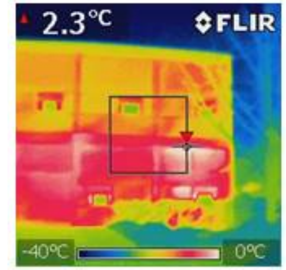
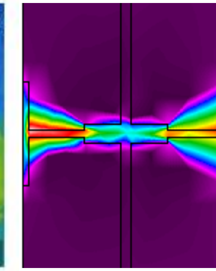
CAE 331/513
Building Science
Fall 2018





November 1, 2018
Ventilation and indoor air quality (part 2)

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QUANTIFYING IAQ

Units of measurement for air pollutants

- **Number concentrations** (# per volume of air, #/m^3)
  - # of molecules per m^3 (highly reactive species, e.g., OH radical)
  - # of particles per m^3 (particulate matter)
  - # of cells or colony forming units per m^3 (biological)
- **Mass concentrations** (mass per volume of air)
  - ng/m^3 typical for metals and SVOCs
  - μg/m^3 typical for indoor VOCs and particulate matter
  - mg/m^3 big sources, e.g., ETS, cooking, industrial hygiene
- **Molar concentrations** (variations on $y_i = \mathrm{mol}_i/\mathrm{mol}_{air}$)
  - Mole fraction (y_i) = mol/mol
  - % concentration = moles per 100 moles = 100*y_i
  - Parts per million by **volume** (ppm_v) (or just "ppm")

$$1 \text{ ppm} = \frac{1 \text{ mol of } i}{10^6 \text{ moles of air}} = 10^{-6} \frac{\text{moles of } i}{\text{moles of air}} = 10^{-6} * y_i$$

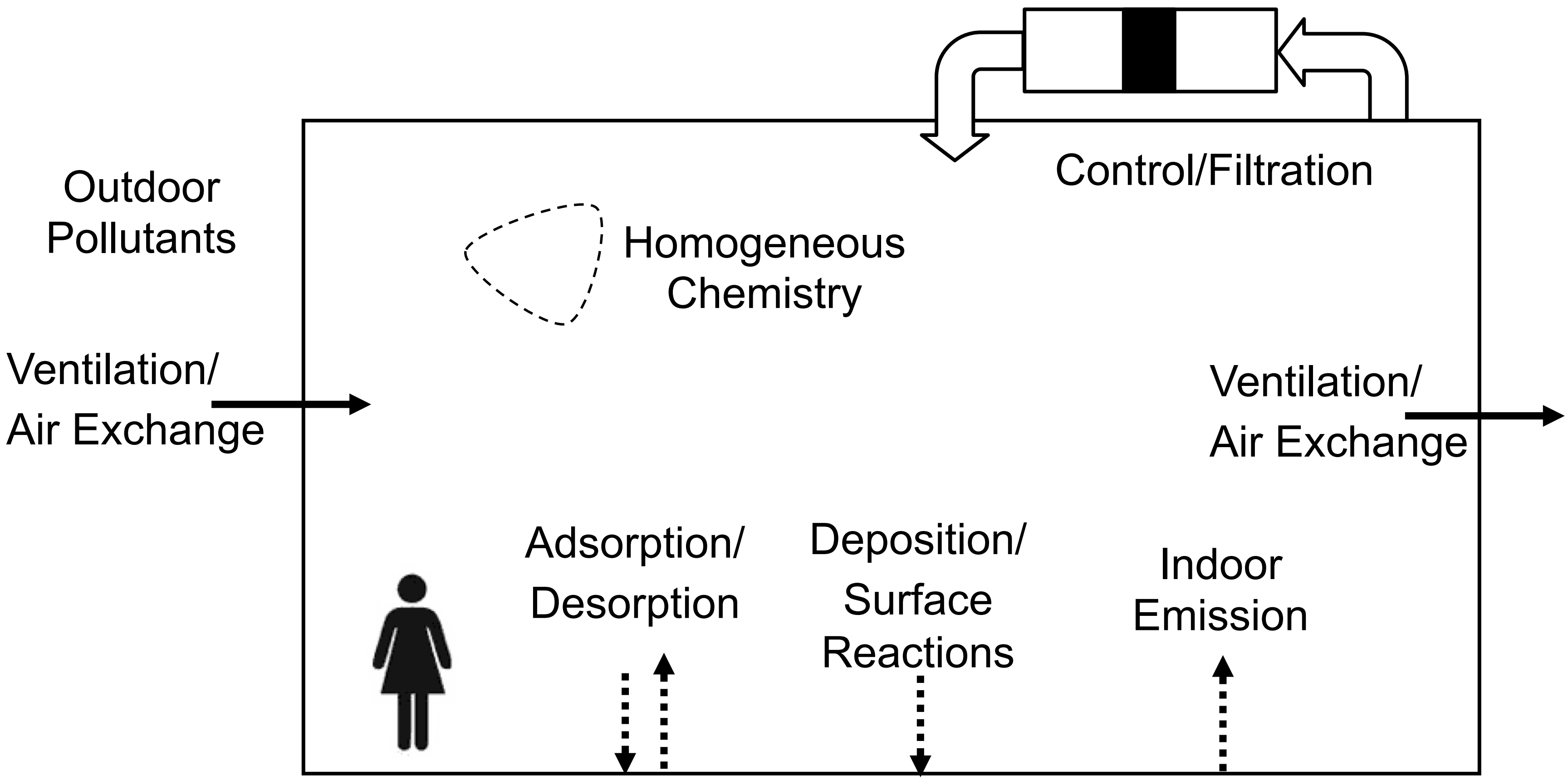
  - Parts per billion by **volume** (ppb_v) (or just "ppb")

$$1 \text{ ppb} = \frac{1 \text{ mol of } i}{10^9 \text{ moles of air}} = 10^{-9} \frac{\text{moles of } i}{\text{moles of air}} = 10^{-9} * y_i$$

For gases, we can use the ideal gas law to convert between molar and mass concentrations (revisit this later)

Indoor environment: <u>Mass balances</u>

To understand the levels of airborne pollutants that we are exposed to, we need to understand the underlying physical, chemical, and biological mechanisms that drive pollutant emission, transport, and control



Indoor environment: Mass balance

- Simplest case (**inert gas**)
  - Neglecting indoor physics/chemistry
    - No deposition, no reaction

$$\begin{pmatrix}\text{Mass}\\ \text{accumulation}\\ \text{rate}\\ [\text{mass / time}]\end{pmatrix} = \begin{pmatrix}\text{Mass flow in}\\ [\text{mass / time}]\end{pmatrix} - \begin{pmatrix}\text{Mass flow out}\\ [\text{mass / time}]\end{pmatrix} + \begin{pmatrix}\text{Mass emitted}\\ [\text{mass / time}]\end{pmatrix}$$

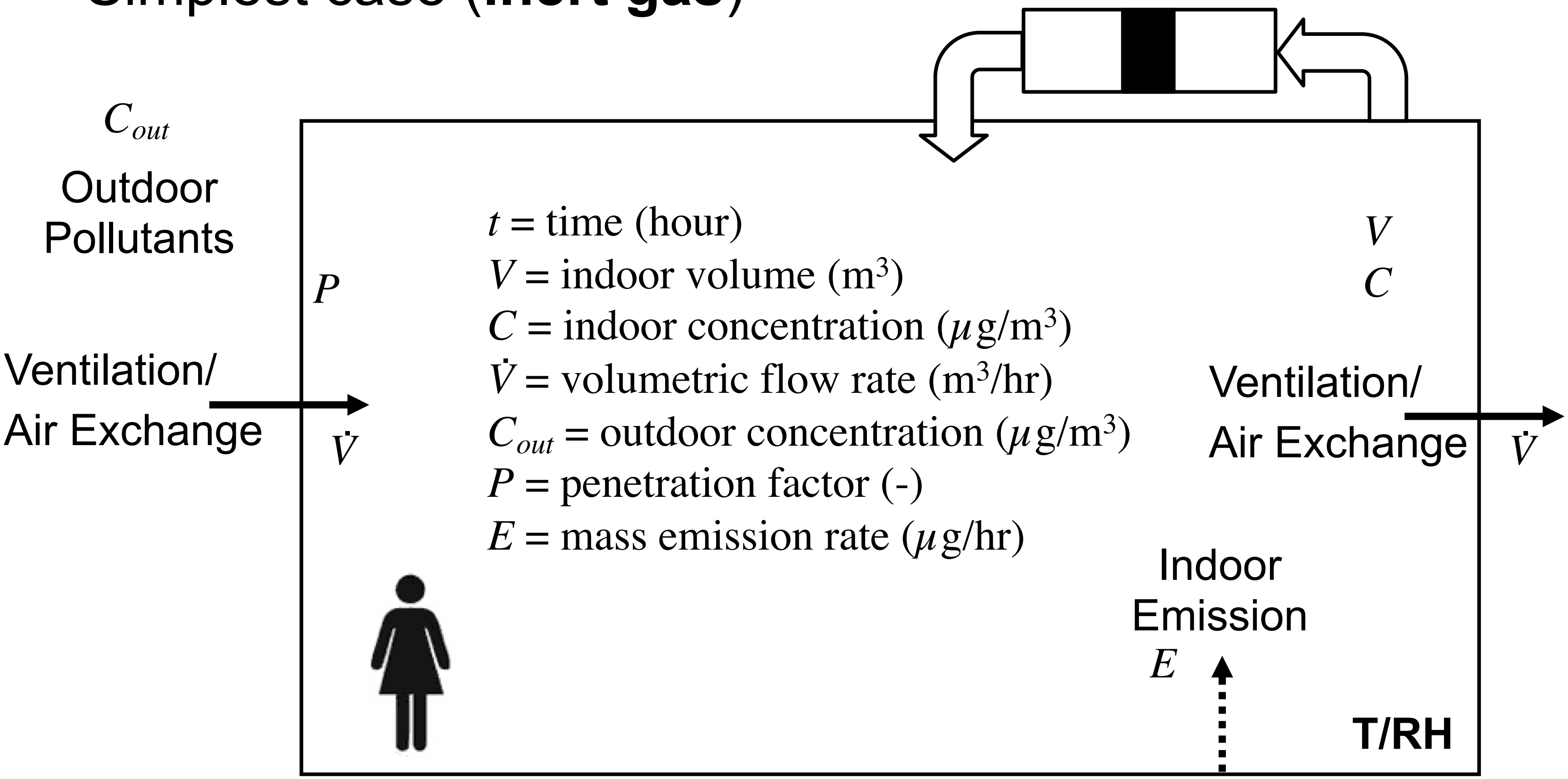
$$\frac{dm}{dt} = \frac{dCV}{dt} = V\frac{dC}{dt} + C\cancelto{0}{\frac{dV}{dt}}$$

Assumptions:

- Building/room can be treated as well-mixed

Indoor environment: Mass balance

- Simplest case (**inert gas**)



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

Indoor environment: Mass balance

- Simplest case (**inert gas**)

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

- Divide by volume:

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

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

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

Indoor environment: Mass balance

- Assume steady-state conditions:

$$\cancelto{0}{\frac{dC}{dt}} = P\lambda C_{out} - \lambda C + \frac{E}{V} \longrightarrow \boxed{C_{ss} = PC_{out} + \frac{E}{\lambda V}}$$

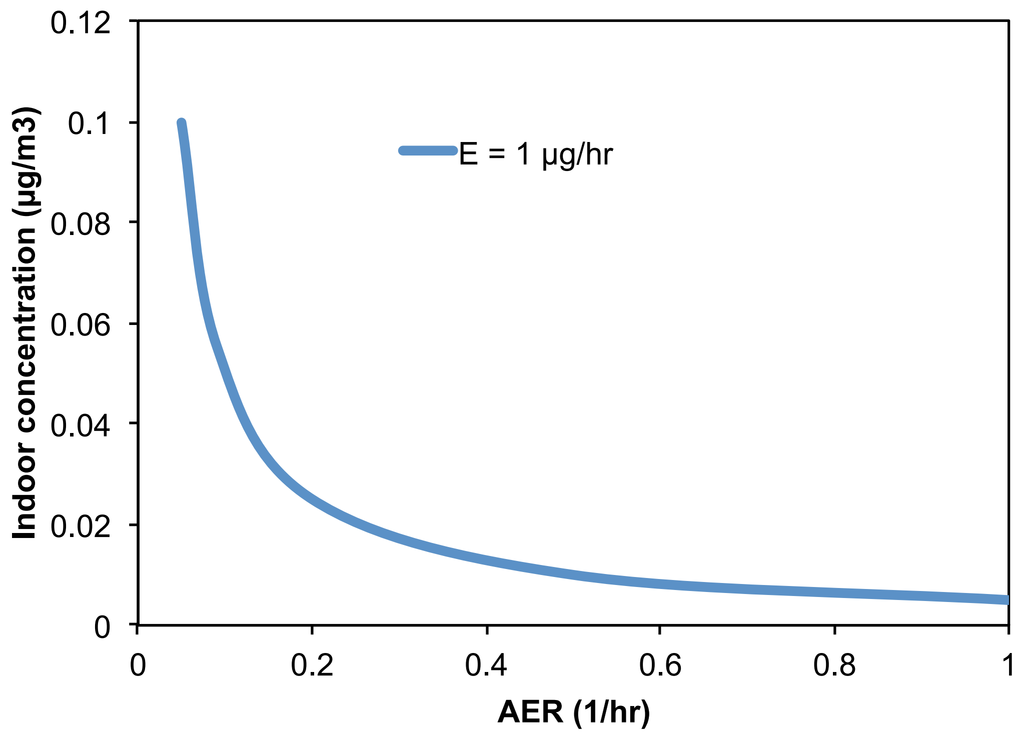
Assumptions:

- Building/room can be treated as well-mixed
- Ventilation/air exchange rate is constant
- Outdoor pollutant concentration is constant
- Indoor sources emit at a constant rate

- If λ is large (and/or E is small): $PC_{out} >> E/\lambda V$
  – C approaches C_{out} (depending on P)
  – This means outdoor sources are relatively more important
- If λ is small (and/or E is large): $PC_{out} << E/\lambda V$
  – C approaches E/λV
  – This means indoor sources are relatively more important

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 μg/hr: how are C_{ss} and λ related?



What impacts air exchange rates?

Outdoor air exchange can be divided into two main categories:

Ventilation

Intentional introduction of outdoor air into a building

Subdivided into:

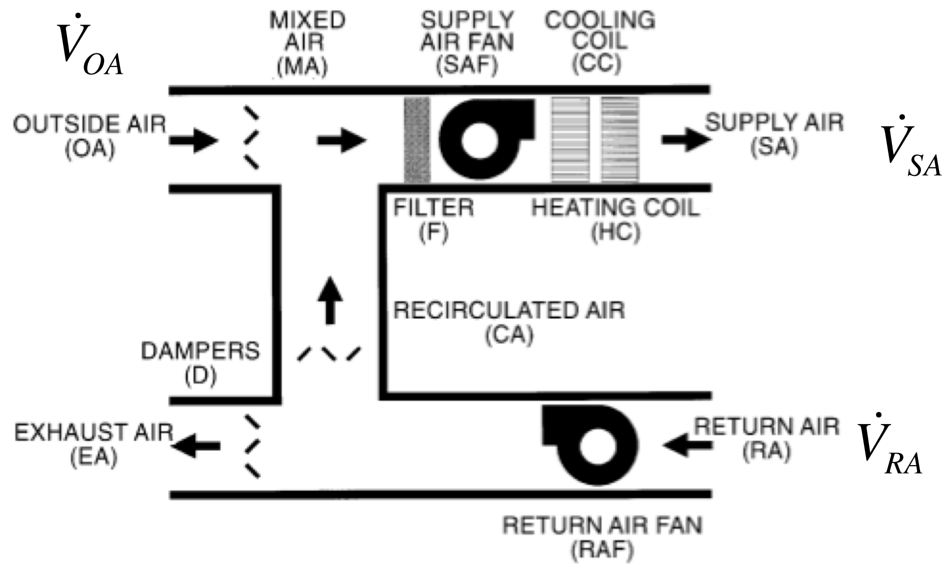
- **Mechanical (forced) ventilation:** The intentional movement of air into and out of a building using fans, intake vents, and exhaust vents
- **Natural ventilation:** The flow of air through open windows, doors, grilles, and other planned envelope penetrations, driven largely by natural or artificially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

Dealing with ventilation vs. infiltration

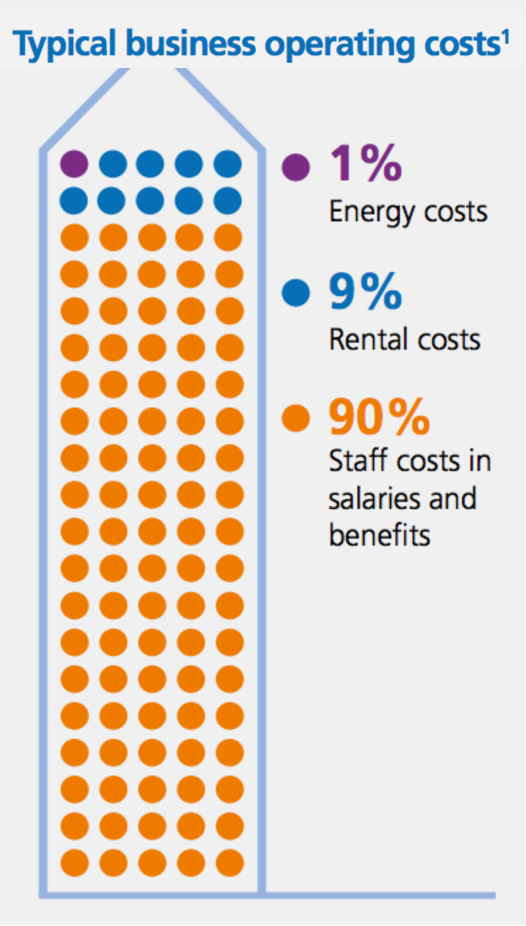
- **Mechanical ventilation** is straightforward
  - Fans move air through known openings
  - Flow rates typically known or at least measurable
- **Natural ventilation** is conceptually straightforward but physically complex
  - Known openings but highly varying wind speeds and directions
- **Infiltration** 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

"Four principles for achieving good indoor air quality"

- Minimize indoor emissions
- Keep buildings dry
- Ventilate well
- Protect against outdoor pollution

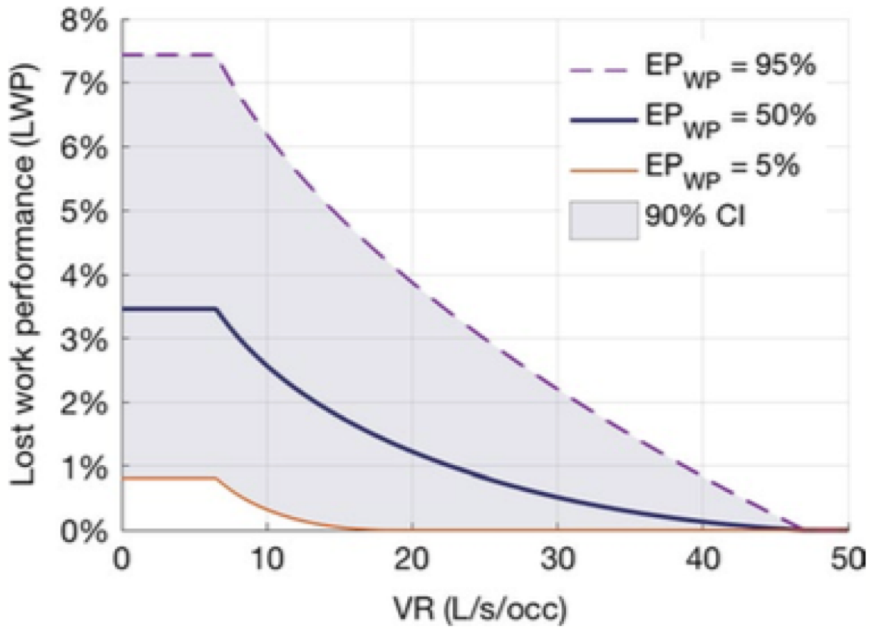


Nazaroff **2013** *Indoor Air*

Importance of ventilation

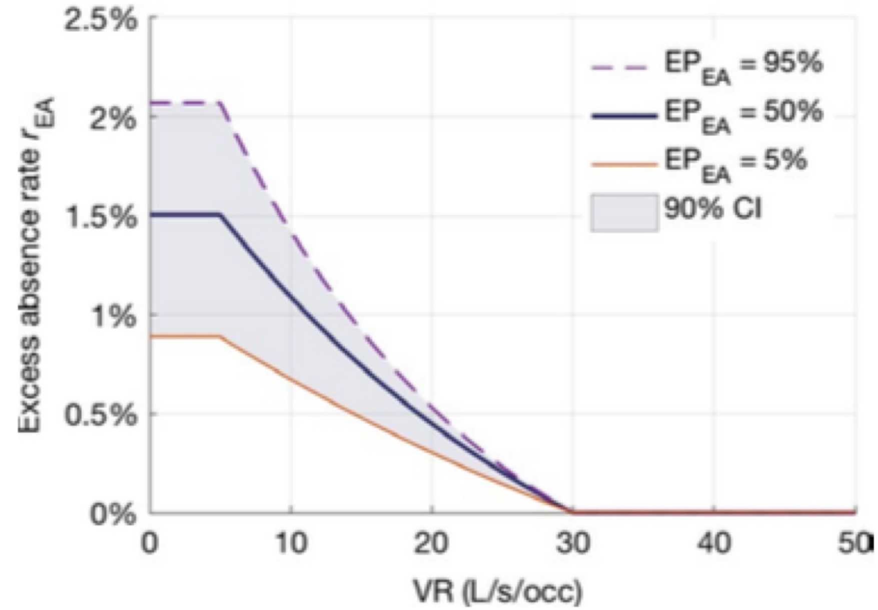
- Outdoor air ventilation dilutes indoor-generated pollutants

Worker performance



Seppänen et al. **2006** *Indoor Air*

Work absences



Milton et al. **2000** *Indoor Air*

Rackes et al. **2018** *Indoor Air*

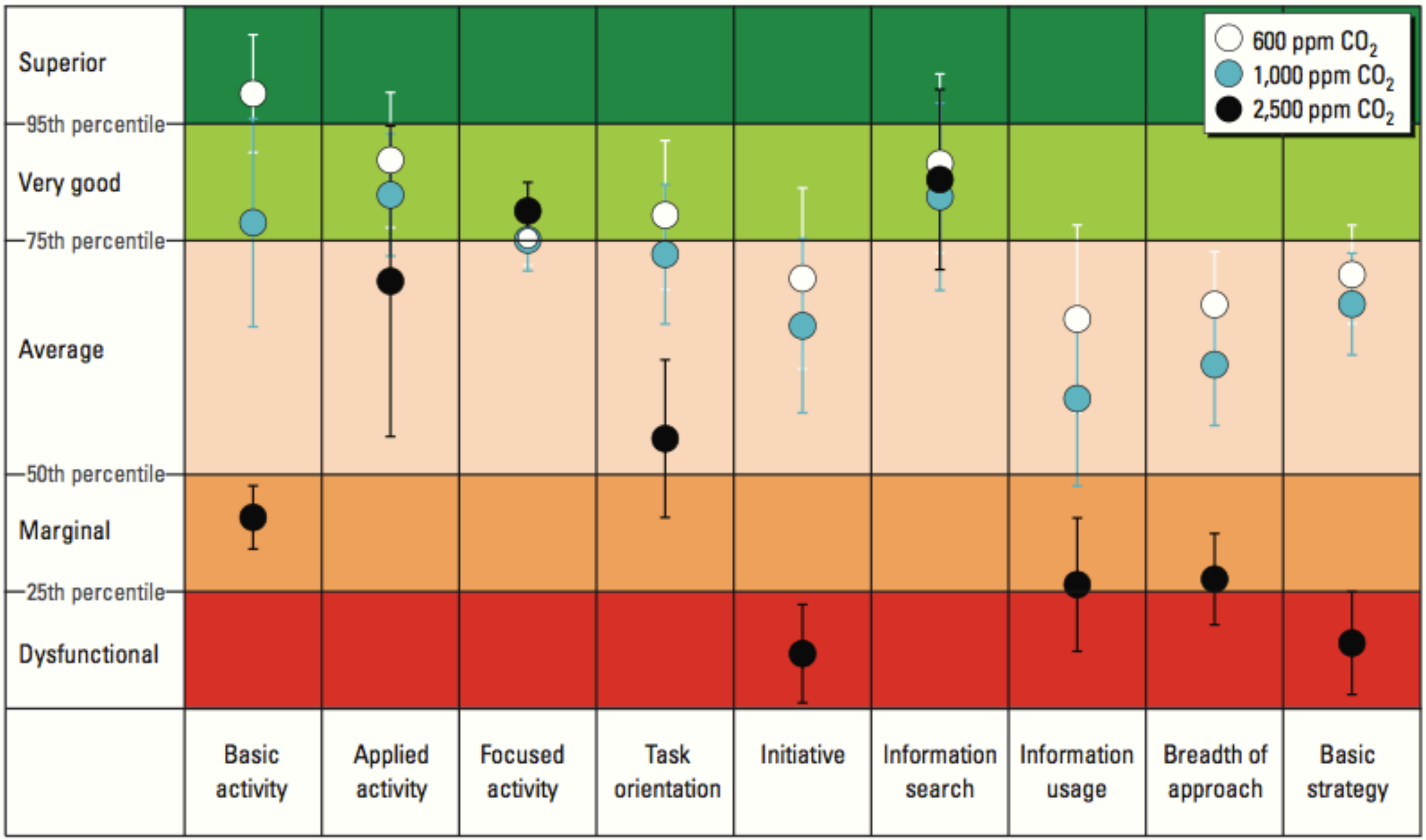
Ventilation and CO_2

- CO_2 is often used as a surrogate for IAQ
  - Imperfect, but instructive
  - CO_2 concentrations will be elevated in poorly ventilated spaces

- The average CO_2 production rate per person at an activity level of 1.0-1.2 met is often assumed to be ~0.003 L/s
  - ~21 g/hr at standard temperature and pressure conditions

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

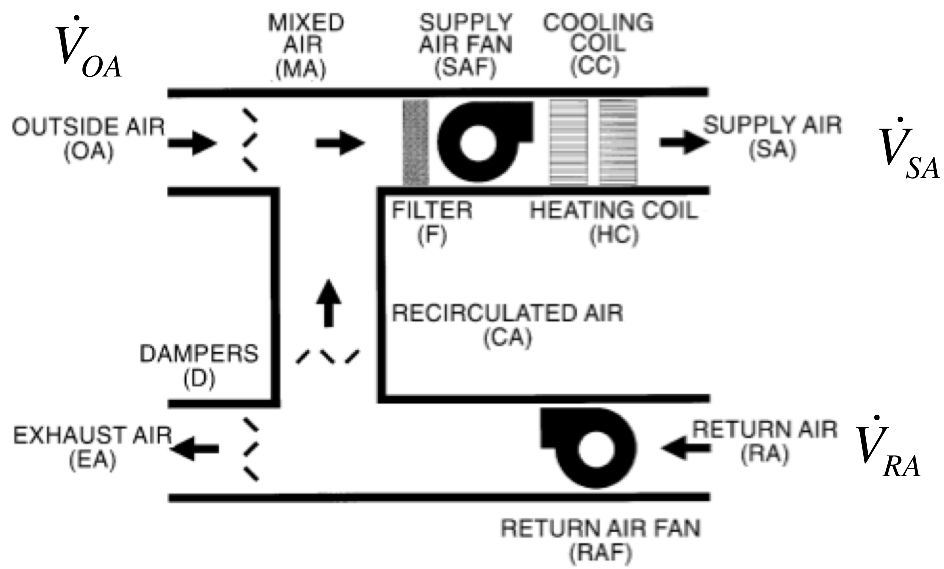
Ventilation and CO_2



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

Mass balance example problem w/ CO_2

- In a 150 m^3 room with 30 people present, what would be the required (a) air exchange rate, (b) outdoor airflow rate, and (c) per person ventilation flow rate to keep the indoor CO_2 concentration below 1000 ppm?
  - Assume outdoors is 400 ppm
  - And CO_2 production (activity level of 1.2 met) = 21 g/hr per person



Converting between mass and molar concentrations

- Treat air and its constituents as an ideal gas:

$$PV = nRT \longrightarrow \frac{n}{V} = \frac{P}{RT} \qquad P_i = y_i P_{tot}$$

Mole fraction

$$400\ \text{ppm} \Rightarrow \frac{n_i}{V} = y_i \frac{P_{tot}}{RT} = \frac{400\ \text{mol}_\text{i}}{10^6\ \text{mol}_\text{air}} \frac{1\ \text{atm}}{\left(8.205\times10^{-5}\ \frac{\text{atm}\cdot\text{m}^3}{\text{mol}\cdot\text{K}}\right)\times 293\ \text{K}}$$

20°C, 68°F

- Gives you # of moles per m^3 of air
- Multiply by MW_i to get g/m^3 of air

$$\#\ \text{of}\ \frac{\text{g}}{\text{m}^3} = \frac{\#\ \text{mol}_\text{i}}{\#\ \text{mol}_\text{air}} * \frac{P_{tot}}{RT} MW_i$$

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.

$$V_{bz} = R_p \cdot P_z + R_a \cdot A_z \qquad (6\text{-}1)$$

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

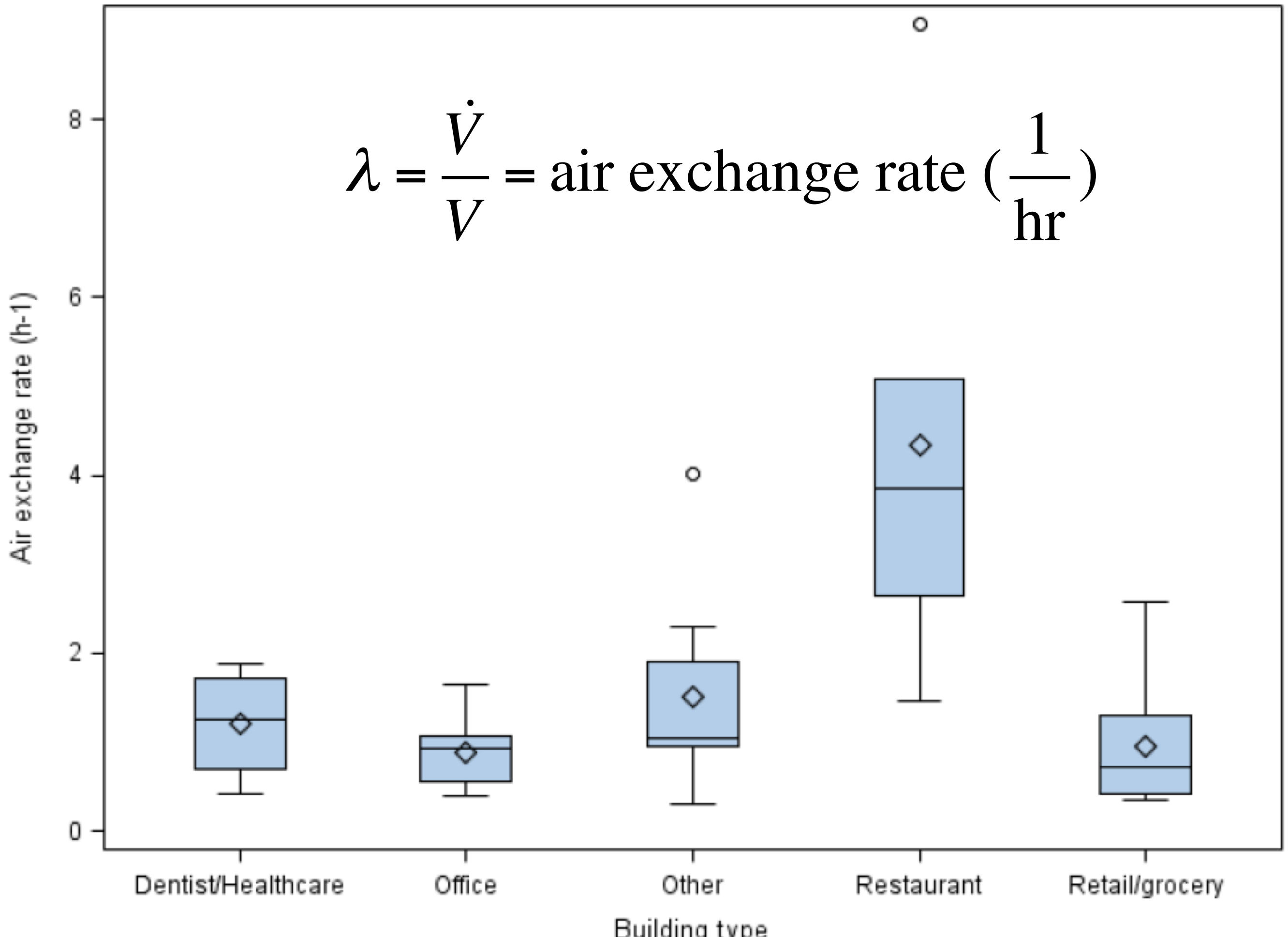
ASHRAE Standard 62.1: Commercial buildings VRP

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



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

Bennett et al. **2011** CEC Report

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

CO_2 concentration in the classroom

- Estimate the ventilation rate in this classroom using measured CO_2 concentrations

- How does it compare to the ASHRAE 62.1 minimum ventilation rate requirement?

ASHRAE Standard 62.2: Residential ventilation

ANSI/ASHRAE Standard 62.2-2007
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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

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Ventilation Air Requirements, L/s

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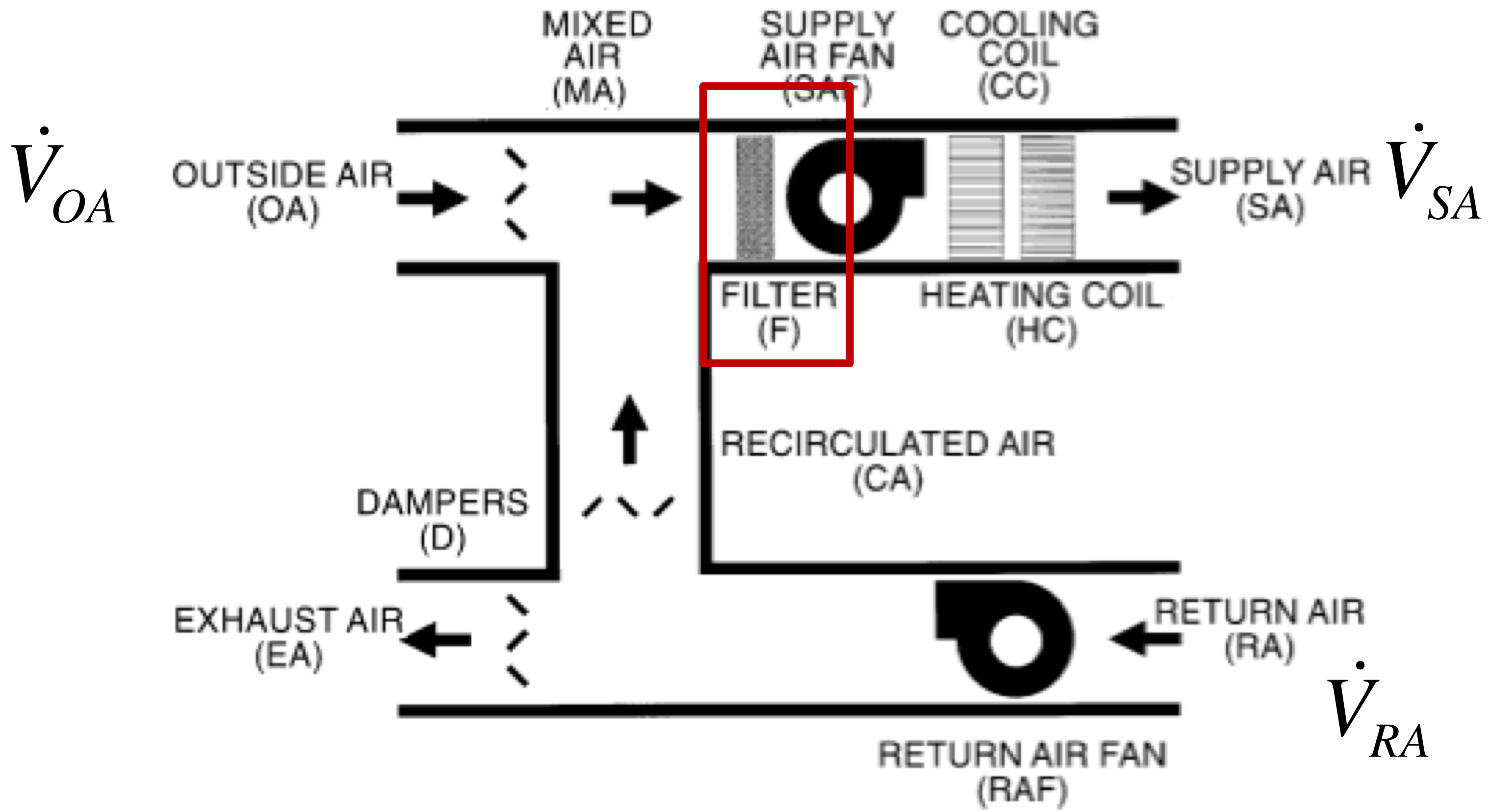
418.1–557	35	42	50	57	64
557.1–697	42	50	57	64	71
>697	50	57	64	71	78

AIR CLEANING/FILTRATION

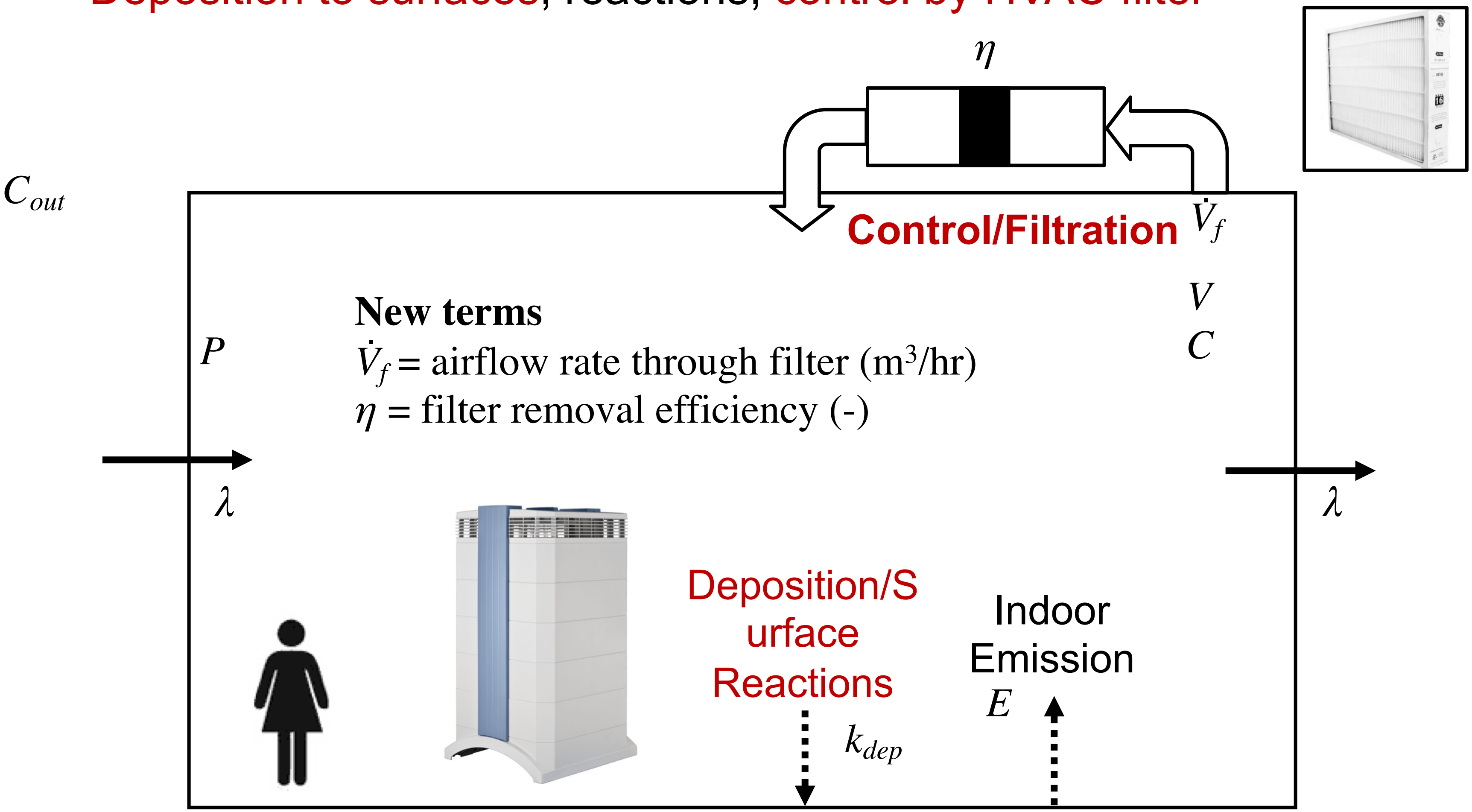
Forced air distribution: Filtration

Typical commercial HVAC system:



What if we add HVAC filtration?

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



Mass balance with filtration and deposition

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

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

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

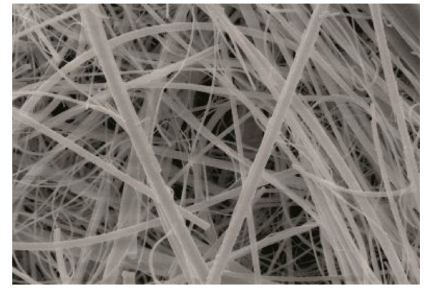
- Assume steady state for now, divide by λ, and solve for C:

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

- 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?



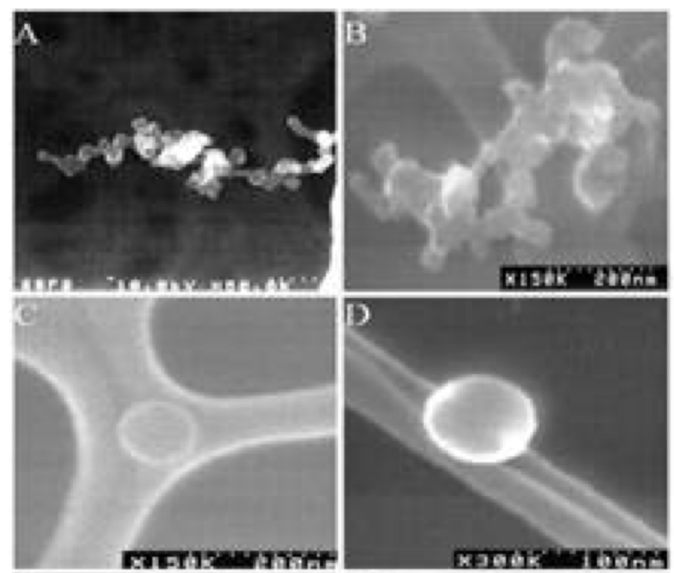
- Particles
  - Fibrous filters
  - Electrostatic precipitators
  - Every forced air HVAC system will have some kind of particle filter
- Gases
  - Activated carbon
    - Relies on adsorption of VOCs/other gases to high surface area carbon
  - Very few buildings will have gas-phase filtration

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

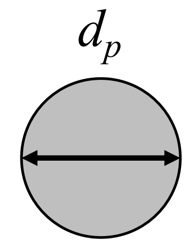
- Visibility effects outdoors



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



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

Important units:

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

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

Particle sizes

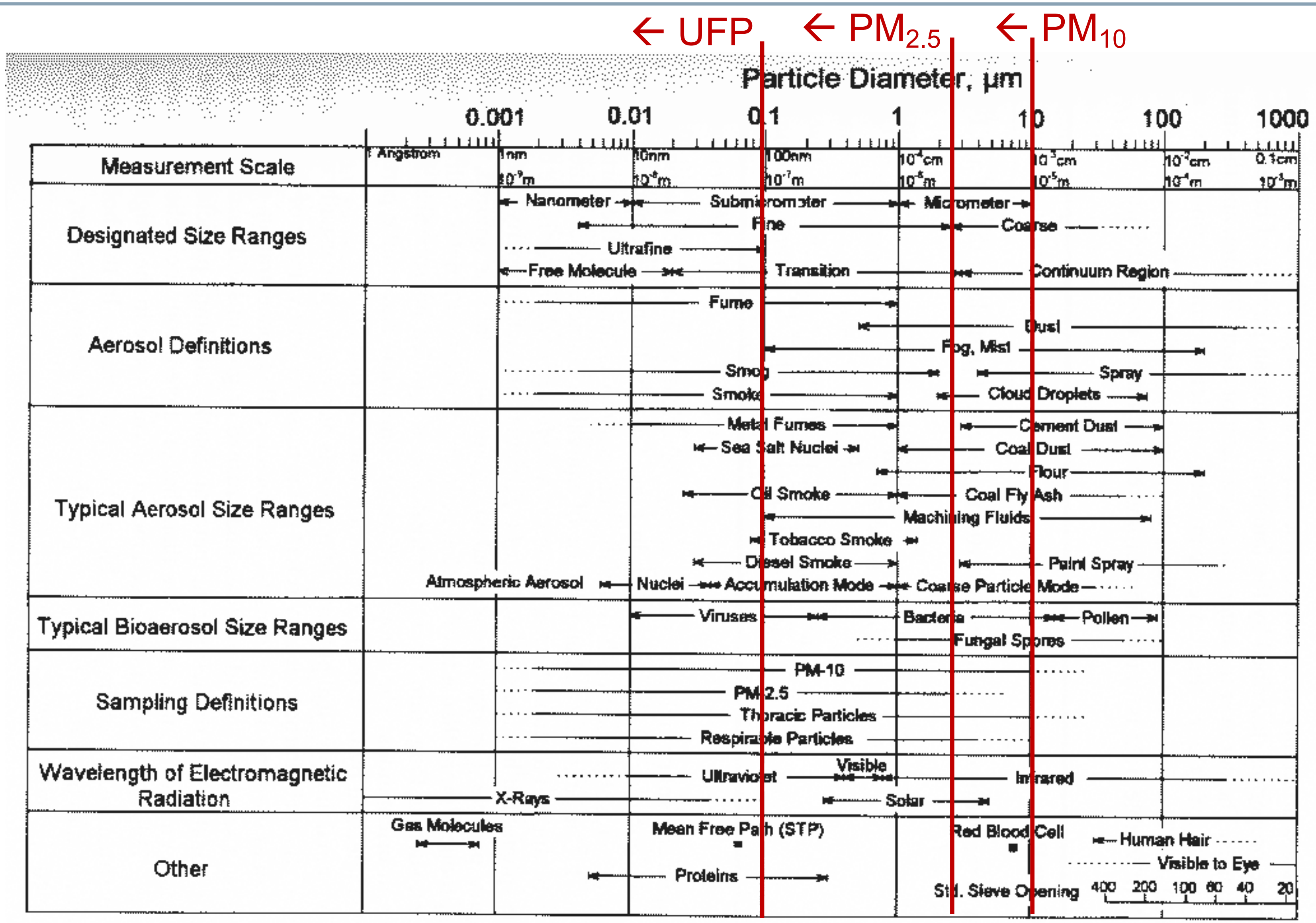
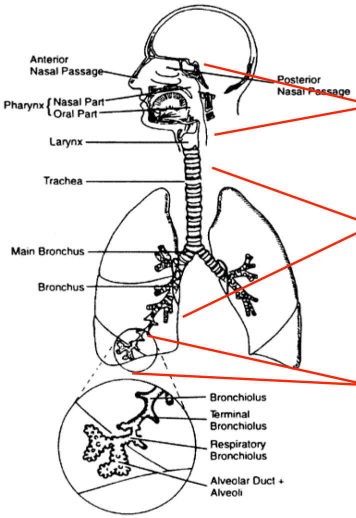


FIGURE 1.6 Particle size ranges and definitions for aerosols.

Hinds 1999

Particle deposition in respiratory system



Nasopharyngeal

Tracheobronchial

(N&T regions "cleaned" by mucus)

Alveolar

Hinds, 1999 Ch. 11

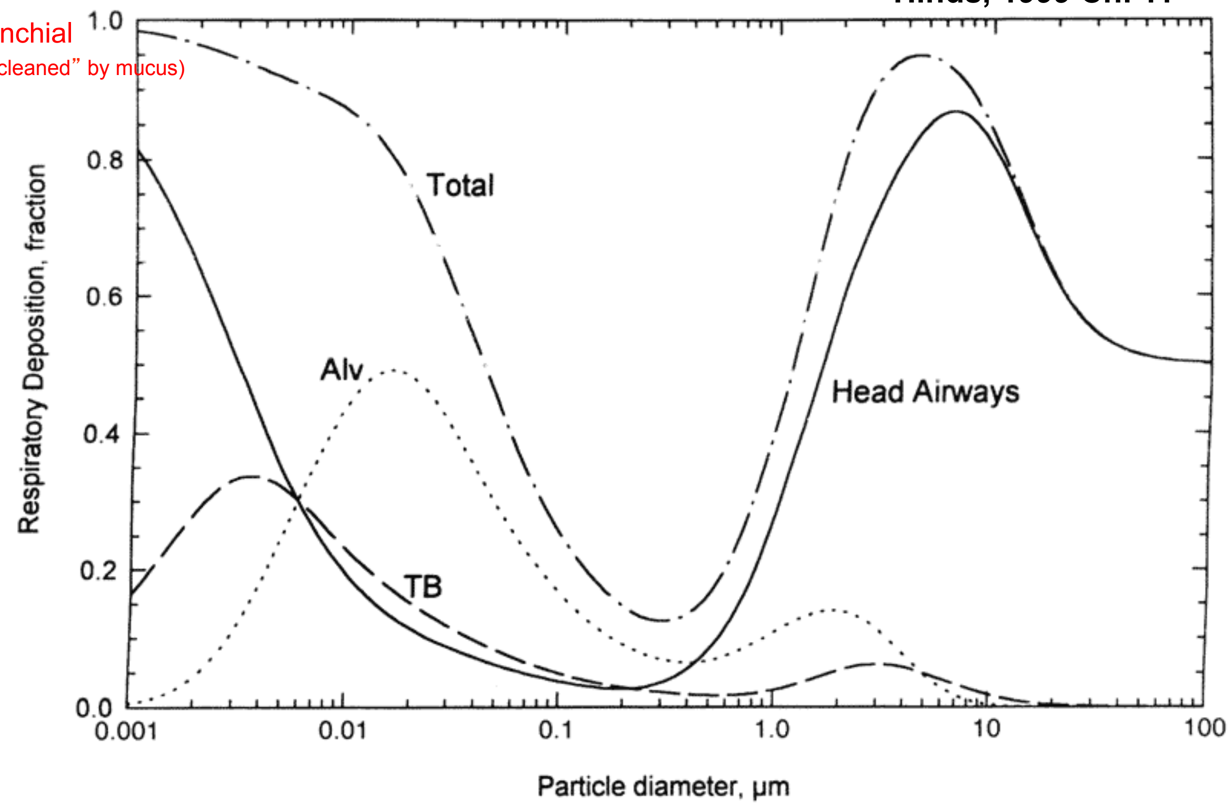


FIGURE 11.3 Predicted total and regional deposition for light exercise (nose breathing) based on ICRP deposition model. Average data for males and females.

Total efficiency for an example filter

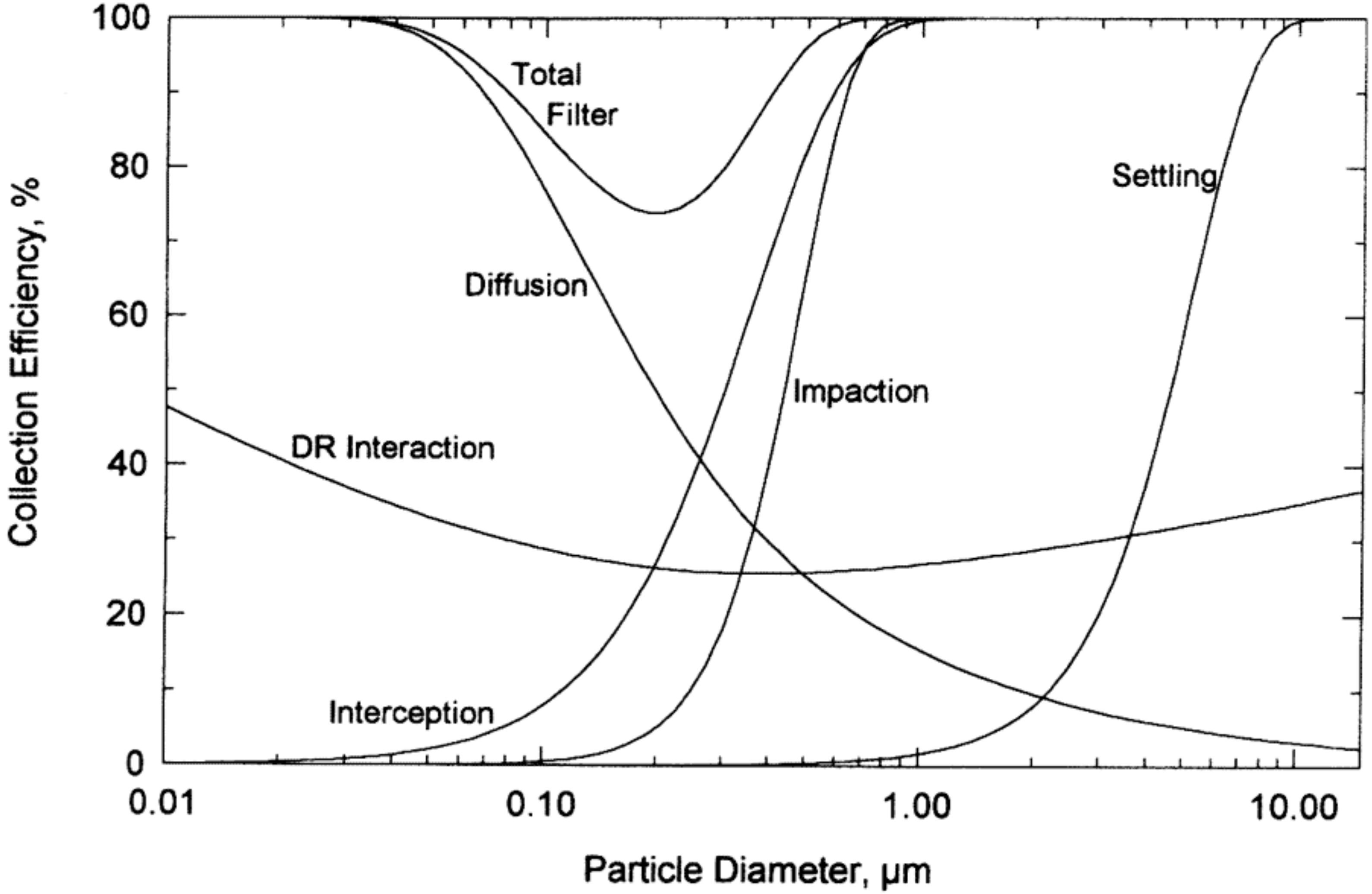


FIGURE 9.8 Filter efficiency for individual single-fiber mechanisms and total efficiency; $t = 1$ mm, $\alpha = 0.05$, $d_f = 2$ µm, and $U_0 = 0.10$ m/s. [10 cm/s].

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

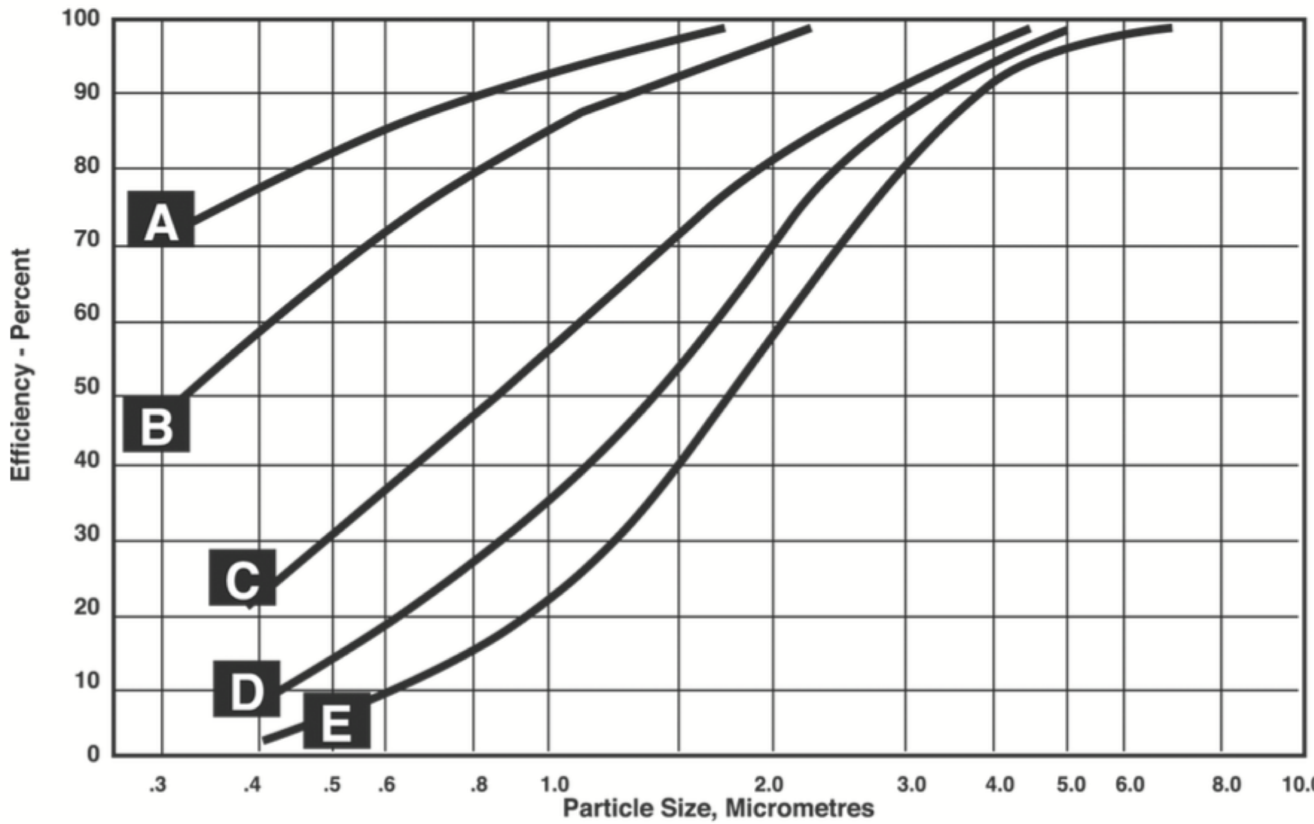
ASHRAE Standard 52.2

- 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

Approximate Efficiency vs. Particle Size for Typical Air Filters



- A 90-95% Efficiency, MERV 14: Superflow V, Rigid Air, Precisioncell, Precisioncell 2, Precision Pak
- B 80-85% Efficiency, MERV 13: Superflow V, Rigid Air, Precisioncell, Precisioncell 2, Precision Pak, PrePleat M13
- C 60-65% Efficiency, MERV 11: Superflow V, Rigid Air, Precisioncell, Precisioncell 2, Precision Pak, 62RM11
- D 50-55% Efficiency, MERV 10: Precision Pak
- 40-45% Efficiency, MERV 9: Rigid Air
- 30% Efficiency, MERV 8: PrePleat 40
- E 25-30% Efficiency, MERV 7: PrePleat 40 (Economy)

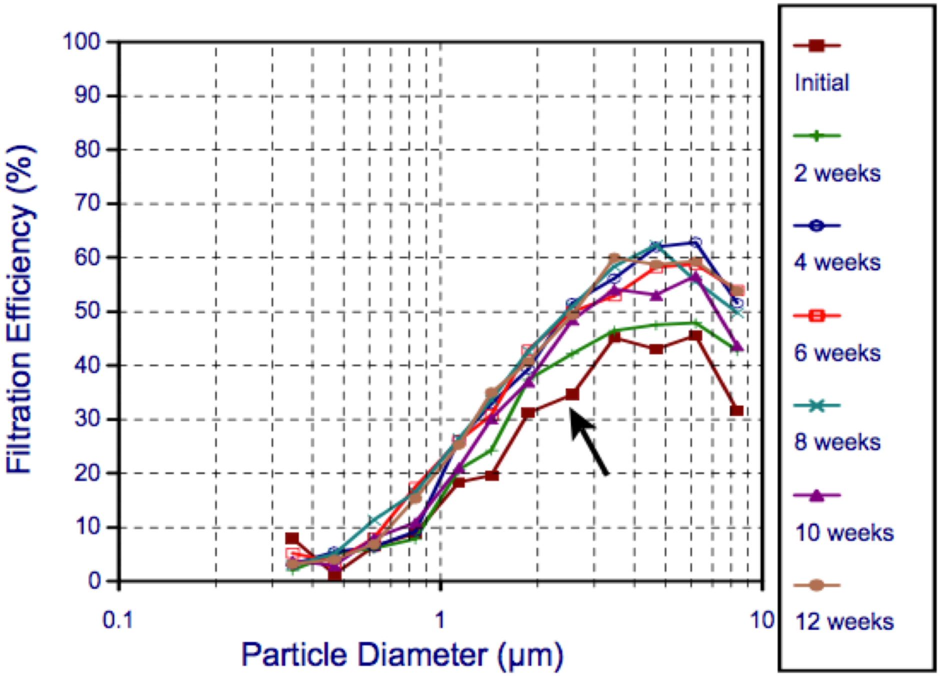
TABLE 12-1 Minimum Efficiency Reporting Value (MERV) Parameters

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

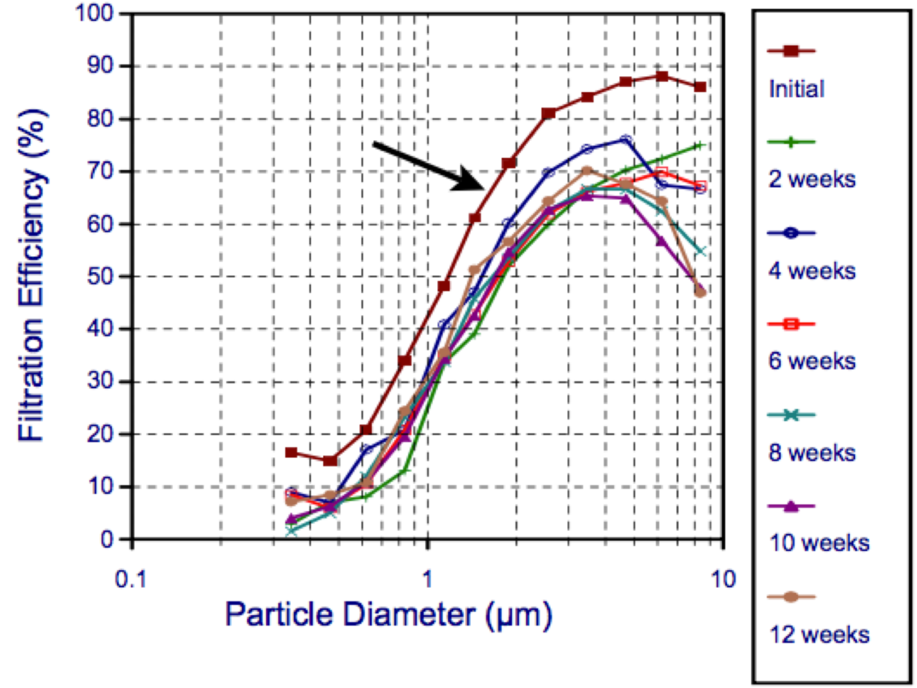
HEPA → 99.9% or greater removal efficiency for most particle sizes

Filter efficiency and dust loading

Non-electret media filters (MERV 5 when clean)



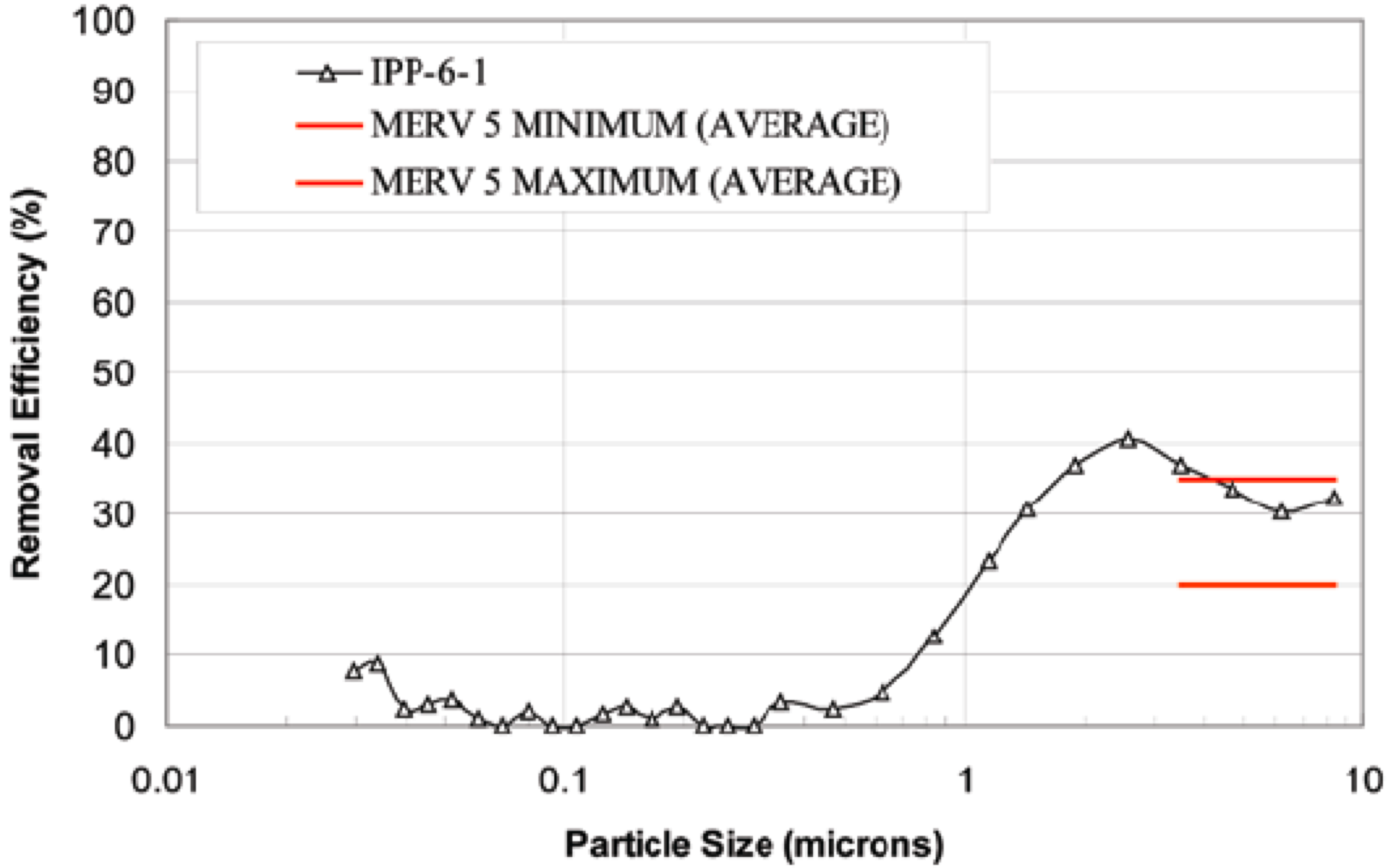
Electret media filters (MERV 11 when clean)



Hanley and Owen **2003** ASHRAE Research Project Final Report 1190-RP
Owen et al. **2013** ASHRAE Research Project Final Report 1360-RP

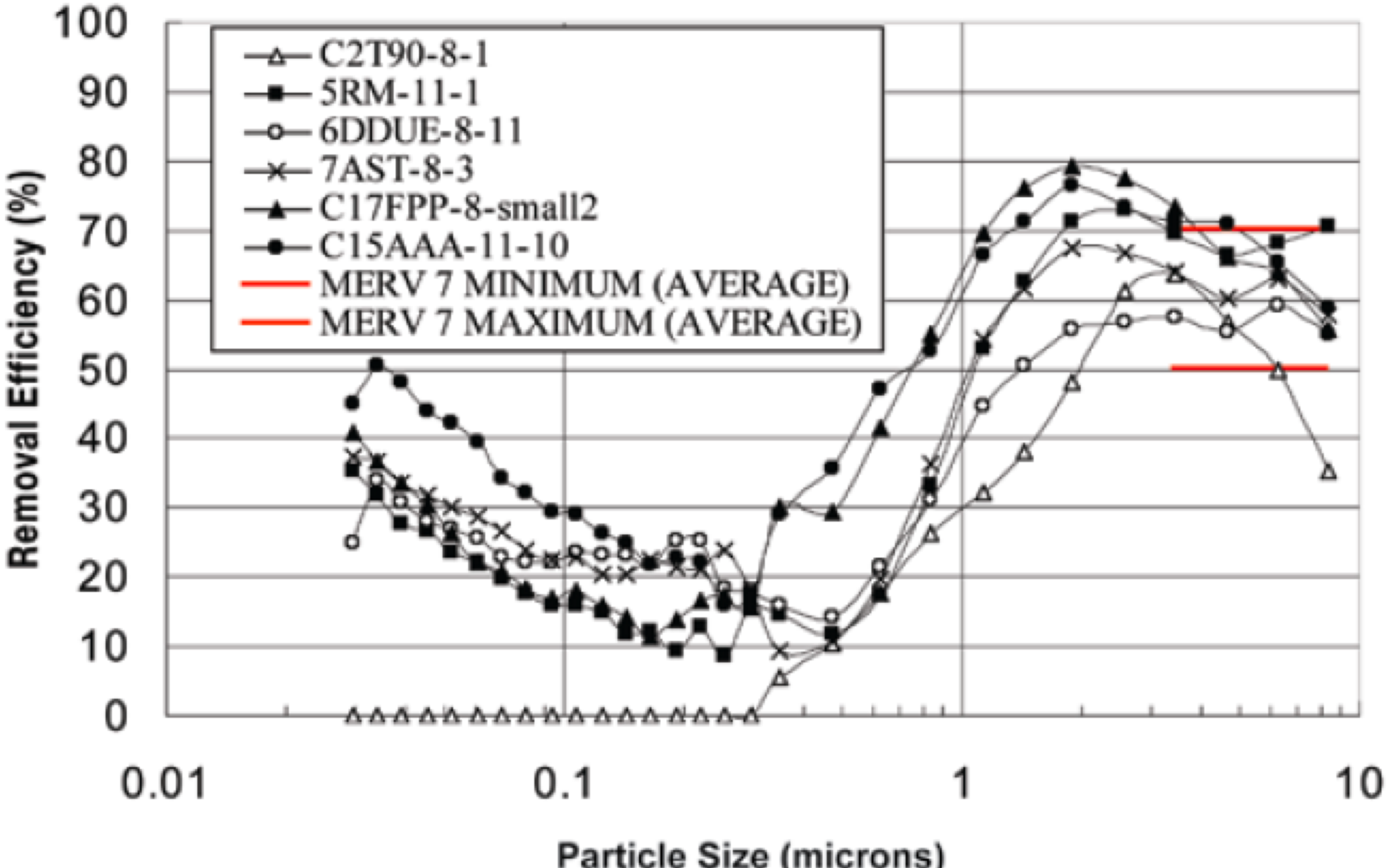
Newer measurements of filtration efficiency

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



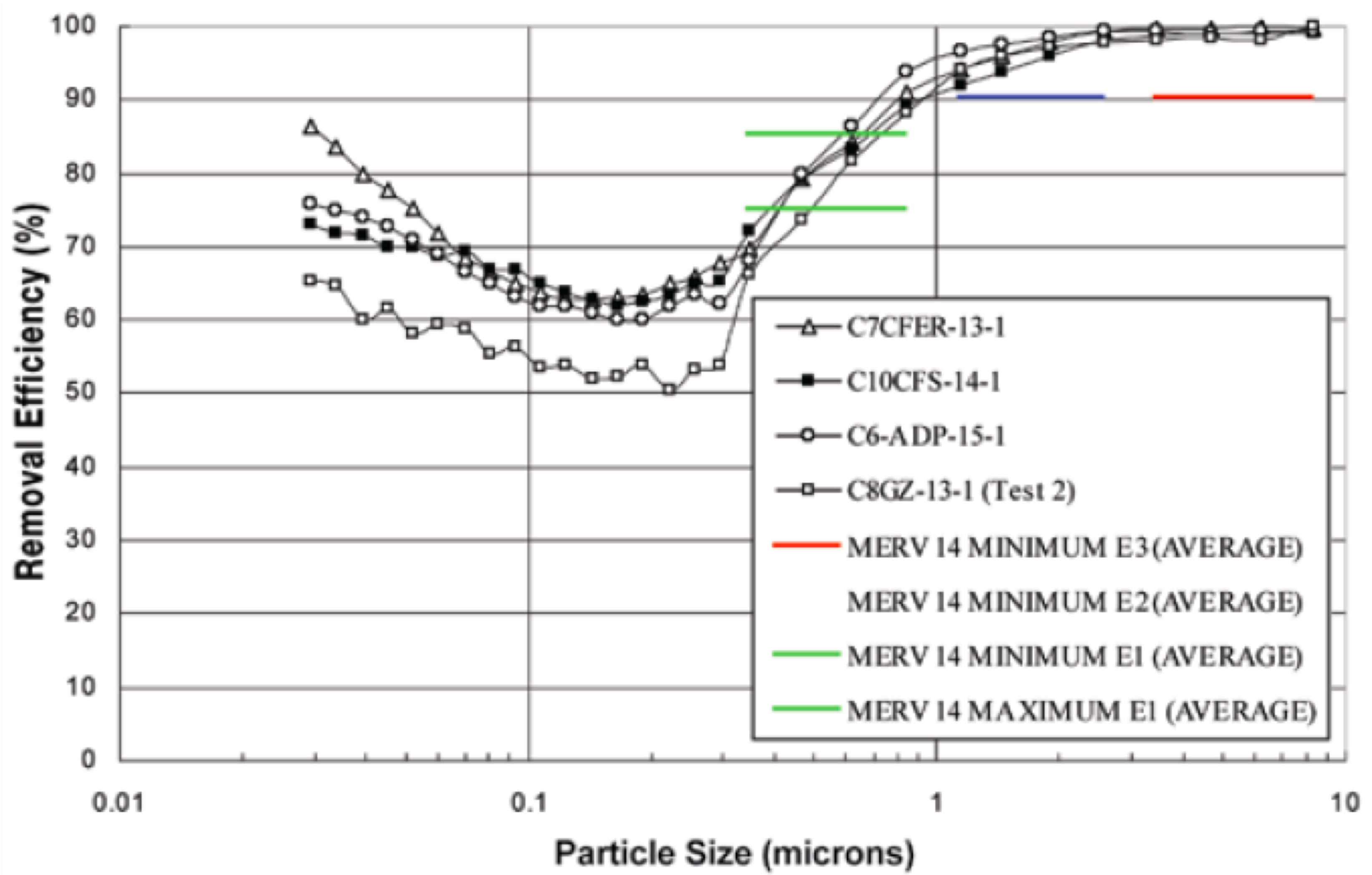
Hecker and Hofacre, 2008 EPA Report 600/R-08/013

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

- A 500 m^3 restaurant that still allows smoking has a constant volume HVAC system with an air filter installed that has 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 ETS concentration is zero
  - The indoor ETS deposition rate is 0.3 per hour
  - The outdoor airflow rate is 20 cfm per person
  - The return airflow rate is 40 cfm per person
  - The supply airflow rate is 60 cfm per person

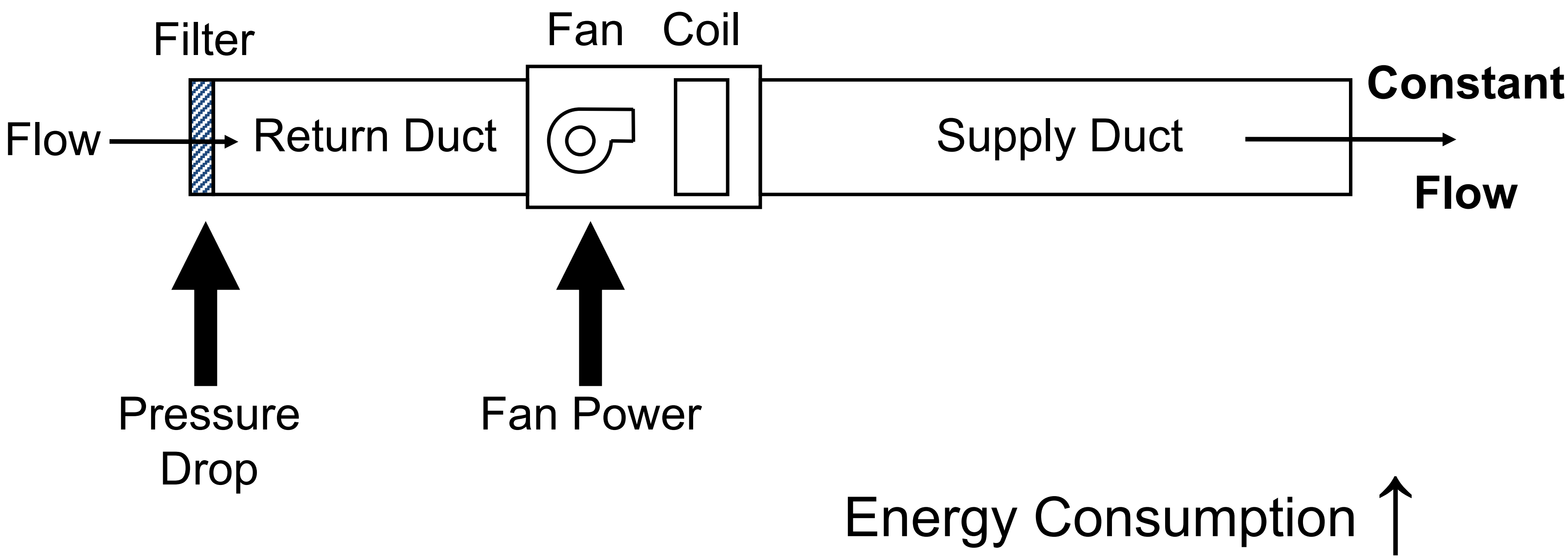
- What is the steady-state concentration of ETS in the building?

Pressure, flow, and energy relationships

- Higher efficiency filters usually have a higher pressure drop
  - Widely assumed to increase energy consumption

Energy consequences of filters

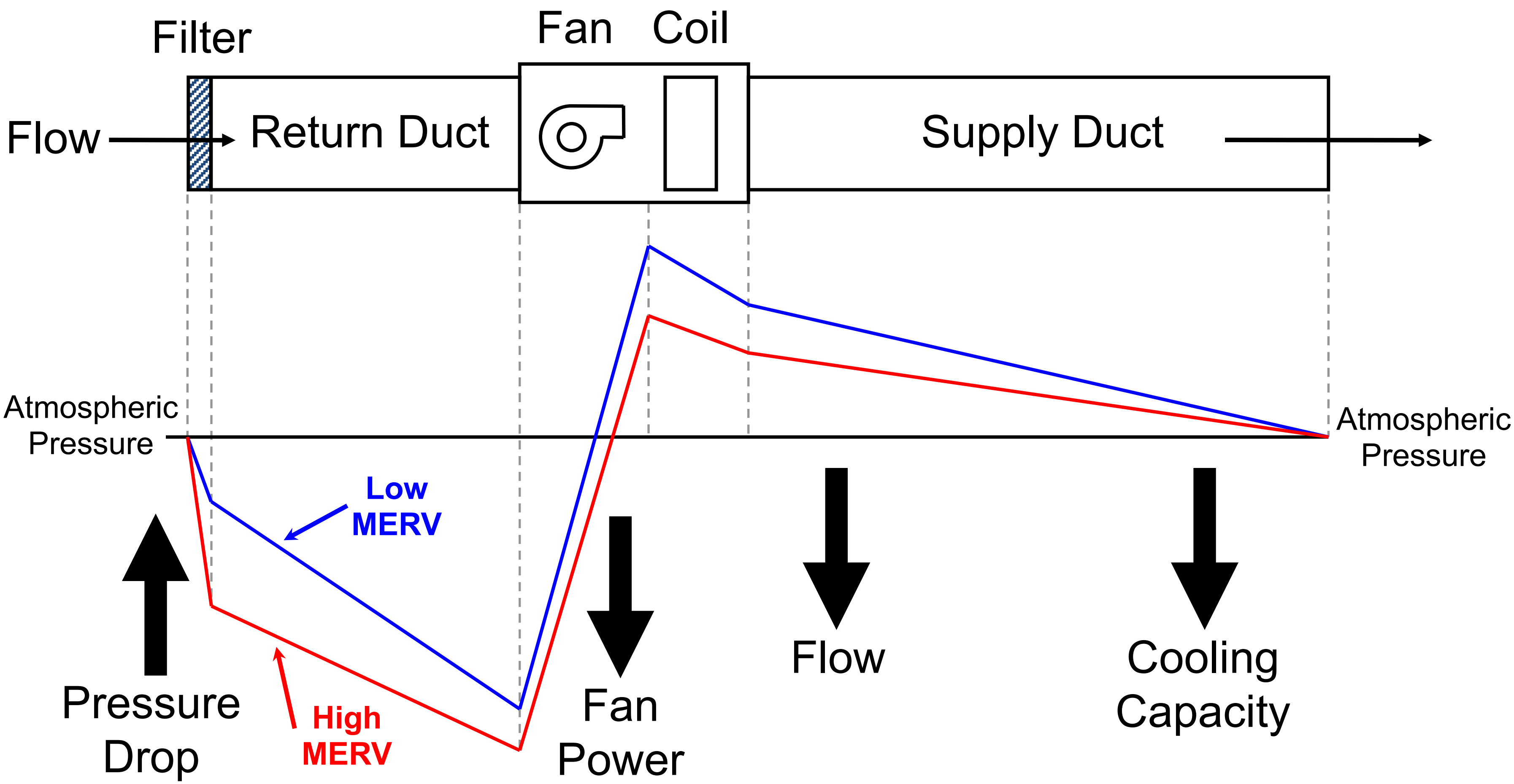
- In large commercial buildings with **variable speed fans**…



$$\boxed{W_{fan} = \frac{\Delta P \cdot \dot{V}}{\eta_{fan}}}$$

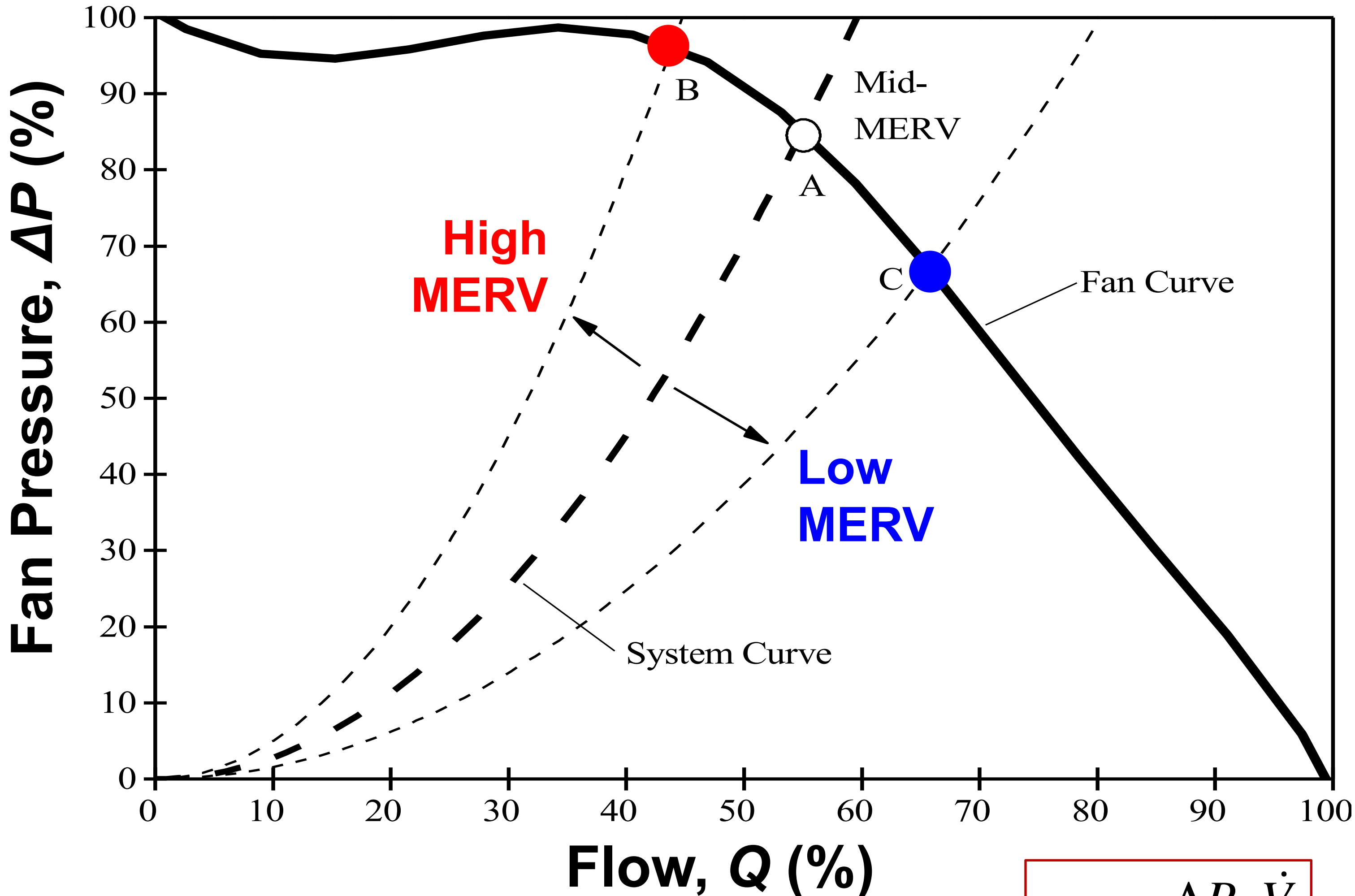
Residential and light-commercial buildings

PSC blower w/ constant speed fan



How does overall energy consumption change?

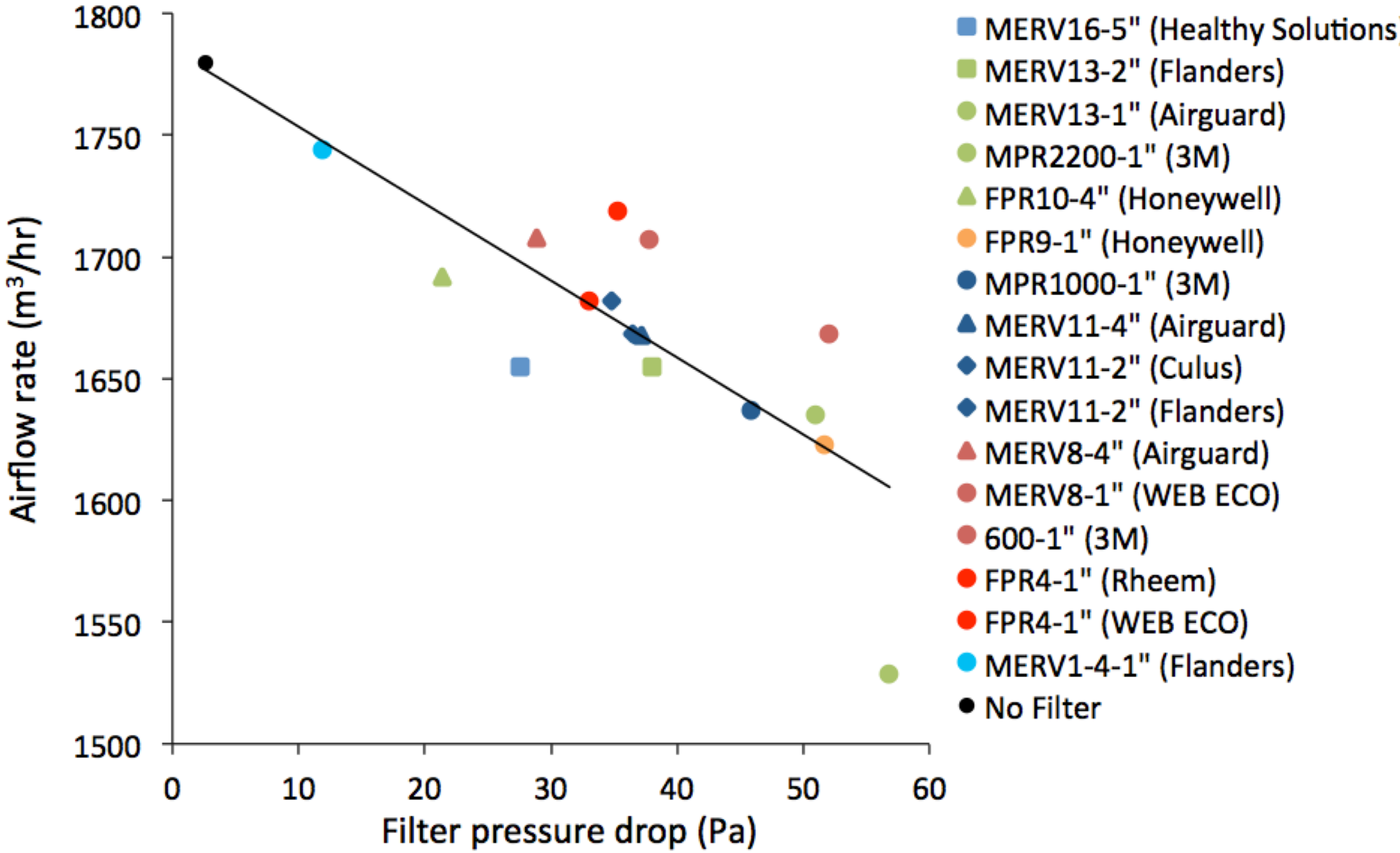
Fan and system curve interactions



$$W_{fan} = \frac{\Delta P \cdot \dot{V}}{\eta_{fan}}$$

Stephens et al., 2010 *HVAC&R Research*

Airflow rates and brand new filters



Data from Built Environment Research Group, Illinois Tech