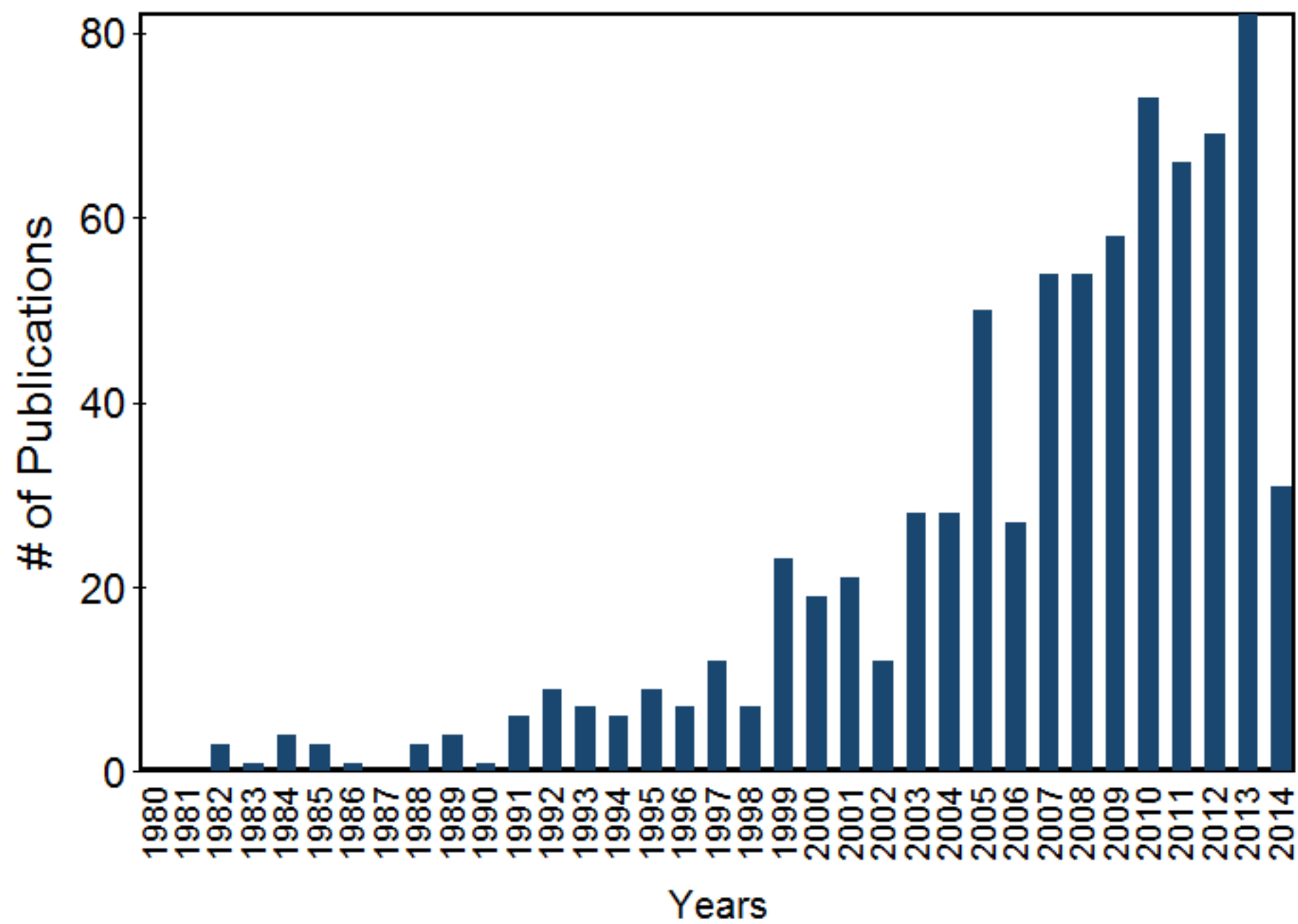


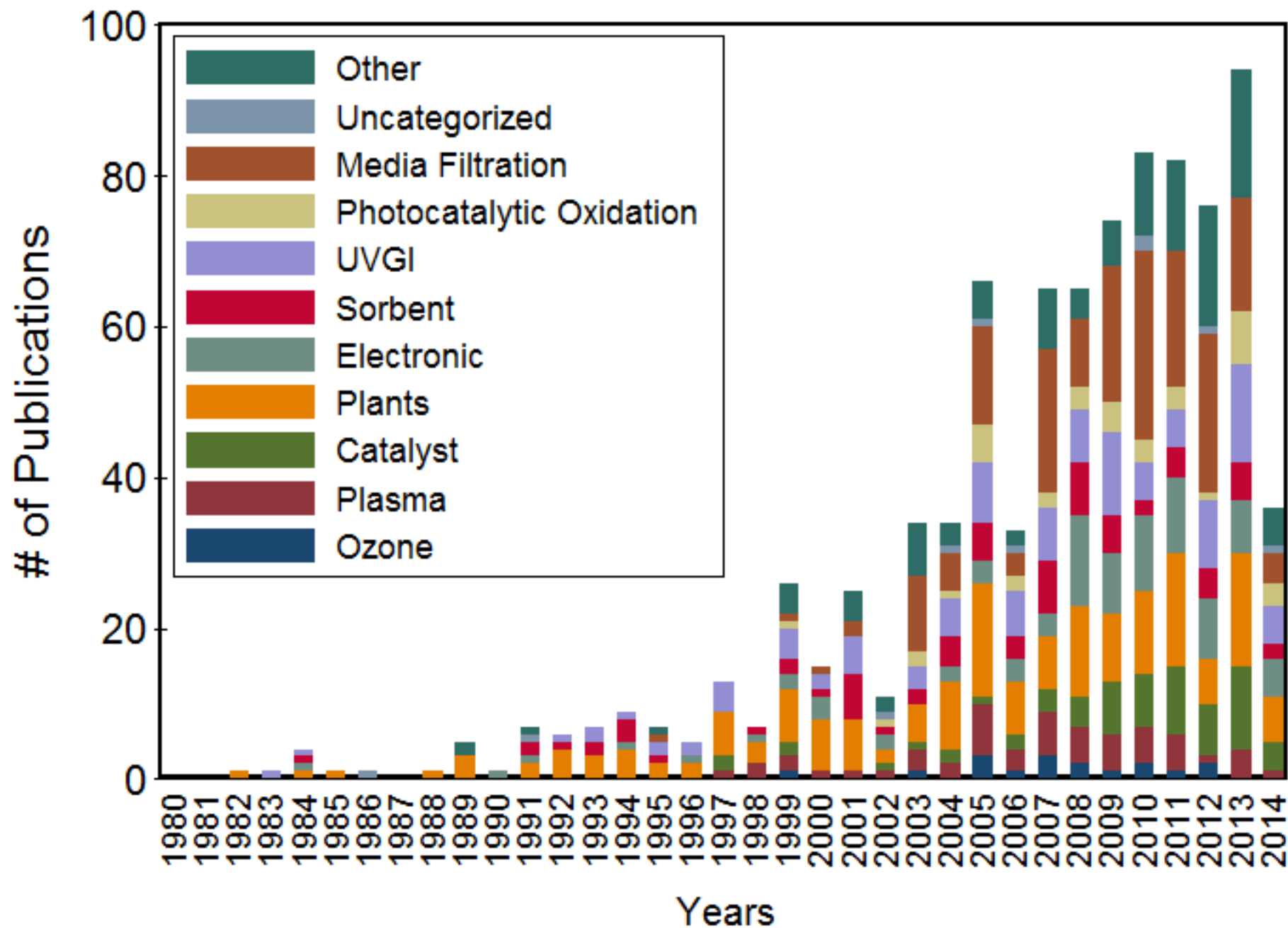
Benefits and Challenges of Particle Filtration and Air Cleaning

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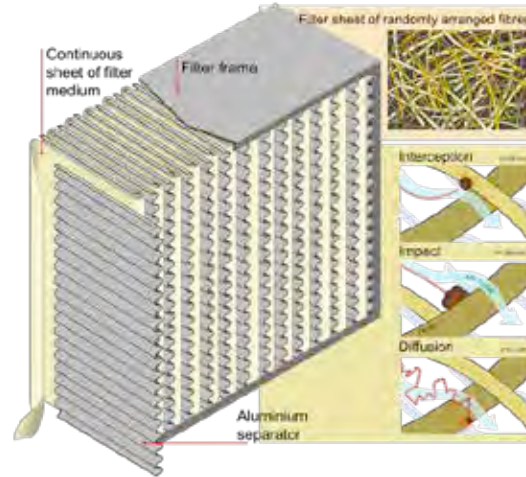




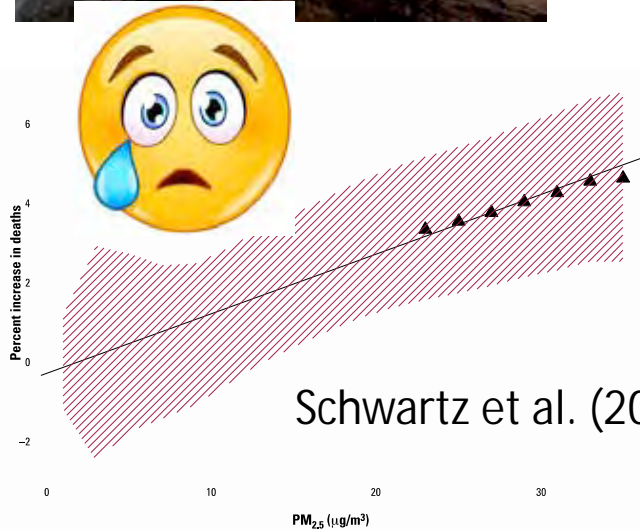
Obvious Benefits



+



=

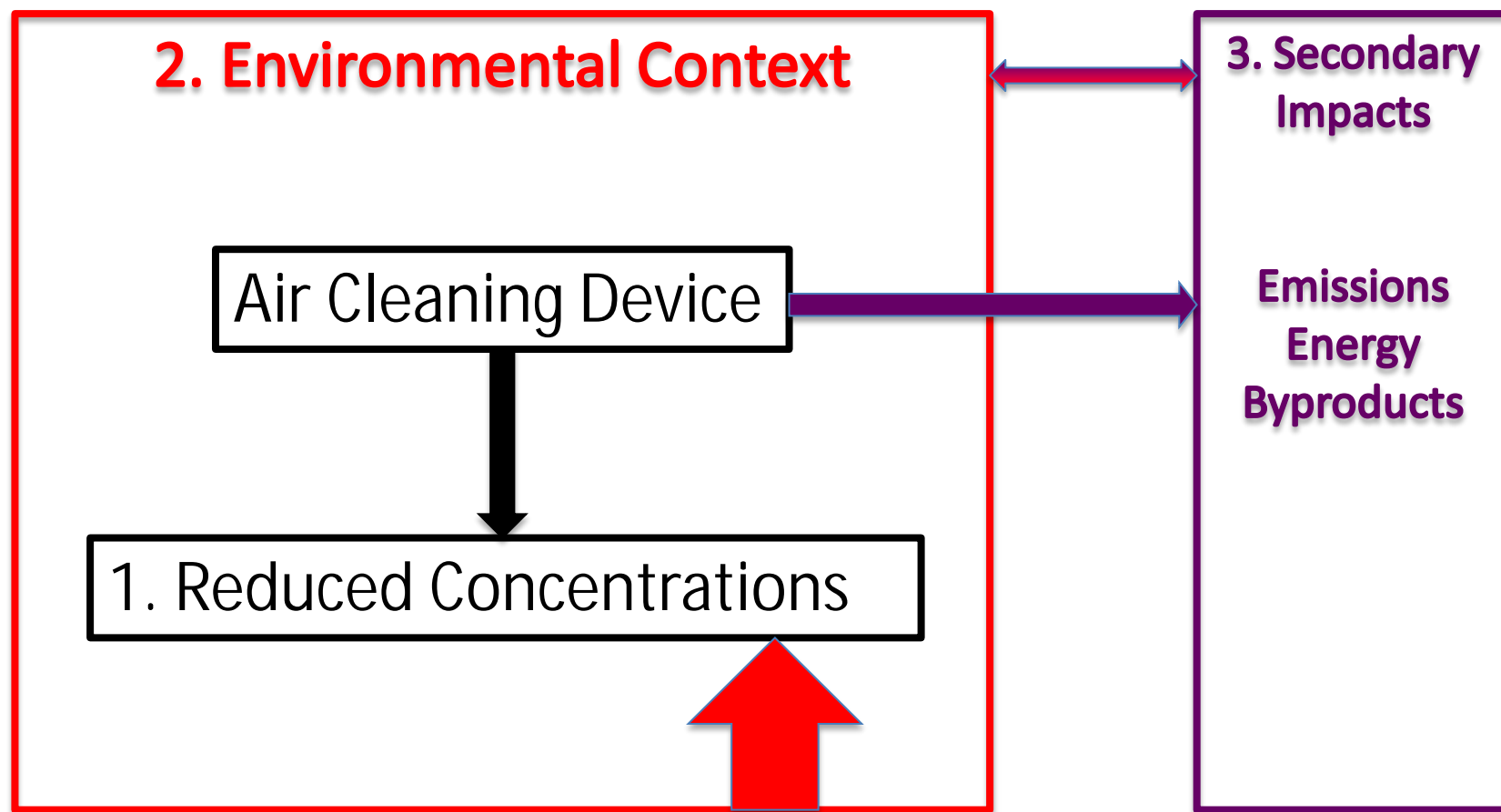


Schwartz et al. (2002) *Environ. Health. Persp.*



images: <http://www.wikihow.com/Brighten-Up-a-Room>,
<https://commons.wikimedia.org/w/index.php?curid=4552953>

Framework for Presentation



Future Directions for Study of Air Cleaning

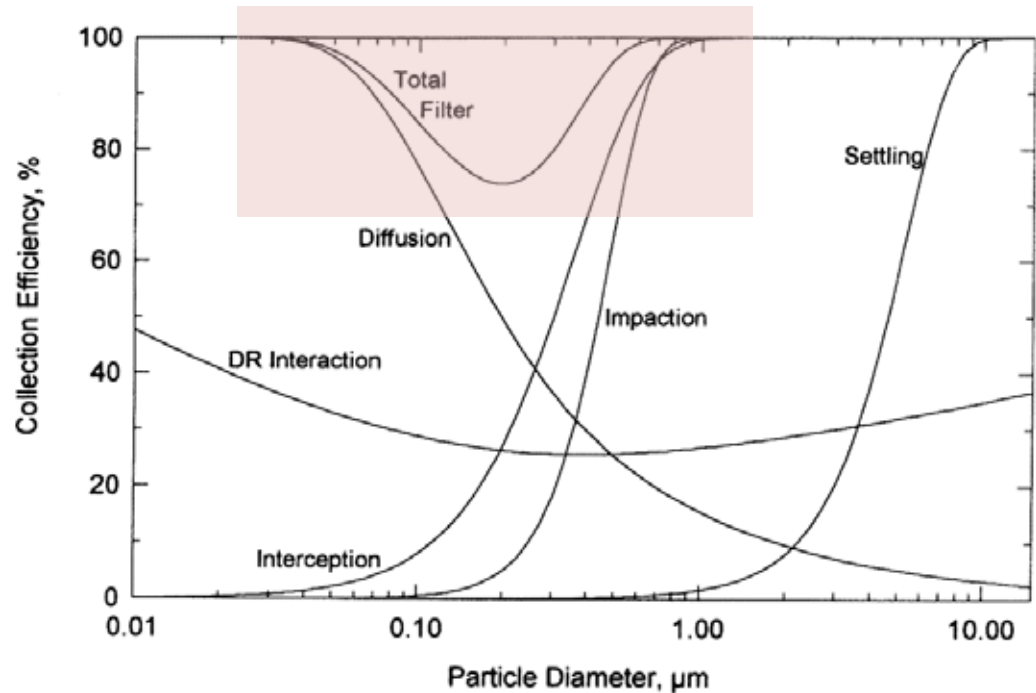
The Filter Matters



Image: <http://www.davedowning.com/blog/>

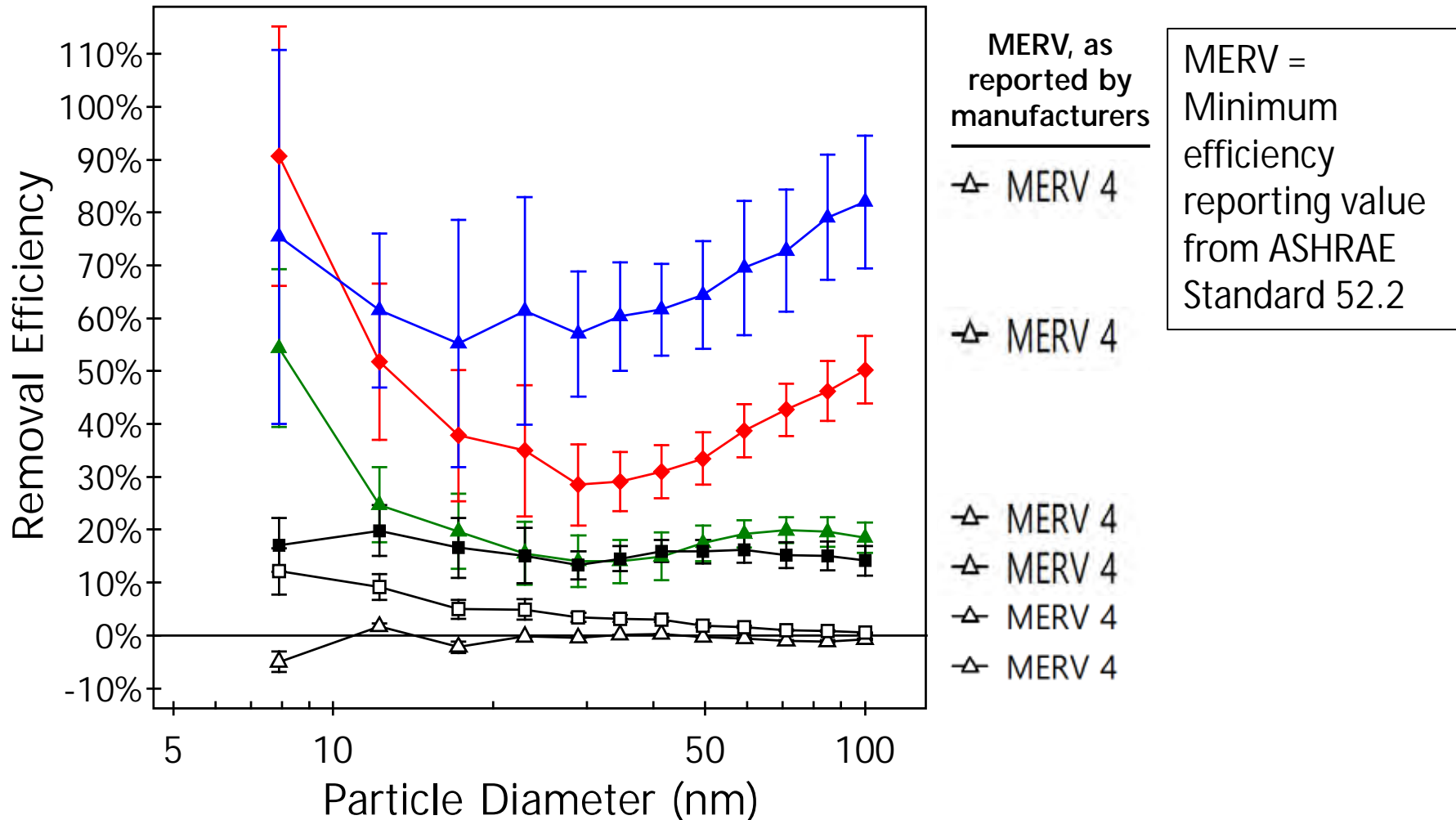
Two Biggest Misconceptions About Filter (or Air Cleaner) Efficiency

1. It is simple
2. It is static

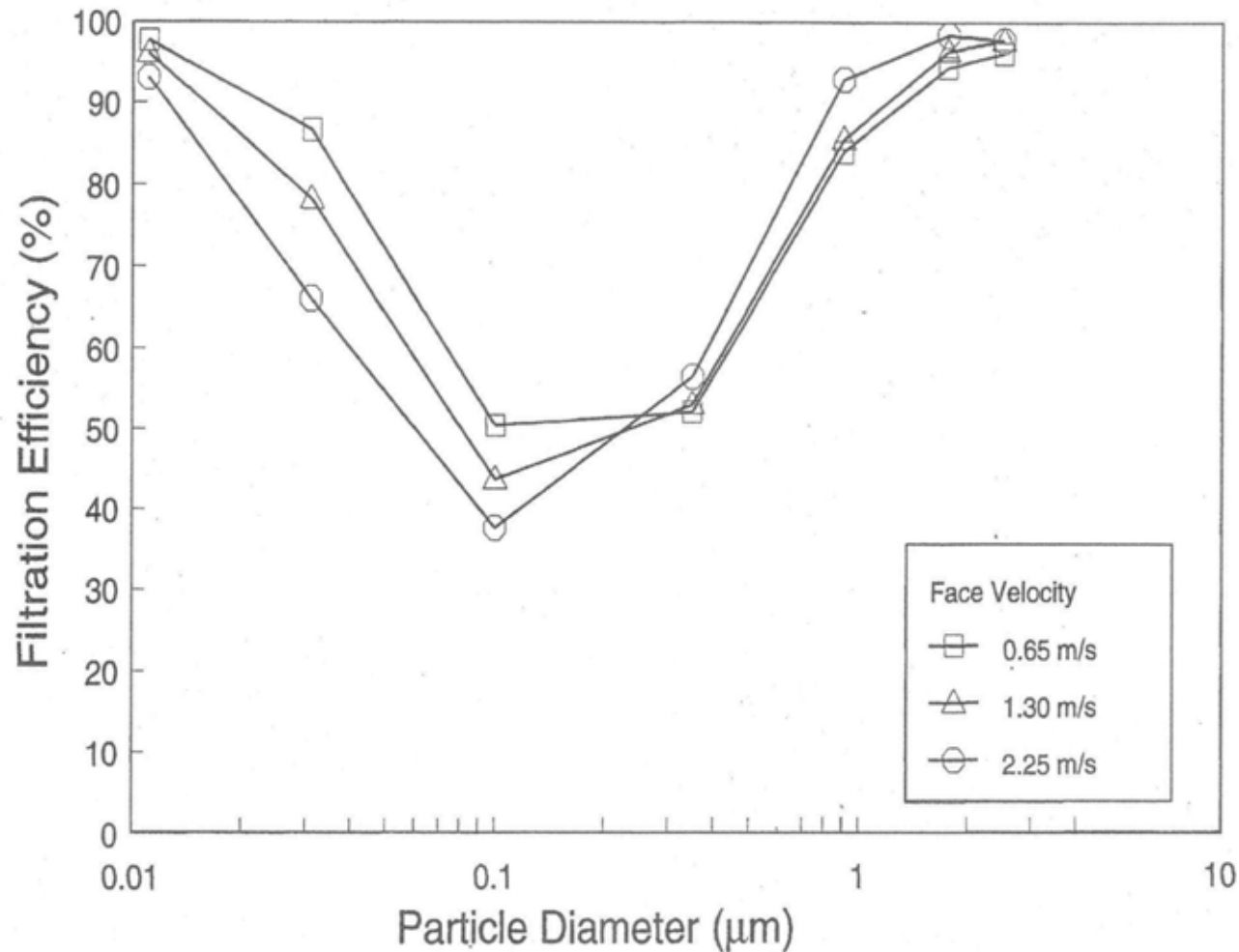


Ref: Hinds (1999) Aerosol Technology

Filters Have Different Efficiencies

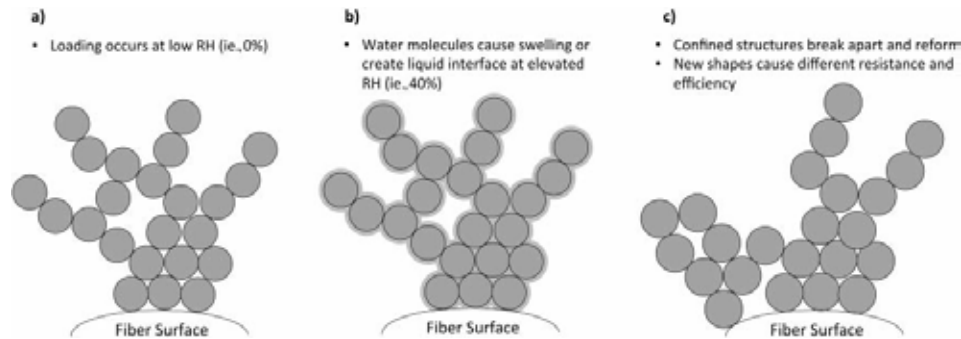


Impact of Face Velocity



Ref: Hanley et al. (1994) *Indoor Air*

Impact of Relative Humidity



en exposed to elevated RH.

Efficiency Changes Over Time

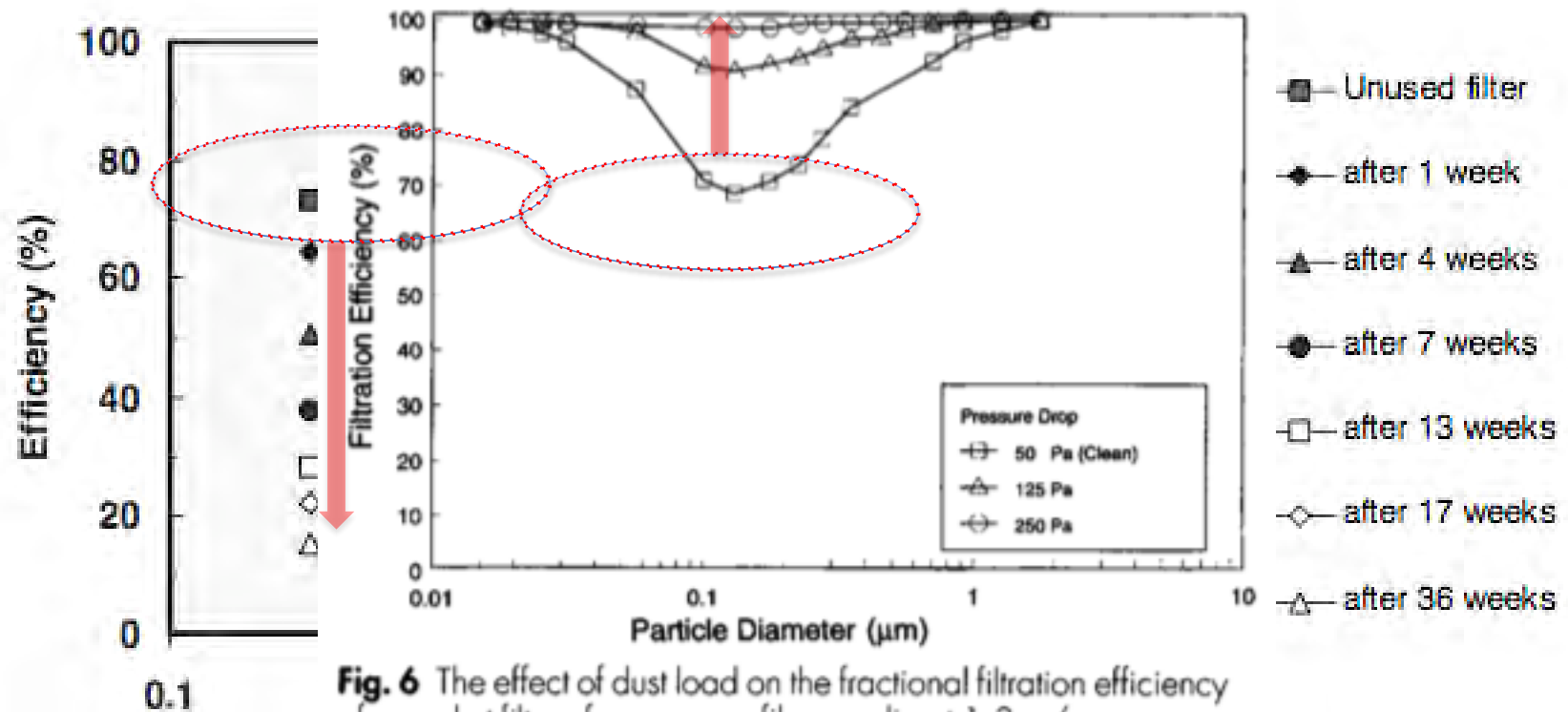
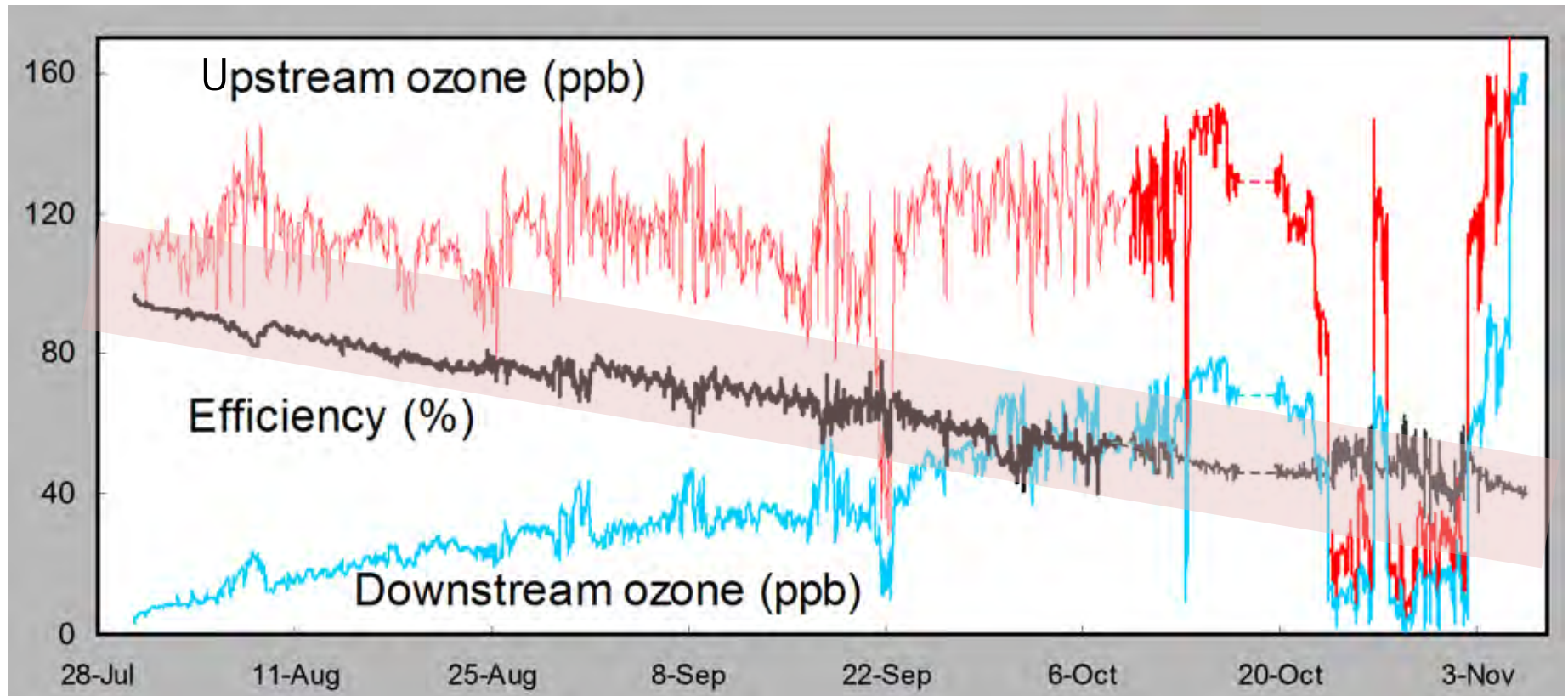


Fig. 6 The effect of dust load on the fractional filtration efficiency of a pocket filter of non-woven fiber media at 1.3 m/s

Particle size (μm)

Refs: Hanley et al. (1994) *Indoor Air*, Lehtimäki et al. (2002) ASHRAE RP-1189 Report

Dynamics: Efficiency Decline of Ozone Removal in Activated Carbon Filter



Ref: Gundel et al. (2002) LBNL-51836

2. Environmental Context

$$C_{ss} = \frac{\lambda_m(1-\eta)C_{out} + \lambda_i p C_{out} + \frac{E}{V}}{\lambda_m + \lambda_i + \lambda_r \eta + \beta}$$

λ air change rate [hr^{-1}]
 m mechanical ventilation
 i infiltration
 r recirculation
 η air cleaner efficiency [-]
 C concentration [e.g., ppb]
 ss steady state
 out outside
 p envelope penetration [-]
 E emission rate [mg m^{-3}]
 V volume [m^3]
 β deposition loss [hr^{-1}]

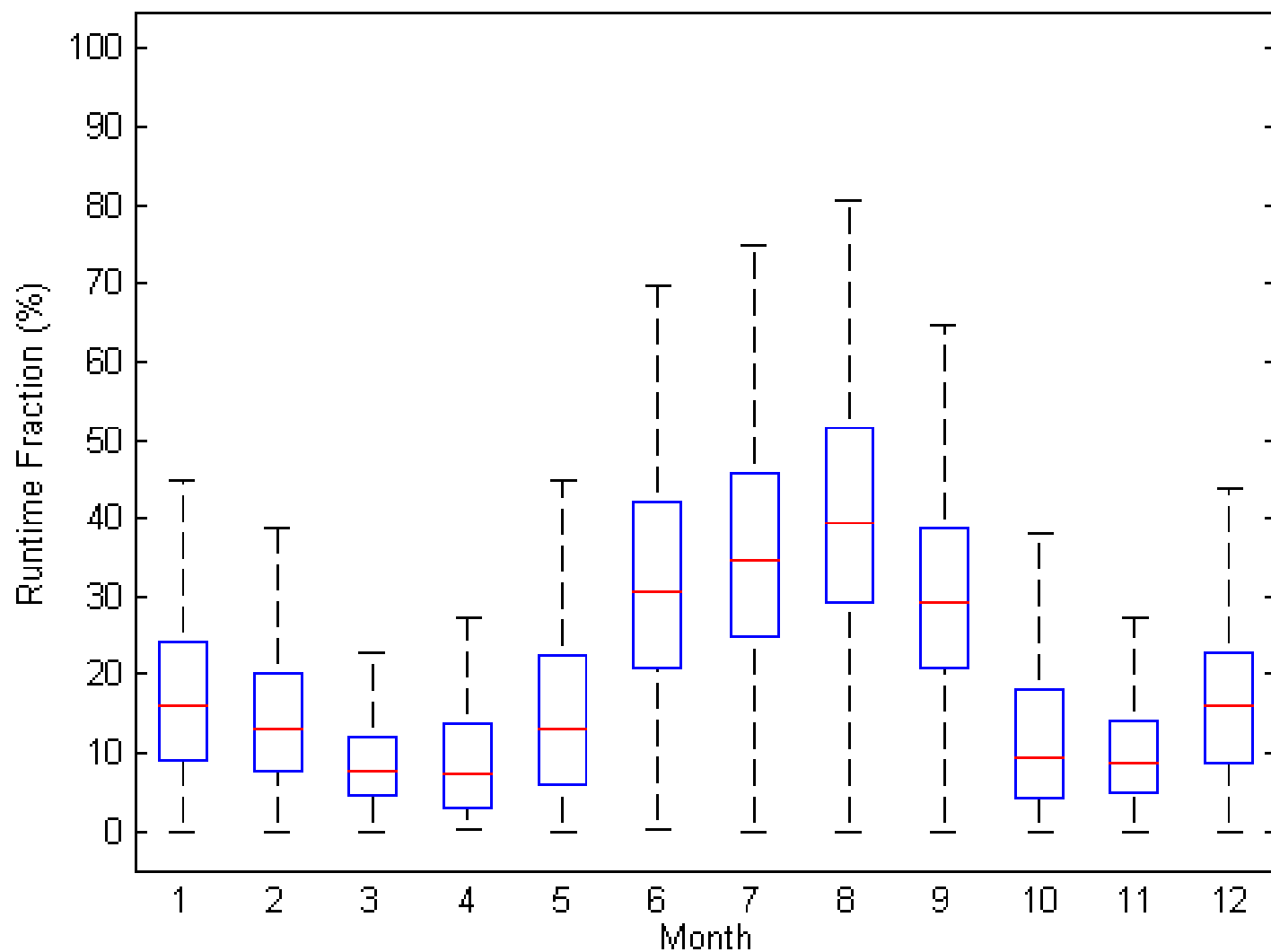
1. Air cleaner efficiency is always associated with a air exchange (or flow) rate
2. Air cleaner removal always has to be seen in context of other losses

Environmental Context – The System Matters

- Run-time and flow rate are often more important than efficiency
 - f fractional runtime
 - Q_r recirculation flow rate

$$C_{ss} = \frac{\lambda_m(1 - \eta_c)C_{out} + \lambda_i p C_{out} + \frac{E}{V}}{\lambda_m + \lambda_i + f \frac{Q_r}{V} \eta_c + \beta}$$

$$f \frac{Q_r}{V} \eta$$



Cetin and Novoselac (2015) *Energy Bldg.*

$$f \frac{Q_r}{V} \eta$$

Flow Rate

- Often discussed, rarely measured well
- Some important points
 - Residential systems often have low flow
 - Commercial system VFDs aren't often used as VFDs



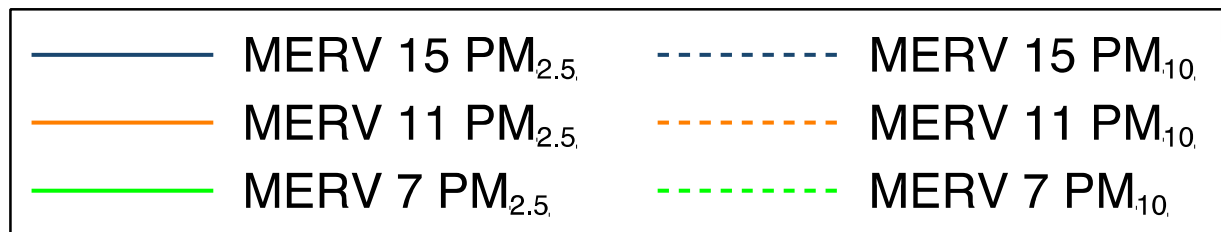
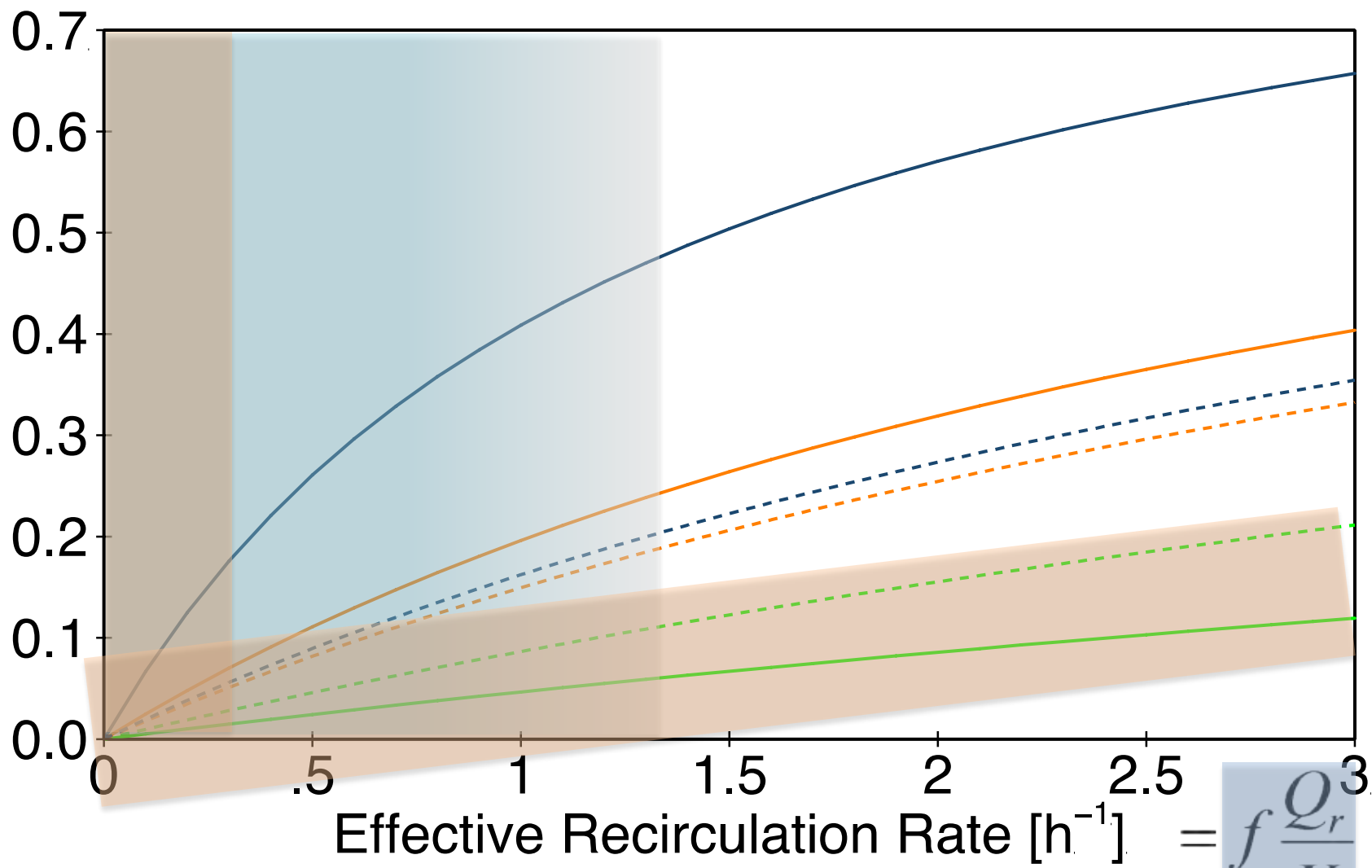
Air Cleaning Effectiveness

- Air cleaning can be contextualized by effectiveness

$$H = 1 - \frac{C_{with\ air\ cleaner}}{C_{no\ air\ cleaner}}$$

Ref: Miller-Leiden et al. (1996) *JA&WMA*

Effectiveness Relative
to MERV 3 Filter



$$\lambda_i = 0.44 \text{ h}^{-1}$$

$$\beta_{2.5} = 0.74 \text{ h}^{-1}$$

$$\beta_{10} = 3.87 \text{ h}^{-1}$$

base case is MERV 3

Environmental Context - System

- Shedding
- Bypass



Bypass gap

Summary So Far

- A good filter with a known efficiency *for the specific environment and over the filter's lifetime* installed and maintained well in an HVAC system that operates enough and with enough flow rate in a building where the filter can effectively compete with other loss mechanisms will reduce indoor concentrations.

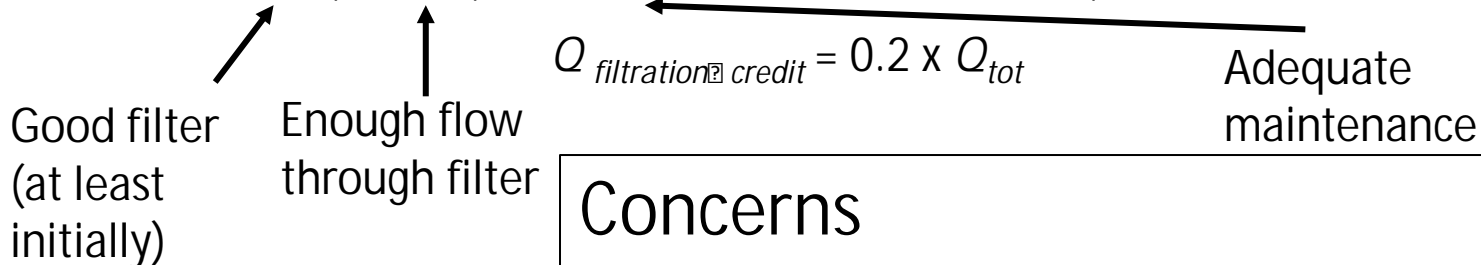
Health and Filtration

- For non-allergic and non-asthmatic individuals
 - “The largest potential benefits of indoor particle filtration may be reductions in morbidity and mortality from reducing indoor exposures to particles from outdoor air.” Ref: Fisk (2013) Indoor Air
- Why?
 - Particle composition?
 - Short duration and nature of indoor sources?
 - Actual effectiveness of filters?

Replacing Ventilation With Filtration

- ASHRAE Standard 62.1 – IAQ Procedure
- ASHRAE Standard 62.2 Add K. – Filtration credit

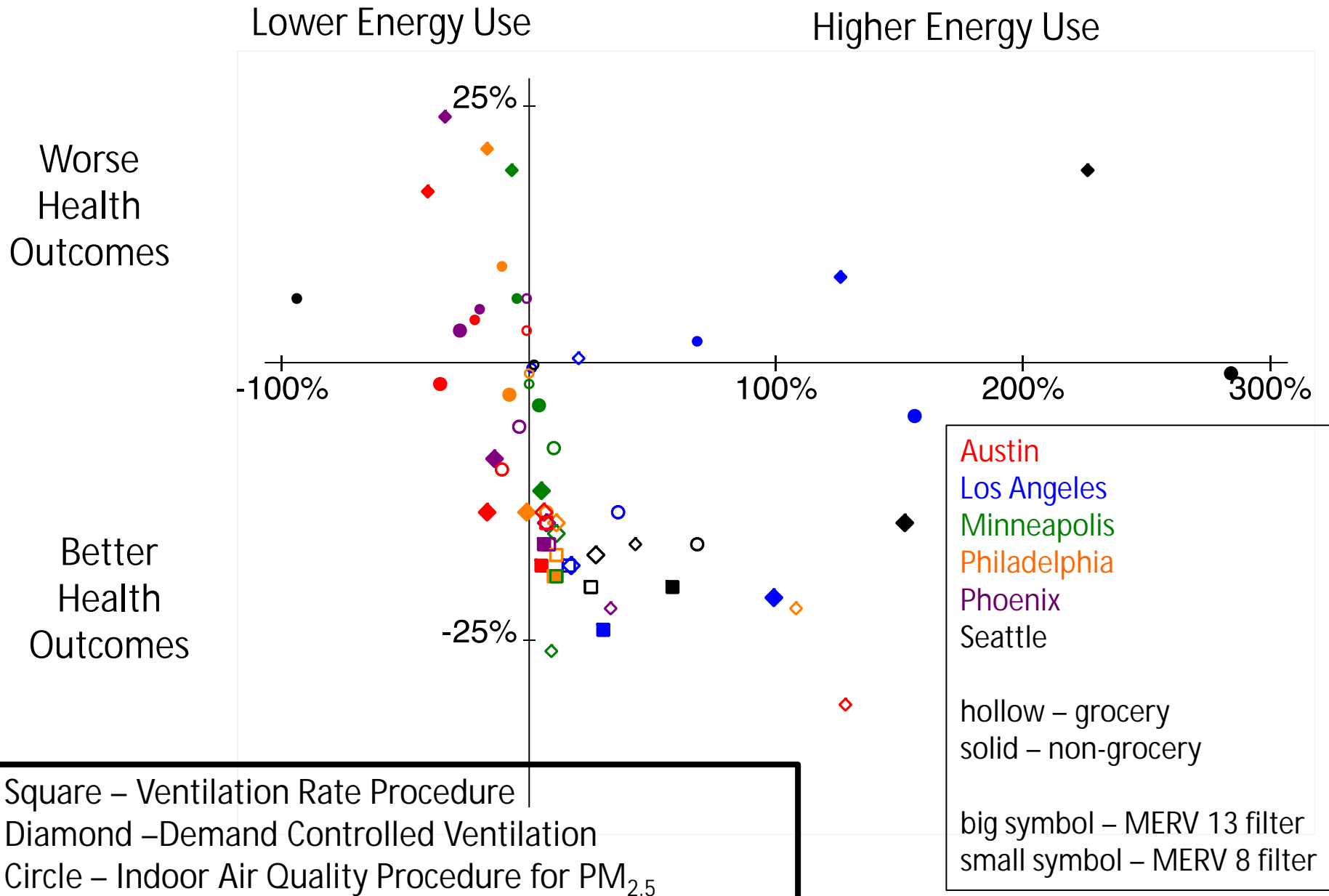
4.1.4 Ventilation-Rate Reduction for Particle Filtration. This section describes the requirements necessary to apply a credit against the minimum total ventilation rate of this standard. This credit applies during any period in which the requirements of Sections 4.1.4.1, 4.1.4.2, and 4.1.4.3 are met. In these cases,



Concerns

- Filter performance in the *particular* home
- Non-particulate contaminants
- Odours/air acceptability

Relative to Ventilation Rate Procedure with MERV 8 Filters

Zaatari et al. (2016) *Bldg. Environ.*

" This is a suitable place to give a most earnest warning against the use of so-called secret remedies and patent medicines...."

Pettenkoffer (1883)



Give your baby healthy air. Make baby's nursery a healthy place, with our state-of-the-art air purifier and ionizer! **Wonderful for respiratory systems that are still developing.** Purifies up to 200 square feet, **trapping particles as small as 100 microns.**

Thanks to Brent Stephens, Rich Corsi, Laura Siegel

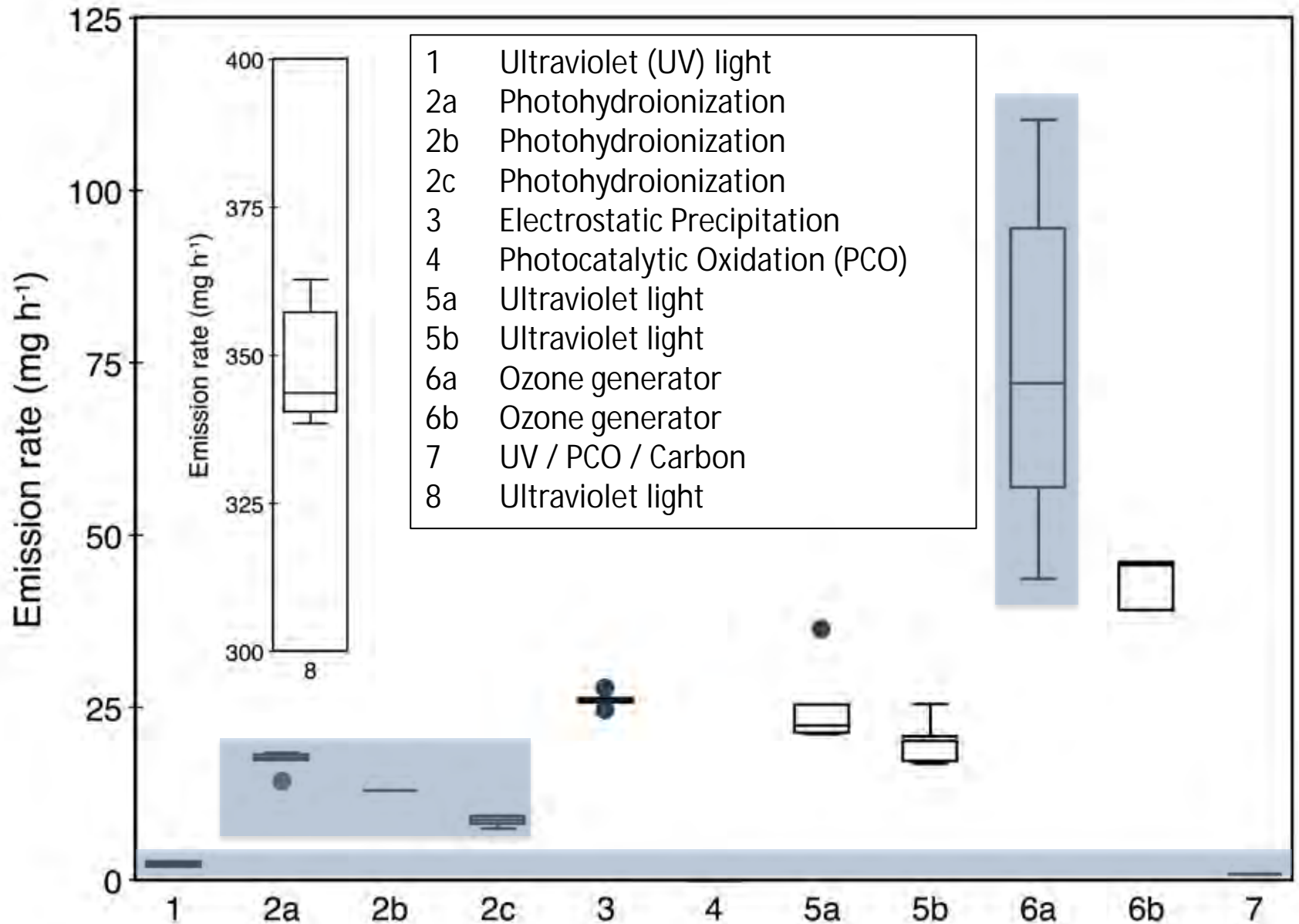


We have developed the best air purifier on the market. xxxx combines the beauty of a sleek flowerpot with the technology to reduce dangerous indoor pollution.

3. Secondary Consequences (1)

- Ozone Emission
 - Two technologies used in air cleaners can emit ozone
 - Ultraviolet lamps
 - High voltage coronas or pins
 - Ozone is a respiratory irritant and oxidant
 - Can result in formation of formaldehyde, ultrafine PM, etc.

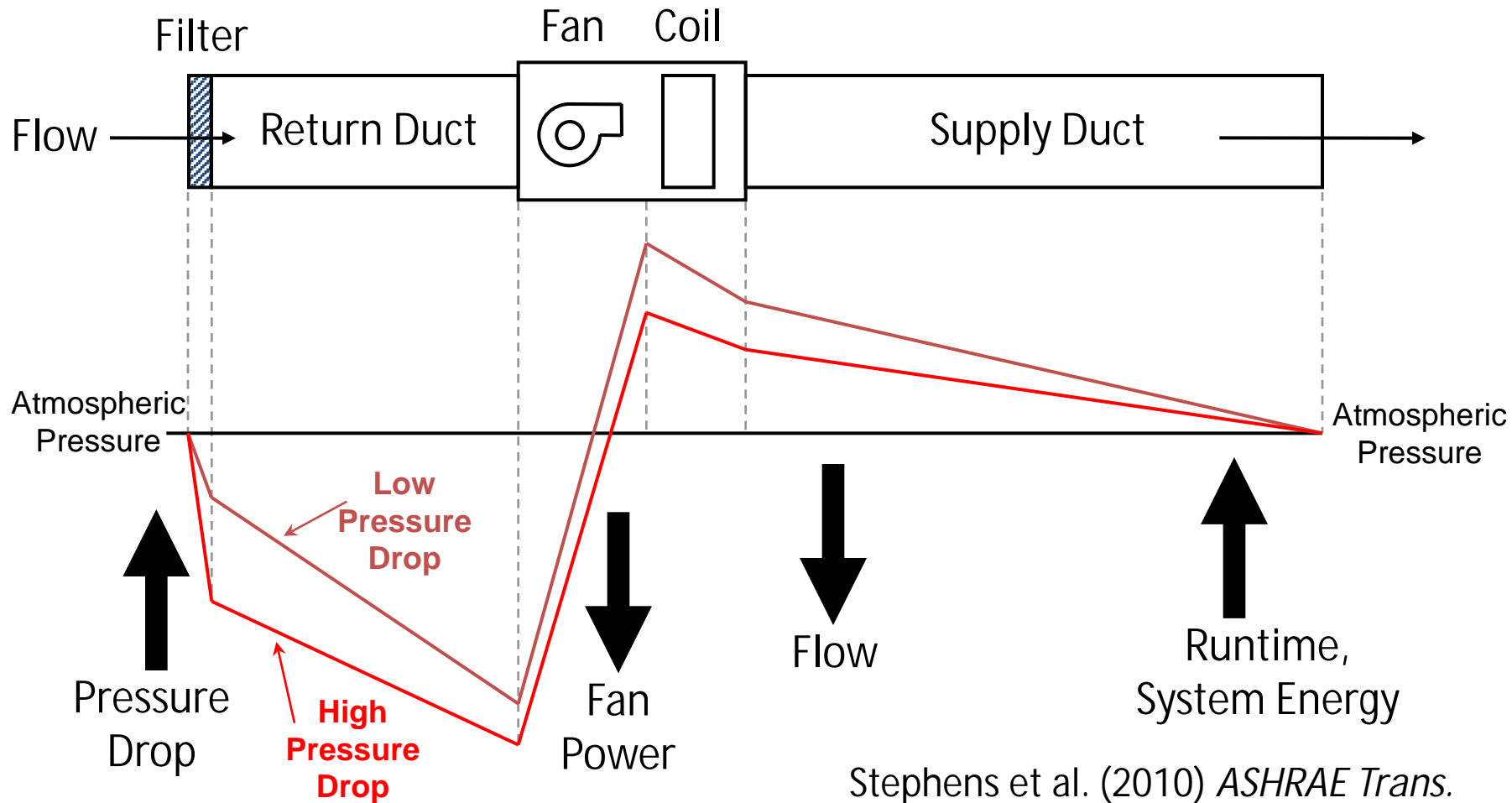
Ozone Emission From In-Duct Air Cleaners



Secondary Consequences: Energy Use

- Air cleaners often use energy
 - Fan energy
 - Device energy
- HVAC systems
 - Fan operation becomes critical
 - A higher pressure drop filter will **save** energy in many systems
 - Key question is whether fan speed control is used

Summary of Systemic Effects

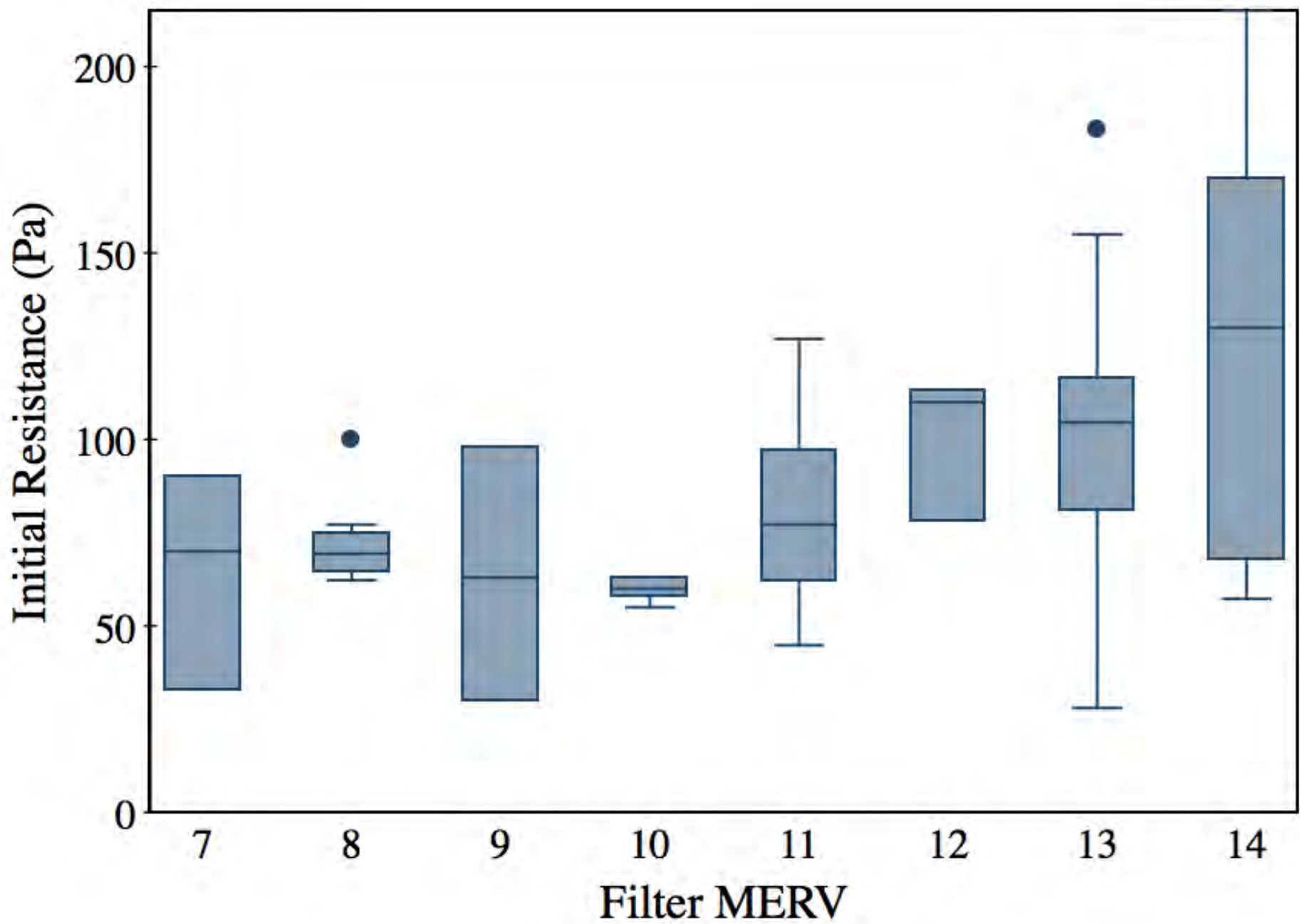


Stephens et al. (2010) *ASHRAE Trans.*
Stephens et al. (2010) *HVAC&R Res.*
Walker et al. (2013) *ASHRAE Trans.*
Zaatari et al. (2014) *Bldg. & Environ.*

Residential Filters And Energy

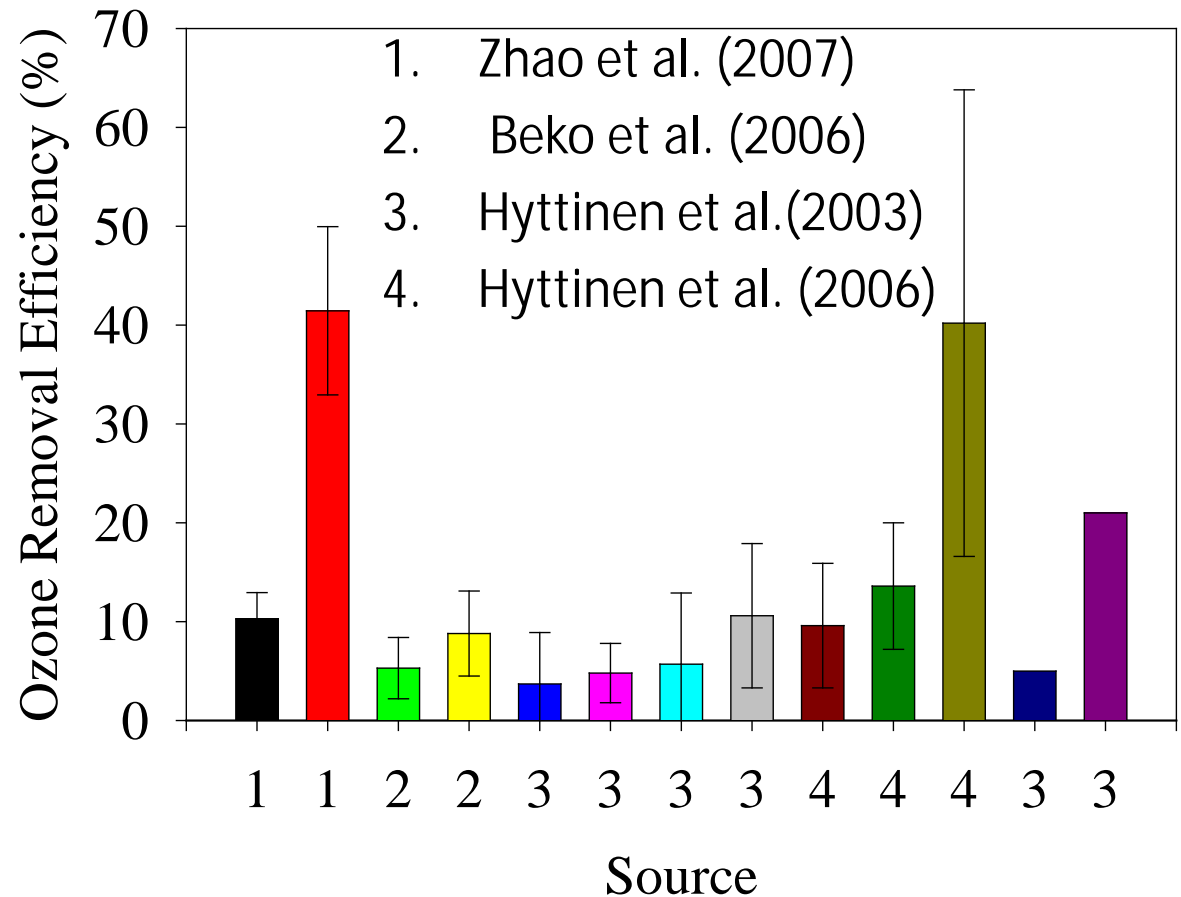
PM _{2.5} Filter Efficiency	Flow [m ³ hr ⁻¹]	Run-Time Fraction	PM _{2.5} CADR [m ³ hr ⁻¹]	Cooling Power Draw Increase
15%	1699	14.9%	38	
30%	1572	15.9%	75	0.5%
50%	1529	17.3%	132	0.4%

- Drop in flow is more than compensated for by increase in efficiency (and runtime)
- Energy change is negligible

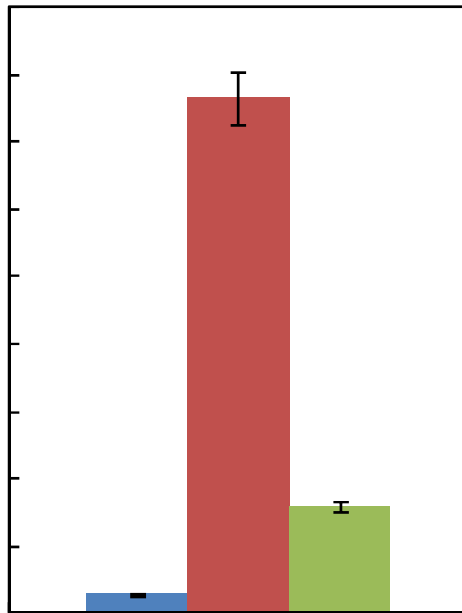


Secondary Consequences: Byproduct Formation

- Ozone can react with air cleaners
 - Odors
 - Byproducts
 - Media degradation



Formaldehyde Production



Fiberglass with Heavy
Tackifier

Polyester with
medium Tackifier

Cotton/polyester
without Tackifier

Summary Thus Far

1. Understand and differentiate technology and approaches for air cleaning
2. Put air cleaning in context of the environment in which it operates
3. Explore secondary consequences

Future Directions 1

Air Cleaning and Health

- We know much more about air cleaners ability to reduce concentrations than we do about its ability to improve health
 - Particle filtration: Fisk (2013) *Indoor Air*
 - Smattering of information on other technologies
- **Need carefully designed and controlled investigations of air cleaner impact on health**
 - Some recent work in China

Air Cleaners and Health

- The role of filtration on the indoor microbiome
- We are surrounded by microorganisms
- Some are starting to argue that filters are not healthy because they filter everything and thus lead to lower diversity



Prebiotic and probiotic approaches are being done!



“Homebiotic is a spray and leave on treatment that lasts 6 months. Bacterial cultures take up residence and prevent mold growth.”

Benefits:

- Maintains a healthy balance of microbes in your home
- 1 application covers 1000 square feet
- Non-toxic, GMO-free, **Gluten-free**
- Pleasant citrus smell from organic botanical oils



Reviewed by: **Tatortodd** Verified Reviewer



Posted: 12/15/15

TOOK AWAY MOLDY SMELL OUT OF OUR HOUSE

We had some roof leak/flooding and could always smell it. Used this item and it has taken away the smell when we walk into our kitchen. What a relief!!

<http://www.bulletproof.com/homebiotic-concentrate-4oz>

Future Directions 2

Secondary Consequences of Air Cleaning

- Many secondary consequences are not well explored
- **Need novel research that documents and explains secondary impacts**

nd high ($\nu = 0.5$ m/s) face velocity experiments.

Ref: Sidheswaran et al. (2013) *ES&T*

Future Directions 3

Fundamental Understanding of η

- Removal efficiency is dynamic
- Our ability to model air cleaning performance is predicated on understanding dynamics
- Dynamics are dependent on nature of air cleaner and loading
- **Need to understand fundamental mechanisms that lead to changes in performance**

Montgomery et al. (2015) AS&T, Owen et al. (2013) ASHRAE RP-1390

Future Directions 4: Other Benefits?

I  dirty filters

- Filters are a spatially and temporally integrated long-term sampler of particles
- Have the potential to assess an exposure-relevant concentration of particle-bound contaminants

A Partial Chemical Analysis of Atmospheric Dirt Collected for Study of Soiling Properties[△]

By C. E. Moore*, Chicago, Ill., Robert McCarthy**, and R. F. Logsdon†, Louisville, Ky.

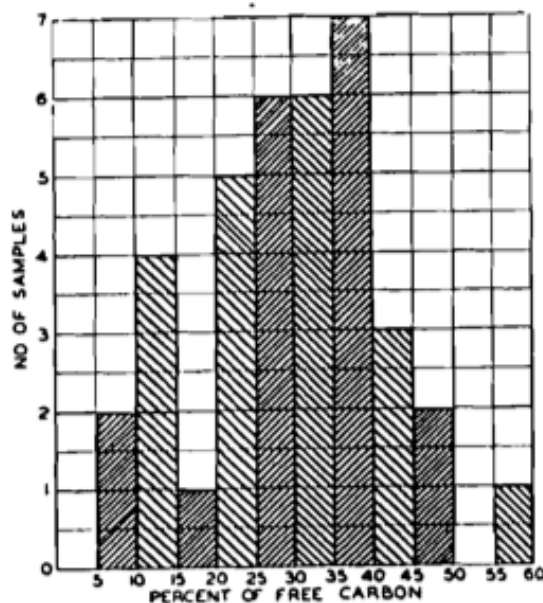


Fig. 4—Percent of free carbon in samples

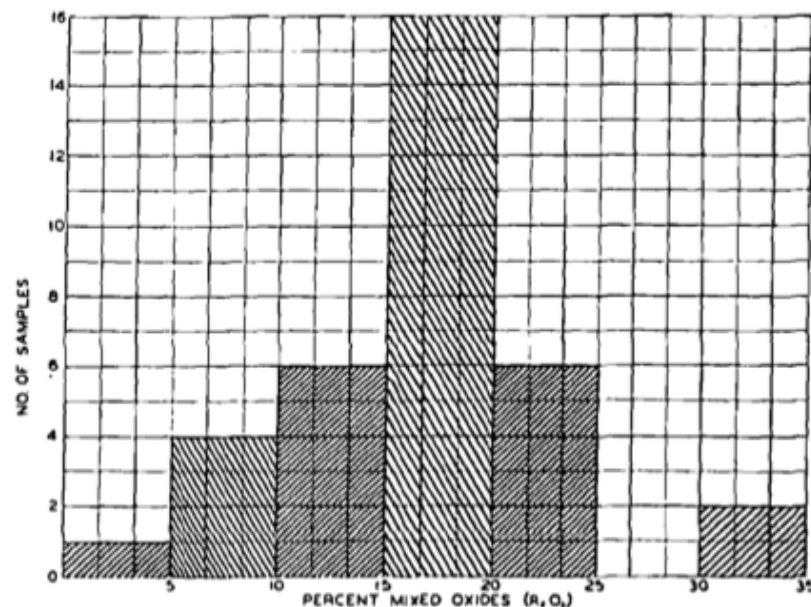
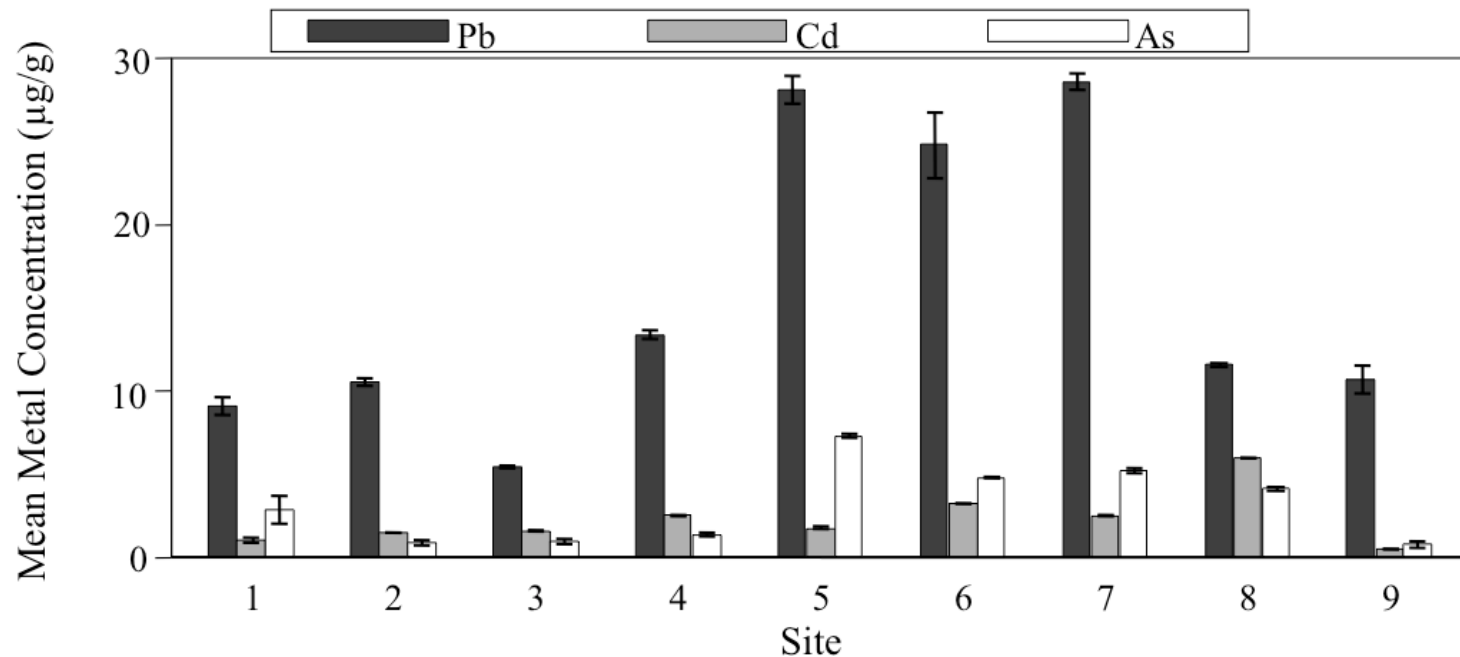


Fig. 7—Percent of mixed oxides in samples



Noris et al. (2009) *ASHRAE Trans.*

Echavarria et al. (2000) *J. Clin Microbio* - Detection of Adenoviruses (AdV) in Culture-Negative Environmental Samples by PCR during an AdV-Associated Respiratory Disease Outbreak

Quantitative Filter Forensics

- Allows an assessment of the integrated concentration of any particle bound contaminant that can be extracted from dust

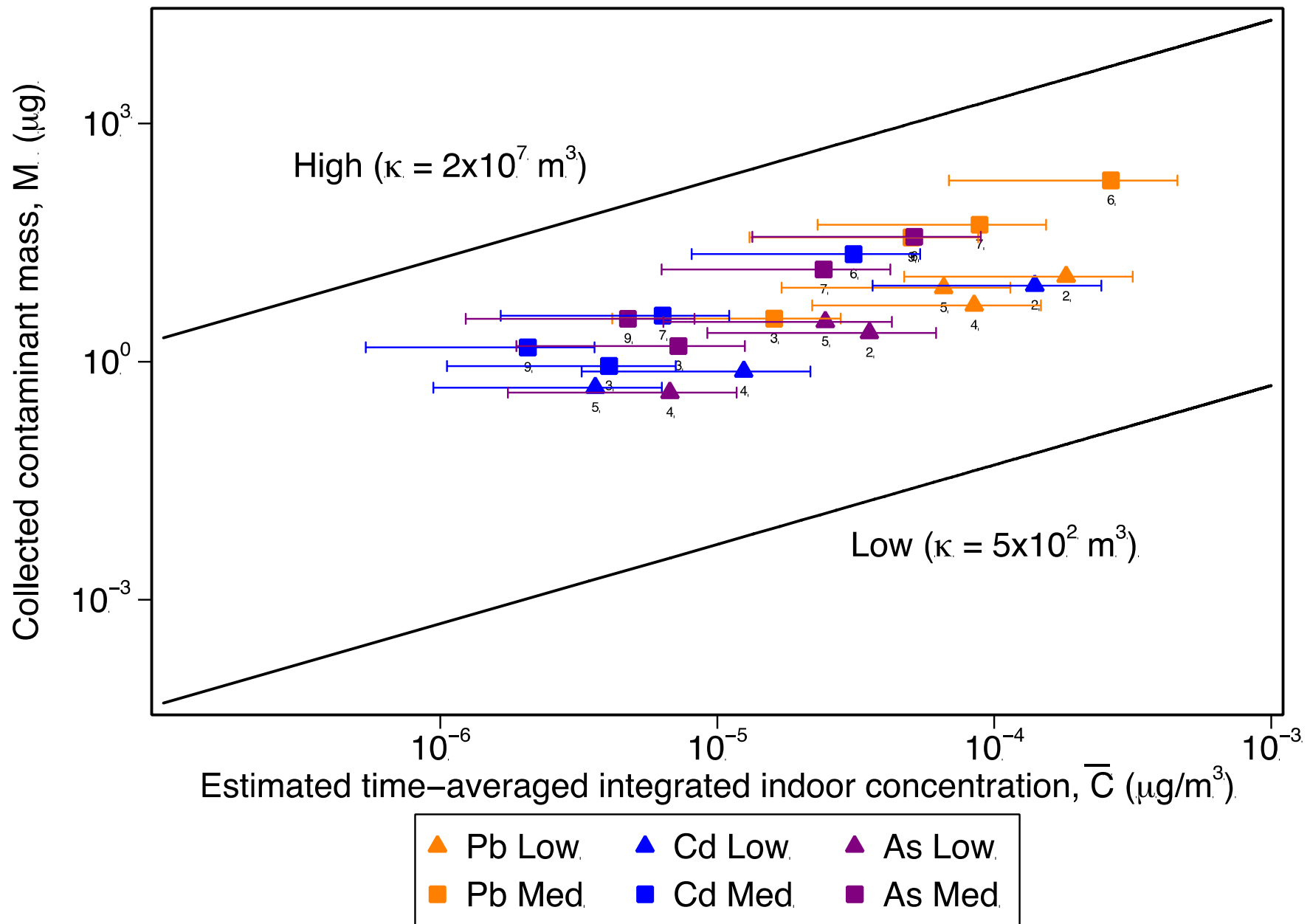
$$\bar{C} = \frac{Mf}{tQ\bar{\eta}}$$

$$\kappa = tQ\bar{\eta}$$

κ = effective filtration volume [m³]

\bar{C} = avg. air concentration [μg/m³]
 M = mass of dust [mg]
 f = fraction of contaminant in dust [μg/mg]
 t = run time [h]
 Q = flow rate [m³/h]
 $\bar{\eta}$ = integrated filter efficiency

Situation	κ [m ³]
10 LPM particle sample (8 h)	5
Portable air cleaner	3×10 ²
Lower bound residential	6×10 ⁴
Residential/Commercial	7×10 ⁵
Institutional	1×10 ⁶



refs: Noris et al. 2009 *ASHRAE Trans.*, Haaland and Siegel (in press) *Indoor Air*

Parting Thoughts

- We are in a “golden age” of air cleaning research: It is a complicated problem
- Some situations where air cleaning is preferable or complementary to ventilation
- We need better communication/discussion between researchers, manufacturers, users, government

What I am excited about

- ASHRAE RP1649
- Year-long tests in 18 homes in Toronto
- 3-4 different levels of filtration in each home
- Very well-characterized homes, HVAC systems, filters, indoor particle concentrations
- Research questions
 - Do filters matter in residences?
 - How does particle composition influence efficiency?

Acknowledgements

- Students: UT Austin, UofT
- Funders: e.g., NSERC, Sloan Foundation, ASHRAE