Indoor exposures to outdoor air pollution

CE 260: Fundamentals of Environmental Engineering
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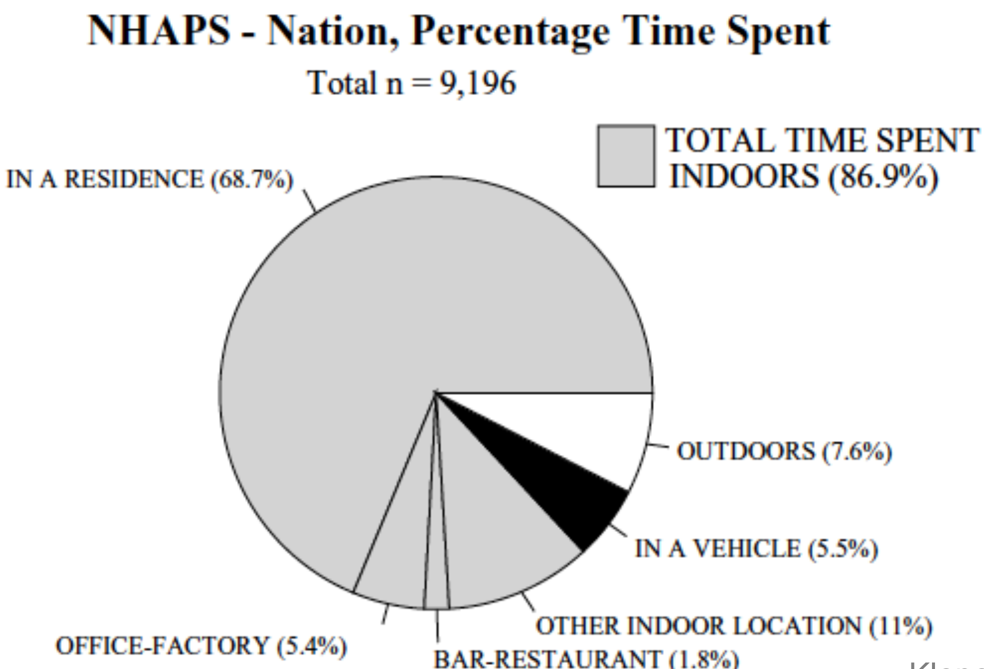
What do you think of when you hear “air pollution?”

What do I think of when I hear "air pollution?"



Americans spend almost 90% of their time indoors

~75% at home or in an office

Klepeis et al., *J Exp. Anal. Environ. Epidem.* **2001**, 11, 231-252

Indoor vs. outdoor air pollution

Air pollution is both an indoor and an outdoor issue

- Many indoor pollutant sources
- Outdoor pollutants also infiltrate and persist indoors

Thatcher et al. **2003** *AS&T*; Rim et al. **2010** *ES&T*; Chen and Zhao **2011** *AE*; Kearney et al **2011** *AE*

Much of our exposure to outdoor air pollution occurs indoors

Janssen et al., **2005** *OEM*; Meng et al., **2005** *JESEE*; Weschler, **2006** *EHP*; Wallace and Ott, **2011** *JESEE*

Indoor exposures are difficult to assess

- Time-consuming, invasive, and costly

Many connections are already made with outdoor pollutants

- There remains a need to **advance knowledge of indoor exposures**
  - Improve connections to health effects (reduce exposure error)
  - Inform how building design and operation impacts exposures

Baxter et al., **2010** *JESEE*; Meng et al., **2005** *ES&T*; Allen et al., **2012** *EHP*; MacNeill et al, **2013** *AE*

A few outdoor airborne pollutants are regulated

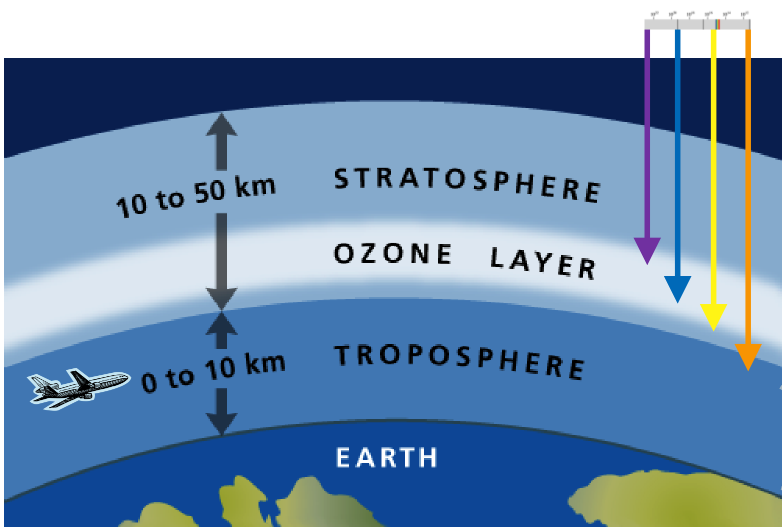
National Ambient Air Quality Standards (NAAQS)

- US EPA and the Clean Air Act (1970)
- Set limits for 6 “criteria” pollutants

Pollutants Regulated Outdoors
Carbon monoxide (CO)
Lead (Pb)
Nitrogen dioxide (NO_2)
Ozone (O_3)
Particulate matter $PM_{2.5}$ and PM_{10}
Sulfur dioxide (SO_2)

Outdoor ozone

Good up high

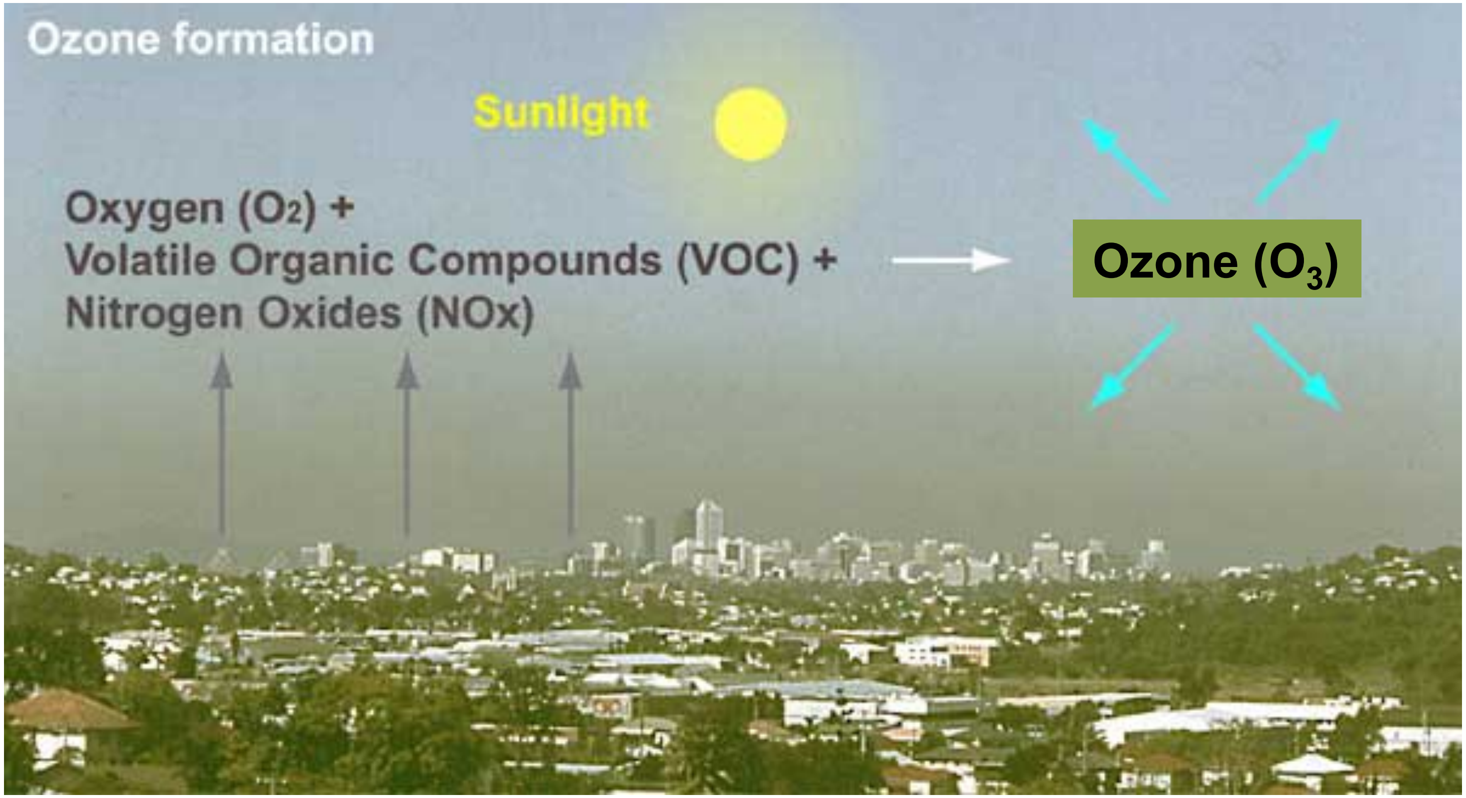


Ozone layer absorbs high frequency (small wavelength) UV light from the sun

Bad nearby

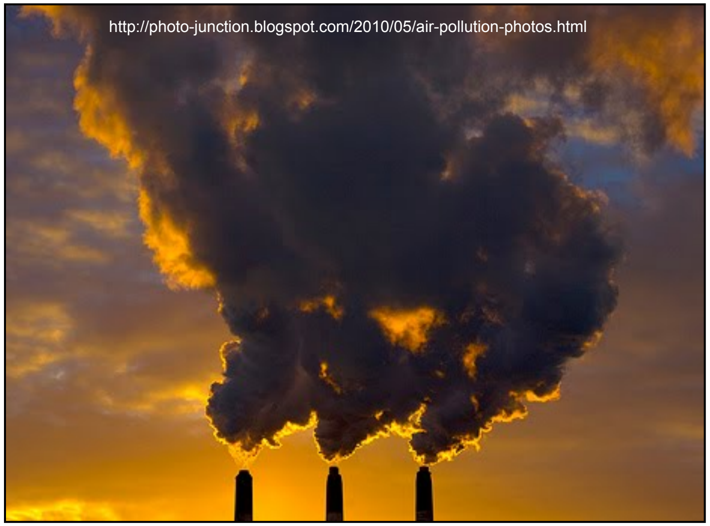
Low-level (tropospheric) ozone in the troposphere is a primary contributor to smog

Ozone chemistry (simplified)

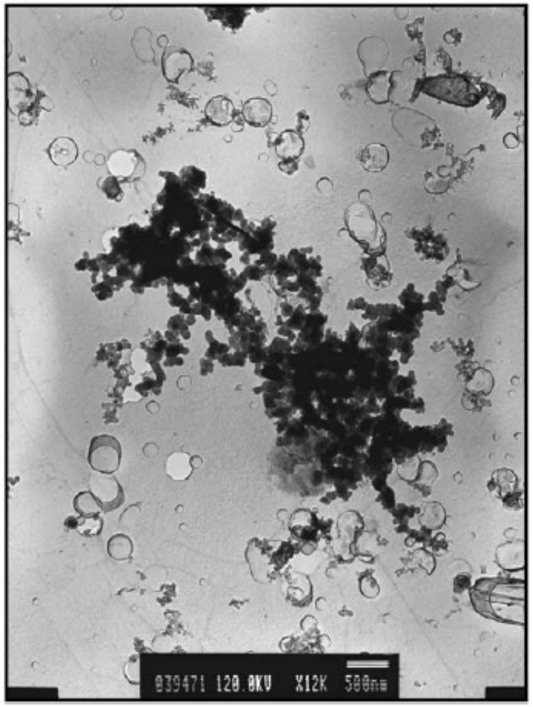


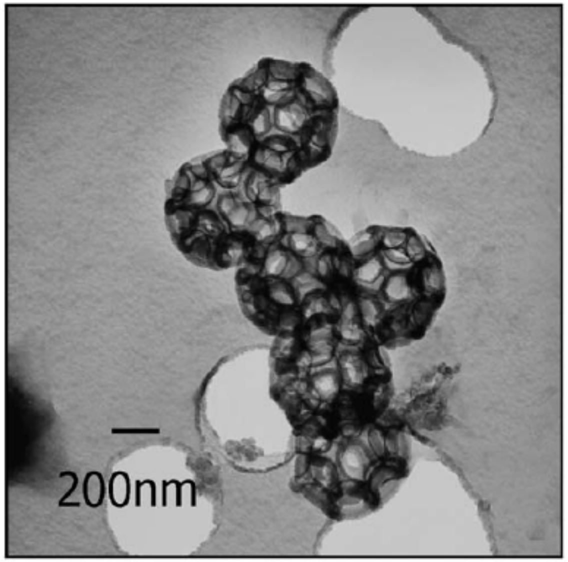
Source: Queensland EPA

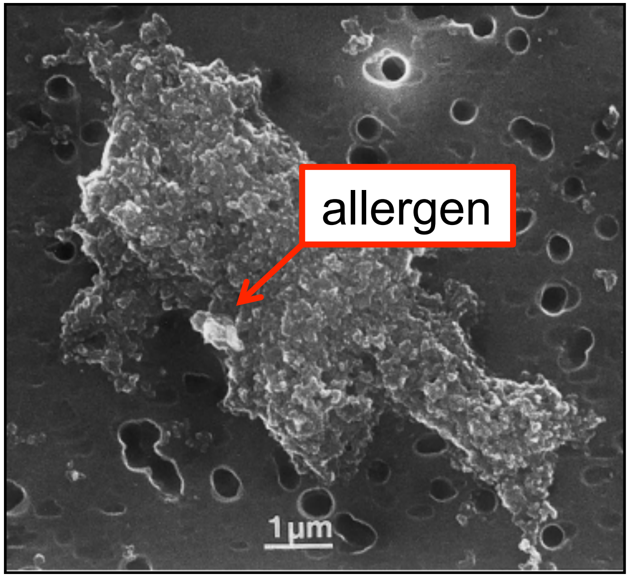
Outdoor particulate matter

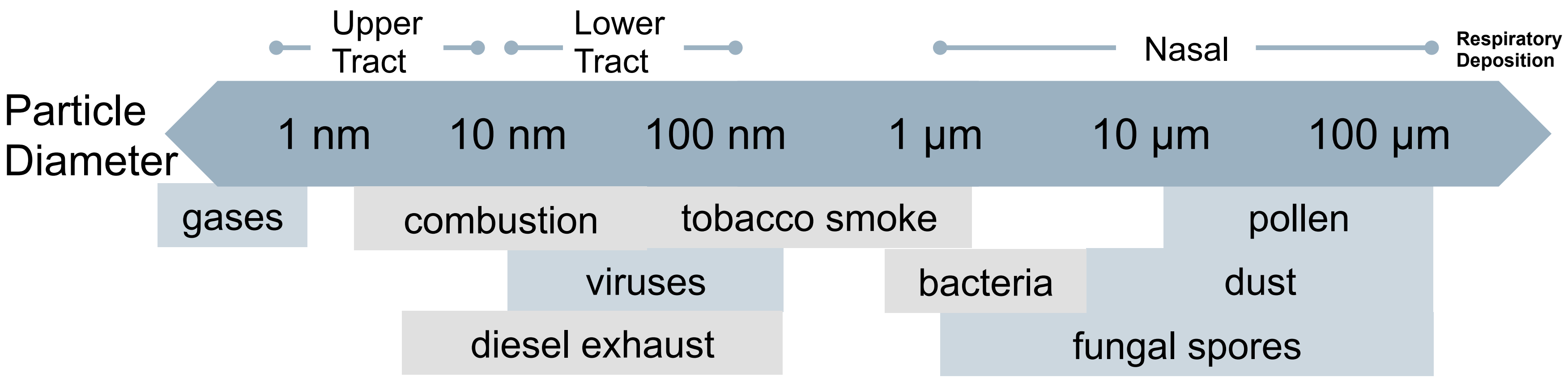


Particulate matter: Up close



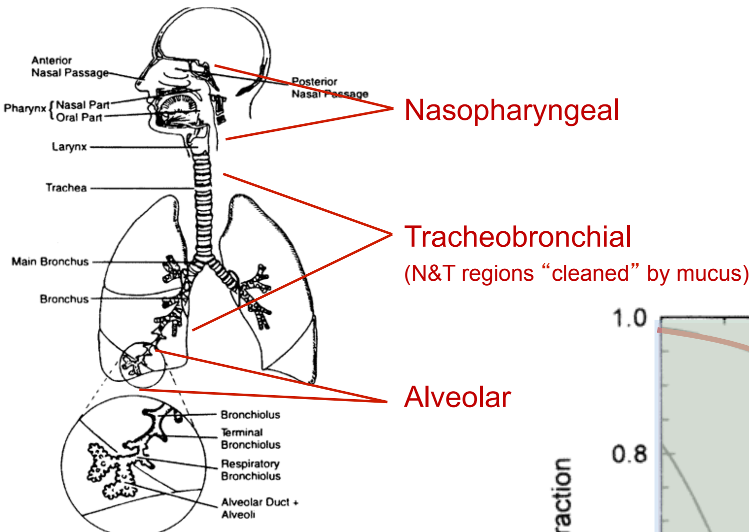


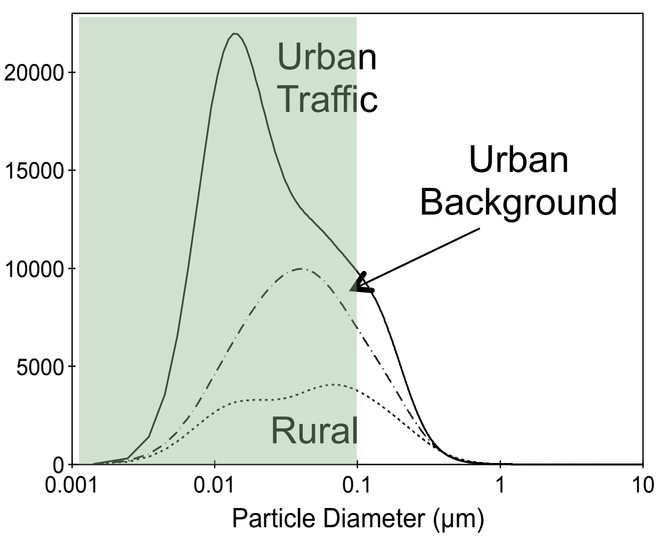


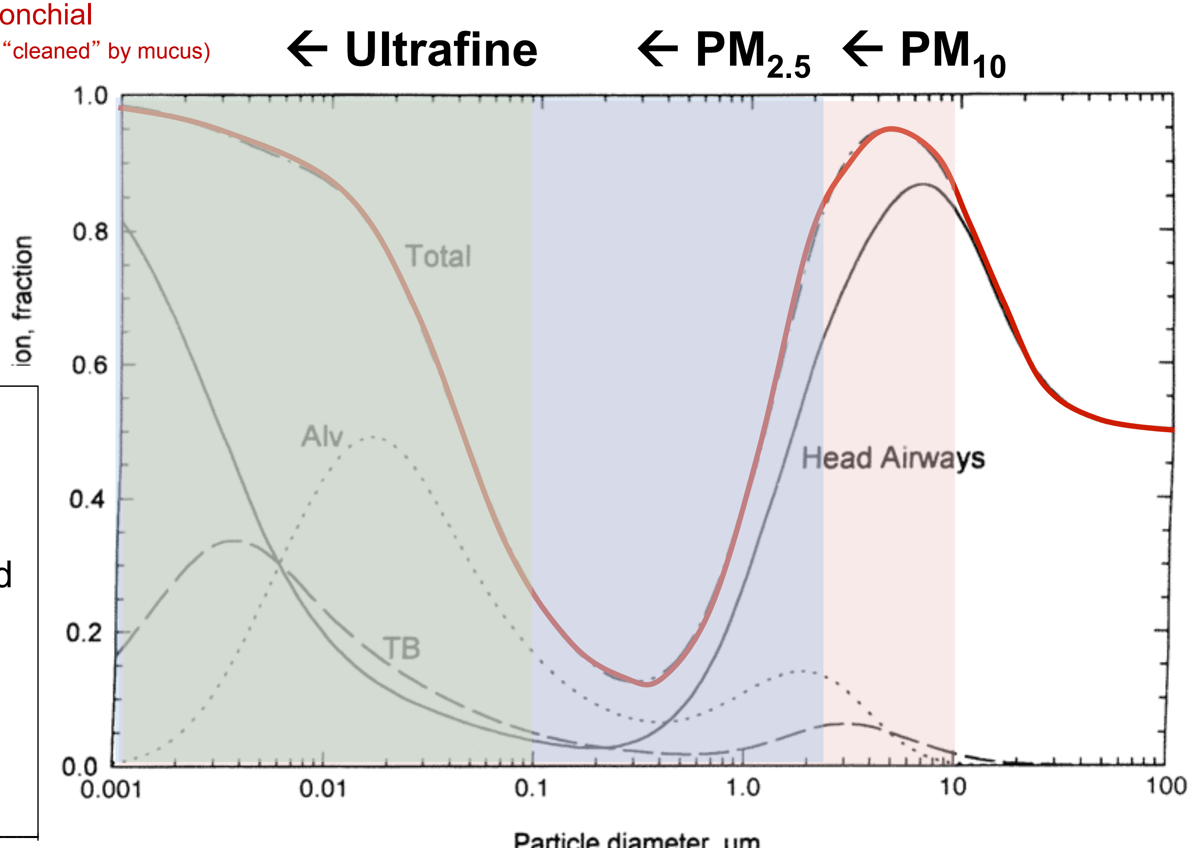


Casuccio et al., **2004** *Fuel Process. Technol.*; Ormstad, **2000** *Toxicol.;* Hinds, **1999** *Aerosol Technol.*

Particle deposition in the respiratory system







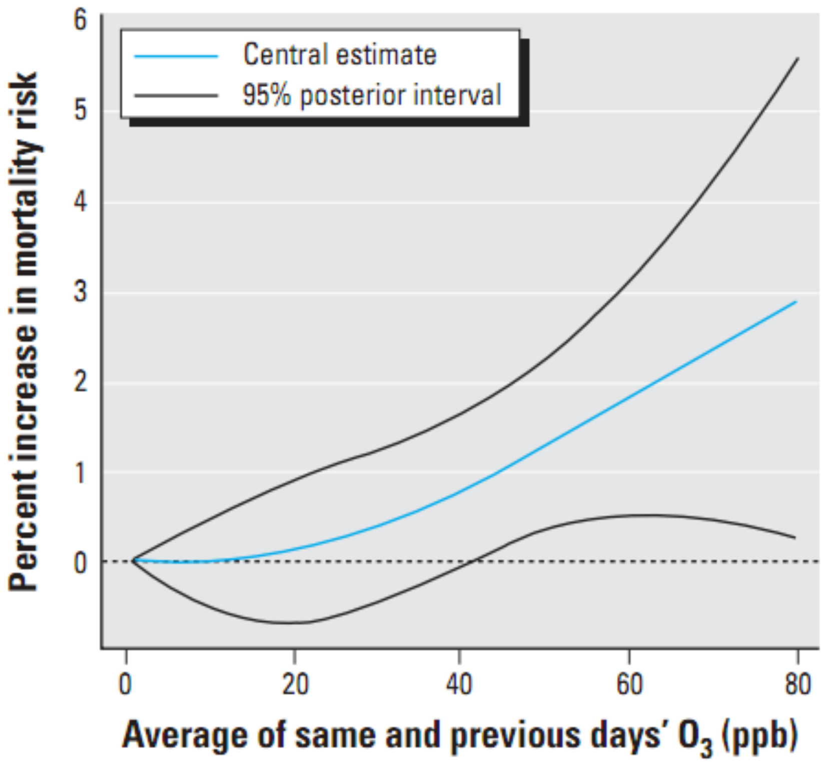
Hinds, 1999 Ch. 11

Costabile et al., **2009**
Atmos Chem Phys

Most particles of outdoor origin are smaller than 100 nm

Outdoor air pollution and mortality

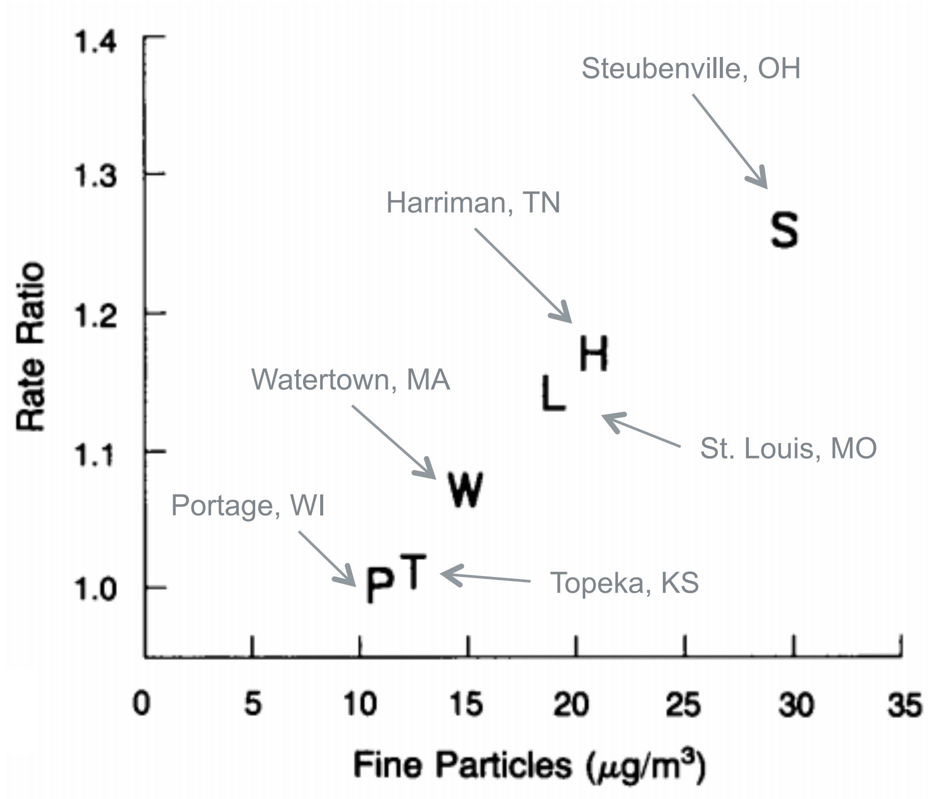
Ozone



Ozone data measured outdoors in 98 US communities from 1987 to 2000

Bell et al., **2006** *Environ Health Persp*

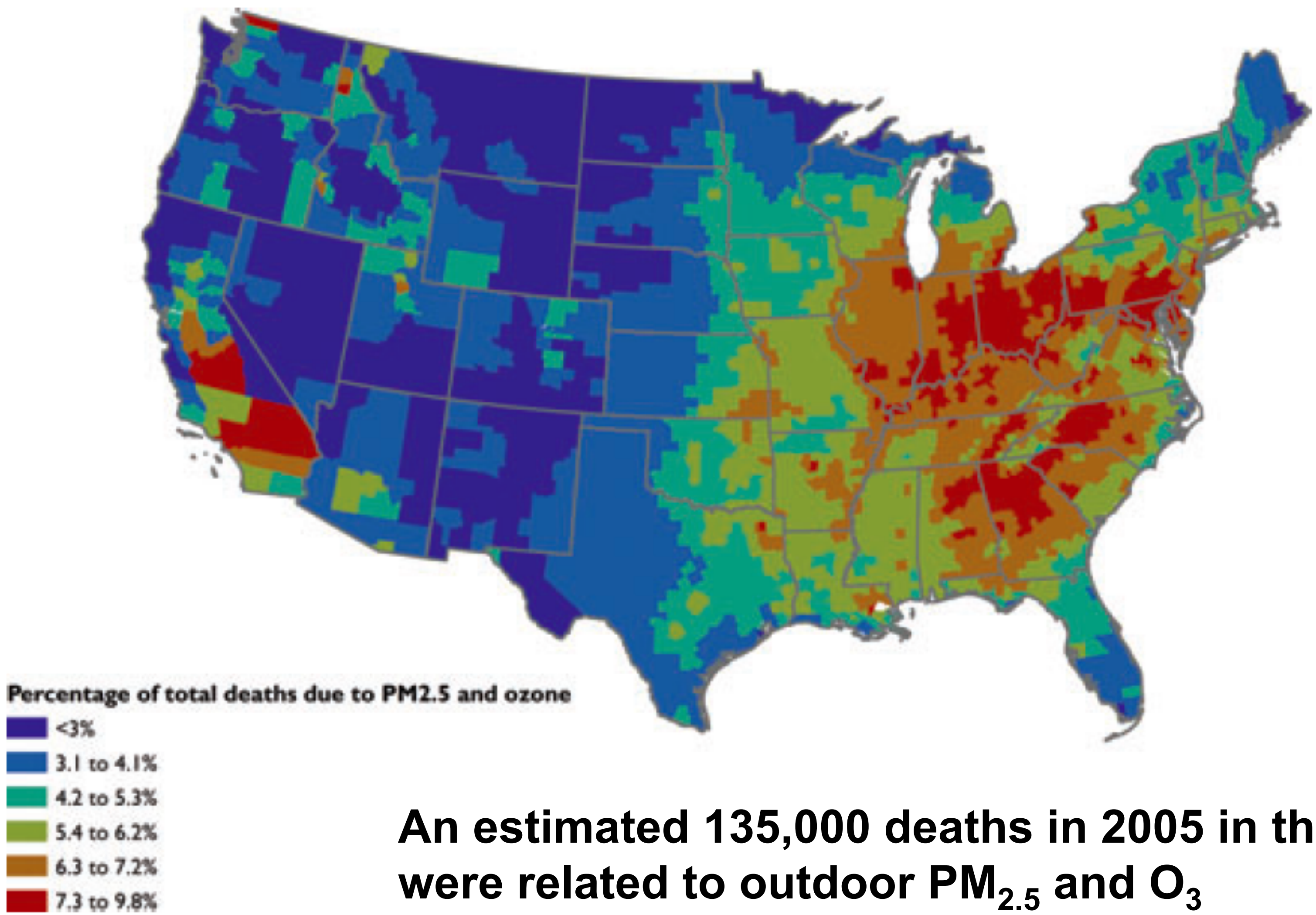
Particulate Matter ($PM_{2.5}$)



Mean $PM_{2.5}$ concentration measured outdoors in six cities over several years in the 1980s

Dockery et al., **1993** *New Engl J Med*

Health effects: Outdoor air pollution and mortality



An estimated 135,000 deaths in 2005 in the US were related to outdoor $PM_{2.5}$ and O_3

As high as 10% of deaths in Los Angeles

Fann et al., **2012** *Risk Analysis*

Outdoor ozone and particulate matter

- Elevated outdoor concentrations → health effects

Particulate Matter (PM)	**Ozone (O_3)**
Respiratory symptoms, cardiovascular mortality, lung cancer	Hospital admissions, respiratory illness, short-term mortality
Pope et al., **2002** *J Am Med Assoc*; Pope and Dockery, **2006** *J Air Waste Manag Assoc*; Miller et al., **2007** *New Engl J Med*; Ostro et al., **2010** *Environ Health Persp*	Gent et al., **2003** *J Am Med Assoc*; Bell et al., **2004** *J Am Med Assoc*; Hubbell et al., **2005** *Environ Health Persp*; Jerrett et al., **2009** *New Engl J Med*

- Americans spend most of their time indoors (nearly 90%)

- Outdoor PM and O_3 infiltrate into buildings

PM: Chen and Zhao, **2011** *Atmos Environ*
O_3: Avol et al., **1998** *Environ Sci Technol*; Romieu et al., **1998** *J Air Waste Manage Assoc*; Weschler, **2000** *Indoor Air*

- Exposure to outdoor PM and O_3 (+ rxns) often occurs indoors

PM: Meng et al., **2005** *J Exp Anal Environ Epidem*; Kearney et al., **2010** *Atmos Environ*
O_3: Weschler, **2006** *Environ Health Persp*

We can use environmental engineering principles to improve exposure estimates

Objectives of this work

- Develop/refine methods to measure infiltration of O_3 and PM
  - No one has ever measured ozone infiltration
  - A few groups have measured PM infiltration, but with some issues
- Apply in unoccupied test house and homes around Austin, TX

  *This work was performed while I was a graduate student at the University of Texas
- Quickly characterize buildings / assess exposure implications

Environmental Science & Technology

Article

pubs.acs.org/est

Measuring the Penetration of Ambient Ozone into Residential Buildings

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Stephens et al., *Environ. Sci. Technol.* **2012** 46(2), 929-936

Penetration of Ambient Submicron Particles Into Single-Family Residences and Associations With Building Characteristics

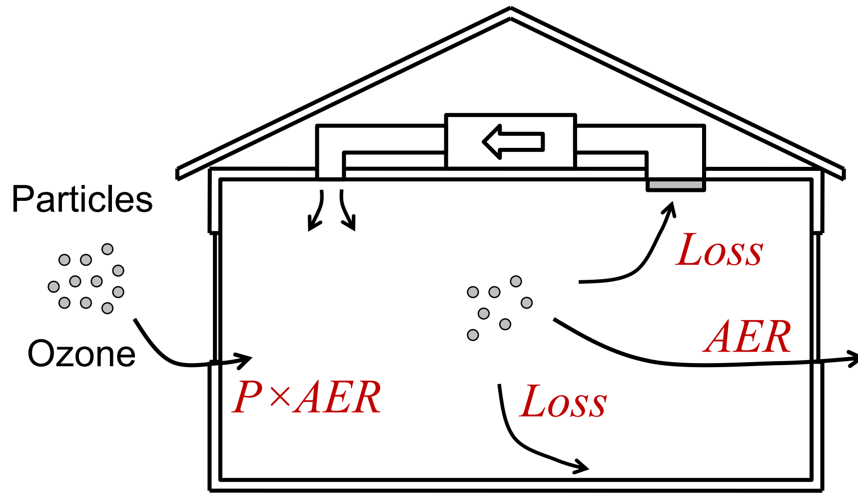
Brent Stephens and Jeffrey A. Siegel

Accepted manuscript online: 8 MAR 2012 03:39AM EST | DOI: 10.1111/j.1600-0668.2012.00779.x

Abstract | PDF(231K) | Request Permissions

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

Infiltration through building envelopes



Penetration from outdoors

Indoor/Outdoor pollutant concentration, "infiltration factor"

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

Removal by air exchange

Removal by deposition to or reaction with surfaces, homogenous reactions, and/or HVAC system

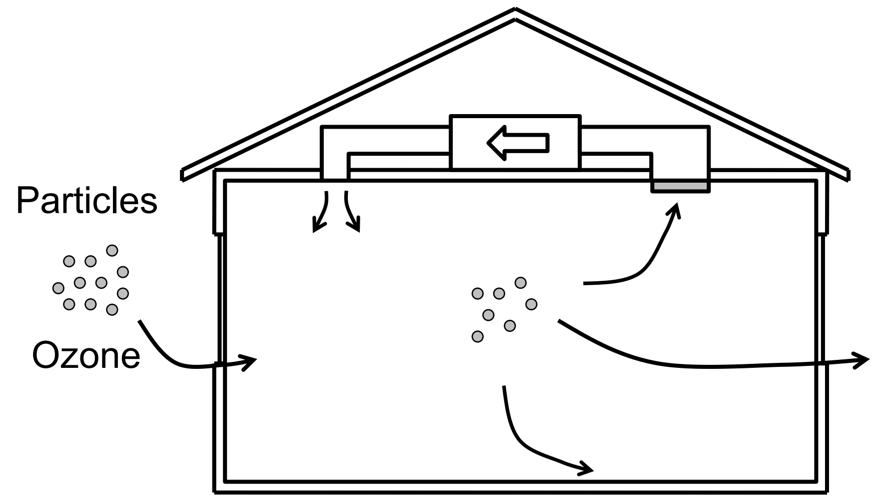
"Penetration Factor"

If *P* = 1:
The envelope offers no protection

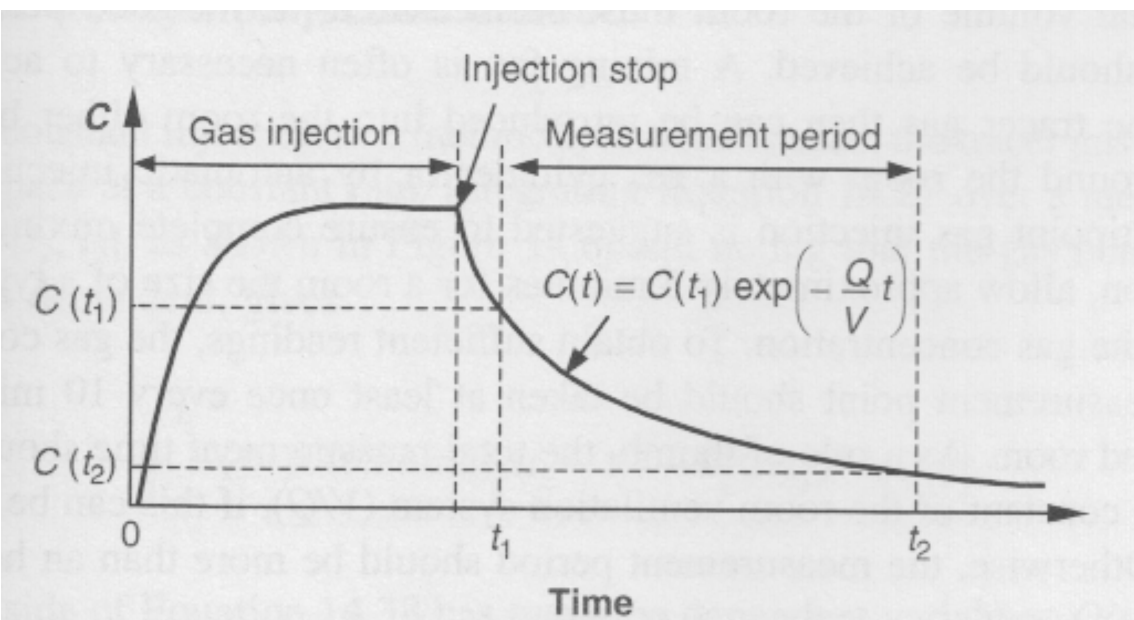
If *P* = 0:
The envelope offers complete protection

Infiltration through building envelopes: Challenges

There are some challenges with estimating *AER*, *P*, and *Loss*



- How do we measure each?
  - Or estimate from measured data?



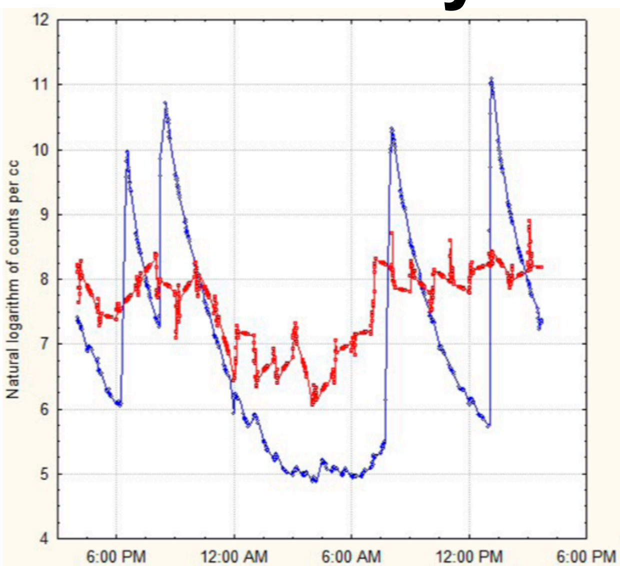
$$\frac{C_{in}}{C_{out}} = \frac{P \times AER}{AER + Loss}$$

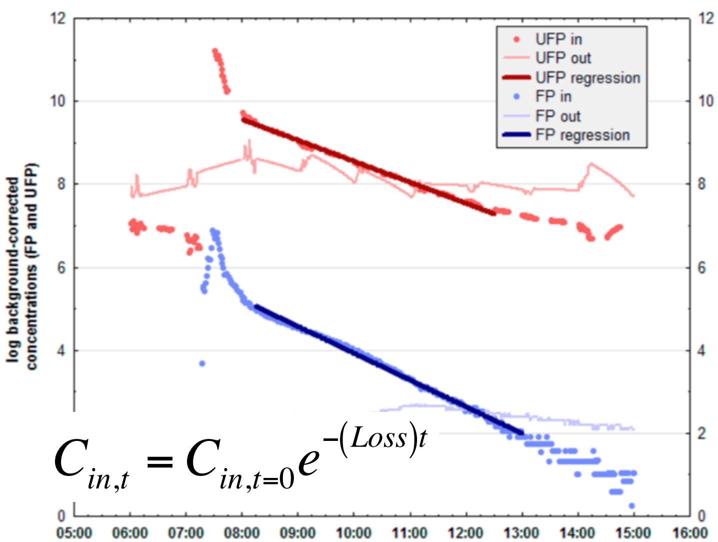
AER: Tracer decay
Inject an inert tracer gas, and measure the decay from C(t=0) after time t=0

What about *P* and *Loss*?

Measuring P and $Loss$: Use of mass balances

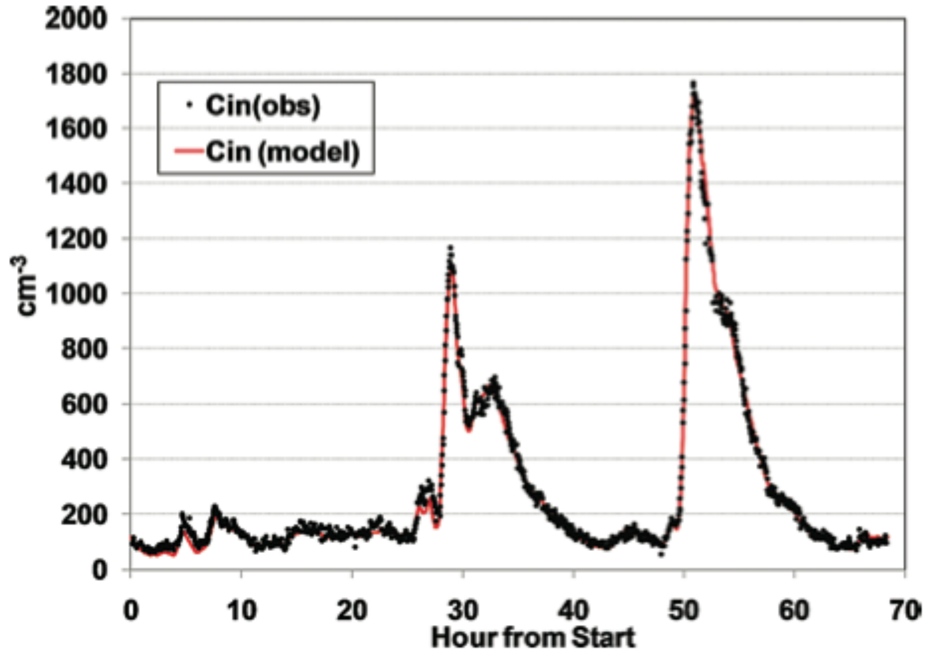
$Loss$ only





$$C_{in,t} = C_{in,t=0}e^{-(Loss)t}$$

Both P and $Loss$

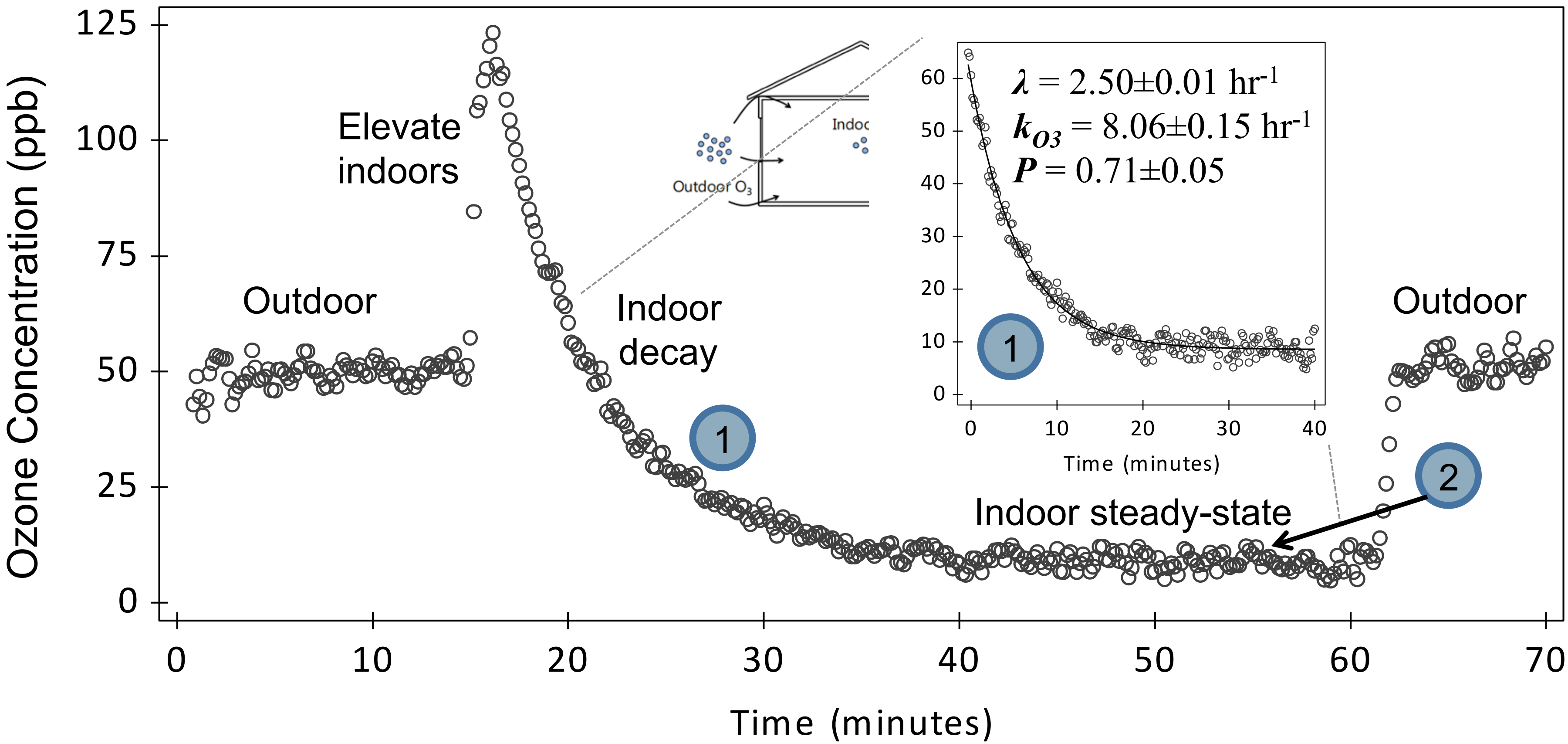


$$\frac{dC_{in}}{dt} = PaC_{out} - (a + k_{comp})C_{in}$$

$$C_{in,t} = Pa_tC_{out,t}\Delta t + (1 - (a_t + k_{comp})\Delta t)C_{in,t-1}$$

One equation, two unknowns

Ozone penetration: New test method



① $$\frac{dC_{in}}{dt} = P\lambda C_{out} - (\lambda + k_{O3})C_{in}$$

Ozone

② $$P = \frac{C_{in}}{C_{out}} \frac{\lambda + k_{O3}}{\lambda}$$

Ozone

λ $$\frac{dC_{t,in}}{dt} = P\lambda C_{t,out} - \lambda C_{t,in}$$

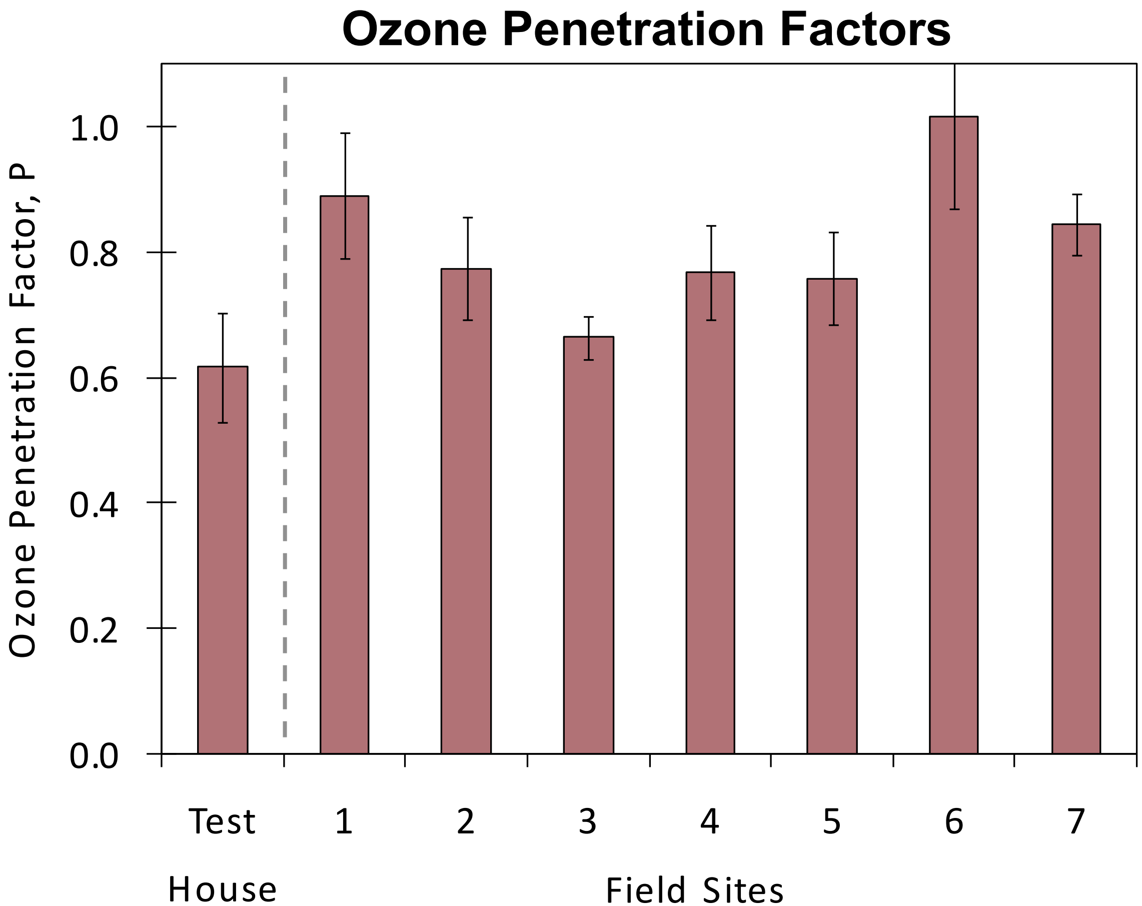
Tracer = CO_2

Stephens et al., *Environ. Sci. Technol.* **2012** 46(2), 929-936

Ozone penetration field testing

Stephens et al., *Environ. Sci. Technol.* **2012** 46(2), 929-936

Ozone penetration results



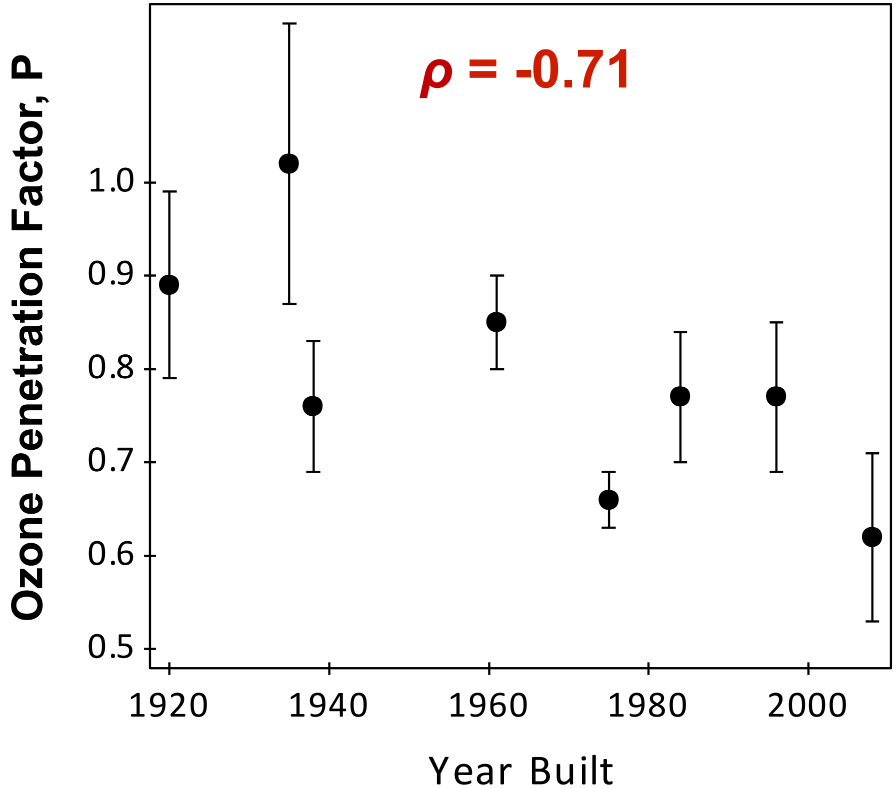
- Mean (± SD) = 0.79 ± 0.13 | Range = 0.62 ± 0.09 to 1.02 ± 0.15
- Usually assumed P = 1

Weschler, **2006** *EHP*; Gall et al., **2011** *Atmos Environ*; Chen et al., **2011** *Environ Health Persp*

Stephens et al., *Environ. Sci. Technol.* **2012** 46(2), 929-936

Exploration of ozone results: What can we learn?

Spearman rank correlations ($p \le 0.05$)



Ozone infiltration was lower in newer homes (tiny sample)

Stephens et al., *Environ. Sci. Technol.* **2012** 46(2), 929-936

Implications for ozone exposure

$$F_{inf} = \frac{C_{in}}{C_{out}} = \frac{P \times AER}{AER + Loss_{O3}}$$

- Assume mean $Loss_{O3}$ = 2.8 hr^{-1}

Lee at al., **1999** *JAWMA*

Least protective home, 1920

- P_{O3} = 0.89 ± 0.10
- AER = 0.93 ± 0.02 hr^{-1}
- **I/O O_3 = 0.22**

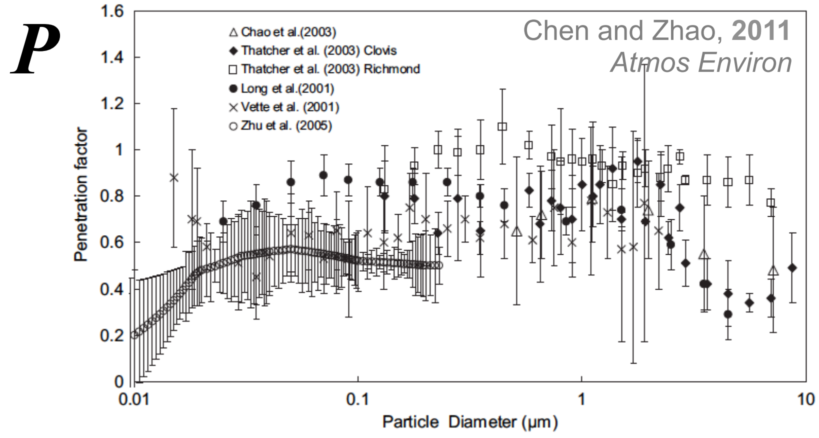
Most protective home, 2008

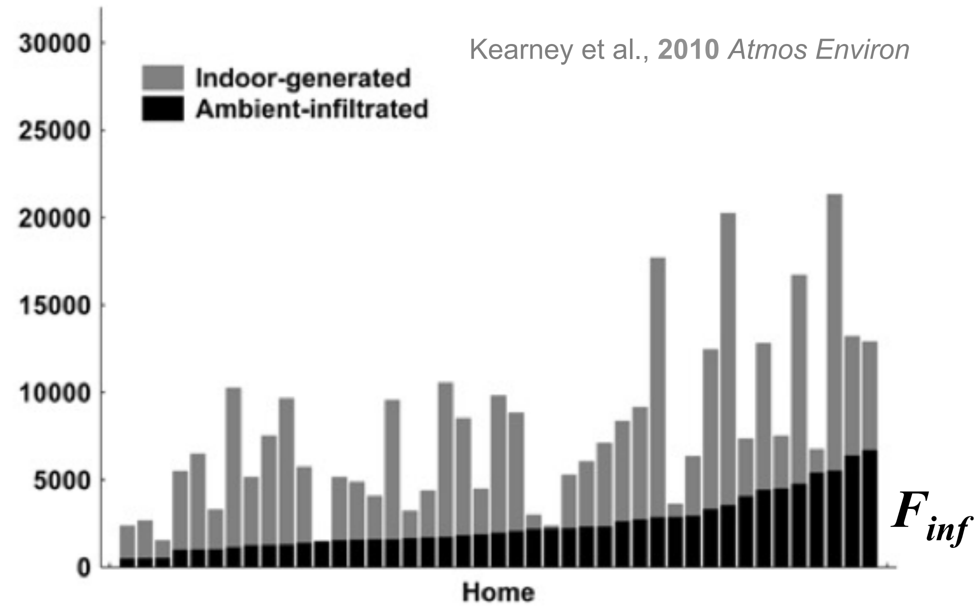
- P_{O3} = 0.62 ± 0.09
- AER = 0.24 ± 0.06 hr^{-1}
- **I/O O_3 = 0.05**

Factor of ~4.5

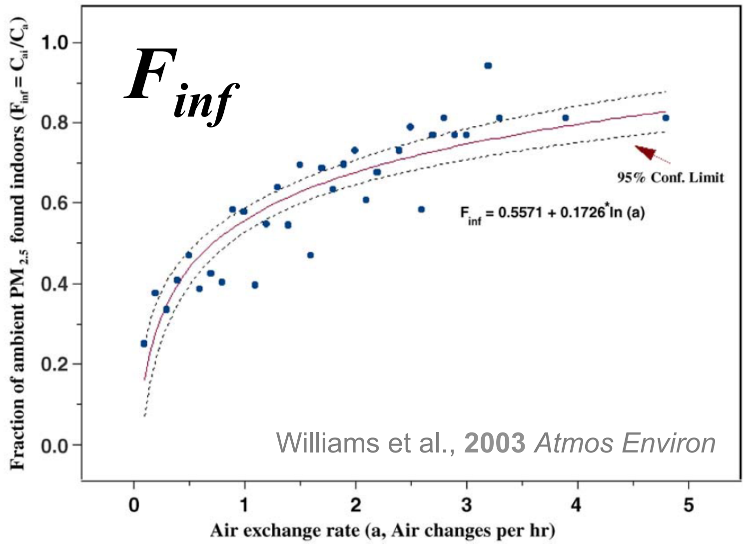
PARTICULATE MATTER INFILTRATION

Indoor proportion of outdoor particles





Outdoor particles infiltrate into and persist within buildings with varying efficiencies

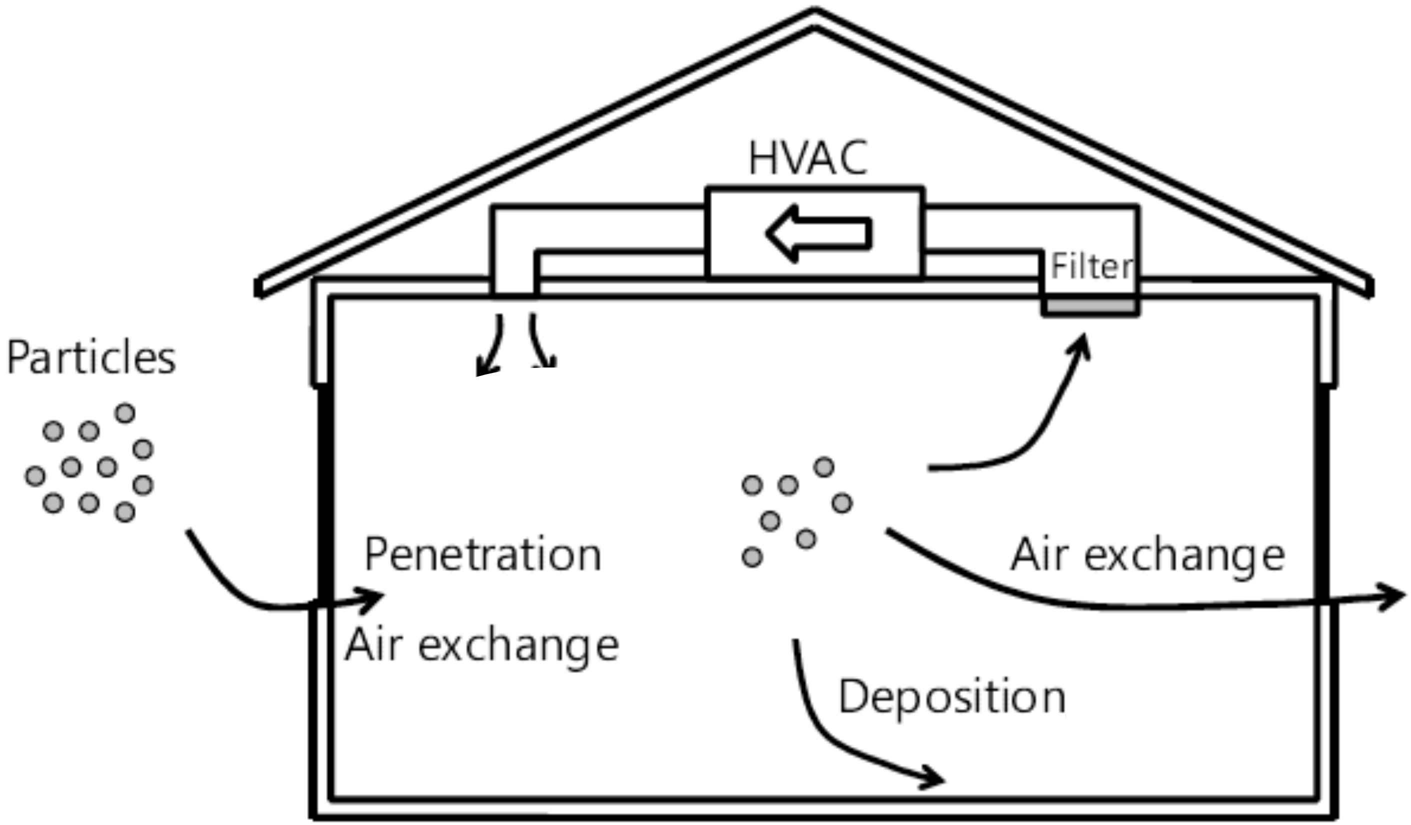


Exposure to outdoor PM often occurs indoors

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



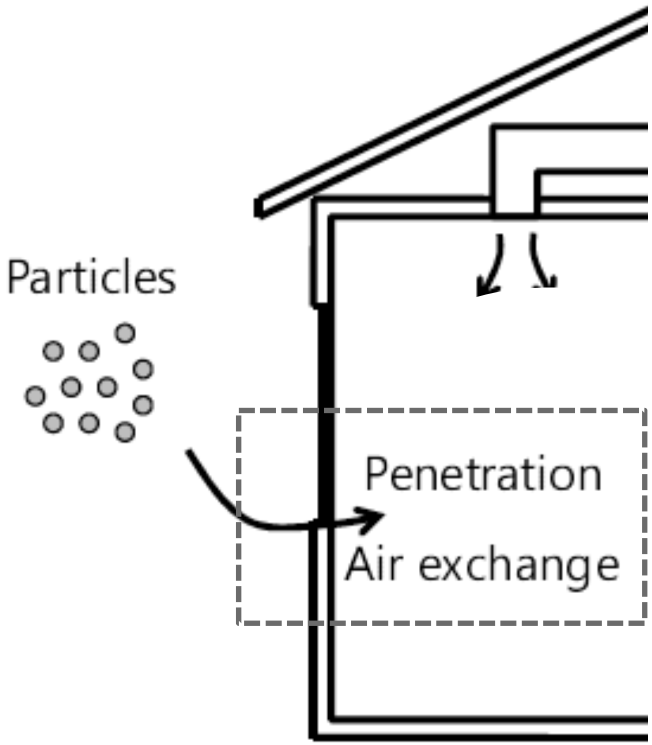
C_{in} = indoor concentration (#/m^3)
C_{out} = outdoor concentration (#/cm^3)
P = penetration factor (-)
λ = air exchange rate (1/hr)
k = surface deposition rate (1/hr)
f = fractional HVAC runtime (-)
η = filter removal efficiency (-)
Q = HVAC airflow rate (m^3/hr)
V = indoor air volume (m^3)

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

Penetration from outdoors

Air exchange
Deposition
HVAC filter removal

Mechanisms that impact indoor exposures to outdoor PM



"Penetration Factor"
If *P* = 1:
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The envelope offers complete protection

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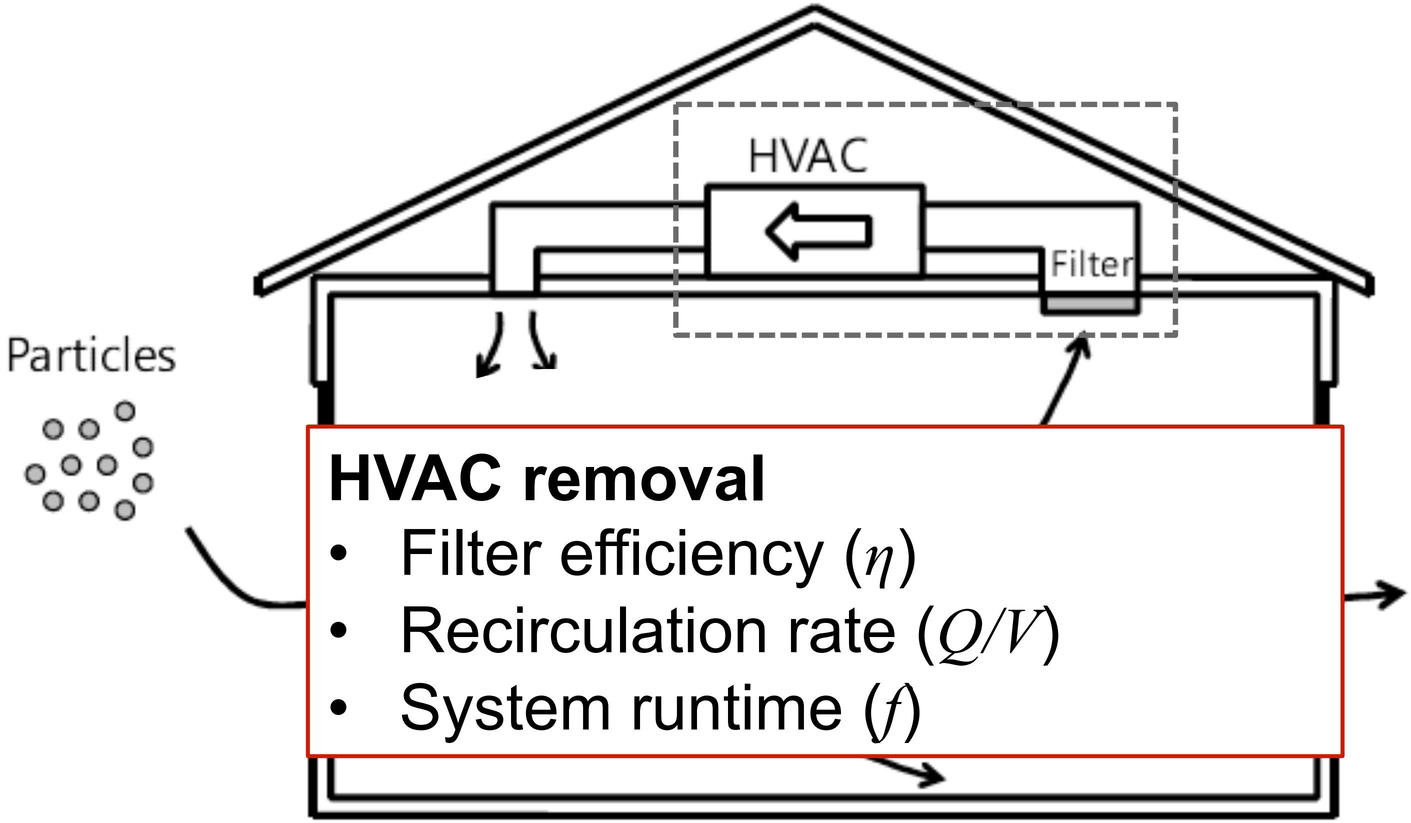
Penetration from outdoors

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)
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)

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

Filter removal
HVAC operation

Goals of this work

- Further explore the impacts of **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

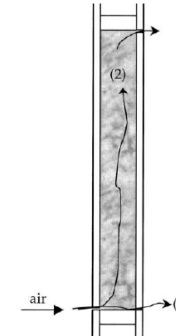
- Using recently measured data from recent studies on residential (and some small commercial) buildings

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

Measuring particle infiltration

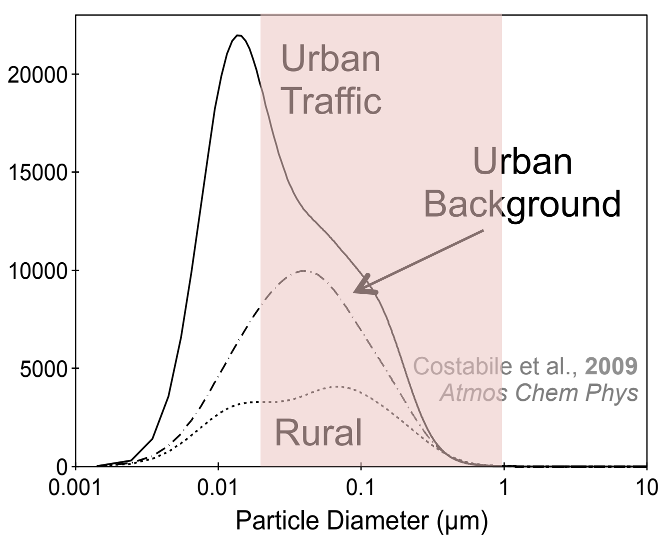
- Particles can penetrate through cracks in building envelopes
  - Theoretically a function of:
    - Crack geometry
    - Air speed through leaks

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*

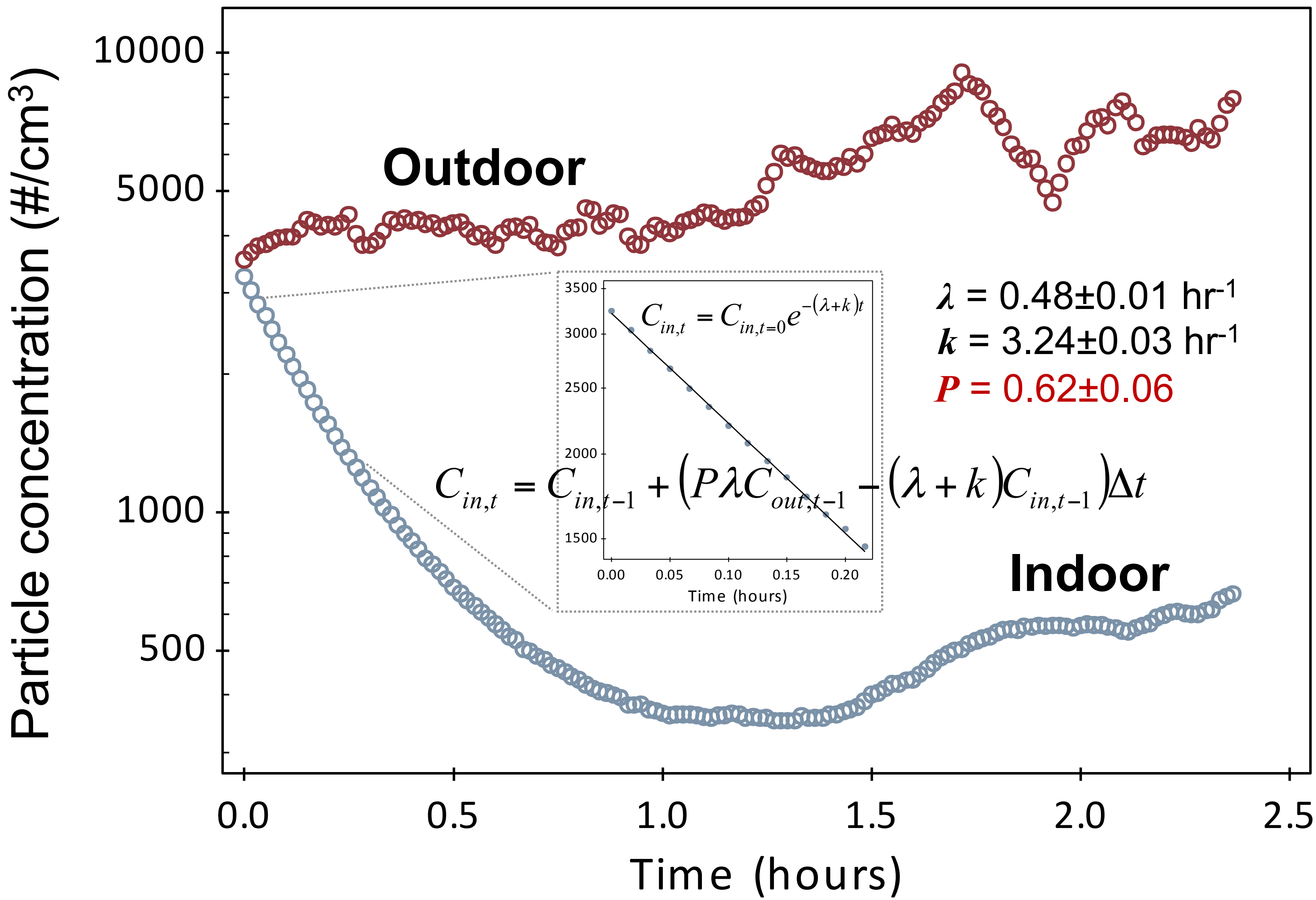


TSI P-Traks
20 – 1000 nm

PM infiltration: Test homes

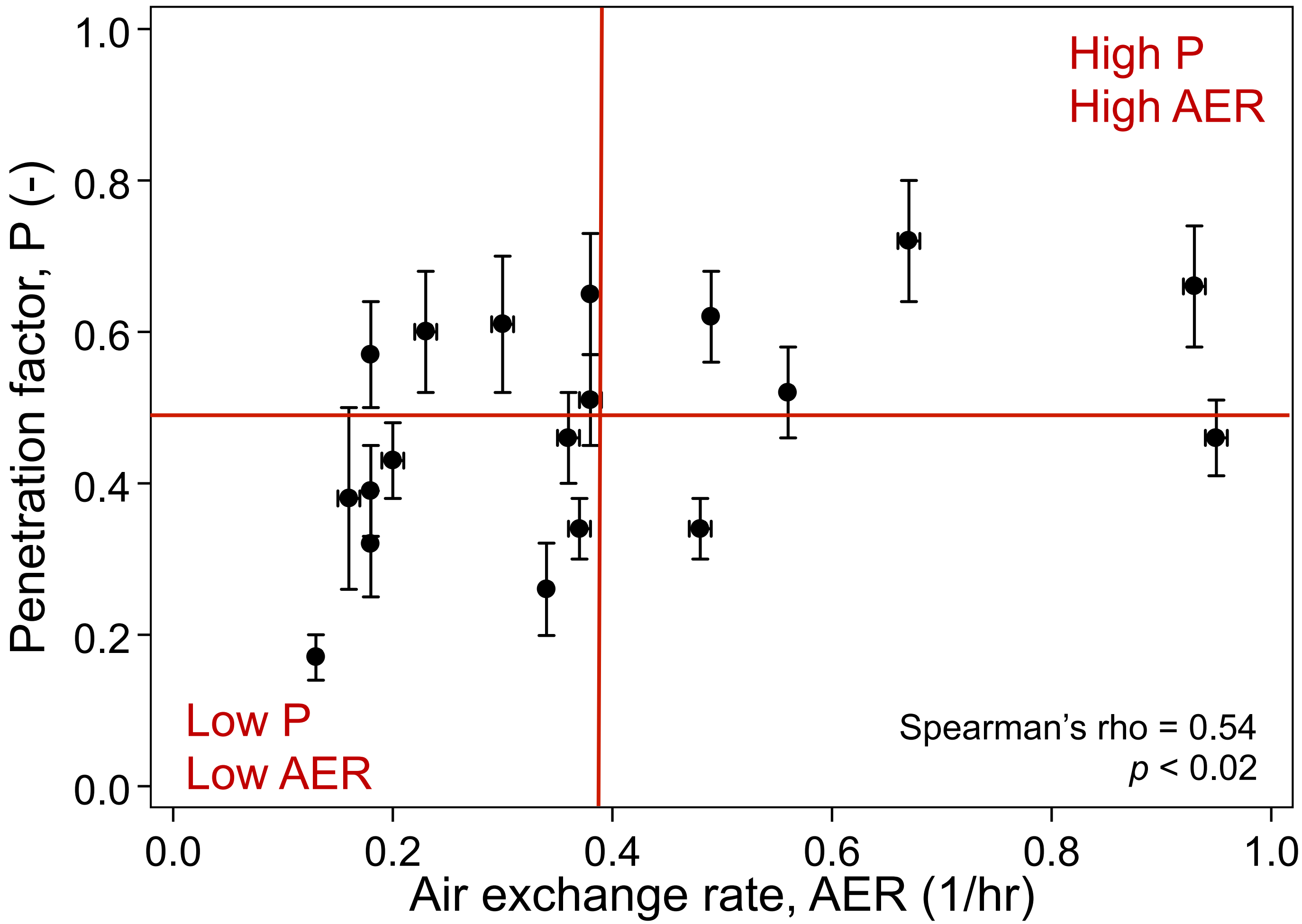
Stephens and Siegel, *Indoor Air* **2012** 22(6):501-512

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



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

Particle infiltration results: P and AER



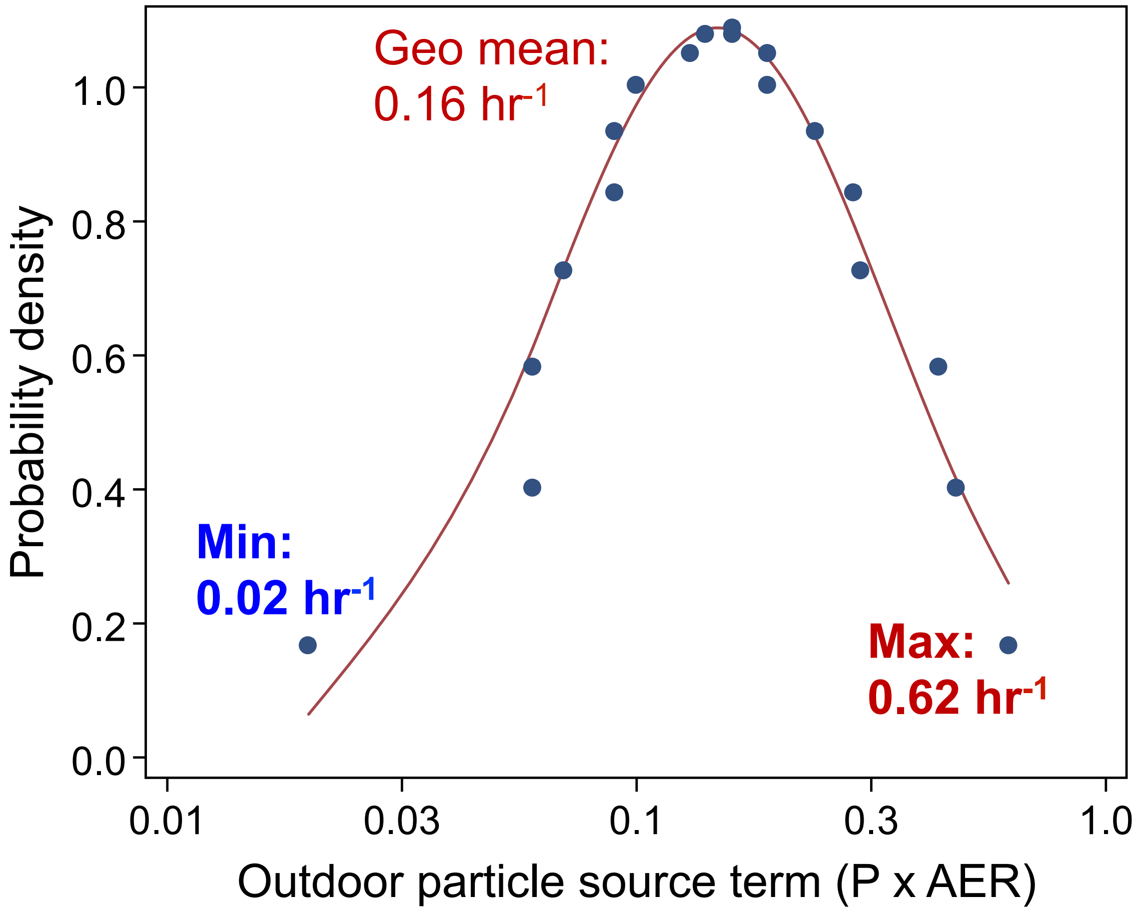
Penetration factors: Mean = 0.47 Range = 0.17 to 0.72

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

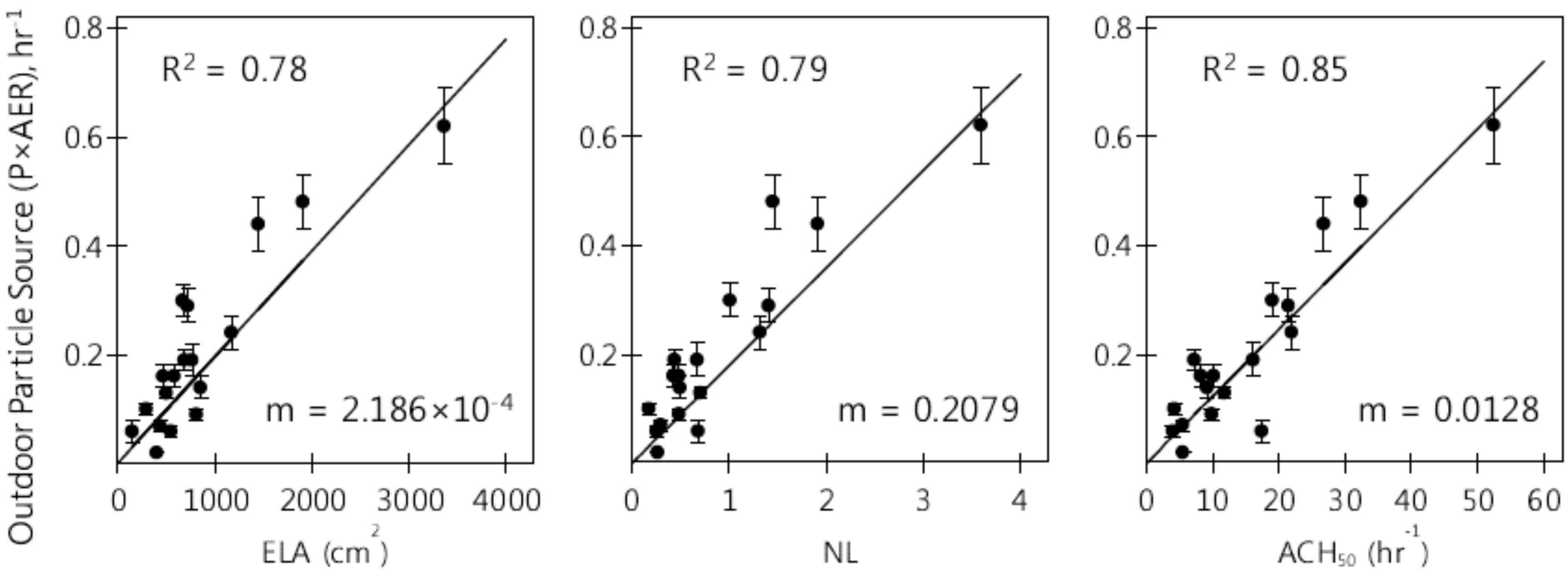
Outdoor particle source terms: P×AER

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



PM infiltration: Outdoor particle source and air leakage

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



Leakier homes had much higher outdoor particle source rates

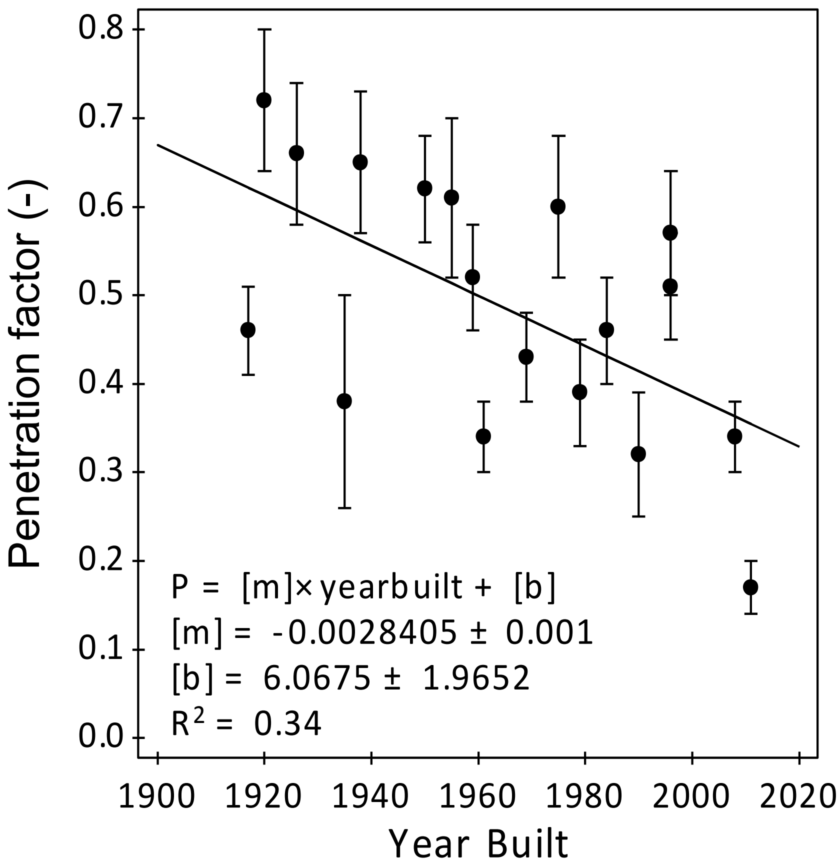
- Potential socioeconomic implications: low-income homes are leakier

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

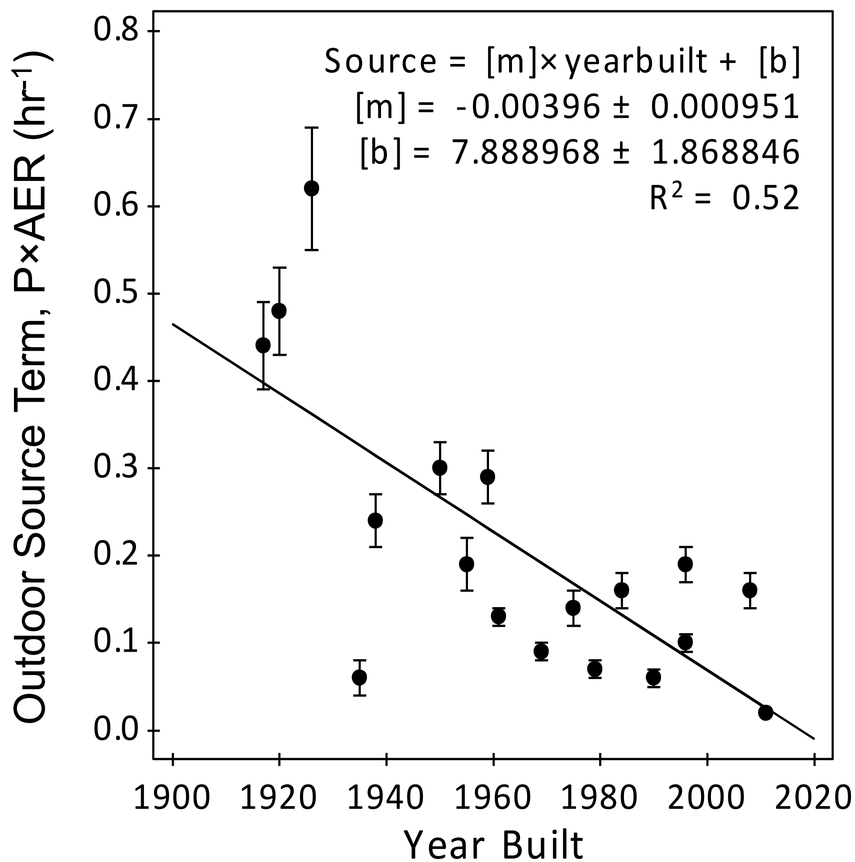
Stephens and Siegel, *Indoor Air* **2012** 22(6):501-512

PM infiltration and age of homes

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



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



Older homes also had much higher outdoor particle source rates

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

Implications for particle exposure

$$F_{inf} = \frac{C_{in}}{C_{out}} = \frac{P \times AER}{AER + Loss_{PM}}$$

- Assume mean $Loss_{PM}$ = 1 hr^{-1}

Mean from this study

Least protective home, 1926

- P_{PM} = 0.66 ± 0.08
- AER = 0.93 ± 0.01 hr^{-1}
- **I/O PM = 0.32**

Most protective home, 2011

- P_{PM} = 0.17 ± 0.03
- AER = 0.13 ± 0.01 hr^{-1}
- **I/O PM = 0.02**

Factor of ~16

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

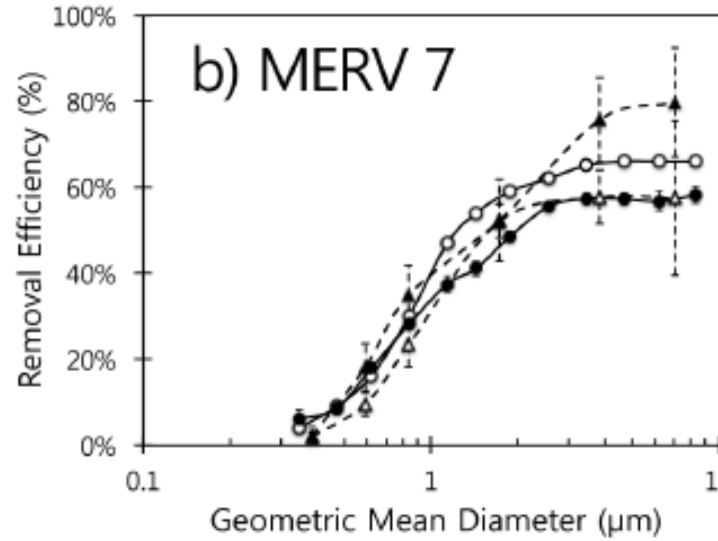
MERV 11

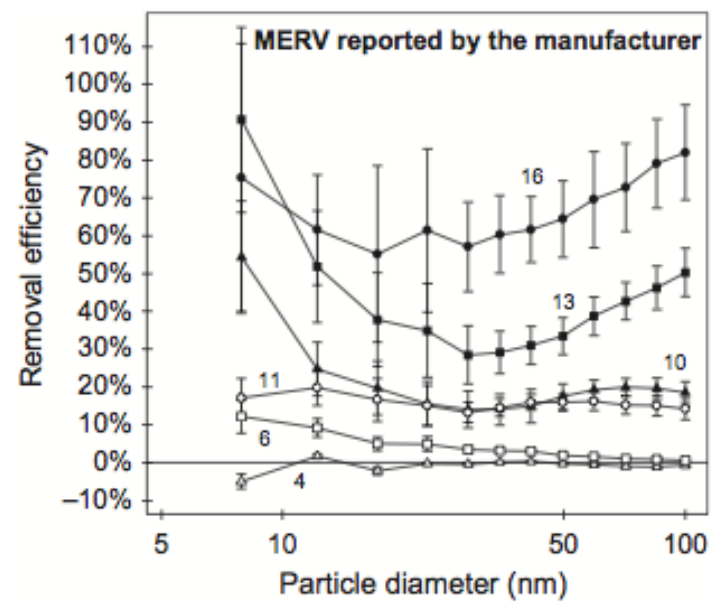
5-inch depth

MERV 10

MERV 13

MERV 16





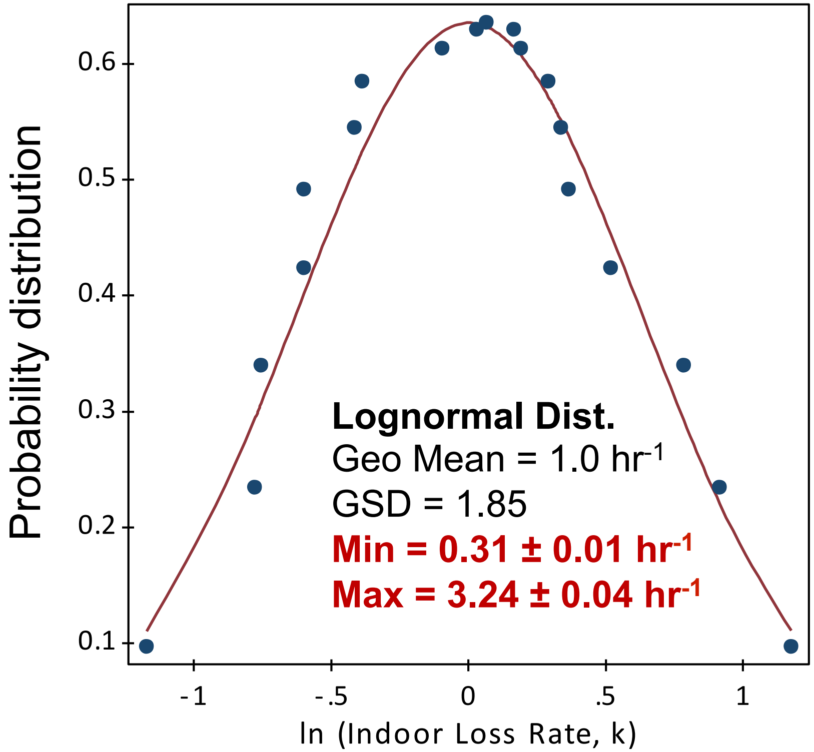
Stephens and Siegel, *Aerosol Sci. Technol.* **2012** 46(5), 504-513
Stephens and Siegel, *Indoor Air* **2013**

Indoor particle removal rates

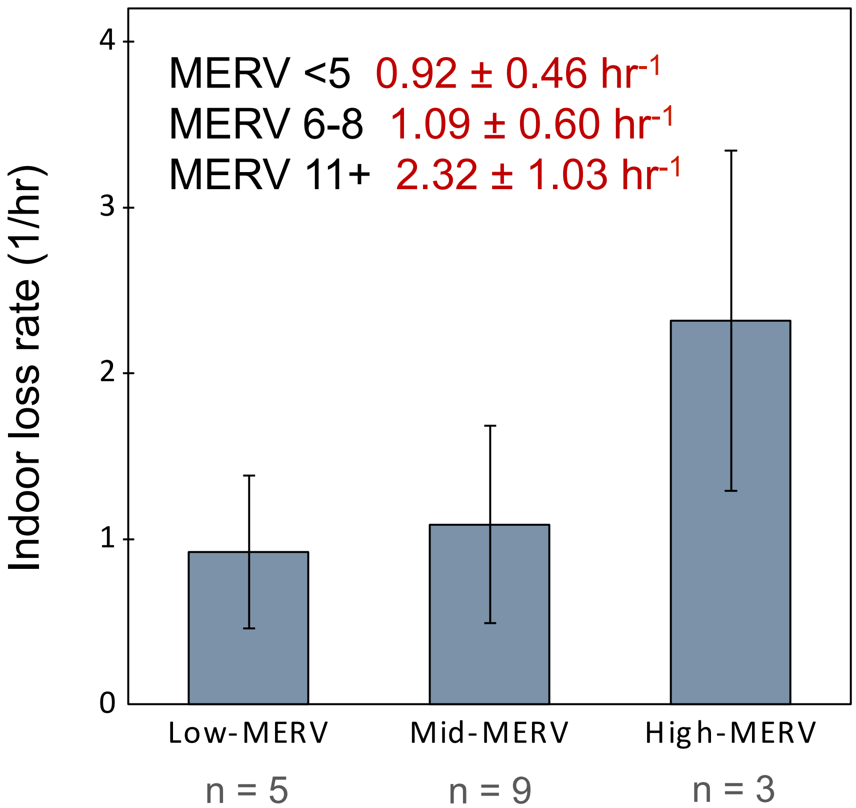
- Submicron particle loss with HVAC system operating 100%

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

where f = 1



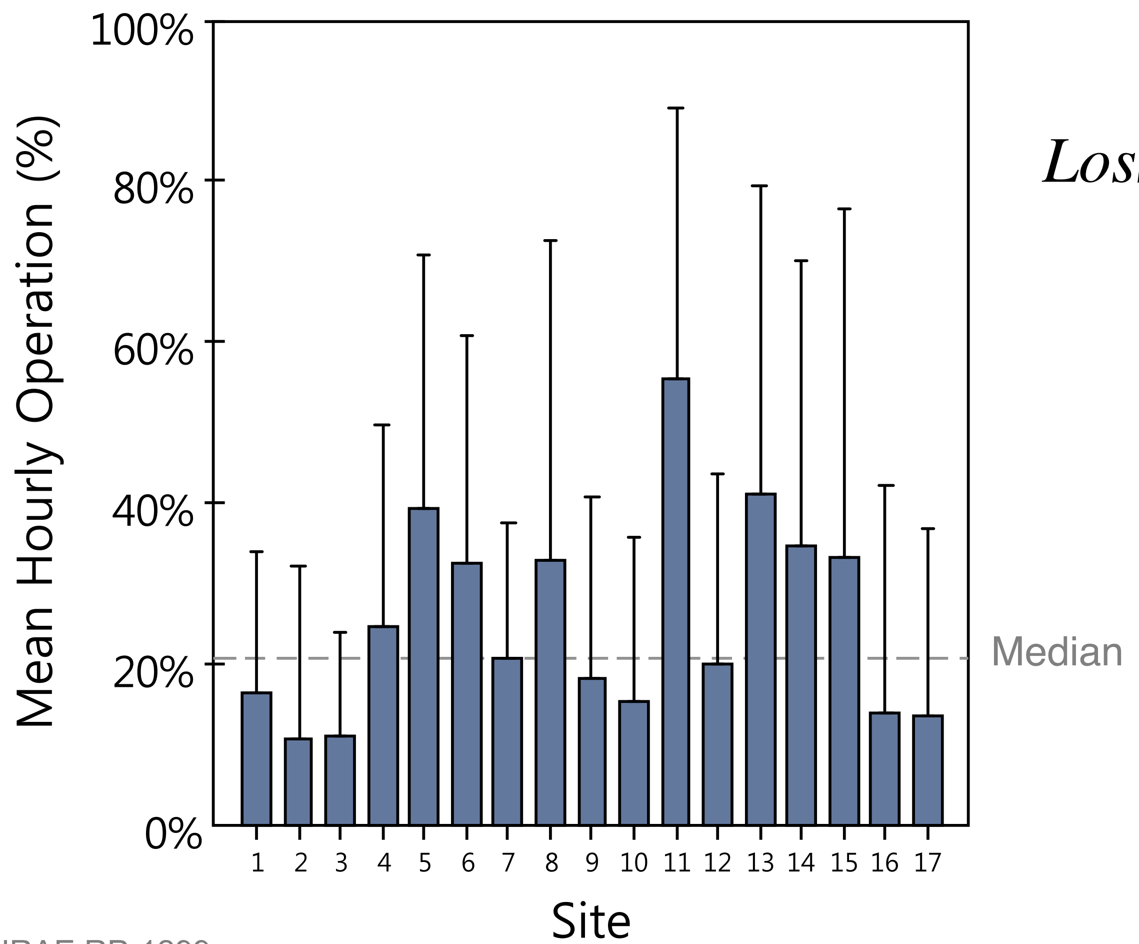
Split by filter type



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)



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

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

LARGER VARIATIONS IN PM 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: $F_{\inf} = \dfrac{C_{in}}{C_{out}} = \dfrac{P \times AER}{AER + k + f\dfrac{\eta Q}{V}}$

	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

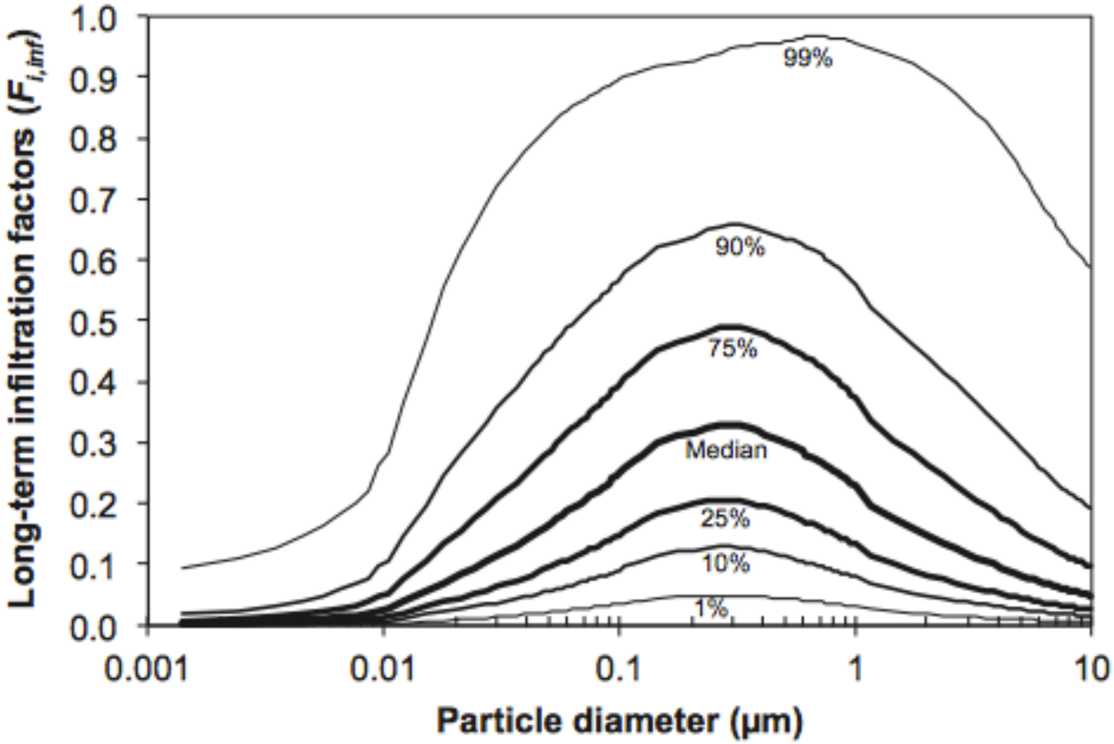
- Some potential for predictive ability using:
  - Age of home
  - Building airtightness test results
  - Knowledge of HVAC filter type
  - I/O climate conditions

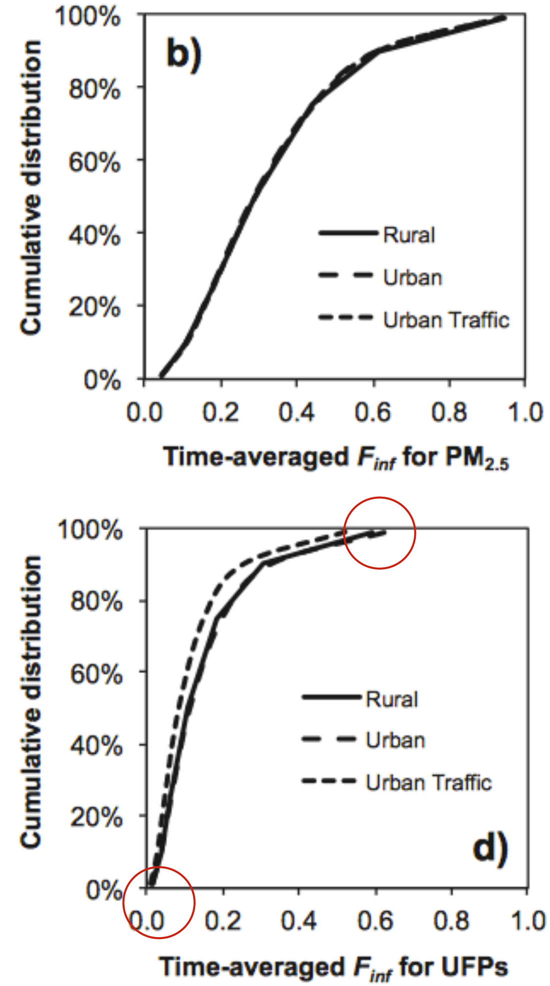
Modeling size-resolved indoor PM of outdoor origin

Predictions and determinants of size-resolved particle infiltration factors in single-family homes in the U.S.

Zeineb El Orch [a], Brent Stephens [a,*], Michael S. Waring [b]

[a] Civil, Architectural and Environmental Engineering, Illinois Institute of Technology, Chicago, IL, USA
[b] Civil, Architectural and Environmental Engineering, Drexel University, Philadelphia, PA, USA





El Orch et al., **2014** *Building and Environment* 74:106-118

Summary of outdoor pollutant infiltration work

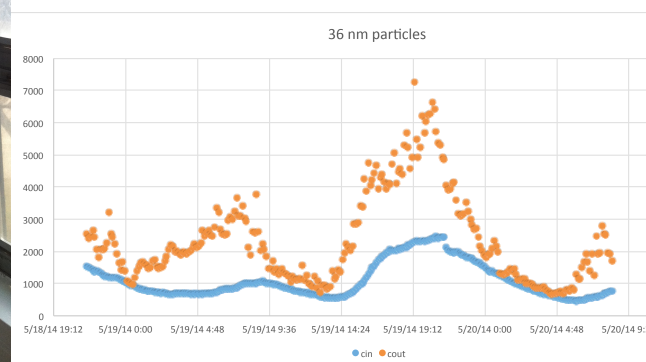
- Building characteristics and building operation have a large influence on indoor exposures to pollutants of outdoor origin
  - We are starting to really understand this for particulate matter
  - We know much less about ozone

- This large variation is likely important to capture in epidemiology studies

- We are working to simplify collection of these kinds of data

Next steps: PM and O_3 infiltration in Chicago

studioE
Suite for Testing Urban Dwellings and their Indoor and Outdoor Environments

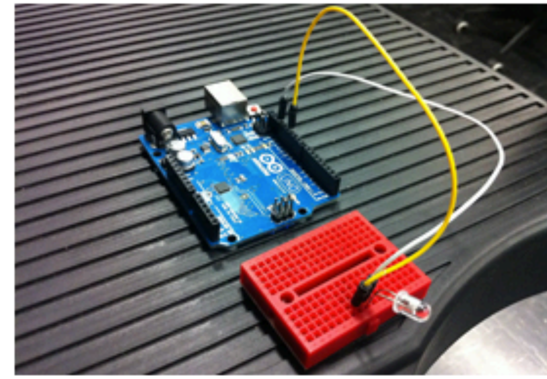


Other recent/ongoing work

Particle emissions from 3D printers

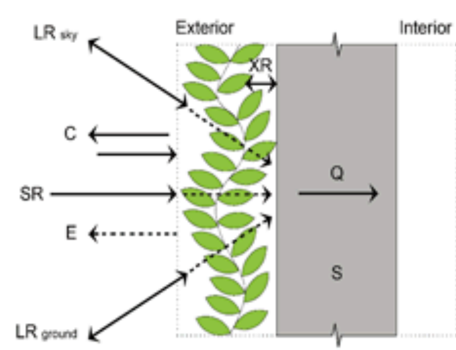
Hospital Microbiome Project

Open source building science sensors



Thermal performance of enclosures

Thermal performance of vegetated walls



CYDI greenhouse construction

The Built Environment Research Group

advancing energy, environmental, and sustainability
research within the built environment
at Illinois Institute of Technology

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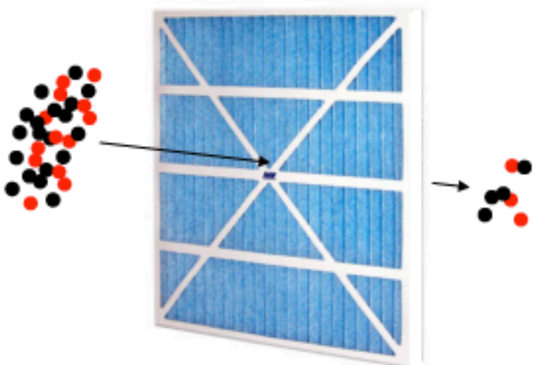
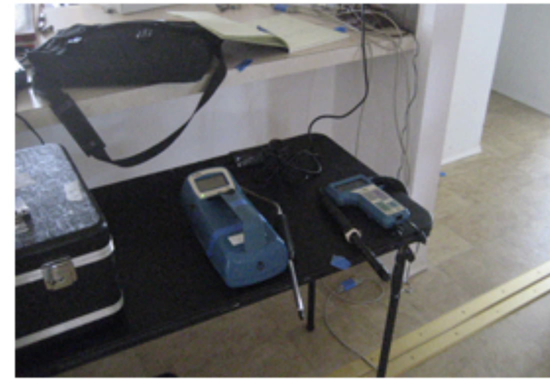
Other recent/ongoing work

Filtration of infectious aerosols



Energy impacts of duct design in homes

Particle infiltration into homes



Ozone infiltration into homes

HVAC filter testing

Energy audit analysis

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Questions/Comments

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