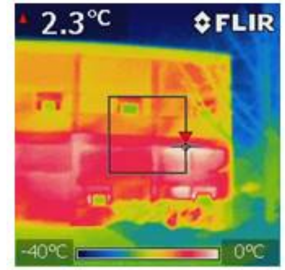
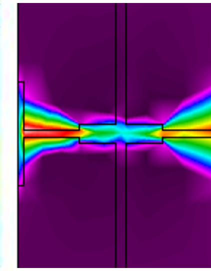
CAE 331/513
Building Science
Fall 2014



Week 10: October 28, 2014
Ventilation and indoor air quality (cont.)

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

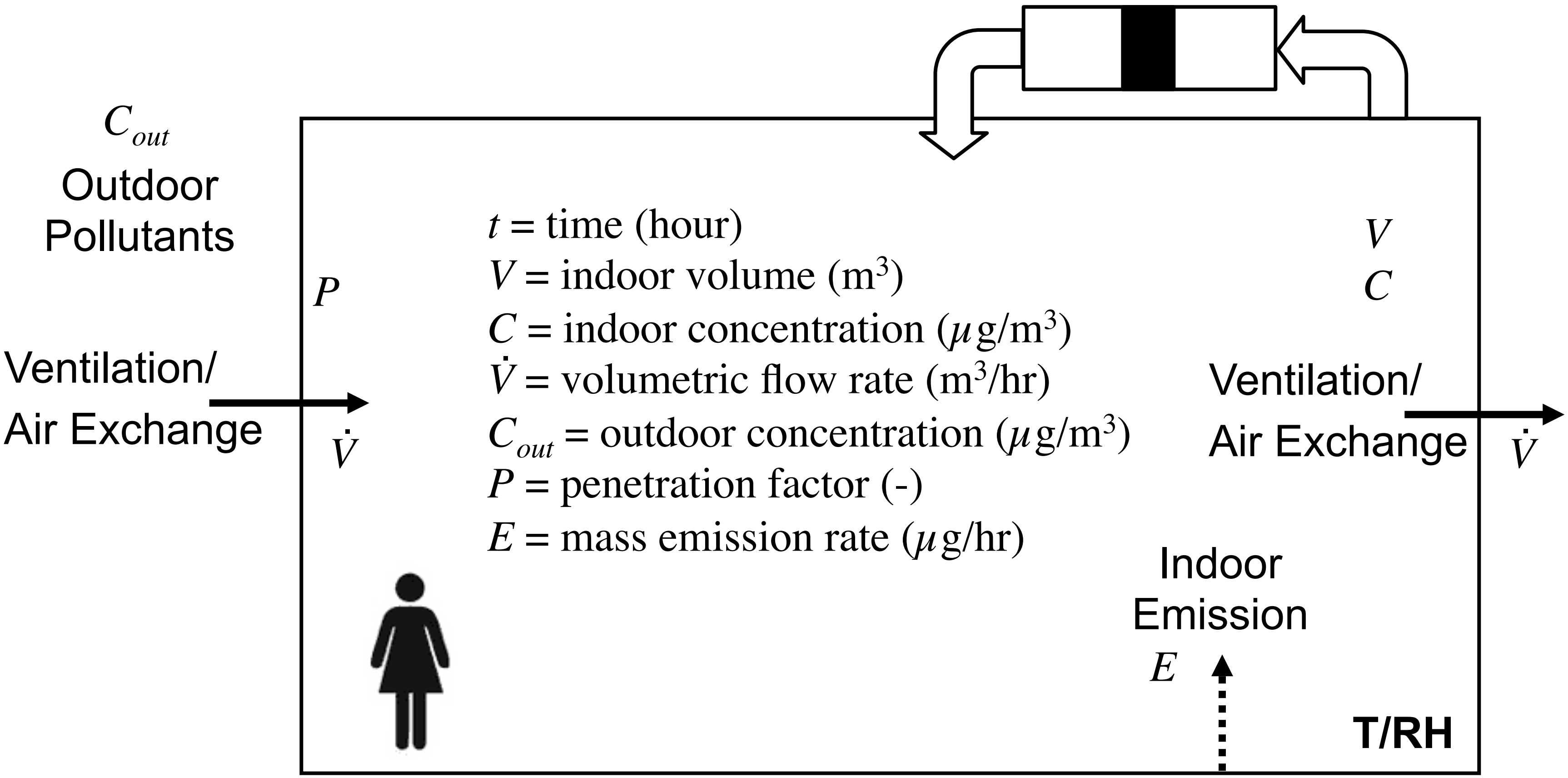
Last time

- Finished HVAC systems
  - COP/EER/SEER, power draw, and energy consumption
  - Fluid flow: Friction losses and increases/decreases in systems
  - Fan and pump curves (relating pressure, flow, and power)
- Introduced ventilation and indoor air quality (IAQ)
- Indoor air quality: we spend most of our time indoors
- Outdoor air ventilation can both dilute indoor sources of pollutants and bring in pollutants from outdoors
- Key topics:
  - Mass balances
  - Air exchange rate
  - Ventilation rates

Slight revision to HW 4

- Don't have to report answer in Problem 1 in units of **ppb**
  - Only in **μg/m³**

Indoor environment: Mass balance

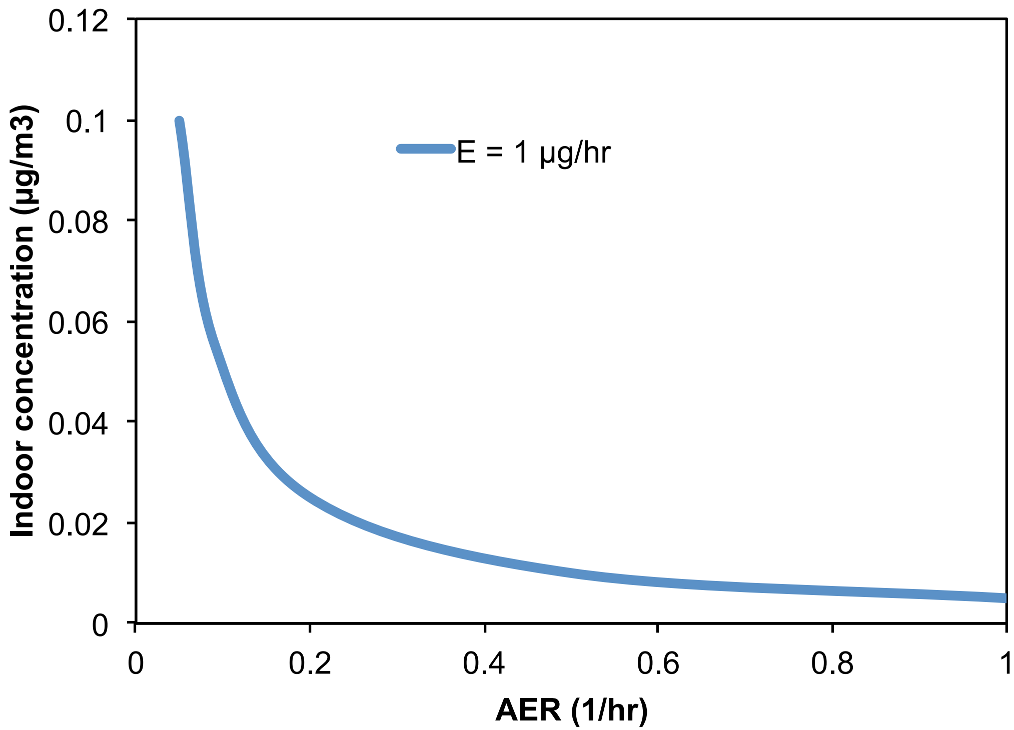


$$\frac{dC}{dt} = P\lambda C_{out} - \lambda C + \frac{E}{V}$$

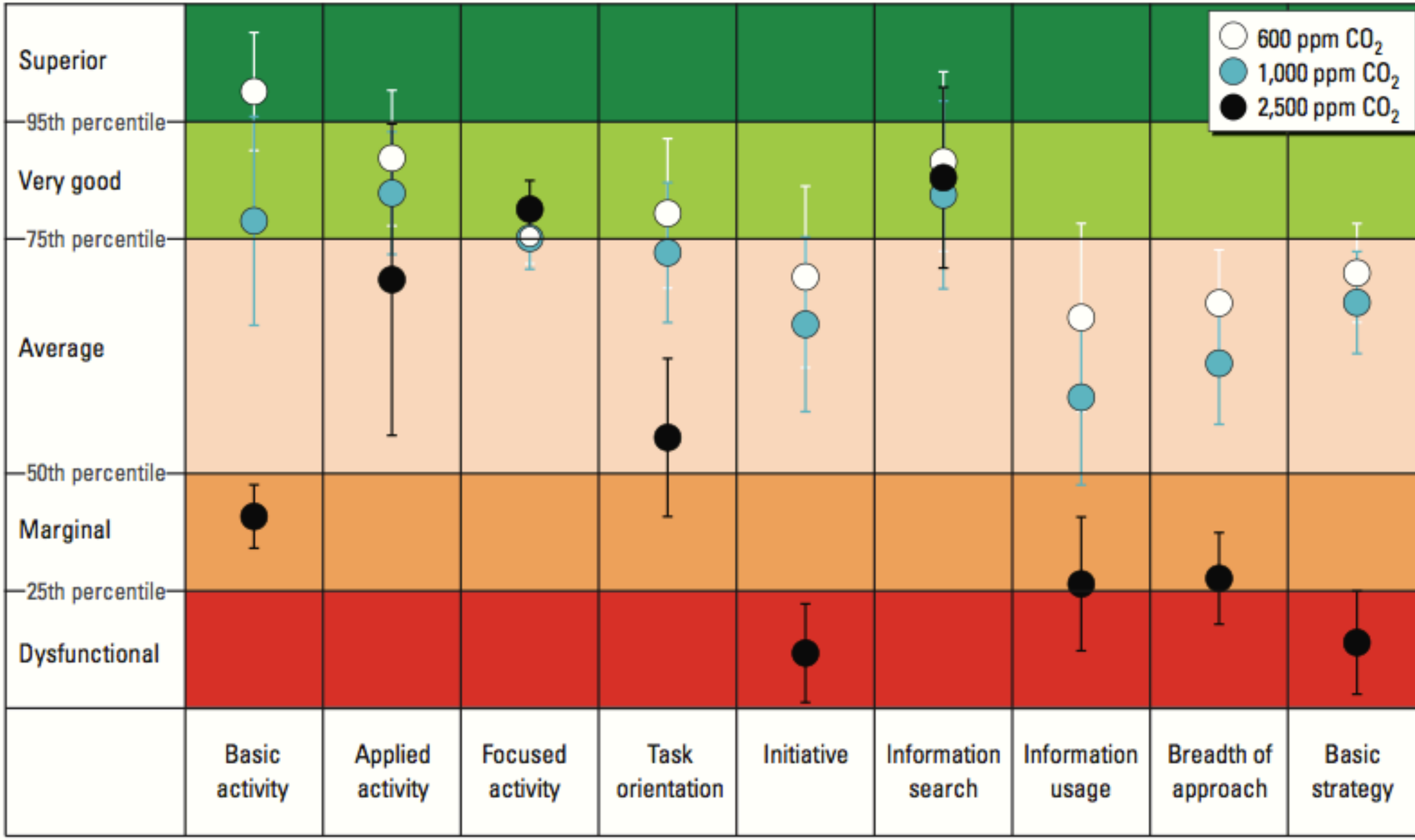
$$\lambda = \frac{\dot{V}}{V} = \text{air exchange rate } \left(\frac{1}{\text{hr}}\right)$$

Steady state mass balance and air exchange

- Example steady state calculations: $C_{ss} = PC_{out} + \frac{E}{\lambda V}$
- Assume $C_{out} = 0$: $C_{ss} = \frac{E}{\lambda V}$
- Assume $V = 200\ m^3$ and $E = 1\ \mu g/hr$: how are C_{ss} and λ related?



Ventilation and CO_2



Satish et al **2012** *Environ Health Perspectives*

Today's objectives

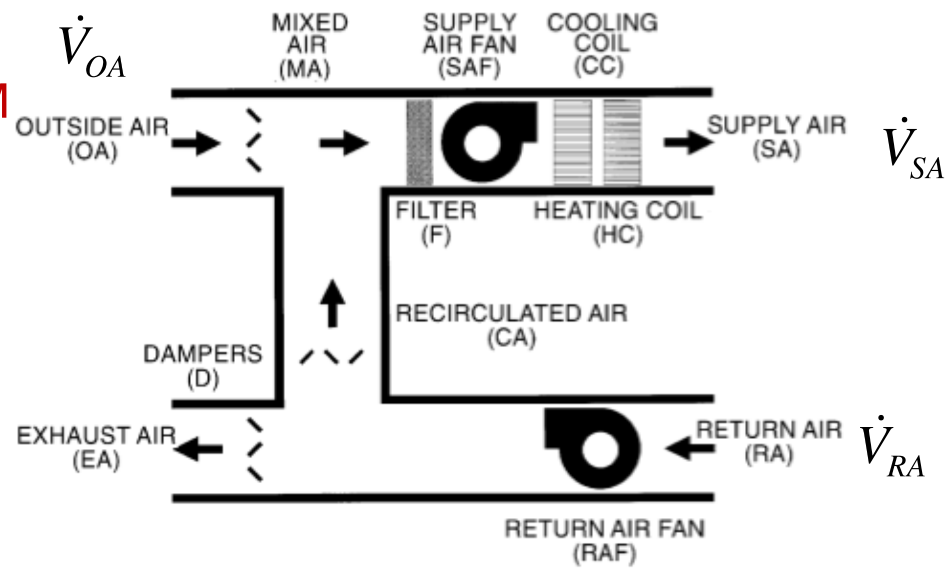
- Finish ventilation (and "infiltration")
- Particulate matter and HVAC filtration

Mass balance example problem w/ CO_2

- What outdoor airflow rate is needed per occupant to keep the indoor CO_2 concentration below 1000 ppm?
  - Assume outdoors is 400 ppm
  - CO_2 production (activity level of 1.2 met) = 0.005 L/s per person
- In a 150 m^3 room with 30 people present, what would be the required air exchange rate?

532 CFM required

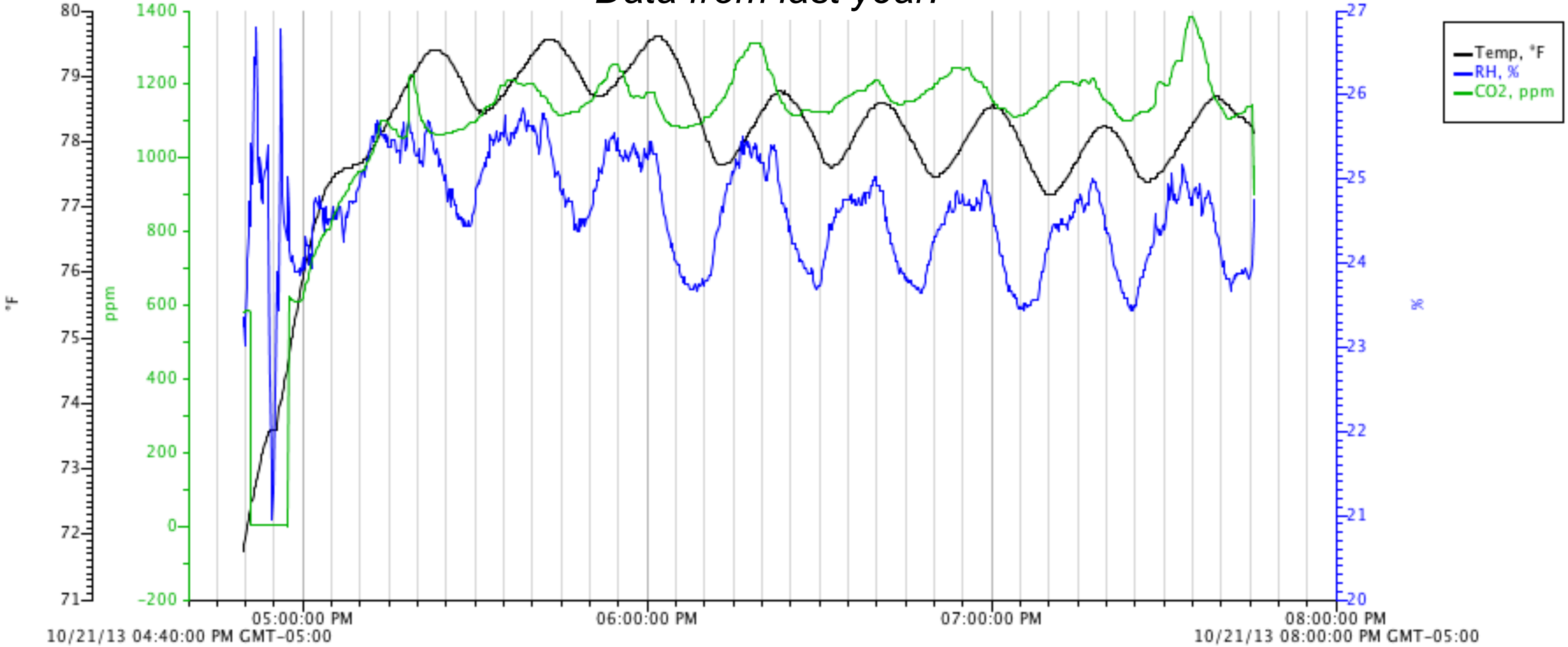
$$F_{OA} = \frac{\dot{V}_{OA}}{\dot{V}_{SA}} = \frac{\dot{V}_{OA}}{\dot{V}_{OA} + \dot{V}_{CA}}$$



Ventilation rate in this classroom

- Let's measure CO_2 concentrations in the classroom and estimate the ventilation rate at the end of the class period

Data from last year:



Ventilation and IAQ

- How do we determine the correct (or ***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

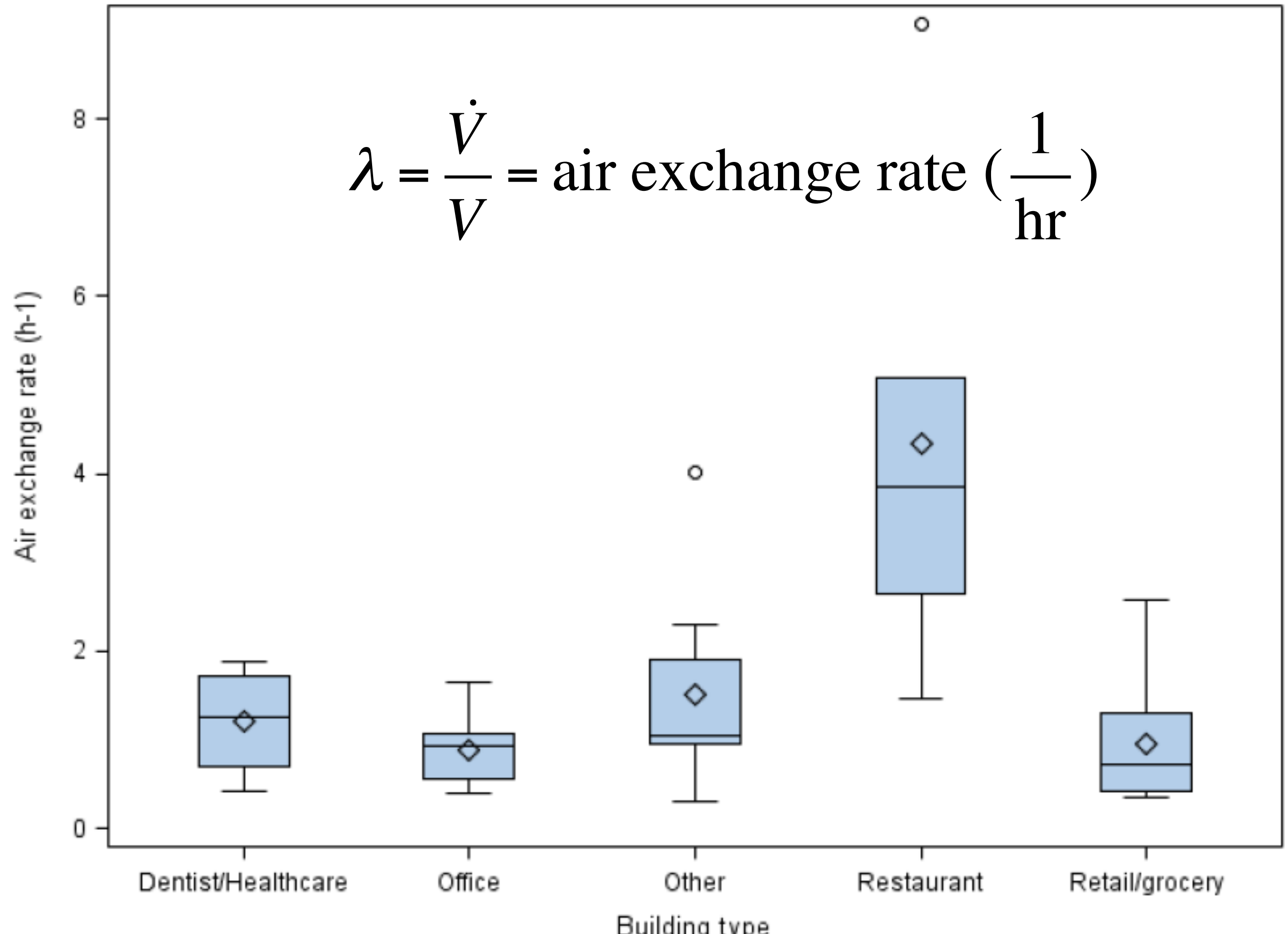
ASHRAE Standard 62.1: Commercial buildings VRP

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·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

WHAT ABOUT VENTILATION IN RESIDENCES (HOMES)?

Air exchange: Ventilation and infiltration

Outdoor air exchange can be divided into two main categories:

Ventilation

Intentional introduction of outdoor air into a building

Subdivided into:

- *Mechanical (forced) ventilation:* The intentional movement of air into and out of a building using fans, intake vents, and exhaust vents
- *Natural ventilation:* The flow of air through open windows, doors, grilles, and other planned envelope penetrations, driven largely by natural or artificially induced pressure differences

Infiltration

Flow of outdoor air into a building through cracks, leaks, and other unintentional openings in the envelope (includes normal use of exterior doors) … i.e., *leakage*

Typical air leakage sites in homes

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

General models for air flows through leaks

- Given an opening:

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

A = area of opening, ft^2 (m^2)
ΔP = 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 ventilation and infiltration: Δ*P*

- Three primary mechanisms generate pressure differences (**driving forces**)
  - **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 also a function of temperature
  - **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
  - **Mechanical air handling equipment (fans)**
    - Fans are used to supply, recirculate, exhaust, and otherwise balance pressures and flows in buildings

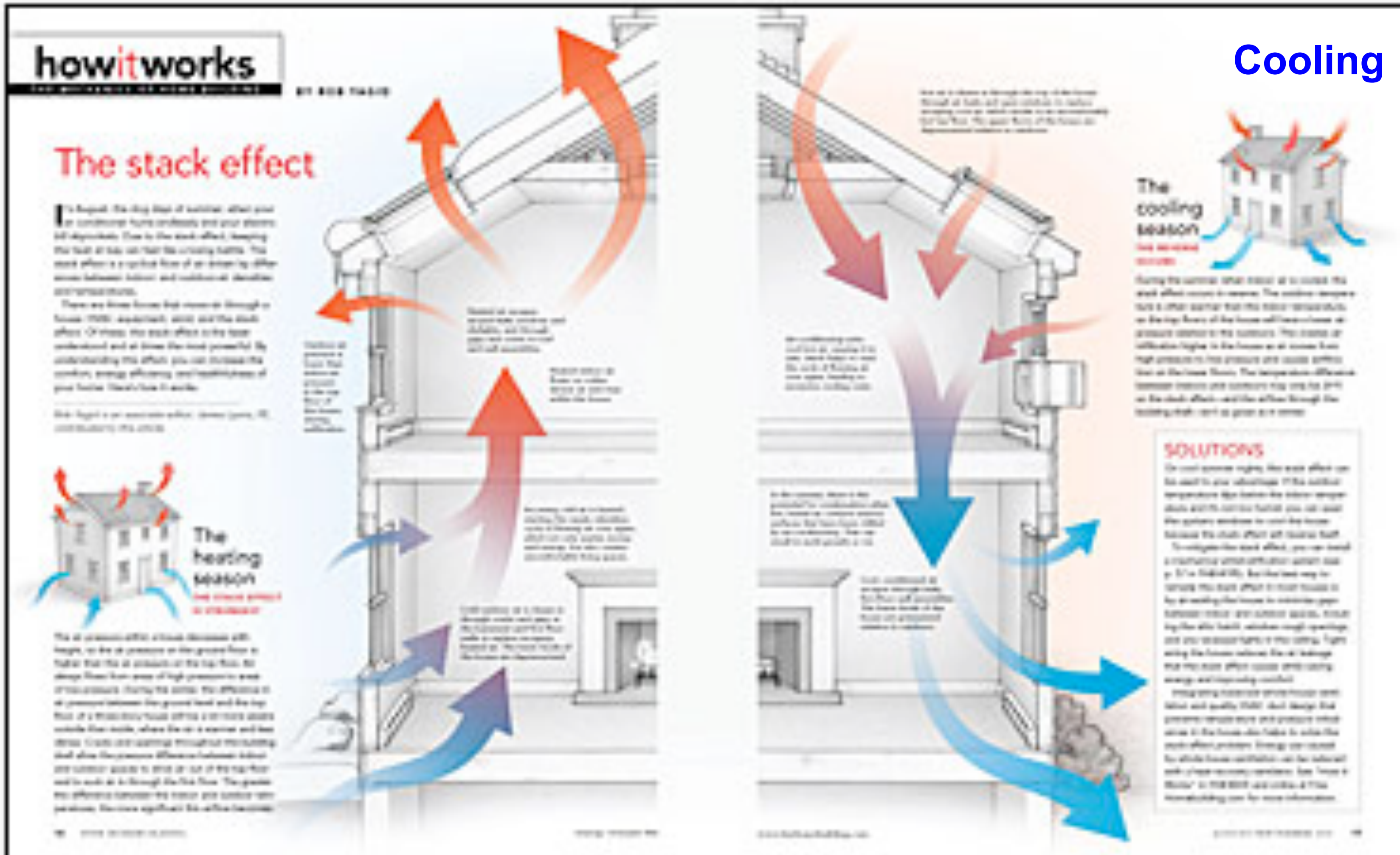
$$\Delta P = \Delta P_{wind} + \Delta P_{stack} + \Delta P_{vent}$$ (+ when causing flow to interior)

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 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: winter vs. summer



Cooling

Heating

Wind pressures

- From velocity component of Bernoulli Equation:

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

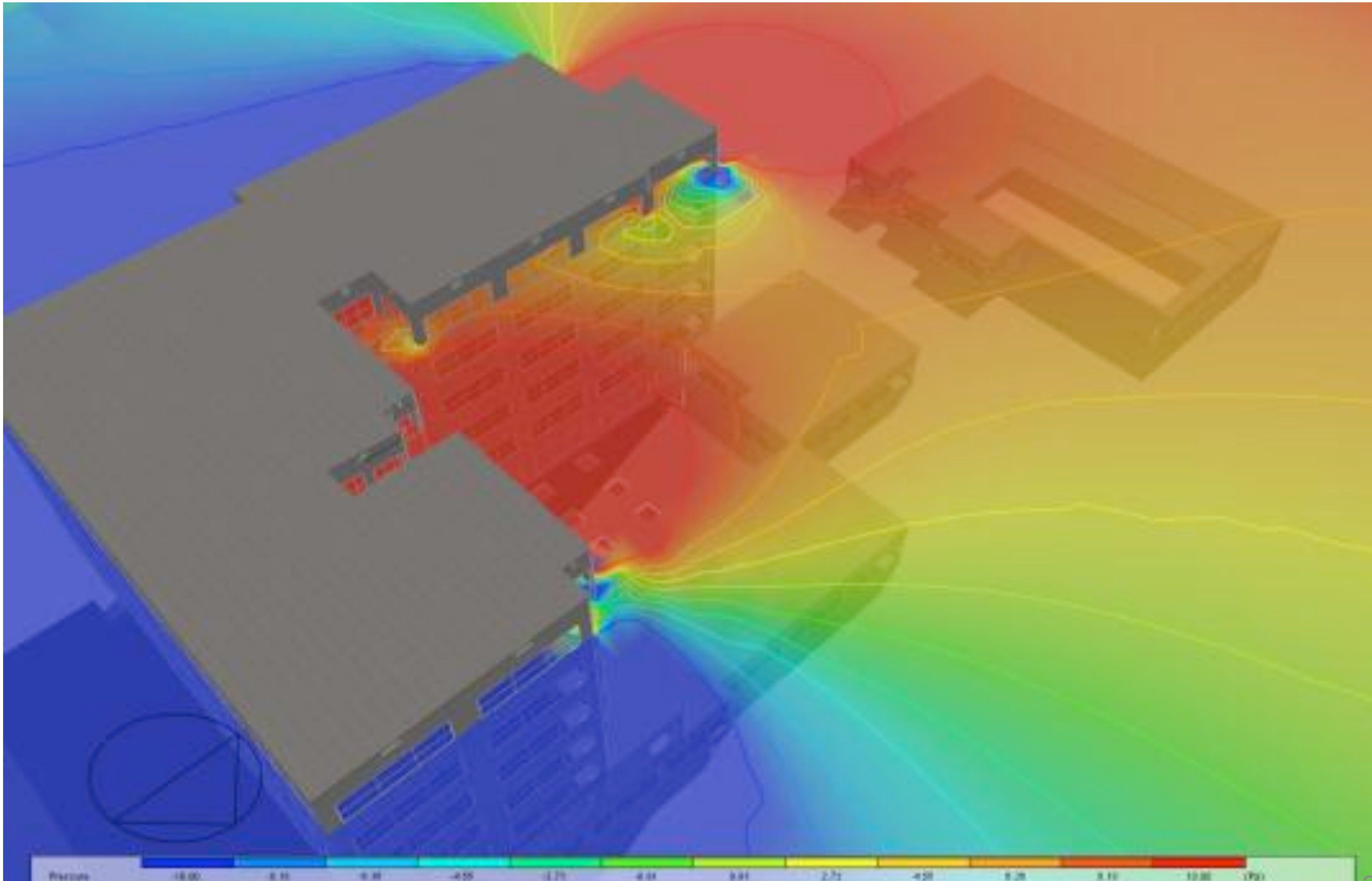
$P_{velocity}$ = wind velocity pressure; U_h = air velocity at building height, h; ρ_{air} = air density

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

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

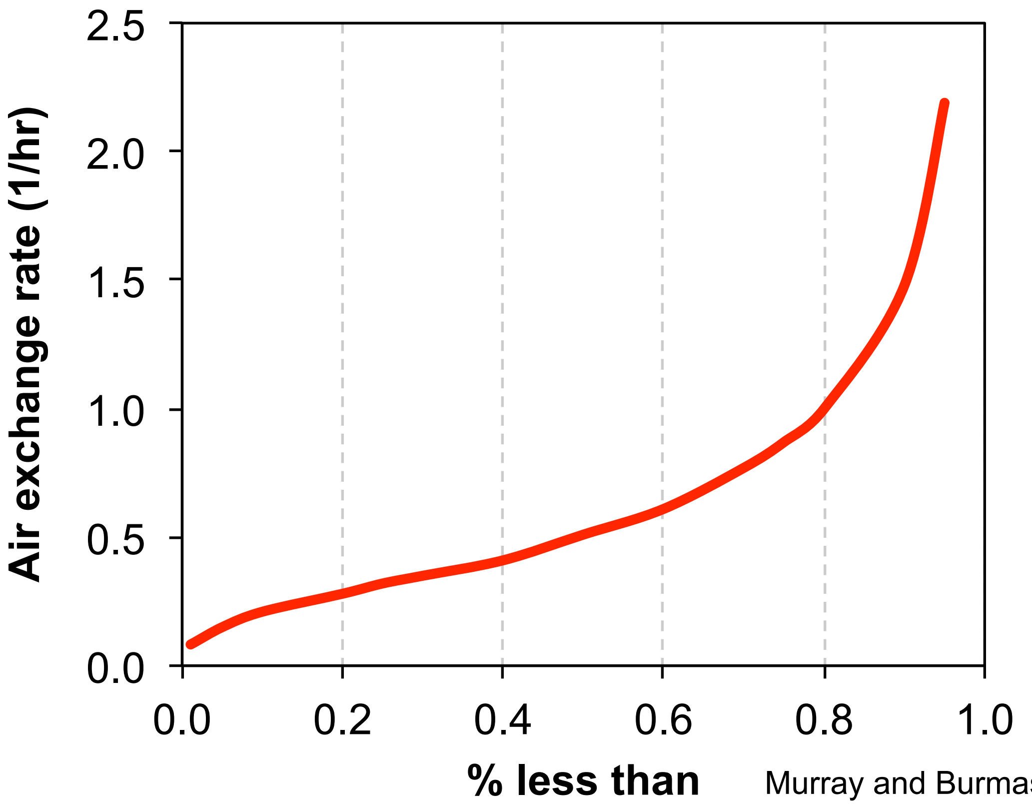
  - Get C_P (+ or -) from measurements or from *ASHRAE Handbook of Fundamentals 2013* Chapter 24 “Airflow around buildings”

Wind pressure coefficients (C_p) vary around buildings



What are typical 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*

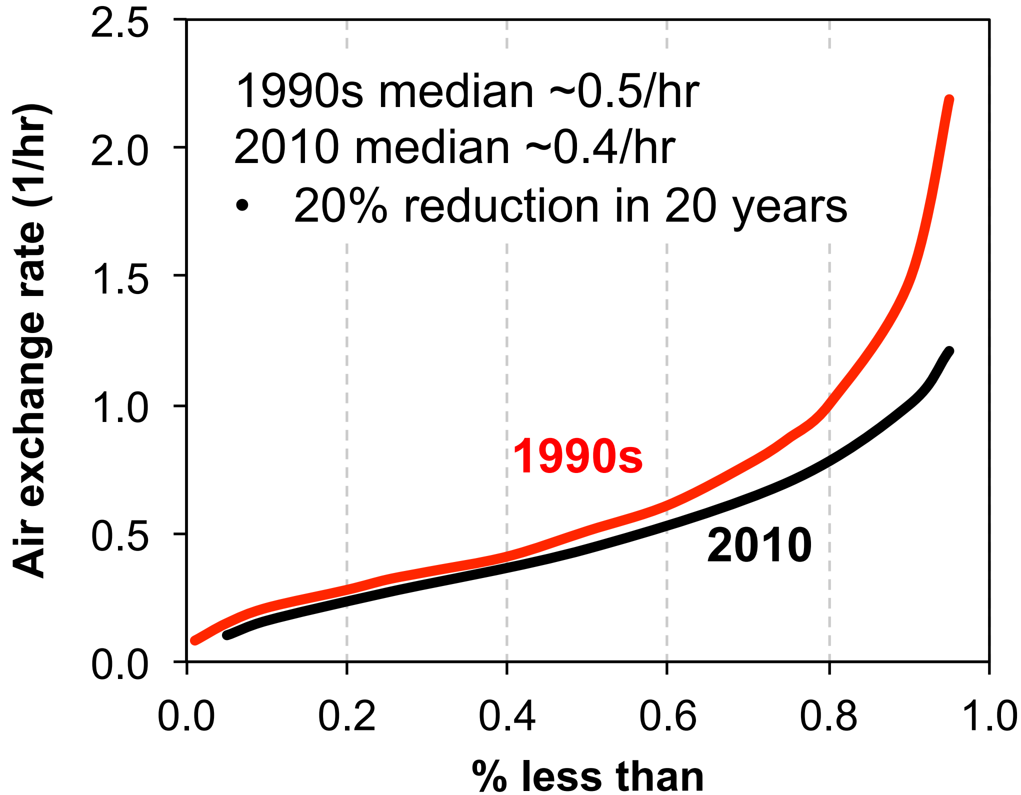
Mostly due to infiltration

In the past, we seldom use mechanical ventilation systems in single-family homes

- What do you think this curve looks like now?

What are typical AERs in homes?

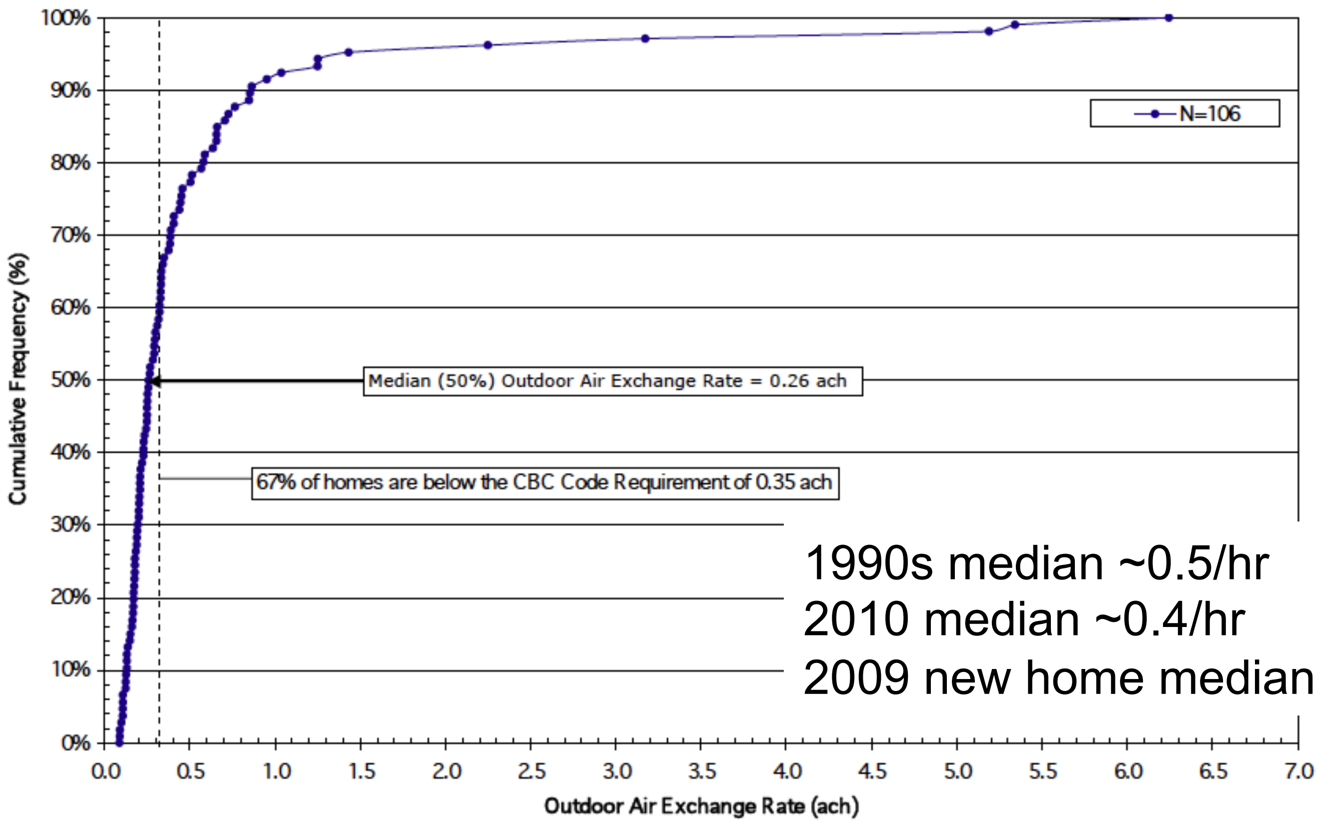
- New distribution of AERs U.S. homes
  - Early 1990s and revisited in 2010 (Persily et al. 2010)



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

What are typical values of λ (AER)?

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



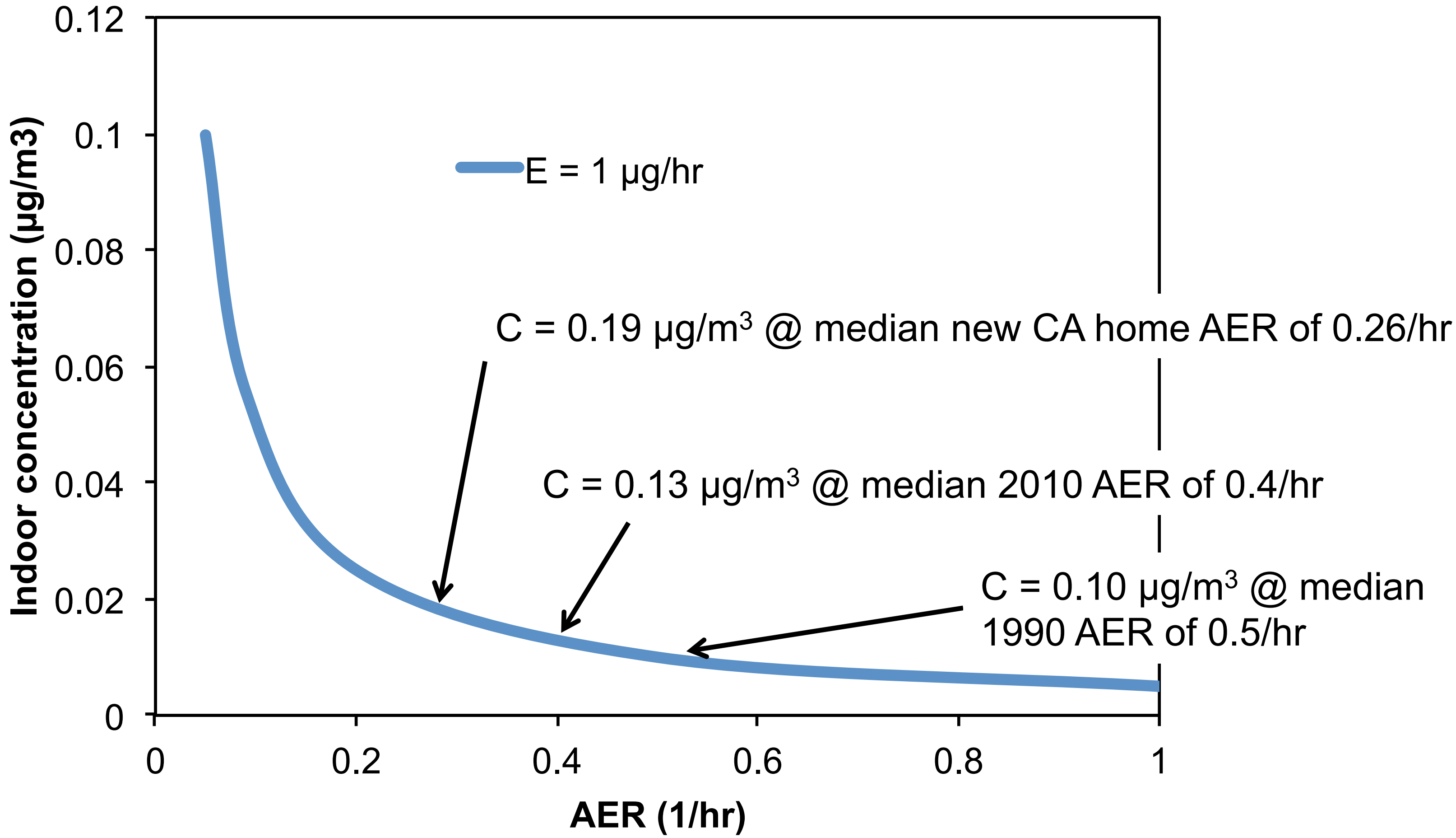
1990s median ~0.5/hr
2010 median ~0.4/hr
2009 new home median ~0.26/hr

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

Offermann et al. 2009 CEC PIER Report

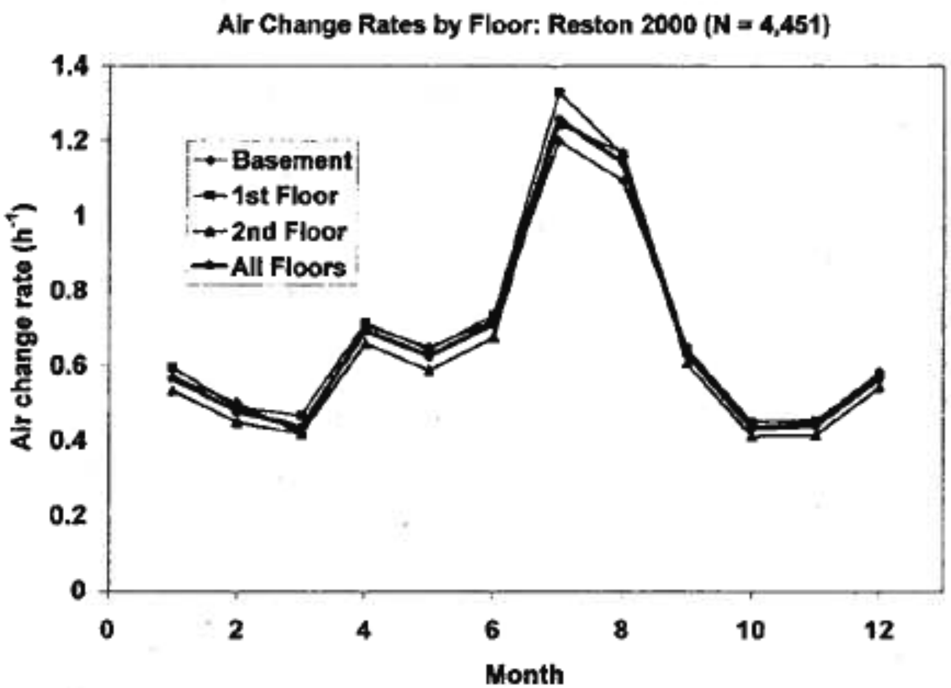
Steady state mass balance and real AERs

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

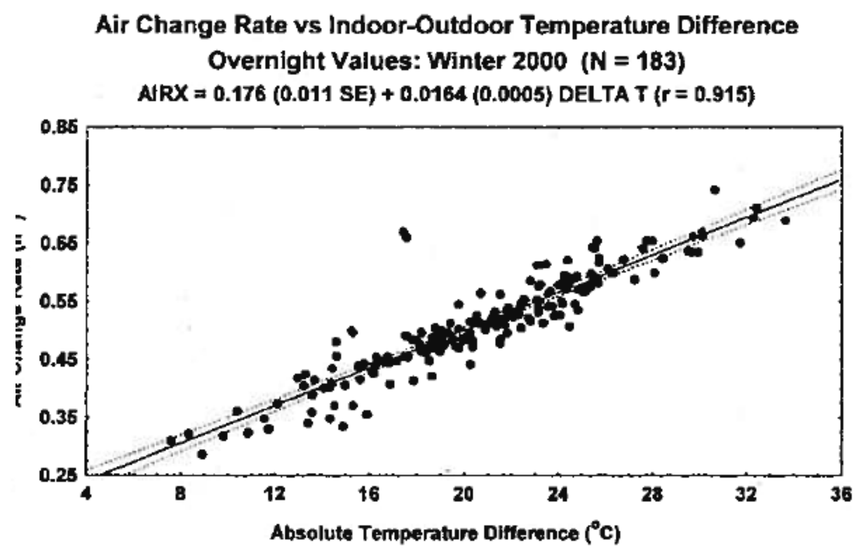


Variation in infiltration AER with driving forces

- Air exchange rates differ both between buildings and within buildings
  - Differences vary by driving forces and building characteristics
- 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*

Modeling air leakage (infiltration only)

- There are several models for estimating infiltration rates in buildings
- One common model is the LBL Model for Air Leakage
  - aka Sherman-Grimsrud Model

$$\dot{V}_{\inf} = A_{leak}\sqrt{a_s \Delta T + a_w v_w^2} \quad \text{[L/s]}$$

A_{leak} = building equivalent leakage area [cm^2]

ΔT = interior-outdoor temp difference [K]

a_s = stack effect coefficient [$\frac{(\text{L/s})^2}{\text{cm}^4\text{K}}$]

a_w = wind coefficient [$\frac{(\text{L/s})^2}{\text{cm}^4(\text{m/s})^2}$]

v_w = wind speed [m/s]

LBL Air Leakage Model

Table 4 Basic Model Stack Coefficient C_s

	House Height (Stories)		
	One	**Two**	**Three**
Stack coefficient	0.000 145	0.000 290	0.000 435

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 the street from the 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 that are immediately adjacent (closer than one house height): e.g., neighboring houses on the same side of the street, trees, bushes, etc.

Table 6 Basic Model Wind Coefficient C_w

Shelter Class	House Height (Stories)		
	One	**Two**	**Three**
1	0.000 319	0.000 420	0.000 494
2	0.000 246	0.000 325	0.000 382
3	0.000 174	0.000 231	0.000 271
4	0.000 104	0.000 137	0.000 161
5	0.000 032	0.000 042	0.000 049

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.

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

where

Q_{fan} = fan flow rate, cfm

A_{floor} = floor area, ft^2

N_{br} = number of bedrooms; not to be less than one

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

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

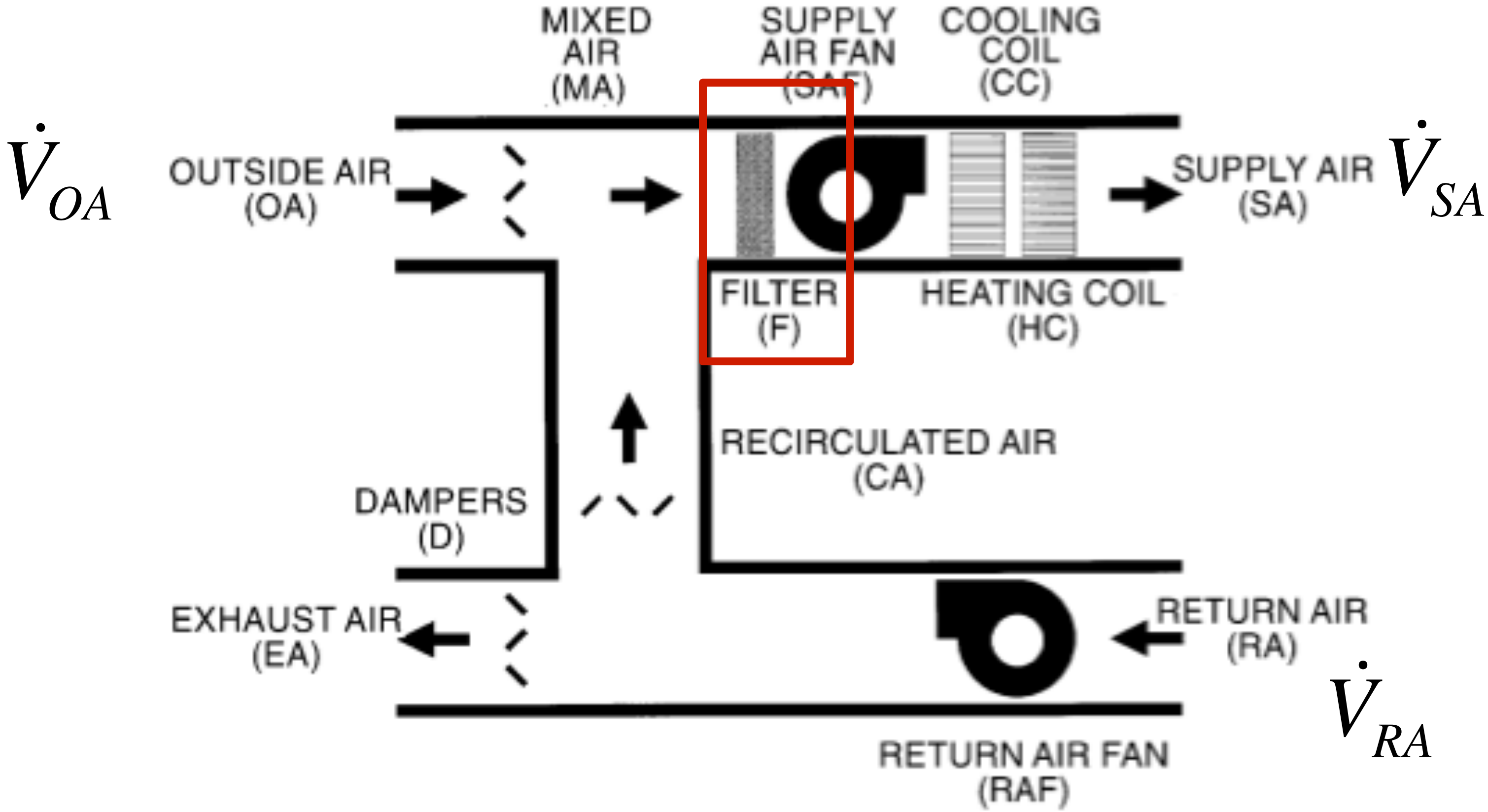
TABLE 4.1b (SI)
Ventilation Air Requirements, L/s

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

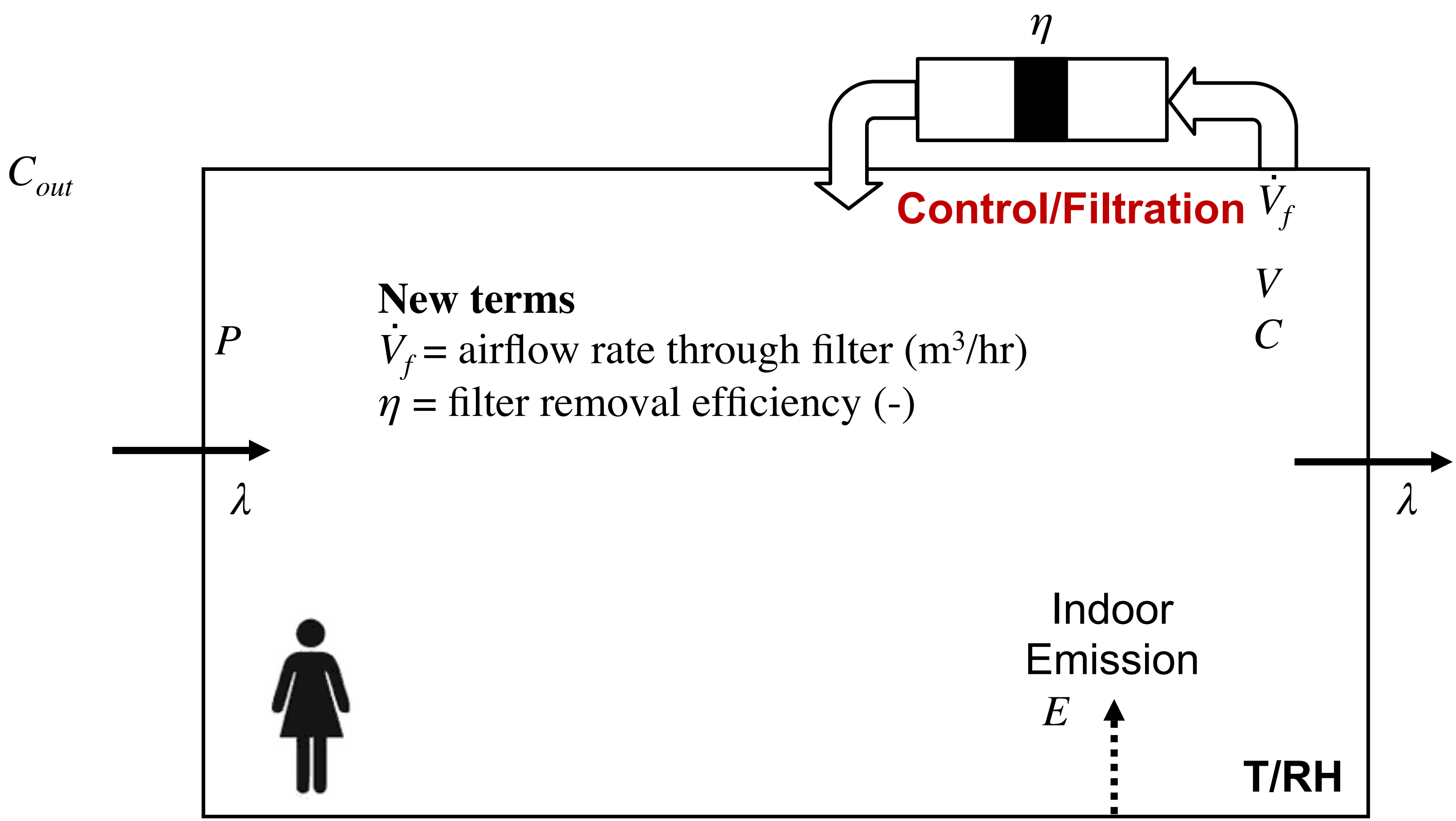
Forced air distribution: Filtration

Typical commercial HVAC system:



What if our pollutant has another loss term?

- Rarely are we working with only inert compounds
  - Other loss mechanisms are important
  - Deposition to surfaces, control by HVAC filter, reaction, etc…



Mass balance with filtration

- New term to mass balance:

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

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

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

$$C = \frac{PC_{out} + \dfrac{E}{\lambda V}}{1 + \dfrac{\eta\dot{V}_f}{\lambda V}} \longrightarrow C = \frac{PC_{out} + \dfrac{E}{\lambda V}}{1 + \dfrac{CADR}{\lambda V}}$$

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

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

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

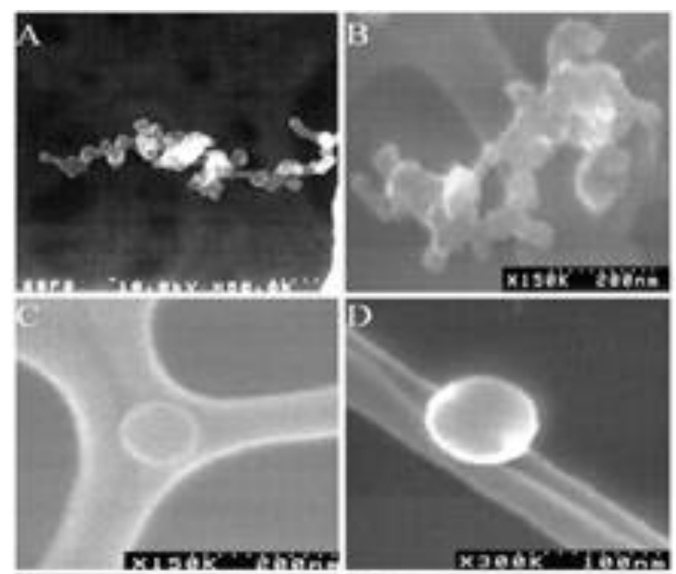
Filtration efficiency: ASHRAE Standard 52.2

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, others

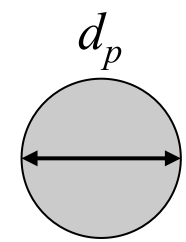
- Visibility effects outdoors



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



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

Important units:

- Micrometer (µm)
  - 1 µm = 10^{-6} m

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

Particle sizes

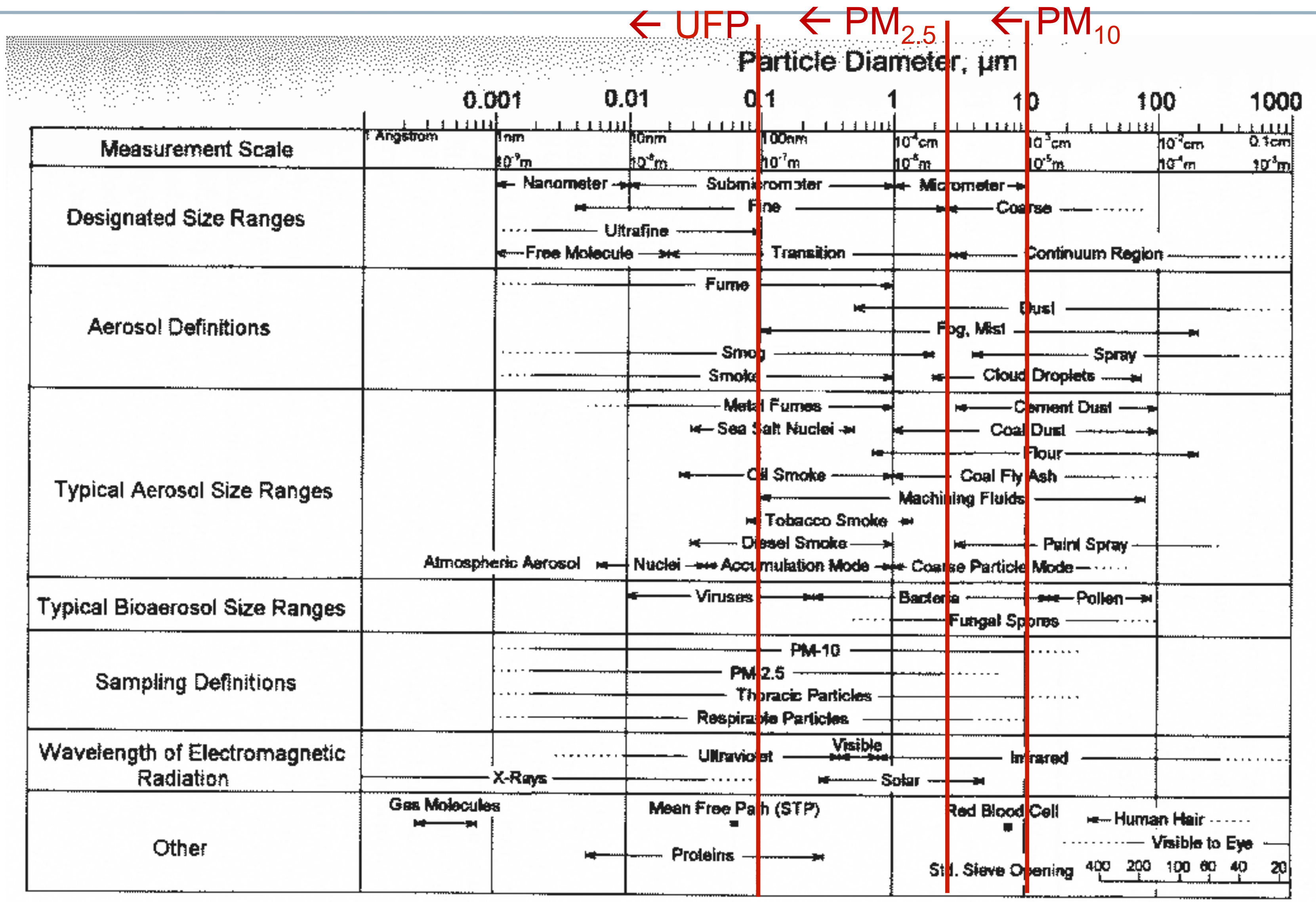
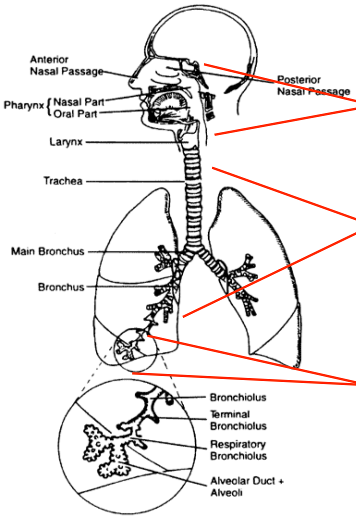


FIGURE 1.6 Particle size ranges and definitions for aerosols.

Hinds 1999

Particle deposition in respiratory system



Nasopharyngeal

Tracheobronchial

(N&T regions “cleaned” by mucus)

Alveolar

Hinds, 1999 Ch. 11

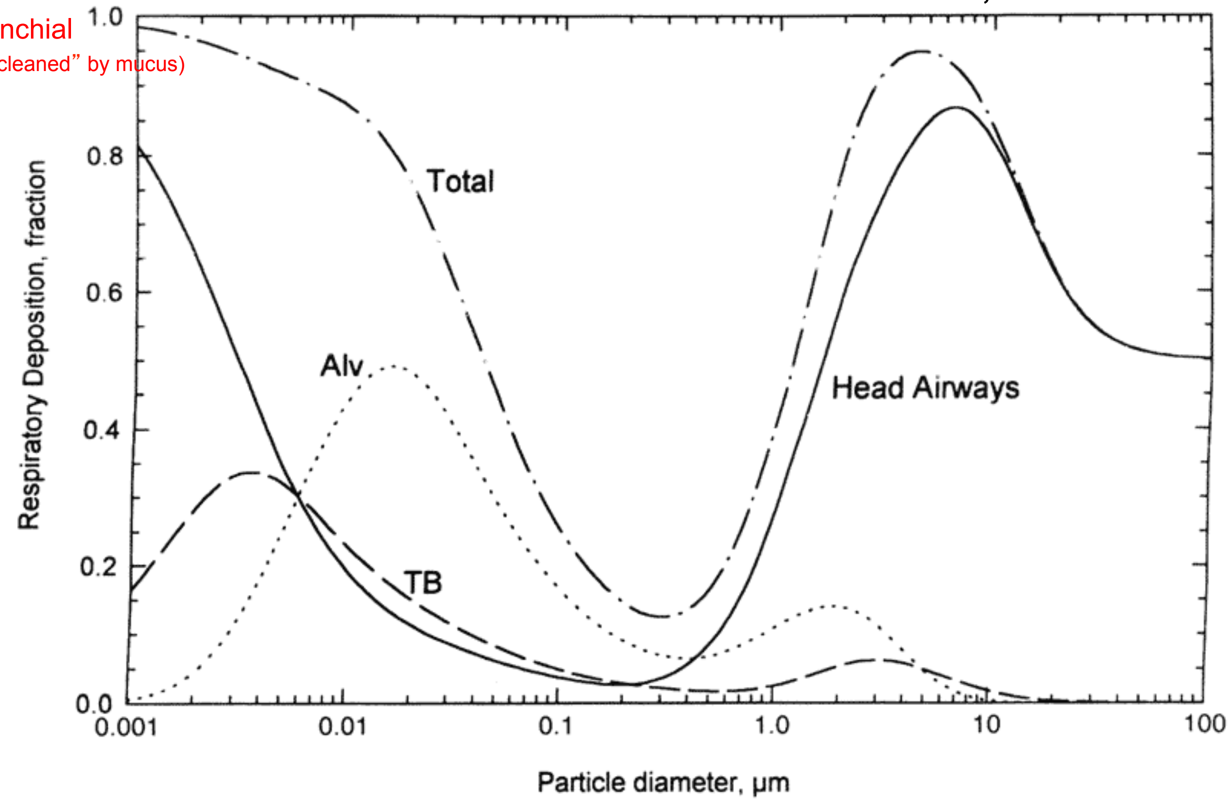


FIGURE 11.3 Predicted total and regional deposition for light exercise (nose breathing) based on ICRP deposition model. Average data for males and females.

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

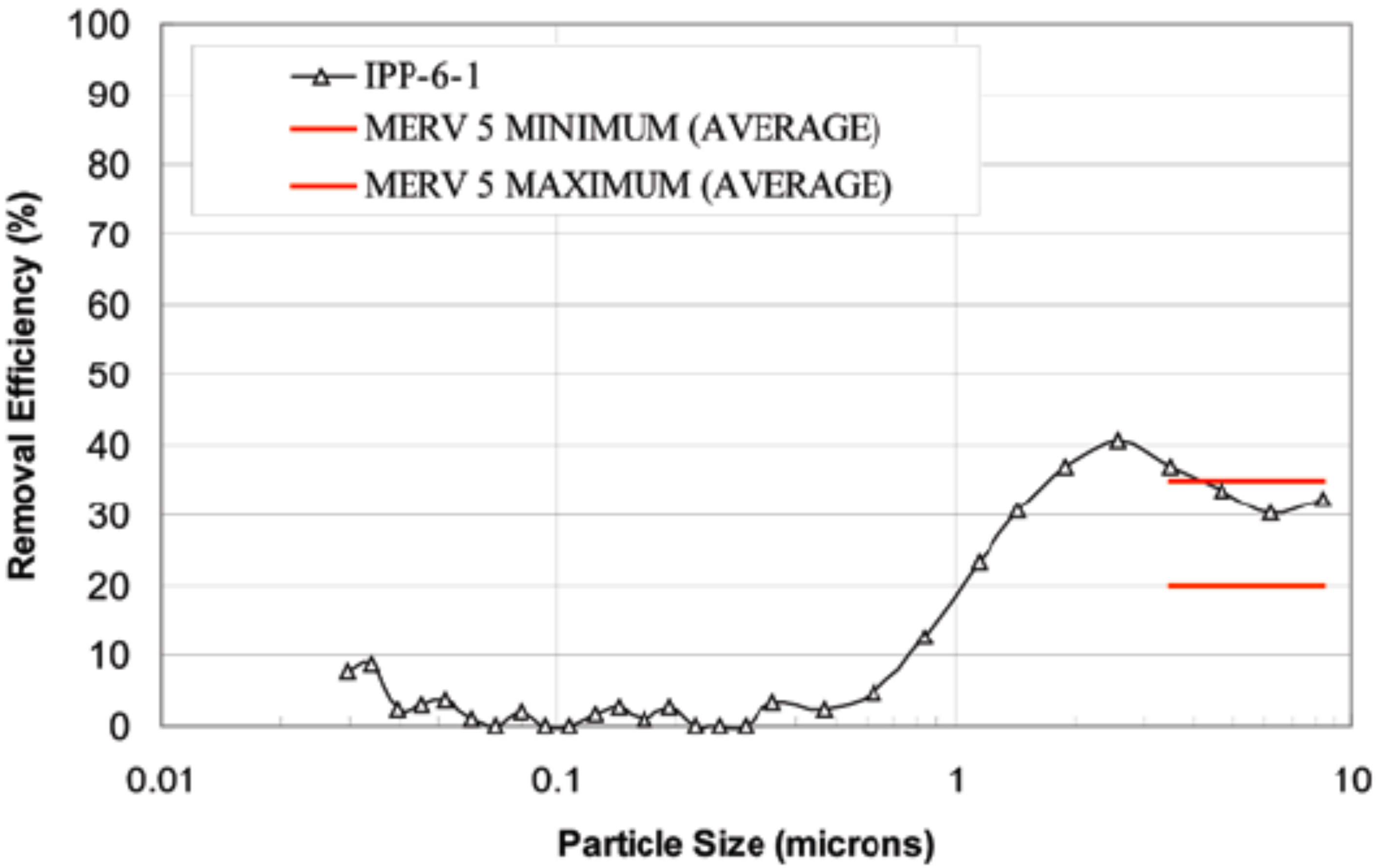
TABLE 12-1 Minimum Efficiency Reporting Value (MERV) Parameters

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	$E_3 < 20$	$65 \le A_{avg} < 70$	75	0.3
3	n/a	n/a	$E_3 < 20$	$70 \le A_{avg} < 75$	75	0.3
4	n/a	n/a	$E_3 < 20$	$75 \le A_{avg}$	75	0.3
5	n/a	n/a	$20 \le E_3 < 35$	n/a	150	0.6
6	n/a	n/a	$35 \le E_3 < 50$	n/a	150	0.6
7	n/a	n/a	$50 \le E_3 < 70$	n/a	150	0.6
8	n/a	n/a	$70 \le E_3$	n/a	150	0.6
9	n/a	$E_2 < 50$	$85 \le E_3$	n/a	250	1.0
10	n/a	$50 \le E_2 < 65$	$85 \le E_3$	n/a	250	1.0
11	n/a	$65 \le E_2 < 80$	$85 \le E_3$	n/a	250	1.0
12	n/a	$80 \le E_2$	$90 \le E_3$	n/a	250	1.0
13	$E_1 < 75$	$90 \le E_2$	$90 \le E_3$	n/a	350	1.4
14	$75 \le E_1 < 85$	$90 \le E_2$	$90 \le E_3$	n/a	350	1.4
15	$85 \le E_1 < 95$	$90 \le E_2$	$90 \le E_3$	n/a	350	1.4
16	$95 \le E_1$	$95 \le E_2$	$95 \le E_3$	n/a	350	1.4

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

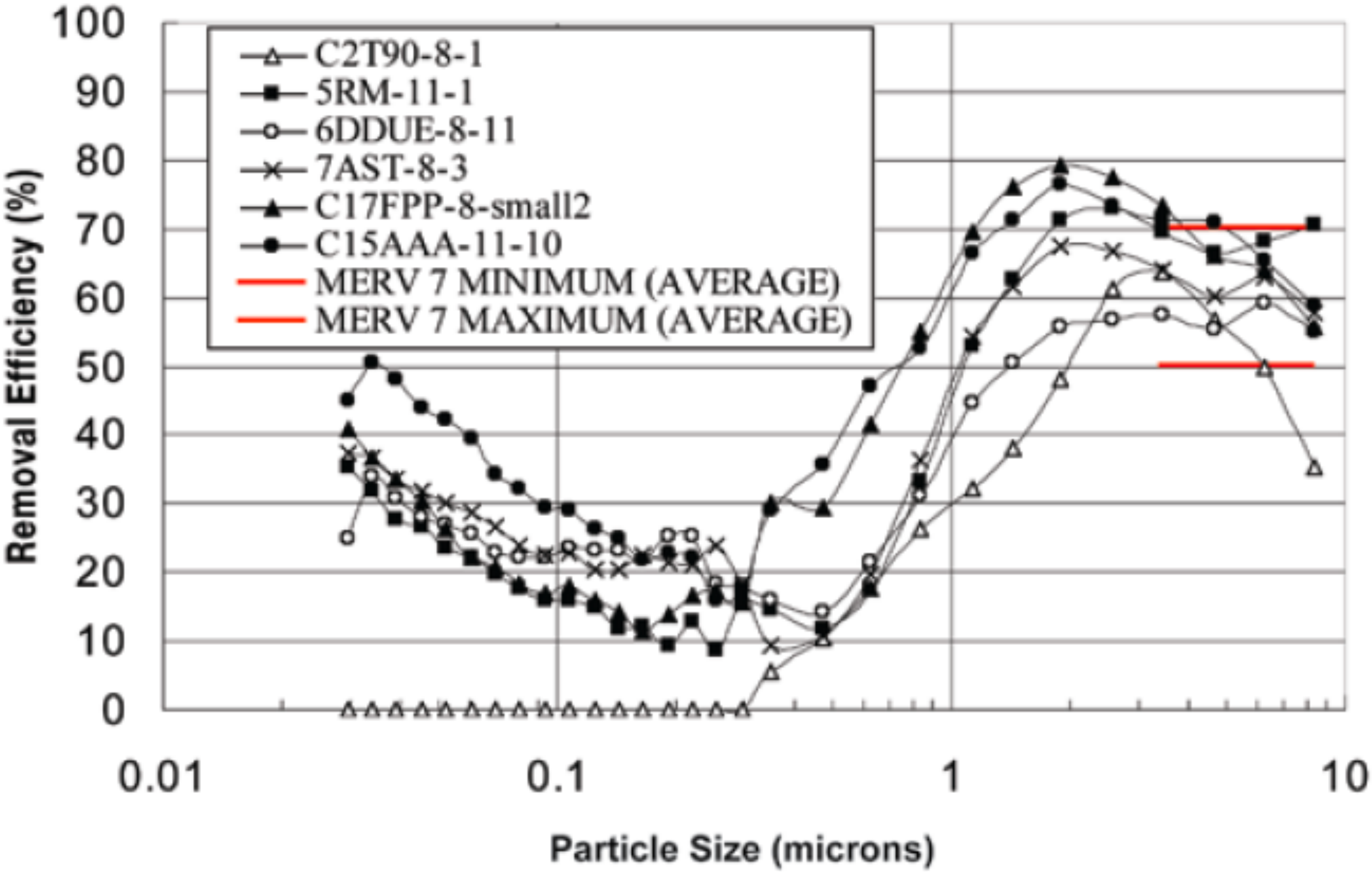
Newer measurements of filtration efficiency

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



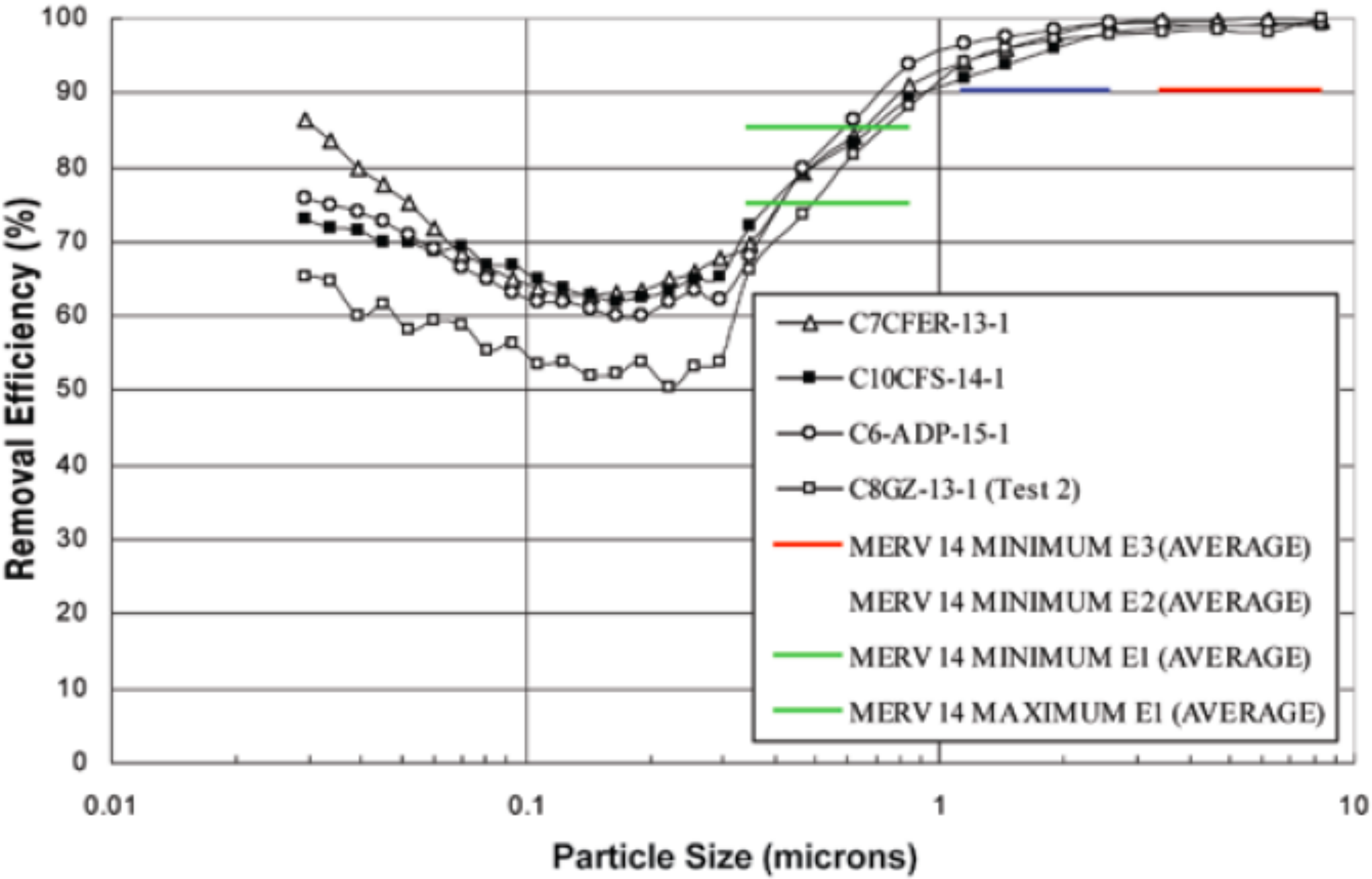
Hecker and Hofacre, 2008 EPA Report 600/R-08/013

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

Filtration and ventilation example problem: ETS

- An office building with a constant volume HVAC system has an air filter installed with an efficiency of 70% for environmental tobacco smoke (ETS)
  - There are 10 occupants; 3 are smokers
  - Each cigarette emits 7.5 μg/s of ETS
  - The outdoor airflow rate is 20 cfm per person
  - The outdoor ETS concentration is zero
  - The return airflow rate is 40 cfm per person
  - The supply airflow rate is 60 cfm per person

- What is the concentration of ETS in the building?
  - Ok to ignore deposition indoors