ENVE 576
Indoor Air Pollution
Spring 2013

Lecture 9: March 26, 2013
Particulate matter: Infiltration/penetration

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Review from last time

- Last time: March 12, 2013:
  - Particle filtration
  - HW 4 was due
    - Now graded and returned (missing a few from you)
  - HW 1-3 solutions are online now
- Today:
  - Finish particle filtration: portable air cleaners
    - Another loss term
  - Particle penetration/infiltration
    - Another particle source term
- After tonight (starting right now):
  - Your take-home exam is assigned
  - You have 1 week to complete (due in class Tuesday April 2nd)
  - Exam can be found under “exam 1” content folder on BB
    - pdf, docx, and xlsx

Review from last time

- Filter collection mechanisms vary by particle size:

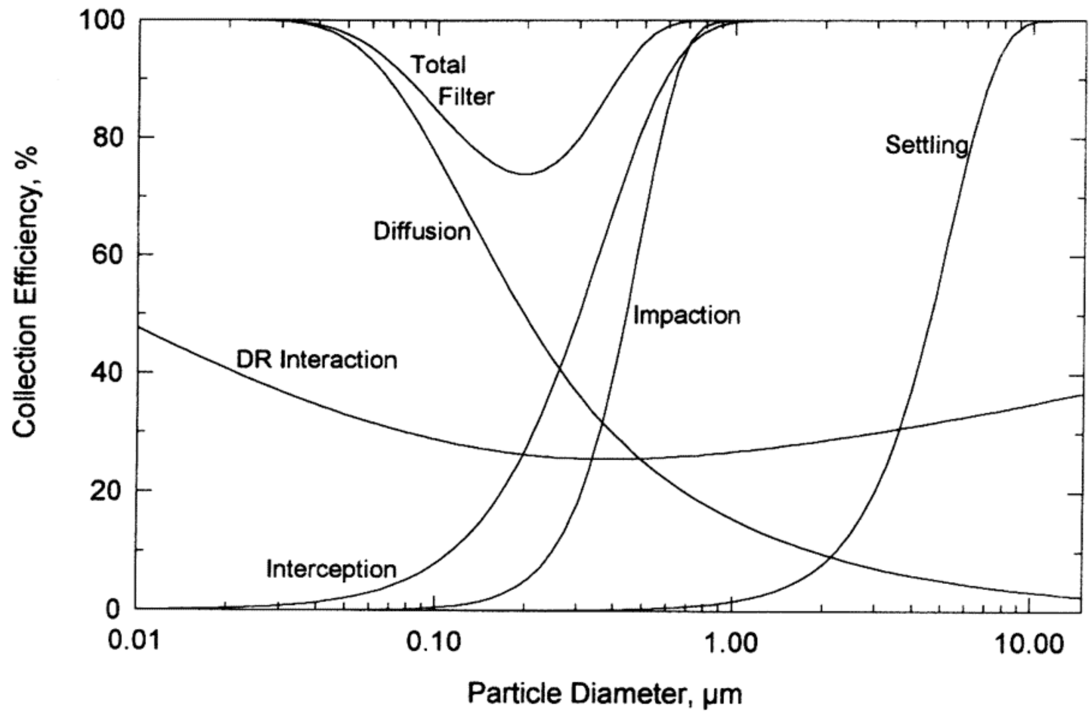


FIGURE 9.8 Filter efficiency for individual single-fiber mechanisms and total efficiency; $t = 1$ mm, $\alpha = 0.05$, $d_f = 2$ μm, and $U_0 = 0.10$ m/s. [10 cm/s].

- Filter performance versus manufacturer ratings can vary
- Energy impacts of filters are complex and not always intuitive

STAND-ALONE AIR CLEANERS

Another type of particle filtration

Stand-alone air cleaners

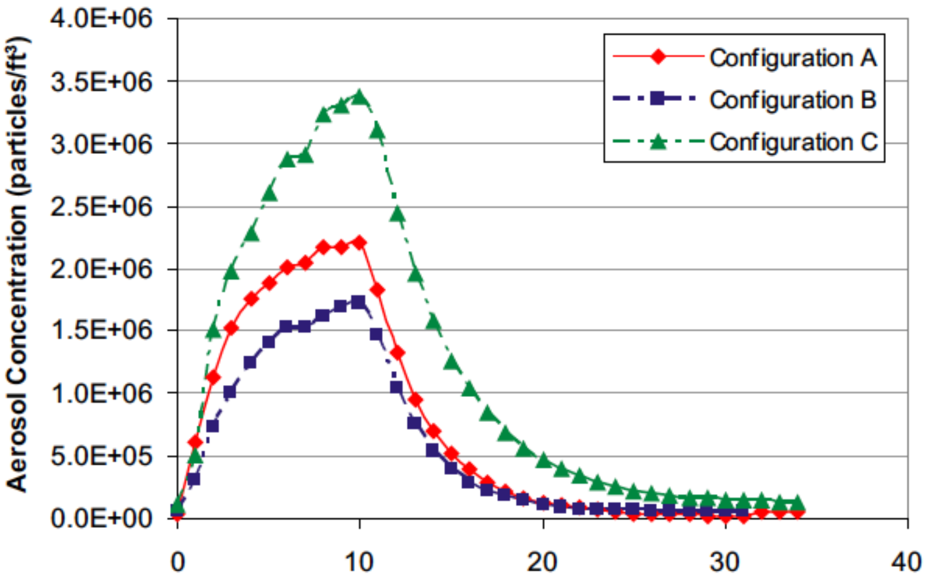
- Another major type of filter is a stand-alone air cleaner
  - i.e. ‘room air cleaners’ or ‘portable air cleaners’

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

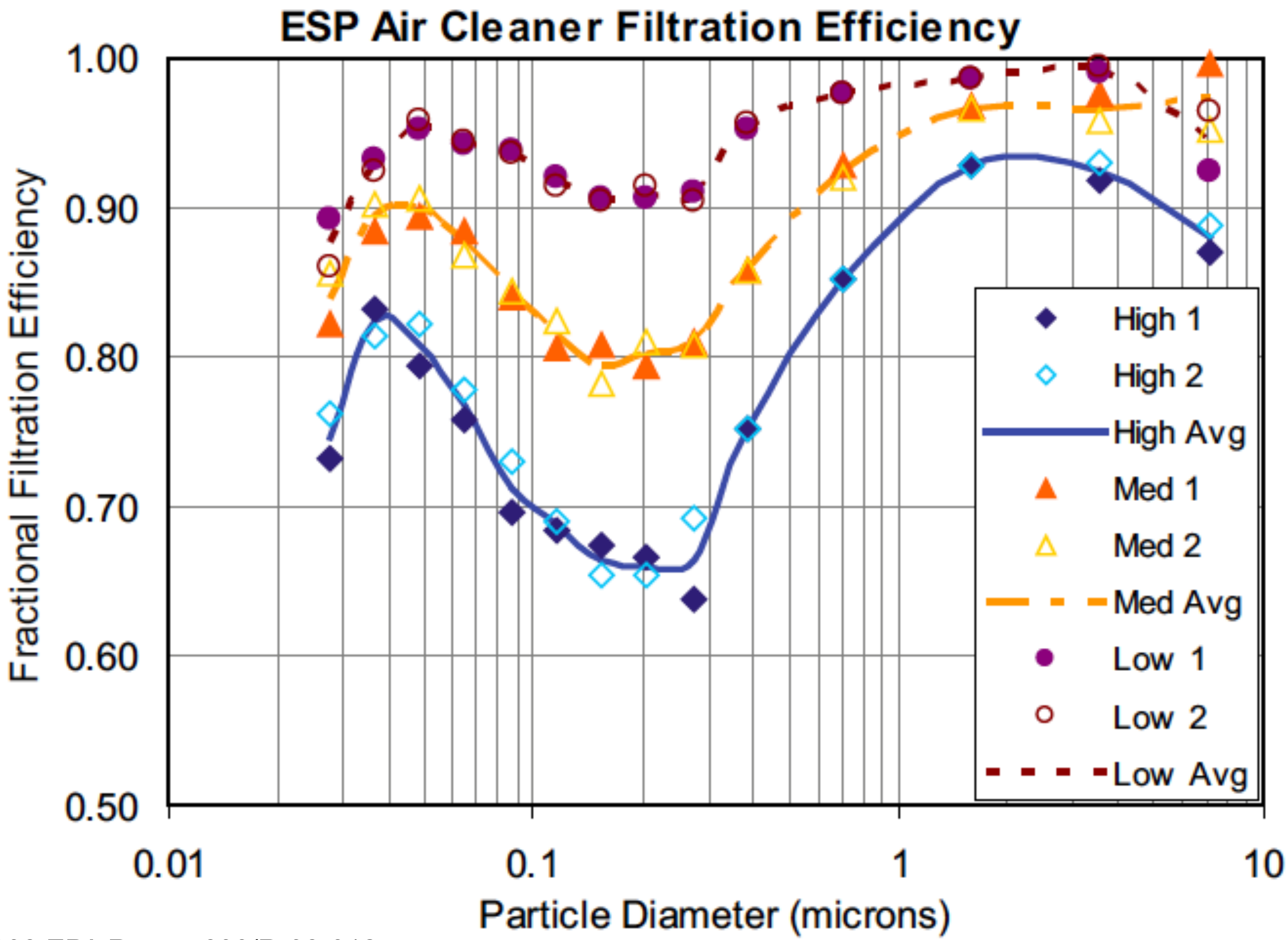
$$CADR = V\left(L_{AC} - L_{noAC}\right)$$



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

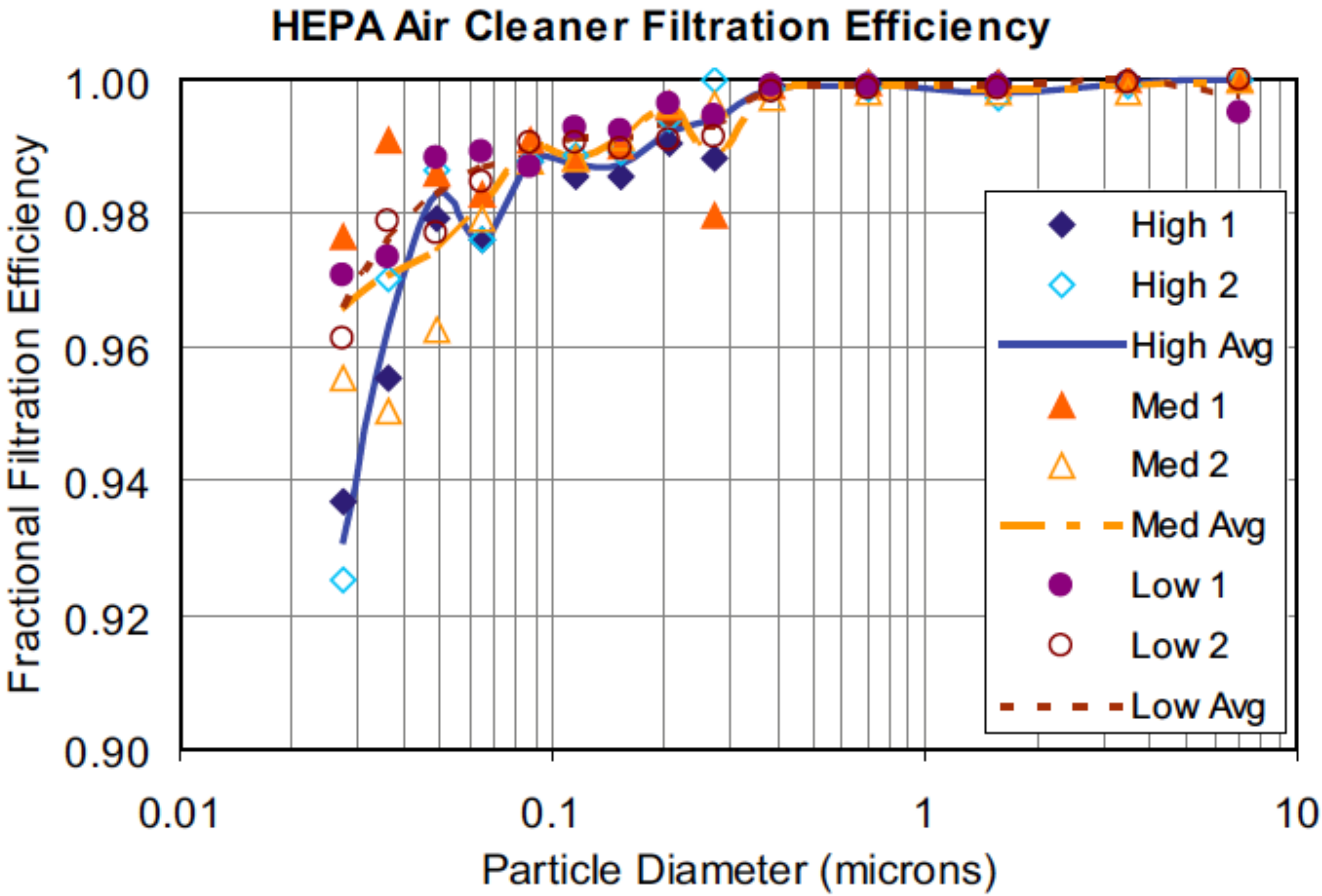
Recent testing of portable air cleaners

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



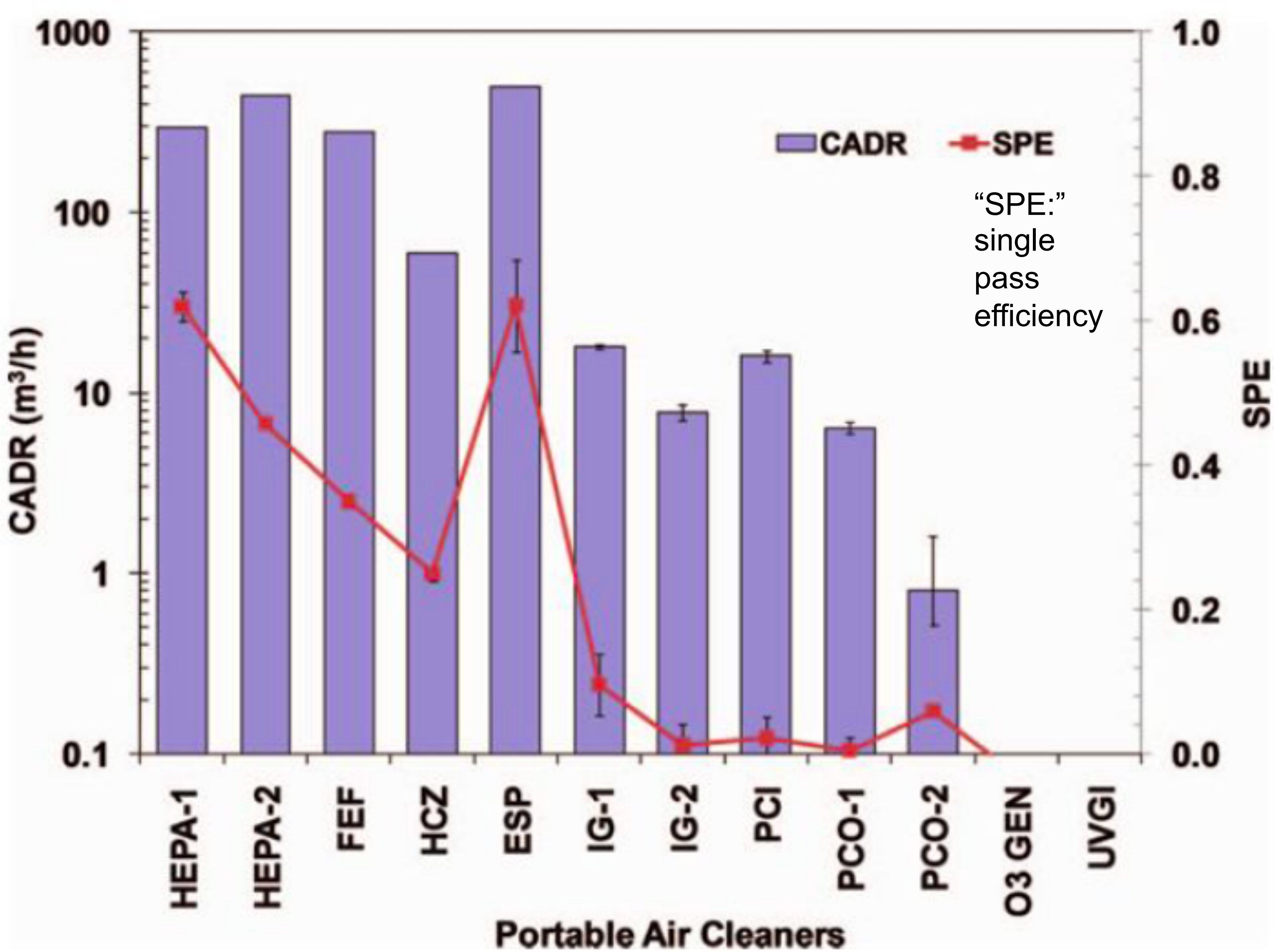
Kogan et al., 2008 EPA Report 600/R-08-012

Recent testing of portable air cleaners



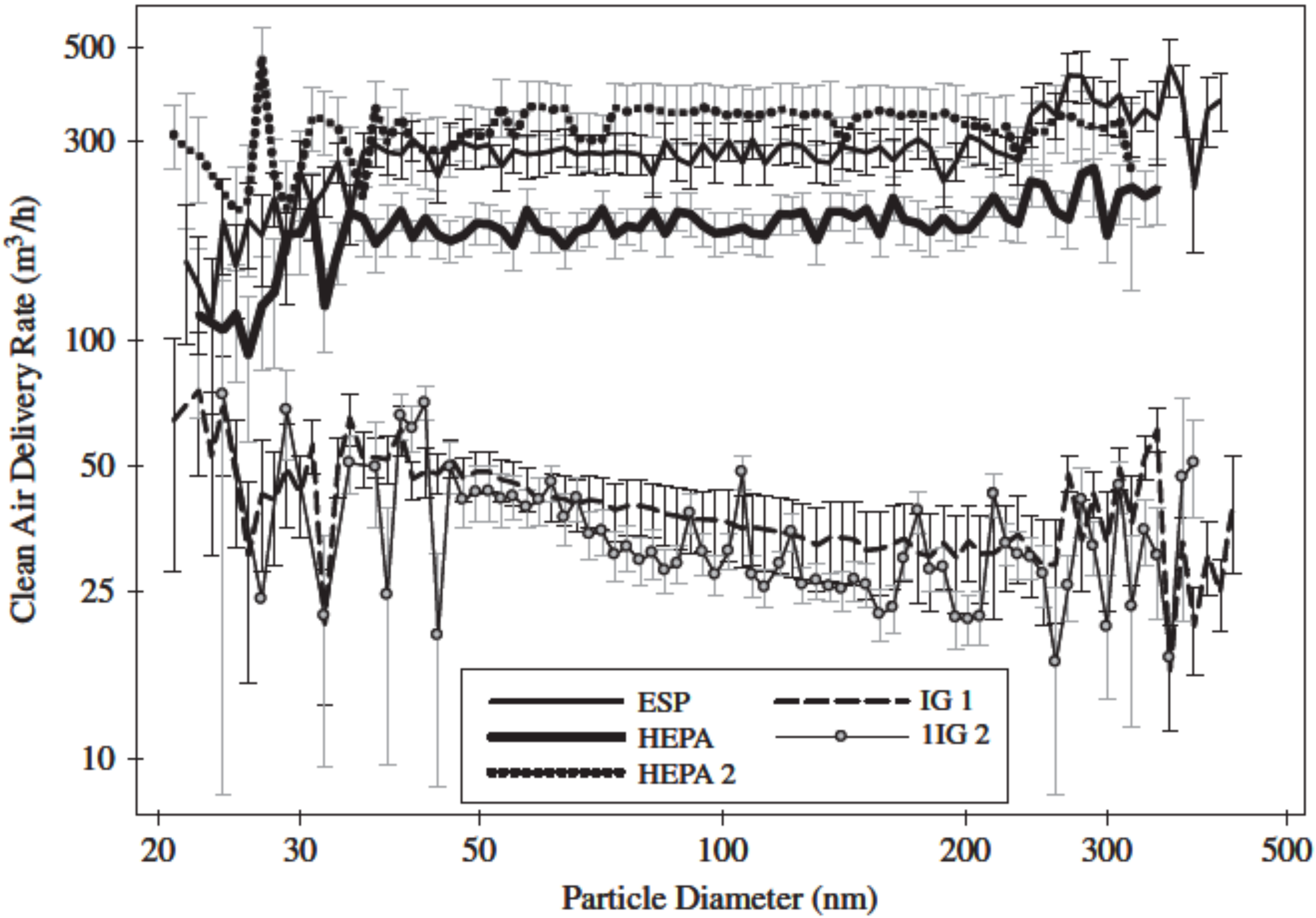
Kogan et al., 2008 EPA Report 600/R-08-012

Recent testing of portable air cleaners: UFPs



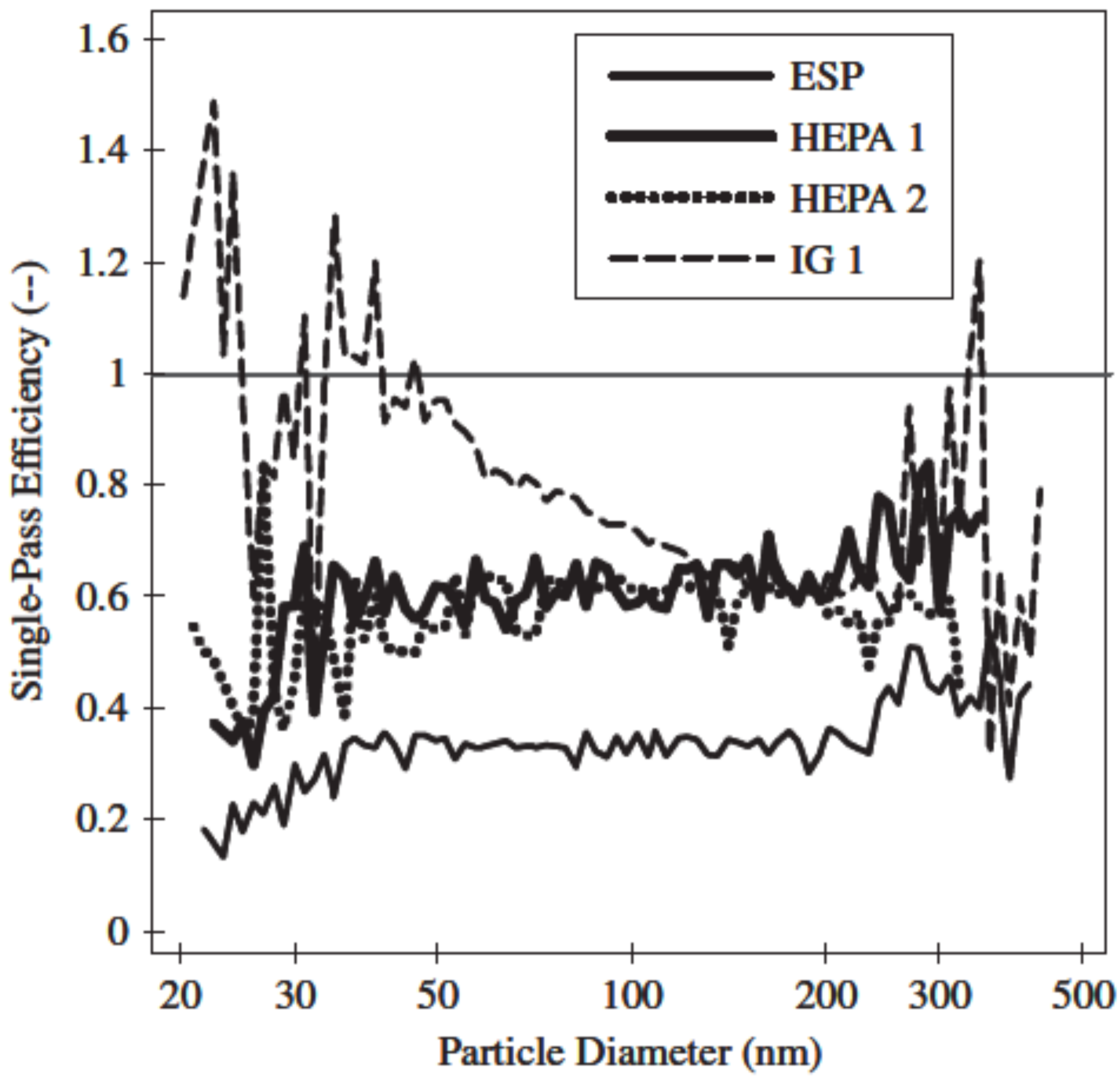
Sultan et al., 2011 *HVAC&R Research*

Recent testing of portable air cleaners



Waring et al., 2009 *Atmos Environ*

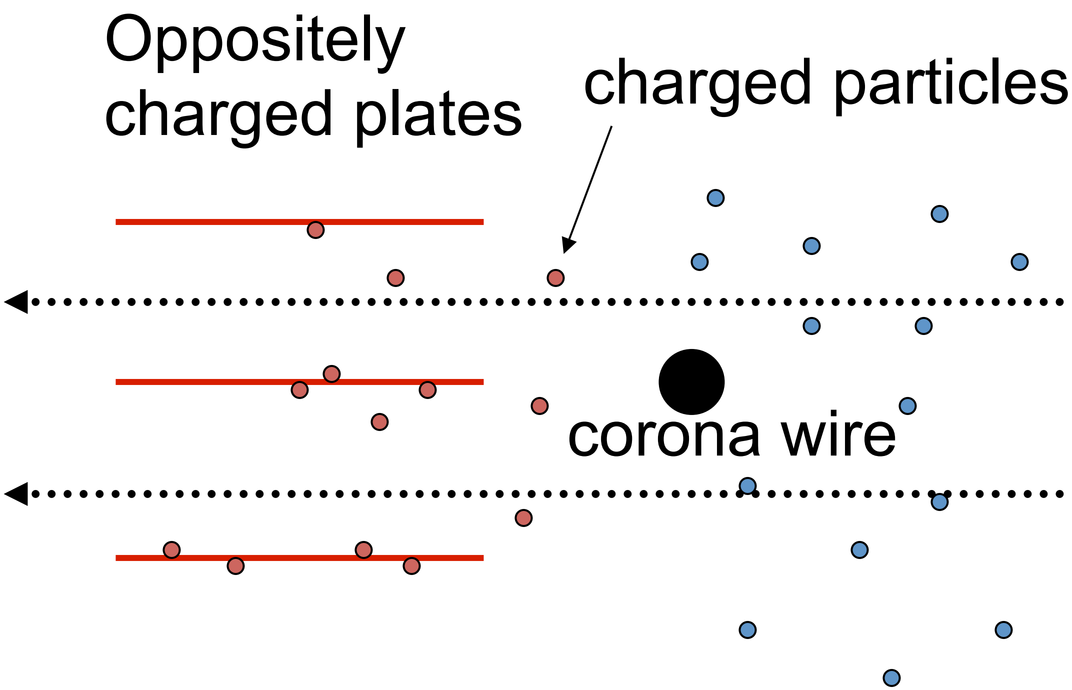
Recent testing of portable air cleaners



Waring et al., 2009 *Atmos Environ*

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

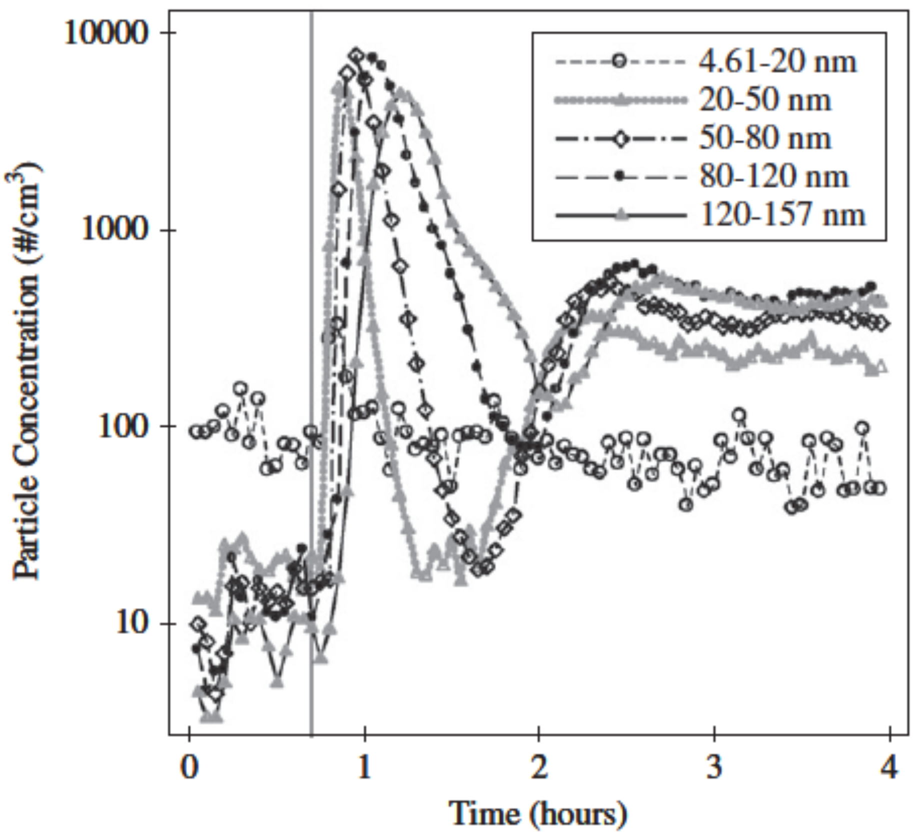
Air cleaner	Ozone emission rate ($mg\,h^{-1}$)	$V = 50\,m^3$		$V = 392\,m^3$	
		C^* (ppb)	ΔC_{out} (ppb)	C^* (ppb)	ΔC_{out} (ppb)
ESP	3.8 ± 0.2	8.6	77	1.1	9.9
IG 1	3.3 ± 0.2	7.5	67	1.0	8.6
IG 2	4.3 ± 0.2	9.7	88	1.2	11

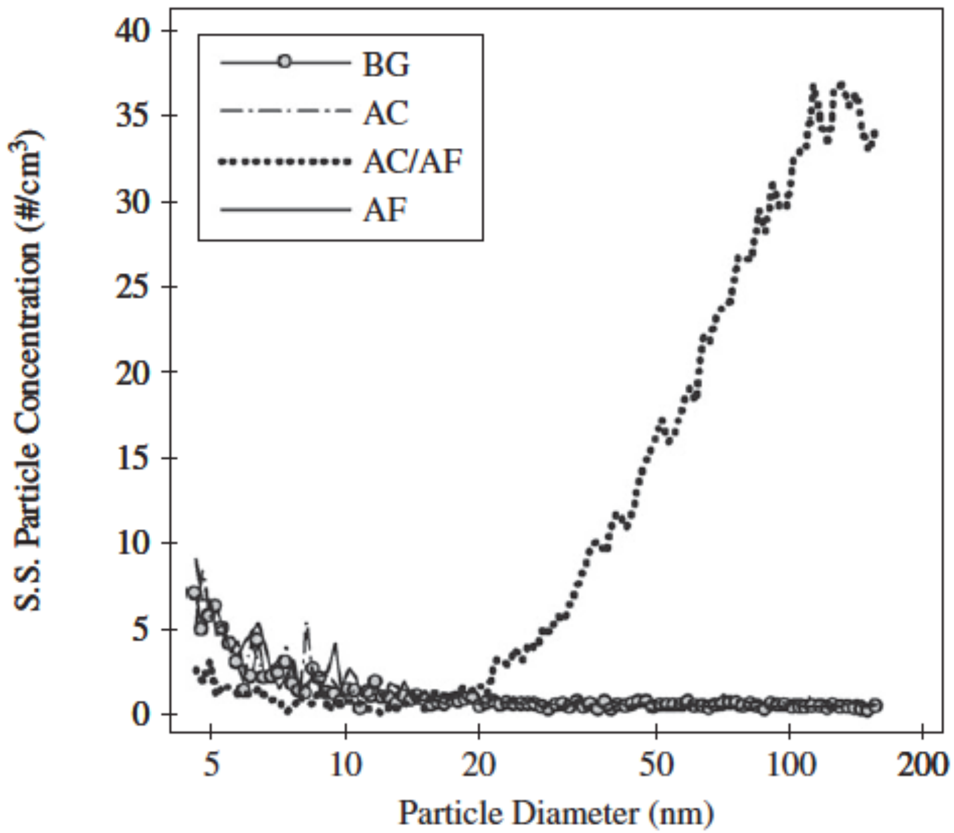
- Byproduct formation from reactions between ozone and terpene products
  - Formation products include SOA (secondary organic aerosols)
  - This means your particle removing air cleaner can lead to generation of particles!

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!



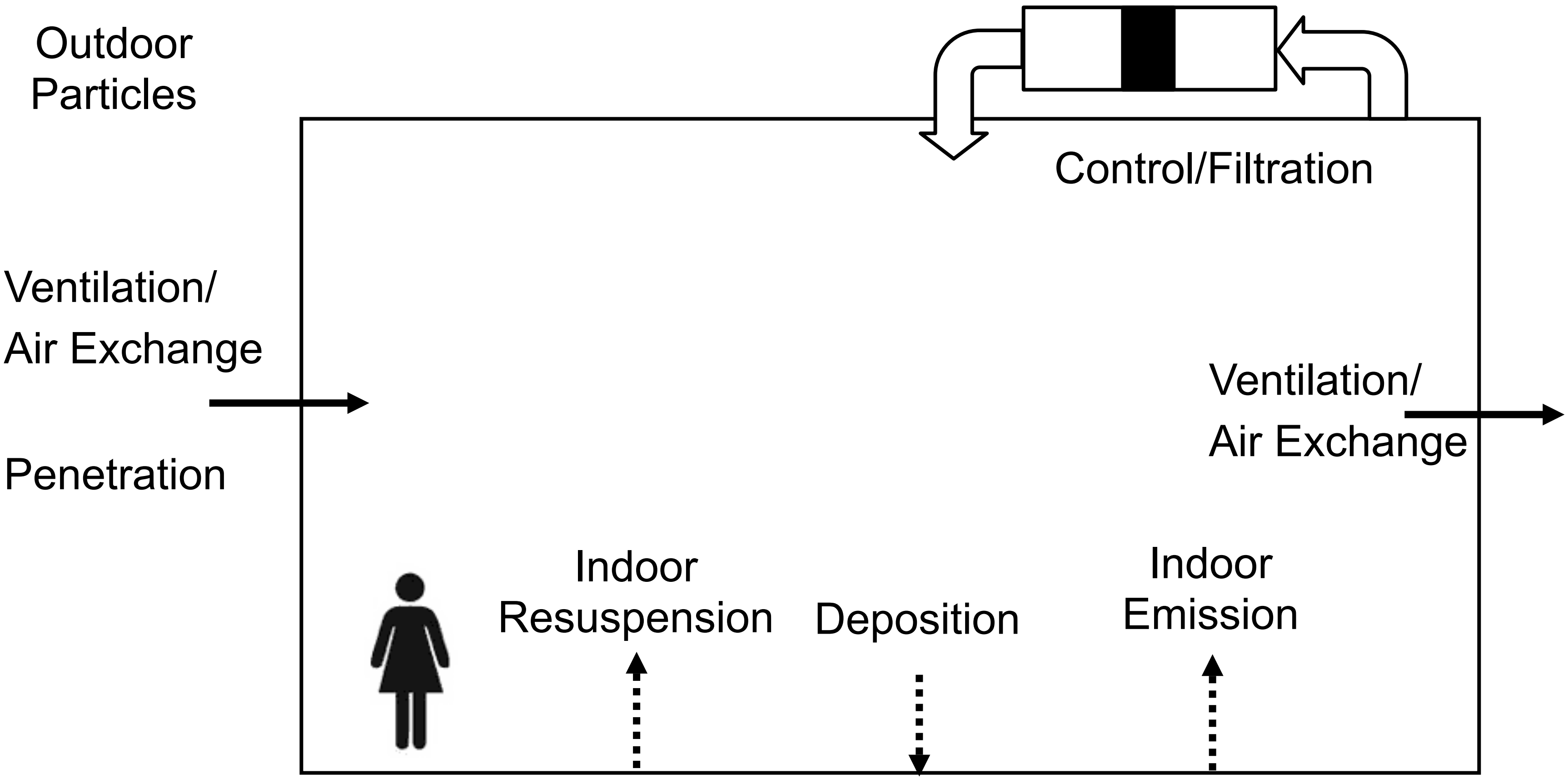


Waring et al., 2009 *Atmos Environ*

PARTICLE ‘PENETRATION’ (I.E., ‘INFILTRATION’)

Either a removal term or a source term, depending…

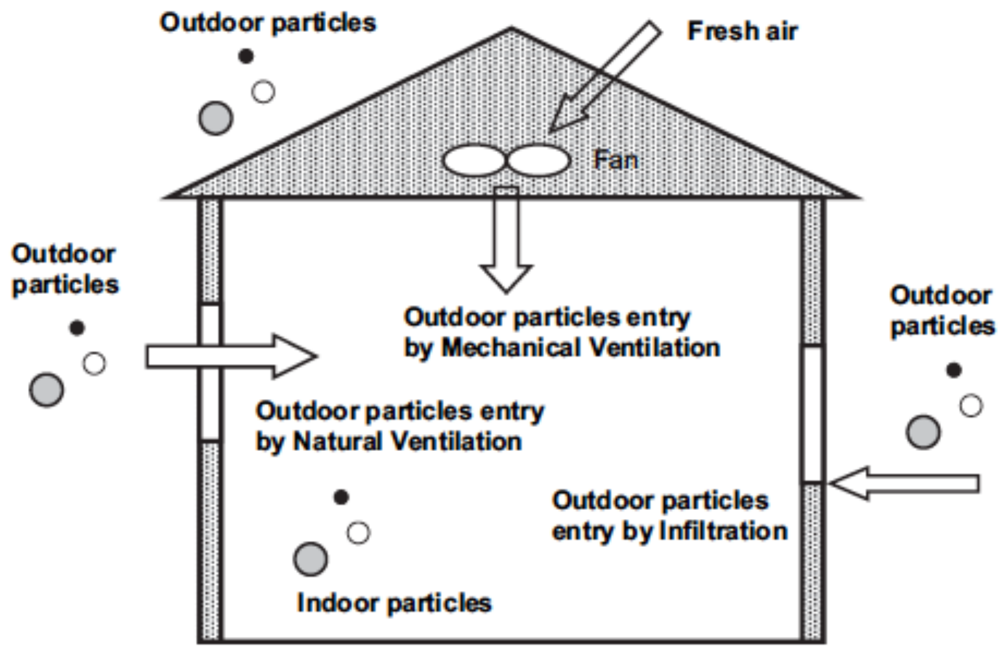
Particle penetration



Indoor/outdoor particle sources

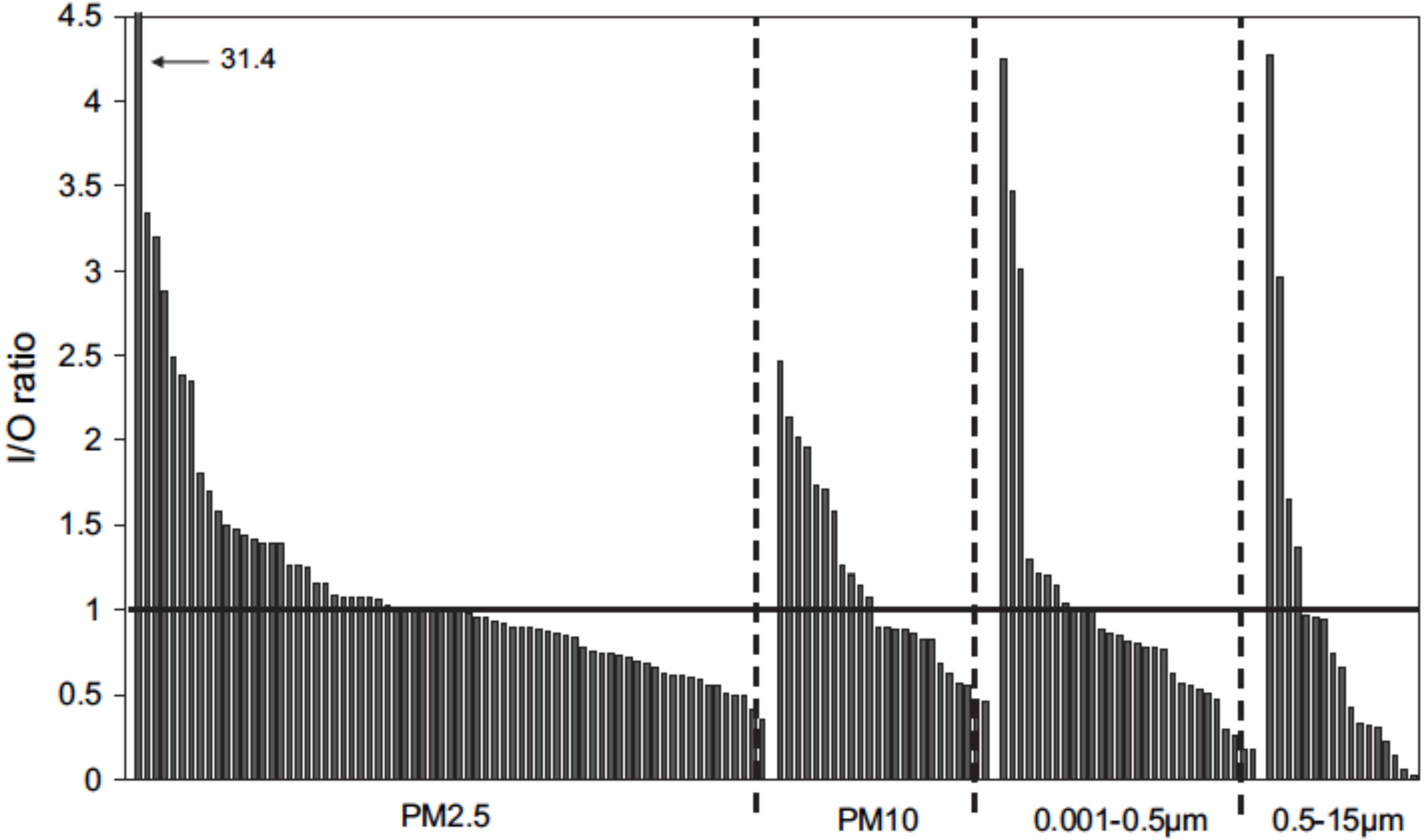
Review of relationship between indoor and outdoor particles: I/O ratio, infiltration factor and penetration factor

- First reviews I/O measurements
- Then focuses on outdoor infiltrated particles only
  - "Infiltration factor"
  - "Penetration factor"



Chen and Zhao, 2011 *Atmos Environ*

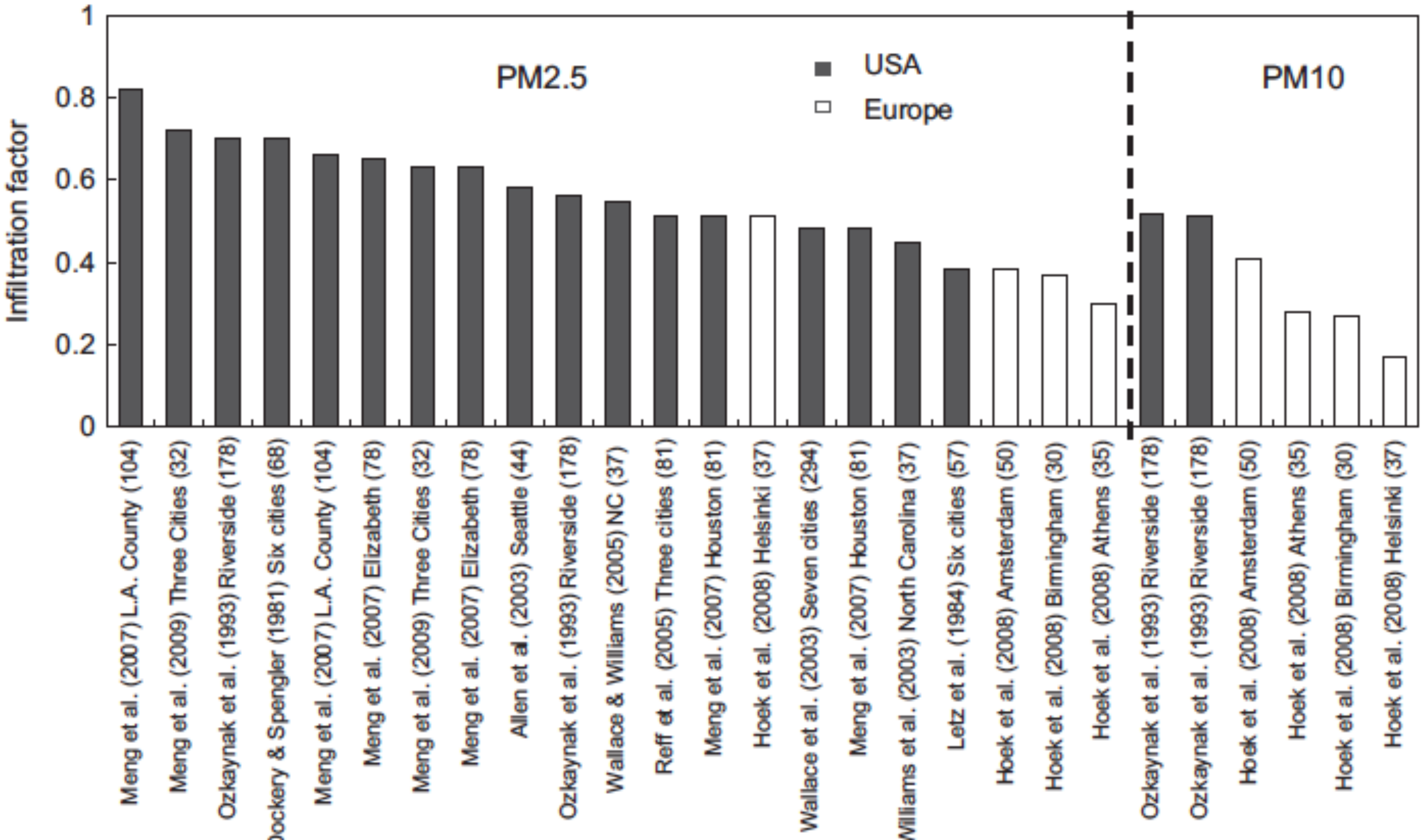
I/O particle ratios: combination of I and O sources



Chen and Zhao, 2011 *Atmos Environ*

Outdoor particle sources: Infiltration factors

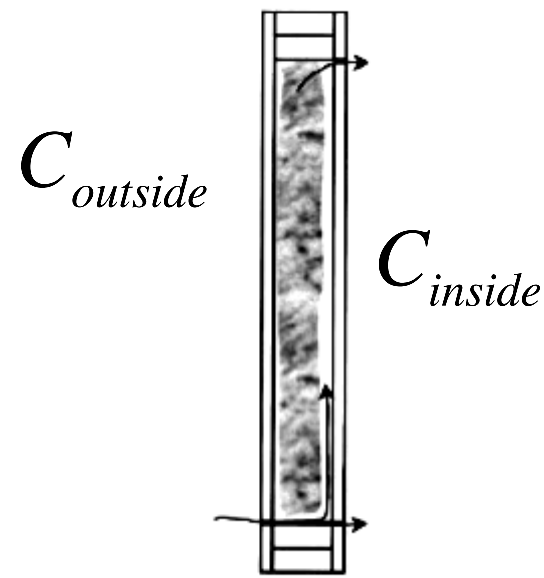
$$IF = \frac{C_{in}}{C_{out}} = \frac{P_i \lambda}{\lambda + k_{dep,i} + \lambda_{filt} \eta_{filt,i}}$$



Chen and Zhao, 2011 *Atmos Environ*

Particle infiltration/penetration

- Last time we learned all about particle filtration
- Particle penetration is another filtration mechanism
  - Probability that a particle penetrates through a building envelope
  - Large value for penetration factors means a larger number of particles infiltrate from outdoors through cracks and gaps in building envelopes
    - Low “envelope efficiency”
  - Large value for penetration factors means high “envelope efficiency”
    - Reduced indoor proportions of outdoor particles



$$P_{envelope} = \frac{C_{inside}}{C_{outside}} = 1 - E_{envelope}$$

Objectives for lecture on *P*

- Discuss previous research on *P*
  - Including recent research from my graduate work

- Discuss how to measure *P*
  - And how to solve for *P*

We’ve used *P* already in one of our HWs

- Riley et al. (2002) used the work of Liu and Nazaroff (2001)
  - Let’s first explore this work
  - “Modeling pollutant penetration across building envelopes”

Liu and Nazaroff (2001) *Atmos Environ*

- Particle penetration through cracks and in fiberglass insulation
  - Also interested in reactive gasses
- **Modeling study**

The deal is:

- All buildings envelopes have leaks
- Leaks are assumed to one of three types of 'cracks'
- If we can understand particle deposition in cracks
  - We should be able to understand particle penetration through leaks

Flow through cracks

- Relationship between pressure and flow

C = 1.5 + n_{bends}
w = crack width

$$\Delta P = \frac{12\mu z}{wd^3}Q + \frac{\rho C}{2d^2w^2}Q^2.$$

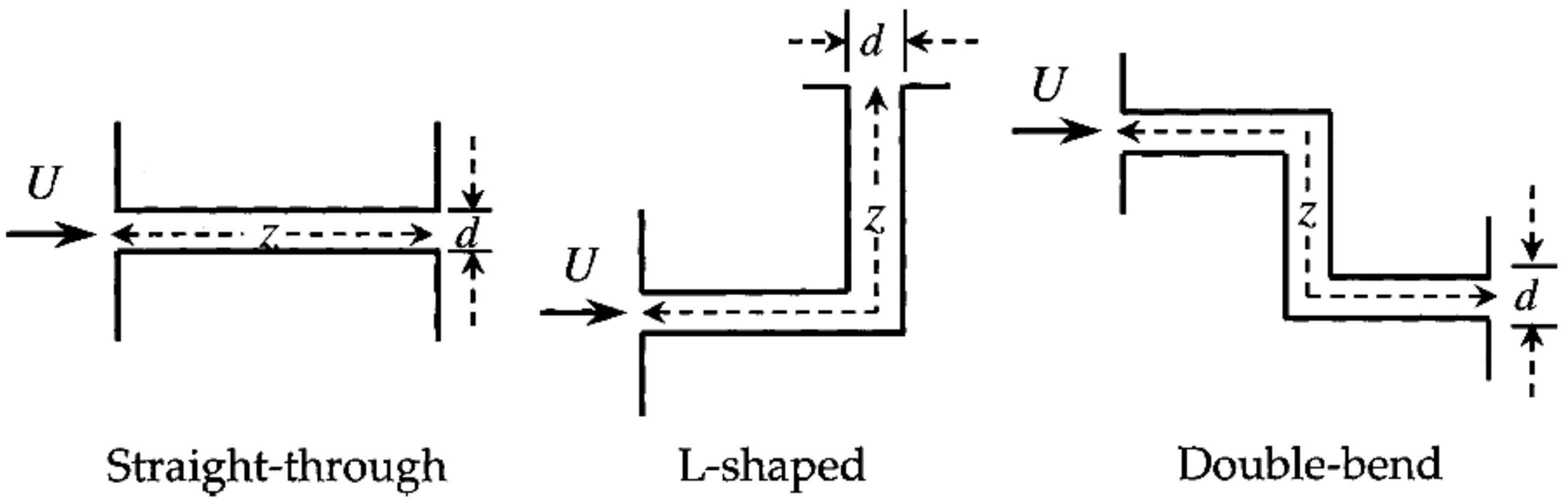


Fig. 1. Configuration of three types of idealized cracks through building envelopes.

Flow through a crack

$$Q = c_d A \sqrt{\frac{2\Delta P}{\rho}}$$

If $Re >> 1$:

$$Q \propto \sqrt{\Delta P}$$

Short, tall flow channel $\rightarrow$ inertial forces dominate

If $Re << 1$:

$$Q \propto \Delta P$$

Long, thin flow channel $\rightarrow$ viscous forces dominate

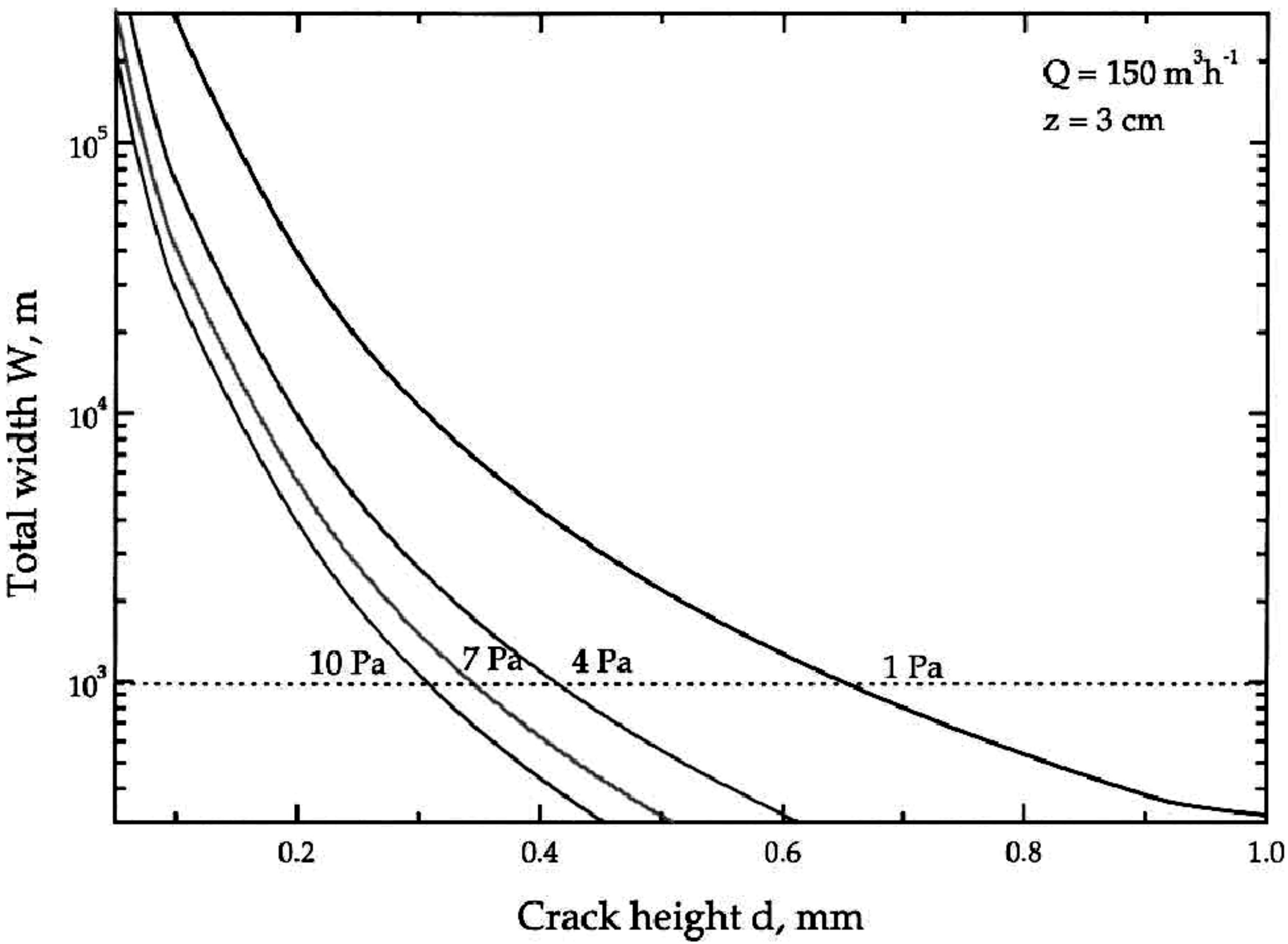
$$\Delta P = \frac{12\mu z}{wd^3} Q + \frac{\rho C}{2d^2 w^2} Q^2$$

What are typical crack dimensions?

- This is a very tough parameter to get
  - We have no metrics that tell us anything about crack size and distribution among envelopes
- A study from the 1950s suggested that crack heights were normally less than 2.5 mm around closed windows
  - Another in the 1970s reported 0.5-7.5 mm crack heights common in buildings
- Not much other information here
  - And cracks/leaks aren’t always obvious
- This remains a big limitation to this modeling study

Assuming flow, crack width, and variety of ΔP…

We can come up with estimates for crack height and total crack width



Modeling particle penetration through cracks

- They considered there major deposition mechanisms:
  - Brownian diffusion
  - Gravitational settling
  - Impaction (found not to be important in a separate analysis)
- Gravitational

$$P_g = 1 - \frac{V_s z}{dU}$$

V_s = particle settling velocity
z = crack length
d = crack height
U = air speed through crack

- Diffusion

$$P_d = 0.915 e^{-1.885 \frac{4Dz}{d^2 U}} + 0.0592 e^{-22.3 \frac{4Dz}{d^2 U}} + 0.026 e^{-152 \frac{4Dz}{d^2 U}} + \dots$$

D = particle diffusion coefficient

$$P_{total} = P_g \times P_d \times P_i$$

Model cracks

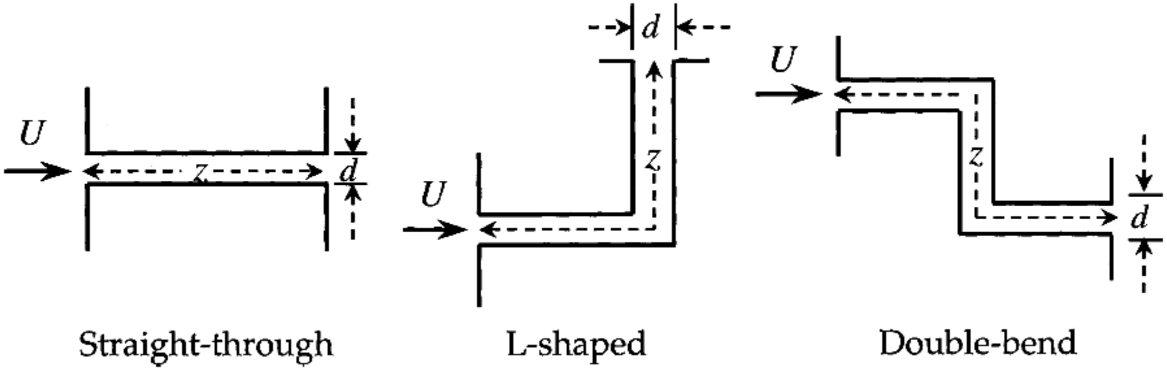


Fig. 1. Configuration of three types of idealized cracks through building envelopes.

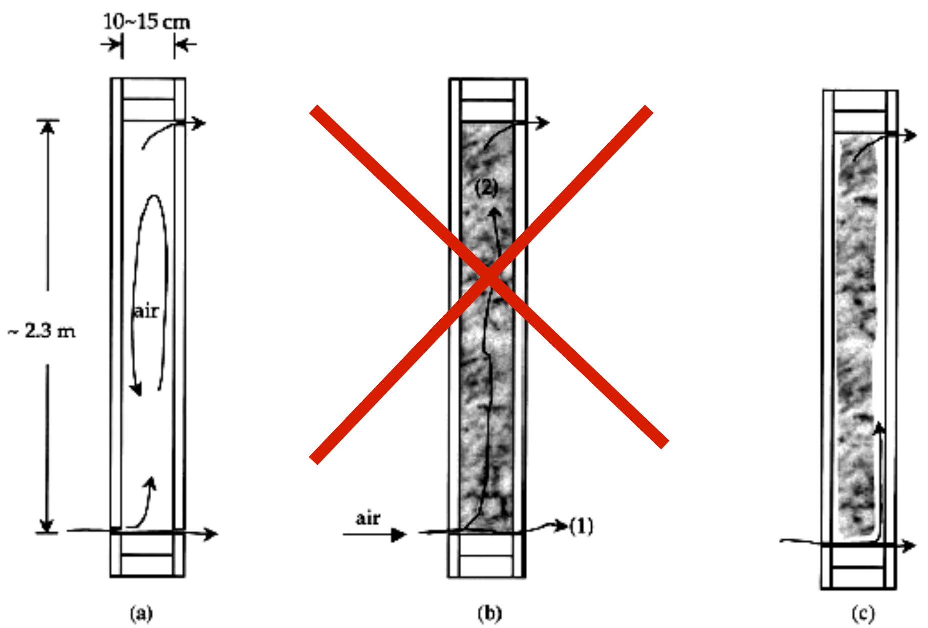


Fig. 3. Schematic of airflow paths through wall cavities in wood-frame construction. (a) Uninsulated wall cavity; (b) Wall cavity filled with fiberglass insulation; and (c) Fiberglass-insulated wall cavity with airflow bypass.

Model results

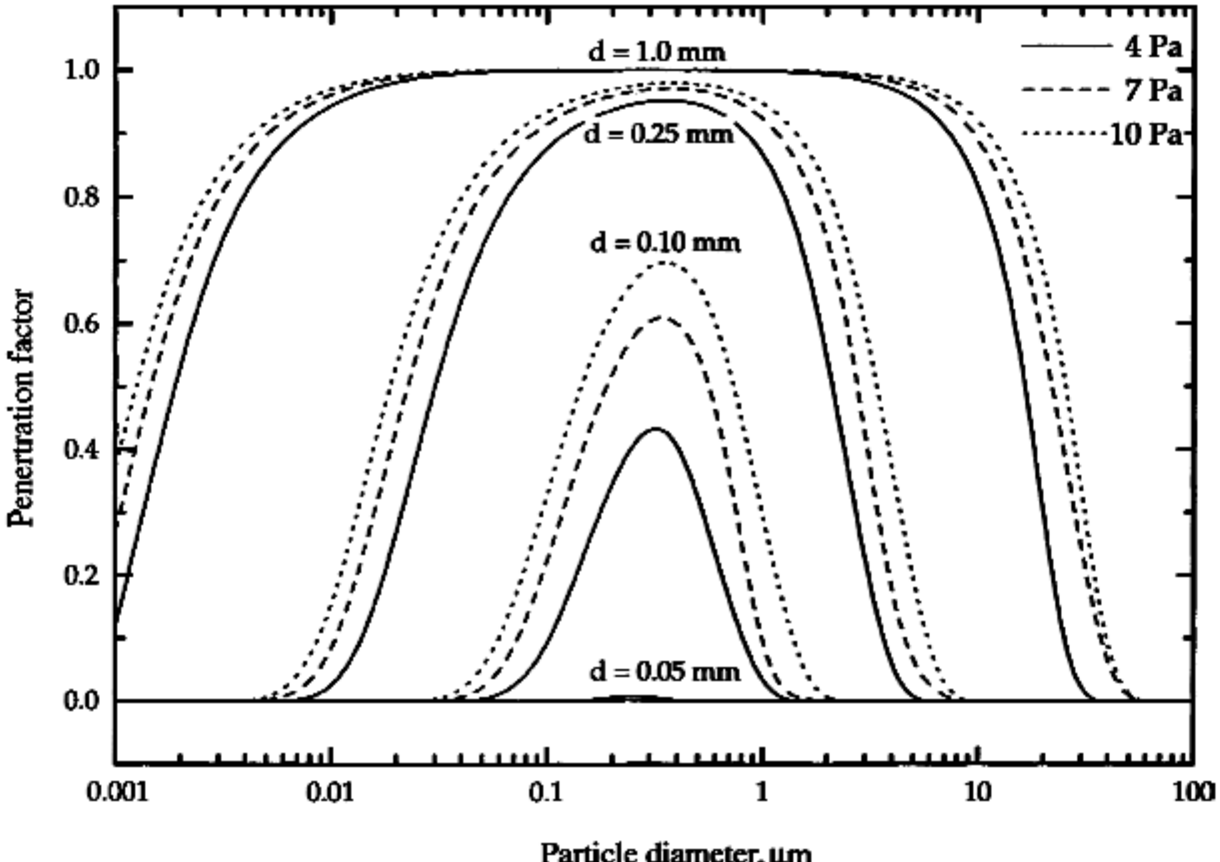


Fig. 4. Particle penetration factor as a function of particle diameter, crack height, and pressure difference for a straight-through crack with flow length $z = 3$ cm.

Model results

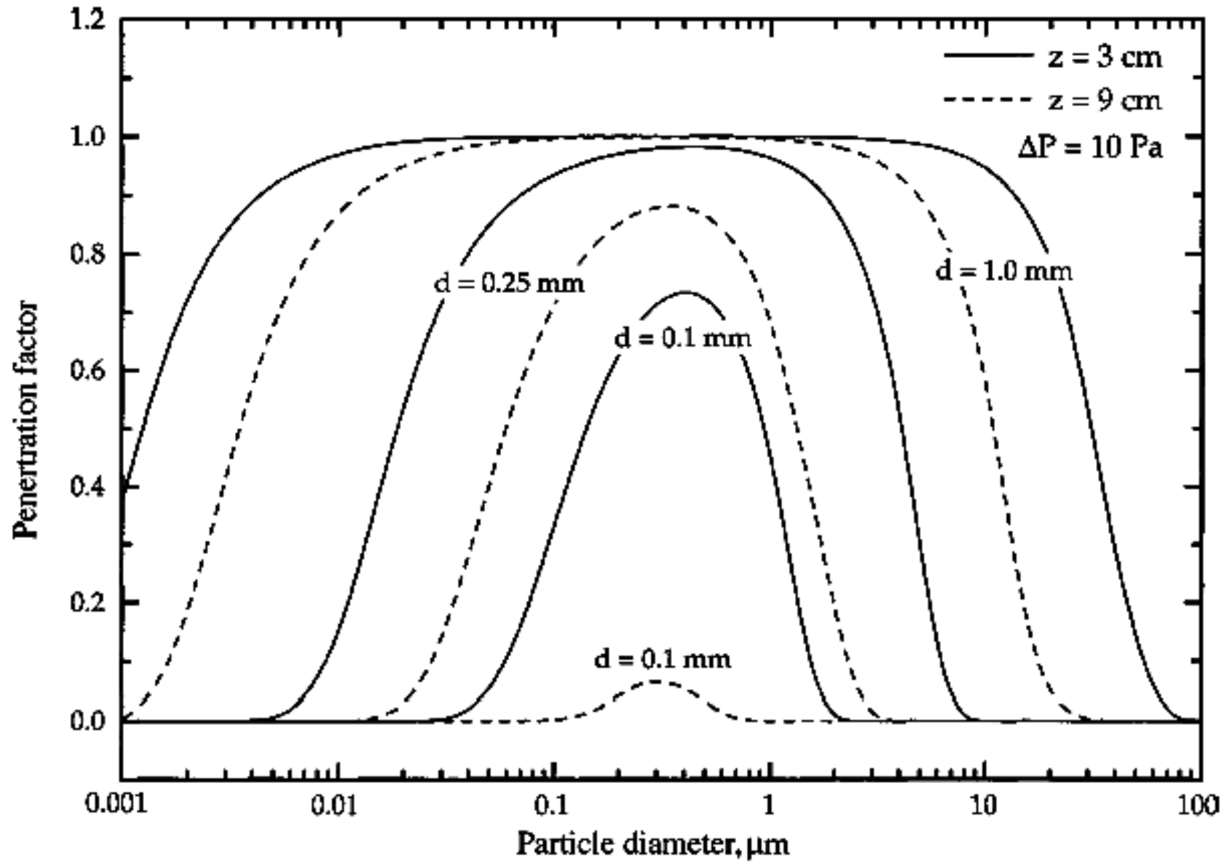


Fig. 5. Particle penetration factor as a function of particle diameter, crack height, and flow length at a fixed pressure drop of $\Delta P = 10\,\text{Pa}$.

Model results

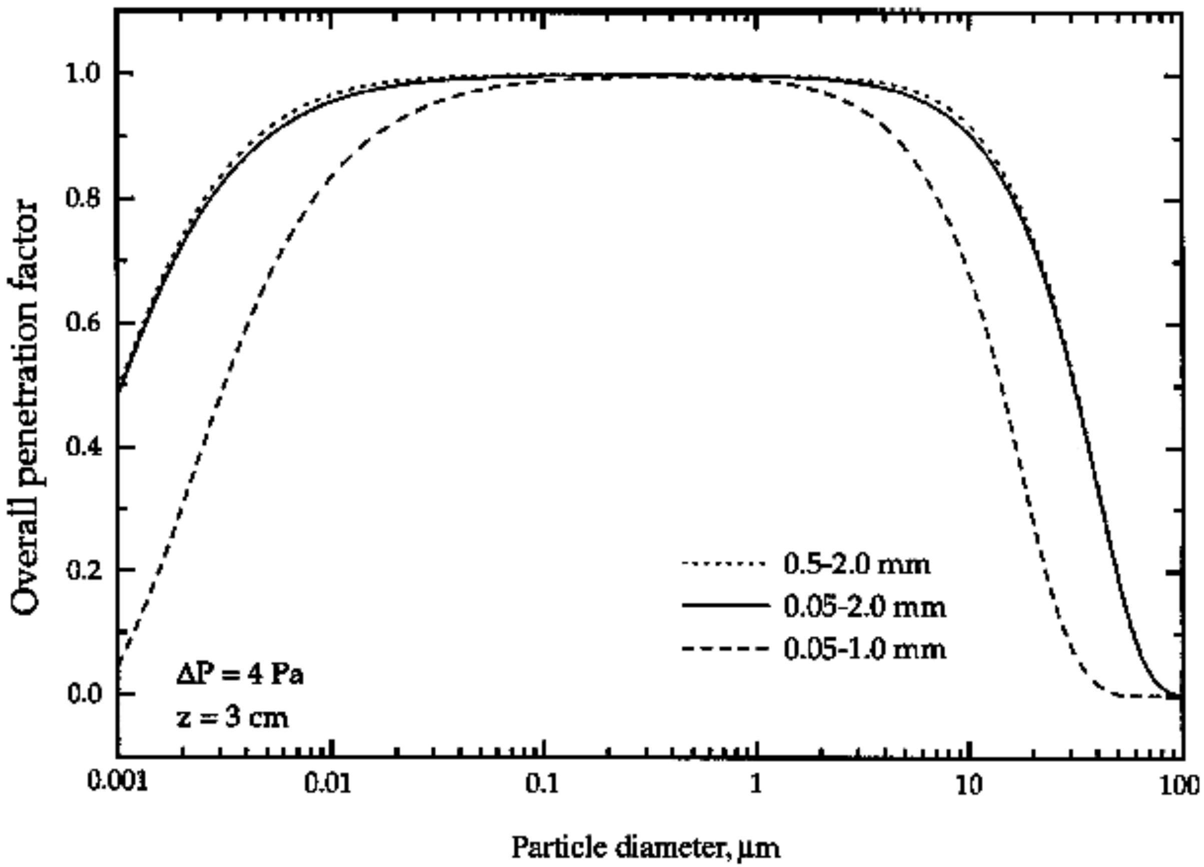
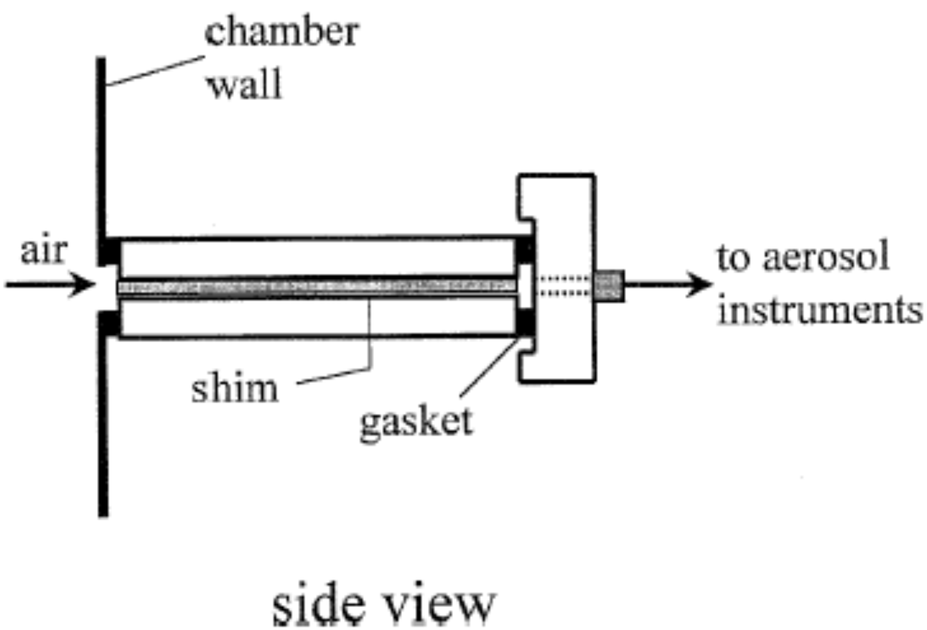


Fig. 6. Overall particle penetration factor for a building with crack area distributed uniformly with respect to crack height. Results are presented for three different ranges of crack sizes.

Comparison of model results to chamber tests

- Follow up study: Liu and Nazaroff (2003)
  - Does the model work?
  - Still using idealized cracks



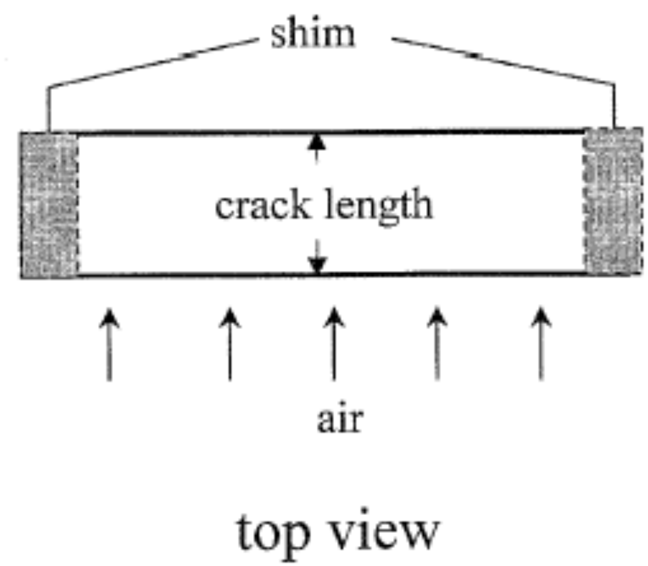


Figure 1. Configuration of crack apparatus (not to scale).

Comparison of model results to chamber tests

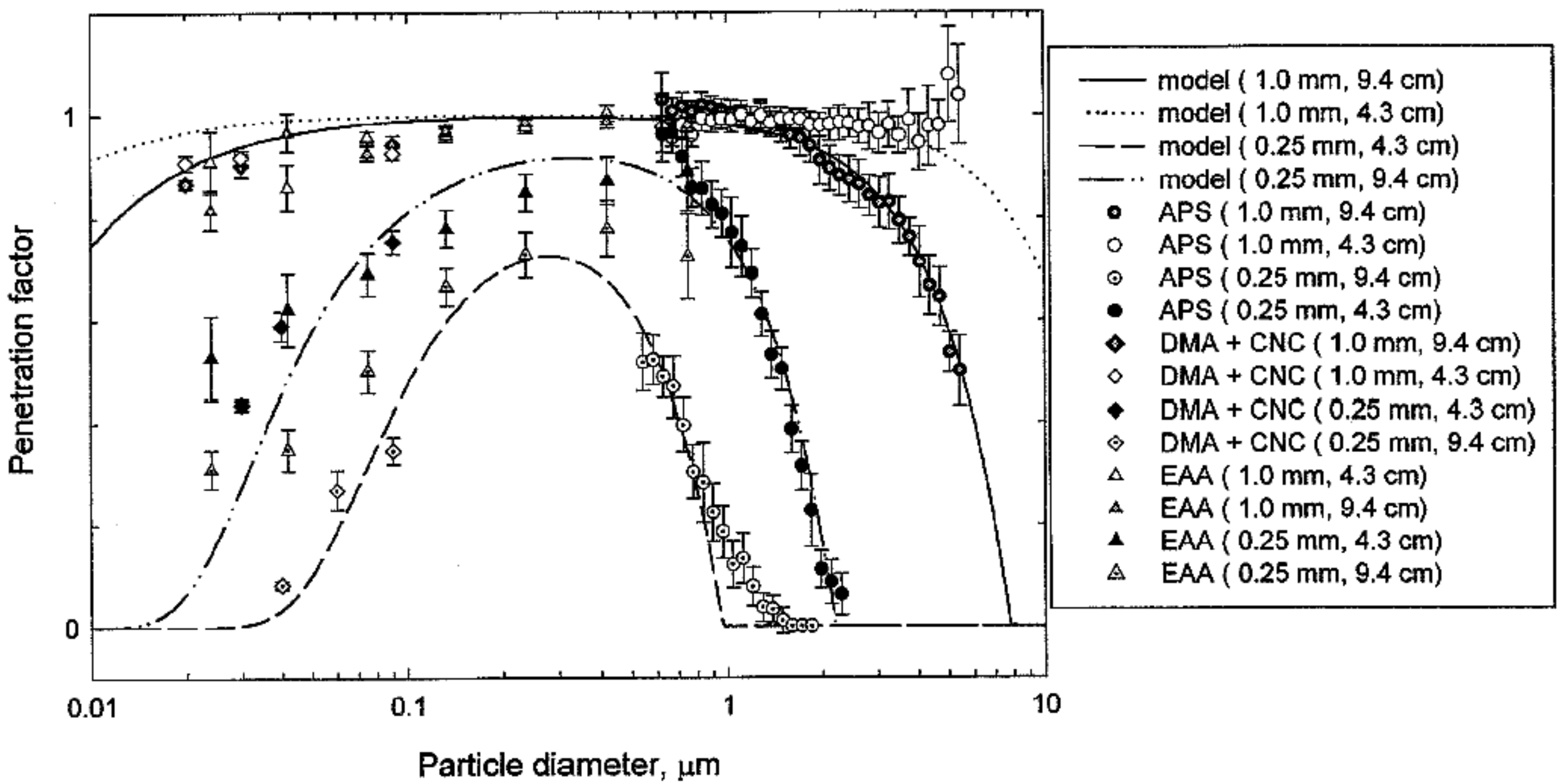


Figure 5. Comparison of model predictions with experimental data for aluminum cracks. Results are presented for four sets of crack dimensions (crack heights of 0.25 mm and 1.0 mm and crack flow lengths of 4.3 cm and 9.4 cm), with an applied pressure difference, $\Delta P = 4$ Pa.

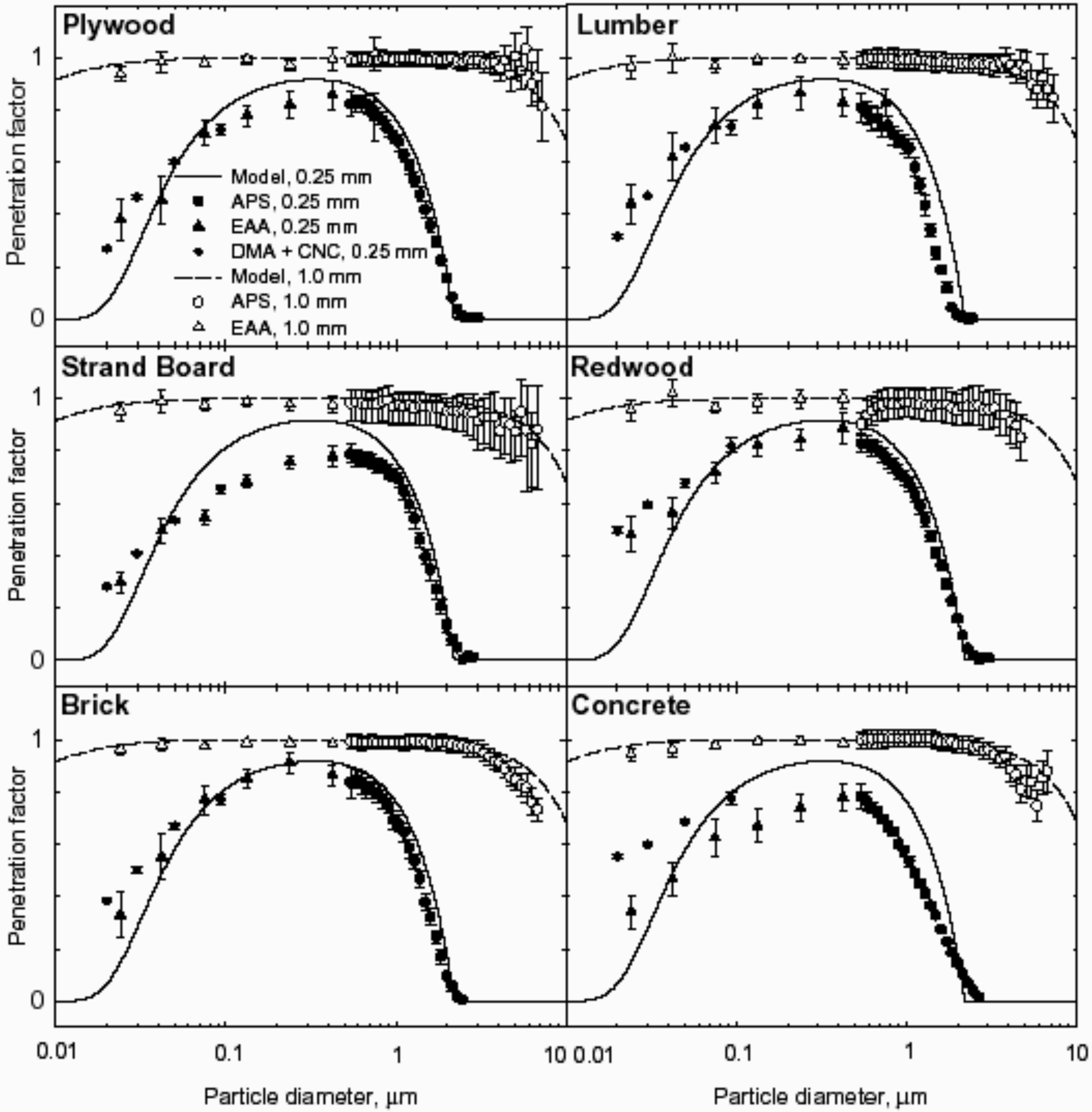


Figure 7. Experimental particle penetration factors for six crack materials at crack heights of 0.25 mm and 1 mm and with $\Delta P =$ 4 Pa, as compared with model predictions.

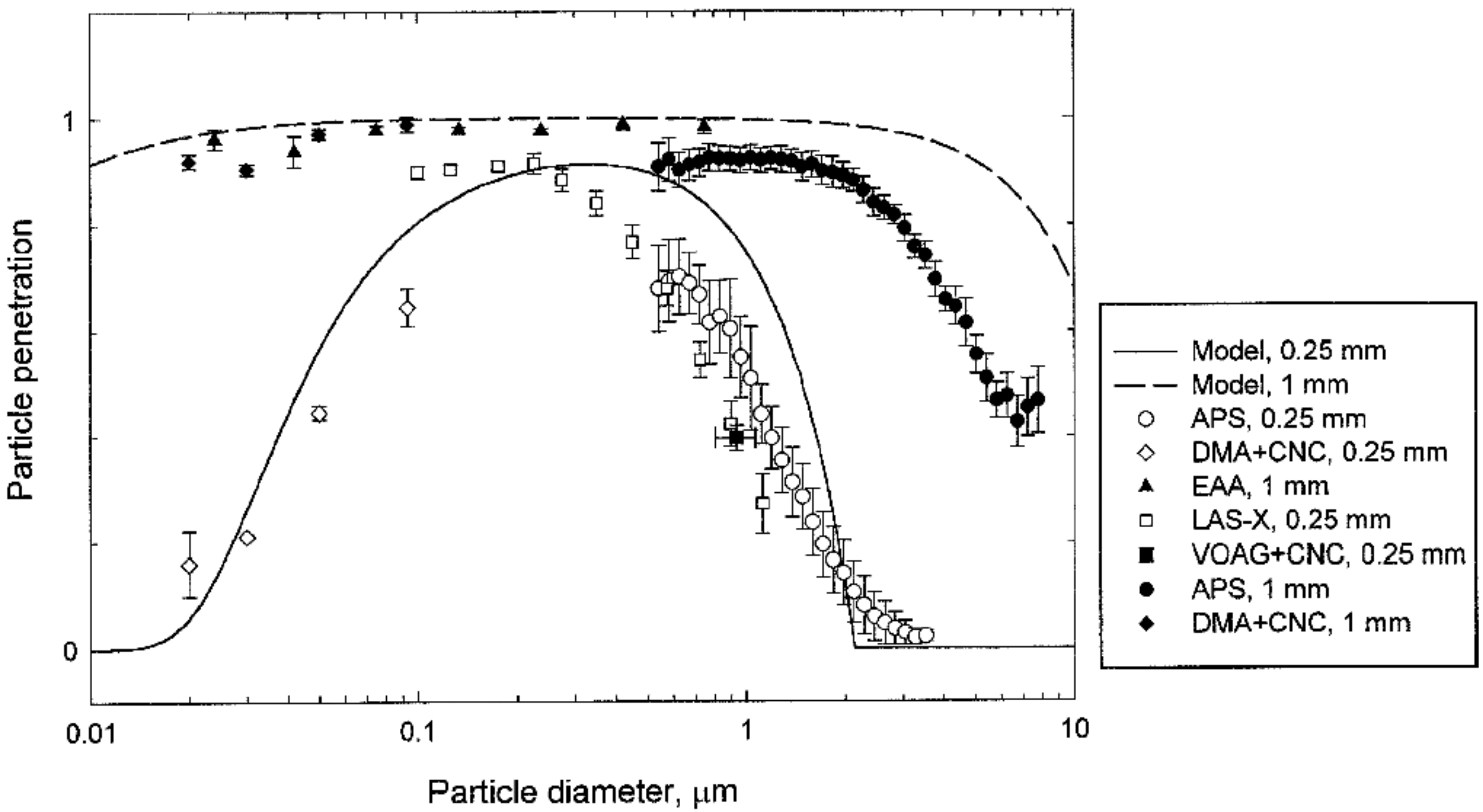


Figure 9. Comparison of model calculations and experimental results for naturally broken brick with crack heights of 0.25 mm and 1 mm.

DATA FROM REAL BUILDINGS

Real building data

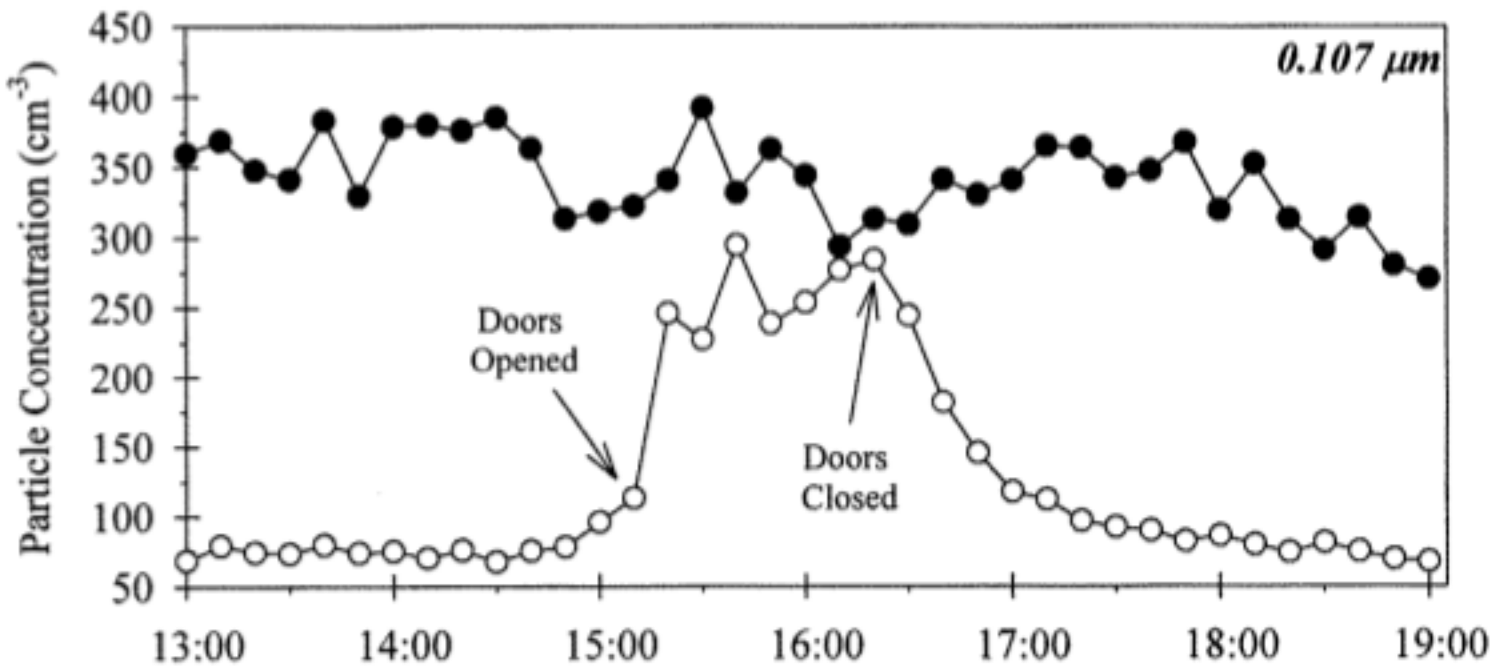
- Models are helpful for understanding:
  - Is a phenomenon important?
  - What impacts the phenomenon?
- Models are severely limited in terms of:
  - Applicability to real environments
- Measurements are absolutely required in real buildings
  - But data can be messy and experiments challenging
  - One issue is that you need fluctuations in the data to solve for two parameters with only one mass balance (loss rates and penetration factors)
  - Another issue is that indoor sources greatly influence your data

Specific measurements of *P*

- Vette et al. 2001 *Aerosol Sci Technol*
- Chao et al. 2003 *Atmos Environ*
- Thatcher et al. 2003
- Rim et al. 2010 *Environ Sci Technol*
- Stephens and Siegel 2012 *Indoor Air*

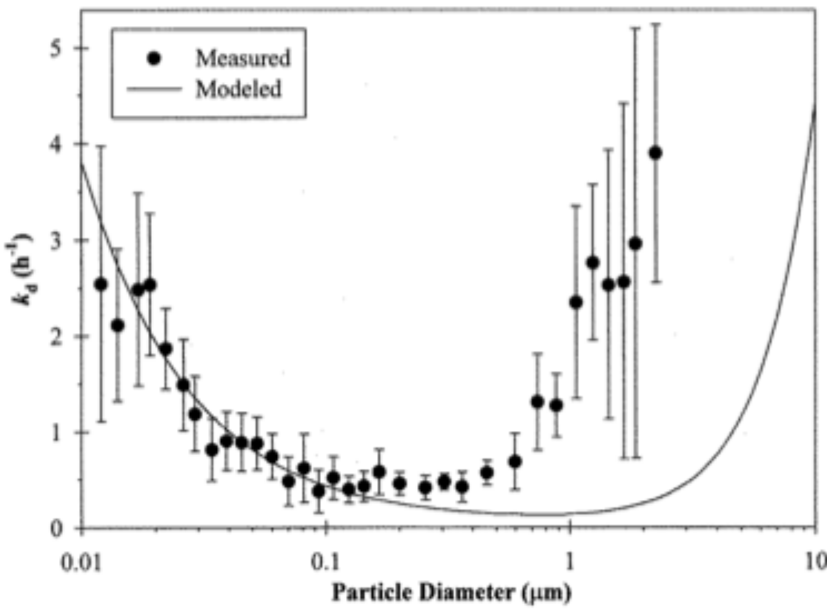
Vette et al. 2001 *Aerosol Sci Technol*

- Single residence – Fresno CA
- Size-resolved indoor and outdoor particle measurements for 2 months
- Deposition rates were first determined by measuring indoor decay after elevation from outdoor particles
  - Simultaneous AER measurements



$$\frac{dC_i}{dt} = -(\alpha + k_d)C_i. \qquad \ln\left(\frac{C_{it}}{C_{i0}}\right) = -(\alpha + k_d)t,$$

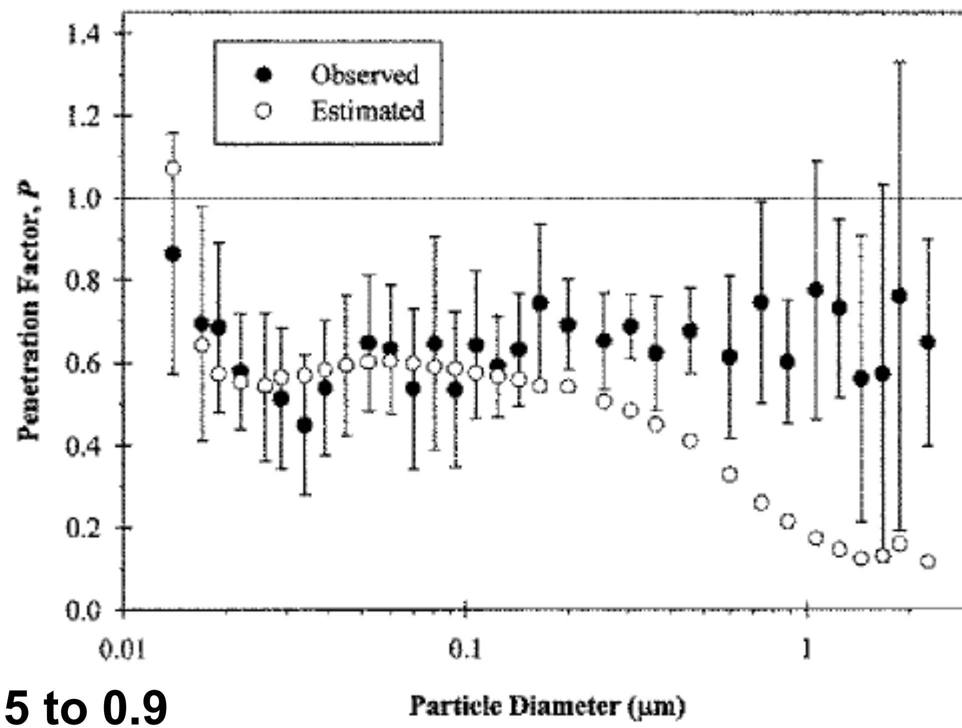
Vette et al. 2001



P was then estimated during nighttime indoor-outdoor measurement periods where there were probably no indoor sources:

$$P = \frac{(\alpha + k_d) C_i}{\alpha C_o}$$

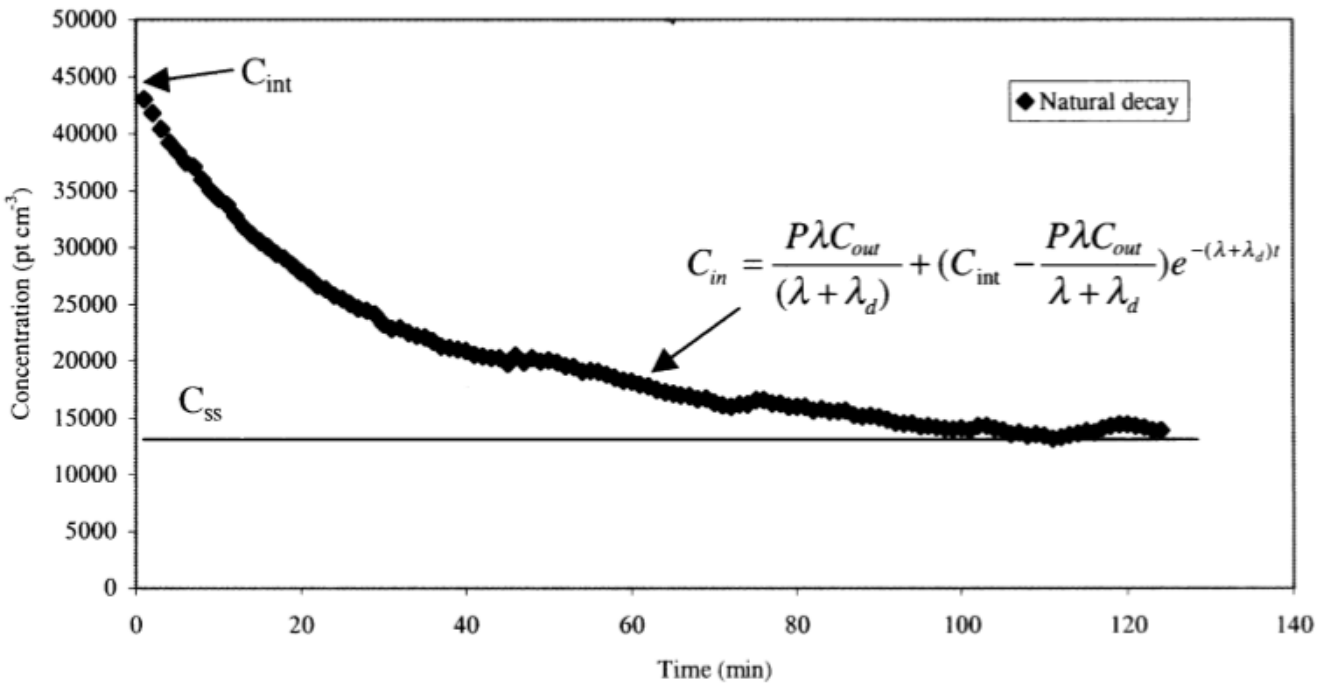
Good estimates of size-resolved deposition rates



Estimates of P ranged from 0.5 to 0.9

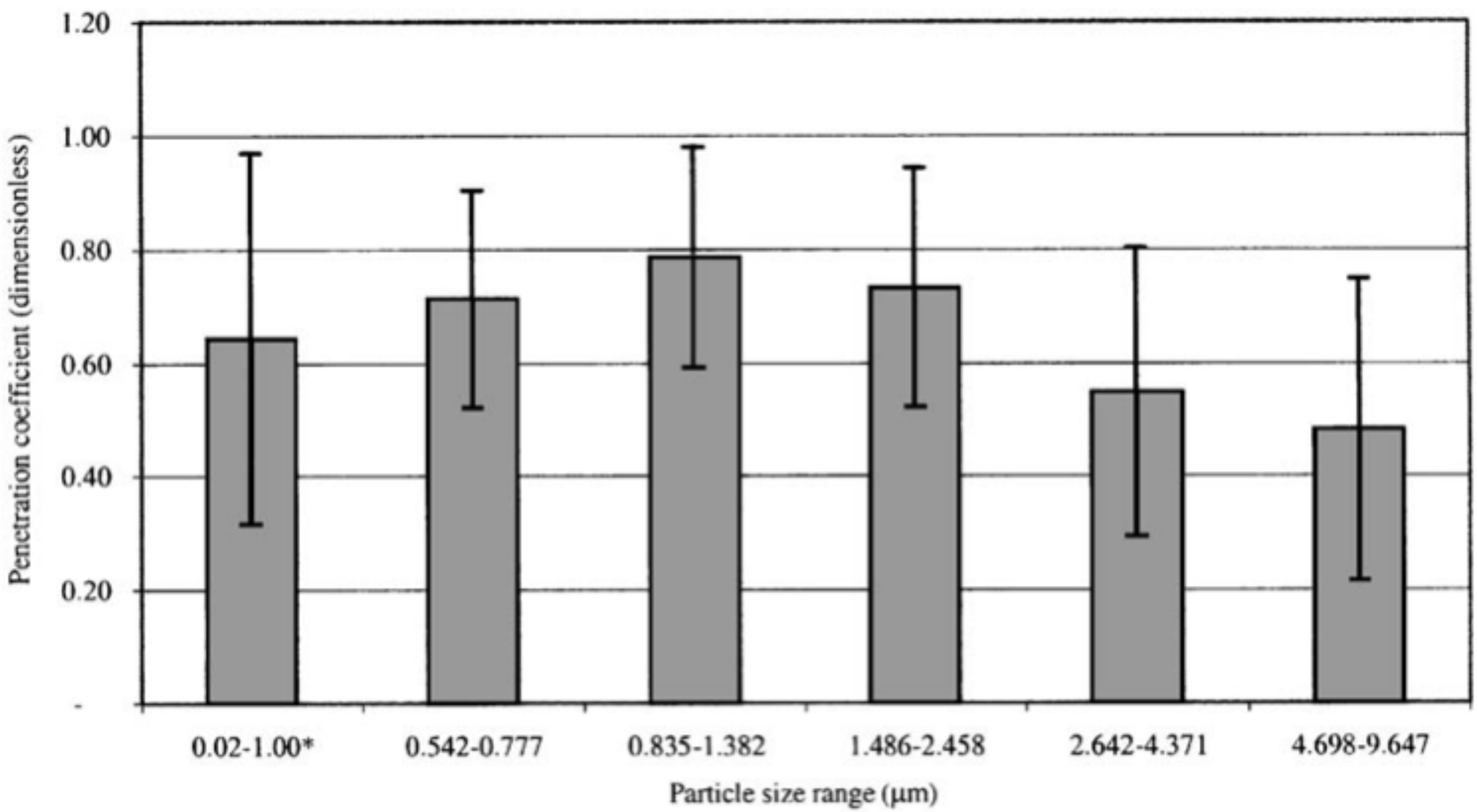
Chao et al. 2003 *Atmos Environ*

- Six non-smoking high-rise apartments
- 0.02-10 μm particles
- Deposition rate estimated from indoor decay data
  - Simultaneous AER measurements
- Penetration factor determined using transient data and estimate of deposition rate



$$P = \left(1 + \frac{\lambda_d}{\lambda}\right)\frac{C_{ss}}{C_{out}}.$$

Chao et al. 2003



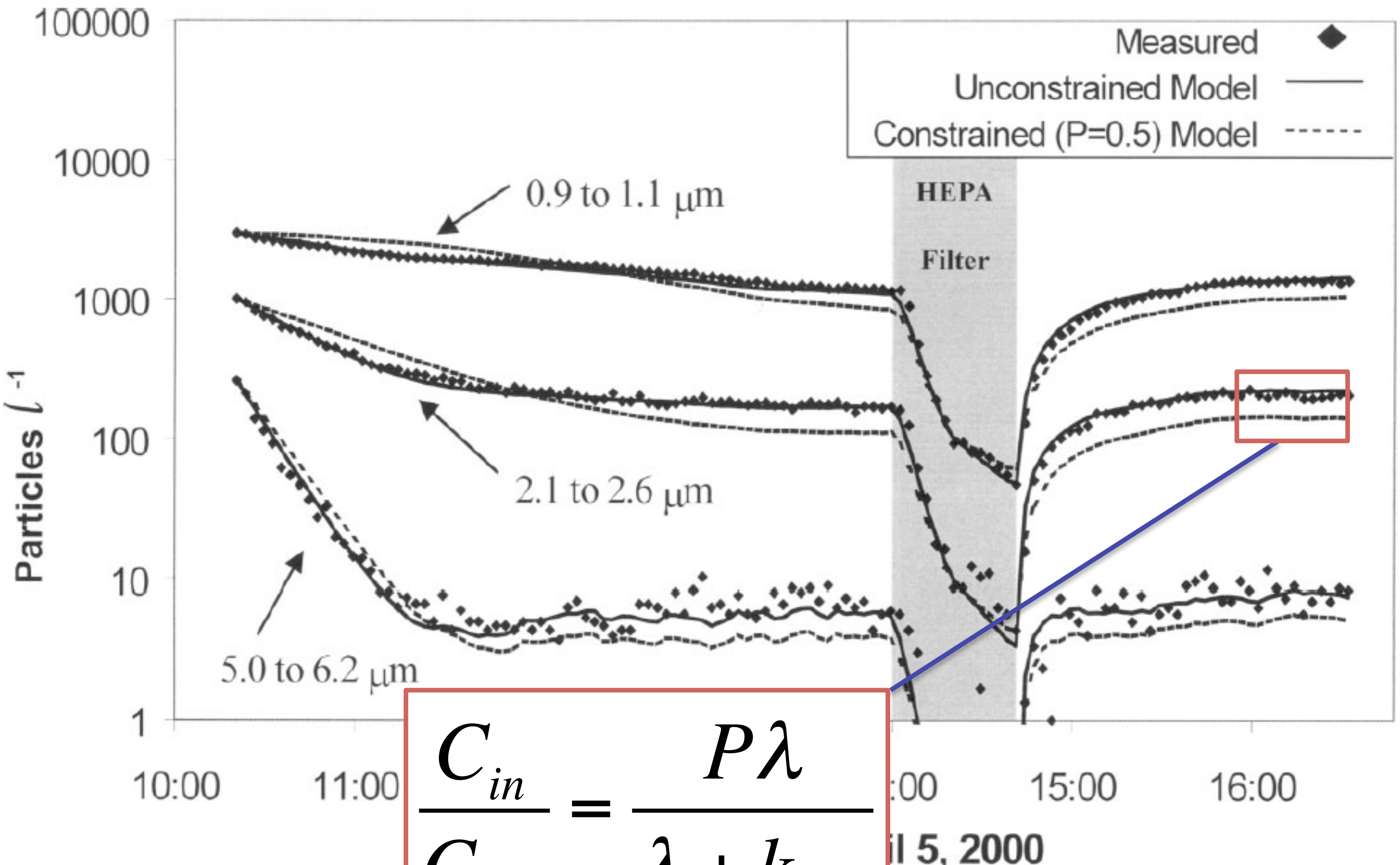
Key:
* Results obtained from P-Trak monitor
The error bar represents one standard deviation from the mean value

Estimates of P ranged from 0.5 to 0.8

Thatcher et al. 2003 *Aerosol Sci Technol*

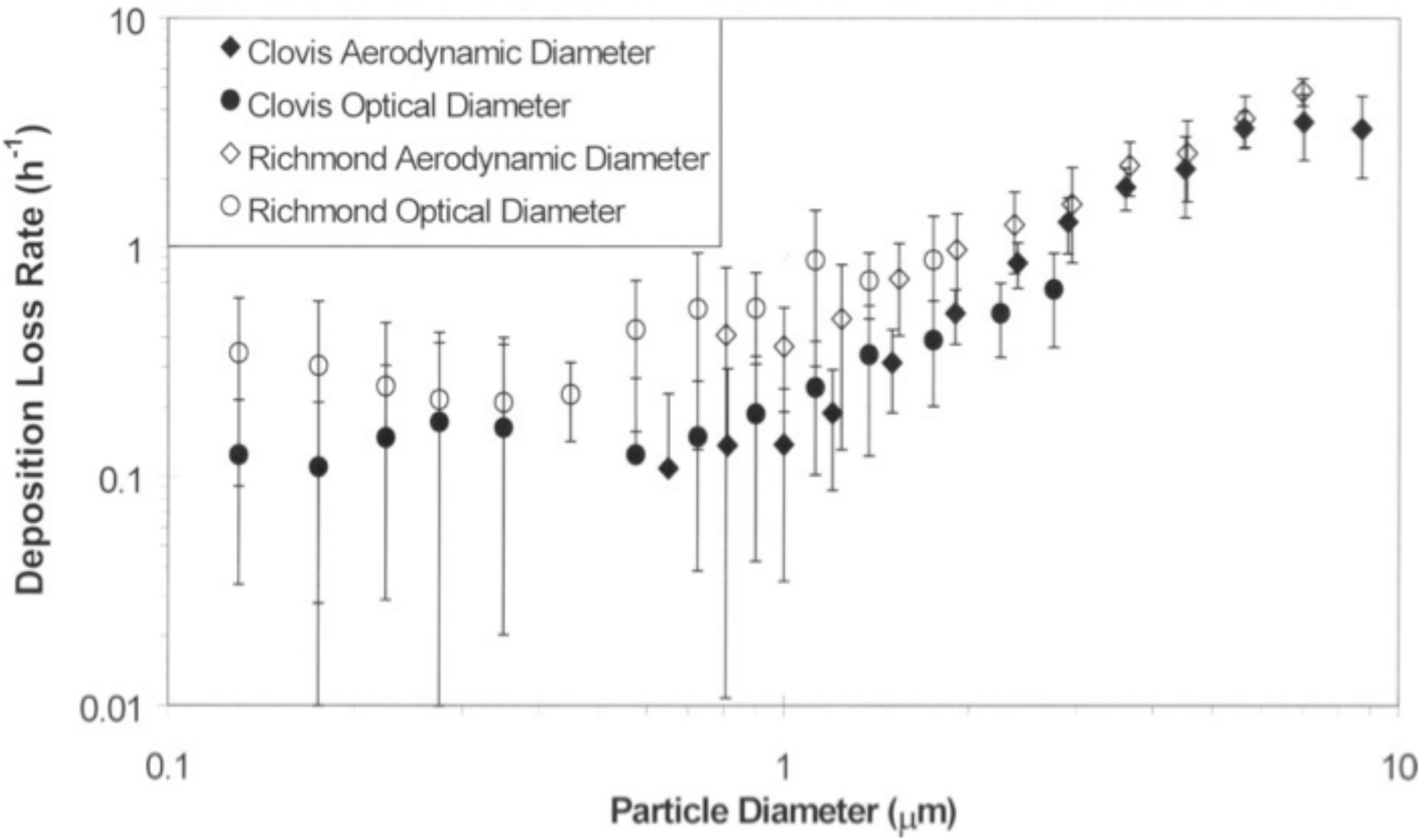
- Two houses in CA
  - Size-resolved 0.3 to 10 μm particles
- New method of measuring P
  - "Concentration rebound method"
  - Involved artificially elevating indoor concentrations to measure decay
  - Then operate a HEPA filter to remove most of the indoor particles
  - Then observe the indoor concentration as it "rebounds" to normal levels due to the infiltration of outdoor particles only
  - Estimate P from steady state I/O ratio
    - Simultaneous AER measurements

Particle rebound method from Thatcher et al. 2003

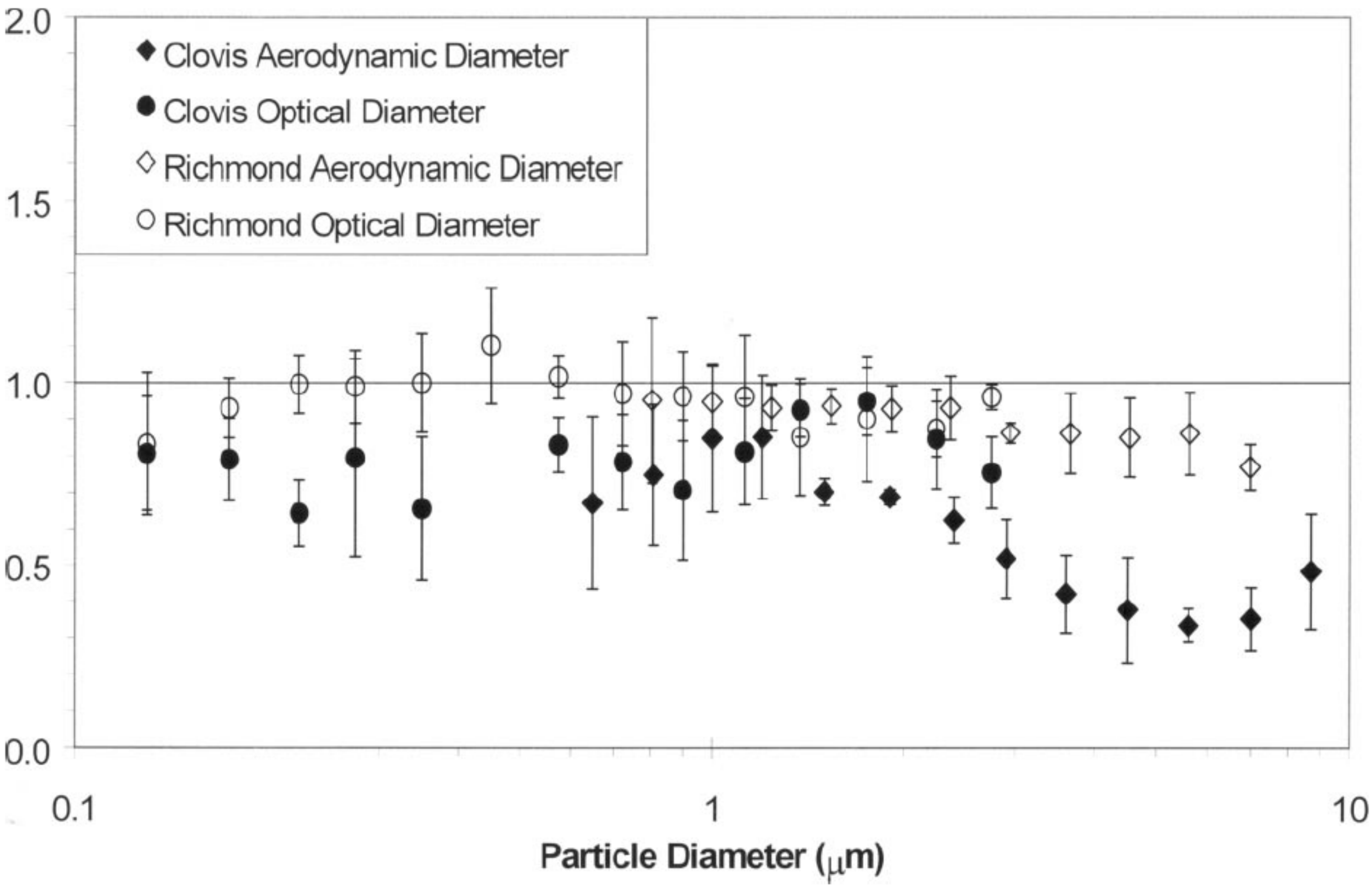


$$\frac{C_{in}}{C_{out}} = \frac{P\lambda}{\lambda + k_{dep}}$$

Thatcher et al. (2003)

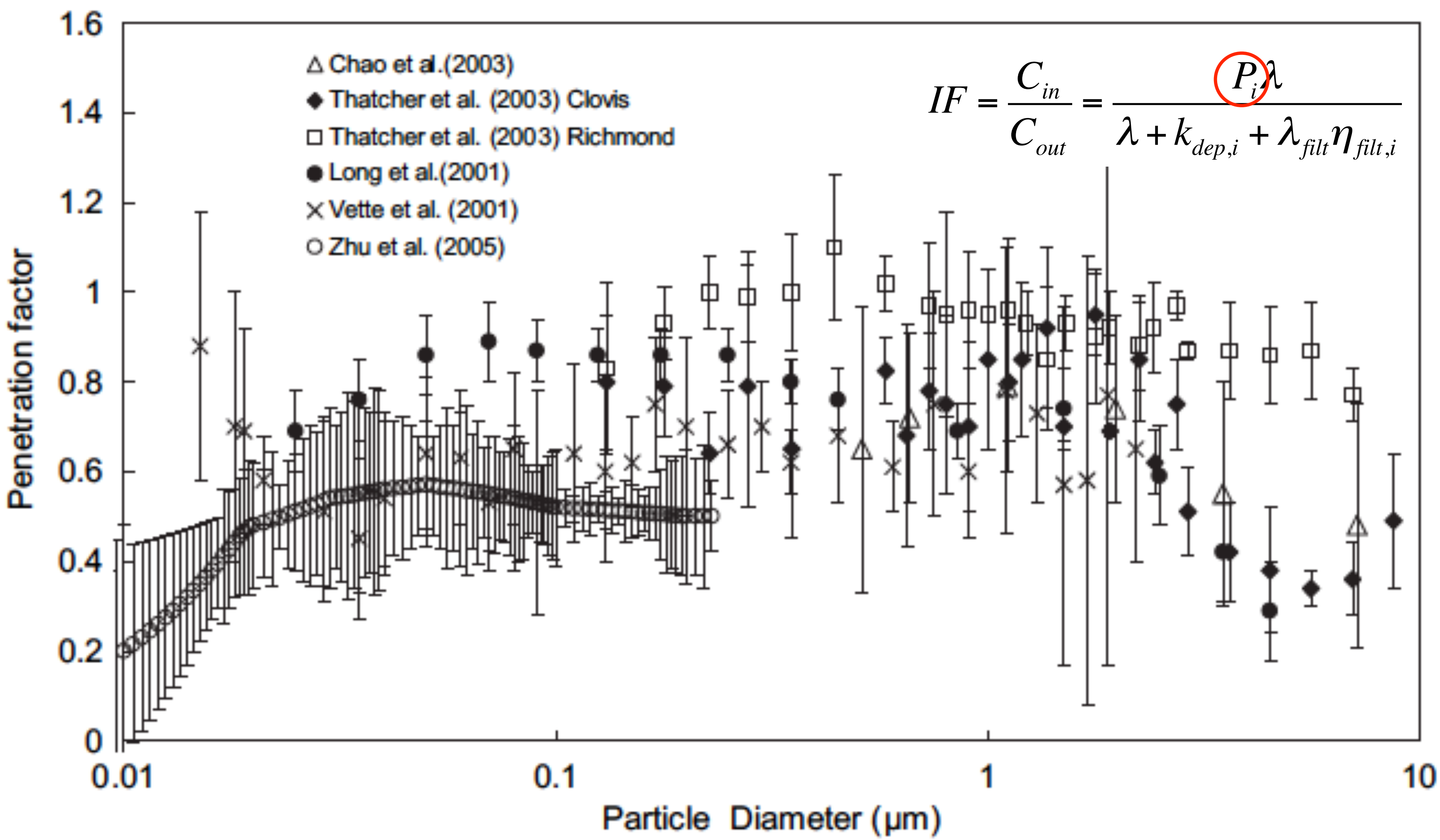


Thatcher et al. (2003)



Estimates of P ranged from 0.3 to 1.0 depending on particle size and home

Summary of penetration factors



Chen and Zhao, 2011 *Atmos Environ*

Rim et al. 2010 *Environ Sci Technol*

- Another method of measuring penetration factor
  - Focused on size-resolved UFPs
- Performed in an unoccupied test house
  - Measurements conducted over entire weekend periods
  - Some with windows closed; some with a window open 8 cm
  - Simultaneous AER measurements
- Data: indoor-outdoor UFPs time-varying for 60 hours
  - AER every 4 hours

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

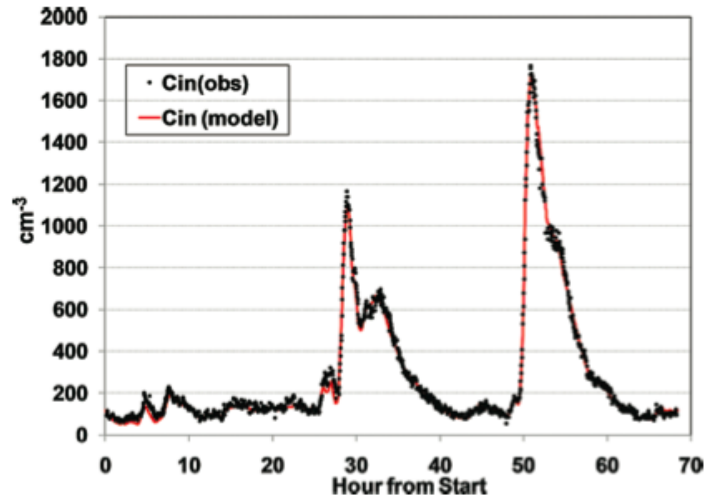
  - Discretized solution to mass balance for each particle size

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

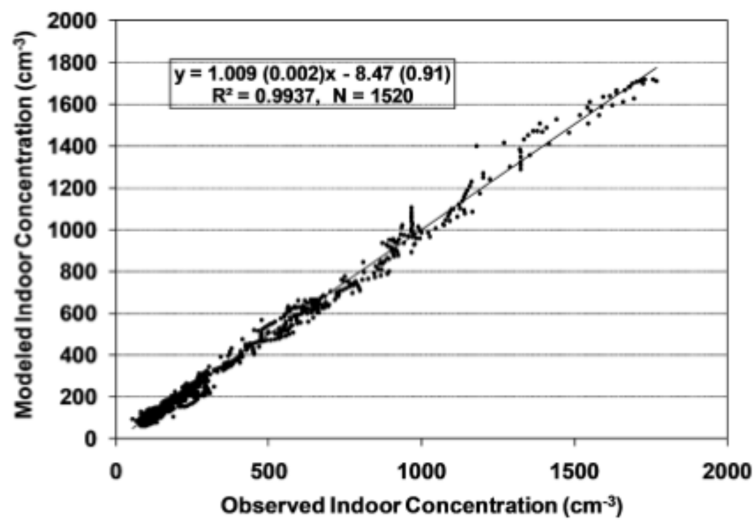
Rim et al. 2010 *Environ Sci Technol*

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

- With 60 hours of data, the best-fitting values of *P* and k_{dep} that fit this equation were found using Excel Solver to minimize the sum of the absolute differences between the modeled and observed indoor number concentrations

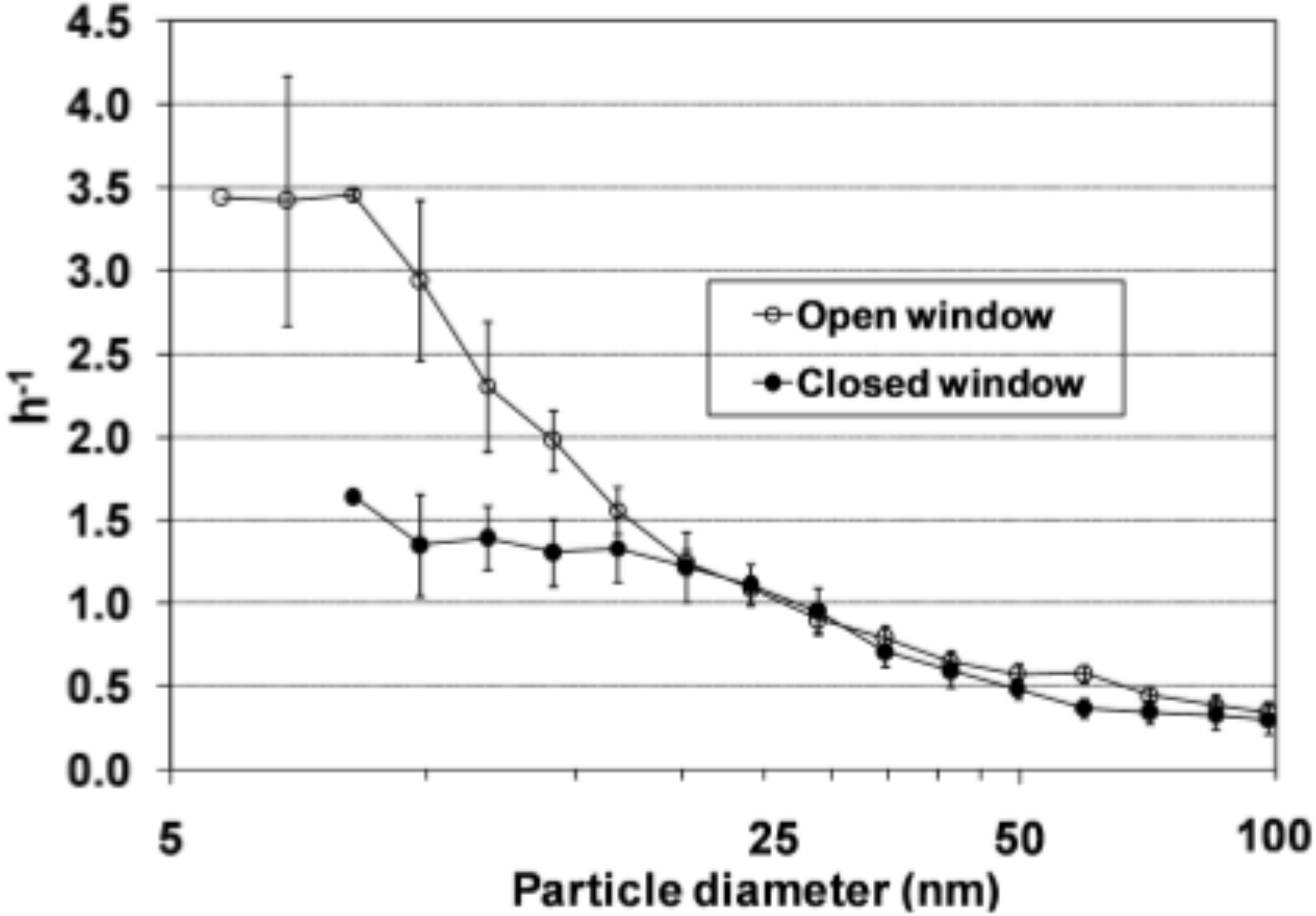


- Measured versus predicted indoor air concentrations compared via linear regression
  - If R^2 was > 0.90, they were happy with their estimates of *P* and k_{dep}

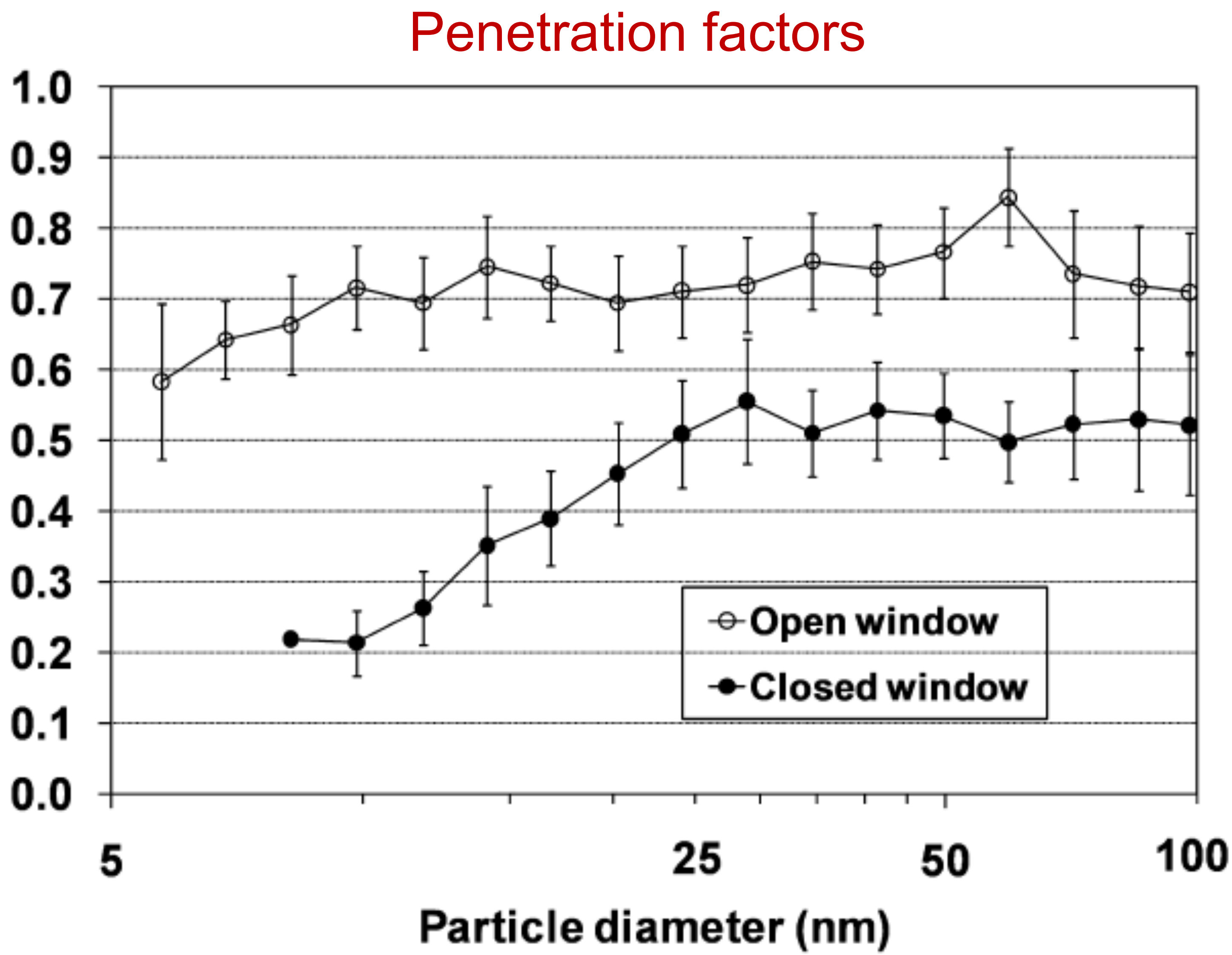


Rim et al. 2010 *Environ Sci Technol*

- Deposition rates



Rim et al. 2010 *Environ Sci Technol*

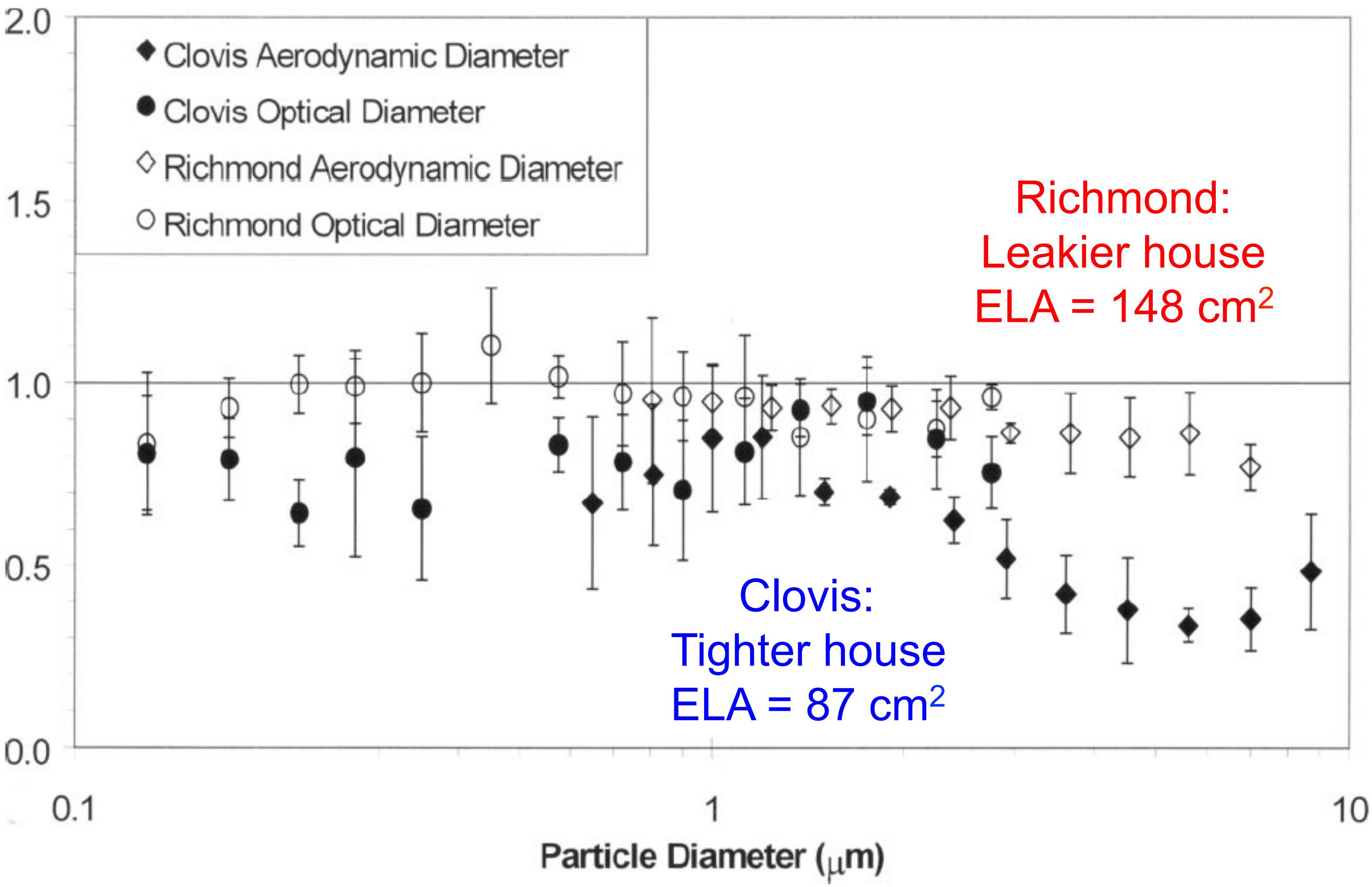


Rim et al., 2010 *Environ Sci Technol*

NEWER WORK

By yours truly

Penetration results from Thatcher et al. (2003)



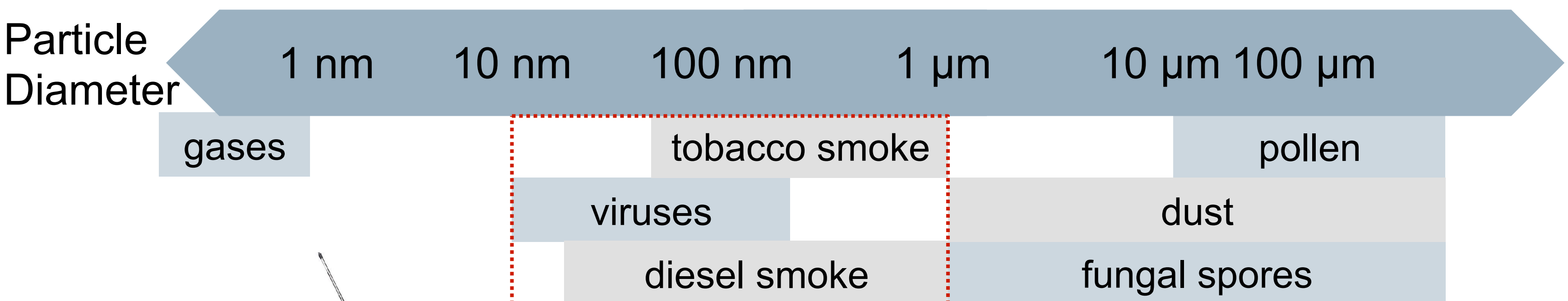
*Estimated Leakage Area (ELA) = *f* (blower door air leakage coefficients & ΔP)

Hypothesis: Particle penetration and building leakage are correlated

- Particles can penetrate through cracks in building envelopes
  - Theoretically a function of:
    - Crack height and length
    - 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
  - Can we learn a lot from a little?
  - Need a better test method for measuring *P* quickly



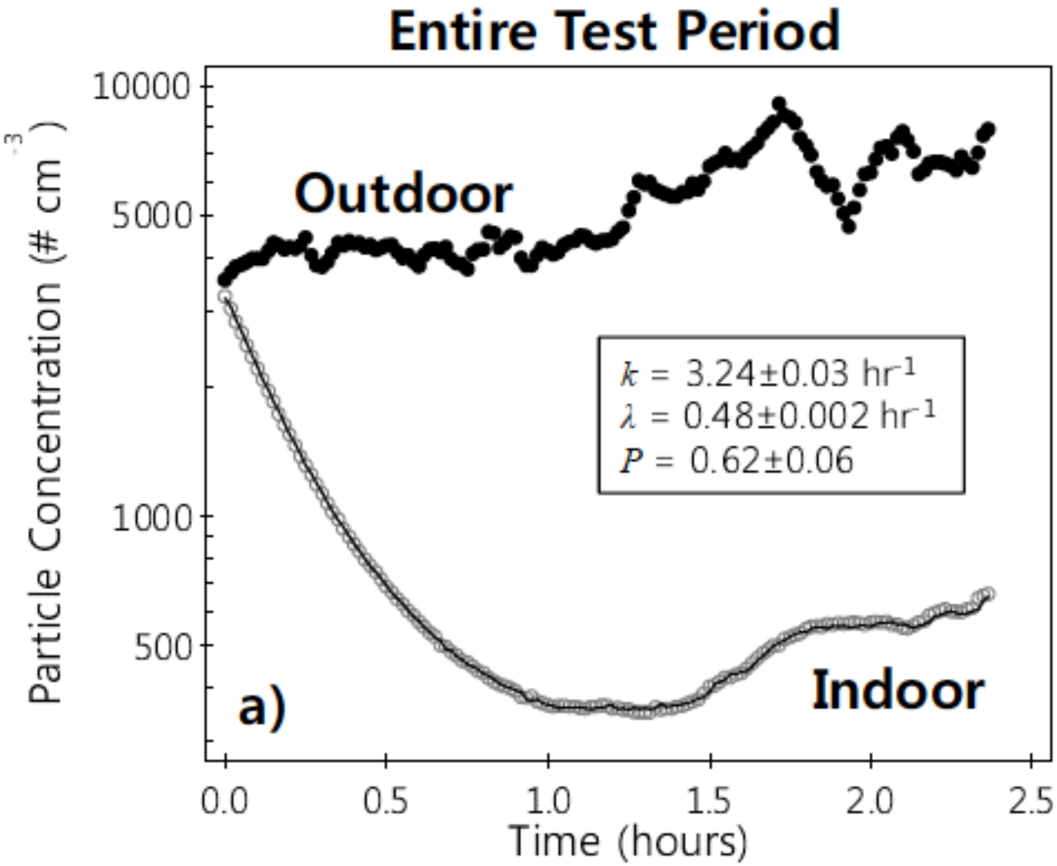
Refined PM penetration test method

- Setup particle monitors indoors and outdoors | TSI P-Traks
  - Logging simultaneously at 1-minute intervals
    - 20 nm to 1 μm

- Perform blower door test (multi-point, de-press. and press.)
  - Afterward: continue pressurizing space, open a door/window across the house
  - Flushes indoor air of any previous indoor PM sources
  - Elevates indoor PM & replaces w/ the same aerosol that exists outdoors
- Close doors and windows, turn on all ceiling, HVAC, and mixing fans
- Elevate indoor CO_2 for air exchange testing | Small CO_2 tank
- Leave the house
  - Measure subsequent decay (+ CO_2 decay | TSI Q-Trak)

- Continue measuring I/O PM and CO_2 decay for ~2-3 hours
  - Solve for k using 1st order decay using data from first ~10-30 minutes
  - Solve for P using forward-marching discretization of mass balance
  - Use estimate of k from previous step
- Total test time: ~3-4 hours

PM infiltration: Refined test method



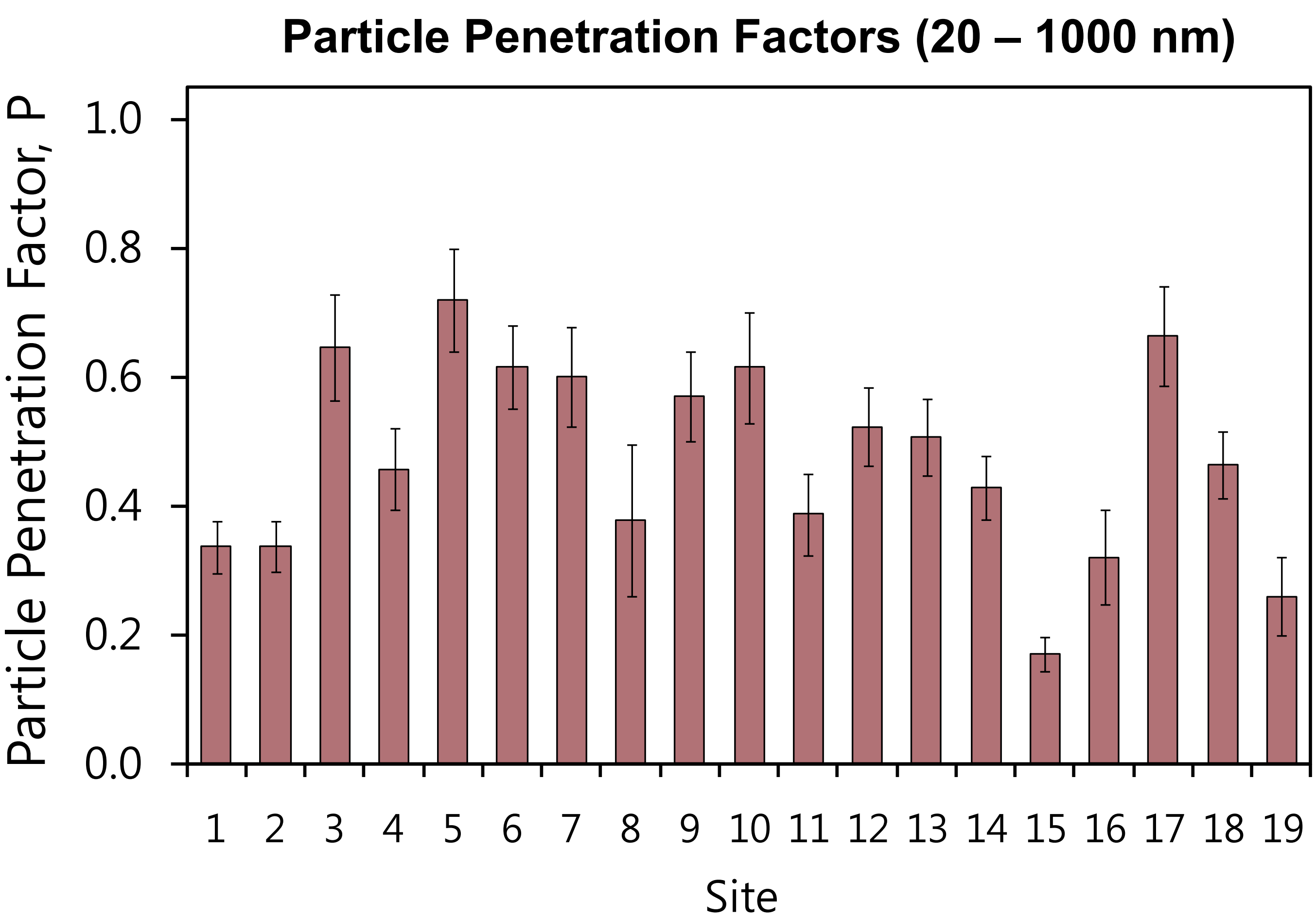
$$C_{in,t} = C_{in,t-1} + \left(P\lambda C_{out,t-1} - (\lambda + k)C_{in,t-1}\right)\Delta t$$

Stephens and Siegel, 2012 *Indoor Air*

PM infiltration: Test homes

Stephens and Siegel, 2012 *Indoor Air*

Particle infiltration results

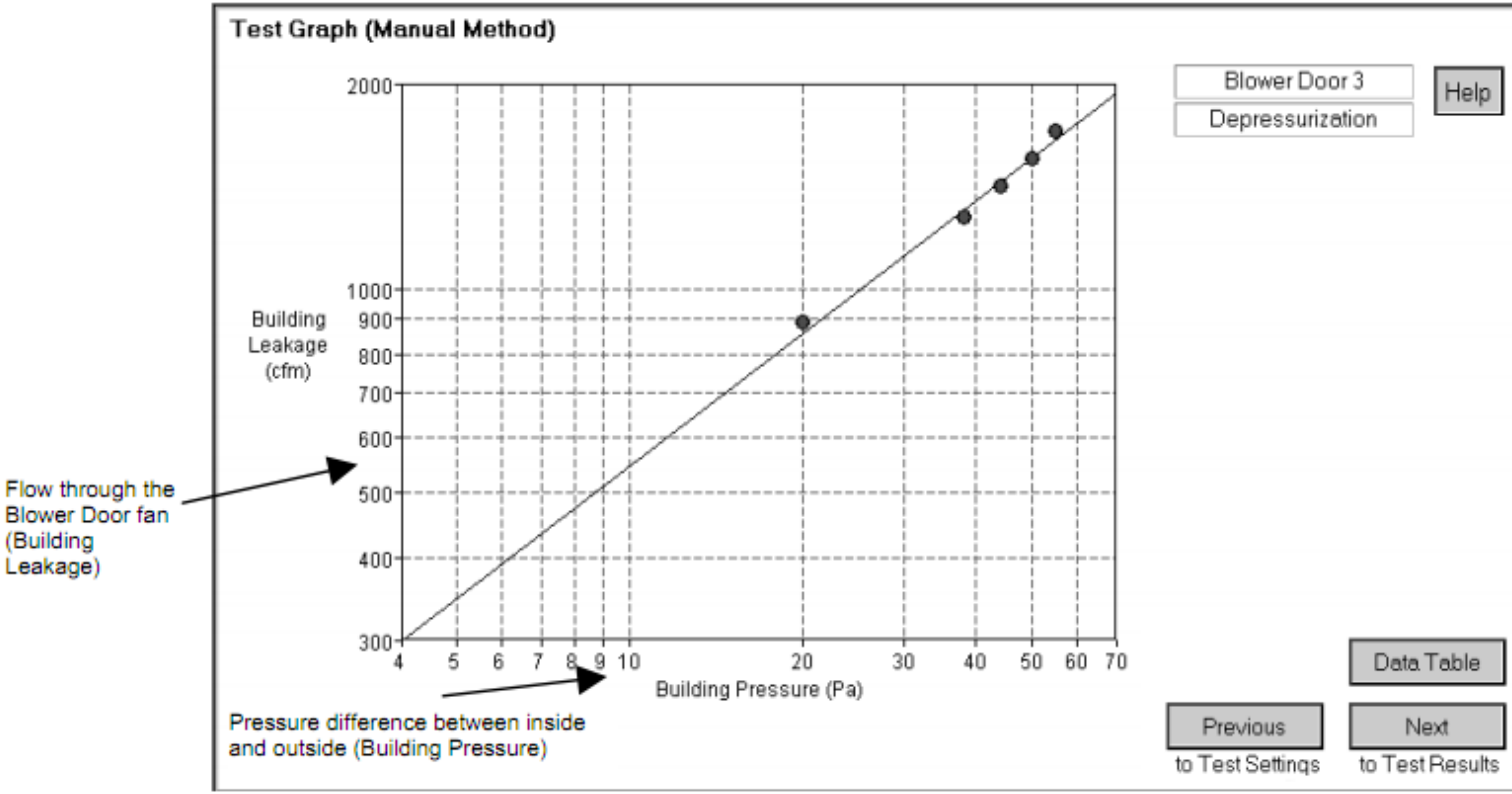


Mean (± SD) = 0.47 ± 0.15 | Range = 0.17 ± 0.03 to 0.72 ± 0.08

Stephens and Siegel, 2012 *Indoor Air*

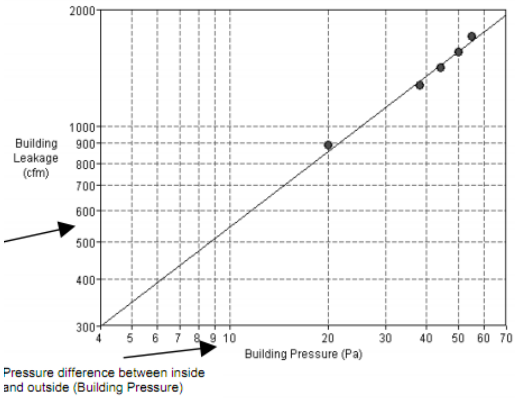
PM infiltration: What can we learn?

- 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)

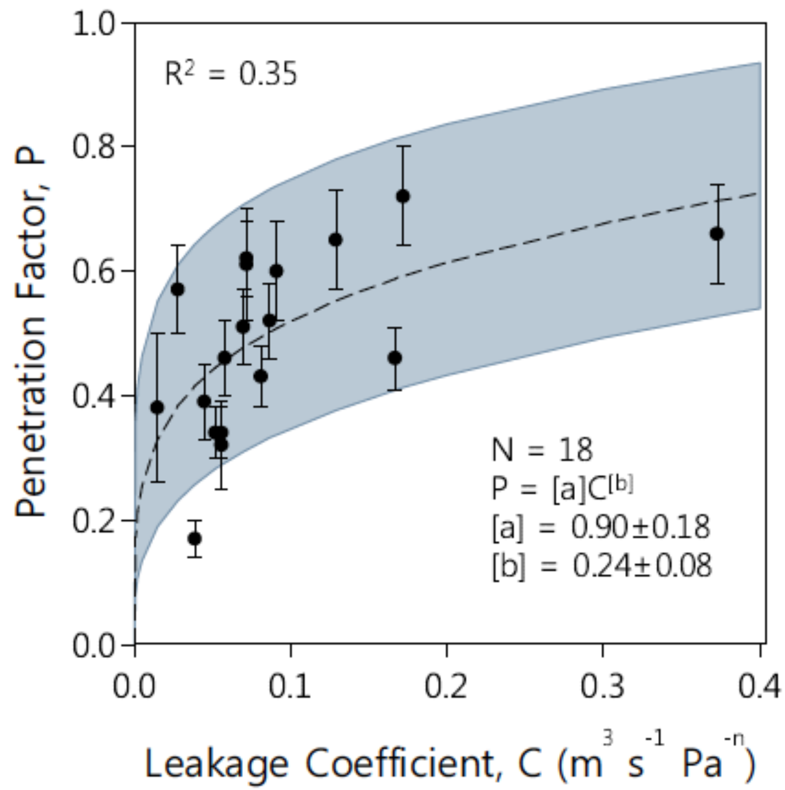
$$ACH_{50} = \frac{Q_{50\ Pa}}{V}$$

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 ($p < 0.001$)

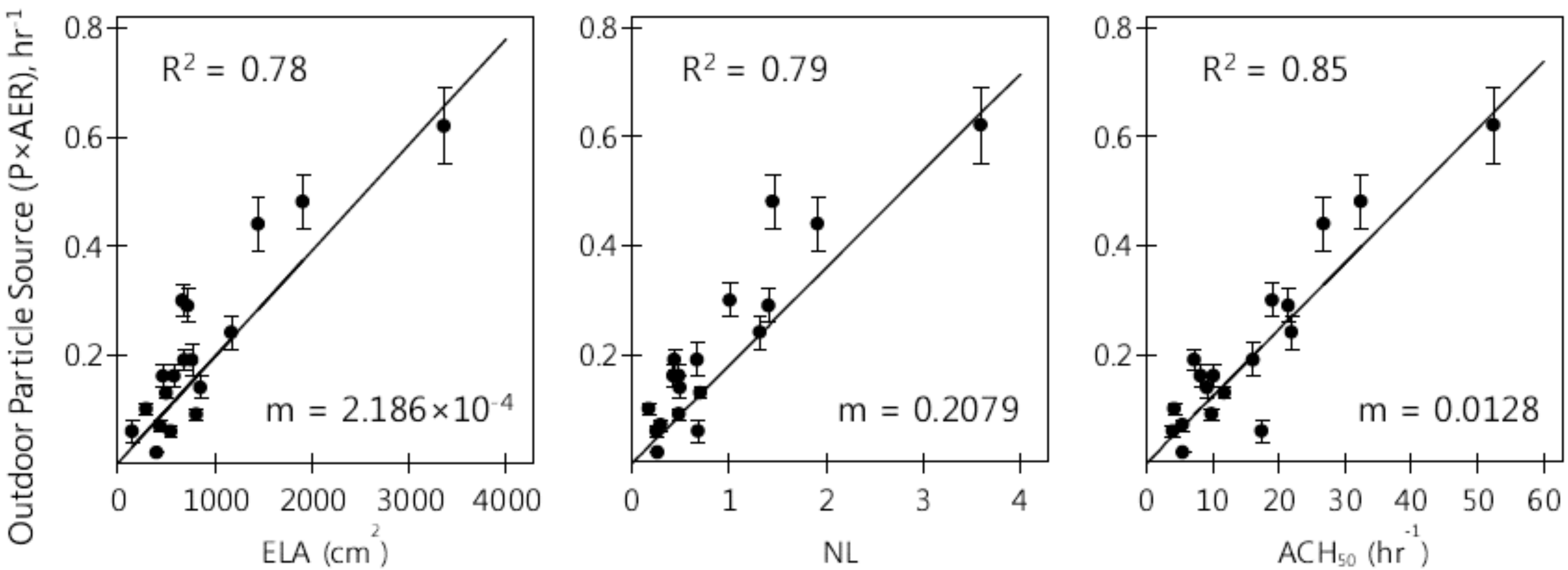


- Association is strong, but predictive ability is low

Stephens and Siegel, accepted to *Indoor Air*, March 2012

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

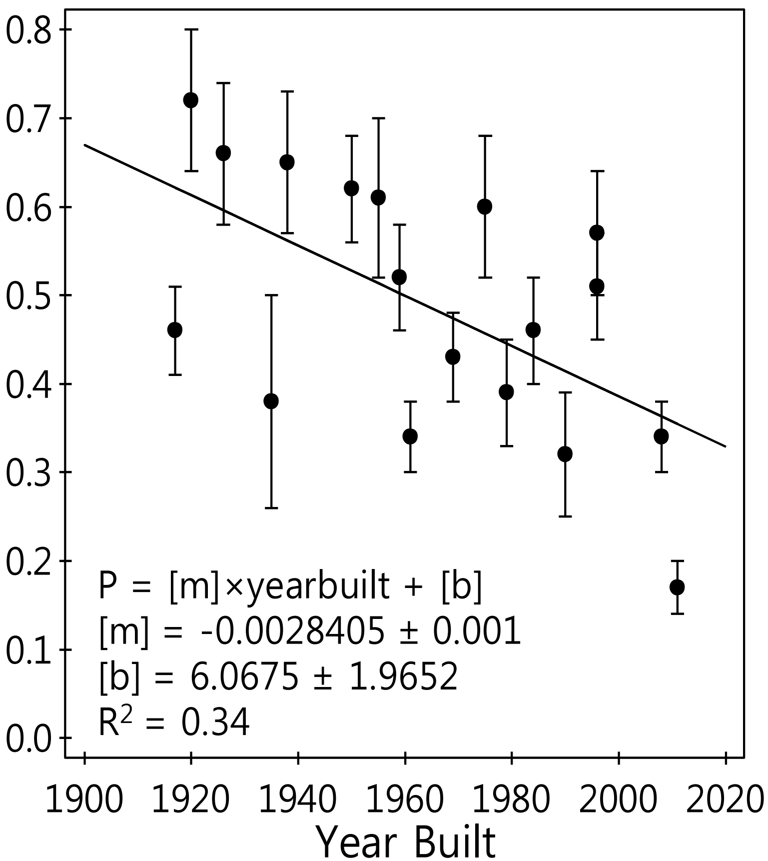
- Potential socioeconomic implications: low-income homes are leakier

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

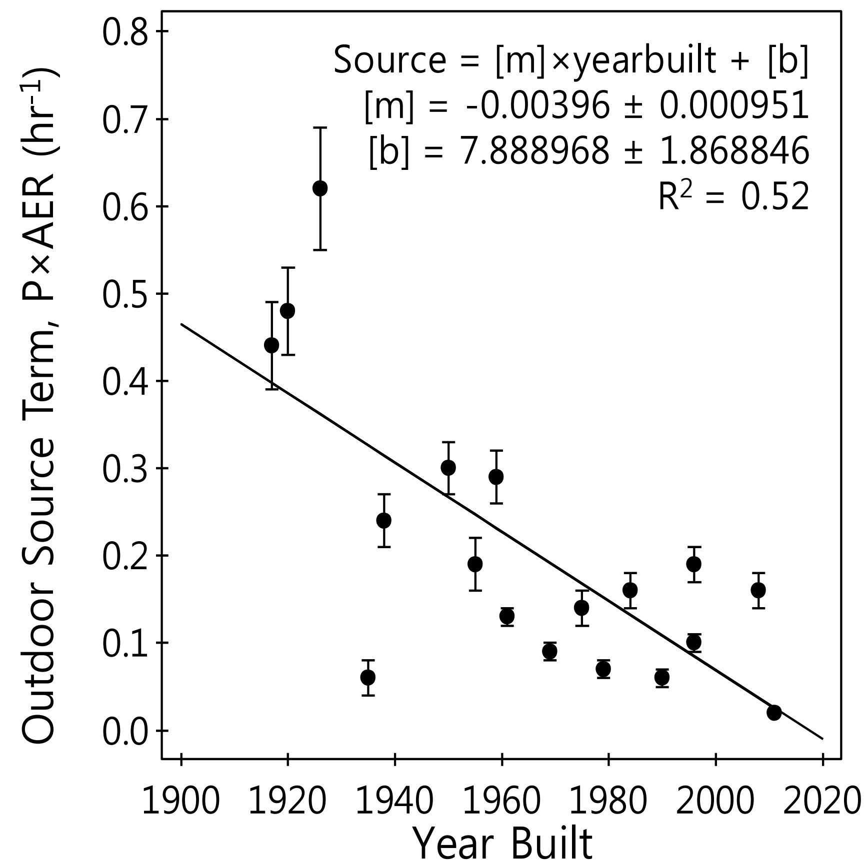
Stephens and Siegel, accepted to *Indoor Air*, March 2012

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, accepted to *Indoor Air*, March 2012

Implications for submicron PM exposure: 19 homes

- Combined effects: $F_{\inf} = \frac{C_{in}}{C_{out}} = \frac{P \times AER}{AER + \beta + f\frac{\eta_{HAC}Q_{HAC}}{V}}$

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

Factor of ~60 to ~70 difference in indoor proportion of outdoor particles between:

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

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

Summary on particle penetration

- In the last 10 years, more measurements of penetration factors through envelopes have been measured
- To date specific penetration measurements have been made in around 40 homes
  - We've made about 20 of these measurements!
- Penetration factors seem to range from ~0.2 to ~1.0 depending on particle size and building envelope characteristics
  - Variations have a big impact on human exposure
- We're continuing to explore potential associations between particle penetration and building characteristics
  - Ultimate goal is to perform a lot of these tests, then never have to perform them gain!

If there is time…

OZONE PENETRATION

Objectives for this work

- Develop method to measure infiltration of O_3
- 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

Brent Stephens,* Elliott T. Gall, and Jeffrey A. Siegel

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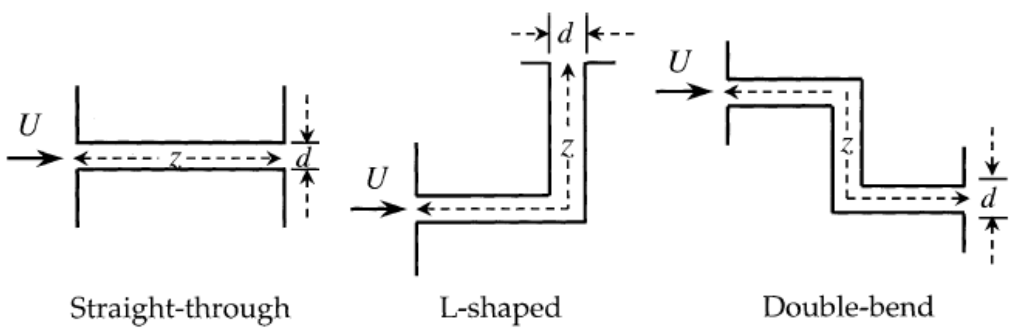
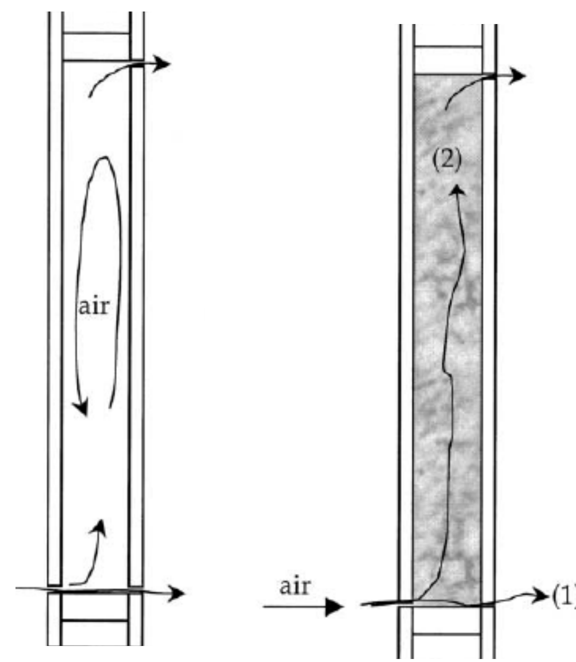
Stephens et al., *Environ. Sci. Technol.* **2012** 46(2), 929-936

Envelope penetration factors

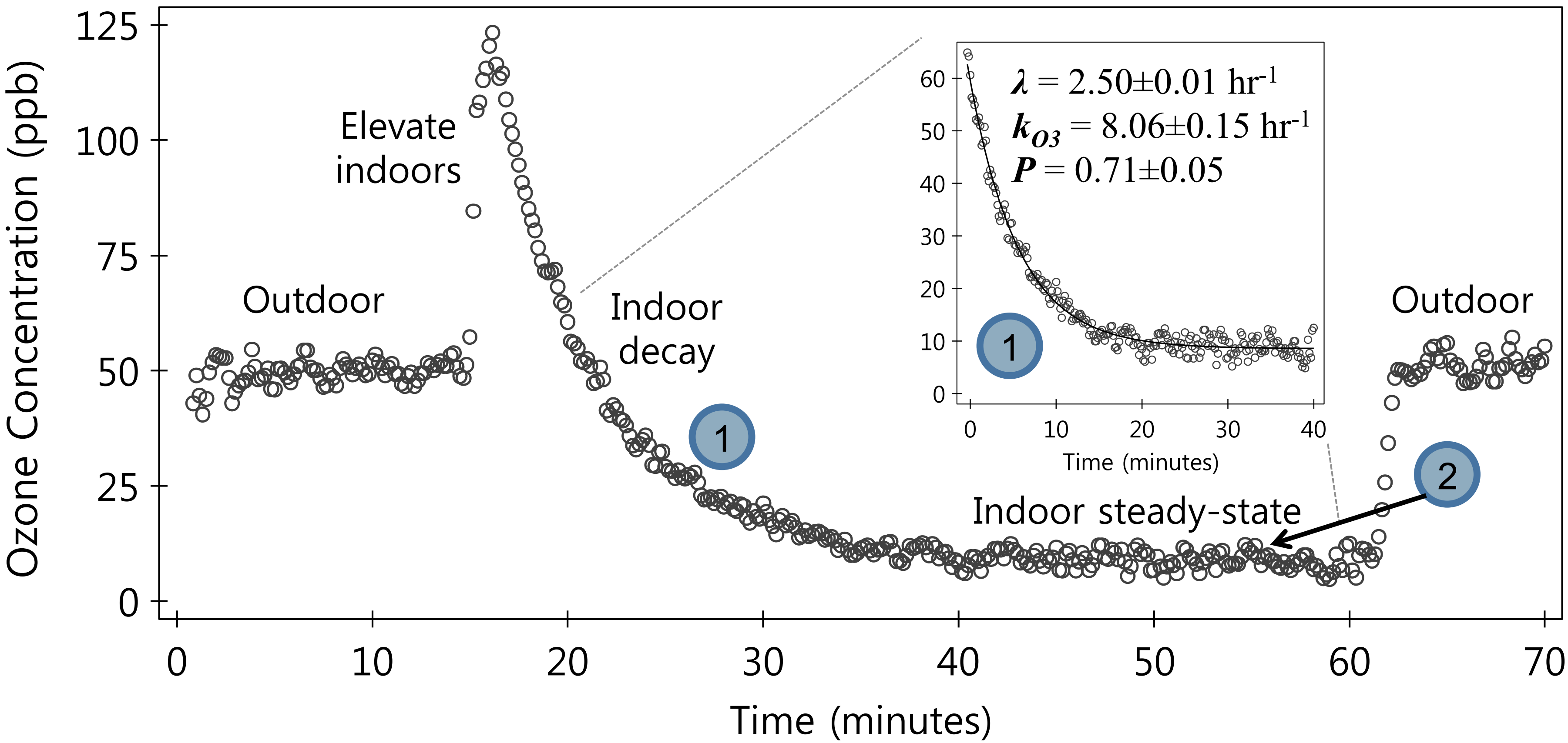
- O_3 can infiltrate through leaks in building envelopes
  - Ozone can react with envelope materials
- No one has ever measured ozone infiltration
  - Some modeling





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

Ozone infiltration: 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) $\frac{dC_{t,in}}{dt} = P\lambda C_{t,out} - \lambda C_{t,in}$

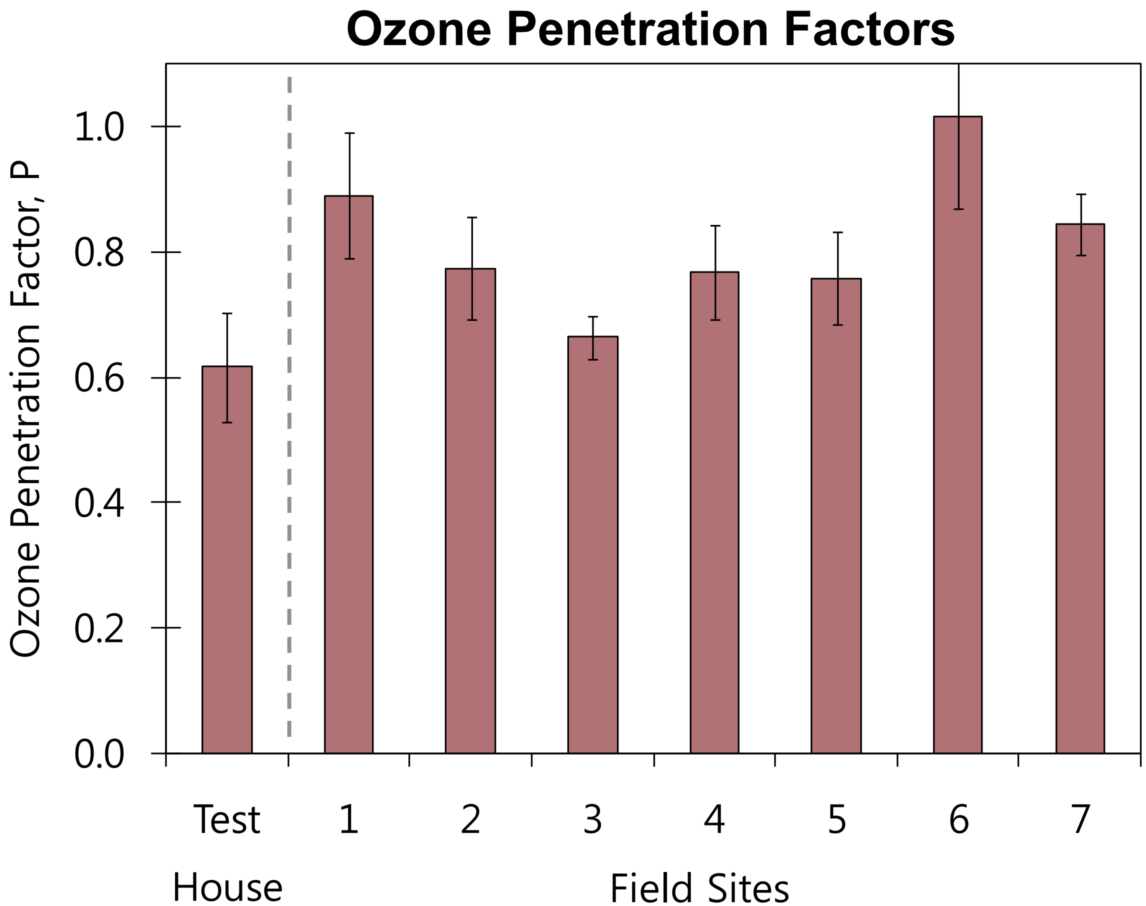
Tracer = CO_2

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

Ozone infiltration field testing

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

Ozone penetration results

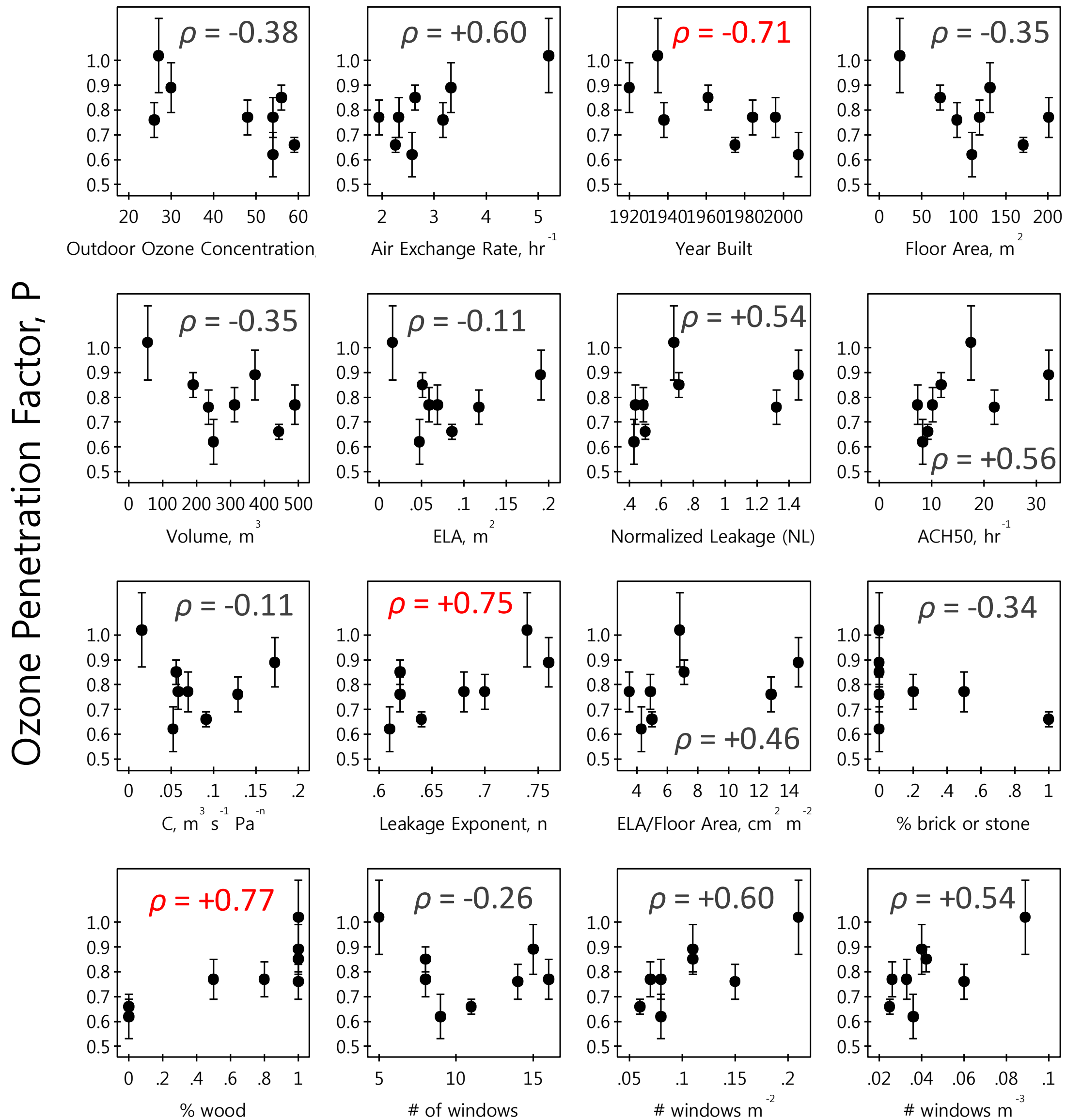


- Mean (± SD) = 0.79 ± 0.13 | Range = 0.62 ± 0.09 to 1.02 ± 0.15
- Usually assumed *P* = 1

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?



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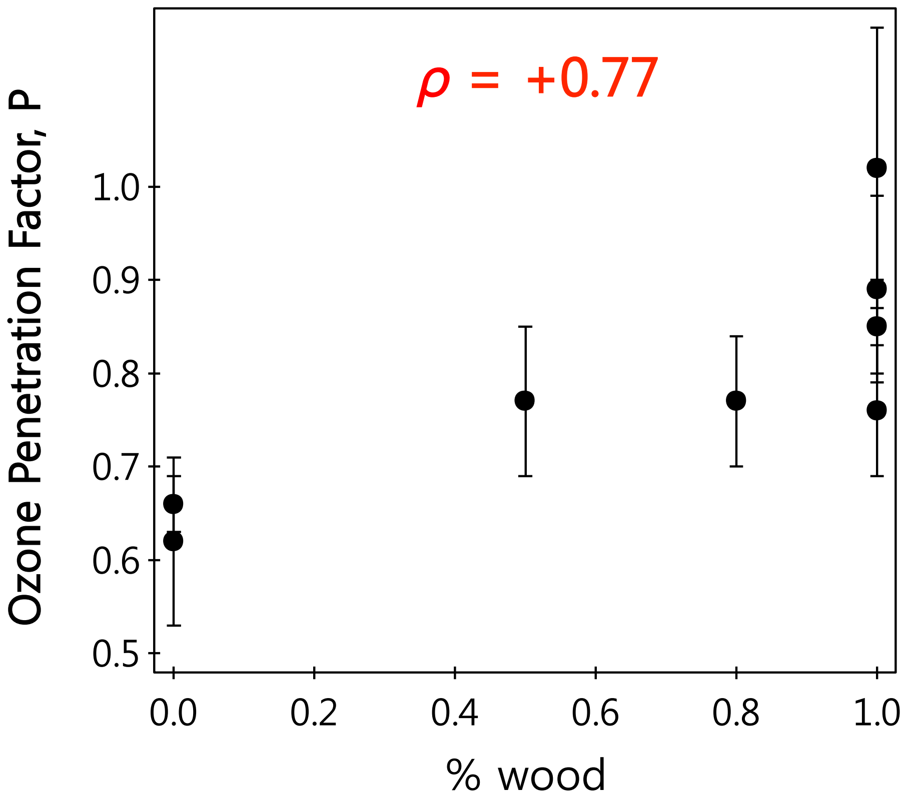
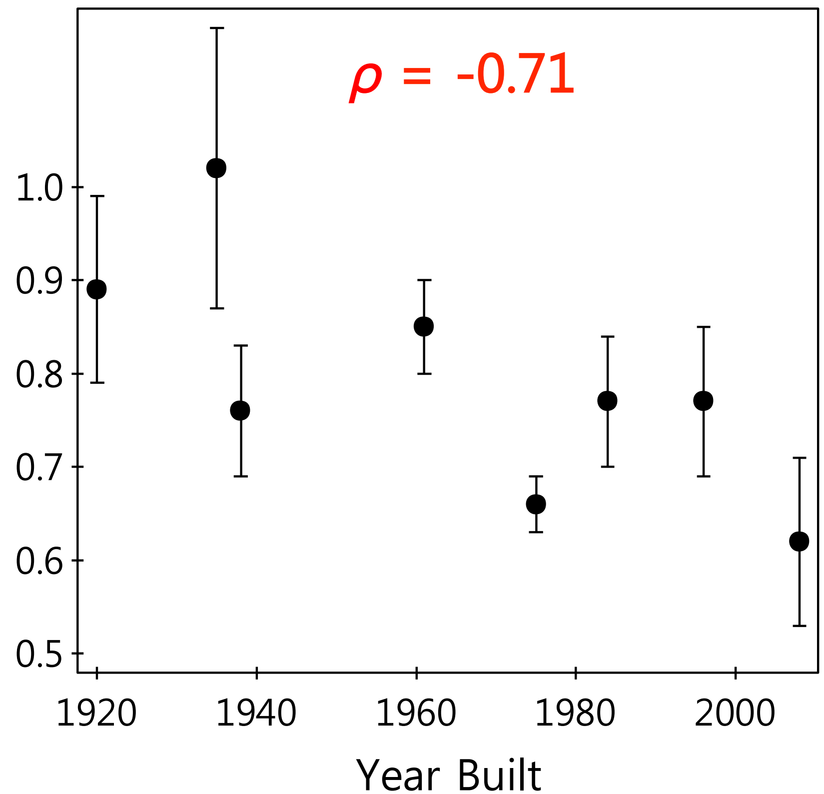
Exploration of ozone results: What can we learn?

Spearman's Rank Correlations

Significant findings ($p \leq 0.05$)



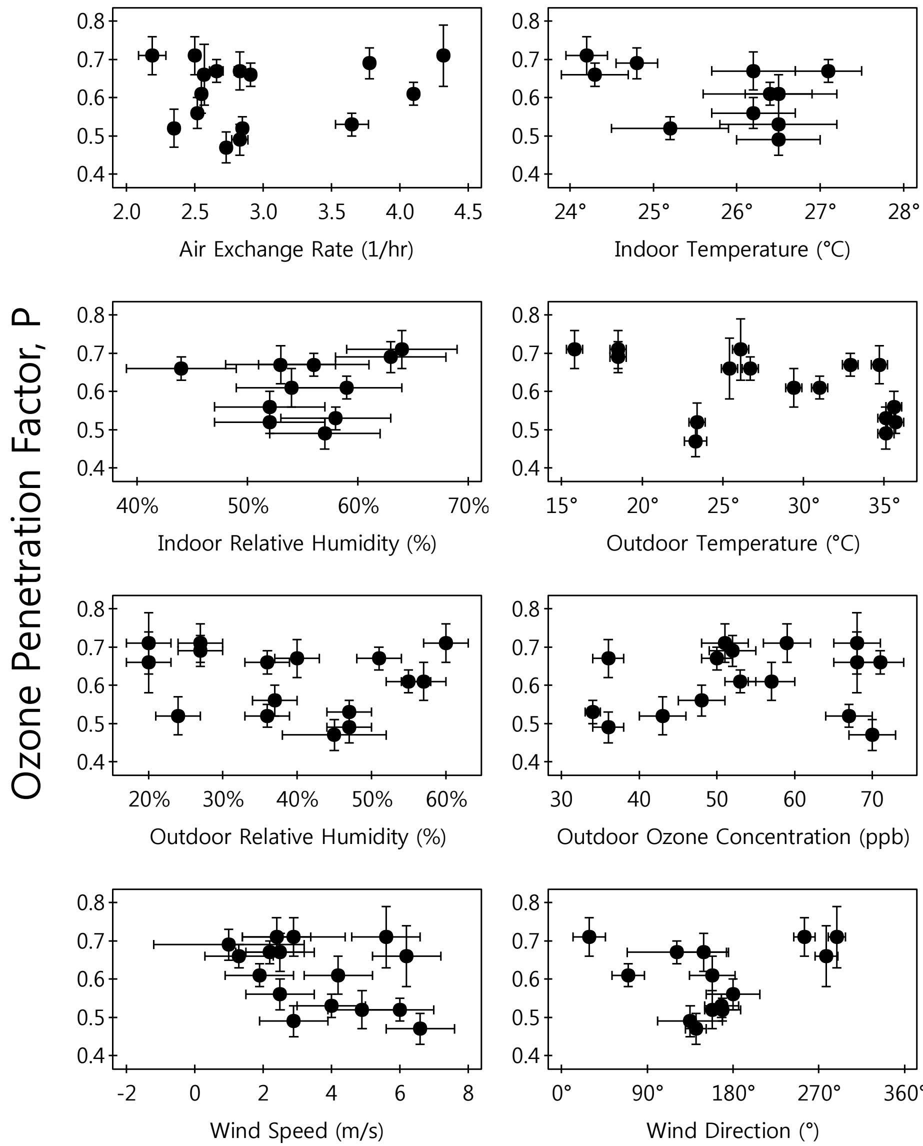


Ozone infiltration was significantly lower in newer homes
And lower in homes with more stone or brick on the exterior

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

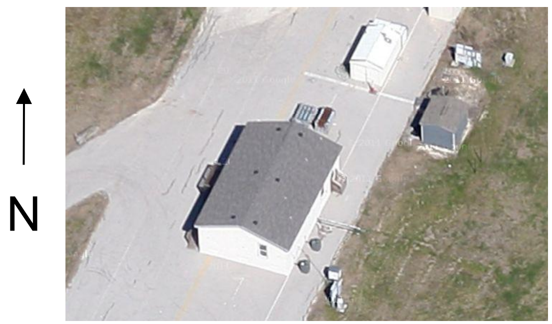
Exploration of results: O_3

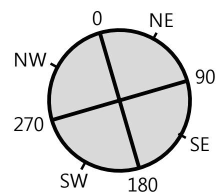
Test House: 16 replicates



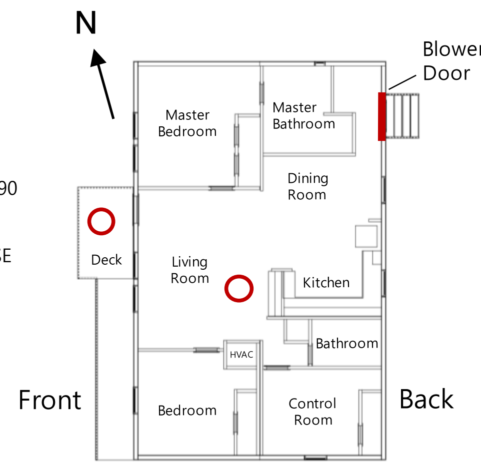
Exploration of results: wind direction

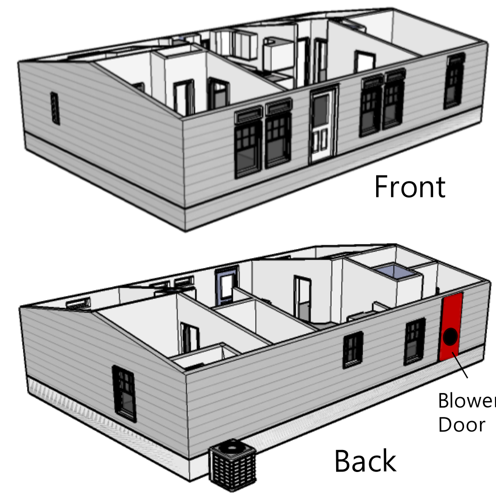
Test House: 14 of 16 replicates

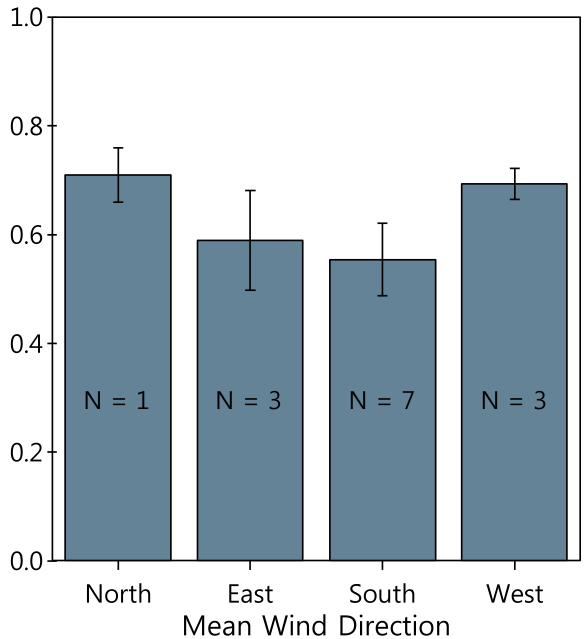




Approaching wind directions





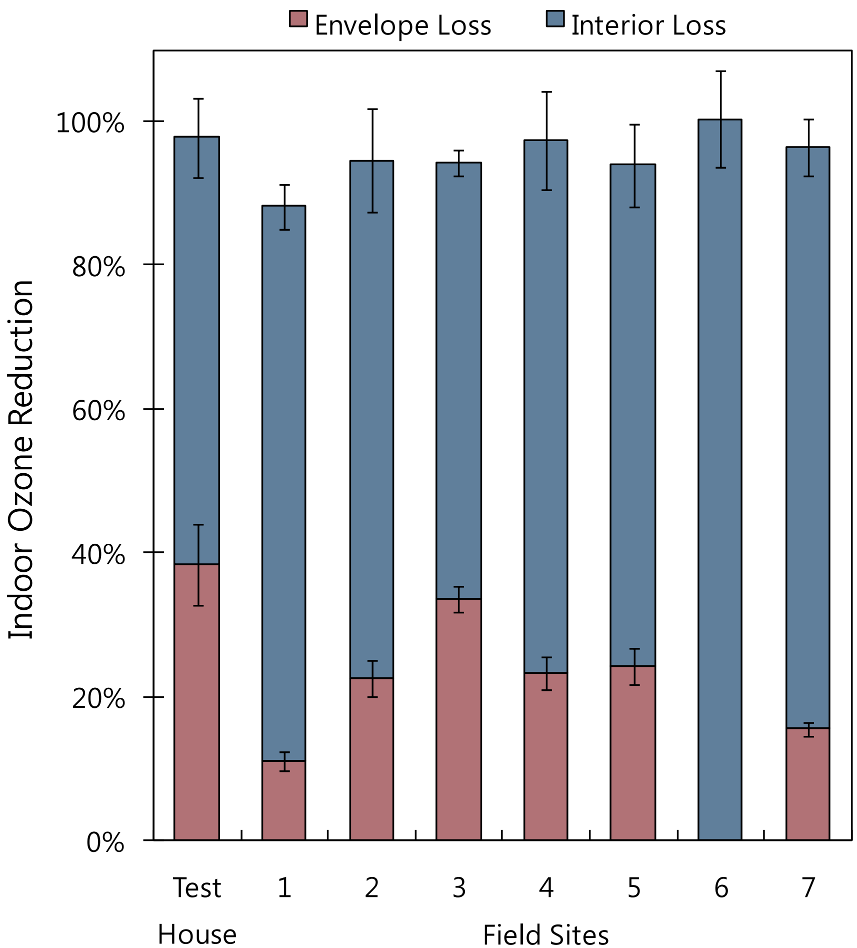


- Winds from N or W:
  - $P = 0.70 \pm 0.03$
- Winds from S or E:
  - $P = 0.57 \pm 0.07$
- Repeatability:
  - Two tests w/ same wind conditions
  - P = 0.52±0.03 and 0.53±0.03

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 (± SD) = 0.79 ± 0.13

k_{O3} ranged from

3.6 ± 0.1 to 16.8 ± 1.1 hr^{-1}

Mean (± SD) = 11.6 ± 6.0 hr^{-1}