ENVE 576
Indoor Air Pollution
Fall 2015

Week 7: October 6, 2015
Particle sources, deposition, resuspension, infiltration

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Scheduling

- HW #3 due today
- Blog post #2 due next Tuesday Oct 13
- Schedule update:
  - Next class is cancelled (Oct 13)
  - Oct 20 class will have a guest lecture by Dr. Stephanie Kunkel on indoor air microbiology

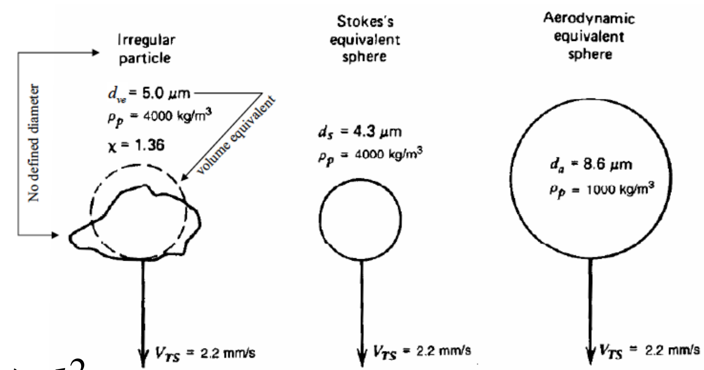
Final project topics: Any topics yet?

Name	Project topic
Anton Losada, Lucas	
Bu, Weisheng	
Del Pino Torres, Julia Del Rosario	
Guo, Qindong	
Jiang, Han	
Khodaei, Saeid	
Li, Juntao	
Liang, Jinzhe	
Liang, Xiangmin	
Qiu, Luanzhizi	
Velez, Daniel	
Xu, Jiayao	
Zhang, Zhe	
Zhao, Xingchao	
Fortune, Roger G.	
Knudsen, Westen R.	
Naik, Prasad Kishor	
Peng, Xuexuan	

Review from last time

- Motion/dynamics of particles

$$V_{TS} = \frac{\rho_p d_p^2 g C_C}{18\mu}$$



$$V_{TS} = \frac{\rho_p g C_C(d_e) d_e^2}{18\mu\chi} = \frac{\rho_0 g C_C(d_a) d_a^2}{18\mu} = \frac{\rho_p g C_C(d_s) d_s^2}{18\mu}$$

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

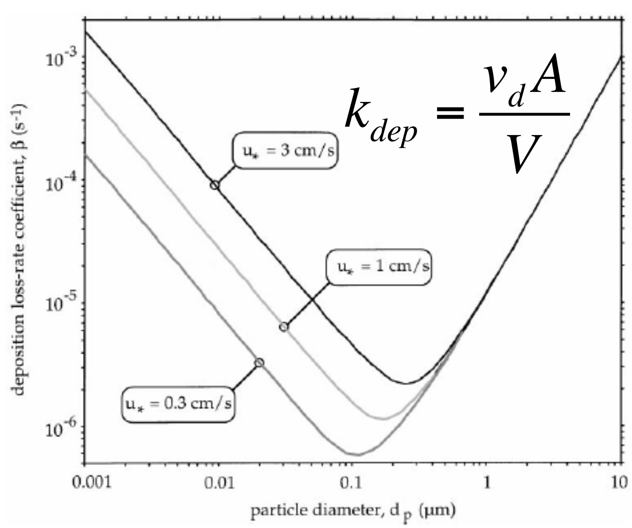
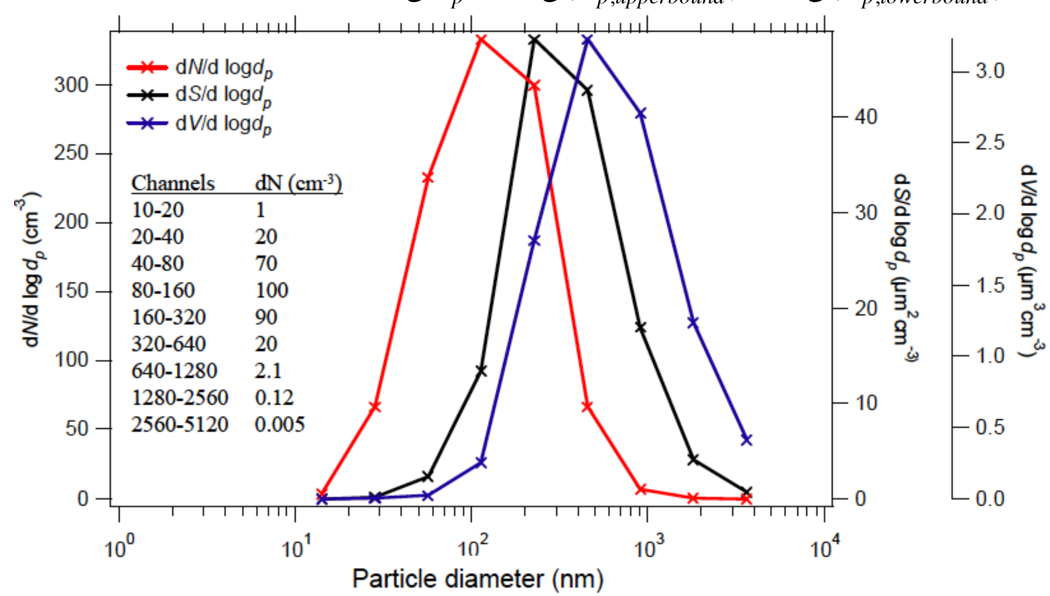
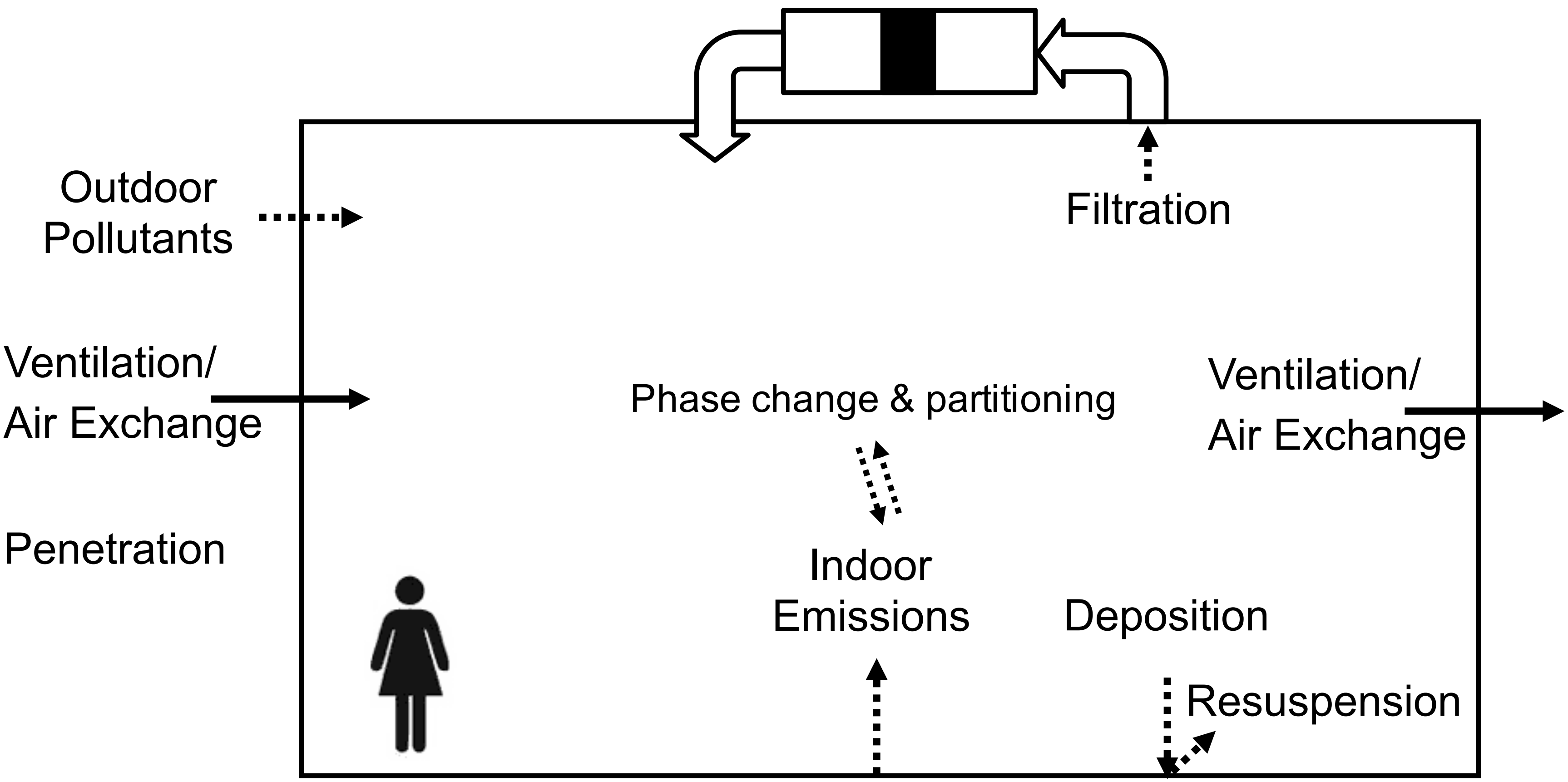


Fig. 5. Particle deposition loss-rate coefficient, β, for typical room dimensions (3 m high × 4 m × 5 m) according to the current model. Friction velocities of 0.3–3 cm s^{-1} approximately span the range expected for mechanically ventilated indoor spaces. Predictions assume air pressure is 1 atm, temperature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

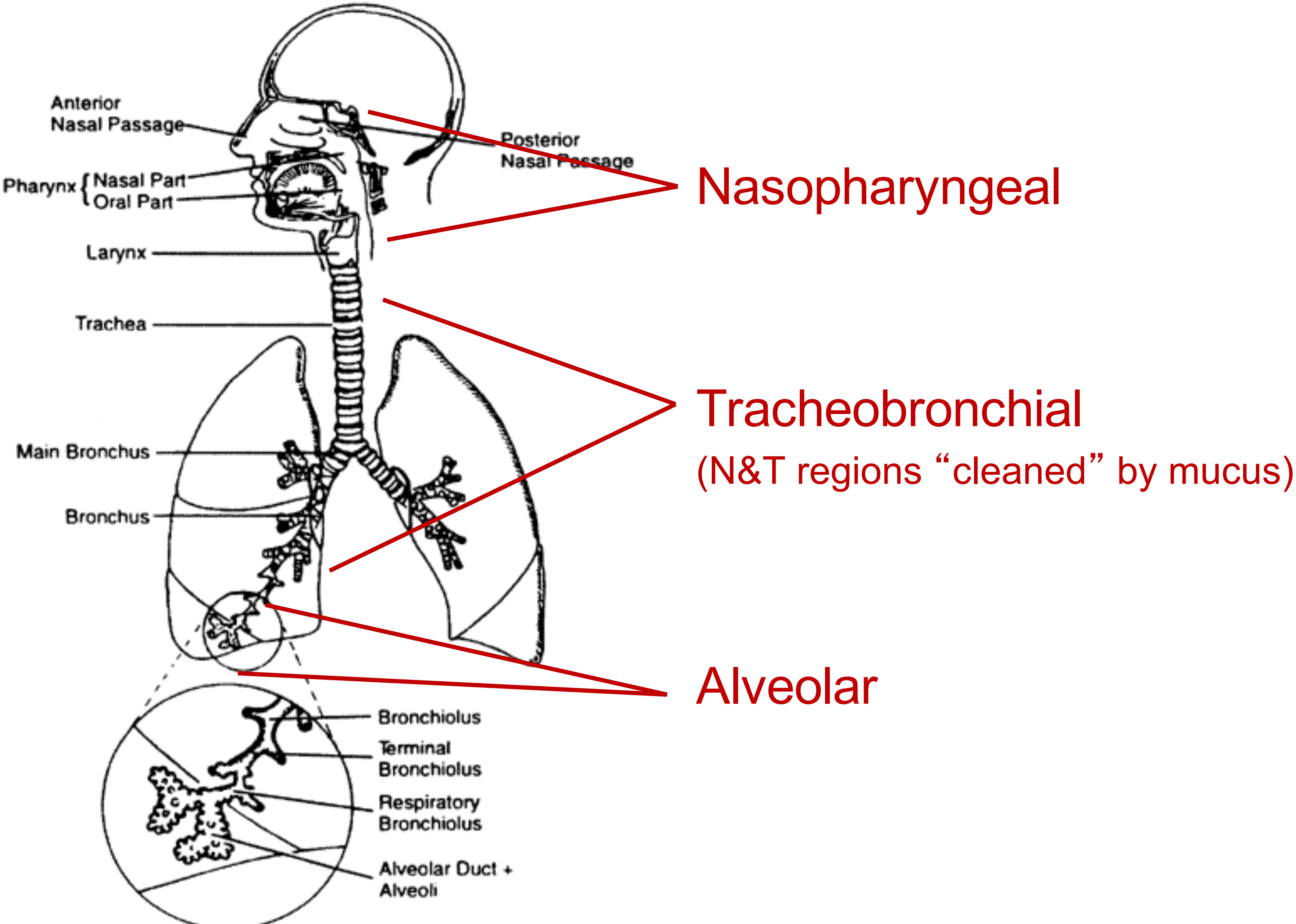
$$\frac{dN}{d\log d_p} = \frac{dN}{\log(d_{p,upperbound}) - \log(d_{p,lowerbound})}$$



Mass (or number) balance approach for particles



Human respiratory system



Hinds, 1999 Ch. 11

Respiratory deposition by region

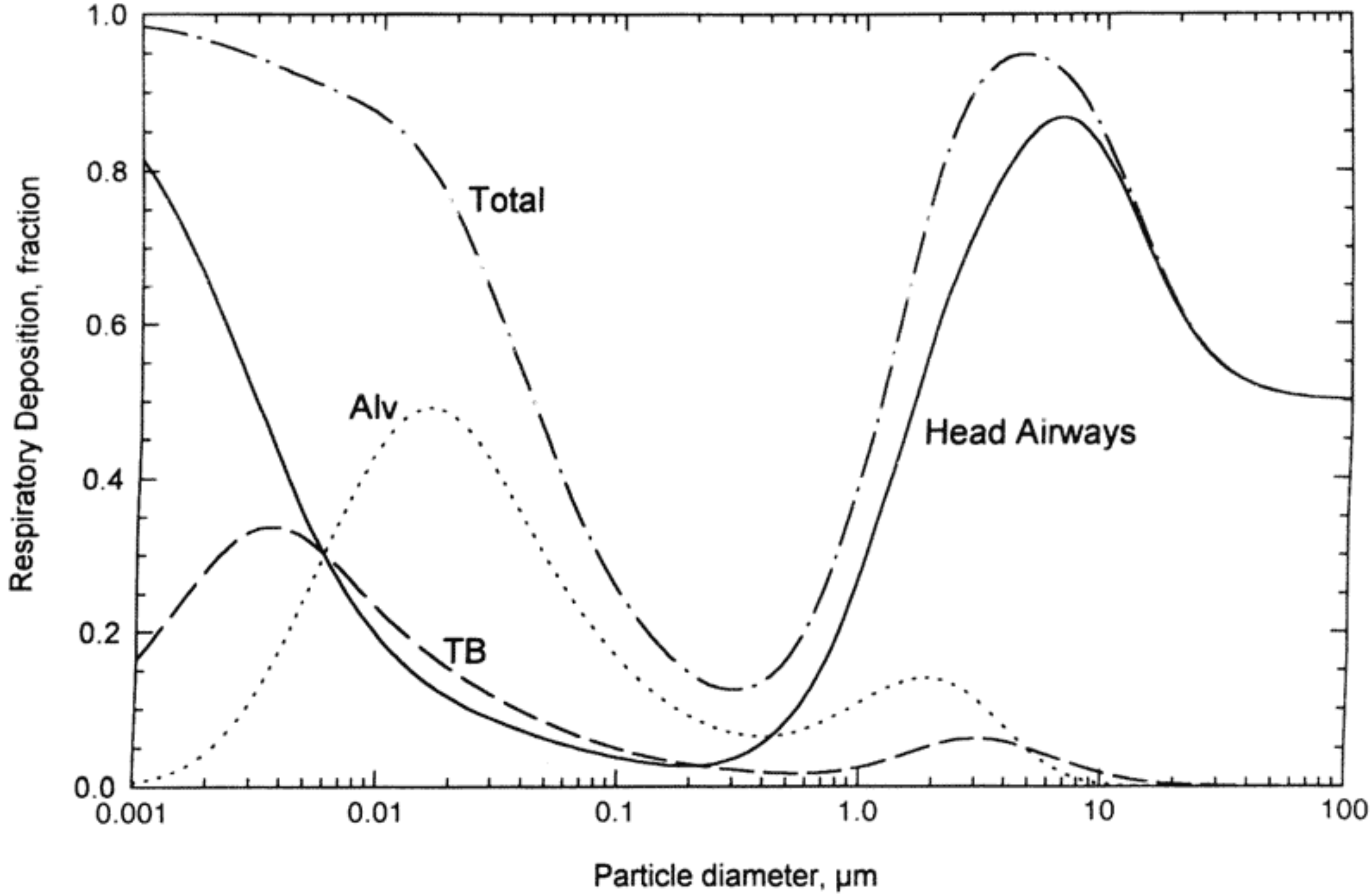


FIGURE 11.3 Predicted total and regional deposition for light exercise (nose breathing) based on ICRP deposition model. Average data for males and females.

Hinds, 1999 Ch. 11

Today's topics

- Integrate particulate matter into our mass balance
  - Particle sources
    - Indoor emissions
    - Resuspension
    - Outdoor transport (infiltration and penetration)
  - Particle losses
    - Deposition
    - Filtration and air cleaners (Oct 27)

PARTICLE SOURCES

Indoors and outdoors

Particle sources

- Indoor and outdoor particle sources vary by particle size

Table 1 Attributes of particle size modes

mode	diameter	indoor source	example composition
ultrafine	$\leq$ 0.1 μm	gas cooking	soot
accumulation	0.1-2 μm	tobacco smoke	organic liquids
coarse	> 2 μm	cleaning	crystal solids

- Indoor emission sources are typically episodic
  - Tend to be brief, intermittent, and highly variable
  - Steady state rarely applies
  - Outdoor particle levels and ventilation rates often vary with time

Nazaroff, 2004 *Indoor Air*

Indoor particle sources

- Combustion processes
  - Incense smoke, candle burning, cigarette smoke

- Cooking
  - Gas and electric cooking both
  - Biomass cookstoves in developing world

- Cleaning activities
  - Resuspension from vacuum cleaners
  - Aerosolization from tap water in humidifiers

Indoor particle sources

- We now understand more about particle sizes
  - And how different size particles deposit in different regions of our respiratory system

- We can examine different sources to determine their sizes
  - e.g., ETS or cooking particles

- And we can examine what particles will deposit in lungs?
  - And in which region?

- Helps elucidate health effects that may be observed

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.

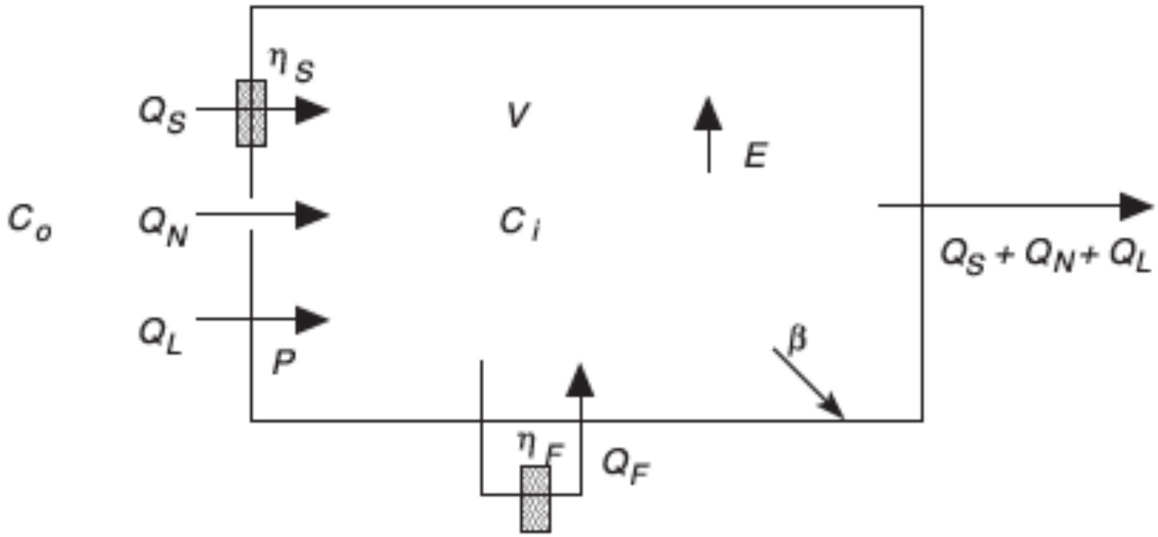
- Modeling exercise
  - Examine emissions from ETS
  - Used lung deposition model to examine where ETS particles end up

- 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

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?

Emissions from ETS

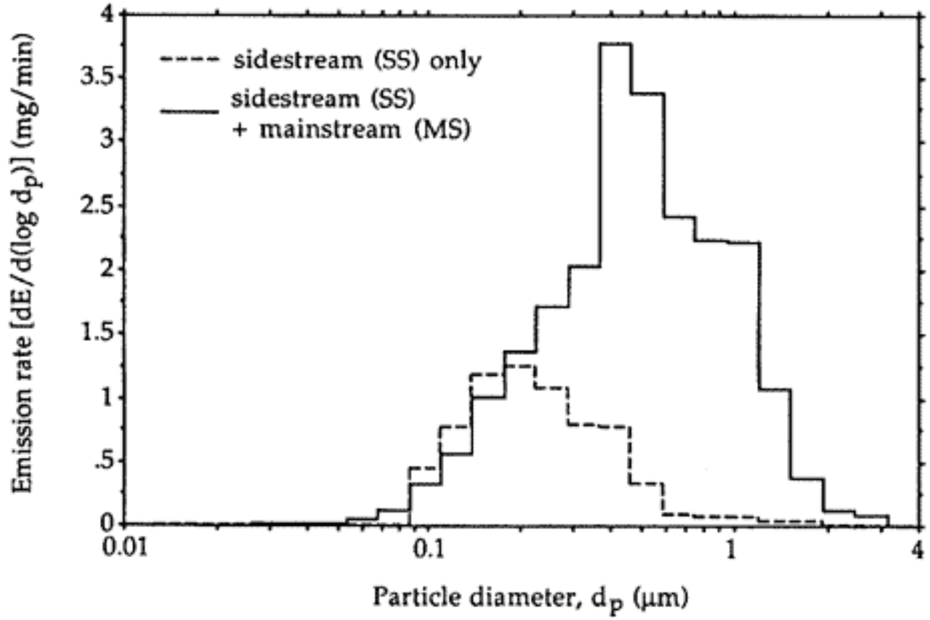
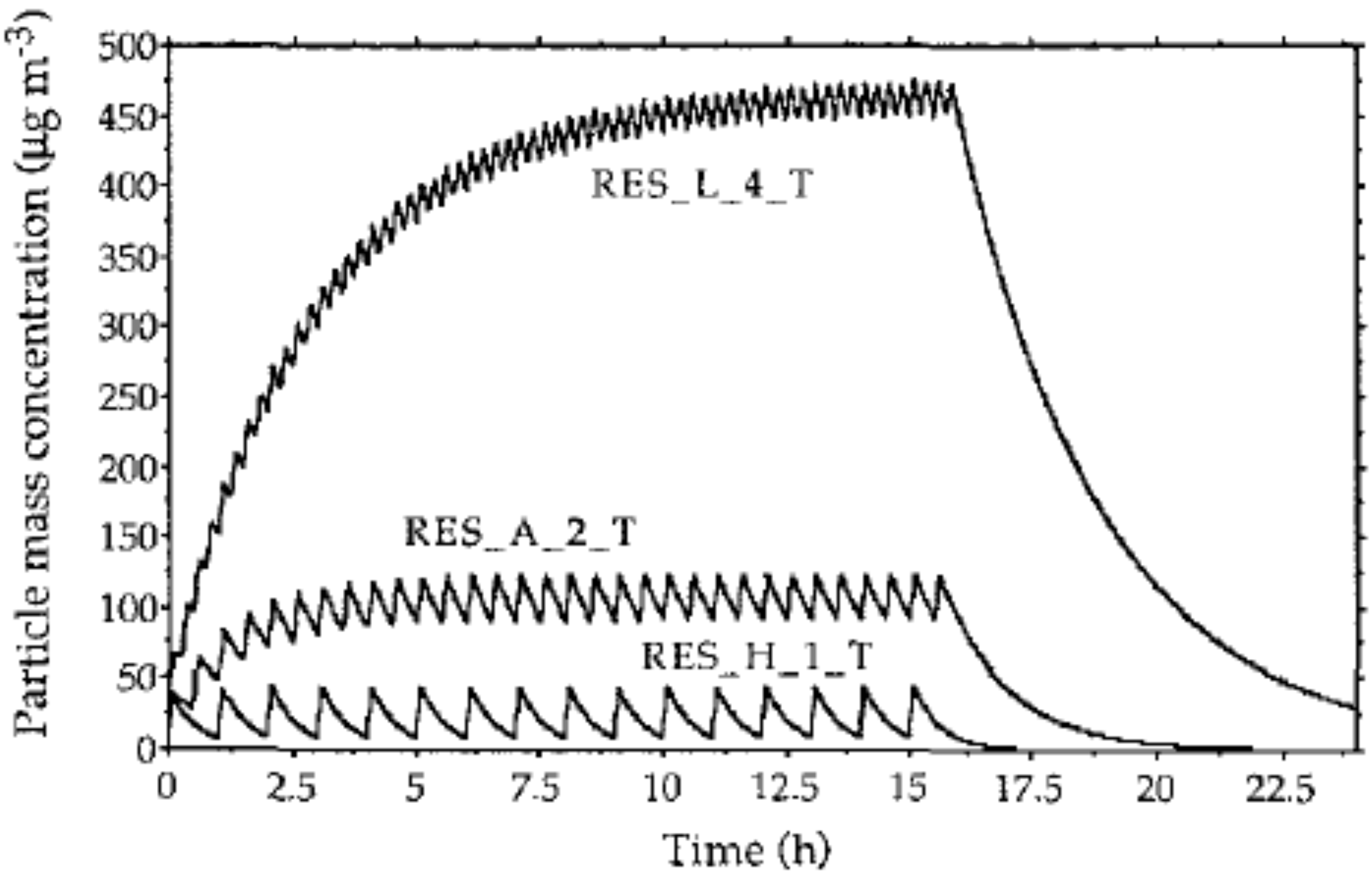


FIGURE 1. Effective particle emission rate from a burning cigarette as a function of particle diameter. The form of the figure is such that the area under a curve between two particle sizes is proportional to the mass emission rate of all particles within those size limits. These experiments were reported 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

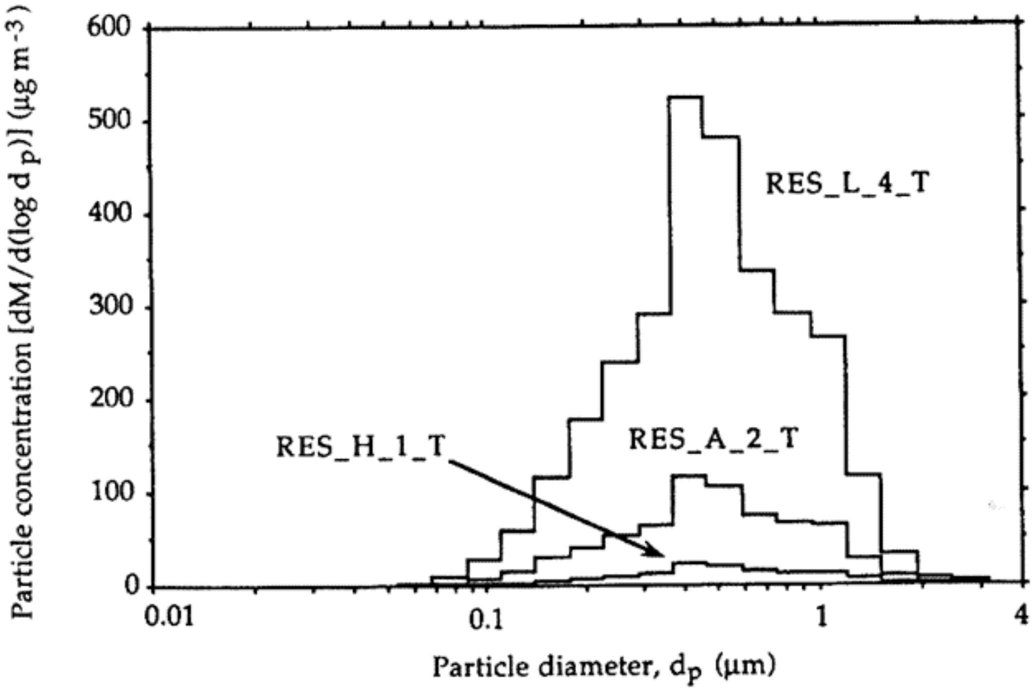


FIGURE 4. Average environmental tobacco smoke particle size distribution over 24-h period for three residential simulations corresponding

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}

cigarette smoking frequency: **1**, **2**, or **4** per hour

Nazaroff et al., 1993 *AS&T*

ETS lung deposition

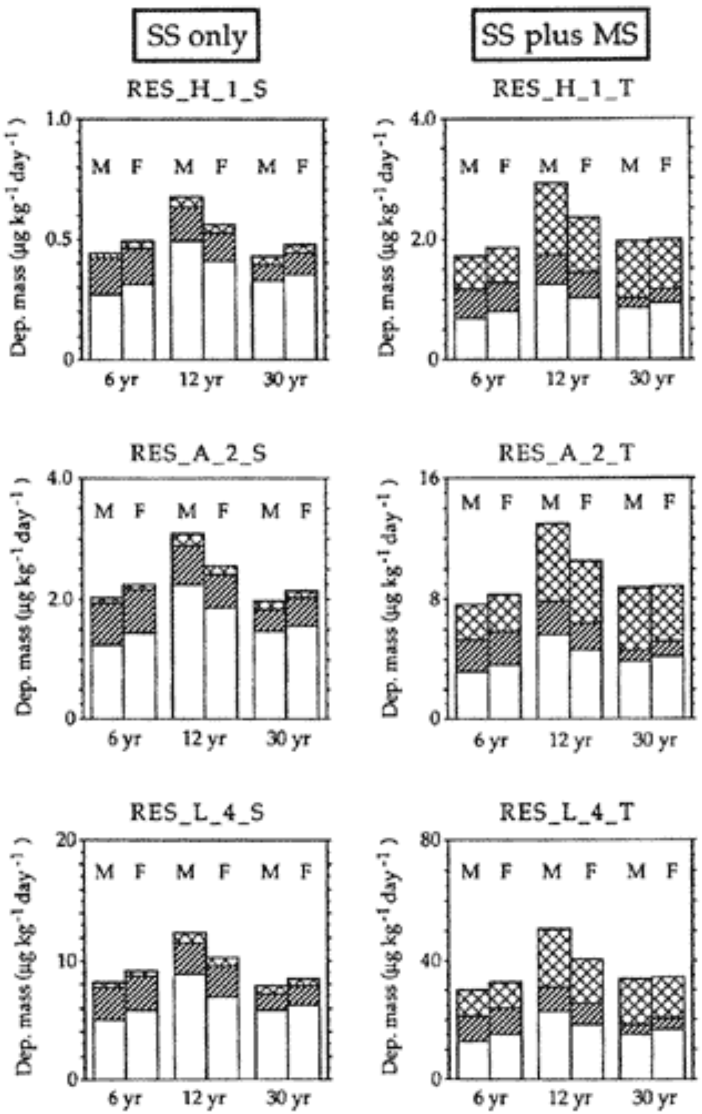
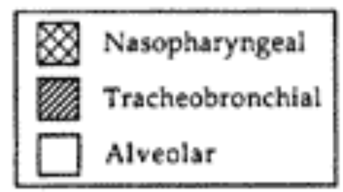
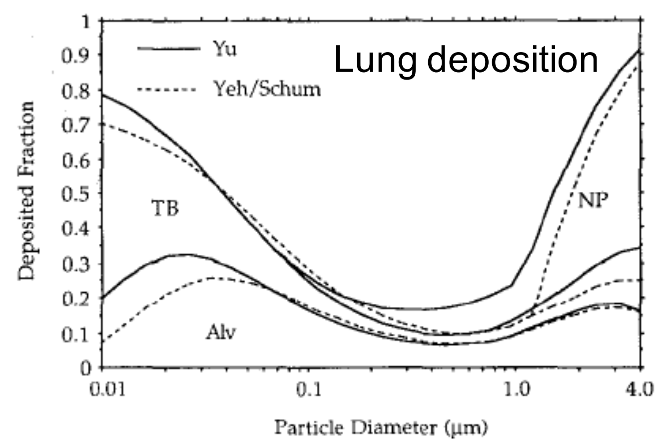


FIGURE 5. Regional lung deposition of environmental tobacco smoke particles from simulations of residential exposure. Each frame shows results for three age groups and each gender for one combination of smoking rate, particle emission profile, and building ventilation rate. The height of each bar gives 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

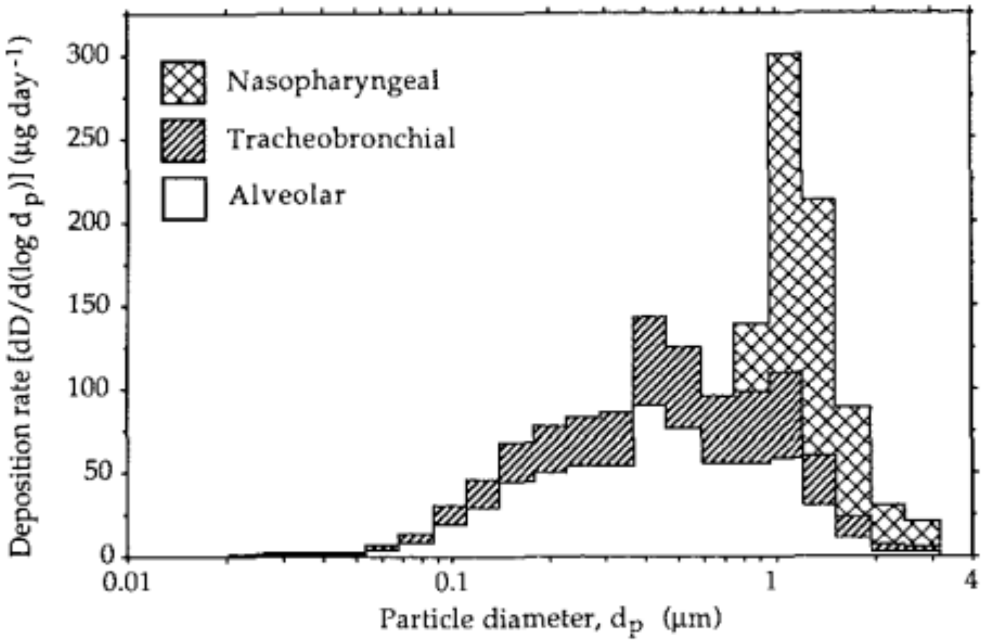
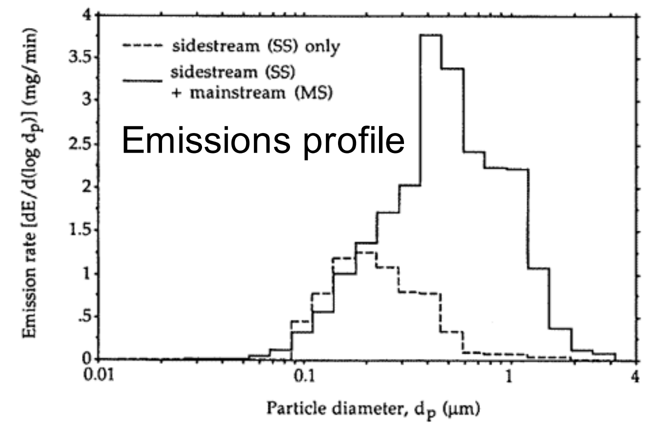
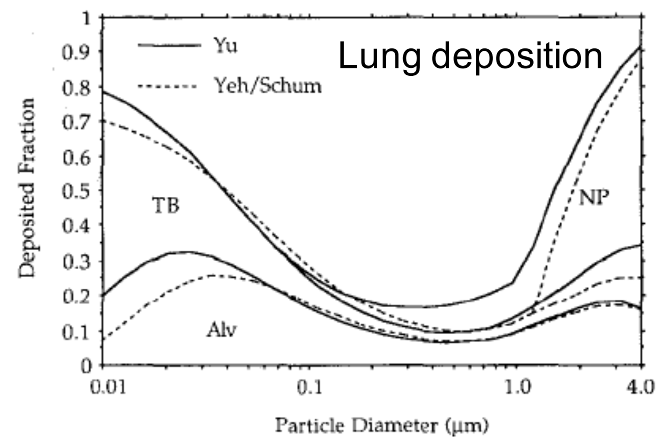


FIGURE 6. Size distribution of deposited mass of environmental tobacco smoke particles in 6-year-old boy for simulation RES_A_2_T. The form of the figure is such that the shaded area between two particle sizes is proportional to the average 24-h mass deposition rate of particles within those size limits.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





Nazaroff et al., 1993 *AS&T*

Indoor particle sources

Indoor Sources of Ultrafine and Accumulation Mode Particles: Size Distributions, Size-Resolved Concentrations, and Source Strengths

- Ultrafine (UFPs: <100 nm) and accumulation mode (0.1-1 μm) particles were monitored in an occupied house for 3 years
  - Data at 5 minute intervals

- The largest emission sources were described in this paper
  - Cooking with a gas stove
  - Toasting with electric toasters and toaster ovens
  - Burning candles and incense
  - Using a gas-powered clothes dryer

Wallace, 2006 *Aerosol Sci Technol*

Indoor particle sources

TABLE 2
Indoor and outdoor contributions to particle number concentrations (cm^{-3})

Size (nm)	N	Total	Outdoor	Indoor	Outdoor contribution (%)
10–18	174092	1109	337	772	30
18–50	258812	2730	1162	1568	43
50–100	258812	1936	1057	879	55
100–200	258812	955	680	275	71
200–450	259174	219	180	40	82
450–950	86611	25	18	7	70

- Biggest contributor to indoor UFPs was indoor sources
- Biggest contributor to 0.1-1 μm particles was outdoors

Wallace, 2006 *Aerosol Sci Technol*

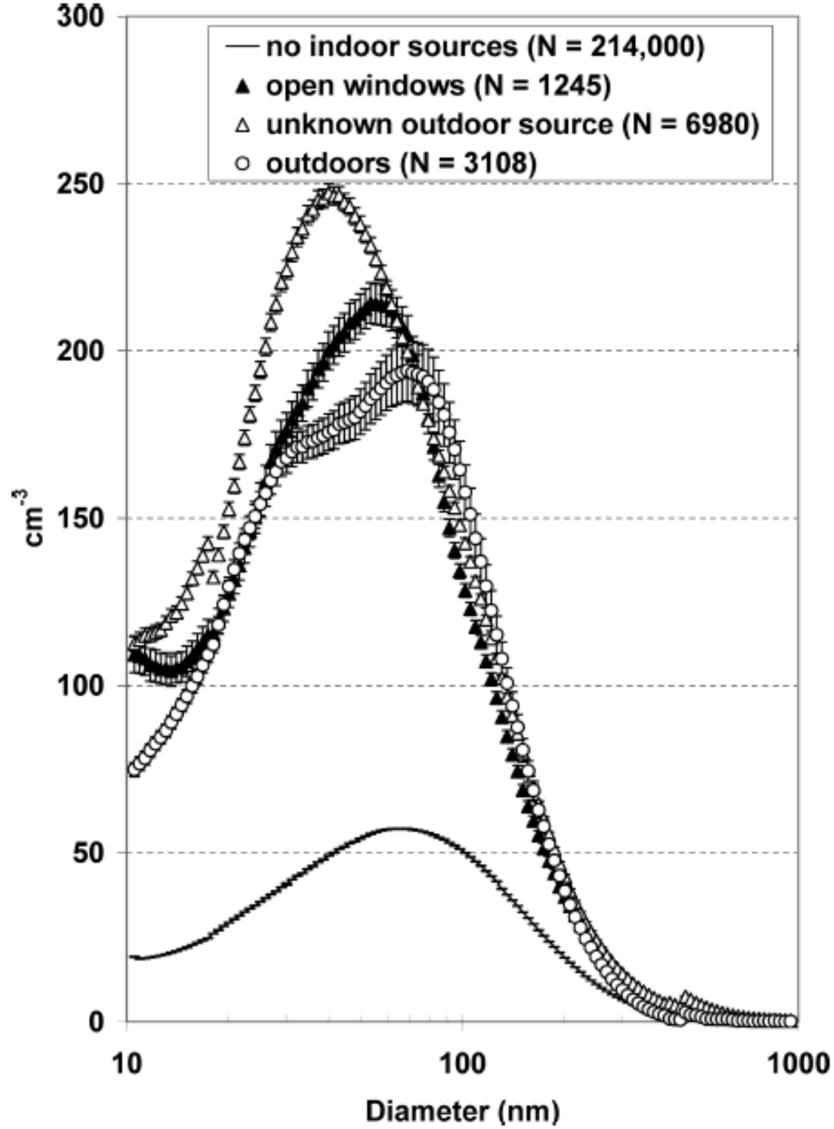
Indoor particle sources

Number and duration[a] of 18 selected activities, with modal diameters for both particle number and volume

Activity	Number of events	Average duration (min)	Modal diameter (nm)	
			Number	Volume
Gas clothes dryer	68	179	<10	181
Tea & toast	375	33	<10	51
Tea	36	31	11	46
Breakfast	149	33	11	66
Stir-fry	24	131	36	118
Unknown indoor sources	451	80	36	131
Dinner	225	83	39	181
Fried eggs	41	51	40	181
Unknown outdoor sources	174	207	40	429
Gas oven	58	19	45	95
Broiled fish, baked potato	217	53	46	98
Citronella candle	54	167	46	638
Open windows	52	120	53	241
Tortillas	221	48	64	146
Incense	11	114	64	250
Outdoors	502	31	69	168
Smoky cooking oil	5	128	69	233
No indoor sources	888	1188	69	269

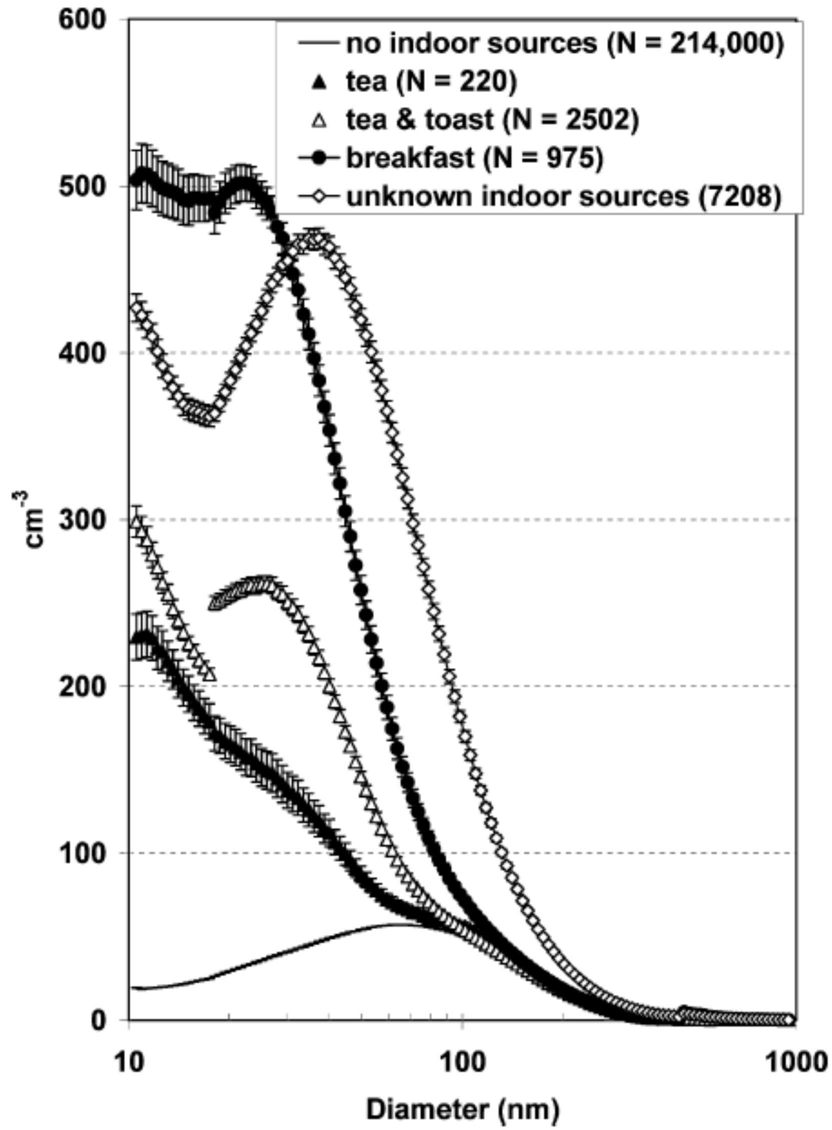
Wallace, 2006 *Aerosol Sci Technol*

Indoor particle sources: Outdoor infiltration



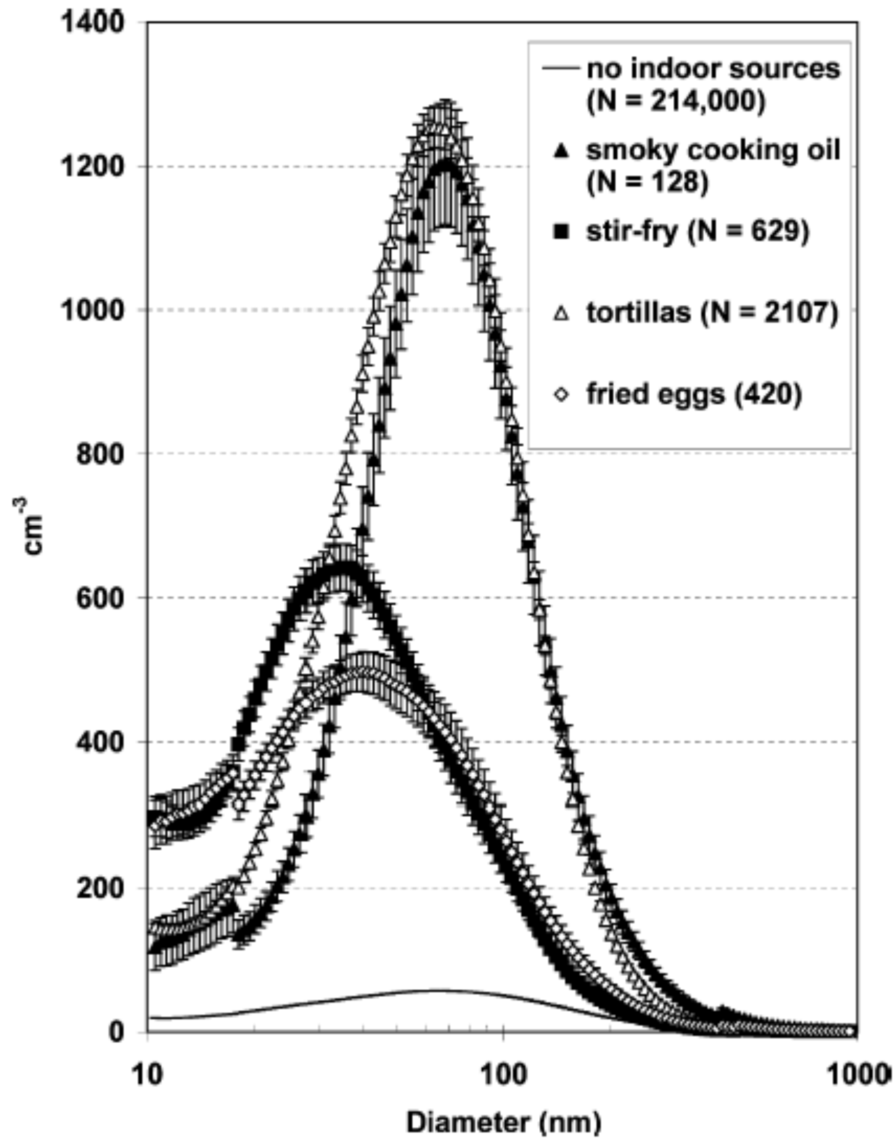
Wallace, 2006 *Aerosol Sci Technol*

Indoor particle sources: Tea, toast, breakfast



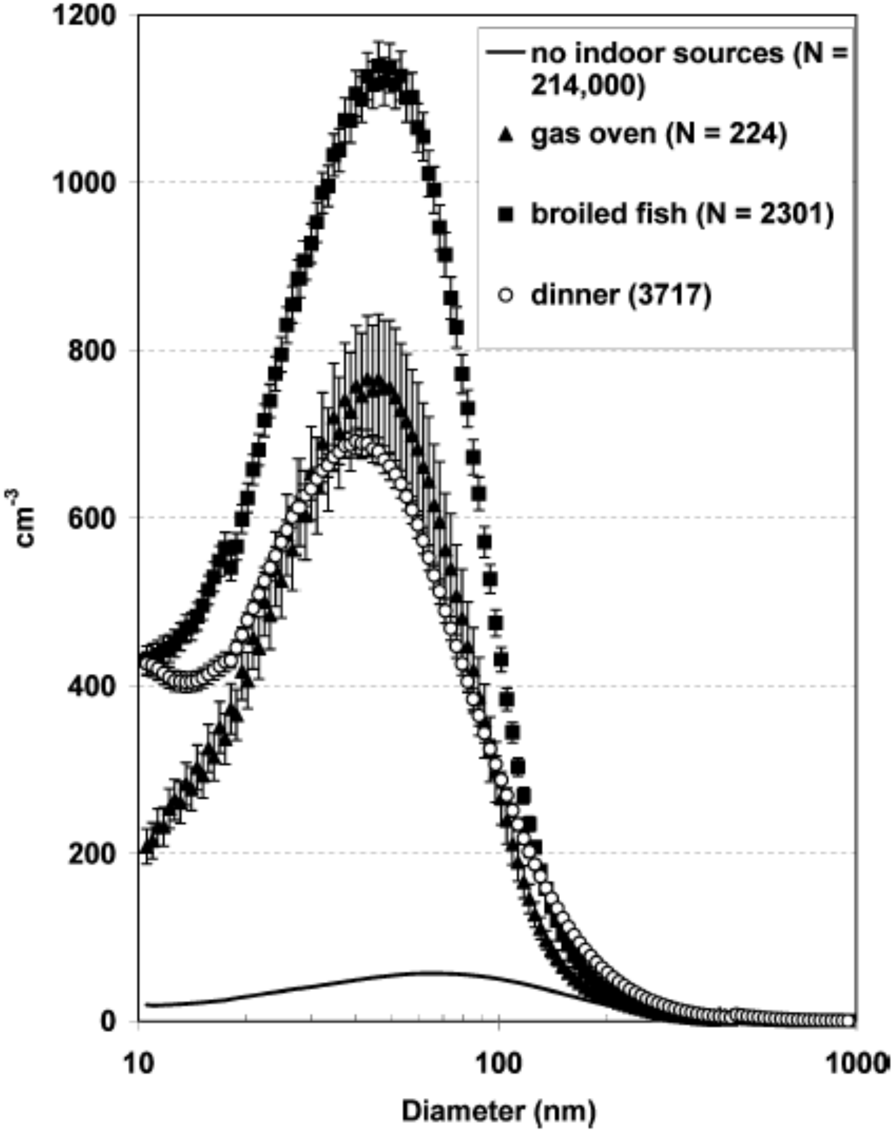
Wallace, 2006 *Aerosol Sci Technol*

Indoor particle sources: heavy cooking



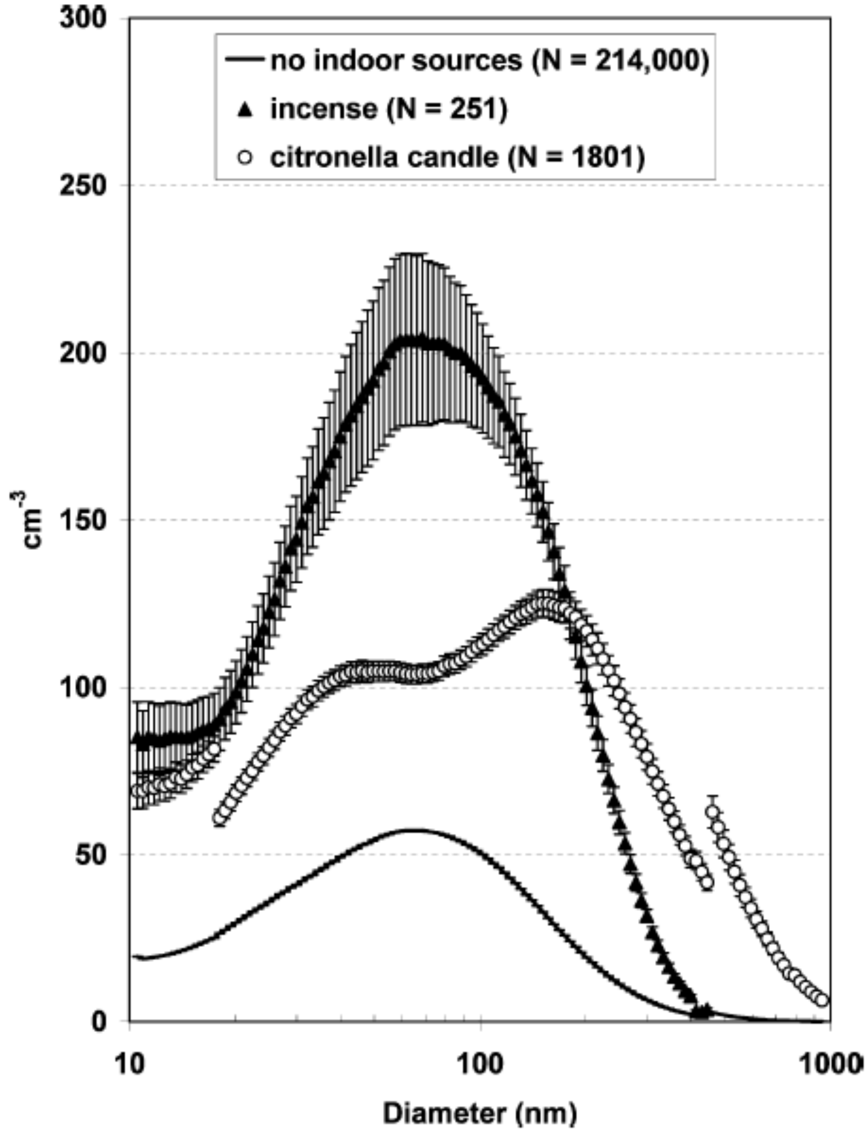
Wallace, 2006 *Aerosol Sci Technol*

Indoor particle sources: Oven cooking



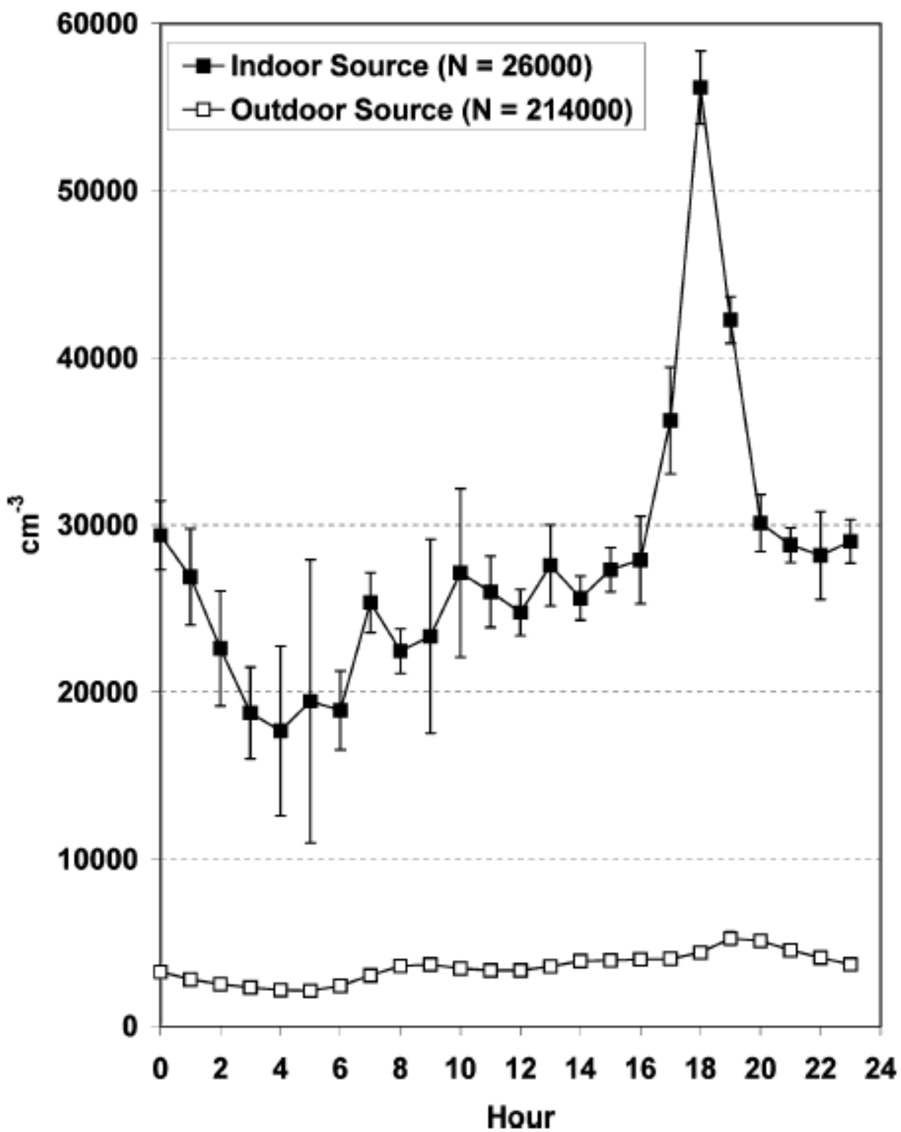
Wallace, 2006 *Aerosol Sci Technol*

Indoor particle sources: Incense and candles



Wallace, 2006 *Aerosol Sci Technol*

Indoor particle sources: Daily profiles



Wallace, 2006 *Aerosol Sci Technol*

Typical indoor UFP emission rates

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)

RESUSPENSION AND DEPOSITION

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
  - 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 source: Resuspension

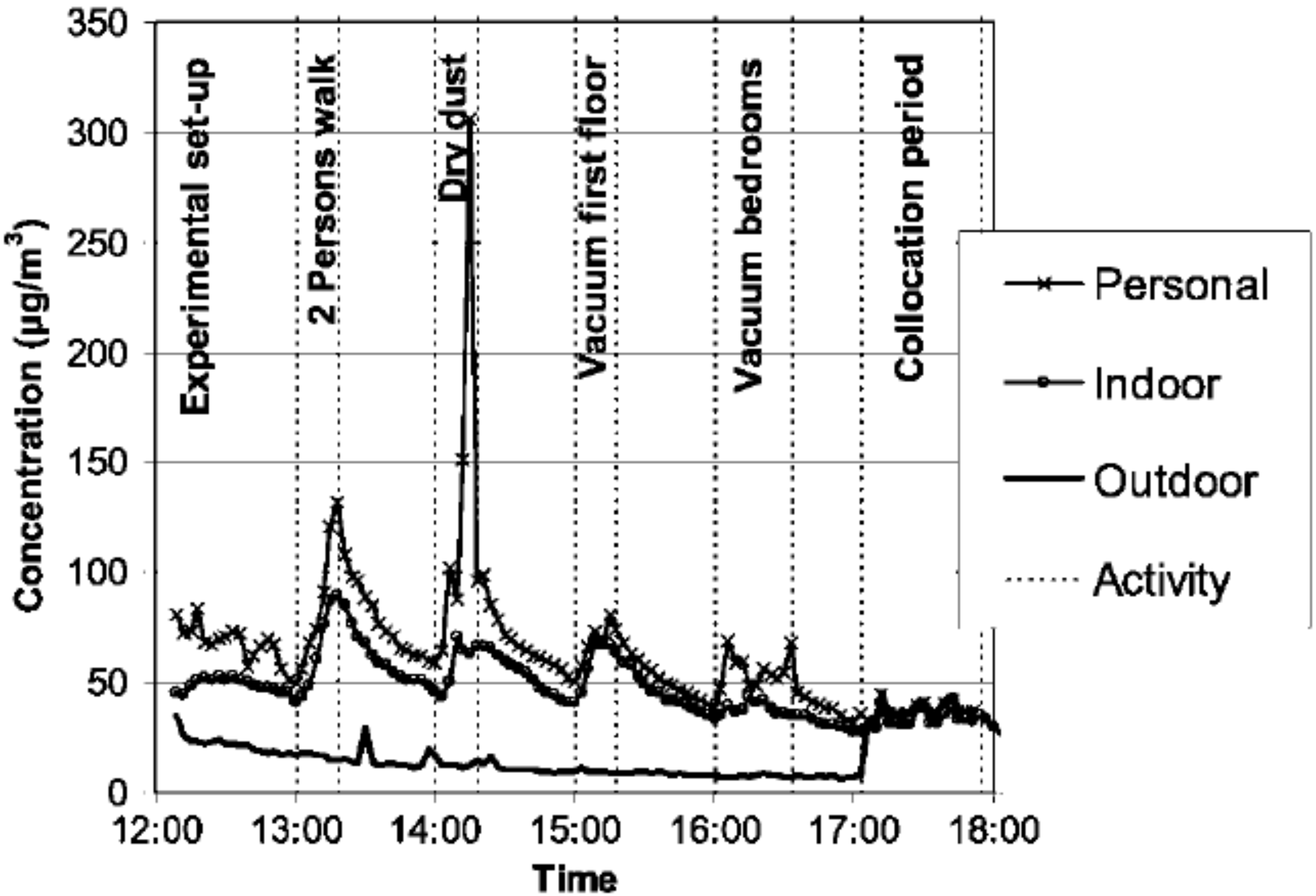
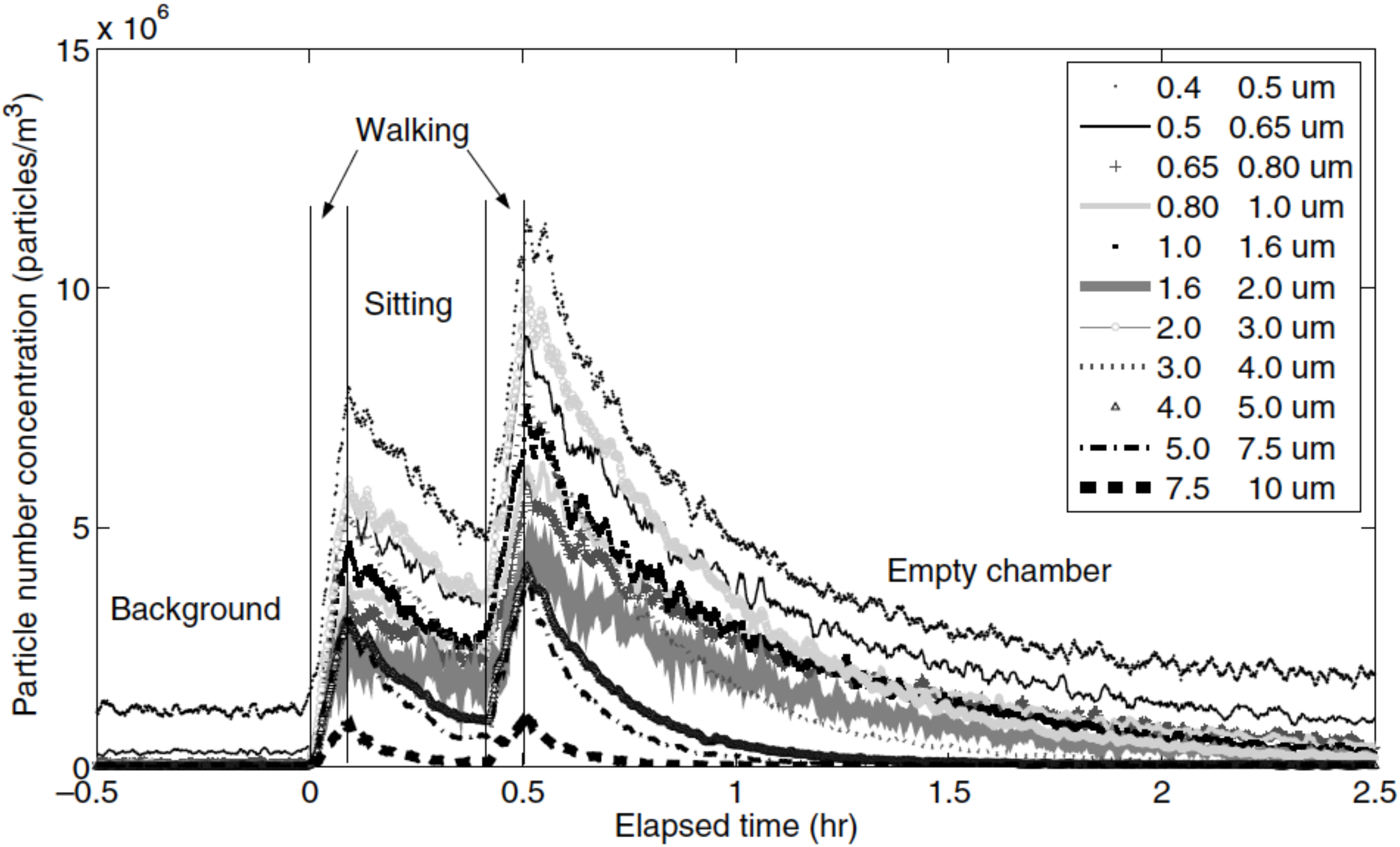


Figure 3. Personal, indoor, and outdoor PM_5 estimated mass concentration time series.

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

Indoor sources: Resuspension



Qian and Ferro, 2008 *Aerosol Sci Technol*

Indoor sources: Resuspension

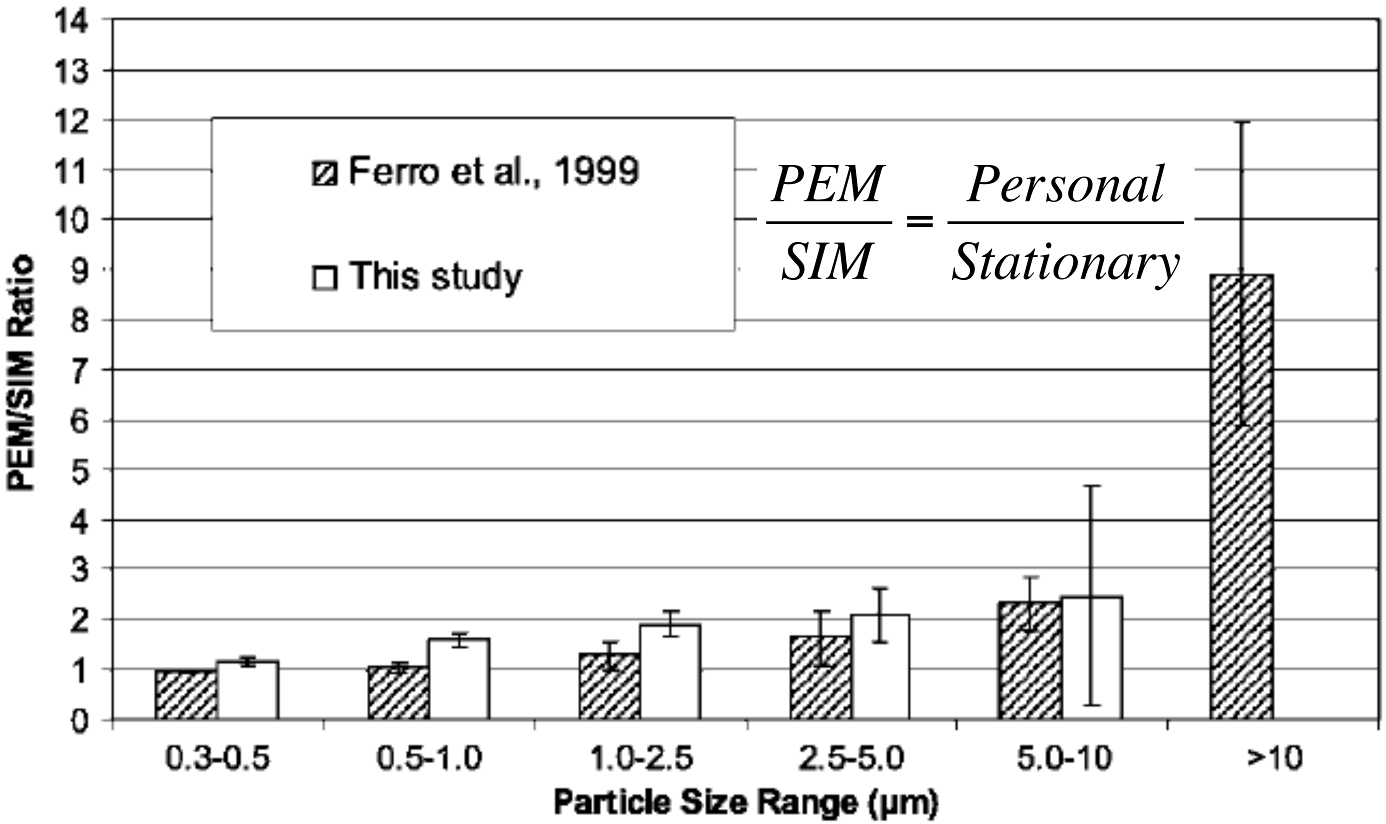


Figure 4. PEM/SIM ratio by particle size during human activity periods for two independent studies. Ferro et al. (1999) collected personal and indoor concentrations using Met-One Model 237B laser particle counters for six vacuuming experiments in a separate Redwood City, CA, USA, residence.

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

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)

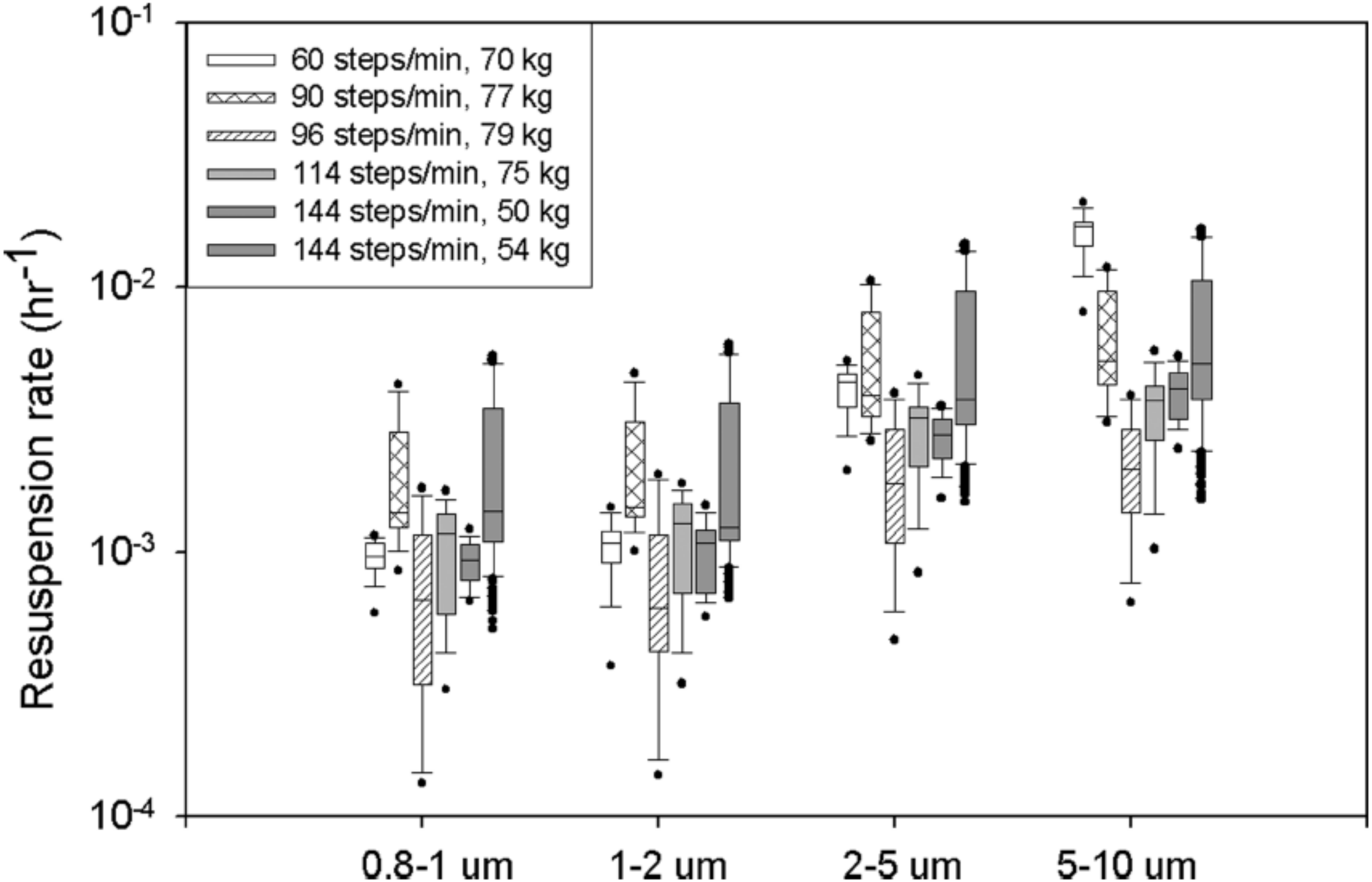
- And incorporate it into mass balance on indoor air:

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

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

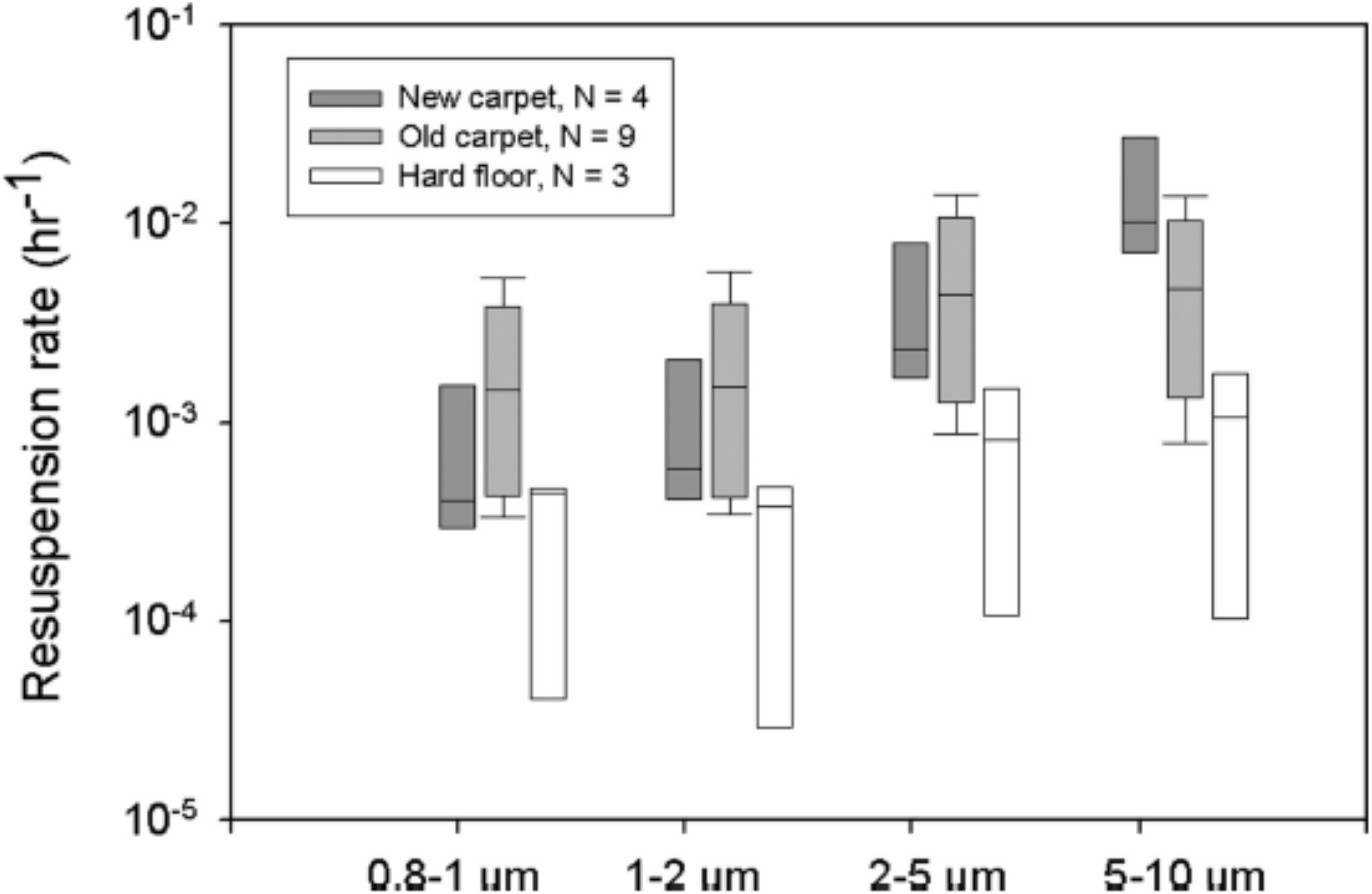
$$A\frac{dL_i}{dt} = k_{dep,i}C_iV - rAL + E_{track-in}$$

Indoor sources: Resuspension



Qian and Ferro, 2008 *Aerosol Sci Technol*

Indoor sources: Resuspension



Qian and Ferro, 2008 *Aerosol Sci Technol*

Indoor losses: Deposition

- We discussed deposition last lecture
  - 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

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

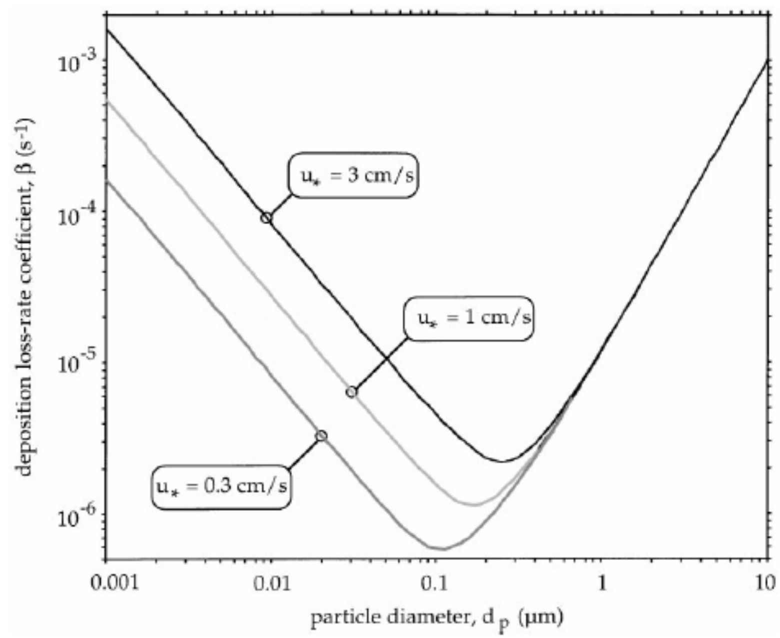


Fig. 5. Particle deposition loss-rate coefficient, β, for typical room dimensions (3 m high $\times$ 4 m $\times$ 5 m) according to the current model. Friction velocities of 0.3–3 cm s^{-1} approximately span the range expected for mechanically ventilated indoor spaces. Predictions assume air pressure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

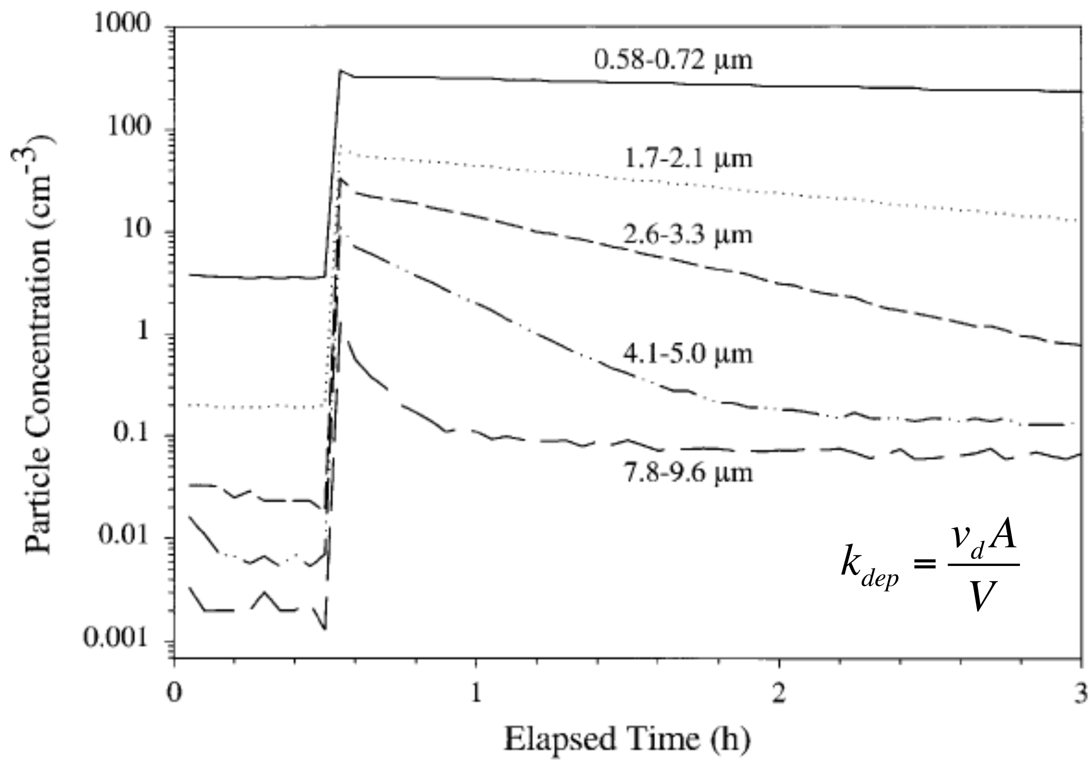
Lai and Nazaroff 2000 *J Aerosol Sci*

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



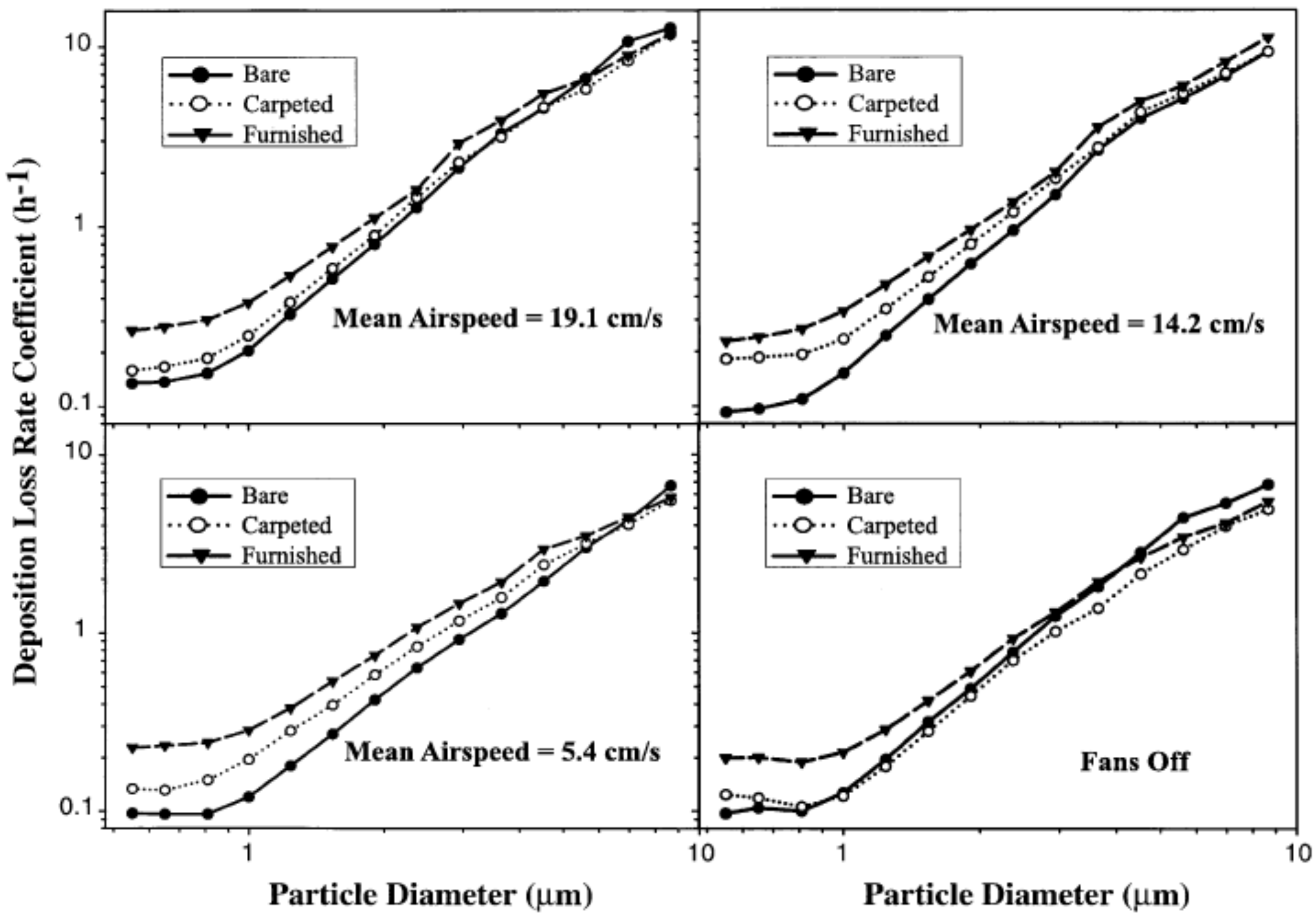
$$k_{dep} = \frac{v_d A}{V}$$

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

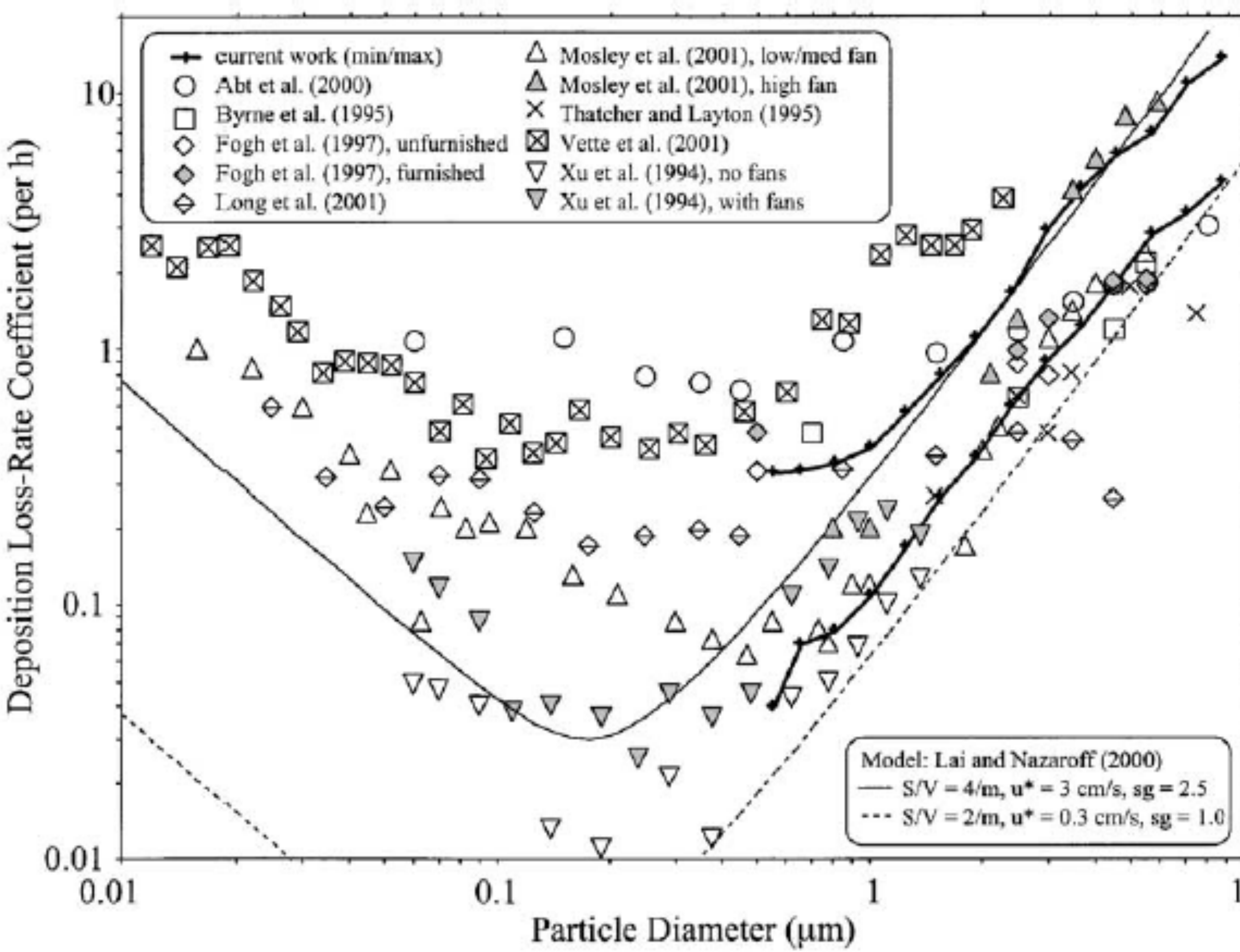
- Deposition in a chamber under different air speeds and furnishing conditions



Thatcher et al. 2002 *Atmos Environ*

Indoor losses: Deposition

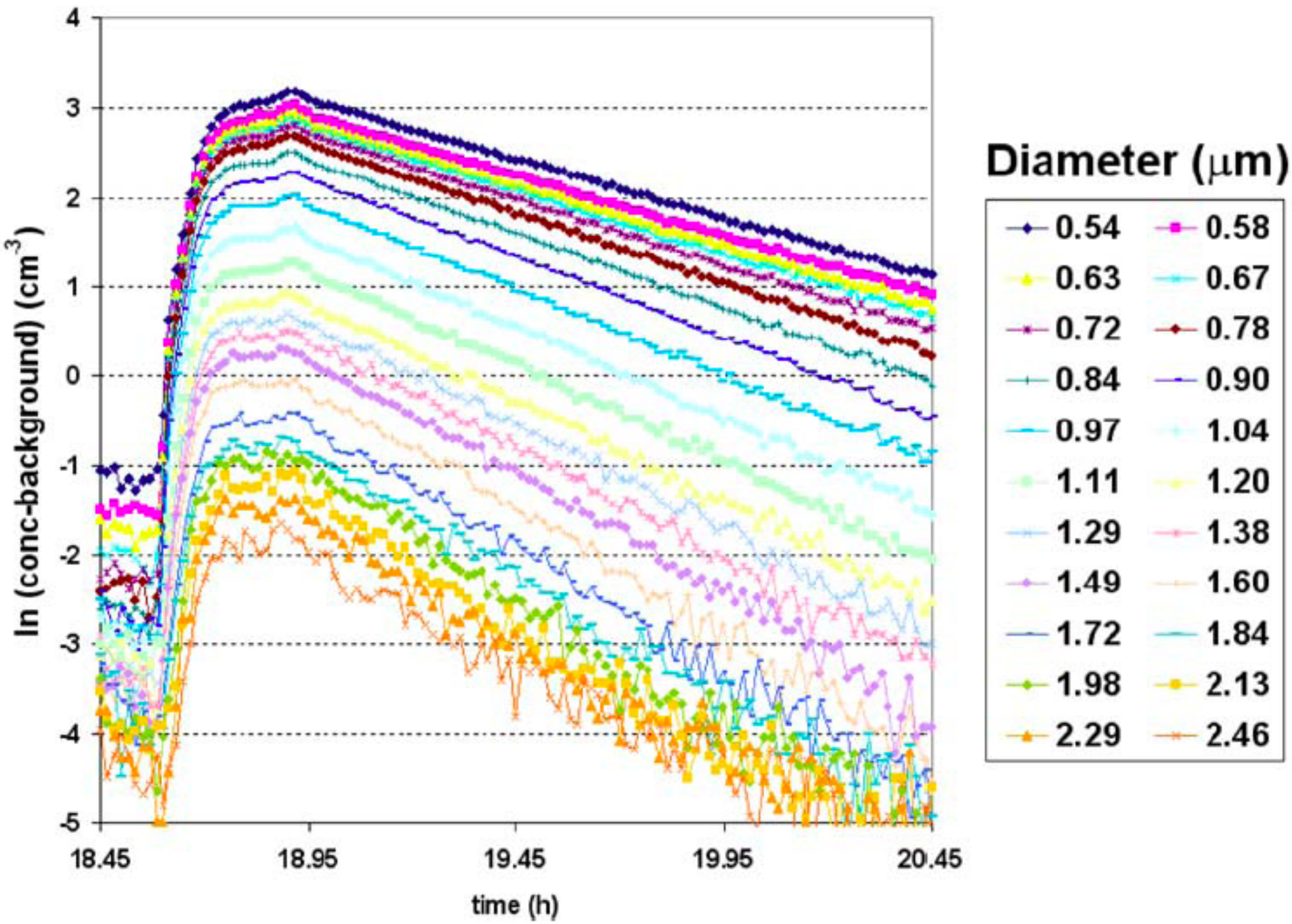
- Review of deposition in a chamber under different scenarios



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

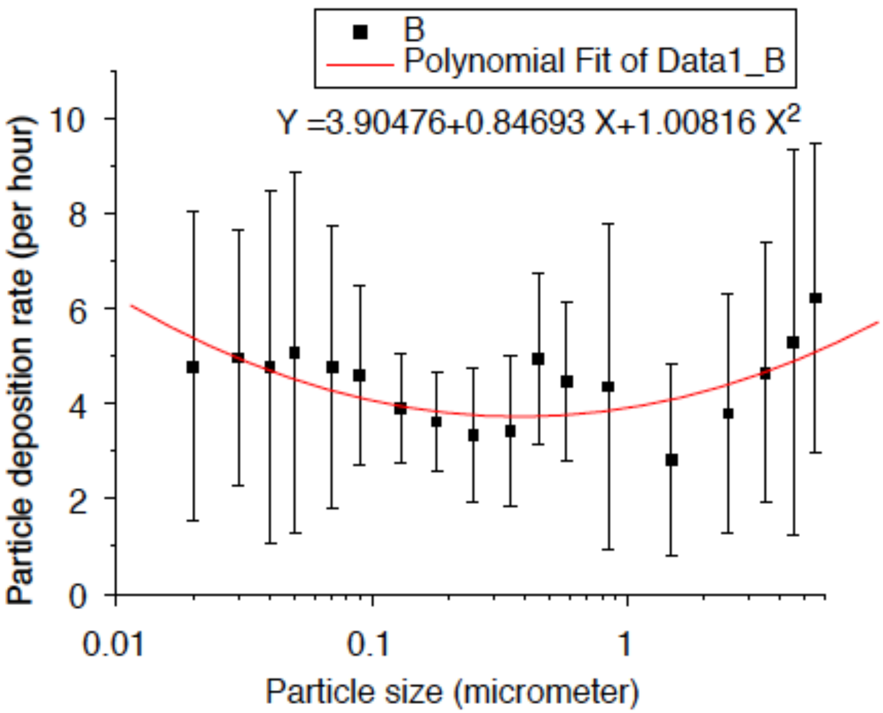


Fig. 3. The average of particle deposition rates for the 18 particle size intervals under normal ventilation conditions (Error bars represent one standard deviation). The polynomial fit line with the correlation coefficient ($R^2 = 0.33$).

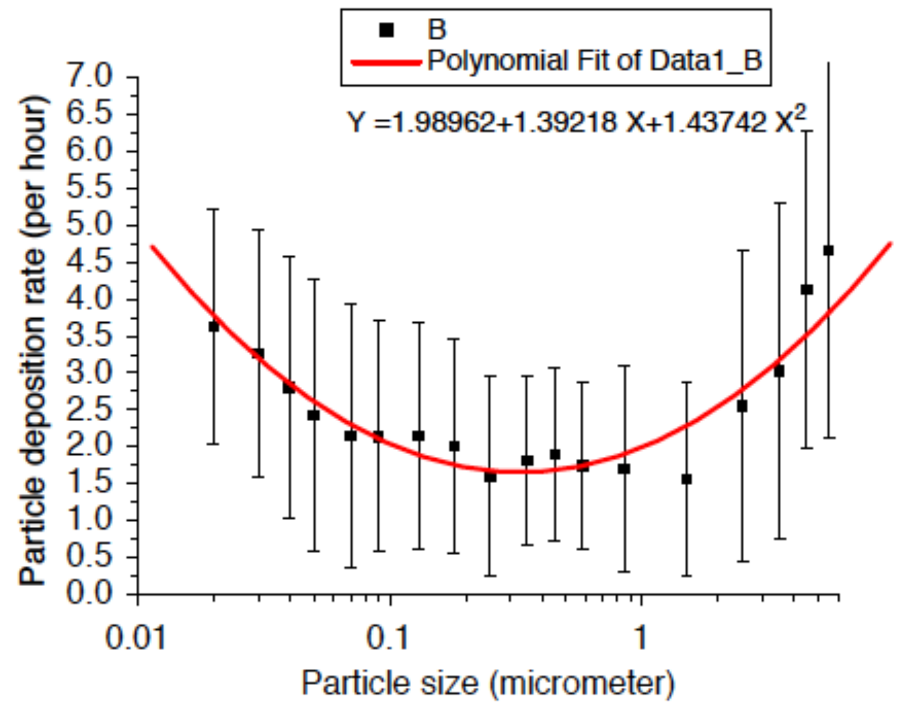
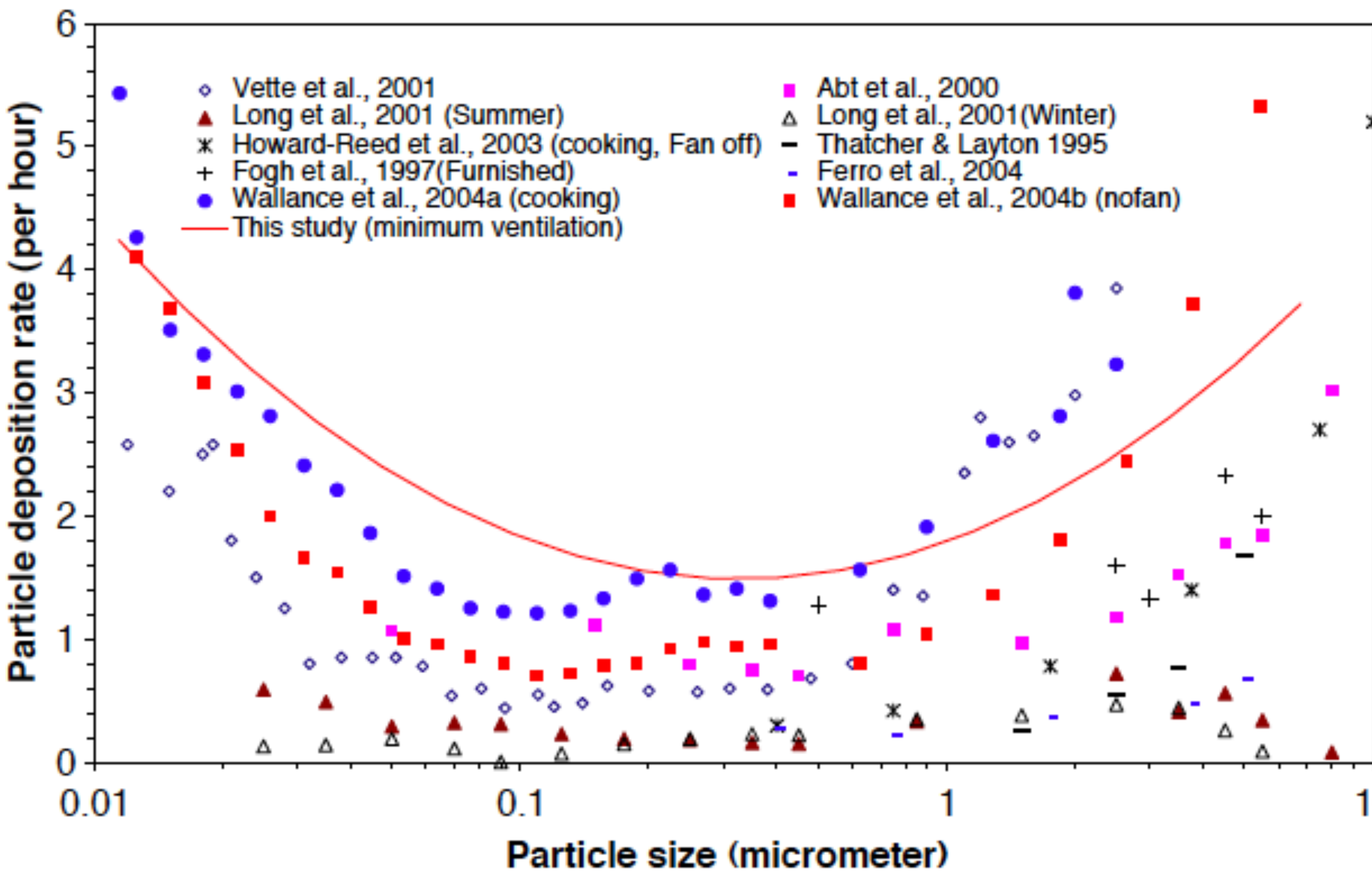


Fig. 4. The average of particle deposition rates for the 18 particle size intervals under minimum ventilation conditions (Error bars represent one standard deviation). The polynomial fit line with the correlation coefficient ($R^2 = 0.84$).

He et al. 2005 *Atmos Environ*

Indoor losses: Deposition

- Deposition in real homes



He et al. 2005 *Atmos Environ*

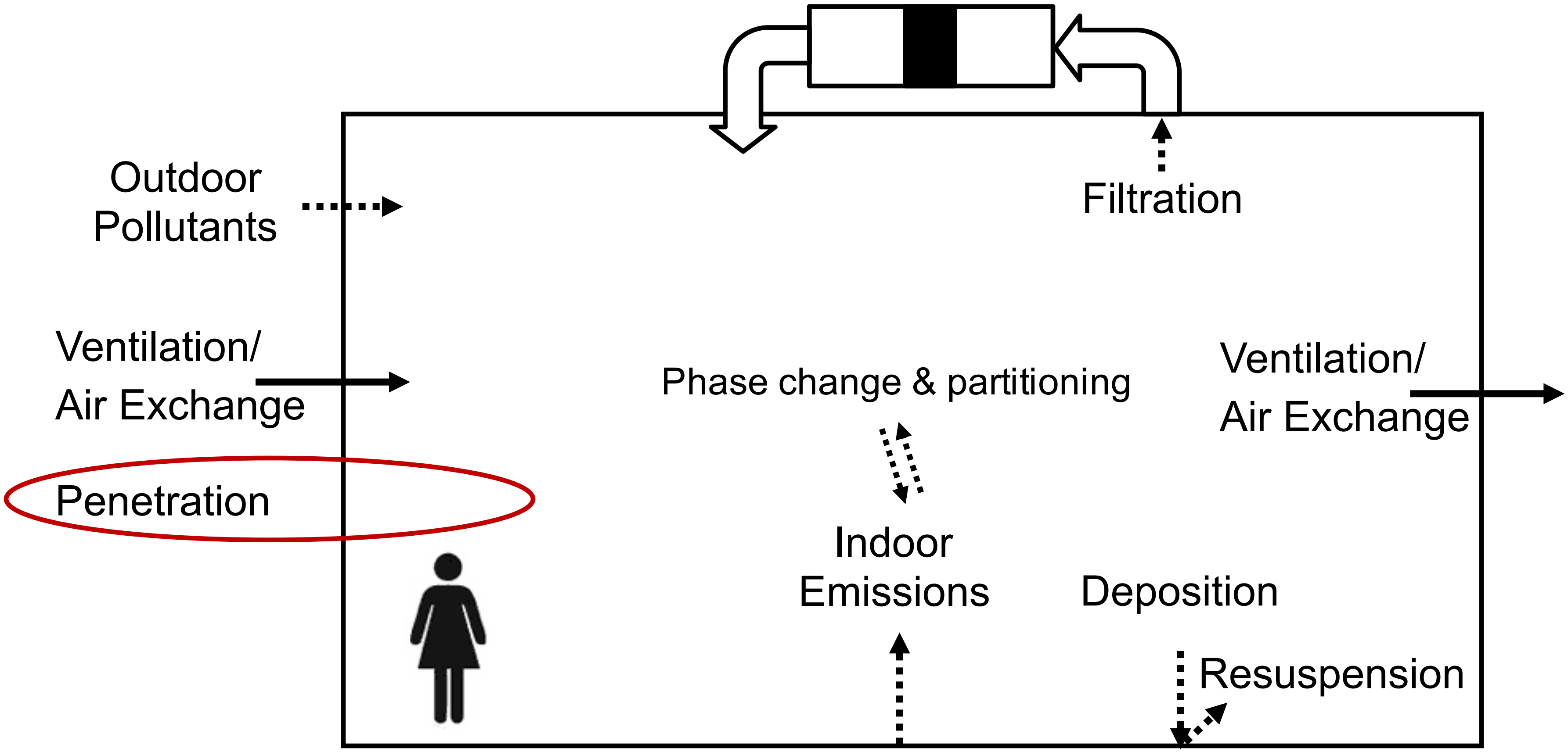
Indoor particles review

- 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:
    - Penetration from outdoors
  - And we still need to focus on a major loss:
    - HVAC or stand-alone air filtration

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

Either a removal term or a source term, depending…

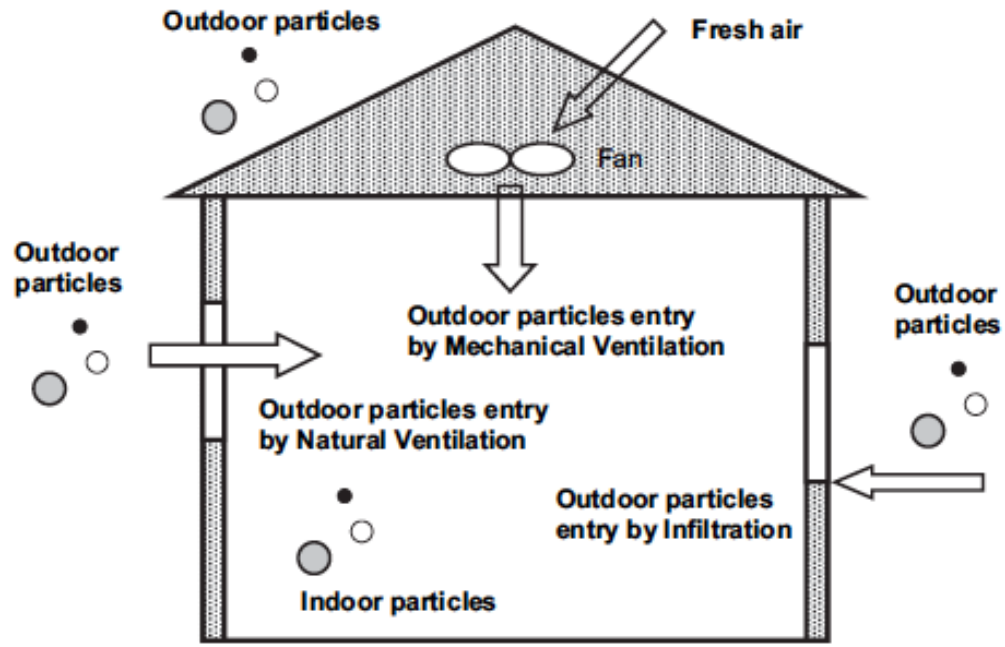
Mass (or number) balance approach for particles



Indoor/outdoor particle sources

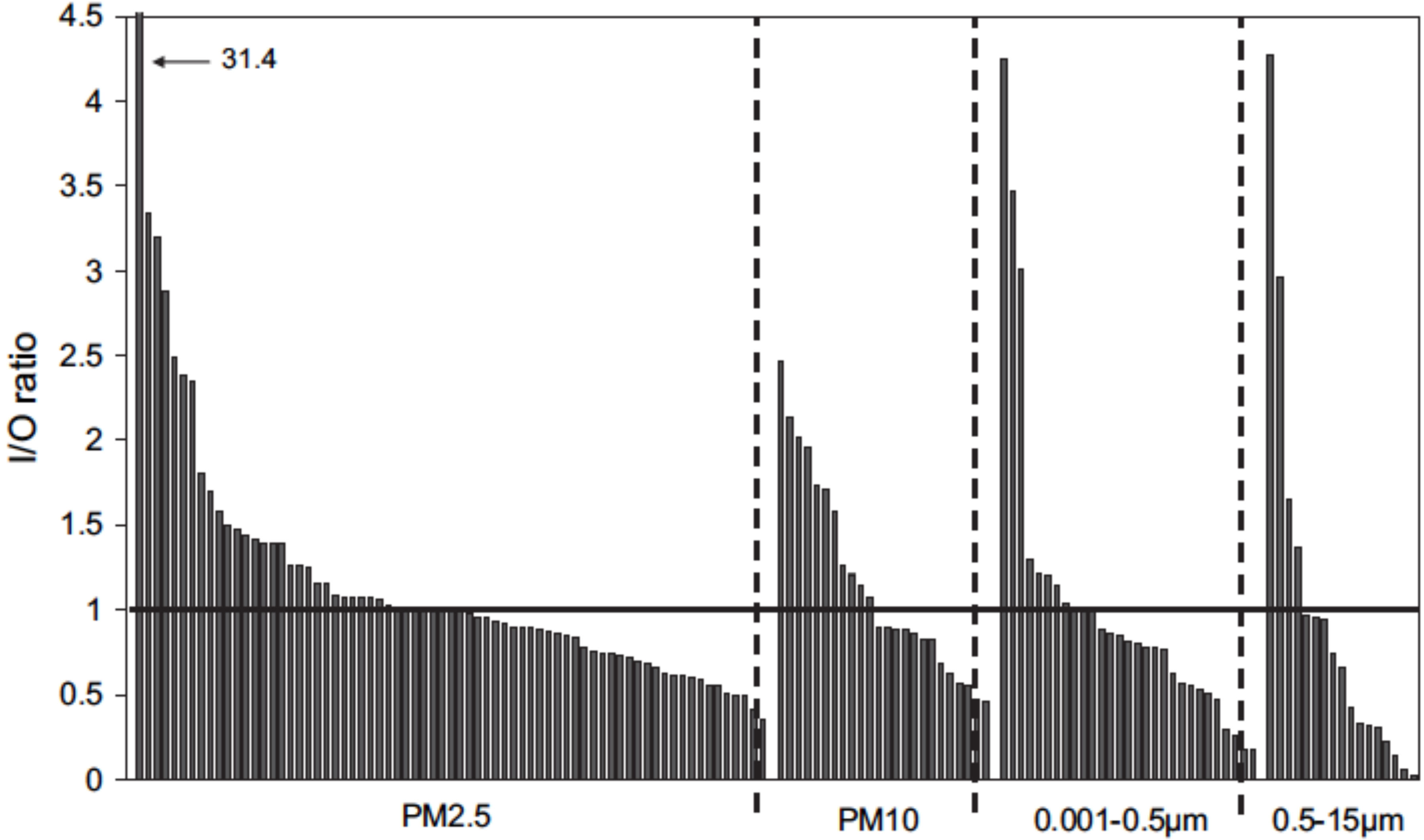
Review of relationship between indoor and outdoor particles: I/O ratio, infiltration factor and penetration factor

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



Chen and Zhao, 2011 *Atmos Environ*

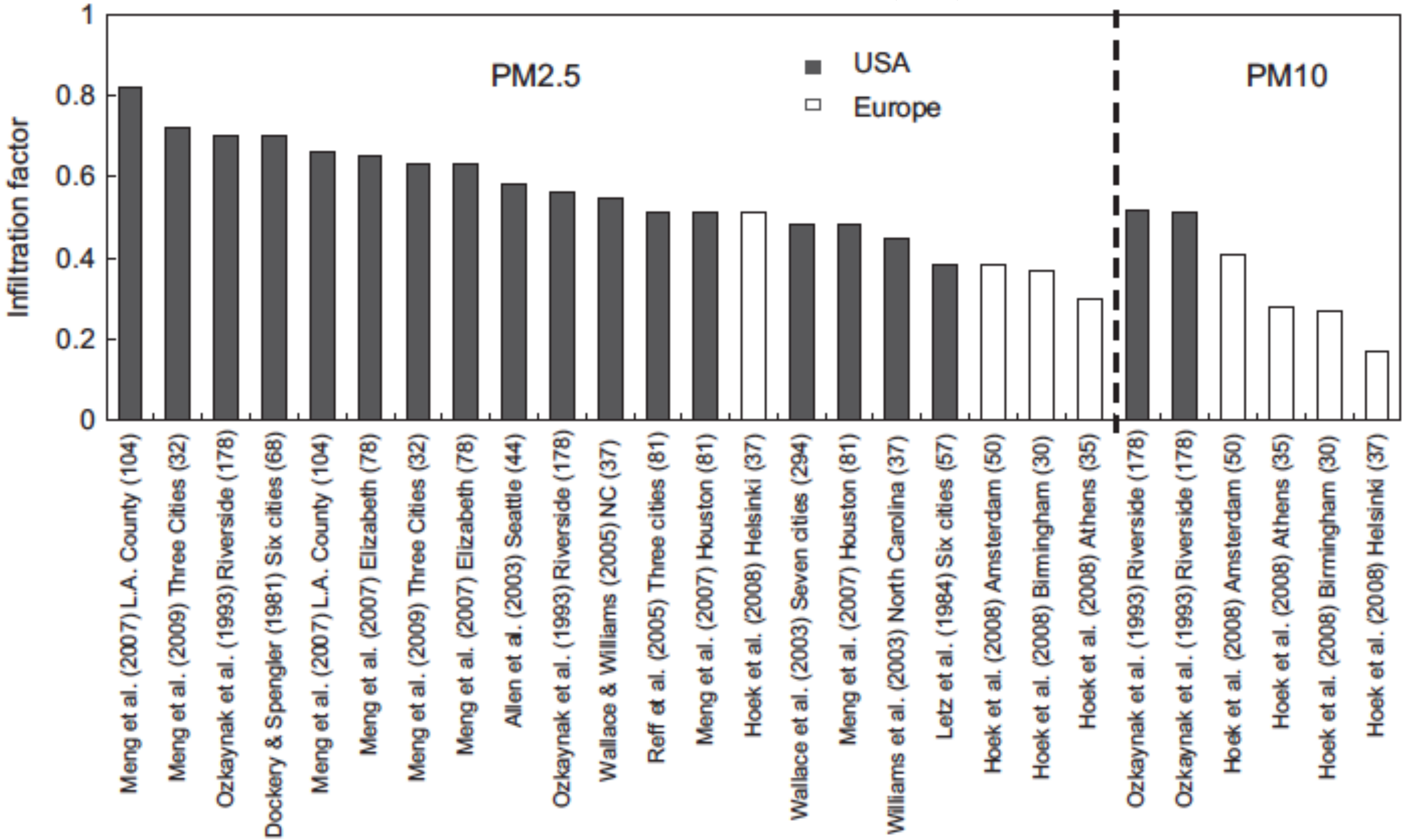
I/O particle ratios: combination of I and O sources



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

- Particle penetration 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"
  – Large value for penetration factors means high "envelope removal efficiency"
    - Reduced indoor proportions of outdoor particles

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

$C_{outside}$

C_{inside}

Liu and Nazaroff 2001 *Atmos Environ*

Objectives for lecture on *P*

- Discuss previous research on *P*
  - Including research from my graduate work
- Discuss how to measure *P*
  - And how to solve for *P*

Liu and Nazaroff (2001) *Atmos Environ*

- Particle penetration through cracks and in fiberglass insulation
  - Also interested in reactive gases
- **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

Liu and Nazaroff 2001 *Atmos Environ*

Flow through cracks

- Relationship between pressure (ΔP) and flow (Q)

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

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

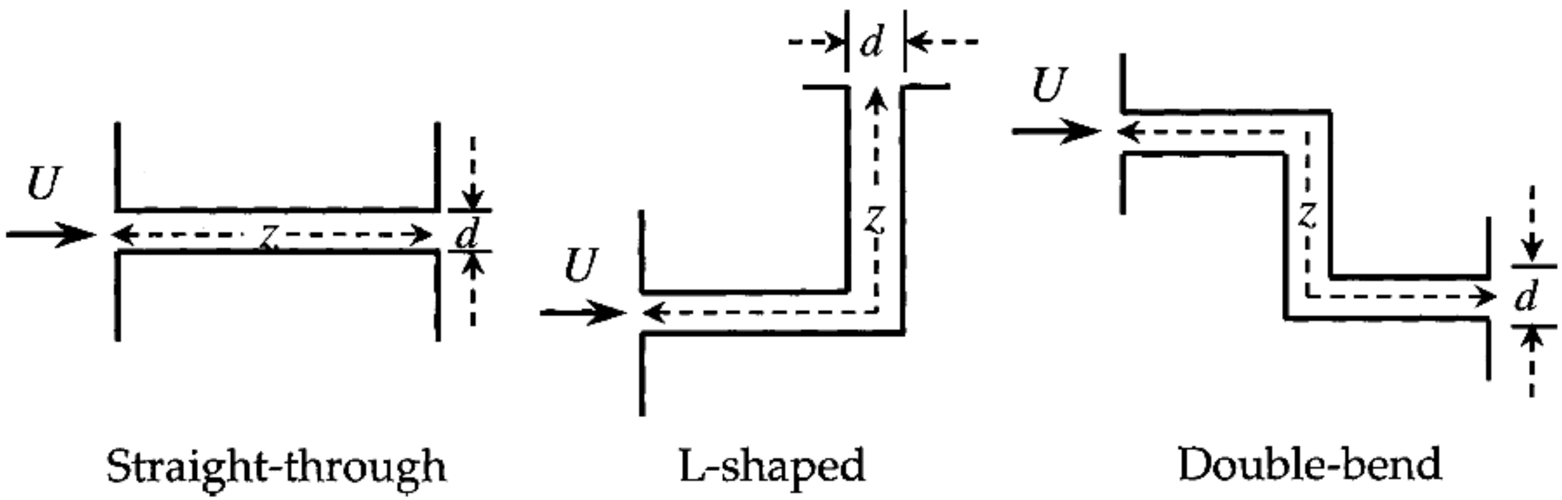


Fig. 1. Configuration of three types of idealized cracks through building envelopes.

Liu and Nazaroff 2001 *Atmos Environ*

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

(Turbulent)

If $Re << 1$:

$$Q \propto \Delta P$$

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

(Laminar)

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

Liu and Nazaroff 2001 *Atmos Environ*

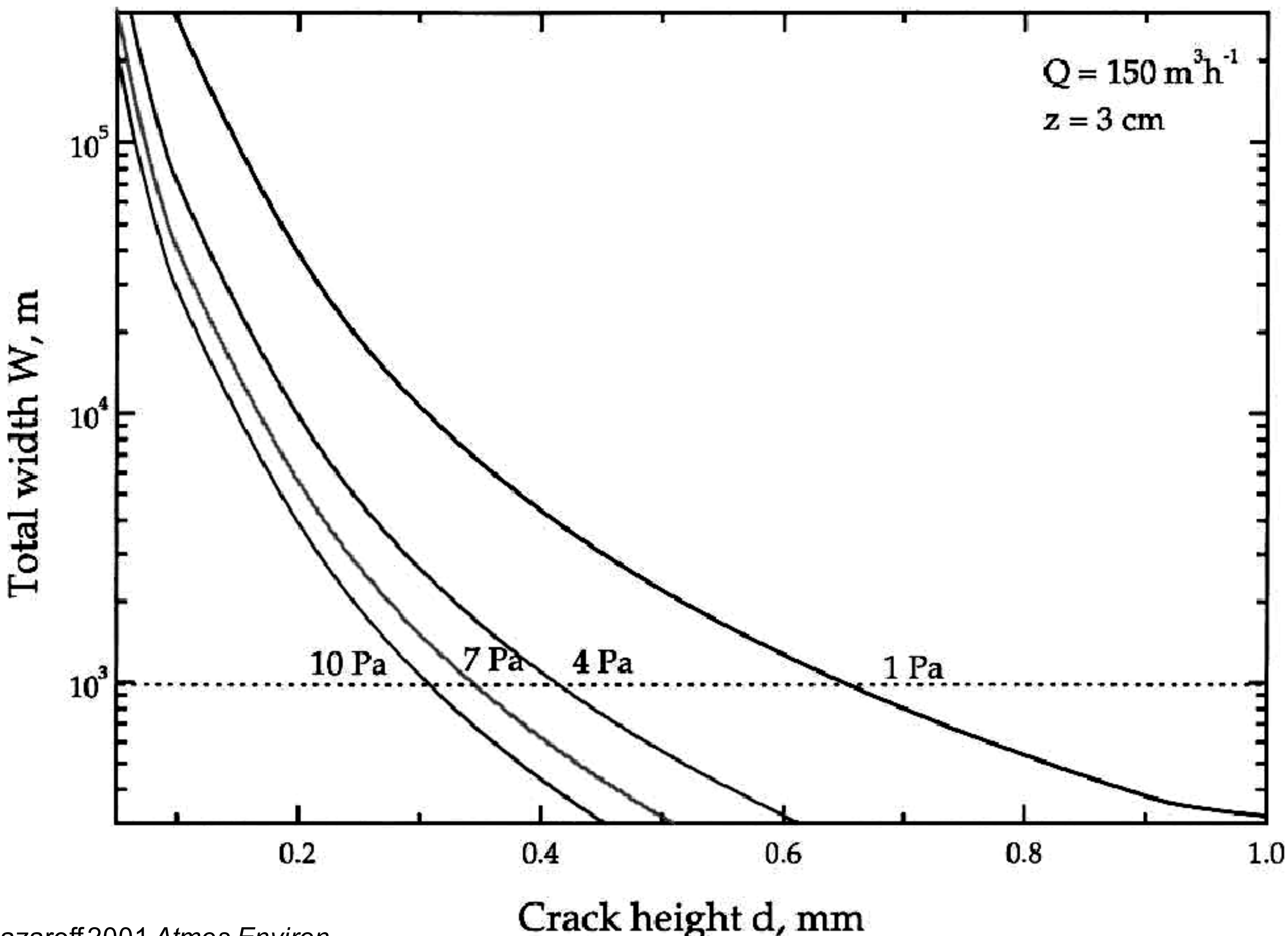
What are typical crack dimensions?

- 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 come up with estimates for crack height and total crack width



Liu and Nazaroff 2001 *Atmos Environ*

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

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

D = particle diffusion coefficient

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

Liu and Nazaroff 2001 *Atmos Environ*

Model cracks

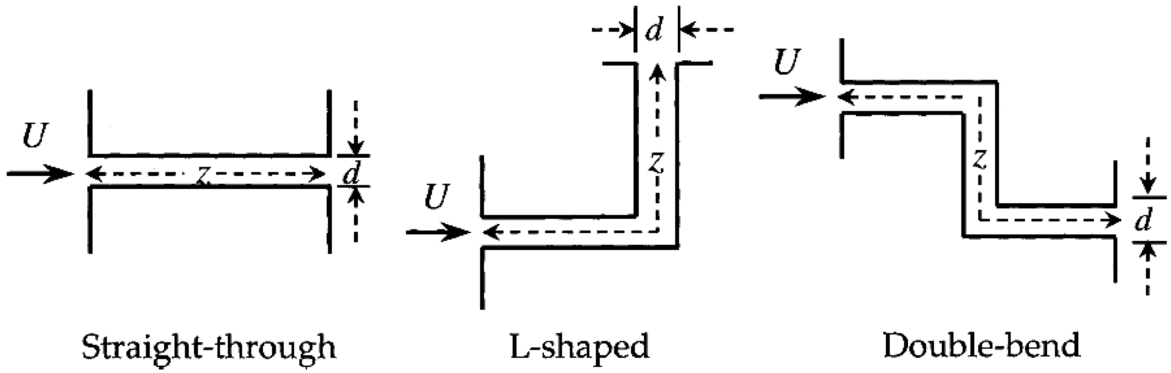


Fig. 1. Configuration of three types of idealized cracks through building envelopes.

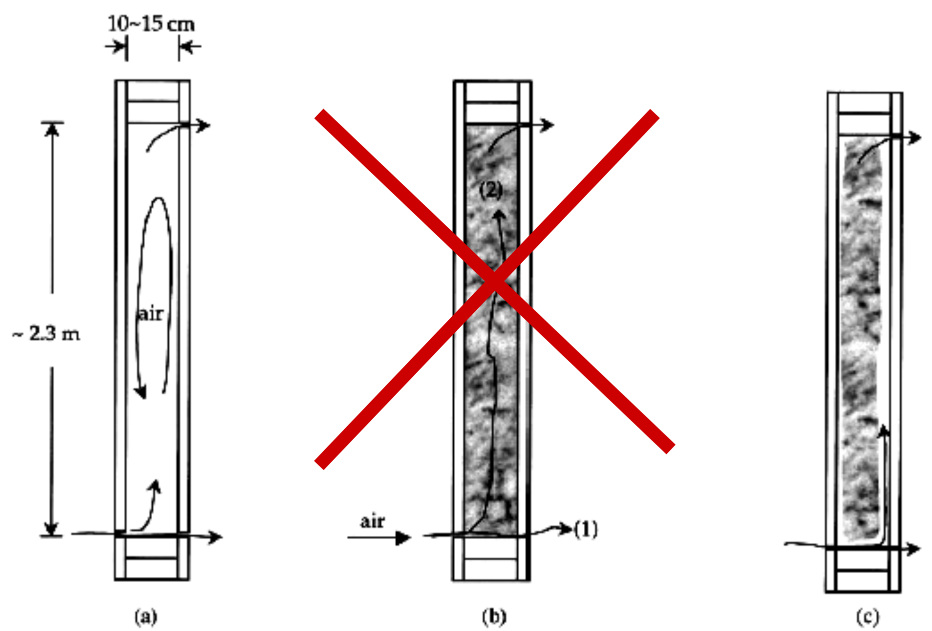


Fig. 3. Schematic of airflow paths through wall cavities in wood-frame construction. (a) Uninsulated wall cavity; (b) Wall cavity filled with fiberglass insulation; and (c) Fiberglass-insulated wall cavity with airflow bypass.

Liu and Nazaroff 2001 *Atmos Environ*

Model results

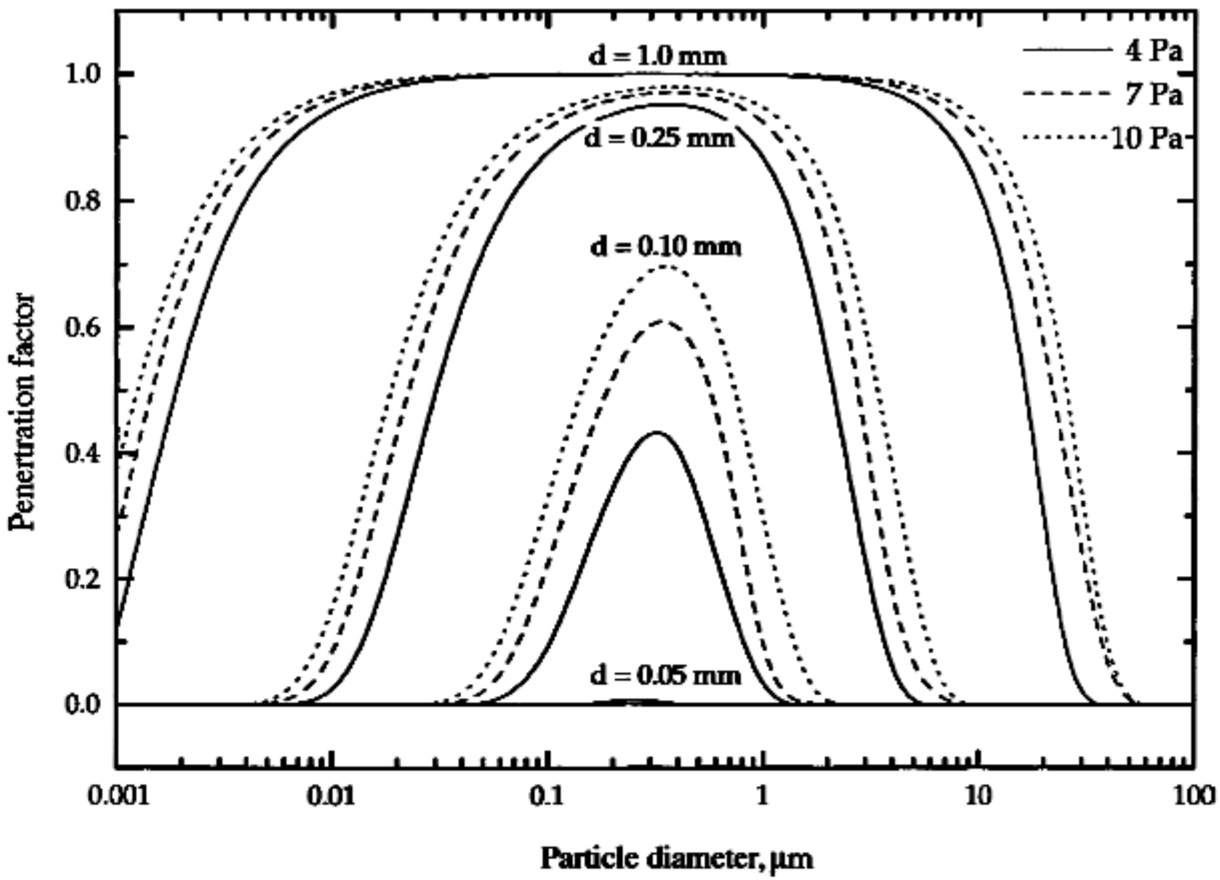


Fig. 4. Particle penetration factor as a function of particle diameter, crack height, and pressure difference for a straight-through crack with flow length $z = 3$ cm.

Liu and Nazaroff 2001 *Atmos Environ*

Model results

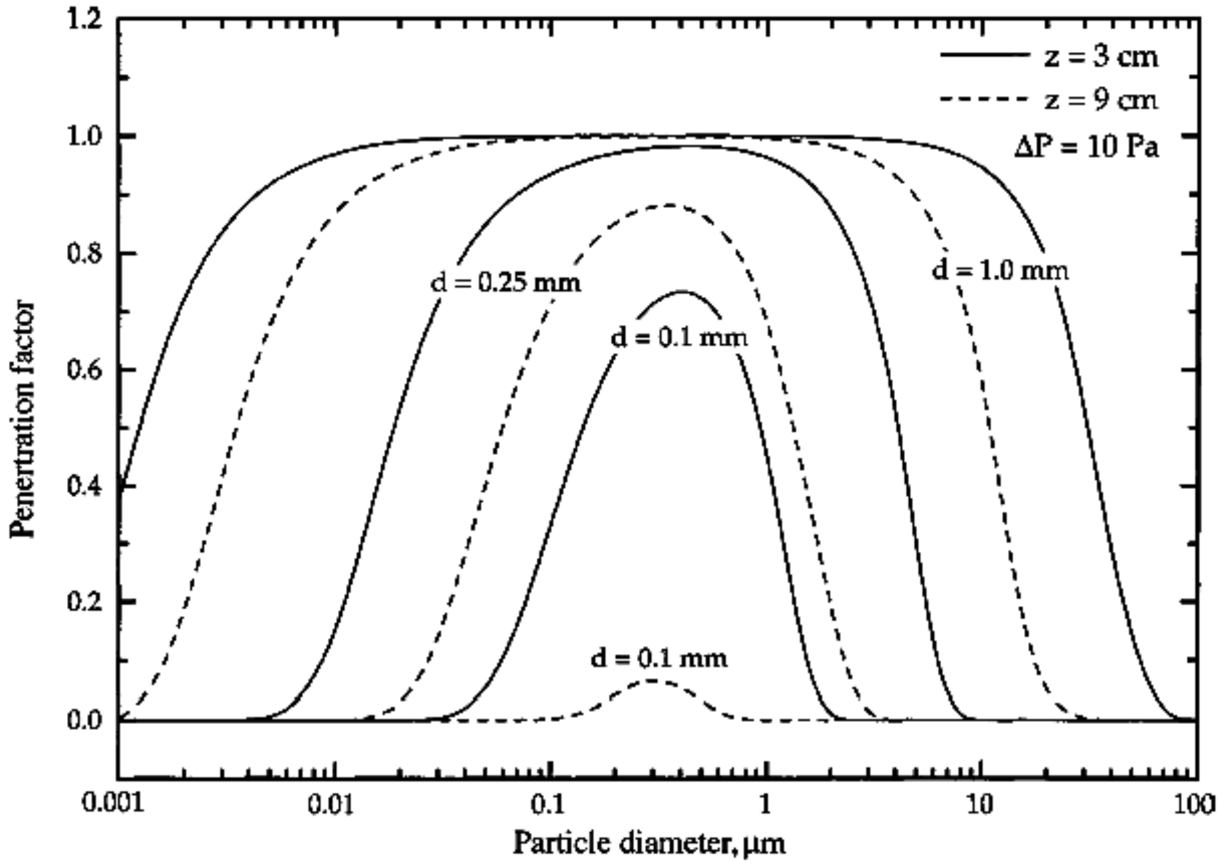


Fig. 5. Particle penetration factor as a function of particle diameter, crack height, and flow length at a fixed pressure drop of $\Delta P = 10\,\text{Pa}$.

Liu and Nazaroff 2001 *Atmos Environ*

Model results

Predicted for real building cracks

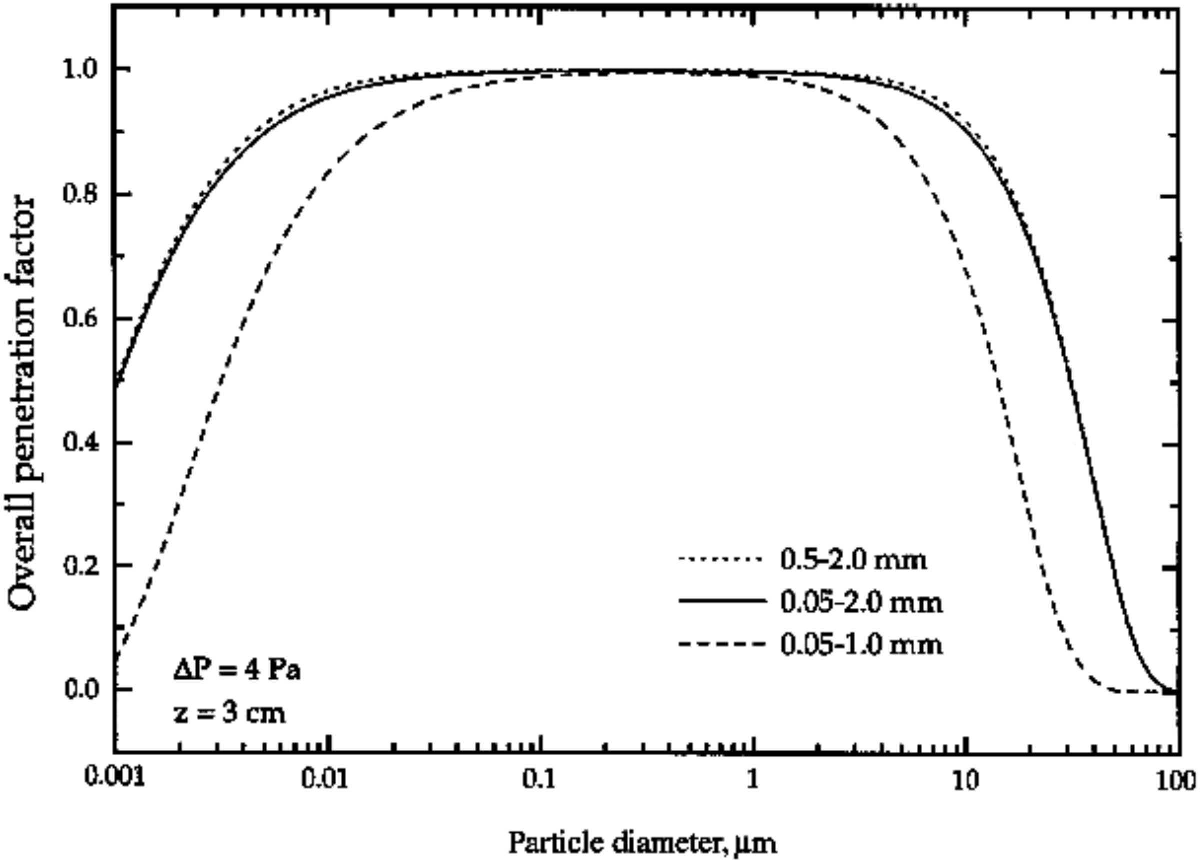


Fig. 6. Overall particle penetration factor for a building with crack area distributed uniformly with respect to crack height. Results are presented for three different ranges of crack sizes.

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

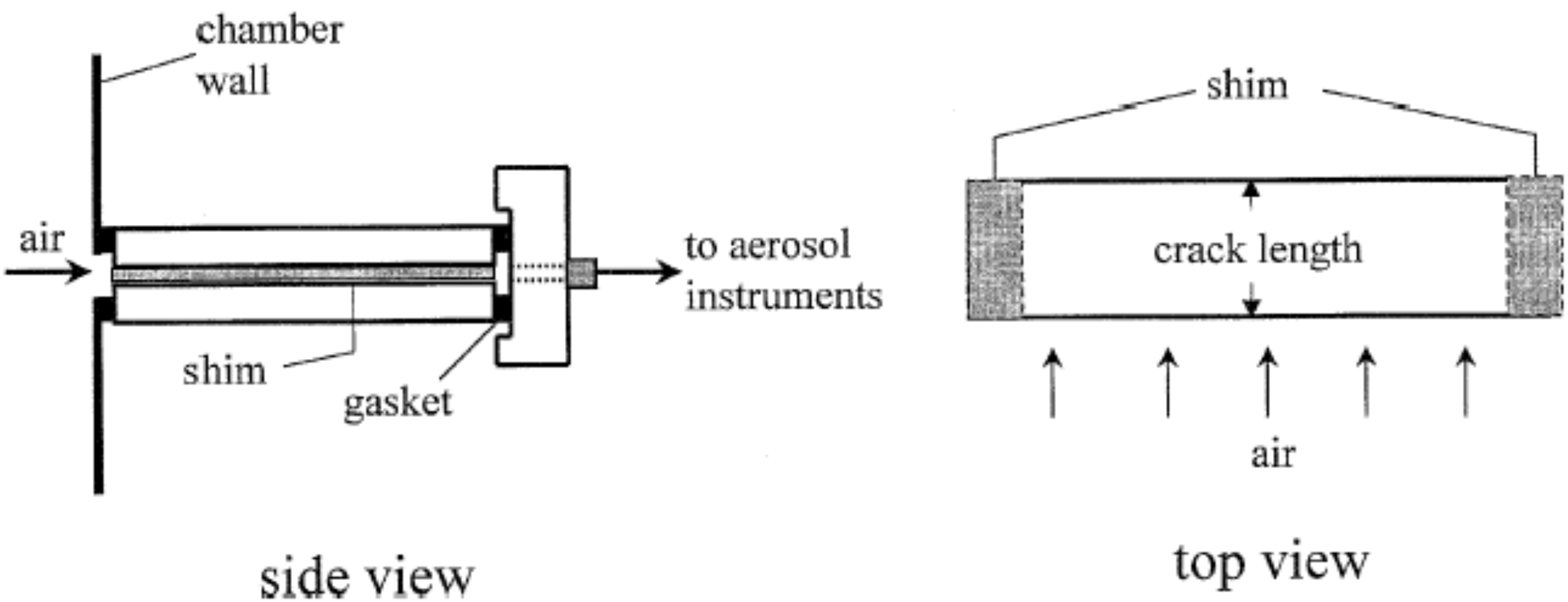


Figure 1. Configuration of crack apparatus (not to scale).

Liu and Nazaroff 2003 *Atmos Environ*

Comparison of model results to chamber tests

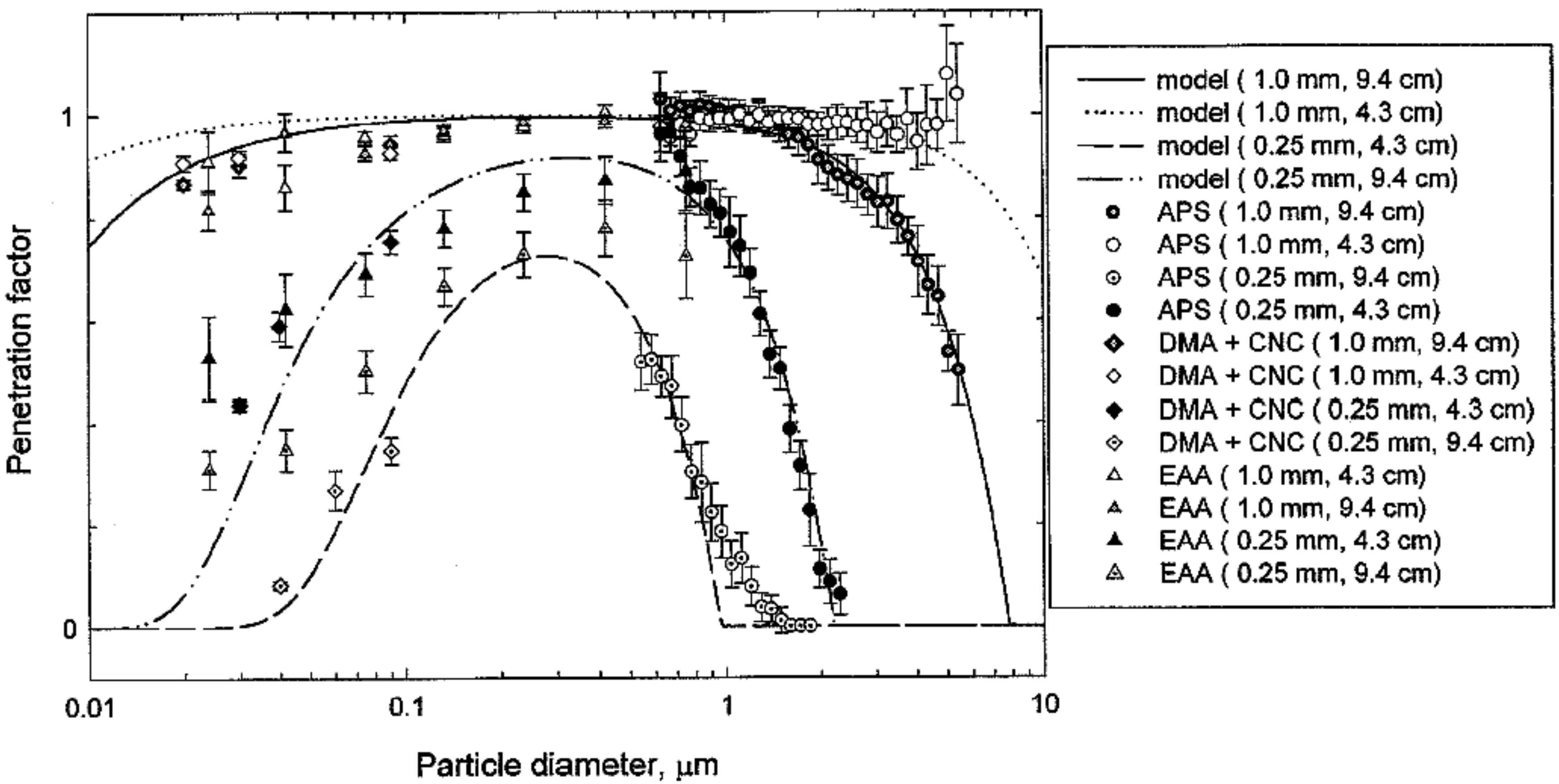


Figure 5. Comparison of model predictions with experimental data for aluminum cracks. Results are presented for four sets of crack dimensions (crack heights of 0.25 mm and 1.0 mm and crack flow lengths of 4.3 cm and 9.4 cm), with an applied pressure difference, $\Delta P = 4$ Pa.

Liu and Nazaroff 2003 *Atmos Environ*

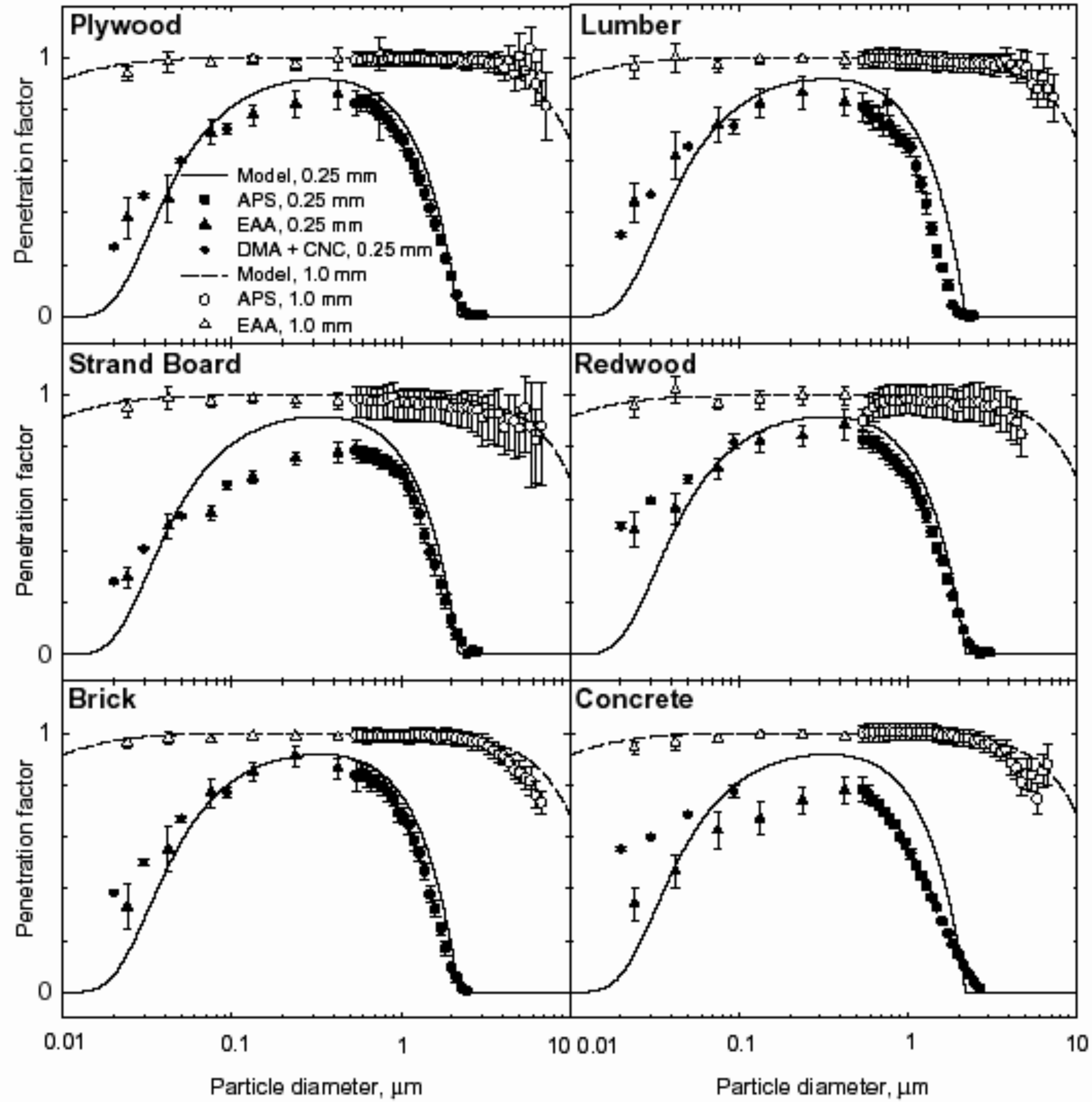


Figure 7. Experimental particle penetration factors for six crack materials at crack heights of 0.25 mm and 1 mm and with $\Delta P =$ 4 Pa, as compared with model predictions.

Liu and Nazaroff 2003 *Atmos Environ*

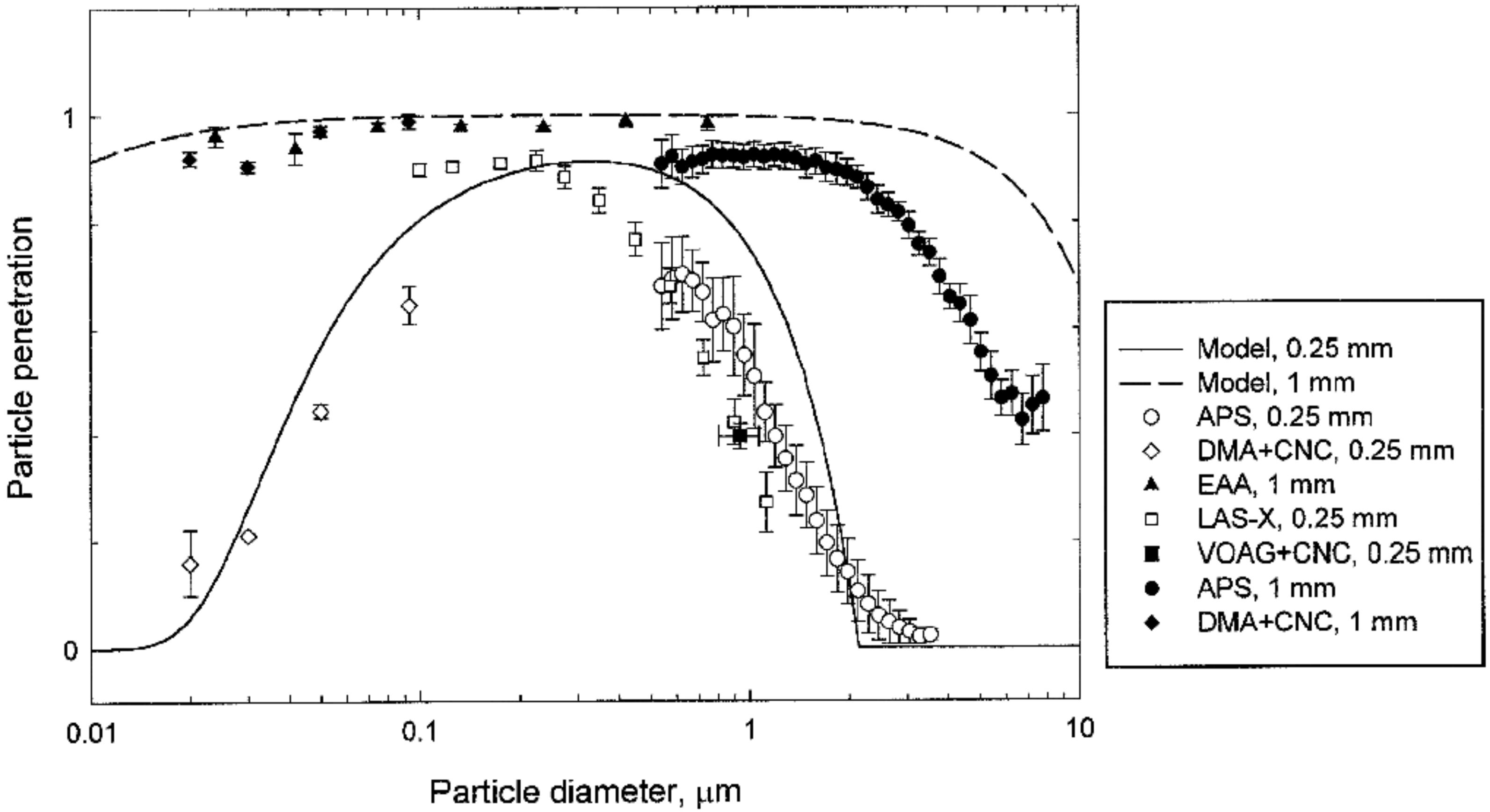


Figure 9. Comparison of model calculations and experimental results for naturally broken brick with crack heights of 0.25 mm and 1 mm.

Liu and Nazaroff 2003 *Atmos Environ*

DATA FROM REAL BUILDINGS

Real building data

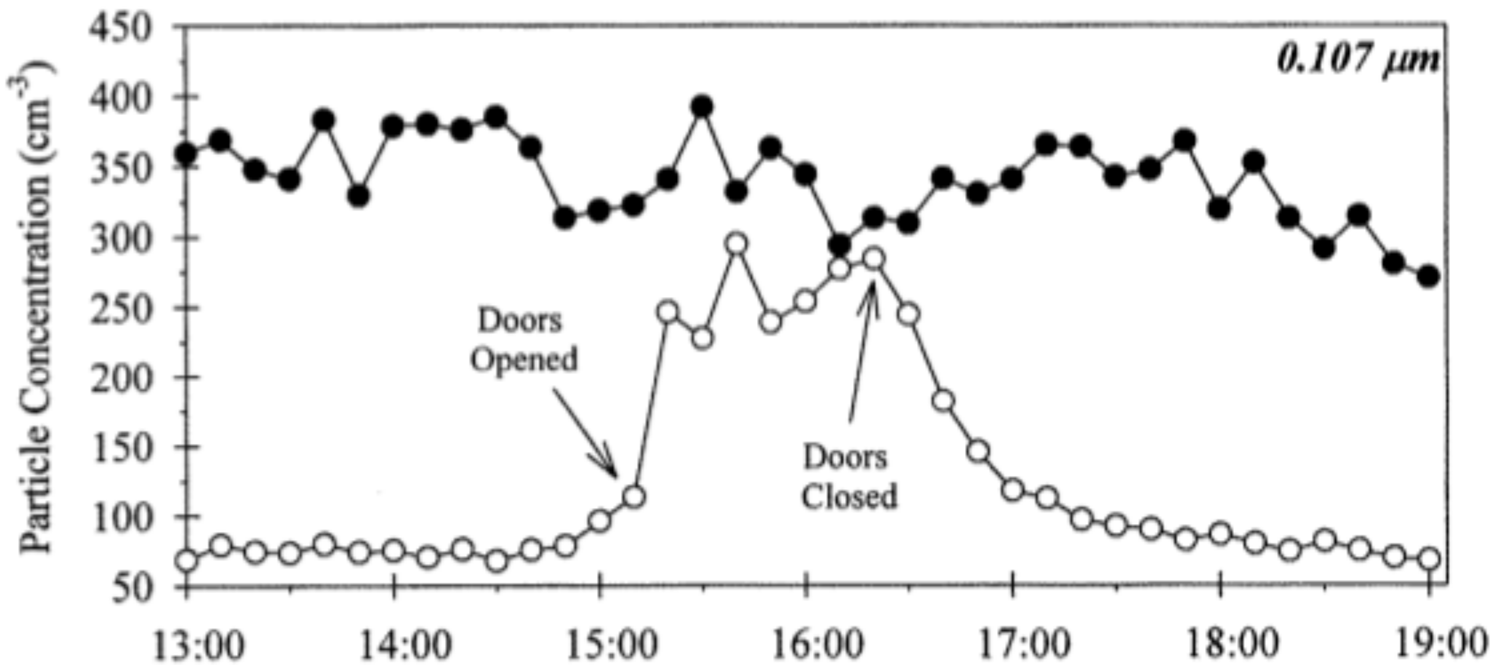
- Models are helpful for understanding:
  - Is a phenomenon important?
  - What impacts the phenomenon?
- Models are severely limited in terms of:
  - Applicability to real environments
- Measurements are absolutely required in real buildings
  - But data can be messy and experiments challenging
  - 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*

Vette et al. 2001 *Aerosol Sci Technol*

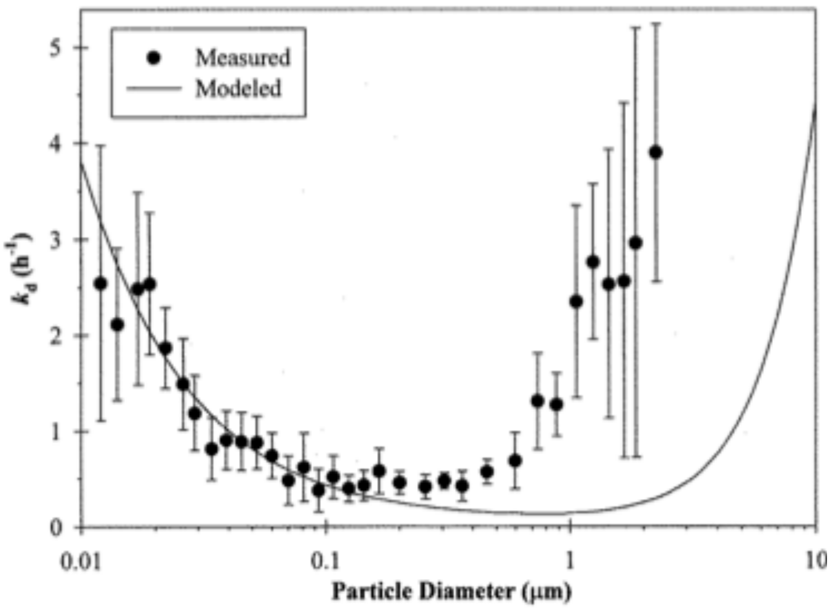
- Single residence – Fresno CA
- Size-resolved indoor and outdoor particle measurements for 2 months
- Deposition rates were first determined by measuring indoor decay after elevation from outdoor particles
  - Simultaneous AER measurements



$$\frac{dC_i}{dt} = -(\alpha + k_d)C_i.$$

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

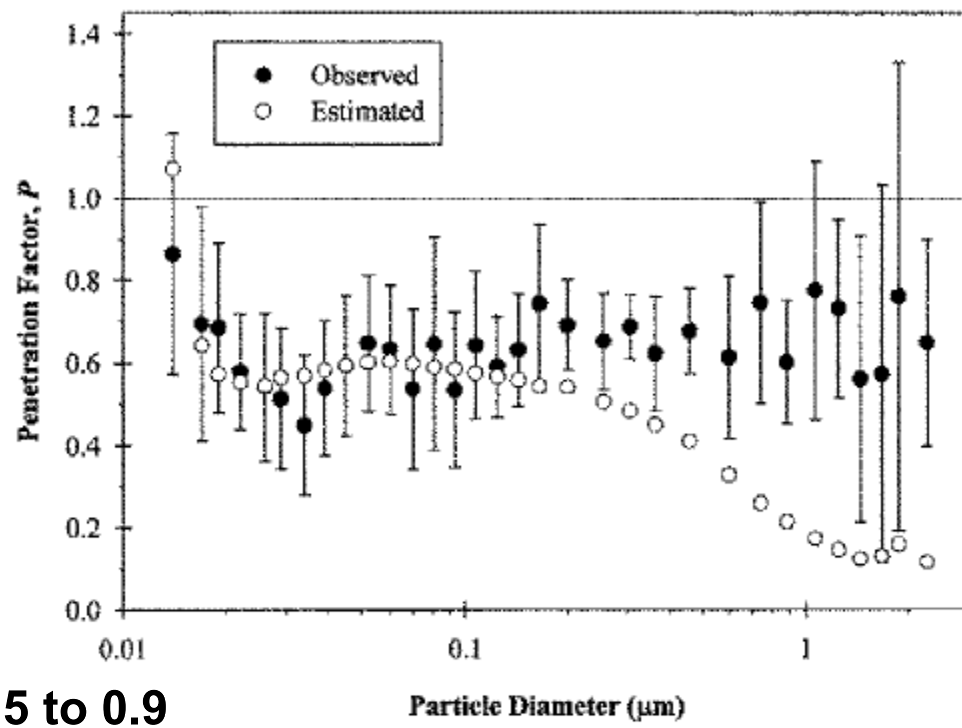
Vette et al. 2001



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

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

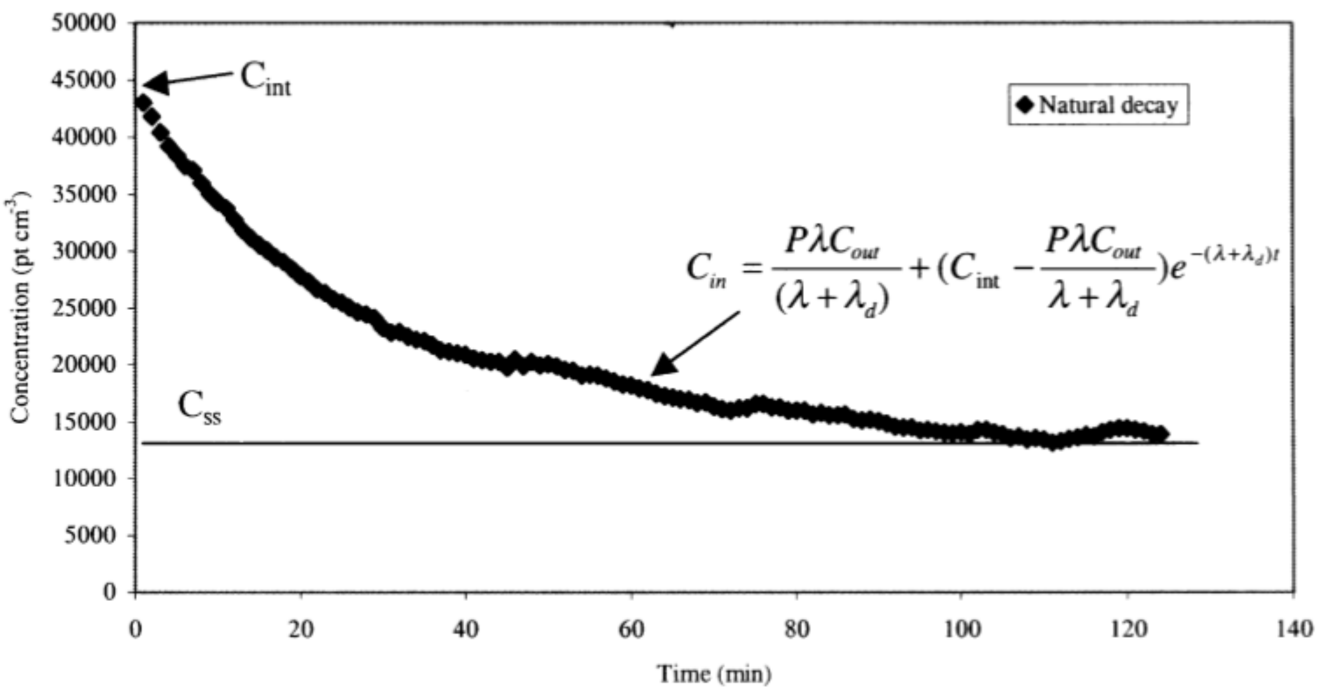
Good estimates of size-resolved deposition rates



Estimates of P ranged from 0.5 to 0.9

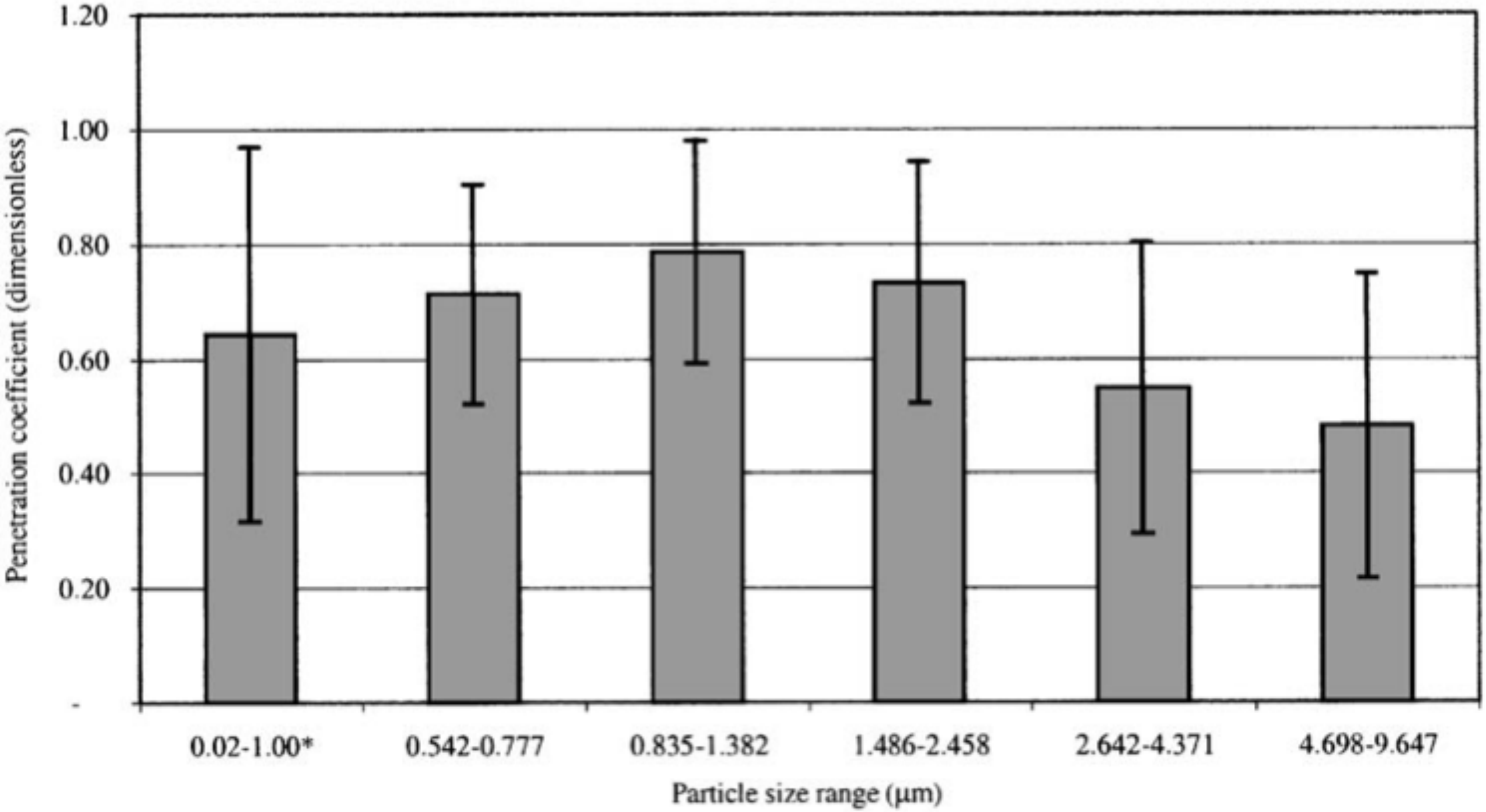
Chao et al. 2003 *Atmos Environ*

- 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

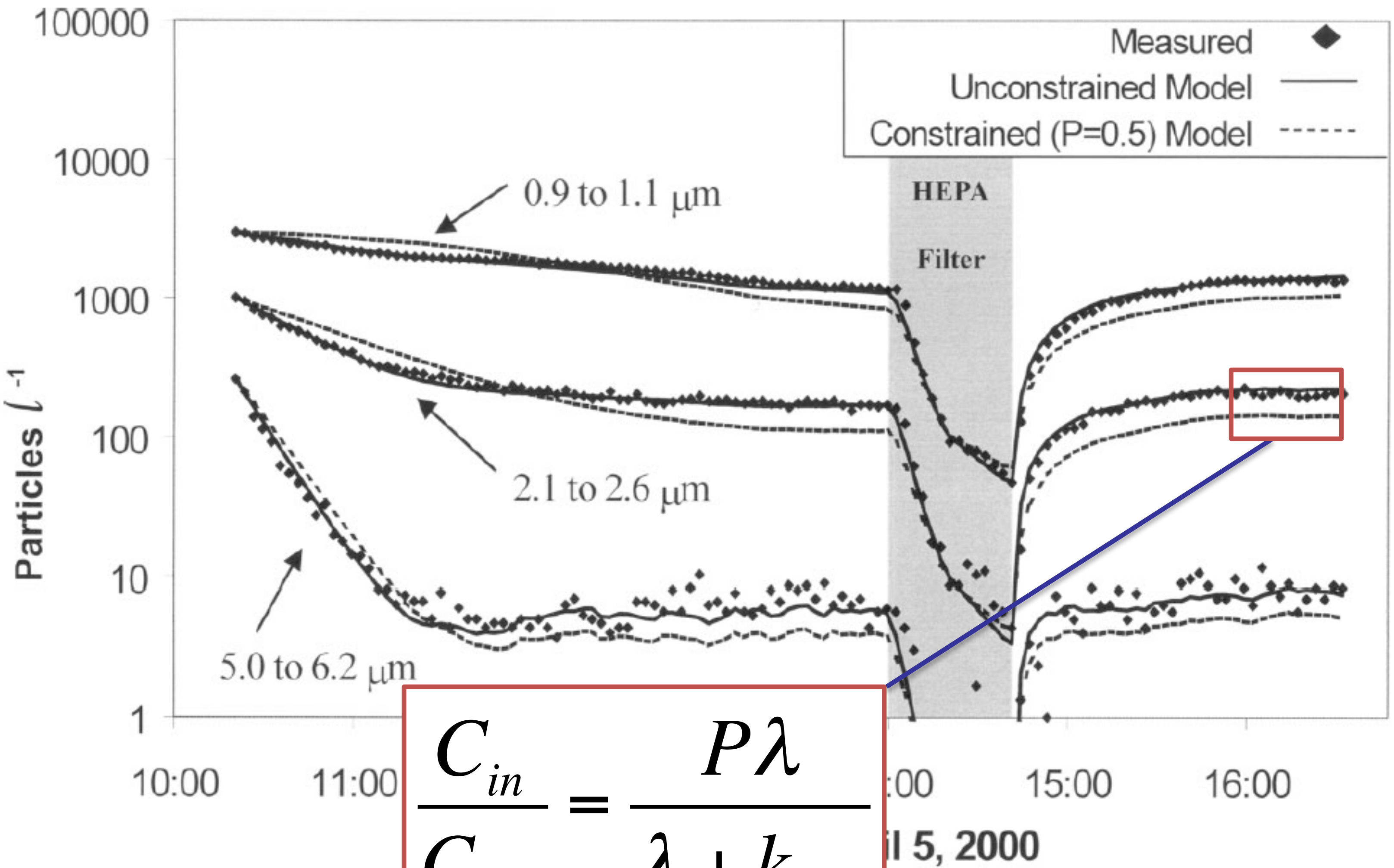
Estimates of P ranged from 0.5 to 0.8

Thatcher et al. 2003 *Aerosol Sci Technol*

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

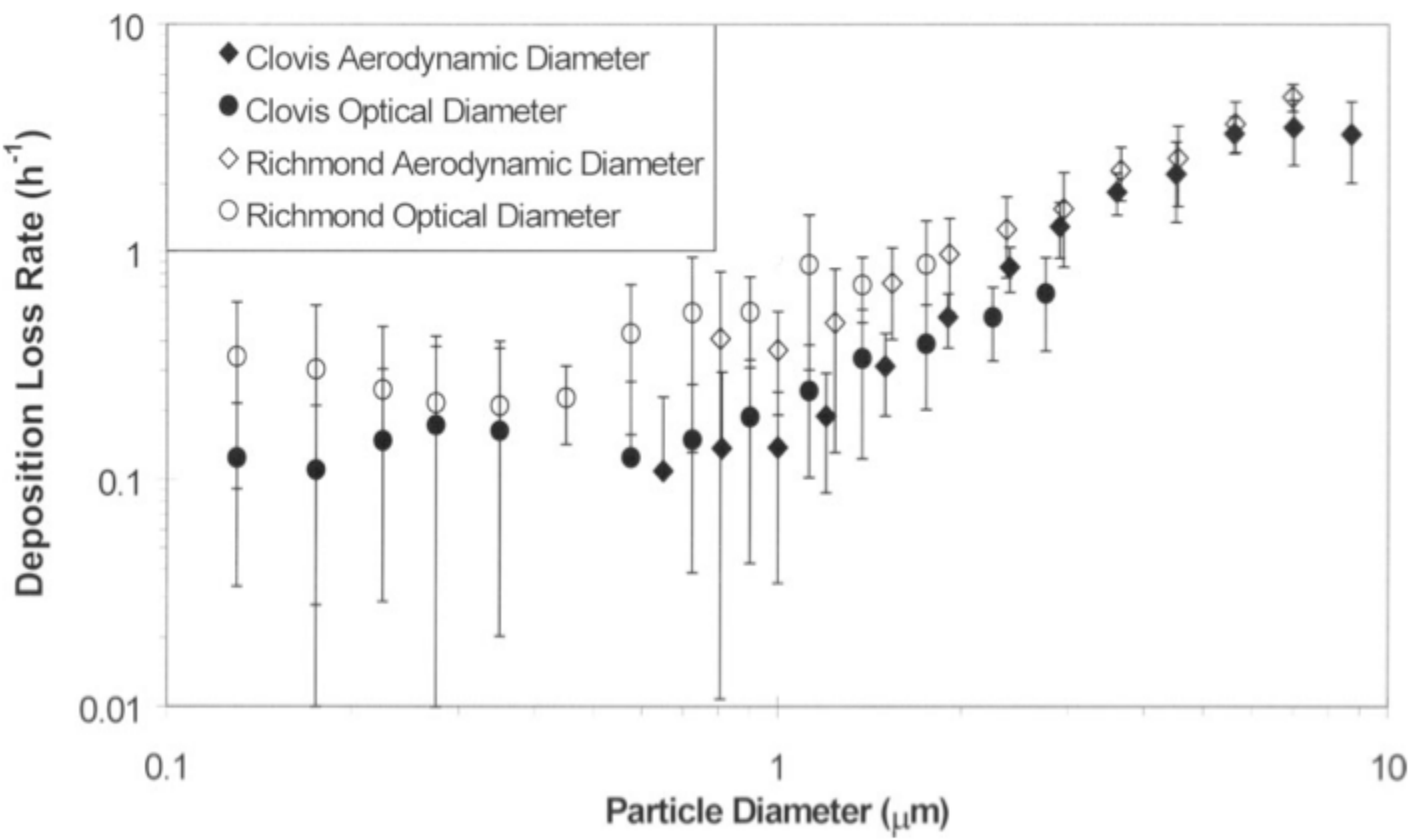
- New method of measuring P
  - "Concentration rebound method"
  - Involved artificially elevating indoor concentrations to measure decay
  - Then operate a HEPA filter to remove most of the indoor particles
  - Then observe the indoor concentration as it "rebounds" to normal levels due to the infiltration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

Particle rebound method from Thatcher et al. 2003

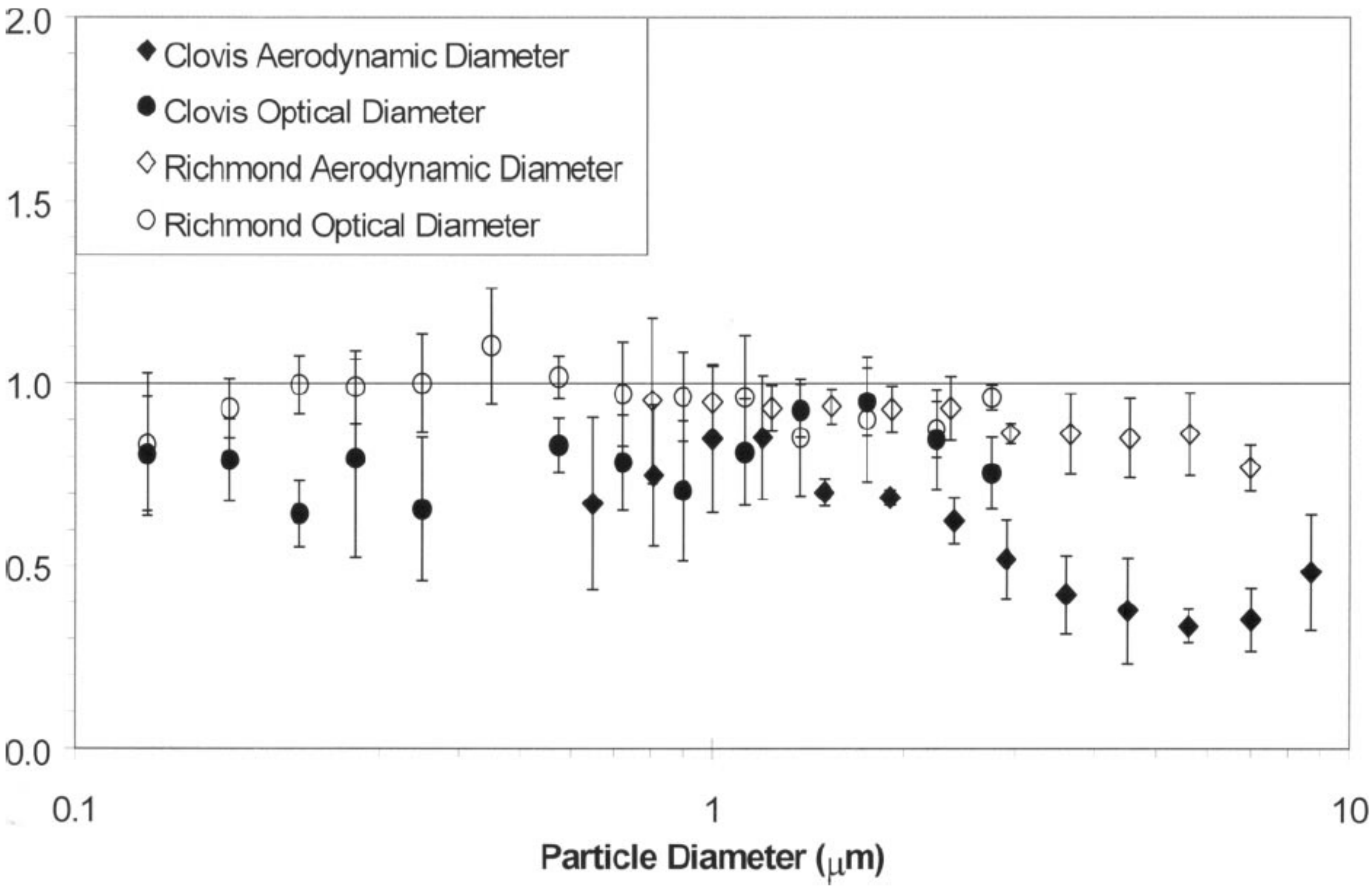


$$\frac{C_{in}}{C_{out}} = \frac{P\lambda}{\lambda + k_{dep}}$$

Thatcher et al. (2003)

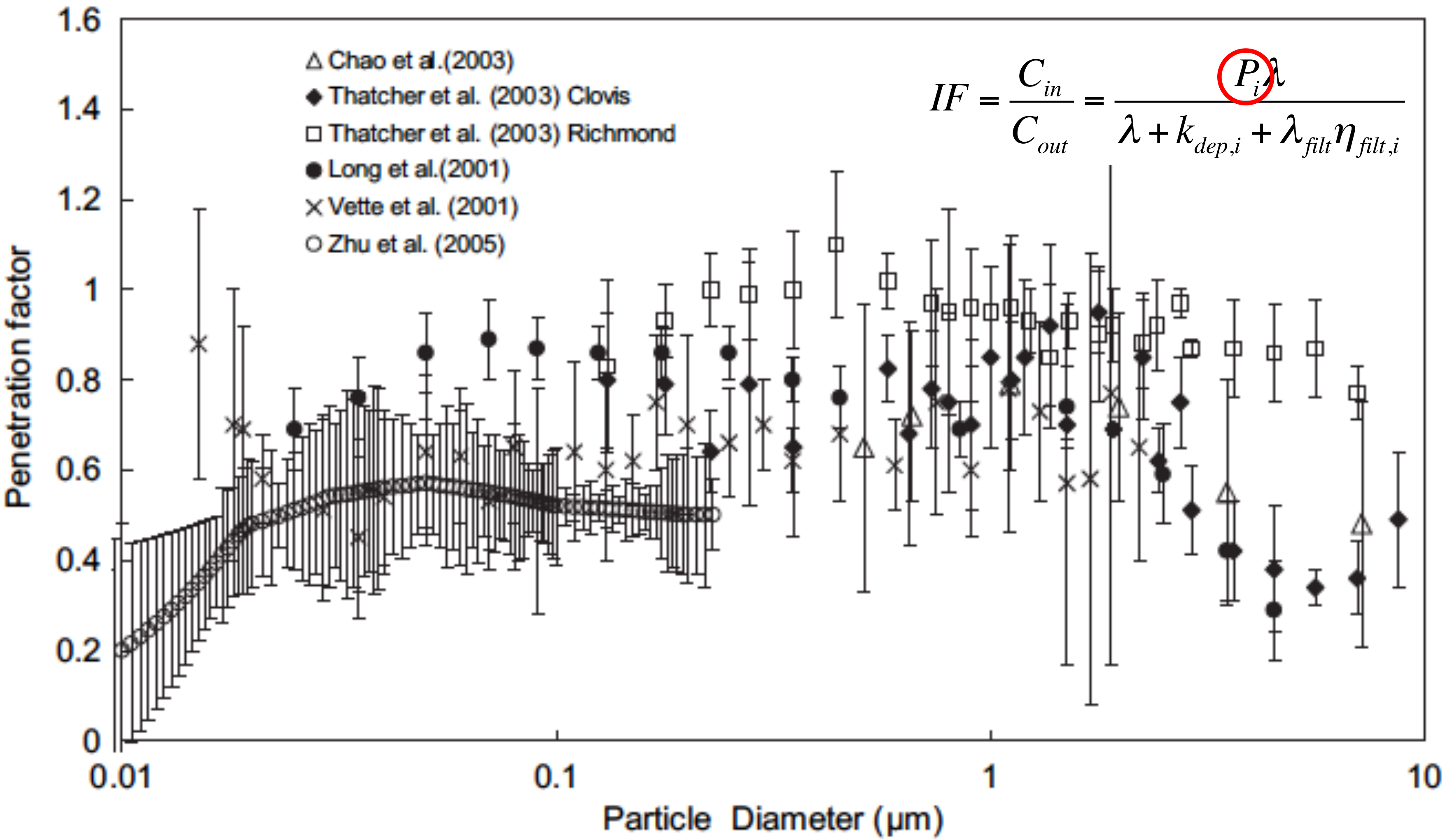


Thatcher et al. (2003)



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

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

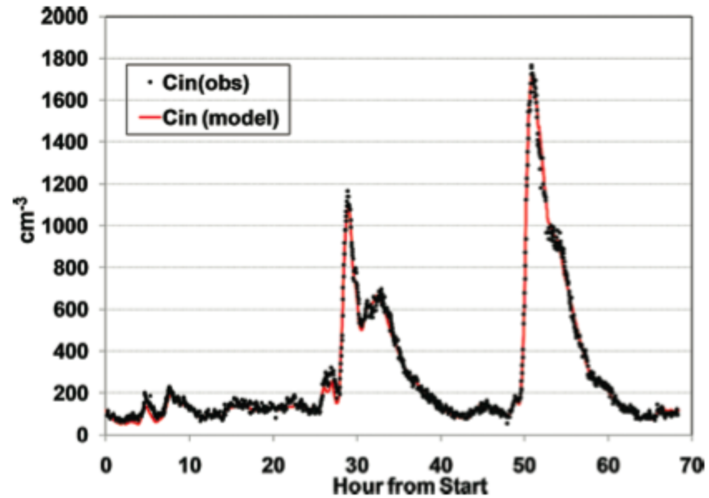
  - Discretized solution to mass balance for each particle size

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

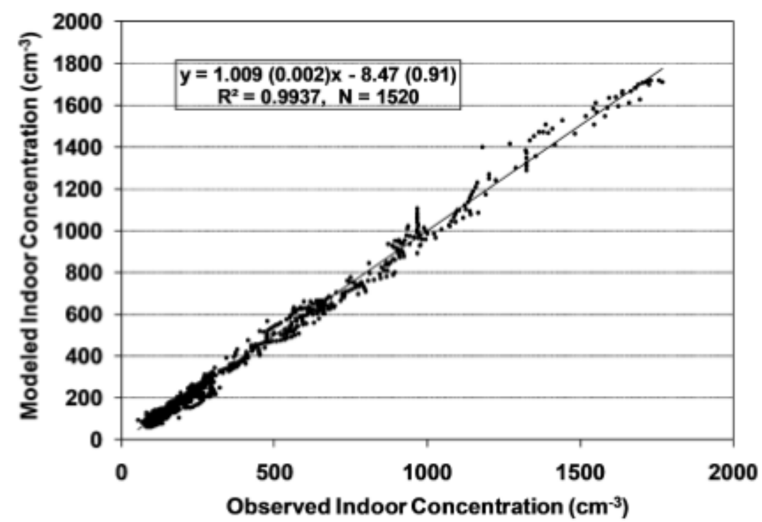
Rim et al. 2010 *Environ Sci Technol*

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

- 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

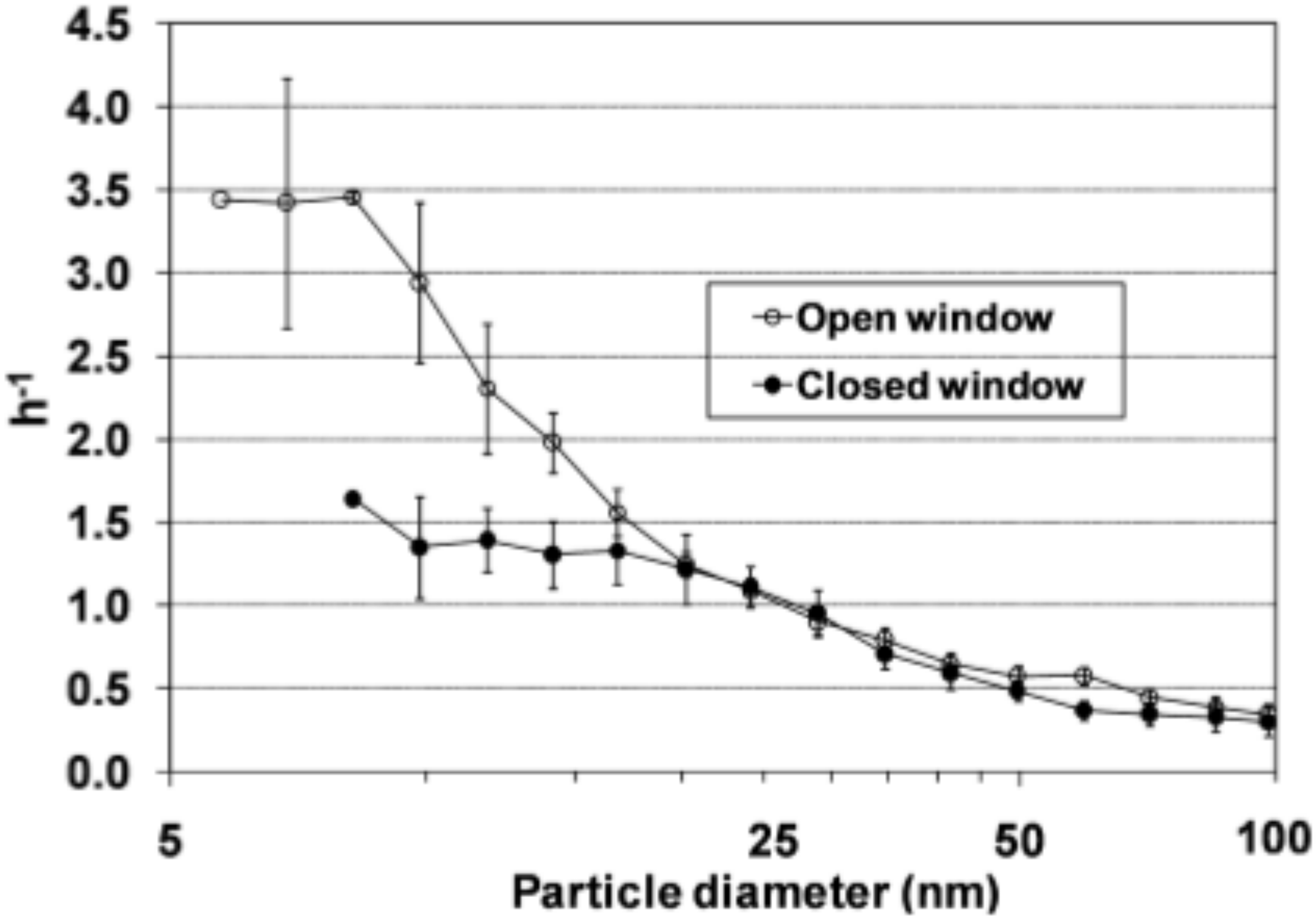


- Measured versus predicted indoor air concentrations compared via linear regression
  - If R^2 was > 0.90, they were happy with their estimates of *P* and k_{dep}

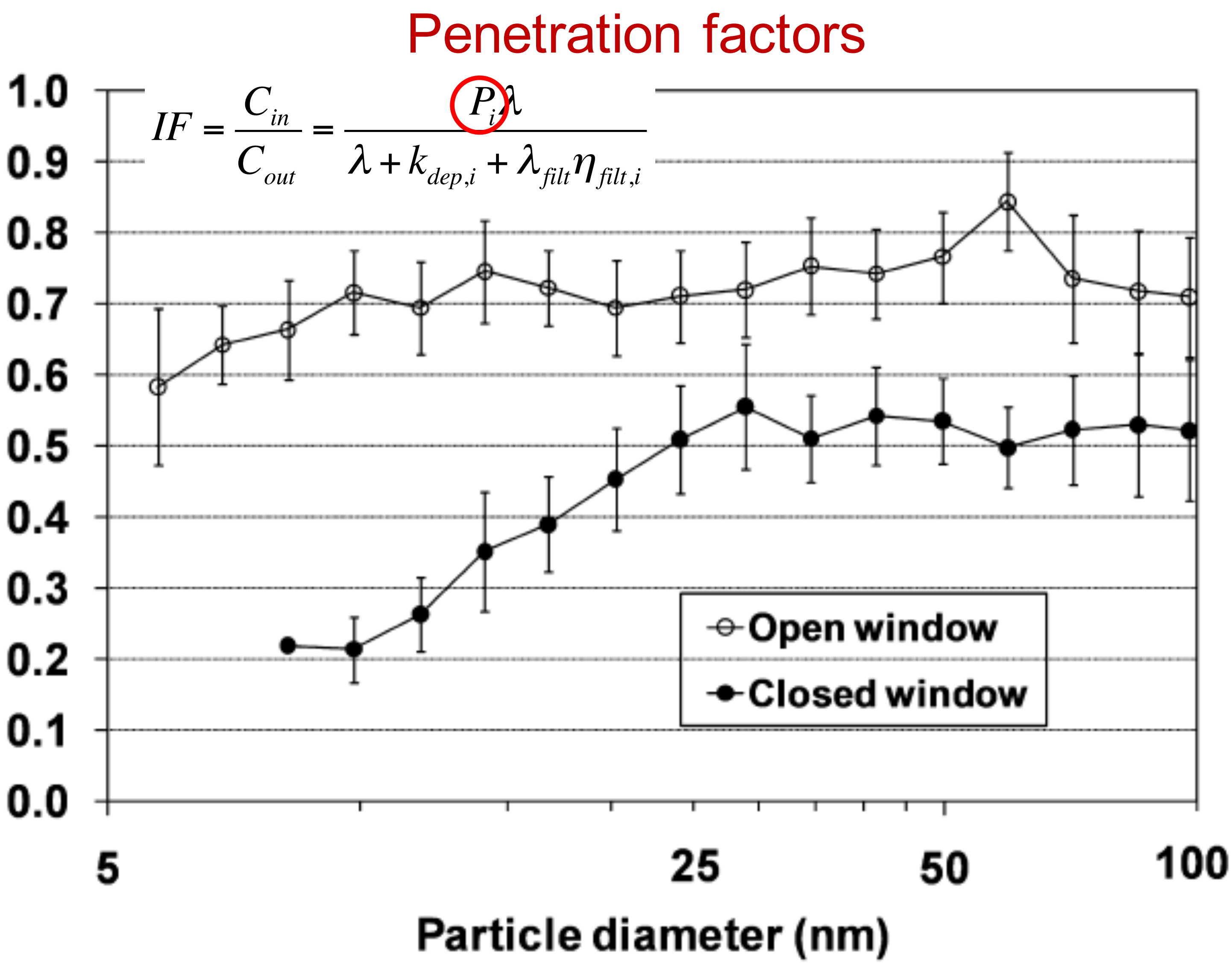


Rim et al. 2010 *Environ Sci Technol*

- Deposition rates



Rim et al. 2010 *Environ Sci Technol*

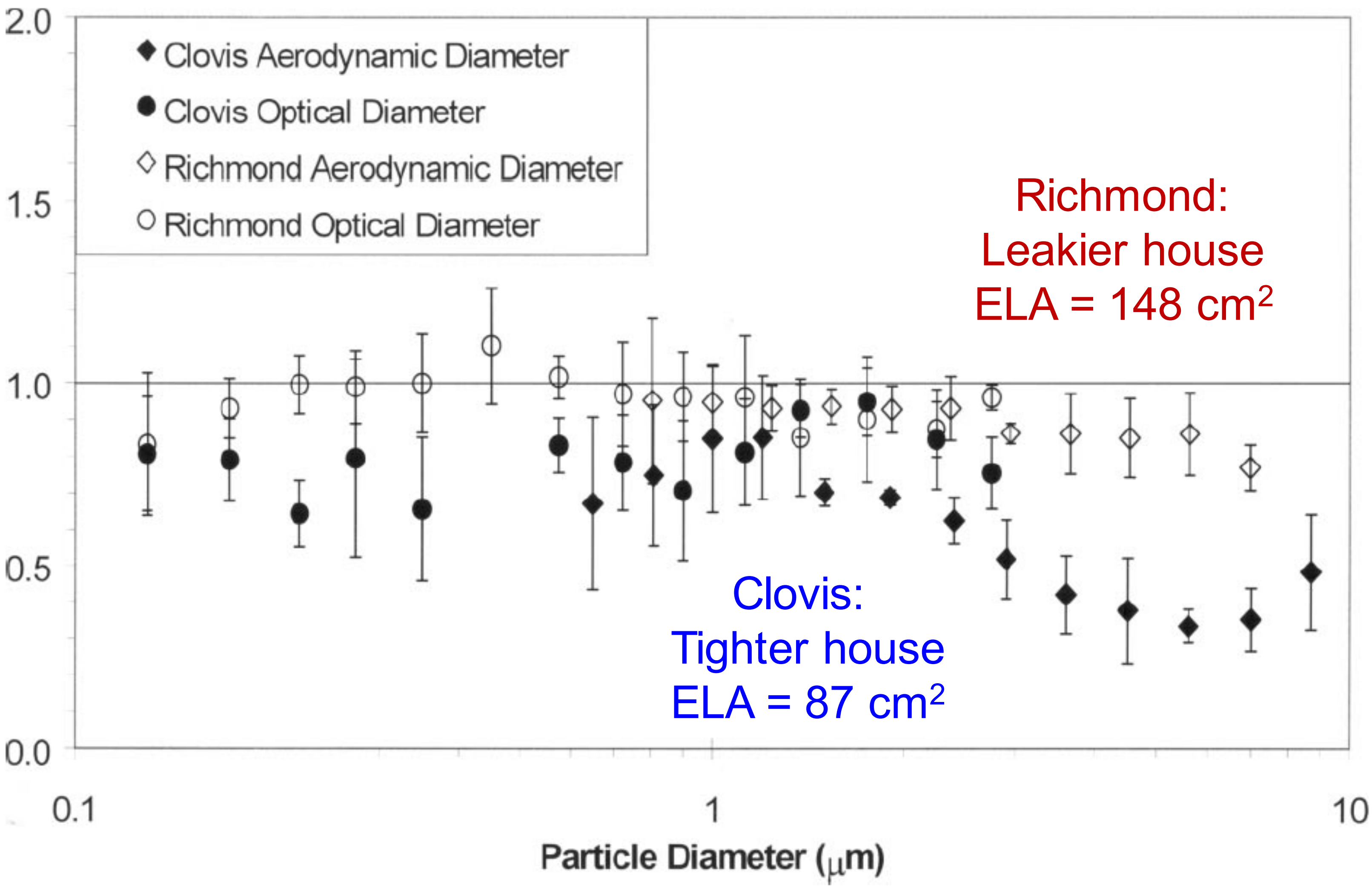


Rim et al., 2010 *Environ Sci Technol*

NEWER WORK

By me (as a graduate student)

Penetration results from Thatcher et al. (2003)



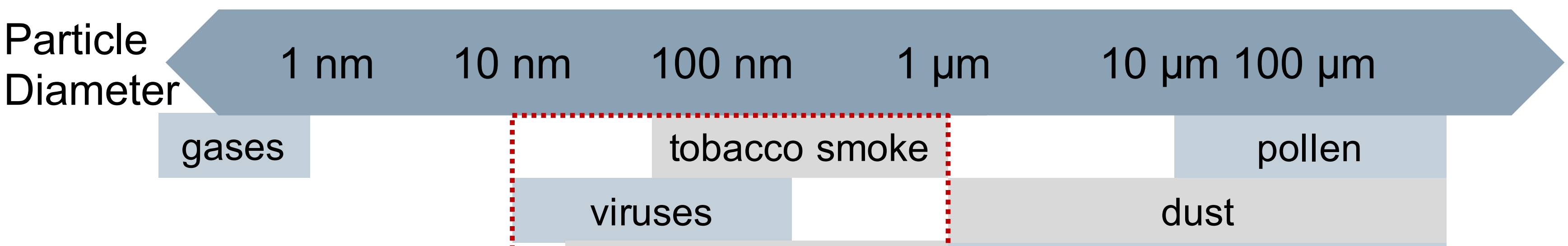
*Estimated Leakage Area (ELA) = *f* (blower door air leakage coefficients & ΔP)

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



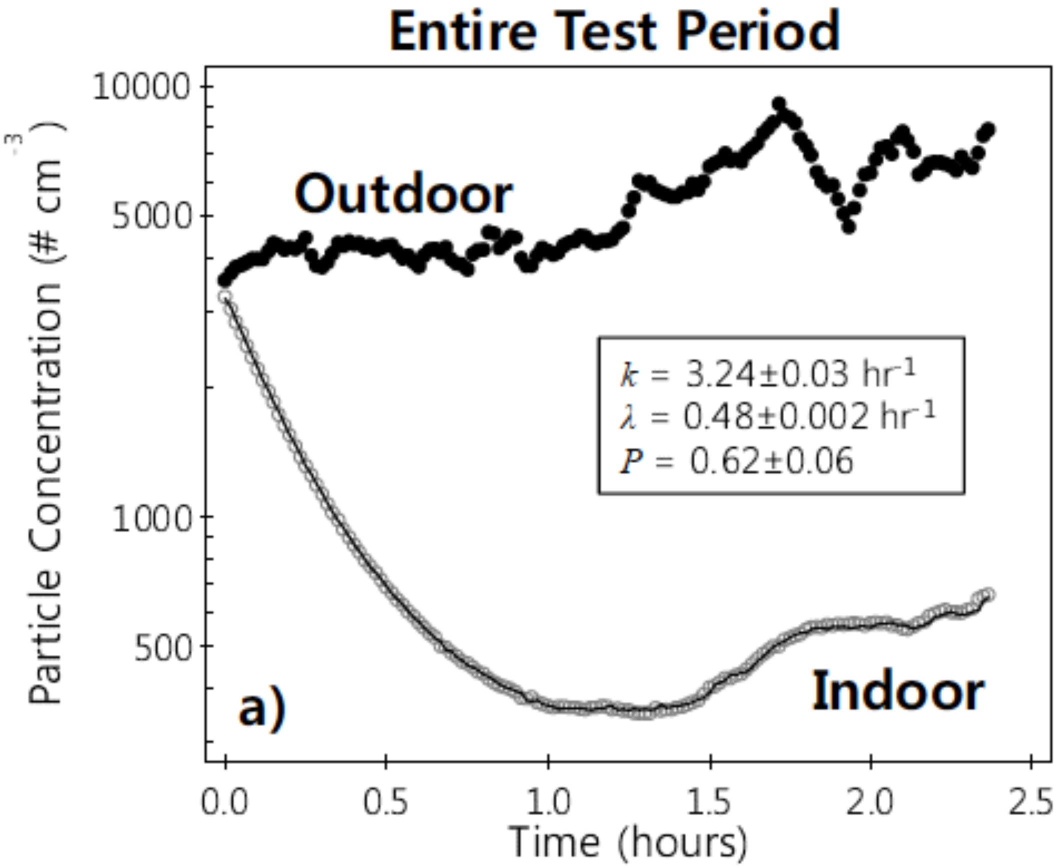
Refined PM penetration test method

- 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



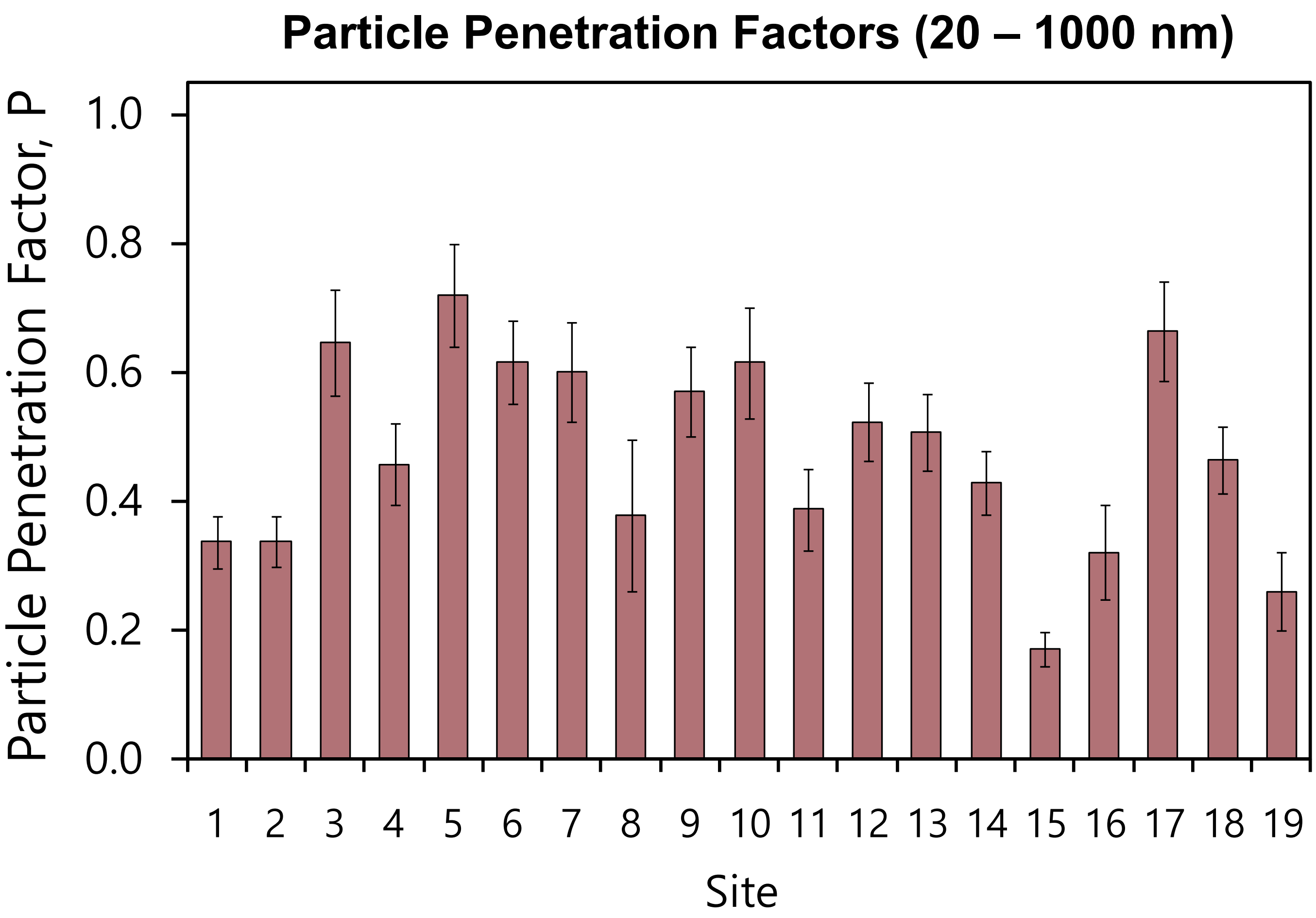
$$C_{in,t} = C_{in,t-1} + \left(P\lambda C_{out,t-1} - (\lambda + k)C_{in,t-1}\right)\Delta t$$

Stephens and Siegel, 2012 *Indoor Air*

PM infiltration: Test homes

Stephens and Siegel, 2012 *Indoor Air*

Particle infiltration results

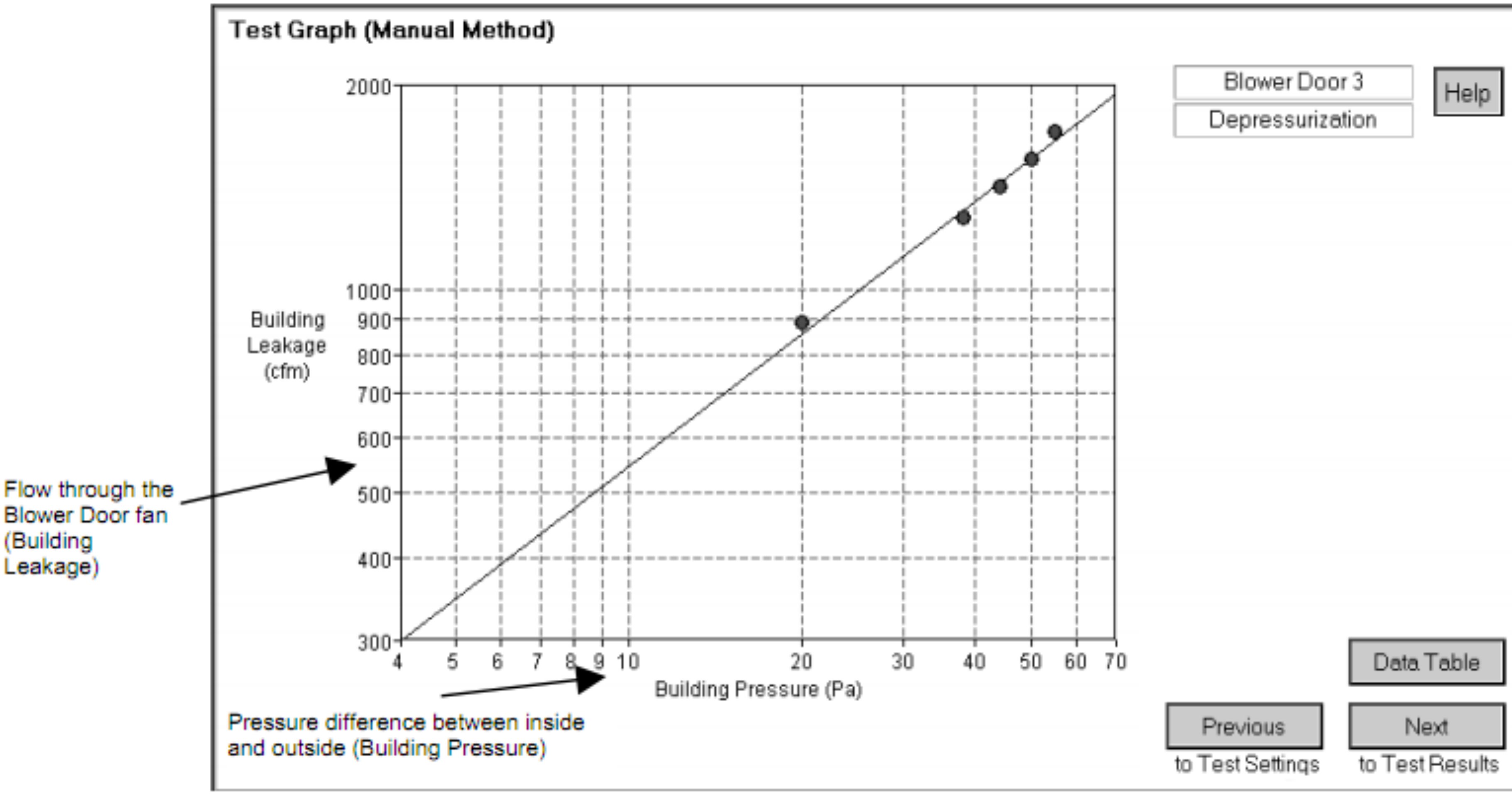


Mean (± SD) = 0.47 ± 0.15 | Range = 0.17 ± 0.03 to 0.72 ± 0.08

Stephens and Siegel, 2012 *Indoor Air*

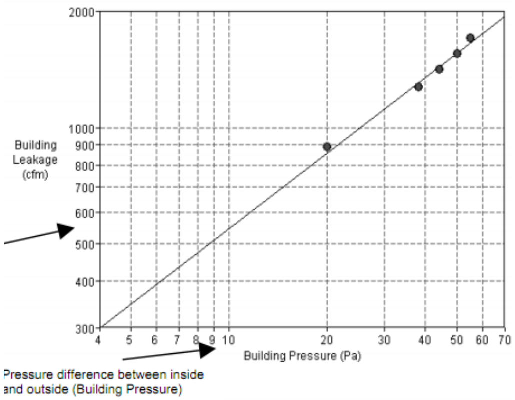
PM infiltration: What can we learn?

- 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)

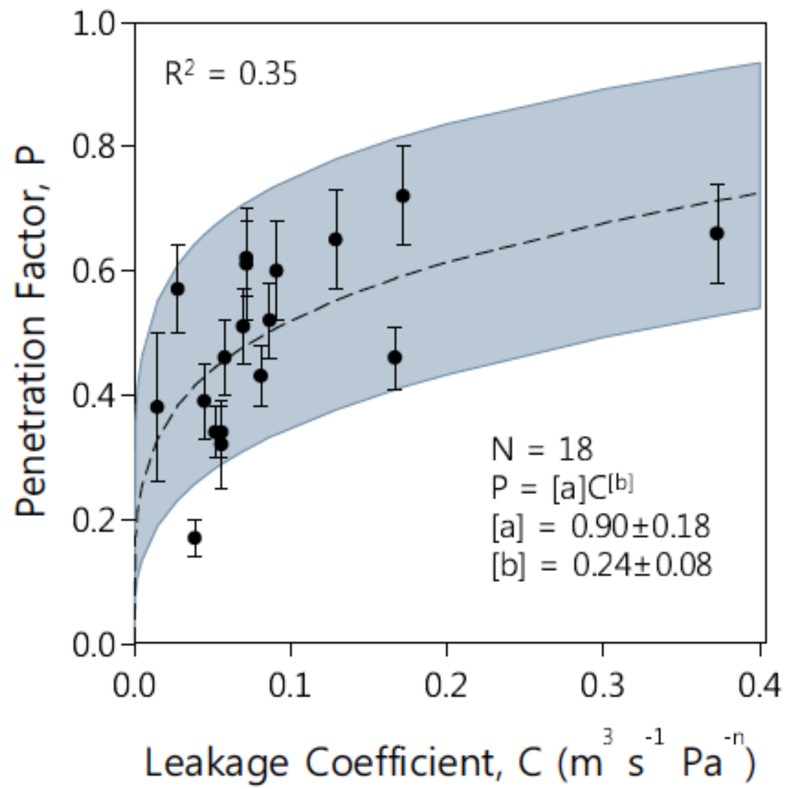
$$ACH_{50} = \frac{Q_{50\ Pa}}{V}$$

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 $\rho = 0.71$ ($p < 0.001$)

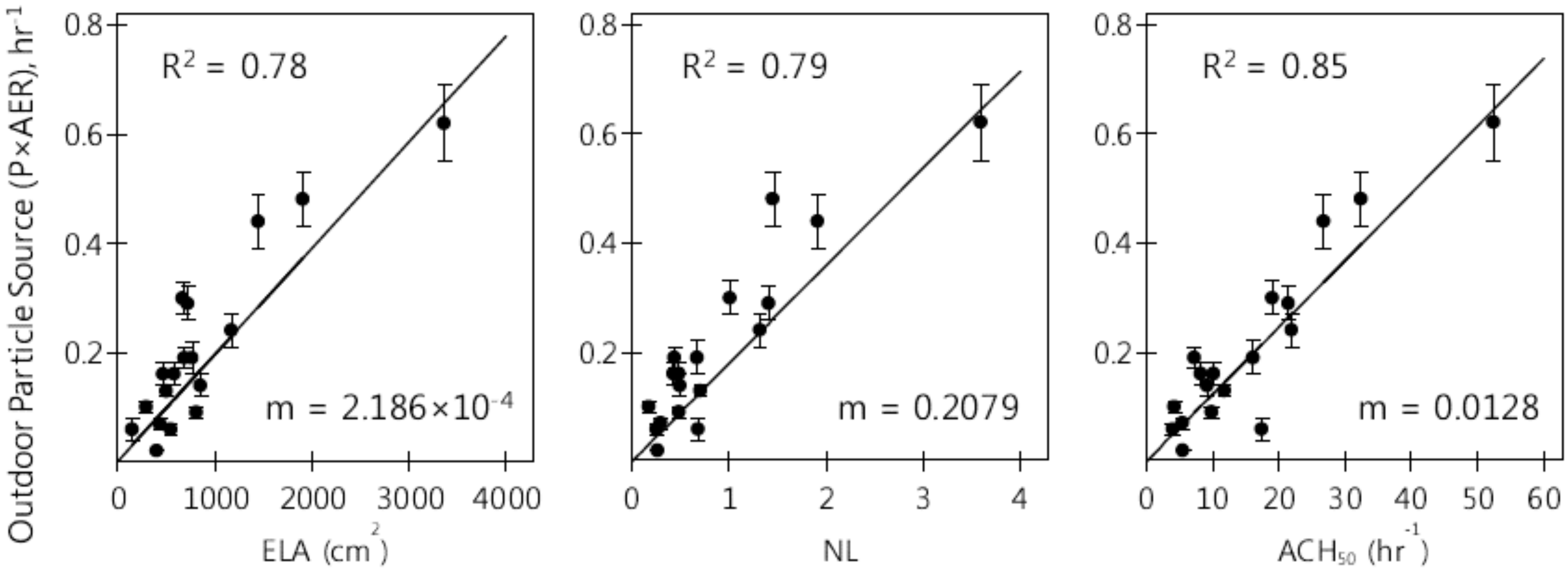


- Association is strong, but predictive ability is low

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

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

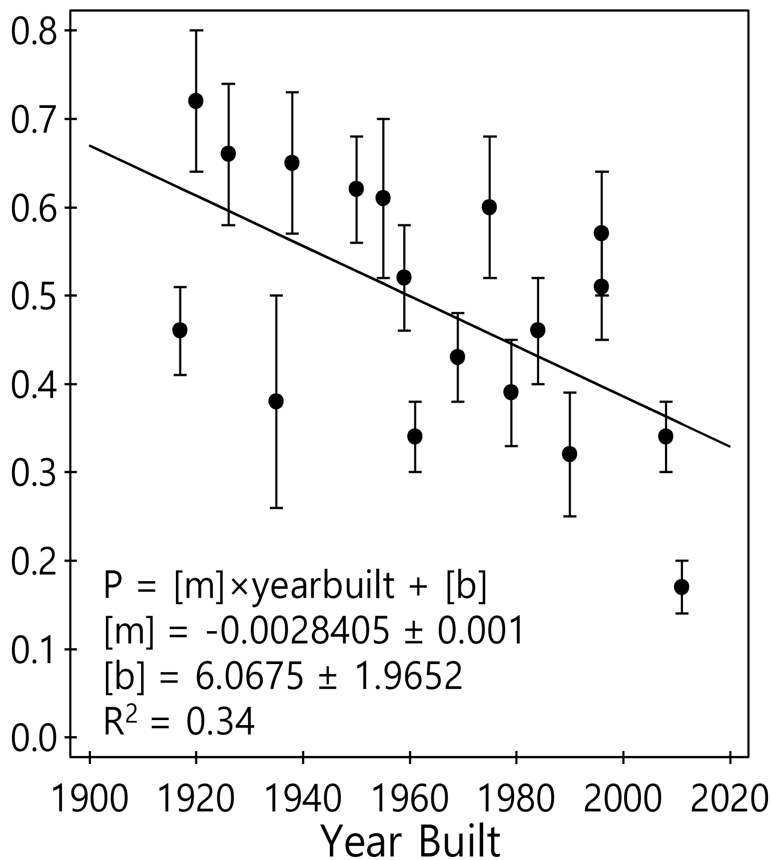
- Potential socioeconomic implications: low-income homes are leakier

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

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

PM infiltration and age of homes

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



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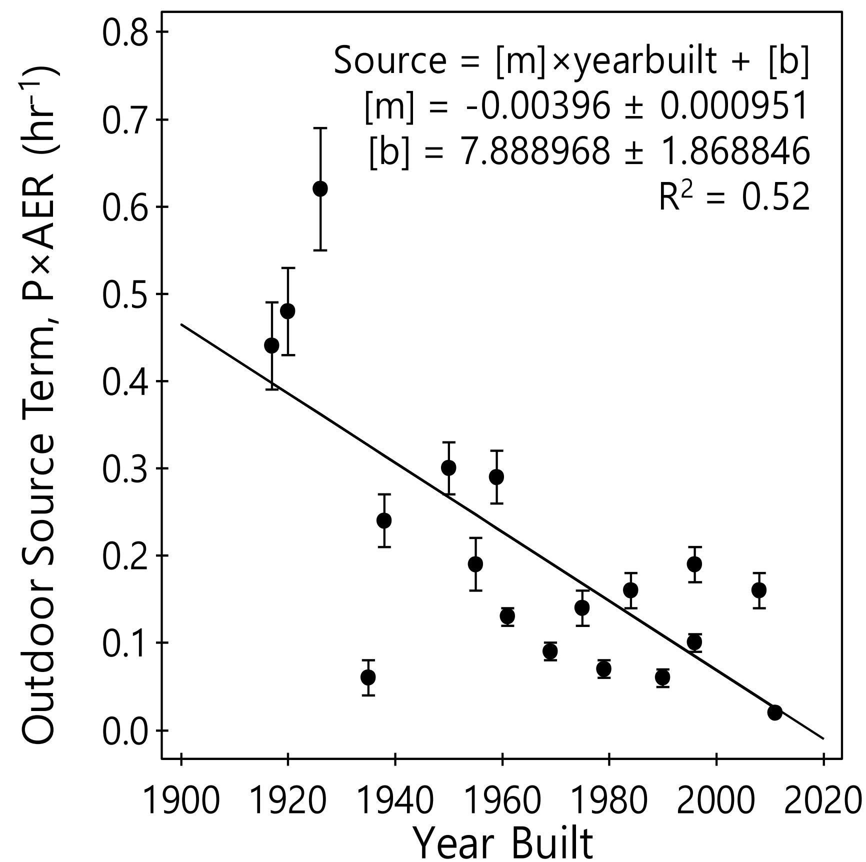

Older homes also had much higher outdoor particle source rates

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

Implications for submicron PM exposure: 19 homes

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

	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

Stephens **2015** *Sci Technol Built Environ*

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 again