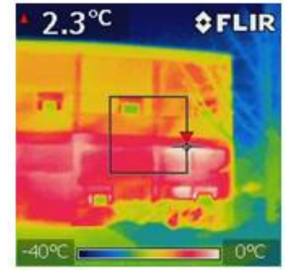
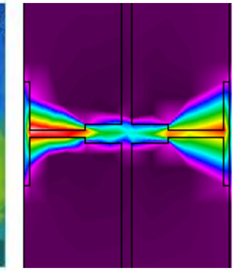
CAE 331/513
Building Science
Fall 2016





Week 12: November 10, 2016
Finishing ventilation and IAQ

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Internship opening in Chicago

seventhwave

Energy Engineer Intern

We are seeking an energy engineer intern with a desire to apply both reason and creativity towards the creation of a sustainable energy society. We are a private non-profit organization that is mission-driven, independent, and objective. We seek practical solution paths among a world of competing interests.

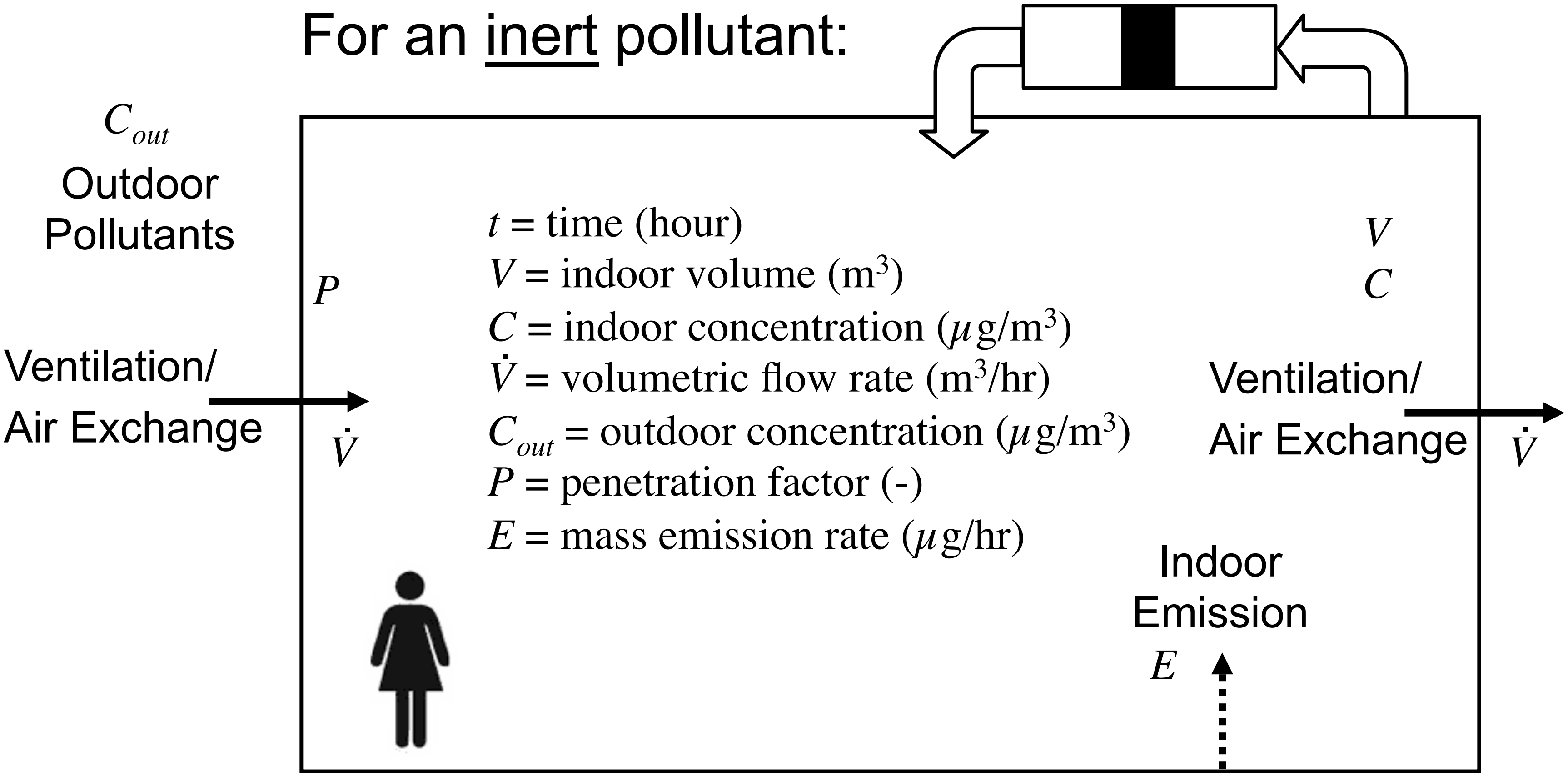
Primary responsibilities:

- Assist engineers with evaluating energy efficiency and renewable energy strategies in buildings, campus, and community settings
- Quantify energy system performance, life cycle cost economics, and emissions reduction potential
- Develop building geometry and required inputs to energy modeling software
- Minimum requirements:
- Pursuing undergraduate or graduate level standing in related field
- Proficiency with basic computer software such as MS Office
- Ability to work in a team environment
- Excellent communications skills

http://www.seventhwave.org/sites/default/files/intern-092616.pdf

Last time: Mass balances

For an <u>inert</u> pollutant:



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

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

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

$$\lambda = \frac{\dot{V}}{V} = \text{air exchange rate } \left(\frac{1}{\text{hr}}\right)$$

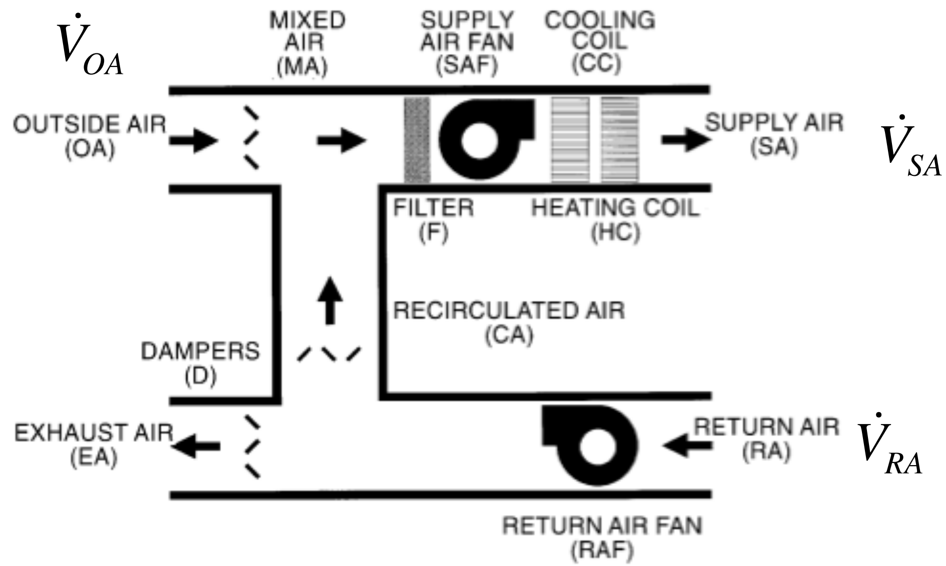
Dealing with ventilation vs. infiltration

- **Mechanical ventilation** is straightforward
  - Fans move air through known openings
  - Flow rates typically known or at least measurable

- **Natural ventilation** is conceptually straightforward but physically complex
  - Known openings but highly varying wind speeds and directions

- **Infiltration** is complex
  - Typically unknown openings and multiple driving forces

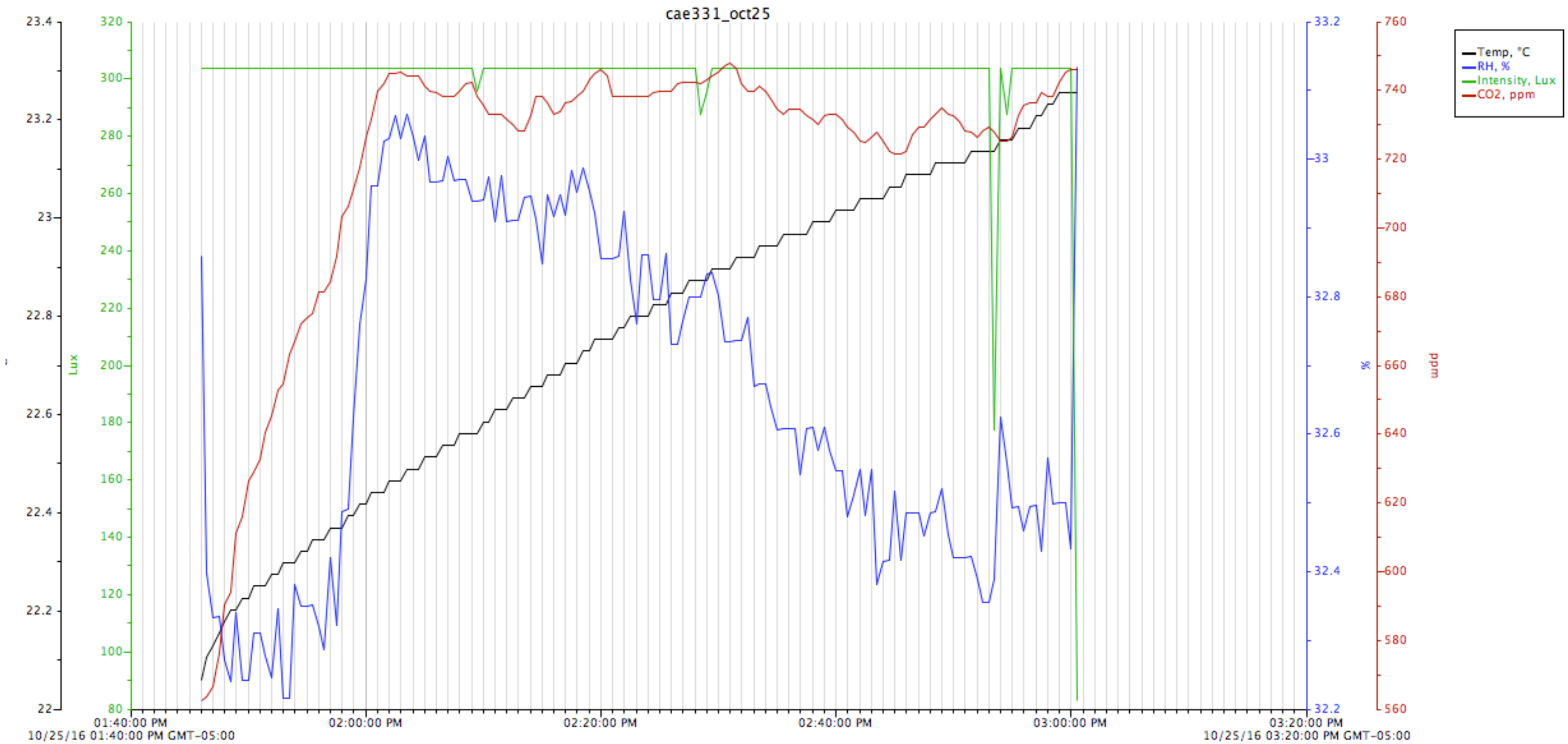
- Need to know airflows through each of these in order to quantify IAQ and energy impacts



VENTILATION

CO_2 concentration in the classroom (last class)

Estimate the ventilation rate in the classroom using CO_2 data

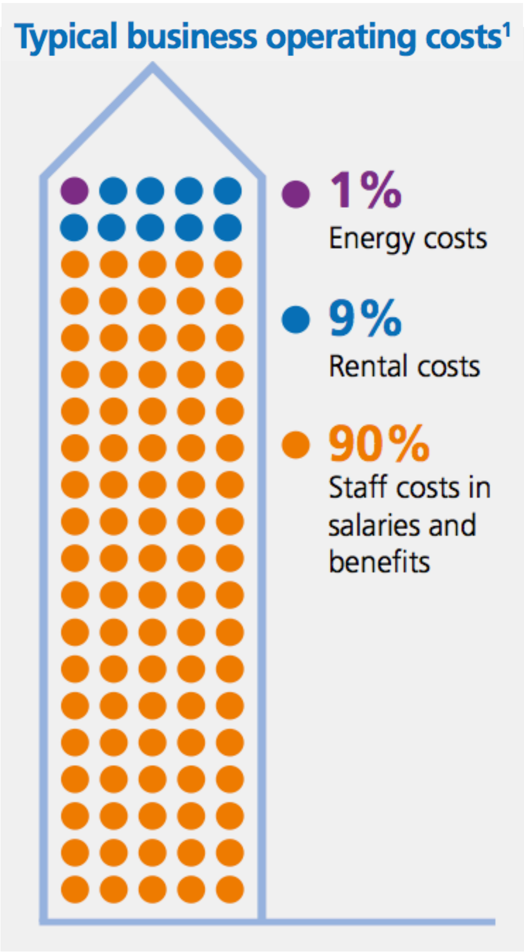


Answer: ~4.7 per hour

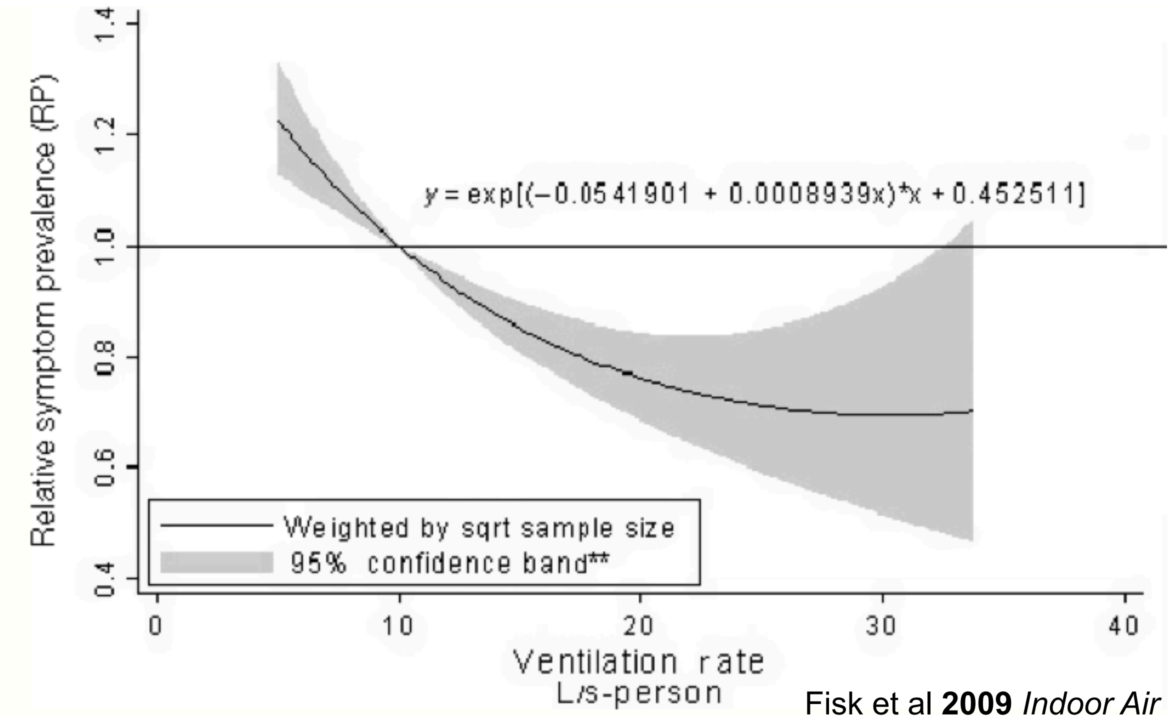
(530 m^3/hr = 147 L/s = 9.8 L/s/person

Importance of ventilation

- Outdoor air ventilation is used to dilute indoor-generated pollutants



Quantitative relationship of sick building syndrome symptoms with ventilation rates



Fisk et al **2009** *Indoor Air*

Ventilation and CO_2

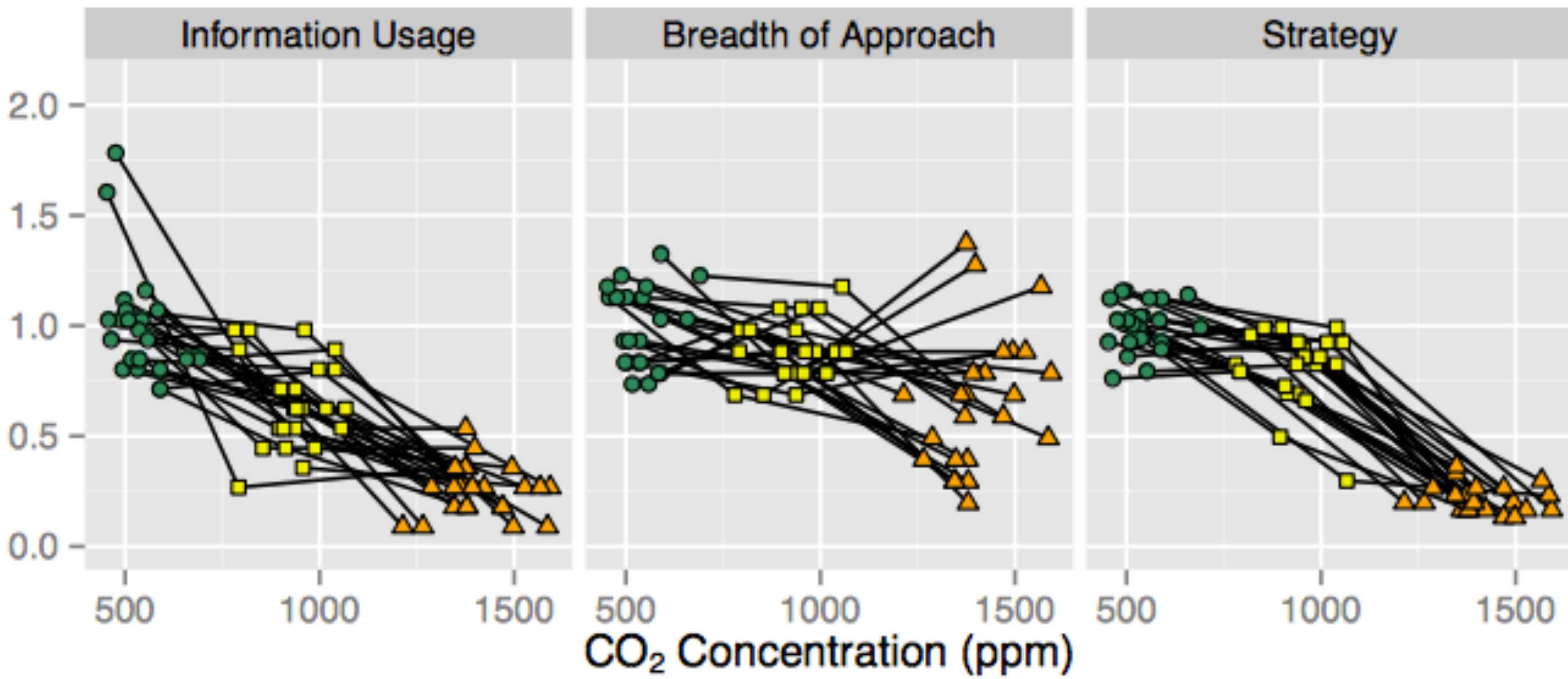
- CO_2 is often used as a surrogate for IAQ
  - Imperfect, but instructive

- The average CO_2 production rate per person at an activity level of 1.2 met is typically assumed to be 0.005 L/s (~35 g/hr at typically T & P)
  - Typical CO_2 emission rates are ~21 g/hr (or about 0.003 L/s) for lower met levels (e.g., sitting in a classroom)
  - Either way, CO_2 concentrations will be elevated in poorly ventilated spaces

- Recent evidence also suggests that CO_2 might be a pollutant on its own
  - Affecting decision making

Ventilation and CO_2

Scientists report a surprising link between indoor carbon dioxide levels and cognitive function



Allen et al **2015** *Environ Health Perspectives*

https://www.washingtonpost.com/news/energy-environment/wp/2015/10/27/why-your-office-air-could-be-crimping-your-productivity/

Ventilation and IAQ

- How do we determine the correct (or at least ***required***) ventilation rate?
  - ASHRAE Standard 62.1 (commercial) and 62.2 (residential)

ASHRAE Standard 62.1: Commercial buildings

ANSI/ASHRAE Standard 62.1-2010
(Supersedes ANSI/ASHRAE Standard 62.1-2007)
Includes ANSI/ASHRAE addenda listed in Appendix J

ASHRAE STANDARD

Ventilation for Acceptable Indoor Air Quality

1. PURPOSE

1.1 The purpose of this standard is to specify minimum ventilation rates and other measures intended to provide indoor air quality that is acceptable to human occupants and that minimizes adverse health effects.

1.2 This standard is intended for regulatory application to new buildings, additions to existing buildings, and those changes to existing buildings that are identified in the body of the standard.

1.3 This standard is intended to be used to guide the improvement of indoor air quality in existing buildings.

2. SCOPE

2.1 This standard applies to all spaces intended for human occupancy except those within single-family houses, multifamily structures of three stories or fewer above grade, vehicles, and aircraft.

2.2 This standard defines requirements for ventilation and air-cleaning system design, installation, commissioning, and operation and maintenance.

ASHRAE Standard 62.1: Commercial buildings

Ventilation rate procedure (VRP)

6.2.2.1 Breathing Zone Outdoor Airflow. The outdoor airflow required in the breathing zone of the occupiable space or spaces in a *ventilation zone*, i.e., the breathing zone outdoor airflow (V_{bz}), shall be no less than the value determined in accordance with Equation 6-1.

$$V_{bz} = R_p \cdot P_z + R_a \cdot A_z \tag{6-1}$$

where

A_z = zone floor area: the net occupiable floor area of the *ventilation zone* ft^2 (m^2)

P_z = zone population: the number of people in the *ventilation zone* during typical usage.

R_p = outdoor airflow rate required per person as determined from Table 6-1

Note: These values are based on adapted occupants.

R_a = outdoor airflow rate required per unit area as determined from Table 6-1

ASHRAE Standard 62.1: Commercial buildings VRP

TABLE 6-1 MINIMUM VENTILATION RATES IN BREATHING ZONE
(This table is not valid in isolation; it must be used in conjunction with the accompanying notes.)

Occupancy Category	People Outdoor Air Rate R_p		Area Outdoor Air Rate R_a		Notes	Default Values: Occupant Density (see Note 4)	Default Values: Combined Outdoor Air Rate (see Note 5)		Air Class
	cfm/person	L/s·person	cfm/ft^2	L/s·m^2		#/1000 ft^2 or #/100 m^2	cfm/person	L/s·person	
Correctional Facilities									
Cell	5	2.5	0.12	0.6		25	10	4.9	2
Dayroom	5	2.5	0.06	0.3		30	7	3.5	1
Guard stations	5	2.5	0.06	0.3		15	9	4.5	1
Booking/waiting	7.5	3.8	0.06	0.3		50	9	4.4	2
Educational Facilities									
Daycare (through age 4)	10	5	0.18	0.9		25	17	8.6	2
Daycare sickroom	10	5	0.18	0.9		25	17	8.6	3
Classrooms (ages 5–8)	10	5	0.12	0.6		25	15	7.4	1
Classrooms (age 9 plus)	10	5	0.12	0.6		35	13	6.7	1
Lecture classroom	7.5	3.8	0.06	0.3		65	8	4.3	1
Lecture hall (fixed seats)	7.5	3.8	0.06	0.3		150	8	4.0	1
Art classroom	10	5	0.18	0.9		20	19	9.5	2
Science laboratories	10	5	0.18	0.9		25	17	8.6	2
University/college laboratories	10	5	0.18	0.9		25	17	8.6	2
Wood/metal shop	10	5	0.18	0.9		20	19	9.5	2
Computer lab	10	5	0.12	0.6		25	15	7.4	1

ASHRAE Standard 62.1: Commercial buildings VRP

TABLE 6-1 MINIMUM VENTILATION RATES IN BREATHING ZONE *(Continued)*
(This table is not valid in isolation; it must be used in conjunction with the accompanying notes.)

Occupancy Category	People Outdoor Air Rate R_p		Area Outdoor Air Rate R_a		Notes	Default Values: Occupant Density (see Note 4)	Default Values: Combined Outdoor Air Rate (see Note 5)		Air Class
	cfm/person	L/s·person	cfm/ft^2	L/s·m^2		#/1000 ft^2 or #/100 m^2	cfm/person	L/s·person	
Office Buildings									
Breakrooms	5	2.5	0.12	0.6		50	7	3.5	1
Main entry lobbies	5	2.5	0.06	0.3		10	11	5.5	1
Occupiable storage rooms for dry materials	5	2.5	0.06	0.3		2	35	17.5	1
Office space	5	2.5	0.06	0.3		5	17	8.5	1
Reception areas	5	2.5	0.06	0.3		30	7	3.5	1
Telephone/data entry	5	2.5	0.06	0.3		60	6	3.0	1
Miscellaneous Spaces									
Bank vaults/safe deposit	5	2.5	0.06	0.3		5	17	8.5	2
Banks or bank lobbies	7.5	3.8	0.06	0.3		15	12	6.0	1
Computer (not printing)	5	2.5	0.06	0.3		4	20	10.0	1
General manufacturing (excludes heavy industrial and processes using chemicals)	10	5.0	0.18	0.9		7	36	18	3

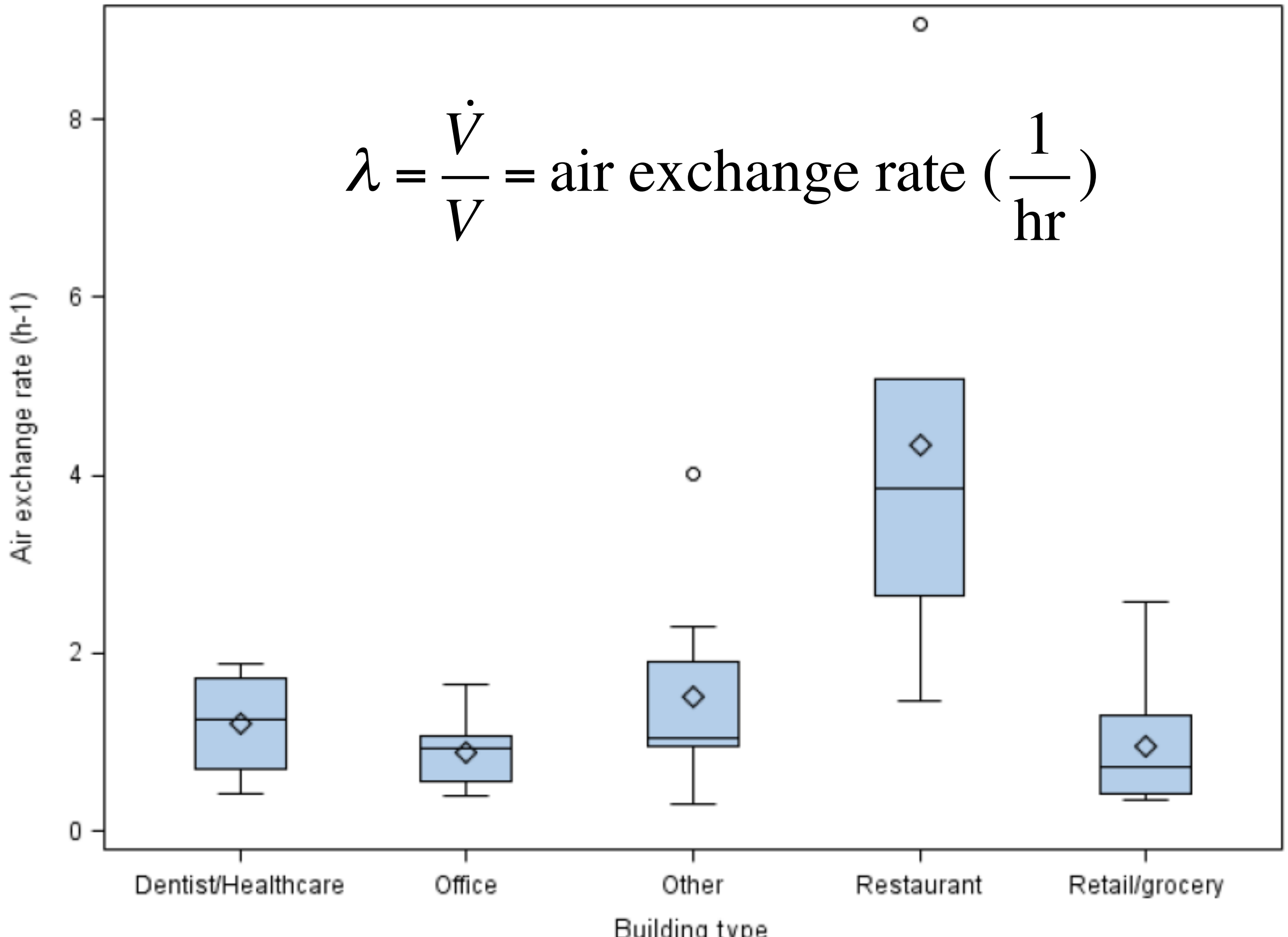
ASHRAE Standard 62.1: Commercial buildings VRP

TABLE 6-4 Minimum Exhaust Rates

Occupancy Category	Exhaust Rate, cfm/unit	Exhaust Rate, cfm/ft^2	Notes	Exhaust Rate, L/s·unit	Exhaust Rate, $L/s \cdot m^2$	Air Class
Arenas	–	0.50	B	–	–	1
Art classrooms	–	0.70		–	3.5	2
Auto repair rooms	–	1.50	A	–	7.5	2
Barber shops	–	0.50		–	2.5	2
Beauty and nail salons	–	0.60		–	3.0	2
Cells with toilet	–	1.00		–	5.0	2
Copy, printing rooms	–	0.50		–	2.5	2
Darkrooms	–	1.00		–	5.0	2
Educational science laboratories	–	1.00		–	5.0	2
Janitor closets, trash rooms, recycling	–	1.00		–	5.0	3
Kitchenettes	–	0.30		–	1.5	2
Kitchens—commercial	–	0.70		–	3.5	2
Locker/dressing rooms	–	0.25		–	1.25	2
Locker rooms	–	0.50		–	2.5	2
Paint spray booths	–	–	F	–	–	4
Parking garages	–	0.75	C	–	3.7	2
Pet shops (animal areas)	–	0.90		–	4.5	2
Refrigerating machinery rooms	–	–	F	–	–	3
Residential kitchens	50/100	–	G	25/50	–	2
Soiled laundry storage rooms	–	1.00	F	–	5.0	3
Storage rooms, chemical	–	1.50	F	–	7.5	4

Measured air exchange rates: Commercial buildings

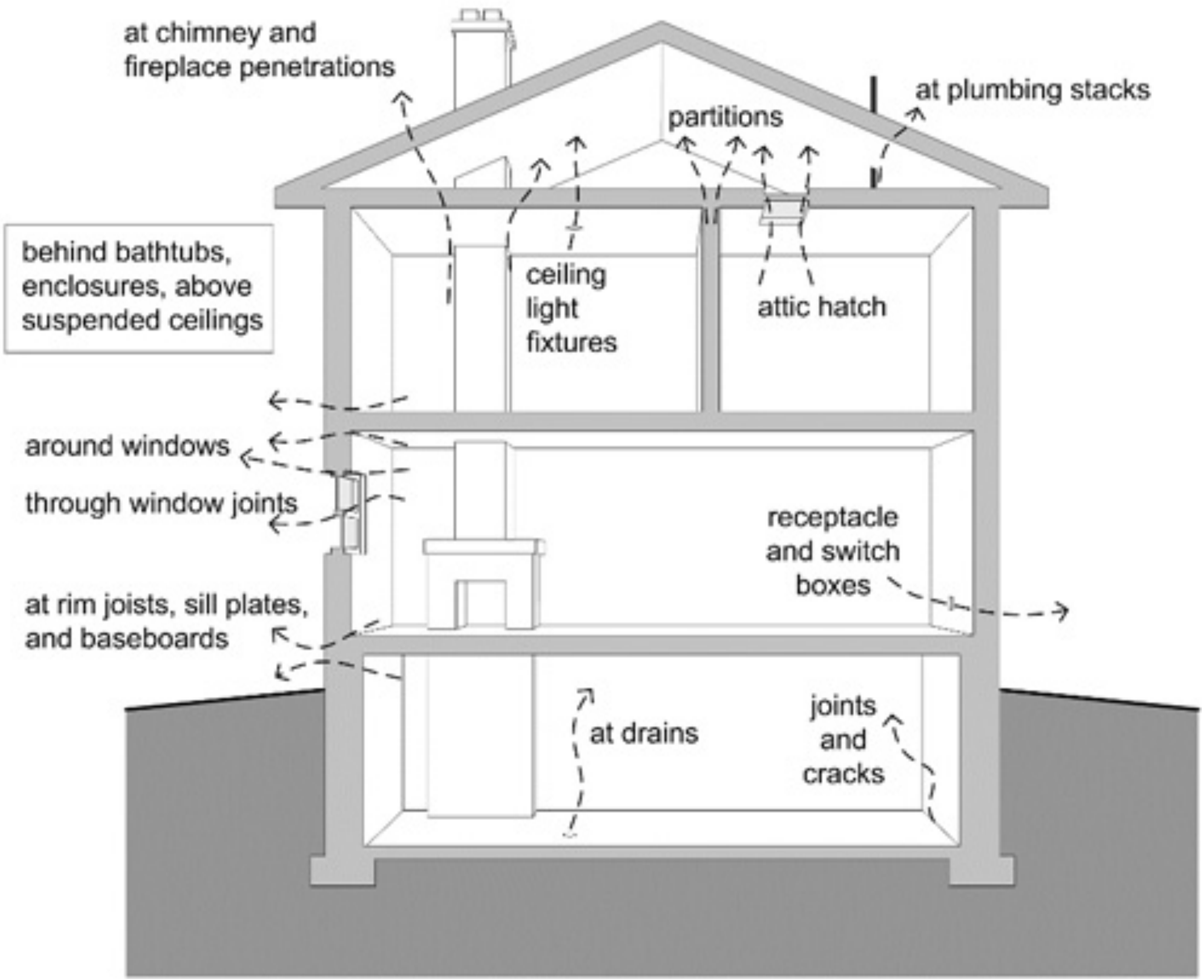
- Recent study of ~40 commercial buildings in California



Bennett et al. **2011** CEC Report

INFILTRATION

Typical air leakage sites in buildings



http://buildingscience.com.678elmp02.blackmesh.com/sites/default/files/migrate/jpg/Figure_07_Typical_air_leaka.jpg

General models for air flows through leaks

- Given an opening (i.e., a leak, crack, or open window):

$$\dot{V} = AC\Delta P^{n}$$

A = area of opening, ft^2 (m^2)
Δ*P* = pressure difference between inside and outside, in WG (Pa)
C = flow coefficient, ft/(min inWG^n) [m/(s Pa^n)]
n = exponent, between 0.4 and 1.0 (usually 0.65 for buildings)

- For a combination of i openings:

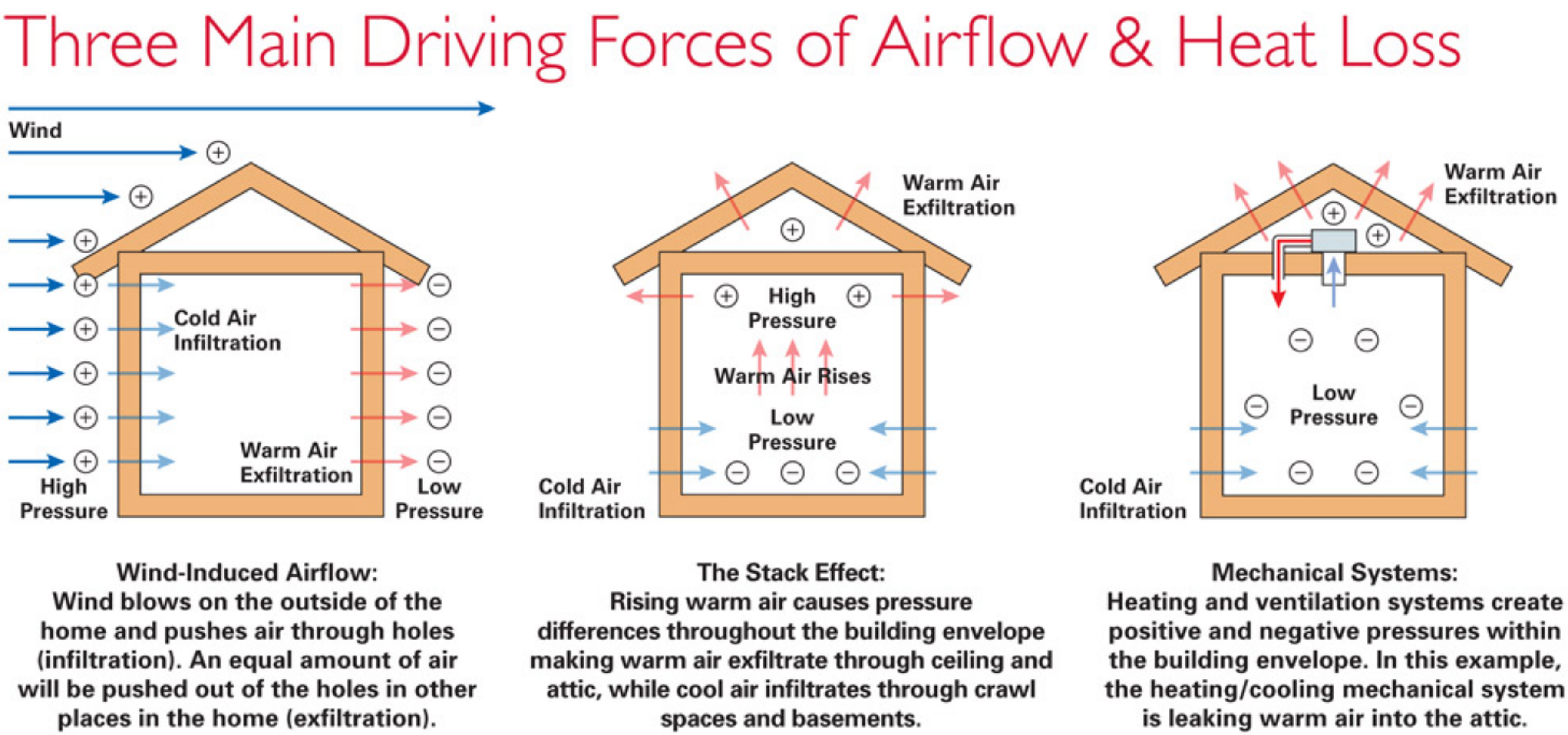
$$\dot{V} = \sum_{i} A_i C_i \Delta P_i^{n_i}$$

Driving forces of infiltration: Δ*P*

- Three primary mechanisms generate pressure differences (**driving forces**)
  - **Wind**
    - Caused by wind impinging on a building, creating a distribution of pressures on the exterior surface
    - Depends on wind direction, wind speed, air density, surface orientation, and surrounding conditions
  - **Stack effect (natural buoyancy)**
    - Caused by the weight of a column of air located inside/outside a building
    - Depends on air density and height above a neutral reference level
      - Density is a function of temperature (so this is temperature driven)
  - **Mechanical air handling equipment (fans)**
    - Fans are used to supply, recirculate, exhaust, and otherwise balance pressures and flows in buildings

$$\Delta P = \Delta P_{wind} + \Delta P_{stack} + \Delta P_{vent}$$ ("+" when causing flow to interior)

Driving forces of infiltration: ΔP



http://www.homepower.com/sites/default/files/articles/ajax/docs/4_HP126_pg40_Connor-2.jpg

Wind pressures

- From velocity component of Bernoulli Equation:

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

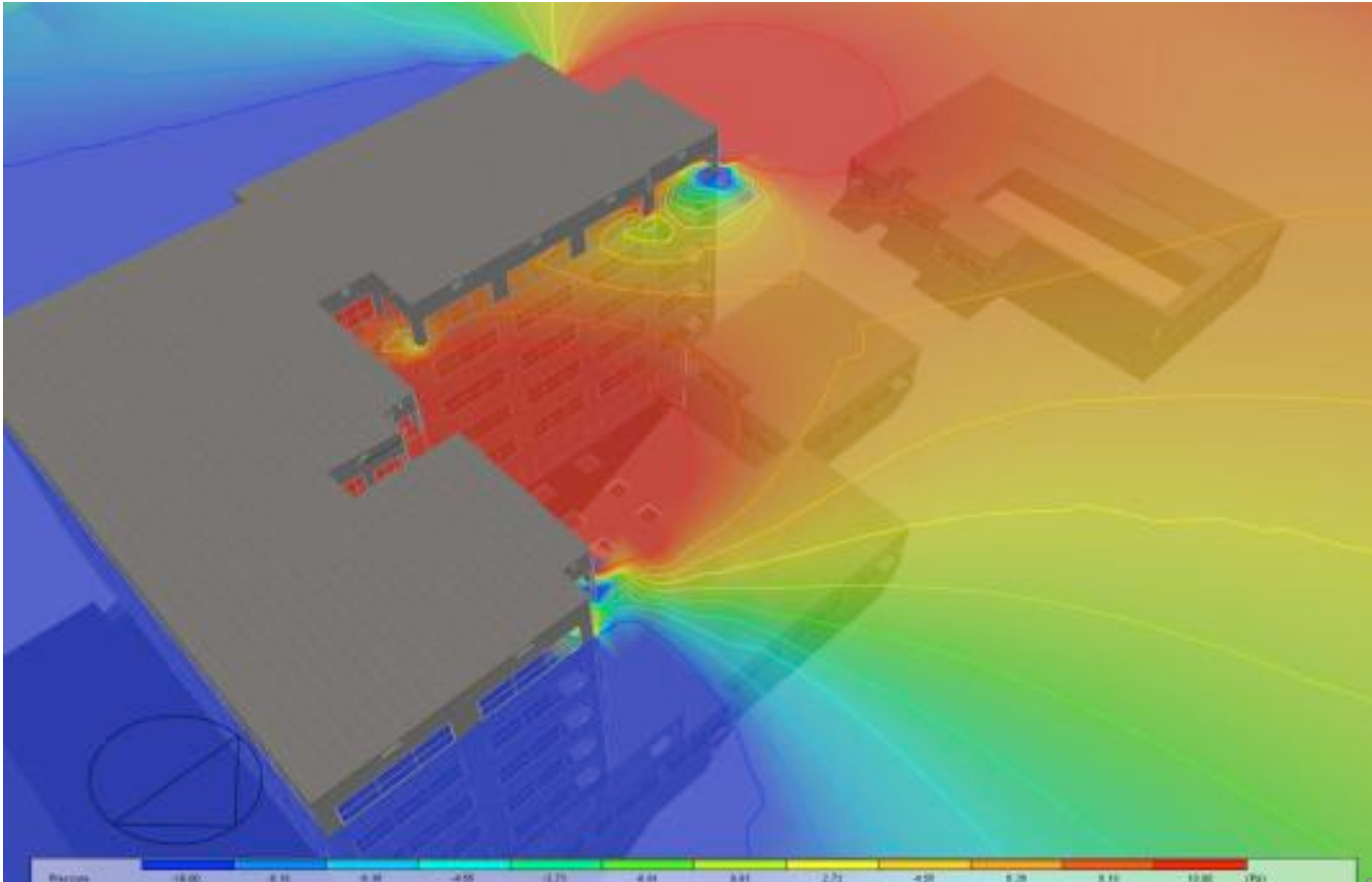
$P_{velocity}$ = wind velocity pressure; U_h = air velocity at building height, h; ρ_{air} = air density

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

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

  - Get C_P (+ or -) from measurements or from *ASHRAE Handbook of Fundamentals 2013* Chapter 24 “Airflow around buildings”

Wind pressure coefficients (C_p) vary around buildings



Stack effect

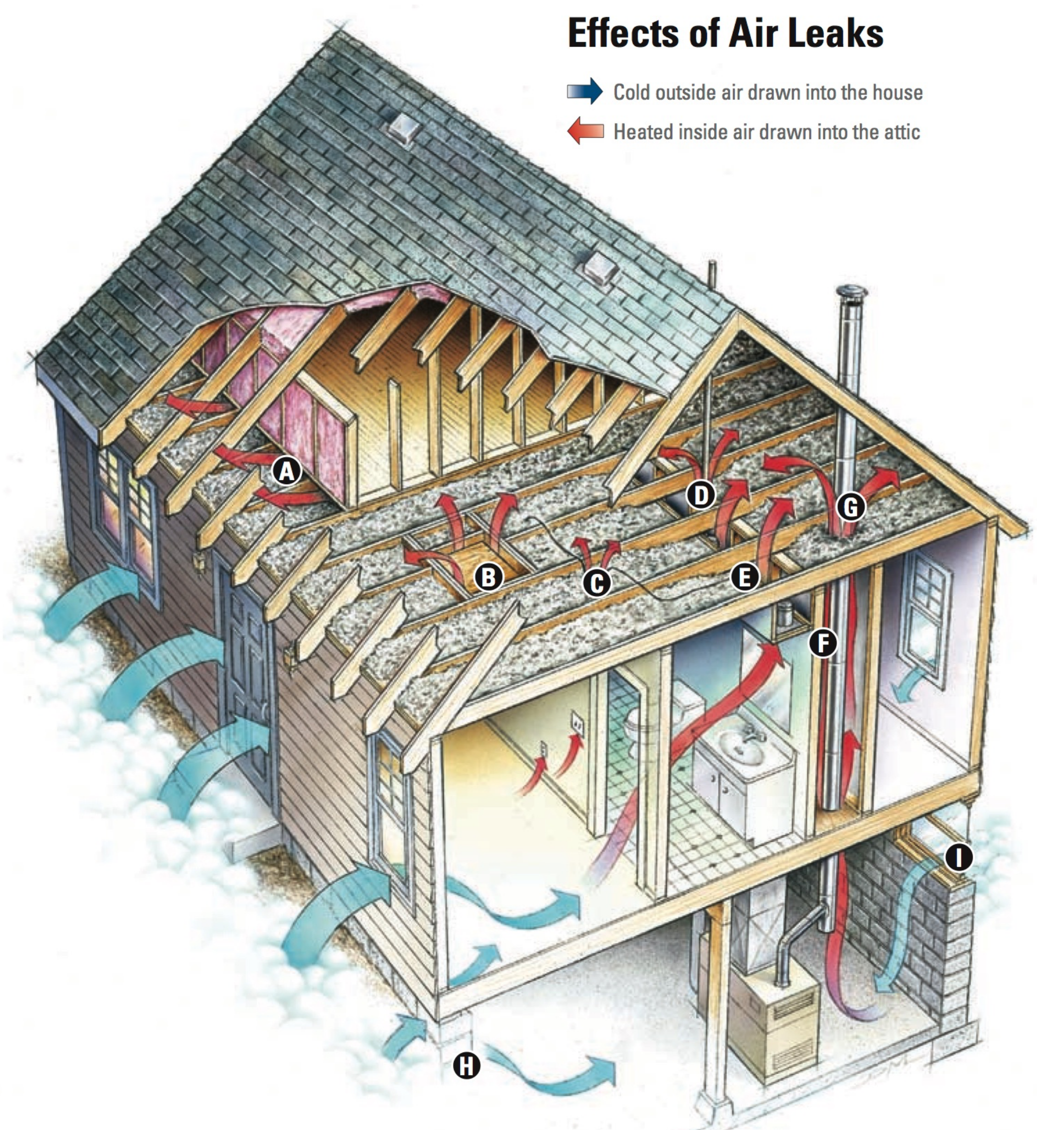
- **In wintertime**
  - Air within a building acts like a bubble of hot air in a sea of cold air
  - Rises to the top
  - Draws **outdoor air in from** cracks/gaps/openings in the **bottom**
  - Indoor air flows out through openings in the top
- **In summertime**
  - Air within a building acts like a 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 is drawn in through openings in the top
    - Temperature differences usually lower in the summer time so the amount of flow is smaller

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

Stack effect in residential buildings

Common Household Air Leaks

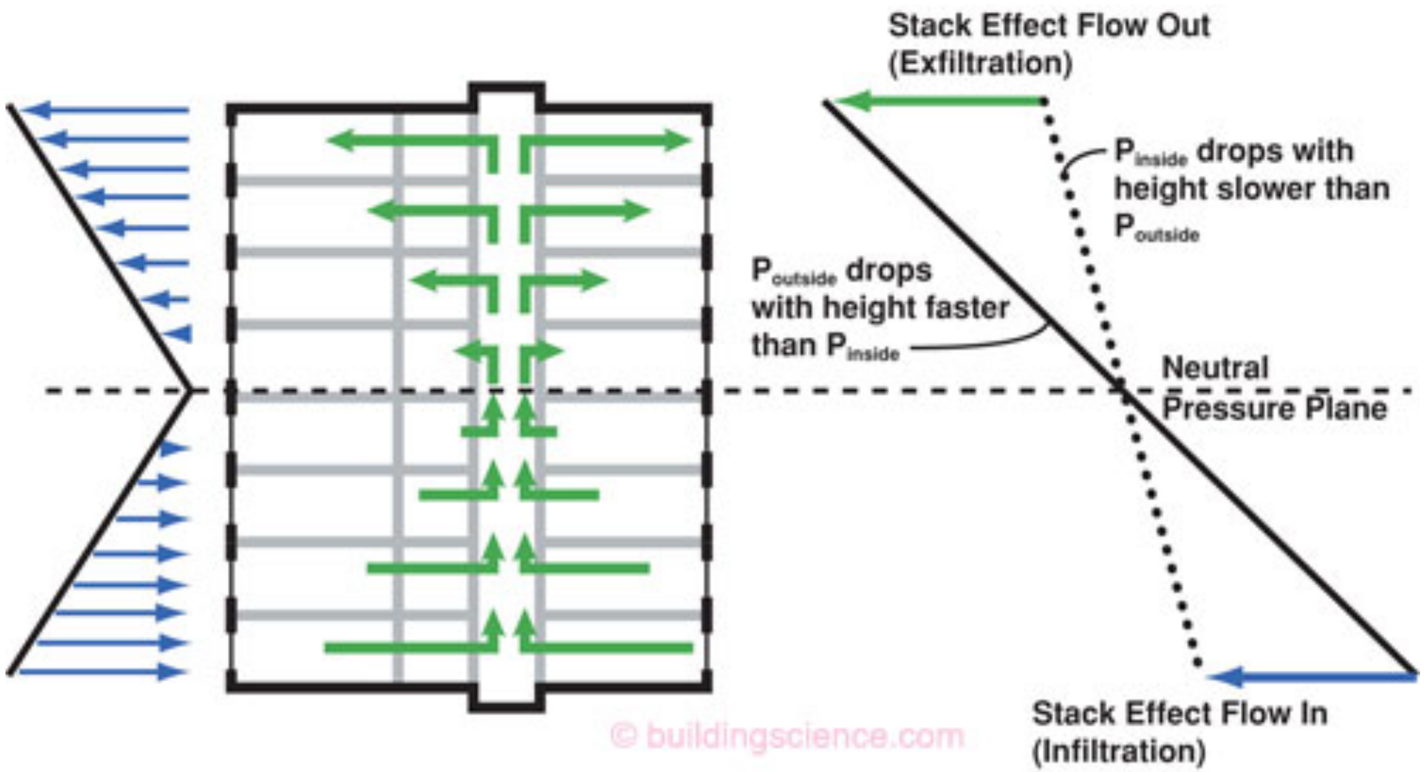
- **A** Behind Kneewalls
- **B** Attic Hatch
- **C** Wiring Holes
- **D** Plumbing Vent
- **E** Open Soffit (the box that hides recessed lights)
- **F** Recessed Light
- **G** Furnace Flue or Duct Chaseways (the hollow box or wall feature that hides ducts)
- **H** Basement Rim Joists (where the foundation meets the wood framing)
- **I** Windows and Doors



http://www.opalco.com/wp-content/uploads/2014/10/House-Image.jpg

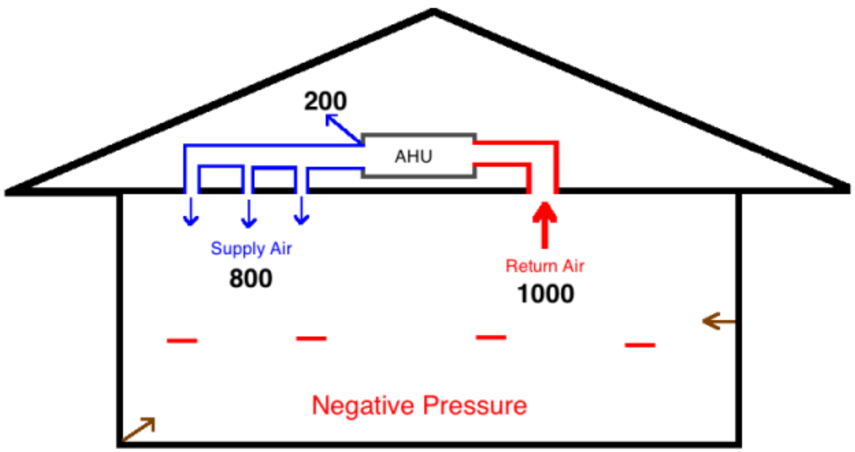
Stack effect in tall buildings

- The stack effect is magnified in taller buildings

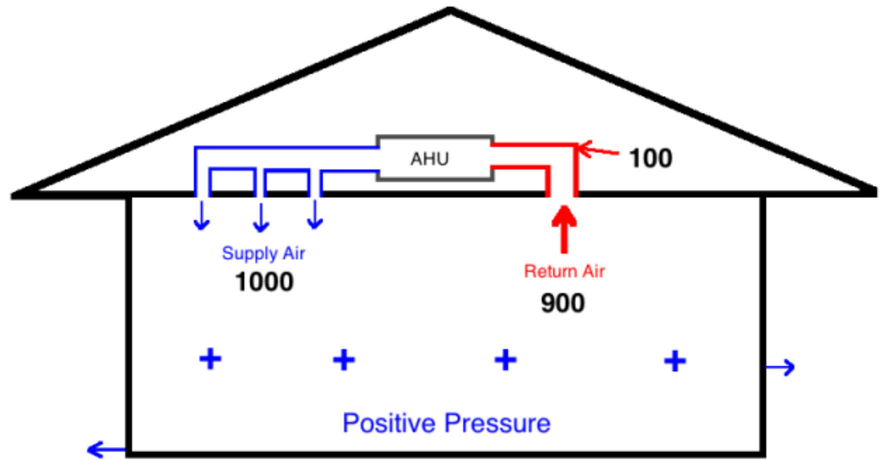


Mechanical system driving forces

- Mostly relates to unbalanced leakage (e.g., duct leakage)



Supply Duct Leakage

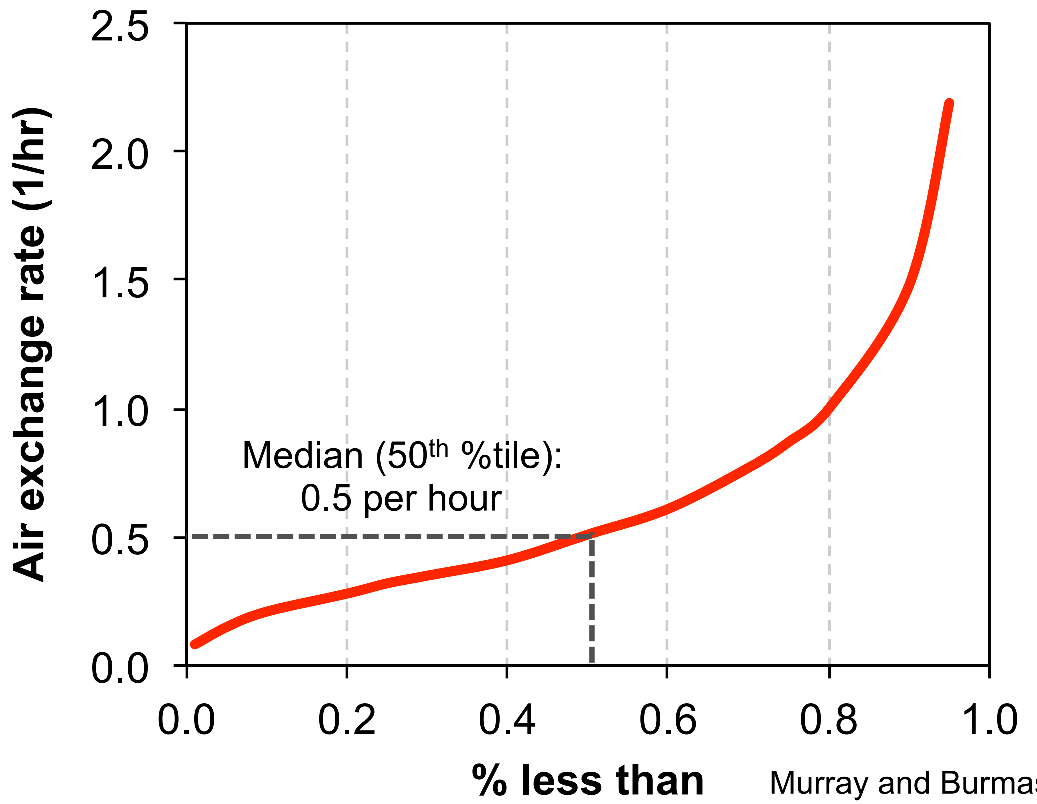


Return Duct Leakage

http://www.greenbuildingadvisor.com/blogs/dept/building-science/how-duct-leakage-steals-twice

What are typical air exchange rates (AERs) in homes?

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



Murray and Burmaster, **1995** *Risk Analysis*

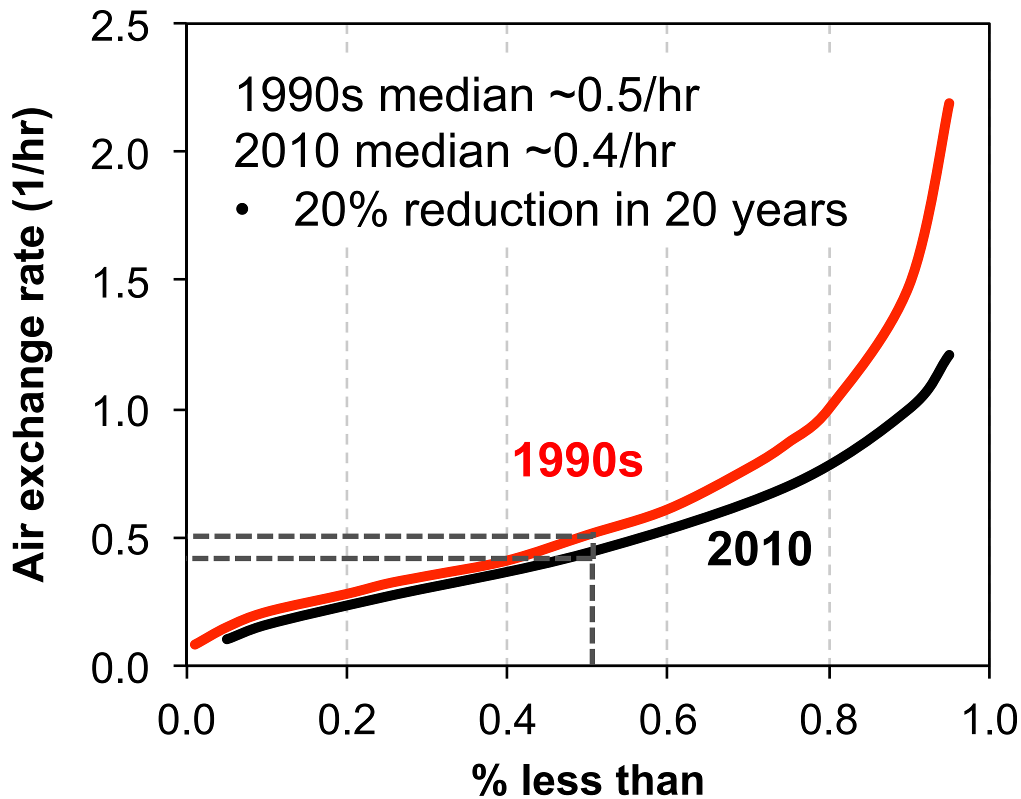
Mostly due to infiltration and window opening

In the past, we seldom used mechanical ventilation systems in single-family homes, but this is changing

- What do you think this curve looks like now?

What are typical air exchange rates (AERs) in homes?

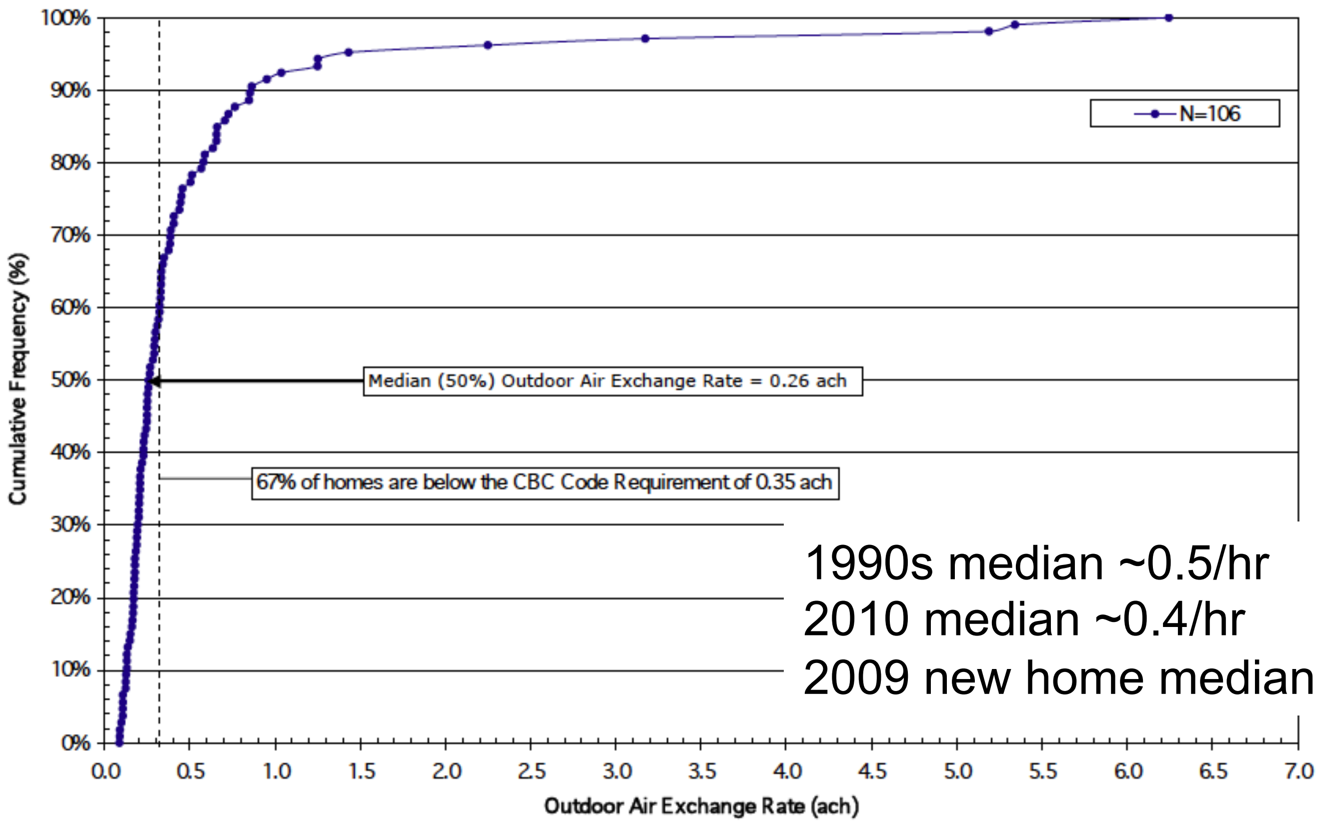
- New distribution of AERs U.S. homes
  - Early 1990s and revisited in 2010 (Persily et al. 2010)



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

What are typical air exchange rates (AERs) in homes?

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



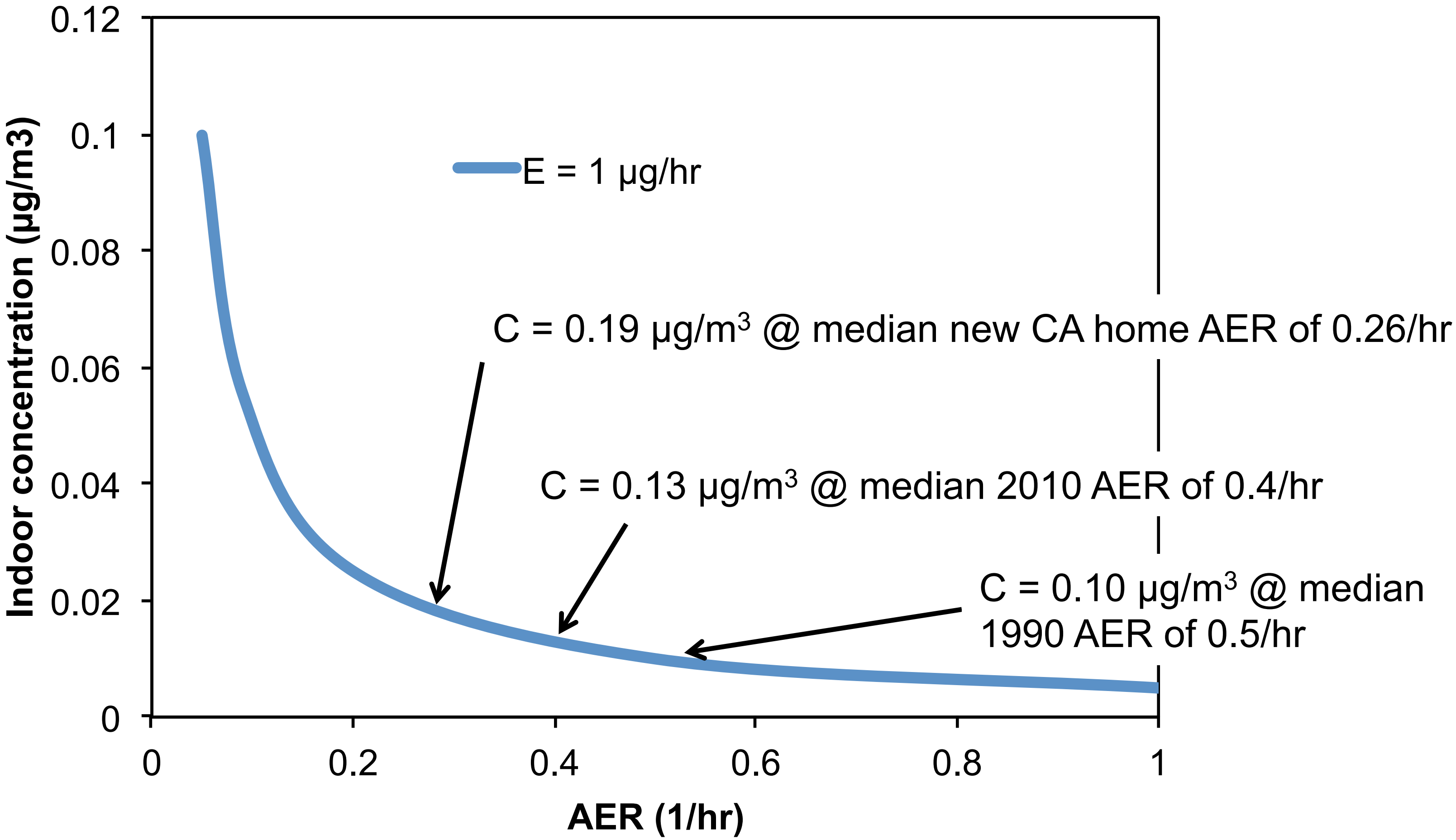
1990s median ~0.5/hr
2010 median ~0.4/hr
2009 new home median ~0.26/hr

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

Offermann et al. 2009 CEC PIER Report

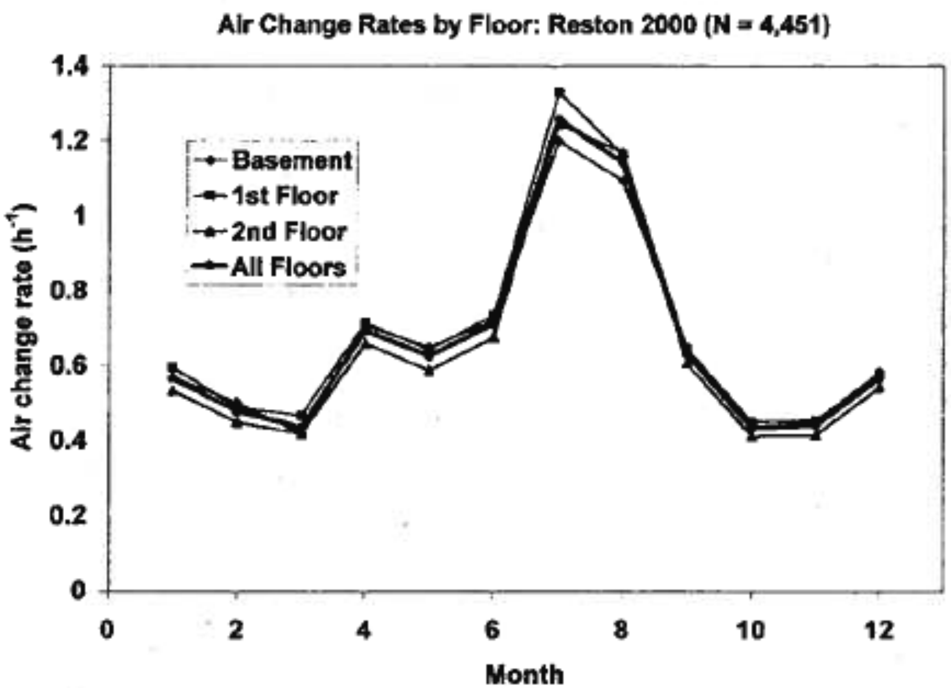
Steady state mass balance and real AERs

- Assume V = 200 m^3 and E = 1 µg/hr
- Lower AER → higher C_{ss}

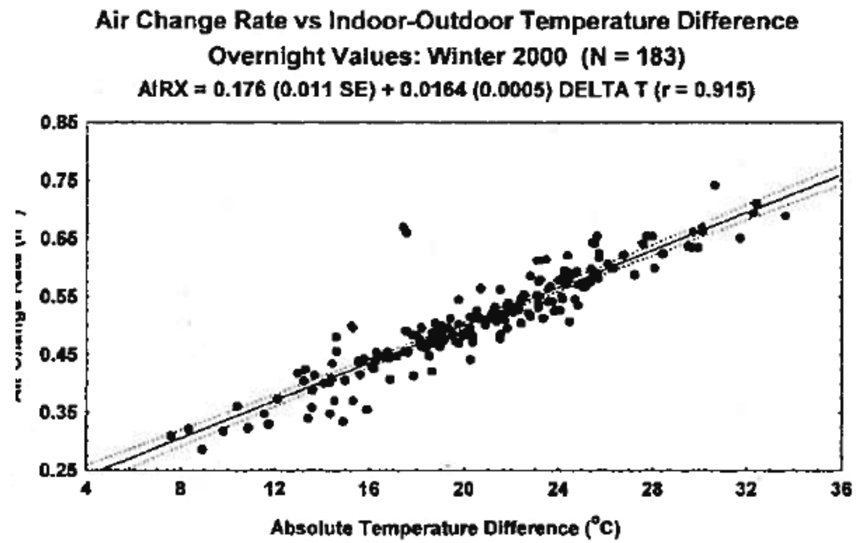


Variation in infiltration AER with driving forces

- Air exchange rates differ both between buildings and within buildings
  - Differences vary by driving forces & building operation (e.g. windows/HVAC)
- Example: 4600 AERs measured by automated SF_6 system in a house for 2 years:



AERs can vary by I/O temperature within seasons



AERs in individual buildings can vary by season

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

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

ASHRAE Standard 62.2: Residential ventilation

ANSI/ASHRAE Standard 62.2-2007
(Supersedes ANSI/ASHRAE Standard 62.2-2004)
Includes ANSI/ASHRAE addenda listed in Appendix C

ASHRAE STANDARD

Ventilation and Acceptable Indoor Air Quality in Low-Rise Residential Buildings

1. PURPOSE

This standard defines the roles of and minimum requirements for mechanical and natural ventilation systems and the building envelope intended to provide acceptable indoor air quality (IAQ) in low-rise residential buildings.

2. SCOPE

This standard applies to spaces intended for human occupancy within single-family houses and multifamily structures of three stories or fewer above grade, including manufactured and modular houses. This standard does not apply to transient housing such as hotels, motels, nursing homes, dormitories, or jails.

2.1 This standard considers chemical, physical, and biological contaminants that can affect air quality. Thermal comfort requirements are not included in this standard (see *ANSI/ASHRAE Standard 55-2004*, *Thermal Environmental Conditions for Human Occupancy*).

2.2 While acceptable indoor air quality is the goal of this standard, it will not necessarily be achieved even if all requirements are met

ASHRAE Standard 62.2: Residential ventilation

4. WHOLE-BUILDING VENTILATION

4.1 Ventilation Rate. A mechanical exhaust system, supply system, or combination thereof shall be installed for each dwelling unit to provide whole-building ventilation with outdoor air each hour at no less than the rate specified in Tables 4.1a and 4.1b or, equivalently, Equations 4.1a and 4.1b, based on the floor area of the conditioned space and number of bedrooms.

$$Q_{fan} = 0.01A_{floor} + 7.5(N_{br} + 1) \qquad (4.1a)$$

where

Q_{fan} = fan flow rate, cfm
A_{floor} = floor area, ft^2
N_{br} = number of bedrooms; not to be less than one

$$Q_{fan} = 0.05A_{floor} + 3.5(N_{br} + 1) \qquad (4.1b)$$

where

Q_{fan} = fan flow rate, L/s
A_{floor} = floor area, m^2
N_{br} = number of bedrooms; not to be less than one

TABLE 4.1a (I-P)
Ventilation Air Requirements, cfm

Floor Area (ft^2)	Bedrooms 0–1	2–3	4–5	6–7	>7
<1500	30	45	60	75	90
1501–3000	45	60	75	90	105
3001–4500	60	75	90	105	120
4501–6000	75	90	105	120	135
6001–7500	90	105	120	135	150
>7500	105	120	135	150	165

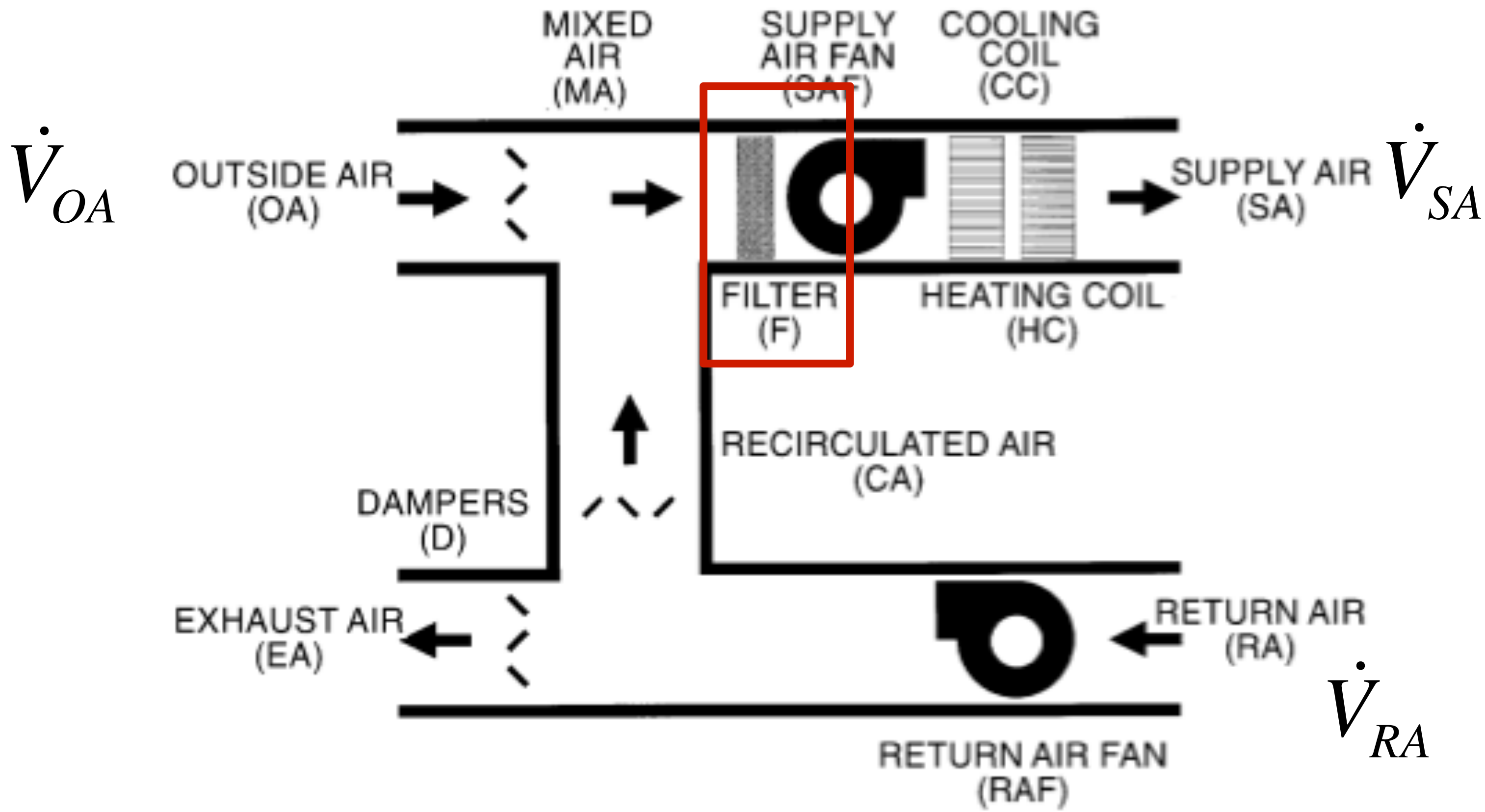
TABLE 4.1b (SI)
Ventilation Air Requirements, L/s

Floor Area (m^2)	Bedrooms 0–1	2–3	4–5	6–7	>7
<139	14	21	28	35	42
139.1–279	21	28	35	42	50
279.1–418	28	35	42	50	57
418.1–557	35	42	50	57	64
557.1–697	42	50	57	64	71
>697	50	57	64	71	78

AIR CLEANING/FILTRATION

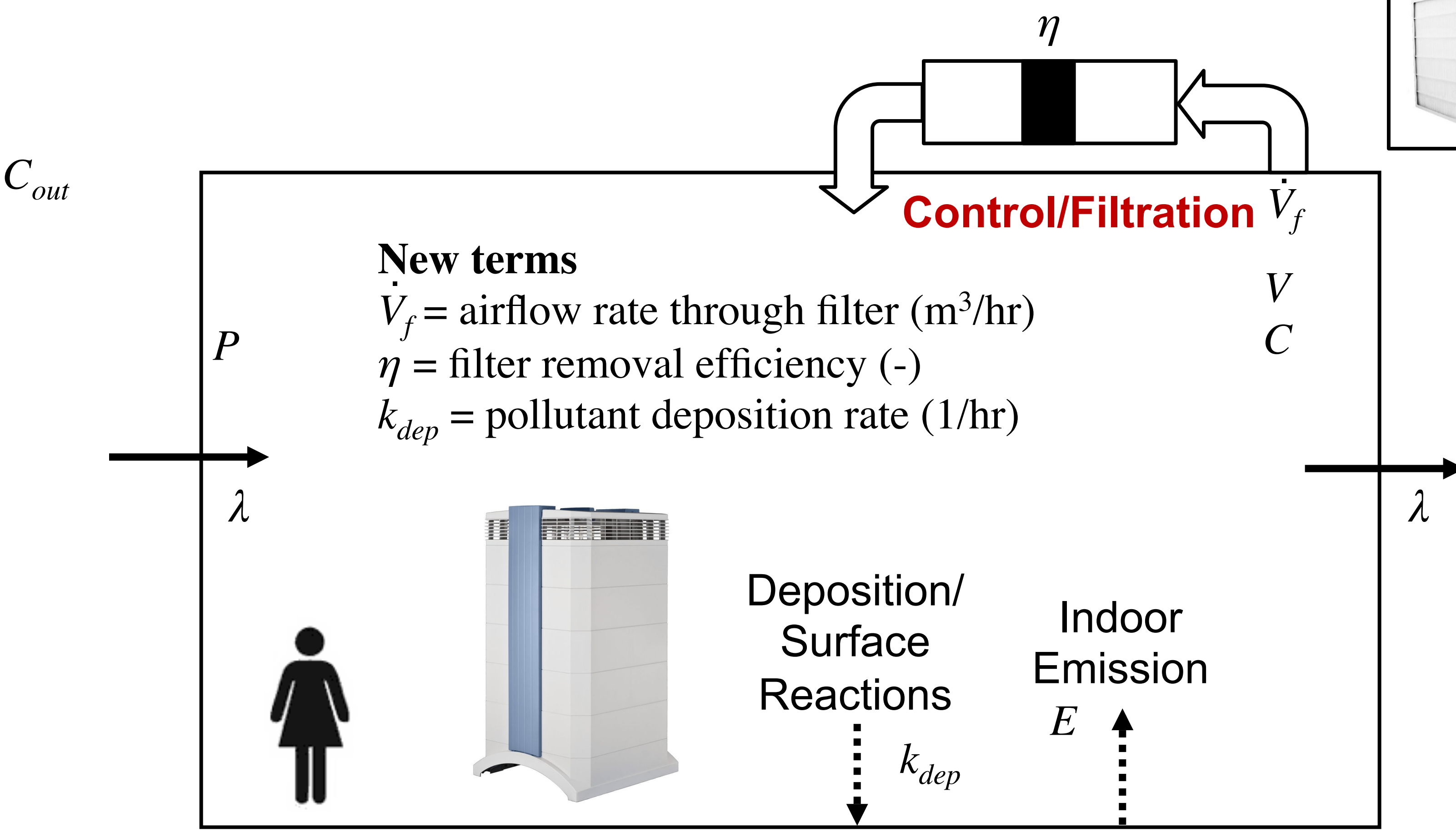
Forced air distribution: Filtration

Typical commercial HVAC system:



Mass balance: What if we add HVAC filtration?

- Other loss mechanisms are important to the mass balance
  - Deposition to surfaces, reactions, control by HVAC filter



New terms

$\dot{V}_f$ = airflow rate through filter (m^3/hr)

η = filter removal efficiency (-)

k_{dep} = pollutant deposition rate (1/hr)

Mass balance with filtration and deposition

- New term to mass balance (derive on the board):

$$V\frac{dC}{dt} = P\dot{V}C_{out} - \dot{V}C + E - \eta\dot{V}_f C - k_{dep}VC$$

$$\cancelto{0}{\frac{dC}{dt}} = P\lambda C_{out} - \lambda C + \frac{E}{V} - \frac{\eta\dot{V}_f}{V}C - k_{dep}C$$

- Assume steady state for now, divide by λ, and solve for C:

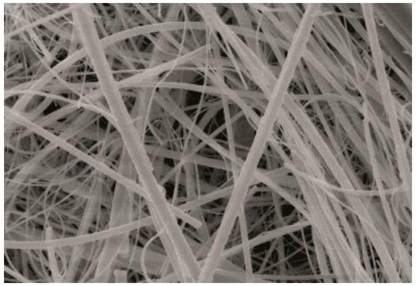
$$C_{ss} = \frac{P\lambda C_{out} + \frac{E}{V}}{\lambda + \frac{\eta\dot{V}_f}{V} + k_{dep}}$$

- CADR = Clear Air Delivery Rate $\longrightarrow$ $CADR = \eta\dot{V}_f$

Units of flow (e.g., CFM or m^3/s)

What can we filter out in buildings?

- Particles
  - Fibrous filters
  - Electrostatic precipitators
  - Every forced air HVAC system will have some kind of particle filter



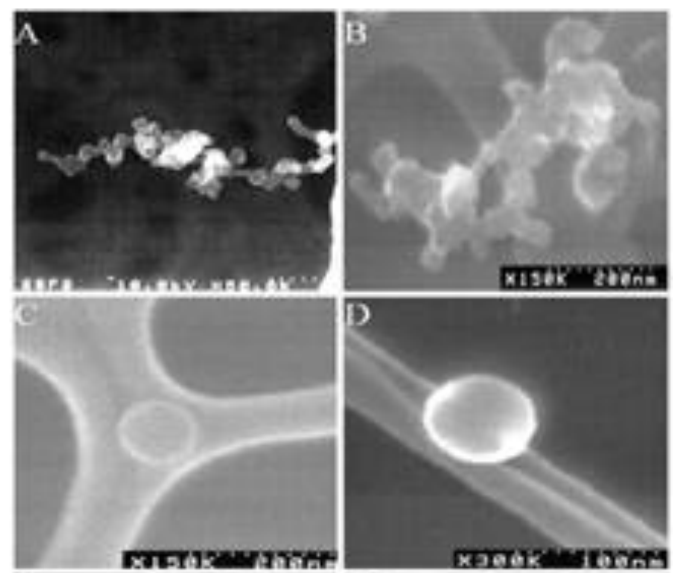
- Gases
  - Activated carbon
    - Relies on adsorption of VOCs/other gases to high surface area carbon
  - Very few buildings will have gas-phase filtration

Particulate matter (PM)

- Particulate matter (PM) is its own class of pollutant
  - PM consists of a mixture of solid particles and liquid droplets suspended in air
  - Primary emissions are emitted directly by sources
    - Outdoors: Industry, construction, roads, smokestacks, fires, vehicles
    - Indoors: Smoking, cooking, resuspension of dust, transport from outdoors
  - Secondary emissions are formed in atmospheric reactions and some indoor reactions

- Health effects
  - Respiratory, cardiovascular, lung cancer, and others

- Visibility effects outdoors

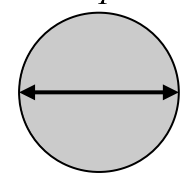


http://www.aerosols.wustl.edu/education/AerosolBasics/What%20is%20an%20aerosol.htm

Particulate matter

- Usually referring to a characteristic dimension
  - Diameter for sphere
  - Diameter for fibers (e.g. asbestos)
  - Equivalent diameter for non-spherical

d_p



$$V = \frac{\pi}{6} d_p^3$$

Important units:

- Micrometer (µm)
  - 1 µm = 10^{-6} m
- Nanometer (nm)
  - 1 nm = 10^{-9} m = 1000 µm

Particle sizes

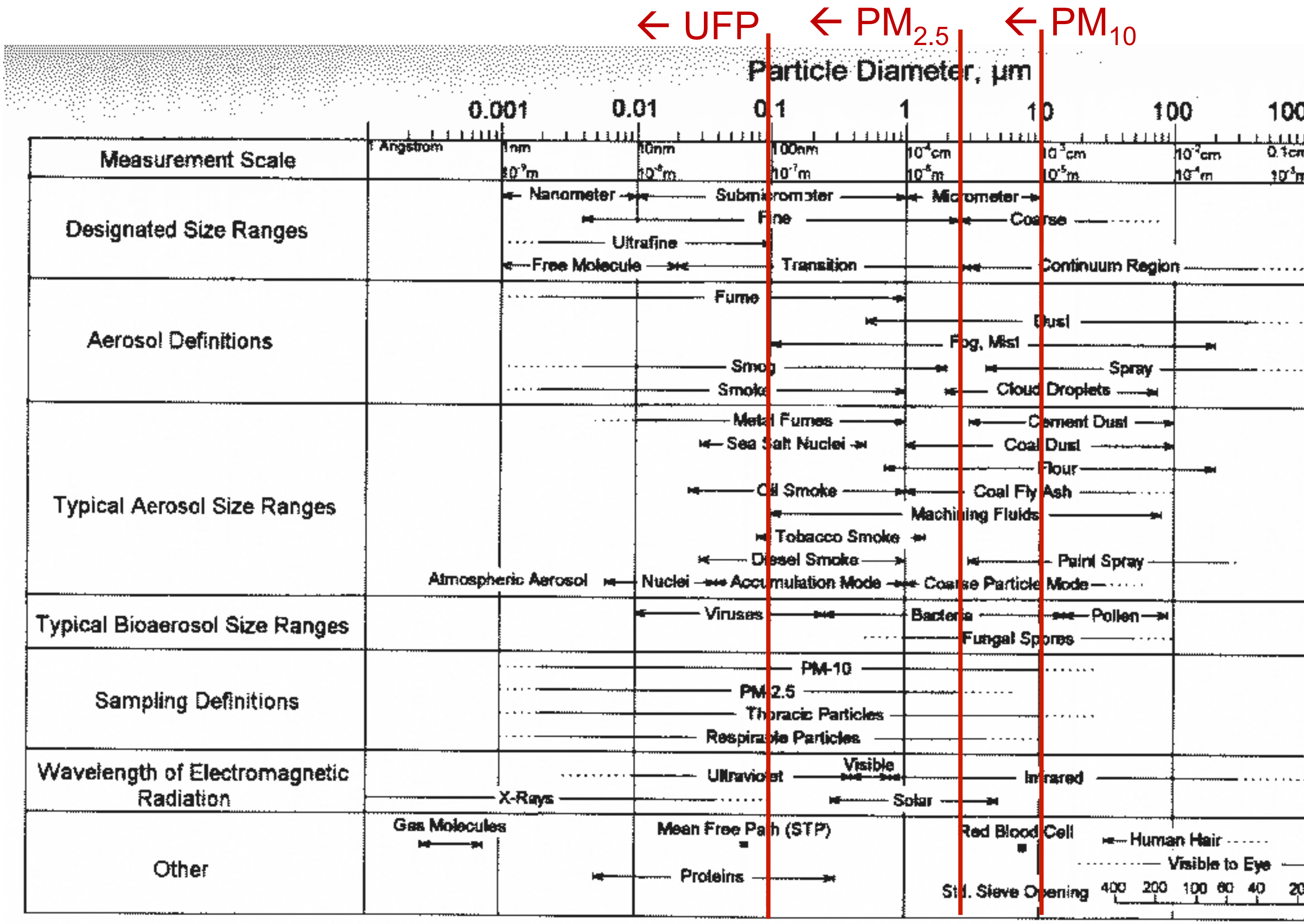
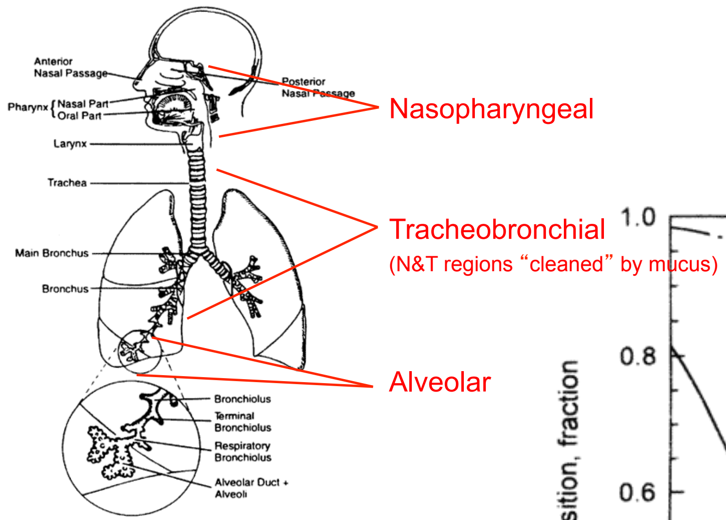


FIGURE 1.6 Particle size ranges and definitions for aerosols.

Hinds 1999

Particle deposition in respiratory system



Hinds, 1999 Ch. 11

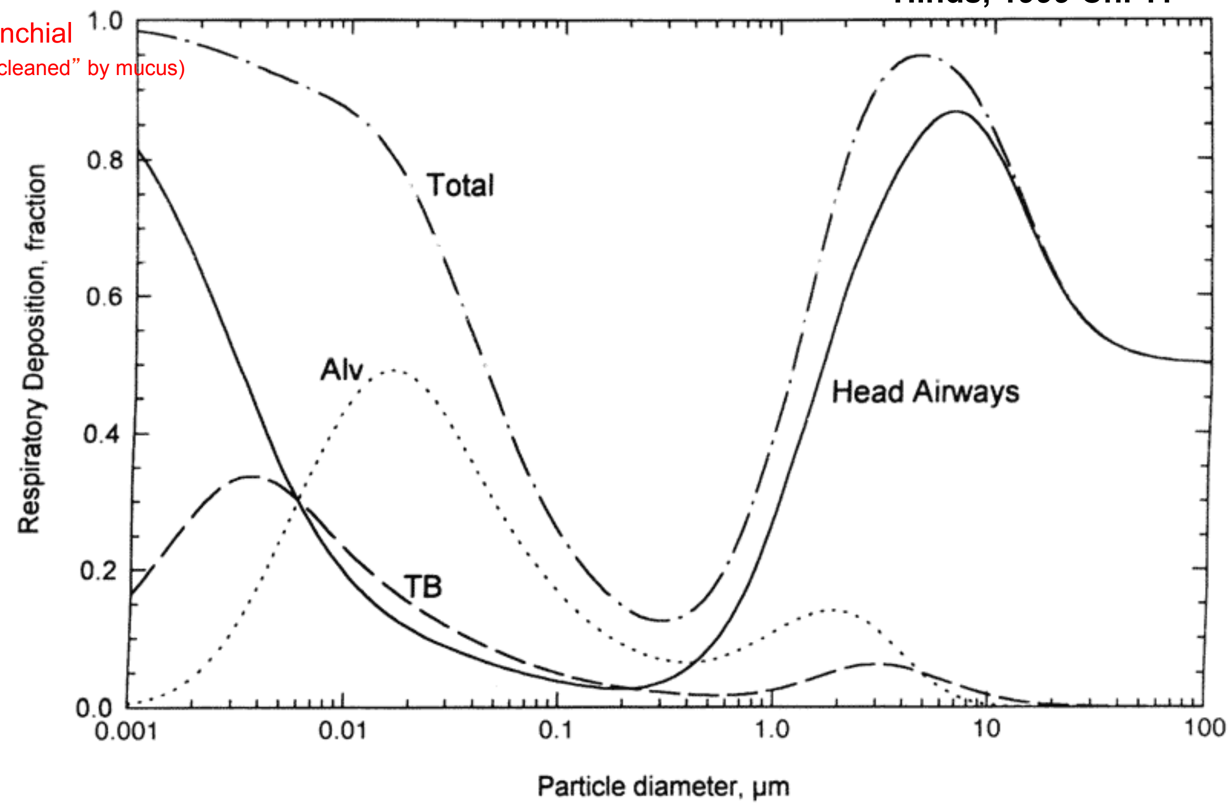


FIGURE 11.3 Predicted total and regional deposition for light exercise (nose breathing) based on ICRP deposition model. Average data for males and females.

High efficiency particle filtration

- Particle filtration efficiency standards for central HVAC filters

MERV: Minimum Efficiency Reporting Value

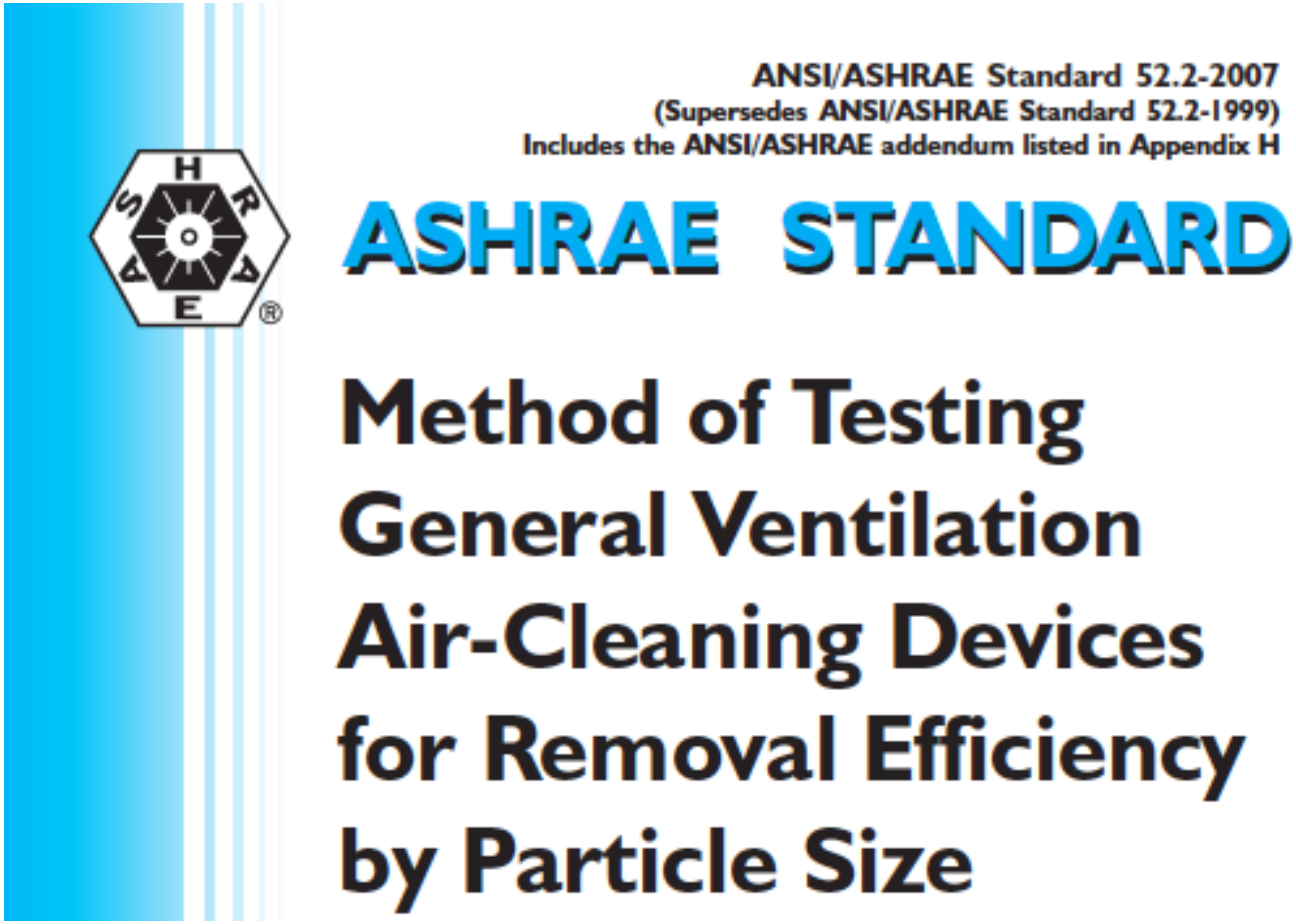
FPR: Filter Performance Rating

MPR: Micro-particle Performance Rating

In general, the higher the rated efficiency, the greater the removal for *most* particle sizes

http://www.king-filters.com/?page_id=58

Filtration efficiency: ASHRAE Standard 52.2



ANSI/ASHRAE Standard 52.2-2007
(Supersedes ANSI/ASHRAE Standard 52.2-1999)
Includes the ANSI/ASHRAE addendum listed in Appendix H

ASHRAE STANDARD

Method of Testing General Ventilation Air-Cleaning Devices for Removal Efficiency by Particle Size

ASHRAE Standard 52.2

- Method of test for filter performance for particles
  - Controlled laboratory conditions
  - Subject filter to test aerosol
  - Measure particle removal efficiency and pressure drop
  - Load filter with dust and test again (and again)

- Result is “**MERV**”
  - “Minimum efficiency reporting value”
  - Based on minimum values for three particle size ranges:
    - E_1: 0.3-1 μm
    - E_2: 1-3 μm
    - E_3: 3-10 μm

ASHRAE Standard 52.2

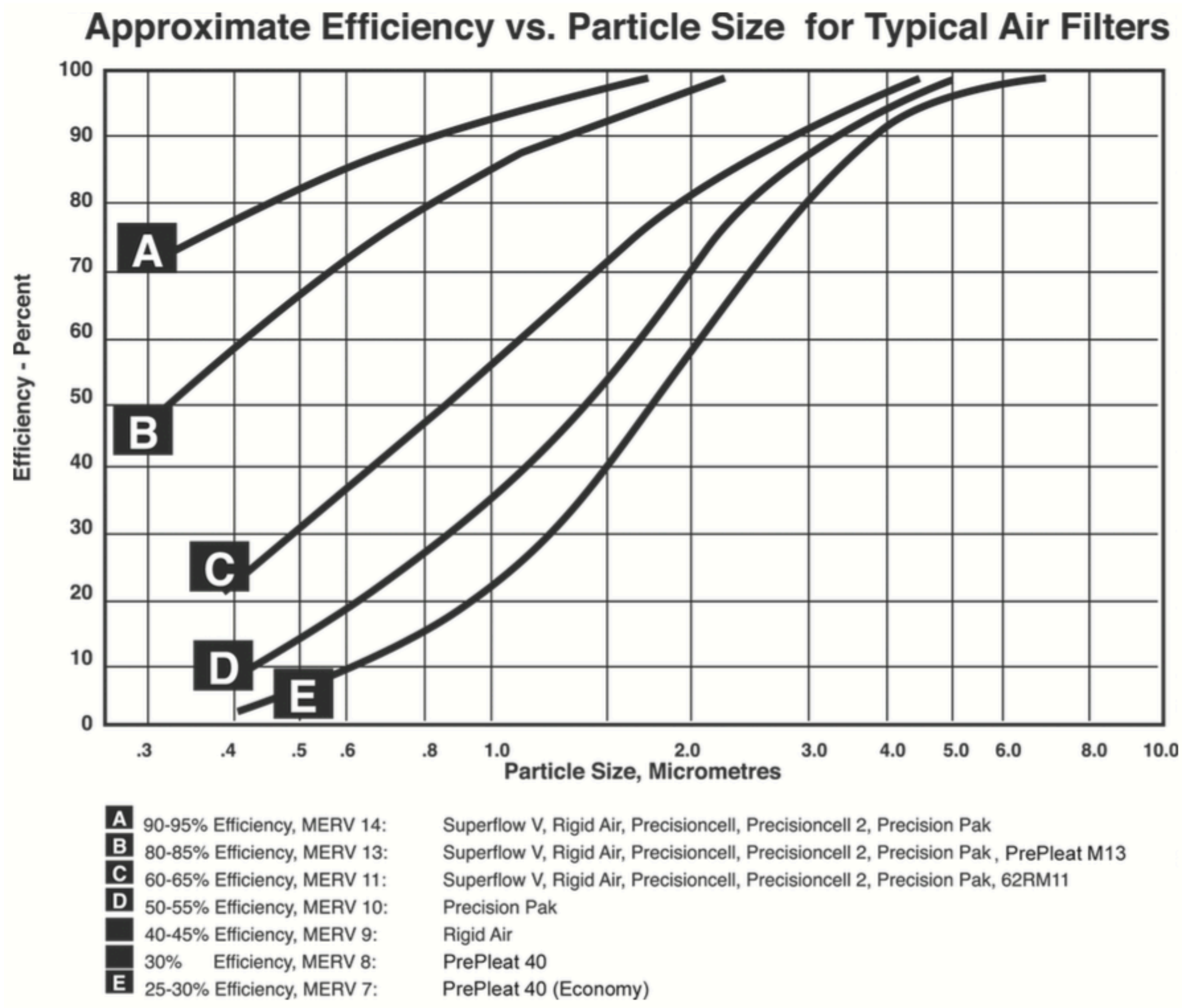


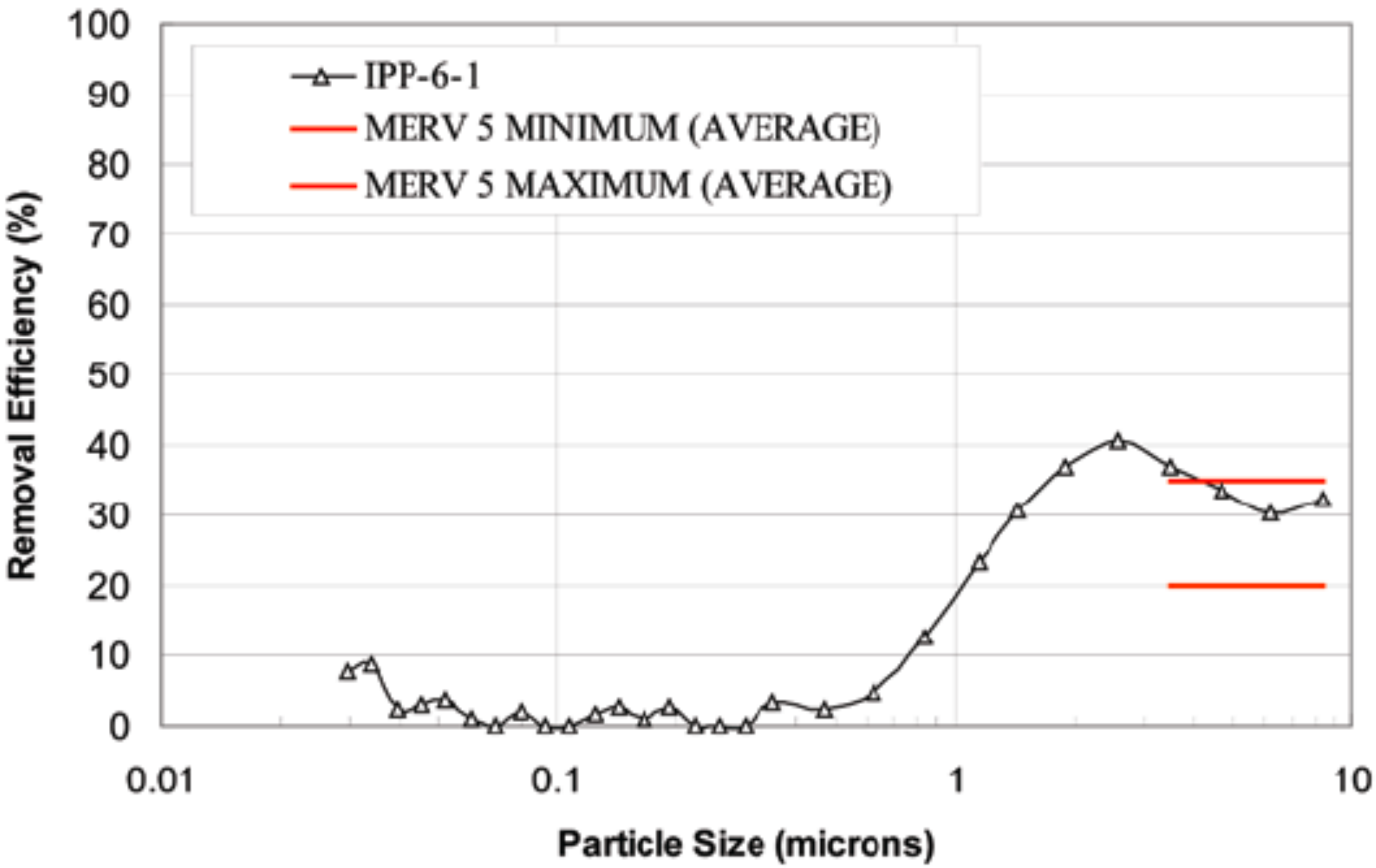
TABLE 12-1 Minimum Efficiency Reporting Value (MERV) Parameters

Standard 52.2 Minimum Efficiency Reporting Value (MERV)	Composite Average Particle Size Efficiency,% in Size Range, µm			Average Arrestance,%, by Standard 52.1 Method	Minimum Final Resistance	
	Range 1 0.30–1.0	Range 2 1.0–3.0	Range 3 3.0–10.0		Pa	in. of water
1	n/a	n/a	$E_3 < 20$	$A_{avg} < 65$	75	0.3
2	n/a	n/a	$E_3 < 20$	$65 \leq A_{avg} < 70$	75	0.3
3	n/a	n/a	$E_3 < 20$	$70 \leq A_{avg} < 75$	75	0.3
4	n/a	n/a	$E_3 < 20$	$75 \leq A_{avg}$	75	0.3
5	n/a	n/a	$20 \leq E_3 < 35$	n/a	150	0.6
6	n/a	n/a	$35 \leq E_3 < 50$	n/a	150	0.6
7	n/a	n/a	$50 \leq E_3 < 70$	n/a	150	0.6
8	n/a	n/a	$70 \leq E_3$	n/a	150	0.6
9	n/a	$E_2 < 50$	$85 \leq E_3$	n/a	250	1.0
10	n/a	$50 \leq E_2 < 65$	$85 \leq E_3$	n/a	250	1.0
11	n/a	$65 \leq E_2 < 80$	$85 \leq E_3$	n/a	250	1.0
12	n/a	$80 \leq E_2$	$90 \leq E_3$	n/a	250	1.0
13	$E_1 < 75$	$90 \leq E_2$	$90 \leq E_3$	n/a	350	1.4
14	$75 \leq E_1 < 85$	$90 \leq E_2$	$90 \leq E_3$	n/a	350	1.4
15	$85 \leq E_1 < 95$	$90 \leq E_2$	$90 \leq E_3$	n/a	350	1.4
16	$95 \leq E_1$	$95 \leq E_2$	$95 \leq E_3$	n/a	350	1.4

HEPA → 99.9% or greater removal efficiency for most particle sizes

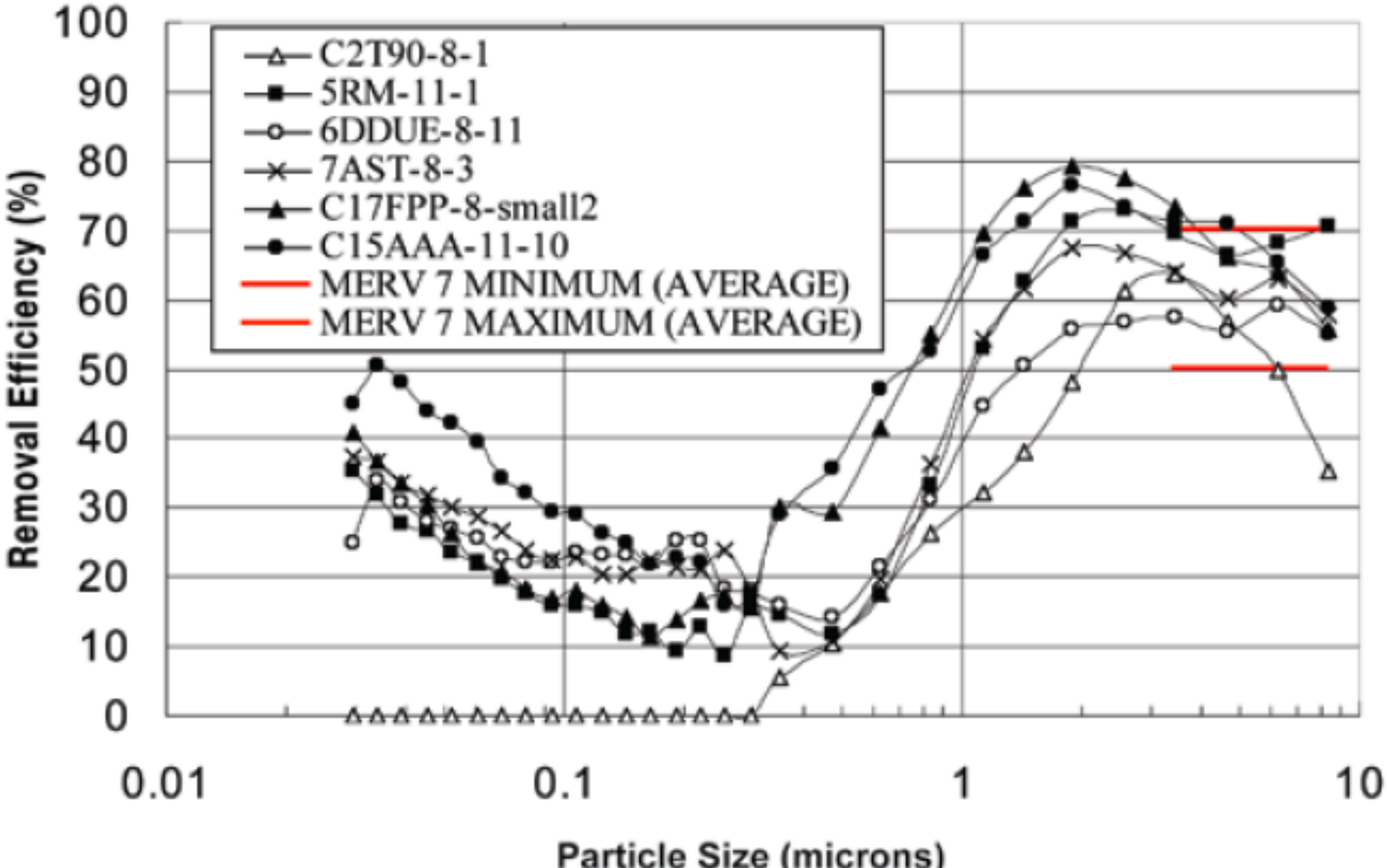
Newer measurements of filtration efficiency

- Recent lab tests covering 30 nm to 10 μm and MERV classified filters (remember MERV only covers 0.3-10 μm):



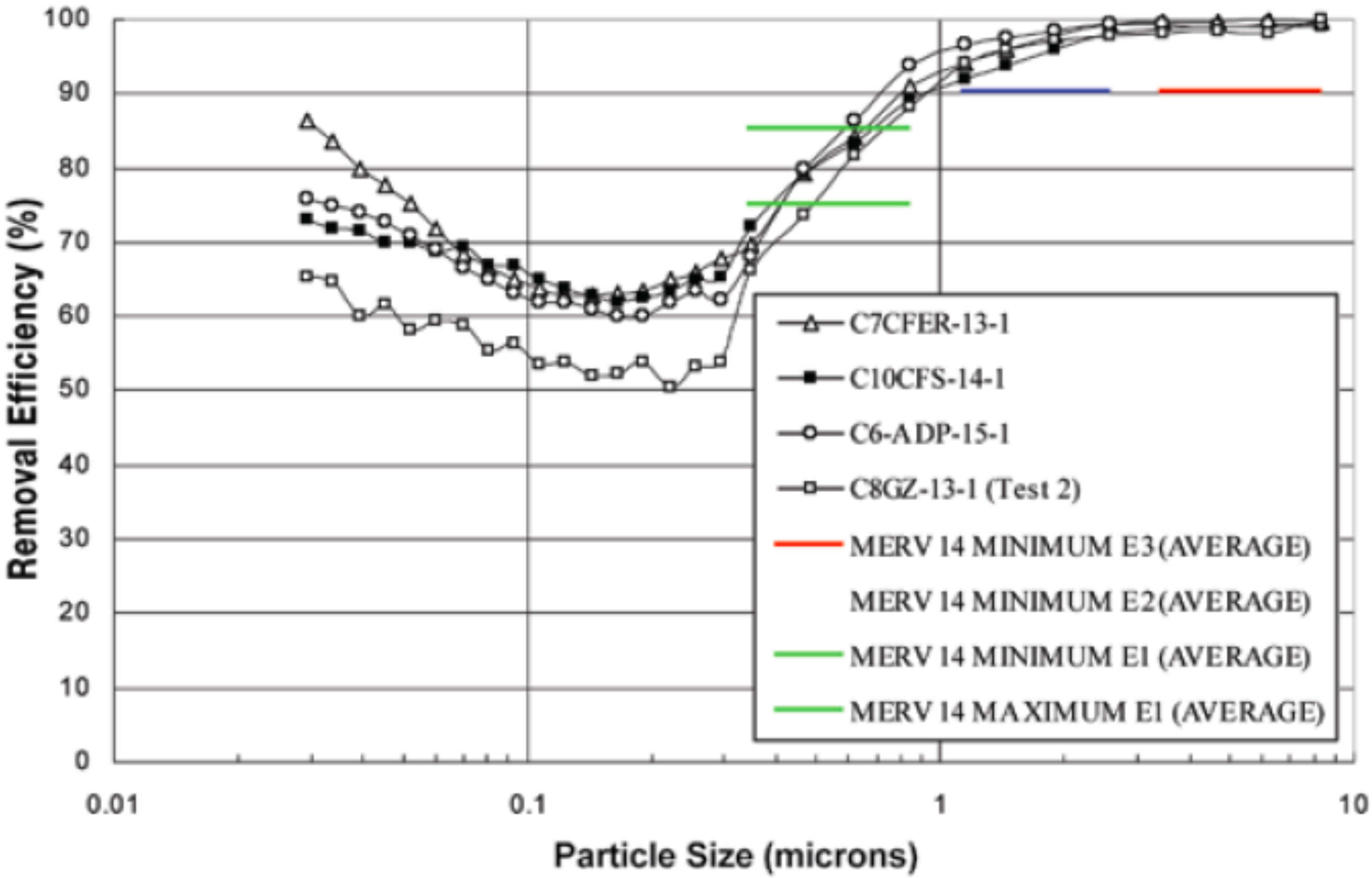
Hecker and Hofacre, 2008 EPA Report 600/R-08/013

Recent MERV 7 lab tests



Hecker and Hofacre, 2008 EPA Report 600/R-08/013

Recent MERV 14 lab tests



Hecker and Hofacre, 2008 EPA Report 600/R-08/013

HW 5 assigned