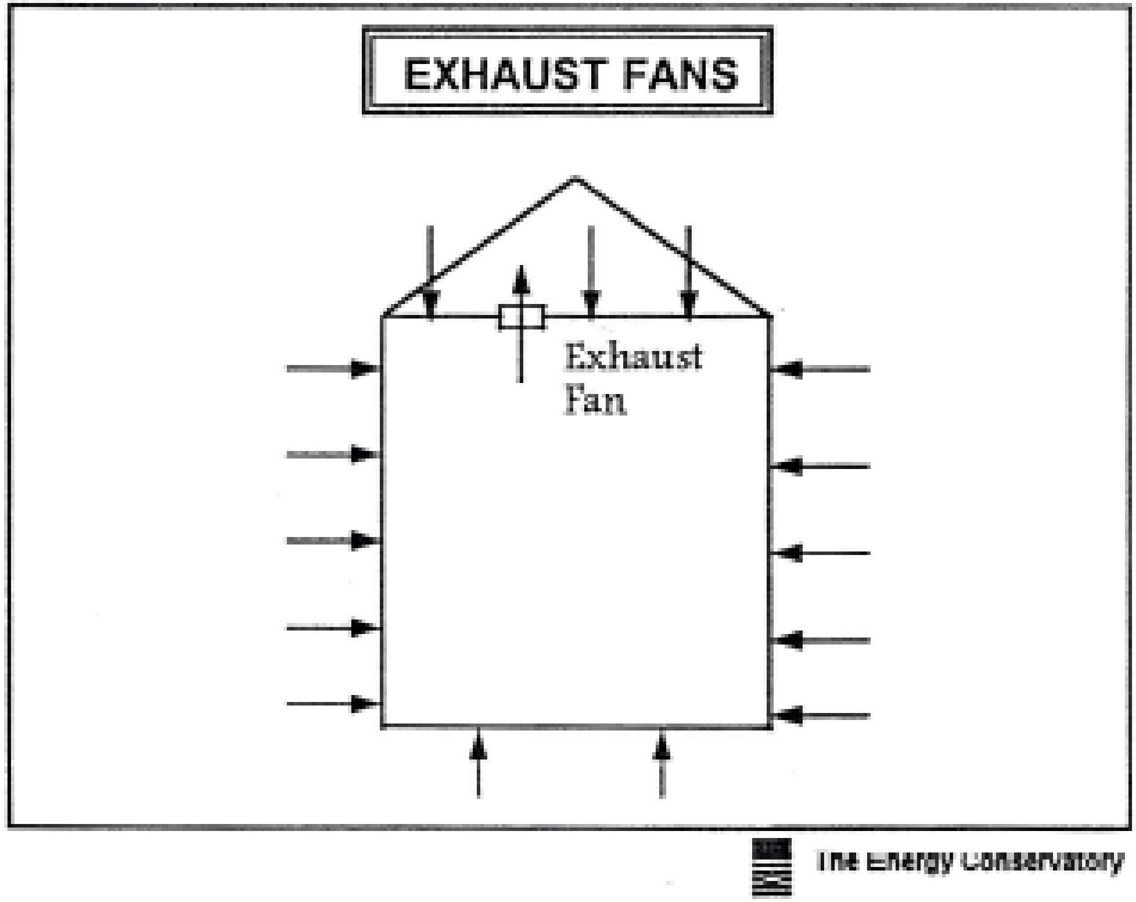
Ventilation



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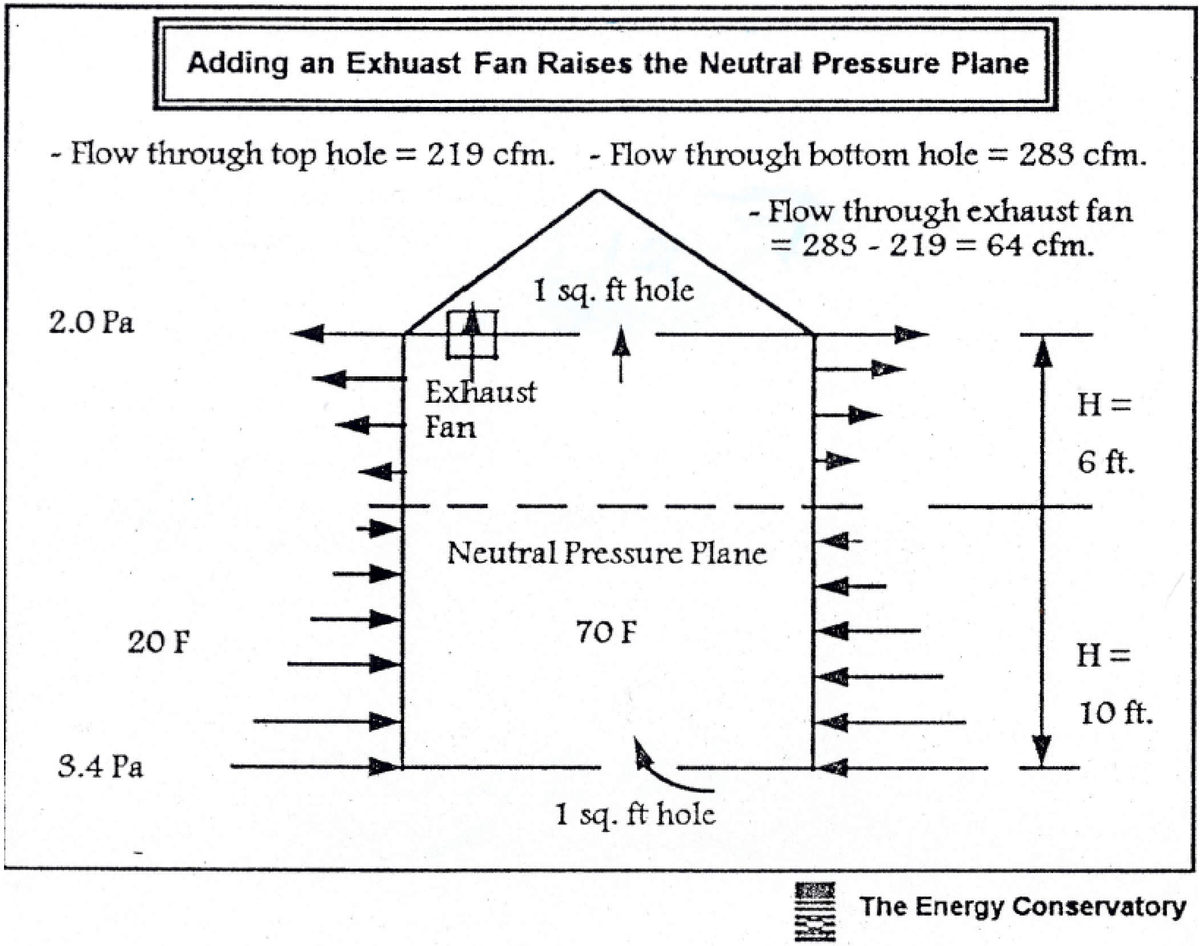
Infiltration & Ventilation



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Infiltration & Ventilation

Added Ventilation From Exhaust Fan

- Before fan was installed, natural ventilation was 253 cfm.
- Exhaust fan was installed which moved 64 cfm.
- Total ventilation for house increased from 253 to 283 cfm.
- Added ventilation = 283 - 253 = 30 cfm. This is approximately one-half of the exhaust fan flow.

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Infiltration & Ventilation

- Superposition

$$Q_{comb} = Q_{bal} + \sqrt{(Q^2_{unbal} + Q^2_{infiltration})}$$

Source: ASHRAE Handbook Fundamentals 2009, Chapter 16 (16.25)

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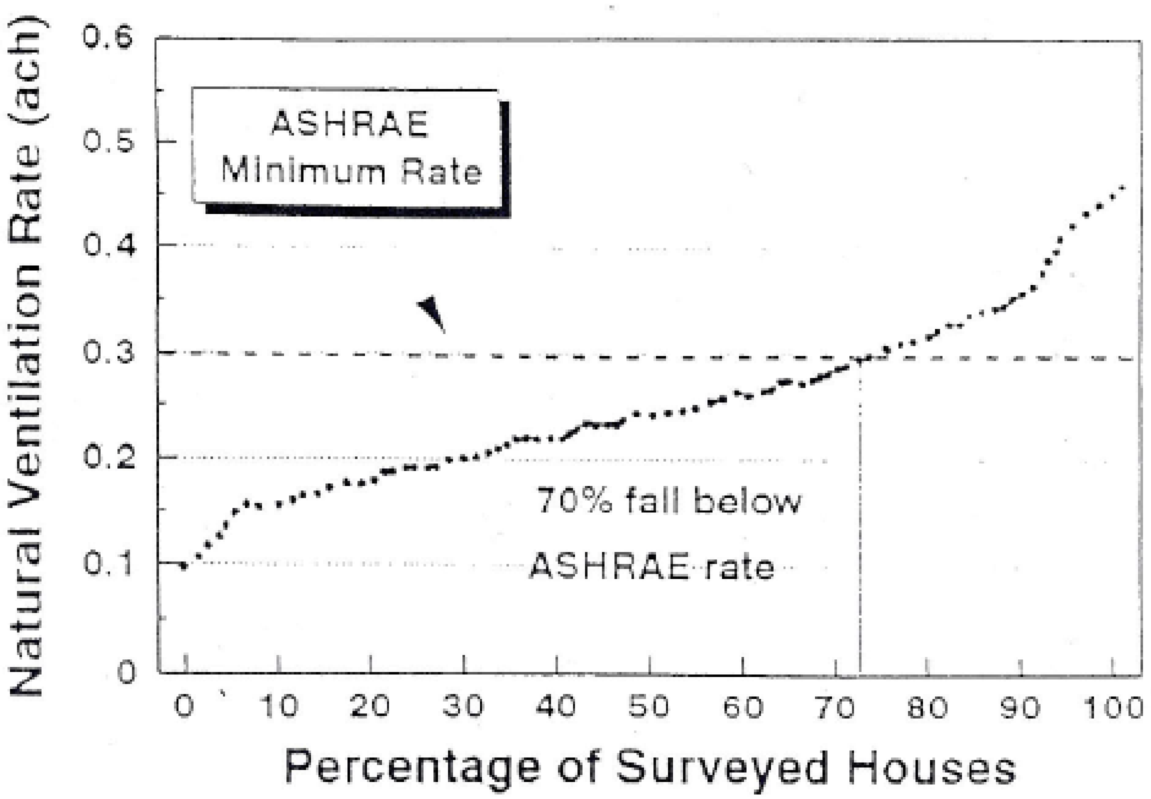
Infiltration & Ventilation



a. Heating season average.

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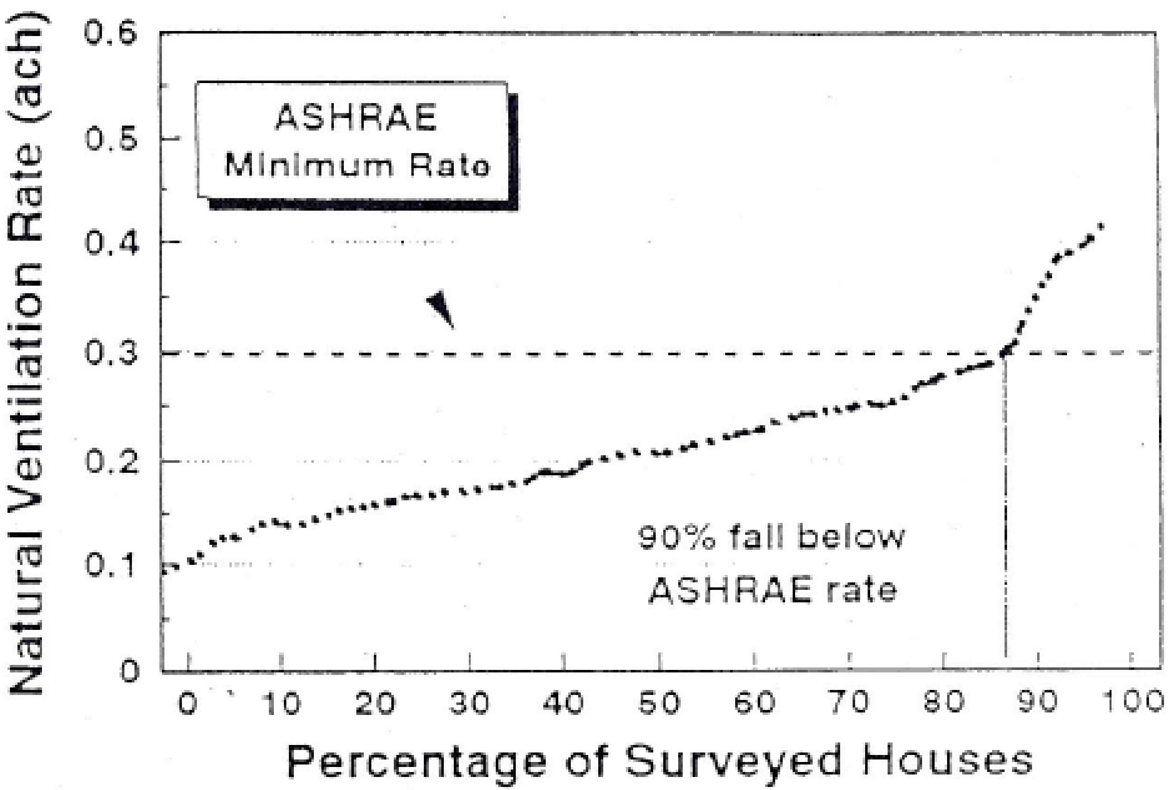
Infiltration & Ventilation



b. Minimum month average.

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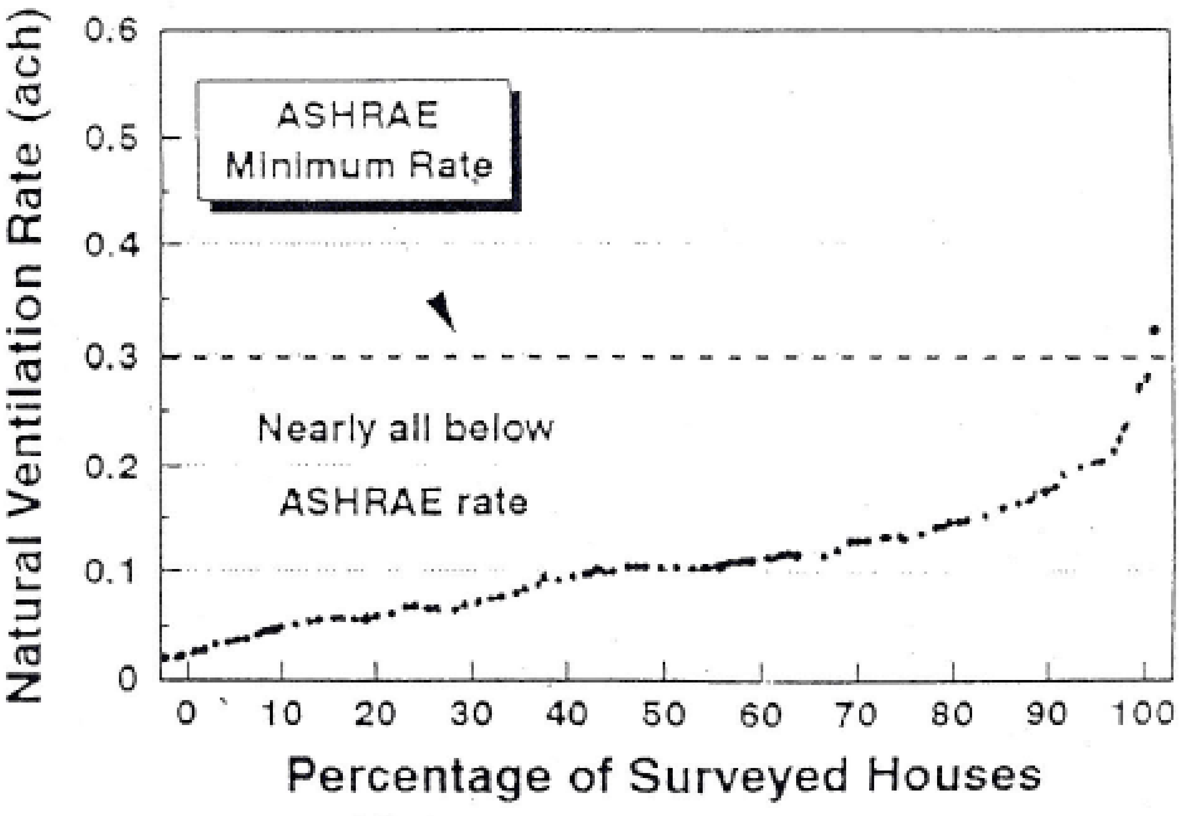
Infiltration & Ventilation



c. Minimum 24-hour average.

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In Summary

Questions and Discussion

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Preview for Next Class

- Thermal Insulation
  - What is R-value?
  - What contributes to a good R-value?
  - What things might reduce the overall R-value?

- Readings
  - HF: Chapter 25 => 25.1 to 25.7
  - HF: Chapter 26 => 26.1 to 26.13
  - HPE: Chapter 3.3.1 to 3.3.4

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The "Original" House of Pressures

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