

# ENVE 576

# Indoor Air Pollution

Fall 2016

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## Week 8: October 11, 2016

Particulate matter: Filtration and air cleaners

Built  
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Research  
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*Advancing energy, environmental, and  
sustainability research within the built environment*

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# Schedule updates

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- Blog post #2 due today
- If you didn't finish HW #3 last time, you can turn it in today
- I will postpone assigning HW #4 until next week

# Final project topics

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Name	Project topic
Boyer, Jeffrey L.	Emissions from humidifying devices
Faramarzi, Afshin	Artificial intelligence for IAQ
Liang, Dejun	Formaldehyde
Liu, Xiaoqi	Chemical stripping from showers
Ma, Peiling	Indoor swimming pool
Meng, Zhenyu	E-cigarette emissions
Rice, Lindsey E.	Ventilation in Carman Hall
Shao, Zhihui (Kevin)	Chemical stripping from showers
Wang, Yintong	E-cigarette emissions
Zeng, Yicheng	Indoor swimming pool
Zhang, Peng (indoorenvir)	Radon control
Zhang, Xu	Restroom bioaerosols
Zhu, Guozhu	Formaldehyde
Angulo Duato, Ana Claudia	IAQ in aircraft cabins

## Remember:

- Teams of up to 2
- Project topic justification due October 4<sup>th</sup>

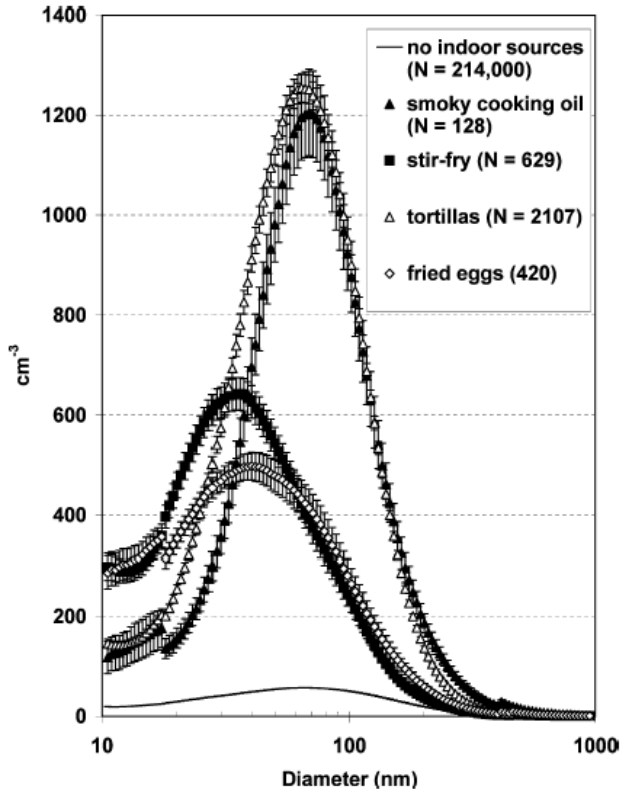
## Last time we covered:

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- Particle sources/emissions
- Particle resuspension
- Particle deposition
- Particle infiltration/penetration from outdoors

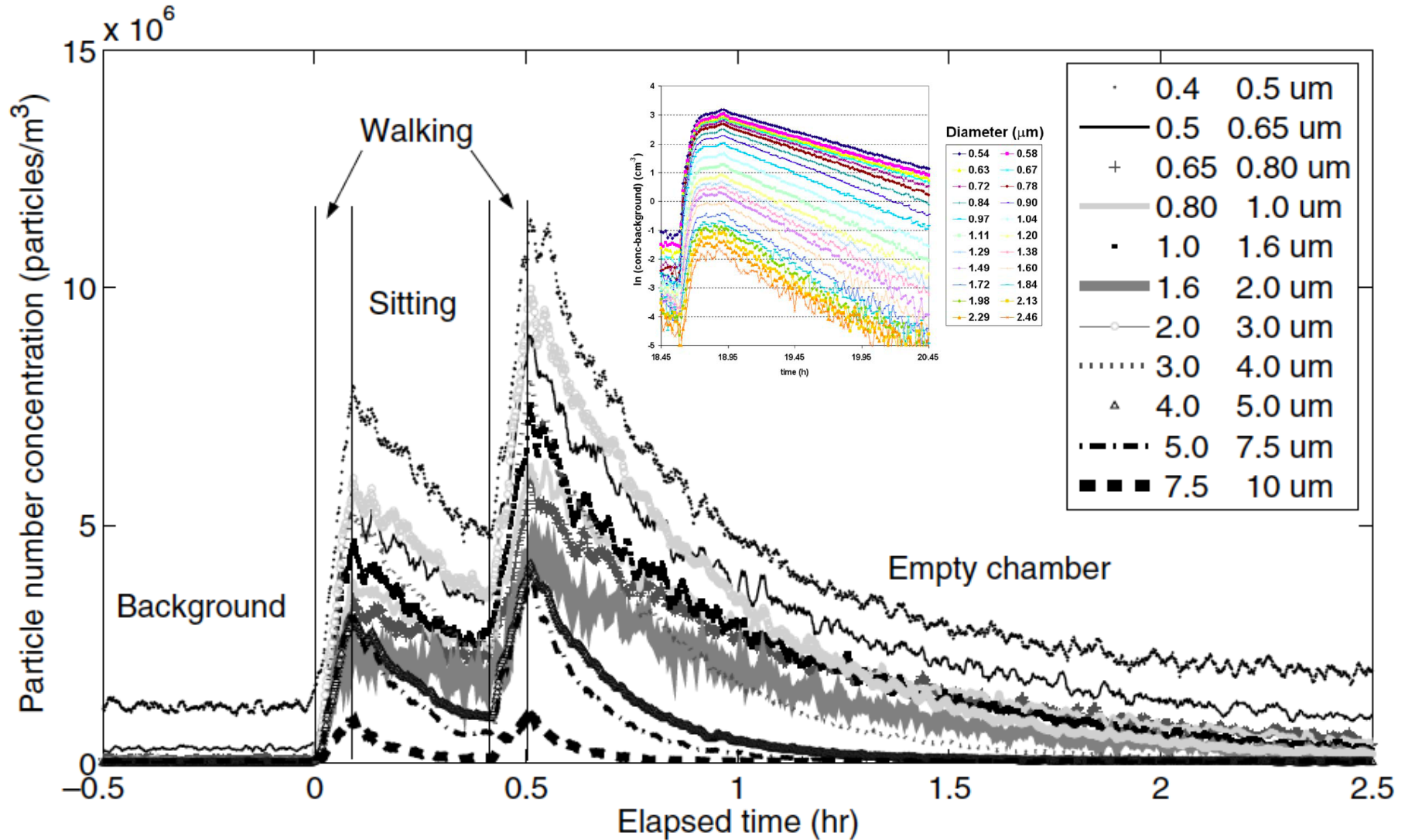


# Particle emissions

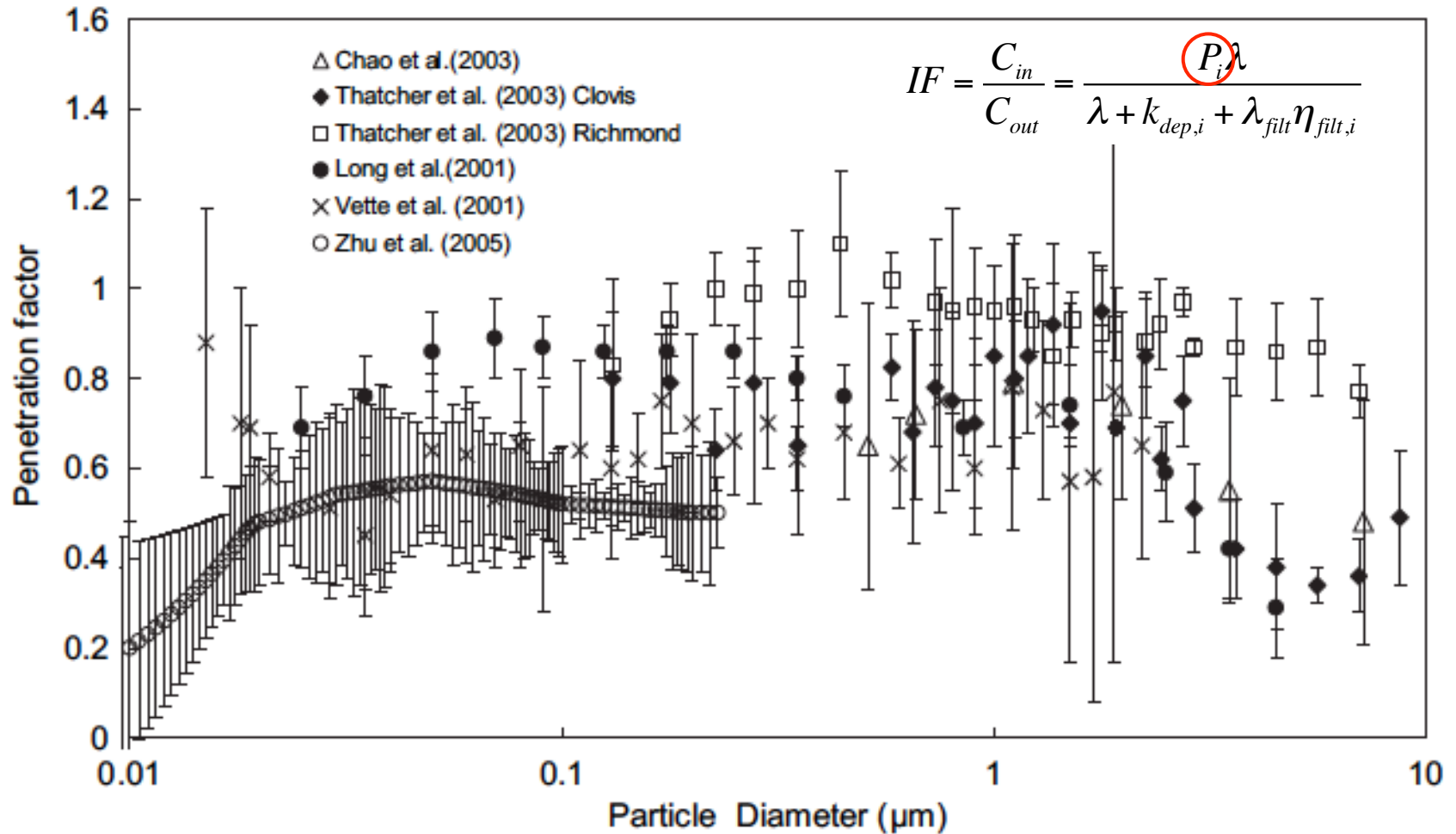


UFP emitting device	Size range	Emission rate (#/min)	Reference
Flat iron with steam	20-1000 nm	$6.0 \times 10^9$	Afshari et al. (2005)
Electric frying pan	10-400 nm	$1.1-2.7 \times 10^{10}$	Buonano et al. (2009)
3D printer w/ PLA	10-100 nm	$\sim 2.0 \times 10^{10}$	Stephens et al. (2013)
Vacuum cleaner	20-1000 nm	$3.5 \times 10^{10}$	Afshari et al. (2005)
Scented candles	20-1000 nm	$8.8 \times 10^{10}$	Afshari et al. (2005)
Gas stove	20-1000 nm	$1.3 \times 10^{11}$	Afshari et al. (2005)
3D printer w/ ABS	10-100 nm	$\sim 1.9 \times 10^{11}$	Stephens et al. (2013)
Cigarette	20-1000 nm	$3.8 \times 10^{11}$	Afshari et al. (2005)
Electric stove	20-1000 nm	$6.8 \times 10^{11}$	Afshari et al. (2005)
Frying meat	20-1000 nm	$8.3 \times 10^{11}$	Afshari et al. (2005)
Radiator	20-1000 nm	$8.9 \times 10^{11}$	Afshari et al. (2005)
Laser printers	6-3000 nm	$4.3 \times 10^9$ to $3.3 \times 10^{12}$	He et al. (2010)
Cooking on a gas stove	10-400 nm	$1.1-3.4 \times 10^{12}$	Buonano et al. (2009)

# Particle resuspension and deposition



# Outdoor particle infiltration



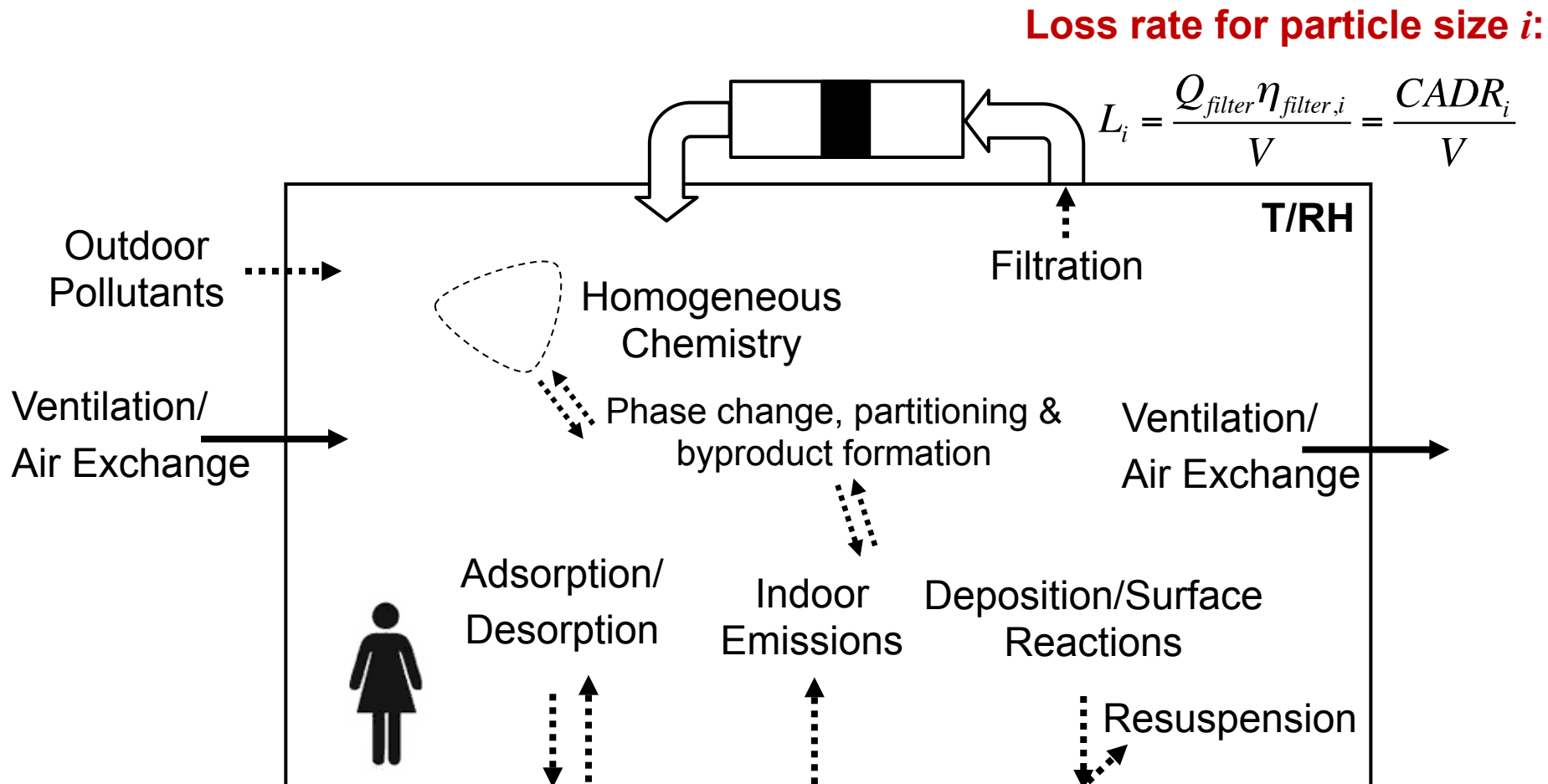
# Today's topics

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- Particle filtration: HVAC filters and stand-alone air cleaners

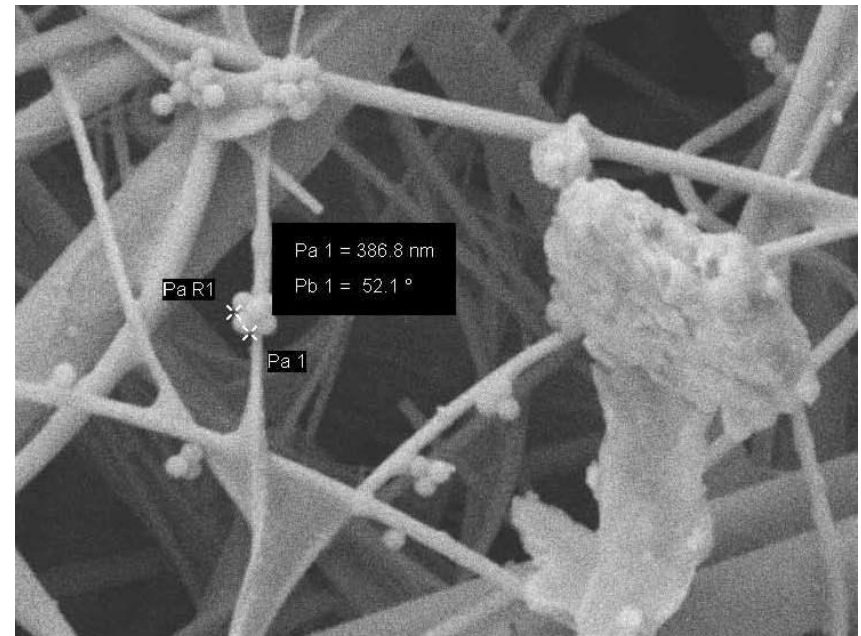
# **PARTICLE FILTRATION**

# Indoor environment: Mass balance



# Particle filtration and air cleaners

- We've already covered deposition to surfaces and lung deposition
  - Gravitational settling, Brownian diffusion, impaction, electrostatic forces, thermophoretic forces
- Particle filtration takes advantage of these mechanisms to purposefully capture airborne particles
  - Fibrous filters are an economical means for collecting aerosols



# What is the purpose of a filter?

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- To protect human health?
- To protect equipment?
  - Both
- Who sets filter standards?
  - ASHRAE (US), Eurovent (EU), manufacturers, retail stores
- How does a filter work?
  - Fibrous filter capture
  - Also electrostatic filters (not going in depth)



# Fibrous filtration

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- Fibrous filters are mostly air
  - Porosity ranging from ~70% to ~99%
  - Fibers range in size from  $< 1 \mu\text{m}$  to  $100 \mu\text{m}$



[http://www.king-filters.com/?page\\_id=58](http://www.king-filters.com/?page_id=58)

# Important filter terminology

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- Efficiency ( $E$ ,  $\eta$ )

$$E = \eta = \frac{C_{in} - C_{out}}{C_{in}} = 1 - \frac{C_{out}}{C_{in}}$$

- Penetration ( $P$ ) =  $1 - \eta$

$$P = \frac{C_{out}}{C_{in}} = 1 - E = 1 - \eta$$

- Face velocity ( $U_0$ )

$$U_0 = \frac{Q}{A}$$

- Velocity inside filter ( $U$ )

– Higher than  $U_0$

$$U = \frac{Q}{A(1 - \alpha)}$$

- Solidity ( $\alpha$ ) = (1 – porosity)

– Also called *packing density*

– Typically between 0.01 and 0.3

$$\alpha = \frac{\text{fiber volume}}{\text{total volume}}$$

- *How do these impact filter efficiency?*

# Fibrous filter capture

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- Imagine fibrous filters as many thin layers of filters
  - Each has a certain probability of capturing particles of a given size
- The filtration efficiency for monodispersed particles will increase with the thickness of the filters
- The number of particles captured ( $n_c$ ) can be described in terms of the number concentration ( $N$ ) entering a differentially thin layer ( $dt$ ) and the fractional capture per unit thickness ( $\gamma$ ):

$$n_c = N\gamma dt$$

- The decrease of particles through the layer is equal to  $-n_c$ :

$$dN = -n_c = -N\gamma dt$$

# Fibrous filter capture

$$dN = -n_c = -N\gamma dt \quad \longrightarrow \quad \frac{1}{N} dN = -\gamma dt$$

- Integrating:

$$\int_{N_{in}}^{N_{out}} \frac{1}{N} dN = -\gamma \int_0^t dt$$

$$\ln\left(\frac{N_{out}}{N_{in}}\right) = -\gamma t$$

$$\frac{N_{out}}{N_{in}} = P = e^{-\gamma t}$$

$$E = 1 - P = 1 - e^{-\gamma t}$$

$\gamma$  depends on particle size, face velocity, solidity, and fiber size

Particle penetration decreases (filtration efficiency increases) exponentially with thickness

# Single fiber efficiency

- We analyze filters as a collection of individual fibers
  - Correlates very well with experimental results
  - Does not work for non-fibrous filters (e.g., membrane filters)

## Flow around a filter fiber with diameter $d_f$ :

$$\text{Re}_f = \frac{\rho_g d_f U}{\mu}$$

$\rho_g$  = gas (air) density

$d_f$  = fiber diameter

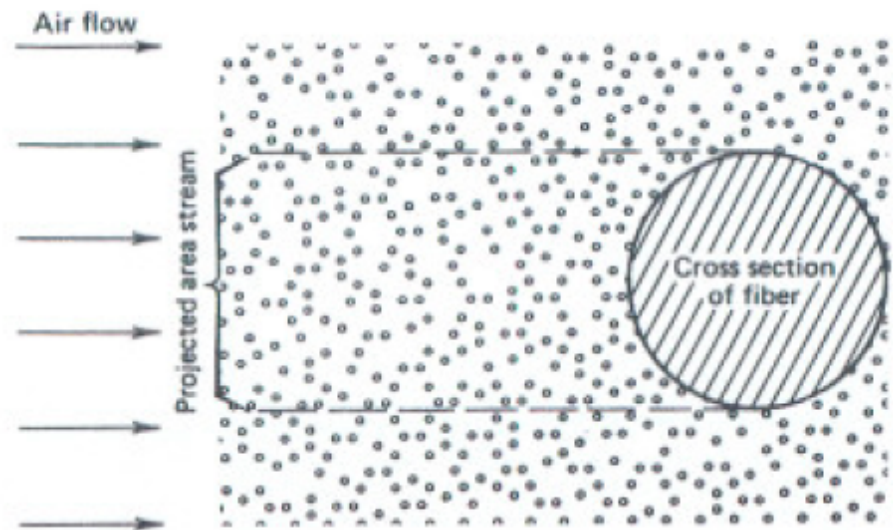
$U$  = air velocity

$\mu$  = viscosity

*\*Laminar under most conditions*

$E_\Sigma$  = single fiber efficiency

$$E_\Sigma = \frac{\text{number collected on unit length}}{\text{number incident on unit length}}$$



# Single fiber efficiency

- Assuming all fibers in a filter have the same diameter (not always the case), the total length  $L$  of fiber in a unit volume of the filter can be obtained from knowing its solidity and treating the fiber as a cylinder

$$(V_f = \pi d_f^2 L / 4):$$

$$L = \frac{4\alpha}{\pi d_f^2} \quad \alpha = \frac{\text{fiber volume}}{\text{total volume}}$$

- The number of particles collected when a unit volume of aerosol passes the cross-sectional area ( $d_f L$ ) over a thickness  $dt$ :

$$n_c = N E_\Sigma d_f L dt \longrightarrow \gamma = E_\Sigma d_f L \longrightarrow \gamma = \frac{4\alpha E_\Sigma}{\pi d_f}$$

- Particle penetration through filter:

$$P = 1 - E = e^{-\gamma t} = e^{-\frac{4\alpha E_\Sigma}{\pi d_f} t}$$

$\alpha$  = solidity  
 $E_\Sigma$  = single fiber efficiency  
 $t$  = thickness

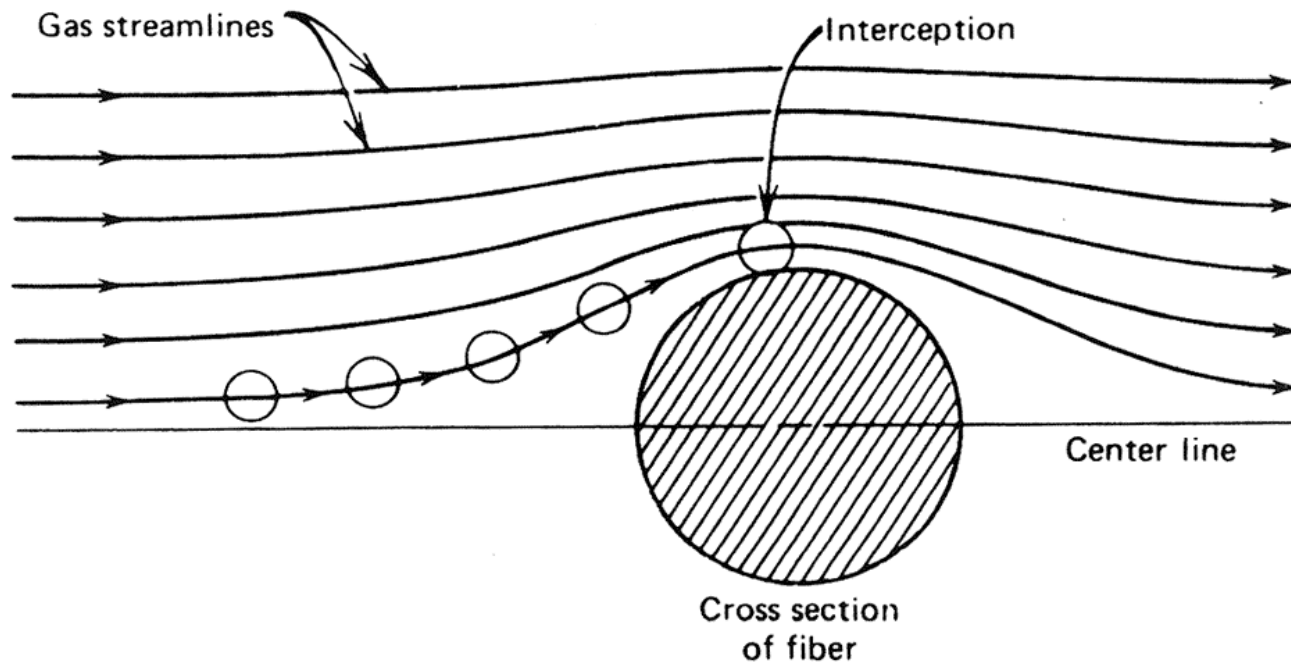
# Deposition mechanisms for single fiber removal

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- Five basic mechanisms:
  - Interception
  - Inertial impaction
  - Diffusion
  - Gravitational settling
  - Electrostatic attraction
- Theoretical analysis is complex
  - We will just show basic (derived) equations
  - Generally valid for the following conditions:
    - $0.005 < \alpha < 0.2$
    - $0.001 < U_0 < 2$  m/s
    - $0.1 < d_f < 50$   $\mu\text{m}$
    - $Re_f < 1$  (laminar)

# Interception

- Interception occurs when a particle follows a gas streamline that happens to come within one particle radius of the surface of a fiber



**FIGURE 9.5** Single-fiber collection by interception.



# Single fiber interception ( $E_R$ )

- Interception depends on  $R$ ,  $\alpha$ , and  $Ku$ 
  - Note lack of dependence on velocity

$$E_R \leq 1 + R$$

$$E_R = \frac{(1 - \alpha)R^2}{Ku(1 + R)}$$

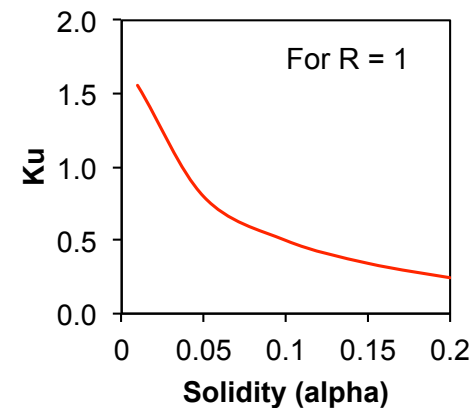
$$R = \frac{d_p}{d_f}$$

$d_f$  = fiber diameter  
 $d_p$  = particle diameter  
 $\alpha$  = solidity  
 $Ku$  = Kuwabara factor  
 $E_R$  = efficiency due to interception

$$Ku = -\frac{\ln \alpha}{2} - \frac{3}{4} + \alpha - \frac{\alpha^2}{4}$$

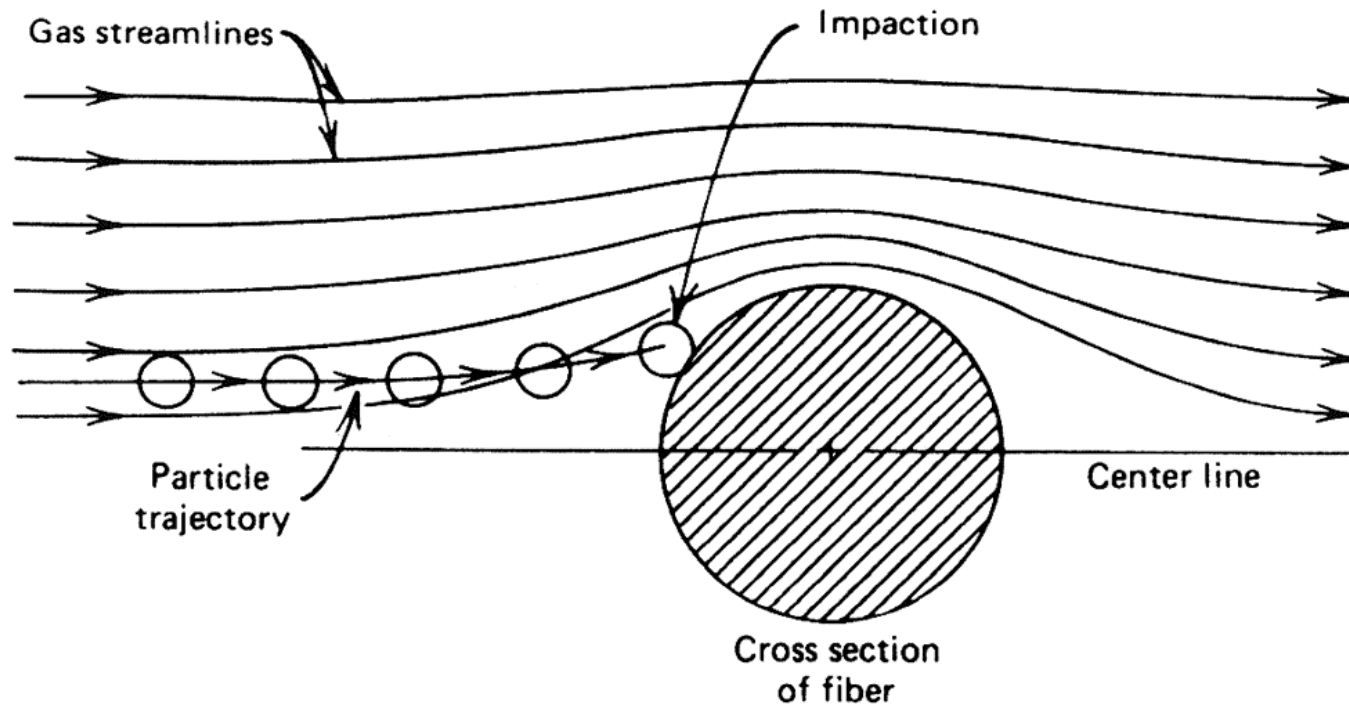
Kuwabara hydrodynamic factor ( $Ku$ ) takes into account distortion in flow because of other fibers

$$0.005 \leq \alpha \leq 0.2, d_f > 2\mu\text{m}$$



# Inertial impaction

- Inertial impaction occurs when a particle, because of inertia, is unable to adjust quickly enough to abruptly changing streamlines near the fiber; it crosses streamlines and hits the fiber



**FIGURE 9.6** Single-fiber collection by impaction.

# Single fiber impaction ( $E_I$ )

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$$E_I = \frac{(Stk)J}{2Ku^2} \quad E_R + E_I \leq 1 + R$$

$$J = (29.6 - 28\alpha^{0.62})R^2 - 27.5R^{2.8} \text{ for } R < 0.4$$

$$J \approx 2 \text{ for } R > 0.4$$

$$Ku = -\frac{\ln \alpha}{2} - \frac{3}{4} + \alpha - \frac{\alpha^2}{4}$$

$$Stk = \frac{\rho_p d_p^2 C_c U_0}{18\eta d_f} \quad R = \frac{d_p}{d_f}$$

$Stk$  = particle Stokes number (ratio of stopping distance of particle to a characteristic dimension of obstacle)

$J$  = empirical factor

$d_f$  = fiber diameter

$d_p$  = particle diameter

$U_0$  = face velocity

$\eta$  = air viscosity

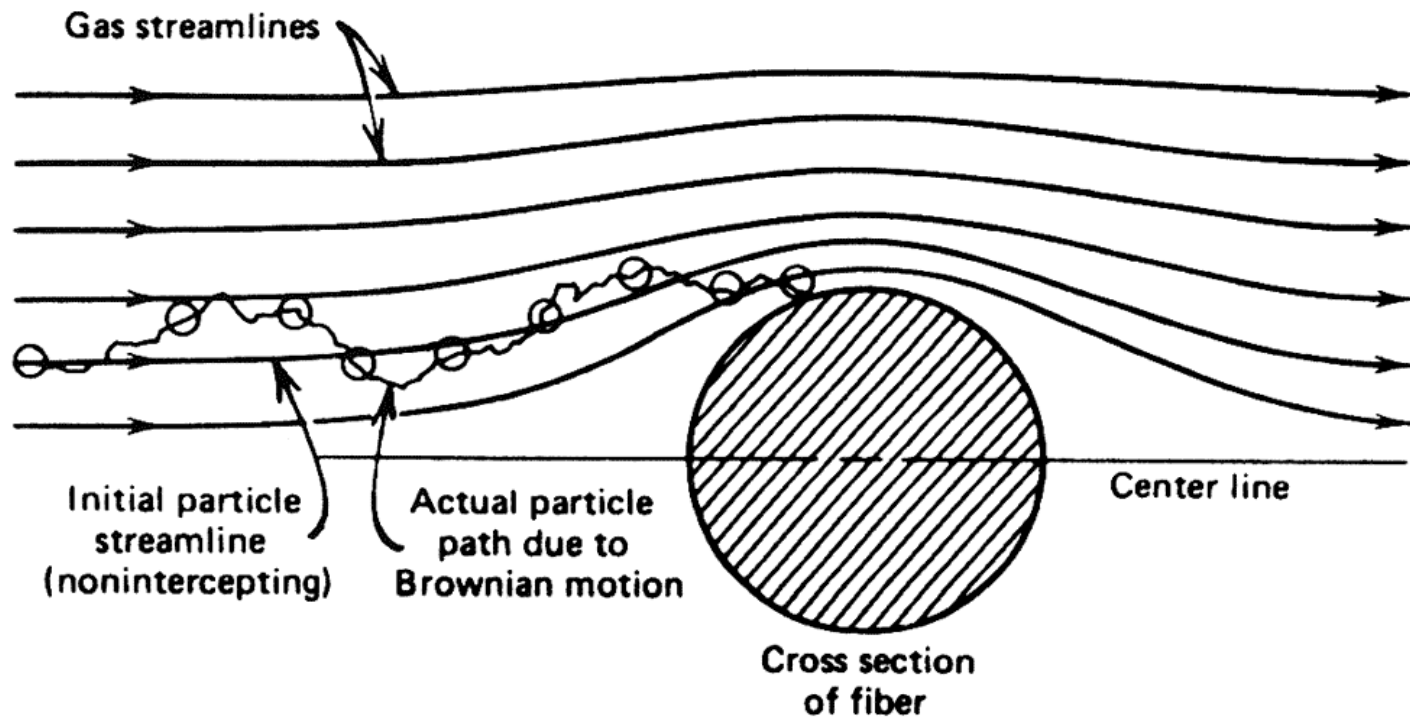
$\rho_p$  = particle density

$C_c$  = Cunningham correction factor

$\alpha$  = solidity

# Brownian diffusion

- Brownian motion (random path) of small particles is sufficient to greatly enhance the probability of their hitting a fiber while traveling past it in a non-intercepting streamline



**FIGURE 9.7** Single-fiber collection by diffusion.

# Single fiber diffusion ( $E_D$ )

$$E_D = 2Pe^{-\frac{2}{3}}$$

$$Pe = \frac{d_f U_0}{D}$$

Dimensionless  
diffusion  
parameter

For the size range near minimum efficiency, it is necessary to include an interaction term that accounts for enhanced collection due to interception of the diffusing particles:

$Pe$  = Peclet number

$d_f$  = fiber diameter

$U_0$  = face velocity

$D$  = particle diffusion coefficient

$\alpha$  = solidity

$k$  = Boltzmann's constant ( $1.38 \times 10^{-23} \text{ m}^2 \text{ kg s}^{-2} \text{ K}^{-1}$ )

$T$  = temperature (K)

$\eta$  = viscosity (kg/s-m)

$$D = \frac{kTC_c}{3\pi\eta d_p}$$

$$E_{DR} = \frac{1.24R^{\frac{2}{3}}}{\sqrt{Ku Pe}}$$

$$Ku = -\frac{\ln \alpha}{2} - \frac{3}{4} + \alpha - \frac{\alpha^2}{4}$$

$$R = \frac{d_p}{d_f}$$

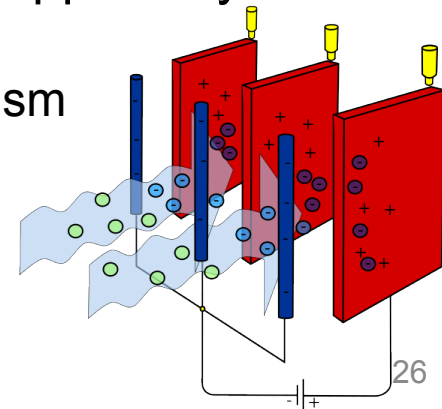
Diffusion is the only single-fiber collection mechanism that increases as particle diameter decreases

# Other Mechanisms

- Gravitational settling:
  - Need very slow face velocities and very large particle sizes to be bigger than interception

$$G = \frac{V_{TS}}{U_0} \quad E_G \approx \begin{array}{l} G(1+R) \text{ when } V_{TS} \text{ and } U_0 \text{ in same direction} \\ -G(1+R) \text{ when } V_{TS} \text{ and } U_0 \text{ in opposite direction} \\ \sim G^2 \text{ when } V_{TS} \text{ and } U_0 \text{ orthogonal} \end{array}$$

- Electrostatic deposition:
  - Involves applying electric charge to filters to capture oppositely charged particles
    - Electrostatic precipitators exclusively use this mechanism
    - Difficult to quantify
    - Need to know charge on particle and on fiber
    - Usually experimental results



# Putting it all together: combined filter efficiency

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- Total single fiber efficiency:

$$E_{\Sigma} = 1 - (1 - E_R)(1 - E_I)(1 - E_D)(1 - E_{DR})(1 - E_G)$$

– Adding this way avoids overestimating collection

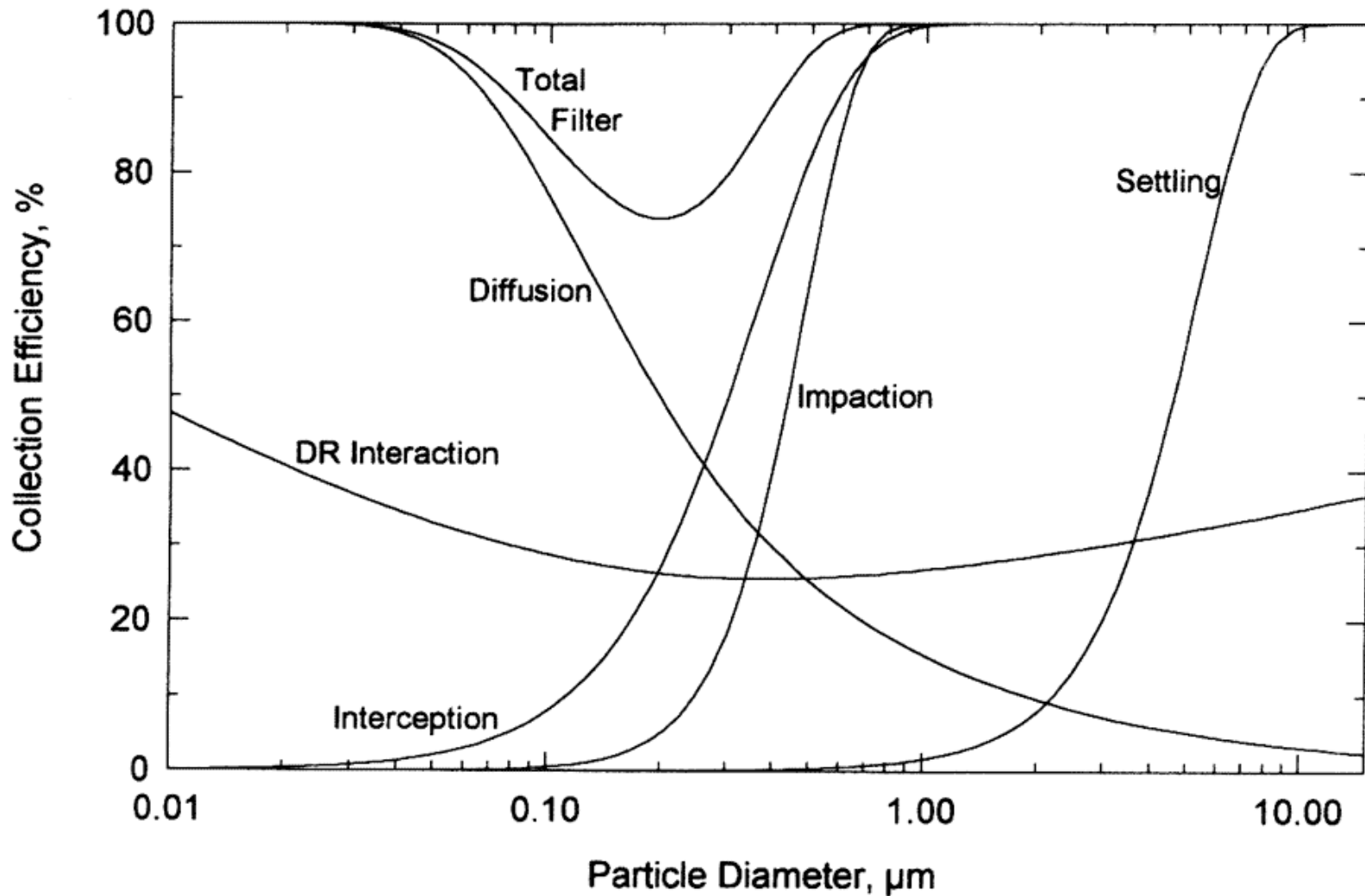
- Competing mechanisms would otherwise be counted twice

- Overall penetration of a filter:  $P_{overall} = e^{\frac{-4\alpha E_{\Sigma}t}{\pi d_f}}$

- Overall efficiency of a filter:

$$E_{overall} = 1 - P_{overall} = 1 - e^{\frac{-4\alpha E_{\Sigma}t}{\pi d_f}}$$

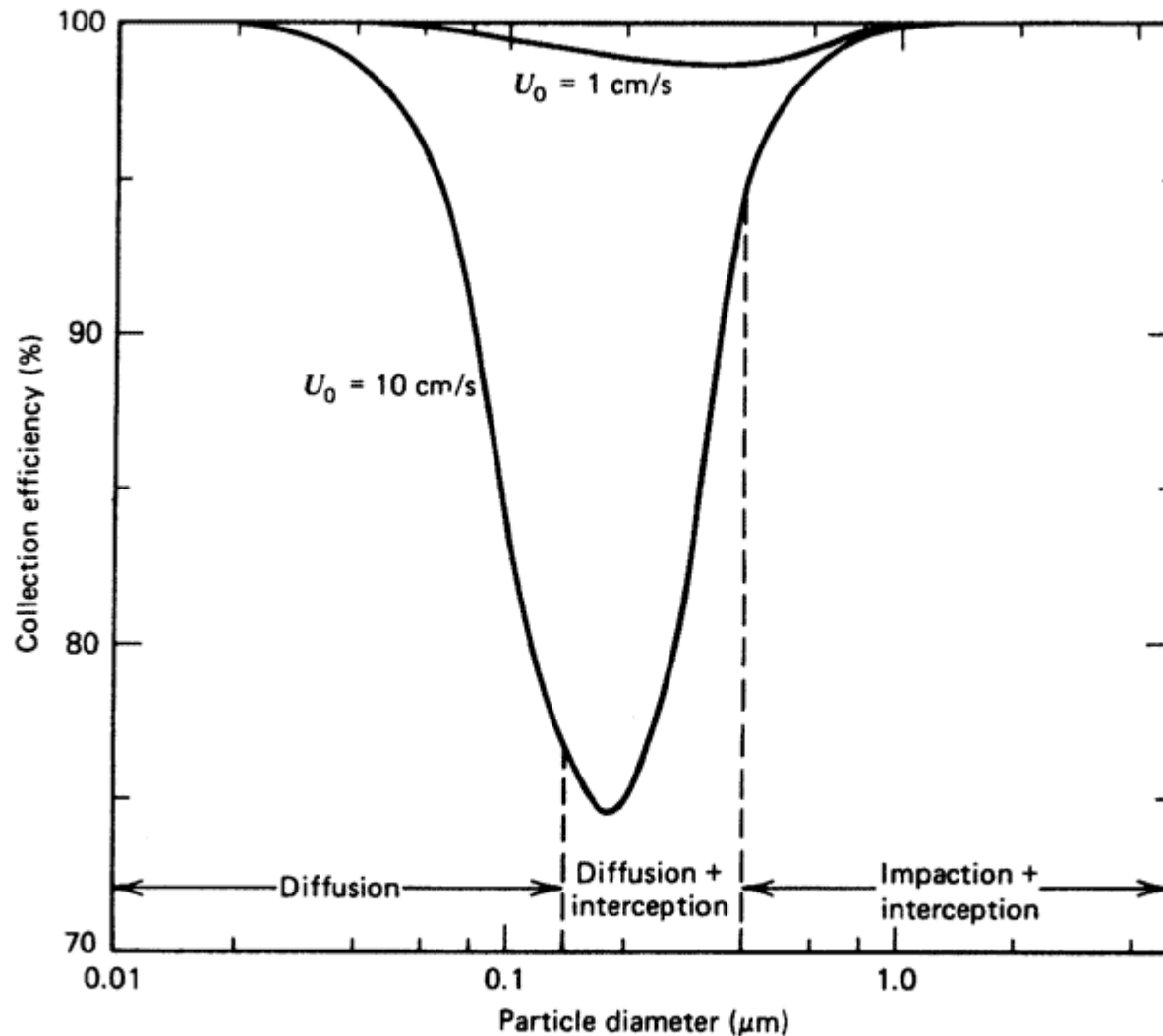
# Total efficiency for an example filter



**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].

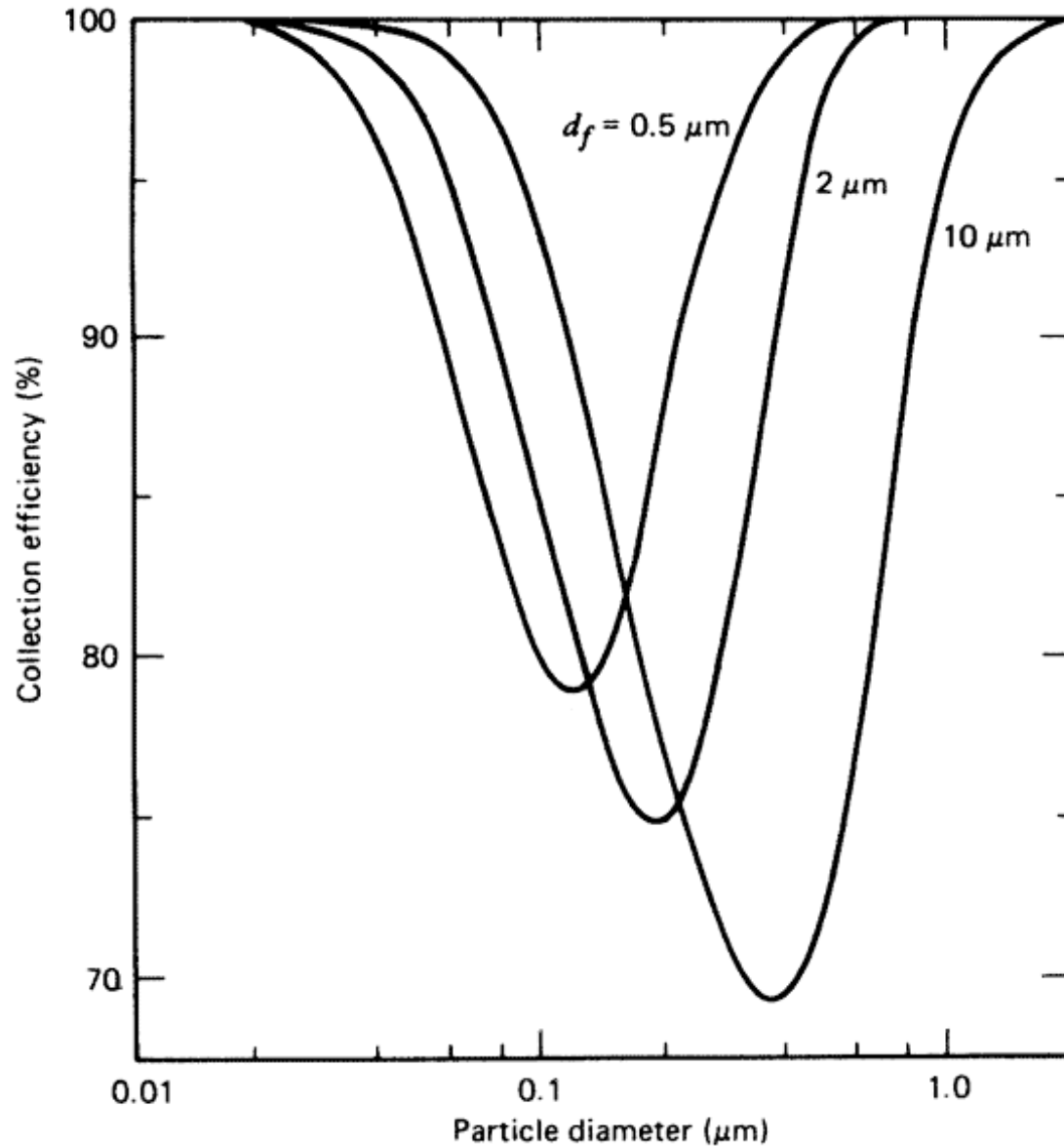


# Filter efficiency and face velocity



**FIGURE 9.9** Filter efficiency versus particle size for face velocities of 0.01 and 0.1 m/s [1 and 10 cm/s];  $t = 1 \text{ mm}$ ,  $\alpha = 0.05$ , and  $d_f = 2 \mu\text{m}$ .

# Filter efficiency for various $d_f$



# Filter pressure drop

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- Another important parameter to consider:
  - Filter pressure drop
- The structure of a filter creates a resistance to air flowing through it
  - This is called the *pressure drop*  $\Delta p$
- Quasi-empirical formulation:

$$\Delta p = \frac{\mu t U_0 f(\alpha)}{d_f^2}$$

$\Delta p$  = pressure drop (Pa)

$\mu$  = dynamic viscosity (Pa·s)

$d_f$  = fiber diameter (m)

$U_0$  = face velocity (m/s)

$\alpha$  = solidity (-)

t = thickness (m)

$$f(\alpha) = 64\alpha^{1.5} (1 + 56\alpha^3) \text{ for } 0.006 < \alpha < 0.3$$

$$d_f > 1 \mu\text{m}$$

**TABLE 9.1 Characteristics of Some Common Aerosol-Sampling Filter Materials**

Filter	Type	Material	Thickness (mm)	Fiber Diameter or Pore Diameter ( $\mu\text{m}$ )	Solidity	Pressure Drop <sup>a</sup> (kPa)	Efficiency <sup>a,b</sup>	Filter Quality <sup>a,b</sup> ( $\text{kPa}^{-1}$ )
Whatman 41	Fiber	Cellulose	0.19	3–20	0.35	2.5 <sup>c</sup>	72 <sup>c</sup>	0.52
Nuclepore	CPM <sup>d</sup>	Polycarbonate	0.01	0.8	0.85	5.9	90 <sup>e</sup>	0.39
Microsorban	Fiber	Polystyrene	1.5	0.7	0.04	2.9	99.5	1.10
MSA 1106B	Fiber	Glass	0.23	0.1–4	0.10	2.0 <sup>c</sup>	99.93 <sup>c</sup>	3.70
Millipore AA	Membrane	Cellulose ester	0.15	0.8	0.19	9.5 <sup>c</sup>	99.98 <sup>c</sup>	0.93

<sup>a</sup>At  $U_0 = 0.27$  m/s [27 cm/s].

<sup>b</sup>For  $d_p = 0.3$   $\mu\text{m}$ .

<sup>c</sup>From Lippmann (1995).

<sup>d</sup>CPM = capillary pore membrane.

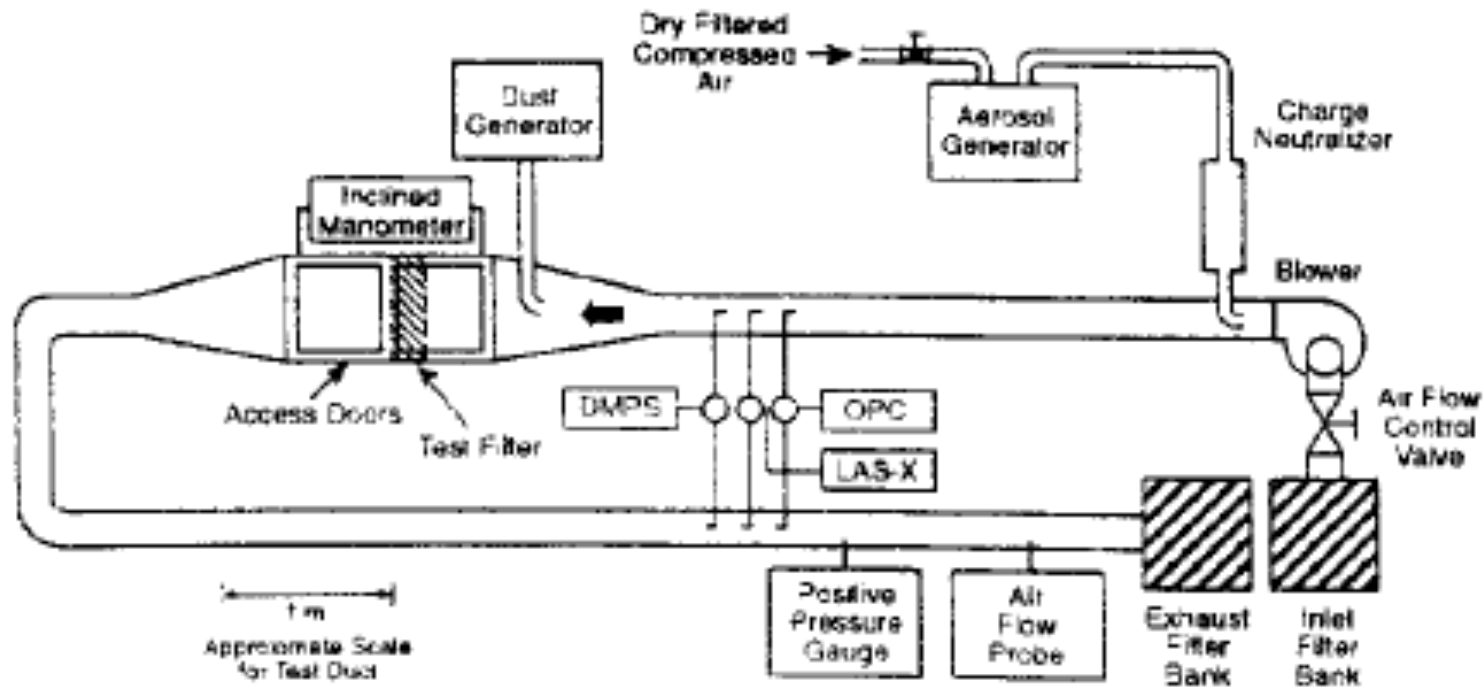
<sup>e</sup>Estimated.

## MEASURED VALUES OF FILTER EFFICIENCY AND PRESSURE DROP

What do real values look like?

# Hanley et al. (1994) *Indoor Air*

- This was really the first complete paper on laboratory testing of HVAC filters
  - Also led to the first widely used test standard in the US



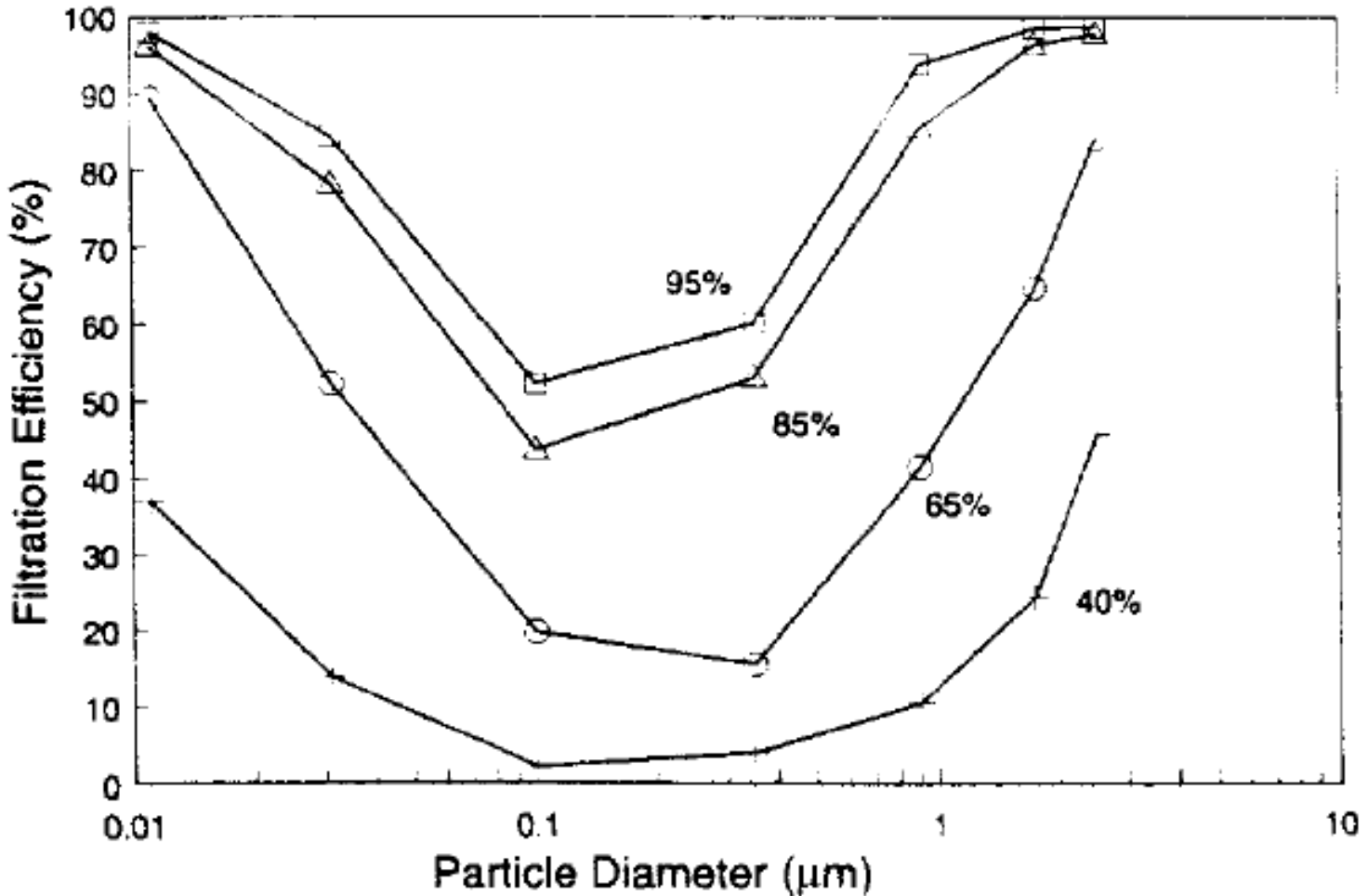
**Fig. 1** Schematic diagram of RTI's air cleaner test facility

# Hanley et al. (1994) Indoor Air

**Table 1** Description of air cleaners

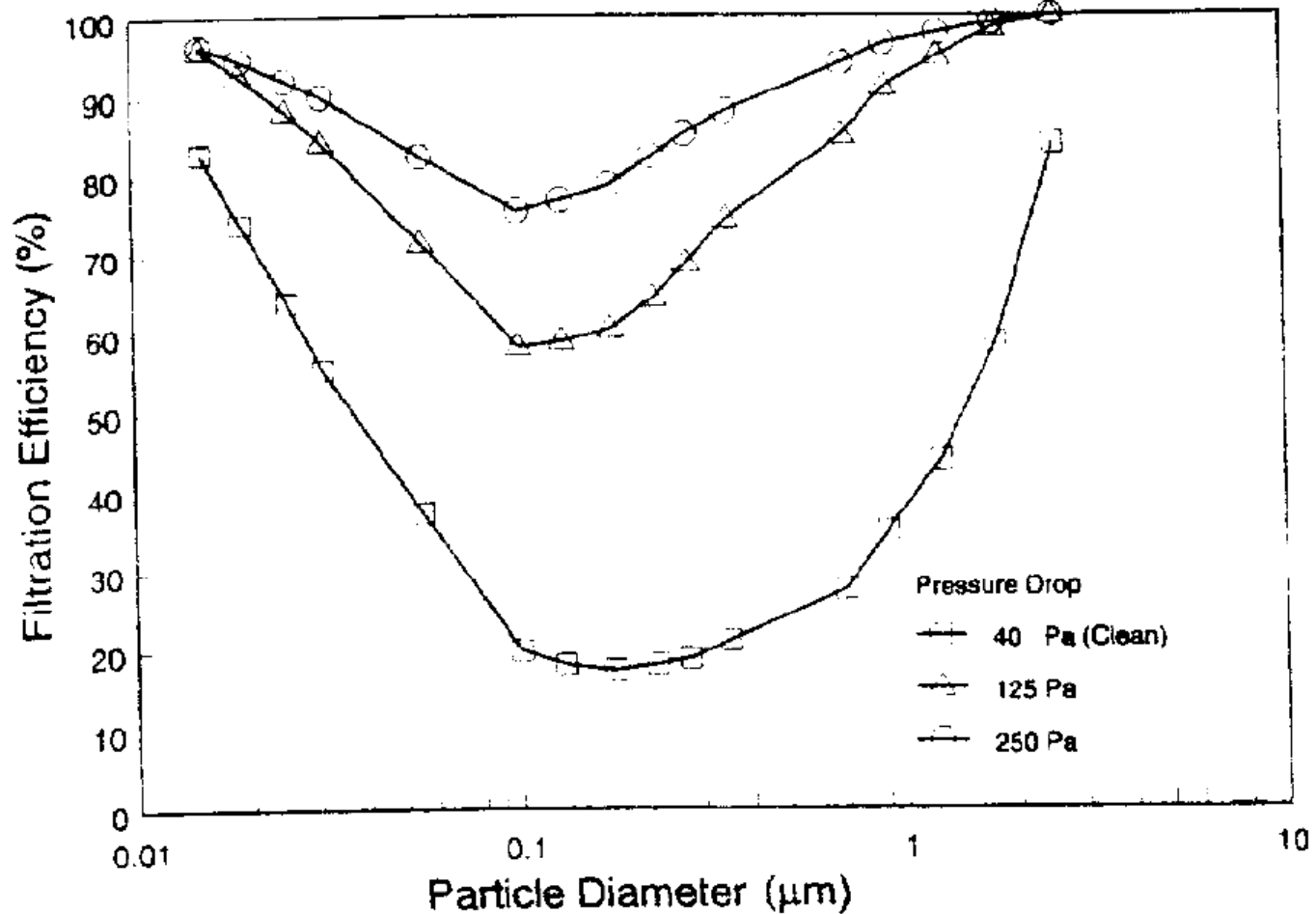
Description	Test results shown in Figure(s)	Experimental Conditions
Pleated Paper-Media Filter 305×610×152mm (12×24×6") 95% ASHRAE Dust Spot Average Efficiency	2	1.3 m/s Face Velocity Clean Filters
Pleated Paper-Media Filter 305×610×152mm (12×24×6") 85% ASHRAE Dust Spot Average Efficiency	2 and 3	Face Velocities: 0.65, 1.3, and 2.25 m/s
Pleated Paper-Media Filter 305×610×152mm (12×24×6") 65% ASHRAE Dust Spot Average Efficiency	2	1.3 m/s Face Velocity Clean Filters
Pleated Paper-Media Filter 305×610×51mm (12×24×2") 40% ASHRAE Dust Spot Average Efficiency	2	1.3 m/s Face Velocity Clean Filters
Residential Electronic Air Cleaner 406×660×178mm (16×25×7") Two stage electrostatic precipitator Consisted of 28 ionizing wires and 114 collection plates The unit operated at 1.12 mA at 6.8 kV	4	Face Velocities: 0.45, 0.90, and 1.80 m/s
Pleated Panel Filter 508×508×25mm (20×20×1") 25–30% ASHRAE Dust Spot Average Efficiency	5	1.87 m/s Face Velocity Clean: 68 Pa Naturally and Artificially Loaded @ 125 Pa
Pocket Filter 610×610×560mm (24×24×22") 95% ASHRAE Dust Spot Average Efficiency 8 pockets, nonwoven fiber media	6	1.3 m/s Face Velocity Clean and Dust-Loaded Filters @ 50, 125, and 250 Pa
Pleated Paper-Media Filter 610×610×150mm (24×24×6") 65% ASHRAE Dust Spot Average Efficiency	7	1.3 m/s Face Velocity Clean and Dust-Loaded Filters @ 40, 125, and 250 Pa
Furnace Filter 610×610×25mm (24×24×1") Spun fiberglass in a cardboard frame	8	1.3 m/s Face Velocity Clean and Dust-Loaded Filters @ 10, 125, and 250 Pa
Panel Electronic Filter 610×610×25mm (24×24×1") Consists of high voltage screens sandwiched between dielectric fiber media	9	1.3 m/s Face Velocity Clean and Dust-Loaded Filters @ 50, 125, and 250 Pa
Self-Charging Panel Filter 610×610×25mm (24×24×1") Contains static prone materials intended to develop a static charge as air flows through the media thereby increasing filtration efficiency	10	1.3 m/s Face Velocity Clean and Dust-Loaded Filters @ 35, 125, and 250 Pa
Permanently-Charged Panel Filter 610×610×25mm (24×24×1") The media consists of permanently charged electret fibers	11	1.3 m/s Face Velocity Clean and Dust-Loaded Filters @ 50 and 250 Pa

# Filtration efficiency and filter type (old system)



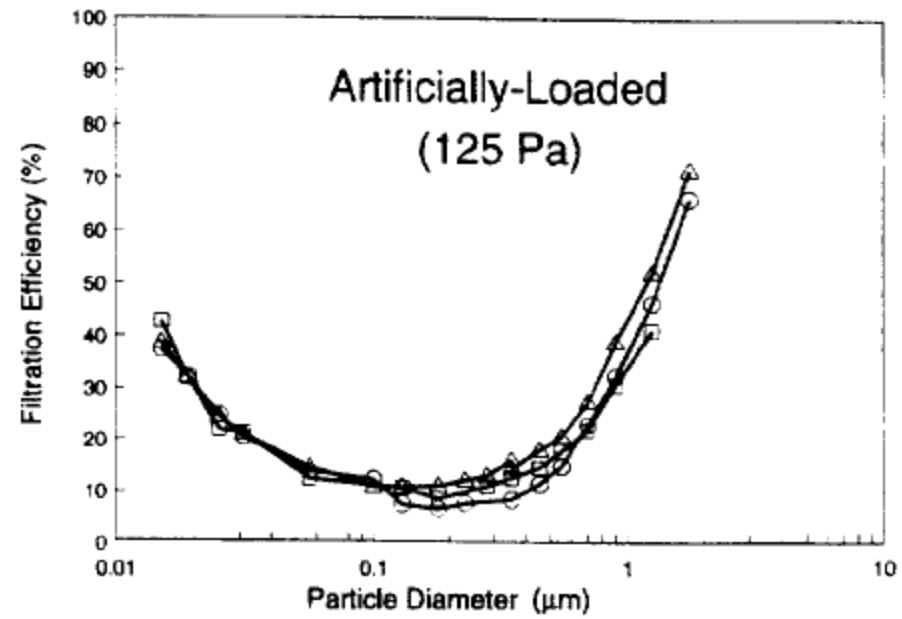
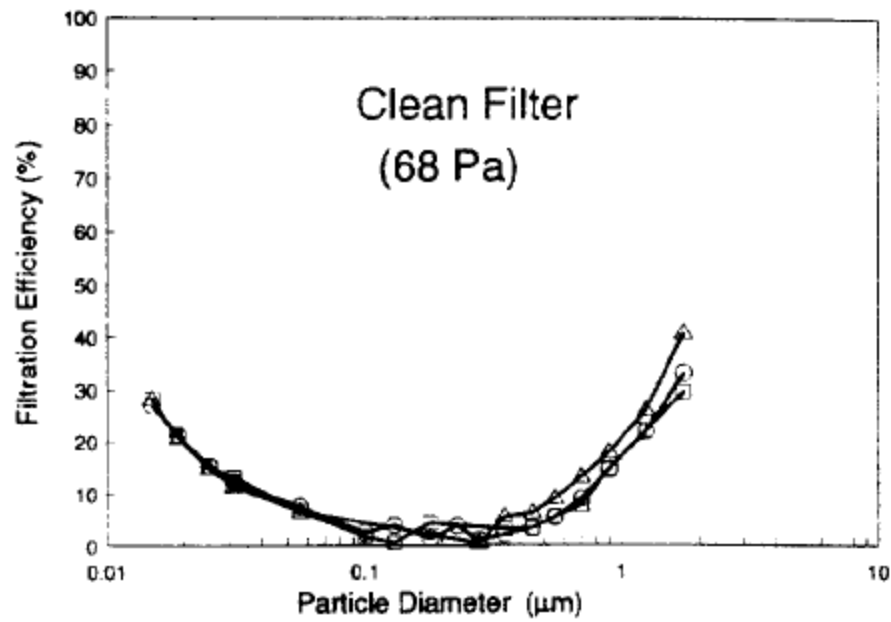
**Fig. 2** Fractional filtration efficiency of four ASHRAE-rated filters at 1.3 m/s face velocity

# Filter efficiency and dust loading

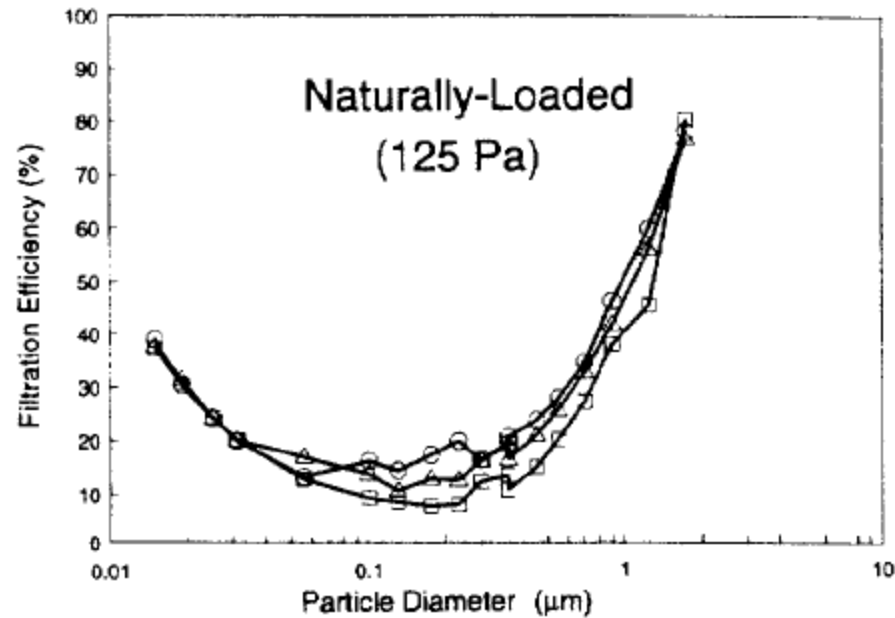


**Fig. 7** The effect of dust load on the fractional filtration efficiency of a pleated paper filter at 1.3 m/s





Hanley et al., 1994 *Indoor Air*



**Fig. 5** Comparison of clean, artificially loaded, and naturally loaded fractional filtration efficiency for a pleated panel filter

# **FILTRATION STANDARDS**

# 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

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- Method of test for filter performance
  - Controlled laboratory conditions
  - Subject filter to test aerosol
  - Measure 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  $\mu\text{m}$
  - $E_2$ : 1-3  $\mu\text{m}$
  - $E_3$ : 3-10  $\mu\text{m}$

**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, $\mu\text{m}$			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  $\rightarrow$  99.9% or greater removal efficiency for most particle sizes

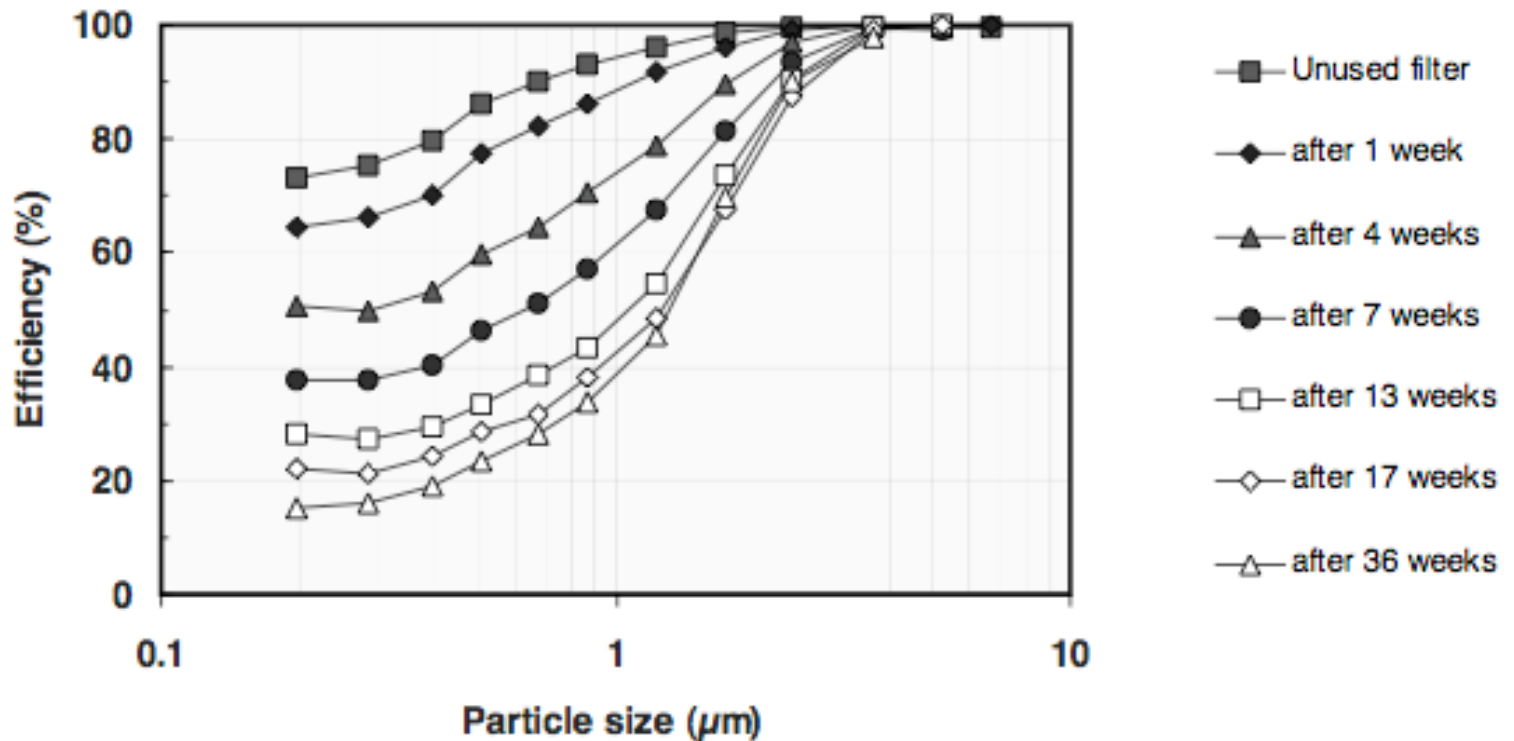
# Some concerns about 52.2 test standard

---

- Not an in-situ test
  - See ASHRAE Guideline 26
- Does not address small particles
  - Why not?
- Can test at whatever flow rate you want

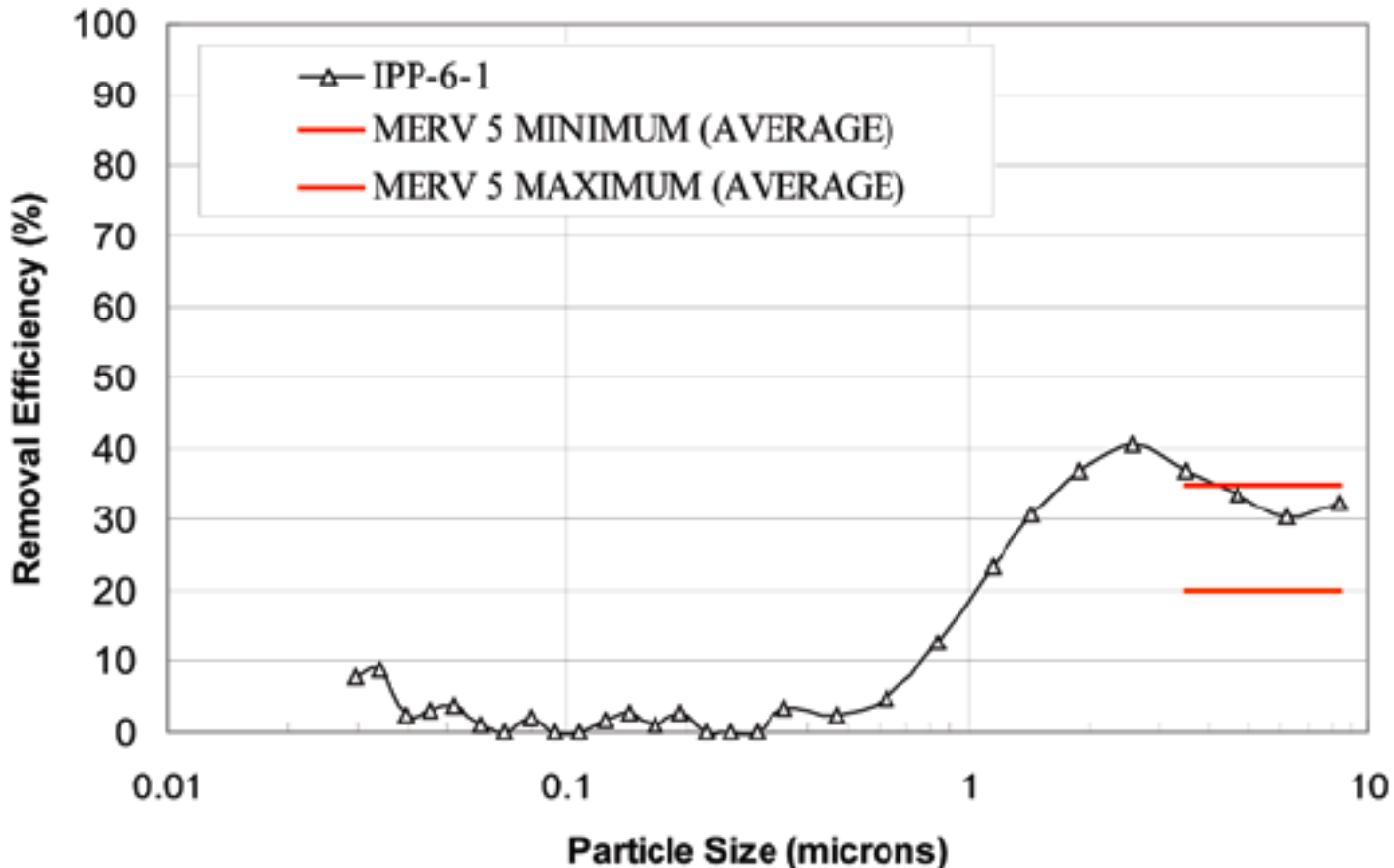
# More concerns about 52.2 test standard

- Electrostatic filters
  - Lose charge after short period
  - Not captured in 52.2 test
    - Currently optional (there is an addendum for dealing with lost charge)



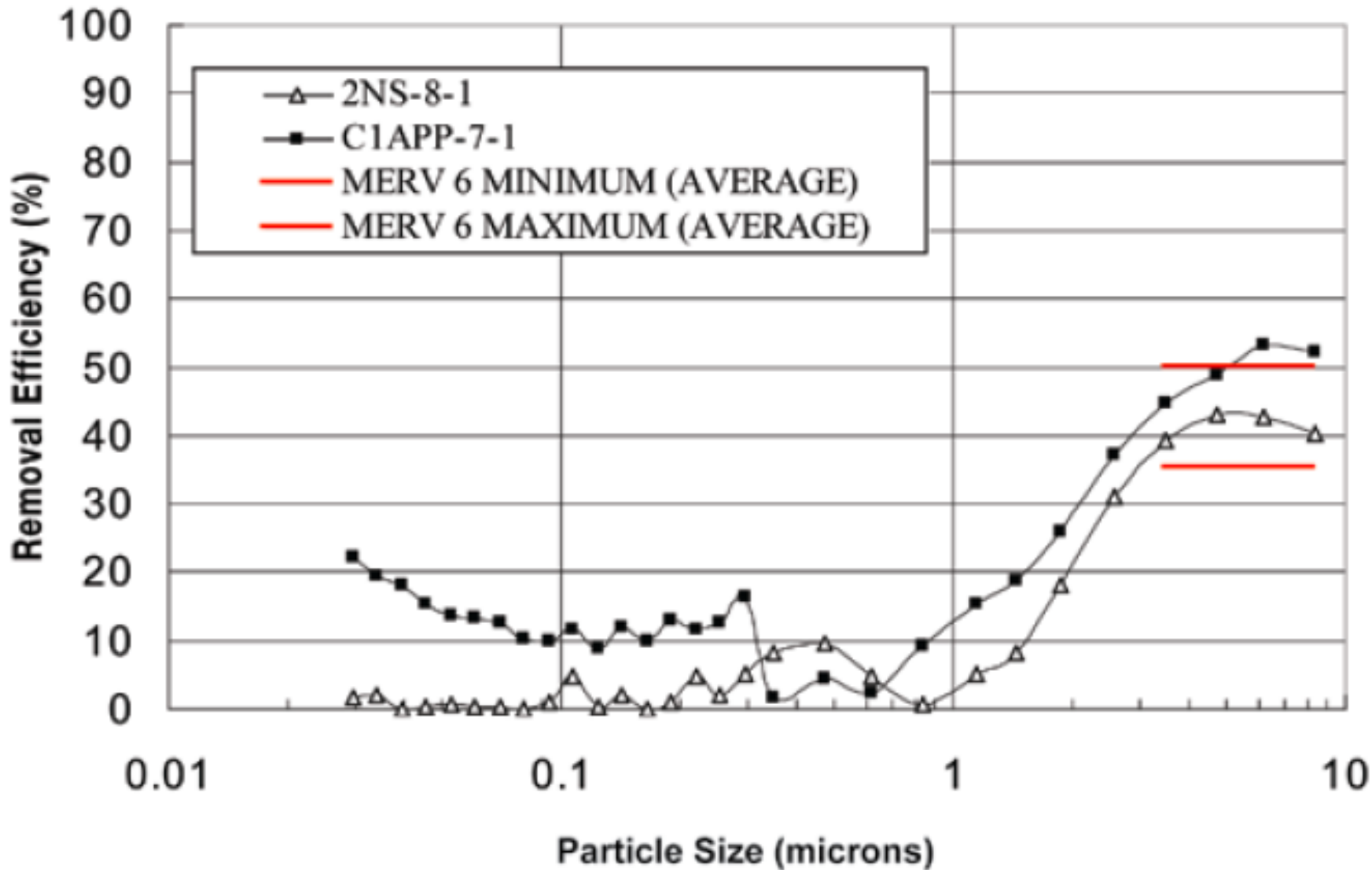
# Newer measurements of filtration efficiency

- Recent lab tests covering 30 nm to 10  $\mu\text{m}$  and MERV classified filters (remember MERV only covers 0.3-10  $\mu\text{m}$ ):

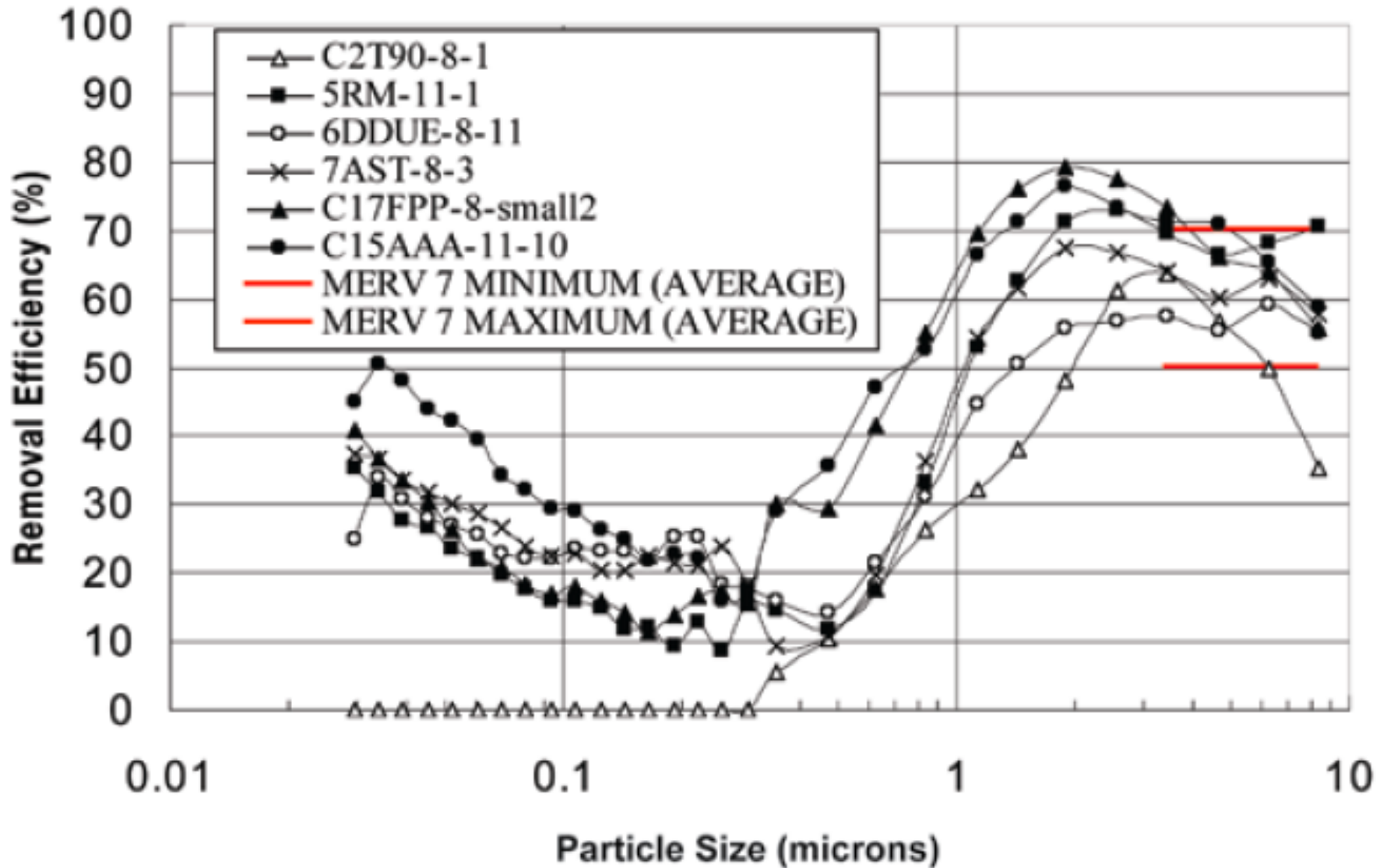




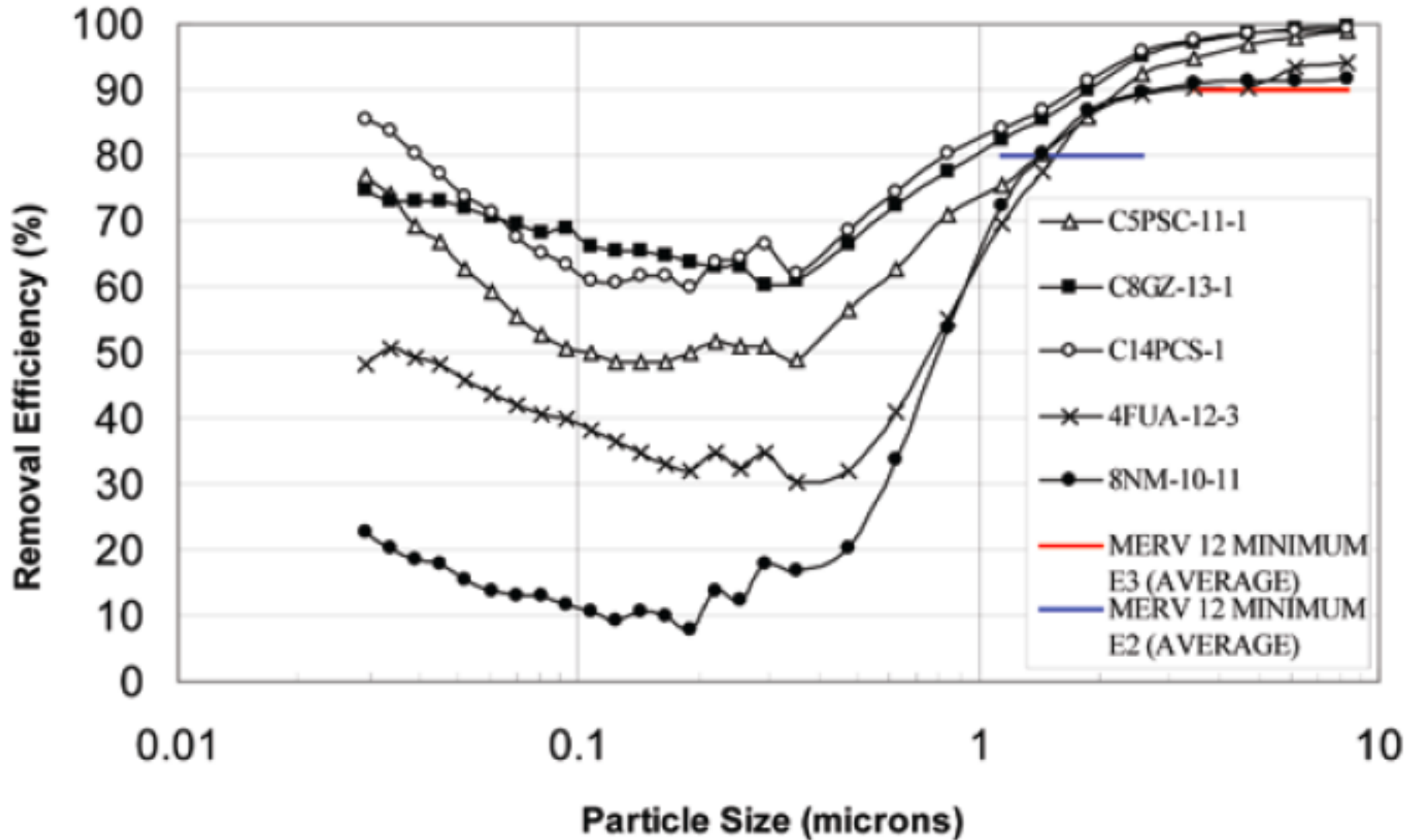
# Recent MERV 6 lab tests



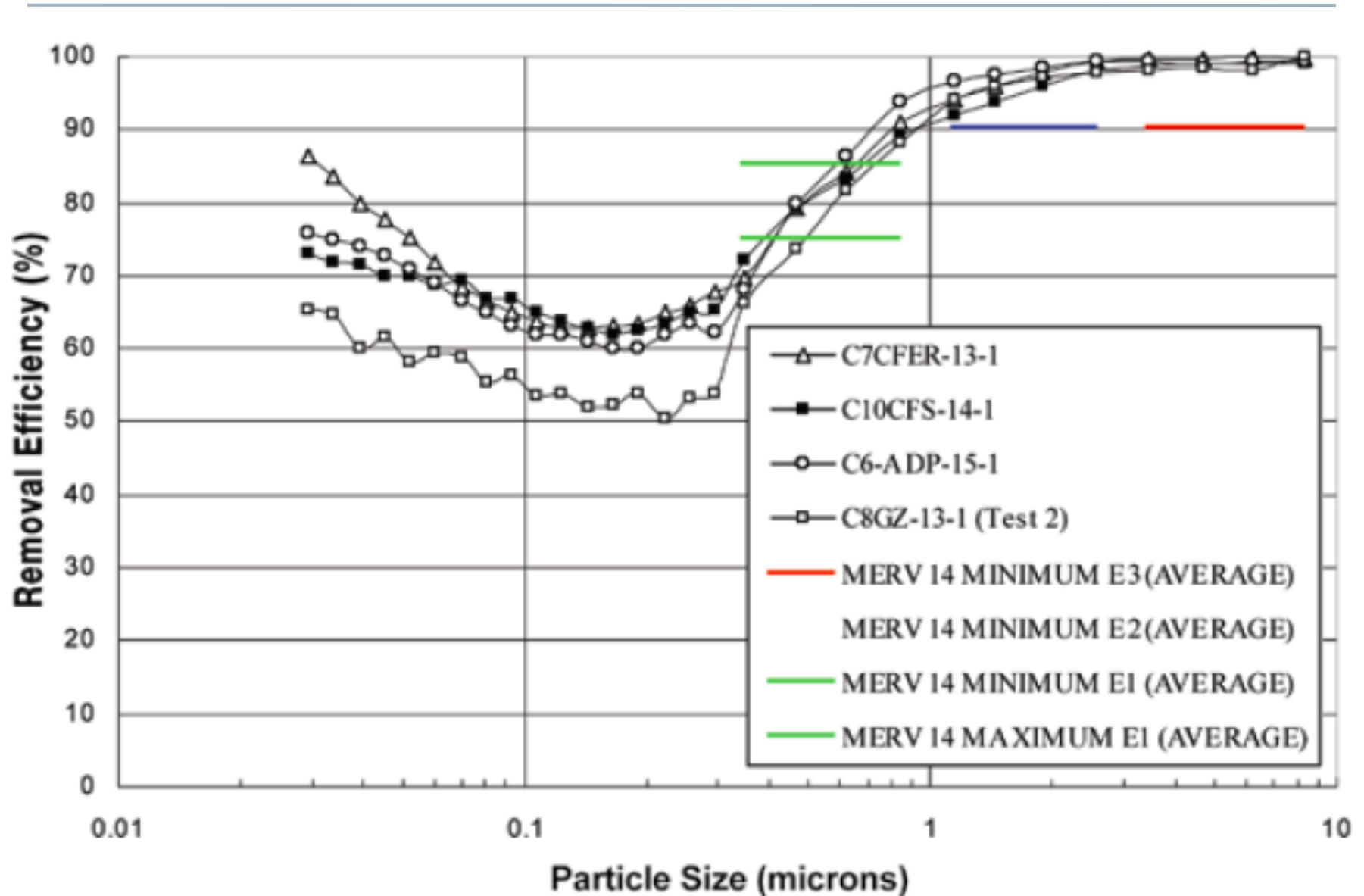
# Recent MERV 7 lab tests



# Recent MERV 12 lab tests



# Recent MERV 14 lab tests



# **IN-SITU TESTING OF FILTERS**

# In-situ filter testing

---

- I previously worked on a method to measure the in-situ particle removal efficiency of HVAC systems and filters
  - Applied in a test house
  - Compared with other field and laboratory tests



## Comparison of Test Methods for Determining the Particle Removal Efficiency of Filters in Residential and Light-Commercial Central HVAC Systems

**Brent Stephens and Jeffrey A. Siegel**

*Department of Civil, Architectural, and Environmental Engineering, Cockrell School of Engineering,  
The University of Texas at Austin, Austin, Texas, USA*

Stephens and Siegel, *Aerosol Sci. Technol.* **2012** 46(5), 504-513

# In-situ filter testing

---

- Filters are typically evaluated only by laboratory tests
  - ASHRAE Standard 52.2 tests particle removal efficiency
    - MERV = Minimum Efficiency Reporting Value
  - Unrealistic particle concentrations, compositions, airflow rates, pressure drops, temperature and humidity levels
  - No standardized tests for field performance
- Residential and light-commercial challenges
  - No fresh air intake
  - Cycling operation
  - Exterior duct leaks
  - Filter bypass & loading
- How do filters change in time?
  - Evidence of both increased and decreased removal

Hanley et al., **1994** *Indoor Air*; Hanley et al., **1999** *Proceedings of IA 1999*;  
Raynor and Chae **2003** *Filtration + Separation*; Lehtimäki et al., **2005** *ASHRAE RP-1189*

# In-situ filter testing

---

**Two primary in-situ test methods:**



# In-situ filter testing

---

## Two primary in-situ test methods:

### Upstream/Downstream

Burroughs and Kinzer, 1998 *ASHRAE Journal*  
Fugler et al., 2000 *ASHRAE Transactions*  
Jamriska et al., 2000 *Indoor Air* (Commercial HVAC)  
ASHRAE Guideline 26, 2008 (Commercial HVAC)

#### Advantages

Relatively quick  
Isolates filter

#### Disadvantages

Ignores duct system  
Multiple particle counters  
Difficult to sample in HVAC

### Whole-House Decay

Offermann et al., 1992 *ASHRAE Journal*  
Howard-Reed et al., 2003 *Atmos Environ*  
Wallace et al., 2004 *Atmos Environ*  
MacIntosh et al., 2008 *JAWMA*

#### Advantages

Includes duct system  
Captures full picture

#### Disadvantages

Time intensive  
More assumptions  
More types of instrumentation

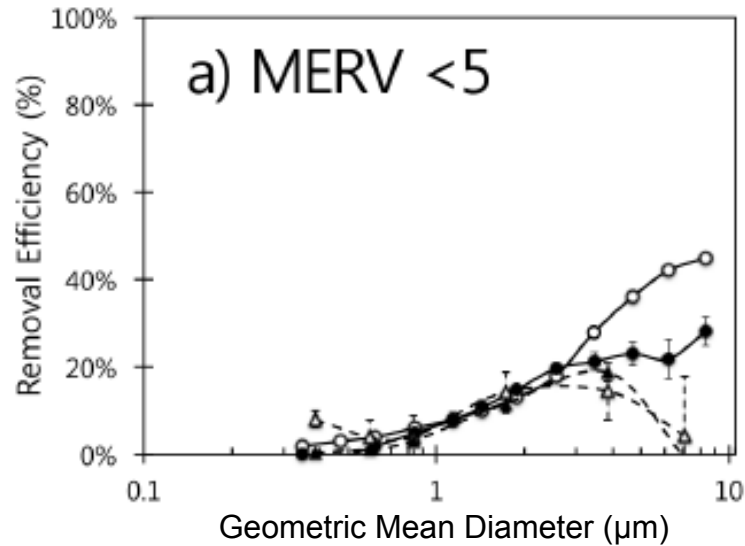
# In-situ filter test method (decay based)

---

- Well-mix air by several oscillating fans\*
- Inject CO<sub>2</sub> tracer gas and elevate particle concentrations
  - Burn incense (< 1 μm) & shake vacuum bag (> 1 μm)
- Supply HEPA-filtered outdoor air to pressurize\*
  - Eliminates infiltration if  $\Delta P > 0$ ; shortens test time to ~ 1 hour
- Measure decay of CO<sub>2</sub> and particles (OPC, 0.3-10 μm)
  - (1) HVAC off (2) w/out HVAC filter (3) w/ HVAC filter
  - Perform non-linear regression to estimate loss terms\*
- Measure HVAC airflow rate and house volume\*
  - Calculate removal efficiency\*

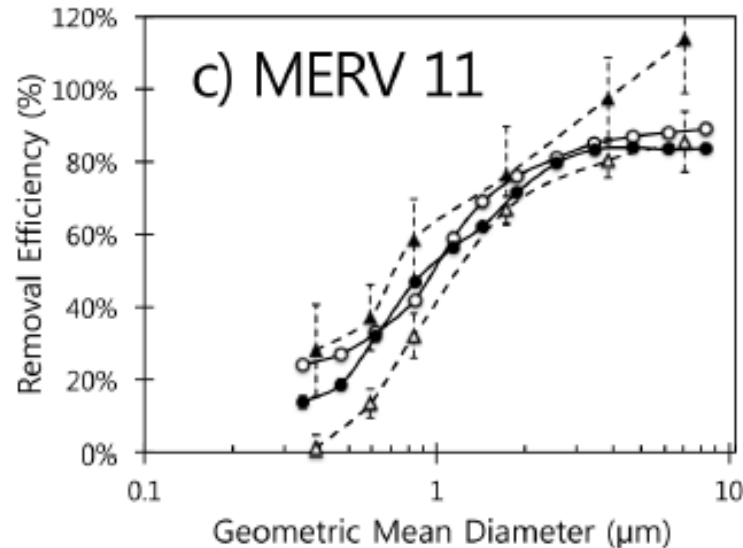
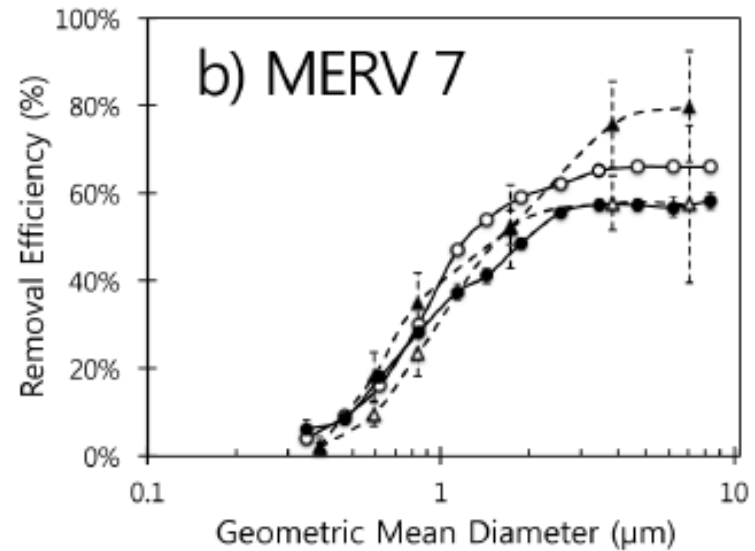
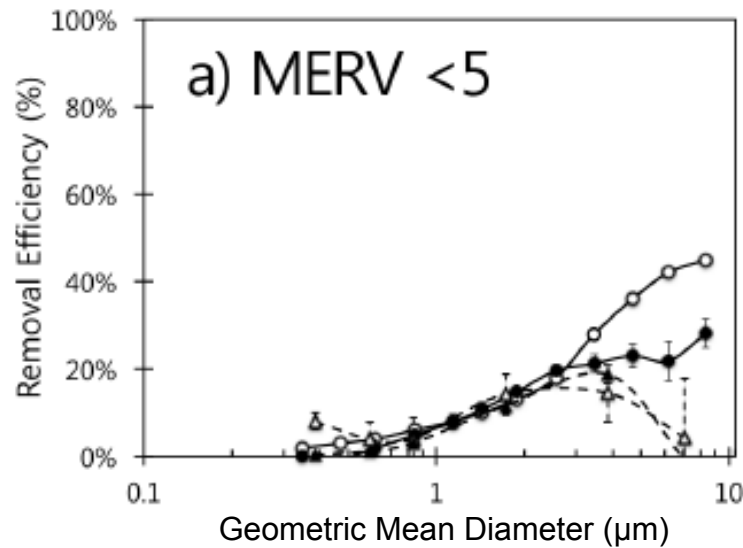
(\*) Represents a novel advance from other methods in Offermann et al., 1992 and MacIntosh et al., 2008  
Stephens and Siegel, 2012 *Aerosol Sci Technol*

# In-situ particle removal efficiency



Four test methods agreed reasonably well, particularly for smaller particles

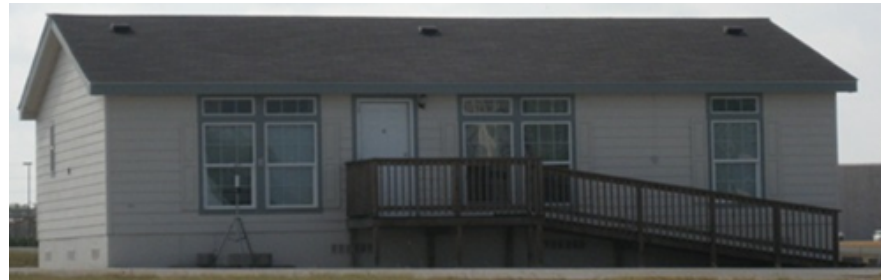
# In-situ particle removal efficiency



Four test methods agreed reasonably well, particularly for smaller particles

# In-situ ultrafine particle filtration tests

- Similar procedure performed but measuring 7-100 nm particles
- ASHRAE Standard 52.2 does not require UFP measurements
- Whole-house filter test method in UTest House
  - Burn incense only (smaller particles)



1-inch depth

5-inch depth



MERV 4



MERV 6



MERV 11



MERV 10

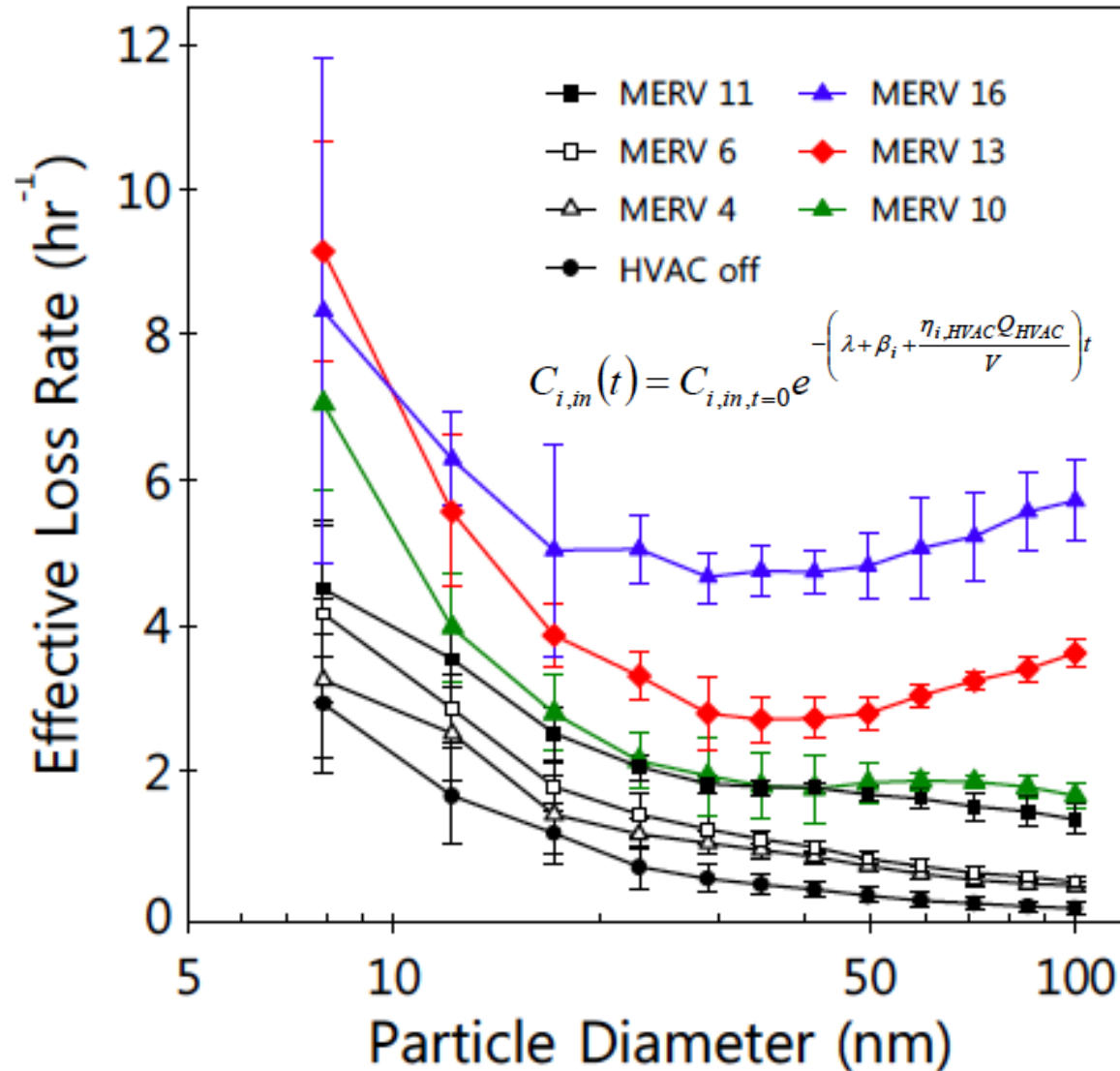


MERV 13

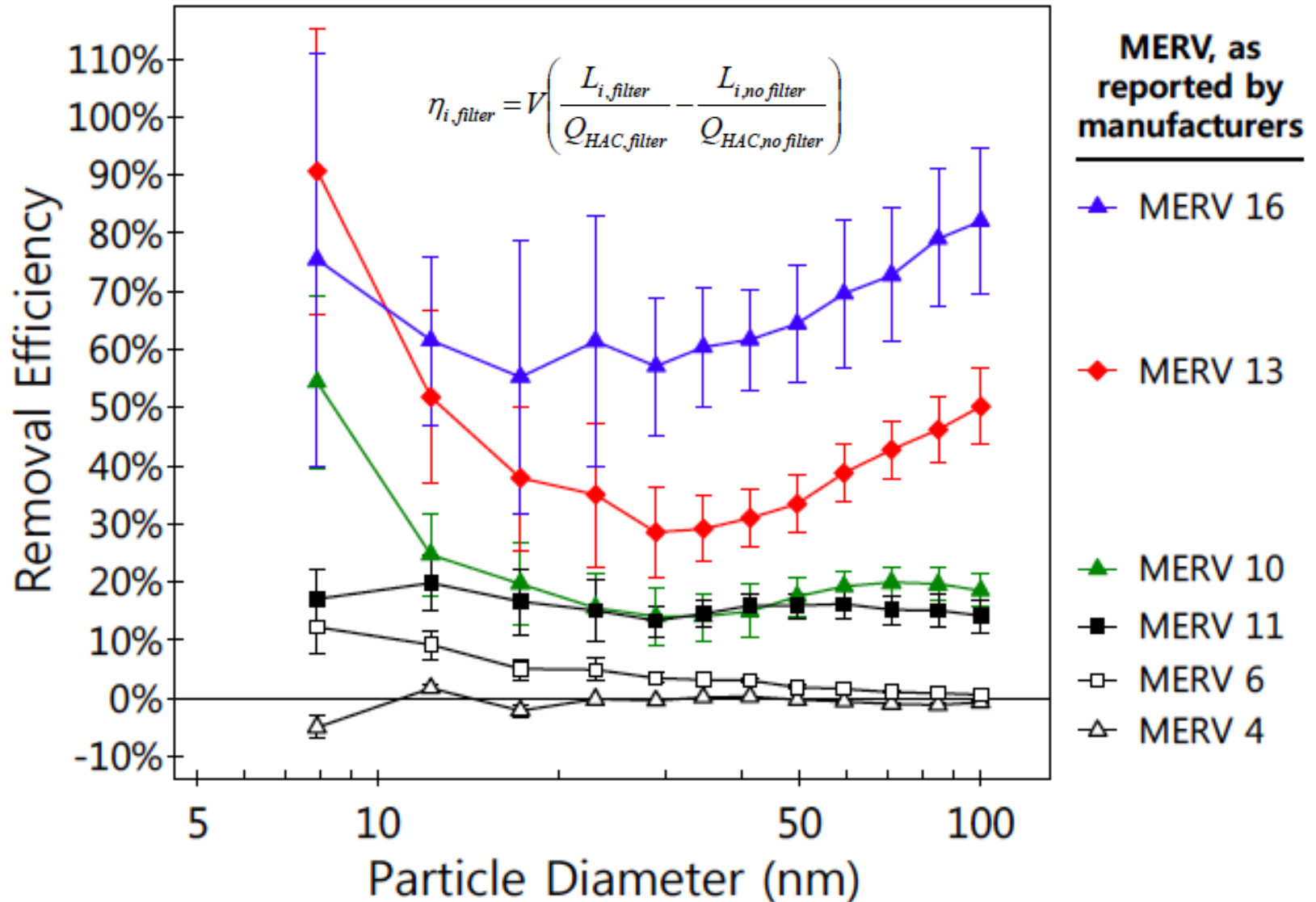


MERV 16

# In-situ ultrafine particle filtration tests



# In-situ ultrafine particle filtration tests



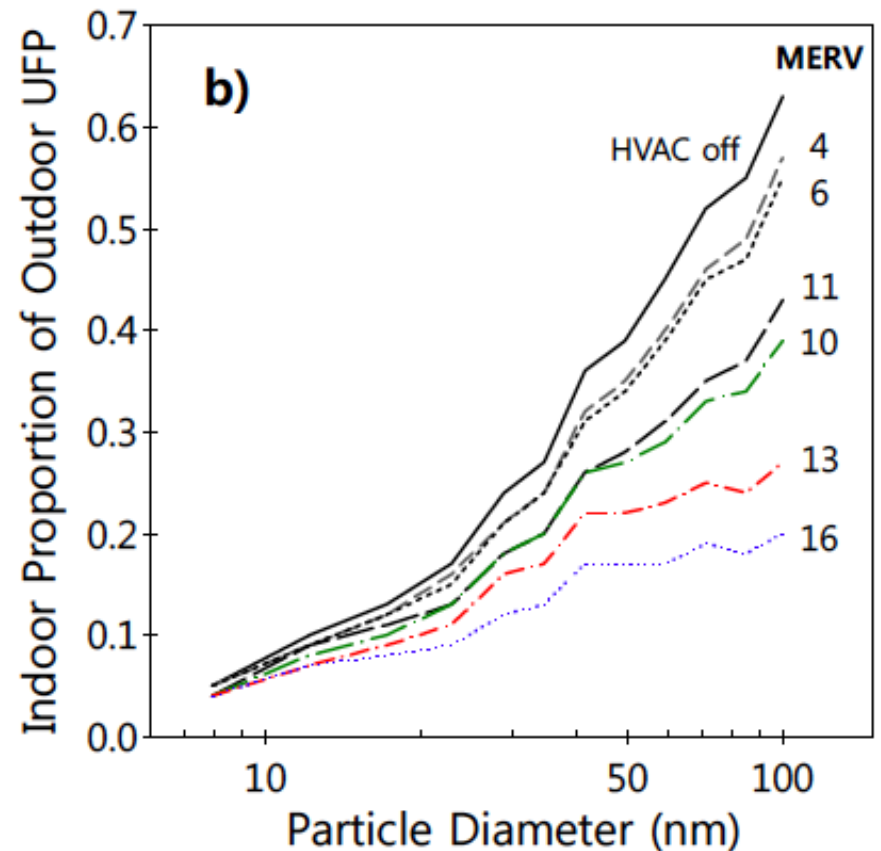
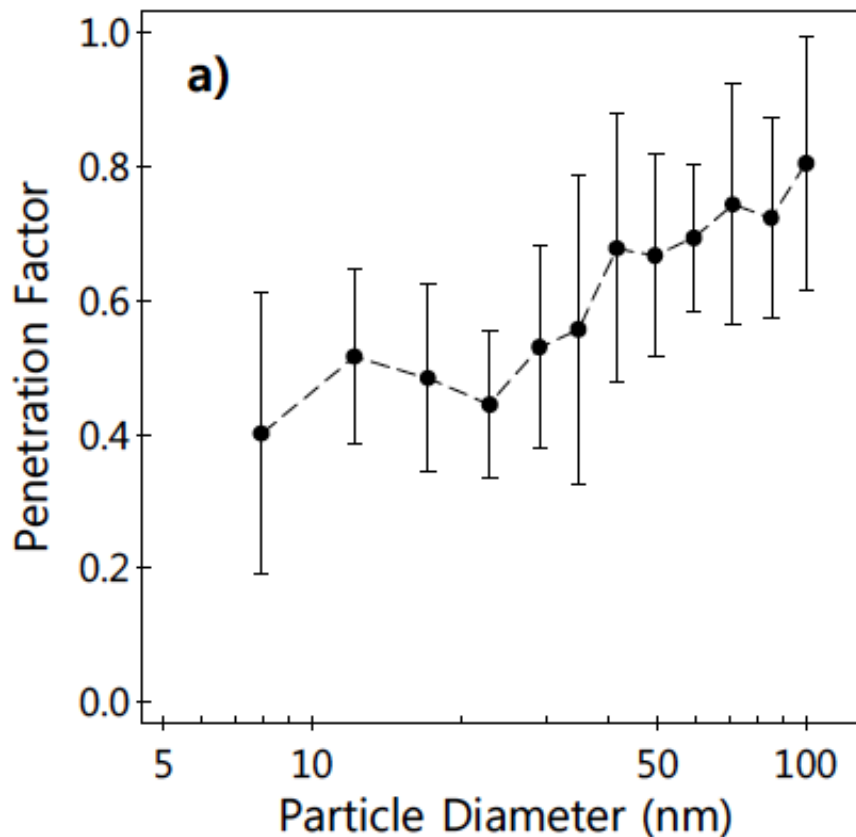
# Modeling impacts on indoor UFPs of outdoor origin

$$\frac{C_{i,in}}{C_{i,out}} = \frac{P_i \lambda}{\lambda + L_{i,background} + L_{i,filter} f}$$

$\lambda = 0.41 \text{ hr}^{-1}$  (average from this study)

$P_i$  measured for this study

$f = 20.6\%$  runtime (Stephens et al. 2011 *Bldg and Env*)

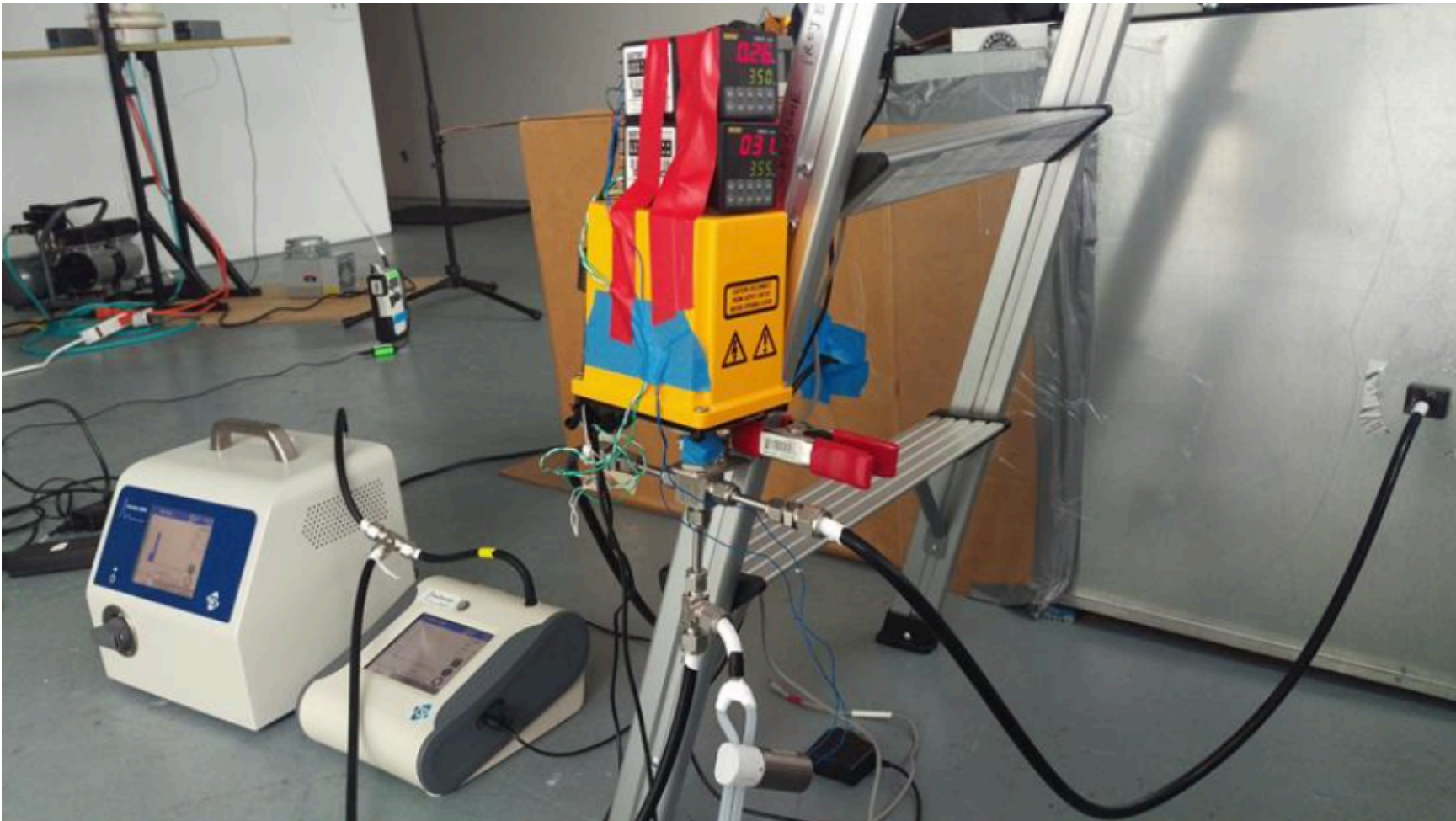




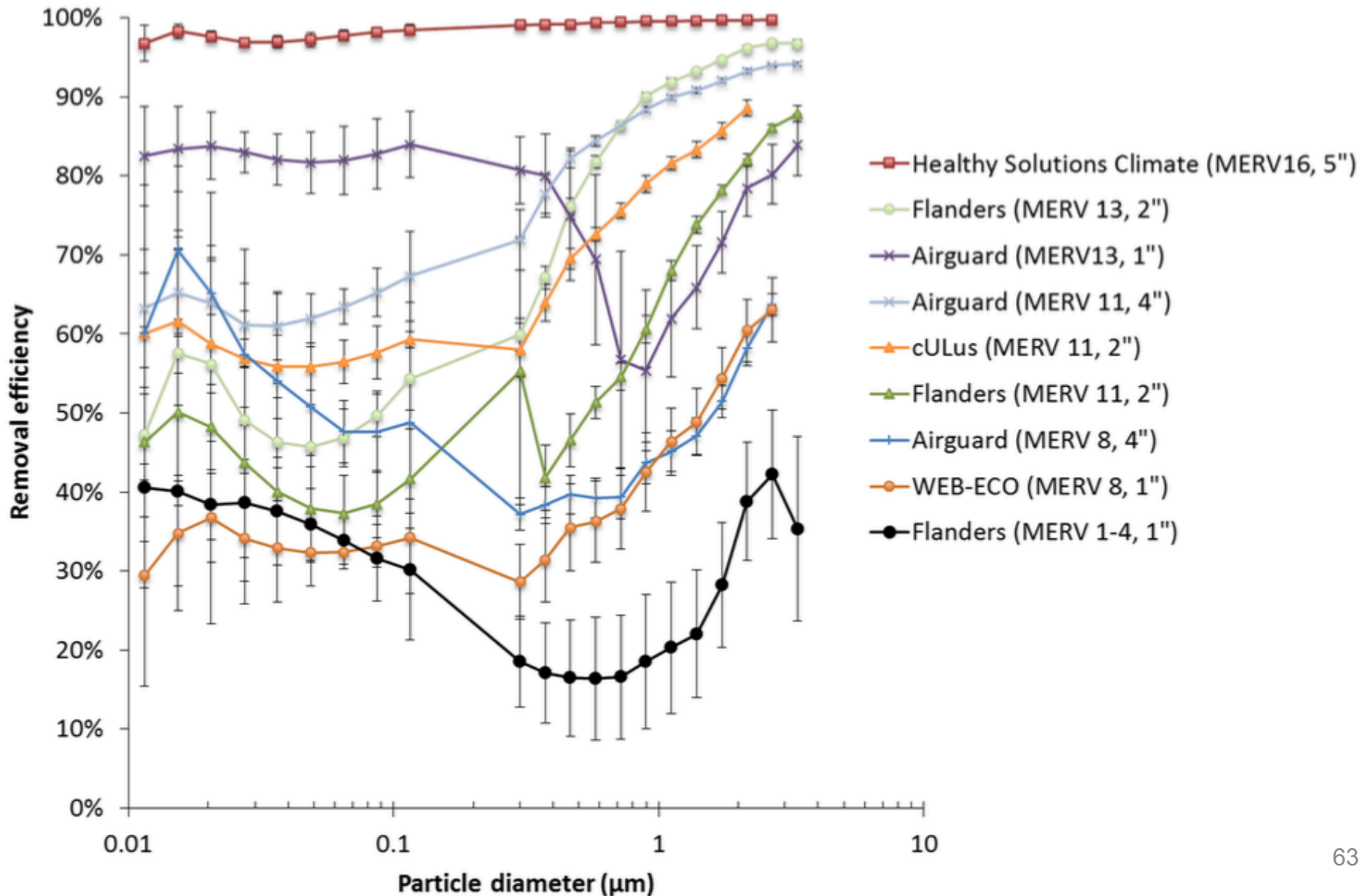
# In-situ particle removal efficiency (up/down method)



# In-situ particle removal efficiency (up/down method)



# In-situ particle removal efficiency (up/down method)



# **HVAC FILTER PRESSURE AND FLOW RELATIONSHIPS**

# Pressure, flow, and energy relationships

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





# Conventional wisdom

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“A dirty filter will slow down air flow and make the system work harder to keep you warm or cool – wasting energy.”<sup>1</sup>

“Clogged, dirty filters block normal air flow and reduce a system's efficiency significantly.... Keeping the filter clean can lower your air conditioner's energy consumption by 5%–15%.”<sup>2</sup>



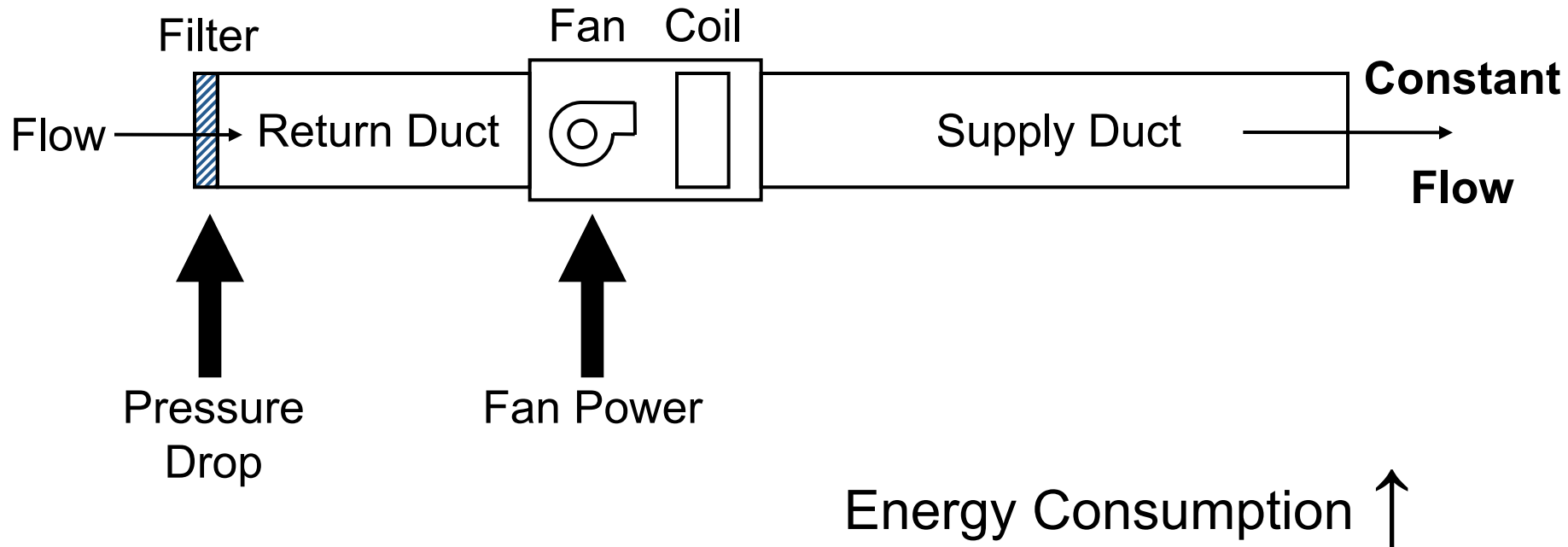
U.S. Department of Energy  
**Energy Efficiency and Renewable Energy**

<sup>1</sup>[http://www.energystar.gov/index.cfm?c=heat\\_cool.pr\\_hvac](http://www.energystar.gov/index.cfm?c=heat_cool.pr_hvac)

<sup>2</sup>[http://apps1.eere.energy.gov/consumer/your\\_home/space\\_heating\\_cooling/index.cfm](http://apps1.eere.energy.gov/consumer/your_home/space_heating_cooling/index.cfm)

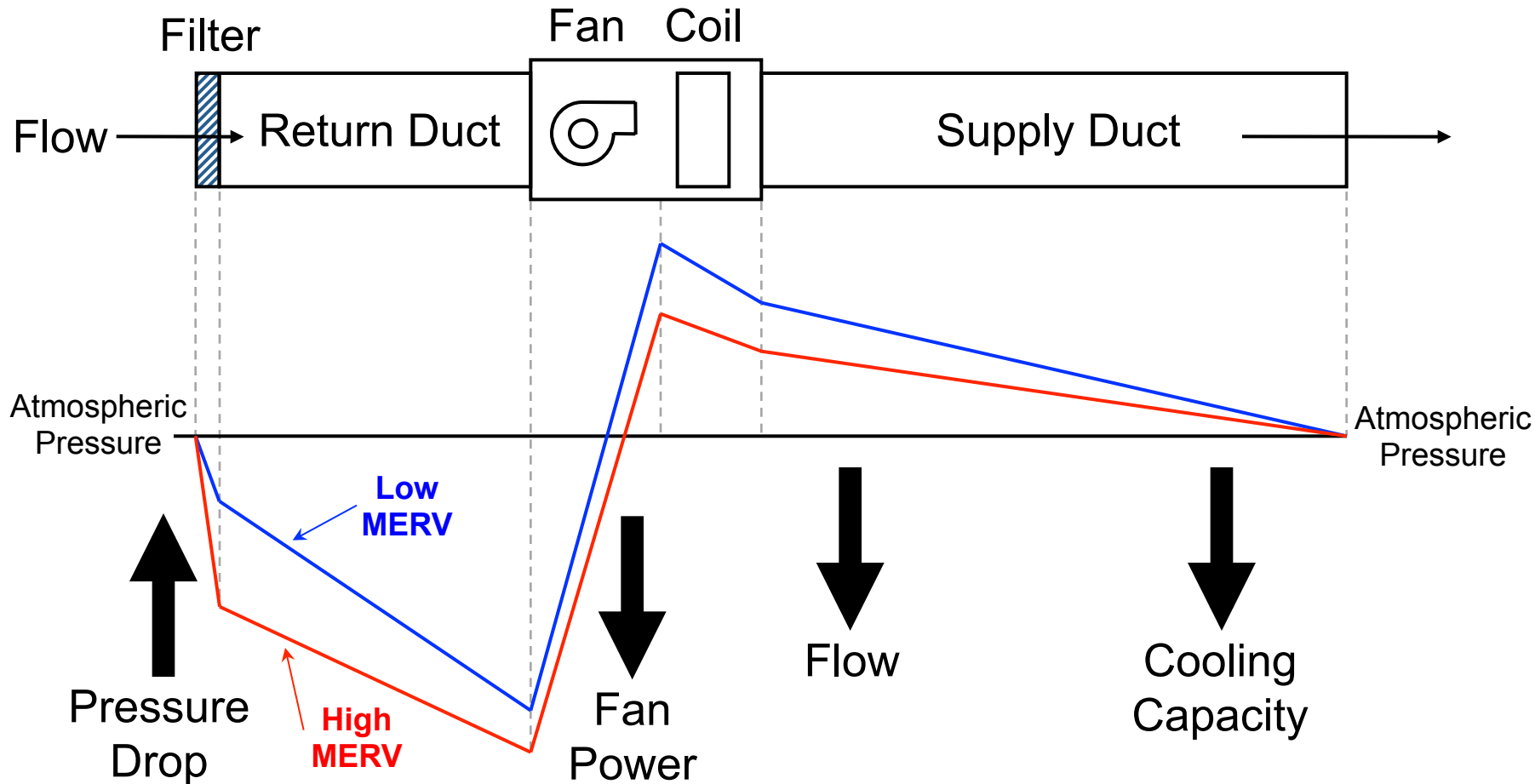
# Energy consequences of filters

- In large commercial buildings with variable speed fans...



# Residential and light-commercial buildings

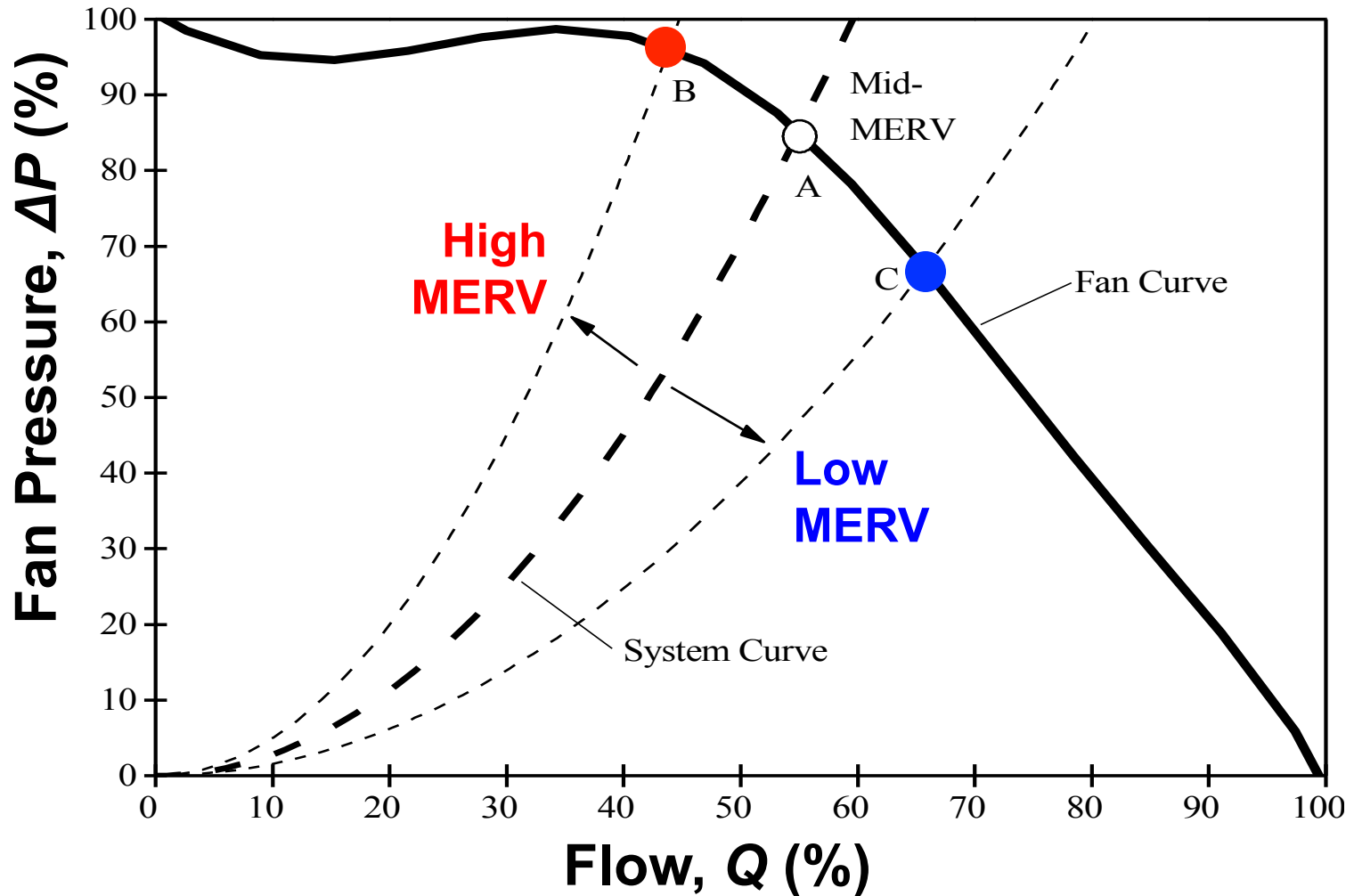
## PSC blower w/ constant speed fan



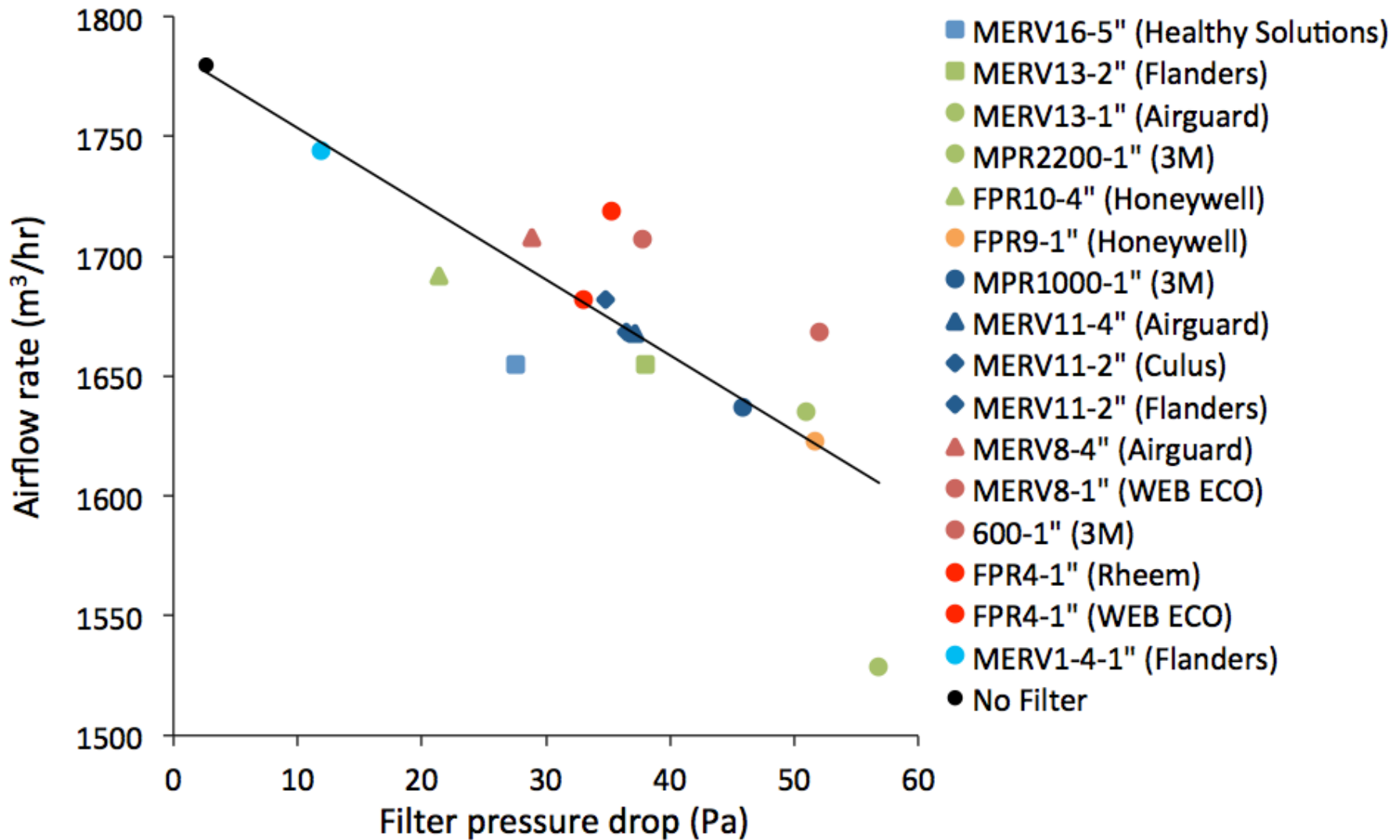
How does overall energy consumption change?



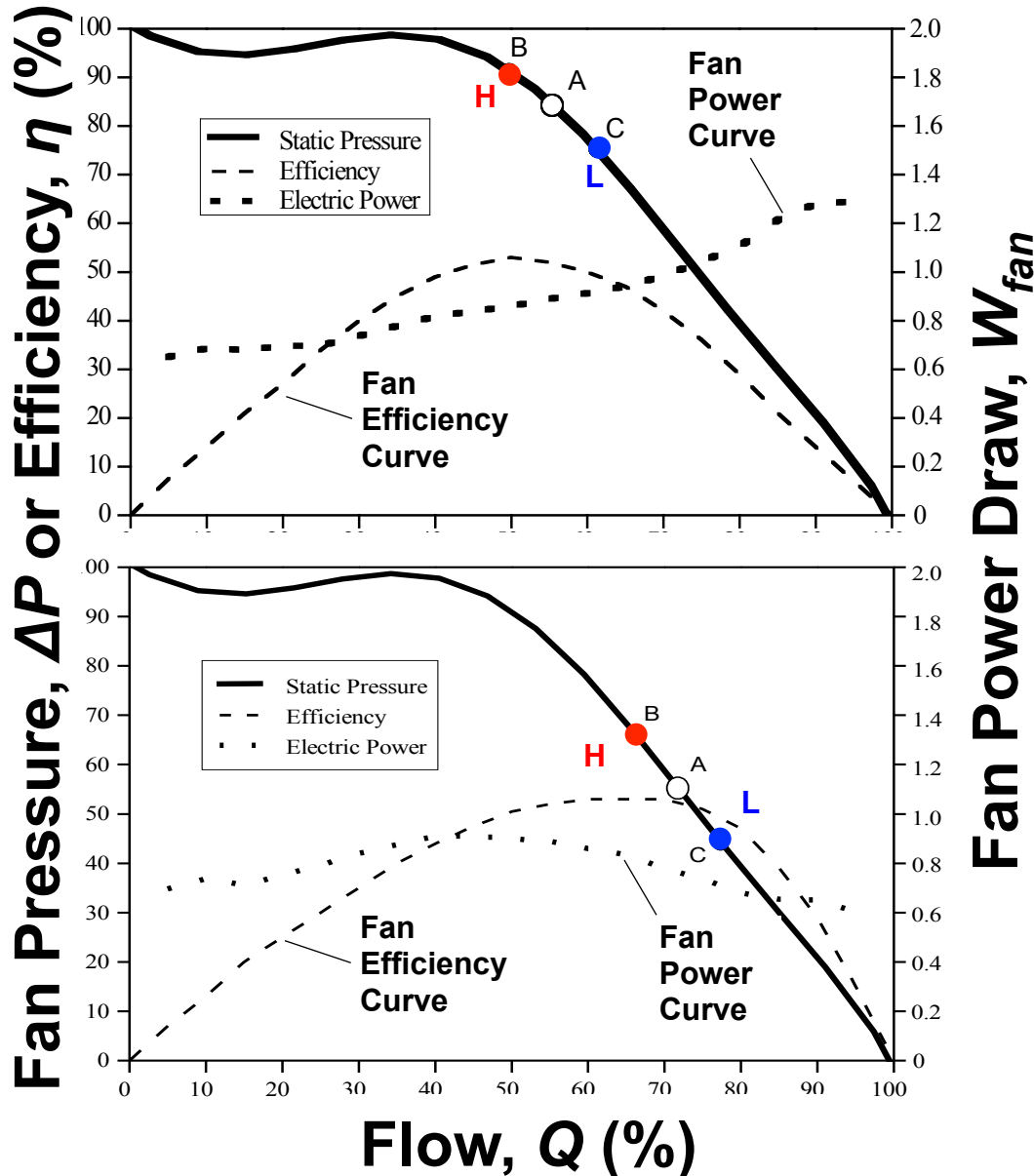
# Fan and system curve interactions



# Airflow rates and brand new filters



# Fan power draw impacts



$$W_{fan} = \frac{Q \Delta P_{total}}{\eta_{elec}}$$

Power draw may increase or decrease in response to higher pressure (and lower flow for PSC blowers) depending on type of fan

# ASHRAE RP-1299: Experimental investigation

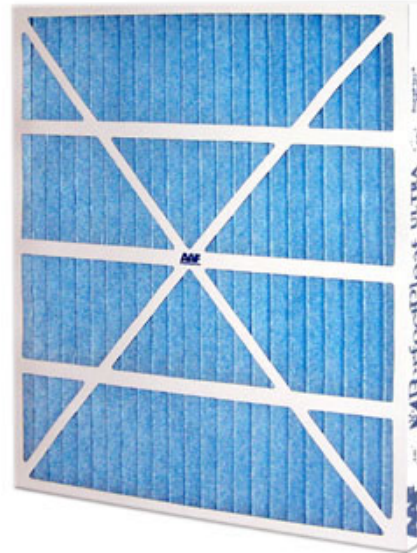
---

- 3 rated filter efficiencies
  - Low (MERV <4)
  - Medium (MERV 6-8)
  - High (MERV 11-12)
- Occupied field sites
  - 8 residential & 9 light-commercial systems
  - 1 visit per month for a year (~270 total visits)
  - Influenced by climate and occupant behavior
- Unoccupied test house
  - 2 systems continuously monitored for 6 months
  - Controlled thermostats
  - Binned analysis isolates climate and occupant impacts

# Filter examples



Low-MERV  
(MERV 1 - 4)



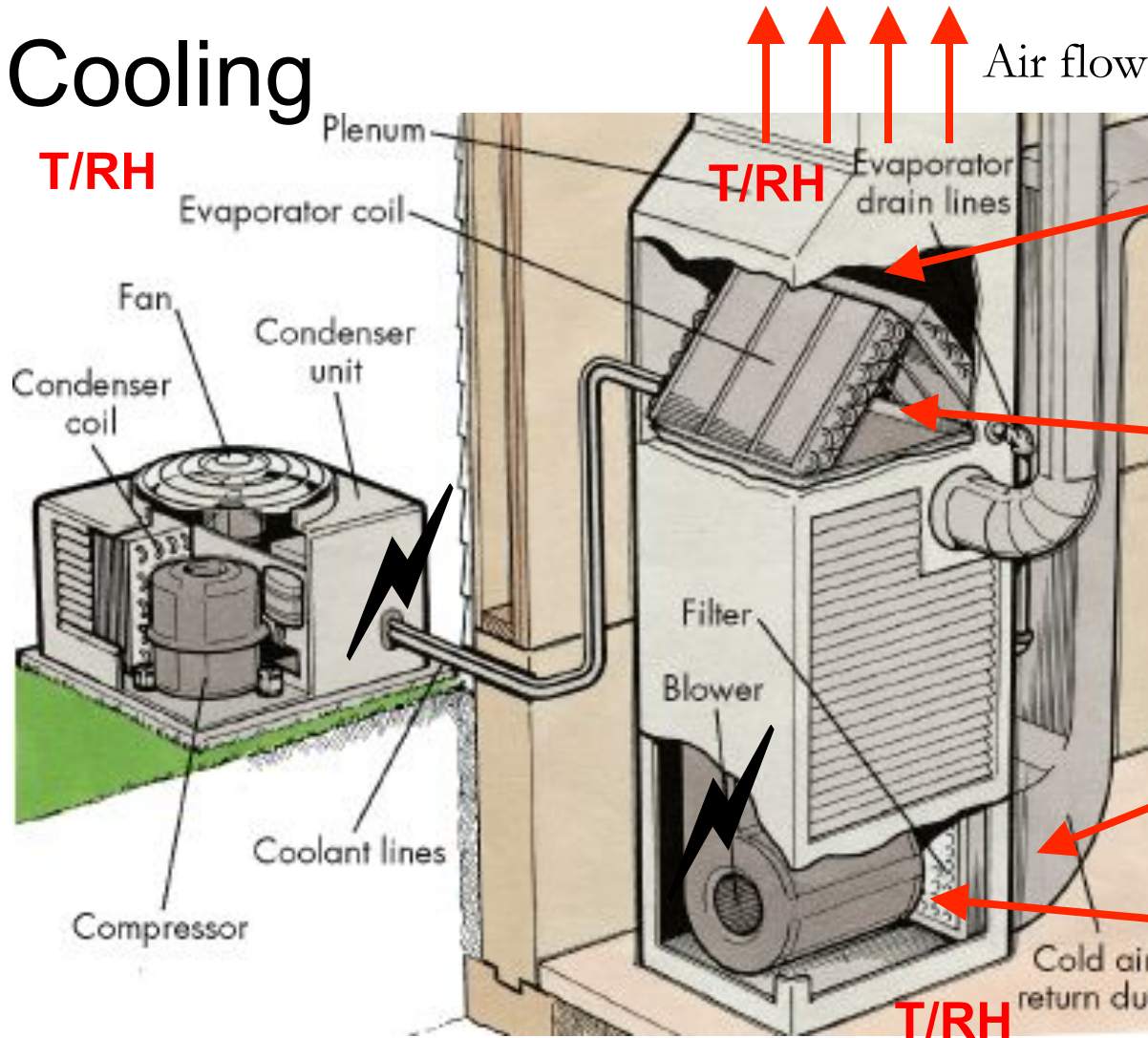
Mid-MERV  
(MERV 5 - 8)



High-MERV  
(MERV 9 - 12)

# Field measurements

## Cooling



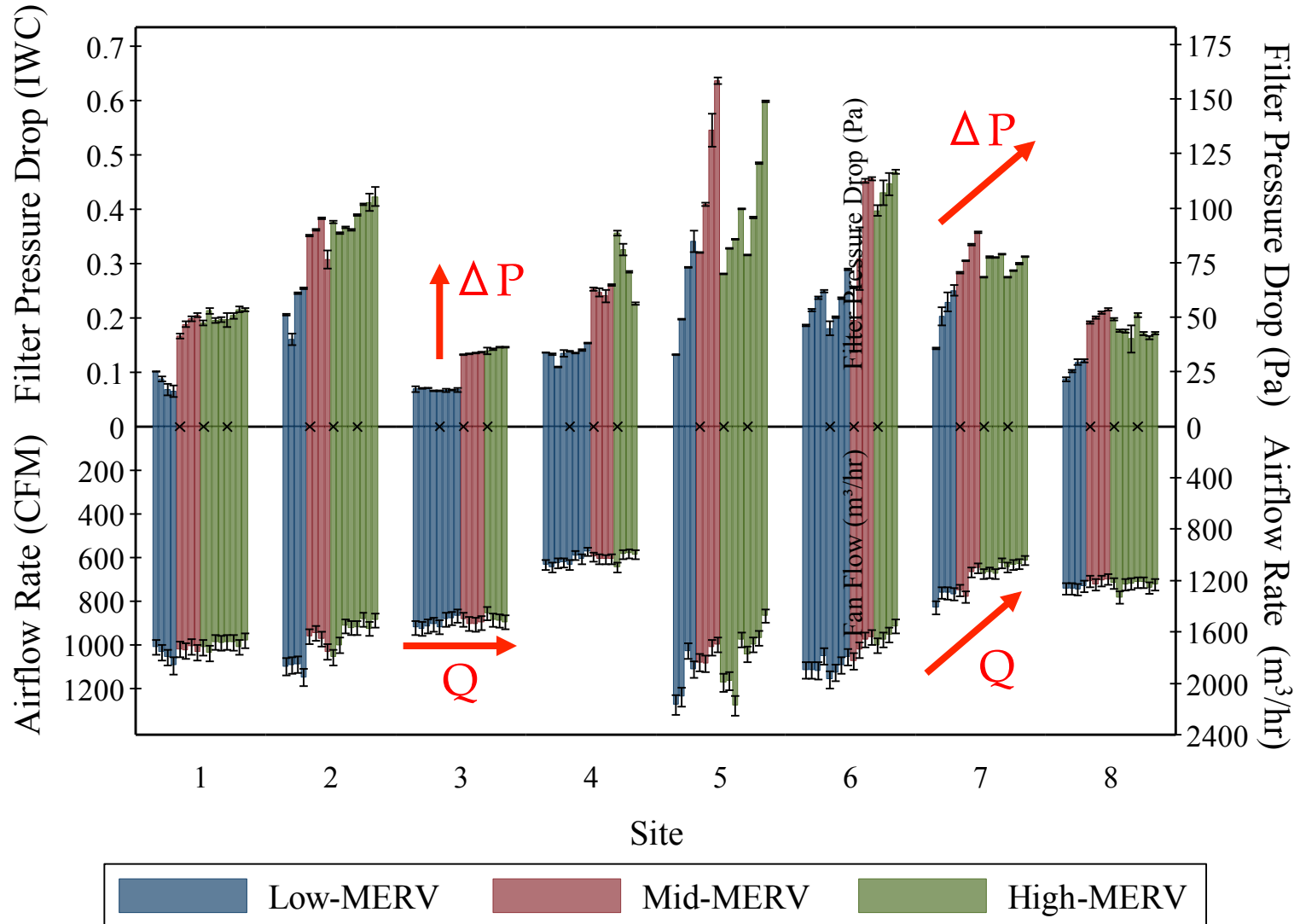


# Test house measurements

- Unoccupied manufactured home at PRC (UT)
- 2 systems continually monitored at 10-second intervals
- Controlled thermostats



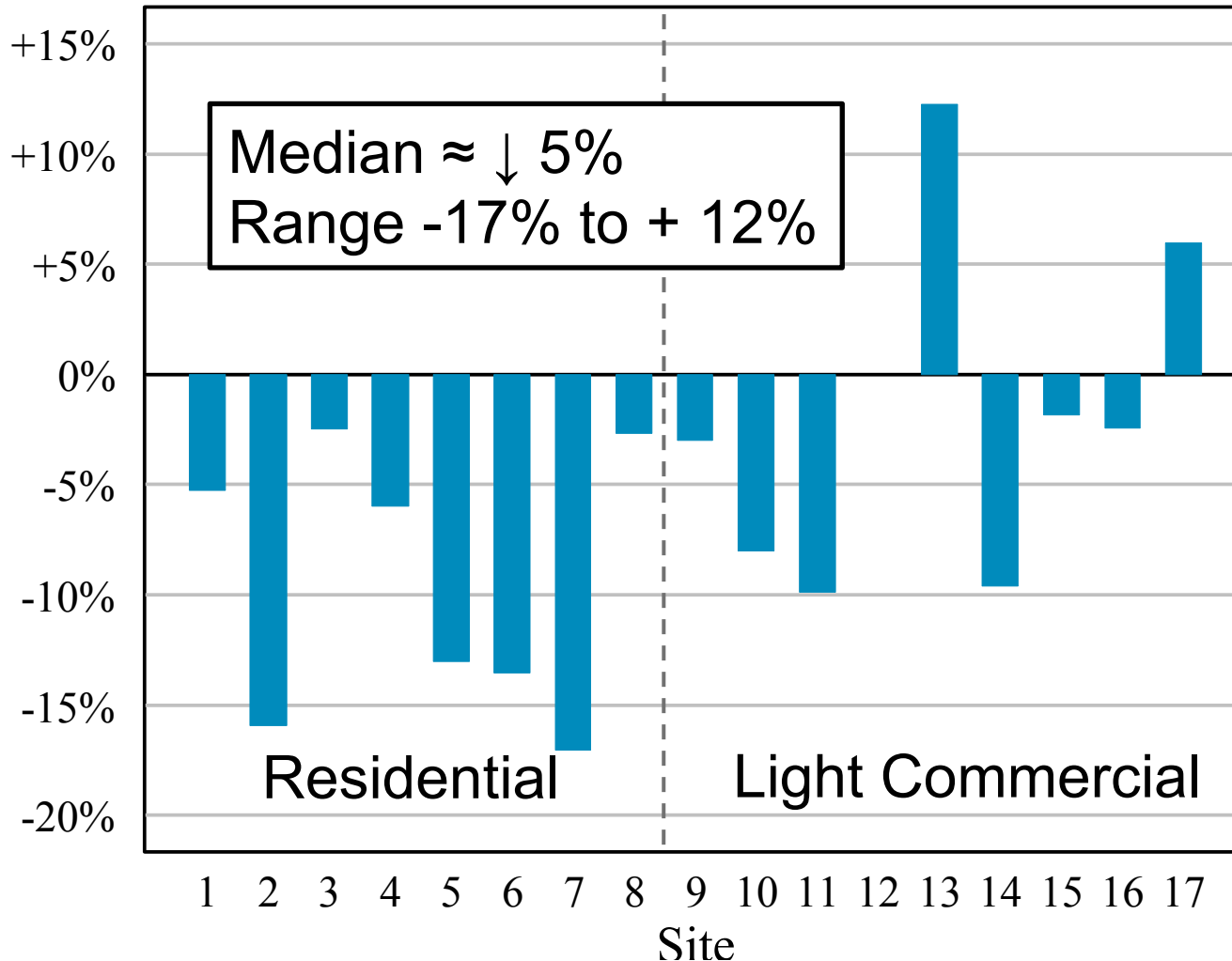
# Residential field results: Filter pressure drop and airflow





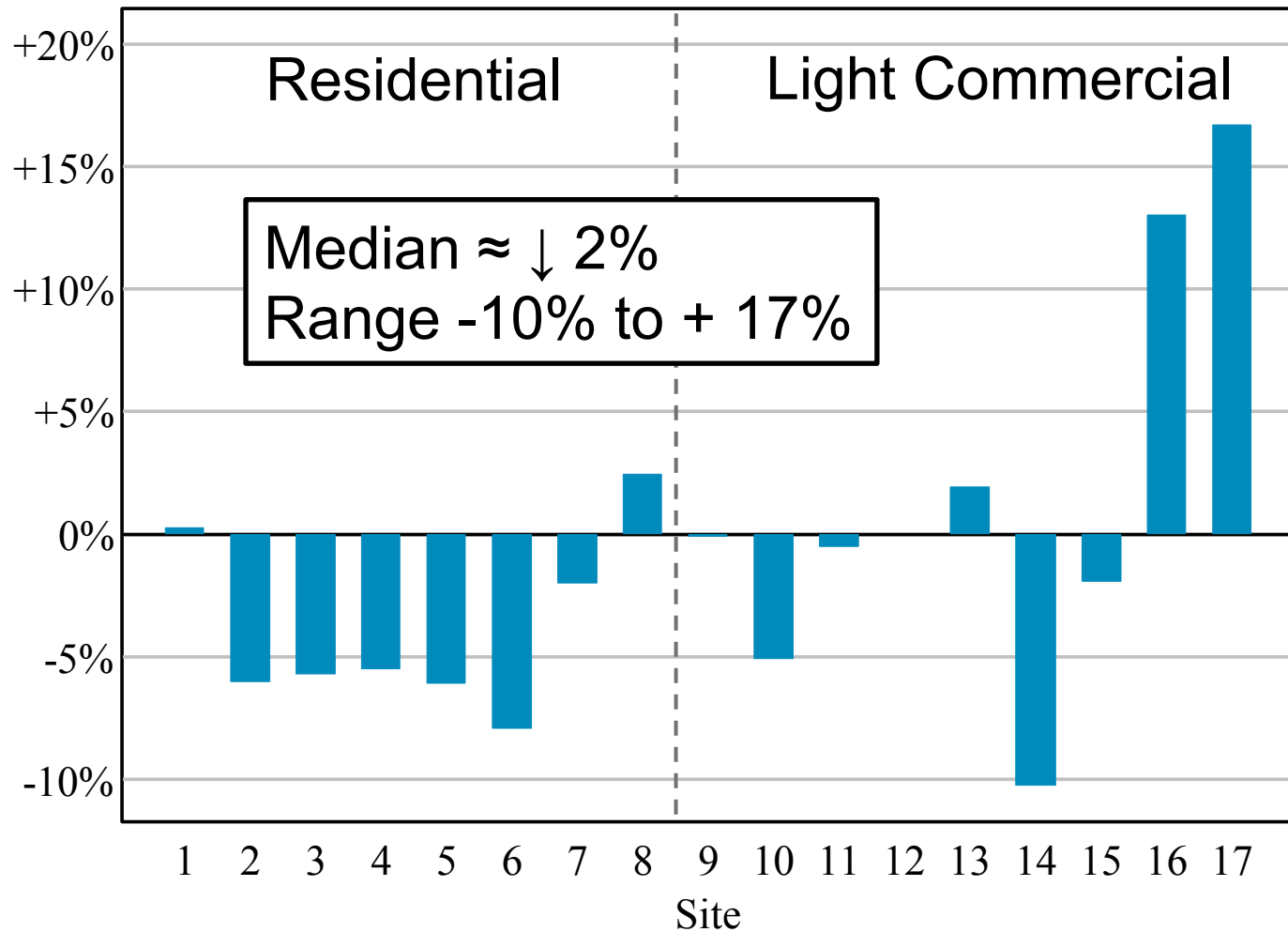
# Median changes in airflow rates

## Moving from low-MERV to high-MERV



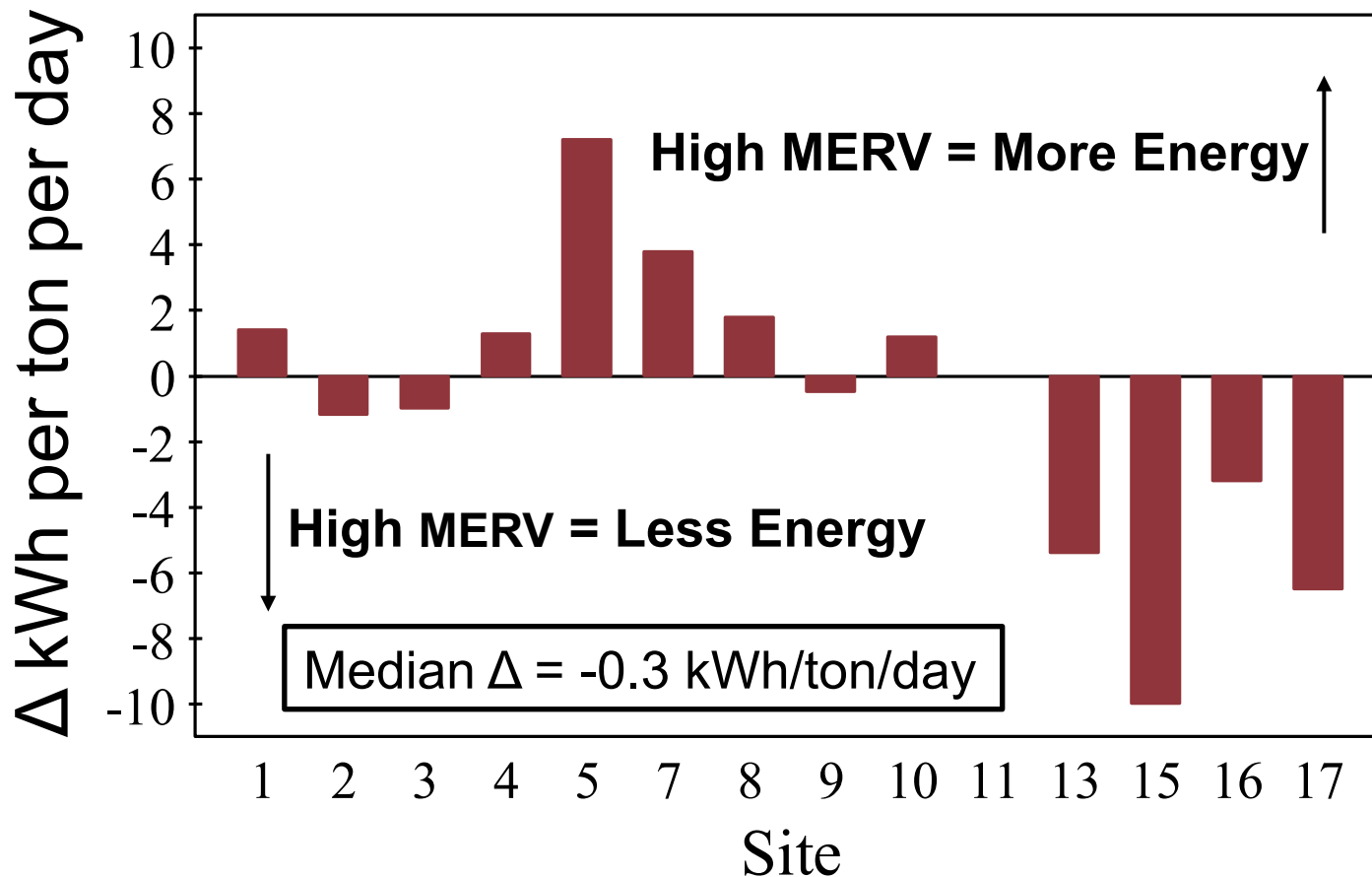
# Median change in fan power draw

## Moving from low-MERV to high-MERV

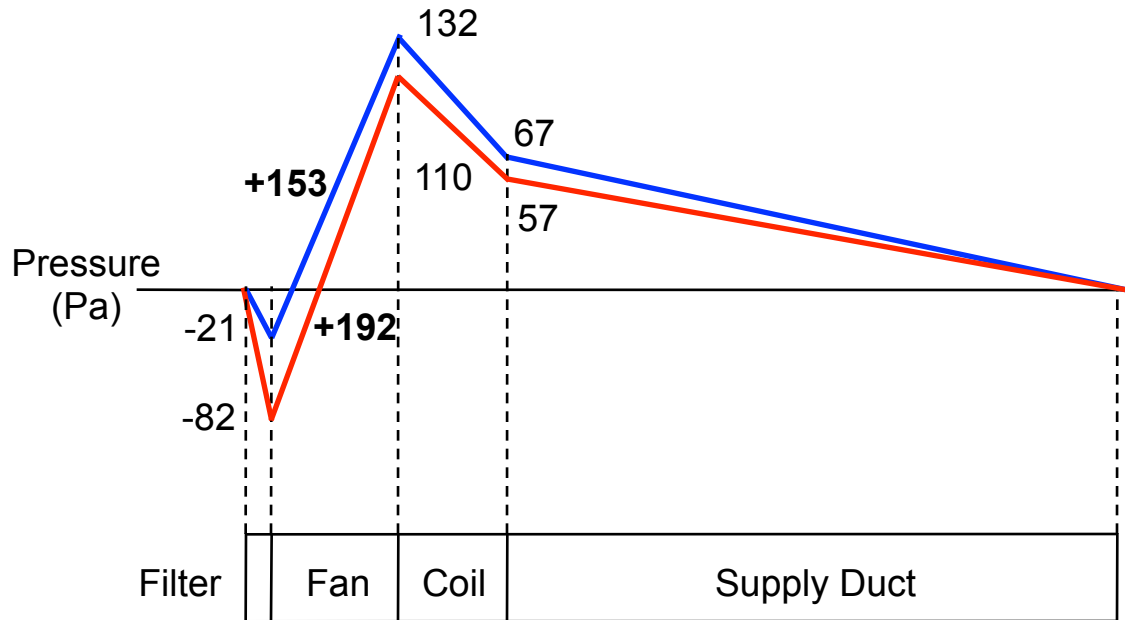


# Range of energy consequences

## Average Change in Daily Energy Consumption Moving from low-MERV to high-MERV

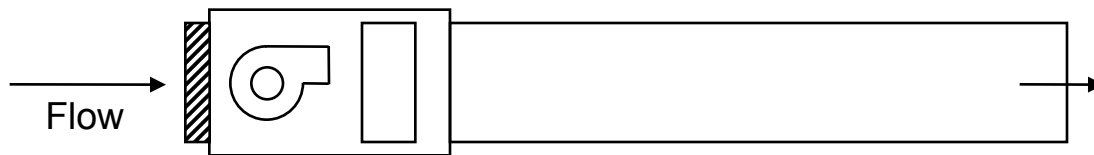


# Test house results: Binned analysis



## High-MERV vs. Low-MERV (Average Change)

- Filter  $\Delta P \uparrow 4x$
- Flow  $\downarrow 9\%$
- Fan Power  $\uparrow 3\%$
- Outdoor Unit Power  $\downarrow 0.5\%$
- Total Power  $\uparrow 0.1\%$
- Total Capacity  $\downarrow 4\%$



**Low-MERV**  
Avg Flow = 996 CFM

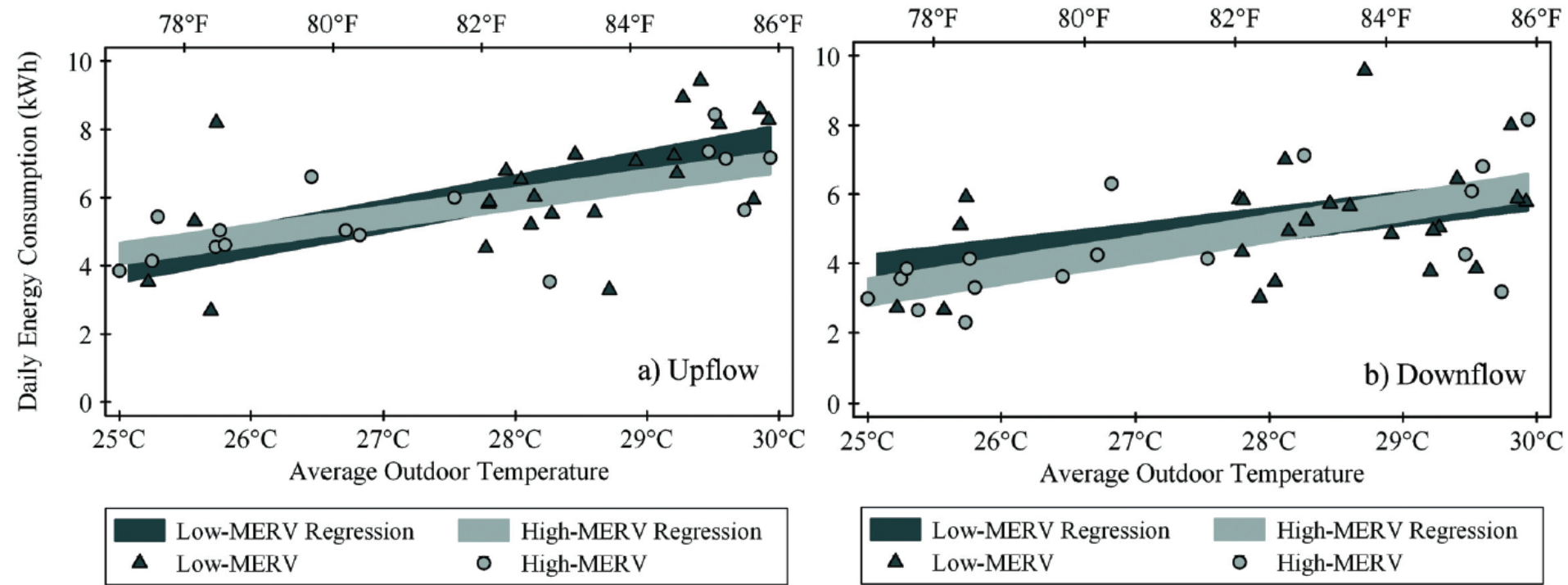
**High-MERV**  
Avg Flow = 909 CFM

$$cap_{tot} = Q_{fan} \rho (C\Delta T + \Delta W h_{fg})$$

Airflow  $\downarrow 9\%$   
 $\Delta T$  across coil  $\uparrow 6\%$   
 $\Delta W$  across coil  $\uparrow 5\%$   
 Total Capacity  $\downarrow 4\%$

# Test house results

## Daily energy consumption versus outdoor air temperature

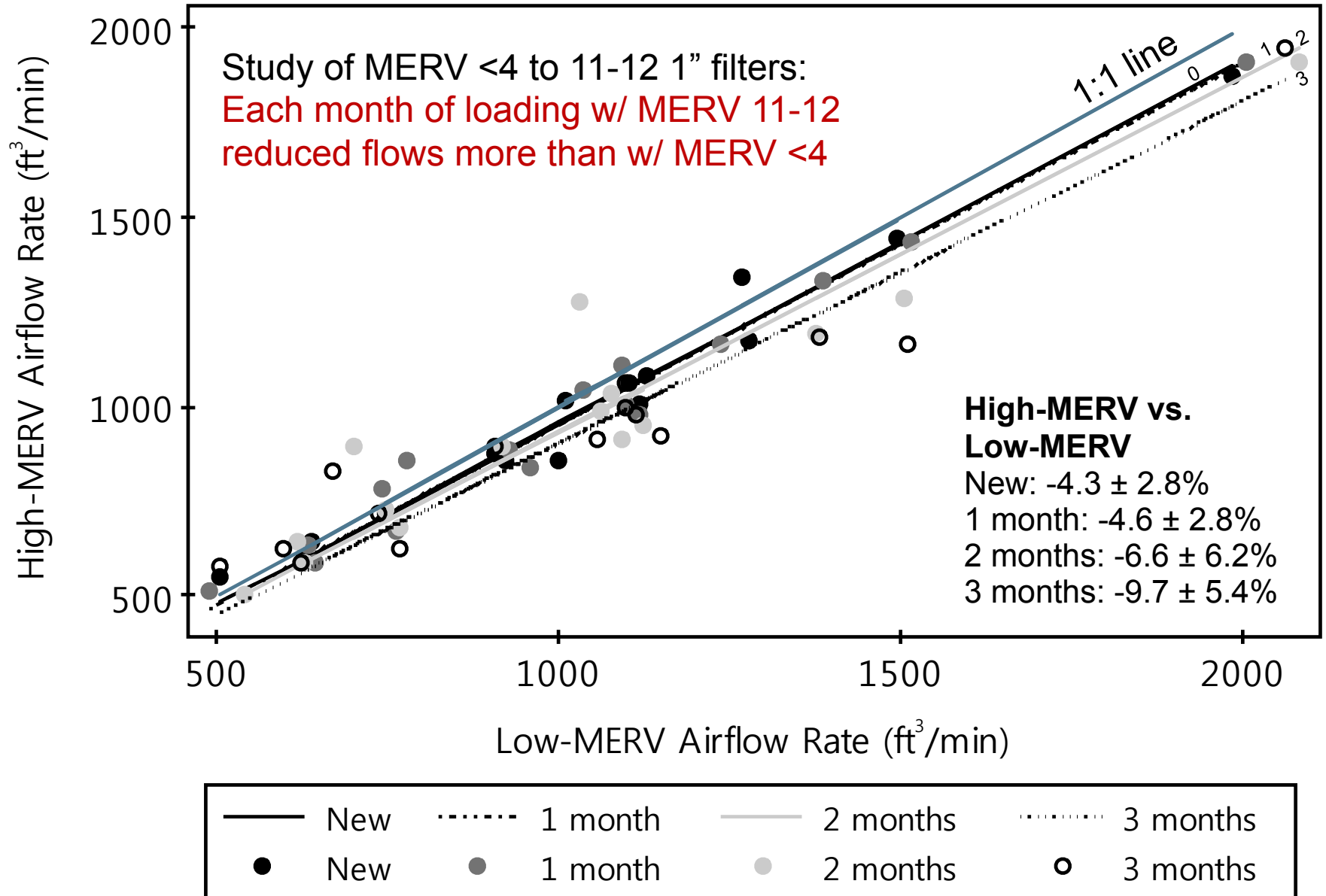


Test House System #1

Test House System #2

No measured differences in energy consumption with the low and higher pressure drop filters installed!

# 17 field sites (RP-1299): Impacts of higher-MERV on flow changes during dust loading

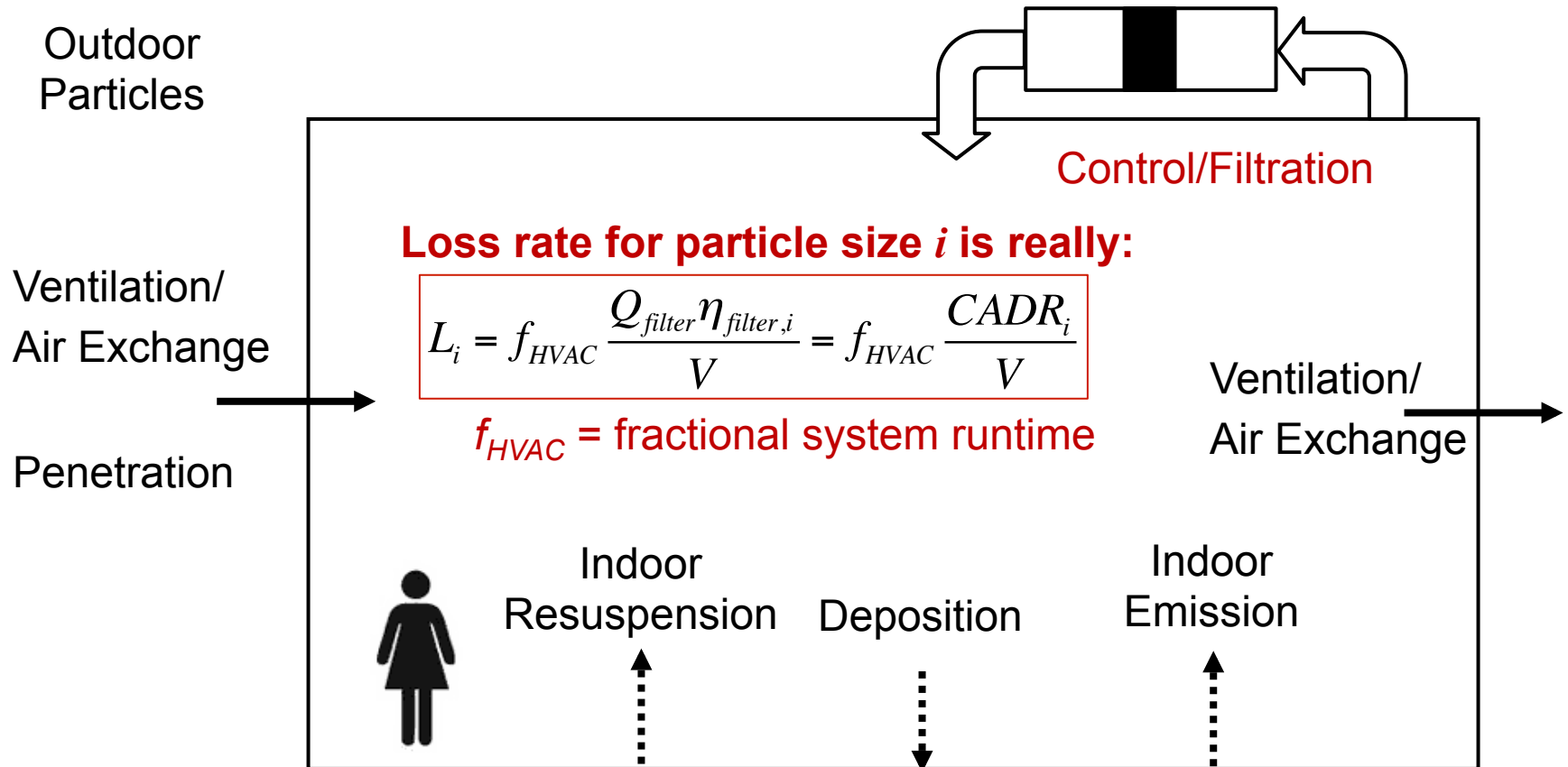


# **SYSTEM RUNTIME**

The last key parameter for filtration

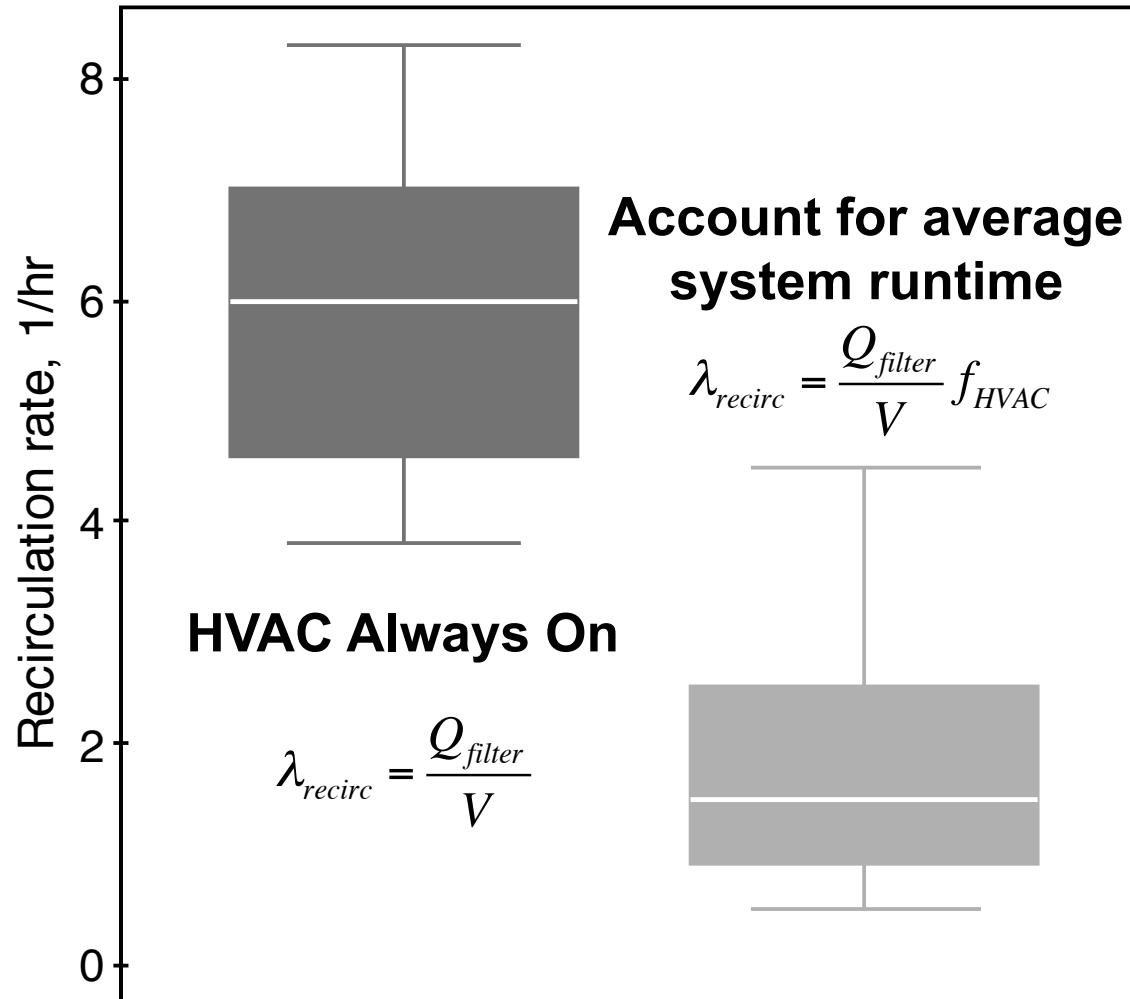
# System runtime

- If an HVAC system doesn't run, it's filter is useless



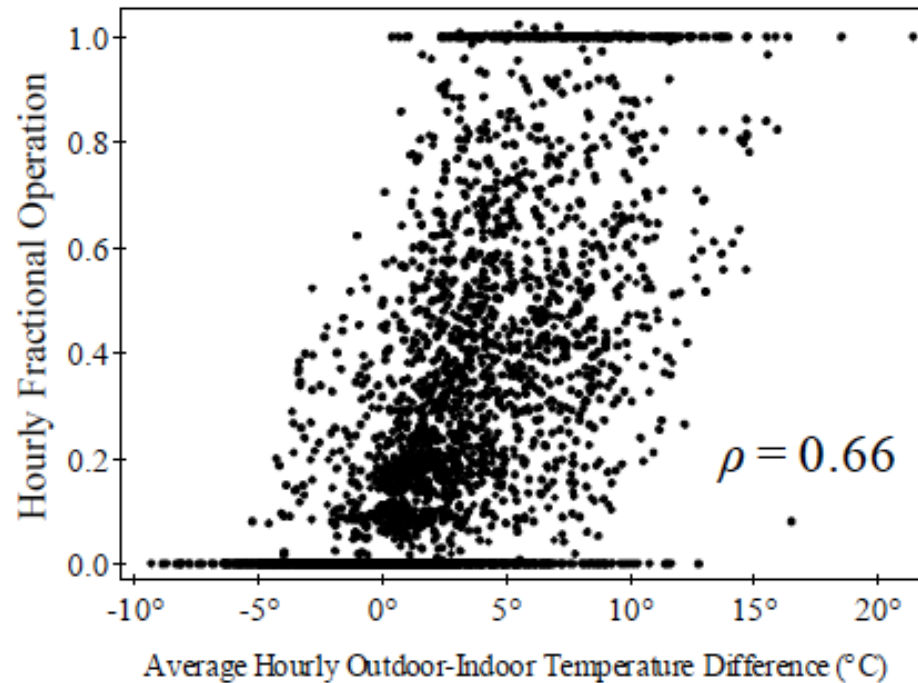


# HVAC system recirculation rates in homes and small commercial buildings



# HVAC system recirculation rates in homes and small commercial buildings

- How does system runtime change with climatic conditions?



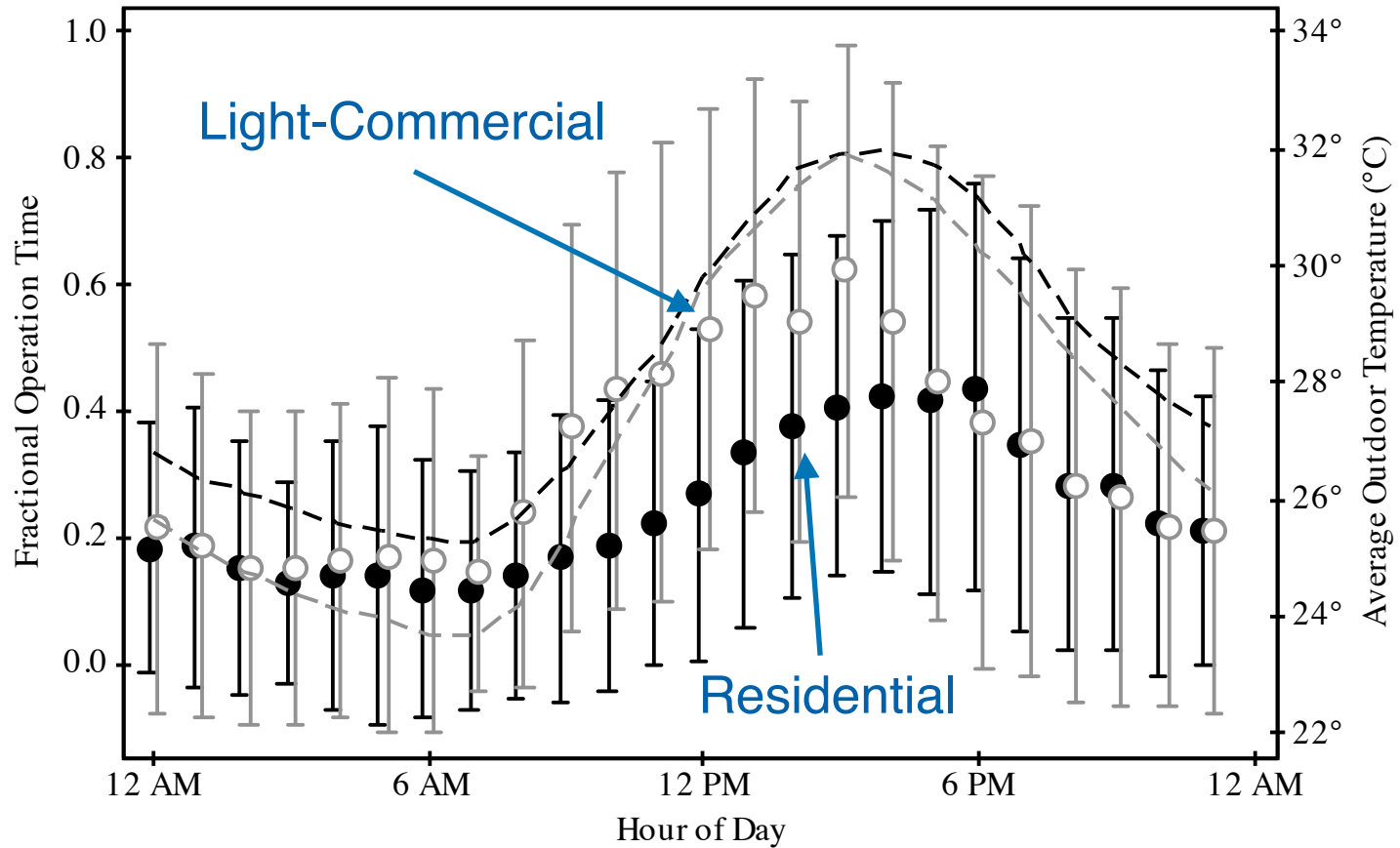
**Increase in hourly duty fraction per °C rise in average hourly indoor-outdoor temperature difference**

Site	% per °C	R <sup>2</sup>	N (hours)
1	6.0%	0.71	175
2	3.7%	0.33	180
3	2.9%	0.68	215
4	7.2%	0.68	226
5	9.3%	0.69	222
6	9.1%	0.80	161
7	4.7%	0.71	204
8	7.3%	0.62	164
9	6.0%	0.69	175
10	4.9%	0.73	171
11	11.3%	0.67	211
12	4.5%	0.68	91
13	7.9%	0.61	218
14	7.1%	0.78	173
15	9.2%	0.63	182
16	4.0%	0.41	152
17	2.4%	0.22	150
Average	6.3%	Total	3070
Median	6.0%		

- Median increase in hourly runtime per °C rise in average indoor-outdoor temperature difference: ~6% per °C

# HVAC system runtime

- How does system runtime change throughout the day?



- 8 am to 5 pm: Commercial systems operated 30-150% more than residential
  - 10-30% absolutely

# Filter summary

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- Five major mechanisms impact filter efficiency
- Filter efficiency spans wide range
  - Strong functions of particle size, fiber diameter, face velocity, solidity
- Filter performance changes over lifetime
  - Usually degrades for electrostatically charged filters
  - Often improves for mechanical mechanism based filters
- Adequate but imperfect test standards
- Some complicated relationships between pressure and flow
  - And energy use too (still an ongoing area of research)
- A good filter is only good if there is air flowing through it!

# **STAND-ALONE AIR CLEANERS**

# Stand-alone air cleaners

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- Another major type of filter is a stand-alone air cleaner
  - i.e. ‘room air cleaners’ or ‘portable air cleaners’



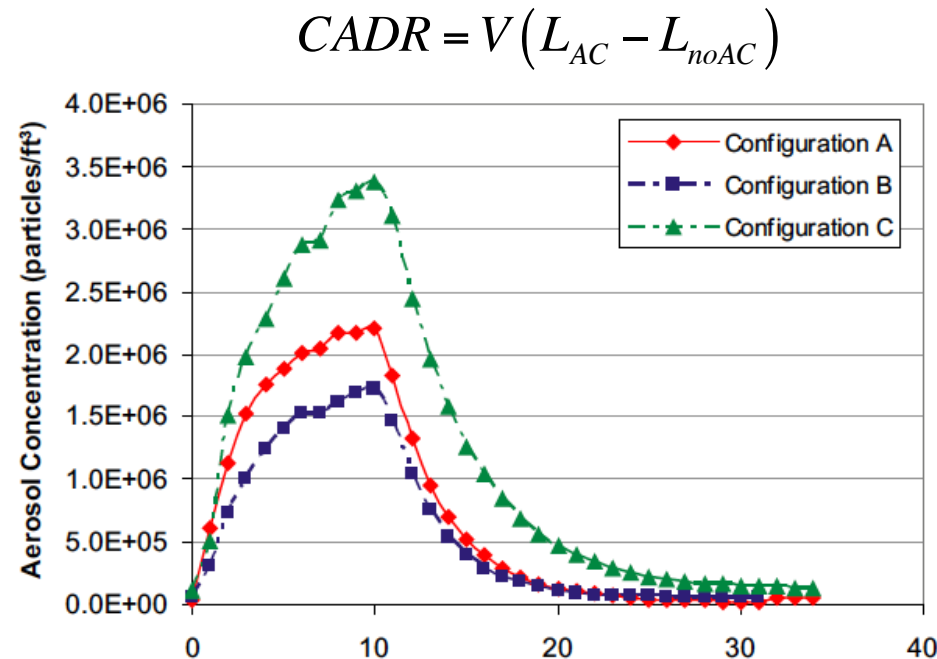
Photo from M.S. Waring and J.A. Siegel

# Recent testing of portable air cleaners

- A few recent studies on particle removal by portable air cleaners
  - First dates back to 1985 (Offermann et al., *Atmos Environ*)
- Basic procedure involves elevating aerosol concentrations
  - Measuring subsequent decay with and without air cleaner operating



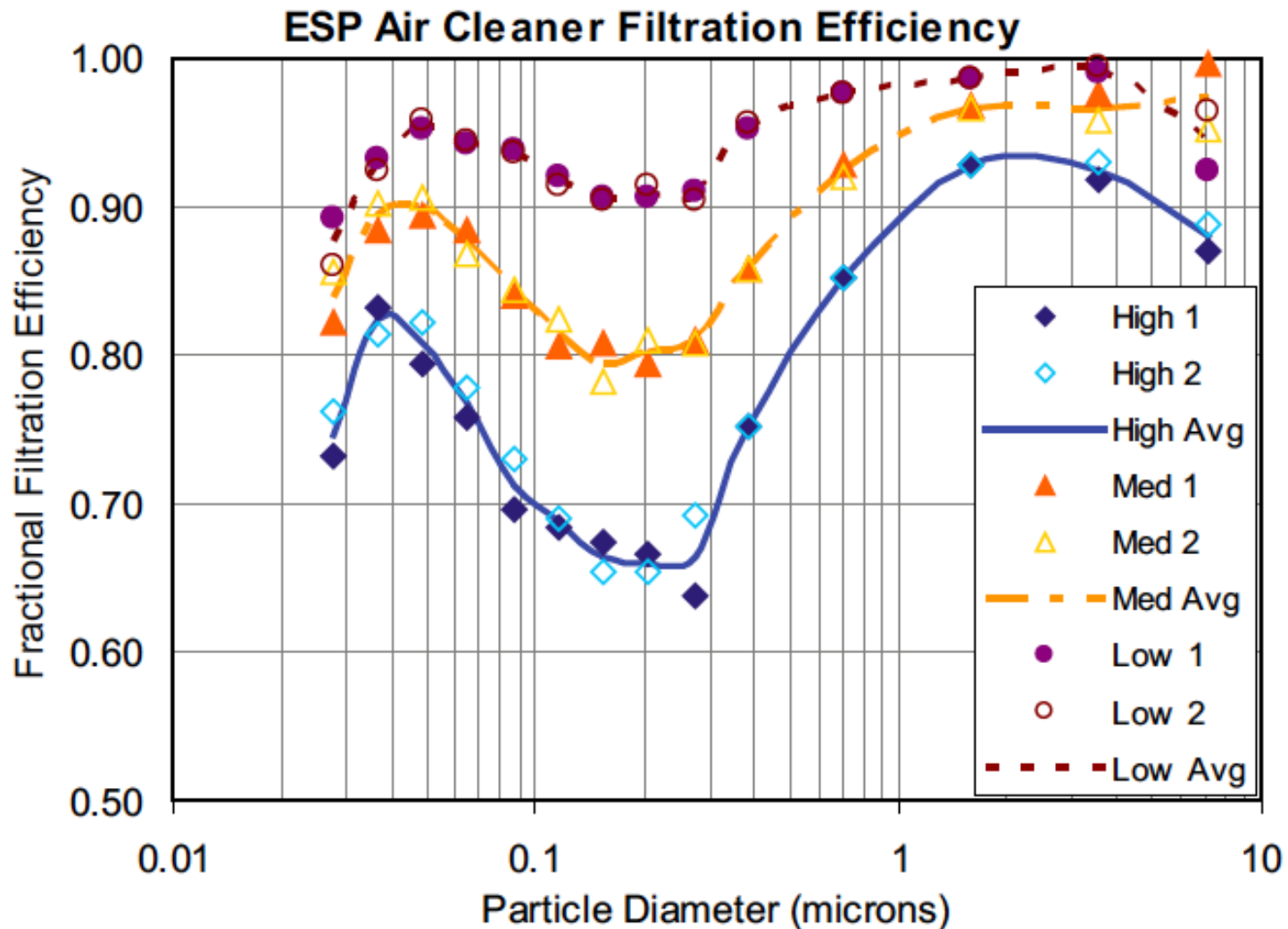
Kogan et al., 2008 EPA Report 600/R-08-012





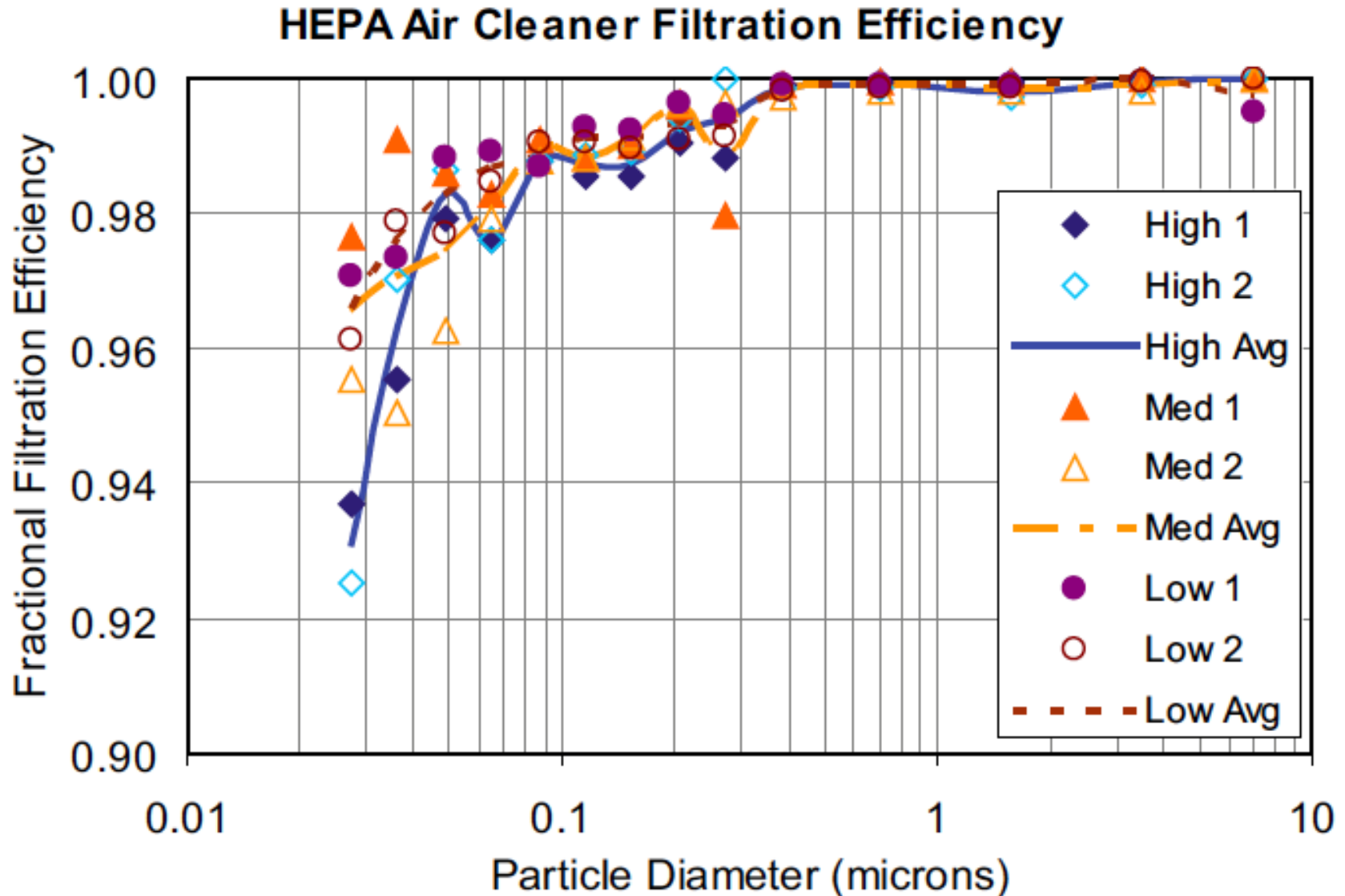
# Recent testing of portable air cleaners

$$CADR = V(L_{AC} - L_{noAC}) \longrightarrow \eta = \frac{CADR}{Q_{AC}}$$

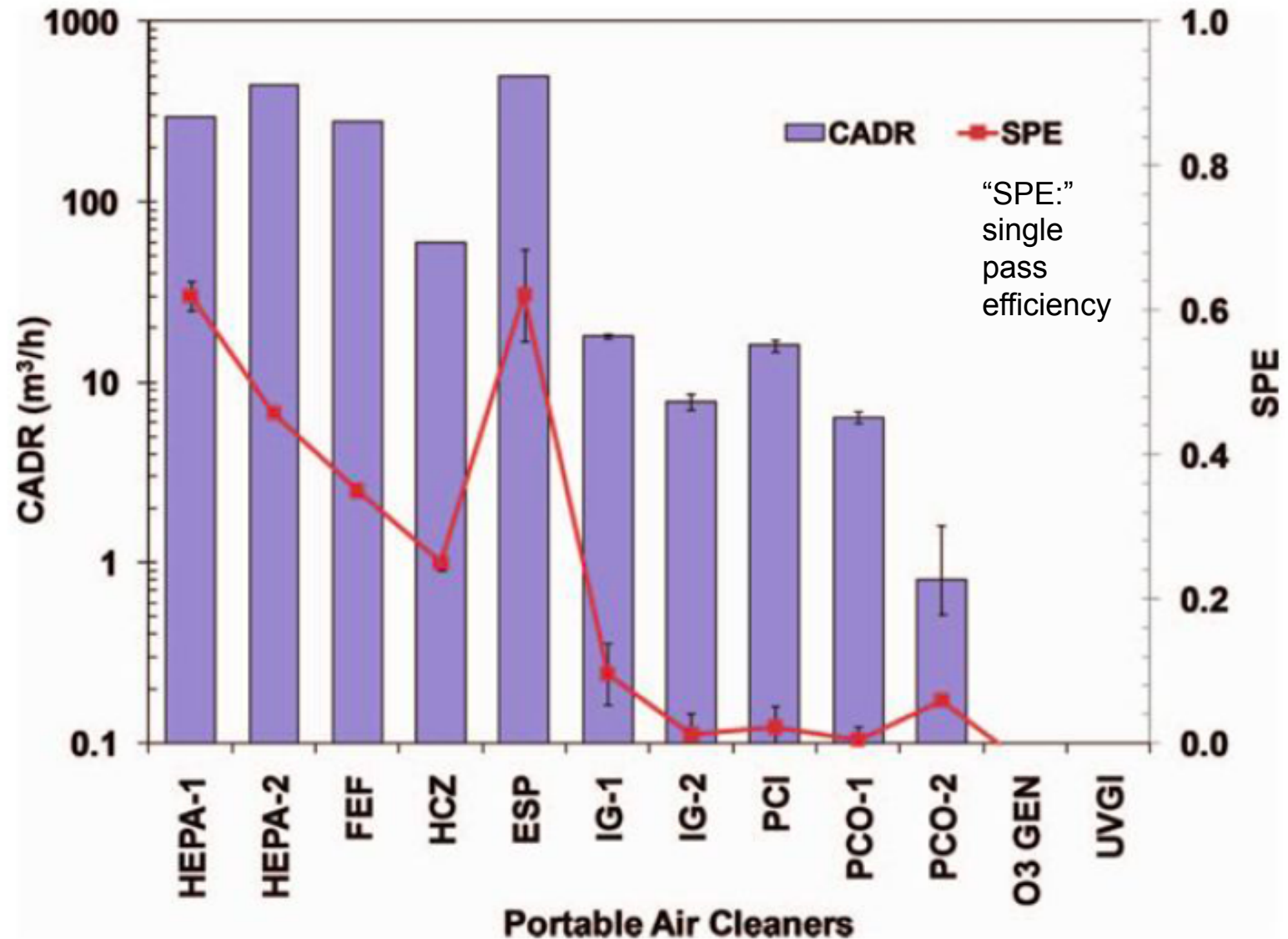




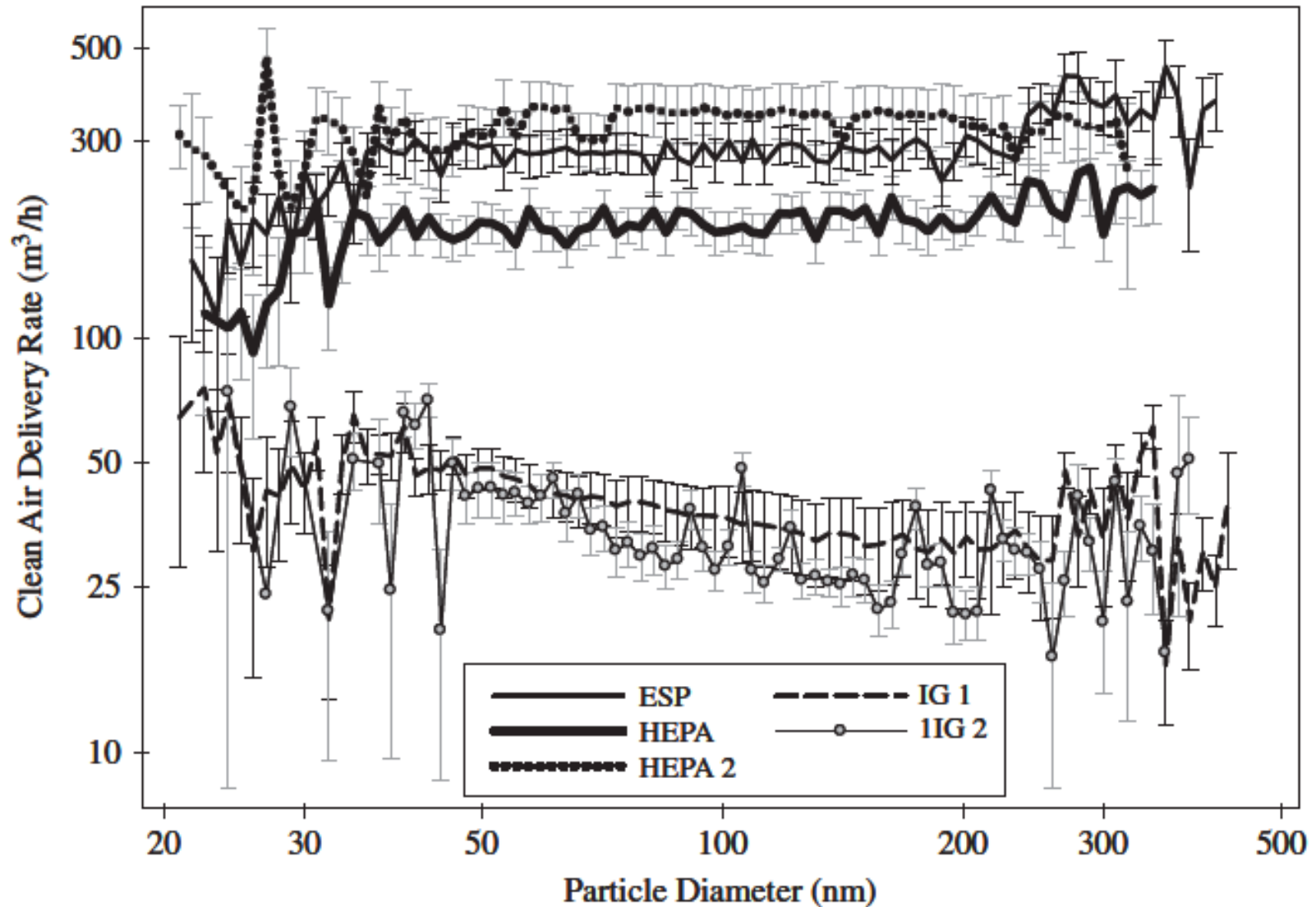
# Recent testing of portable air cleaners



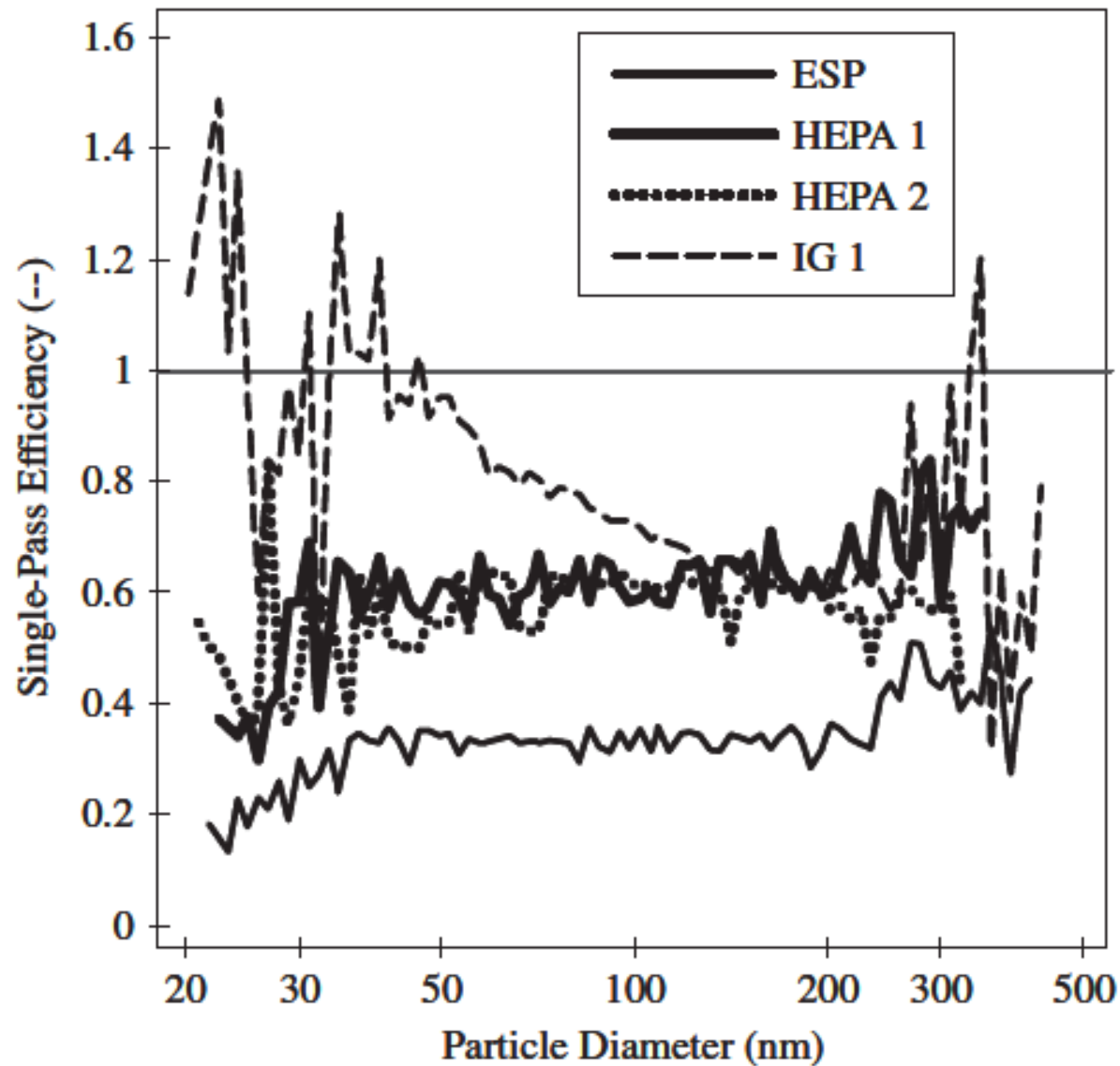
# Recent testing of portable air cleaners: UFPs



# Recent testing of portable air cleaners



# Recent testing of portable air cleaners

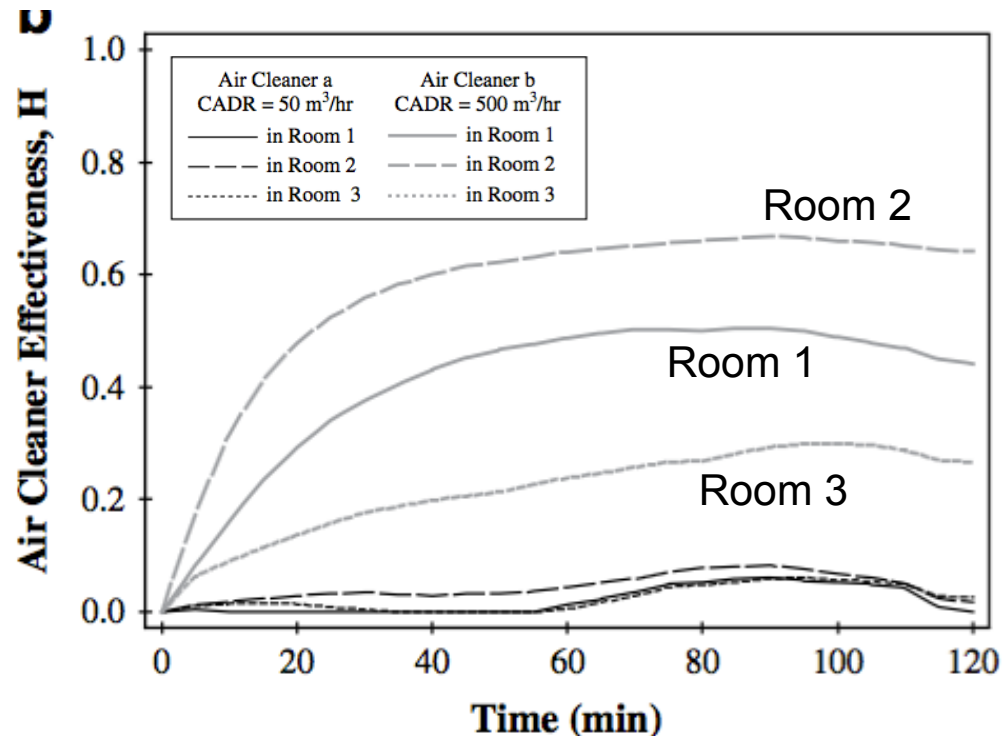
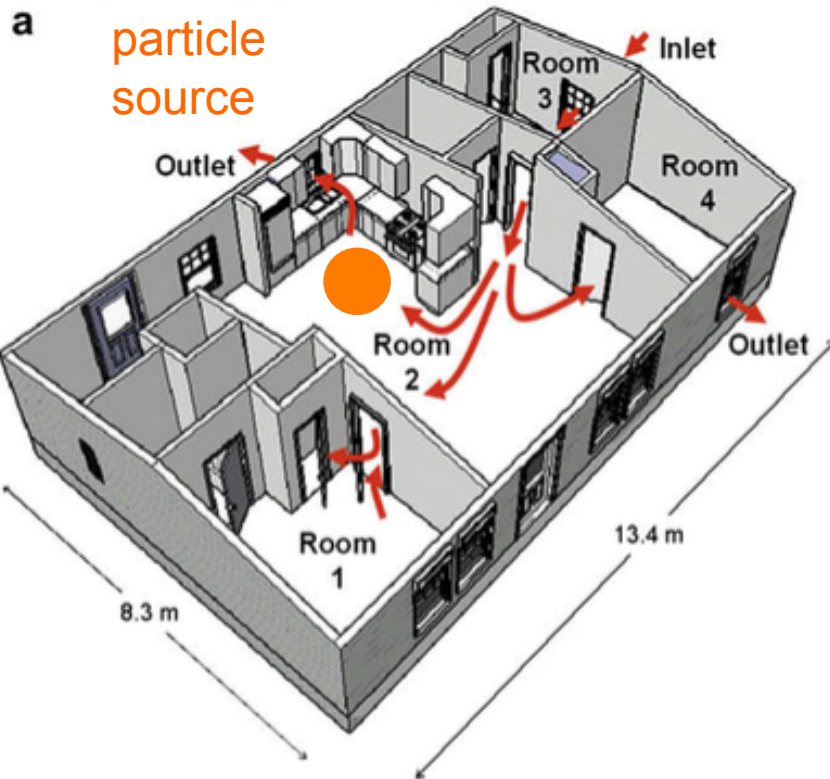


# Air cleaner effectiveness

- Air cleaner location will obviously influence its **effectiveness** in indoor environments
- We define effectiveness as follows:

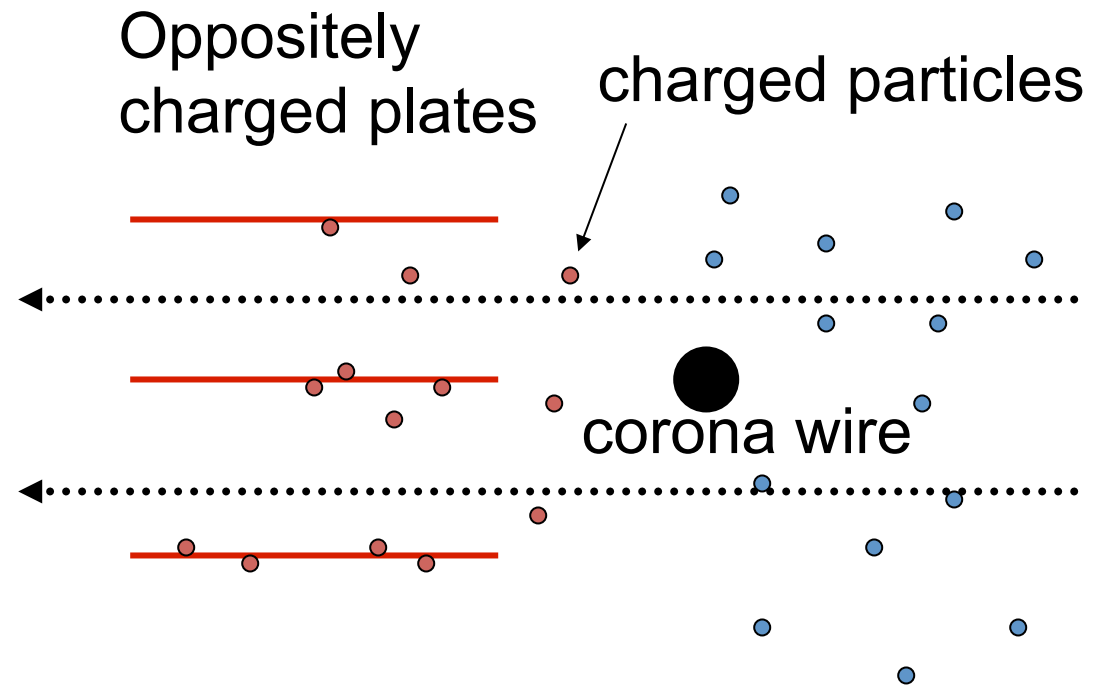
$$1 - \frac{C_{ac}}{C_{no\ ac}}$$

Indoor  
particle  
source



# Ozone emissions for electronic air cleaners

- “Ion generating air cleaners” and electrostatic precipitators
  - Utilize high voltage to ‘excite’ oxygen (make singlet O out of O<sub>2</sub>)
  - O<sub>2</sub> then forms with O to form O<sub>3</sub> (ozone)





# Ozone emissions from electronic air cleaners

- Ozone generation rates

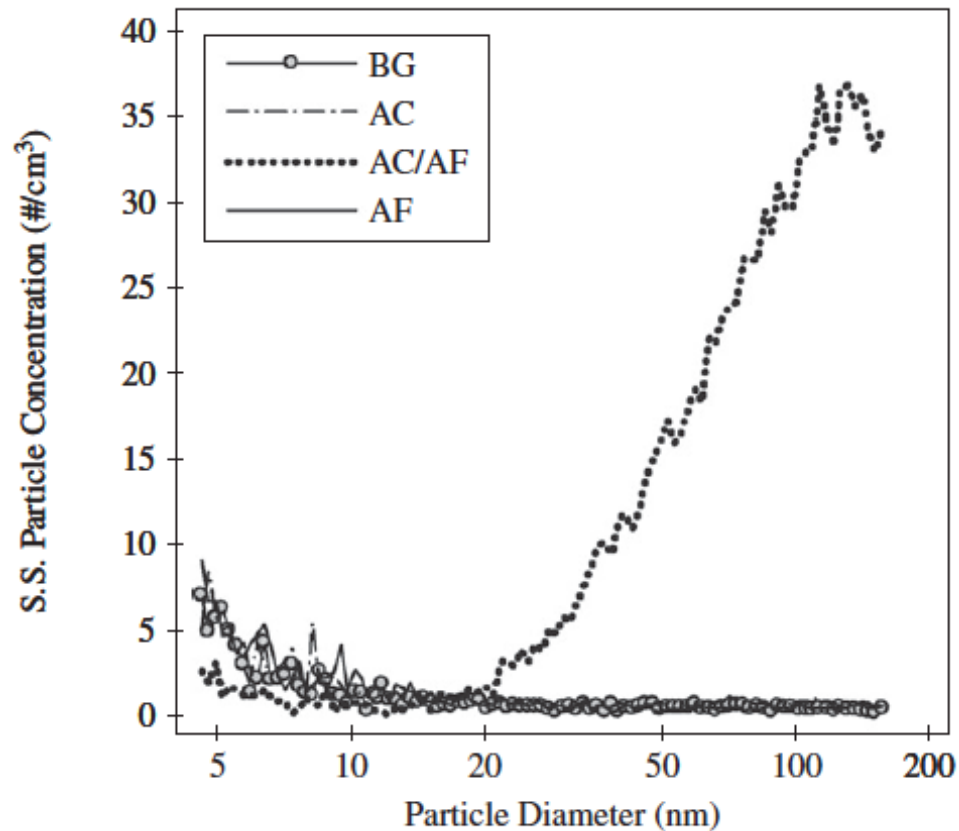
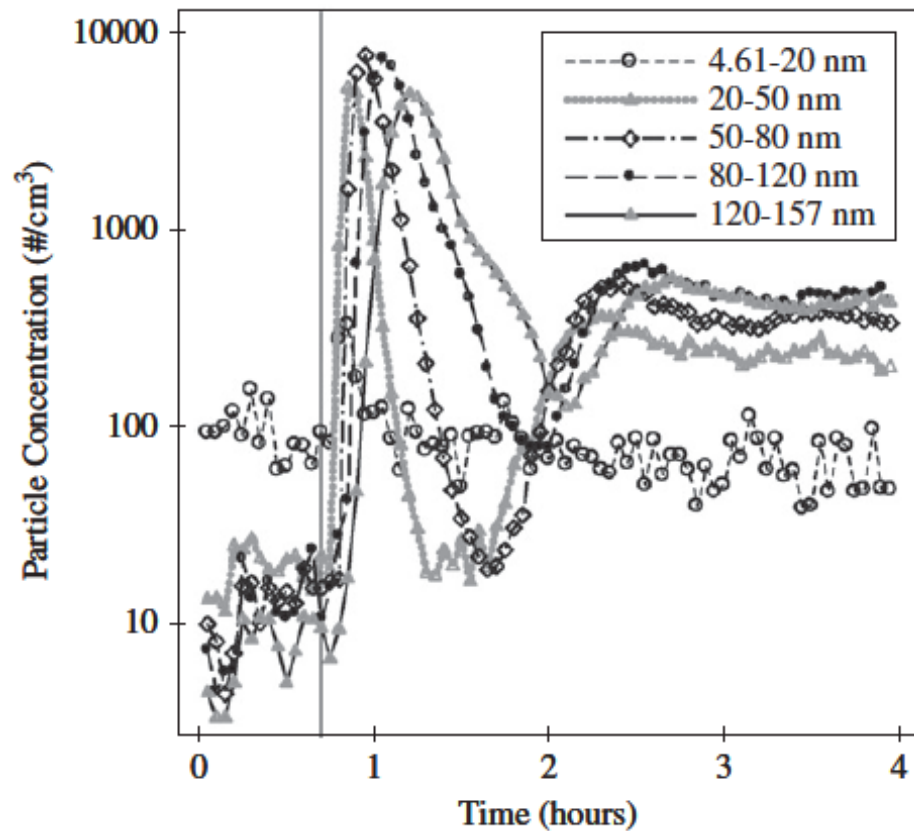
Ozone emission rates for ionizers tested in the first phase, as well as predicted ozone concentration increases,  $C^*$ , and equivalent outdoor ozone increases,  $\Delta C_{out}$ , for a hypothetical residential  $50\text{m}^3$  room and  $392\text{m}^3$  home

Air cleaner	Ozone emission rate ( $\text{mg h}^{-1}$ )	$V = 50\text{m}^3$		$V = 392\text{m}^3$	
		$C^*$ (ppb)	$\Delta C_{out}$ (ppb)	$C^*$ (ppb)	$\Delta C_{out}$ (ppb)
ESP	$3.8 \pm 0.2$	8.6	77	1.1	9.9
IG 1	$3.3 \pm 0.2$	7.5	67	1.0	8.6
IG 2	$4.3 \pm 0.2$	9.7	88	1.2	11

- Byproduct formation from reactions between ozone and terpene products
  - Formation products include SOA (secondary organic aerosols)
  - This means your particle removing air cleaner can lead to generation of particles!

# Ozone emissions from electronic air cleaners and SOA

Operating an ozone generation air cleaner in the presence of terpene based products leads to formation of particles!





# More resources on filtration

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- ASHRAE Standard 52.2
- ASHRAE Technical Committee 2.4 Particulate Air Contaminants and Particulate Contaminant Removal Equipment
  - <https://www.ashrae.org/standards-research--technology/technical-committees/section-2-0-environmental-quality/tc-2-4-particulate-air-contaminants-and-particulate-contaminant-removal-equipment>
- National Air Filtration Association (NAFA)
  - <http://www.nafahq.org>
- EPA Guide to Air Cleaners
  - <http://www.epa.gov/iaq/aircleaners/>