ENVE 576
Indoor Air Pollution
Summer 2020

Lecture 8 - Particle deposition, resuspension, and infiltration

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Dr. Brent Stephens, Ph.D.
Dr. Mohammad Heidarinejad, Ph.D., P.E.
Civil, Architectural, and Environmental Engineering
Illinois Institute of Technology
brent@iit.edu
muh182@iit.edu

Aerosol topic coverage

Last time:

- Particle size distributions
- Respiratory deposition
- Particle sources/emissions

Today (and next lecture):

- Deposition
- Resuspension
- Outdoor infiltration/penetration
- Filtration and air cleaners

Particle size distributions & respiratory deposition

Type	Mode I N (cm^{-3})	Mode I D_p (μm)	Mode I $\log \sigma$	Mode II N (cm^{-3})	Mode II D_p (μm)	Mode II $\log \sigma$	Mode III N (cm^{-3})	Mode III D_p (μm)	Mode III $\log \sigma$
Urban	9.93×10^4	0.013	0.245	1.11×10^3	0.014	0.666	3.64×10^4	0.05	0.337
Marine	133	0.008	0.657	66.6	0.266	0.210	3.1	0.58	0.396
Rural	6650	0.015	0.225	147	0.054	0.557	1990	0.084	0.266
Remote continental	3200	0.02	0.161	2900	0.116	0.217	0.3	1.8	0.380
Free troposphere	129	0.007	0.645	59.7	0.250	0.253	63.5	0.52	0.425
Polar	21.7	0.138	0.245	0.186	0.75	0.300	3×10^{-4}	8.6	0.291
Desert	726	0.002	0.247	114	0.038	0.770	0.178	21.6	0.438

Source: Jaenicke (1993).

$$\frac{dN}{d\log d_p} = \sum_{i=1}^{n} \frac{N_i}{\sqrt{2\pi}\log\sigma_i} e^{\left(-\frac{(\log d_p - \log \bar{d}_{g,i})^2}{2(\log\sigma_i)^2}\right)}$$

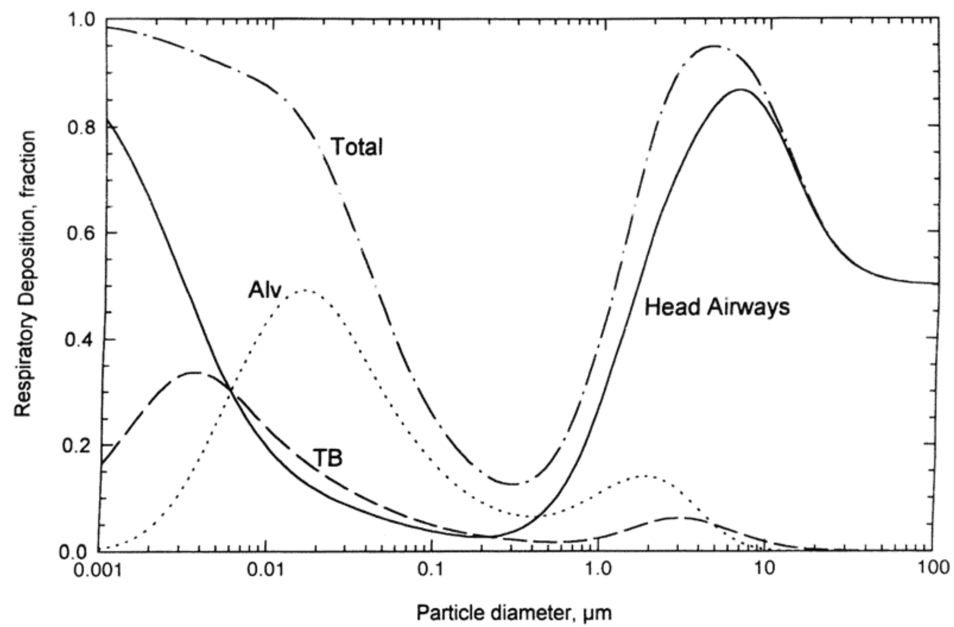
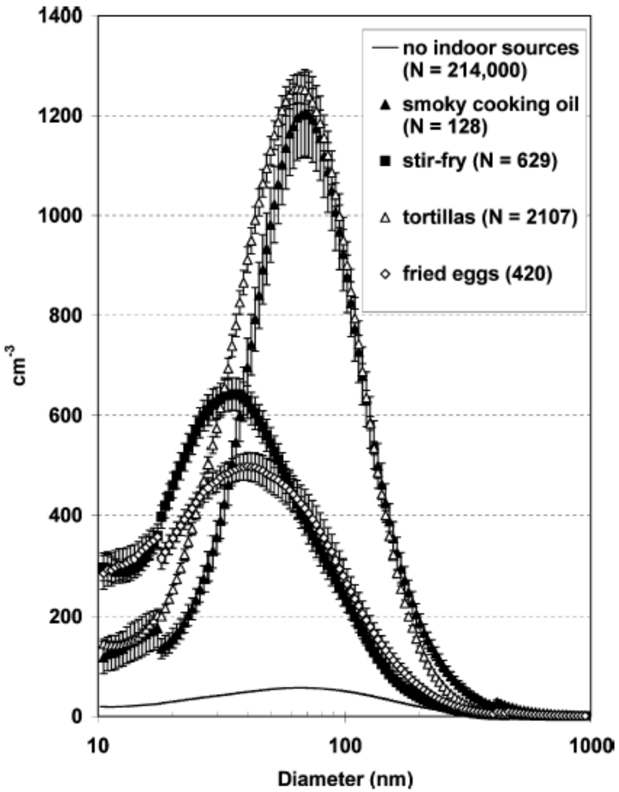


FIGURE 11.3 Predicted total and regional deposition for light exercise (nose breathing) based on ICRP deposition model. Average data for males and females.

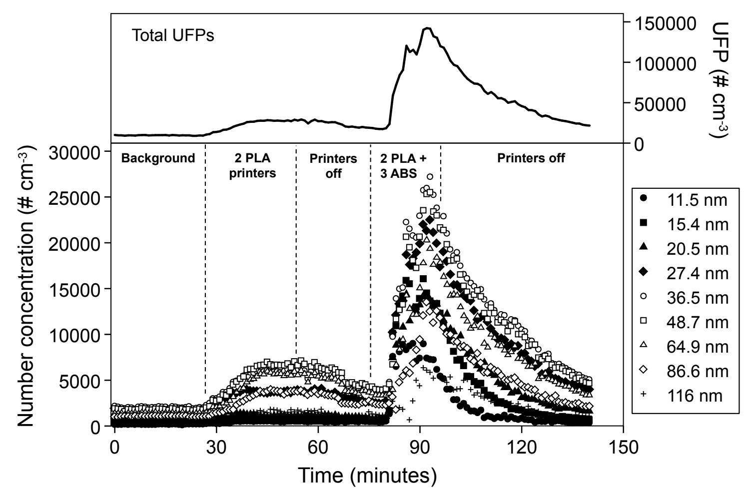
Particle emissions



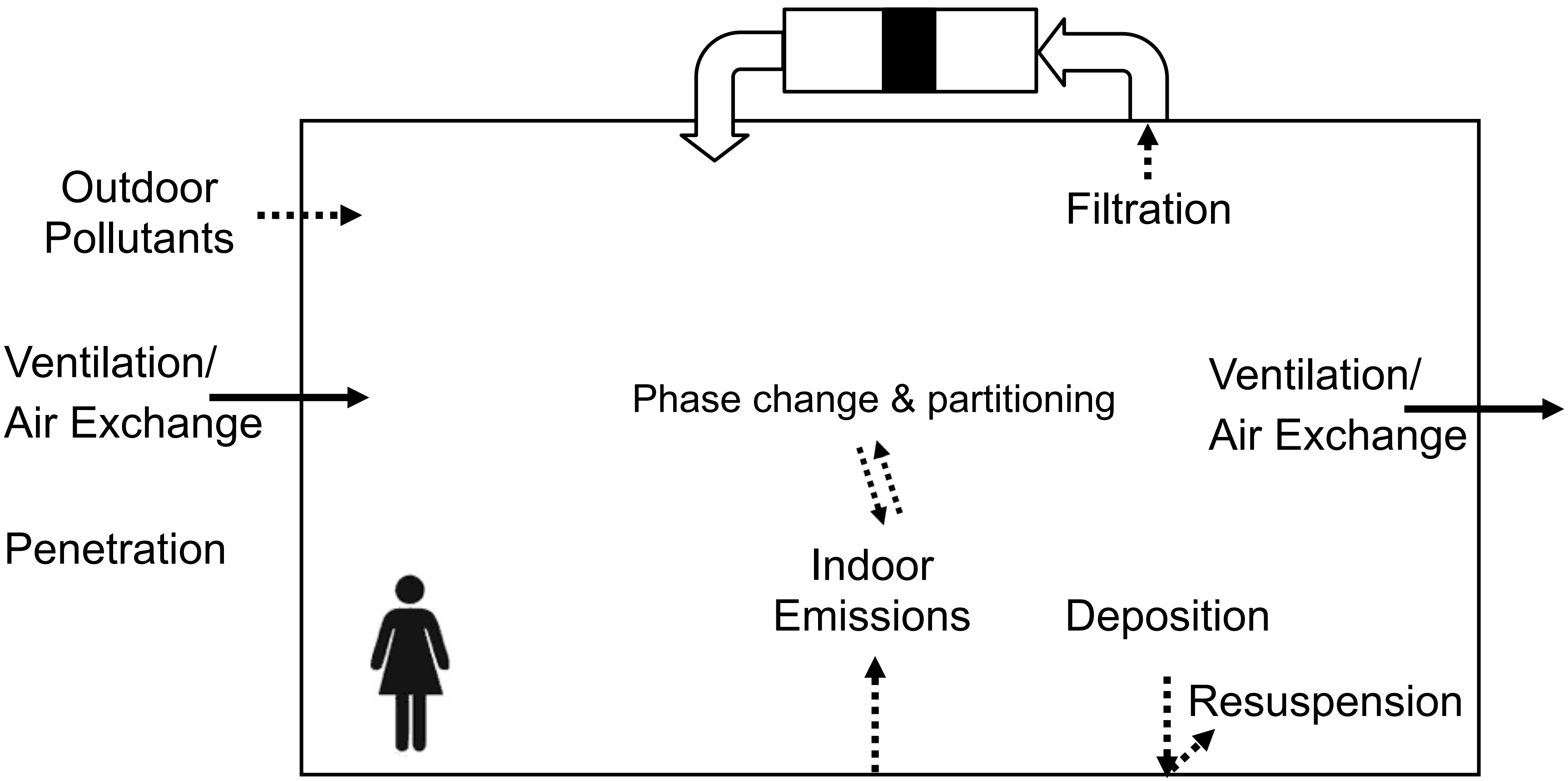
UFP emitting device	Size range	Emission rate (#/min)	Reference
Flat iron with steam	20-1000 nm	6.0×10^{9}	Afshari et al. (2005)
Electric frying pan	10-400 nm	$1.1\text{-}2.7\times10^{10}$	Buonnano et al. (2009)
3D printer w/ PLA	10-100 nm	$\sim2.0\times10^{10}$	Stephens et al. (2013)
Vacuum cleaner	20-1000 nm	3.5×10^{10}	Afshari et al. (2005)
Scented candles	20-1000 nm	8.8×10^{10}	Afshari et al. (2005)
Gas stove	20-1000 nm	1.3×10^{11}	Afshari et al. (2005)
3D printer w/ ABS	10-100 nm	$\sim1.9\times10^{11}$	Stephens et al. (2013)
Cigarette	20-1000 nm	3.8×10^{11}	Afshari et al. (2005)
Electric stove	20-1000 nm	6.8×10^{11}	Afshari et al. (2005)
Frying meat	20-1000 nm	8.3×10^{11}	Afshari et al. (2005)
Radiator	20-1000 nm	8.9×10^{11}	Afshari et al. (2005)
Laser printers	6-3000 nm	4.3×10^{9} to 3.3×10^{12}	He et al. (2010)
Cooking on a gas stove	10-400 nm	$1.1\text{-}3.4\times10^{12}$	Buonnano et al. (2009)

$$C_{i,in}(t) = C_{i,in,t=0}e^{-L_i t} + \left[C_{i,in,ss,bg} + \frac{2(E_{i,PLA}/V) + 3(E_{i,ABS}/V)}{L_i}\right]\left(1 - e^{-L_i t}\right)$$

$$\ln\left(\frac{C_{i,in}(t) - C_{i,in,ss,bg}}{C_{i,in}(t=0) - C_{i,in,ss,bg}}\right) = -L_i t$$

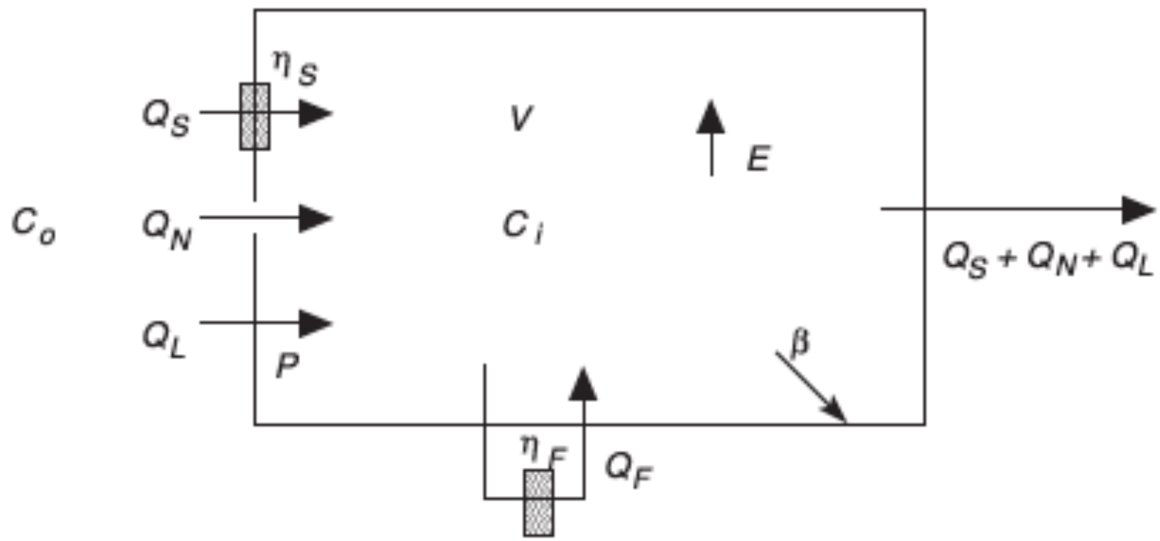


Mass (or number) balance approach for particles



Mass (or number) balance approach for particles

- Basic mass/number balance on particles of diameter i:



$$V\frac{dC_i}{dt} = E_i + C_{out,i}\left[Q_{vent}(1-\eta_{vent,i}) + Q_{nat} + Q_{inf}P_i\right] - C_i\left[Q_{vent} + Q_{nat} + Q_{inf} + v_{d,i}A + Q_{filt}\eta_{filt,i}\right]$$

$$\frac{dC_i}{dt} = \frac{E_i}{V} + C_{out,i}\left[\lambda_{vent}(1-\eta_{vent,i}) + \lambda_{nat} + \lambda_{inf}P_i\right] - C_i\left[\lambda_{vent} + \lambda_{nat} + \lambda_{inf} + k_{dep,i} + \lambda_{filt}\eta_{filt,i}\right]$$

Which parameters vary by particle size?

ETS lung penetration example

- Nazaroff, W. W., Hung, W. Y., Sasse, A. and Gadgil, A. J., 1993. Predicting regional lung deposition of environmental tobacco-smoke particles. *Aerosol Science and Technology* **19**, 243-254

- Modeling exercise
  - Examine emissions from ETS
  - Used lung deposition model to examine where ETS particles end up

- Dynamic model
  - Assumed uniform cigarette smoking rate for first 16 hours of a day
  - Followed by 8 non-smoking hours
  - Varied smoking activity, age of exposed individuals

Emissions from ETS

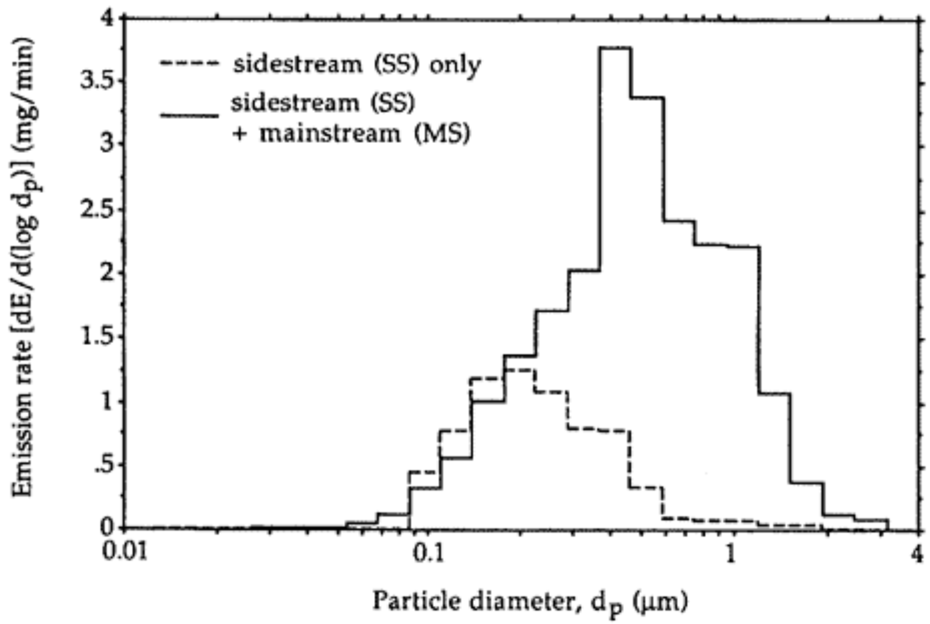
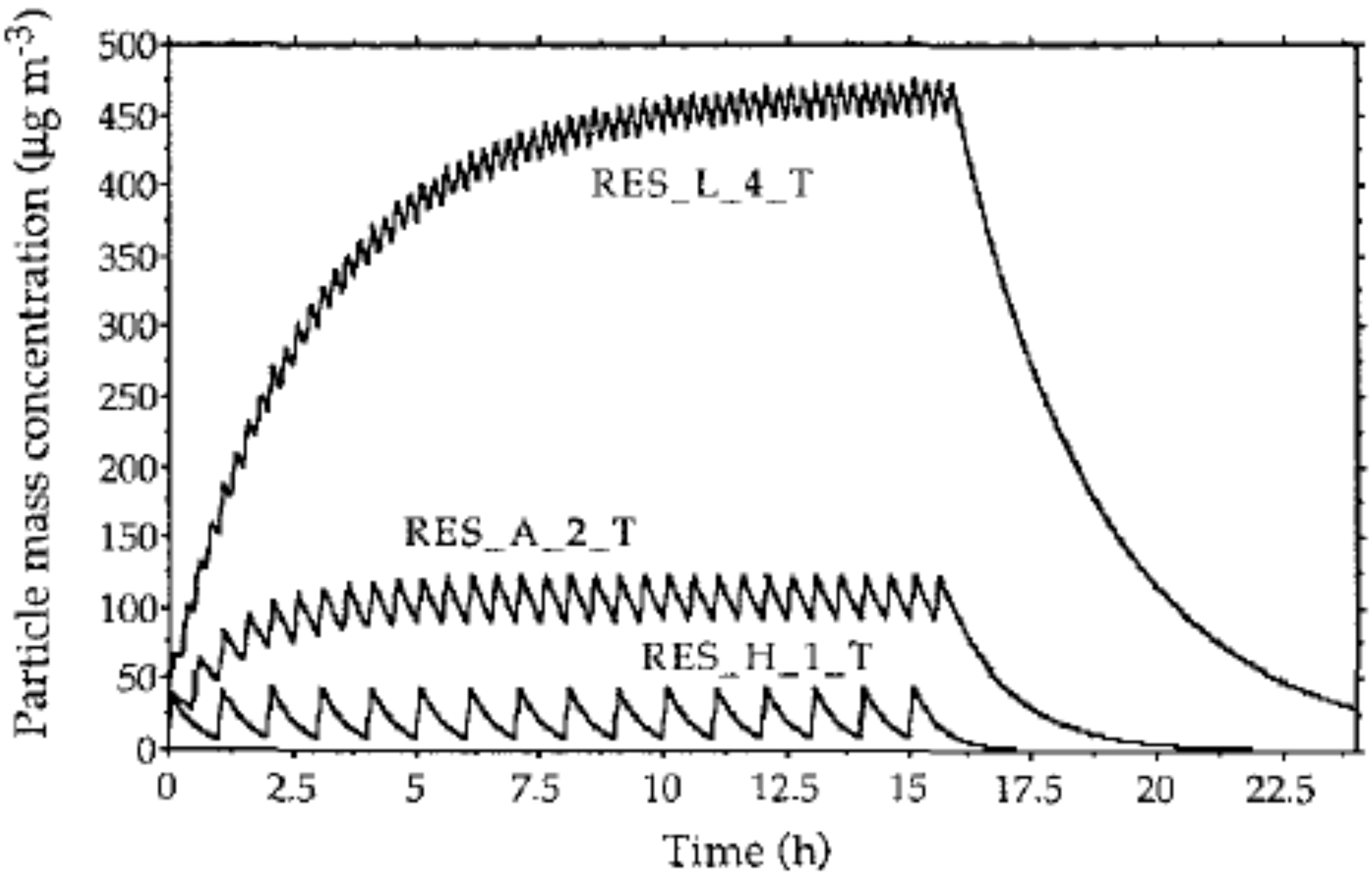


FIGURE 1. Effective particle emission rate from a burning cigarette as a function of particle diameter. The form of the figure is such that the area under a curve between two particle sizes is proportional to the mass emission rate of all particles within those size limits. These experiments were reported by Sextro et al. (1991). The emission profiles are based on a presumed particle density of 1.4 g cm^{-3}.

Nazaroff et al., 1993 *AS&T*

Indoor concentration profiles from ETS



Simulation designations

RES_H_1_S	**RES_A_2_S**	**RES_L_4_S**
RES_H_1_T	**RES_A_2_T**	**RES_L_4_T**

air-exchange rate: **H** = 1.7 h^{-1}; **A** = 0.68 h^{-1}; **L** = 0.28 h^{-1}
cigarette smoking frequency: **1**, **2**, or **4** per hour

Nazaroff et al., 1993 *AS&T*

Mean indoor concentrations from ETS

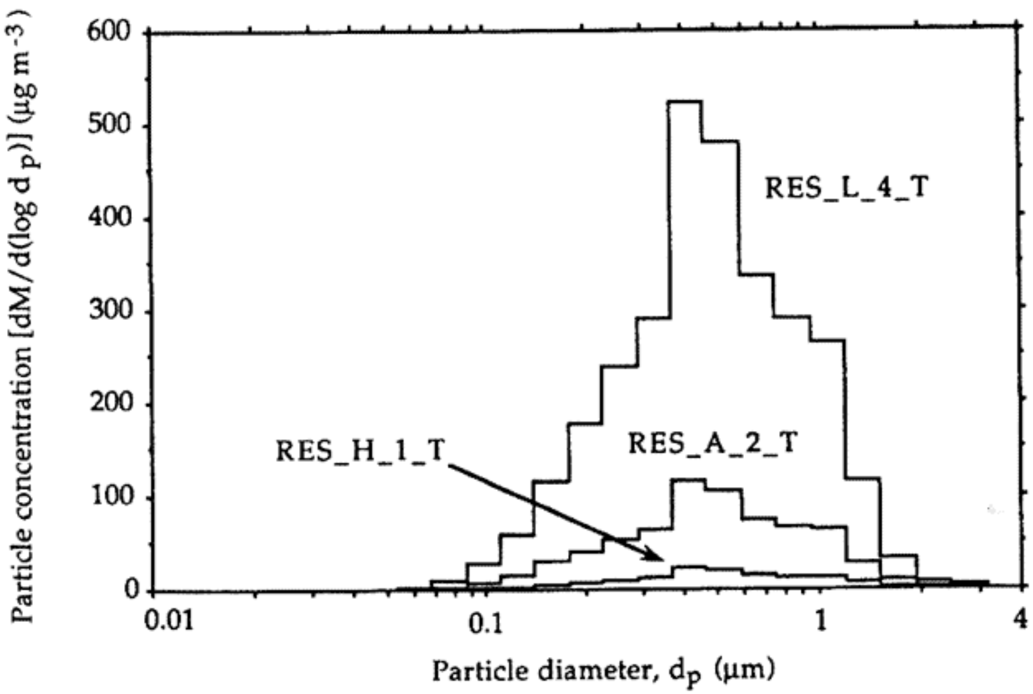


FIGURE 4. Average environmental tobacco smoke particle size distribution over 24-h period for three residential simulations corresponding

Simulation designations

RES_H_1_S	**RES_A_2_S**	**RES_L_4_S**
RES_H_1_T	**RES_A_2_T**	**RES_L_4_T**

air-exchange rate: **H** = 1.7 h^{-1}; **A** = 0.68 h^{-1}; **L** = 0.28 h^{-1}
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Nazaroff et al., 1993 *AS&T*

ETS lung deposition

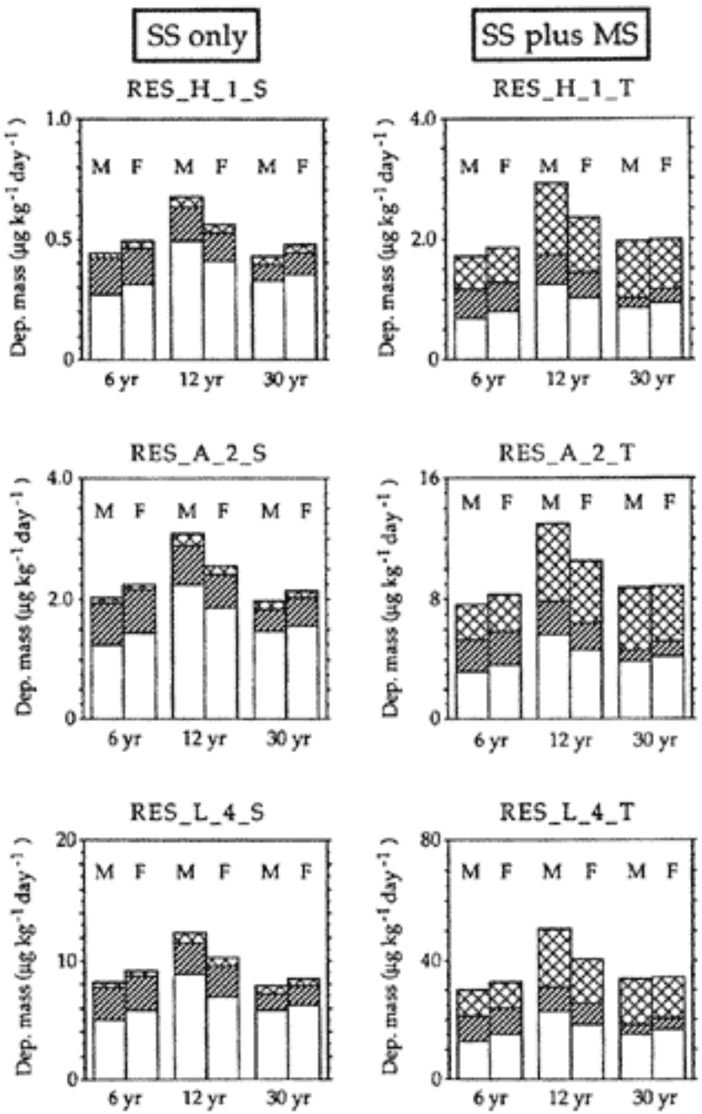
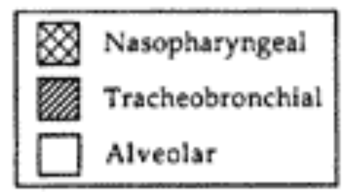
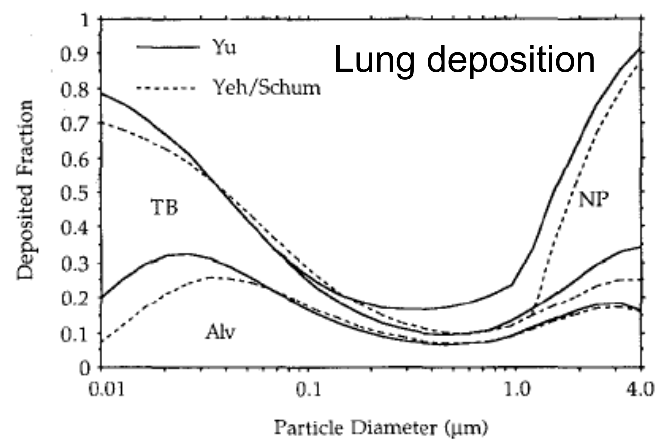


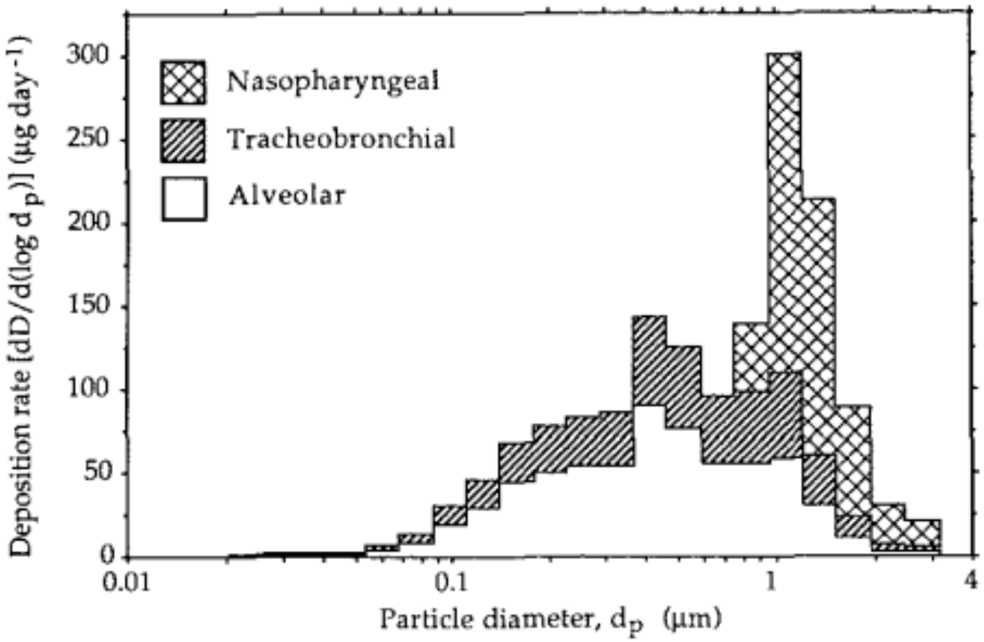
FIGURE 5. Regional lung deposition of environmental tobacco smoke particles from simulations of residential exposure. Each frame shows results for three age groups and each gender for one combination of smoking rate, particle emission profile, and building ventilation rate. The height of each bar gives the total respiratory deposition of particle mass per day per kg of body weight. Refer to Tables 1 and 2 for a description of simulation conditions. Note that the vertical scale varies from frame to frame.

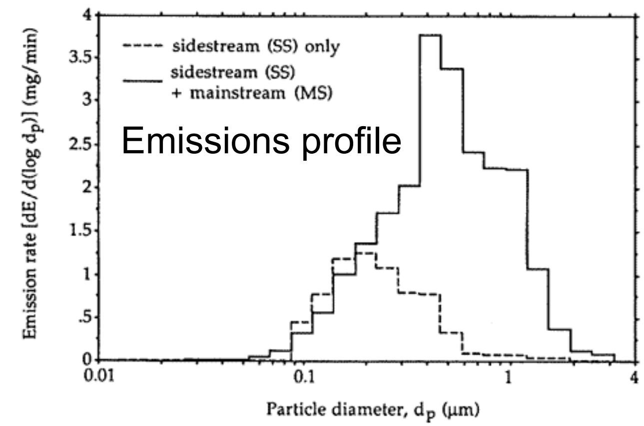




Nazaroff et al., 1993 *AS&T*

ETS lung deposition





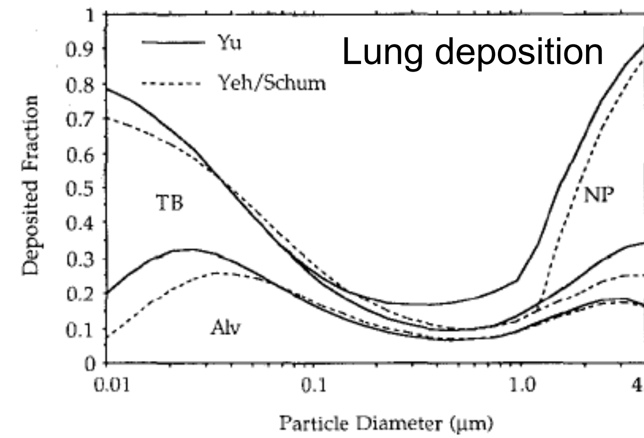
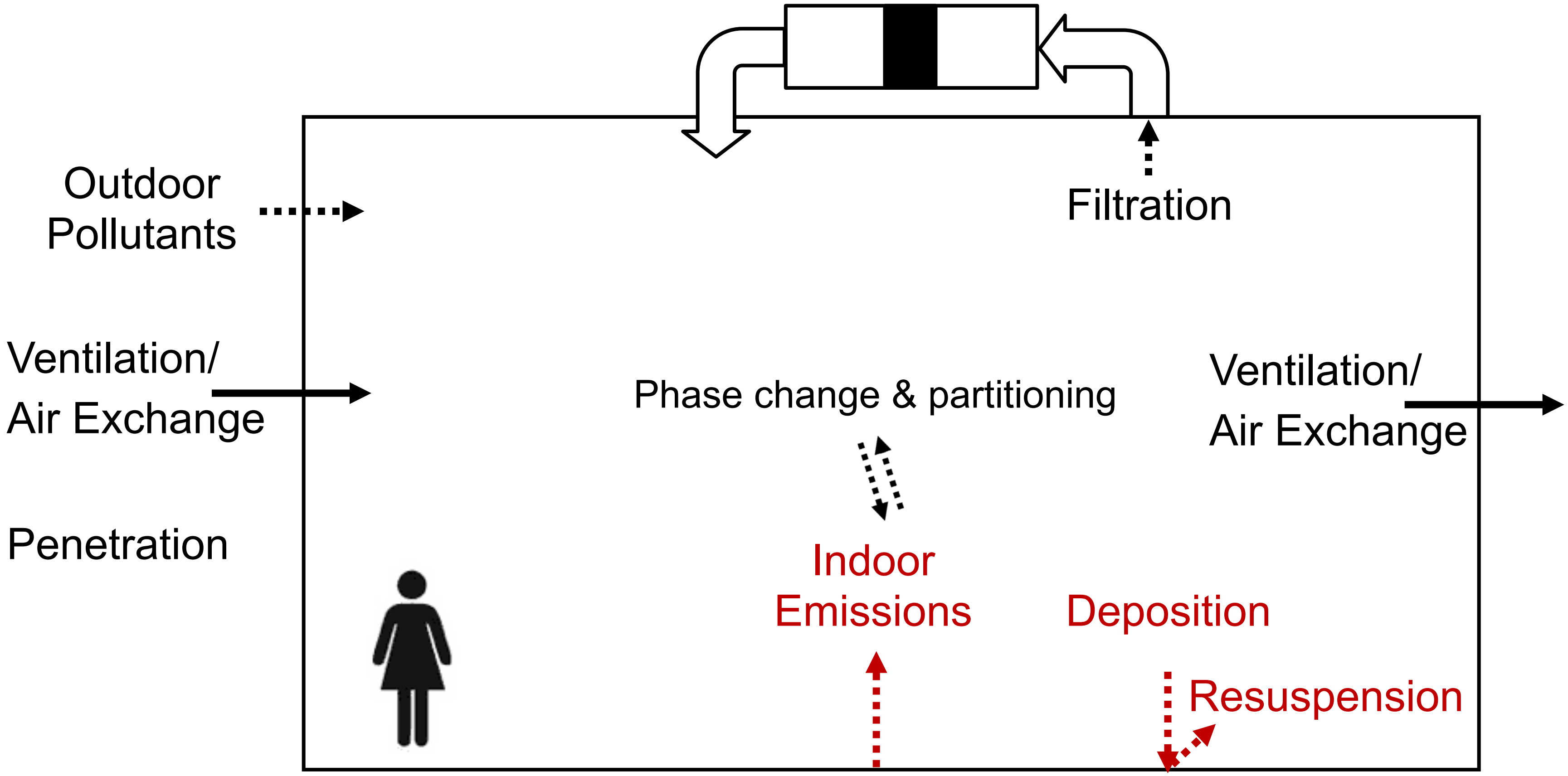


FIGURE 6. Size distribution of deposited mass of environmental tobacco smoke particles in 6-year-old boy for simulation RES_A_2_T. The form of the figure is such that the shaded area between two particle sizes is proportional to the average 24-h mass deposition rate of particles within those size limits. See Tables 1 and 2 for a description of simulation conditions.

Nazaroff et al., 1993 *AS&T*

Mass (or number) balance approach for particles



RESUSPENSION AND DEPOSITION

Indoor losses: Deposition

- We discussed deposition previously
  - Primarily in terms of **settling velocity**
  - Also mentioned diffusion, impaction, thermophoresis, and electrostatic forces
- I showed one of the first good modeling efforts for size-dependent deposition rate loss coefficients in a room:
  - k_{dep} in units of 1/hr

$$k_{dep} = \frac{v_d A}{V}$$

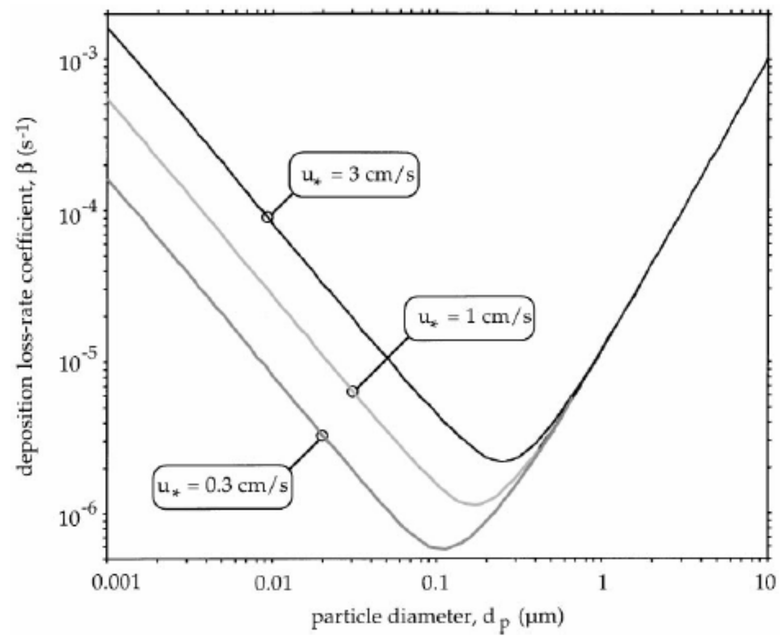


Fig. 5. Particle deposition loss-rate coefficient, β, for typical room dimensions (3 m high $\times$ 4 m $\times$ 5 m) according to the current model. Friction velocities of 0.3–3 cm s^{-1} approximately span the range expected for mechanically ventilated indoor spaces. Predictions assume air pressure is 1 atm, temperature is 293 K and particle density is 1.0 g cm^{-3}.

Lai and Nazaroff 2000 *J Aerosol Sci*

Indoor losses: Deposition

- There have been several studies that measured particle deposition in real environments as well

Procedure for finding deposition rates is similar to finding AER or finding reactive deposition rates

- Inject particles and measure the subsequent decay

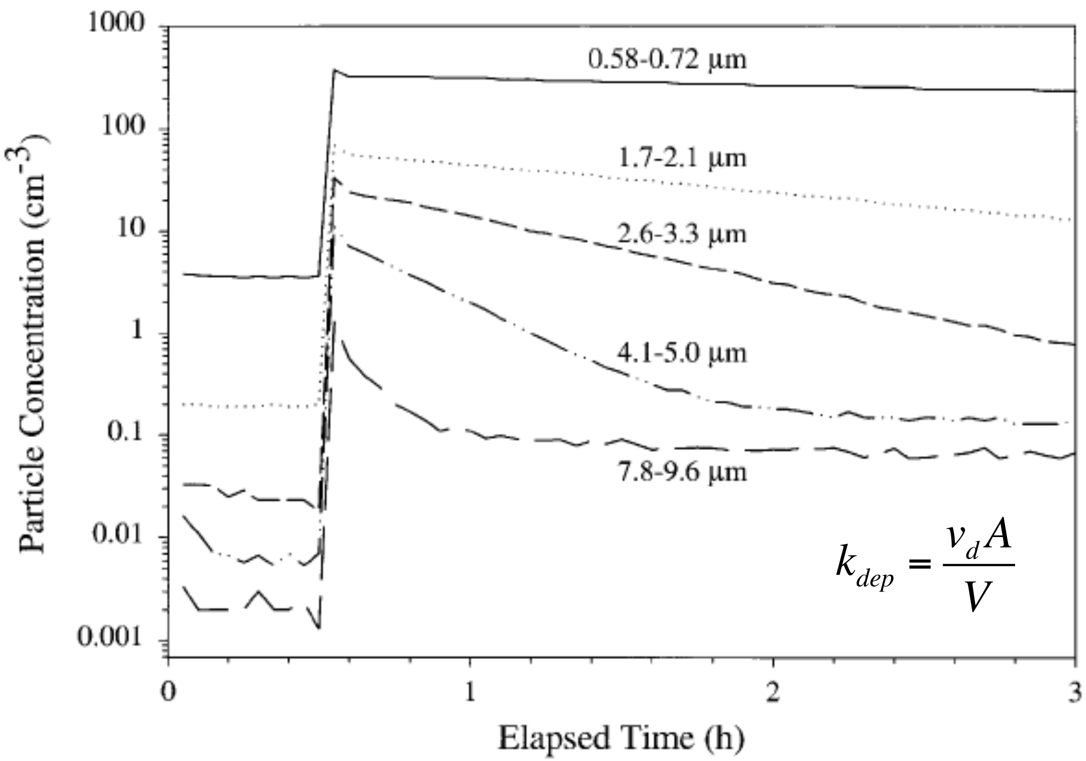
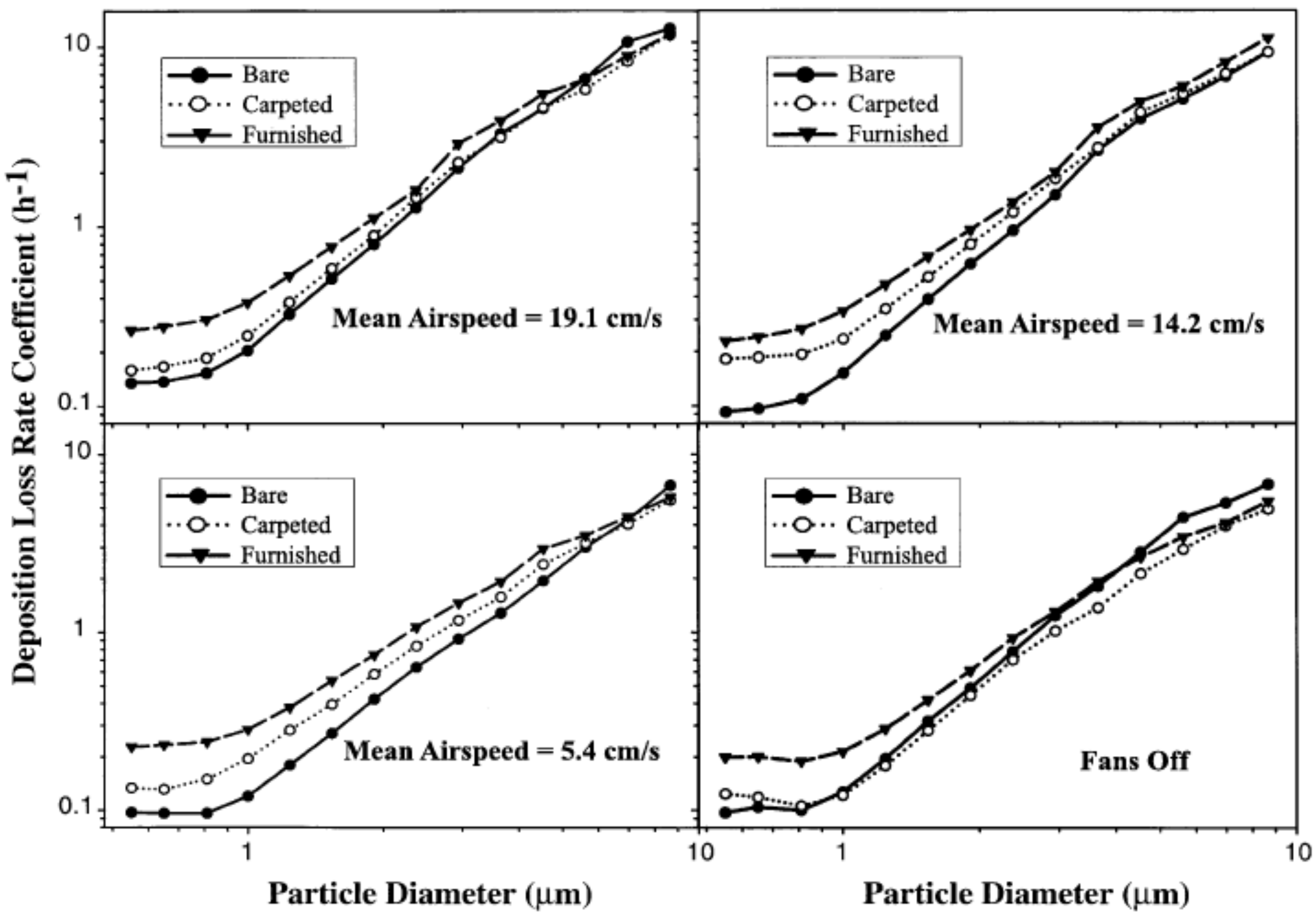


Fig. 2. Typical particle concentration profiles over the course of an experiment for selected particle size ranges. Pulsed particle injection occurred at 0.5 h.

Thatcher et al. 2002 *Atmos Environ*

Indoor losses: Deposition

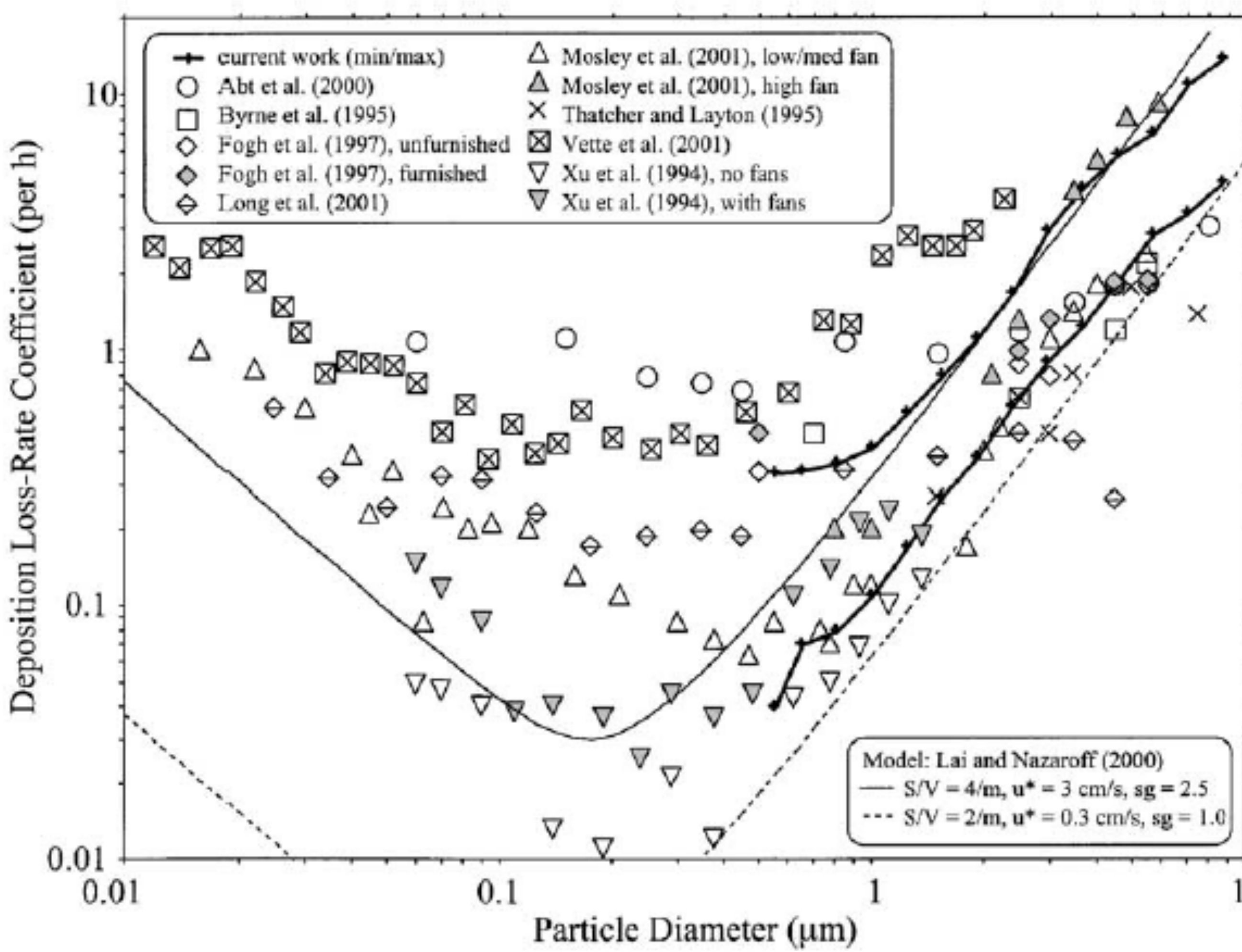
- Deposition in a chamber under different air speeds and furnishing conditions



Thatcher et al. 2002 *Atmos Environ*

Indoor losses: Deposition

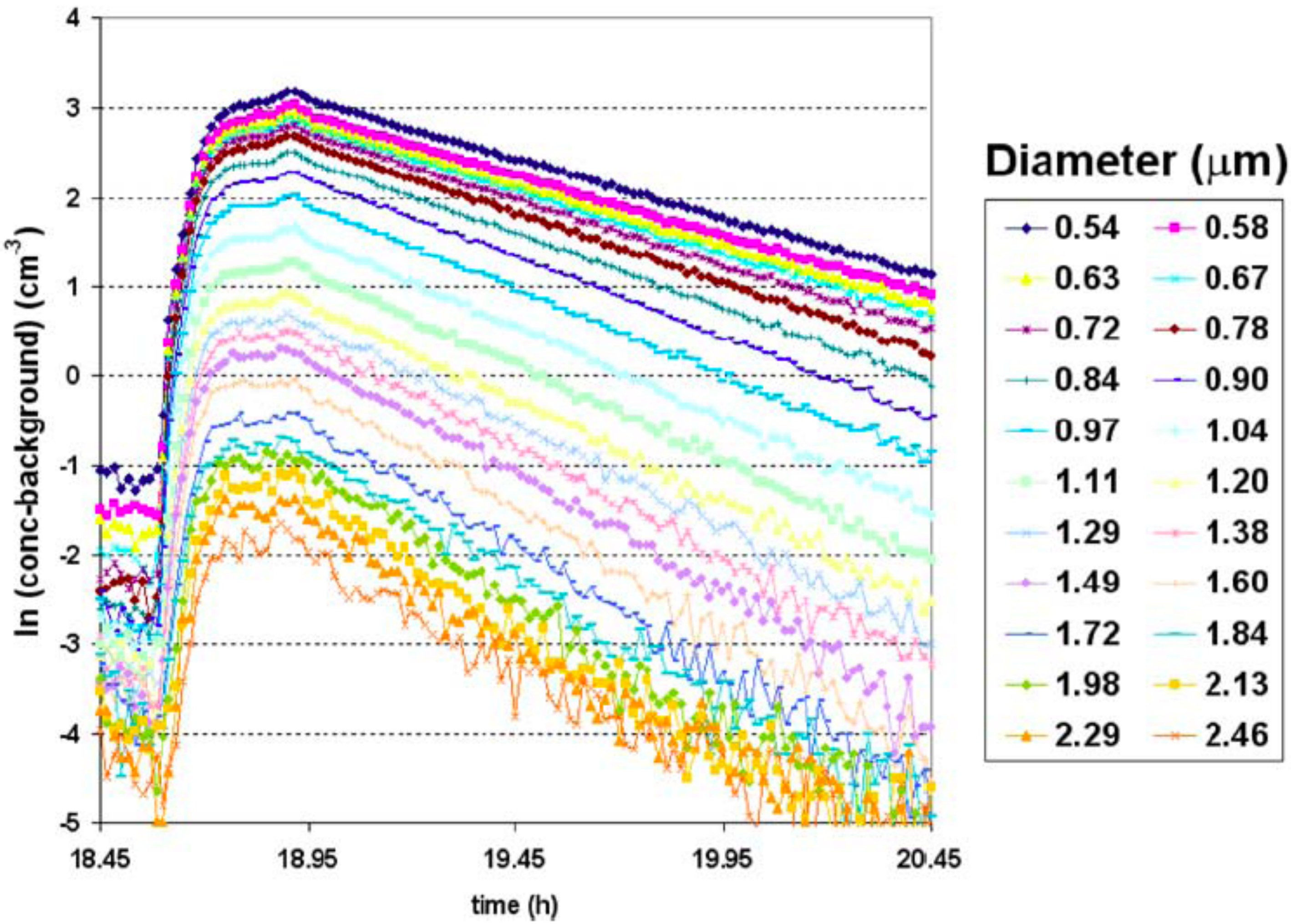
- Review of deposition in a chamber under different scenarios



Thatcher et al. 2002 *Atmos Environ*

Indoor losses: Deposition

- Deposition in real homes



Wallace et al. 2004 *Atmos Environ*

Indoor losses: Deposition

- Deposition in real homes

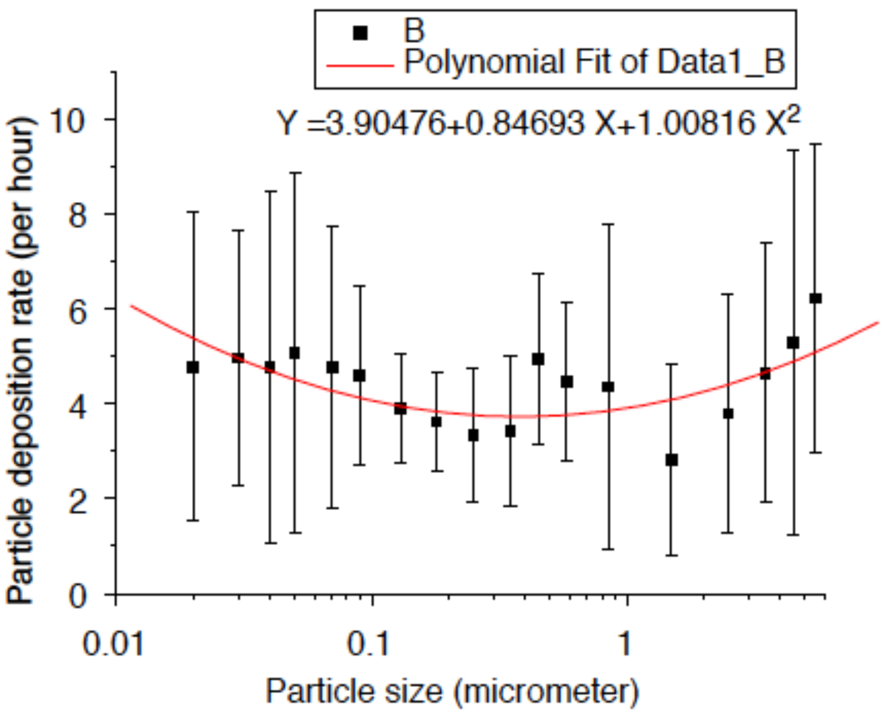


Fig. 3. The average of particle deposition rates for the 18 particle size intervals under normal ventilation conditions (Error bars represent one standard deviation). The polynomial fit line with the correlation coefficient ($R^2 = 0.33$).

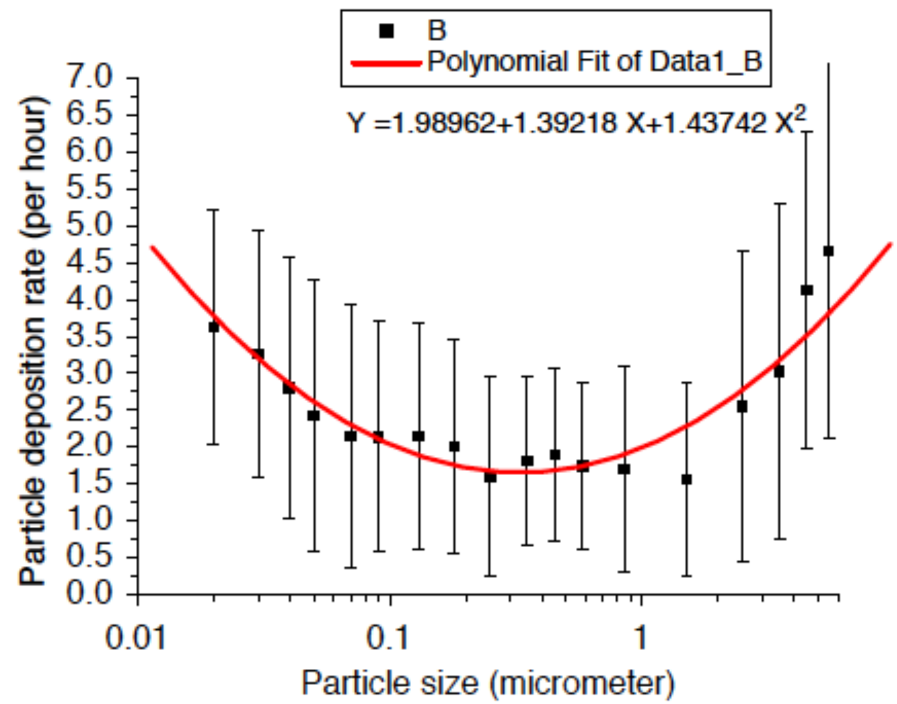
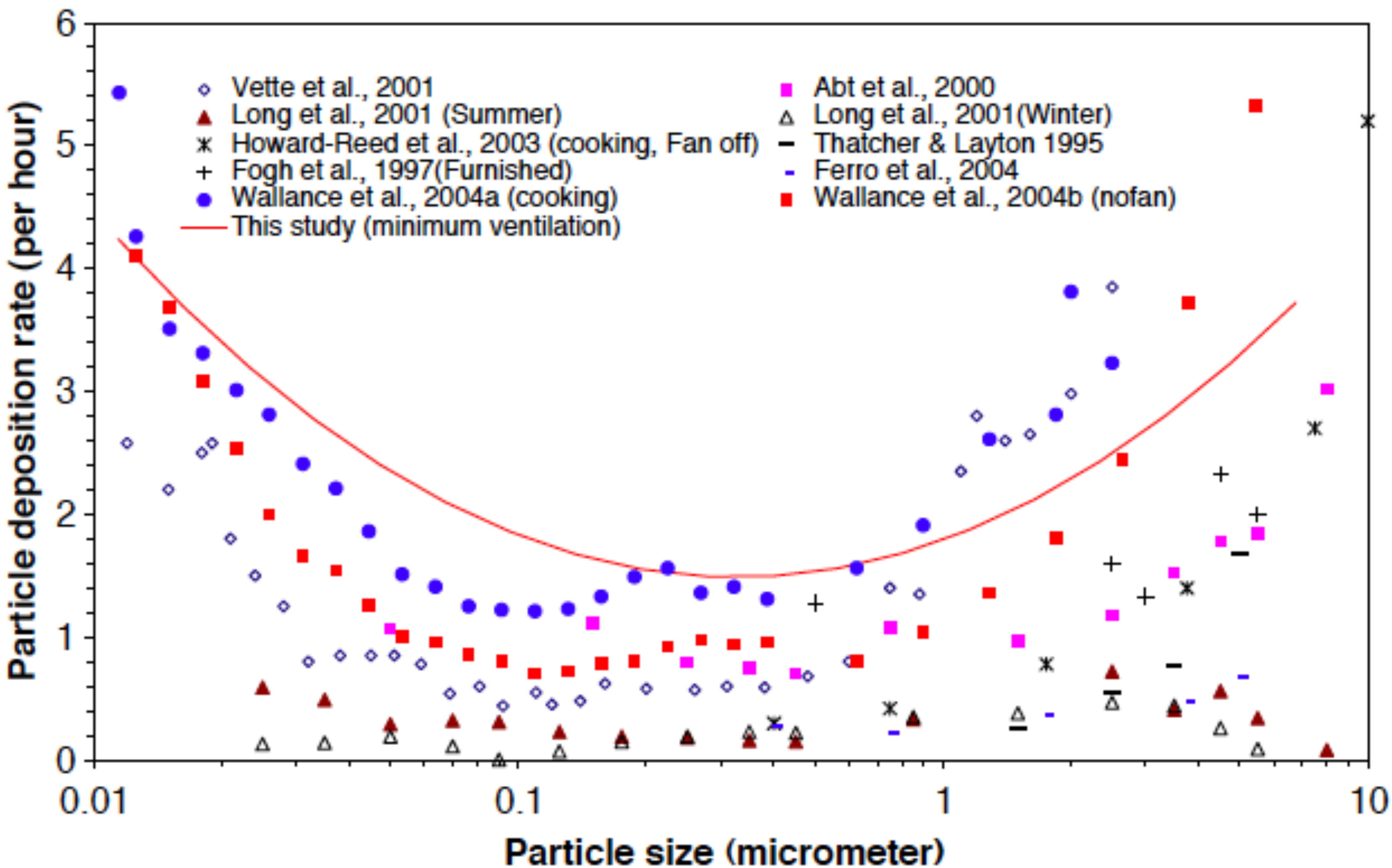


Fig. 4. The average of particle deposition rates for the 18 particle size intervals under minimum ventilation conditions (Error bars represent one standard deviation). The polynomial fit line with the correlation coefficient ($R^2 = 0.84$).

He et al. 2005 *Atmos Environ*

Indoor losses: Deposition

- Deposition in real homes



He et al. 2005 *Atmos Environ*

Indoor source: Resuspension

- Early experiments noticed that indoor particle concentrations were elevated above background during human activities

- This is termed the “personal cloud” effect
  - Basically we disturb dust reservoirs on furniture and textiles
    - e.g., dusting, folding clothes, making a bed

- Deposited particles can “resuspend” into the air
  - We call this “resuspension”
    - The level of vigor of the activity is an important factor in resuspension
  - Resuspension is generally greater for larger particles

Indoor sources: Resuspension

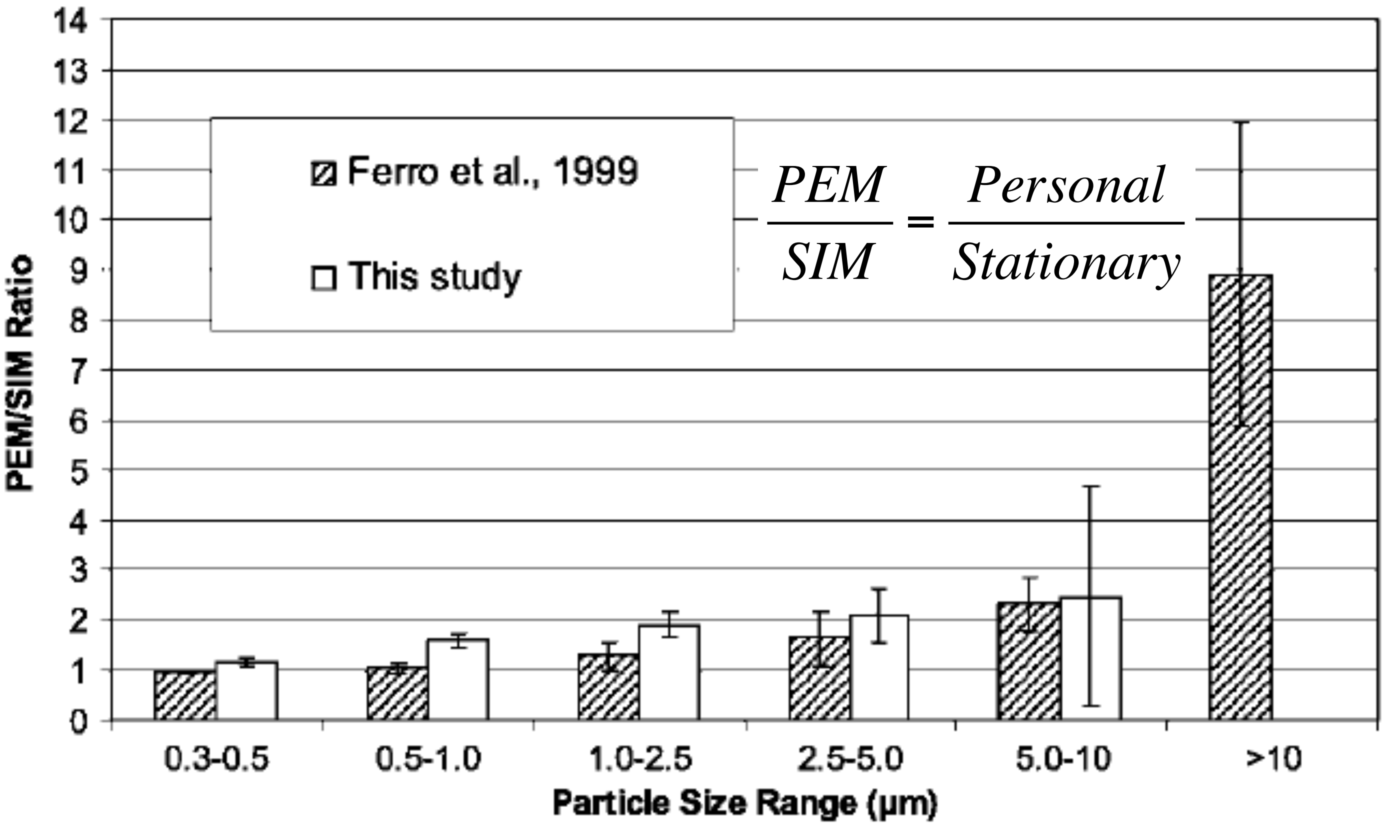


Figure 4. PEM/SIM ratio by particle size during human activity periods for two independent studies. Ferro et al. (1999) collected personal and indoor concentrations using Met-One Model 237B laser particle counters for six vacuuming experiments in a separate Redwood City, CA, USA, residence.

Ferro al., 2004 *J Expo Anal Environ Epidem*

Indoor source: Resuspension

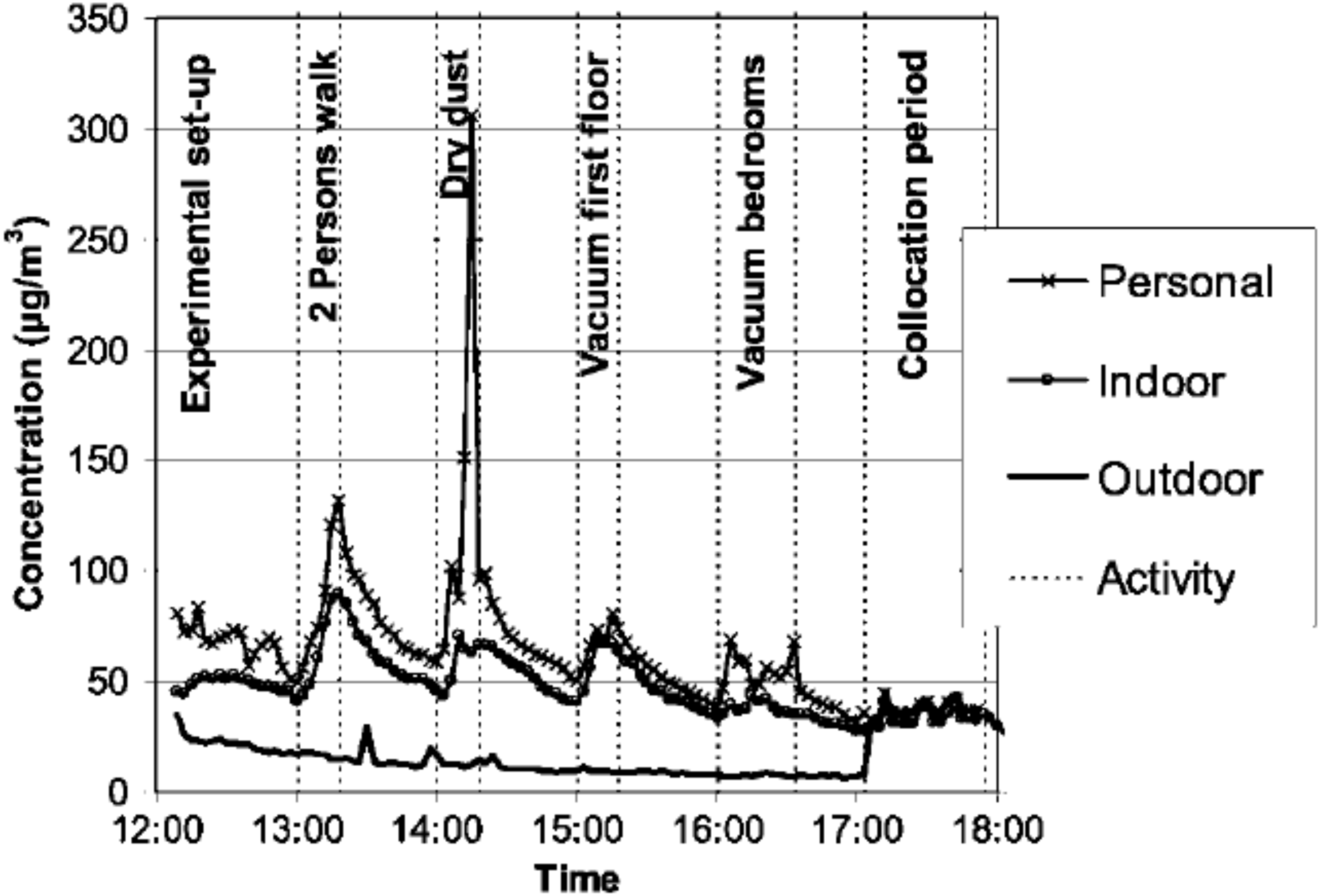
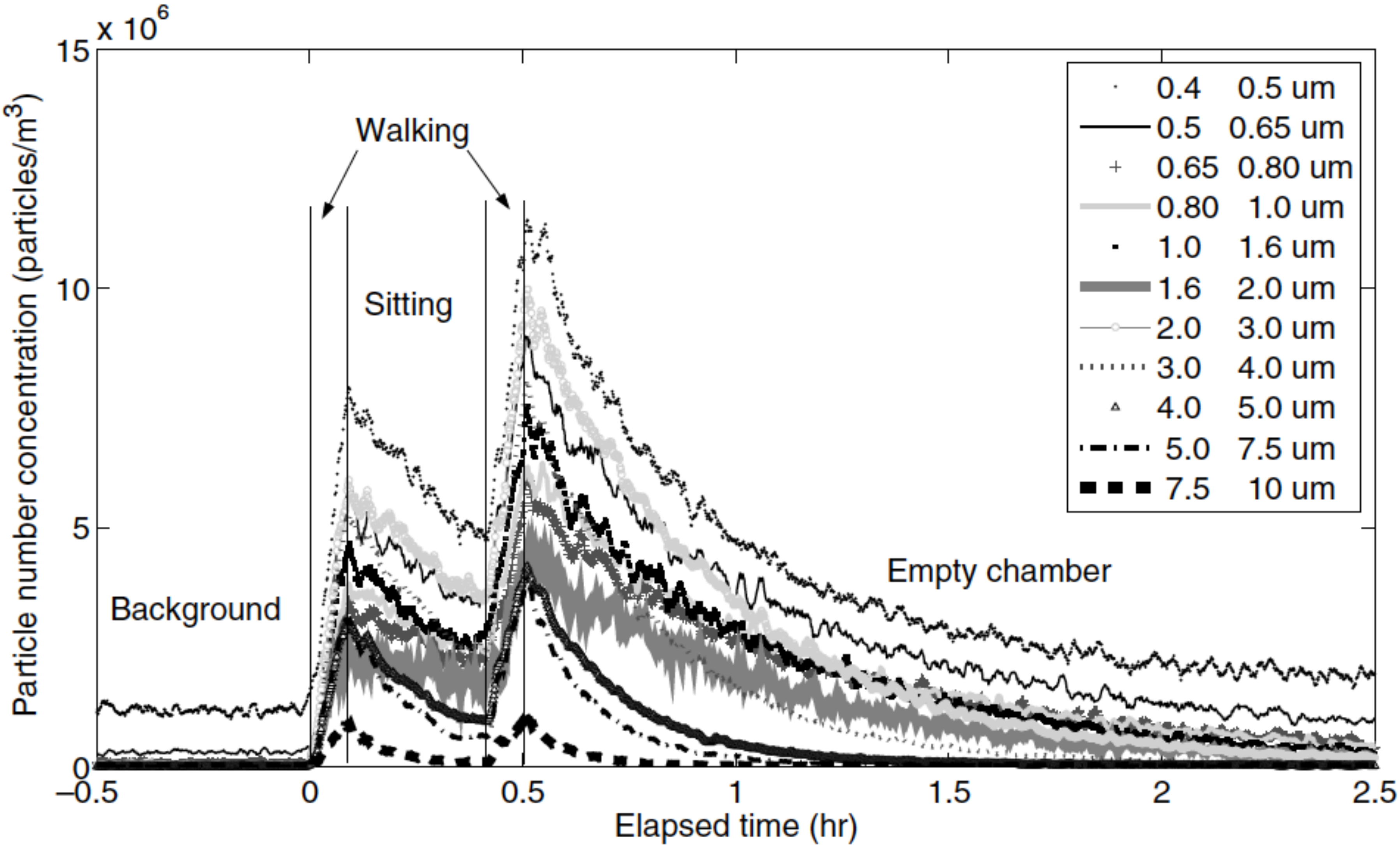


Figure 3. Personal, indoor, and outdoor PM_5 estimated mass concentration time series.

Ferro al., 2004 *J Expo Anal Environ Epidem*

Indoor sources: Resuspension



Qian and Ferro, 2008 *Aerosol Sci Technol*

Quantifying resuspension

- We can define a resuspension rate:

$$r = \frac{R}{L}$$

R = resuspension flux (mg/m^2-hr)
L = surface concentration (mg/m^2)

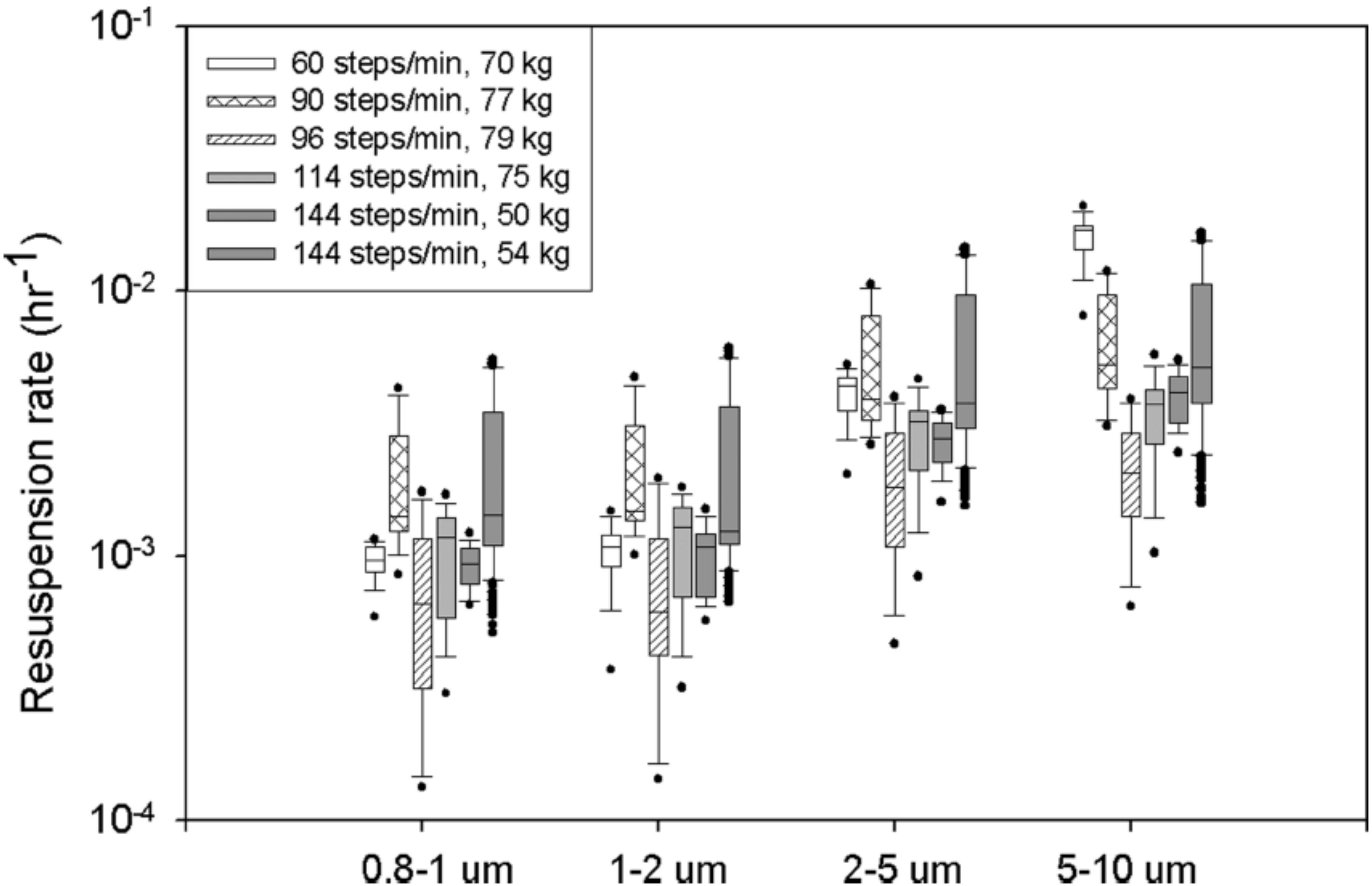
- And incorporate it into mass balance on indoor air:

$$\frac{dC_i}{dt} = \frac{E_i}{V} + C_{out,i}\left[\lambda_{vent}(1-\eta_{vent,i}) + \lambda_{nat} + \lambda_{inf}P_i\right] - C_i\left[\lambda_{vent} + \lambda_{nat} + \lambda_{inf} + k_{dep,i} + \lambda_{filt}\eta_{filt,i}\right] + \frac{rAL}{V}$$

- And tie that into mass balance on surface of interest (A)

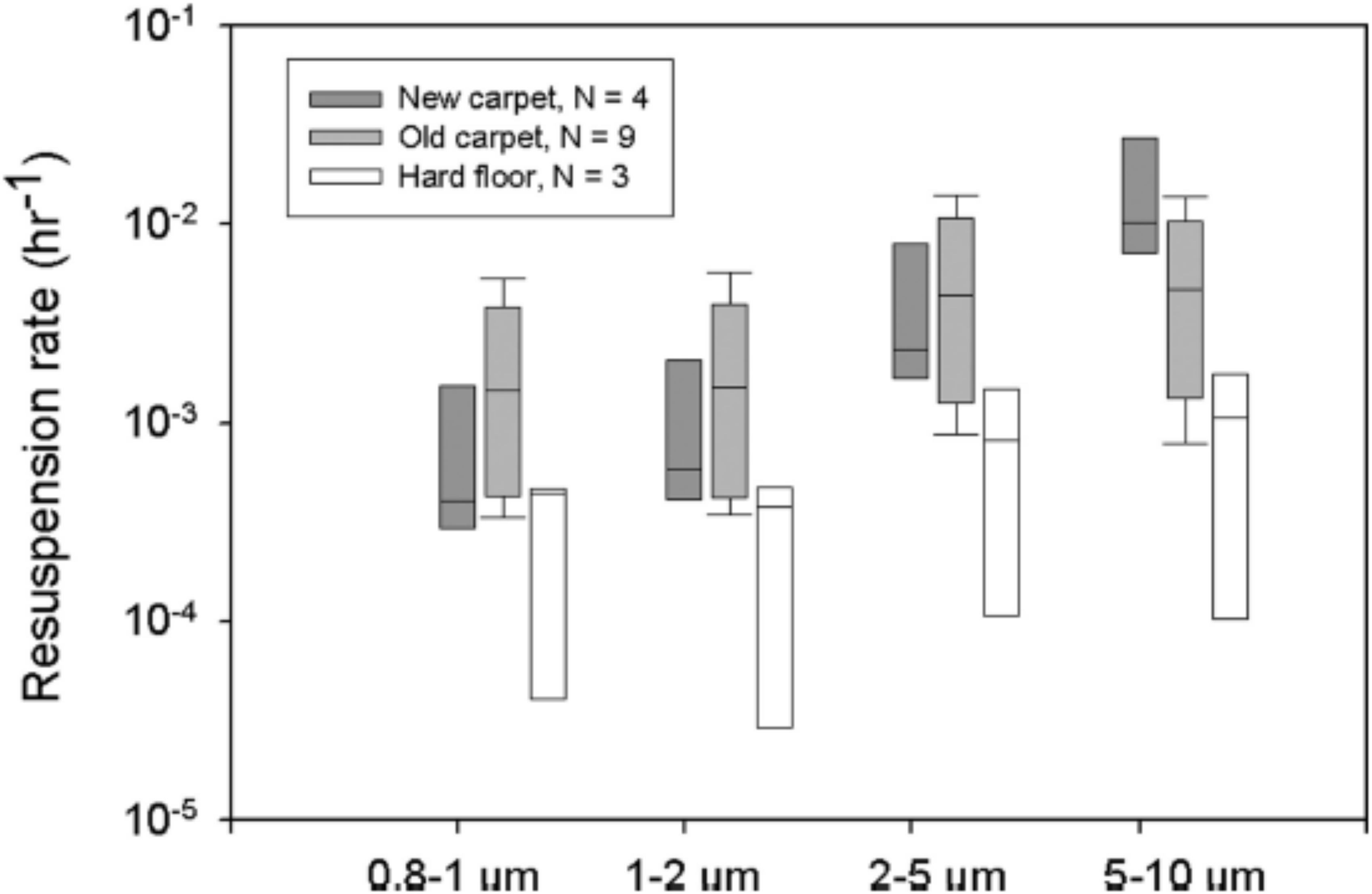
$$A\frac{dL_i}{dt} = k_{dep,i}C_iV - rAL + E_{track-in}$$

Indoor sources: Resuspension



Qian and Ferro, 2008 *Aerosol Sci Technol*

Indoor sources: Resuspension



Qian and Ferro, 2008 *Aerosol Sci Technol*

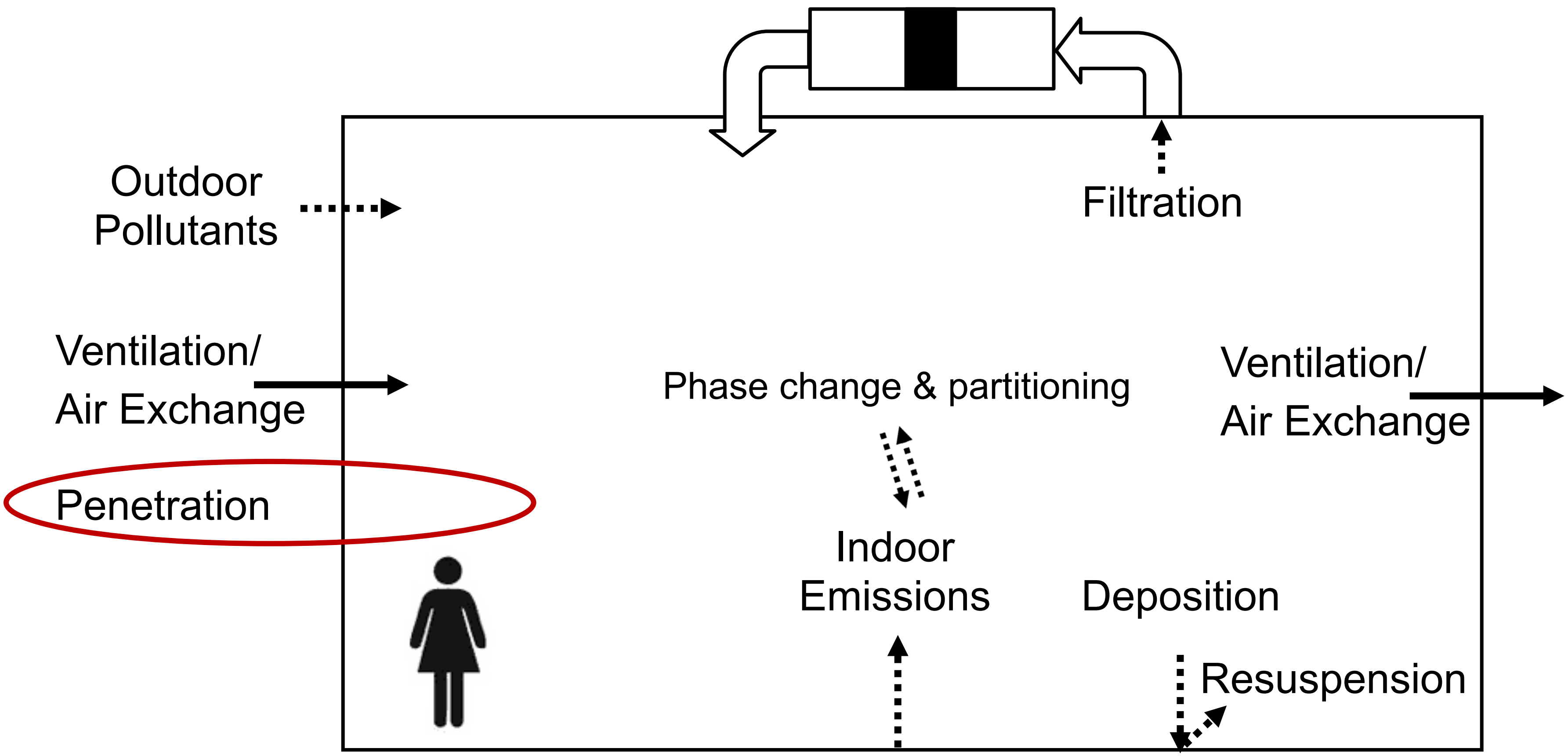
Indoor particles review so far

- What have we learned so far?
- We can describe particle concentrations by size (diameter)
- Particles of various sizes exist indoors
  - The smallest and largest particles are typically indoor generated
  - Medium sized (fine) particles often infiltrated from outdoors
- Once indoors, particles of different sizes deposit on surfaces at different rates
  - And deposit in different regions of our lungs
  - Particle density and shape can also affect this (refer to settling velocity)
- We've seen some ways particle deposition, emission, and resuspension are measured
  - We still need to focus on a major source:
    - <u>Infiltration/Penetration</u> from outdoors
  - And we still need to focus on a major loss:
    - HVAC or stand-alone <u>particle filtration</u>/<u>air cleaning</u>

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

Either a removal term or a source term, depending…

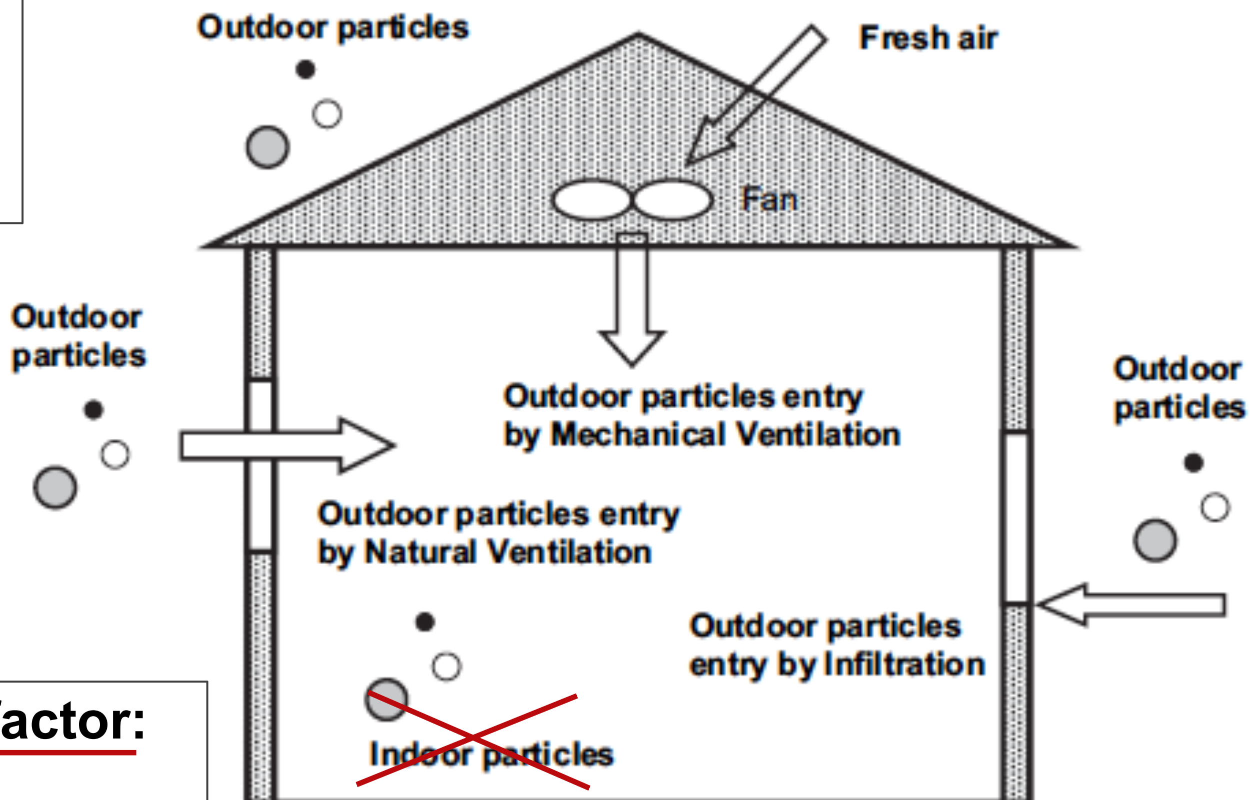
Mass (or number) balance approach for particles



Indoor sources of outdoor PM and key definitions

I/O ratio:

$$I/O = \frac{C_{in}}{C_{out}}$$



Chen and Zhao, **2011** *Atmos Environ*

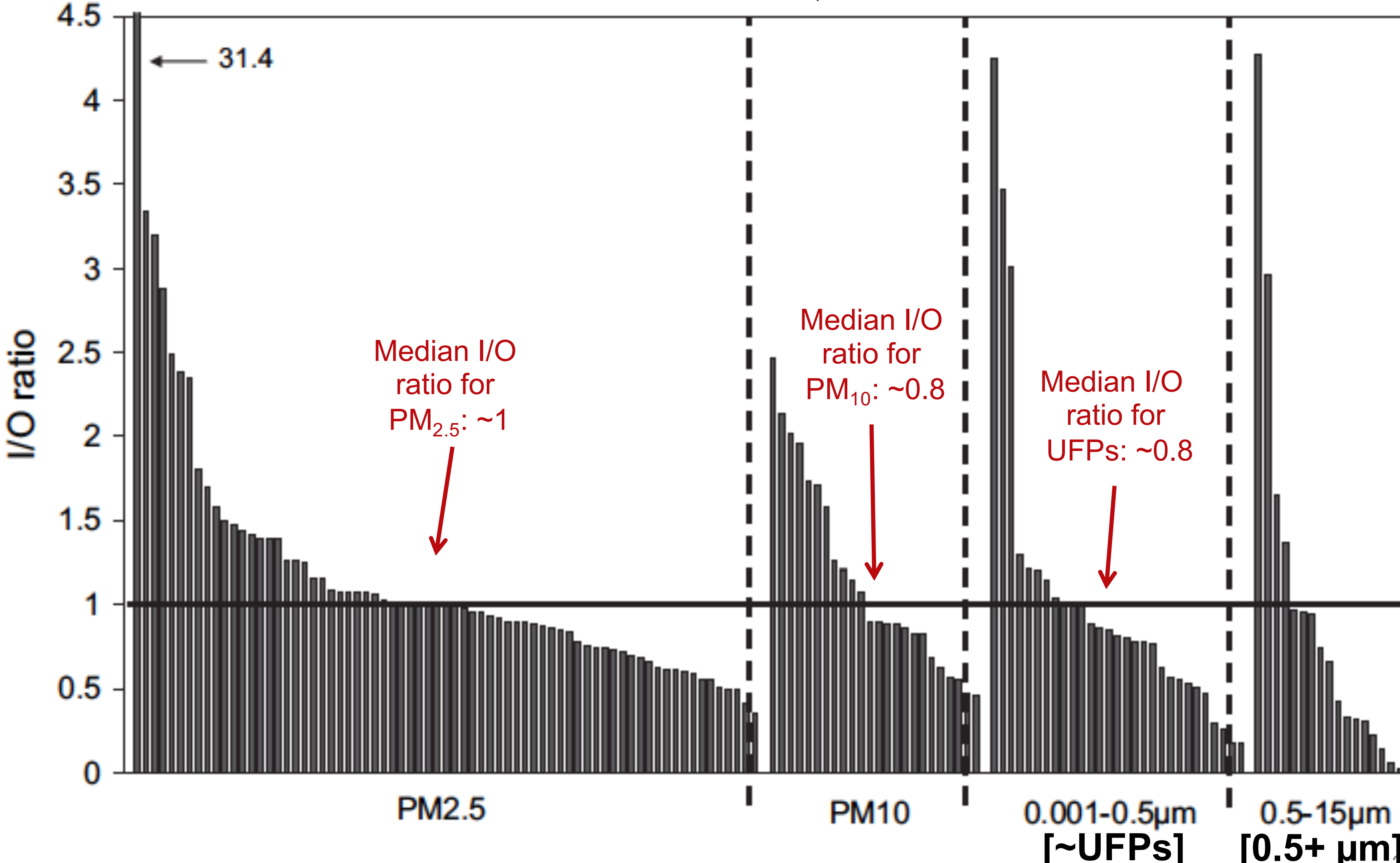
Infiltration factor:

$$F_{\inf} = \left.\frac{C_{in}}{C_{out}}\right|_{no\,indoor\,sources}$$

$$F_{\inf} = \frac{P_i \lambda}{\lambda + k_{dep,i} + \lambda_{filt}\eta_{filt,i}}$$

I/O PM ratios: Indoor + outdoor sources

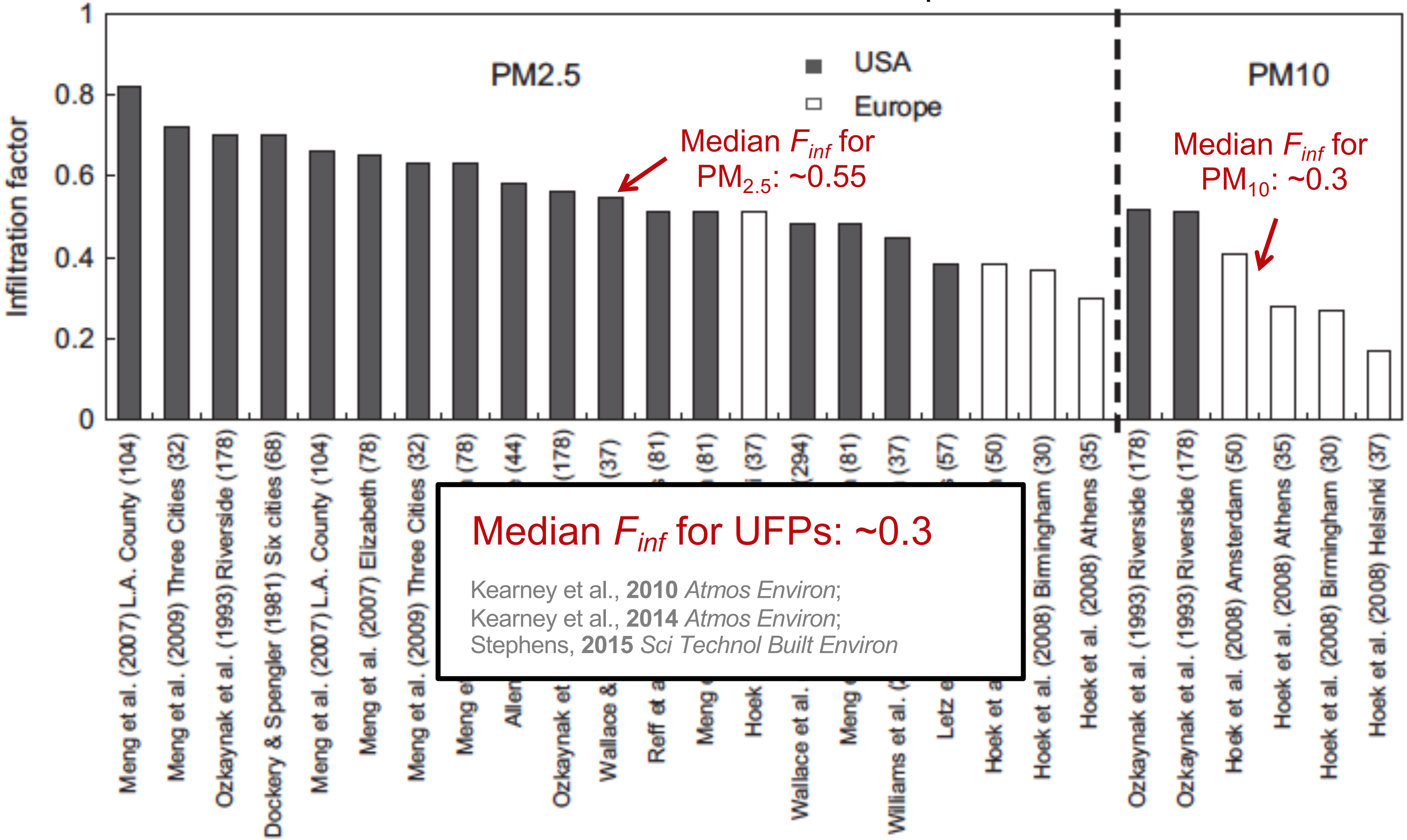
Means from 77 studies and over 4000 homes; includes indoor and outdoor sources



Chen and Zhao, **2011** *Atmos Environ*

<u>Infiltration factors</u>: Outdoor PM sources only

Means from 21 samples of over 20 homes (includes only outdoor PM infiltration)
Total # of homes: ~1000 in the U.S. & ~150 in Europe



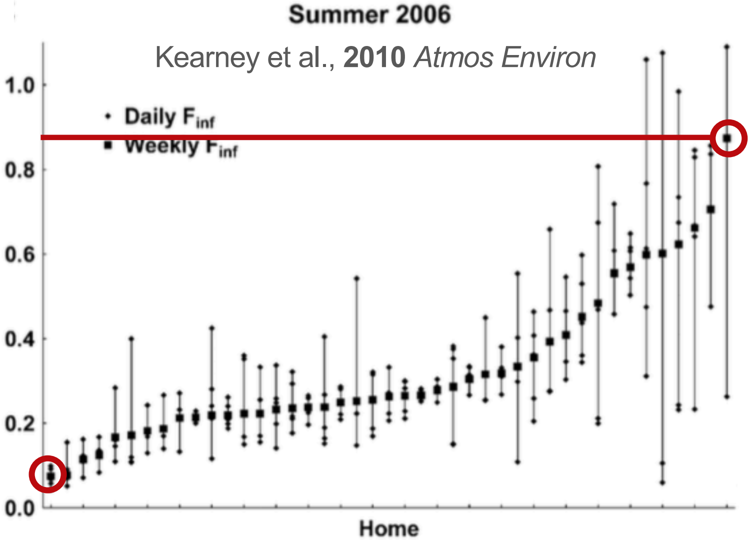
Median F_{inf} for UFPs: ~0.3

Kearney et al., **2010** *Atmos Environ*;
Kearney et al., **2014** *Atmos Environ*;
Stephens, **2015** *Sci Technol Built Environ*

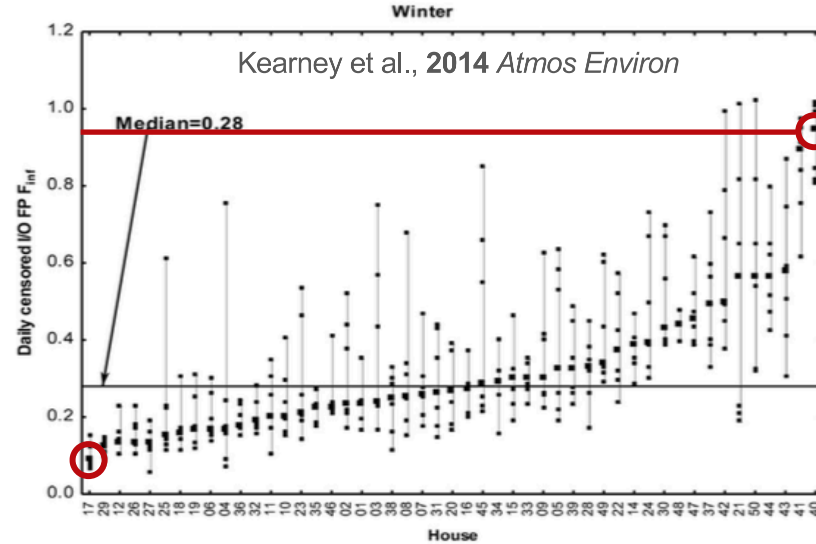
Chen and Zhao, **2011** *Atmos Environ*

Variability in infiltration factors

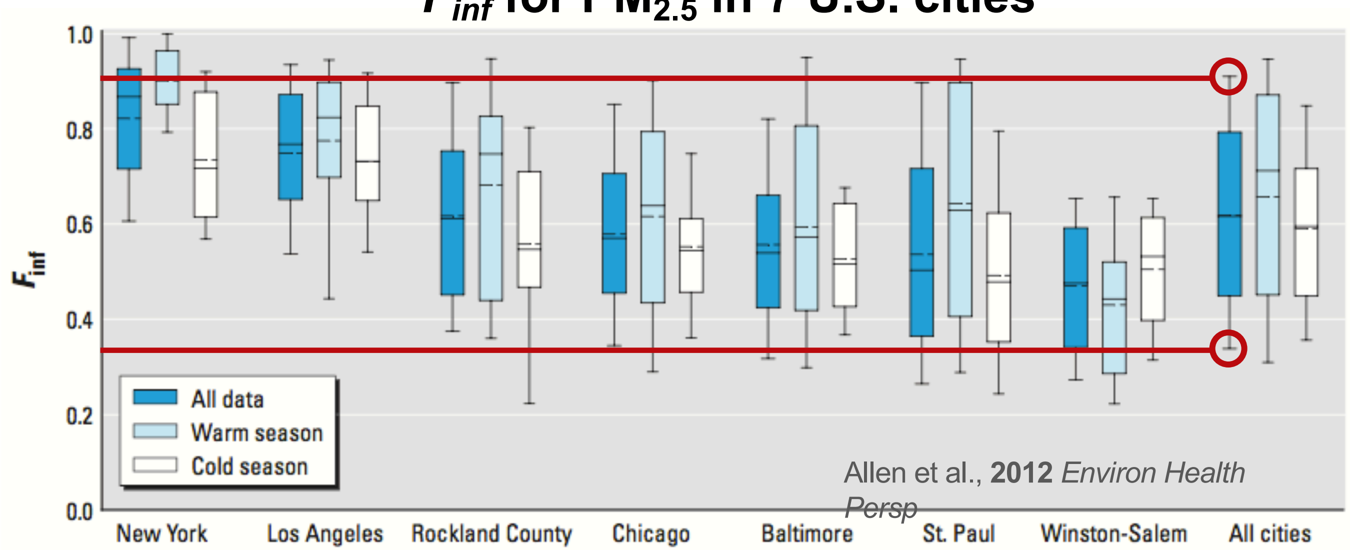
F_{inf} for UFPs in Windsor, ON



F_{inf} for $PM_{2.5}$ in Edmonton, AB



F_{inf} for $PM_{2.5}$ in 7 U.S. cities



Between-home variations:
$0.1 < F_{inf} < 1$

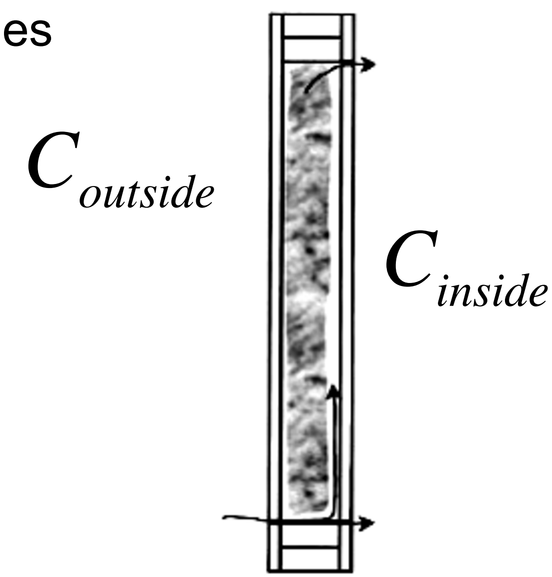
Key drivers of variability in infiltration factors

- Source of ventilation air
  - Infiltration (leaks)
  - Mechanical ventilation
  - Natural ventilation
- Human behaviors (e.g., window opening frequencies)
- Magnitude of the air exchange rate (AER)
  - Meteorological conditions
- Sizes/classes/components of PM
- Building characteristics (e.g., airtightness)
- HVAC system design and operation

Williams et al., **2003** *Atmos Environ*; Allen et al., **2012** *Environ Health Persp*; MacNeill et al, **2012** *Atmos Environ*; MacNeill et al., **2014** *Indoor Air*; El Orch et al., **2014** *Build Environ*; Chen et al., **2012** *Epidemiology*

Particle infiltration/penetration

- Particle penetration through building enclosures is both a source and loss/filtration mechanism
  - Probability that a particle penetrates through a building envelope
  - A large value for penetration factors means a larger number of particles infiltrate from outdoors through cracks and gaps in building envelopes
    - Low “envelope removal efficiency”
  - Small value for penetration factors means high “envelope removal efficiency”
    - Reduced indoor proportions of outdoor particles



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

Liu and Nazaroff 2001 *Atmos Environ*

Objectives for understanding *P*

- Discuss previous research on *P*
  - How to measure and solve for *P*

Liu and Nazaroff (2001) *Atmos Environ*

- Particle penetration through building cracks and through fiberglass insulation
  - Also studied reactive gases (e.g., O_3)
- **Modeling study**

The idea is that:

- 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

Liu and Nazaroff 2001 *Atmos Environ*

Basic fluid mechanics

- Consider mass of air flow into an enclosure element
  - Must equal the mass of air flow out
    - Although water vapor and heat energy can be gained or lost
  - Treat air as incompressible ideal gas
    - Bernoulli's equation
    - Relates velocity, pressure, and location

$$\mathrm{p}_1 + \frac{1}{2}\rho_1 v_1^2 + \rho_1 g h_1 = \mathrm{p}_2 + \frac{1}{2}\rho_2 v_2^2 + \rho_2 g h_2$$

Static pressure | Velocity pressure (kinetic) | Pressure head (potential)

Basic fluid mechanics: flow through a crack

- Given a crack, orifice, or opening in enclosure (channel flow)
  - Assume no height difference ($h_1 = h_2$), constant density ($\rho_1 = \rho_2$), and that v_1 is negligible (very far from the crack)

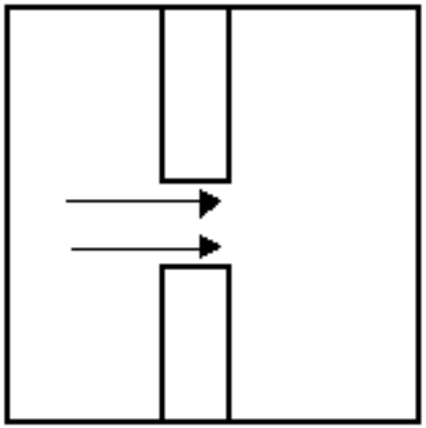
$$\mathrm{p}_1 + \frac{1}{2}\rho_1 v_1^2 + \rho_1 g h_1 = \mathrm{p}_2 + \frac{1}{2}\rho_2 v_2^2 + \rho_2 g h_2$$

- Becomes:

$$\mathrm{p}_1 = \mathrm{p}_2 + \frac{1}{2}\rho_2 v_2^2$$

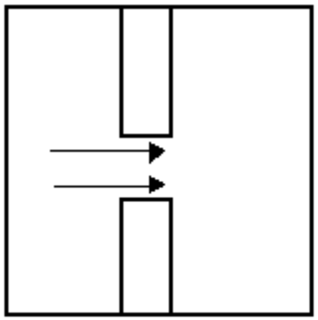
- Rearranging:

$$\frac{2(\mathrm{p}_1 - \mathrm{p}_2)}{\rho} = v^2$$



Basic fluid mechanics: flow through a crack

- Given a crack, orifice, or opening in enclosure (channel flow)
  - Assume no height difference ($h_1 = h_2$), constant density ($\rho_1 = \rho_2$), and that v_1 is negligible (very far from the crack)
  - Velocity through crack can be expressed as:



$$v = \sqrt{\frac{2\Delta P}{\rho}}$$

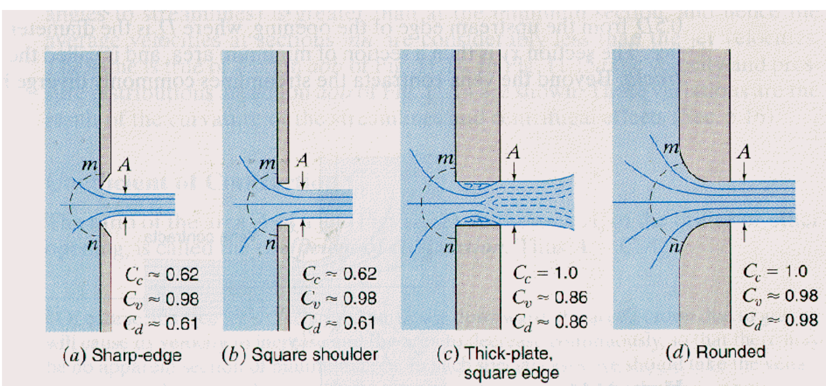
where ΔP is the pressure difference across the opening

Basic fluid mechanics: flow through a crack

- Given an area, A, of the opening/crack/orifice, the airflow rate, Q, will be:

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

  - But only under *ideal* conditions
  - Measurements would deviate from this calculation
    - Ignores losses due to friction and turbulence
    - Enter: the discharge coefficient, C_d
      - Accounts for fluid contraction and friction
      - Typical C_d for sharp-edge orifice is 0.61



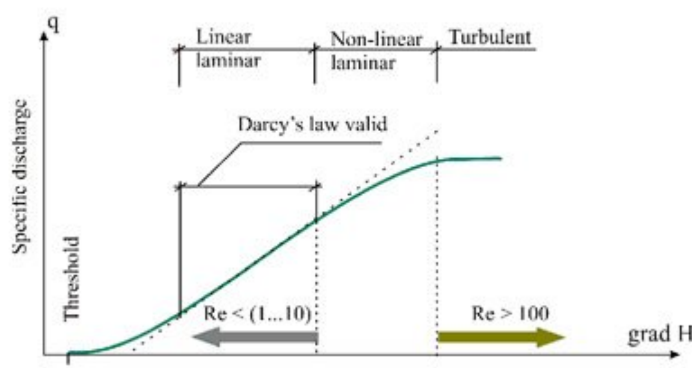
$$Q = C_d A\sqrt{\frac{2\Delta P}{\rho}}$$

Basic fluid mechanics: laminar flow through porous media

- Laminar flow through a crack or porous medium can be described by **Darcy's** equation
  - Airflow related linearly to driving air pressure difference

$$Q = KA\Delta \mathrm{P}$$

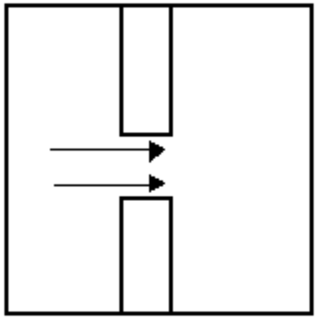
    - K is a proportionality constant (m/Pa-s)
    - Also referred to as air permeance
      - Used much in the same way as vapor permeance



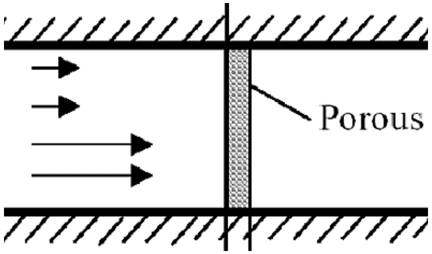
  - Remember that channel flow was just related to the square root of ΔP

Basic fluid mechanics: flow through real cracks

- Two primary flow regimes in **real building cracks**:
  1. Channel flow (mostly turbulent; Bernoulli)
     - Fluid flow behavior is dominated by fluid inertia
       – More chaotic behavior
     - Airflow through larger openings and with higher ΔP

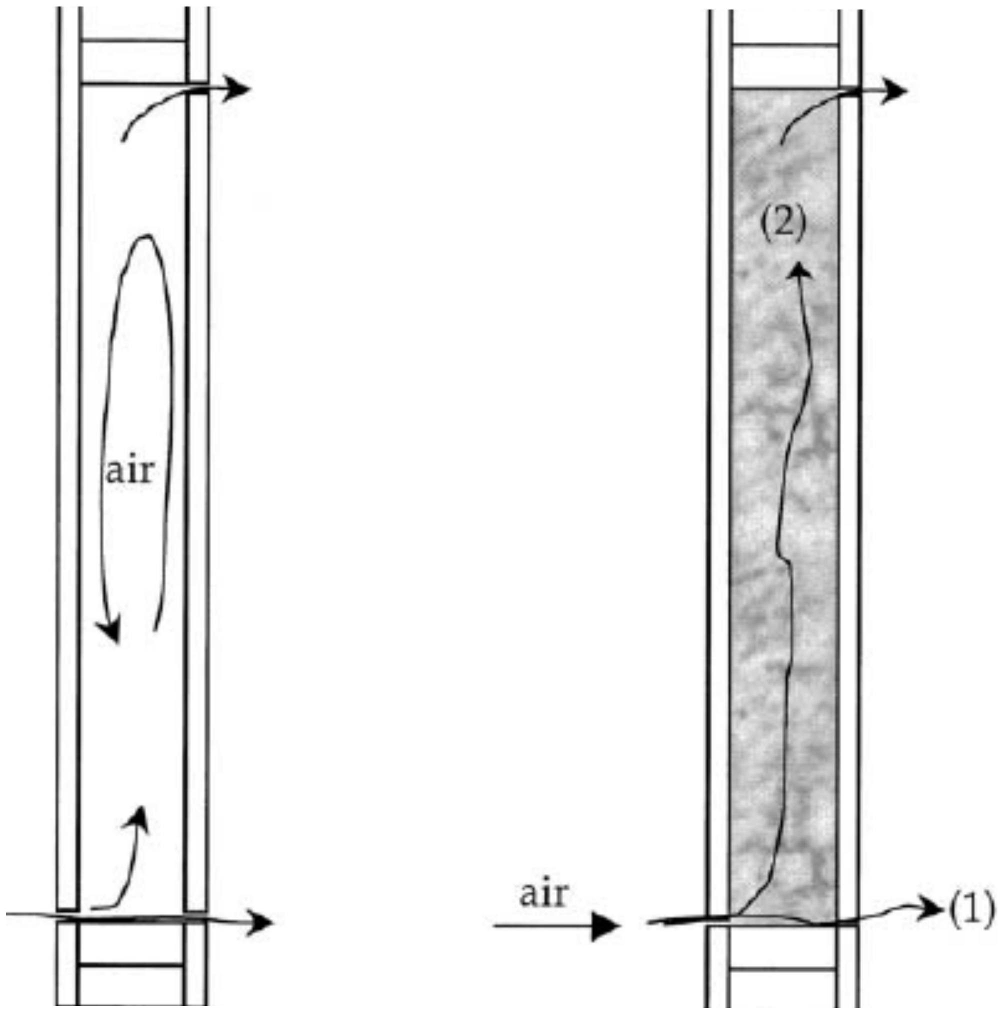


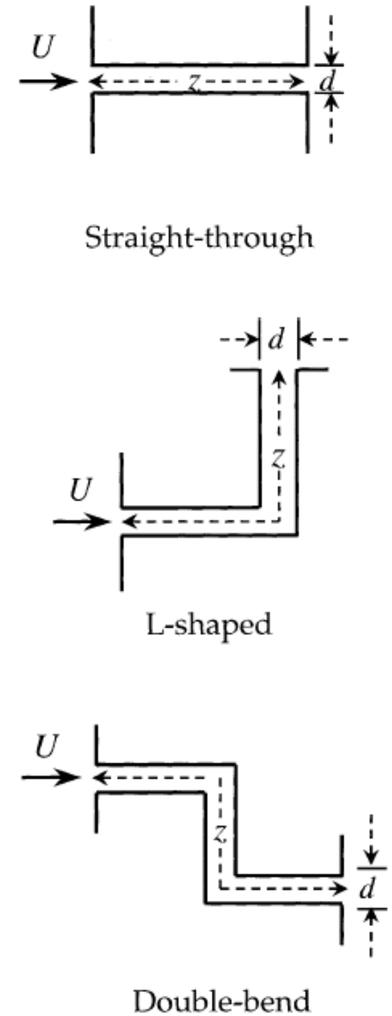
  1. Porous media flow (laminar; Darcy)
     - Fluid flow is dominated by viscosity of the fluid
       – Streamline flow; no disruption between layers
     - Airflow through smaller cracks and pores
       – Under smaller pressure differences



- What do actual flows look like?

Fluid mechanics: Actual flows in enclosures





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

Fluid mechanics: Flow through cracks (Liu and Nazaroff)

- Used a relationship between pressure (ΔP) and flow (Q)

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

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

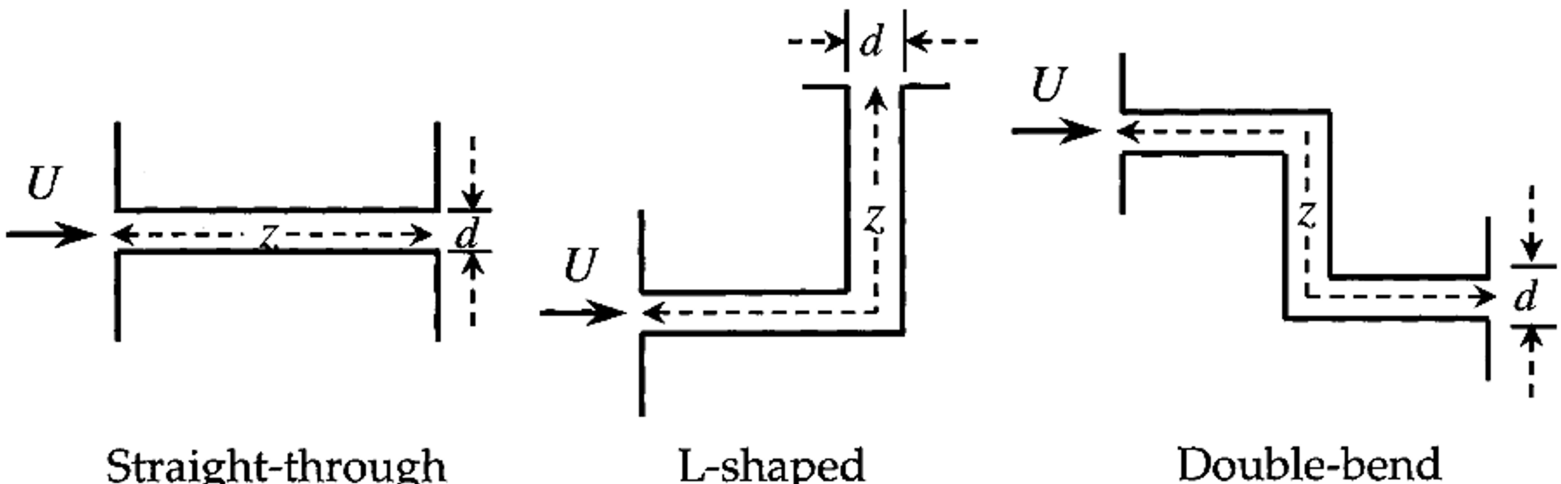


Fig. 1. Configuration of three types of idealized cracks through building envelopes.

Liu and Nazaroff 2001 *Atmos Environ*

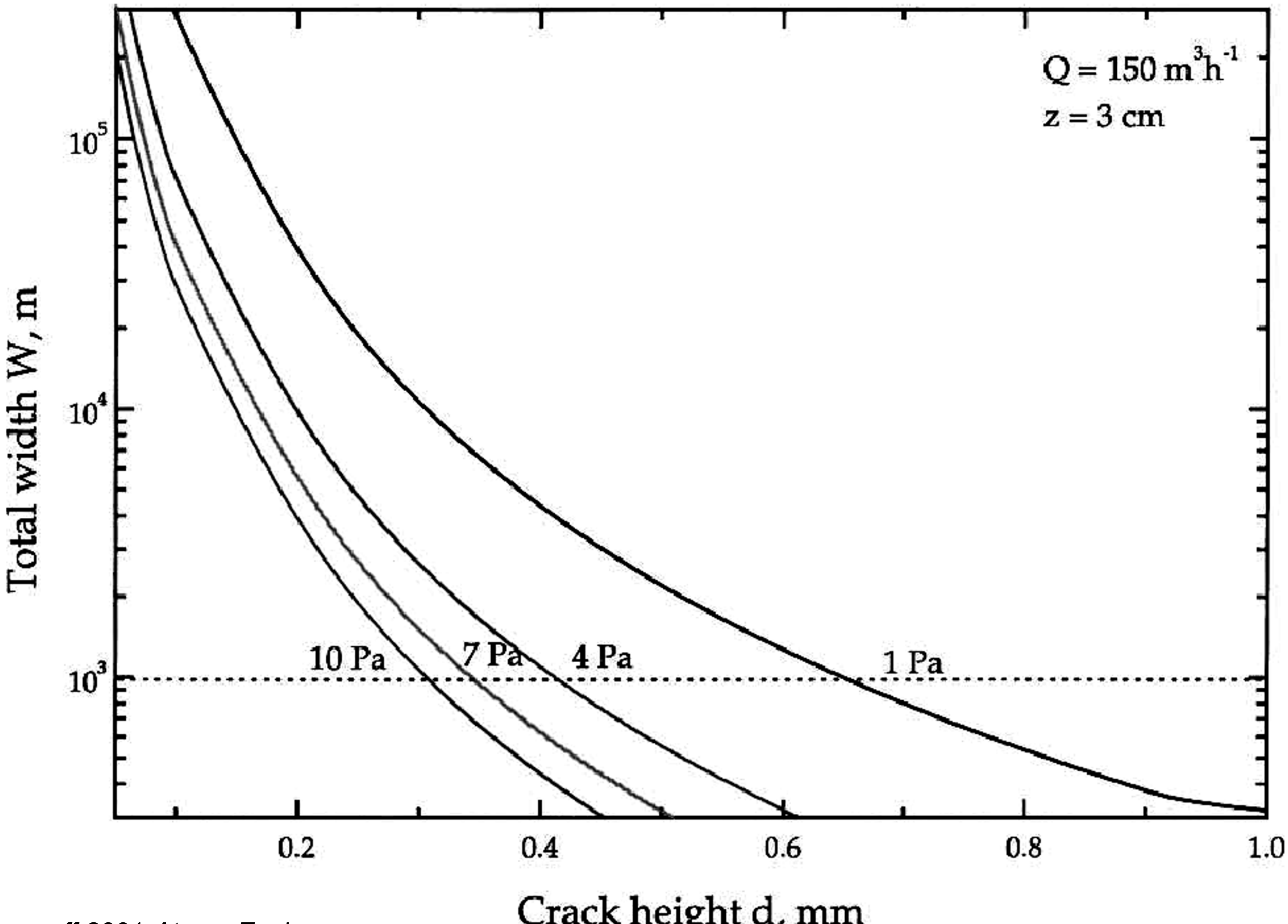
What are typical crack dimensions?

- This is a very tough parameter to measure/assess
  - 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

Liu and Nazaroff 2001 *Atmos Environ*

Assuming flow, crack width, and variety of ΔP…

We can produce estimates for crack height and total crack width



Liu and Nazaroff 2001 *Atmos Environ*

Modeling particle penetration through cracks

- They considered three 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

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

D = particle diffusion coefficient

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

Liu and Nazaroff 2001 *Atmos Environ*

Model cracks

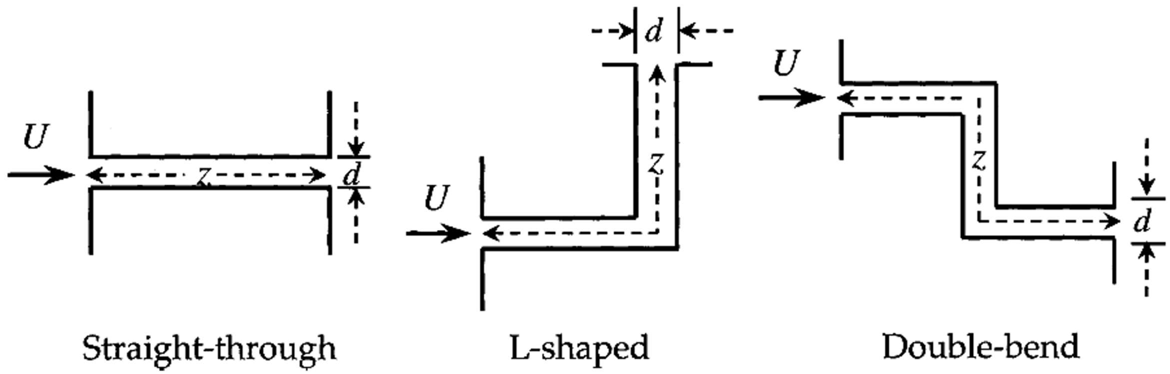


Fig. 1. Configuration of three types of idealized cracks through building envelopes.

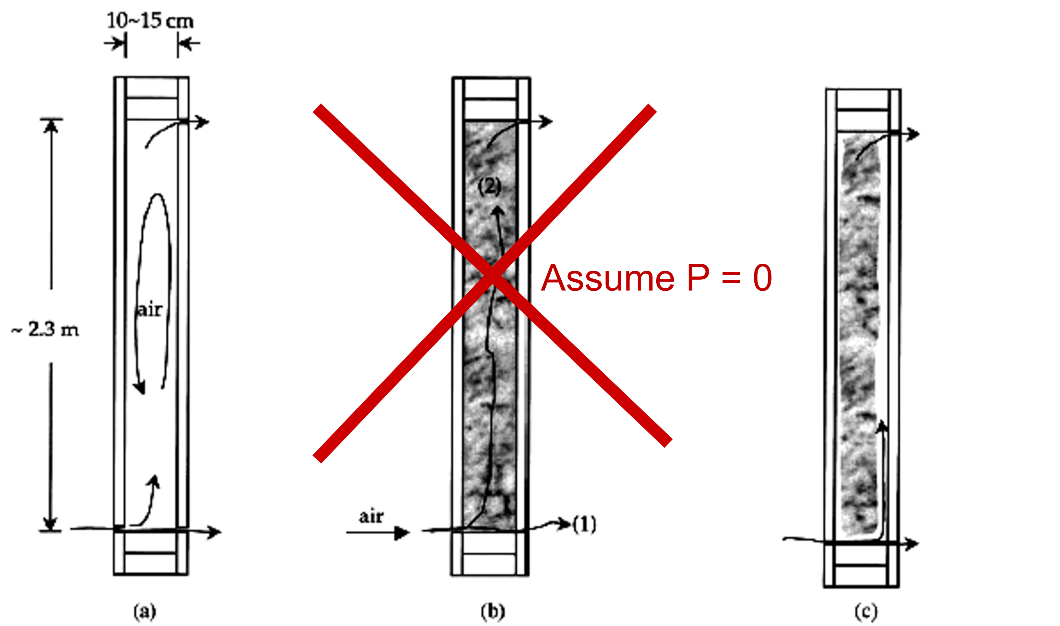


Fig. 3. Schematic of airflow paths through wall cavities in wood-frame construction. (a) Uninsulated wall cavity; (b) Wall cavity filled with fiberglass insulation; and (c) Fiberglass-insulated wall cavity with airflow bypass.

Liu and Nazaroff 2001 *Atmos Environ*

Model results: Ideal cracks

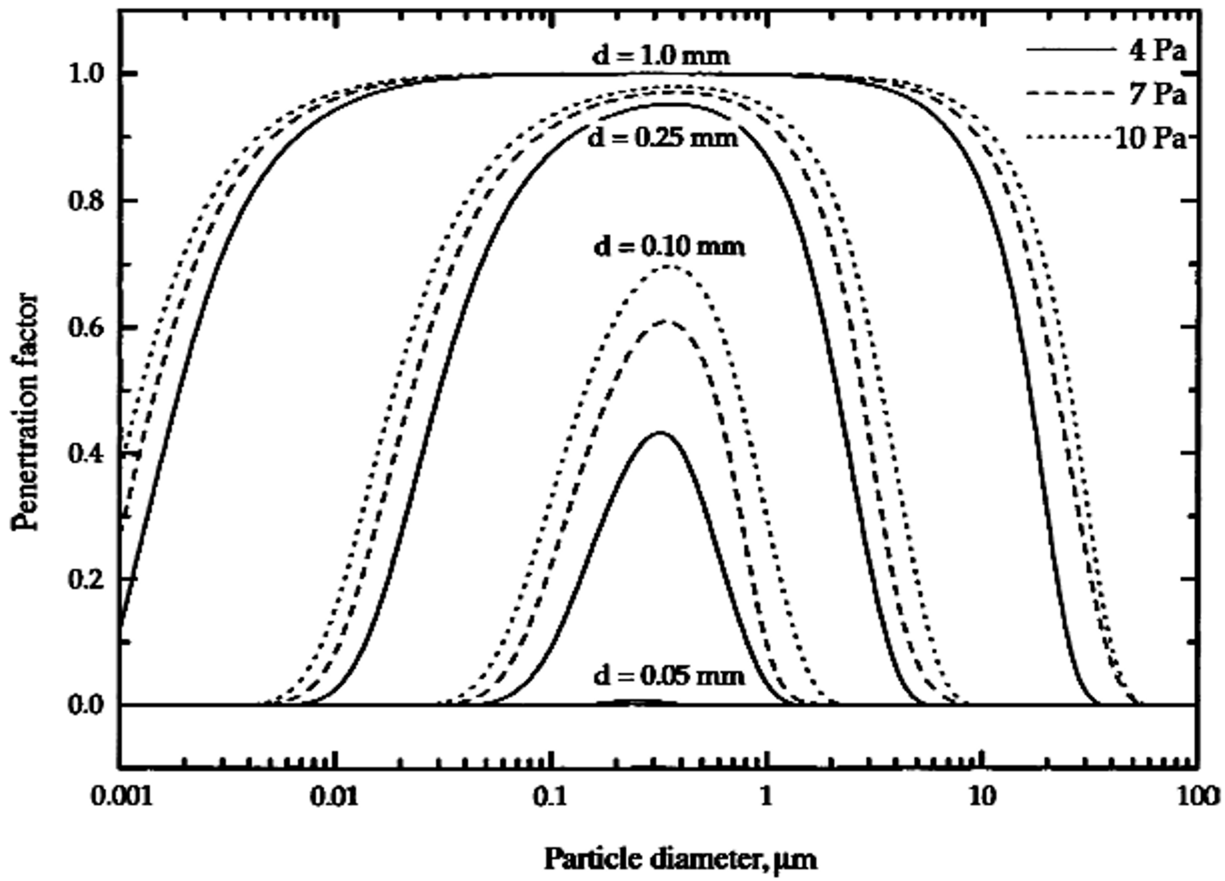


Fig. 4. Particle penetration factor as a function of particle diameter, crack height, and pressure difference for a straight-through crack with flow length $z = 3$ cm.

Liu and Nazaroff 2001 *Atmos Environ*

Model results: Ideal cracks

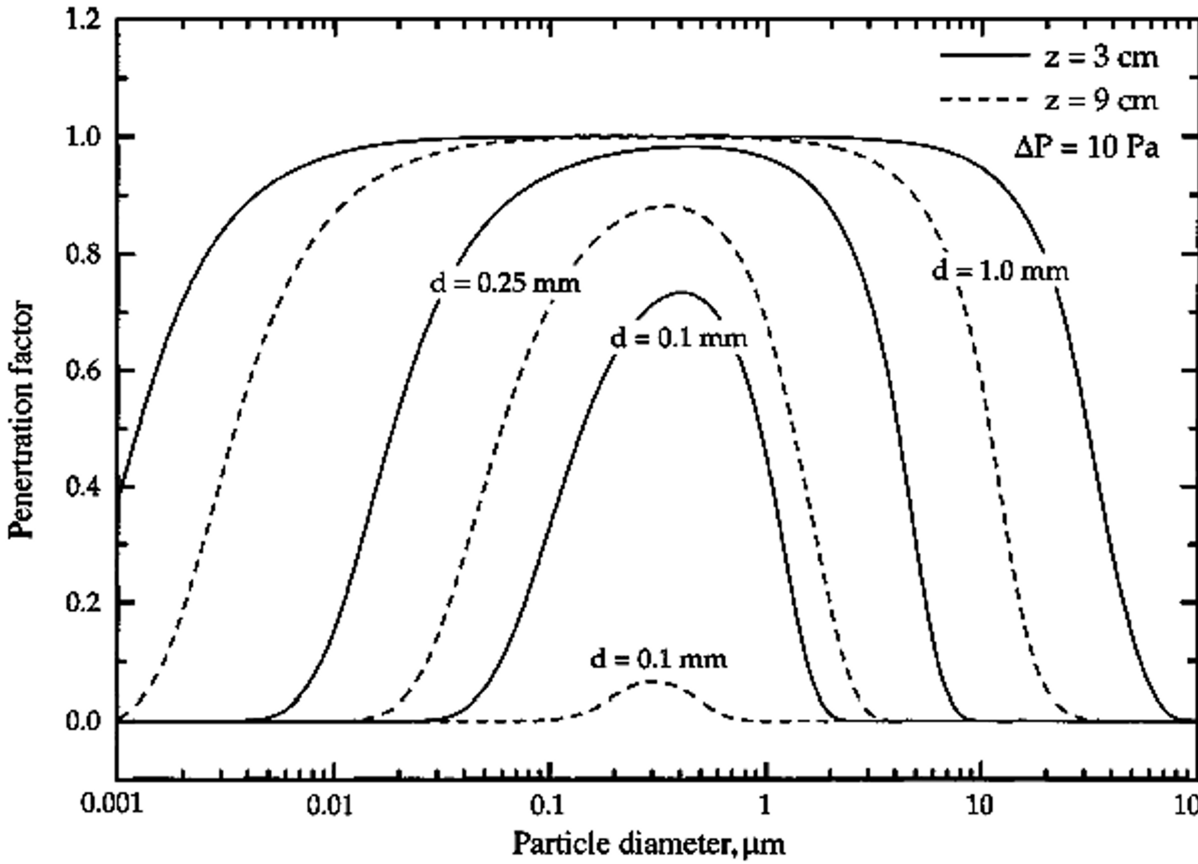


Fig. 5. Particle penetration factor as a function of particle diameter, crack height, and flow length at a fixed pressure drop of $\Delta P = 10\,\mathrm{Pa}$.

Liu and Nazaroff 2001 *Atmos Environ*

Model results: “Real cracks” in enclosures

Predicted for real building cracks

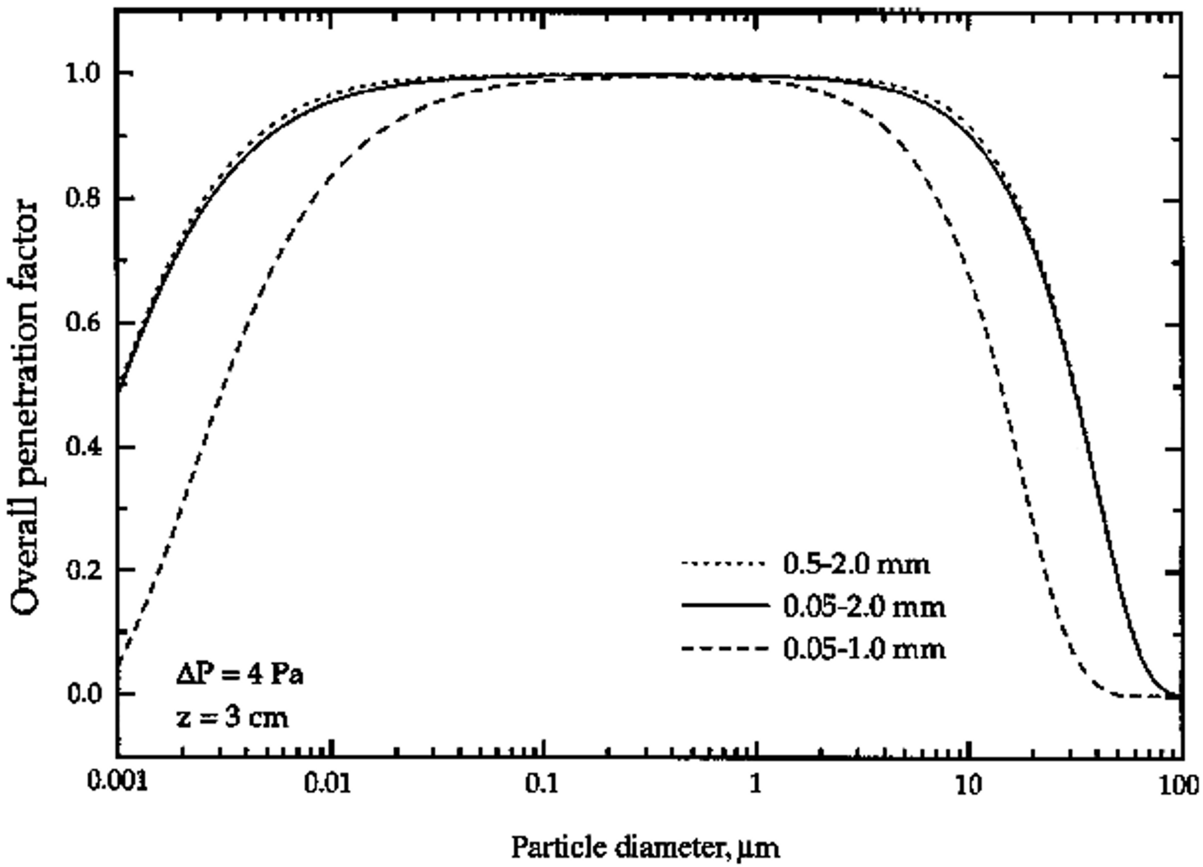


Fig. 6. Overall particle penetration factor for a building with crack area distributed uniformly with respect to crack height. Results are presented for three different ranges of crack sizes.

Liu and Nazaroff 2001 *Atmos Environ*

Comparison of model results to chamber tests

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

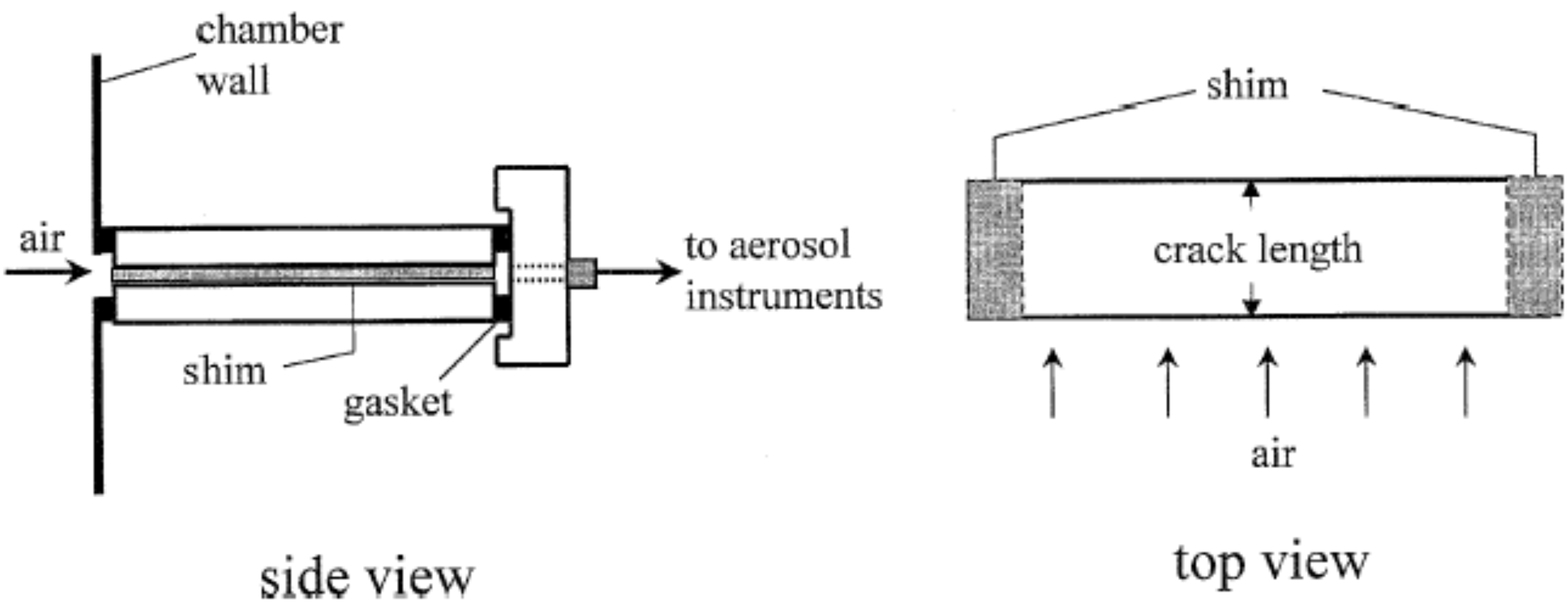


Figure 1. Configuration of crack apparatus (not to scale).

Liu and Nazaroff 2003 *Atmos Environ*

Comparison of model results to chamber tests

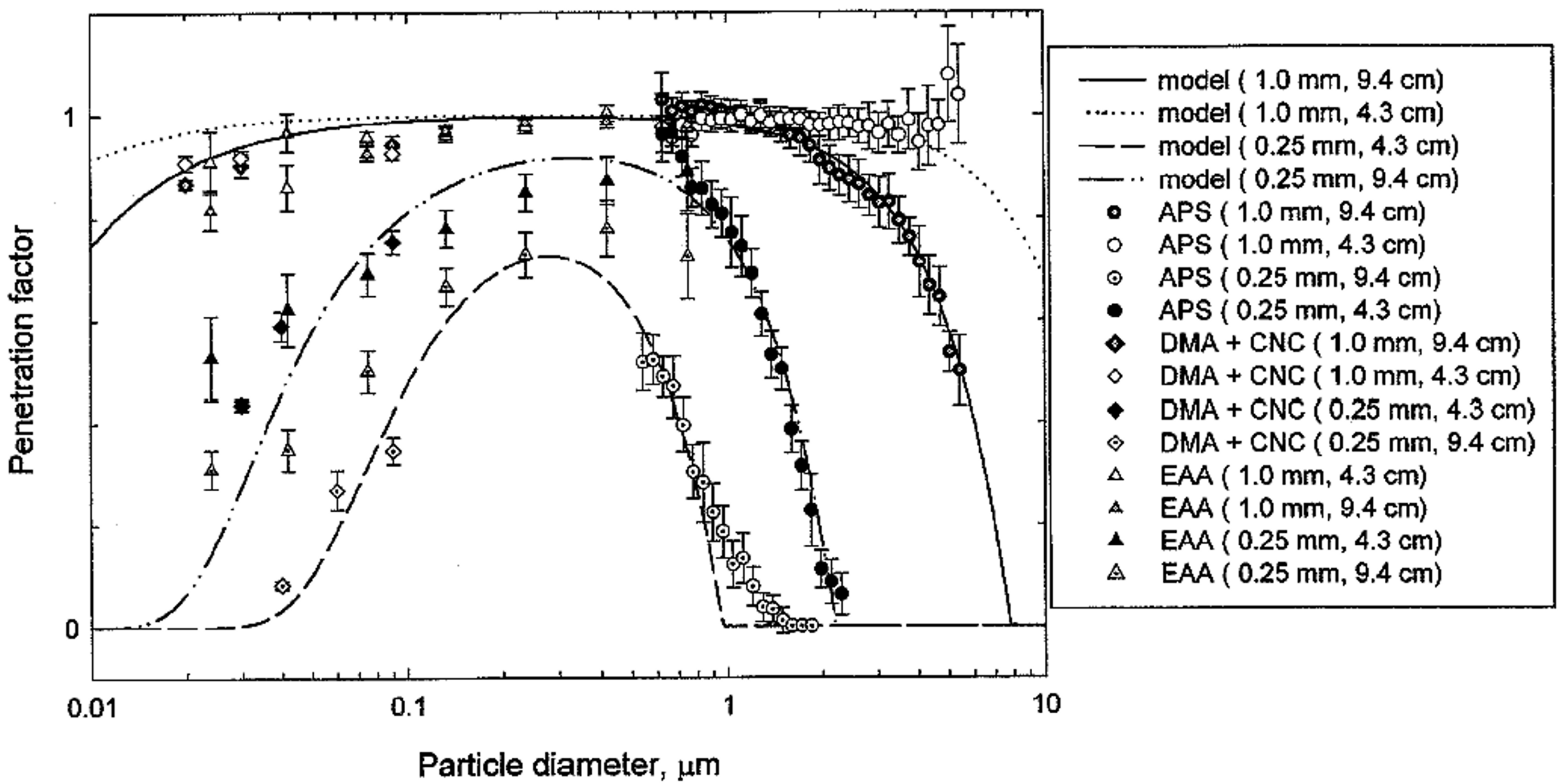


Figure 5. Comparison of model predictions with experimental data for aluminum cracks. Results are presented for four sets of crack dimensions (crack heights of 0.25 mm and 1.0 mm and crack flow lengths of 4.3 cm and 9.4 cm), with an applied pressure difference, $\Delta P = 4$ Pa.

Liu and Nazaroff 2003 *Atmos Environ*

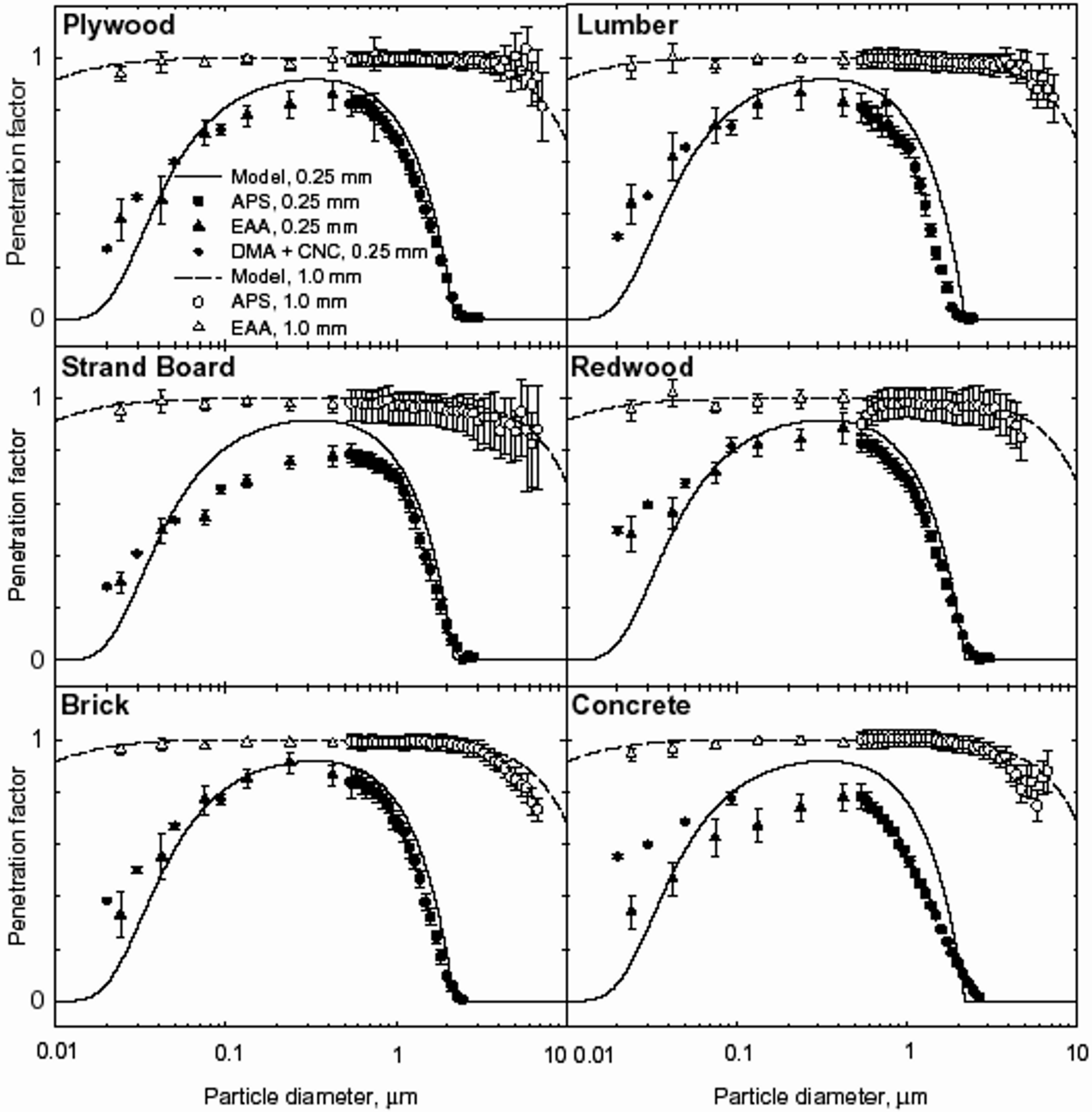


Figure 7. Experimental particle penetration factors for six crack materials at crack heights of 0.25 mm and 1 mm and with $\Delta P =$ 4 Pa, as compared with model predictions.

Liu and Nazaroff 2003 *Atmos Environ*

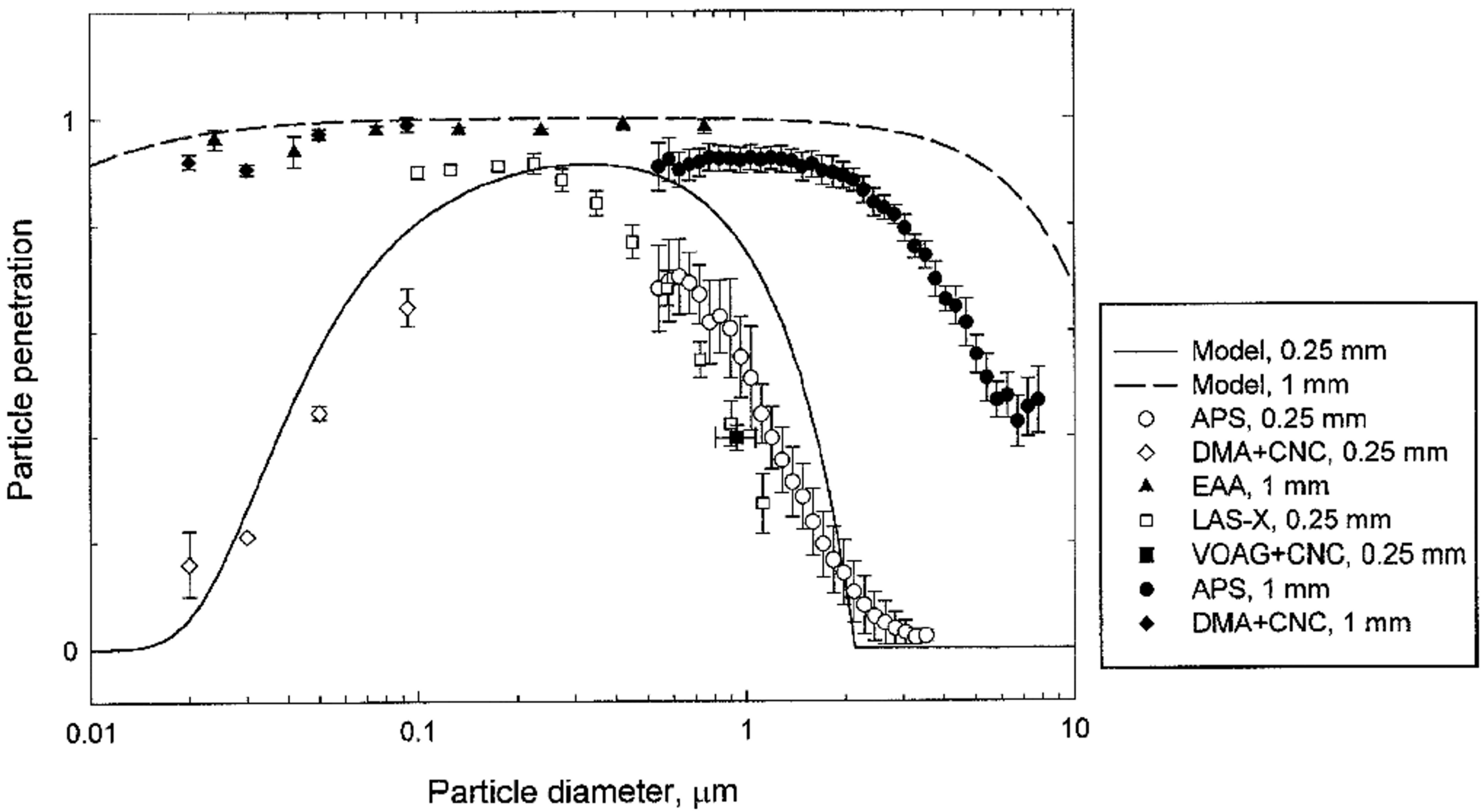


Figure 9. Comparison of model calculations and experimental results for naturally broken brick with crack heights of 0.25 mm and 1 mm.

Liu and Nazaroff 2003 *Atmos Environ*

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

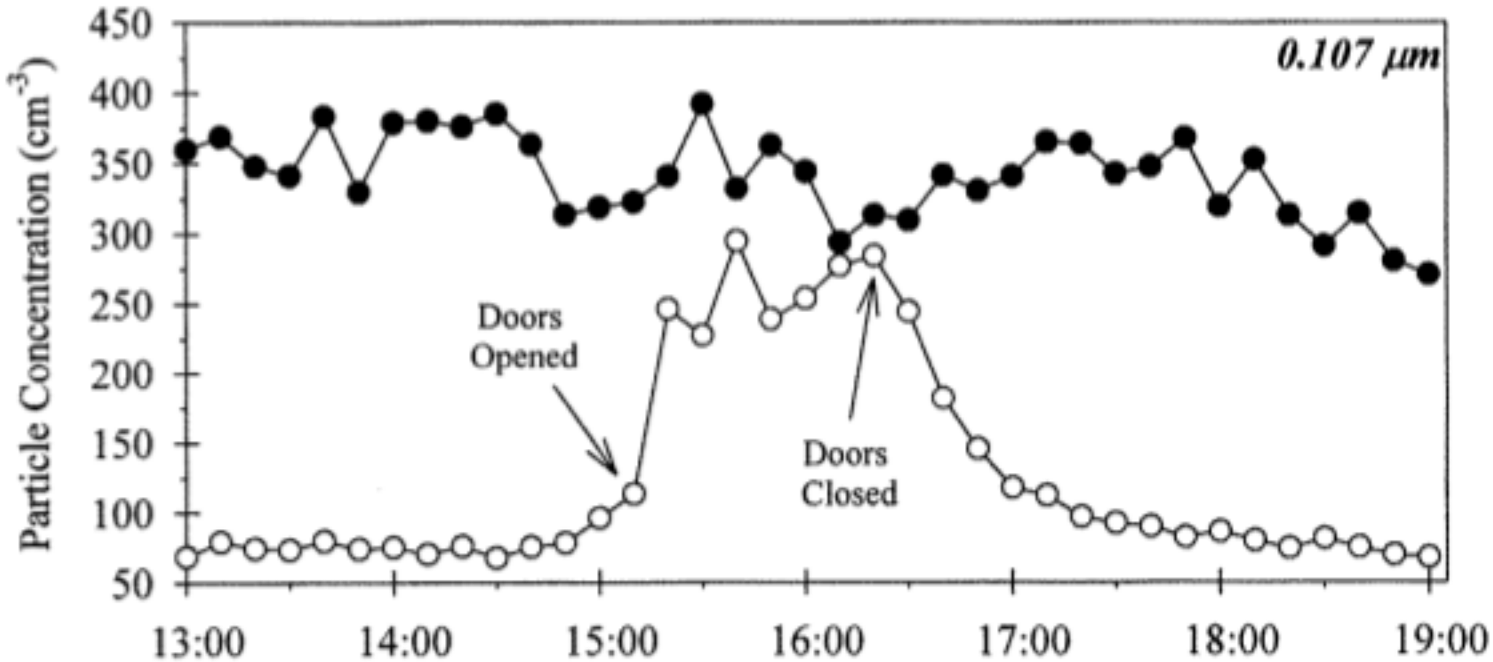
- Measurements are absolutely required in real buildings
  - But data can be messy and experiments challenging
  - One issue is that you need fluctuations in the data to solve for two parameters with only one mass balance (loss rates and penetration factors)
  - Another issue is that indoor sources greatly influence your data

Specific measurements of *P*

- Vette et al. 2001 *Aerosol Sci Technol*
- Chao et al. 2003 *Atmos Environ*
- Thatcher et al. 2003 *Aerosol Sci Technol*
- Rim et al. 2010 *Environ Sci Technol*
- Stephens and Siegel 2012 *Indoor Air*
- Zhao and Stephens 2016 *Indoor Air*

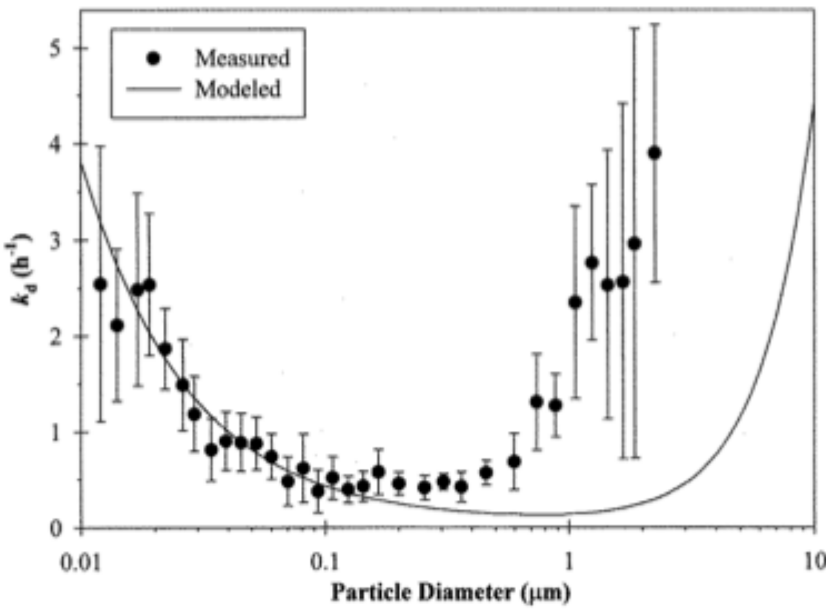
Vette et al. 2001 *Aerosol Sci Technol*

- 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



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

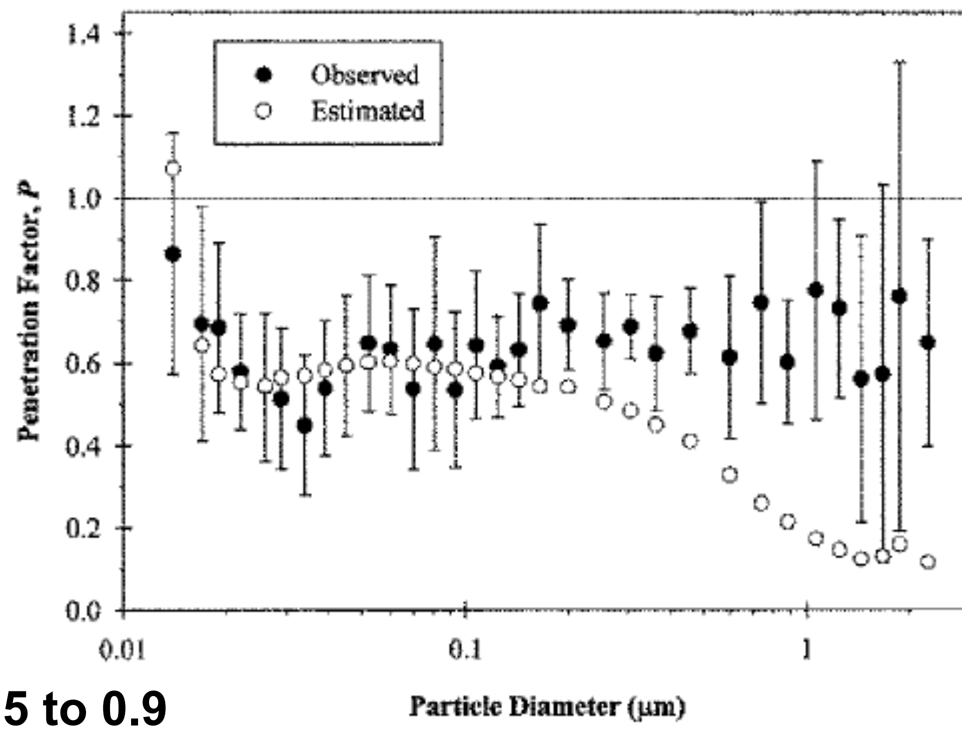
Vette et al. 2001



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

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

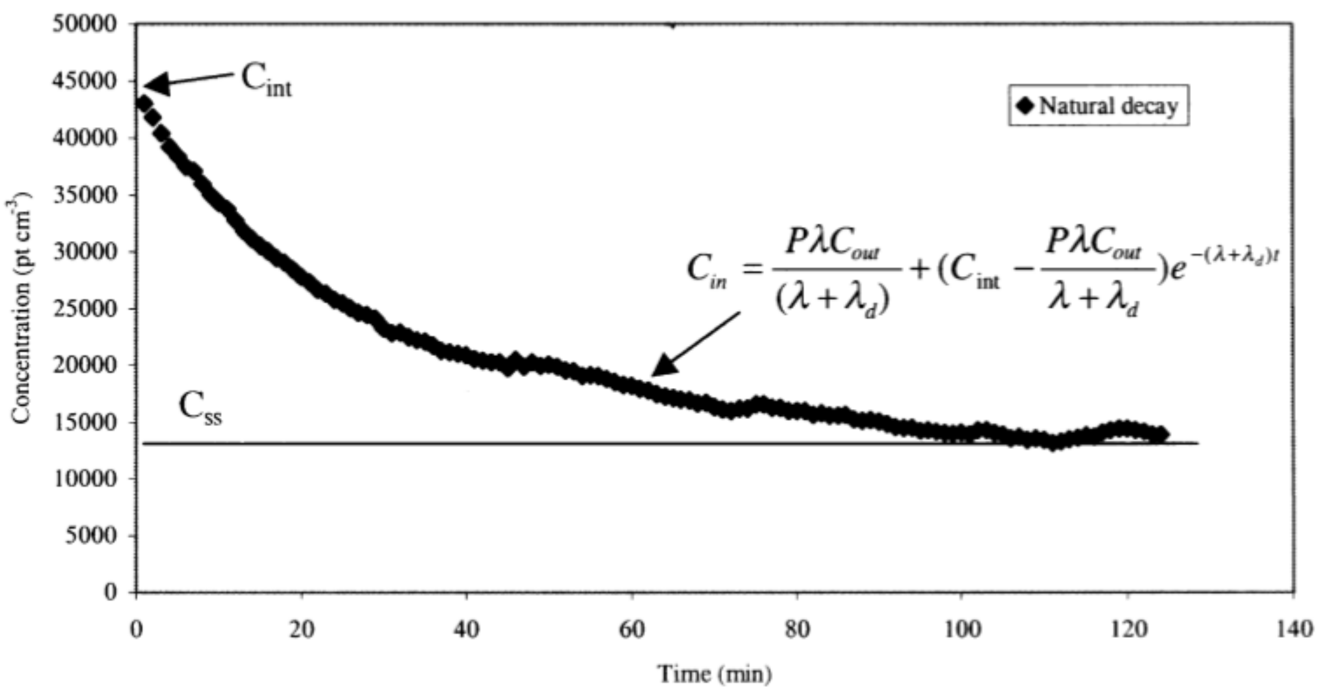
Good estimates of size-resolved deposition rates



Estimates of P ranged from 0.5 to 0.9

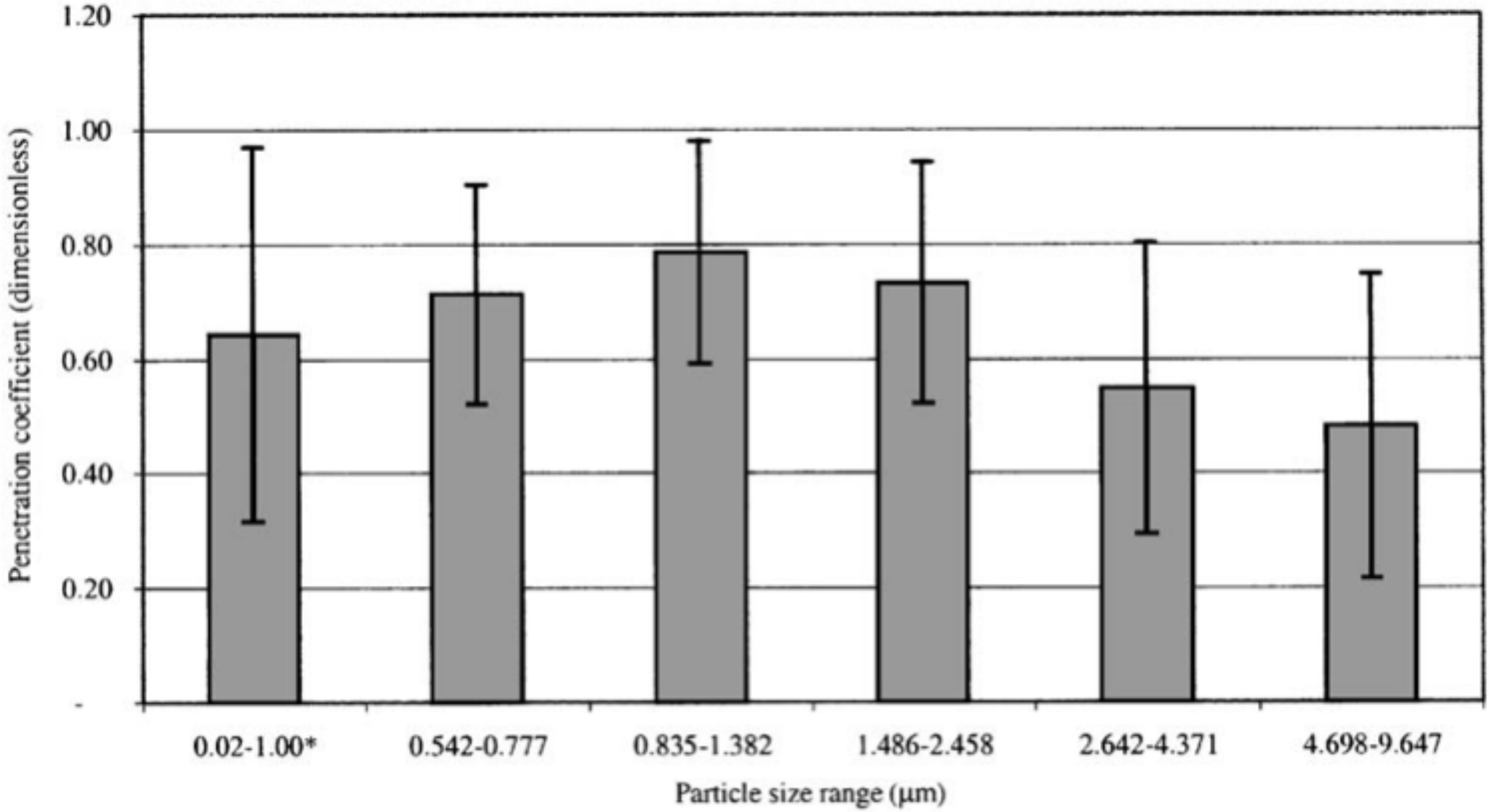
Chao et al. 2003 *Atmos Environ*

- 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

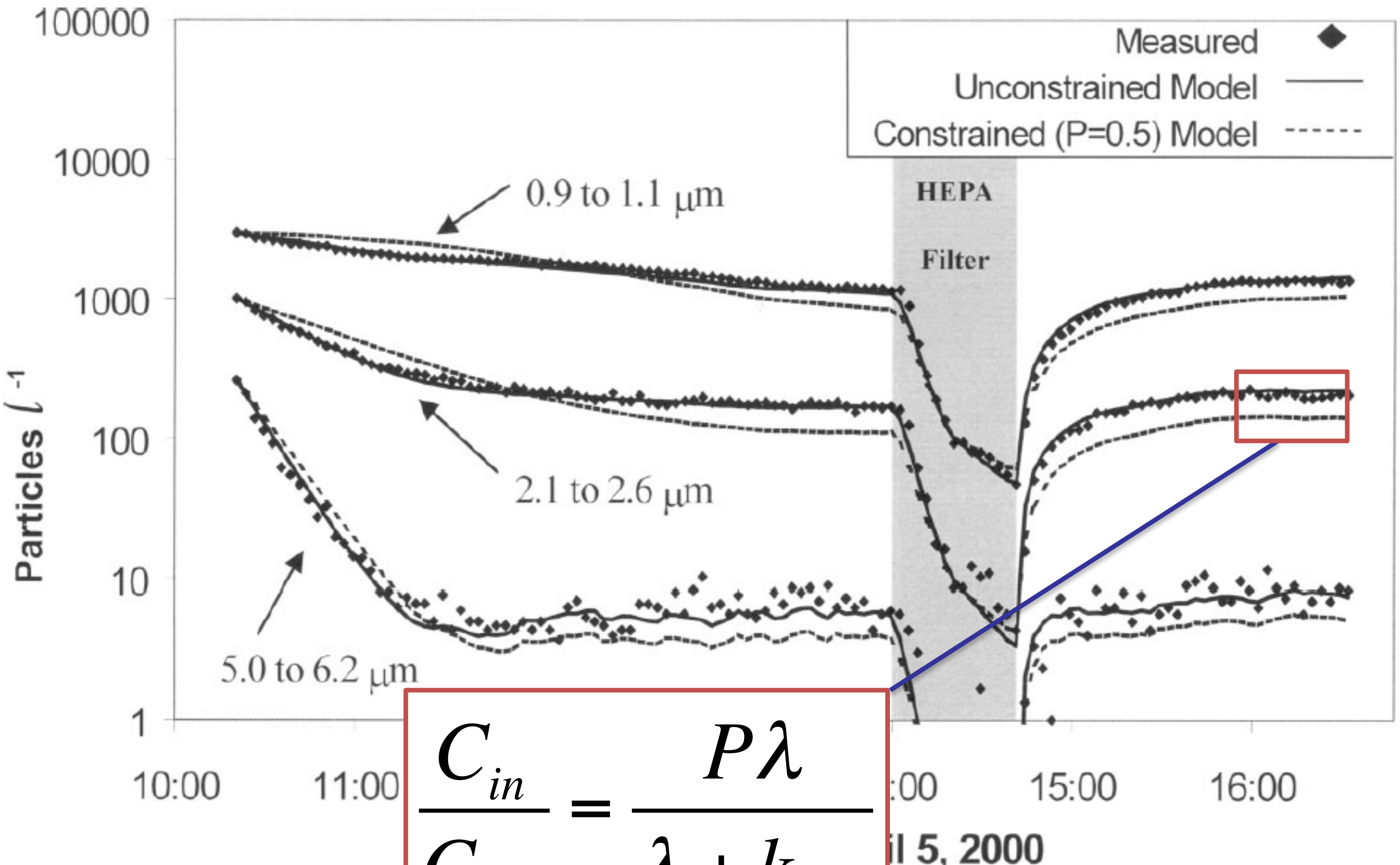
Estimates of P ranged from 0.5 to 0.8

Thatcher et al. 2003 *Aerosol Sci Technol*

- Two houses in CA
  - Size-resolved 0.3 to 10 μm particles

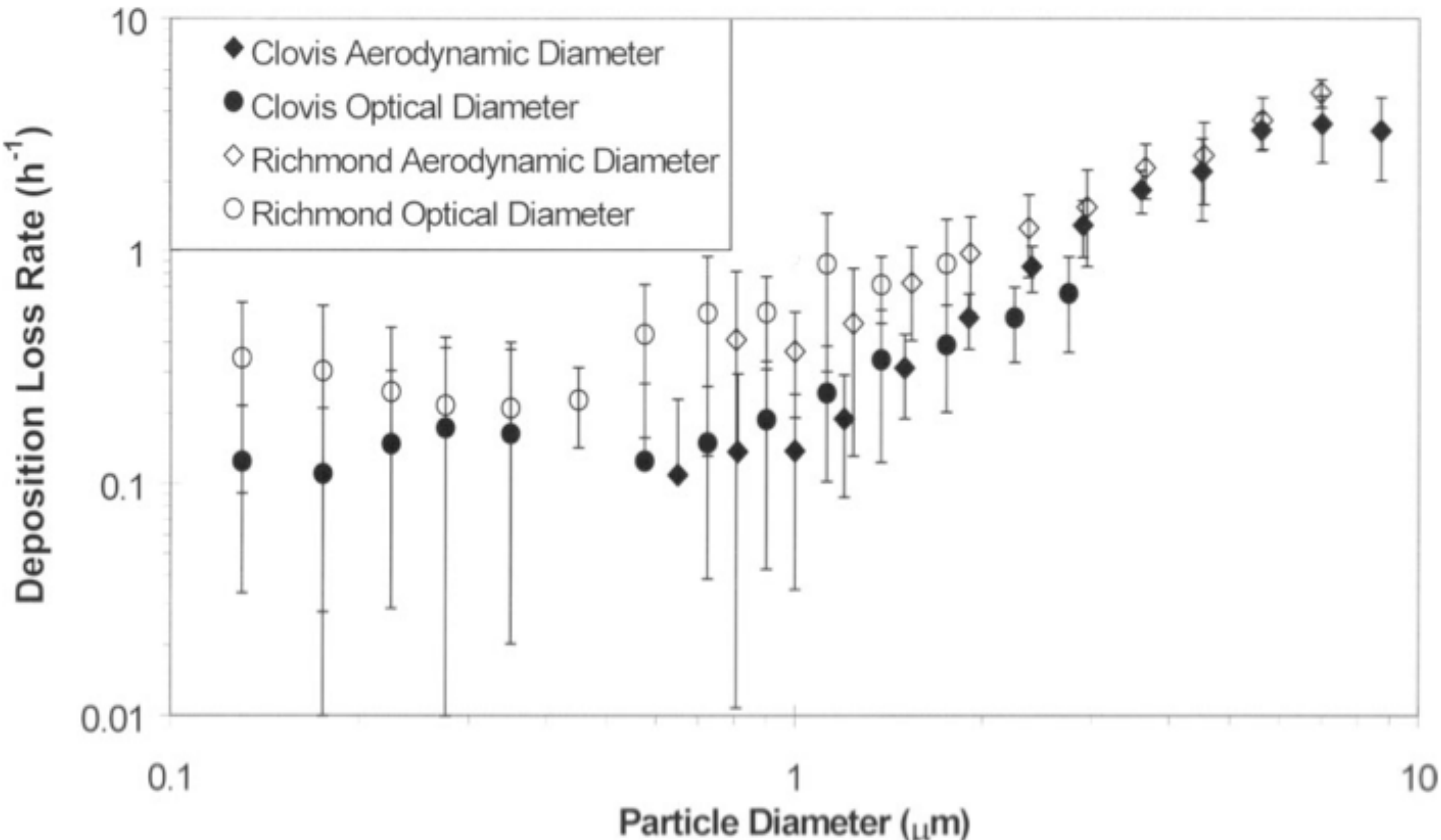
- New method of measuring P
  - “Concentration rebound method”
  - Involved artificially elevating indoor concentrations to measure decay
  - Then operate a HEPA filter to remove most of the indoor particles
  - Then observe the indoor concentration as it “rebounds” to normal levels due to the infiltration of outdoor particles only
  - Estimate P from steady state I/O ratio
    - Simultaneous AER measurements

Particle rebound method from Thatcher et al. 2003

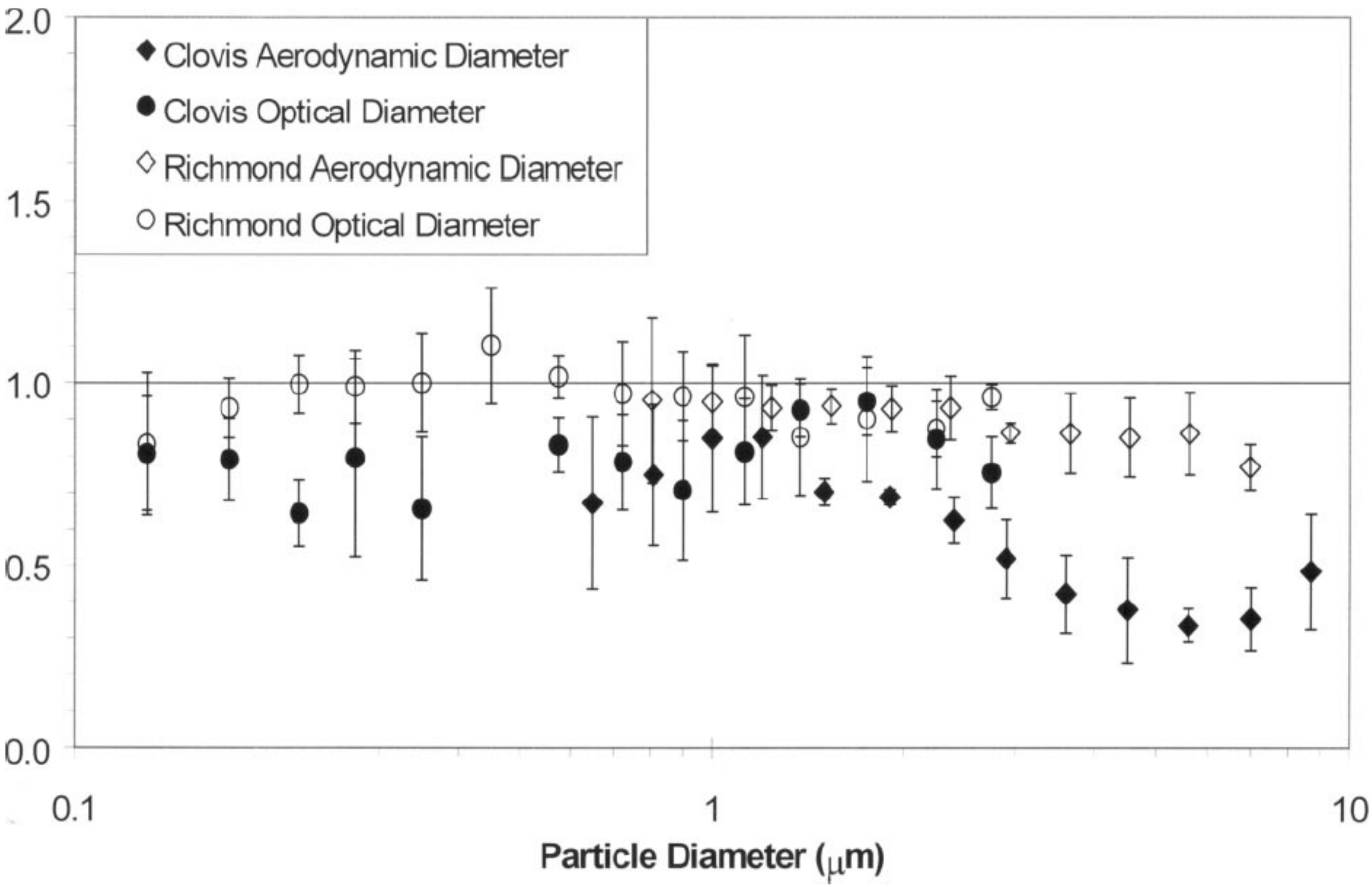


$$\frac{C_{in}}{C_{out}} = \frac{P\lambda}{\lambda + k_{dep}}$$

Thatcher et al. (2003)

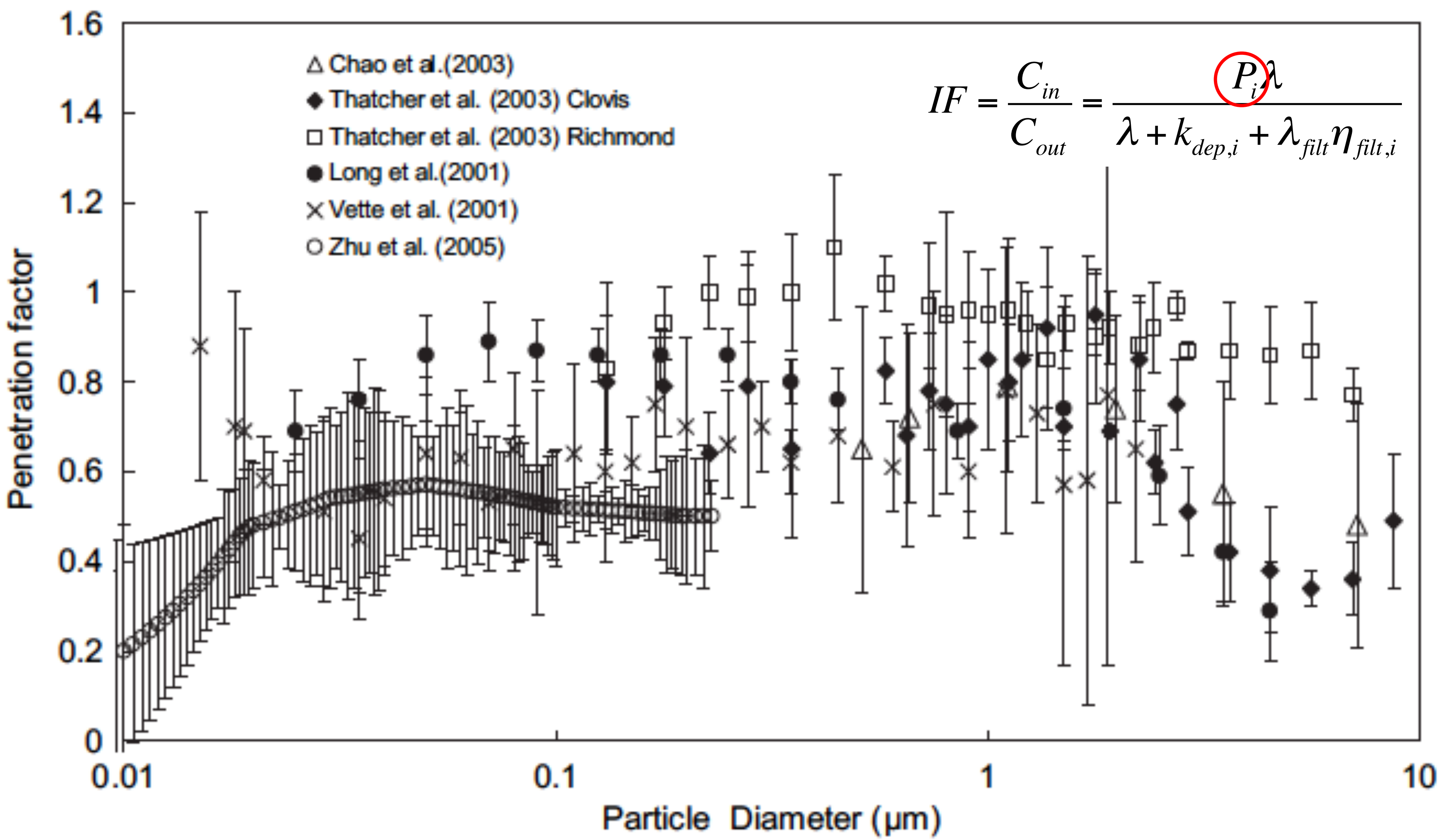


Thatcher et al. (2003)



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

Summary of penetration factors



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

Chen and Zhao, 2011 *Atmos Environ*

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

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

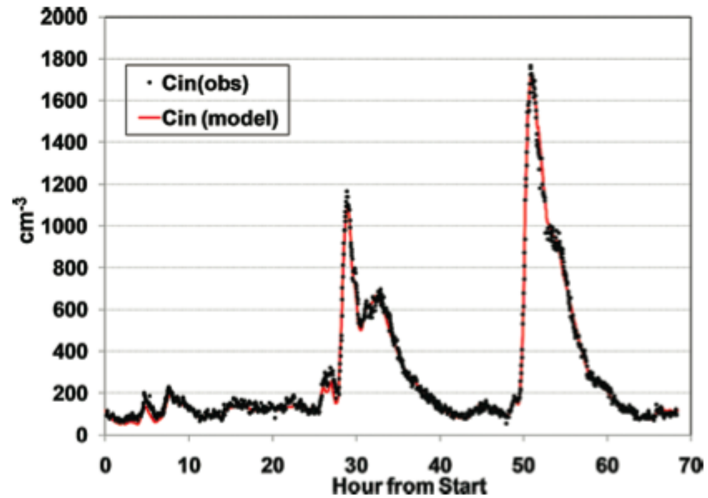
  - Discretized solution to mass balance for each particle size

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

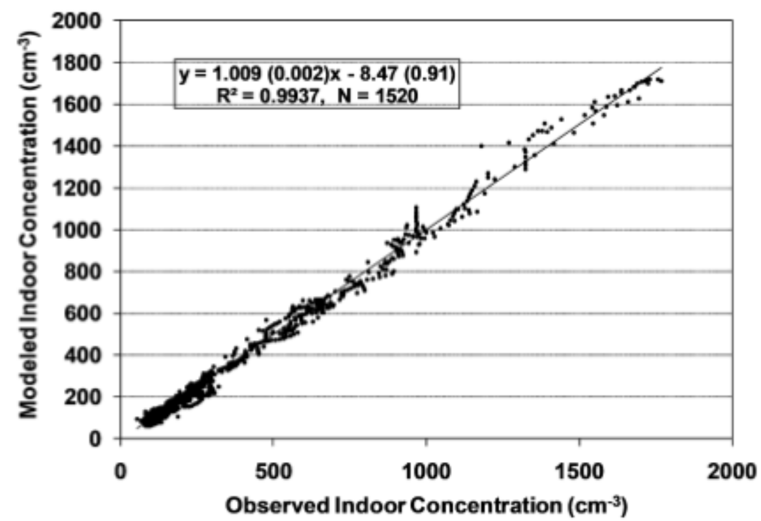
Rim et al. 2010 *Environ Sci Technol*

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

- 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

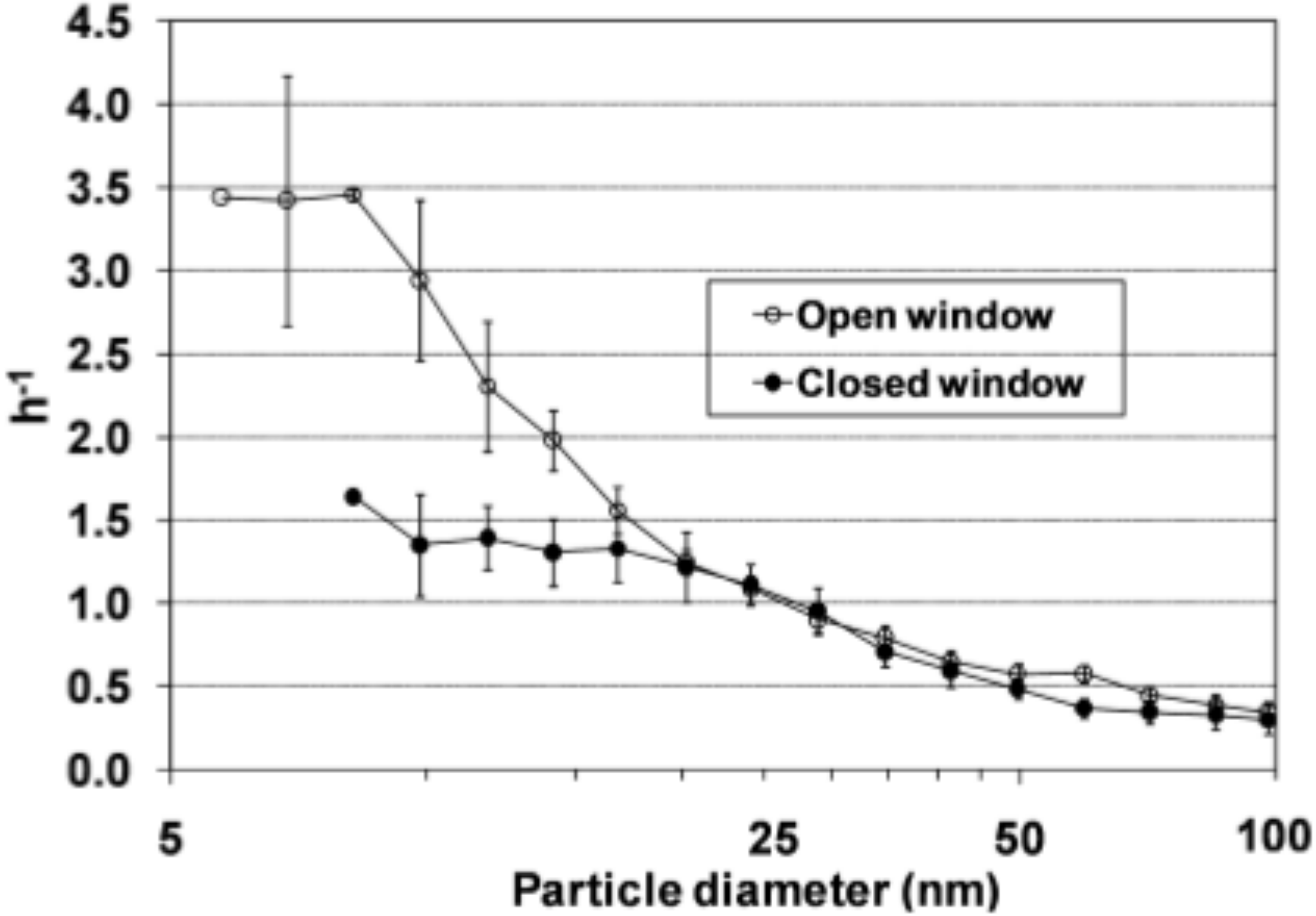


- Measured versus predicted indoor air concentrations compared via linear regression
  - If R^2 was > 0.90, they were happy with their estimates of *P* and k_{dep}



Rim et al. 2010 *Environ Sci Technol*

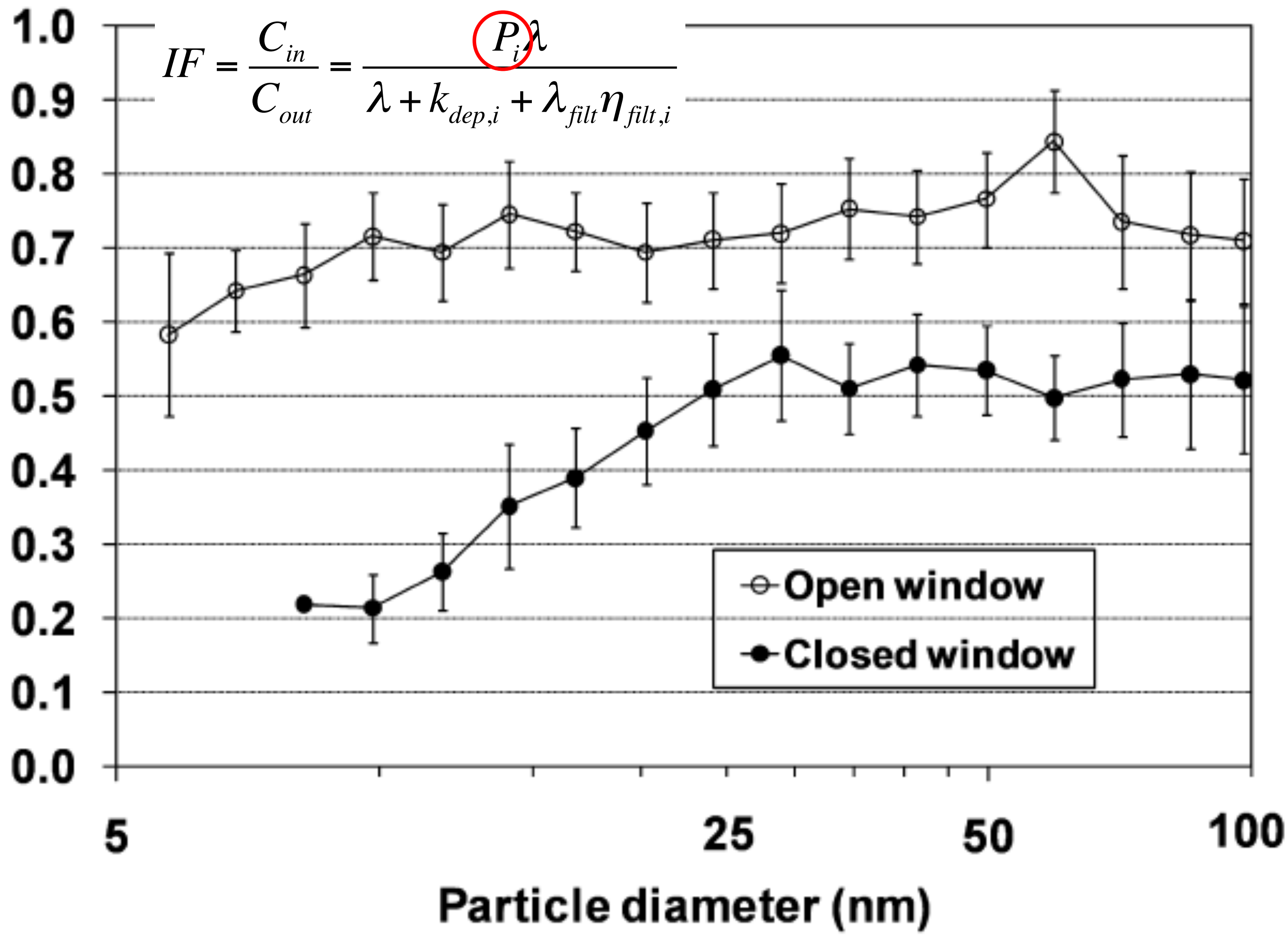
- Deposition rates



Rim et al. 2010 *Environ Sci Technol*

Penetration factors

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



Rim et al., 2010 *Environ Sci Technol*

Refined PM penetration test method

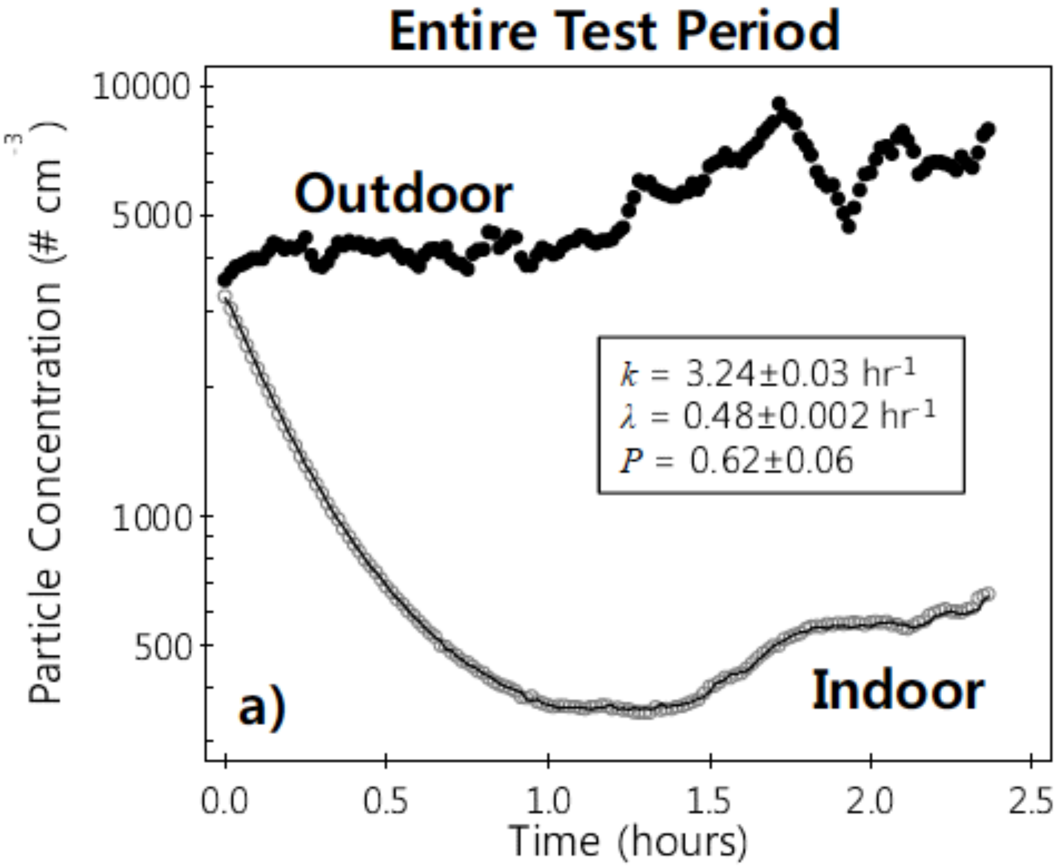
- Setup particle monitors indoors and outdoors | TSI P-Traks
  - Logging simultaneously at 1-minute intervals
    - 20 nm to 1 µm

- 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

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

PM infiltration: Refined test method



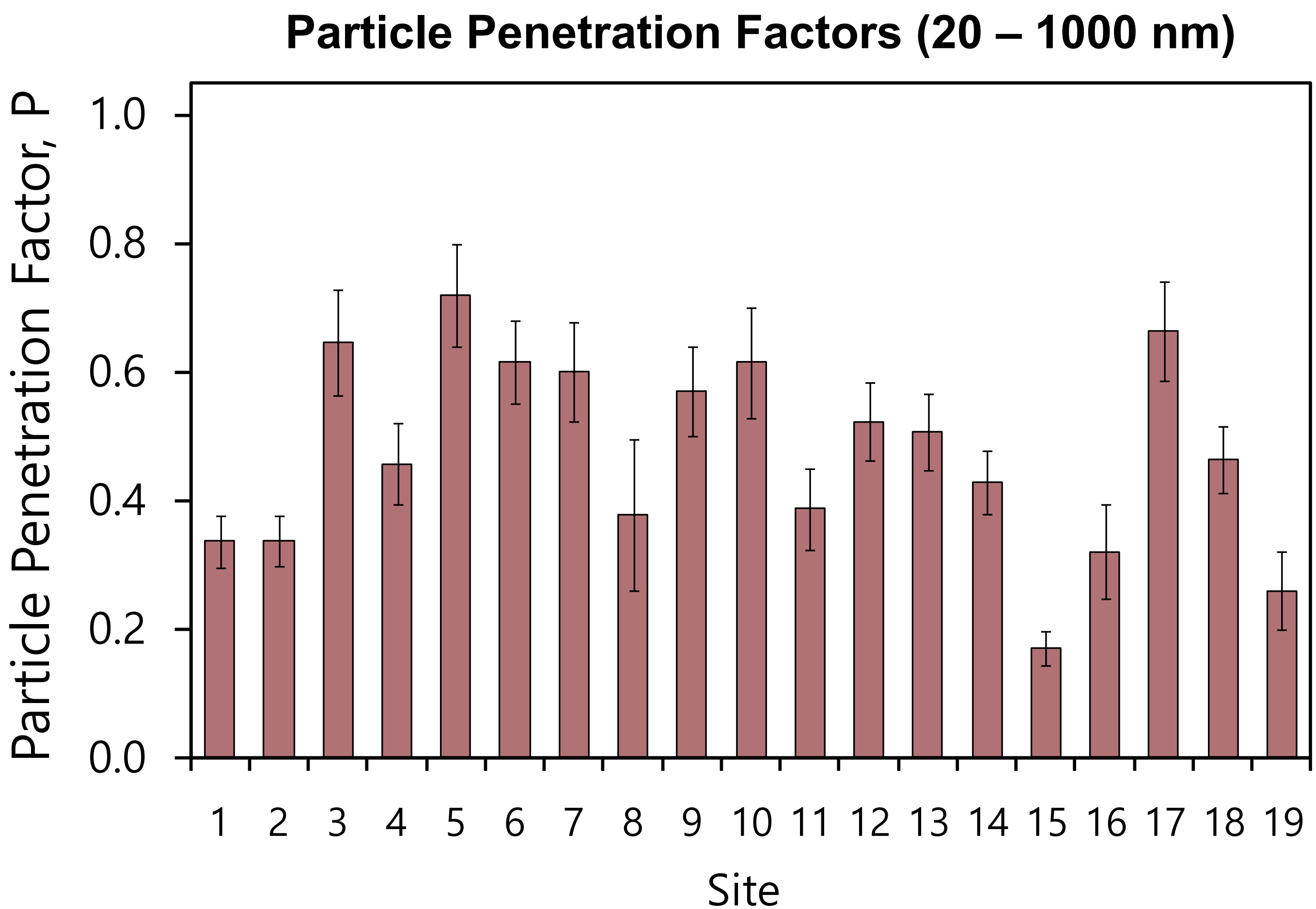
$$C_{in,t} = C_{in,t-1} + \left(P\lambda C_{out,t-1} - (\lambda + k)C_{in,t-1}\right)\Delta t$$

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

PM infiltration: Test homes

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

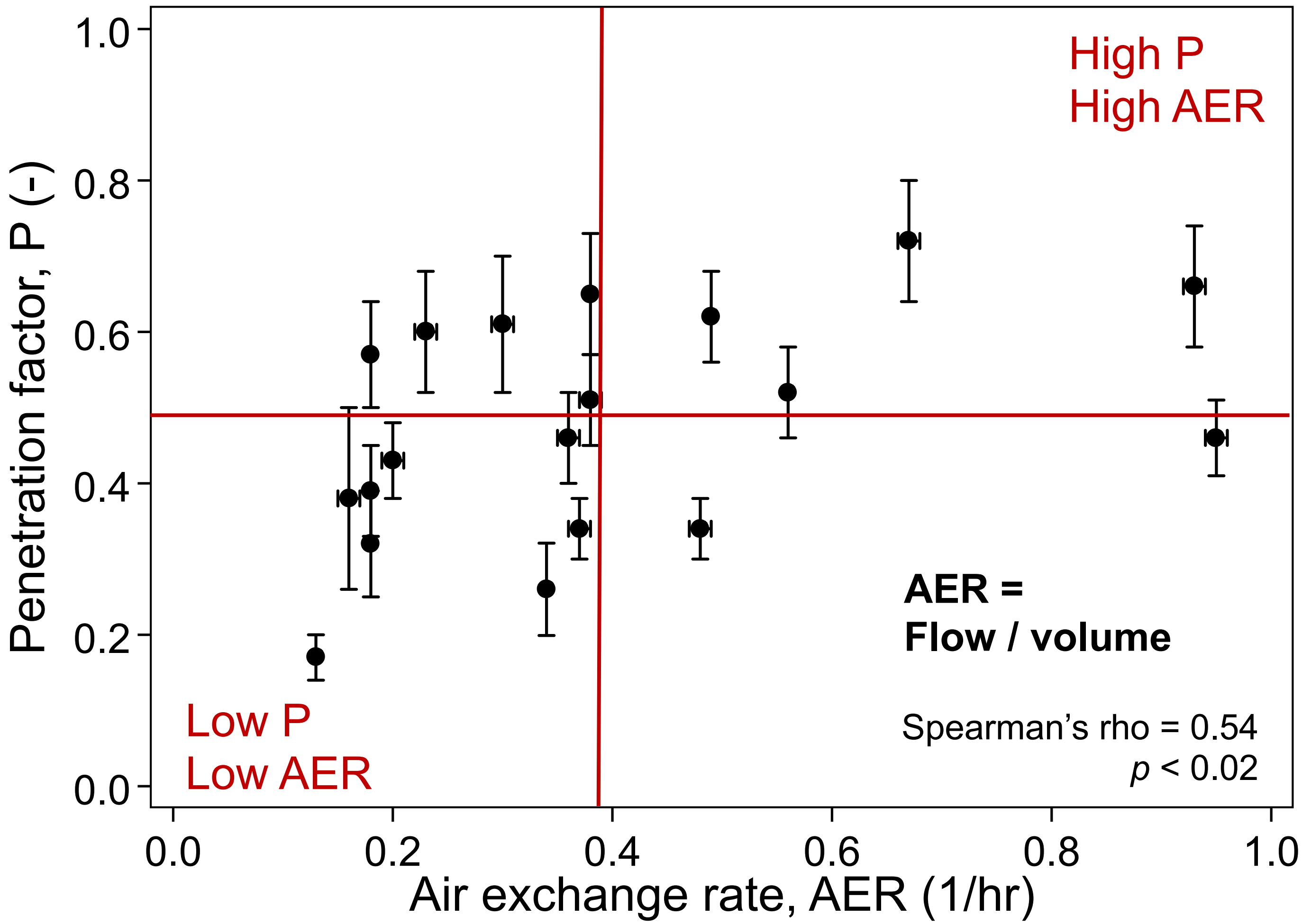
Particle infiltration results



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

UFP penetration results: P vs. AER



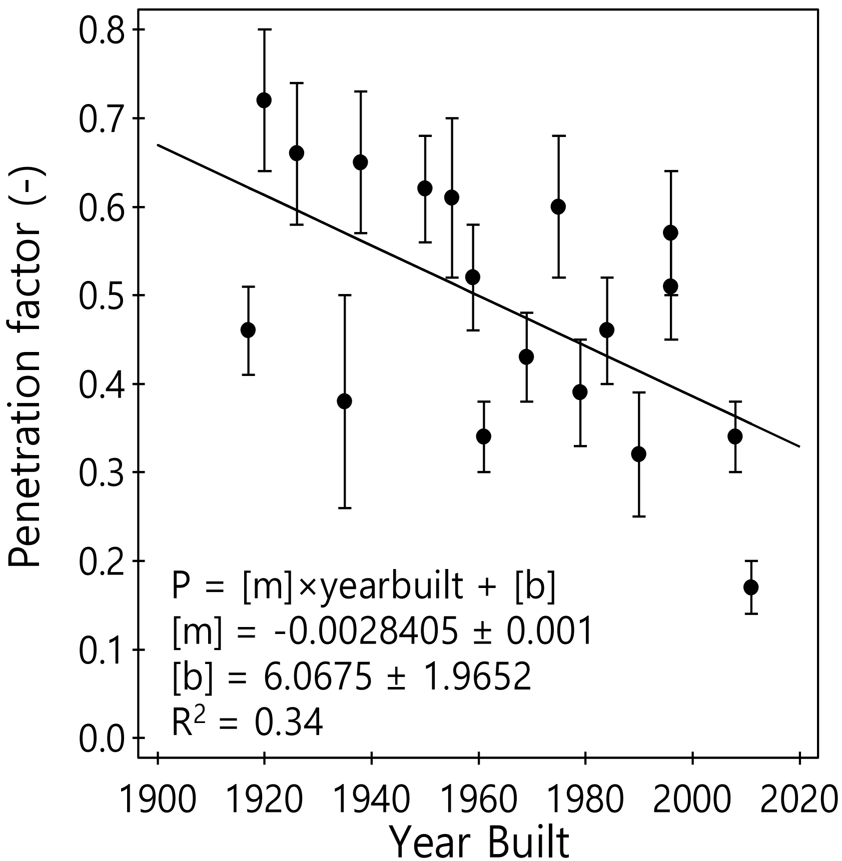
Penetration factors: Mean = 0.47 Range = 0.17 to 0.72

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

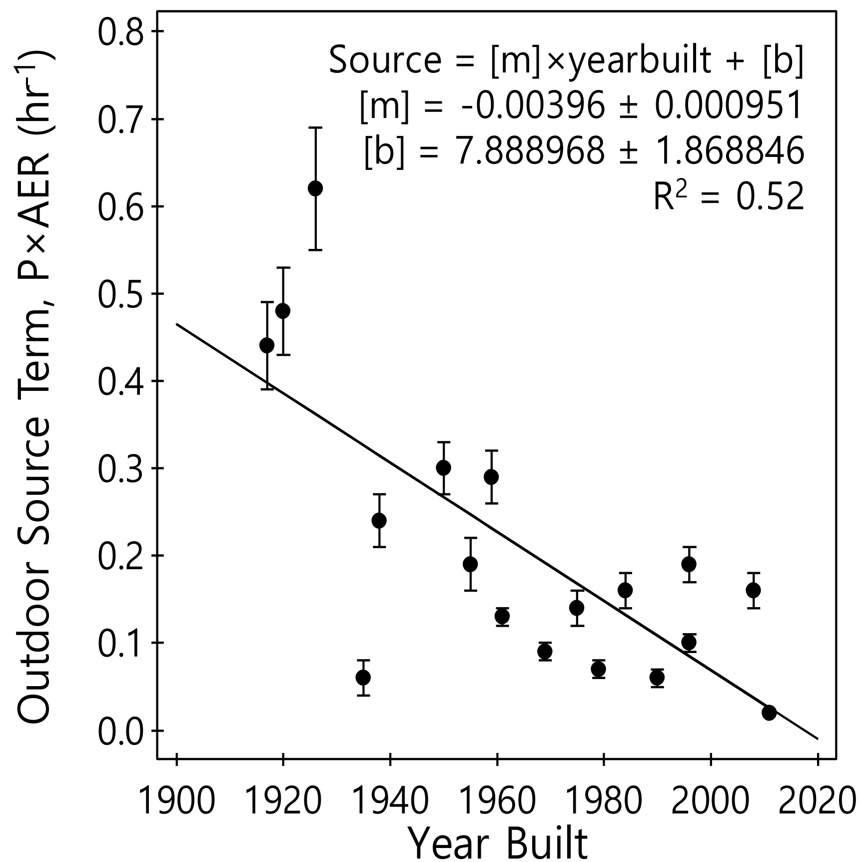
Stephens, *Science and Technology for the Built Environment* **2014** 21:3-13

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 UFP exposure

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

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

Mean from this study

Least protective home, 1926

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

Most protective home, 2011

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

Factor of ~16

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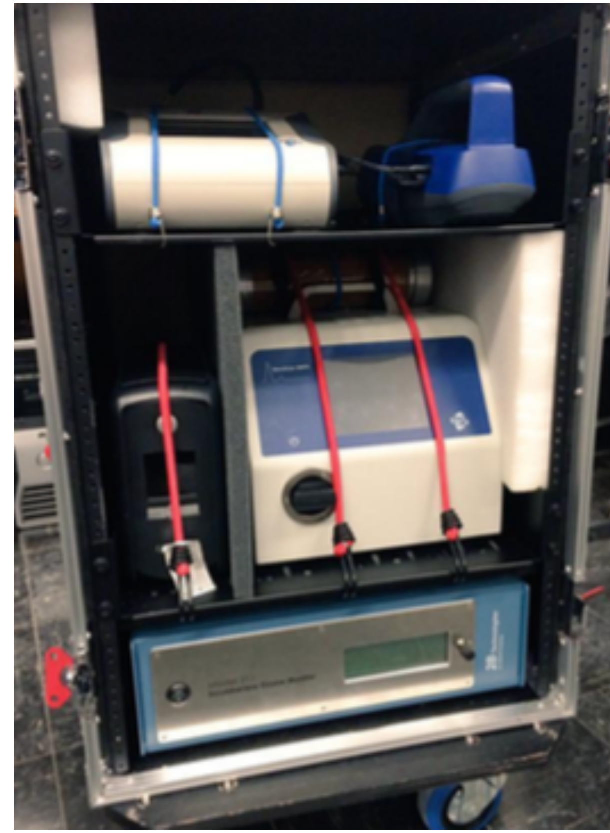
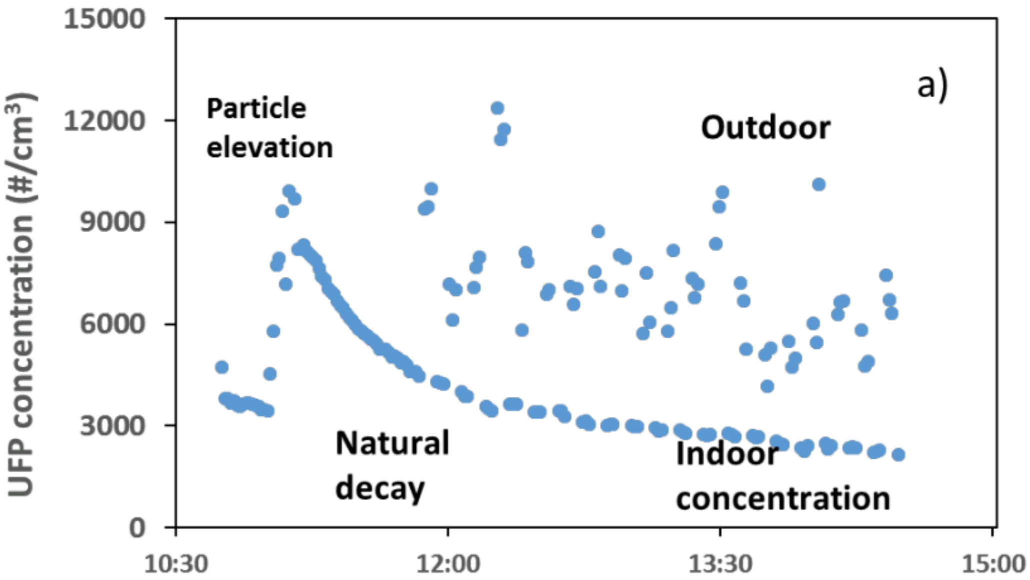
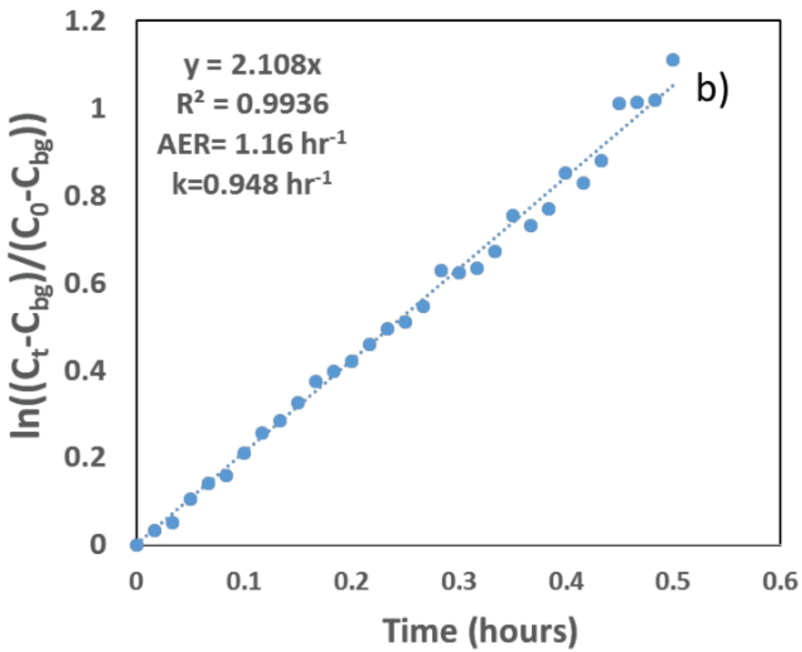


Zhao and Stephens, *Indoor Air* **2016** doi:10.1111/ina.12295

Zhao and Stephens (2016) *Indoor Air*

Example time-series data

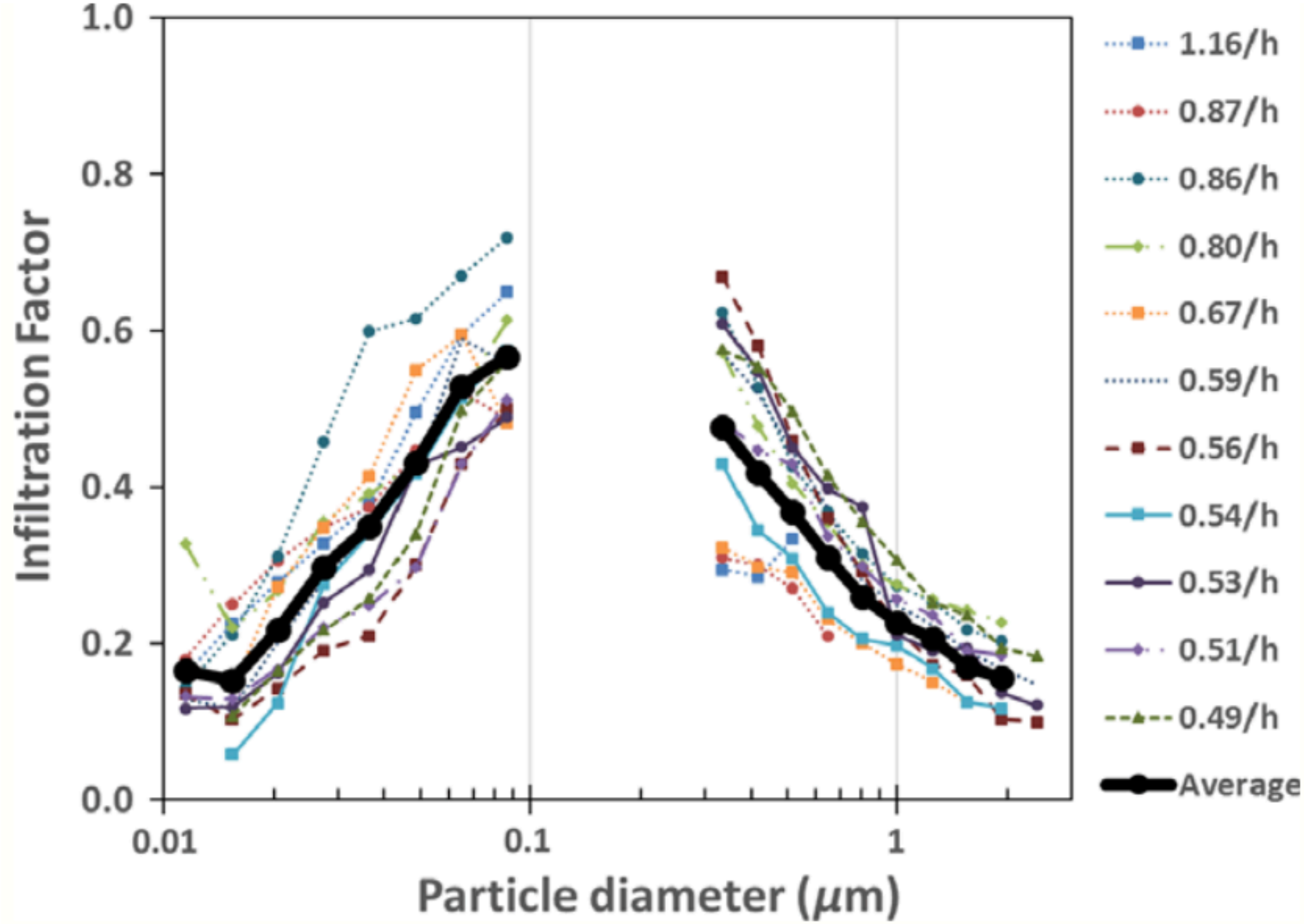




Zhao and Stephens, *Indoor Air* **2016** doi:10.1111/ina.12295

Zhao and Stephens (2016) *Indoor Air*

Size-resolved infiltration factors



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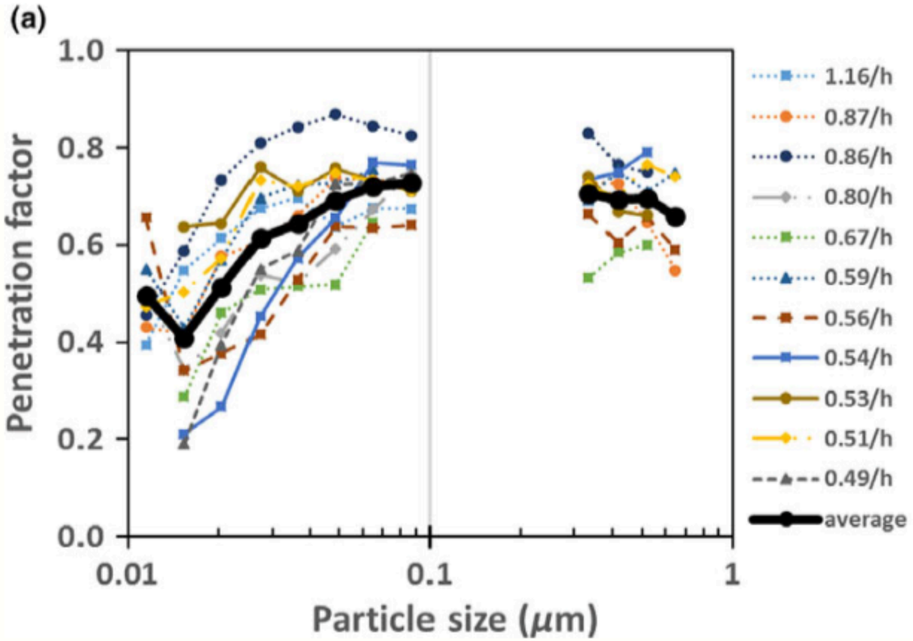
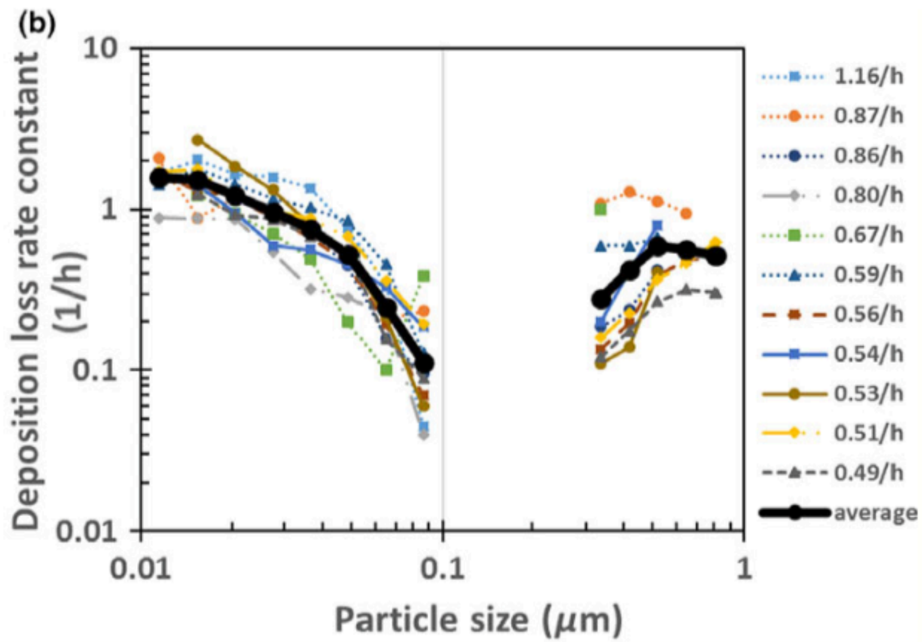
Size-resolved penetration factors and deposition loss rates





Zhao and Stephens, *Indoor Air* **2016** doi:10.1111/ina.12295

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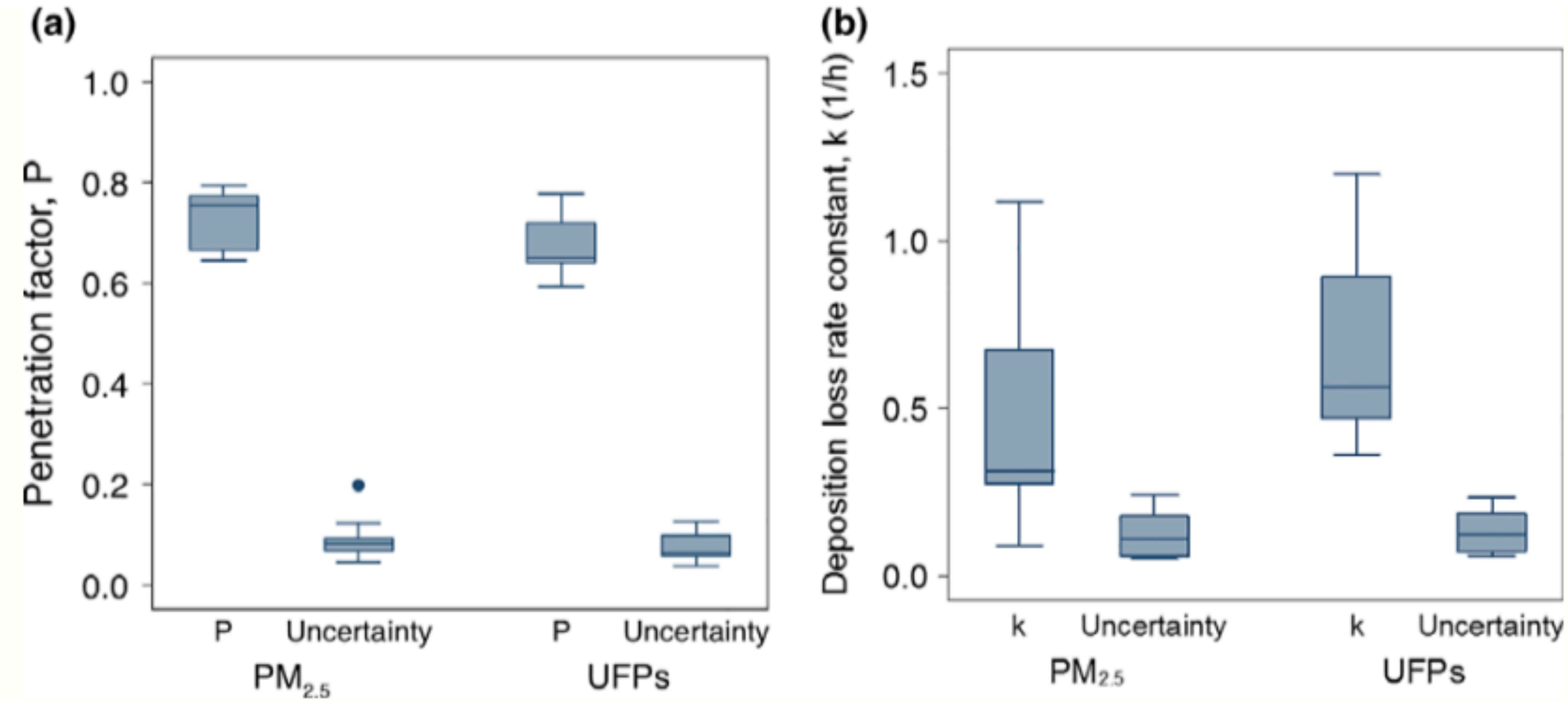
Integral $PM_{2.5}$ and UFP penetration factors and deposition loss rates



Zhao and Stephens, *Indoor Air* **2016** doi:10.1111/ina.12295

Summary on particle penetration

- In the last 10-15 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
  - The ultimate goal is to perform a lot of these tests, then never have to perform them again