CAE 463/524
Building Enclosure Design
Fall 2013

Lecture 12: November 20, 2013
Finish recent building enclosure research
Course wrap-up

Built
Environment
Research
@ IIT

Advancing energy, environmental, and sustainability research within the built environment

www.built-envi.com

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Last time

- Campus project presentations
  - Alumni, E1, Stuart, and Crown Hall

- Building enclosure research
  - Ongoing energy and moisture research
  - Vegetative wall performance
  - Impact of enclosures on IAQ
    - Corrosive ‘Chinese’ drywall

This time and next time

- Two final project presentations
  - Juneyoung
  - Ausrine
- Finish building enclosure research
  - Impact of enclosures on IAQ
- The remaining project presentations will take place Wednesday December 4, 5-7 PM
  - Keep them to 12 minutes max.

Final presentations

BUILDING ENCLOSURES AND OUTDOOR AIR POLLUTION

Indoor vs. outdoor air pollution

Air pollution is both an indoor and an outdoor issue

- Many indoor pollutant sources
- Outdoor pollutants also infiltrate indoors

Much of our exposure to outdoor air pollution occurs indoors

Health effects of 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**
  - Can improve connections to health effects
  - Can inform how building design and operation impacts exposures

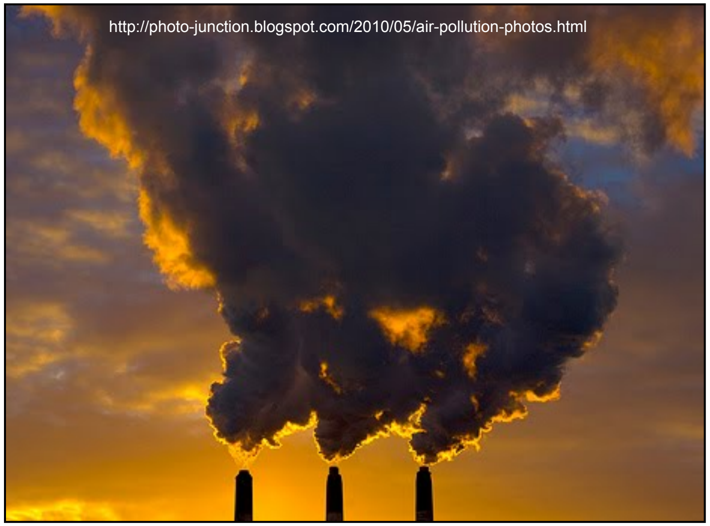
Some outdoor airborne pollutants are regulated

National Ambient Air Quality Standards (NAAQS)

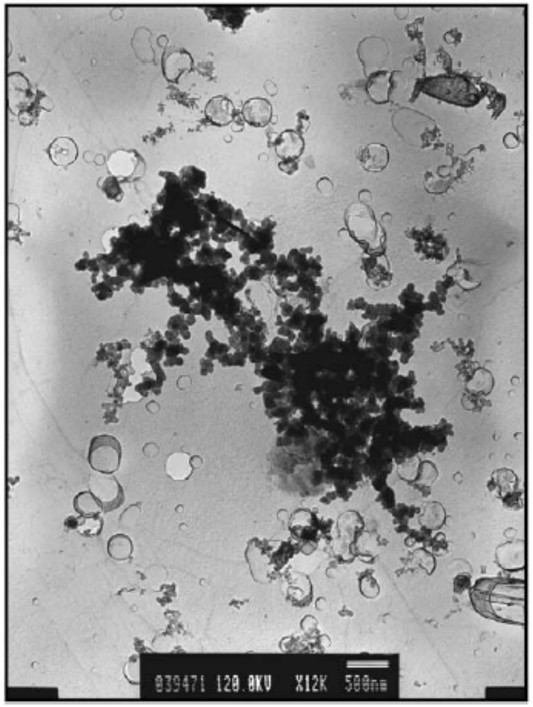
- US EPA and the Clean Air Act (1970)
- Set limits for 6 “criteria” pollutants

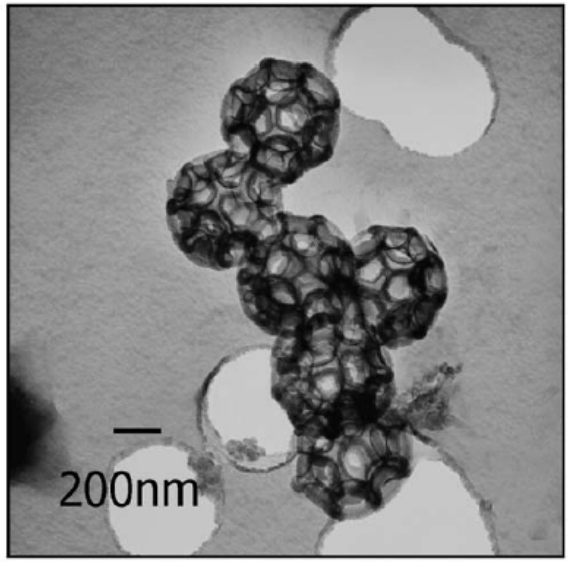
Pollutants Regulated Outdoors
Carbon monoxide (CO)
Lead (Pb)
Nitrogen dioxide (NO_2)
Ozone (O_3)
Particulate matter $PM_{2.5}$ and PM_{10}
Sulfur dioxide (SO_2)

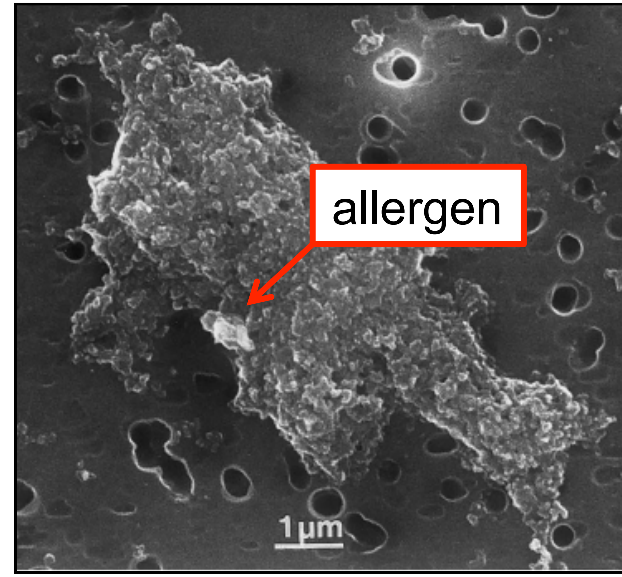
Sources of particulate matter

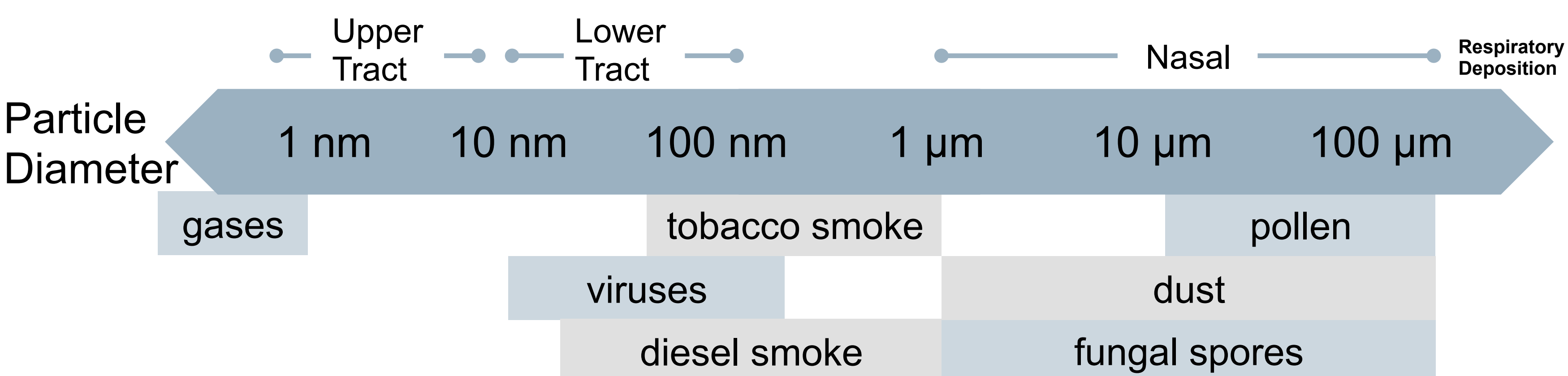


Particulate matter: Up close



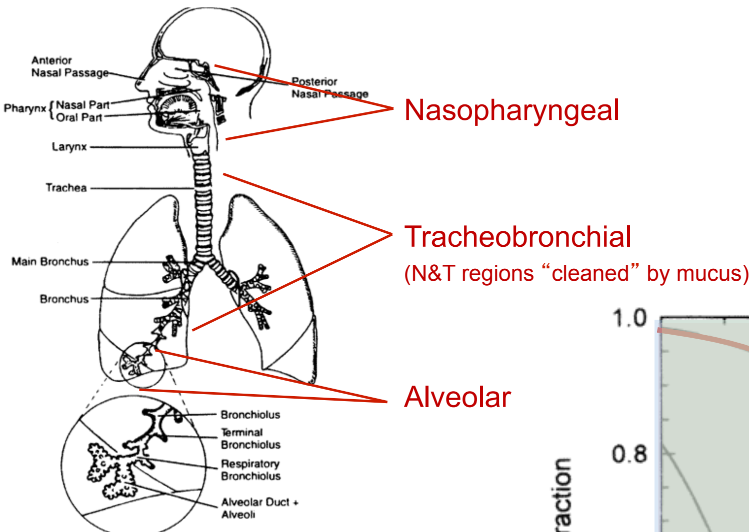


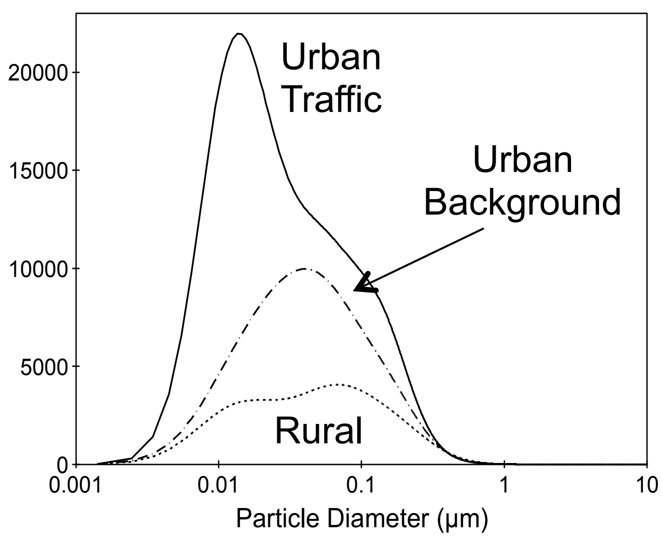




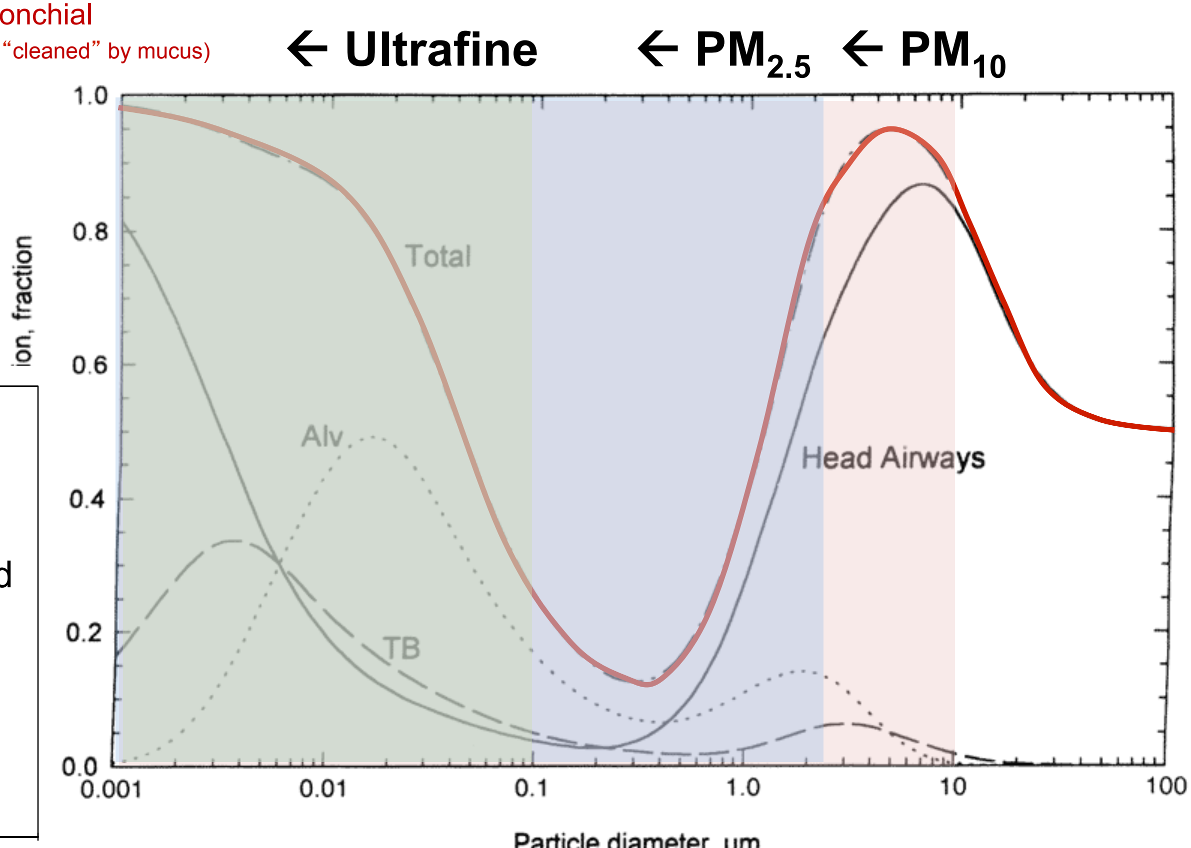
Casuccio et al., **2004** *Fuel Process. Technol.*; Ormstad, **2000** *Toxicol.;* Hinds, **1999** *Aerosol Technol.*

Particle deposition in the respiratory system





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

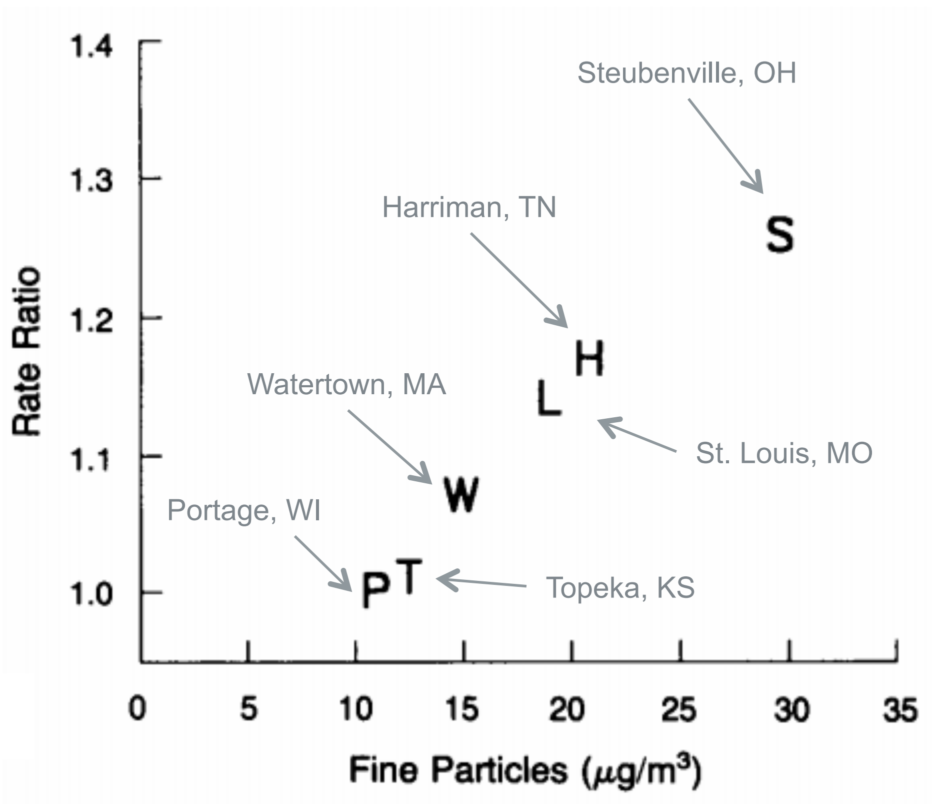


Hinds, 1999 Ch. 11

Most particles of outdoor origin are smaller than 100 nm

Outdoor PM and health effects

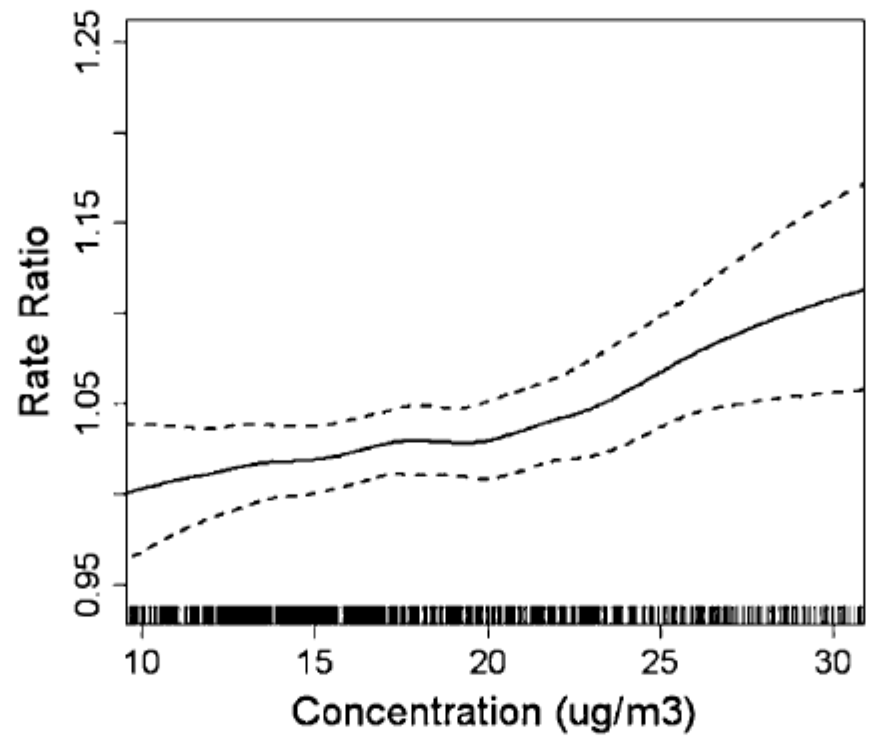
$PM_{2.5}$ and mortality



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

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

$PM_{2.5}$ and pediatric ER visits

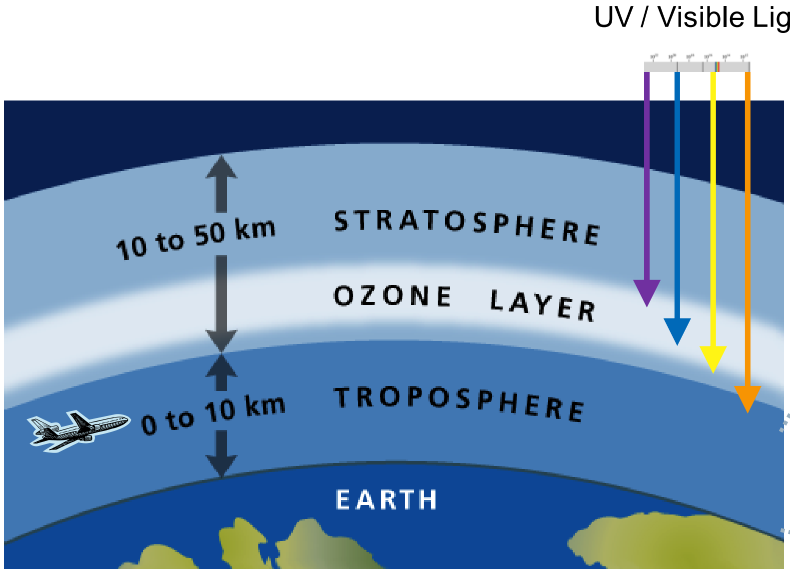


3-day average $PM_{2.5}$data measured outdoors in Atlanta, GA from 1993 to 2004

Strickland et al., **2010** *Am J Respir Crit Care Med*

Ozone

Good up high

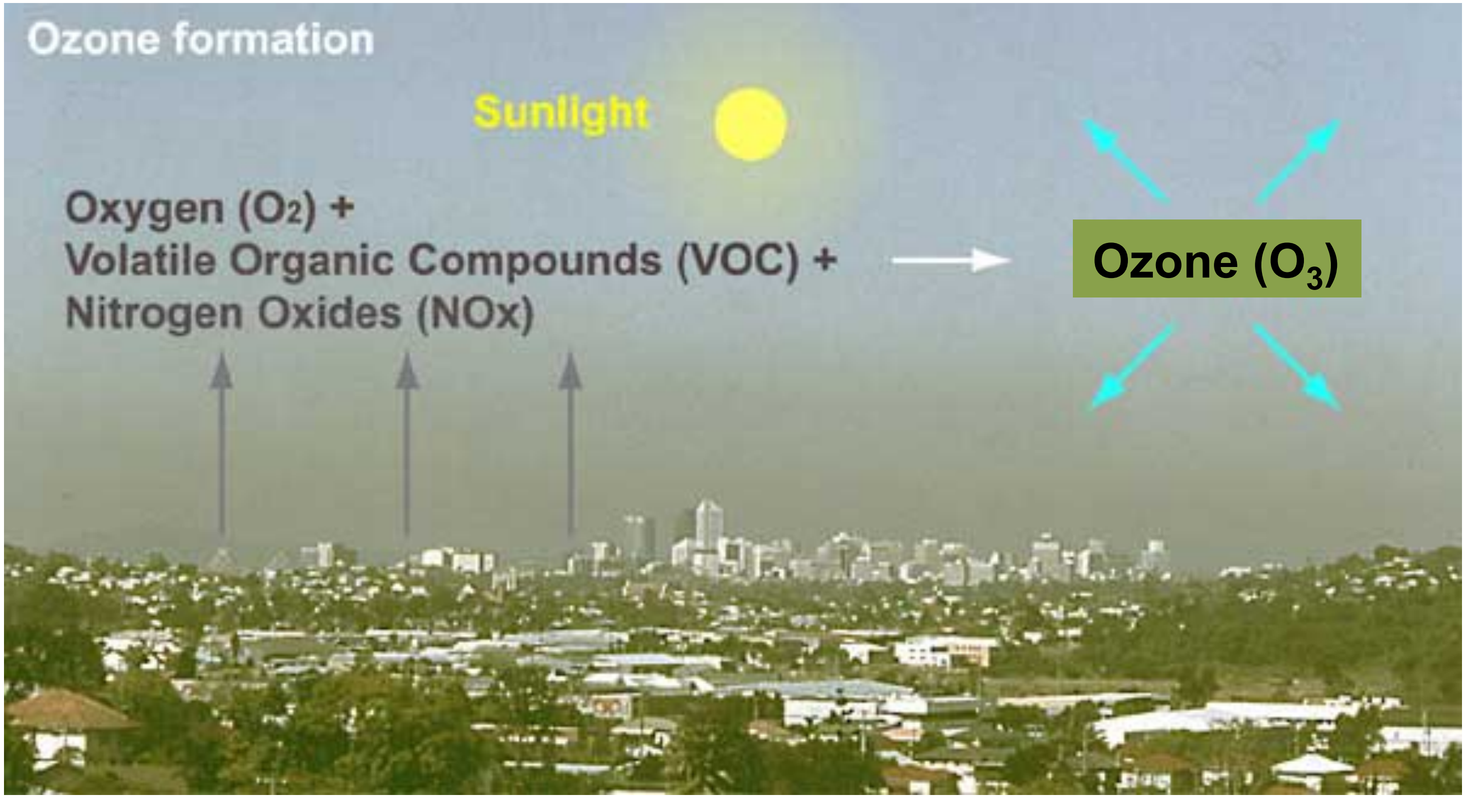


Ozone layer absorbs high frequency (small wavelength) UV light from the sun

Bad nearby

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

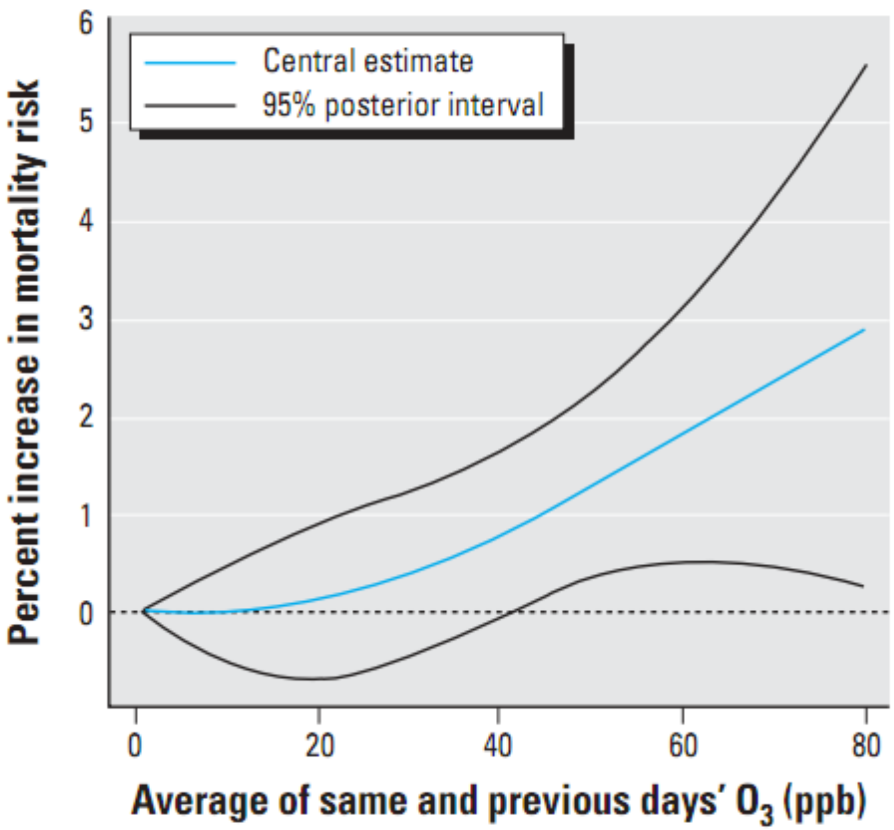
Ozone chemistry (simplified)



Source: Queensland EPA

Outdoor ozone and health effects

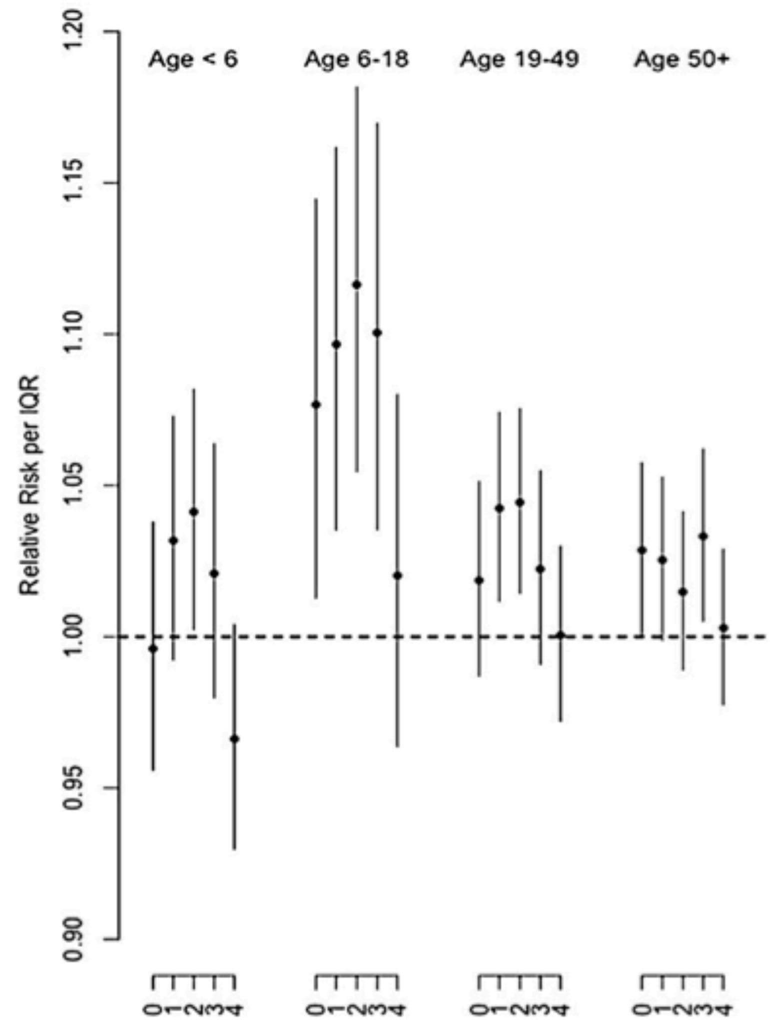
O_3 and mortality



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

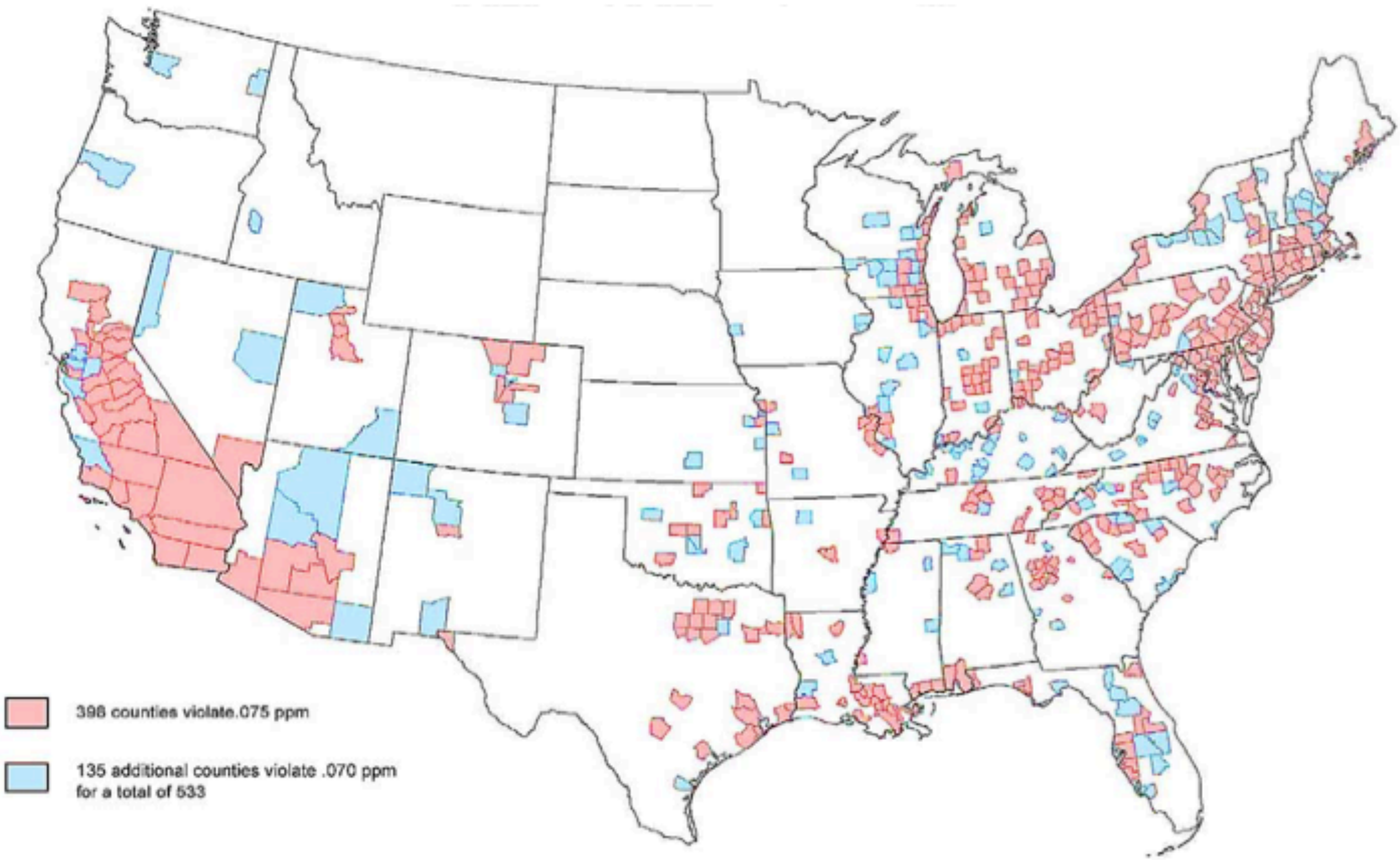
Bell et al., **2006** *Environ Health Persp*

O_3 and asthma

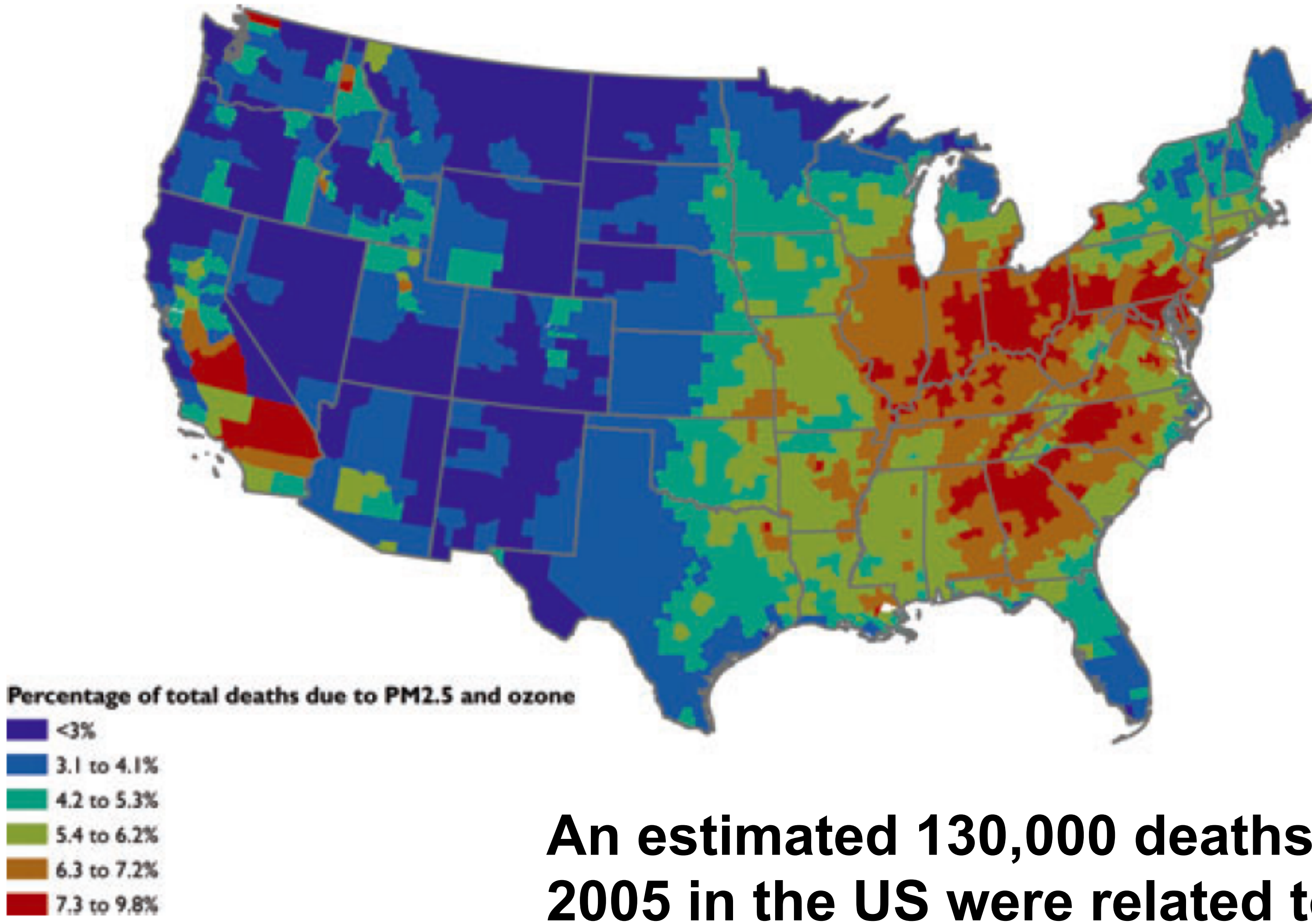


Silverman and Ito, **2005** *J Allergy Clin Immunol*

Ozone nonattainment areas



Health effects: Outdoor air pollution and mortality

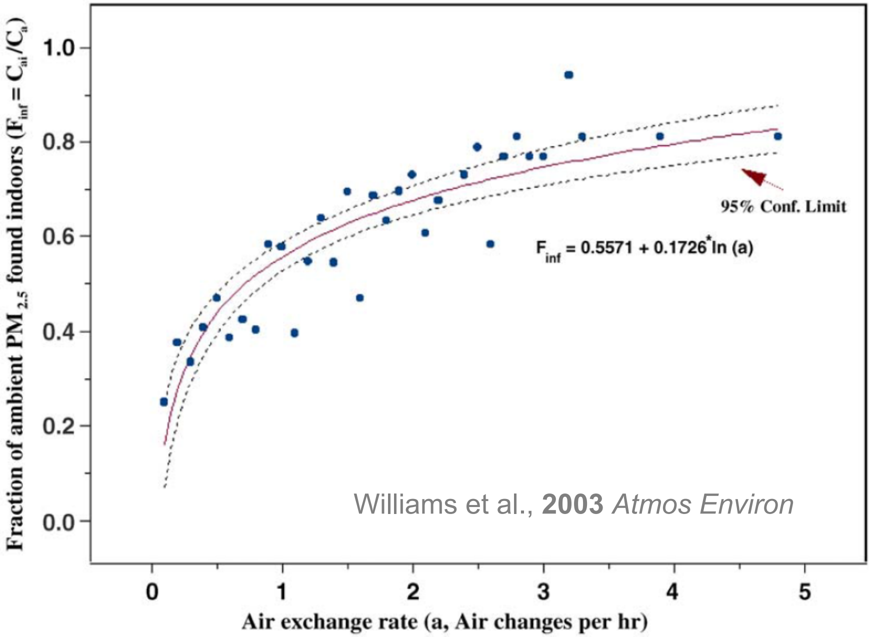


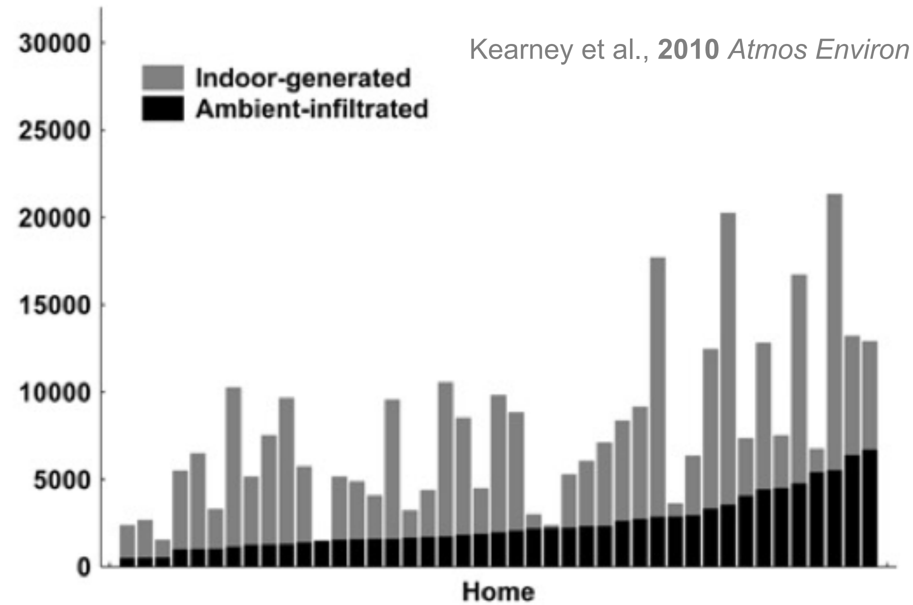
An estimated 130,000 deaths in 2005 in the US were related to outdoor $PM_{2.5}$ (and 5,000 to O_3)

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

PARTICLE INFILTRATION MEASUREMENTS

Indoor proportion of **outdoor** particles





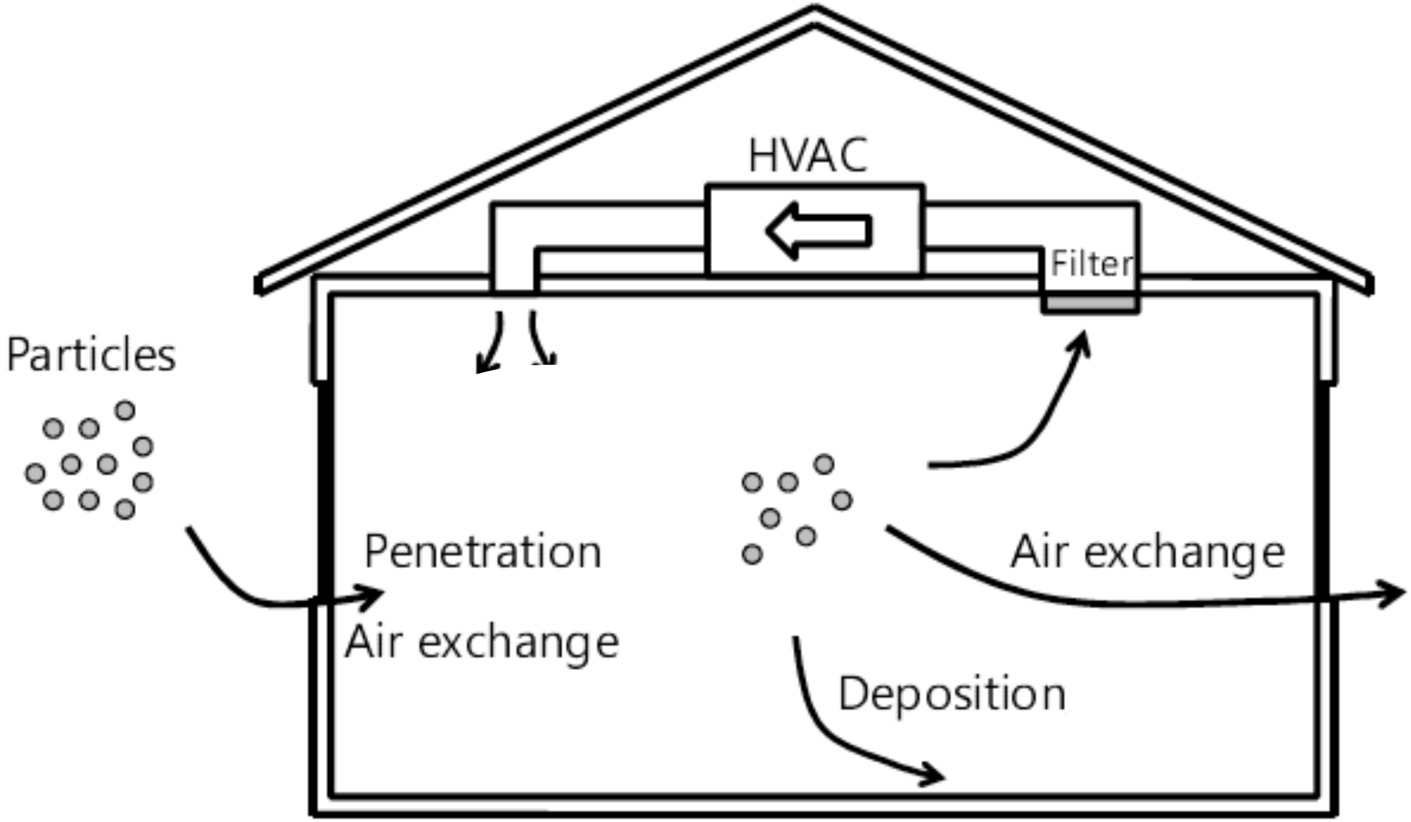
Outdoor particles infiltrate into and persist within buildings with varying efficiencies

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



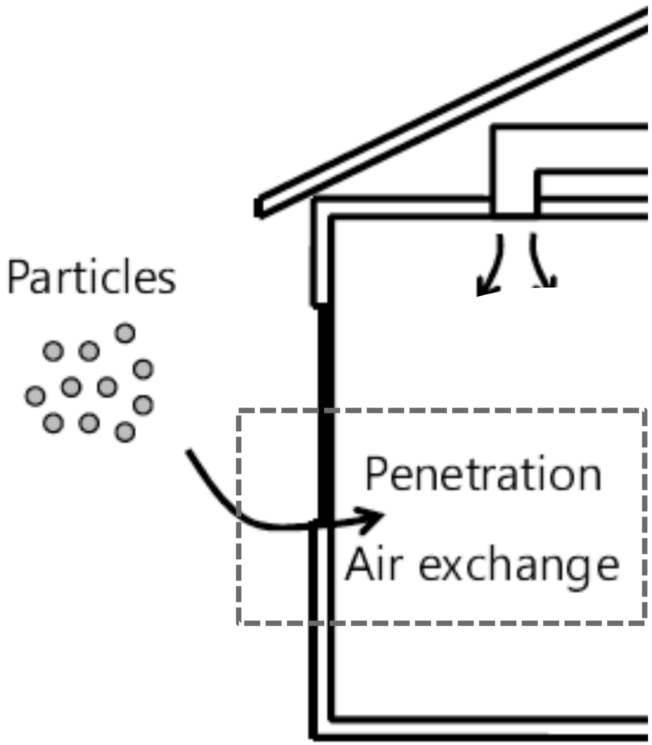
C_{in} = indoor concentration (#/m^3)
C_{out} = outdoor concentration (#/cm^3)
P = penetration factor (-)
λ = air exchange rate (1/hr)
k = surface deposition rate (1/hr)
f = fractional HVAC runtime (-)
η = filter removal efficiency (-)
Q = HVAC airflow rate (m^3/hr)
V = indoor air volume (m^3)

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

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)
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 (-)
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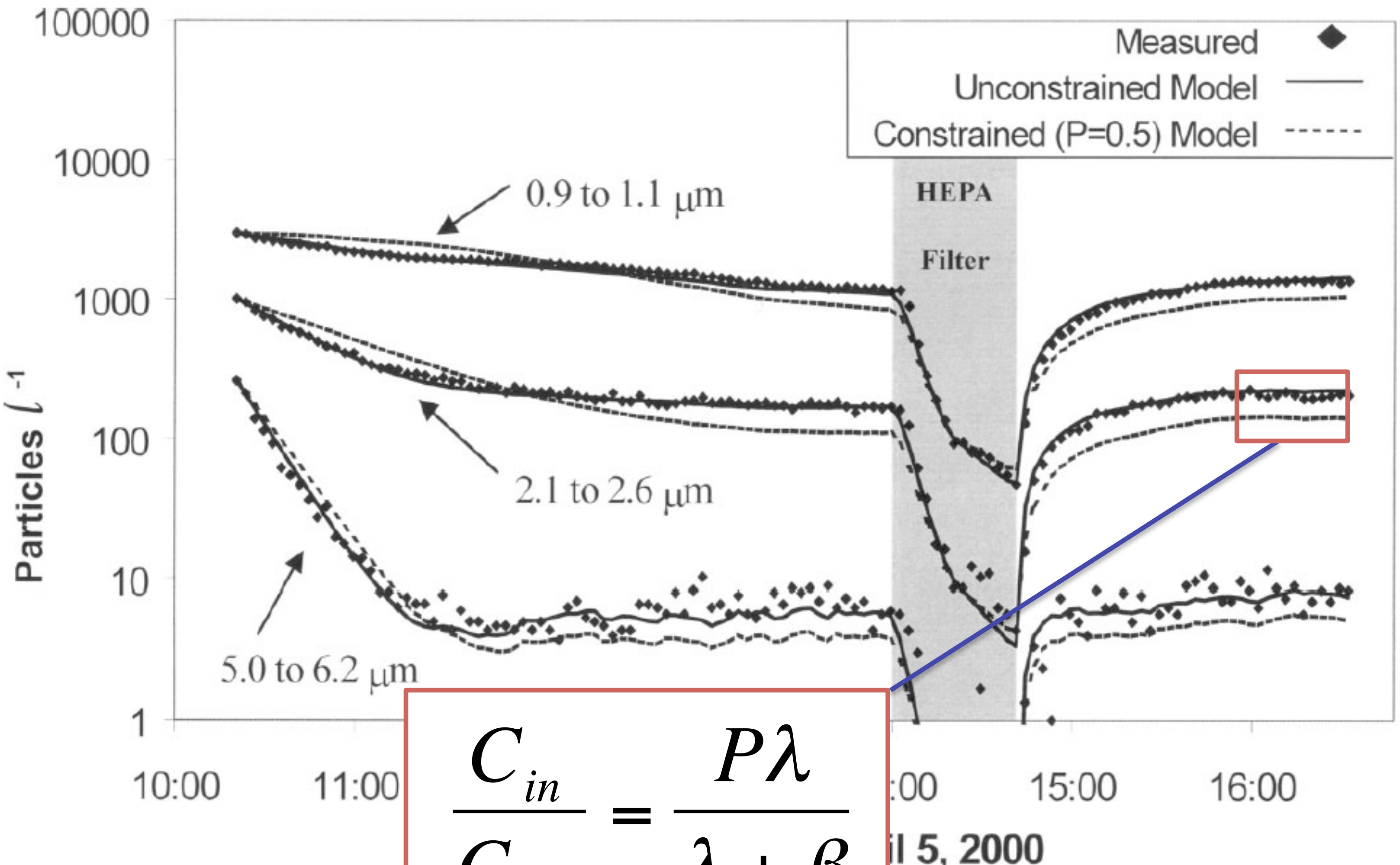
Q = HVAC airflow rate (m^3/hr)
V = indoor air volume (m^3)

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

Penetration from outdoors

Particle Penetration

Particle rebound method (Thatcher et al., 2003)

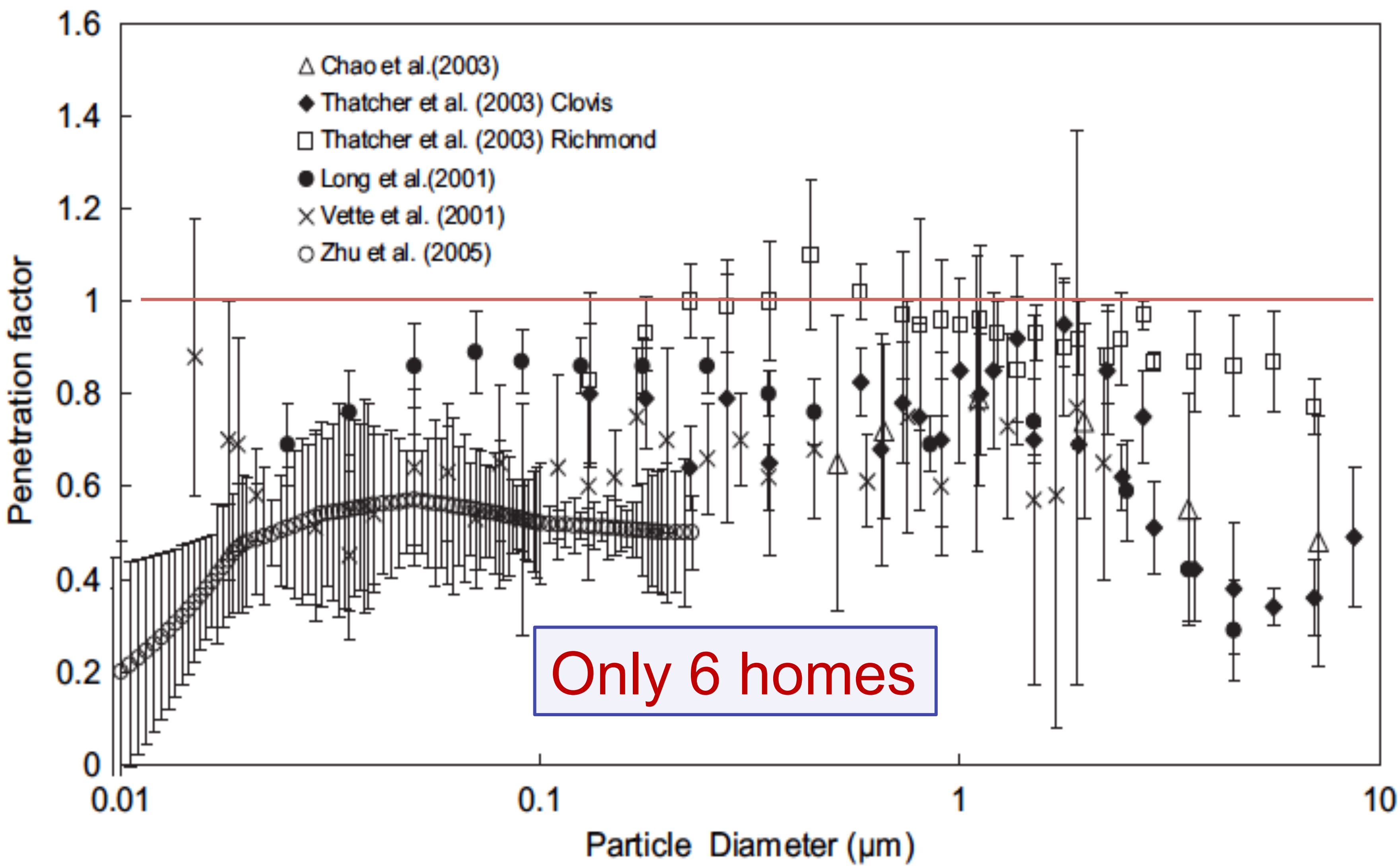


$$\frac{C_{in}}{C_{out}} = \frac{P\lambda}{\lambda + \beta}$$

Thatcher et al., 2003 *Aerosol Sci Tech*

Size-resolved Penetration Factors

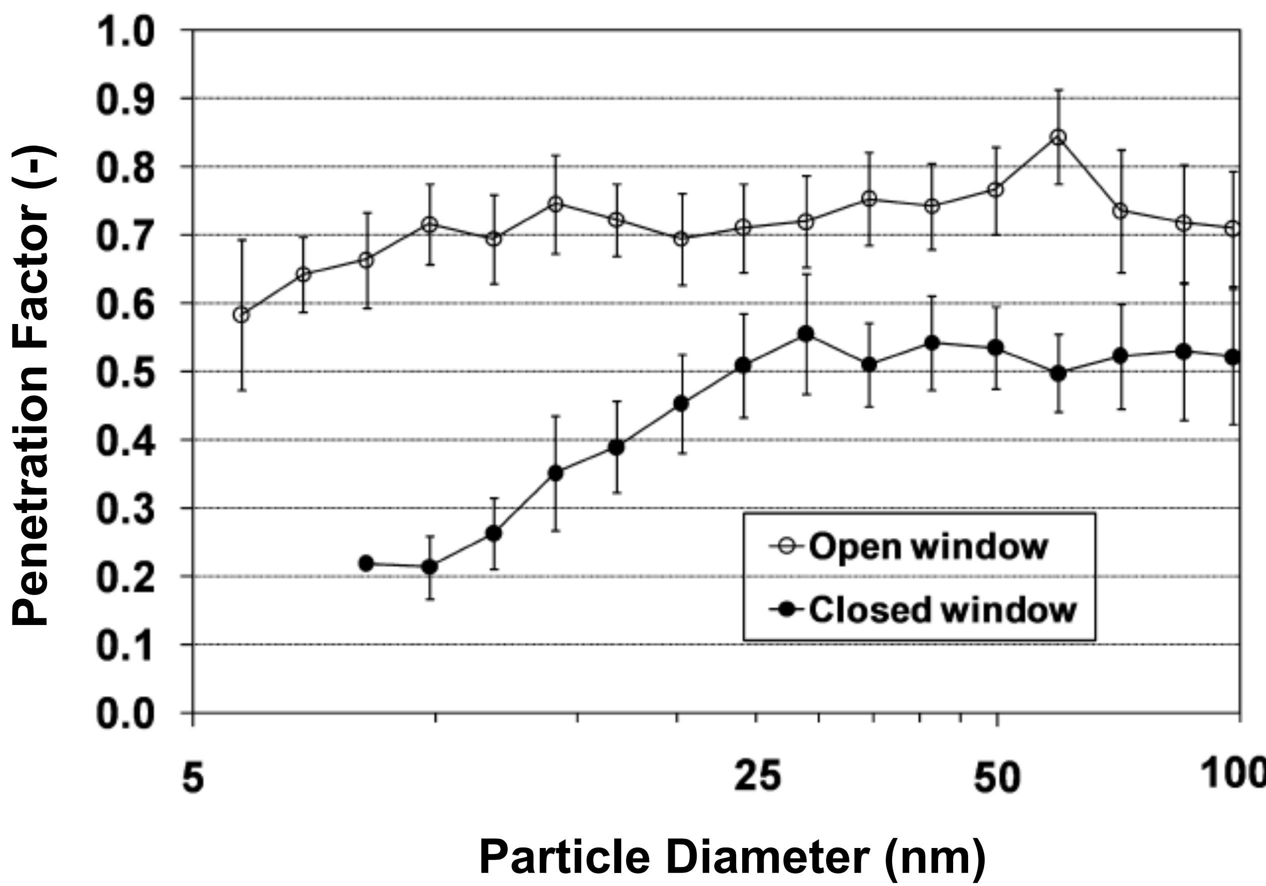
Existing Literature



Chen and Zhao, 2011 *Atmos Environ*

Size-resolved Penetration Factors

- Ultrafine particle penetration into a test house

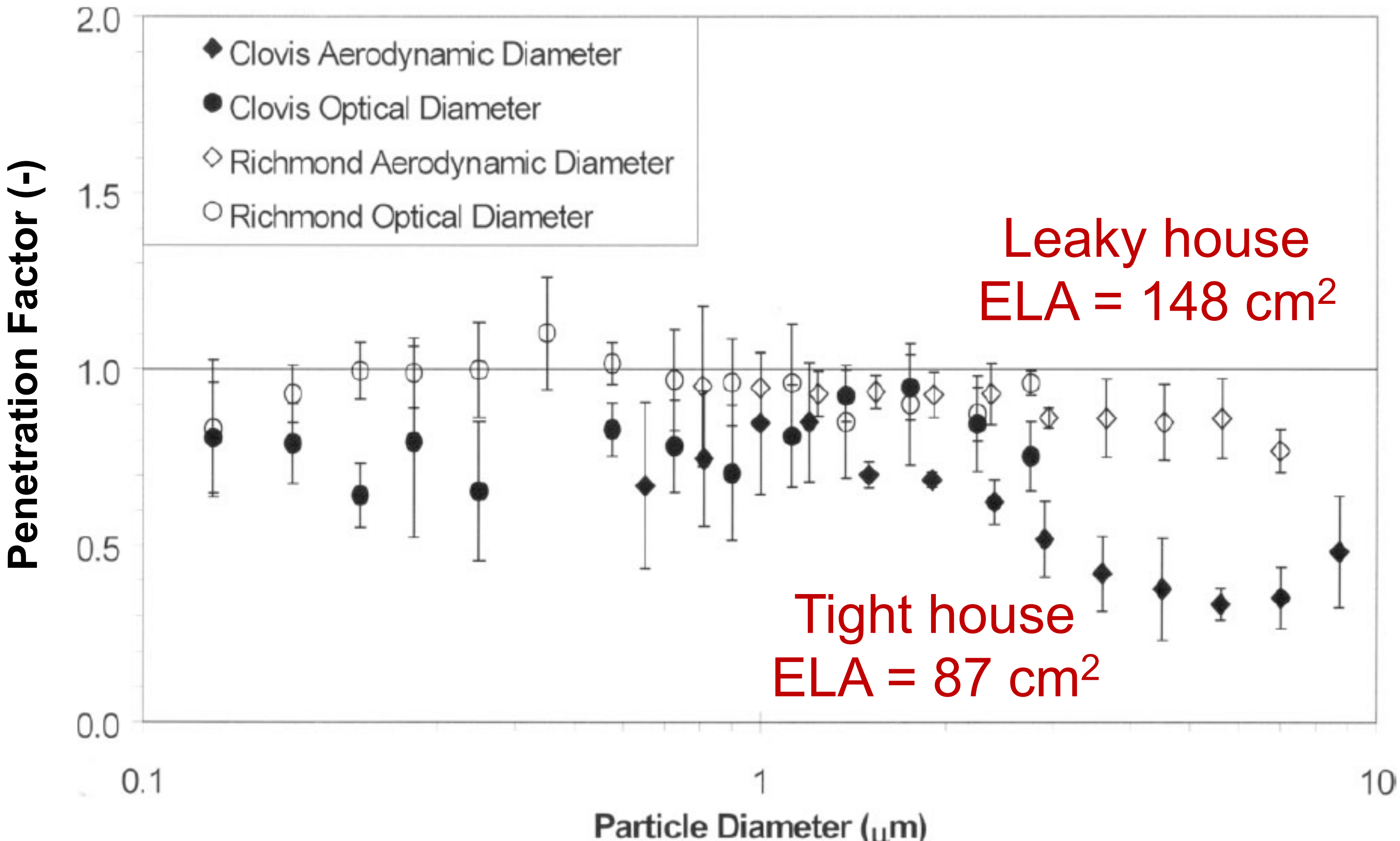


7 homes!

Rim et al., 2010 *Environ Sci Technol*

Particle Penetration

Particle rebound results: 2 homes



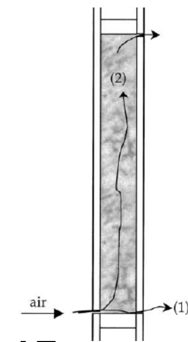
*Estimated Leakage Area (ELA) = *f* (blower door air leakage coefficients & ΔP)

Thatcher et al., 2003 *Aerosol Science and Technology*

Measuring particle infiltration

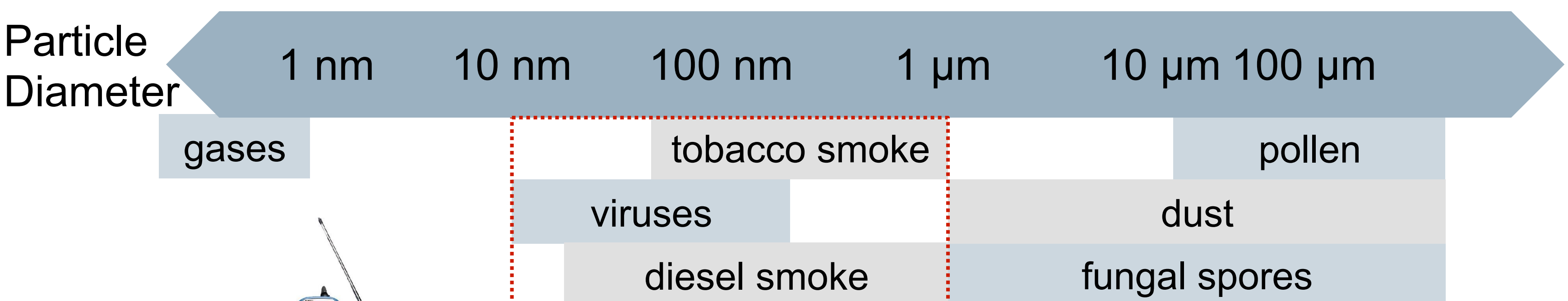
- Particles can penetrate through cracks in building envelopes
  - Theoretically a function of:
    - Crack geometry
    - Air speed through leaks

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



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

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

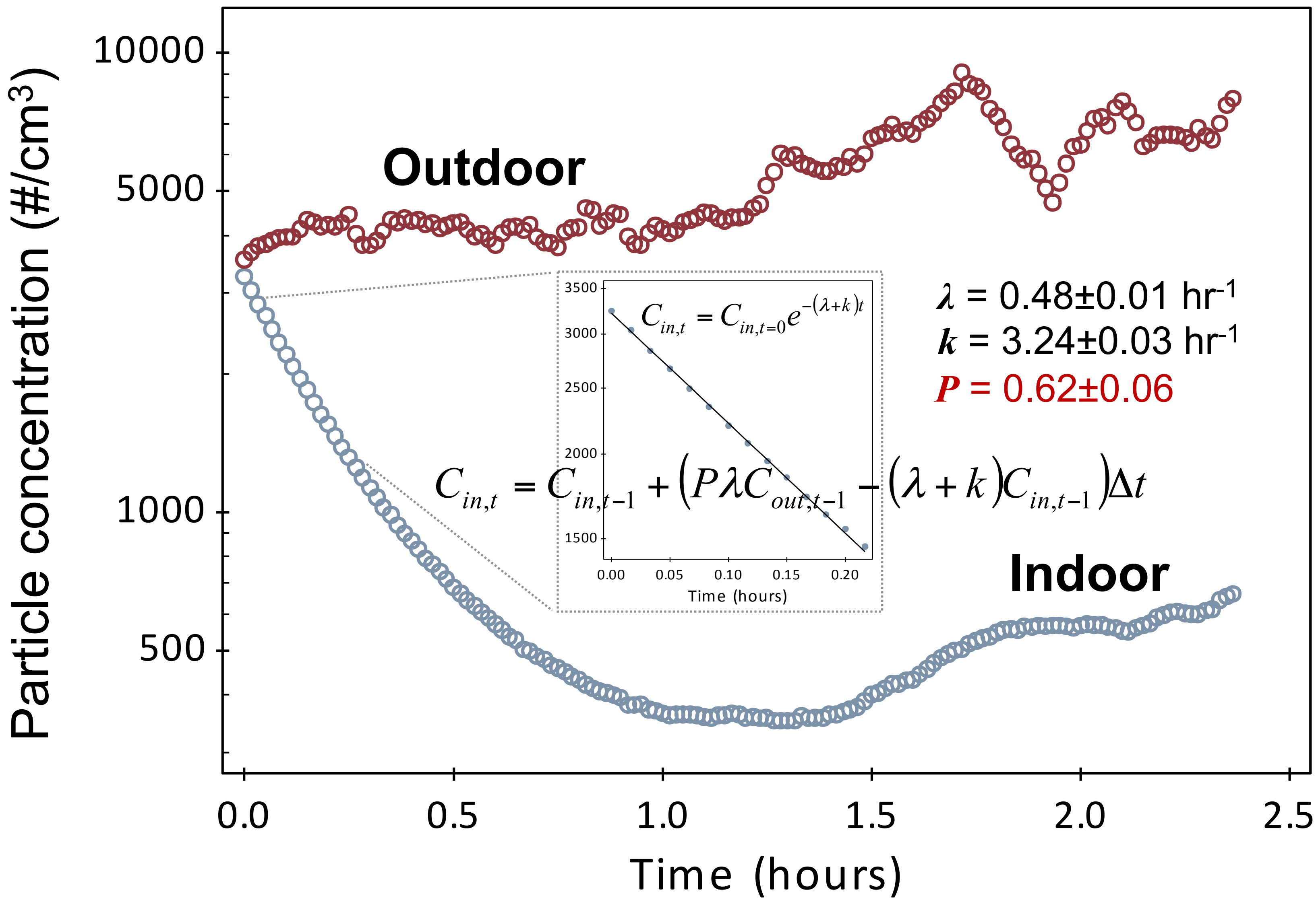


20 – 1000 nm

PM infiltration: Test homes

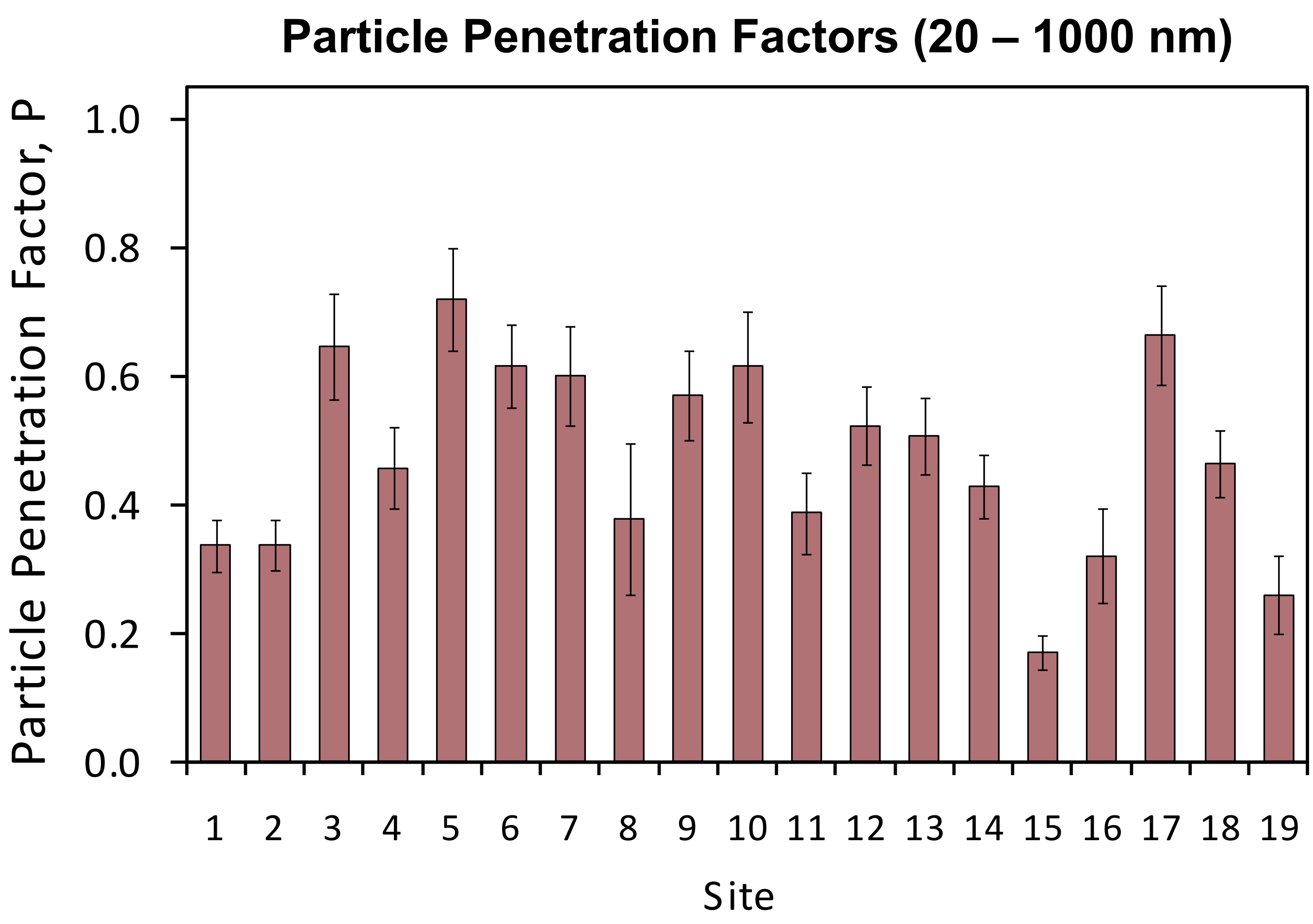
Stephens and Siegel, *Indoor Air* **2012** 22(6):501-512

Test method | Particulate matter (20-1000 nm)



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

Particle infiltration results

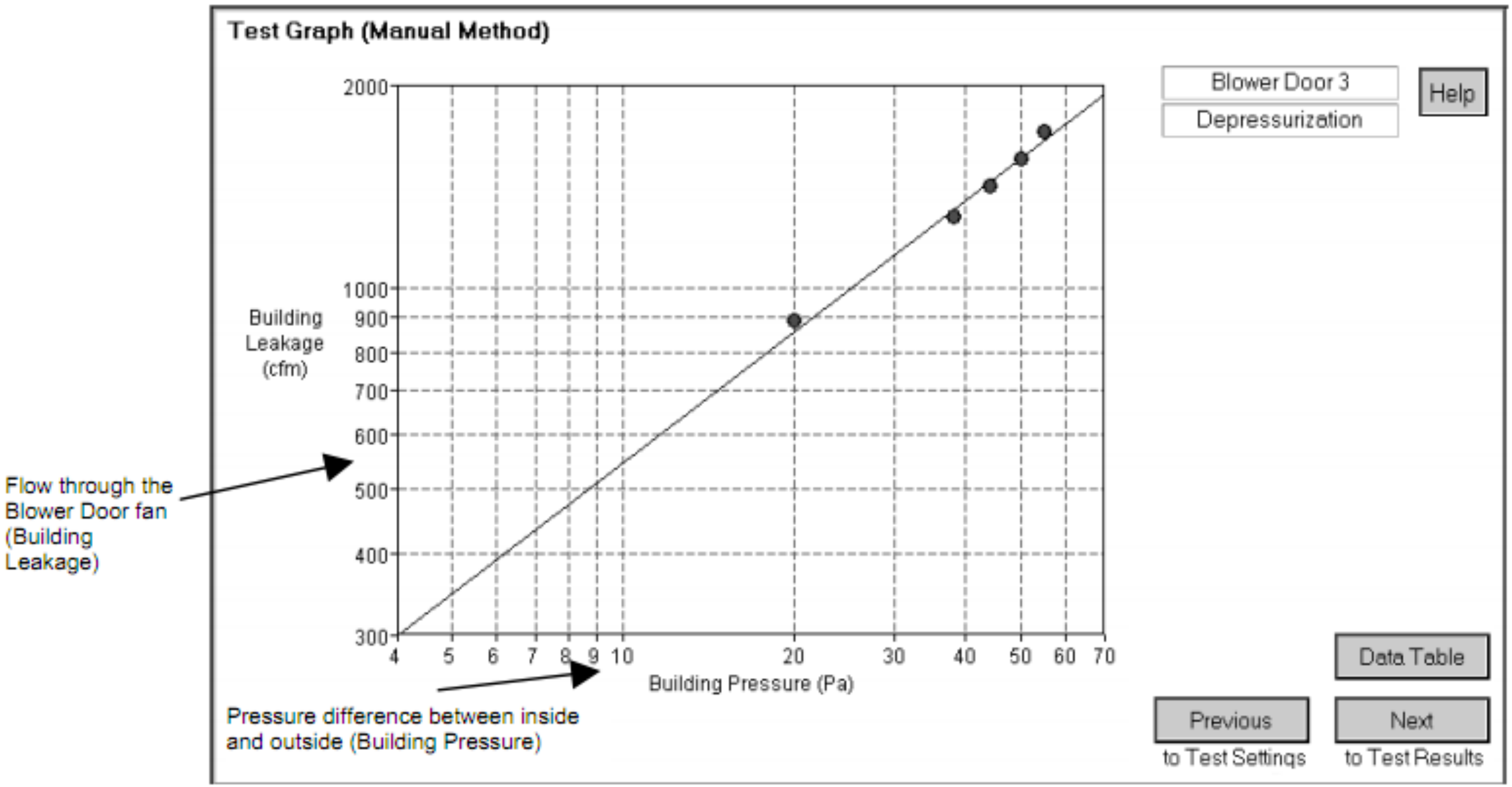


Mean (± SD) = 0.47 ± 0.15 | Range = 0.17 ± 0.03 to 0.72 ± 0.08

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

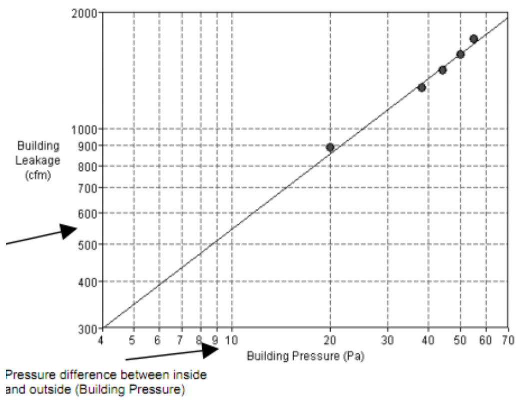
PM infiltration: What can we learn?

- Blower doors



Source: Energy Conservatory Blower Door Manual

Blower door tests



$$Q = C\Delta P^{n}$$

Airflow ($m^3\ s^{-1}$)

Leakage Coefficient ($m^3\ s^{-1}\ Pa^{-n}$)

I/O Pressure Difference (Pa)

Leakage Exponent (dimensionless)

$$ELA = C\Delta P_{ref}^{n-0.5}\sqrt{\frac{\rho}{2}}$$

Estimated Leakage Area (cm^2)

$$NL = 1000\frac{ELA}{Af}\left(\frac{H}{2.5m}\right)^{0.3}$$

Normalized Leakage, NL (dimensionless)

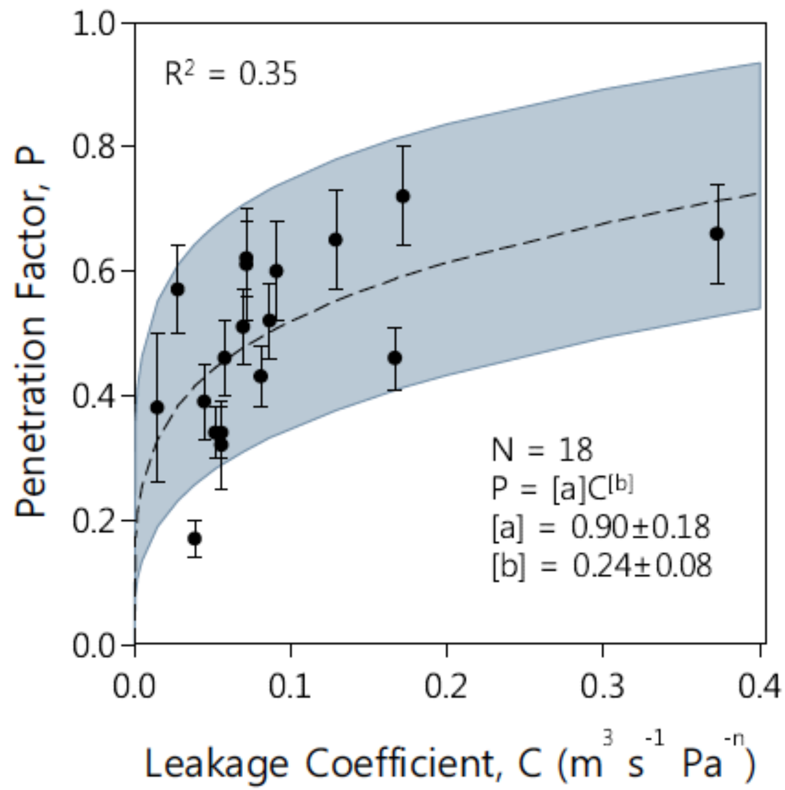
$$ACH_{50} = \frac{Q_{50\ Pa}}{V}$$

Air Changes per Hour @ 50 Pa (hr^{-1})

Source: ASTM E 779 and ASHRAE Standard 119

PM infiltration and air leakage

- Particle penetration factors (P for 20-1000 nm particles)
  - Significantly correlated with coefficient from blower door tests (C)
  - Spearman's ρ = 0.71 ($p < 0.001$)

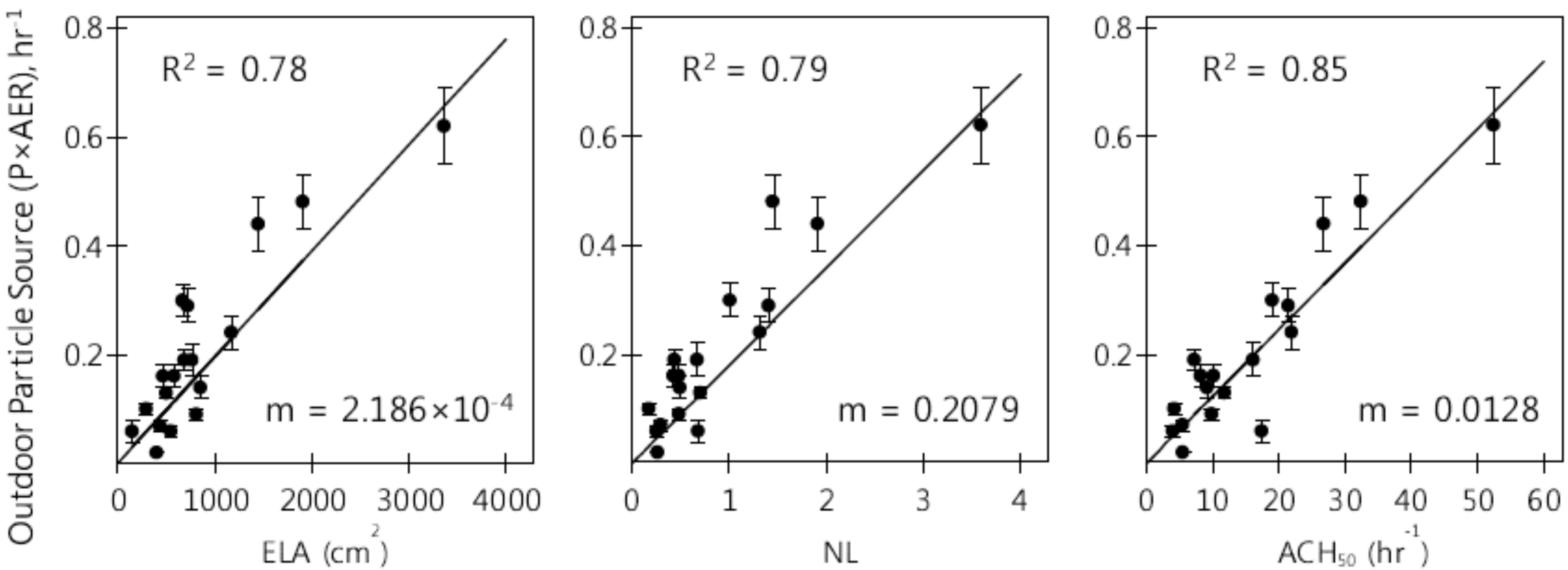


- Association is strong, but predictive ability is low

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

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

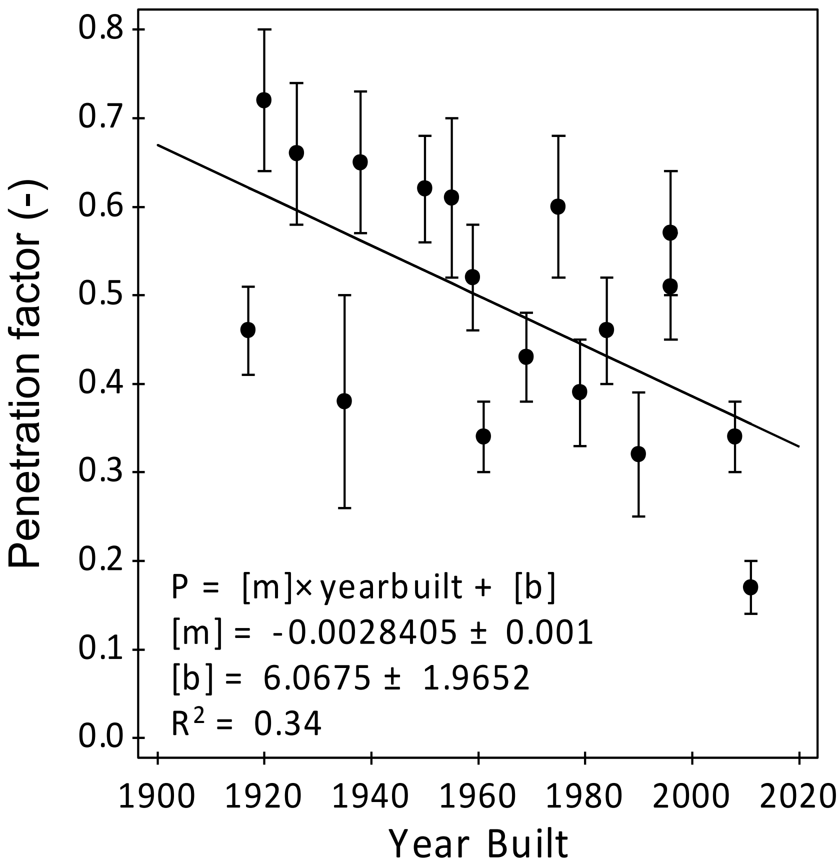
- Potential socioeconomic implications: low-income homes are leakier

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

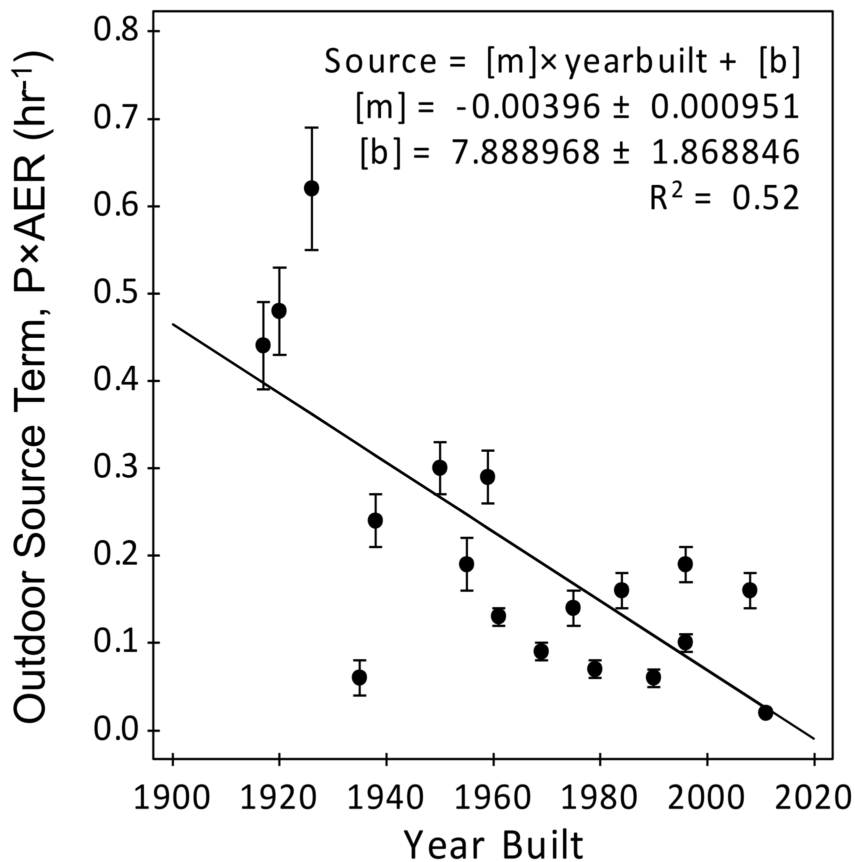
Stephens and Siegel, *Indoor Air* **2012** 22(6):501-512

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

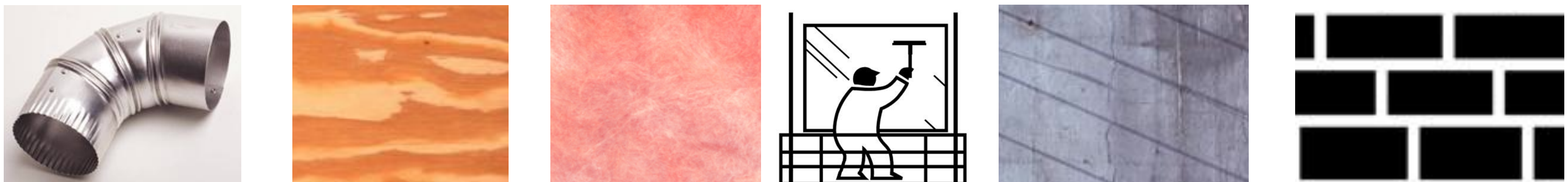
Stephens and Siegel, *Indoor Air* **2012** 22(6):501-512

OZONE INFILTRATION

Envelope penetration factors

- O_3 can infiltrate through leaks in building envelopes
  - Ozone can react with envelope materials

Aluminum | Plywood | Fiberglass | Glass | Concrete | Brick

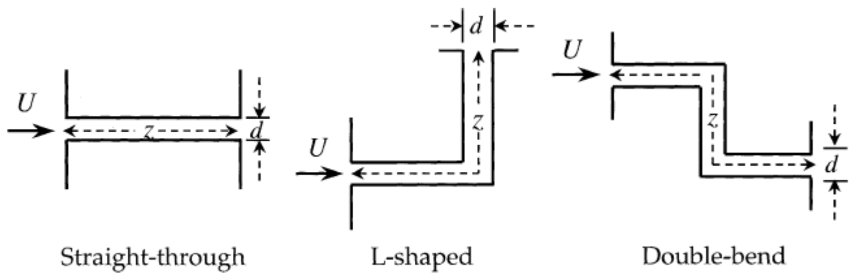


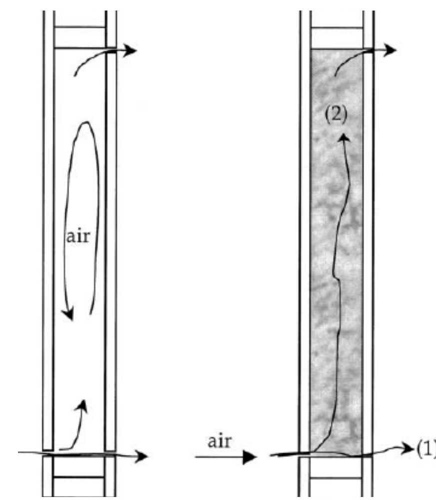
10^{-8} 10^{-7} 10^{-6} 10^{-5} 10^{-4}

Less reactive — Reaction Probability, γ — More reactive

- No one had ever measured ozone penetration factors
  - Some modeling efforts

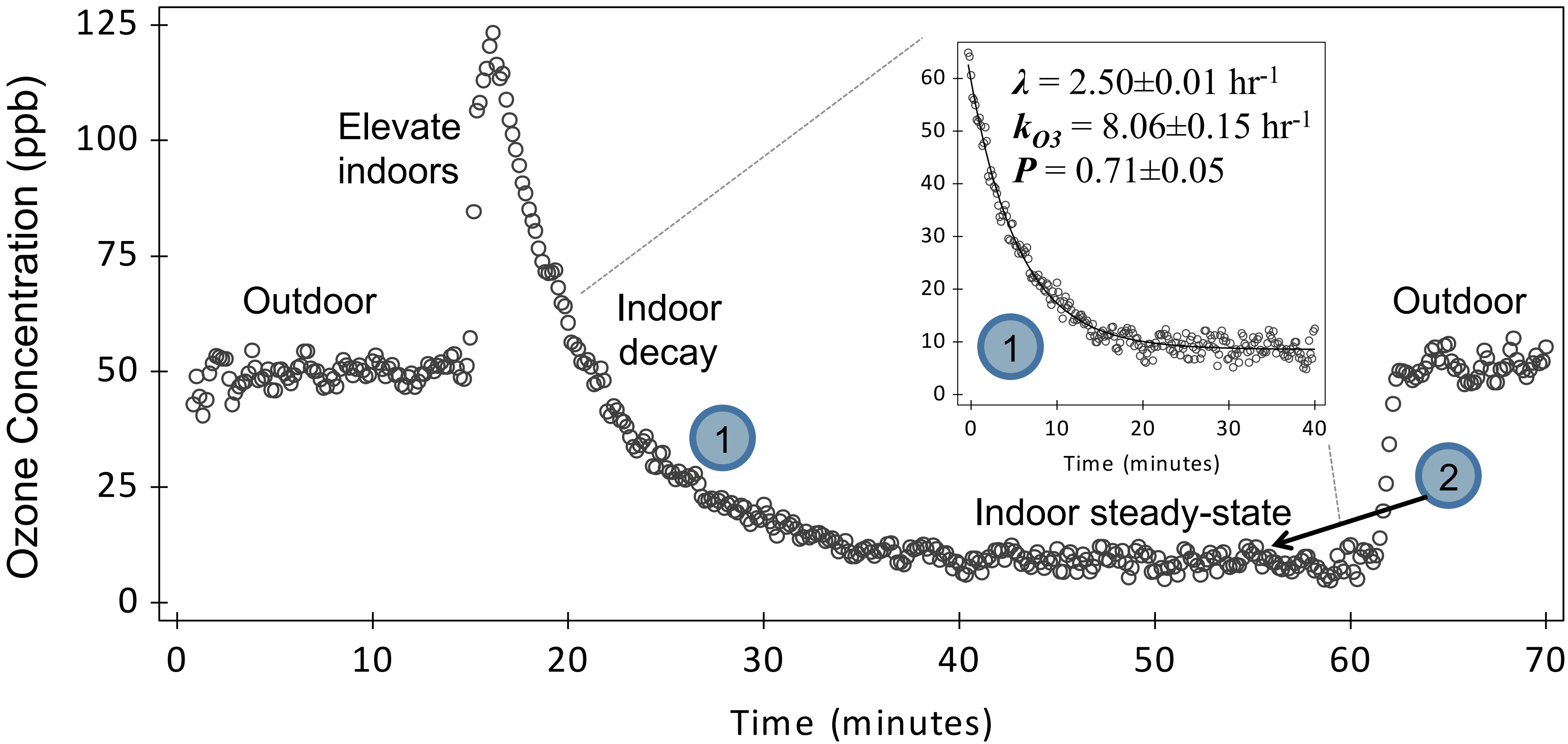
$$\frac{1}{v_d} = \frac{1}{v_t} + \frac{4}{<v>\gamma}$$





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

Ozone infiltration: New test method



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

Ozone

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

Ozone

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

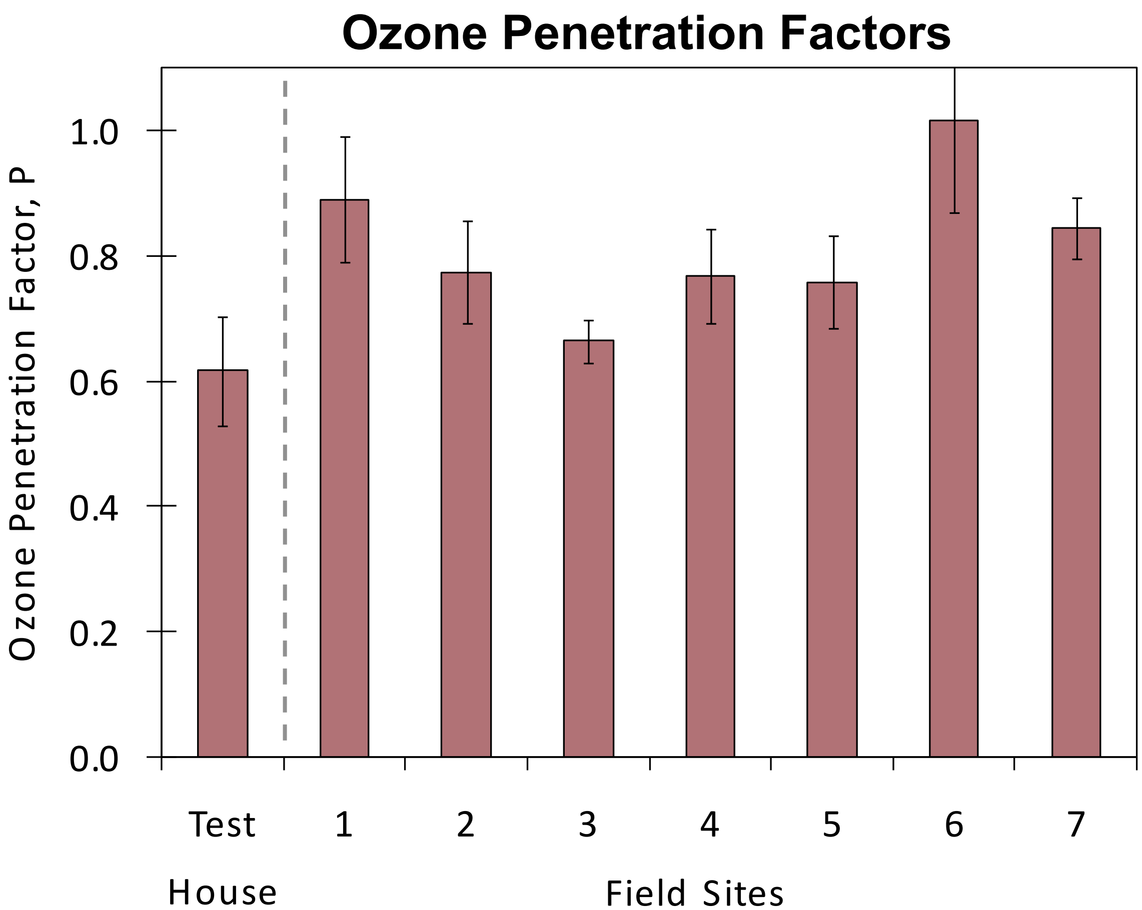
Tracer = CO_2

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

Ozone infiltration 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

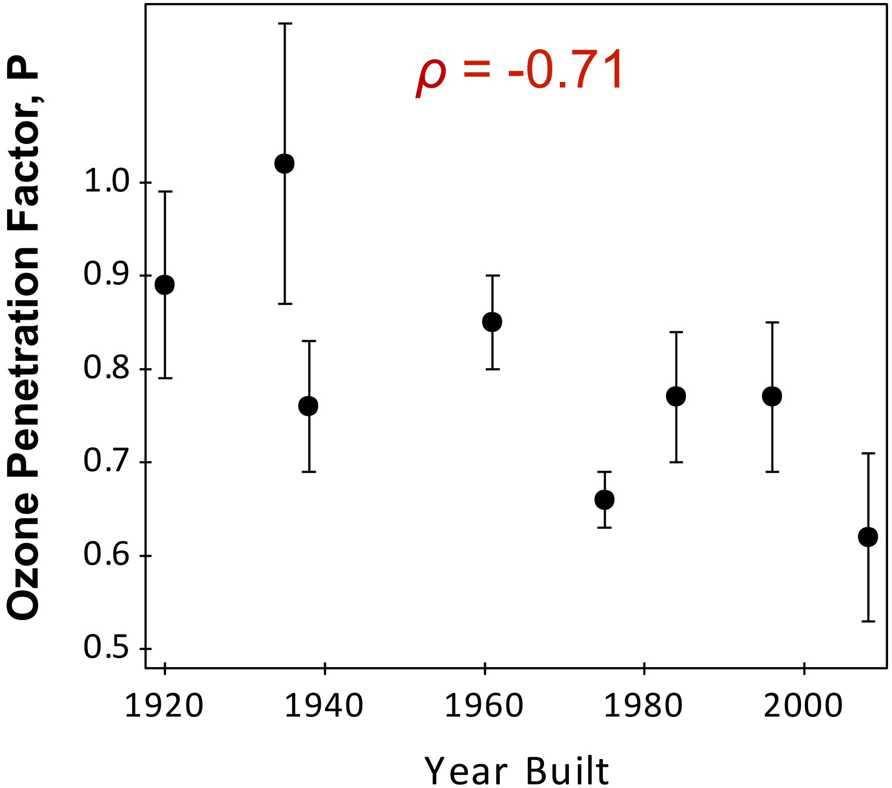
Weschler, **2006** *EHP*; Gall et al., **2011** *Atmos Environ*; Chen et al., **2011** *Environ Health Persp*

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

Exploration of ozone results: What can we learn?

Spearman's Rank Correlations

Significant findings ($p \leq 0.05$)

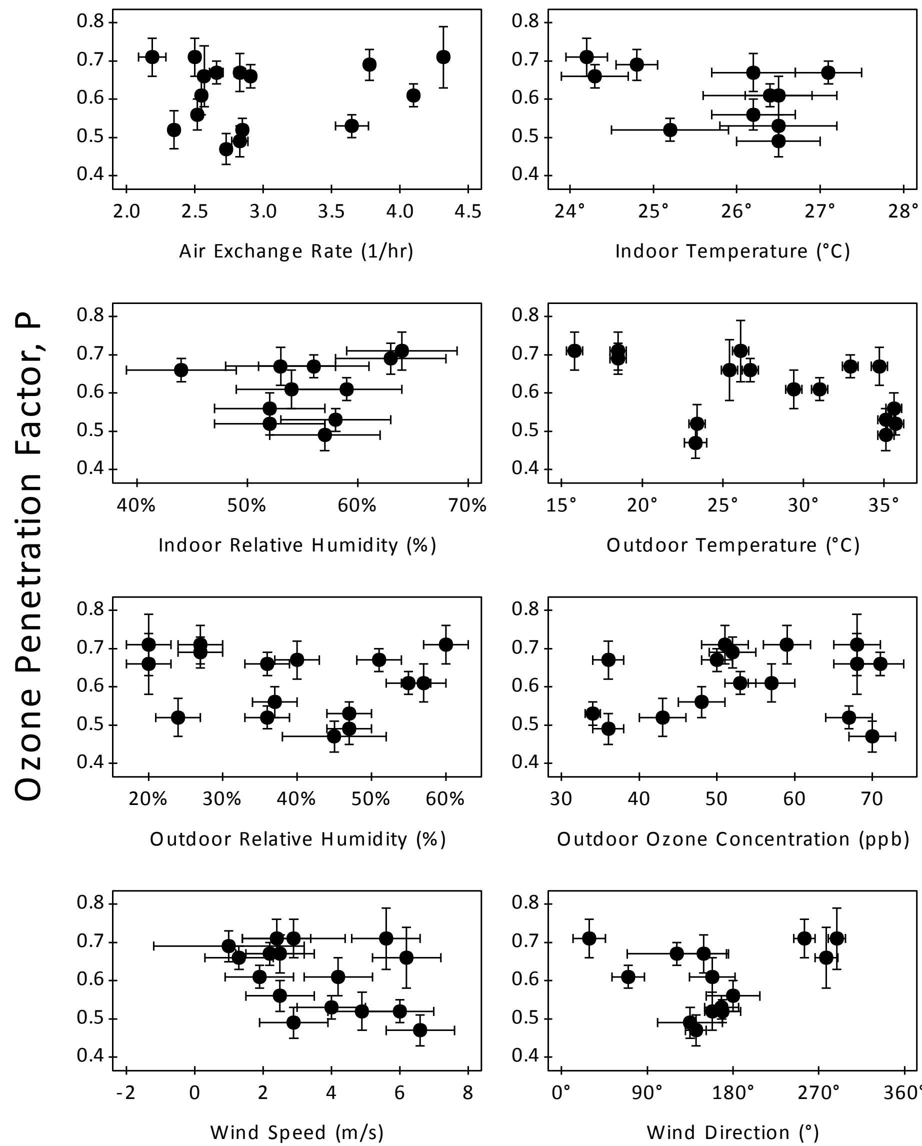


Ozone infiltration was significantly lower in newer homes

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

Exploration of Results: O_3

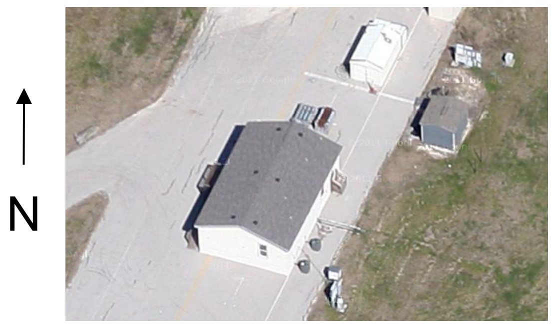
Test House: 16 replicates

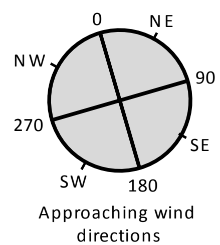


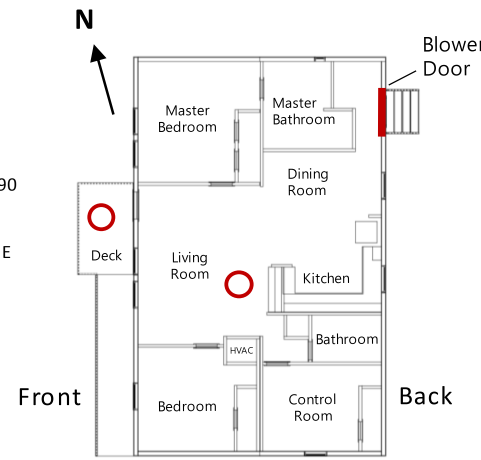
Stephens et al., *Environ. Sci. Technol.* **2012** 46(2), 929-936

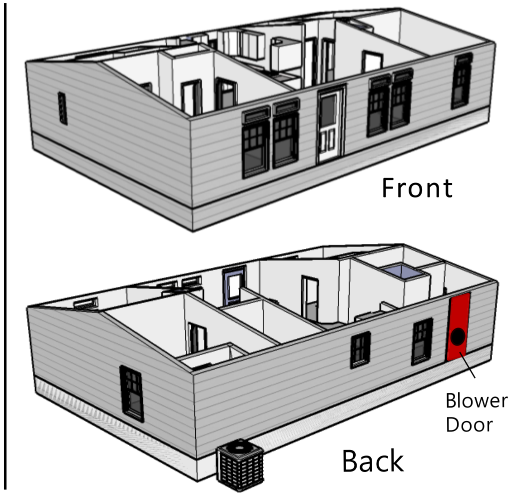
Exploration of Results: Wind Direction

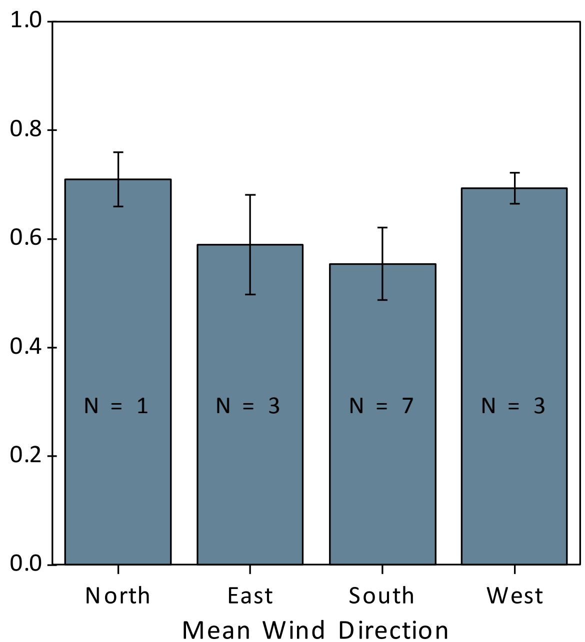
Test House: 14 of 16 replicates











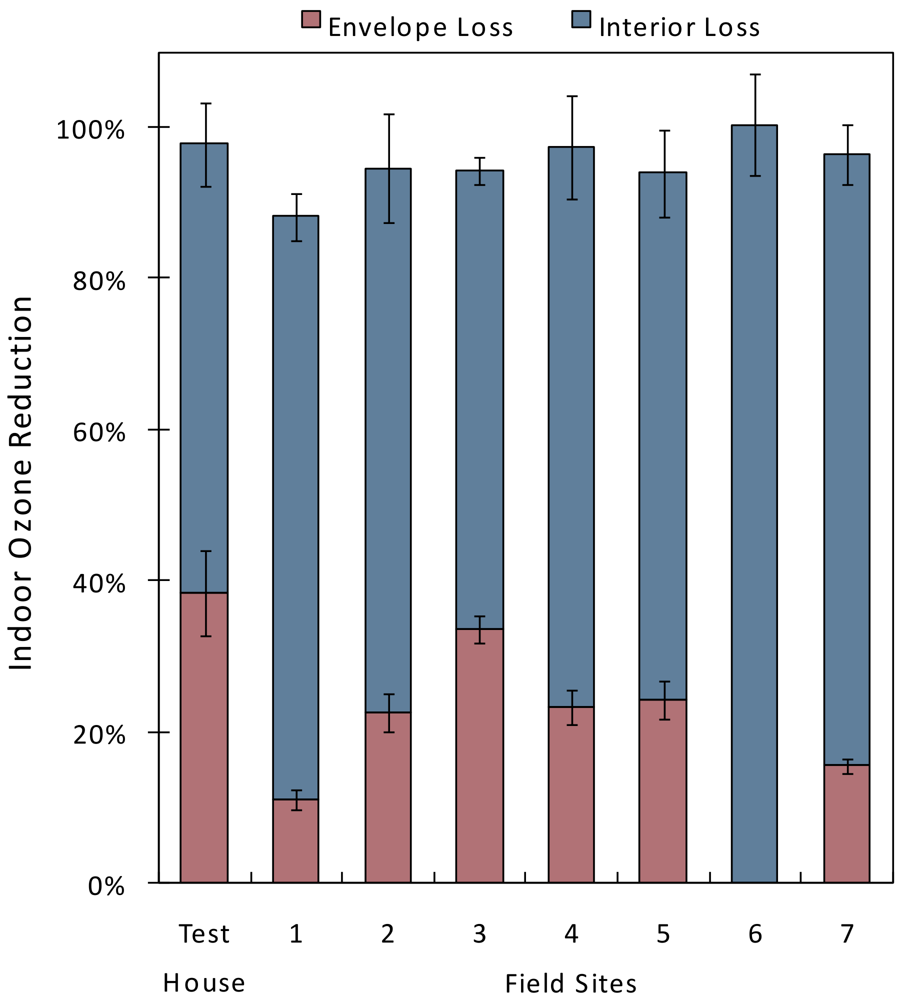
- Winds from N or W:
  - P = 0.70±0.03
- Winds from S or E:
  - P = 0.57±0.07
- Repeatability:
  - Two tests w/ same wind conditions
  - P = 0.52±0.03 and 0.53±0.03

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

Comparing Ozone Losses

Envelope deposition vs. indoor reaction/deposition

- Measured ozone decay rate (k_{O3}, hr^{-1}) during normal conditions
  - Normal except HVAC on + mixing fans operating



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

Summary

***P* ranged from**

0.62 ± 0.09 to 1.02 ± 0.15

Mean ($\pm$ SD) = 0.79 ± 0.13

k_{O3} ranged from

3.6 ± 0.1 to 16.8 ± 1.1 hr^{-1}

Mean ($\pm$ SD) = 11.6 ± 6.0 hr^{-1}

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

FUTURE ENCLOSURE RESEARCH AT IIT

Building enclosure research at IIT

- We are working to build capabilities in this area
  - Energy, HAM, and IAQ

- Ongoing (and upcoming) research themes:
  - Impacts of enclosures on infiltration of pollutants
    - Including weatherization retrofits
  - In-situ assessment of enclosure performance
  - Vegetated wall heat transfer (field measurements & modeling)
    - College of Architecture & University of Chicago
  - Assembly R-value testing (laboratory)
    - Hot box testing facility
  - Life cycle costs of building materials
  - Possibility of getting a unit in Carman Hall

Lab instrumentation: T/RH and power/energy

Temperature/RH

Data logging

Temperature

Heat flux

IR camera

Solar radiation

Electric power

Lab instrumentation: HVAC diagnostics

Blower door
(envelope leakage)

Duct blaster
(duct leakage)

Pressure

TrueFlow
(HVAC airflow rates)

Lab instrumentation: Air quality

NanoScan SMPS
10 to 500 nm

Optical particle sizer
0.3 to 10 µm

CO_2
(for AER)

DustTrak
$PM_{2.5}/PM_{10}$

CPC
< 1 µm

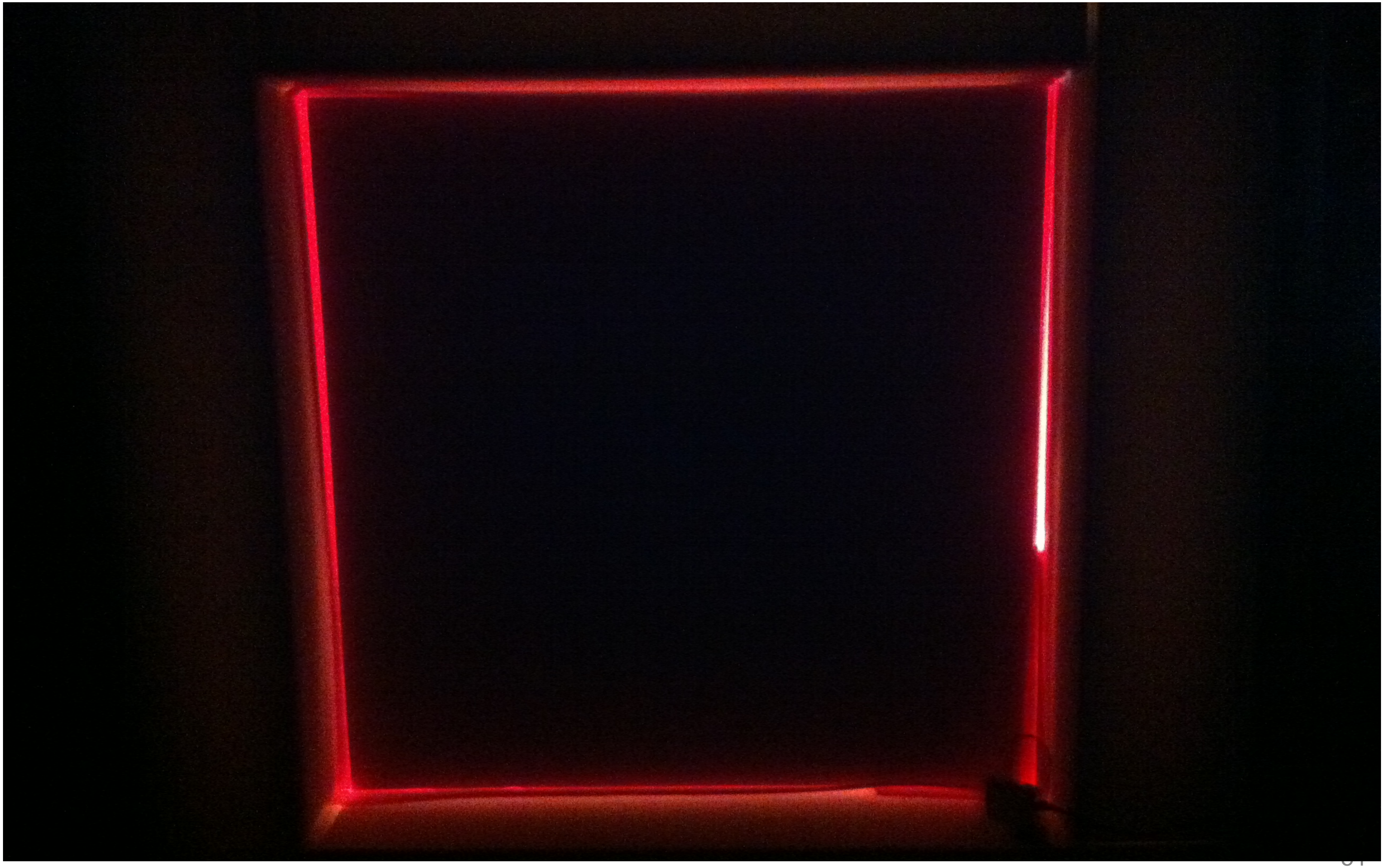
Ozone monitor

Hot box thermal testing facility

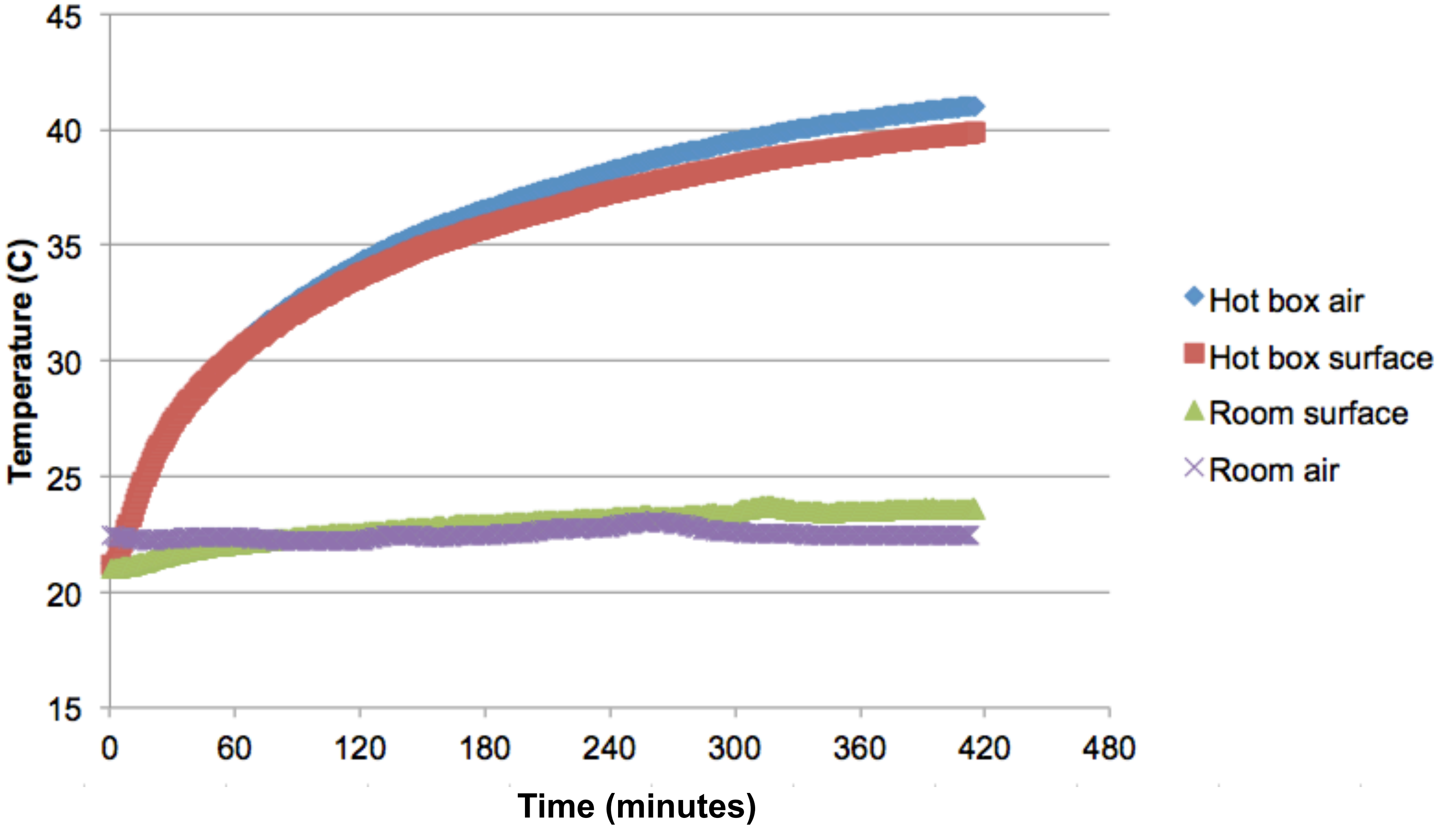
Hot box thermal testing facility

Hot box thermal testing facility

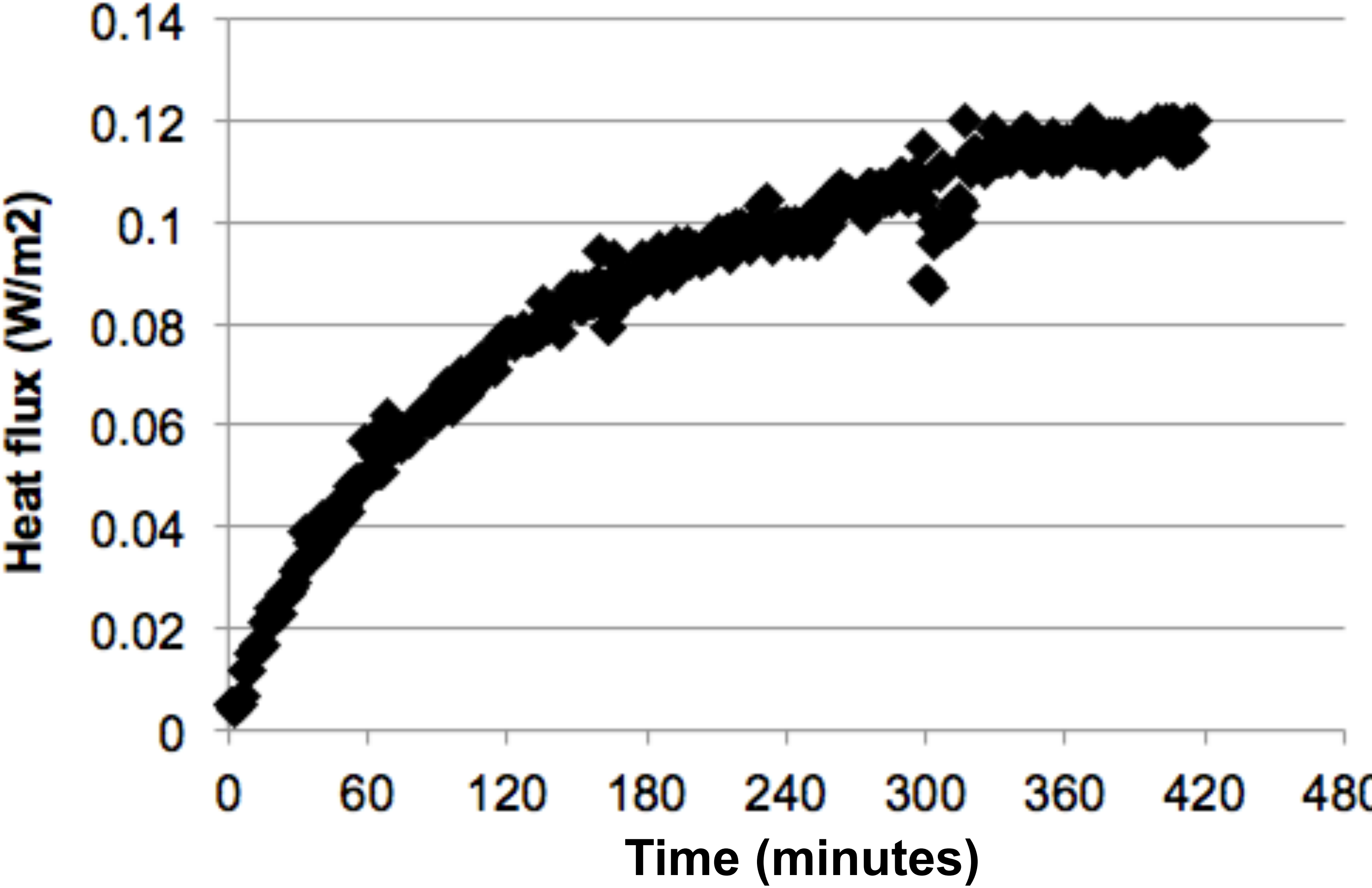
Hot box thermal testing facility



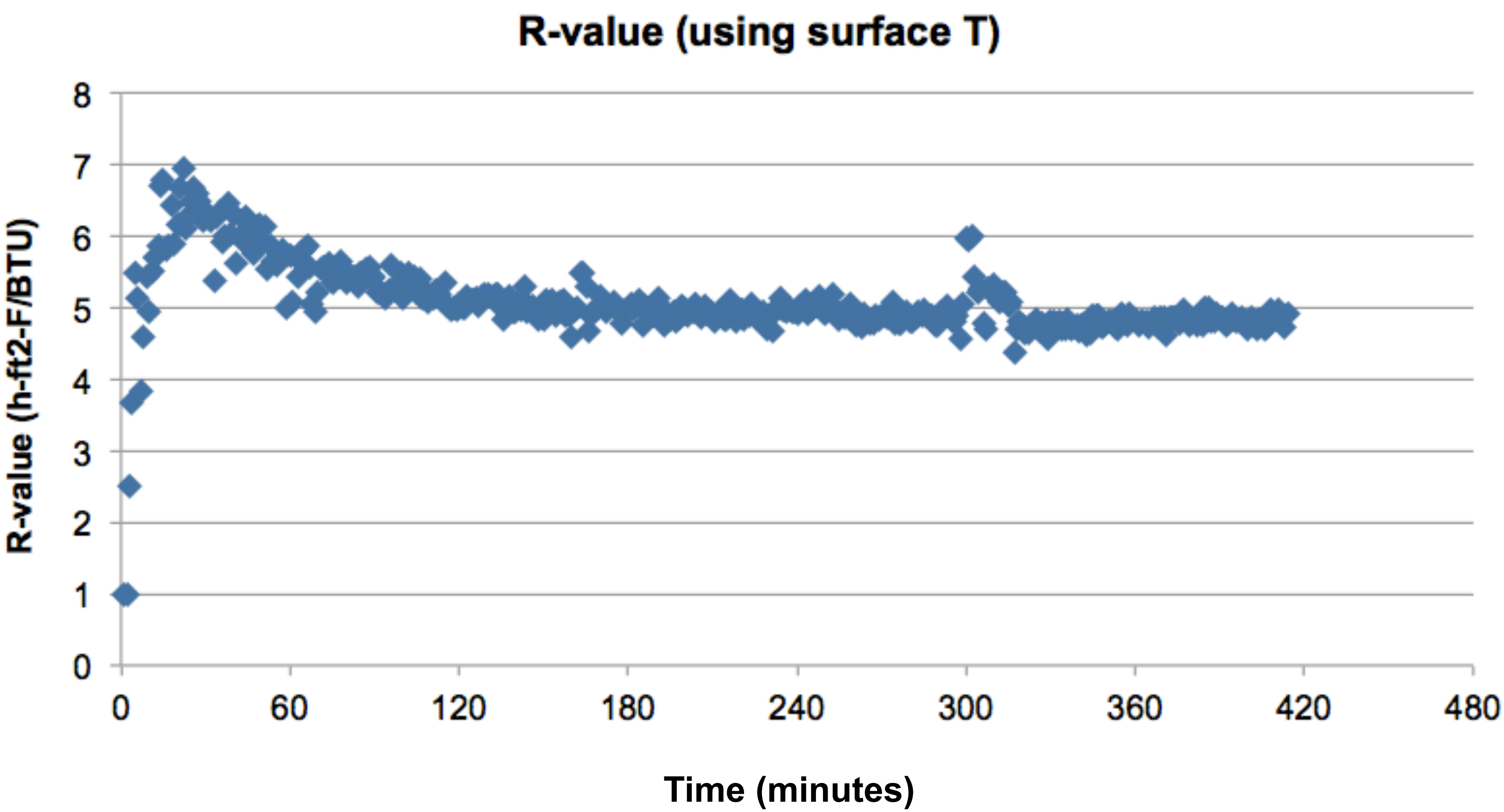
Preliminary hot box data



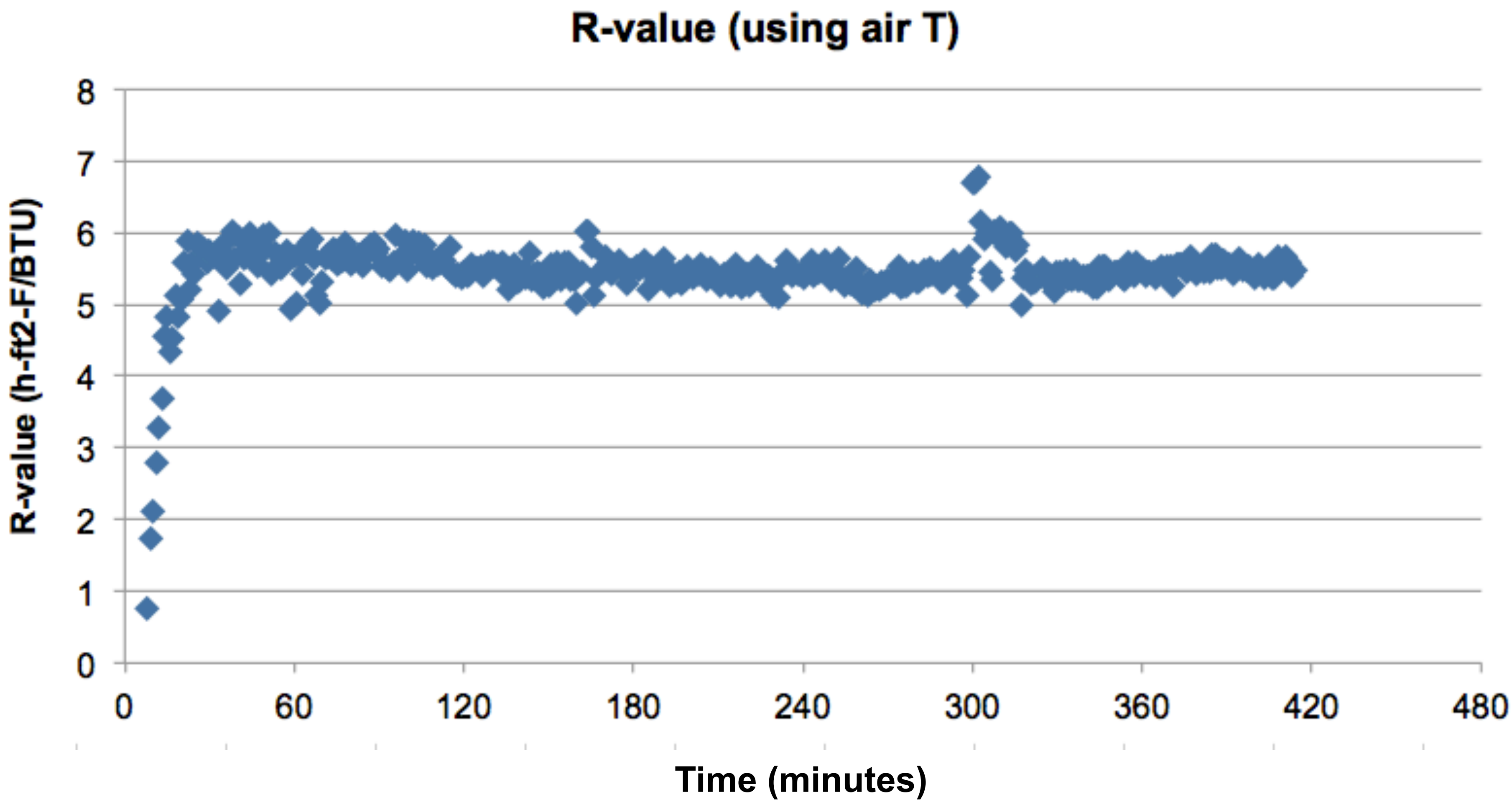
Preliminary hot box data



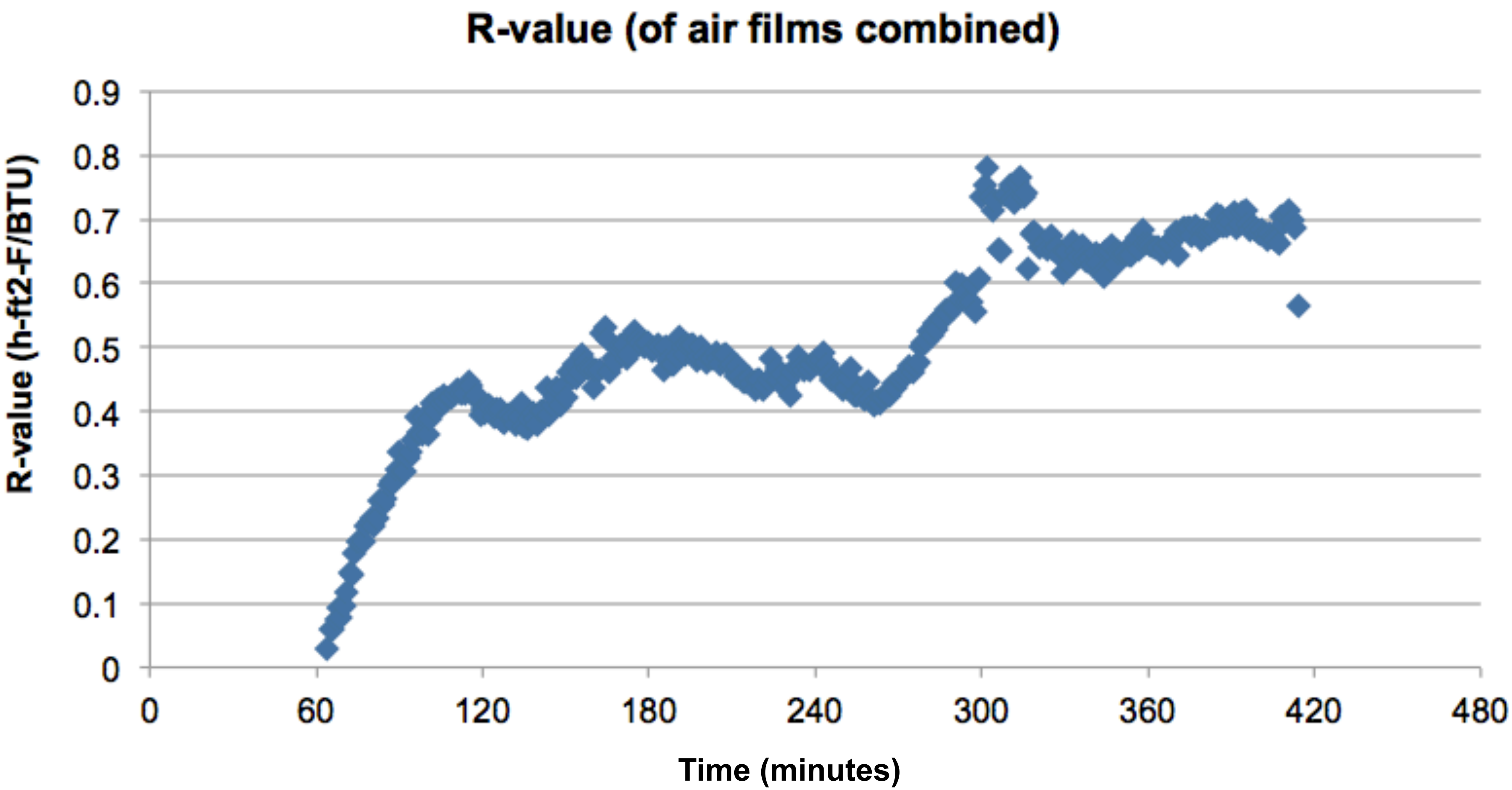
Preliminary hot box data



Preliminary hot box data



Preliminary hot box data



COURSE WRAP-UP

Next time

- No class Wednesday November 27th
- The rest of your presentations Wednesday December 4th
  - 5 pm to 7 pm