Building design and operational choices that impact indoor exposures to outdoor particulate matter inside residences

ASHRAE Winter Conference 2014

Sunday, January 19, 2014

Can low energy buildings be healthy for occupants?

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Session learning objectives and AIA disclaimer

Learning objectives

- Describe methods for assessing and quantifying specific measures of indoor environmental quality.
- Explain how certain aspects of the indoor environment can be degraded or improved by energy conserving design and retrofits.
- Distinguish between building operation measures that can degrade indoor environmental quality from those that can enhance it.
- Explain how the indoor environment can be protected from pollutants in the outdoor environment.
- Distinguish between green building ratings and actual building performance; provide examples of performance parameters.
- Apply design strategies that make for robust buildings - those that achieve high indoor environmental quality and low energy use.

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Acknowledgments

- Jeffrey Siegel, University of Toronto
- All of our homeowners and occupants
- Funding (from Ph.D. work at UT-Austin)
  - University of Texas at Austin Continuing Fellowship
  - NSF IGERT Award DGE #0549428
  - ASHRAE Grant-In-Aid & RP-1299
  - Thrust 2000 Endowed Graduate Fellowship

Motivation: Health effects and outdoor PM

- Epidemiological studies show associations between elevated outdoor particulate matter (PM) and adverse health effects

  Pope et al., **2002** *J Am Med Assoc*; Peng et al., **2005** *Am J Epidem*; Pope and Dockery, **2006** *J Air Waste Manag Assoc*; Miller et al., **2007** *New Engl J Med*; Stölzel et al., **2007** *J Expo Sci Environ Epidem*; Andersen et al., **2010** *Eur Heart J;* Brook et al. **2010** *Circulation*; Ostro et al., **2010** *Environ Health Persp*

  – Effects ranging from respiratory symptoms to mortality

  – $PM_{10,}$ $PM_{2.5,}$ and ultrafine particles (UFP, < 100 nm)

    - Also specific constituents and seasonal differences

- But we spend most of our time indoors

  ~87% of the time on average (~69% at home) Klepeis et al., **2001** *J Expo Anal Env Epi*

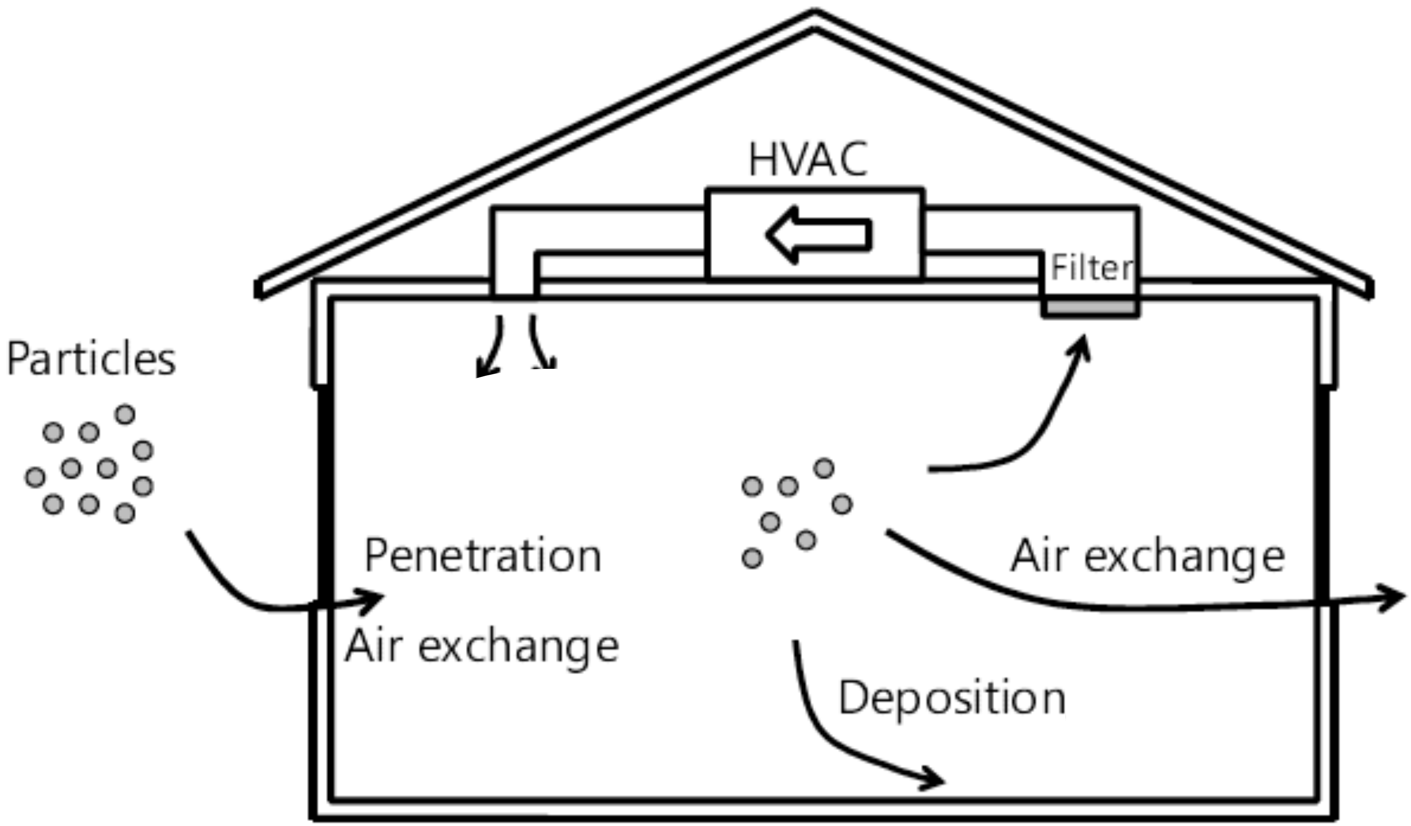
- Outdoor particles can infiltrate and persist in homes with varying efficiencies Chen and Zhao, **2011** *AE;* Williams et al., **2003** *AE;* Kearney et al., **2010** *AE*

- Much of our exposure to outdoor PM often occurs indoors

  – Often at home

  Meng et al., **2005** *J Expo Anal Environ Epidem;* Kearney et al., **2010** *Atmos Environ;* Wallace and Ott **2011** *J Expo Sci Environ Epidem;* MacNeill et al. **2012** *Atmos Environ*

Mechanisms that impact indoor exposures to outdoor PM



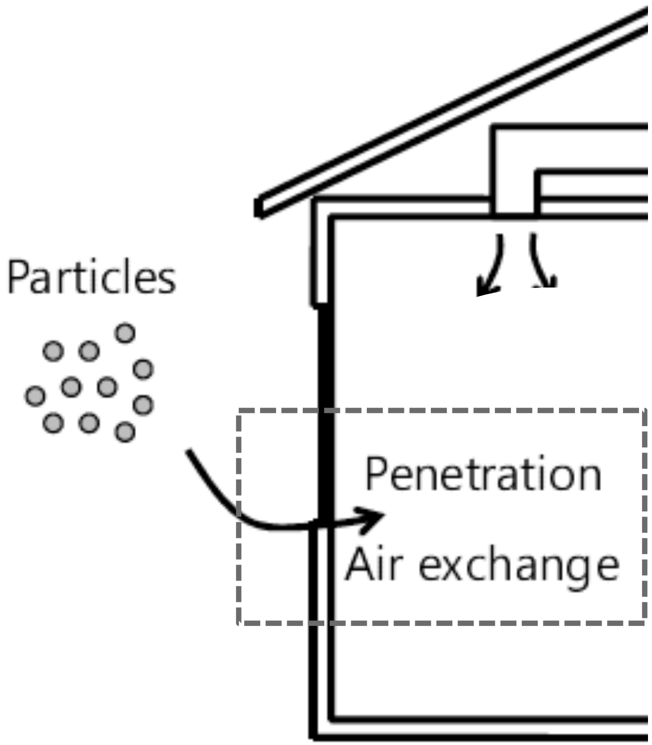
C_{in} = indoor concentration (#/m^3)
C_{out} = outdoor concentration (#/cm^3)
P = penetration factor (-)
λ = air exchange rate (1/hr)
k = surface deposition rate (1/hr)
f = fractional HVAC runtime (-)
η = filter removal efficiency (-)
Q = HVAC airflow rate (m^3/hr)
V = indoor air volume (m^3)

$$\frac{C_{in}}{C_{out}} = F_{\inf} = \frac{P\lambda}{\lambda + k + f\frac{\eta Q}{V}}$$

Penetration from outdoors

Air exchange
Deposition
HVAC filter removal

Mechanisms that impact indoor exposures to outdoor PM



"Penetration Factor"
If *P* = 1:
The envelope offers no protection
If *P* = 0:
The envelope offers complete protection

C_{in} = indoor concentration (#/m^3)
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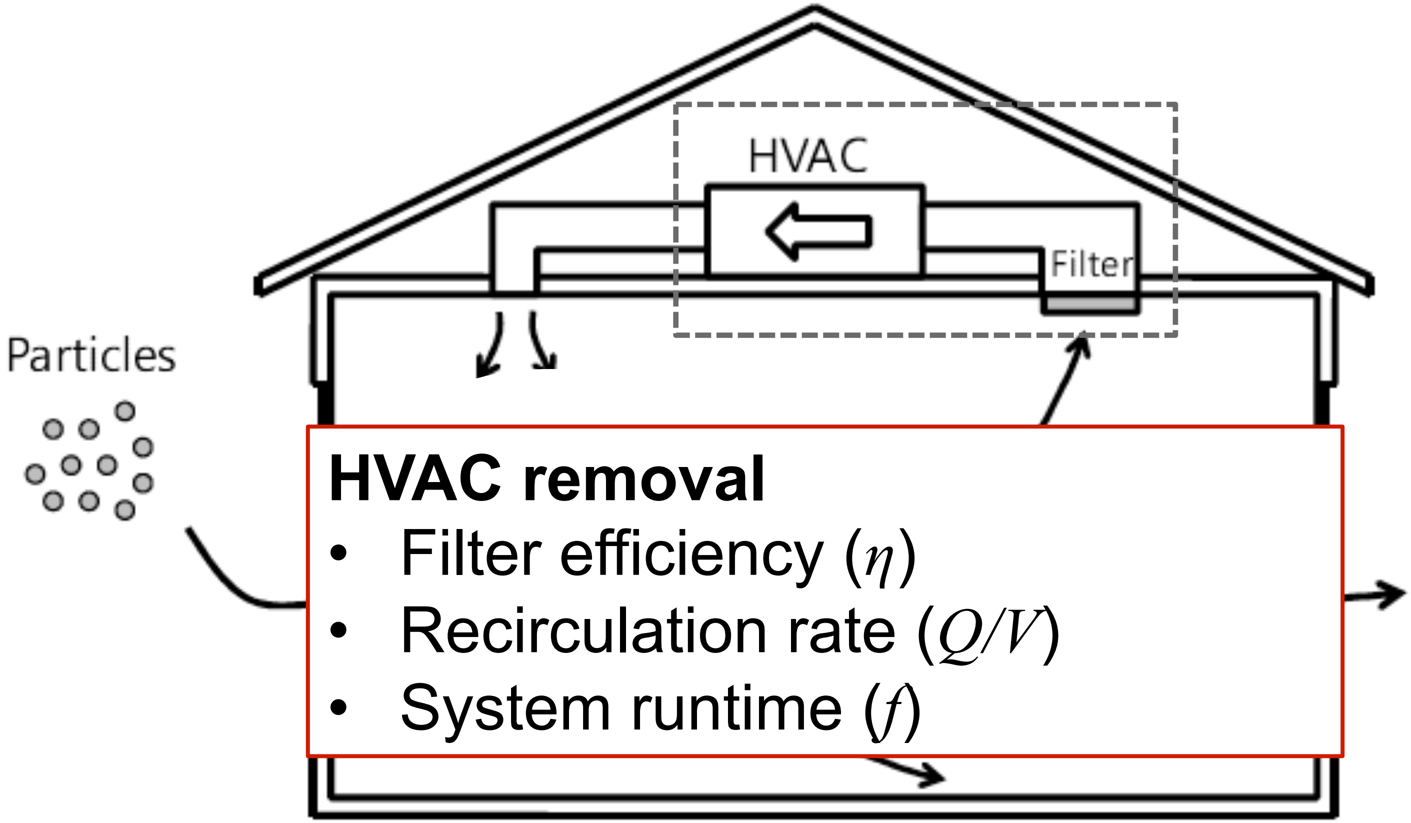
Penetration from outdoors

Mechanisms that impact indoor exposures to outdoor PM



HVAC removal
- Filter efficiency (η)
- Recirculation rate (Q/V)
- System runtime (f)

C_{in} = indoor concentration (#/m^3)
C_{out} = outdoor concentration (#/cm^3)
P = penetration factor (-)
λ = air exchange rate (1/hr)
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$$\frac{C_{in}}{C_{out}} = F_{\inf} = \frac{P\lambda}{\lambda + k + \boxed{f\frac{\eta Q}{V}}}$$

Filter removal
HVAC operation

Importance of source and removal mechanisms

- **Building envelope penetration**
  - Only recently has varying particle infiltration been implicated in observed health disparities with outdoor PM
    - Largely by varying AER, not penetration factor

Hodas et al., **2012** *J Expo Sci Environ Epidem*; Chen et al., **2012** *Epidemiology*

- **HVAC removal**
  - Prevalence of air-conditioning has been shown to be a modifier in $PM_{2.5}$ and PM_{10} mortality
    - Little information on filter removal efficiency and HVAC system runtime

Janssen et al., **2002** *Environ Health Persp*; Franklin et al., **2007** *J Expo Sci Environ Epidem*; Bell et al., **2009** *Epidemiology*

Goals of this work

- Further explore the impacts of building design and operation – including **building envelopes** and **HVAC filters** – on indoor PM of outdoor origin

  Key parameters:
  - Particle penetration factor, P
  - Air exchange rate, λ
  - Particle removal by HVAC filter, $\eta Q/V$
  - HVAC system runtime, f

- Using recently measured data from recent studies on residential (and some small commercial) buildings

- Can we also **predict** these impacts?

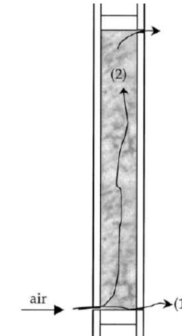
- Describe one case study on a **net zero energy capable home** with mechanical ventilation

RECENT PARTICLE INFILTRATION MEASUREMENTS

Measuring particle infiltration

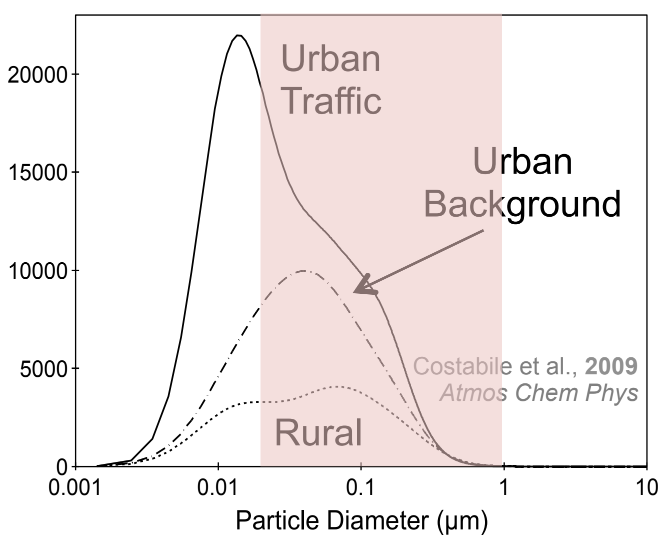
- Particles can penetrate through cracks in building envelopes
  - Theoretically a function of:
    - Crack geometry
    - Air speed through leaks

Liu and Nazaroff, **2001** *Atmos Environ*



- Are building details and particle penetration factors correlated?
  - e.g., air leakage parameters or building age
  - Needed a test method for measuring *P* quickly
- Applied a particle penetration test method in 19 homes

Stephens and Siegel, **2012** *Indoor Air*



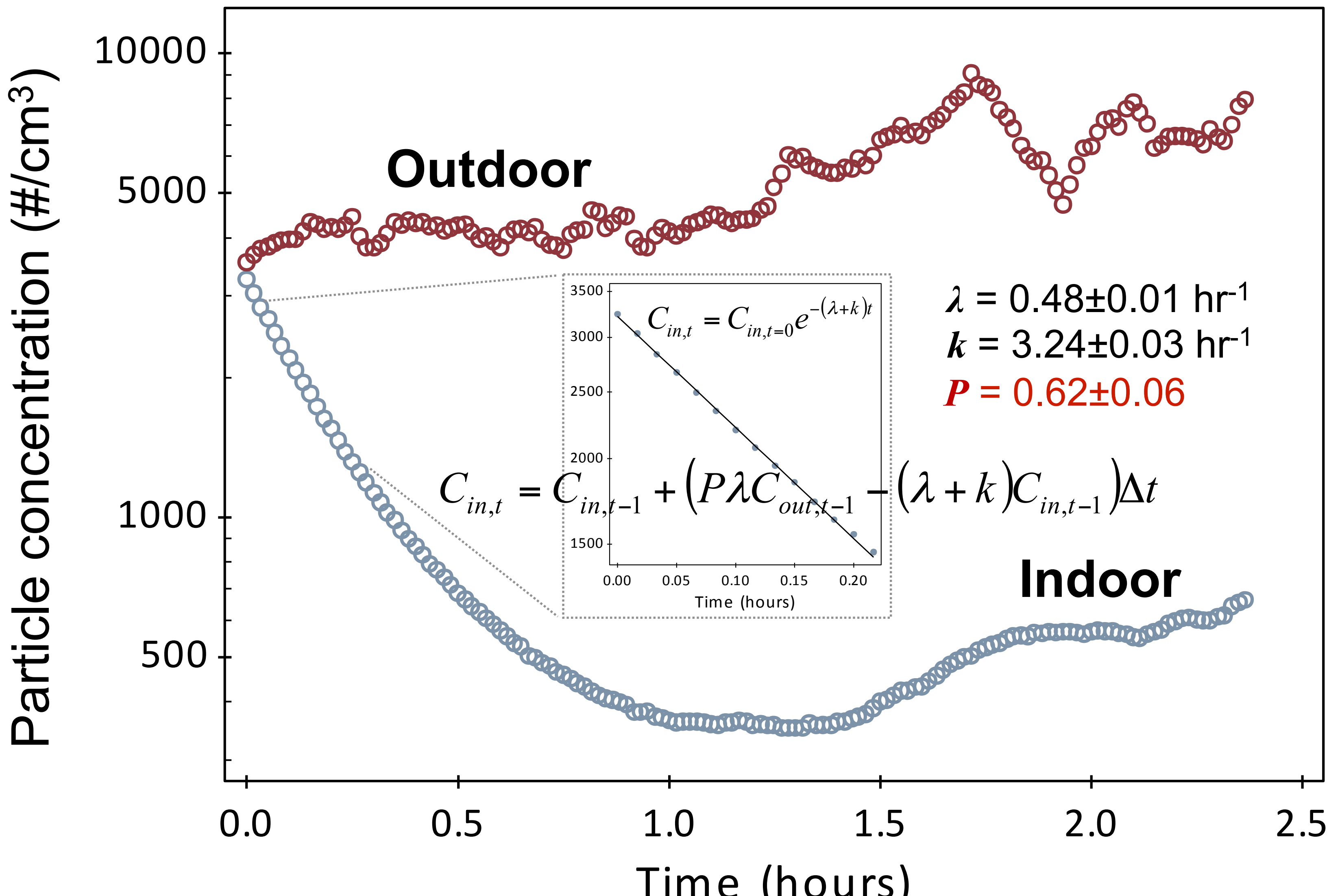
TSI P-Traks
20 – 1000 nm

PM infiltration: Test homes

NZEH

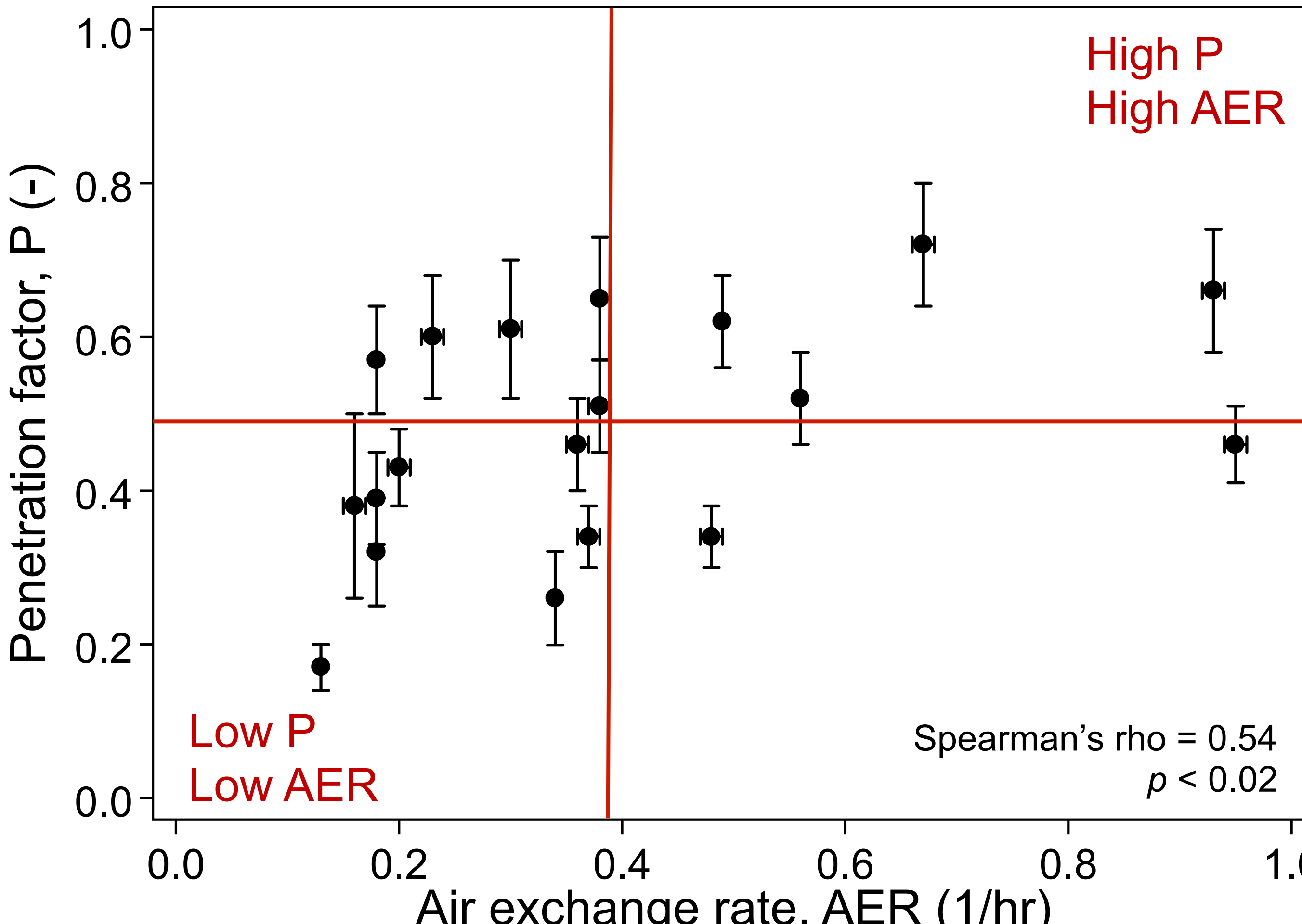
Stephens and Siegel, *Indoor Air* **2012** 22(6):501-512

Test method: Submicron particle infiltration (20-1000 nm)



Stephens and Siegel, *Indoor Air* **2012** 22(6):501-512

Particle infiltration results: P and AER



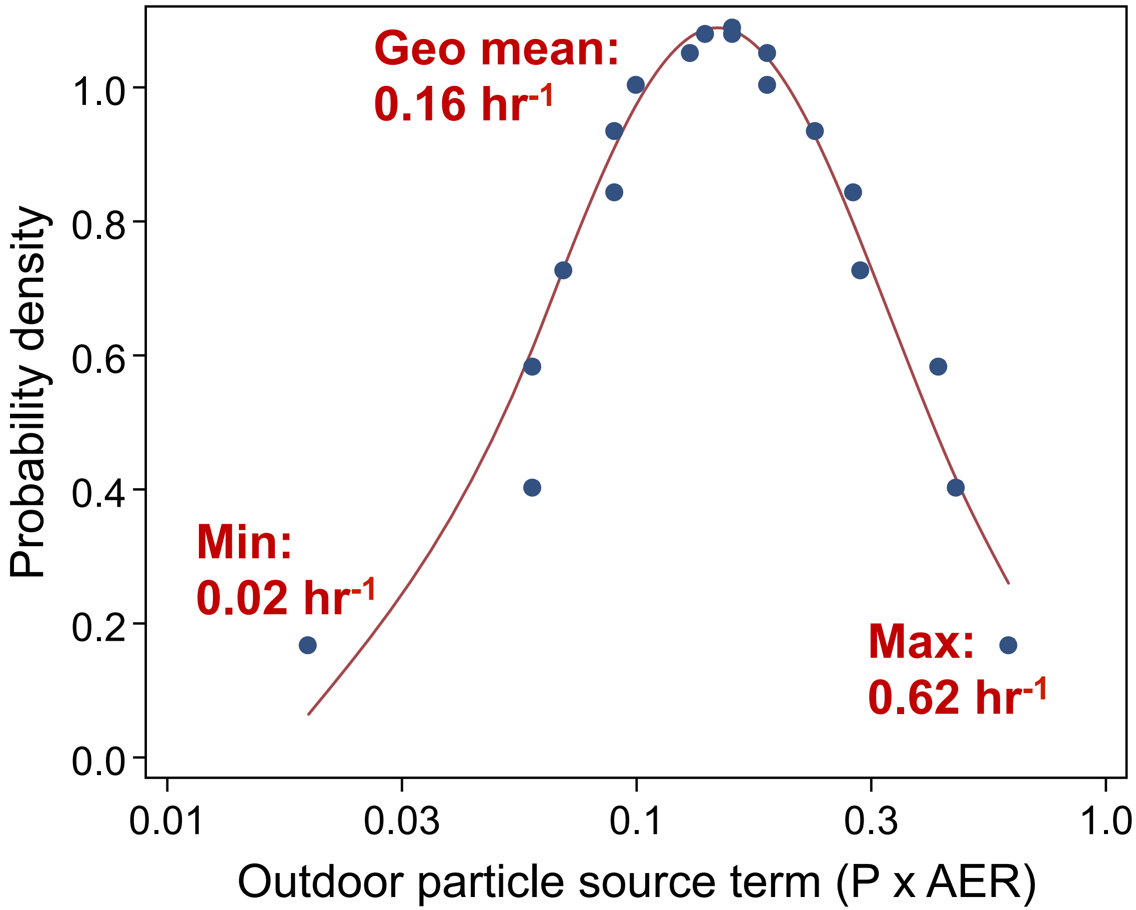
Penetration factors: Mean = 0.47 Range = 0.17 to 0.72

Air exchange rates: Mean = 0.39 hr^{-1} Range = 0.13 to 0.95 hr^{-1}

Stephens and Siegel, *Indoor Air* **2012** 22(6):501-512

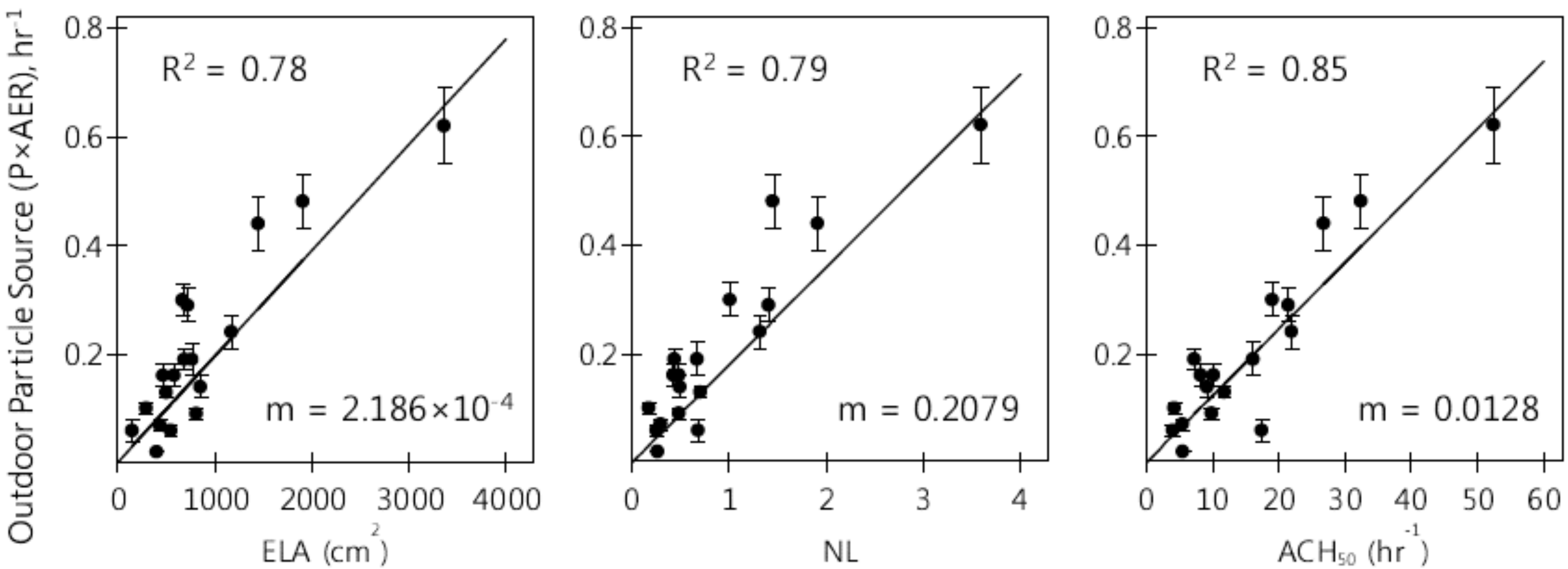
Outdoor particle source terms: P×AER

$$\frac{C_{in}}{C_{out}} = \frac{P \times AER}{AER + Loss}$$



Outdoor particle sources and envelope air tightness

$$\frac{C_{in}}{C_{out}} = \frac{P \times AER}{AER + Loss}$$ vs. blower door test results



Leakier homes had much higher outdoor particle source rates

Older homes also had much higher outdoor particle source rates

- Potential socioeconomic implications: low-income homes are older/leakier

Chan et al., **2005** *Atmos Environ*

Stephens and Siegel, *Indoor Air* **2012** 22(6):501-512

RECENT MEASUREMENTS OF HVAC FILTRATION

HVAC filter removal: Efficiency is not the whole story

$$Loss = k + f\frac{\eta Q}{V}$$

1-inch depth

MERV 4

MERV 6

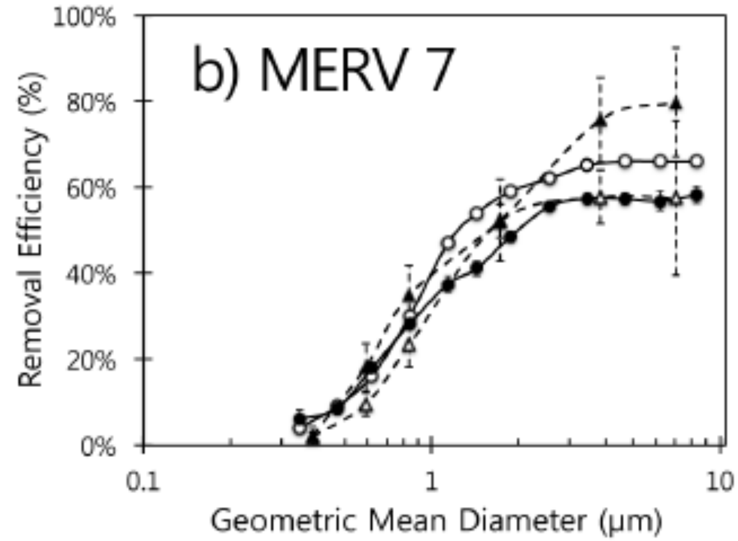
MERV 11

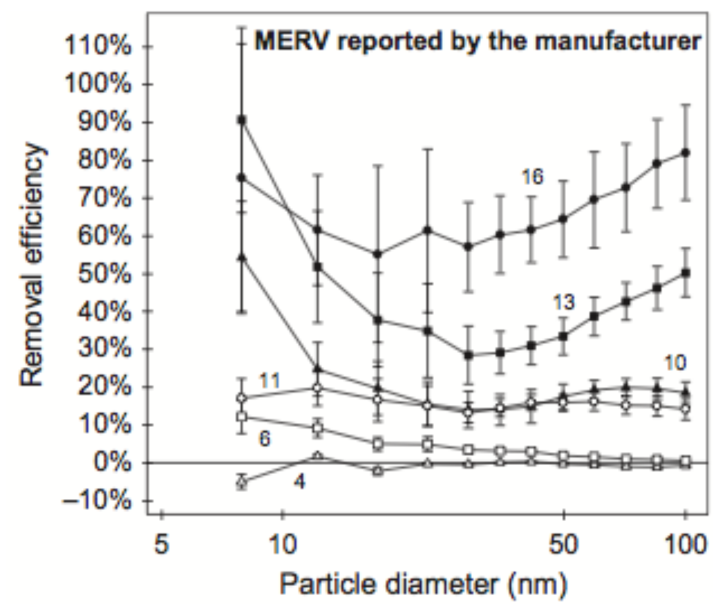
5-inch depth

MERV 10

MERV 13

MERV 16





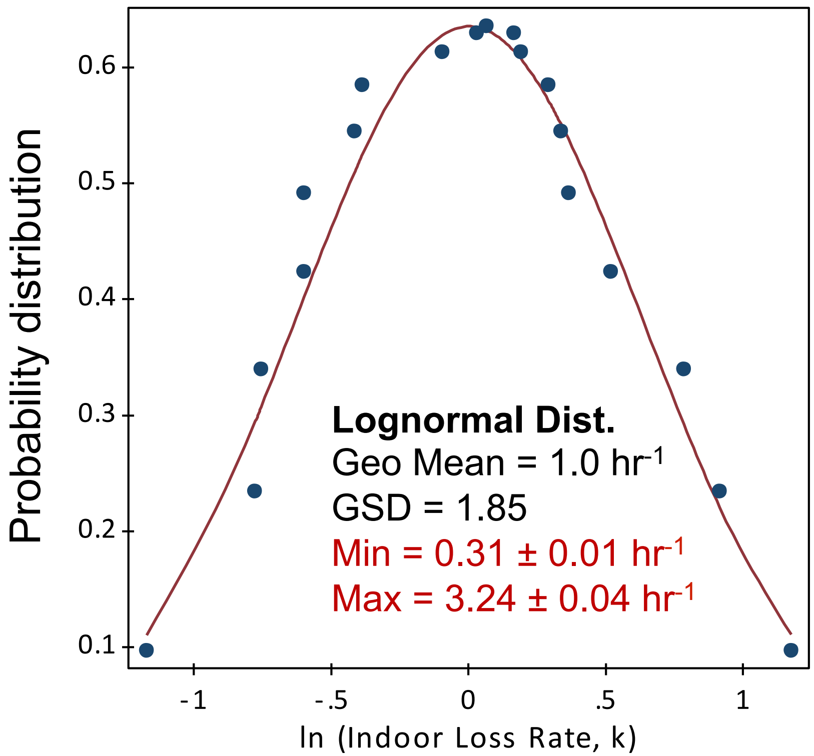
Stephens and Siegel, *Aerosol Sci. Technol.* **2012** 46(5), 504-513
Stephens and Siegel, *Indoor Air* **2013**

Indoor particle removal rates

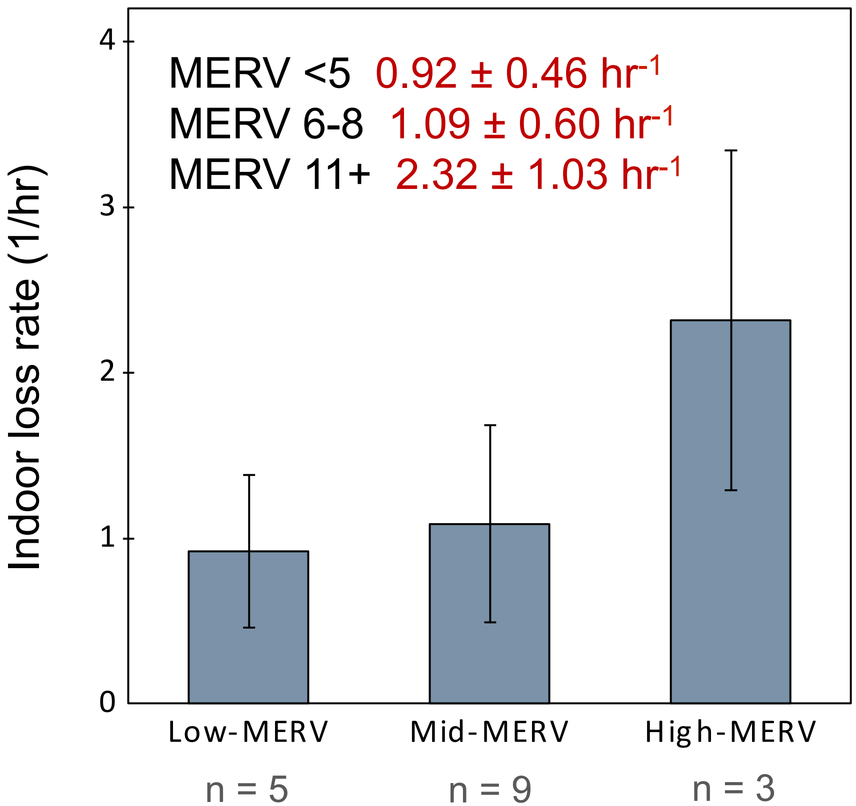
- Submicron particle loss with HVAC system operating 100%

$$Loss = k + f\frac{\eta Q}{V}$$

where f = 1



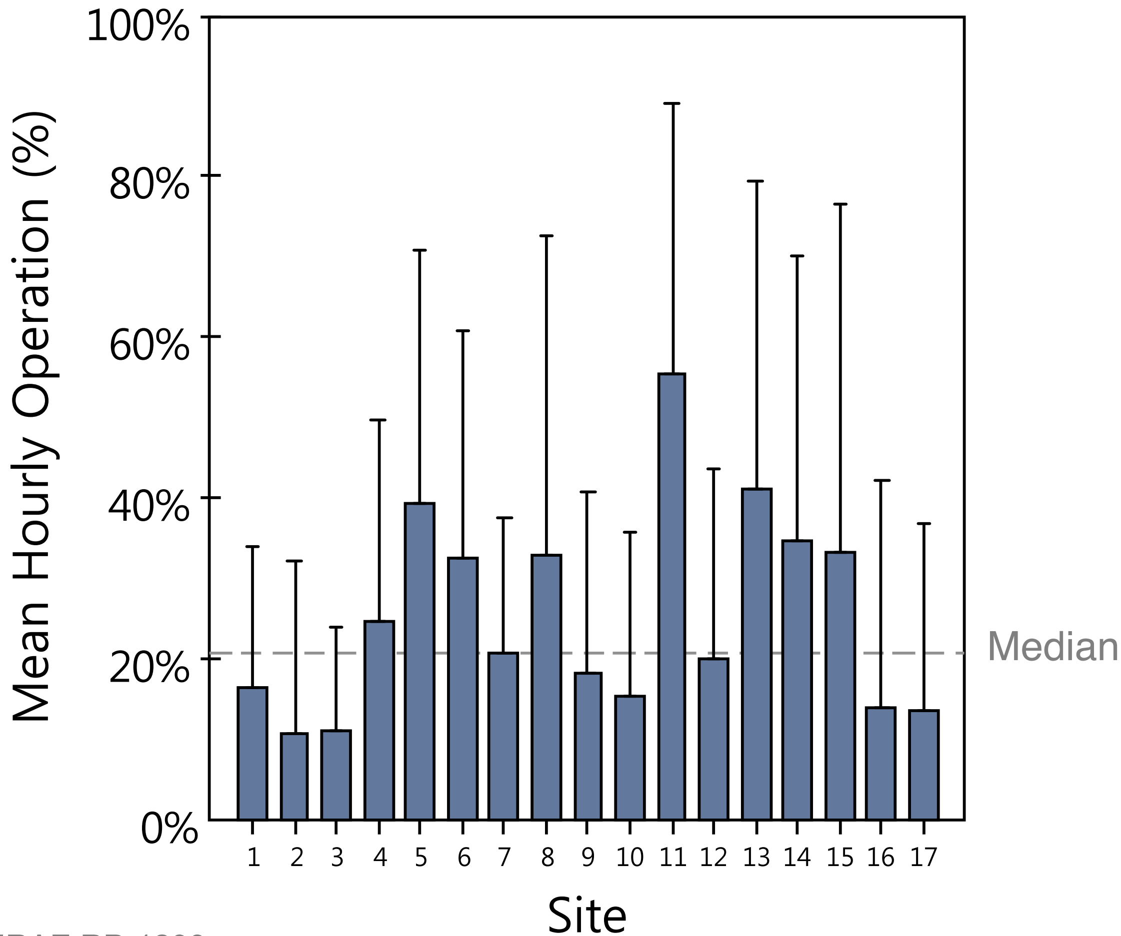
Split by filter type



Stephens and Siegel, *Indoor Air* **2012** 22(6):501-512

HVAC system runtimes in other homes and small offices

- Mean HVAC runtimes in TX ranged 10.7% to 55.3%
  - Median $f \approx 21\%$ (influenced by climate and thermostat settings)



Stephens et al., **2010** ASHRAE RP-1299
Stephens et al., **2011** *Building and Environment* 46(10):1972-1983

VARIATIONS IN EXPOSURES

Across observed range of envelope penetration, filter efficiency, and runtimes

Implications for submicron PM exposure

- Penetration factors ranged 0.17 to 0.72
- AER ranged 0.13 hr^{-1} to 0.95 hr^{-1}
- Outdoor particle source terms ranged 0.02 hr^{-1} to 0.62 hr^{-1}
  - Factor of **~30** difference from lowest to highest
  - Higher in older, leakier homes

- Indoor removal rates ranged 0.31 hr^{-1} to 3.24 hr^{-1}
  - Factor of **~10** difference from least efficient to most efficient filter
  - Varied with rated filter efficiency (particularly for high-efficiency)

- HVAC fractional operation ranged 10.7% to 55.3%
  - Factor of **~5** difference
  - Varied with thermostat settings, occupancy, and outdoor climate

Implications for submicron PM exposure

- Combined effects: $F_{\text{inf}} = \dfrac{C_{in}}{C_{out}} = \dfrac{P \times AER}{AER + k + f\dfrac{\eta Q}{V}}$

	Lower bound	Upper bound
Penetration factor, *P*	0.17	0.72
Air exchange rate, *AER* (1/hr)	0.13	0.95
Outdoor source term, *P*×*AER* (1/hr)	0.02	0.62
Indoor loss rate, $k + \eta Q/V$ (1/hr)	3.24	0.31
Fractional HVAC operation, *f*	55.3%	10.7%
I/O submicron PM ratio (F_{inf})	**0.01**	**0.70**

Factor of **~70** difference in indoor proportion of outdoor particles between:

- A new airtight home with a very good filter and high HVAC operation, and
- A leaky old home with a poor filter and low HVAC operation

- Some potential for predictive ability using:
  - Age of home
  - Building airtightness test results
  - Knowledge of HVAC filter type
  - I/O climate conditions

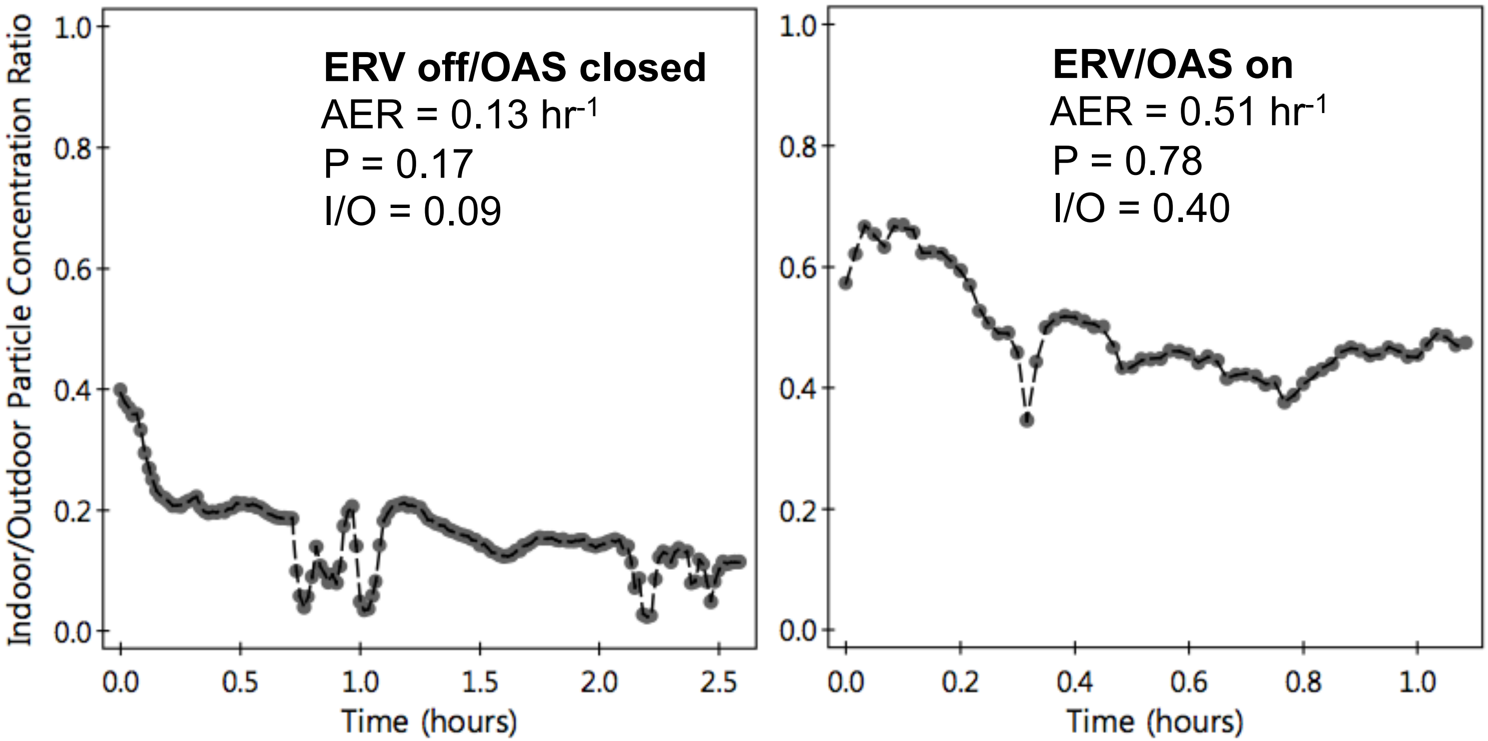
A CAUTIONARY TALE

In a new net-zero energy capable home (built 2011)

Impacts of high-efficiency HVAC systems

- One of the test homes (Site 15) had a dedicated mechanical ventilation system
- Outdoor air supply duct ran through an energy recovery ventilator (ERV) and was installed directly into the HVAC return plenum
- Previous results were only for natural infiltration, when the system was unplugged and capped
  - Relying on envelope leakage alone for ventilation air
- We repeated the test a second time with the ERV/OAS unit operating…

Impacts of mechanical ventilation



- This home was responsible for both the **lowest** and the **highest** envelope penetration factors!
  - Depending on whether or not the ERV was operating
- Problem: The ERV/OAS was ducted to directly ***downstream*** of the HVAC filter

Conclusions

- Outdoor particulate matter (PM) infiltration and persistence can vary greatly between homes
  - Generally lower in newer, tighter homes than in older, leakier homes
    - We also may be able to predict PM infiltration
  - Other design, construction, and operational parameters can further widen this gap between homes
    - HVAC filtration selection and system runtime, among others

- In very low-energy homes, envelopes are probably tight enough to nearly prevent infiltration of outdoor PM
  - Turns focus to indoor-generated pollutants
  - Effects can be *completely reversed* by poor construction!

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