ENVE 576
Indoor Air Pollution
Fall 2015

Week 10: October 27, 2015
Particulate matter: Filtration and air cleaners

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Scheduling updates

- Guest lecture last week
- HW 4 due this Friday
- Take-home exam will be released next week
- Final project teams and topics:

Team	Project
Weisheng Bu and Saeid Khodaei	Indoor formaldehyde emissions/transport
Qindong Guo and Zhe Zhang	Plants as air cleaners
Han Jiang and Jiayao Xu	IAQ in developing countries
Juntao Li and Xuexuan Peng	Natural ventilation and IAQ
Jinzhe Liang and Luanzhizi Qiu	Residential IAQ and CONTAM
Xiangmin Liang and Xingchao Zhao	Penetration of roadway pollutants
Roger Fortune	Noise pollution
Westen Knudsen	Dioxins from trash burning outdoors
Prasad Naik	Soil vapor intrusion

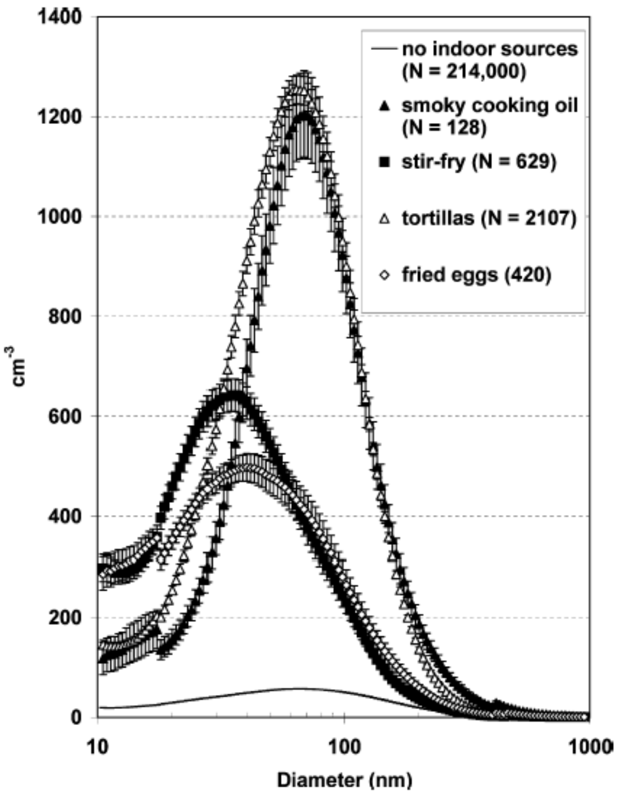
Question about final paper/presentation

- Our final presentations are scheduled for Tuesday night, December 8, 5-7 PM
- I have to be in Washington, DC on December 8-9
- We have a few options:
  1. Reschedule our presentations and keep them as 25% of your grade
     - The week before (canceling a class)
     - During exam week (perhaps Monday)
  2. Cancel our presentations and count only the final paper

Last time

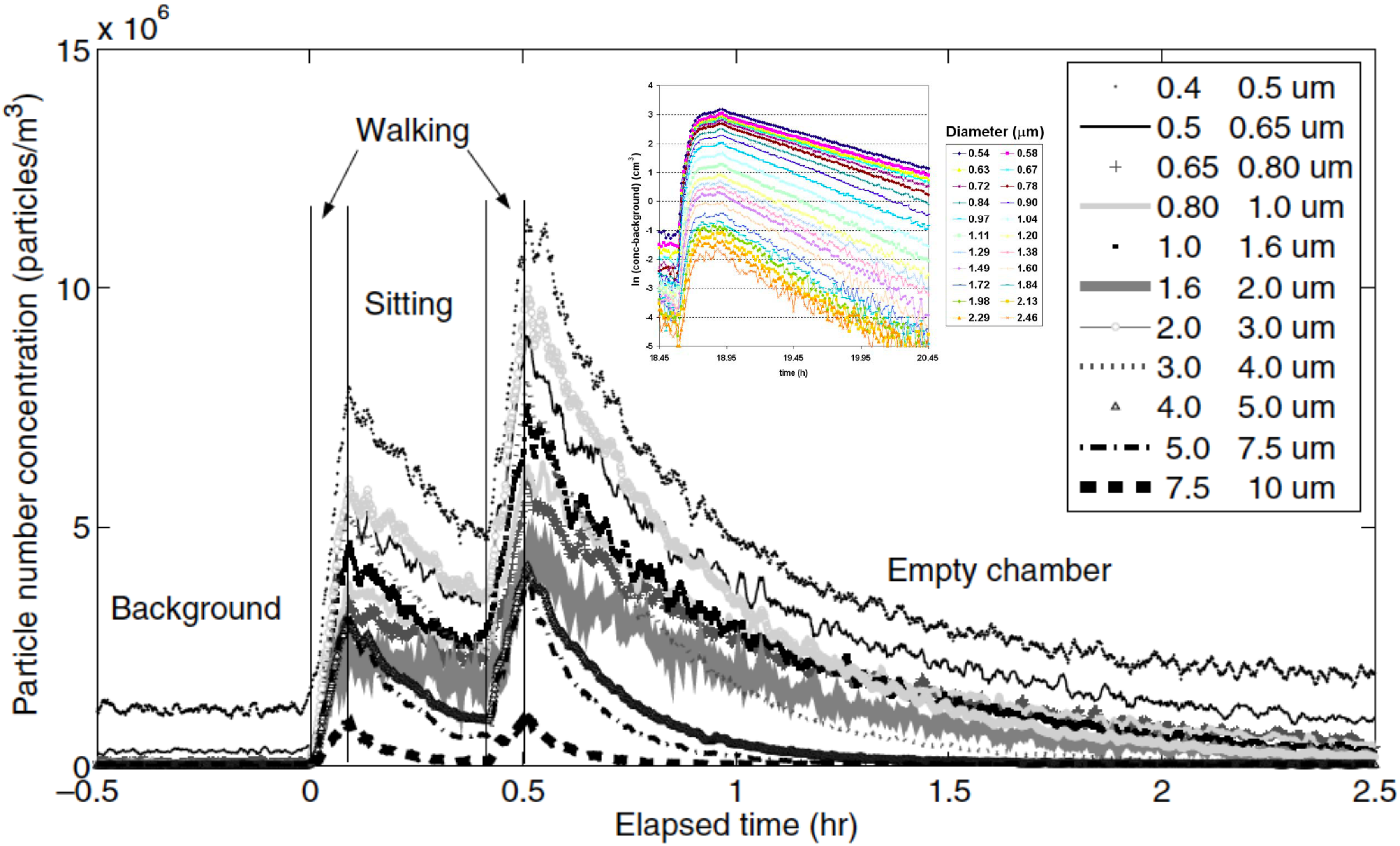
- Particle sources/emissions
- Particle resuspension
- Particle deposition
- Particle infiltration from outdoors

Particle emissions

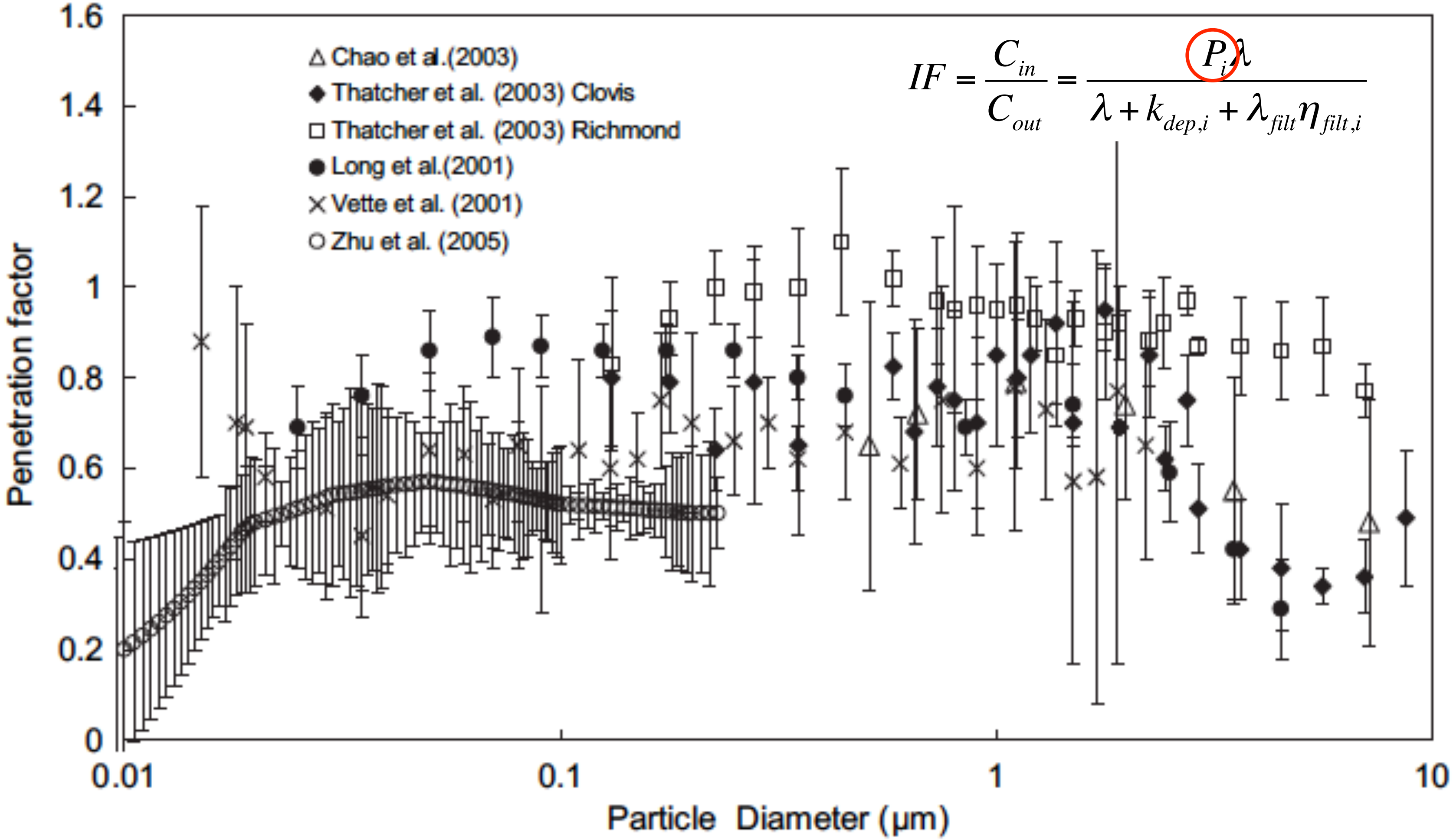


UFP emitting device	Size range	Emission rate (#/min)	Reference
Flat iron with steam	20-1000 nm	6.0×10^{9}	Afshari et al. (2005)
Electric frying pan	10-400 nm	$1.1\text{-}2.7\times10^{10}$	Buonnano et al. (2009)
3D printer w/ PLA	10-100 nm	$\sim2.0\times10^{10}$	Stephens et al. (2013)
Vacuum cleaner	20-1000 nm	3.5×10^{10}	Afshari et al. (2005)
Scented candles	20-1000 nm	8.8×10^{10}	Afshari et al. (2005)
Gas stove	20-1000 nm	1.3×10^{11}	Afshari et al. (2005)
3D printer w/ ABS	10-100 nm	$\sim1.9\times10^{11}$	Stephens et al. (2013)
Cigarette	20-1000 nm	3.8×10^{11}	Afshari et al. (2005)
Electric stove	20-1000 nm	6.8×10^{11}	Afshari et al. (2005)
Frying meat	20-1000 nm	8.3×10^{11}	Afshari et al. (2005)
Radiator	20-1000 nm	8.9×10^{11}	Afshari et al. (2005)
Laser printers	6-3000 nm	4.3×10^{9} to 3.3×10^{12}	He et al. (2010)
Cooking on a gas stove	10-400 nm	$1.1\text{-}3.4\times10^{12}$	Buonnano et al. (2009)

Particle resuspension and deposition



Outdoor particle infiltration



$$IF = \frac{C_{in}}{C_{out}} = \frac{P_i \lambda}{\lambda + k_{dep,i} + \lambda_{filt}\eta_{filt,i}}$$

Today’s topics

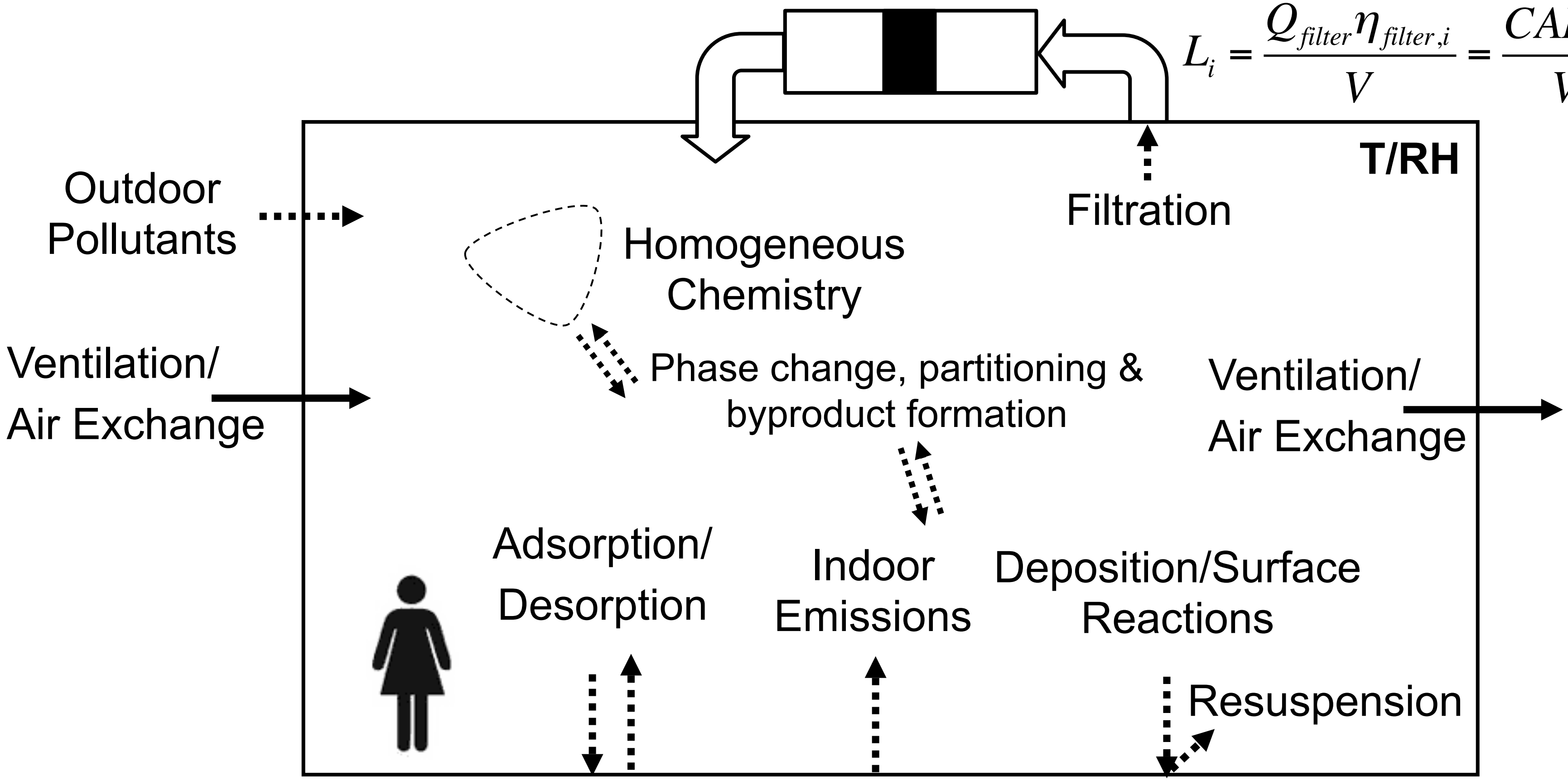
- Particle filtration: HVAC filters and stand-alone air cleaners

PARTICLE FILTRATION

Indoor environment: Mass balance

Loss rate for particle size *i*:

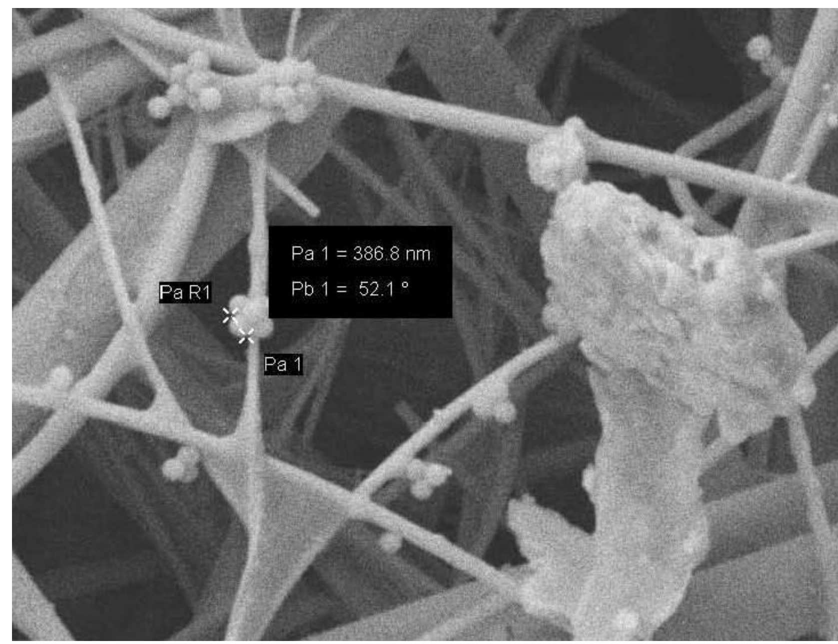
$$L_i = \frac{Q_{filter}\eta_{filter,i}}{V} = \frac{CADR_i}{V}$$



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



http://www.nasa.gov/mission_pages/station/research/experiments/ISS_High_Efficiency_%20Particle_Filter_Analysis1.jpg

What is the purpose of a filter?

- 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

- Fibrous filters are mostly air
  - Porosity ranging from ~70% to ~99%
  - Fibers range in size from < 1 μm to 100 μm

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

Hinds et al., 1999 *Aerosol Technology* Chapter 9: Filtration

Important filter terminology

- Efficiency (*E* , *η*)

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

- Penetration (*P*) = 1 - *η*

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

- Face velocity (U_0)

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

- Velocity inside filter (*U*)
  - Higher than U_0

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

- Solidity (*α*) = (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?*

Hinds et al., 1999 *Aerosol Technology* Chapter 9: Filtration

Fibrous filter capture

- 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 (γ):

$$n_c = N\gamma dt$$

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

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

Hinds et al., 1999 *Aerosol Technology* Chapter 9: Filtration

Fibrous filter capture

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

- Integrating:

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

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

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

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

γ depends on particle size, face velocity, solidity, and fiber size

Particle penetration decreases (filtration efficiency increases) exponentially with thickness

Hinds et al., 1999 *Aerosol Technology* Chapter 9: Filtration

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)

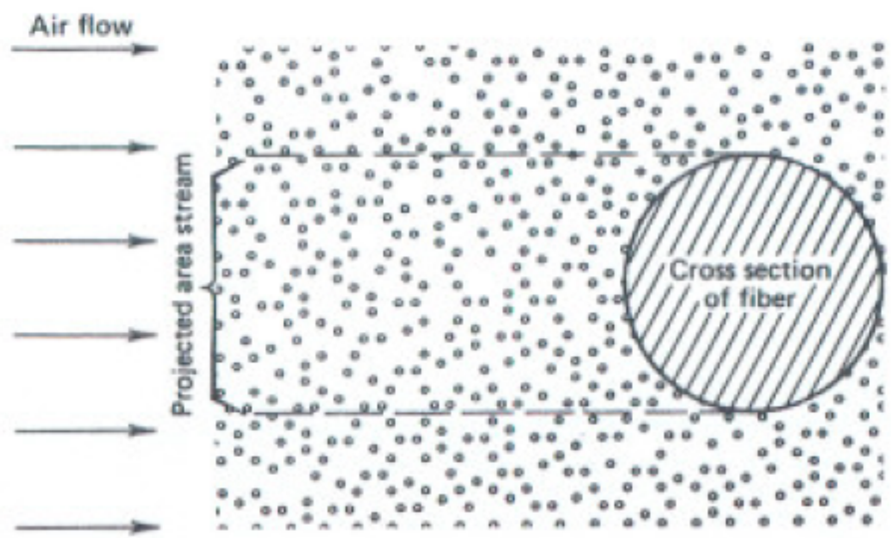
Flow around a filter fiber with diameter d_f:

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

ρ_g = gas (air) density
d_f = fiber diameter
U = air velocity
μ = viscosity
**Laminar under most conditions*

E_Σ = single fiber efficiency

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



Hinds et al., 1999 *Aerosol Technology* Chapter 9: Filtration

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

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

- 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:

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

α = solidity
E_Σ = single fiber efficiency
t = thickness

Hinds et al., 1999 *Aerosol Technology* Chapter 9: Filtration

Deposition mechanisms for single fiber removal

- 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
    - $0.1 < d_f < 50$ μm
    - $Re_f < 1$ (laminar)

Hinds et al., 1999 *Aerosol Technology* Chapter 9: Filtration

Interception

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

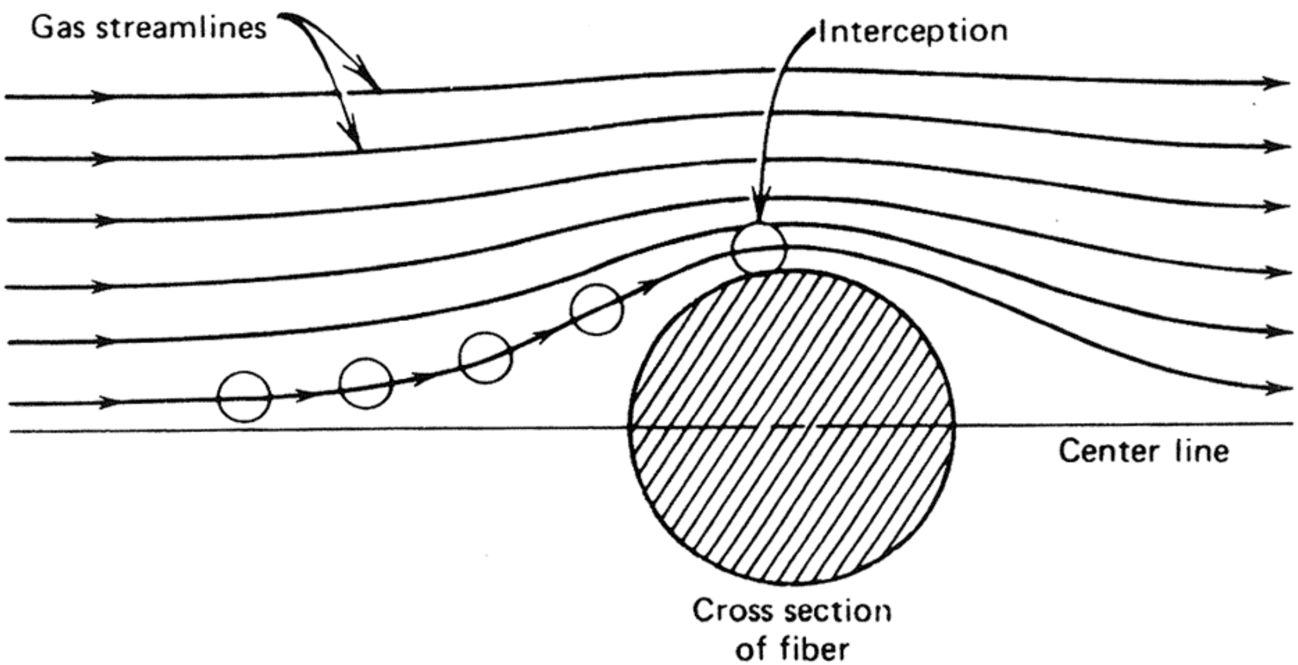


FIGURE 9.5 Single-fiber collection by interception.

Hinds et al., 1999 *Aerosol Technology* Chapter 9: Filtration

Single fiber interception (E_R)

- Interception depends on *R*, *α*, and *Ku*
  - Note lack of dependence on velocity

$$E_R \le 1 + R$$

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

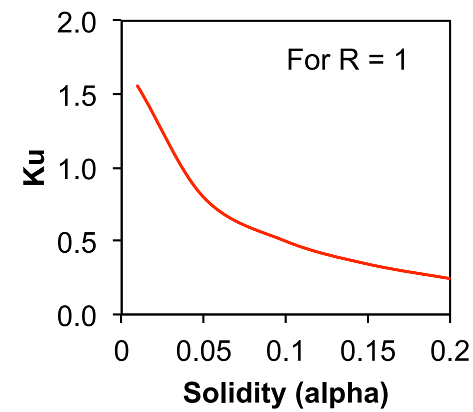
$$R = \frac{d_p}{d_f}$$

d_f = fiber diameter
d_p = particle diameter
α = 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

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



Hinds et al., 1999 *Aerosol Technology* Chapter 9: Filtration

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

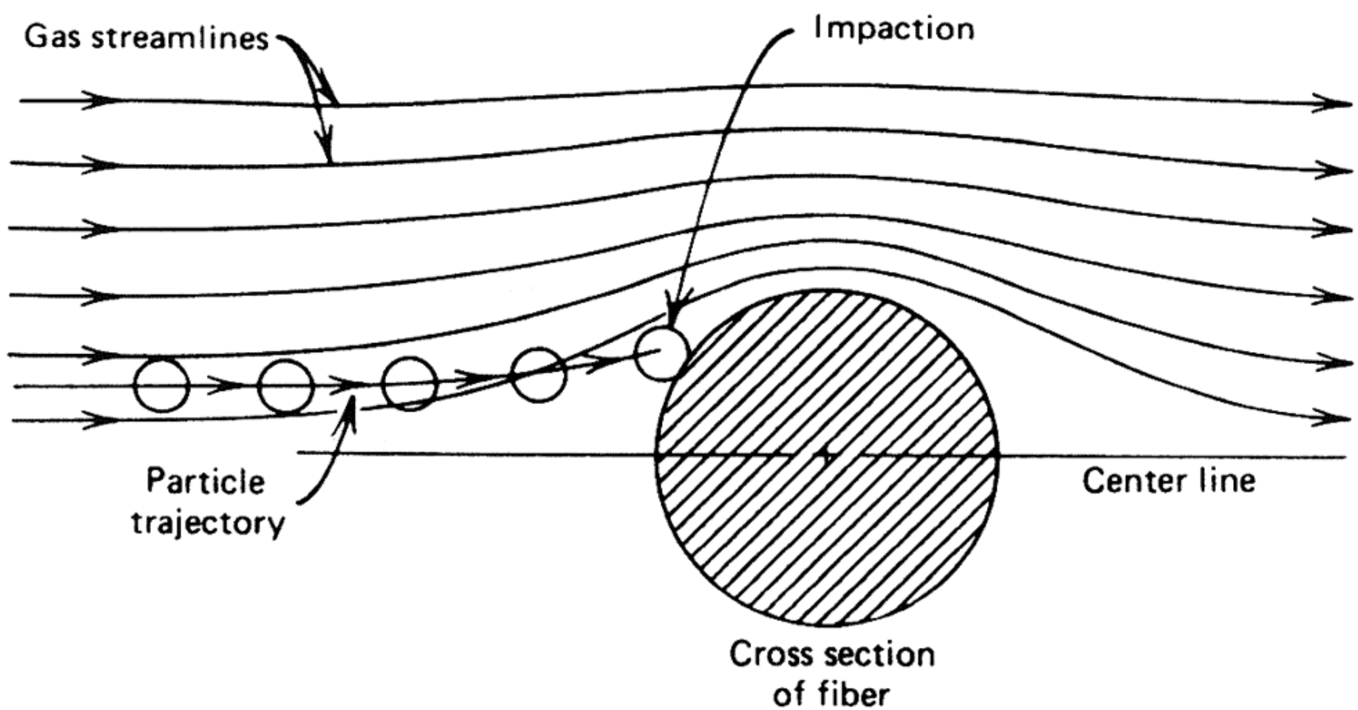


FIGURE 9.6 Single-fiber collection by impaction.

Hinds et al., 1999 *Aerosol Technology* Chapter 9: Filtration

Single fiber impaction (E_I)

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

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

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

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

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

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
η = air viscosity
ρ_p = particle density
C_c = Cunningham correction factor
α = solidity

Hinds et al., 1999 *Aerosol Technology* Chapter 9: Filtration

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

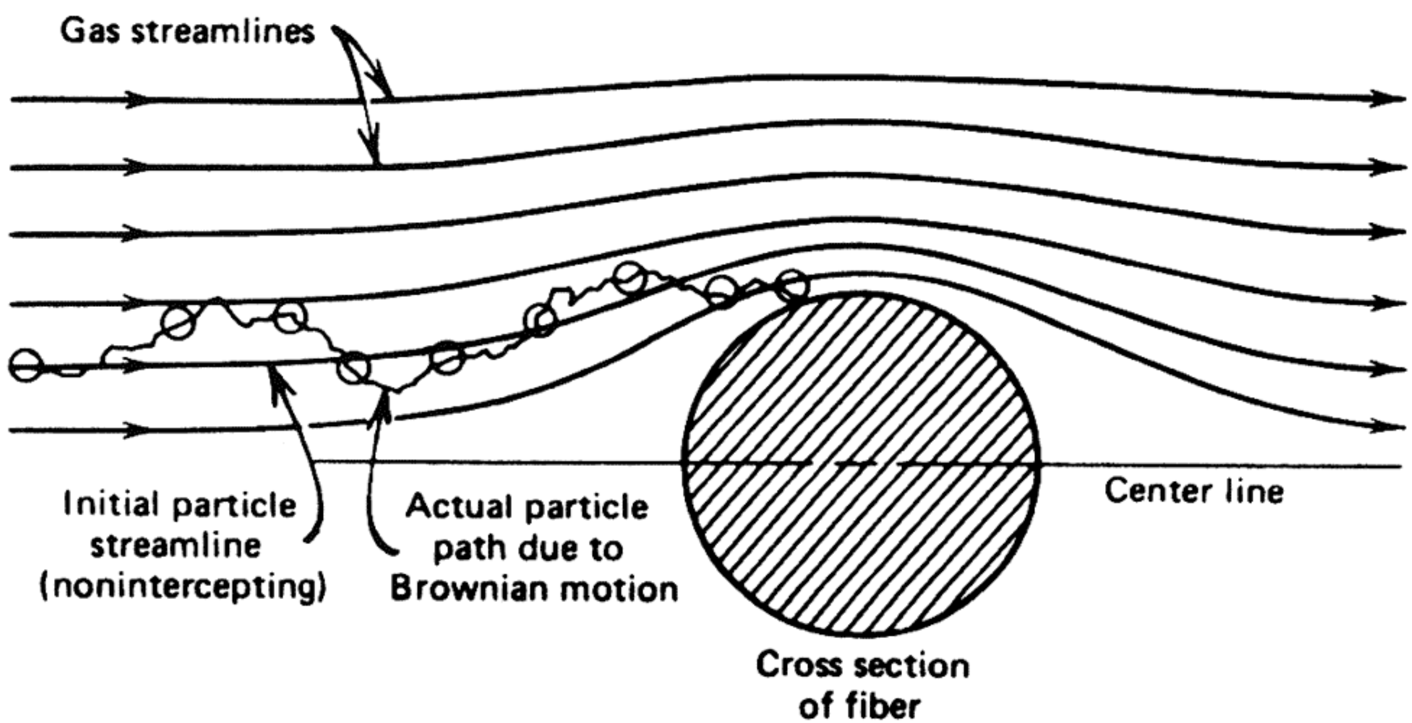


FIGURE 9.7 Single-fiber collection by diffusion.

Hinds et al., 1999 *Aerosol Technology* Chapter 9: Filtration

Single fiber diffusion (E_D)

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

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

Dimensionless diffusion parameter

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

Pe = Peclet number
d_f = fiber diameter
U_0 = face velocity
D = particle diffusion coefficient
α = solidity
k = Boltzmann's constant (1.38 x 10^{-23} m^2 kg s^{-2} K^{-1})
T = temperature (K)
η = viscosity (kg/s-m)

Diffusion is the only single-fiber collection mechanism that <u>increases</u> as particle diameter decreases

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:

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

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

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

Hinds et al., 1999 *Aerosol Technology* Chapter 9: Filtration

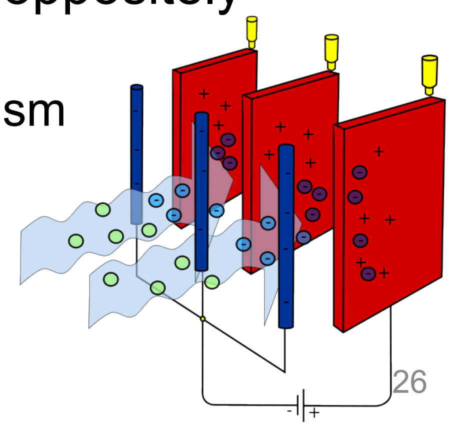
Other Mechanisms

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

$$G = \frac{V_{TS}}{U_0}$$

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

- 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



Hinds et al., 1999 *Aerosol Technology* Chapter 9: Filtration

Putting it all together: combined filter efficiency

- 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:

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

Hinds et al., 1999 *Aerosol Technology* Chapter 9: Filtration

Total efficiency for an example filter

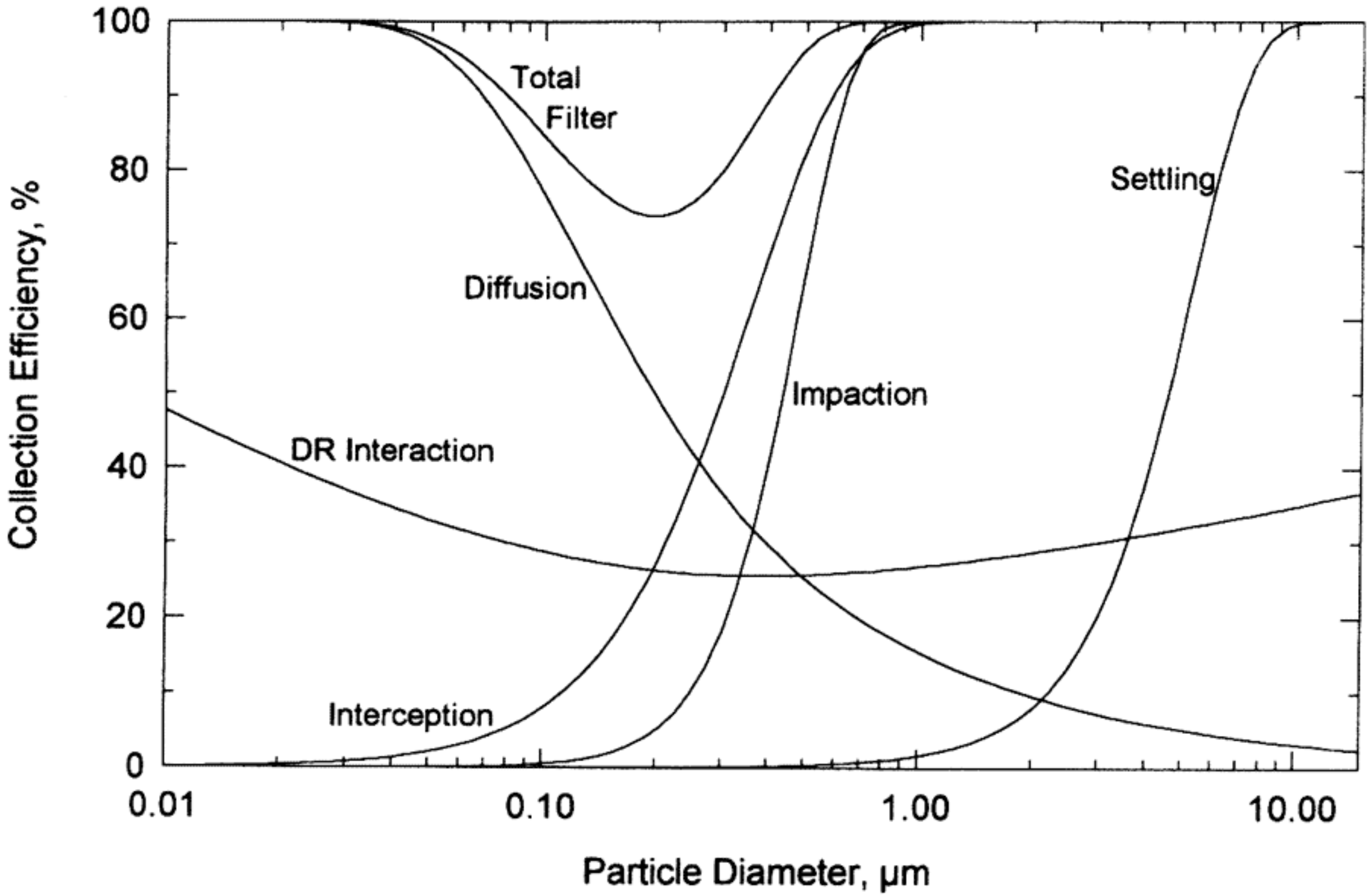


FIGURE 9.8 Filter efficiency for individual single-fiber mechanisms and total efficiency; t = 1 mm, α = 0.05, d_f = 2 µm, and U_0 = 0.10 m/s. [10 cm/s].

Filter efficiency and face velocity

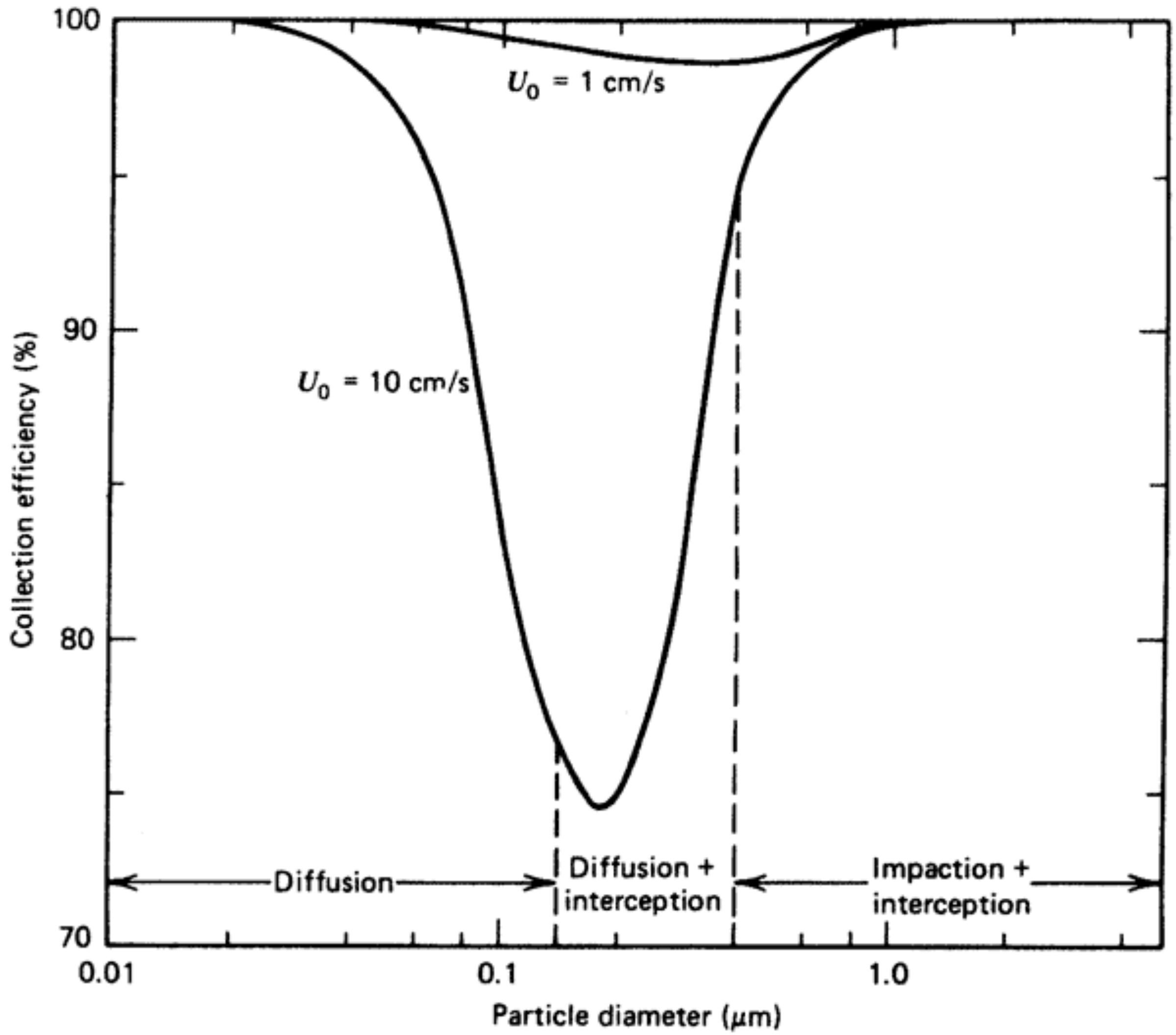
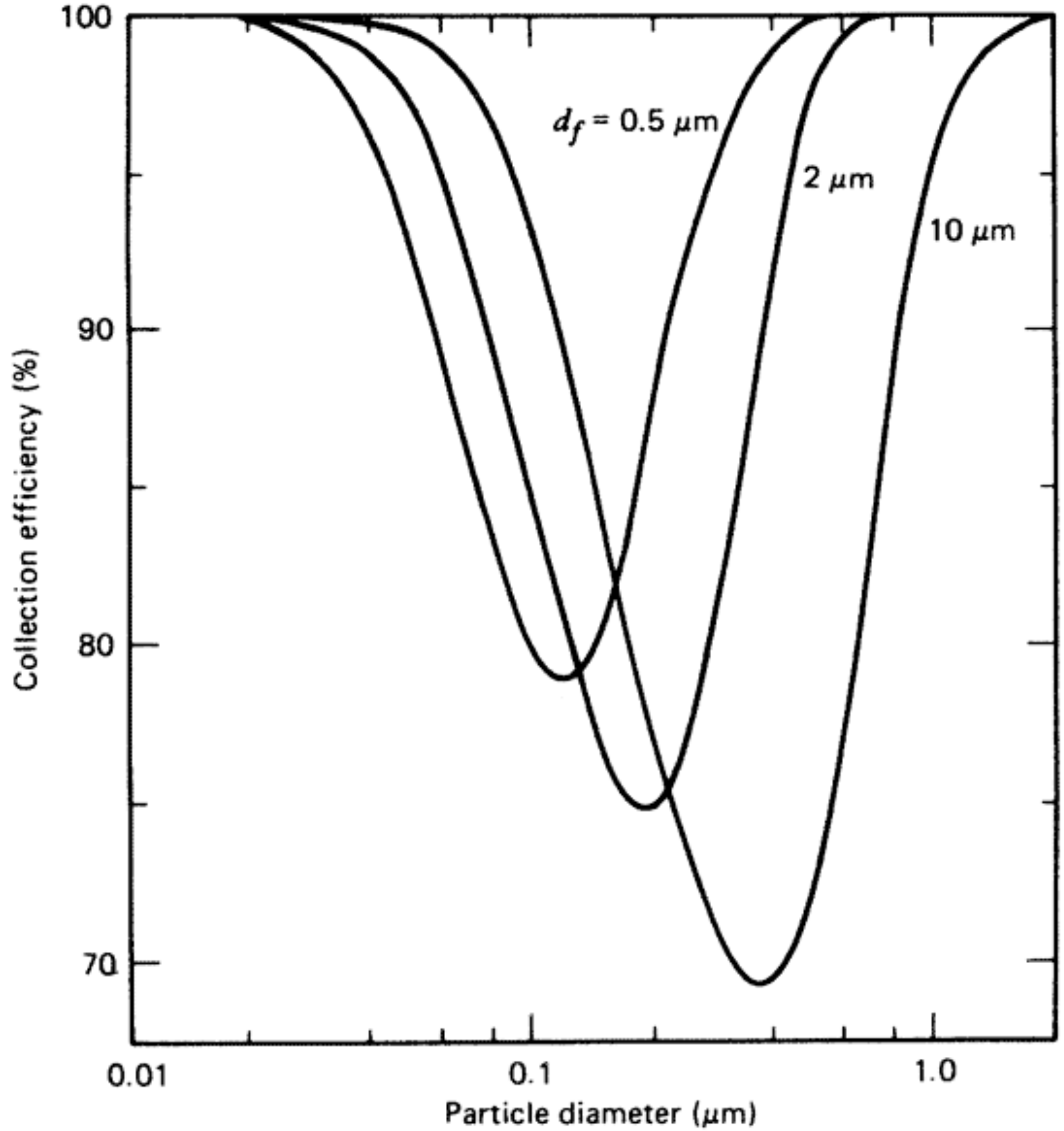


FIGURE 9.9 Filter efficiency versus particle size for face velocities of 0.01 and 0.1 m/s [1 and 10 cm/s]; $t = 1$ mm, $\alpha = 0.05$, and $d_f = 2$ μm.

Hinds et al., 1999 *Aerosol Technology* Chapter 9: Filtration

Filter efficiency for various d_f



Hinds et al., 1999 *Aerosol Technology* Chapter 9: Filtration

Filter pressure drop

- 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* Δp
- Quasi-empirical formulation:

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

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

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

Δp = pressure drop (Pa)
μ = dynamic viscosity (Pa·s)
d_f = fiber diameter (m)
U_0 = face velocity (m/s)
α = solidity (-)
t = thickness (m)

TABLE 9.1 Characteristics of Some Common Aerosol-Sampling Filter Materials

Filter	Type	Material	Thickness (mm)	Fiber Diameter or Pore Diameter (μm)	Solidity	Pressure Drop[a] (kPa)	Efficiency[a,b]	Filter Quality[a,b] (kPa^{-1})
Whatman 41	Fiber	Cellulose	0.19	3–20	0.35	2.5[c]	72[c]	0.52
Nuclepore	CPM[d]	Polycarbonate	0.01	0.8	0.85	5.9	90[e]	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[c]	99.93[c]	3.70
Millipore AA	Membrane	Cellulose ester	0.15	0.8	0.19	9.5[c]	99.98[c]	0.93

[a]At U_0 = 0.27 m/s [27 cm/s].
[b]For d_p = 0.3 μm.
[c]From Lippmann (1995).
[d]CPM = capillary pore membrane.
[e]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

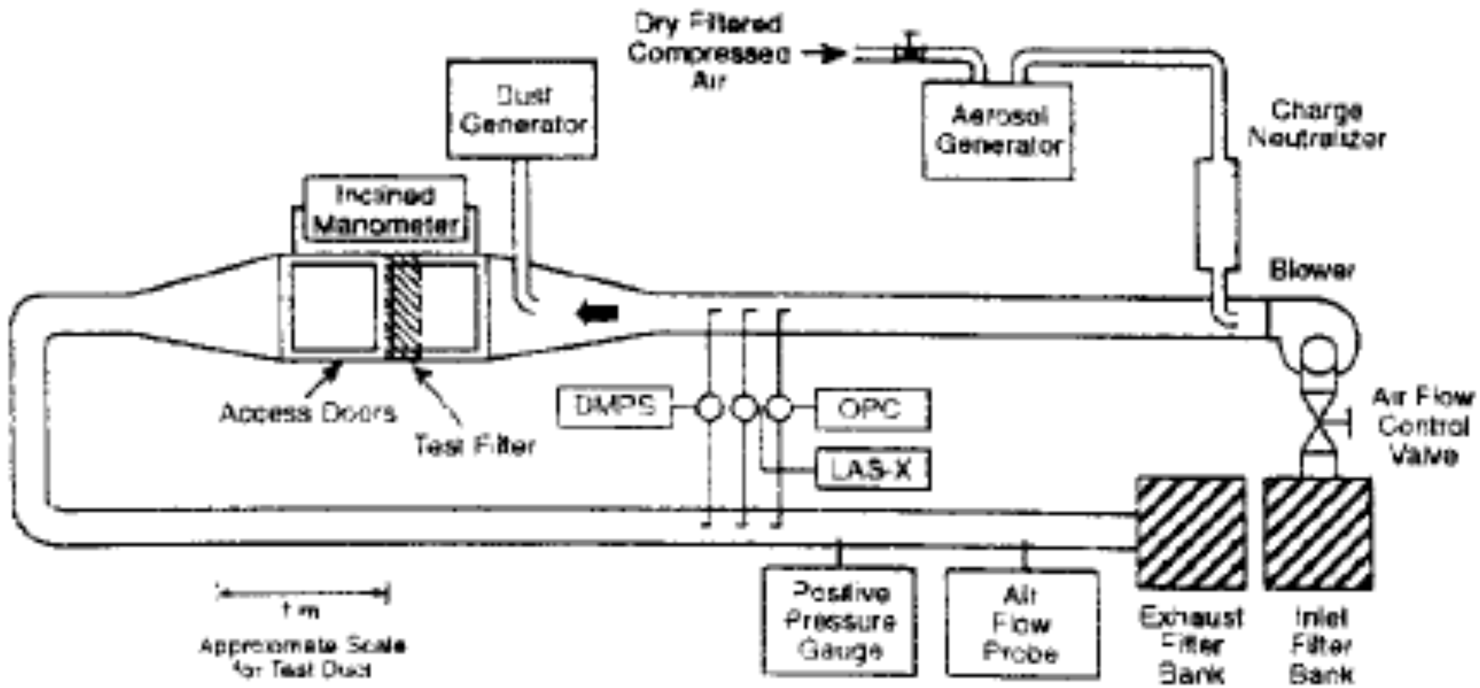


Fig. 1 Schematic diagram of RTI's air cleaner test facility

Hanley et al., 1994 *Indoor Air*

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

Hanley et al., 1994 *Indoor Air*

Filtration efficiency and filter type (old system)

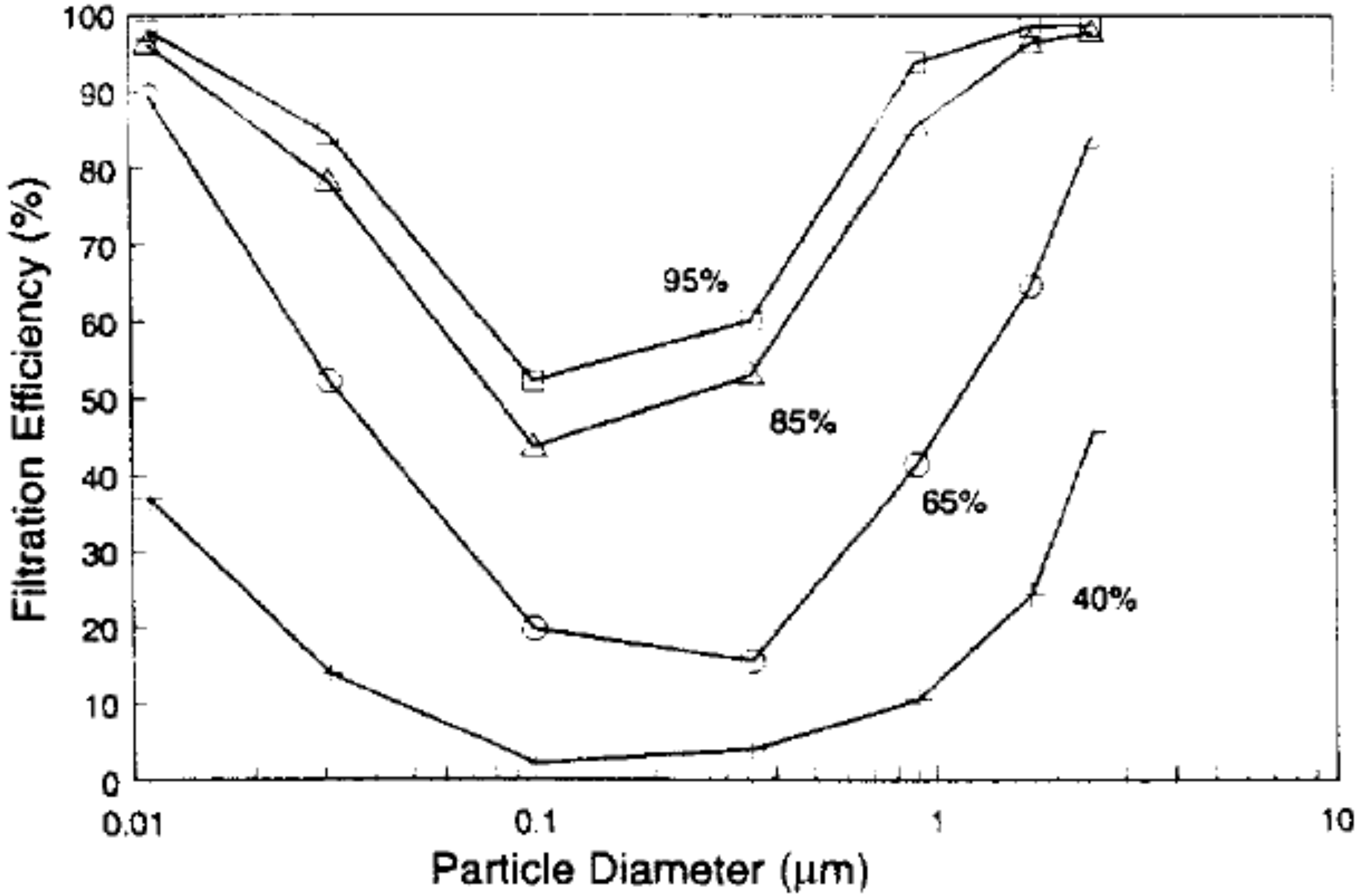


Fig. 2 Fractional filtration efficiency of four ASHRAE-rated filters at 1.3 m/s face velocity

Hanley et al., 1994 *Indoor Air*

Filter efficiency and dust loading

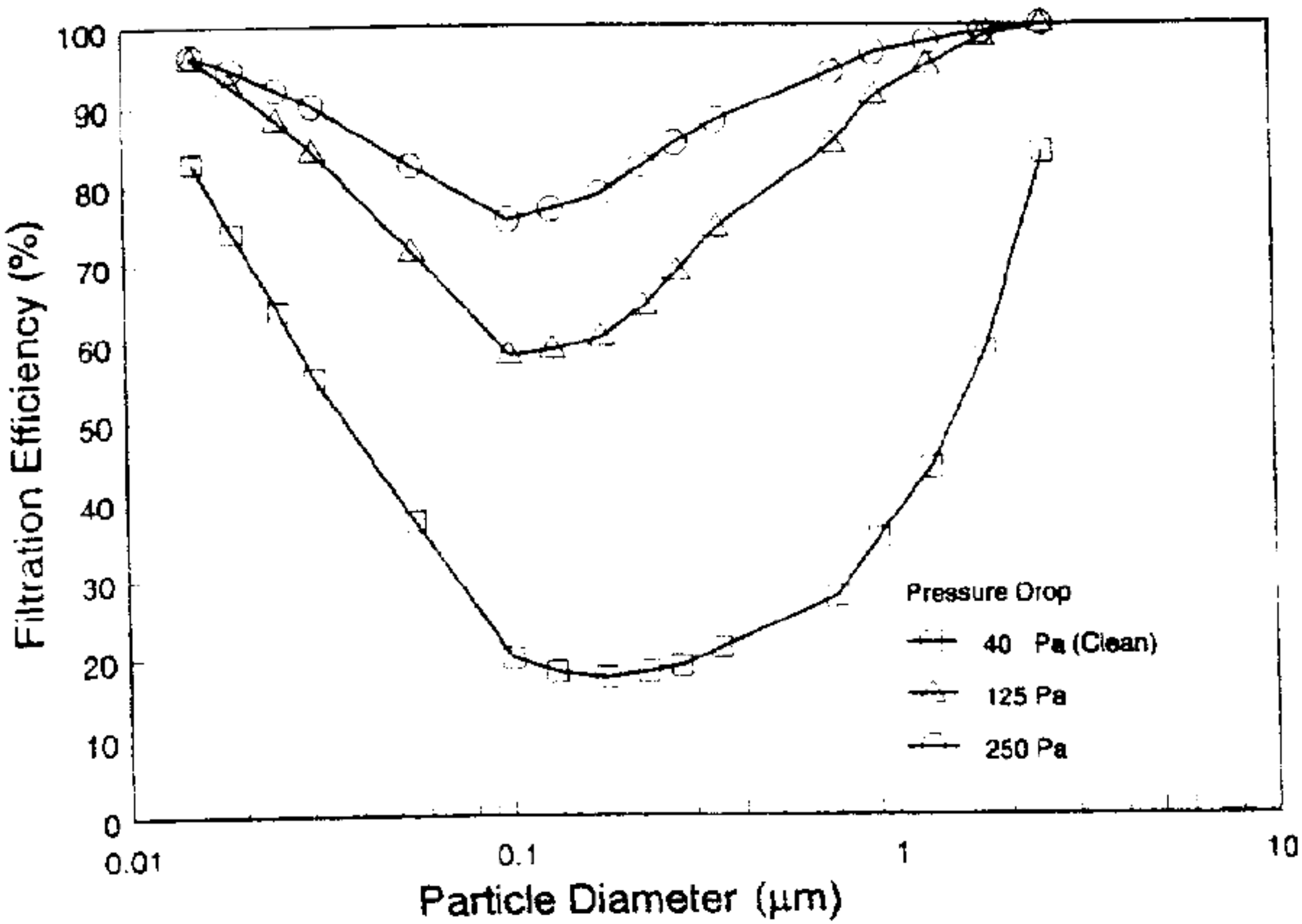
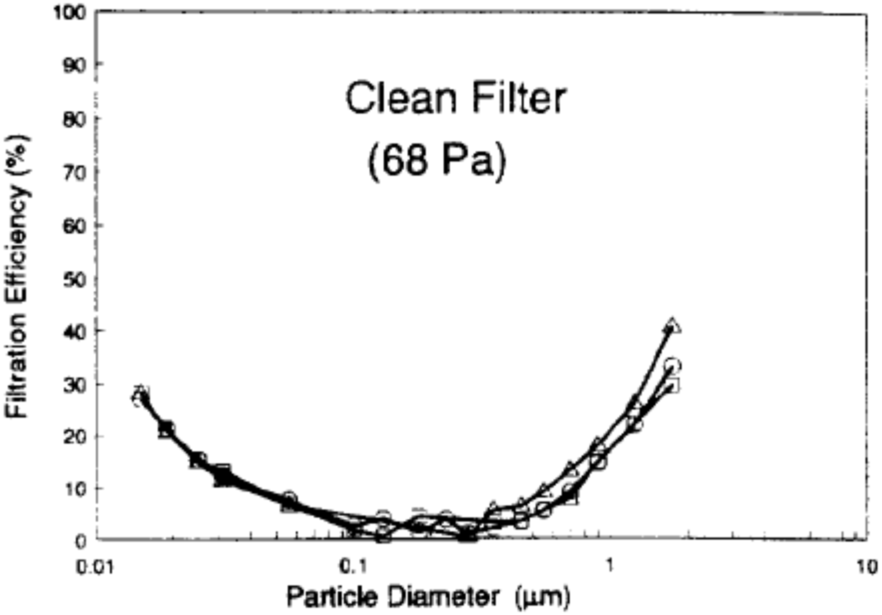
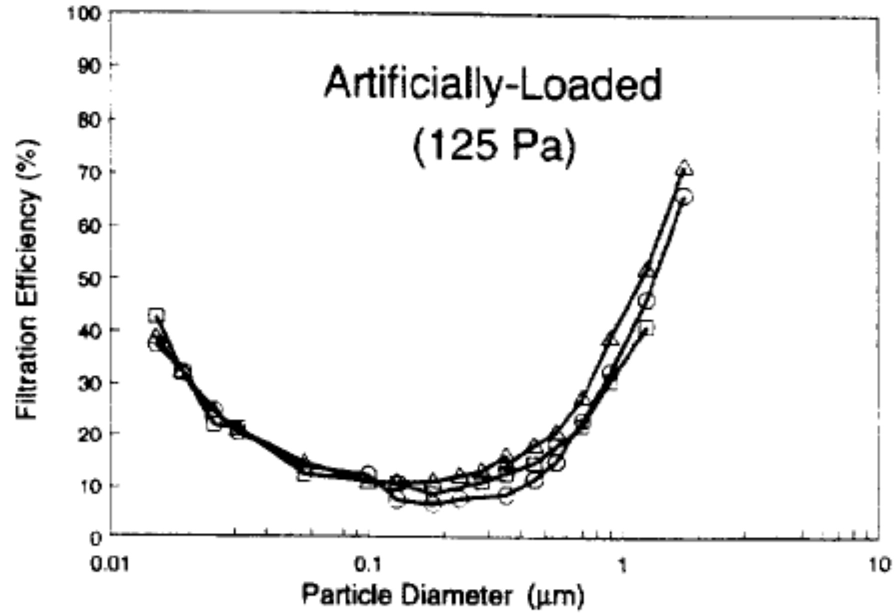


Fig. 7 The effect of dust load on the fractional filtration efficiency of a pleated paper filter at 1.3 m/s

Hanley et al., 1994 *Indoor Air*





Hanley et al., 1994 *Indoor Air*

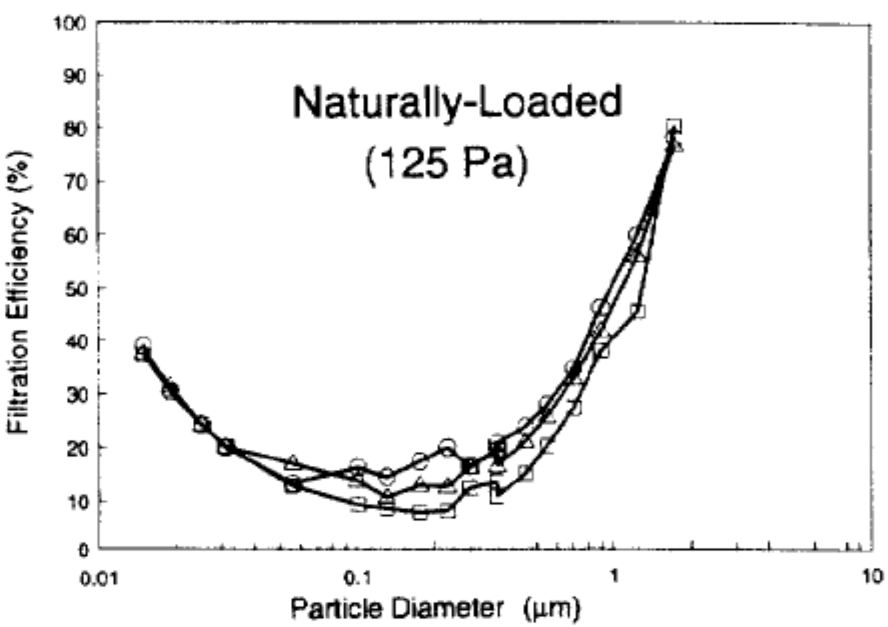


Fig. 5 Comparison of clean, artificially loaded, and naturally loaded fractional filtration efficiency for a pleated panel filter

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

- 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 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

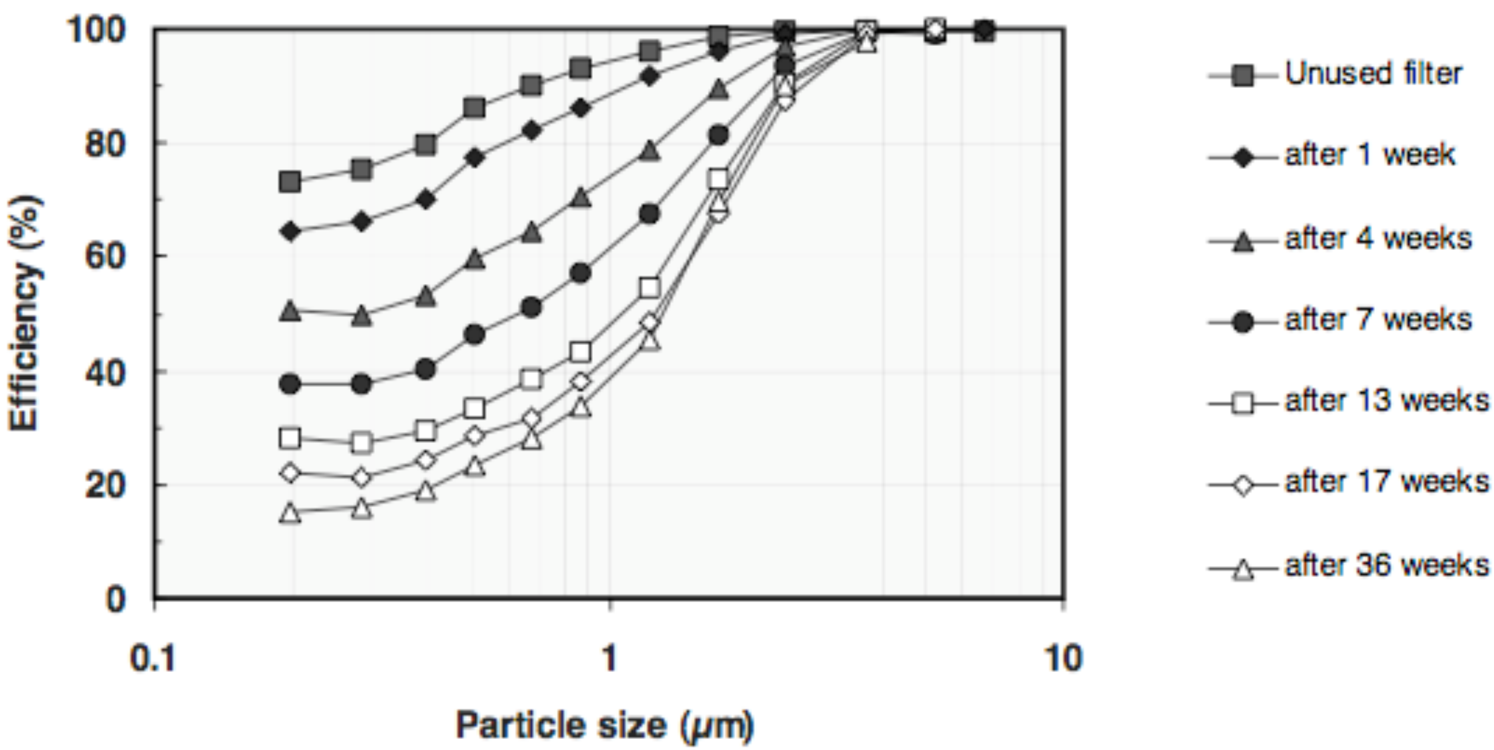
HEPA → 99.9% or greater removal efficiency for most particle sizes

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

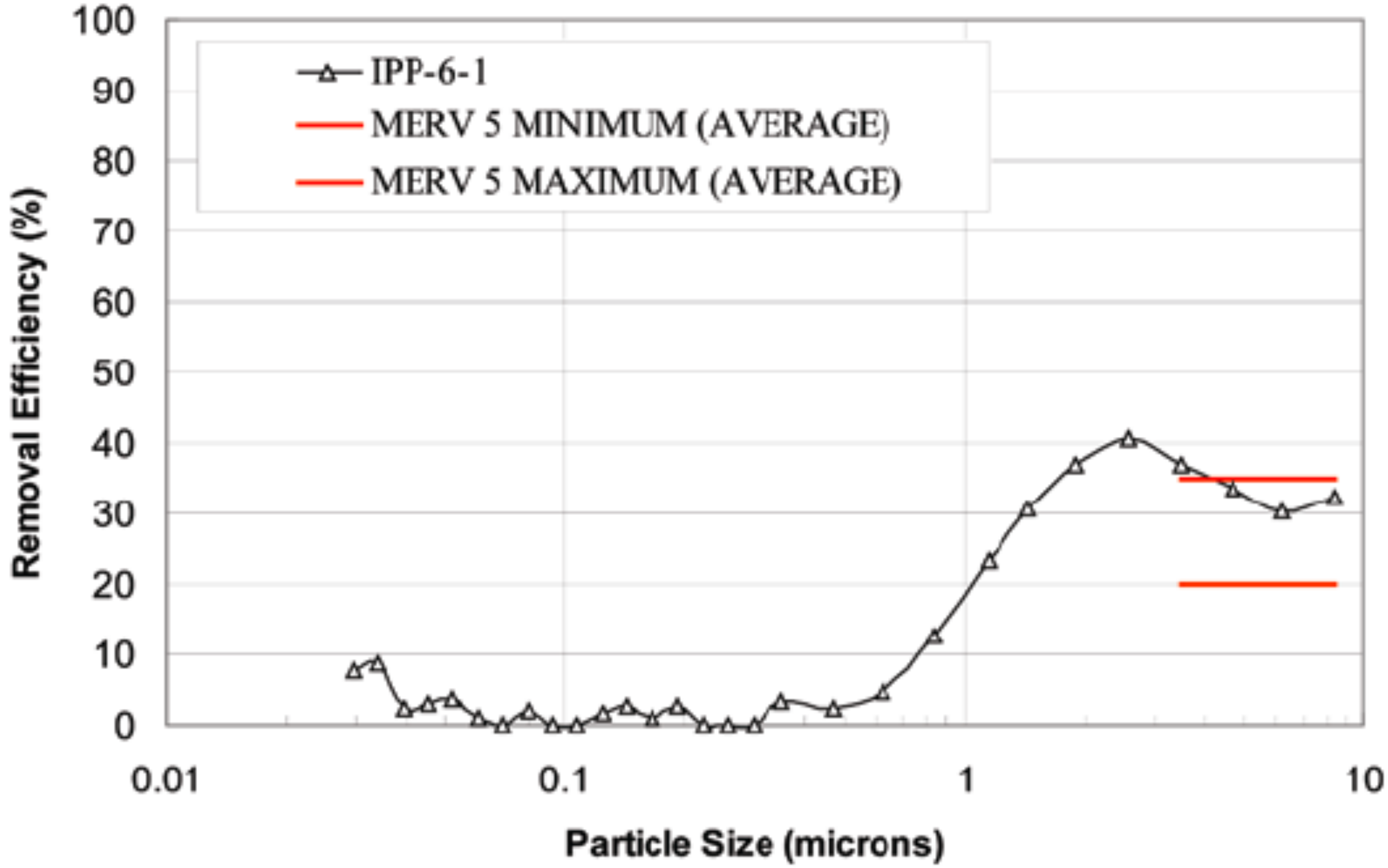
- Electrostatic filters
  - Lose charge after short period
  - Not captured in 52.2 test
    - Currently optional (there is an addendum for dealing with lost charge)



Lehtimäki et al. (2002) *ASHRAE RP-1189 Report*

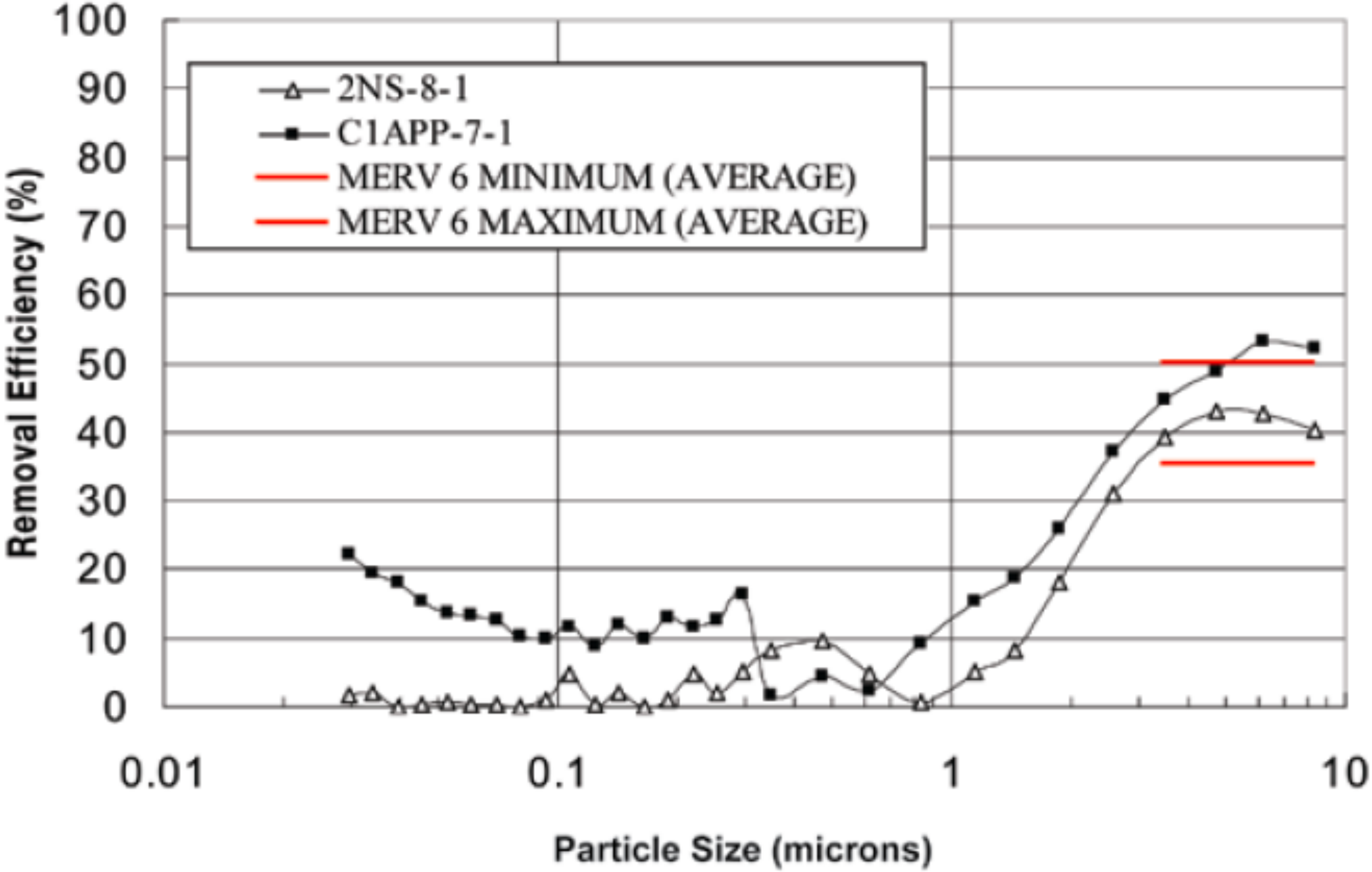
Newer measurements of filtration efficiency

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



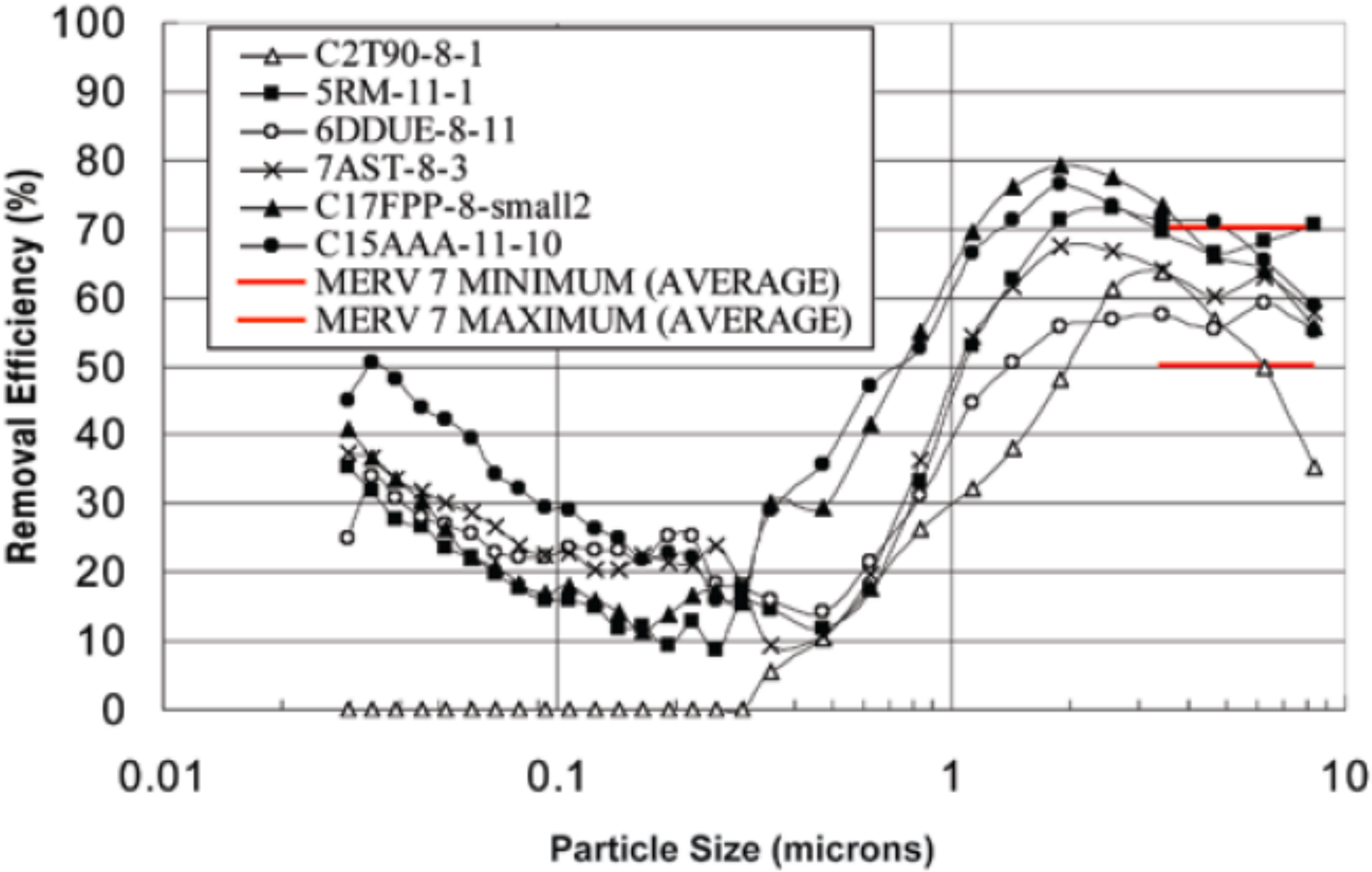
Hecker and Hofacre, 2008 EPA Report 600/R-08/013

Recent MERV 6 lab tests



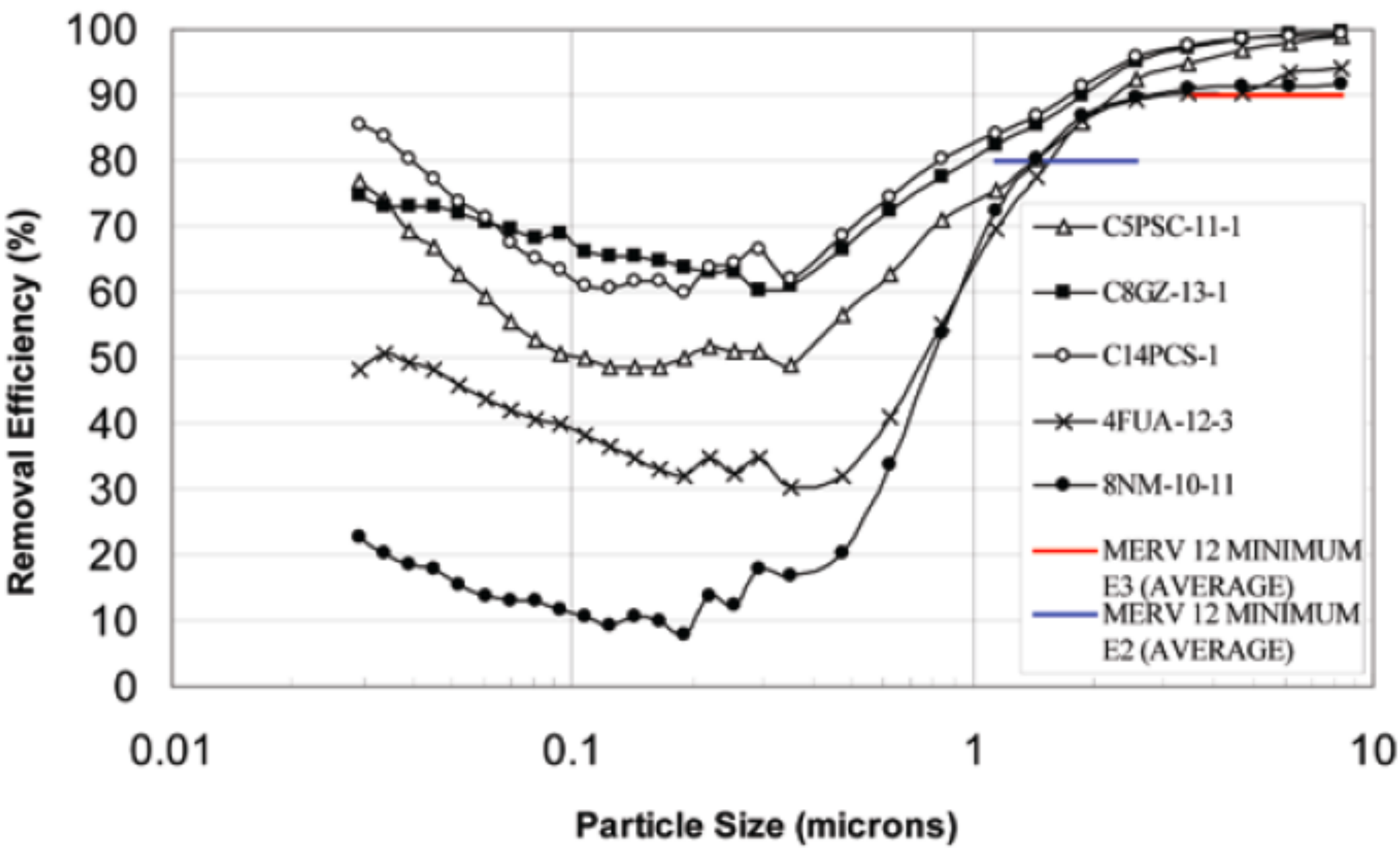
Hecker and Hofacre, 2008 EPA Report 600/R-08/013

Recent MERV 7 lab tests



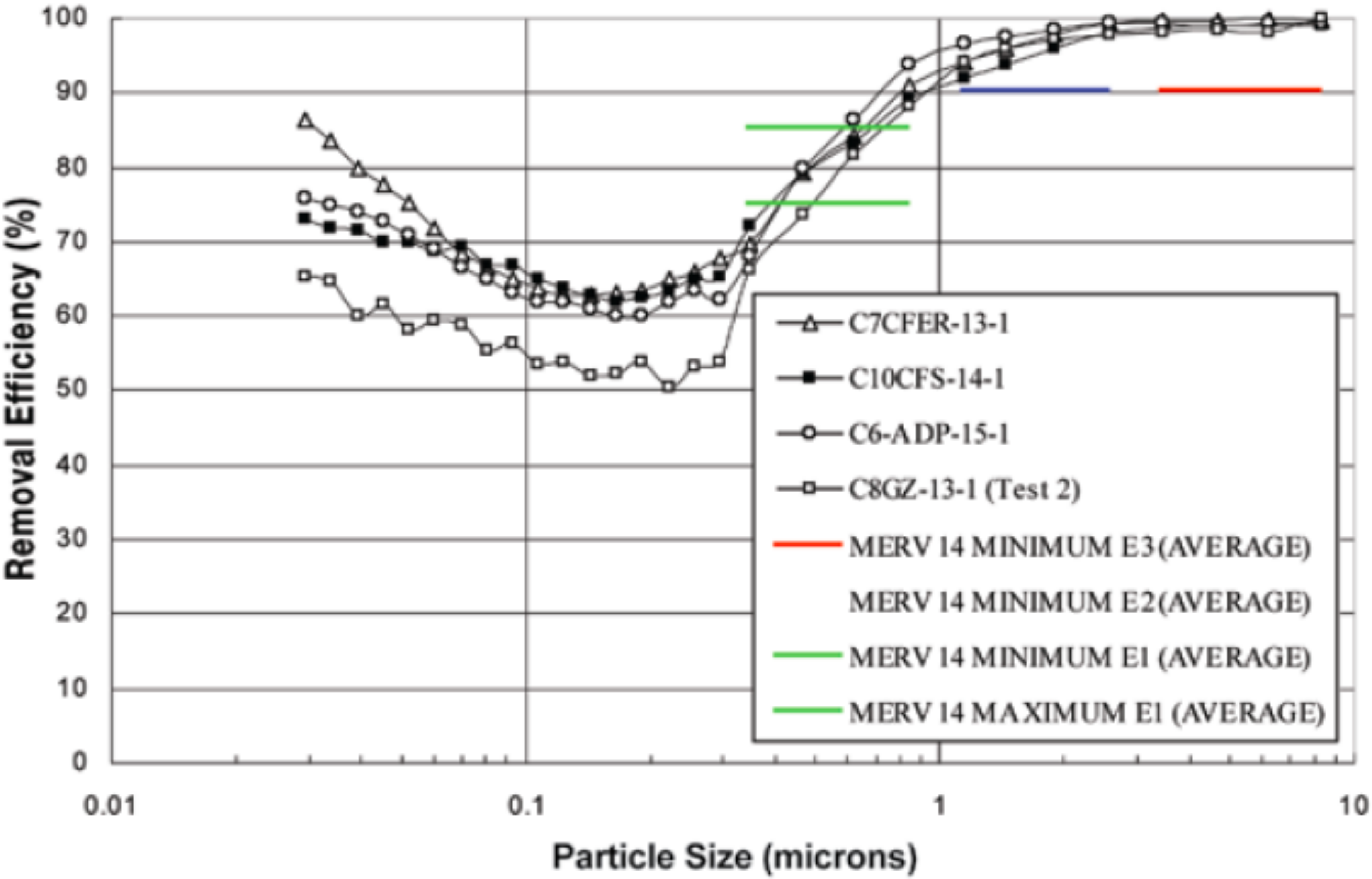
Hecker and Hofacre, 2008 EPA Report 600/R-08/013

Recent MERV 12 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

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
  - Exterior duct leaks
  - Cycling operation
  - 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*

Stephens and Siegel, 2012 *Aerosol Sci Technol*

In-situ filter testing

Two primary in-situ test methods:

Stephens and Siegel, 2012 *Aerosol Sci Technol*

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

Stephens and Siegel, 2012 *Aerosol Sci Technol*

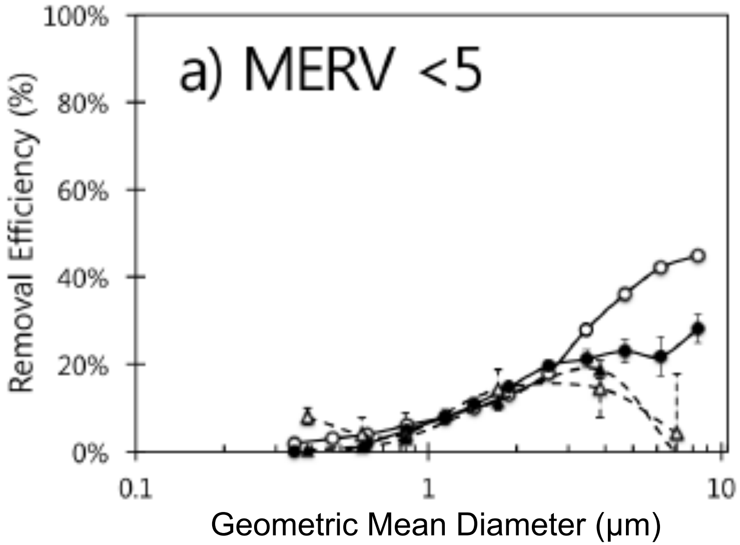
In-situ filter test method

- Well-mix air by several oscillating fans*
- Inject CO_2 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_2 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*

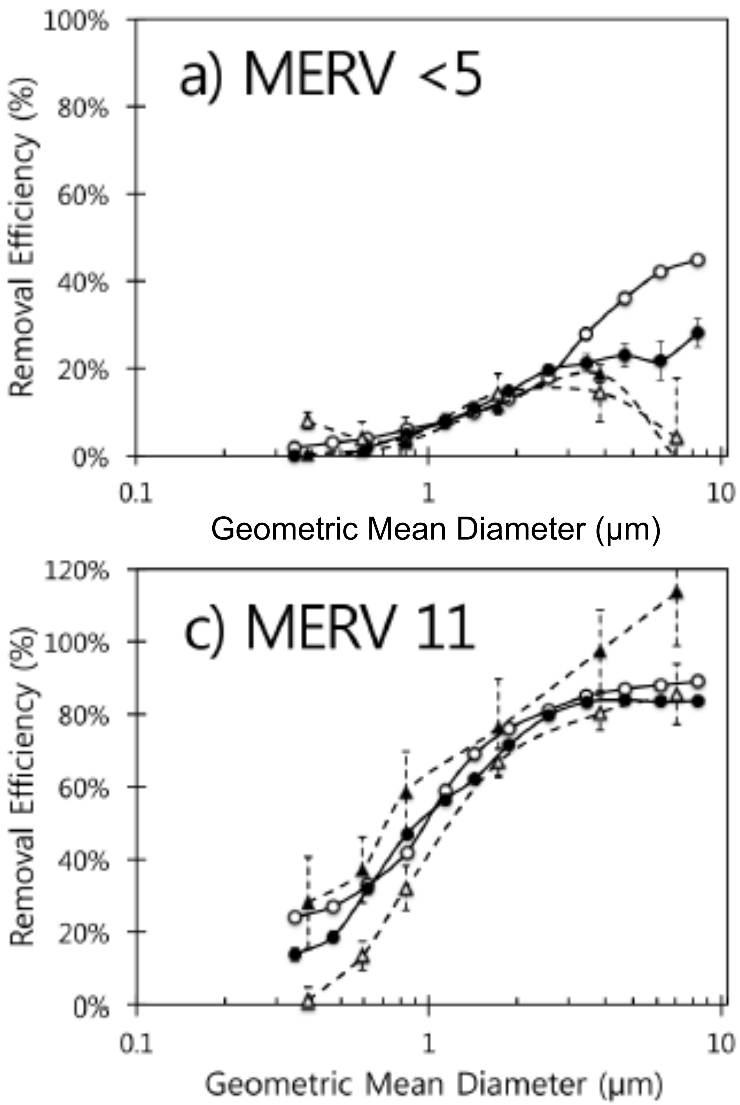
Investigation 1b: Particle removal efficiency



Four test methods agreed reasonably well, particularly for smaller particles

Stephens and Siegel, 2012 *Aerosol Sci Technol*

Investigation 1b: Particle removal efficiency

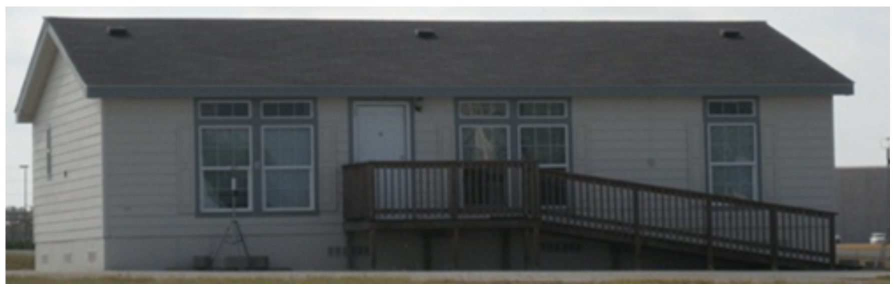


Four test methods agreed reasonably well, particularly for smaller particles

Stephens and Siegel, 2012 *Aerosol Sci Technol*

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

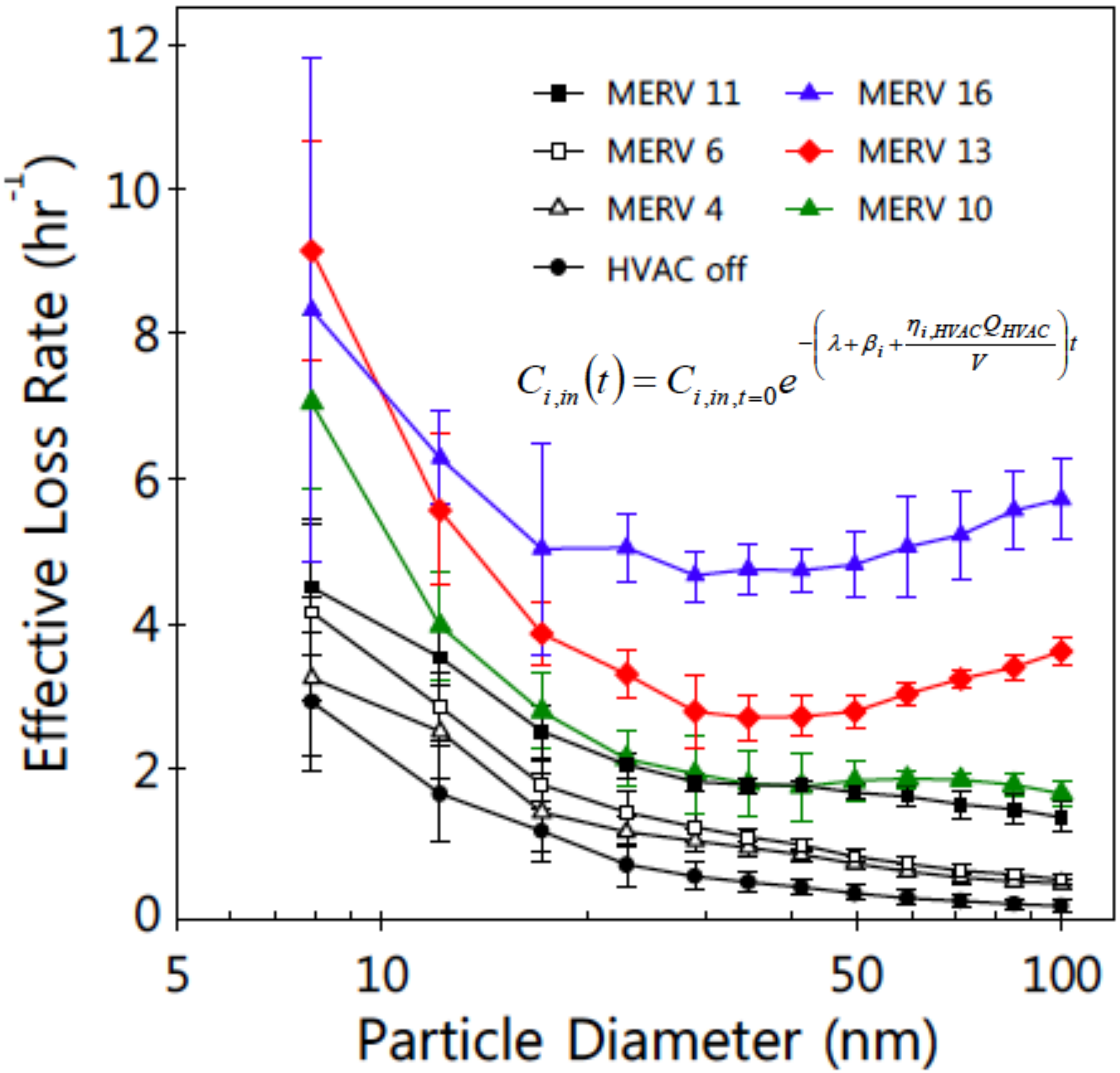
MERV 10

MERV 13

MERV 16

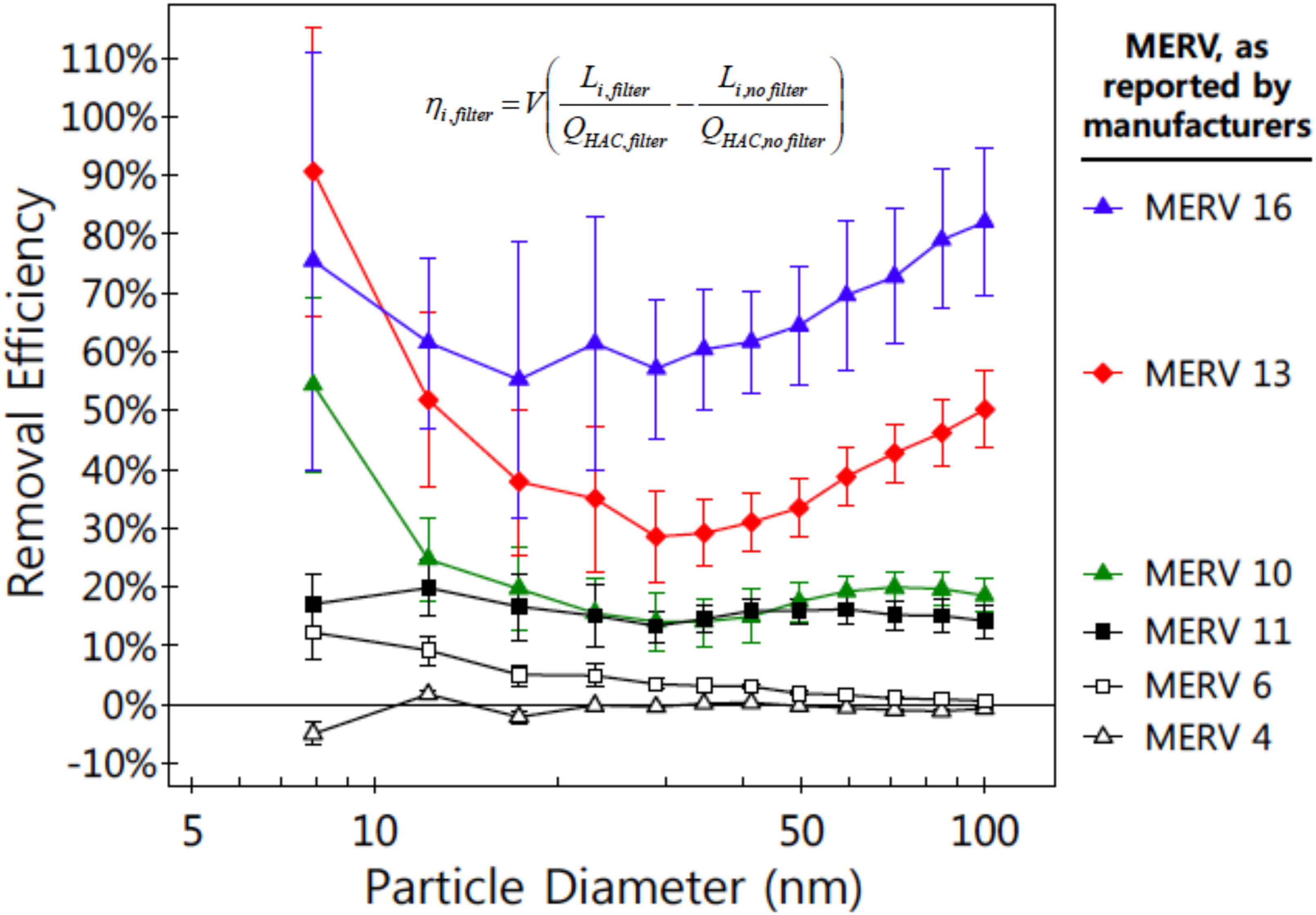
Stephens and Siegel, 2013 currently under review in *Indoor Air*

In-situ ultrafine particle filtration tests



Stephens and Siegel, 2013 currently under review in *Indoor Air*

In-situ ultrafine particle filtration tests

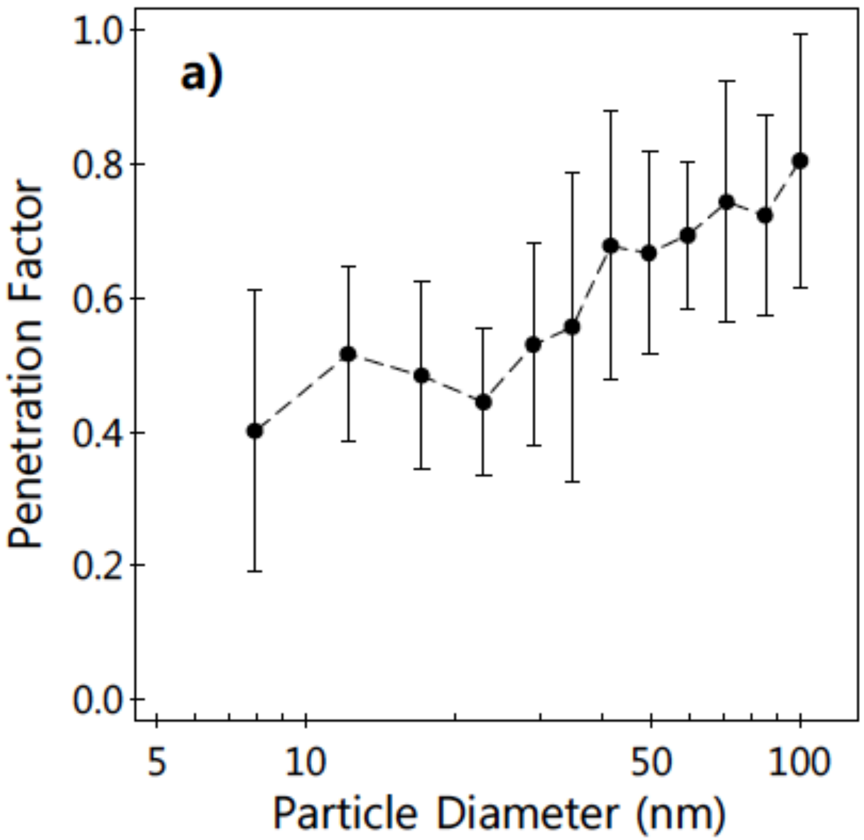


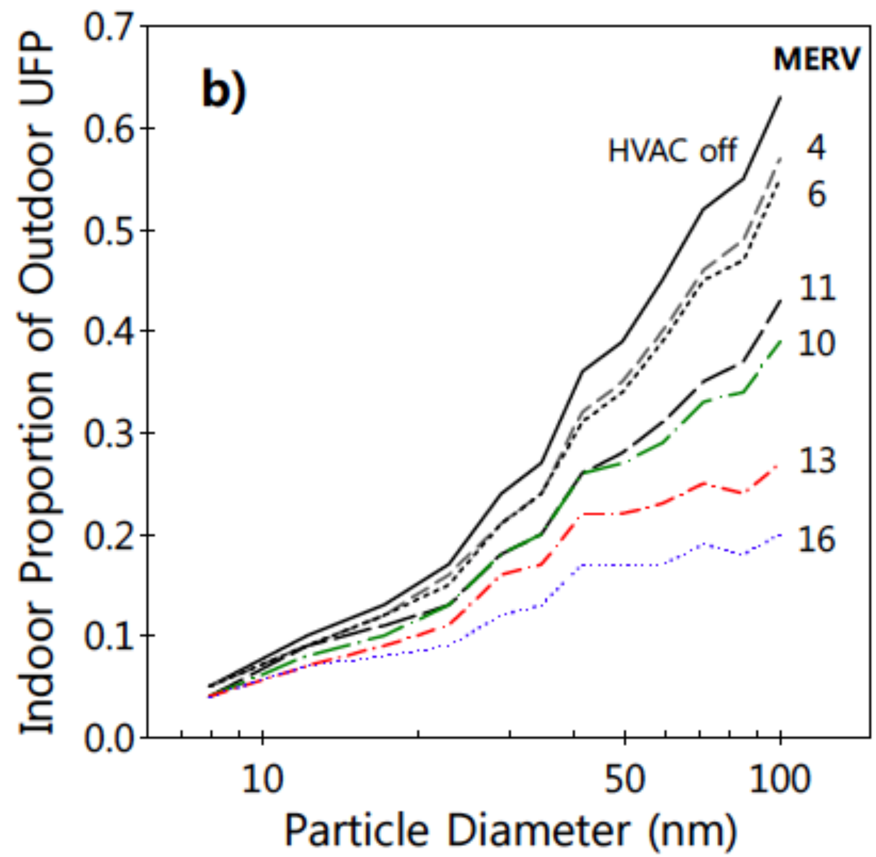
Stephens and Siegel, 2013 currently under review in *Indoor Air*

Modeling impacts on indoor UFPs of outdoor origin

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

λ = 0.41 hr^{-1} (average from this study)
P_i measured for this study
f = 20.6% runtime (Stephens et al. 2011 *Bldg and Env*)





Stephens and Siegel, 2013 currently under review in *Indoor Air*

HVAC FILTER PRESSURE AND FLOW RELATIONSHIPS

Pressure, flow, and energy relationships

- Most of human exposure to airborne particles occurs inside buildings

- High-efficiency filtration in HVAC systems is one way to reduce exposure

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

Conventional wisdom

"A dirty filter will slow down air flow and make the system work harder to keep you warm or cool – wasting energy."[1]

"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%."[2]

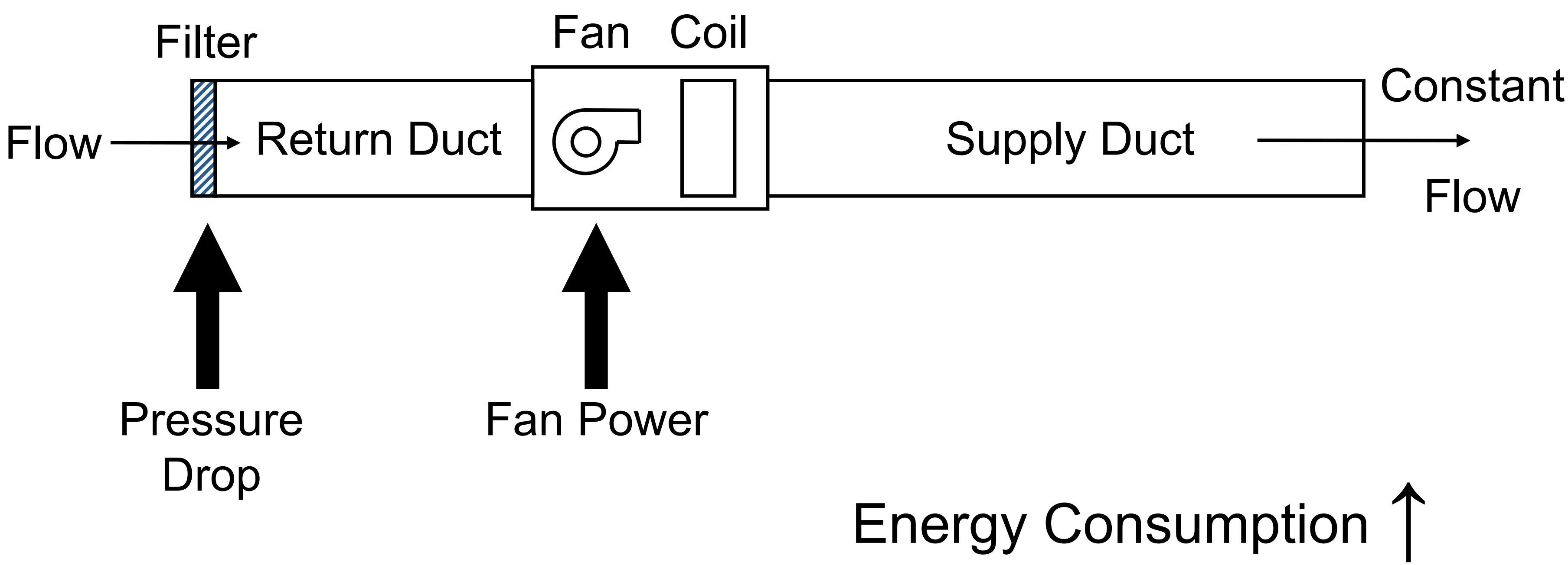
U.S. Department of Energy
Energy Efficiency and Renewable Energy

[1]http://www.energystar.gov/index.cfm?c=heat_cool.pr_hvac

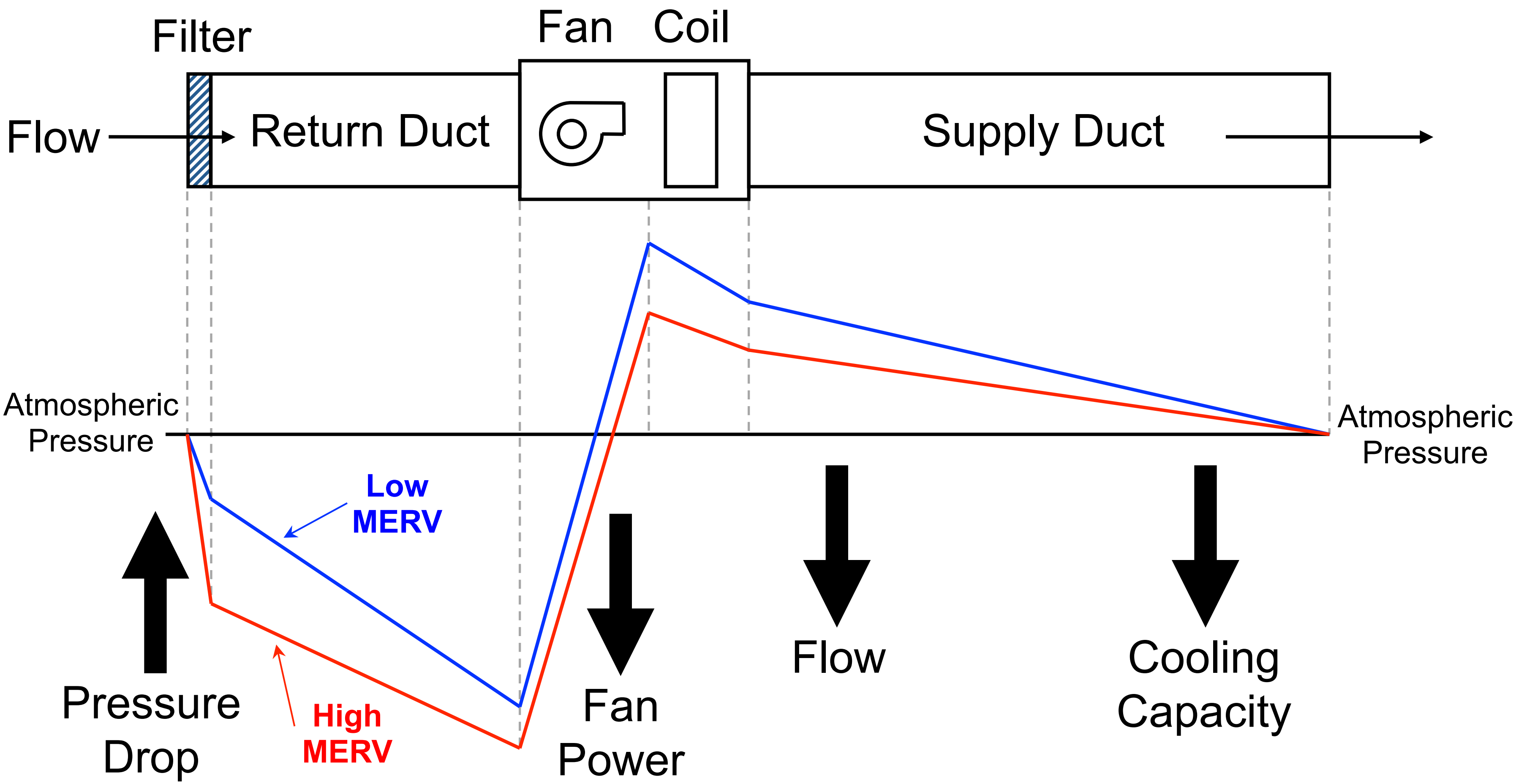
[2]http://apps1.eere.energy.gov/consumer/your_home/space_heating_cooling/index.cfm

Energy consequences of filters

- In large commercial buildings…

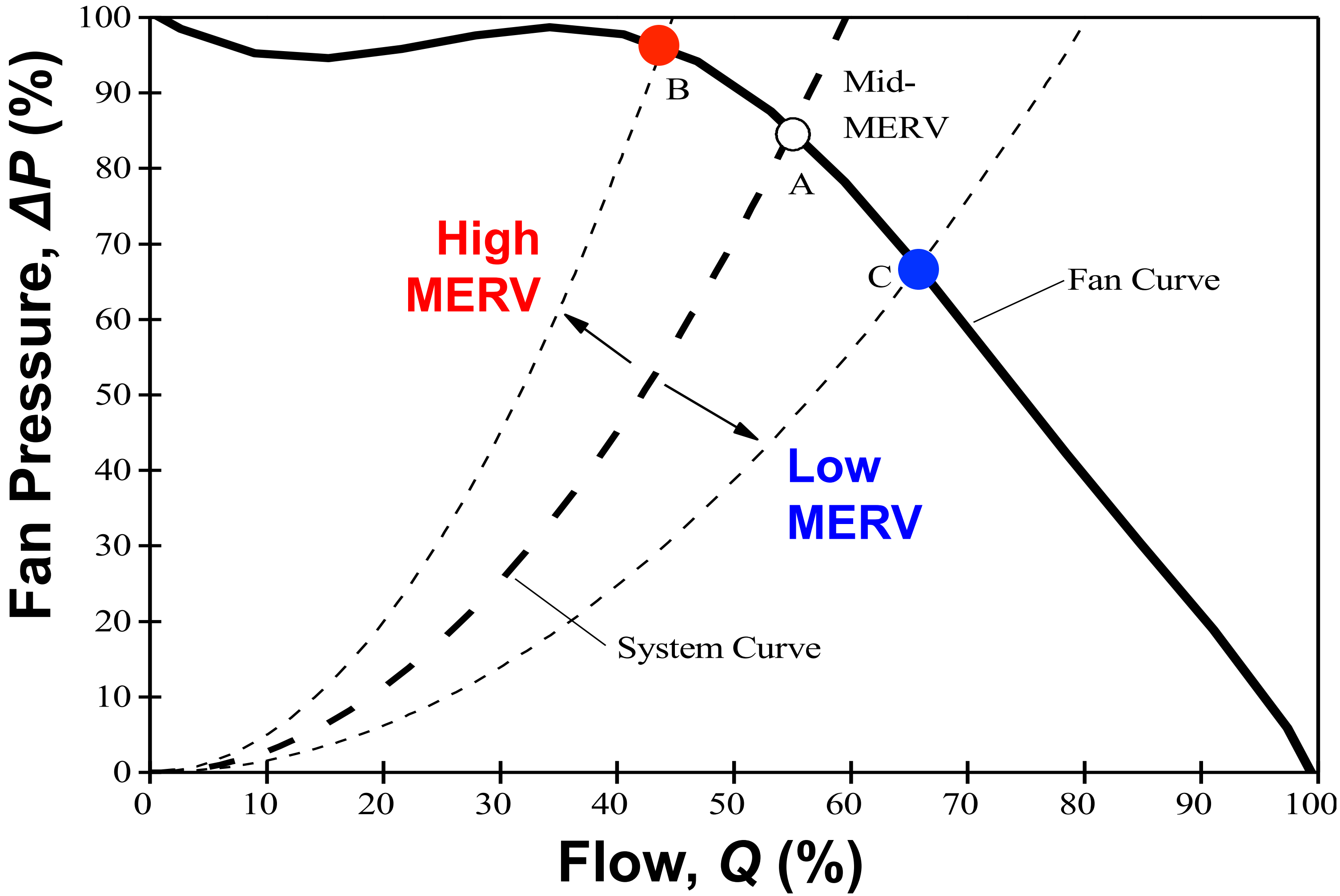


Residential and light-commercial buildings



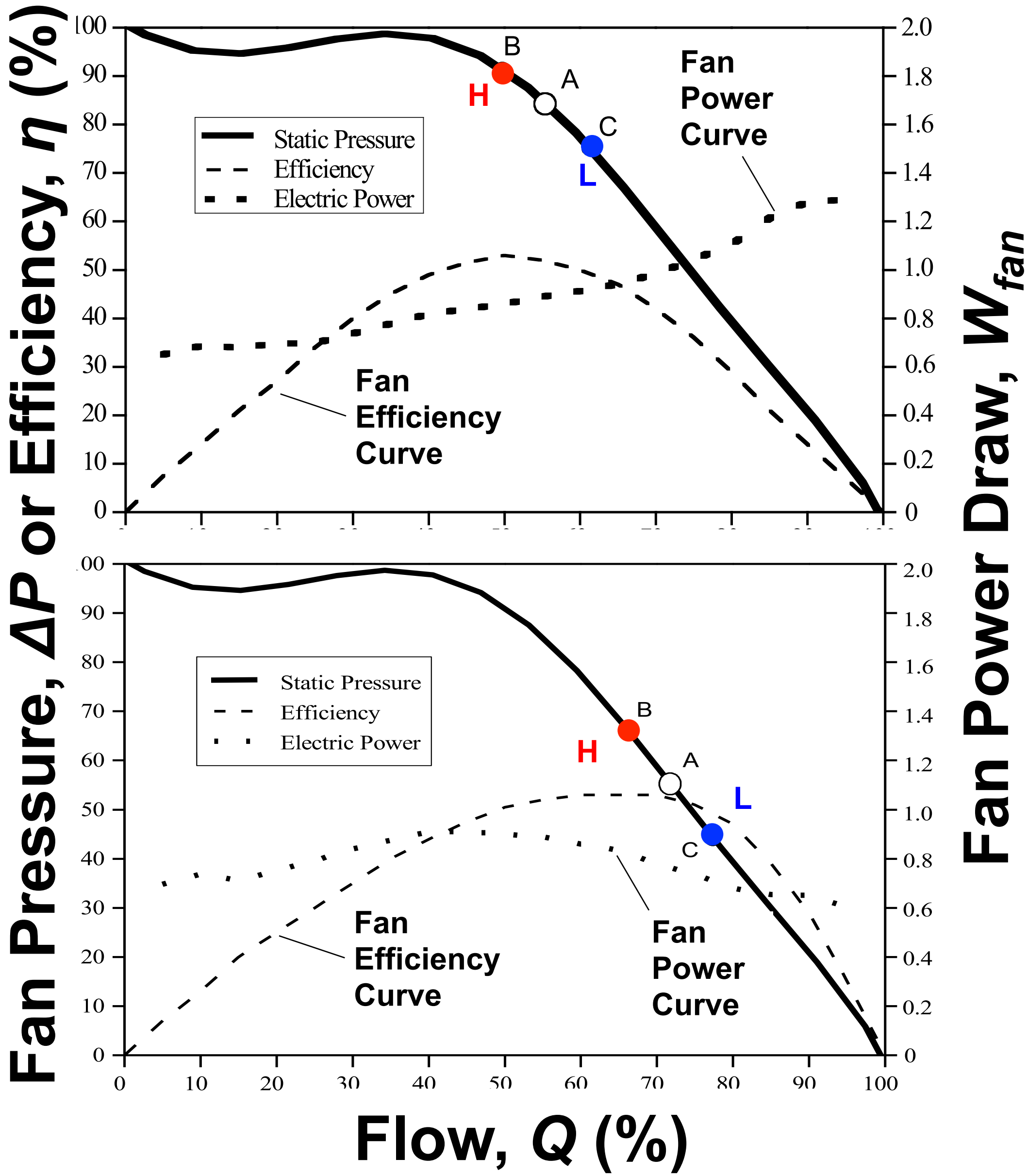
How does overall energy consumption change?

Fan and system curve interactions



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

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

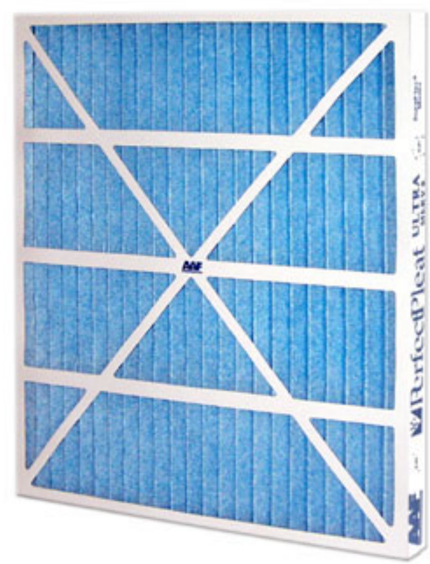
Stephens et al., 2010 *HVAC&R Research*

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)



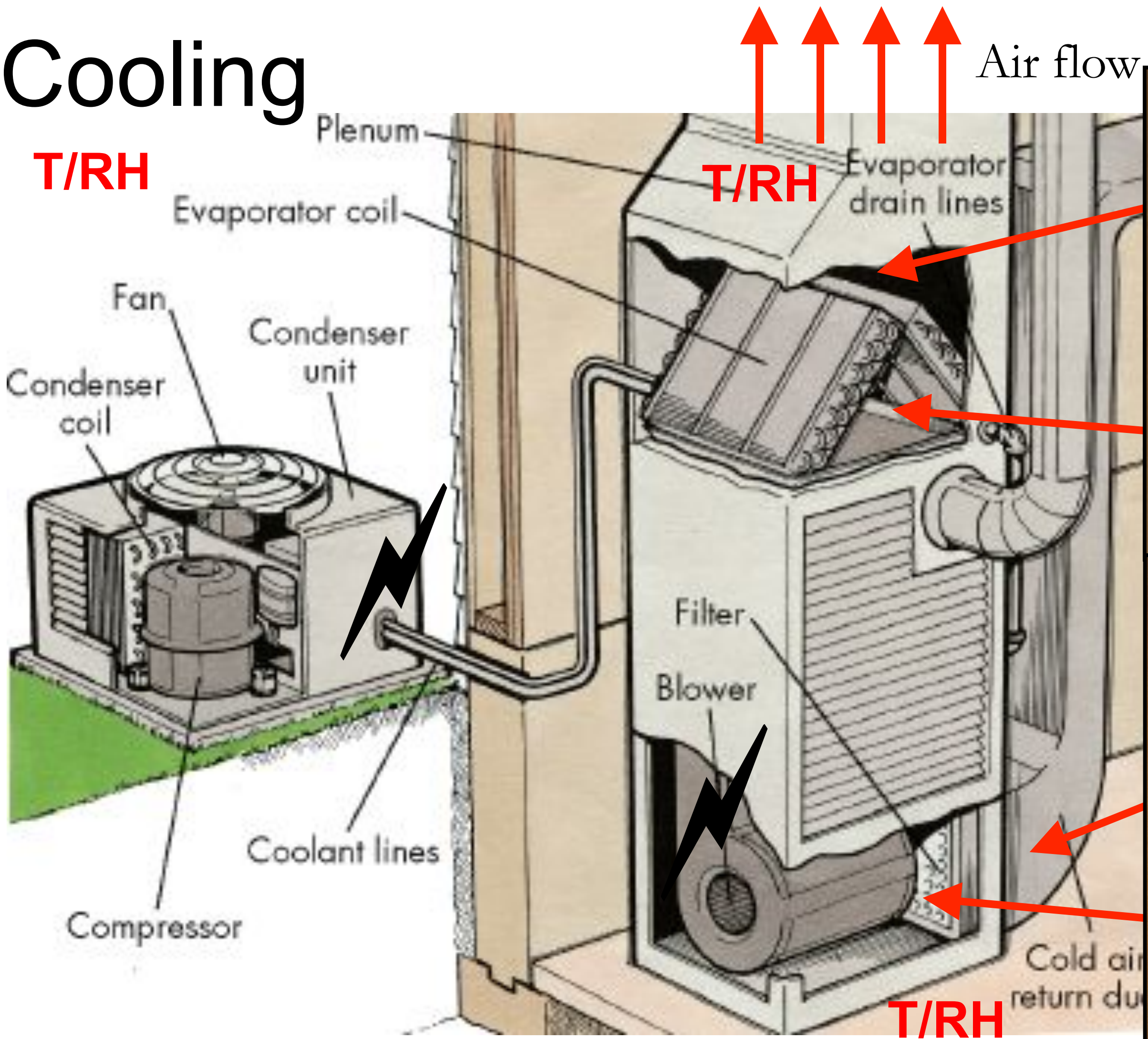
Mid-MERV
(MERV 5 - 8)

High-MERV
(MERV 9 - 12)

Stephens et al., 2010 *ASHRAE Transactions*

Field measurements

Cooling



Fan Only

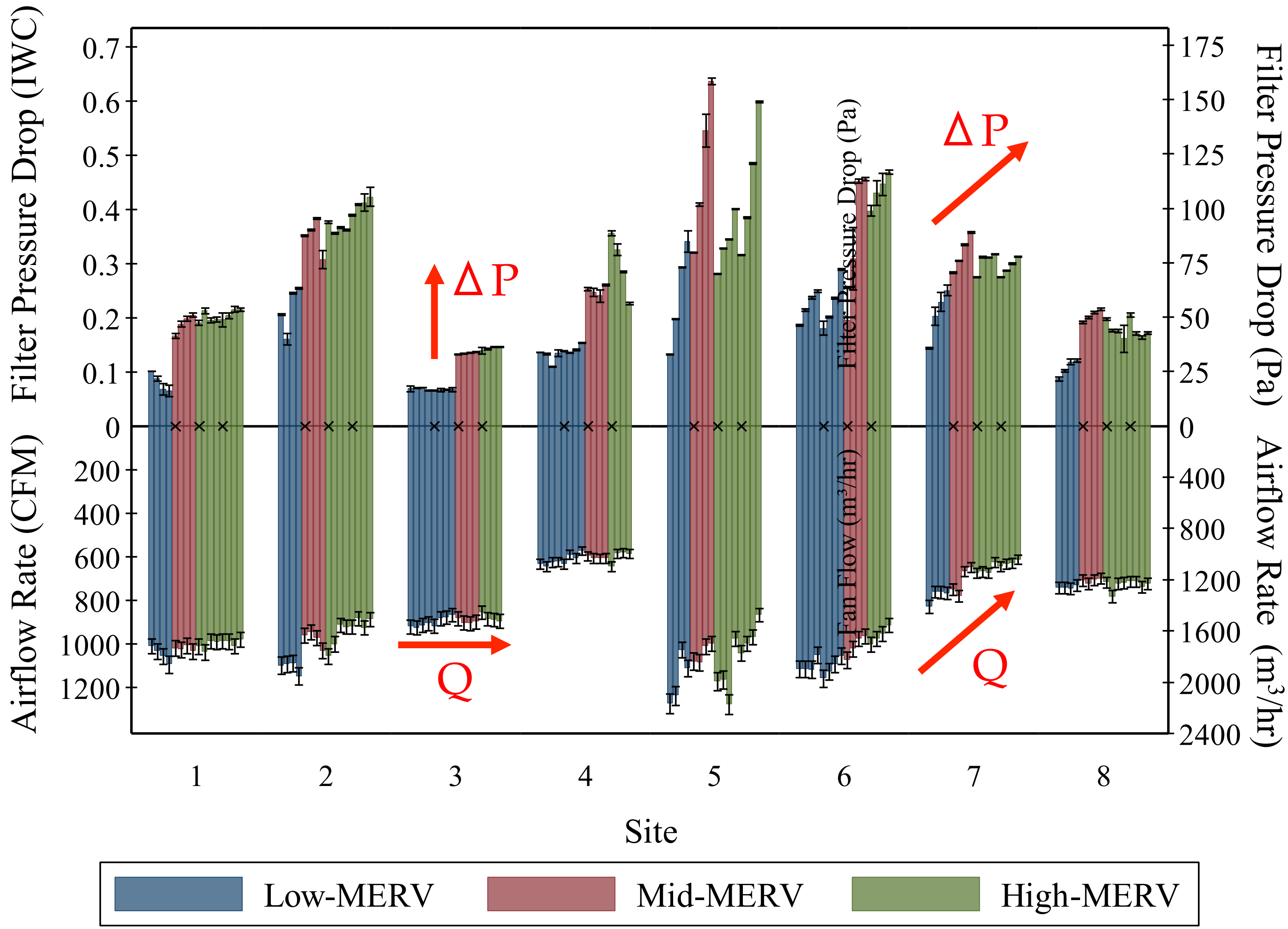
Source: http://static.howstuffworks.com/gif/how-to-troubleshoot-a-central-air-conditioning-system-1.jpg

Test house measurements

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

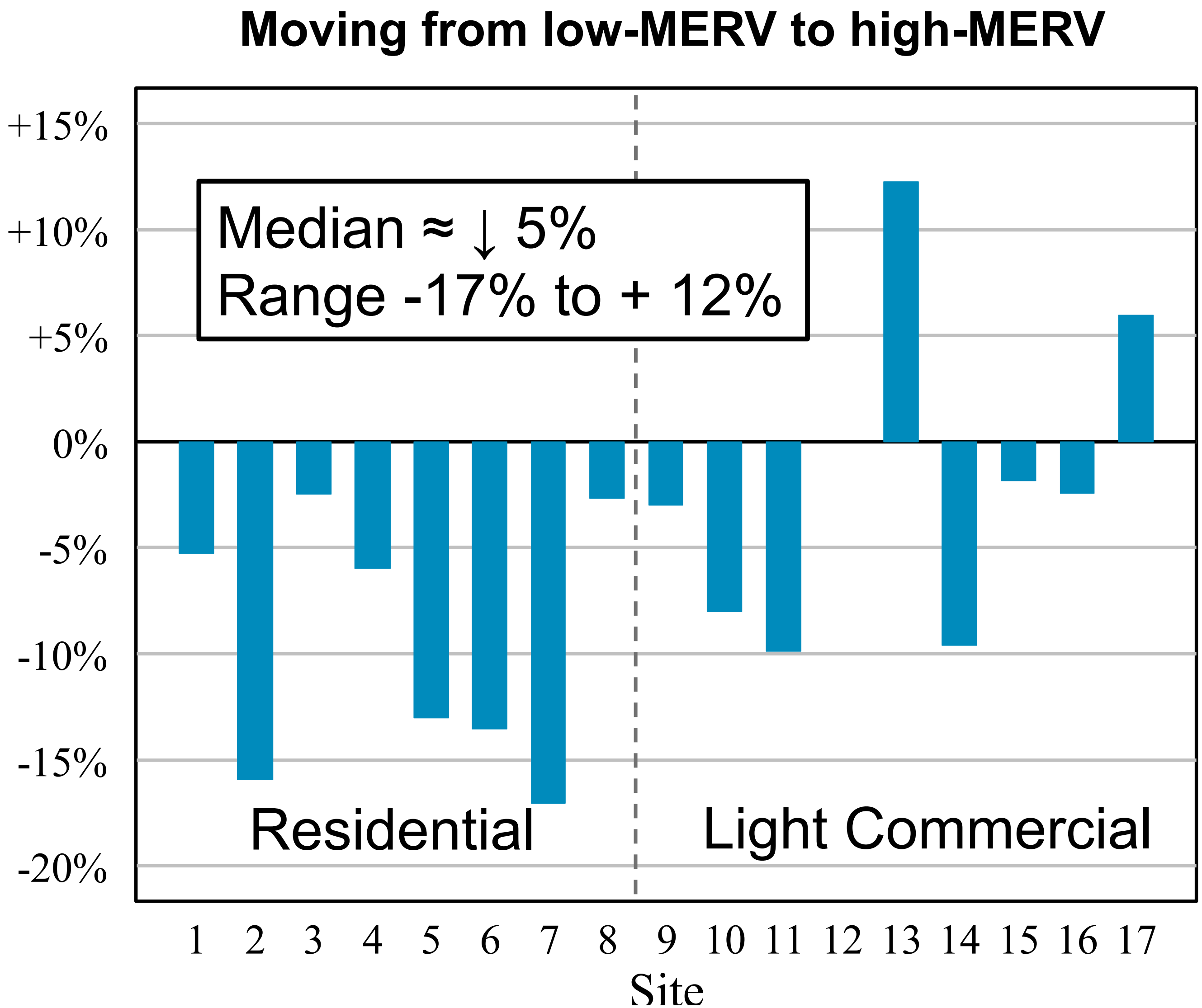
Stephens et al., 2010 *ASHRAE Transactions*

Residential field results: Filter pressure drop and airflow



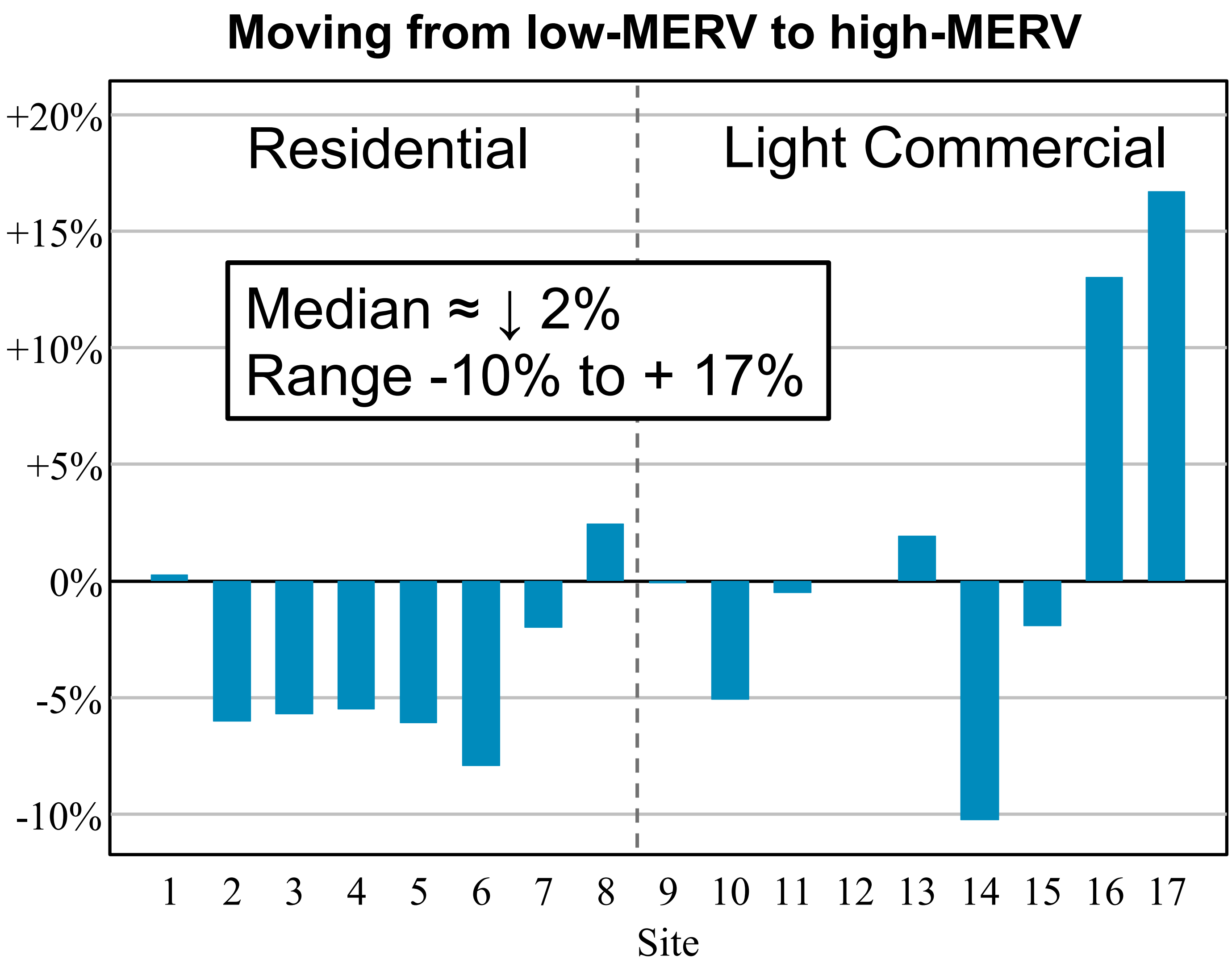
Stephens et al., 2010 *ASHRAE Transactions*

Median changes in airflow rates



Stephens et al., 2010 *ASHRAE Transactions*

Median change in fan power draw

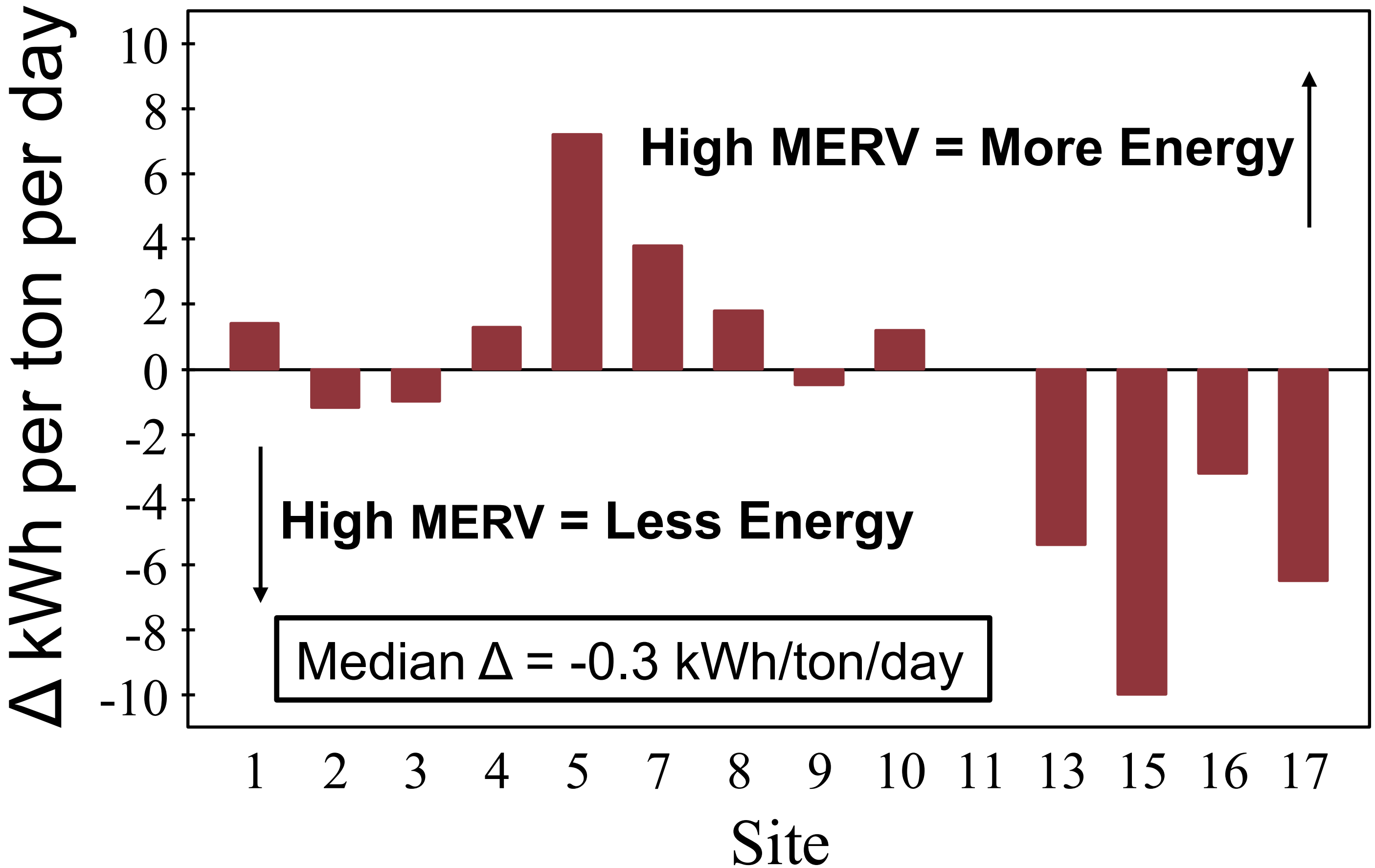


Stephens et al., 2010 *ASHRAE Transactions*

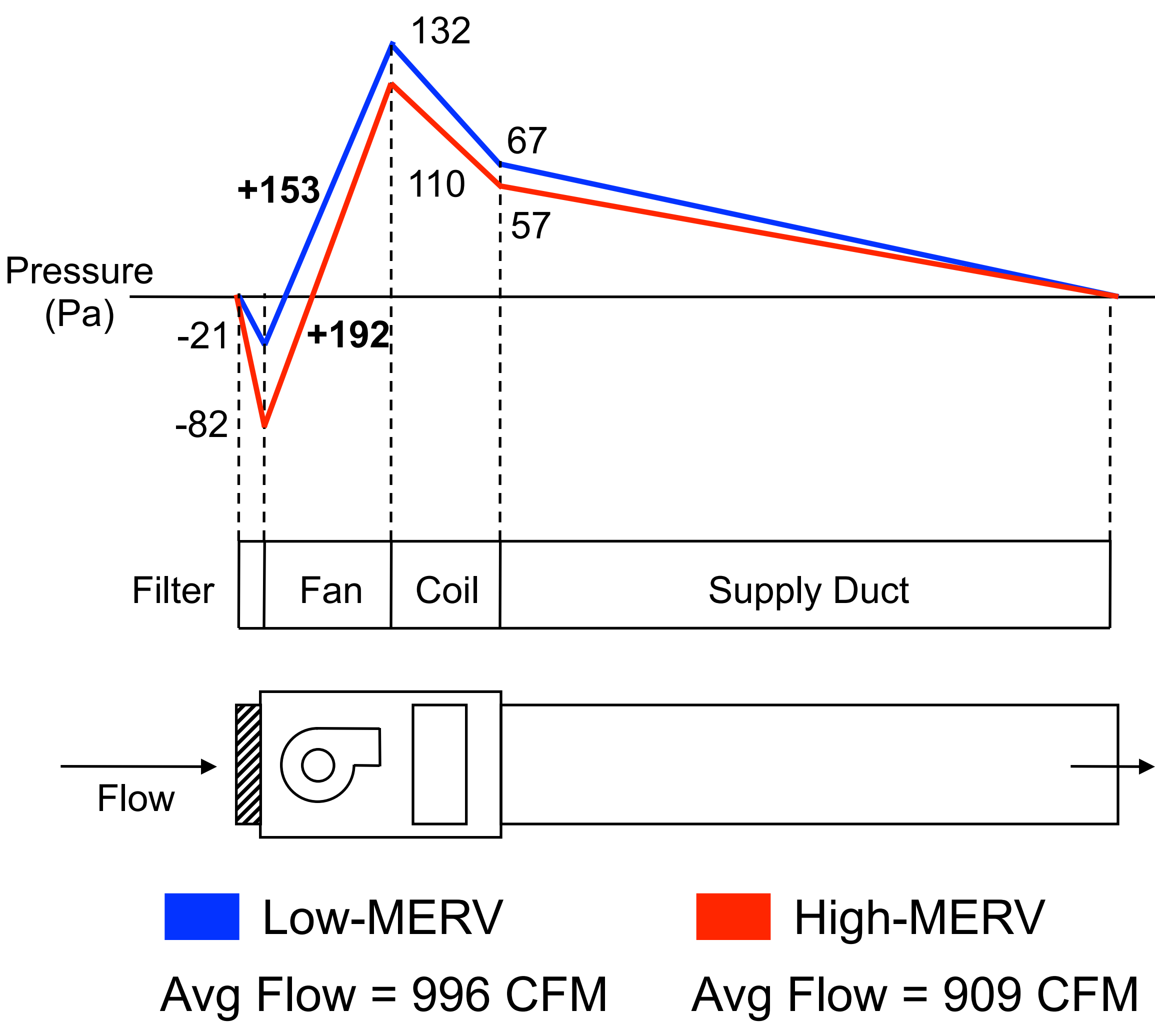
Range of energy consequences

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 ΔP ↑ 4x
- Flow ↓ 9%
- Fan Power ↑ 3%
- Outdoor Unit Power ↓ 0.5%
- Total Power ↑ 0.1%
- Total Capacity ↓ 4%

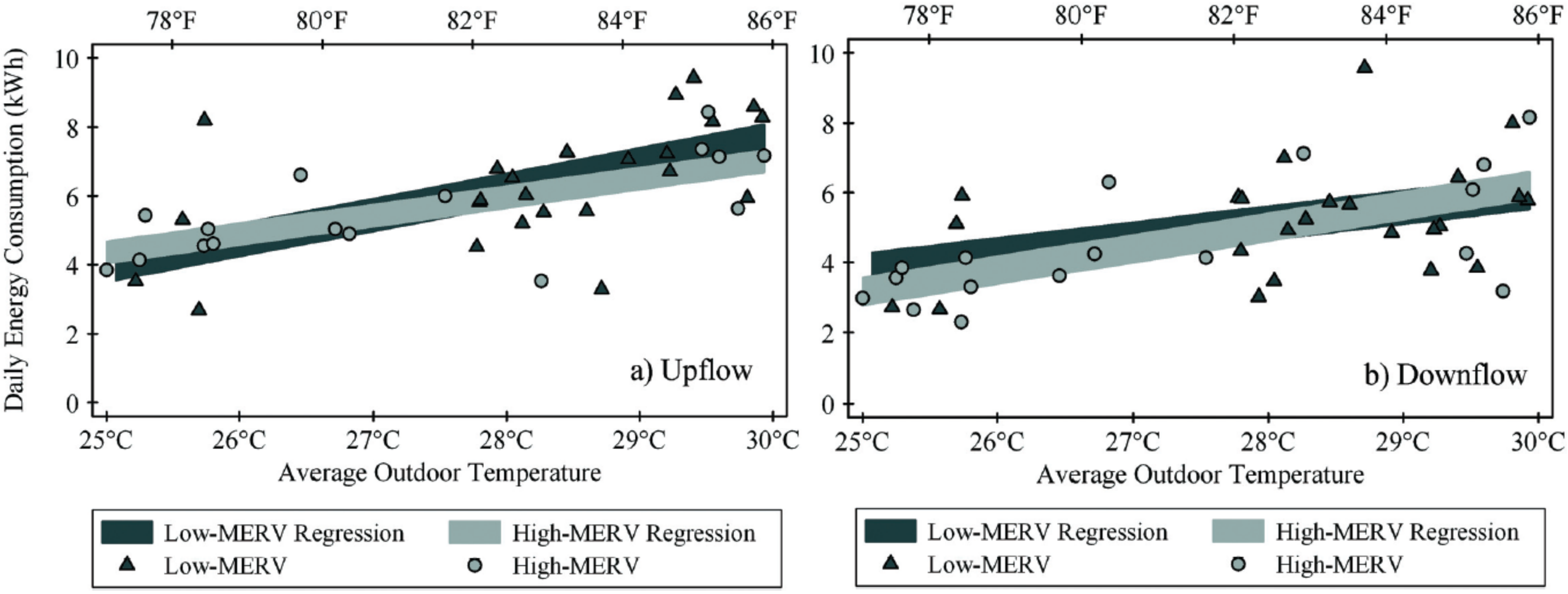
$$cap_{tot} = Q_{fan}\rho(C\Delta T + \Delta W h_{fg})$$

Airflow ↓ 9%
ΔT across coil ↑ 6%
ΔW across coil ↑ 5%
Total Capacity ↓ 4%

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

Test house results

Daily energy consumption versus outdoor air temperature



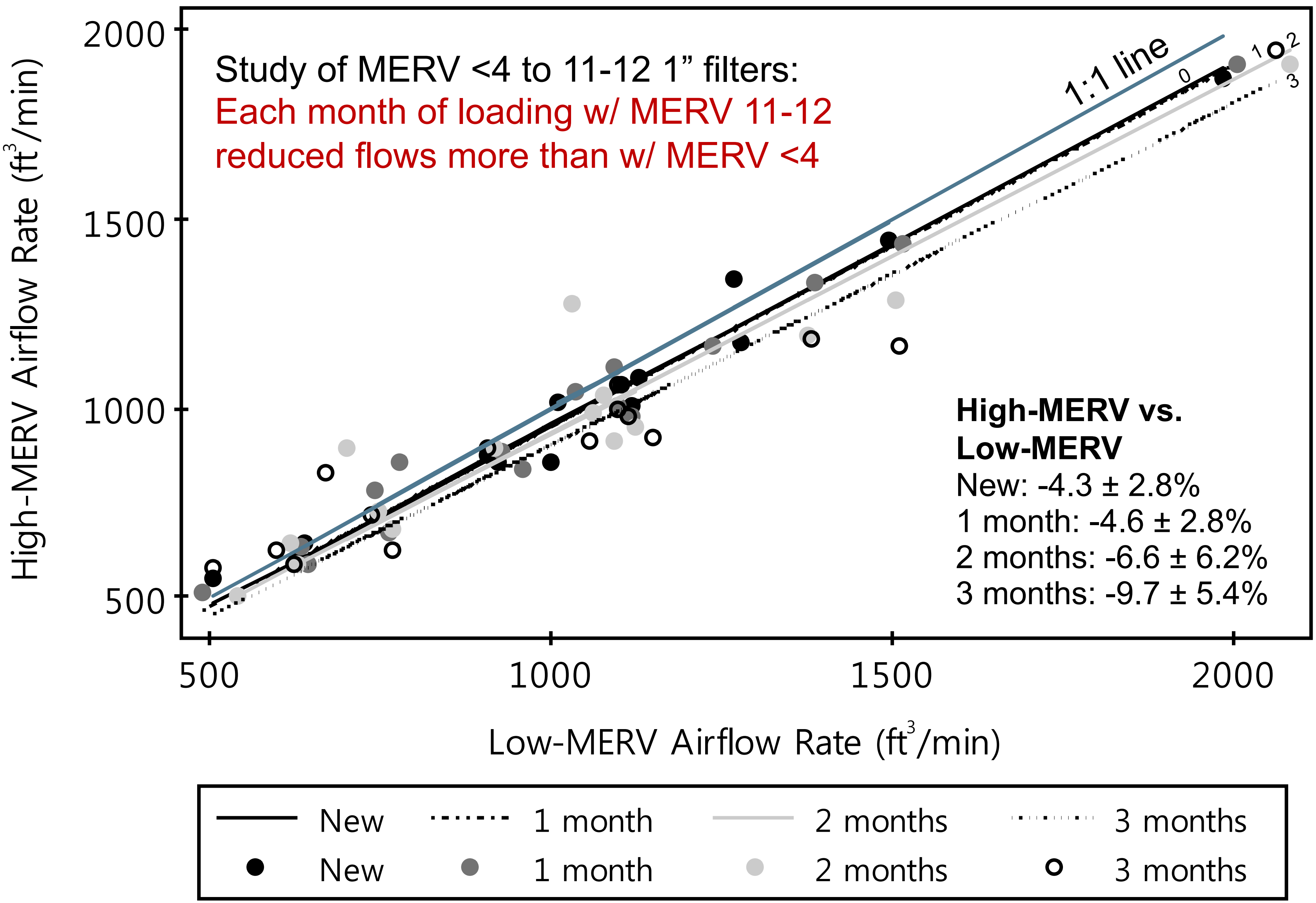
Test House System #1

Test House System #2

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

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

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



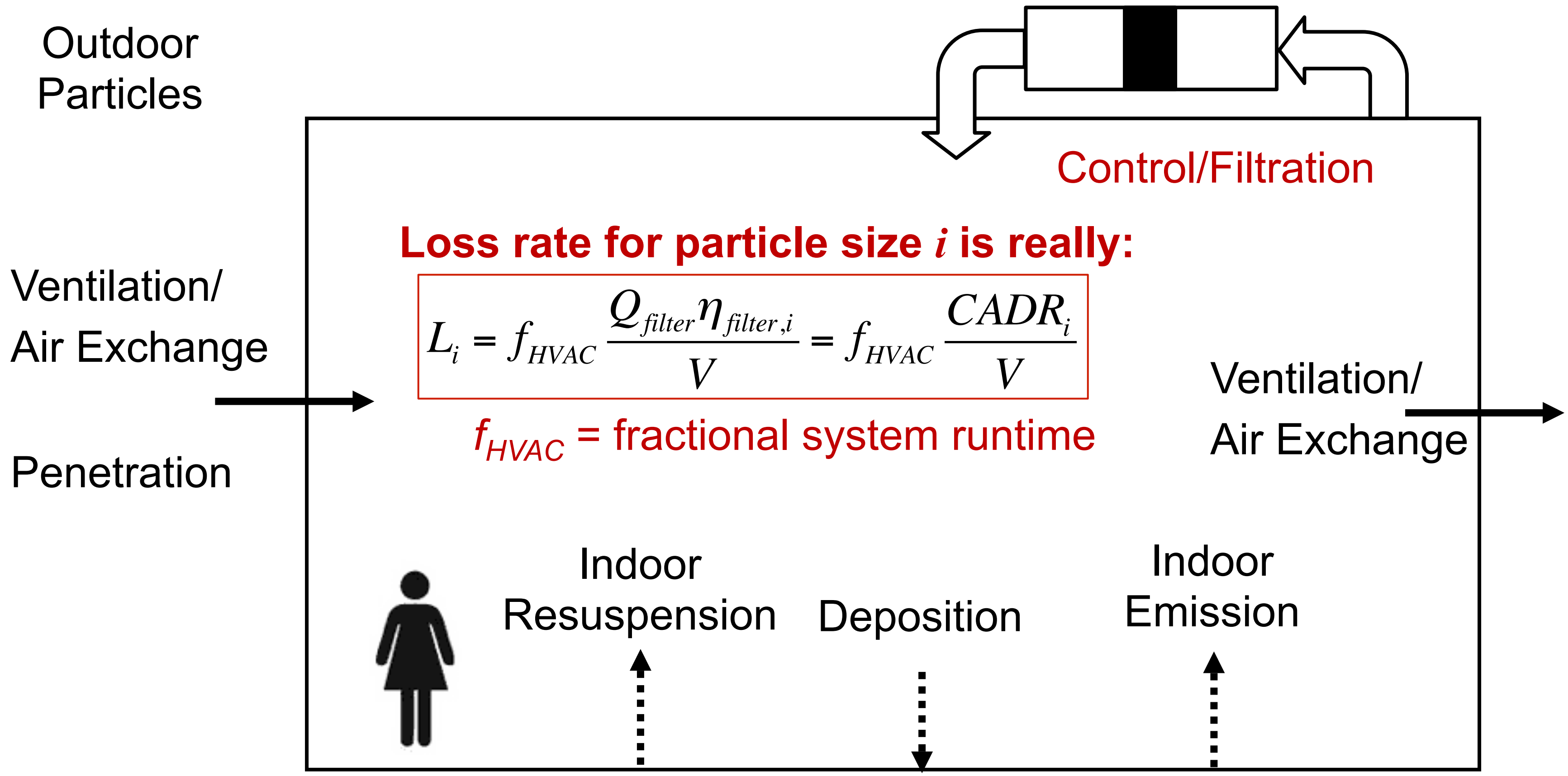
Data from Stephens et al., **2010** *ASHRAE RP-1299*

SYSTEM RUNTIME

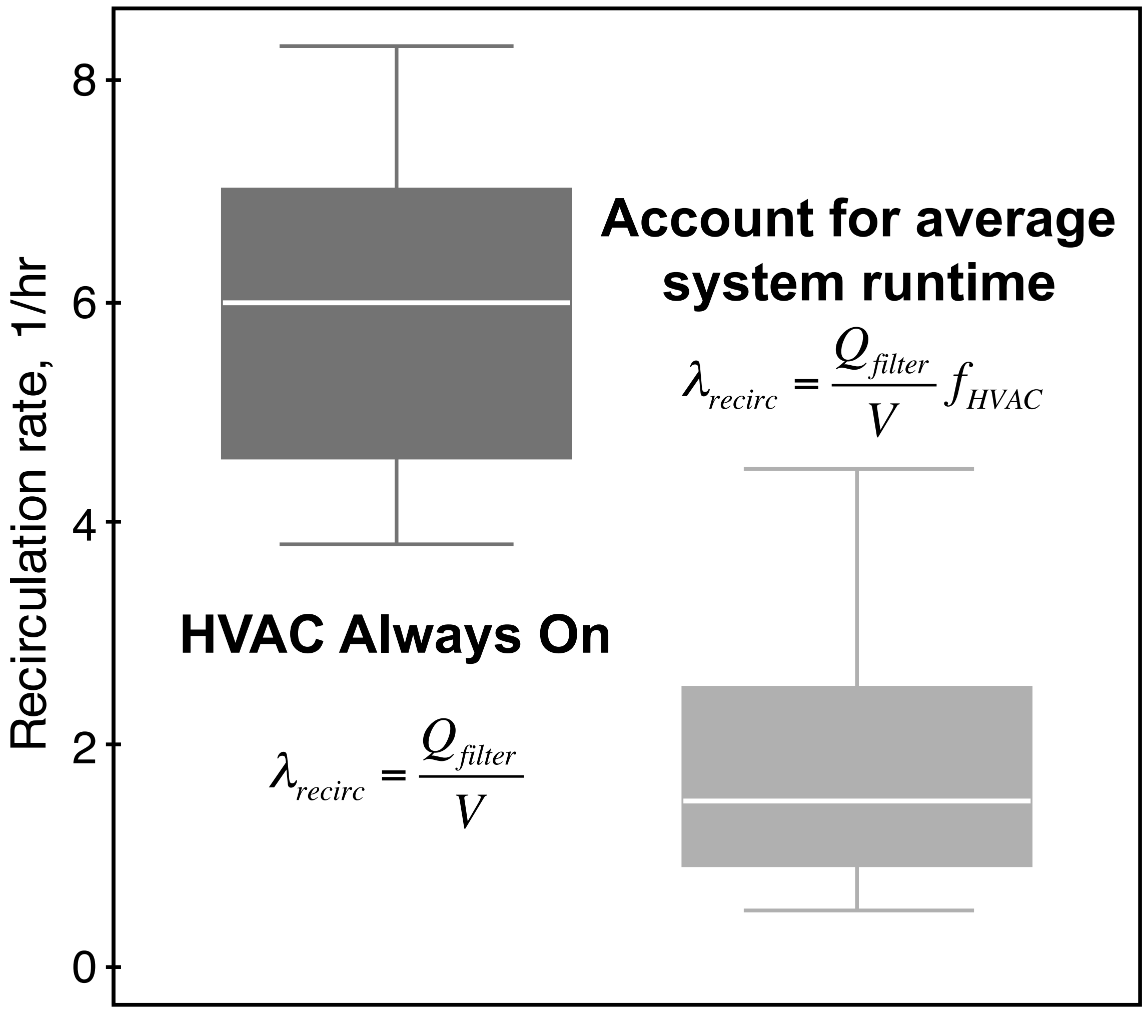
The last key parameter for filtration

System runtime

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



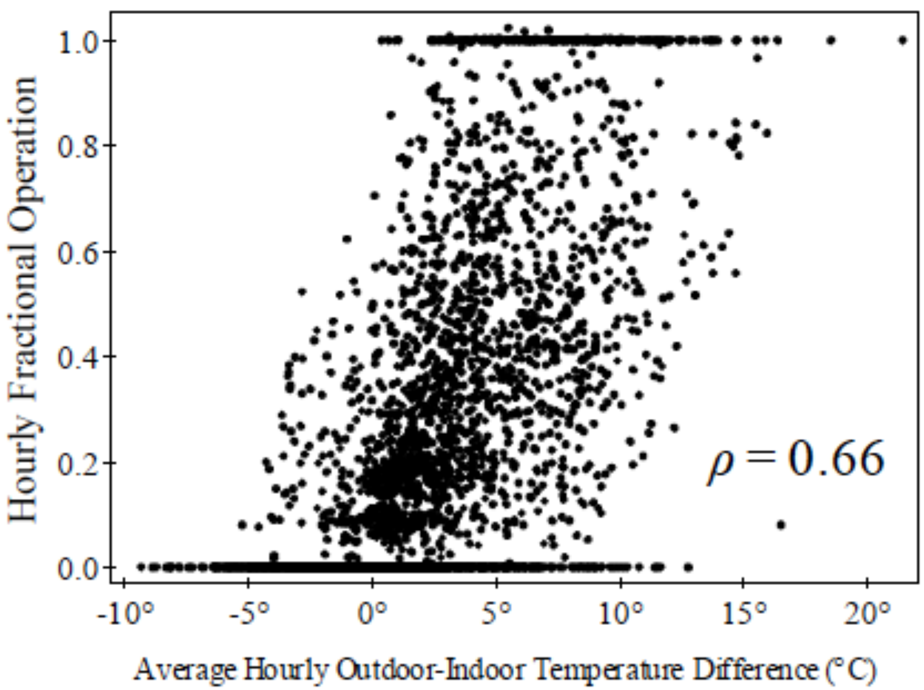
HVAC system recirculation rates in homes and small commercial buildings



Stephens et al., **2011** *Building and Environment*, Data from ASHRAE RP-1299

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

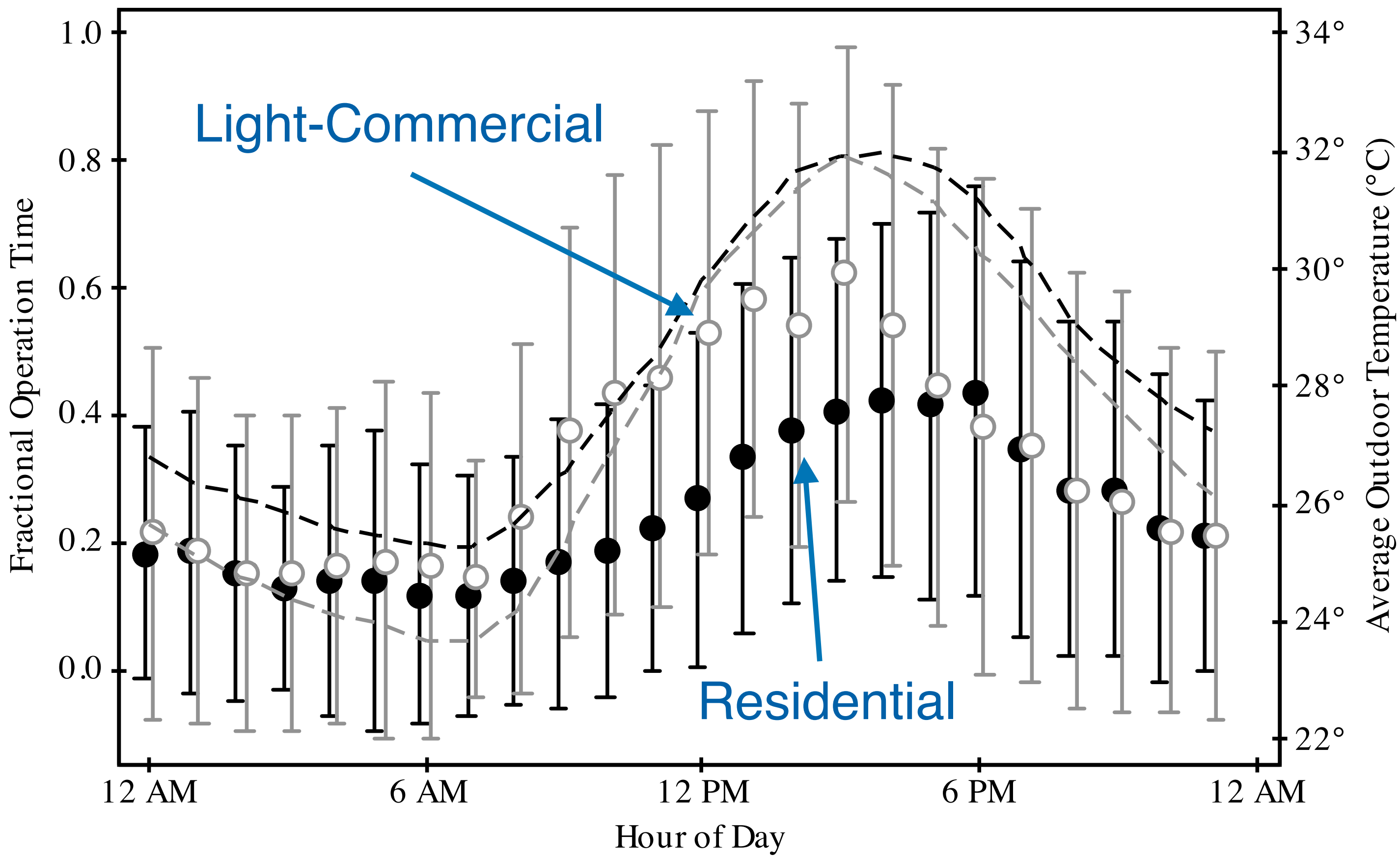
Site	% per °C	R^2	N (hours)
1	6.0%	0.71	175
2	3.7%	0.33	180
3	2.9%	0.68	215
4	7.2%	0.68	226
5	9.3%	0.69	222
6	9.1%	0.80	161
7	4.7%	0.71	204
8	7.3%	0.62	164
9	6.0%	0.69	175
10	4.9%	0.73	171
11	11.3%	0.67	211
12	4.5%	0.68	91
13	7.9%	0.61	218
14	7.1%	0.78	173
15	9.2%	0.63	182
16	4.0%	0.41	152
17	2.4%	0.22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

Stephens et al., **2011** *Building and Environment*, Data from ASHRAE RP-1299

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

Stephens et al., **2011** *Building and Environment*, Data from ASHRAE RP-1299

Filter summary

- 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

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

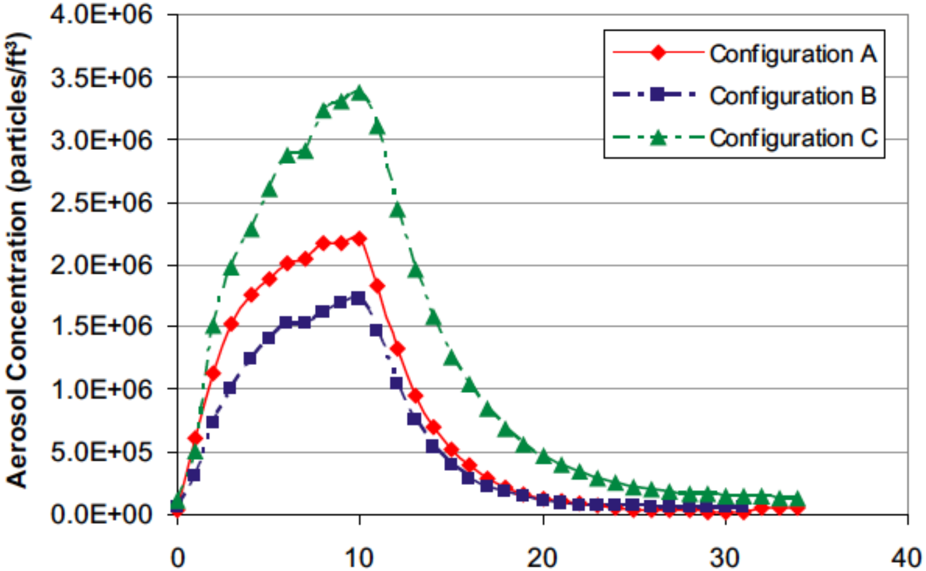
Photo from M.S. Waring and J.A. Siegel

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

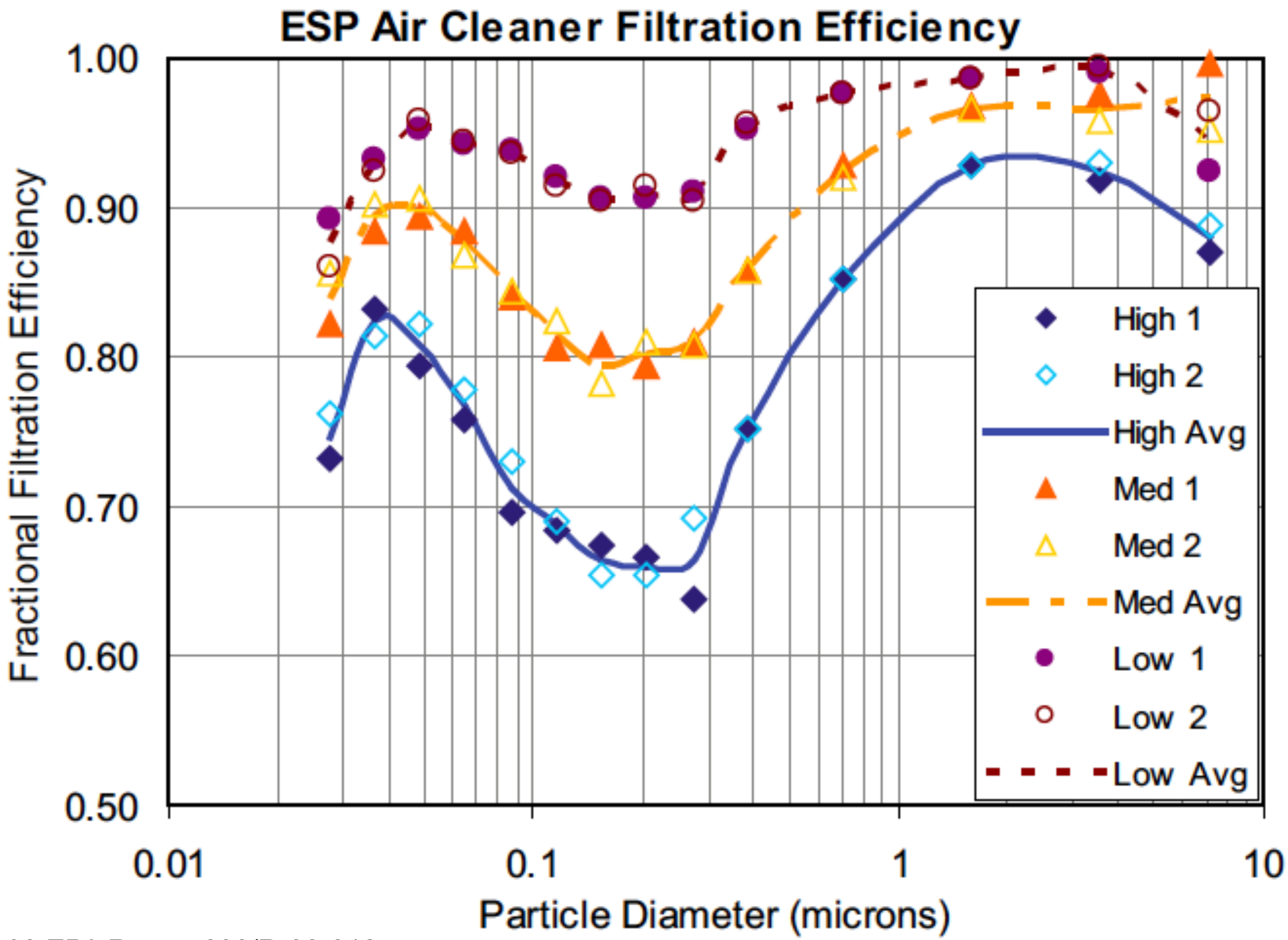
Kogan et al., 2008 EPA Report 600/R-08-012

$$CADR = V\left(L_{AC} - L_{noAC}\right)$$



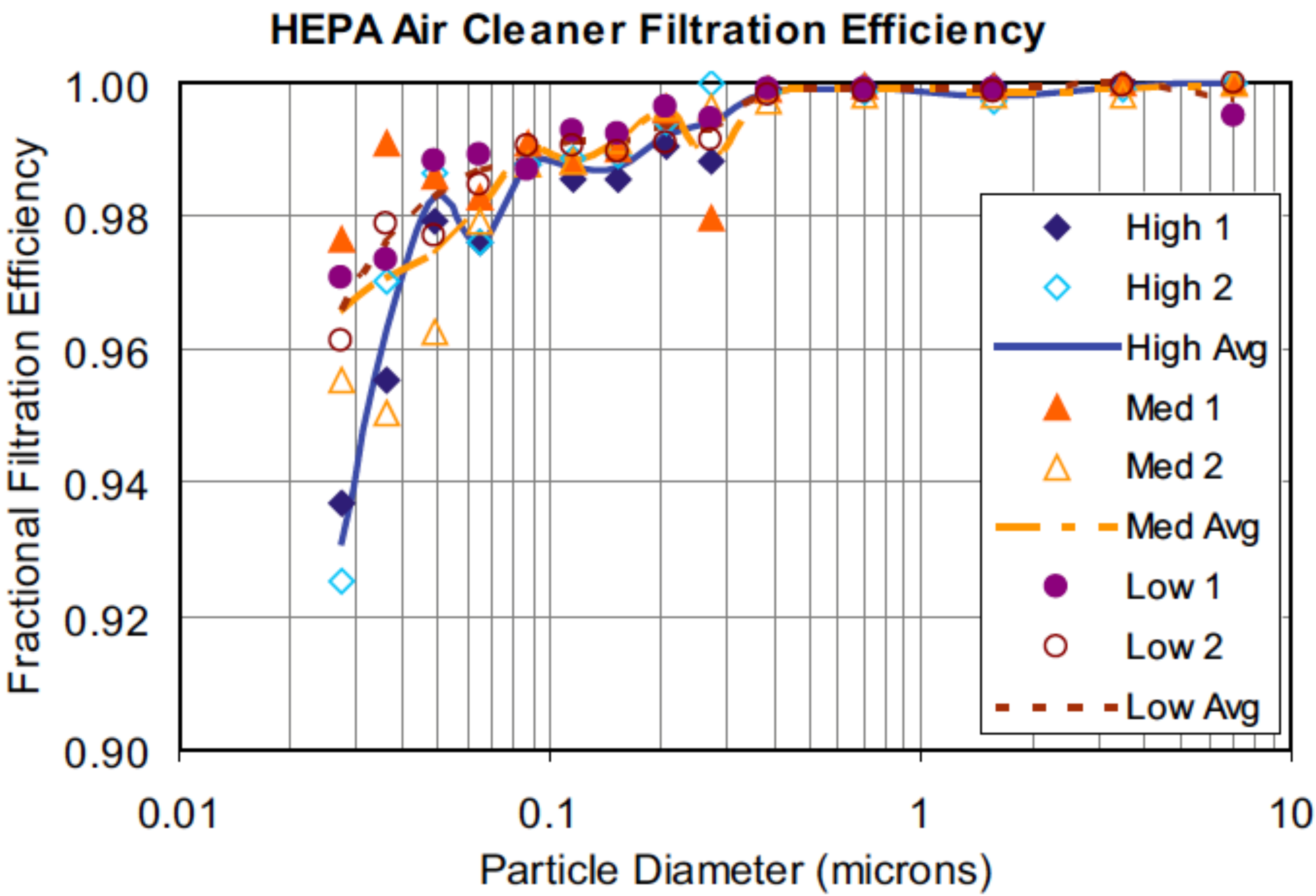
Recent testing of portable air cleaners

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



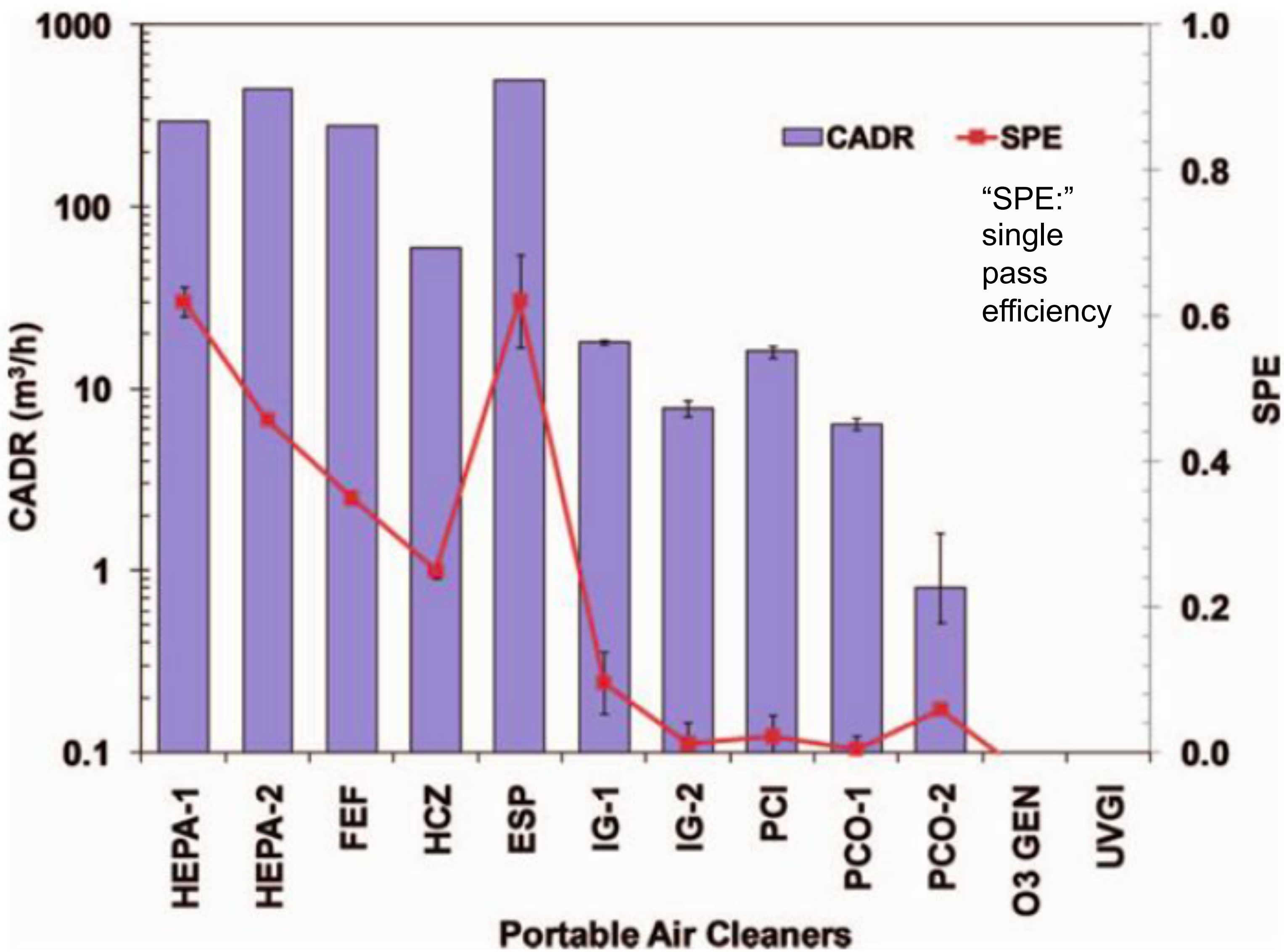
Kogan et al., 2008 EPA Report 600/R-08-012

Recent testing of portable air cleaners



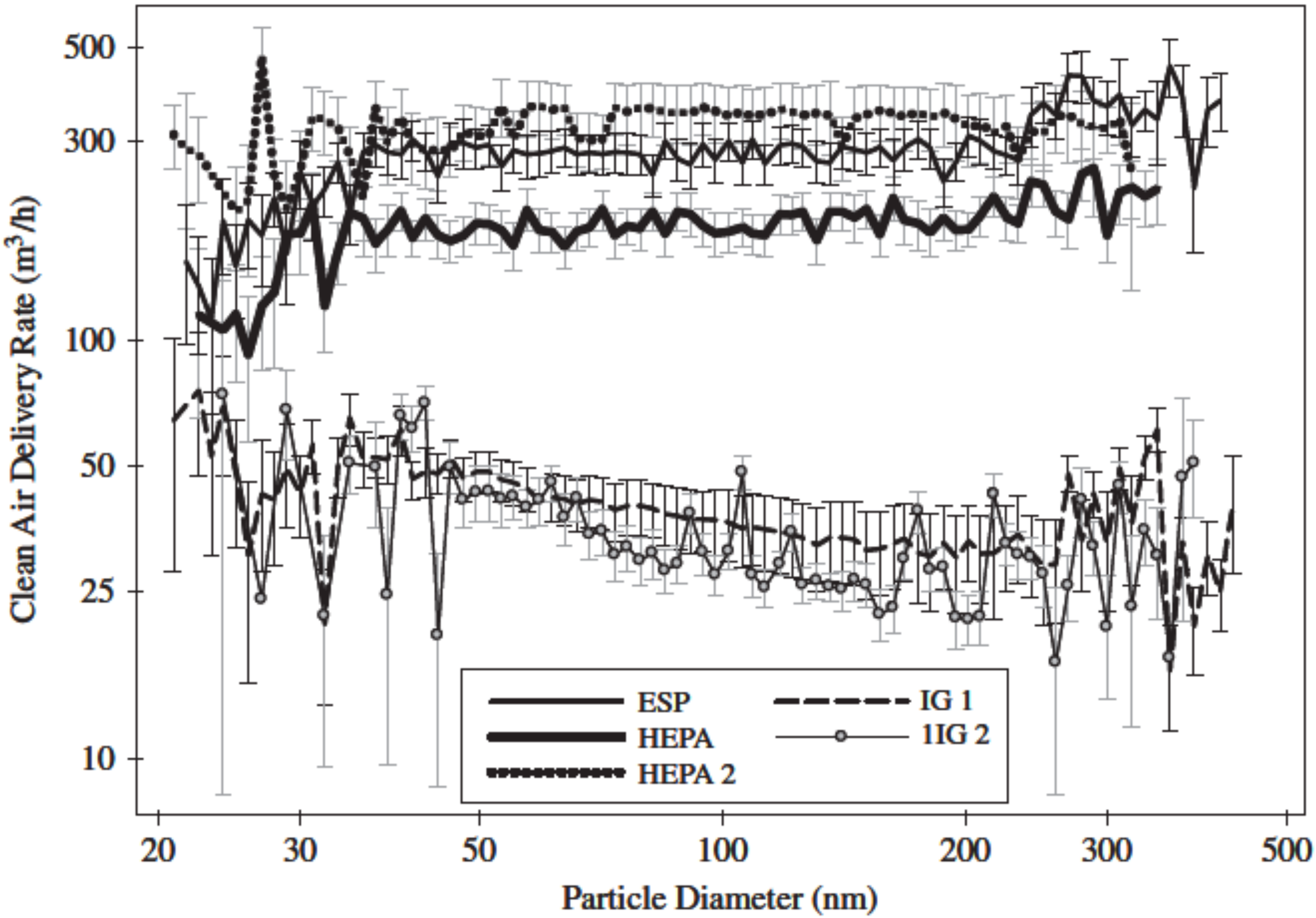
Kogan et al., 2008 EPA Report 600/R-08-012

Recent testing of portable air cleaners: UFPs



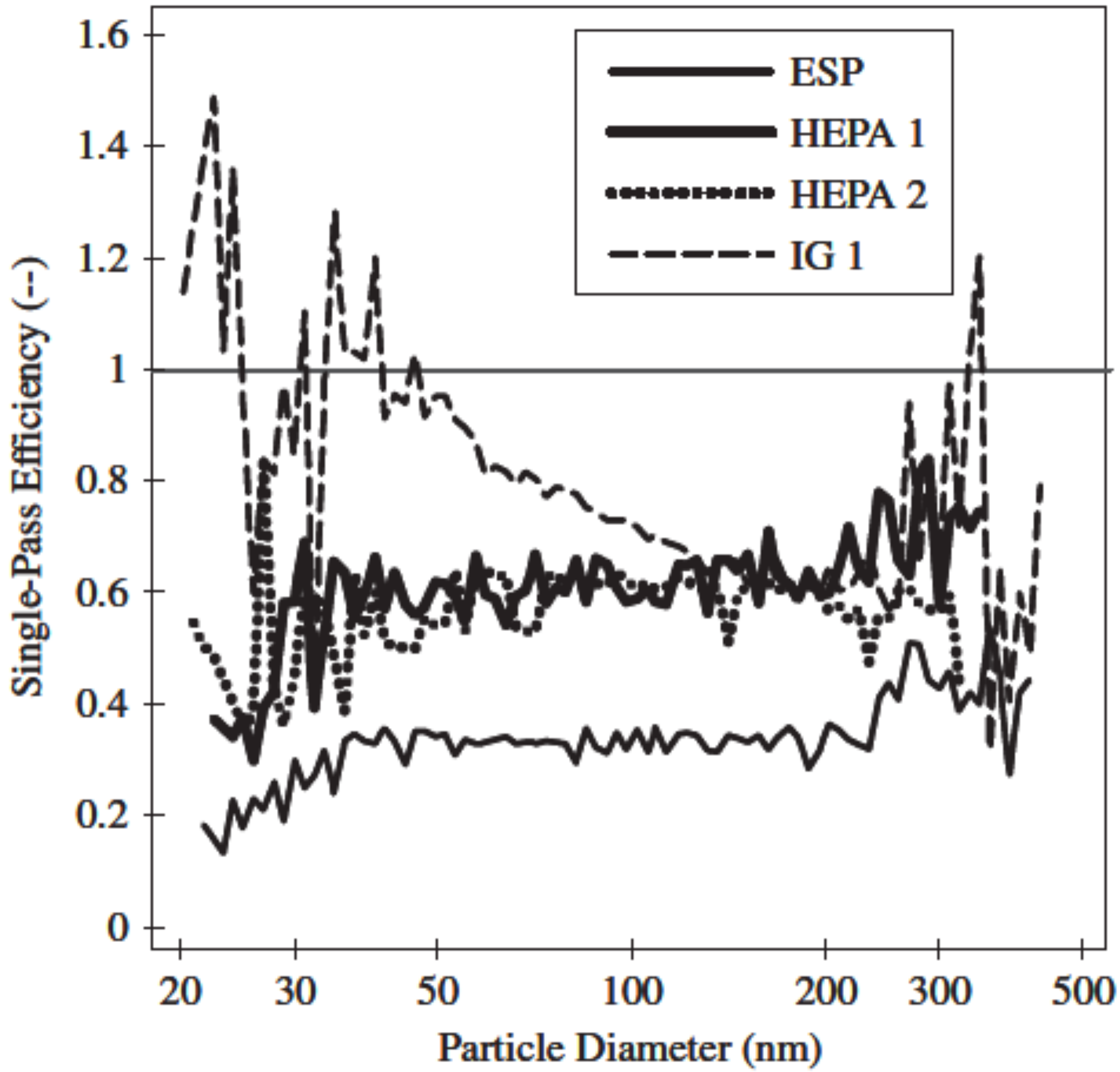
Sultan et al., 2011 *HVAC&R Research*

Recent testing of portable air cleaners



Waring et al., 2009 *Atmos Environ*

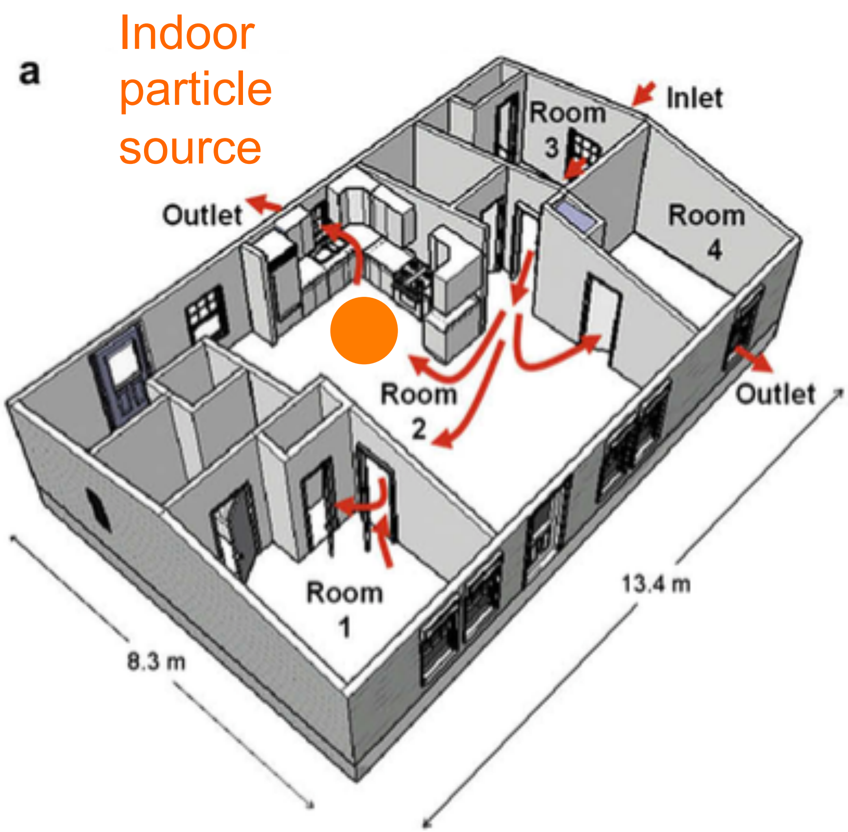
Recent testing of portable air cleaners

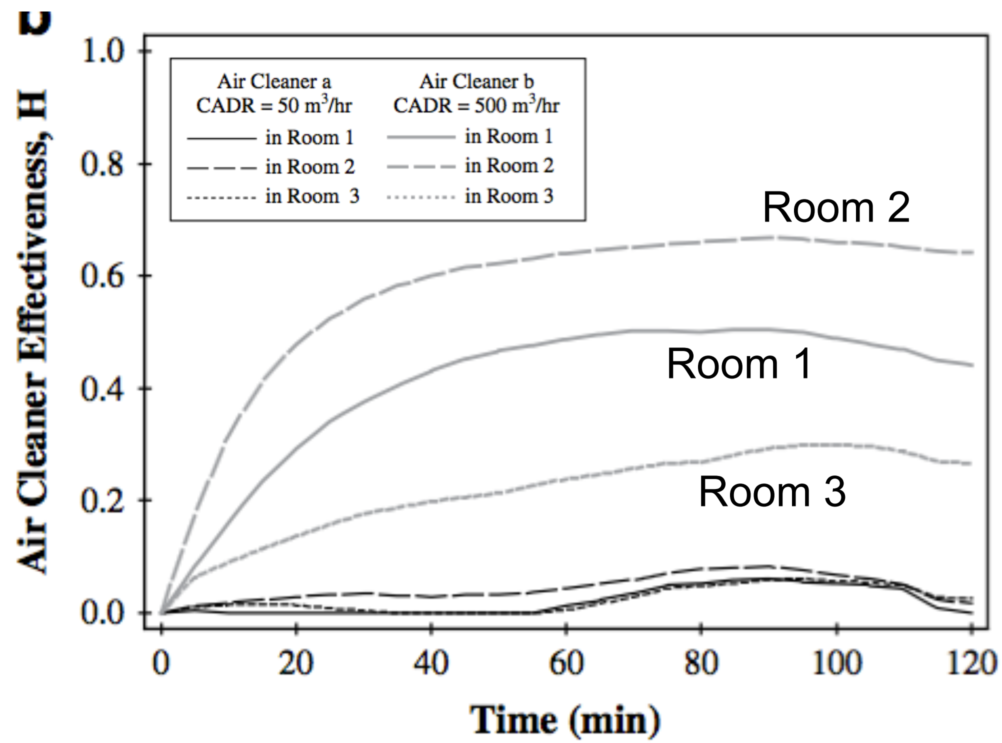


Waring et al., 2009 *Atmos Environ*

Air cleaner effectiveness

- Air cleaner location will obviously influence its <u>**effectiveness**</u> in indoor environments
- We define effectiveness as follows: $1 - \frac{C_{ac}}{C_{no\ ac}}$

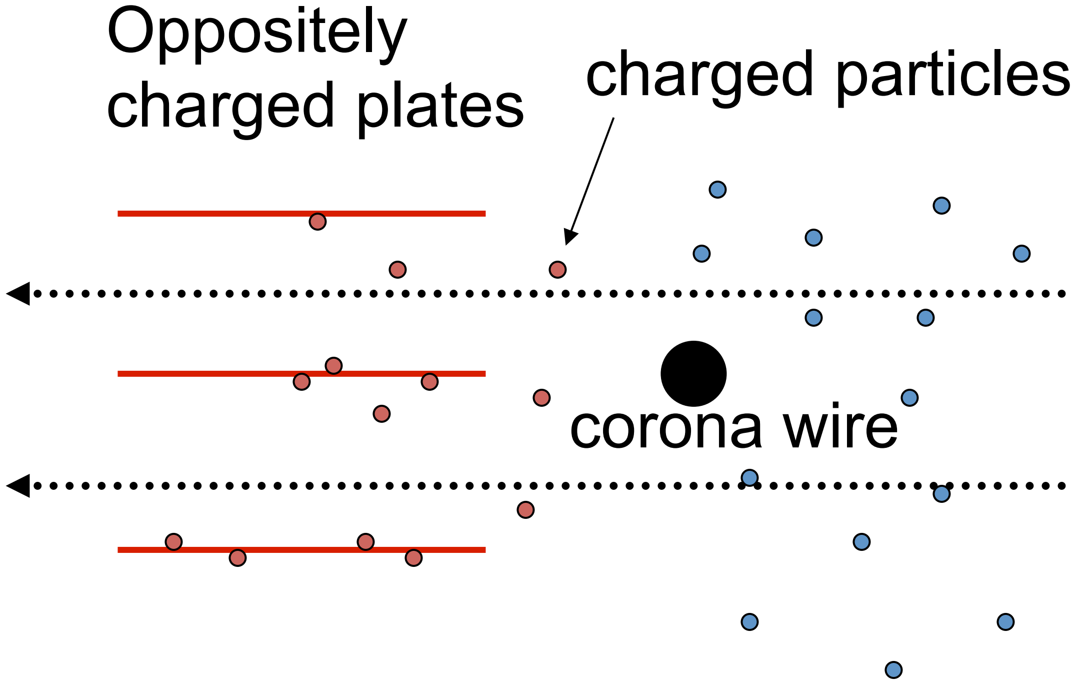




Siegel and Novoselac **2010** *Building and Environment*

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_2)
  - O_2 then forms with O to form O_3 (ozone)



Waring et al., 2009 *Atmos Environ*

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, ΔC_{out}, for a hypothetical residential $50\,m^3$ room and $392\,m^3$ home

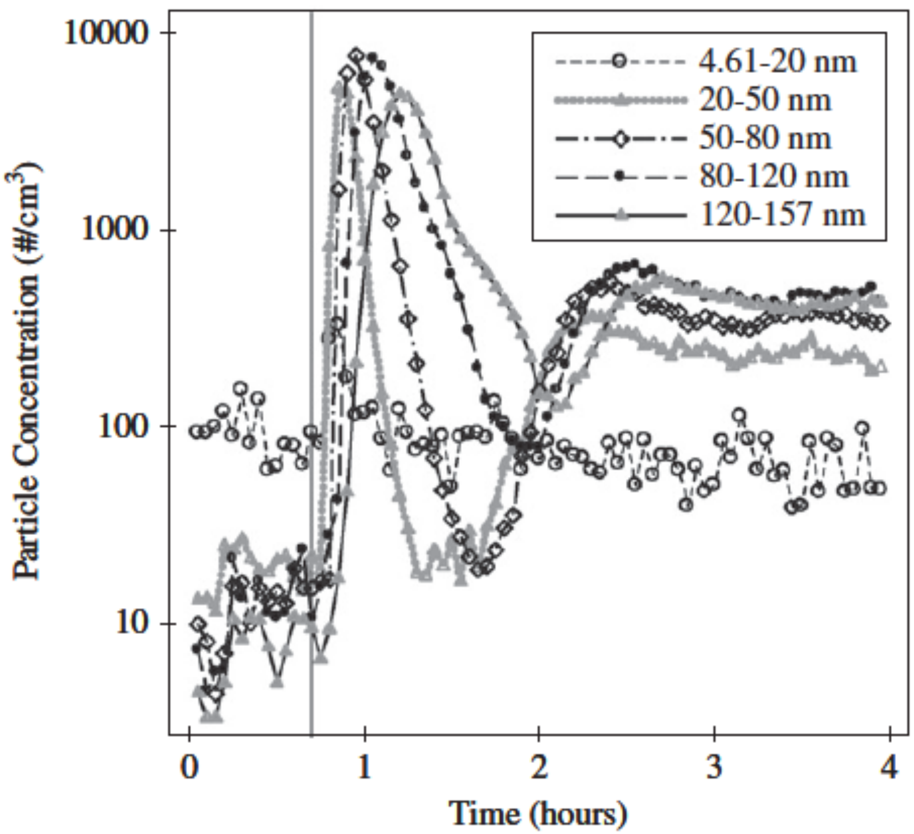
Air cleaner	Ozone emission rate ($mg\,h^{-1}$)	$V = 50\,m^3$		$V = 392\,m^3$	
		C^* (ppb)	ΔC_{out} (ppb)	C^* (ppb)	ΔC_{out} (ppb)
ESP	3.8 ± 0.2	8.6	77	1.1	9.9
IG 1	3.3 ± 0.2	7.5	67	1.0	8.6
IG 2	4.3 ± 0.2	9.7	88	1.2	11

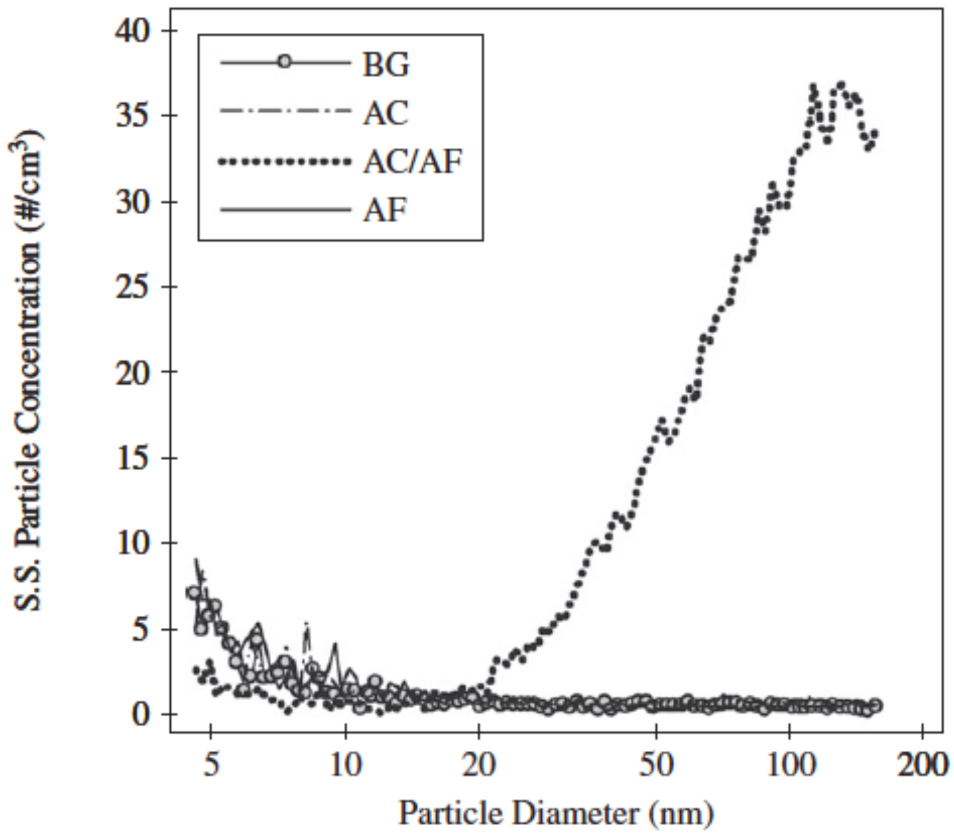
- Byproduct formation from reactions between ozone and terpene products
  - Formation products include SOA (secondary organic aerosols)
  - This means your particle removing air cleaner can lead to generation of particles!

Waring et al., 2009 *Atmos Environ*

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!





Waring et al., 2009 *Atmos Environ*

More resources on filtration

- 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/