ENVE 576
Indoor Air Pollution

Spring 2013

Lecture 7: February 26, 2013

Particulate matter:
Finish lecture 6 on size distributions and lung deposition
Then: sources, deposition, and resuspension

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Review from last time

- Finished up gas-phase chemistry and air cleaning
  - Gave another week on HW 2 on VOC emissions (due today)
  - Your HW 3 on sorption and reactive deposition is also due today

- Began particulate matter
  - Single particle physics and motion
    - Settling velocity
    - Gravity, impaction, diffusion, electrostatic, thermophoresis
  - Particle size distributions

- Today:
  - Continue particulate matter
    - Finish size distributions
    - Respiratory deposition
    - Sources, surface deposition, and resuspension

Finishing up from last week

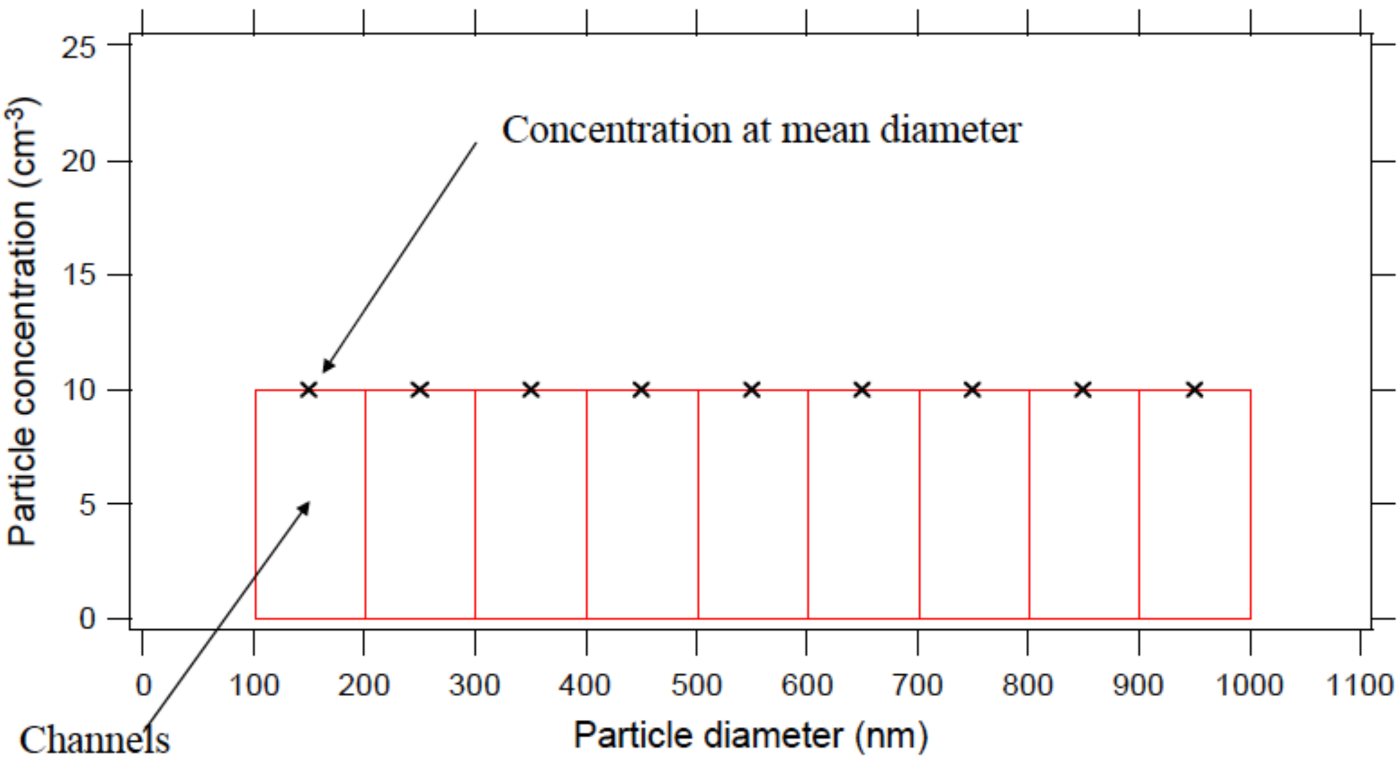
PARTICLE SIZE DISTRIBUTIONS

Particle size distributions

- A monodisperse aerosol (i.e., all particles have the same size) does not exist in the ambient atmosphere
  - Not indoors or outdoors
- What we have are polydispersed aerosols
  - So we need to describe the sizes of aerosol particles with a size distribution, which gives the concentration of particles as a function of particle diameter
  - Practically, a number concentration is determined between ranges of particle sizes: e.g., in the range $d_{p2} - d_{p1}$ or Δd_p or dd_p
    - Number of particles with diameters between d_{p2} and d_{p1}

Size distributions

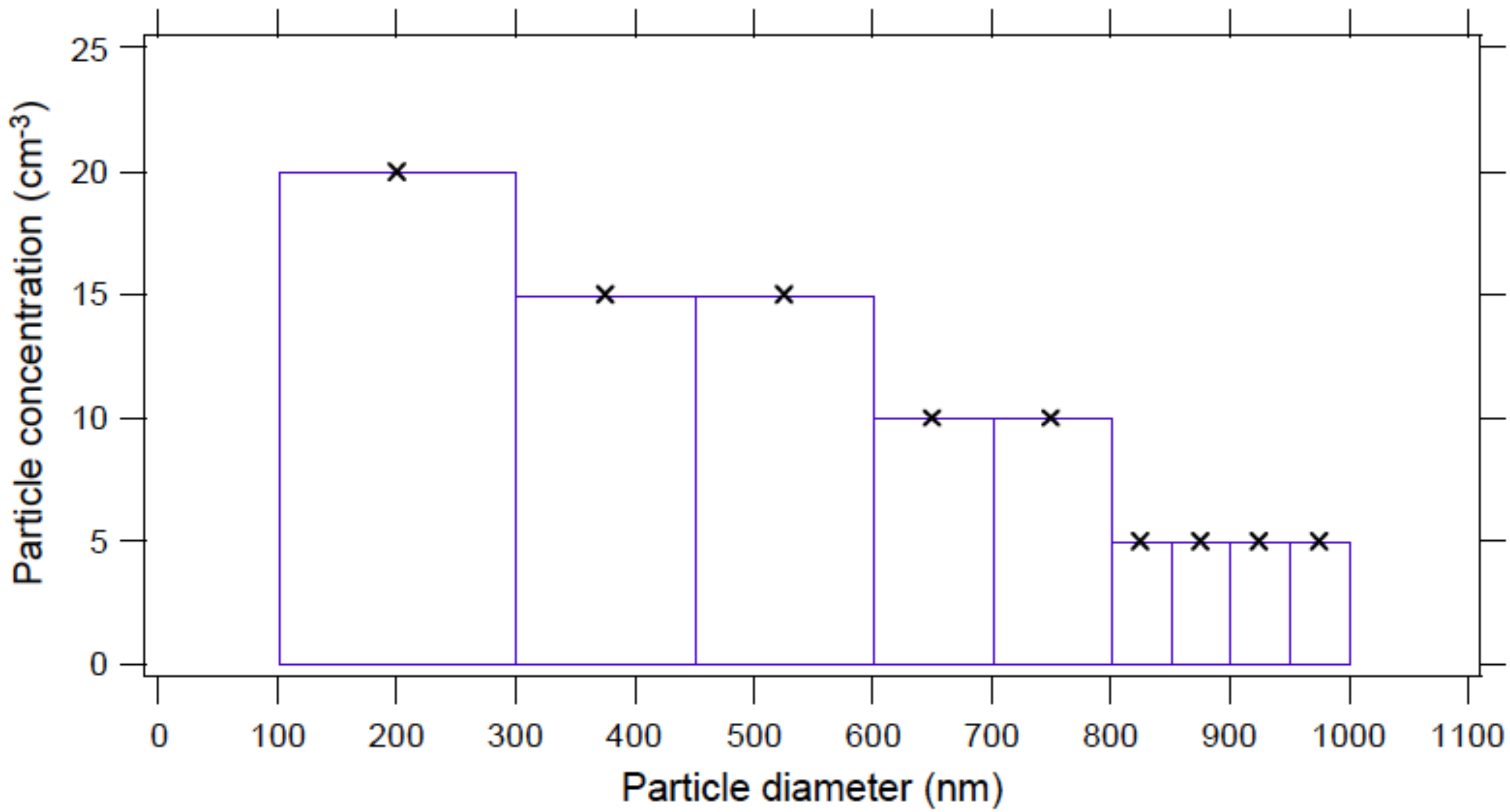
- 9 size channels, width of 100 nm each, each with 10 particles per cm^3
- We consider the measured concentration as $\mathrm{d}N$ in each channel



Schneider, 2010

Size distributions

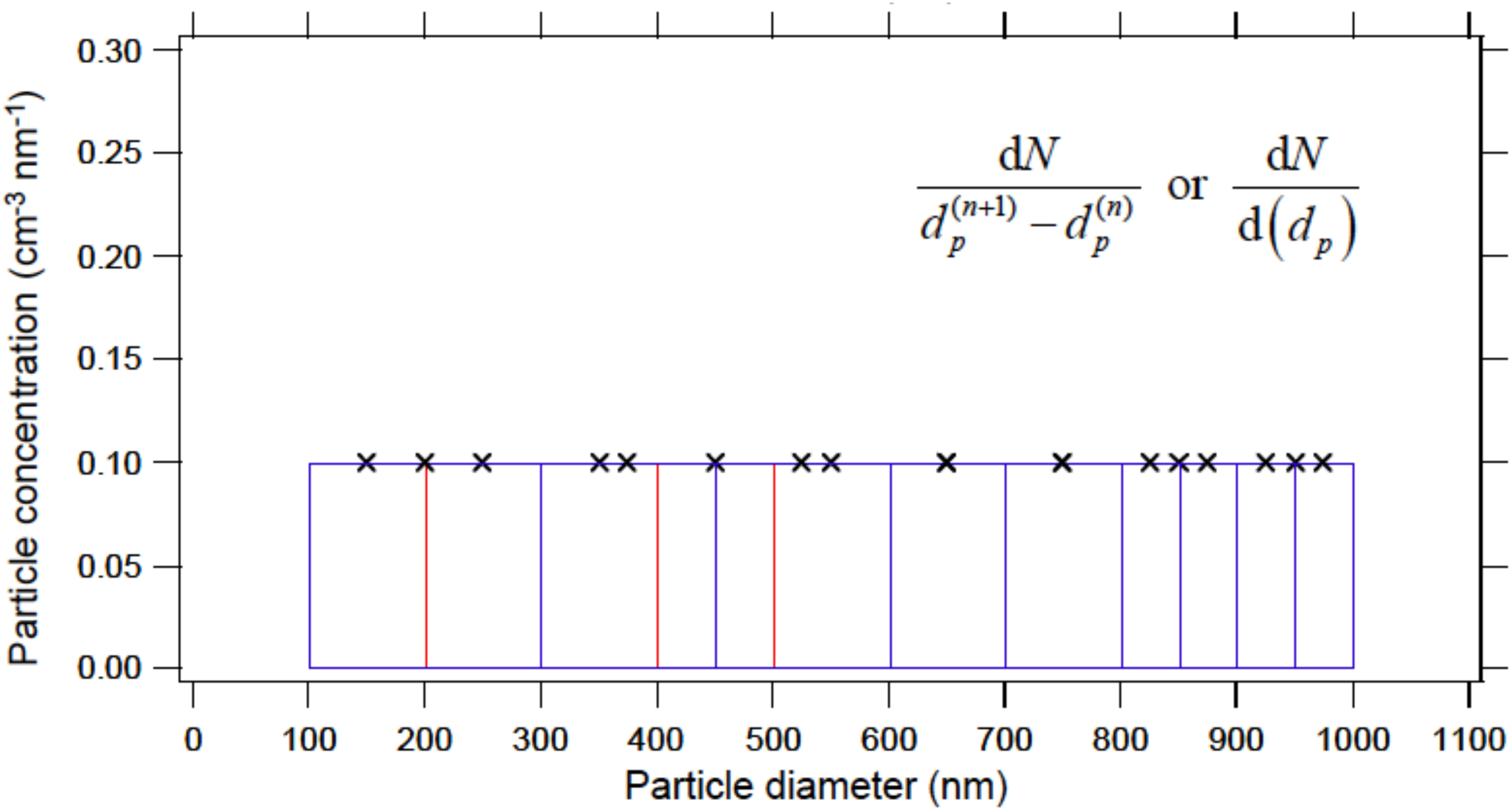
- If we use a different instrument with different channel widths, the shape of the distribution changes:



Schneider, 2010

Size distributions

- To avoid this sizing effect, we divide the measured concentrations (dN) by the width of the size channels



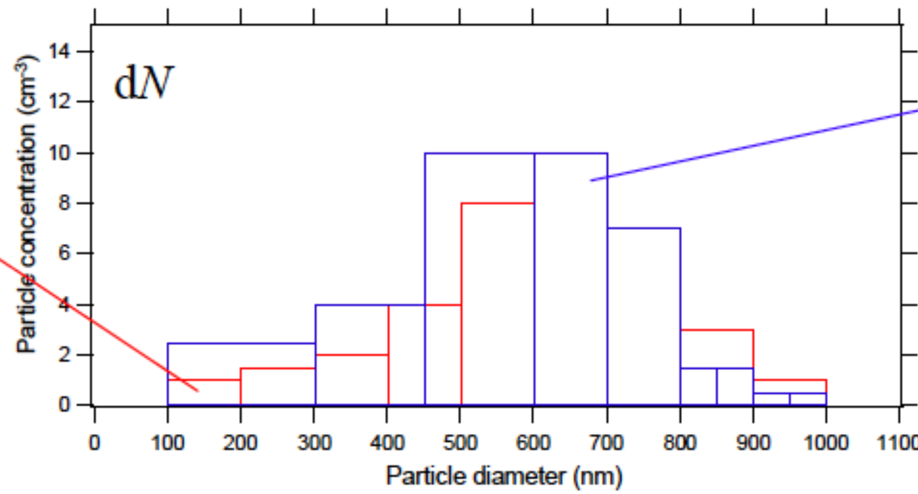
Schneider, 2010

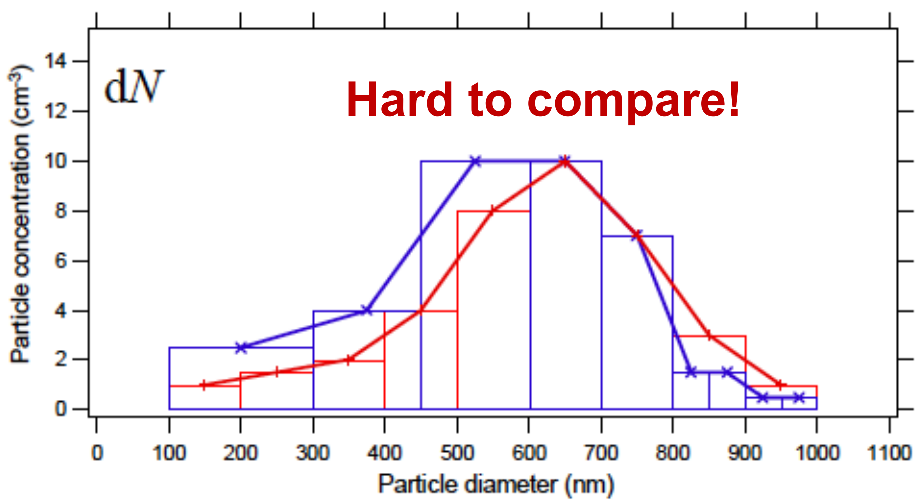
Size distributions

- Similar example but for a more realistic size distribution

"Instrument 1"

Channel	N (cm^{-3})
100-200	1
200-300	1.5
300-400	2
400-500	4
500-600	8
600-700	10
700-800	7
800-900	3
900-1000	1





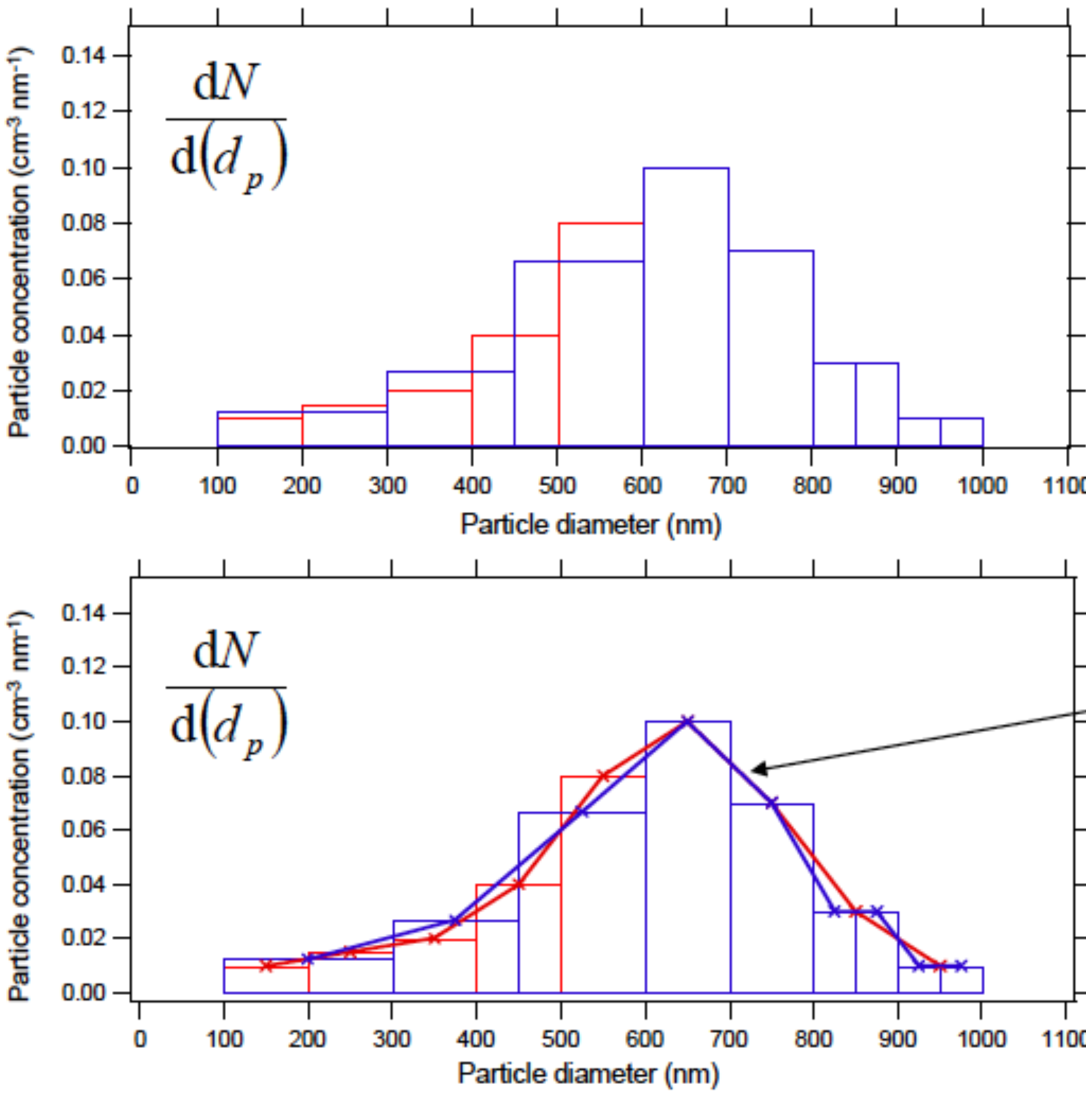
"Instrument 2"

Channel	N (cm^{-3})
100-300	2.5
300-450	4
450-600	10
600-700	10
700-800	7
800-850	1.5
850-900	1.5
900-950	0.5
950-1000	0.5

Schneider, 2010

Size distributions

- Divided by the channel widths… (better)



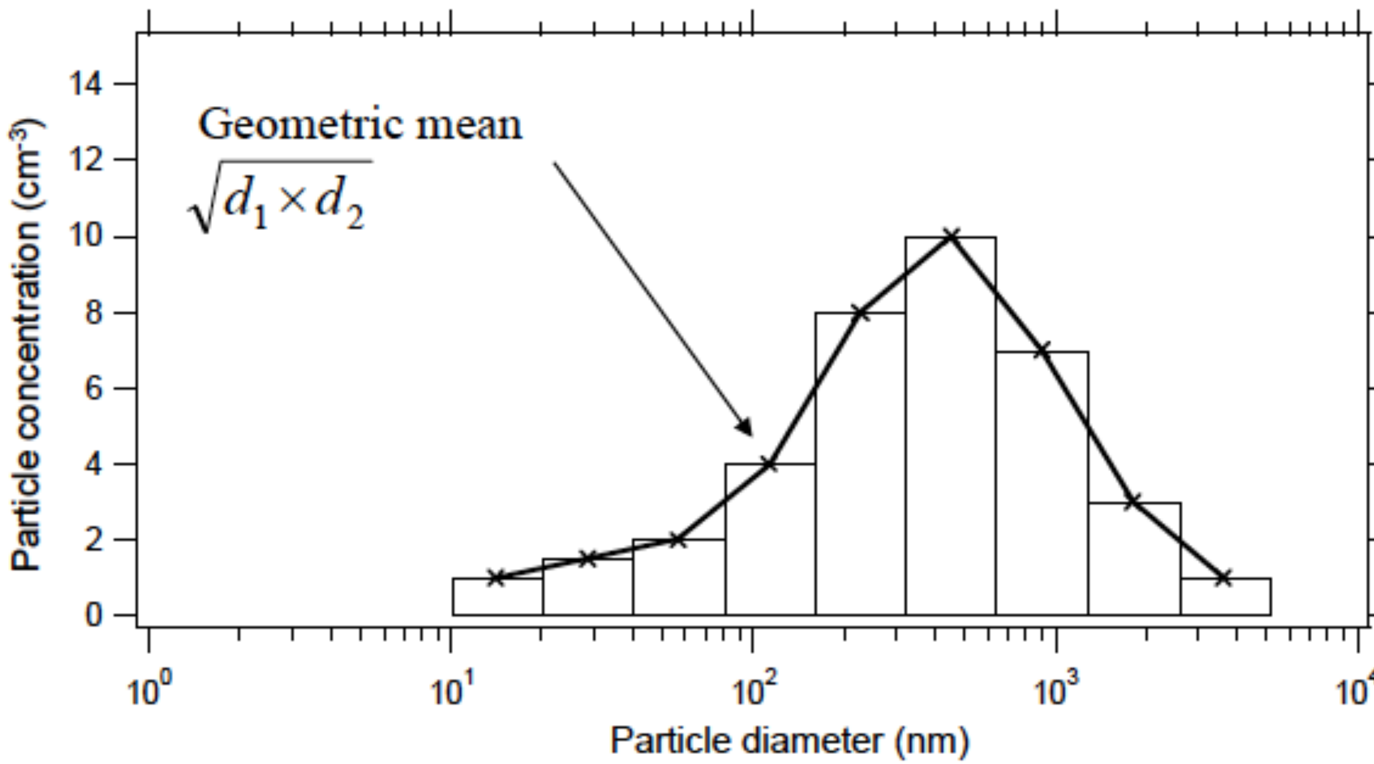
Almost the same distribution despite different measurement channels for the two instruments

Schneider, 2010

Size distributions

- Since the size range of aerosol particles typically ranges over several orders of magnitude, we commonly use log scales for the x-axis (d_p)

Channel	N (cm^{-3})
10-20	1
20-40	1.5
40-80	2
80-160	4
160-320	8
320-640	10
640-1280	7
1280-2560	3
2560-5120	1



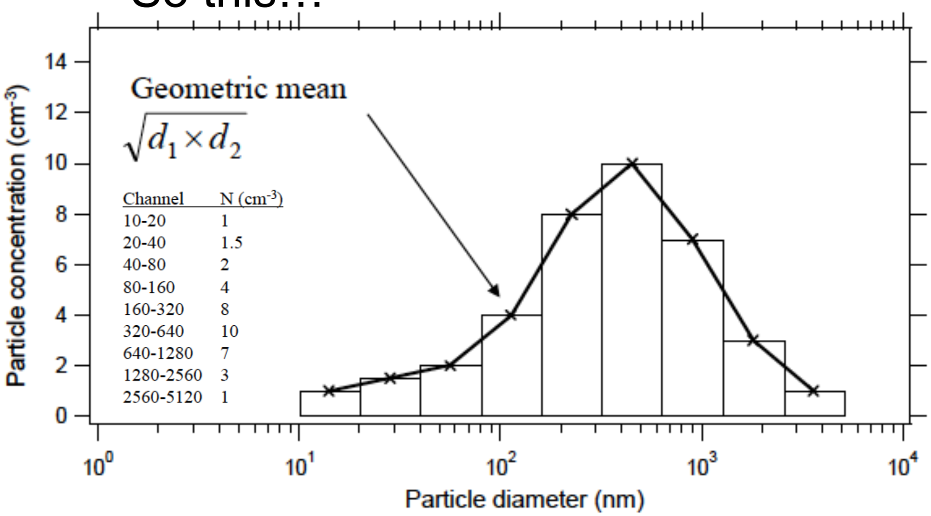
Schneider, 2010

Size distributions

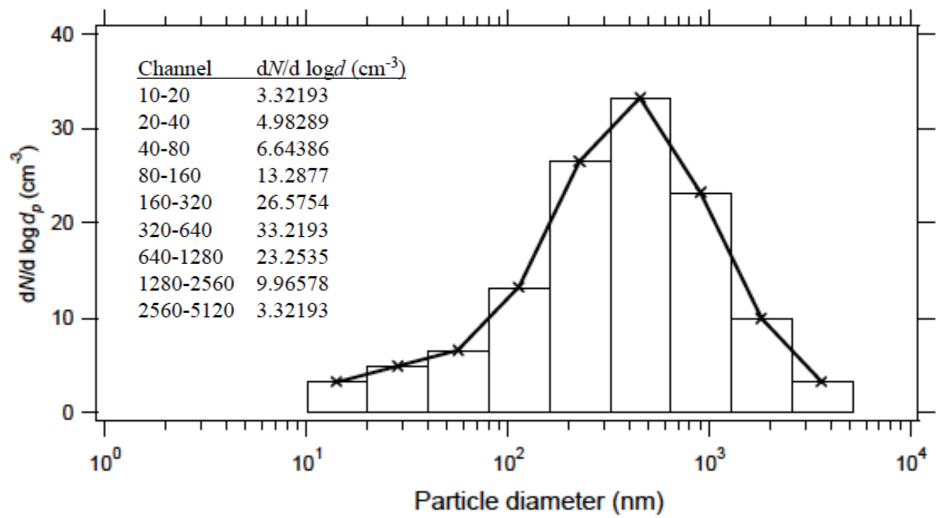
- For log scales we need to account for the channel width differently:

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

So this…



Becomes this…



We have transformed dN into dN/dlogd$_p$,
but the graphs scale similarly

Schneider, 2010

Number, surface area, volume, and mass distributions

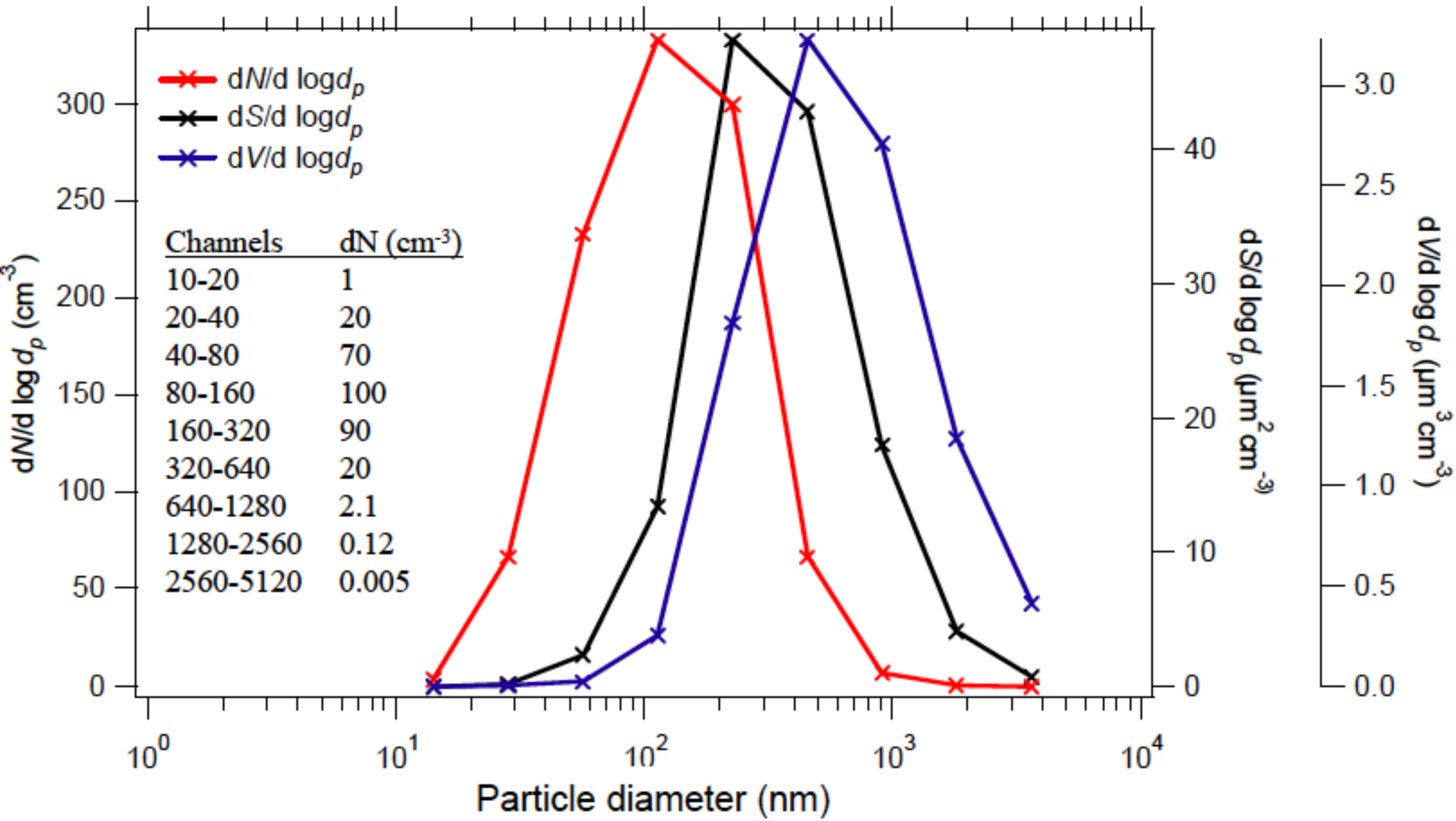
- Assuming spherical particles, the number concentration for each particle diameter can be converted to surface and volume concentrations:

- Surface area (µm2 per cm^3): $dS = \pi d_p^2 dN$

- Volume (µm^3 per cm^3): $dV = \frac{\pi}{6} d_p^3 dN$

- If we know particle density
  - We can estimate the mass distribution (µg per cm^3): $dM = \rho_p \frac{\pi}{6} d_p^3 dN$

Number, surface area, volume, and mass distributions



Schneider, 2010

Describing distributions with simple parameters

- Arithmetic mean particle diameter = 'count mean diameter'

$$CMD = d_{mean} = \bar{d}_p = \frac{1}{N_{tot}} \sum_{k=1}^{n} d_{p,k} N_k$$

n: number of size channels $d_{p,k}$: mean channel diameters,
N_k: number concentrations, N_{tot} : integrated number concentration.

- For continuous distribution $N(d_p)$:

$$\bar{d}_p = \frac{1}{N_{tot}} \int_0^{\infty} d_p N\left(d_p\right) \mathrm{d}d_p$$

- Geometric mean particle diameter (d_g)

$$\log d_g = \frac{1}{N_{tot}} \sum_{k=1}^{n} \log d_{p,k} N_k$$

Schneider, 2010

Describing distributions with simple parameters

- Atmospheric aerosols are often described by a lognormal distribution
  - Allows for characterization of an aerosol with only 3 parameters
- Normal distribution:

$$n(x) = \frac{N}{\sqrt{2\pi}\sigma} e^{\left(-\frac{(x-\bar{x})^2}{2\sigma^2}\right)}$$

- Lognormal distribution:

$$\frac{dN}{d\log d_p} = \frac{N}{\sqrt{2\pi}\log\sigma_g} e^{\left(-\frac{(\log d_p - \log \bar{d}_g)^2}{2(\log\sigma_g)^2}\right)}$$

  - Where:

N: Total particle number concentration

σ_g: Geometric standard deviation

$\bar{d}_g$: Geometric mean diameter: $\log \bar{d}_g = \frac{\sum n_i \log d_i}{N}$

d_g is in units of µm

$\ln(d_g)$ or $\log(d_g)$ is dimensionless

σ_g is dimensionless with a value greater than or equal to 1.0

Schneider, 2010

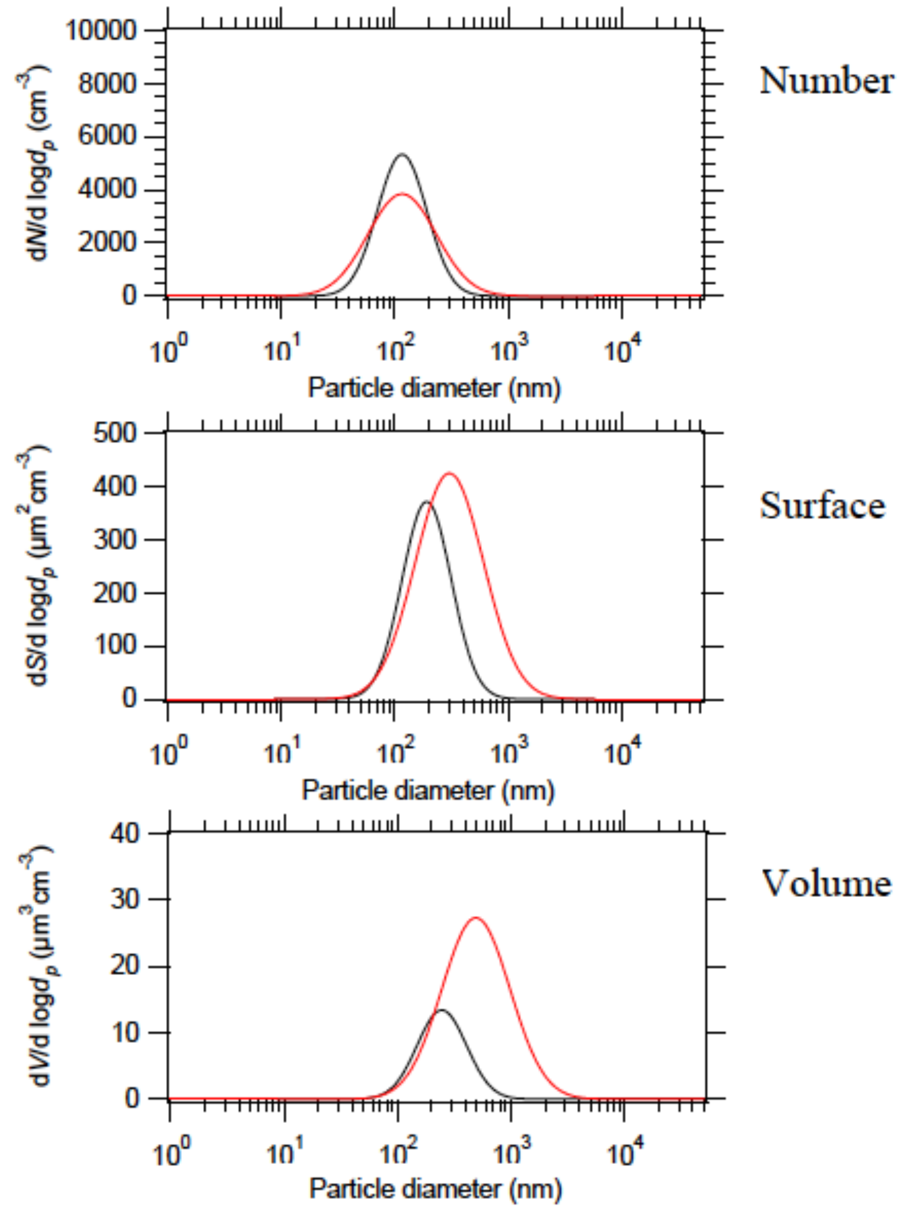
Lognormal distribution: dN, dS, and dV

- Example distribution for one 'mode':

$$N = 2900\ \mathrm{cm}^{-3}$$

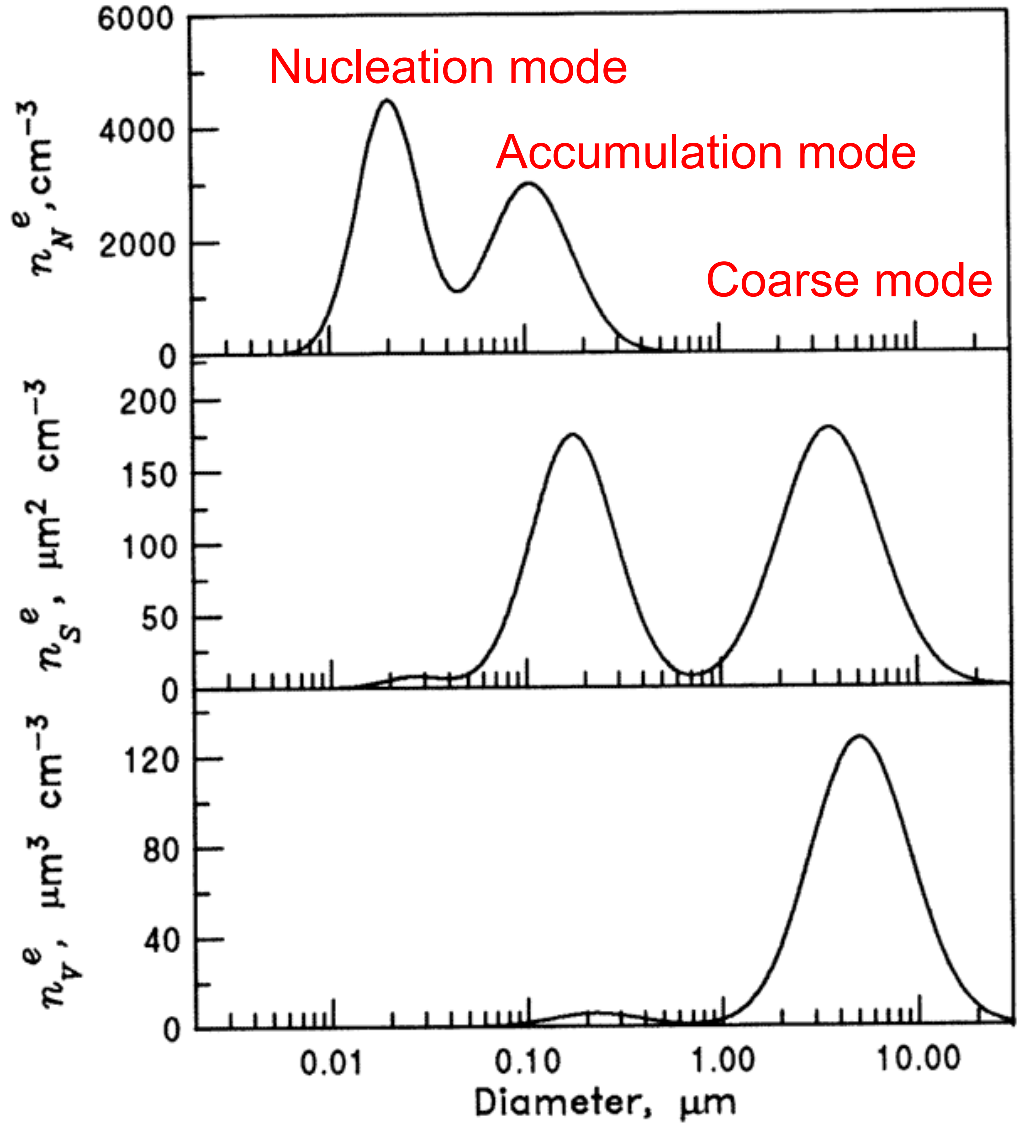
$$\cancel{\sigma_g = 1.65}\quad \sigma_g = 2.0$$

$$\bar{d}_g = 116\ \mathrm{nm}$$



Schneider, 2010

Typical aerosol distributions include multiple 'modes'



Lognormal distributions: summing across modes

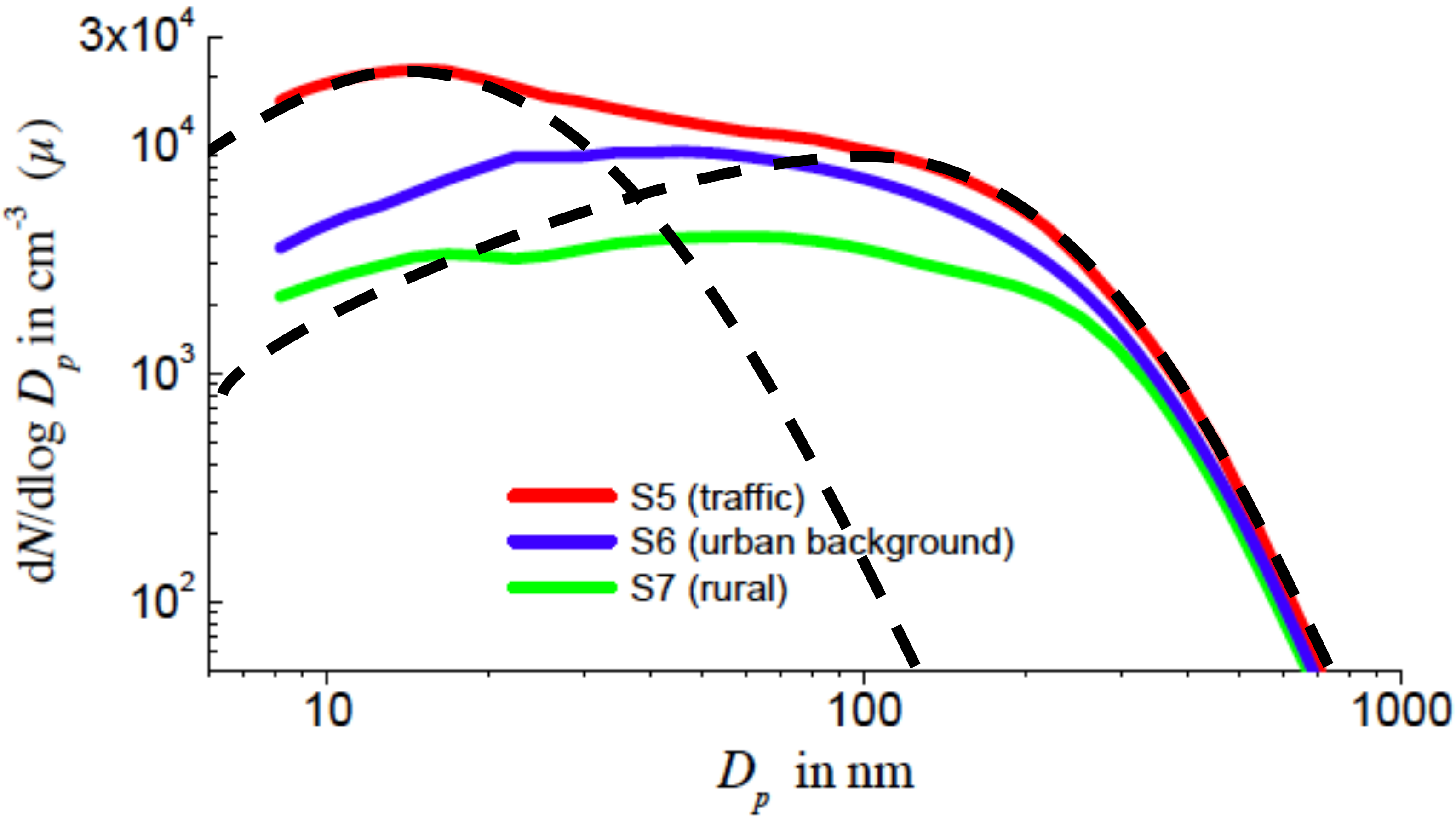
$$\frac{dN}{d\log d_p} = \sum_{i=1}^{n} \frac{N_i}{\sqrt{2\pi}\log\sigma_i} e^{\left(-\frac{(\log d_p - \log \bar{d}_{g,i})^2}{2(\log\sigma_i)^2}\right)}$$

	Mode I			Mode II			Mode III		
Type	N (cm^{-3})	D_p (μm)	$\log\sigma$	N (cm^{-3})	D_p (μm)	$\log\sigma$	N (cm^{-3})	D_p (μm)	$\log\sigma$
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).

Typical aerosol distributions

- Submicron particles outdoors in 3 locations in Germany



Costabile et al. 2009 *Atmos Chem Phys*

RESPIRATORY DEPOSITION

Why are we so concerned about particle size?

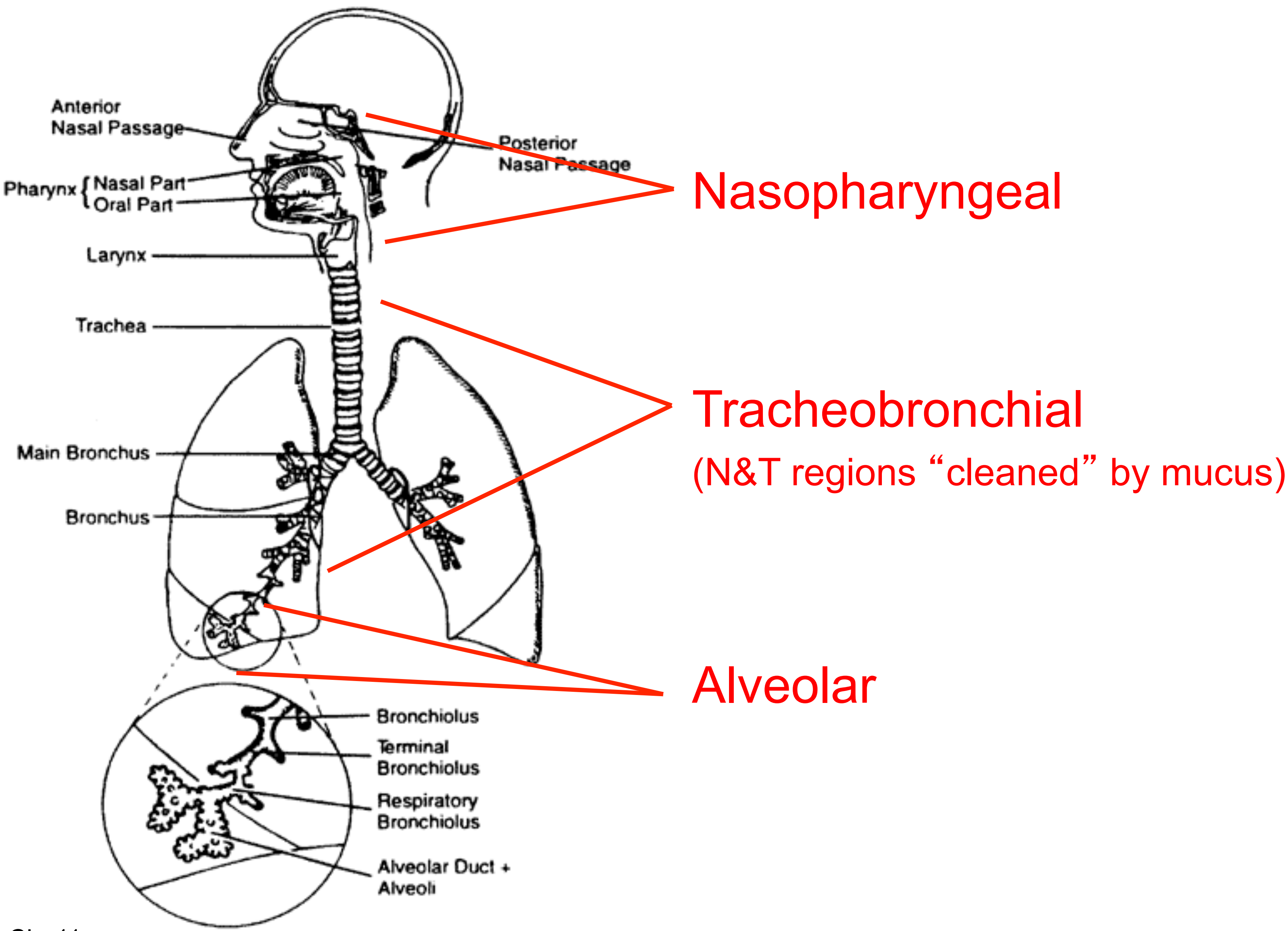
- One reason is because particles of different sizes deposit in different areas of our respiratory system with different efficiencies

- Humans breathe 10-25 m^3/day
  ~0.5 L/breath at rest
  ~12 breaths/minute at rest

- Surface area of lung devoted to gas exchange is ~75 m^2
  – ½ area of singles tennis court in alveolar region

- Velocities range from cm/s to mm/s

Human respiratory system



Hinds, 1999 Ch. 11

Lung parameters

TABLE 11.1 Characteristics of Selected Regions of the Lung[a]

Airway	Generation	Number per Generation	Diameter (mm)	Length (mm)	Total Cross Section (cm^2)	Velocity[a] (mm/s)	Residence Time[b] (ms)
Trachea	0	1	18	120	2.5	3900	30
Main bronchus	1	2	12	48	2.3	4300	11
Lobar bronchus	2	4	8.3	19	2.1	4600	4.1
Segmental bronchus	4	16	4.5	13	2.5	3900	3.2
Bronchi with cartilage in wall	8	260	1.9	6.4	6.9	1400	4.4
Terminal bronchus	11	2000	1.1	3.9	20	520	7.4
Bronchioles with muscles in wall	14	16,000	0.74	2.3	69	140	16
Terminal bronchiole	16	66,000	0.60	1.6	180	54	31
Respiratory bronchiole	18	0.26×10^6	0.50	1.2	530	19	60
Alveolar duct	21	2×10^6	0.43	0.7	3200	3.2	210
Alveolar sac	23	8×10^6	0.41	0.5	72,000	0.9	550
Alveoli		300×10^6	0.28	0.2			

[a]Based on Weibel's model A; regular dichotomy average adult lung with volume. 0.0048 m^3 [4800 cm^3] at about three-fourths maximal inflation. Table adapted from Lippmann (1995).
[b]At a flow rate of 3.6 m^3/hr [1.0 L/s].

Note: based on steady flow

Hinds, 1999 Ch. 11

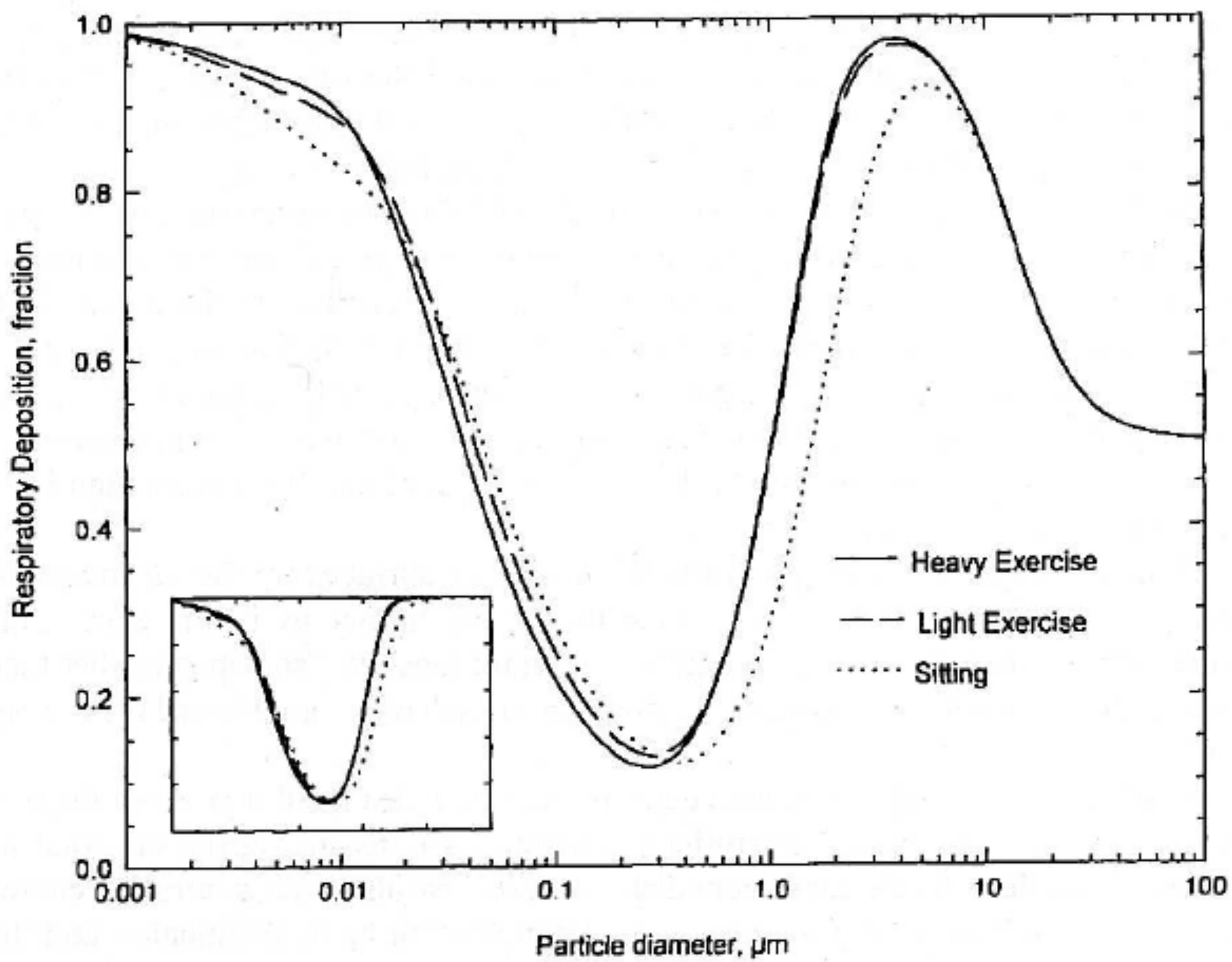
Particle deposition in lungs

- Similar to other systems
  - Diffusion, settling, impaction are primary
  - Can neglect minor electrostatic forces

- Challenges
  - Flow field is developing and unsteady
  - Particles are growing (humidification)

Total respiratory deposition

- Based on ICRP model, average for males/females
  - ICRP = International Commission on Radiological Protection



Hinds, 1999 Ch. 11

Respiratory deposition by region

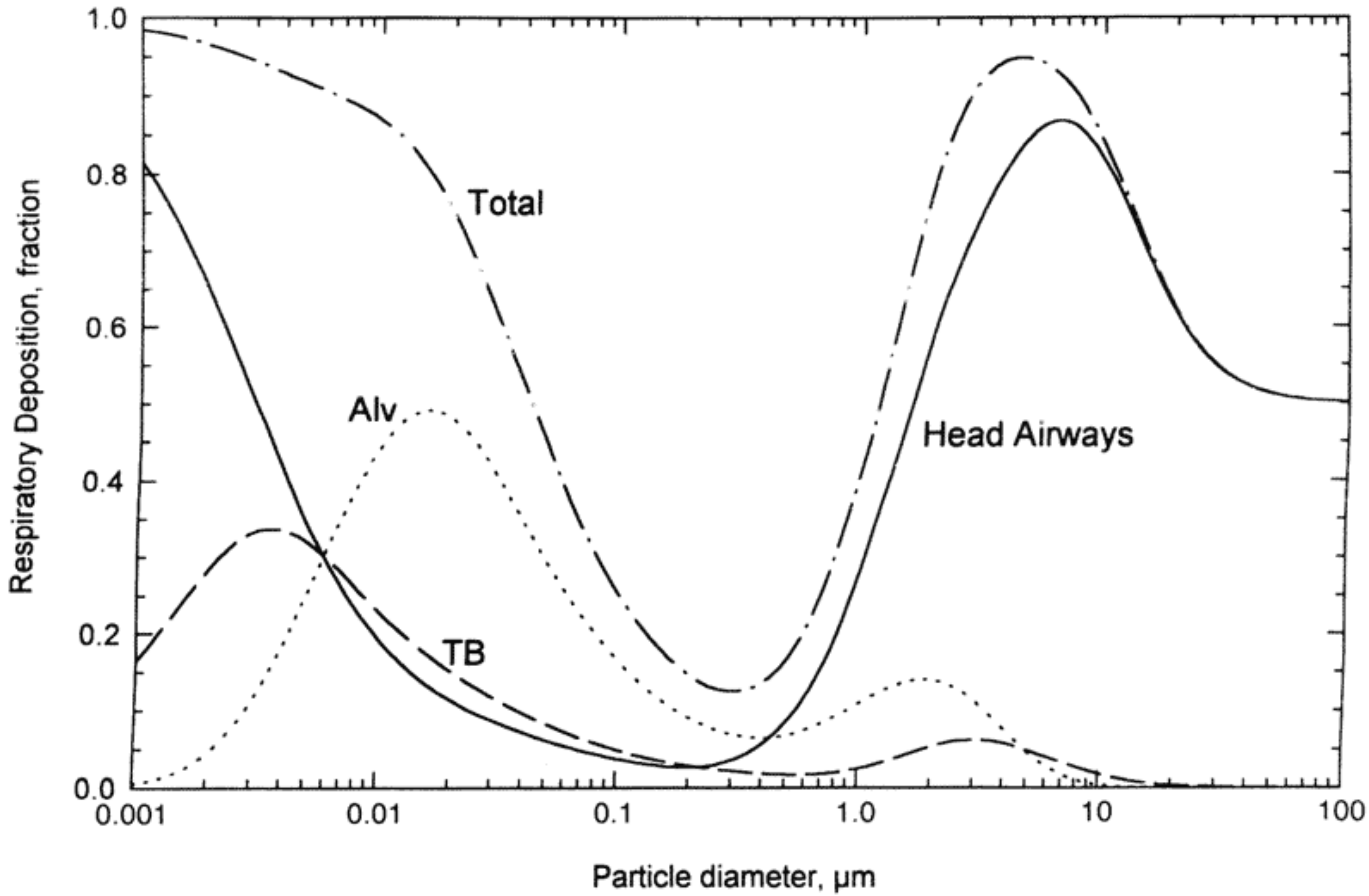
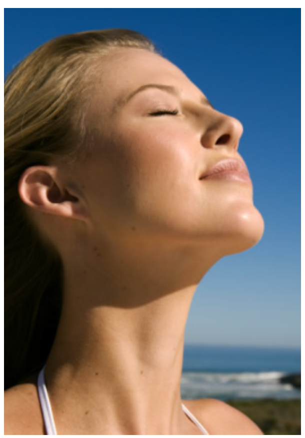


FIGURE 11.3 Predicted total and regional deposition for light exercise (nose breathing) based on ICRP deposition model. Average data for males and females.

Hinds, 1999 Ch. 11

Alveolar deposition by breathing type

Depends on whether you're a nose breather or a mouth breather!



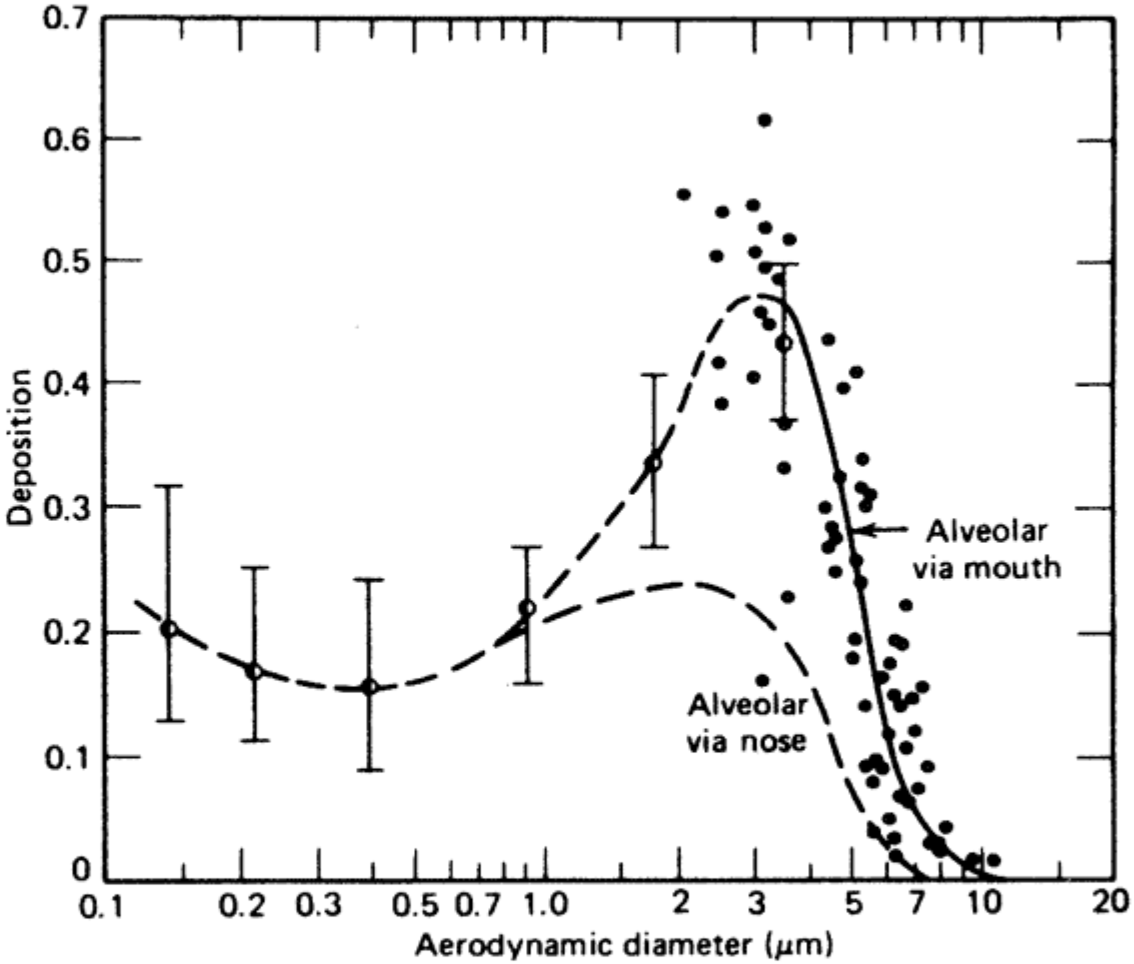


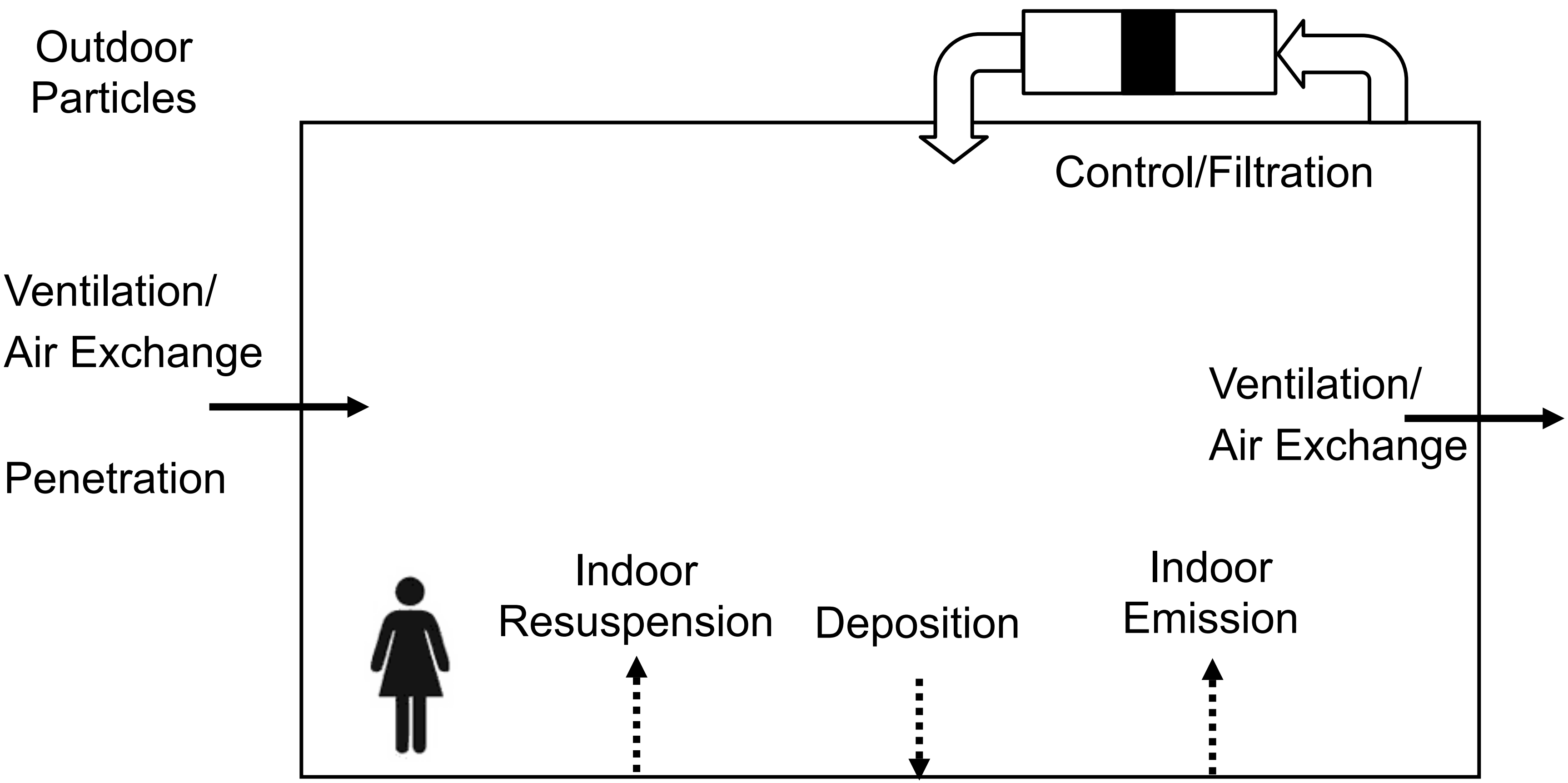
FIGURE 11.4 Experimental data for deposition in the alveolar region. Deposition is expressed as a fraction of mouthpiece inhalation versus aerodynamic diameter (geometric diameter used below 0.5 μm). Reprinted with permission from Lippmann (1977).

Hinds, 1999 Ch. 11

So what?

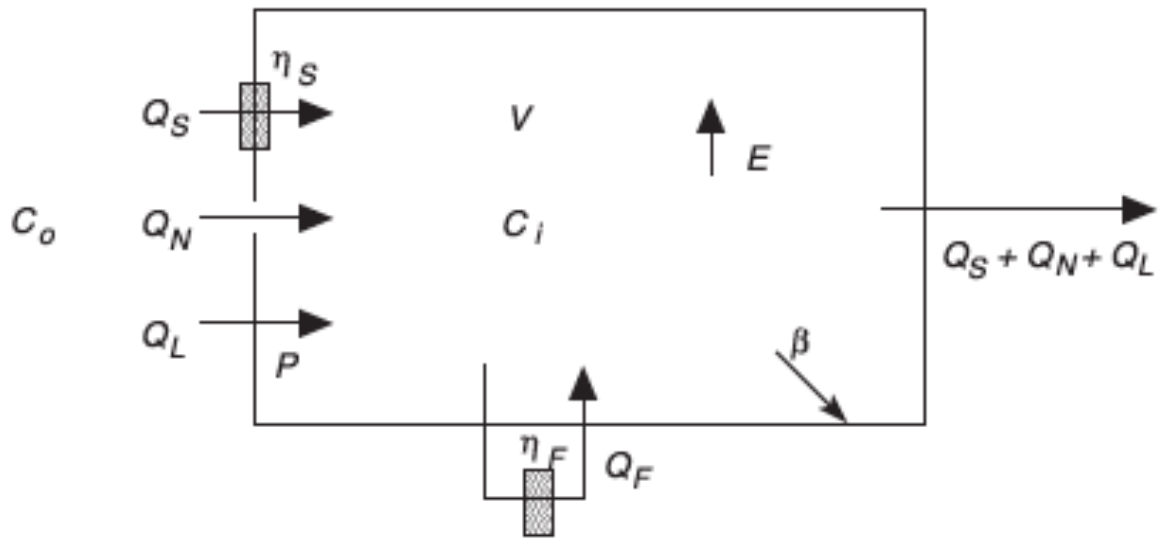
- We now understand more about particle sizes
  - And how different size particles deposit in different regions of our respiratory system
- We can examine different sources to determine their sizes
  - e.g., ETS or cooking particles
- And we can examine what particles will deposit in lungs?
  - And in which region?
- Helps elucidate health effects that may be observed

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

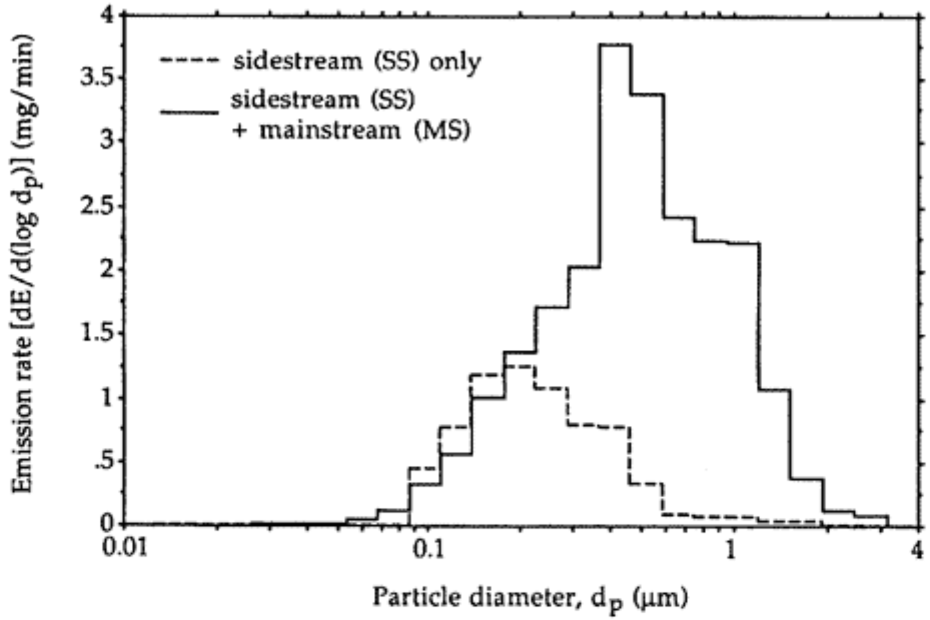
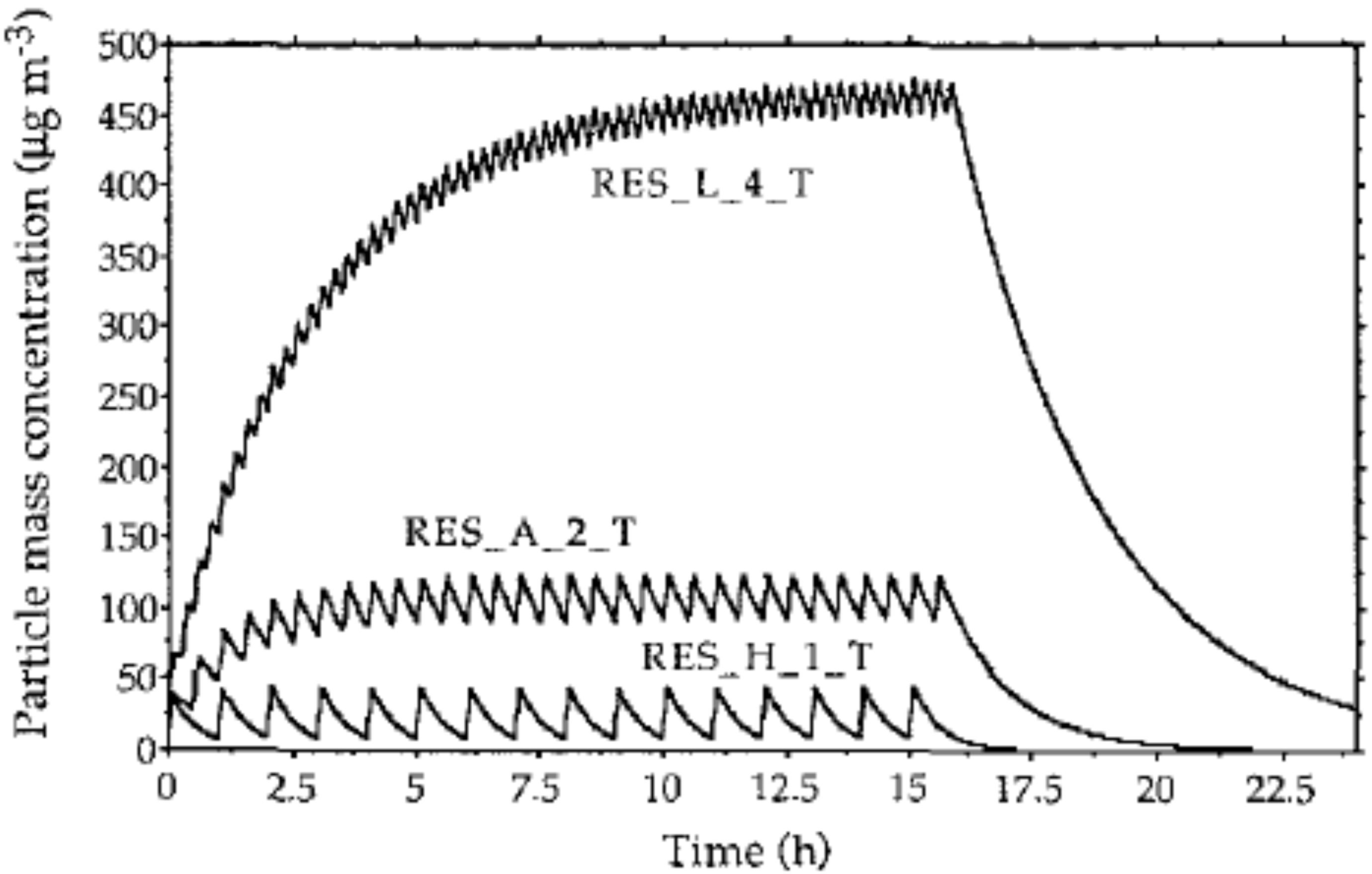


FIGURE 1. Effective particle emission rate from a burning cigarette as a function of particle diameter. The form of the figure is such that the area under a curve between two particle sizes is proportional to the mass emission rate of all particles within those size limits. These experiments were reported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

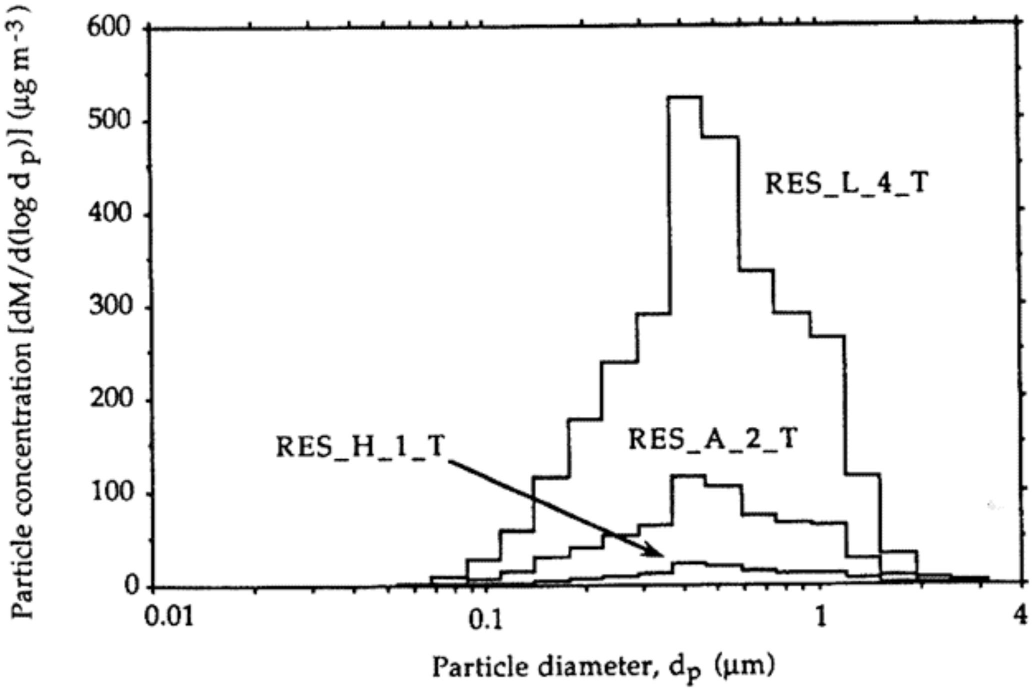


FIGURE 4. Average environmental tobacco smoke particle size distribution over 24-h period for three residential simulations corresponding

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**

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Nazaroff et al., 1993 *AS&T*

ETS lung deposition

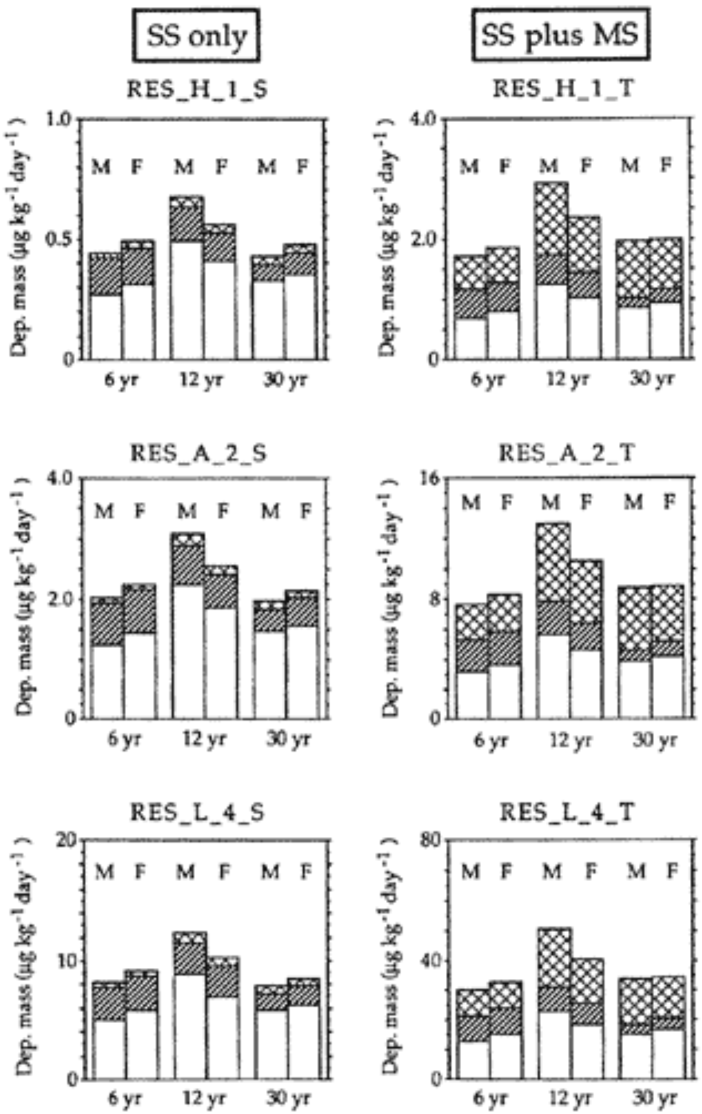
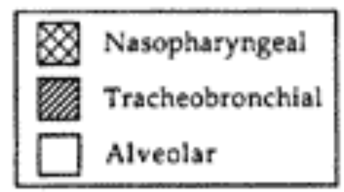
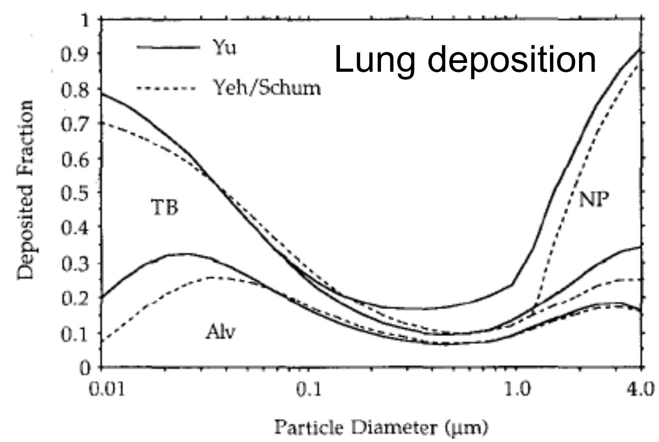


FIGURE 5. Regional lung deposition of environmental tobacco smoke particles from simulations of residential exposure. Each frame shows results for three age groups and each gender for one combination of smoking rate, particle emission profile, and building ventilation rate. The height of each bar gives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

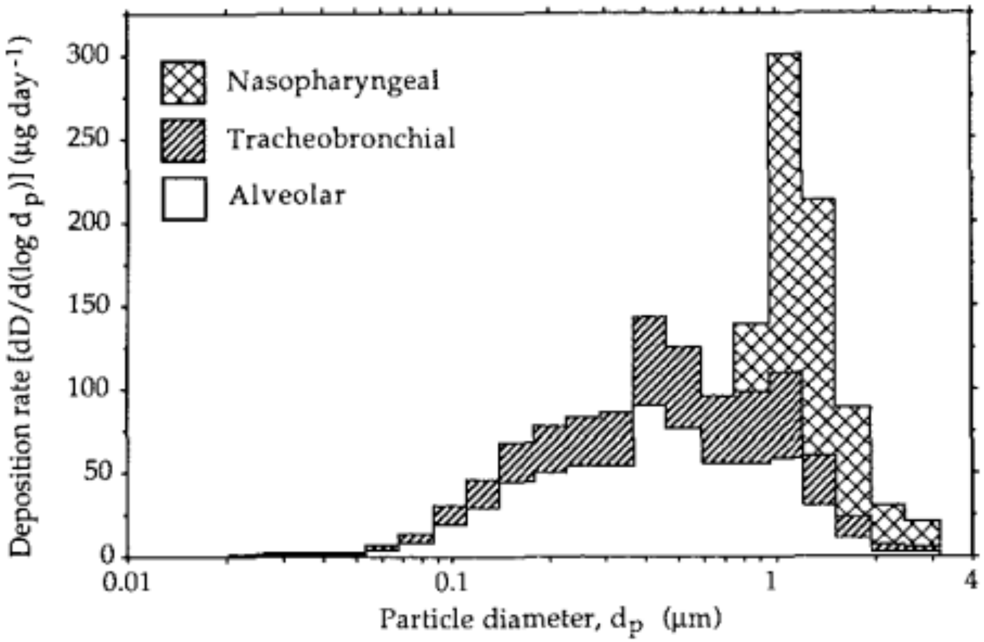
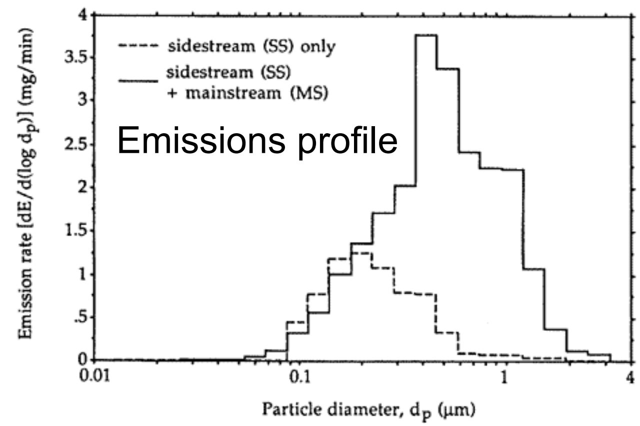
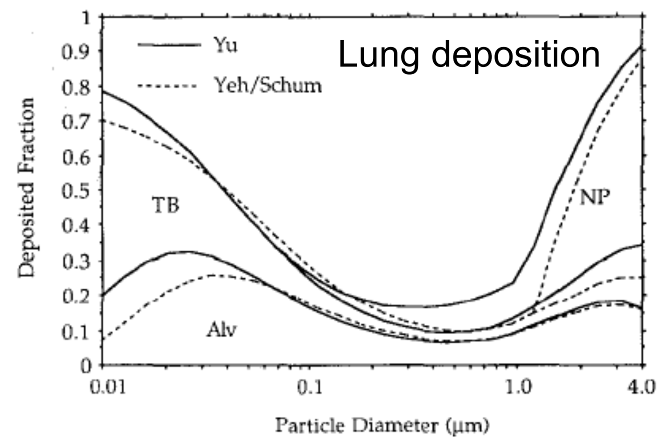


FIGURE 6. Size distribution of deposited mass of environmental tobacco smoke particles in 6-year-old boy for simulation RES_A_2_T. The form of the figure is such that the shaded area between two particle sizes is proportional to the average 24-h mass deposition rate of particles within those size limits.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





Nazaroff et al., 1993 *AS&T*

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

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

- Ultrafine (<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*

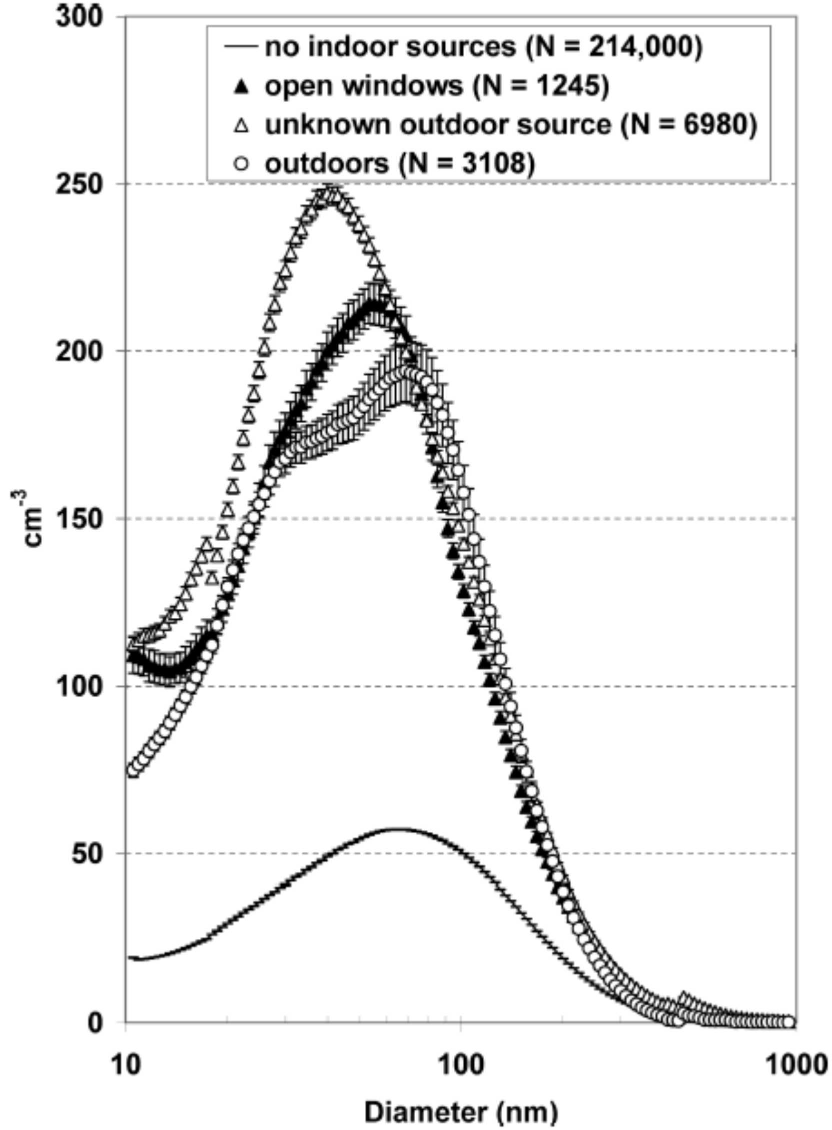
Indoor particle sources

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

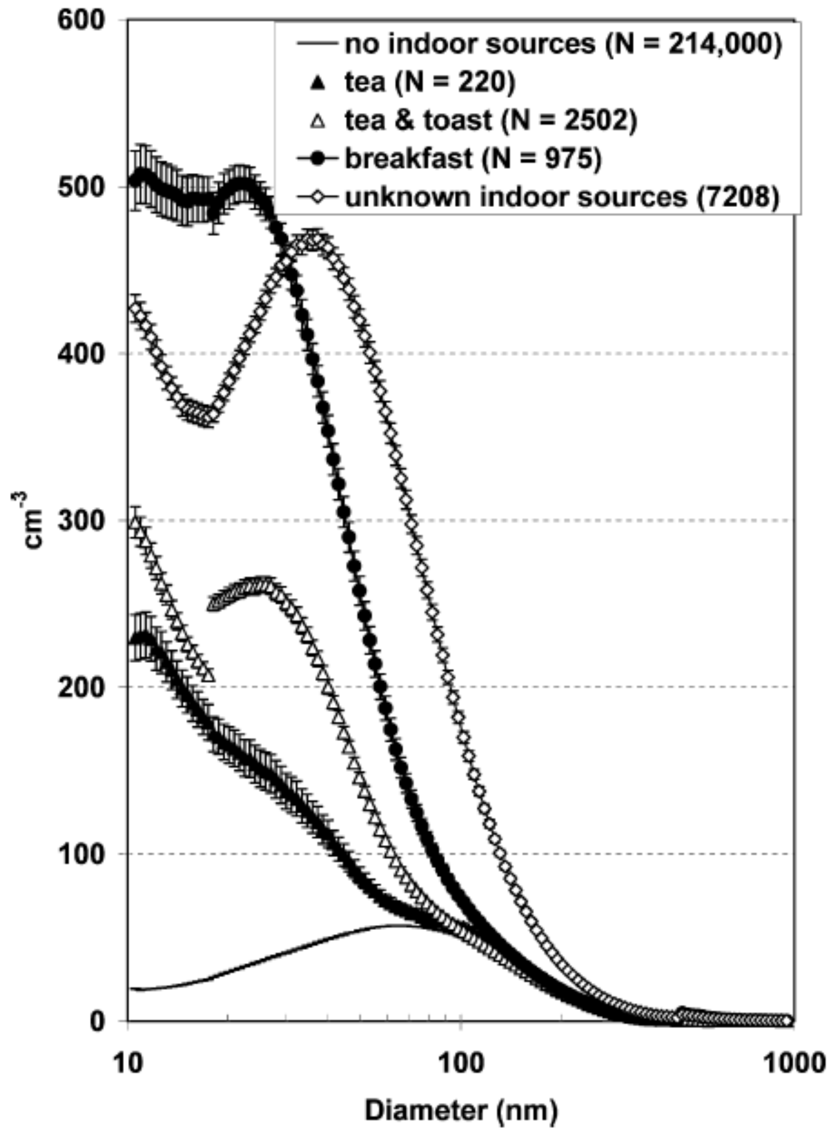
Wallace, 2006 *Aerosol Sci Technol*

Indoor particle sources



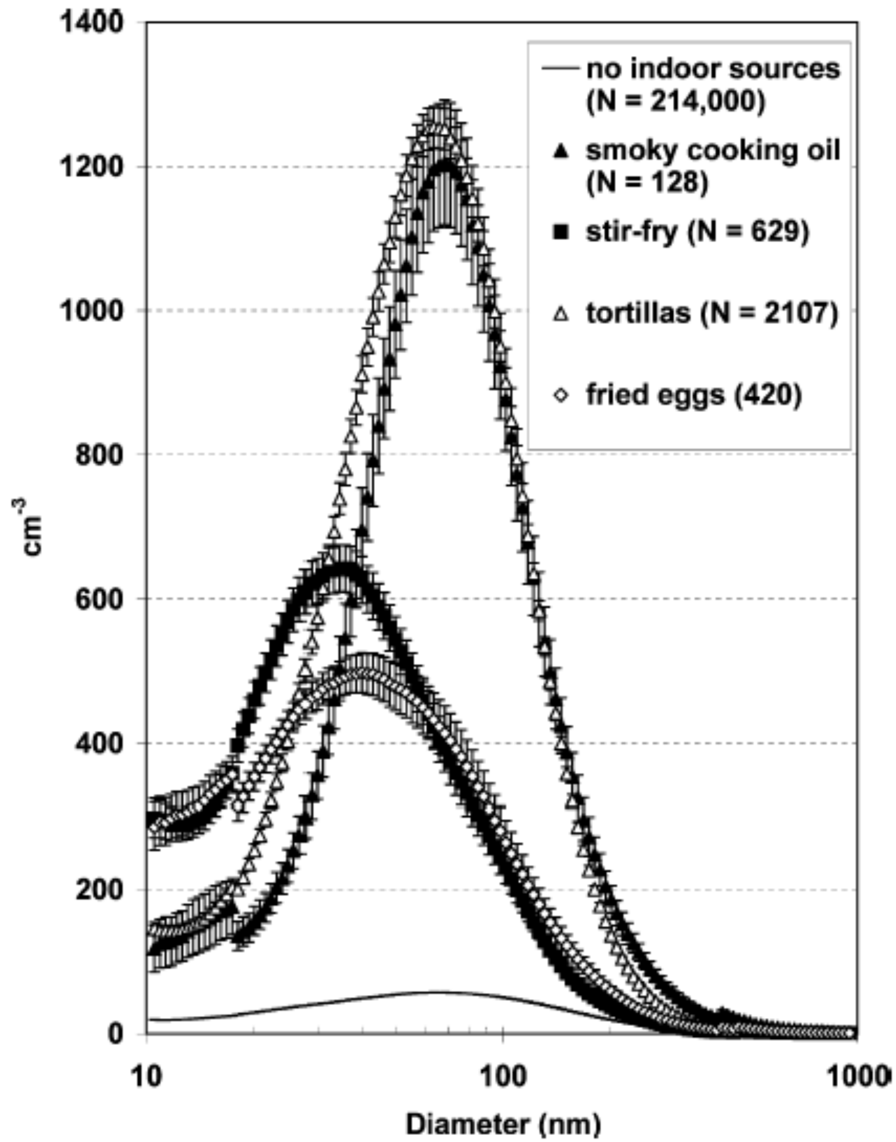
Wallace, 2006 *Aerosol Sci Technol*

Indoor particle sources



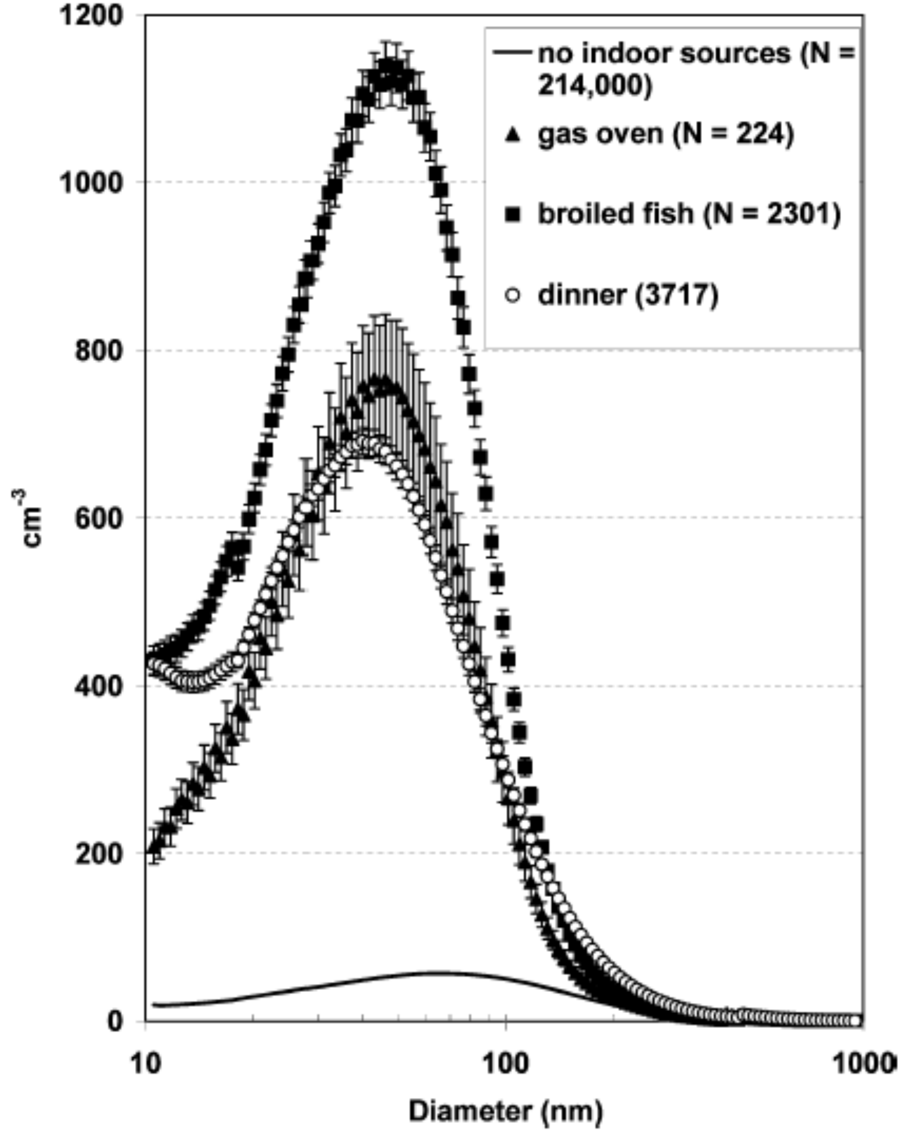
Wallace, 2006 *Aerosol Sci Technol*

Indoor particle sources



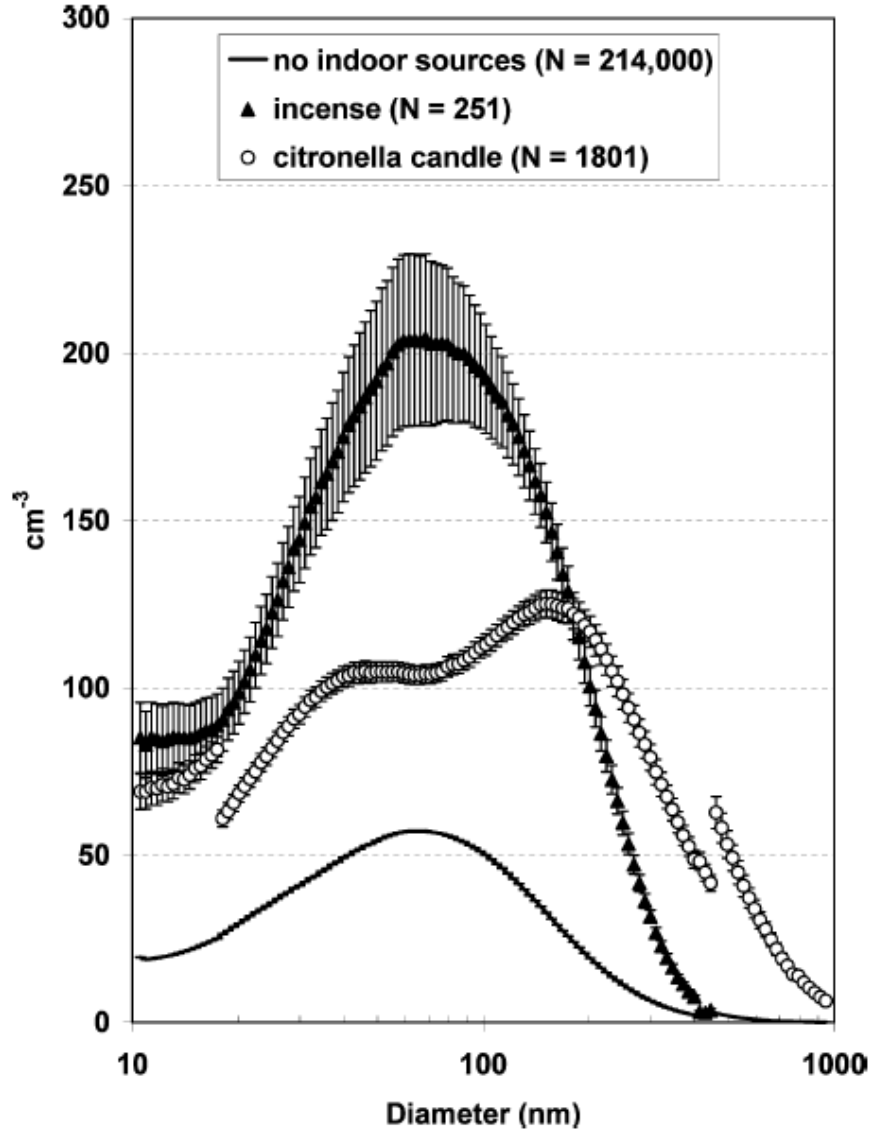
Wallace, 2006 *Aerosol Sci Technol*

Indoor particle sources



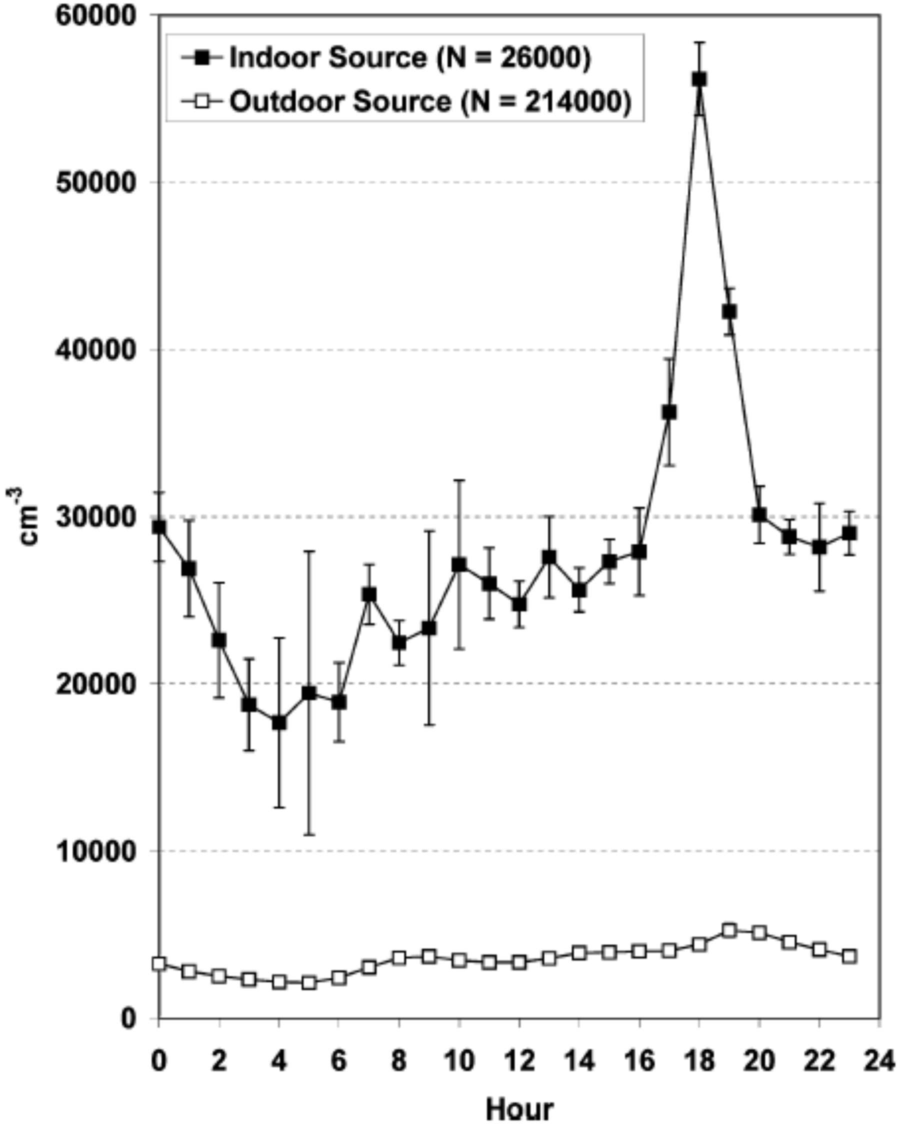
Wallace, 2006 *Aerosol Sci Technol*

Indoor particle sources



Wallace, 2006 *Aerosol Sci Technol*

Indoor particle sources

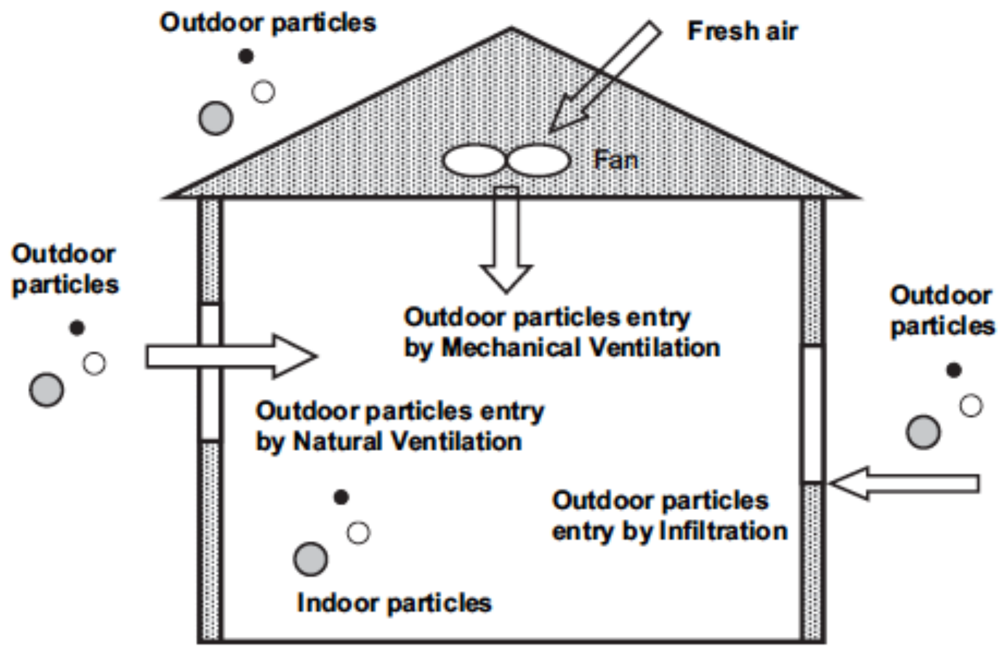


Wallace, 2006 *Aerosol Sci Technol*

Indoor/outdoor particle sources

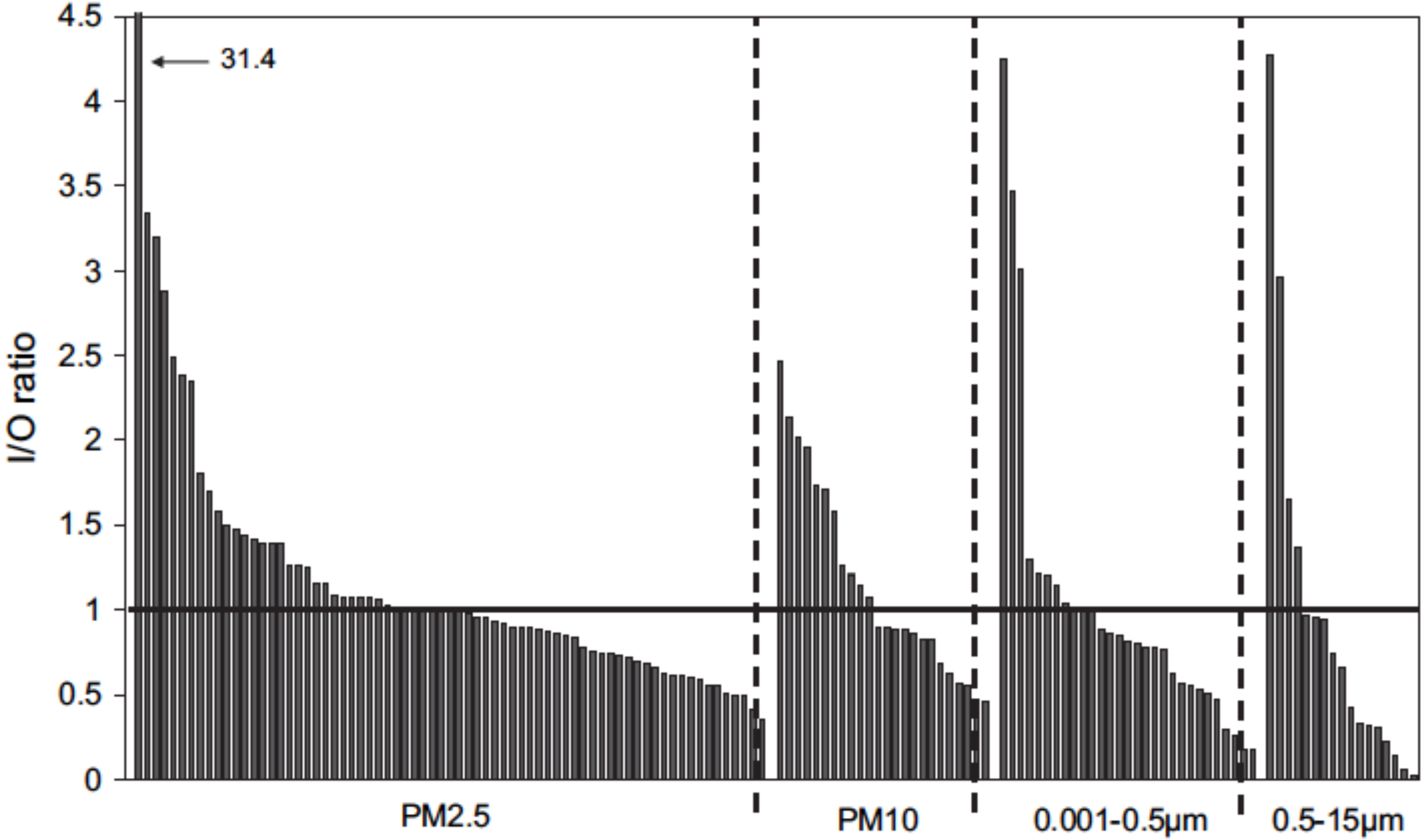
Review of relationship between indoor and outdoor particles: I/O ratio, infiltration factor and penetration factor

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



Chen and Zhao, 2011 *Atmos Environ*

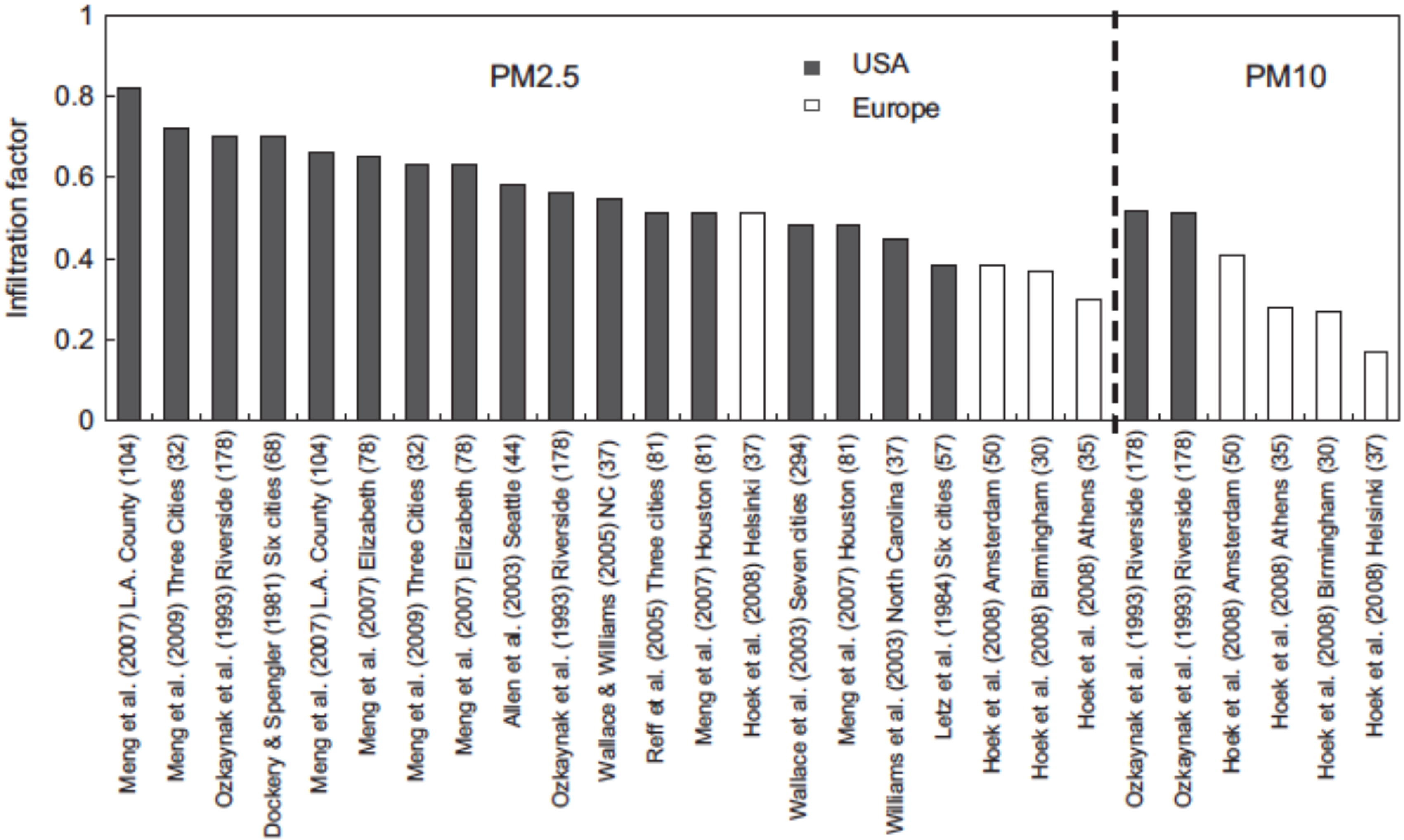
I/O particle ratios: combination of I and O sources



Chen and Zhao, 2011 *Atmos Environ*

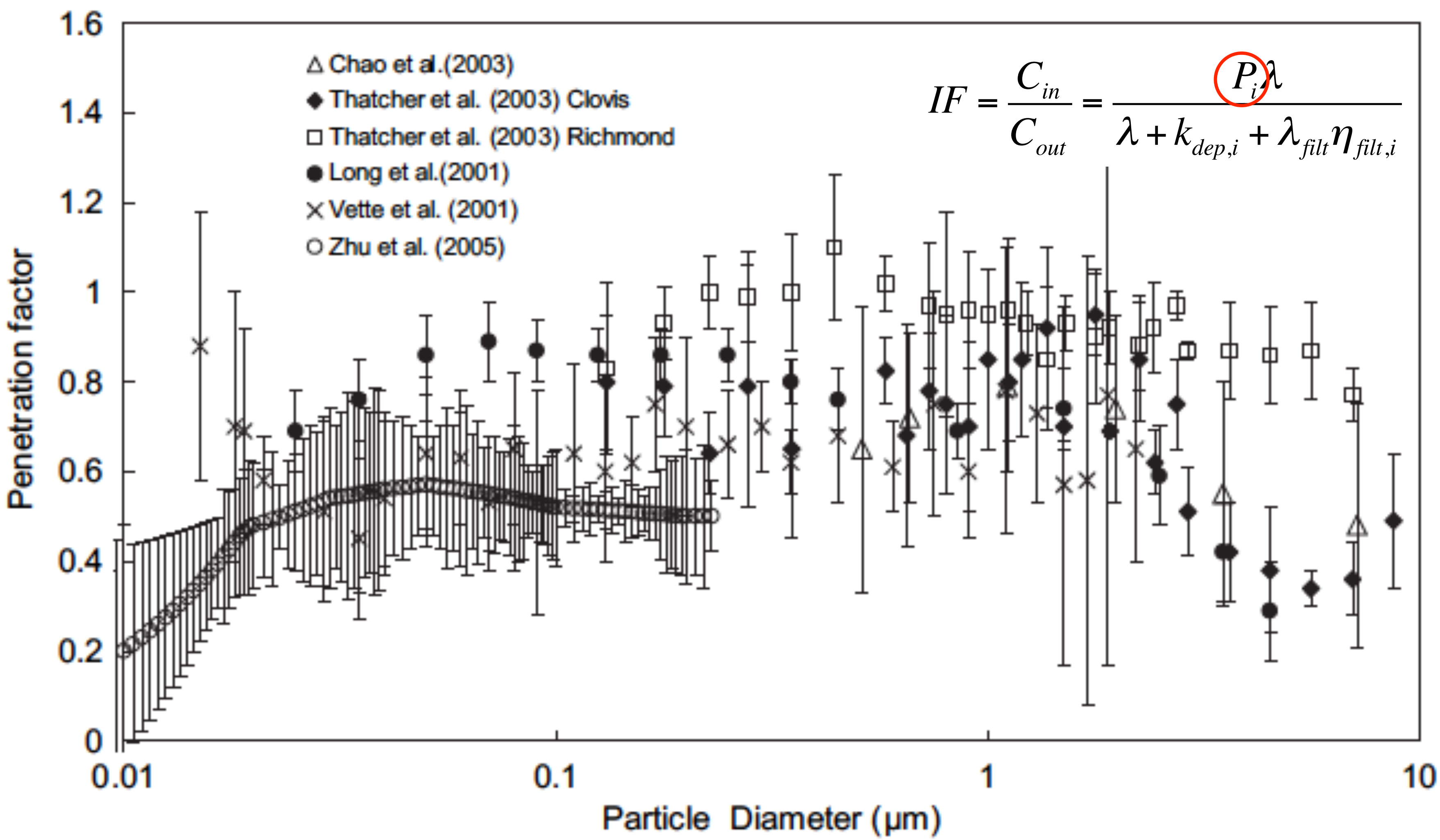
Outdoor particle sources: Infiltration factors

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



Chen and Zhao, 2011 *Atmos Environ*

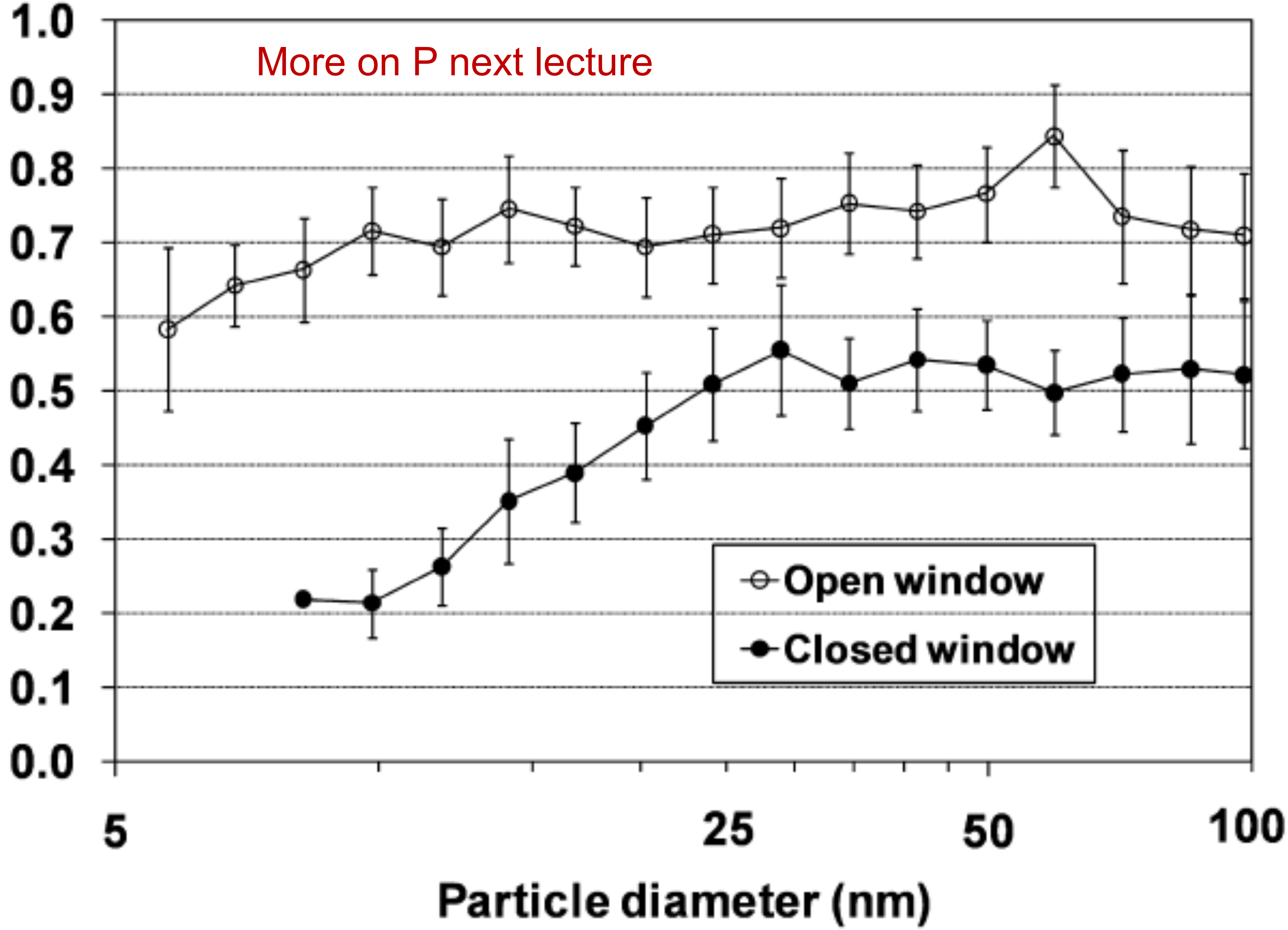
Outdoor particle sources: Penetration factor



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

Chen and Zhao, 2011 *Atmos Environ*

Outdoor particle sources: Penetration factor



Rim et al., 2010 *Environ Sci Technol*

RESUSPENSION AND DEPOSITION

Indoor source: Resuspension

- Early experiments noticed that indoor particle concentrations were elevated above background during human activities
  - We saw this last week when I was kicking the carpet near our OPC

- 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

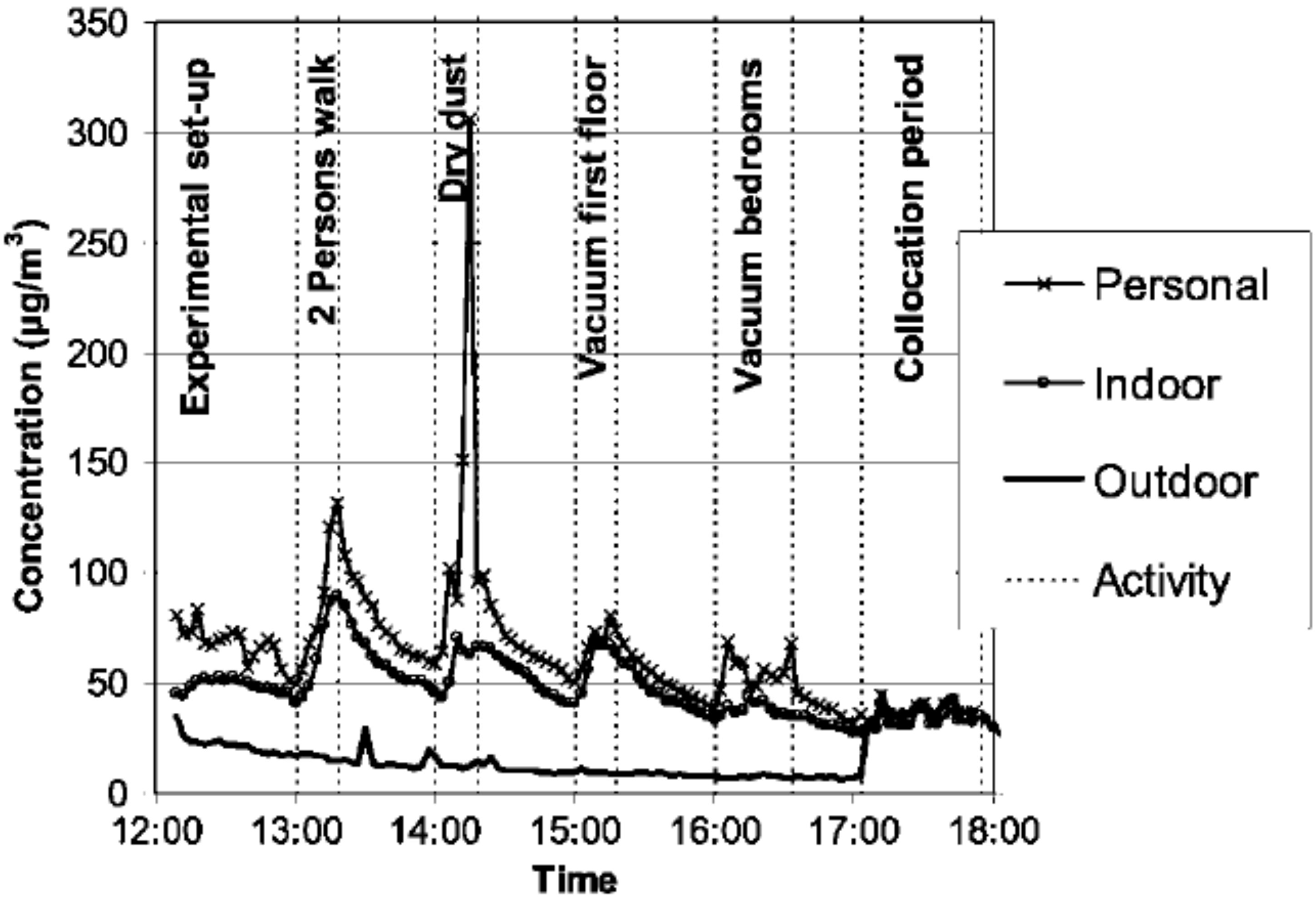
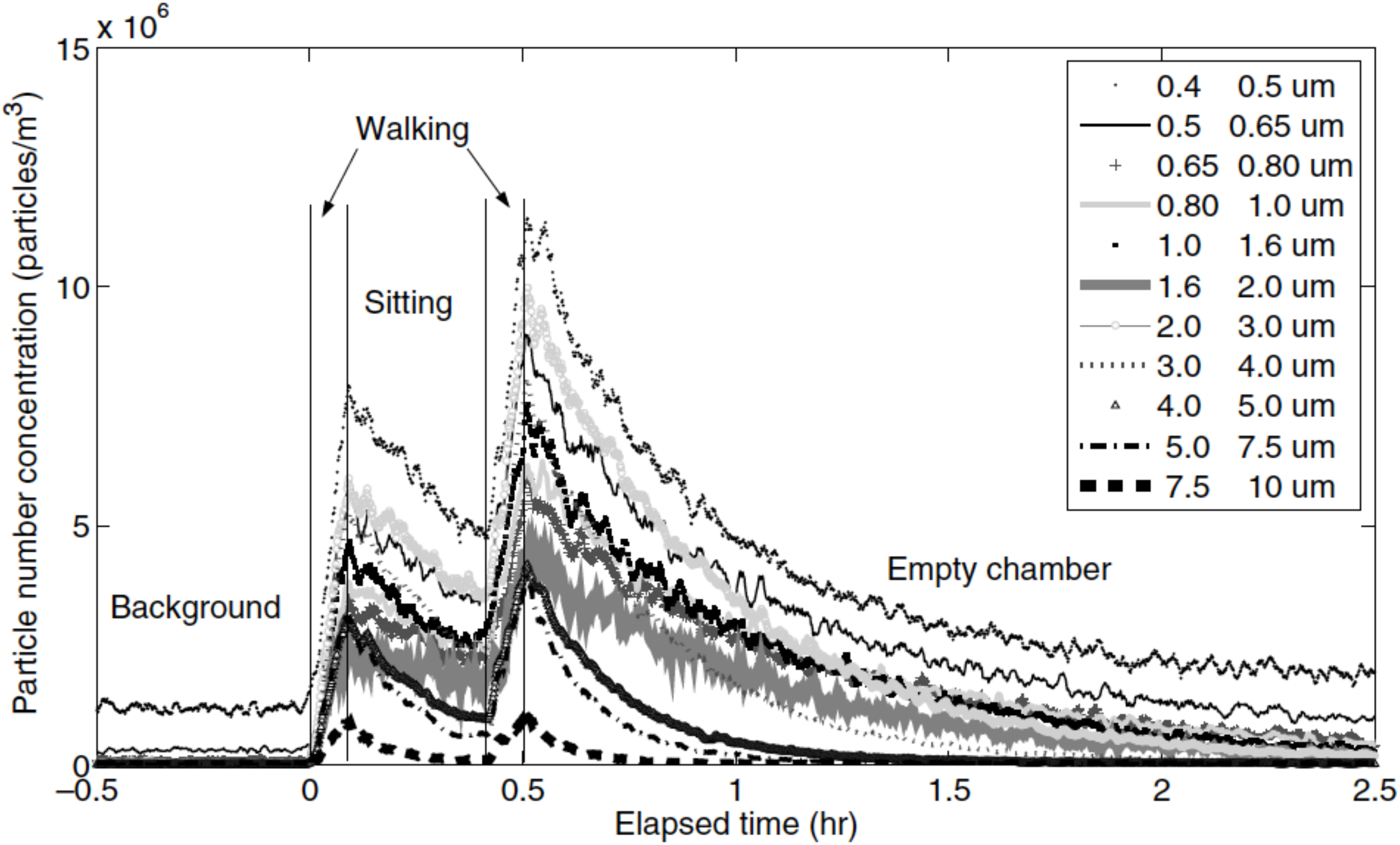


Figure 3. Personal, indoor, and outdoor PM_5 estimated mass concentration time series.

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

Indoor sources: Resuspension



Qian and Ferro, 2008 *Aerosol Sci Technol*

Indoor sources: Resuspension

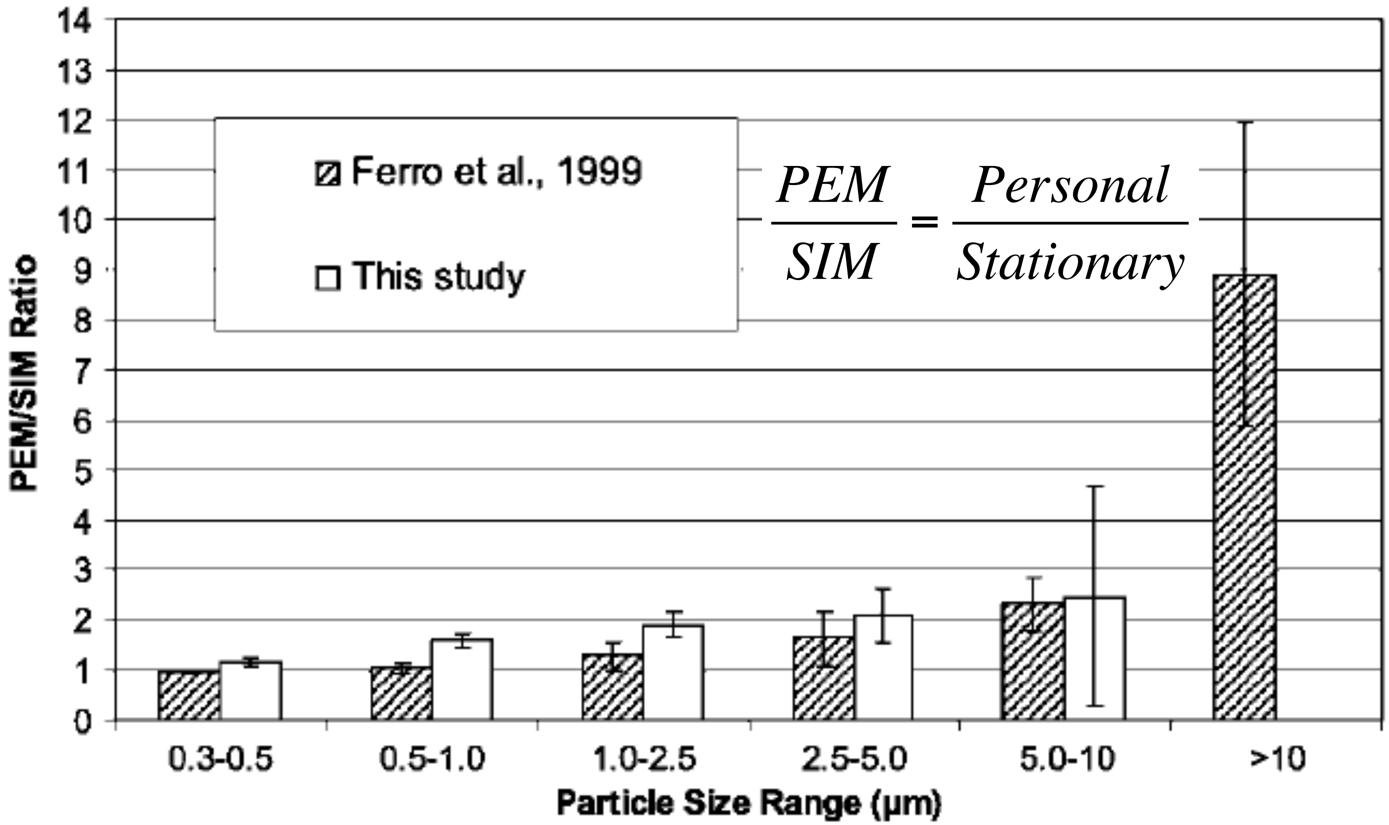


Figure 4. PEM/SIM ratio by particle size during human activity periods for two independent studies. Ferro et al. (1999) collected personal and indoor concentrations using Met-One Model 237B laser particle counters for six vacuuming experiments in a separate Redwood City, CA, USA, residence.

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)

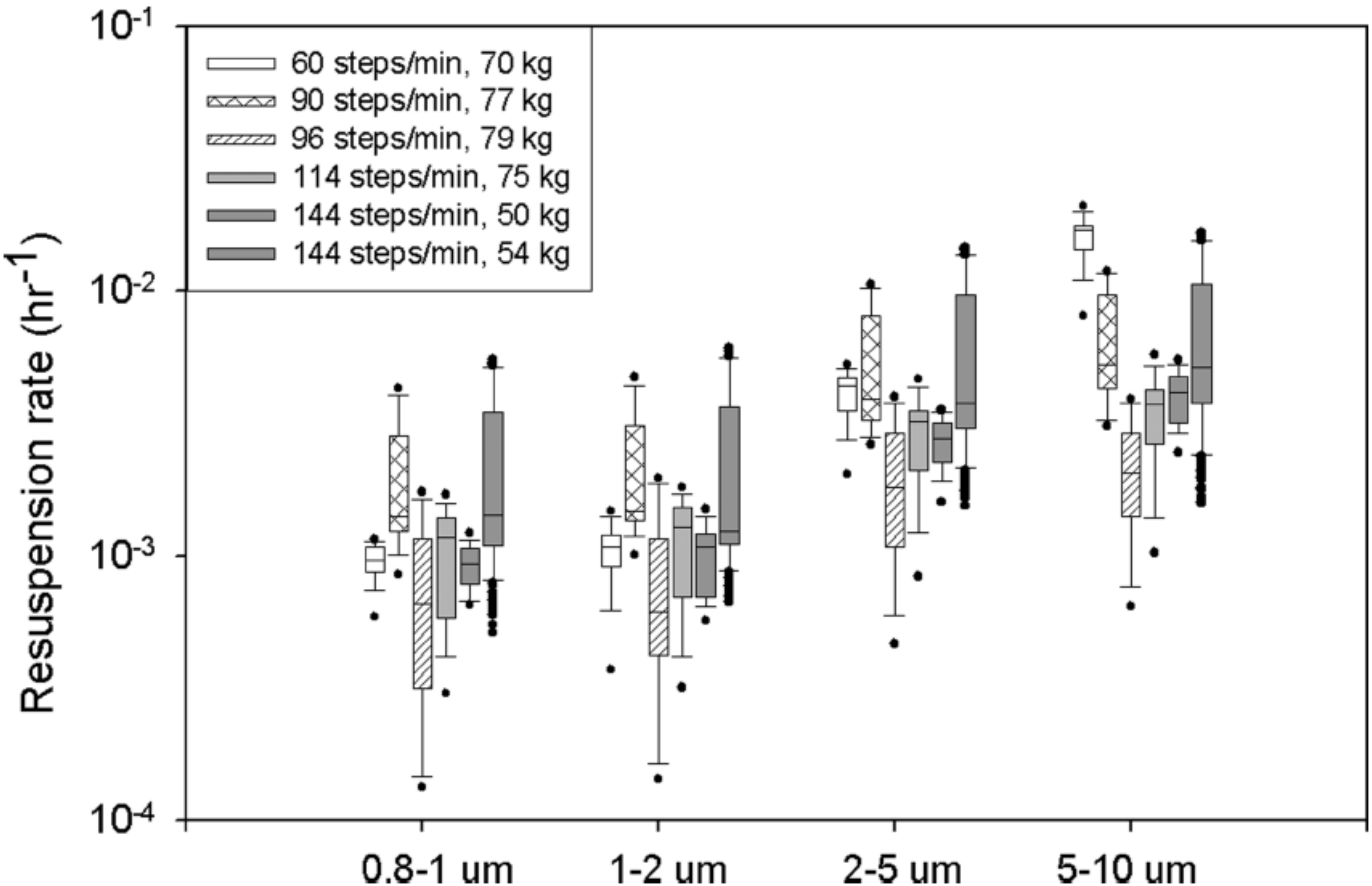
- And incorporate it into mass balance on indoor air:

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

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

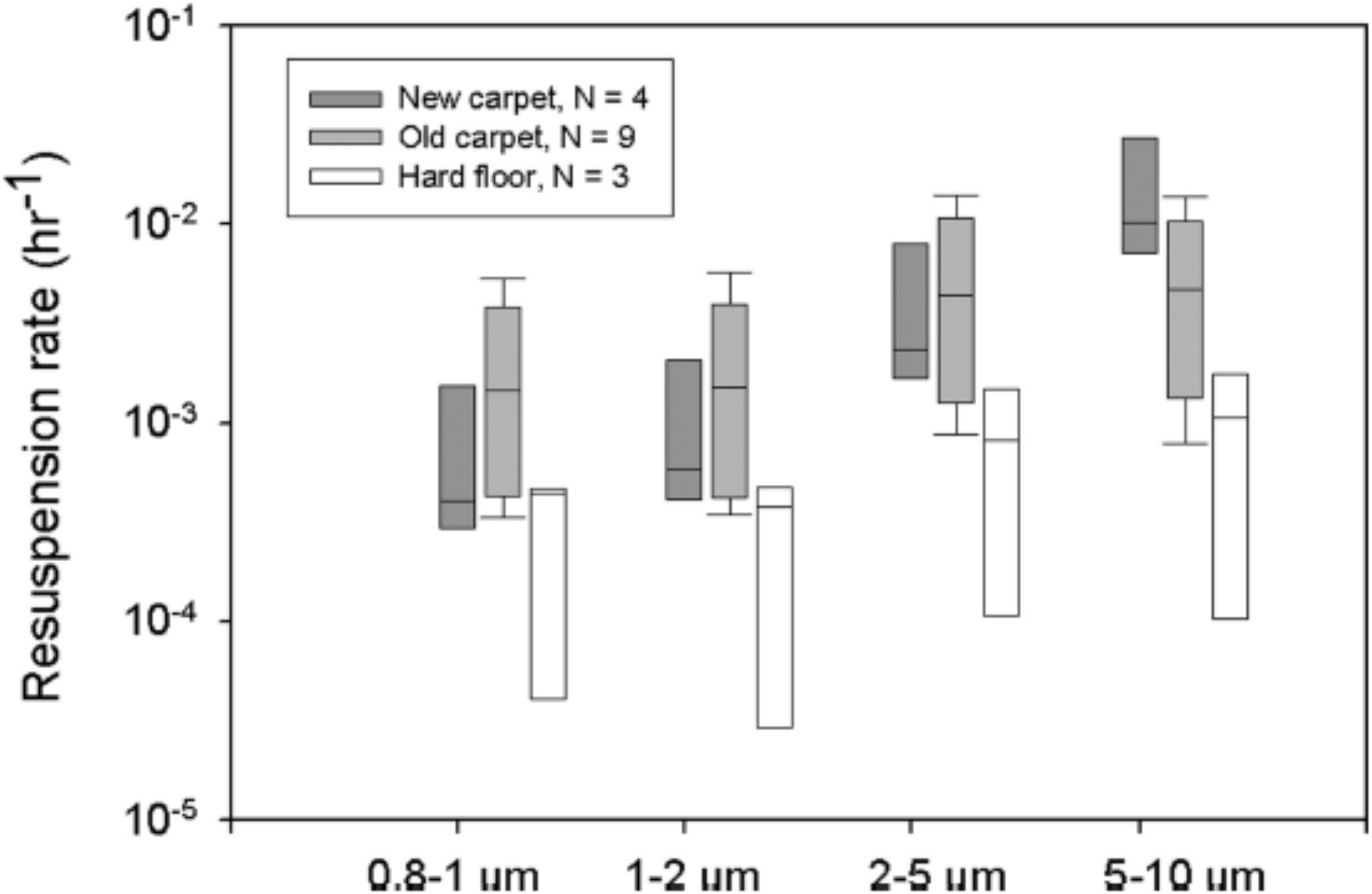
$$A\frac{dL_i}{dt} = k_{dep,i} C_i V - rAL + E_{track-in}$$

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 week
  - Primarily in terms of settling velocity
  - Also included diffusion, impaction, thermophoresis, and electrostatic forces

- I showed one of the first strong modeling efforts for size-dependent deposition in a room:
  - k_{dep} in units of 1/hr

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

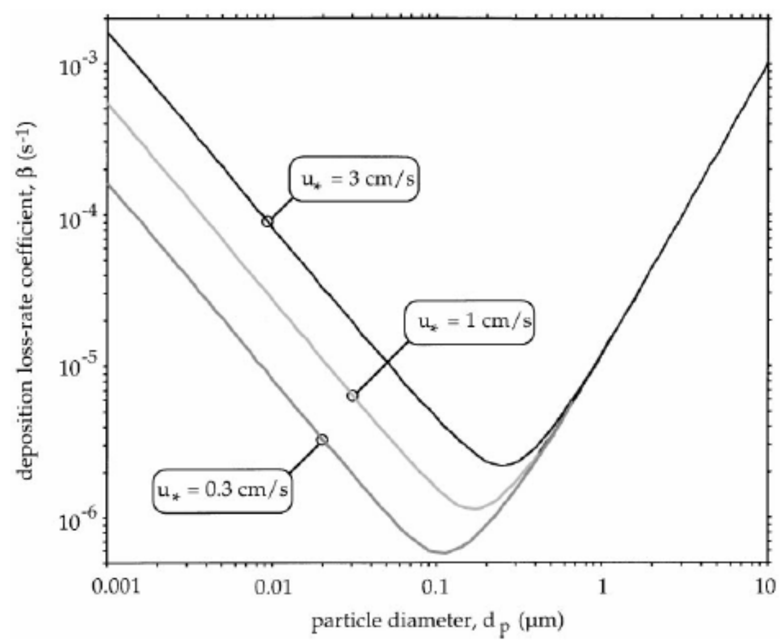


Fig. 5. Particle deposition loss-rate coefficient, β, for typical room dimensions (3 m high × 4 m × 5 m) according to the current model. Friction velocities of 0.3–3 cm s^{-1} approximately span the range expected for mechanically ventilated indoor spaces. Predictions assume air pressure is 1 atm, temperature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

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

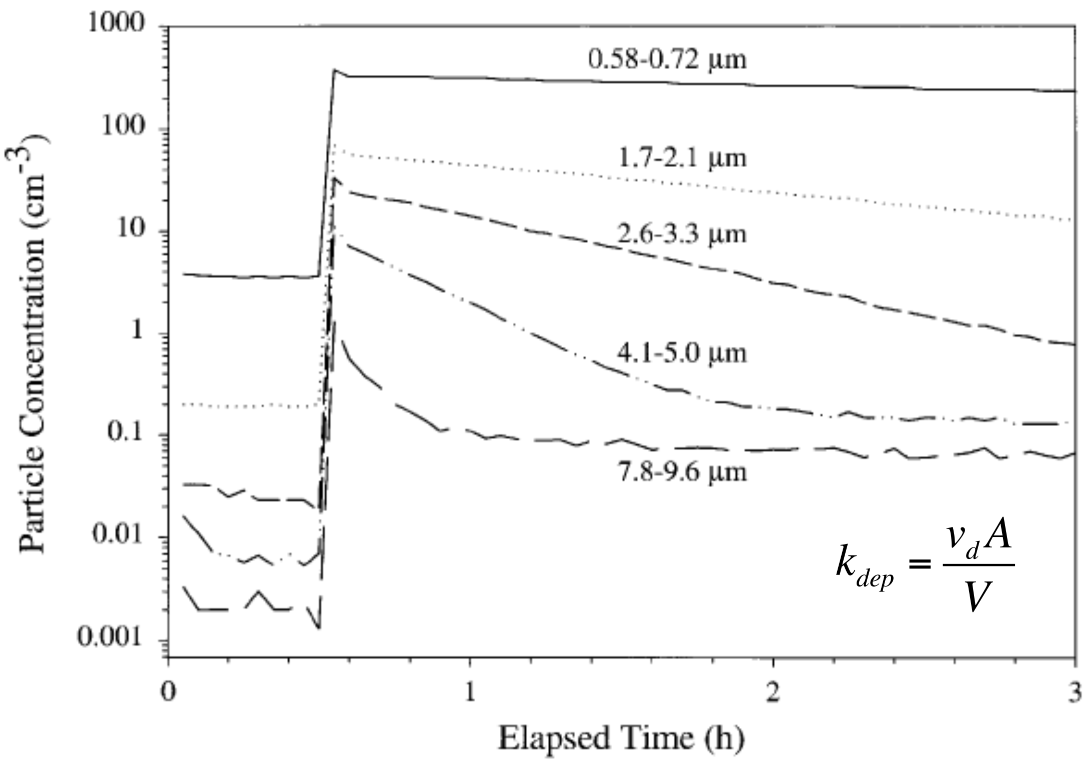
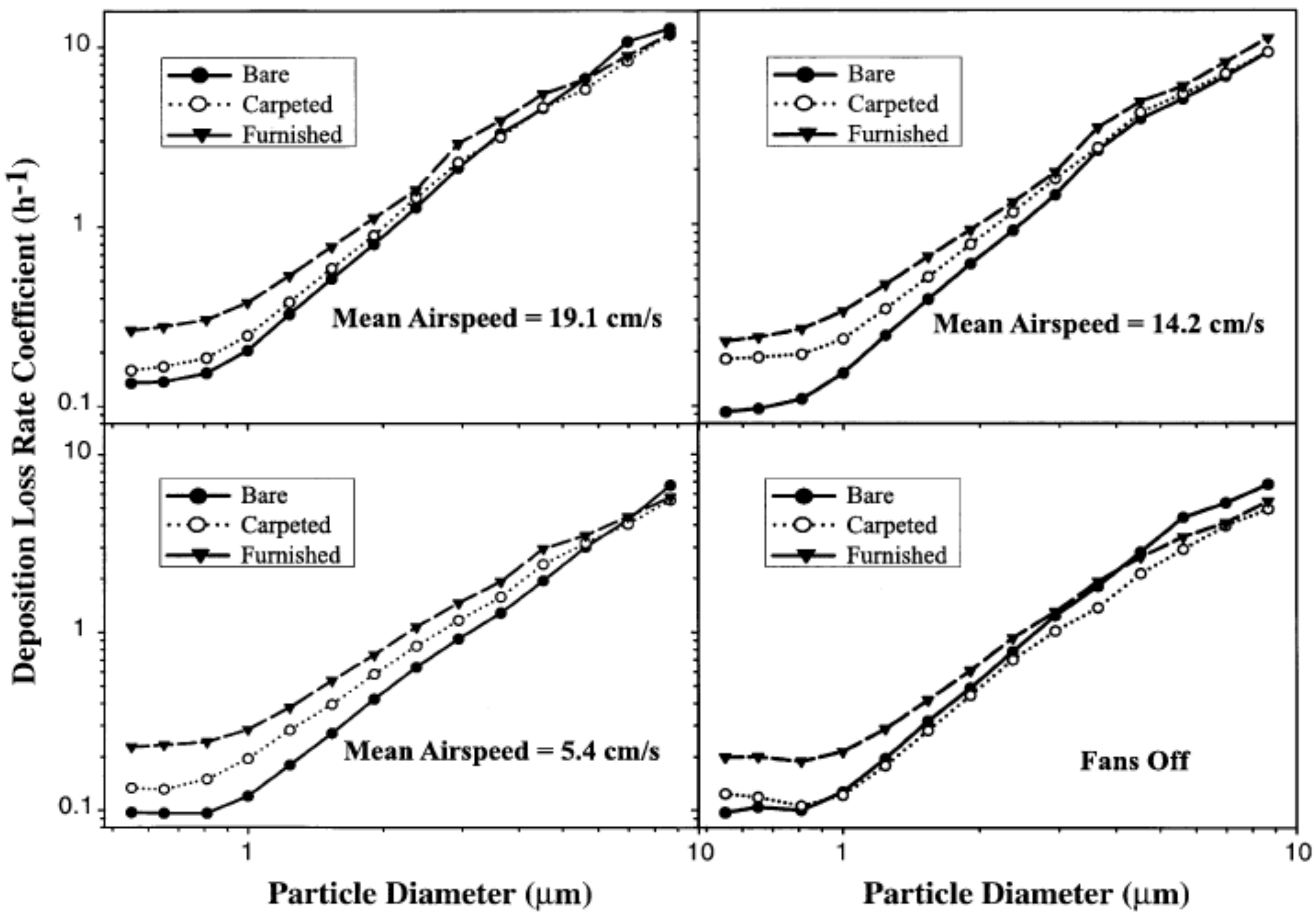


Fig. 2. Typical particle concentration profiles over the course of an experiment for selected particle size ranges. Pulsed particle injection occurred at 0.5 h.

Thatcher et al. 2002 *Atmos Environ*

Indoor losses: Deposition

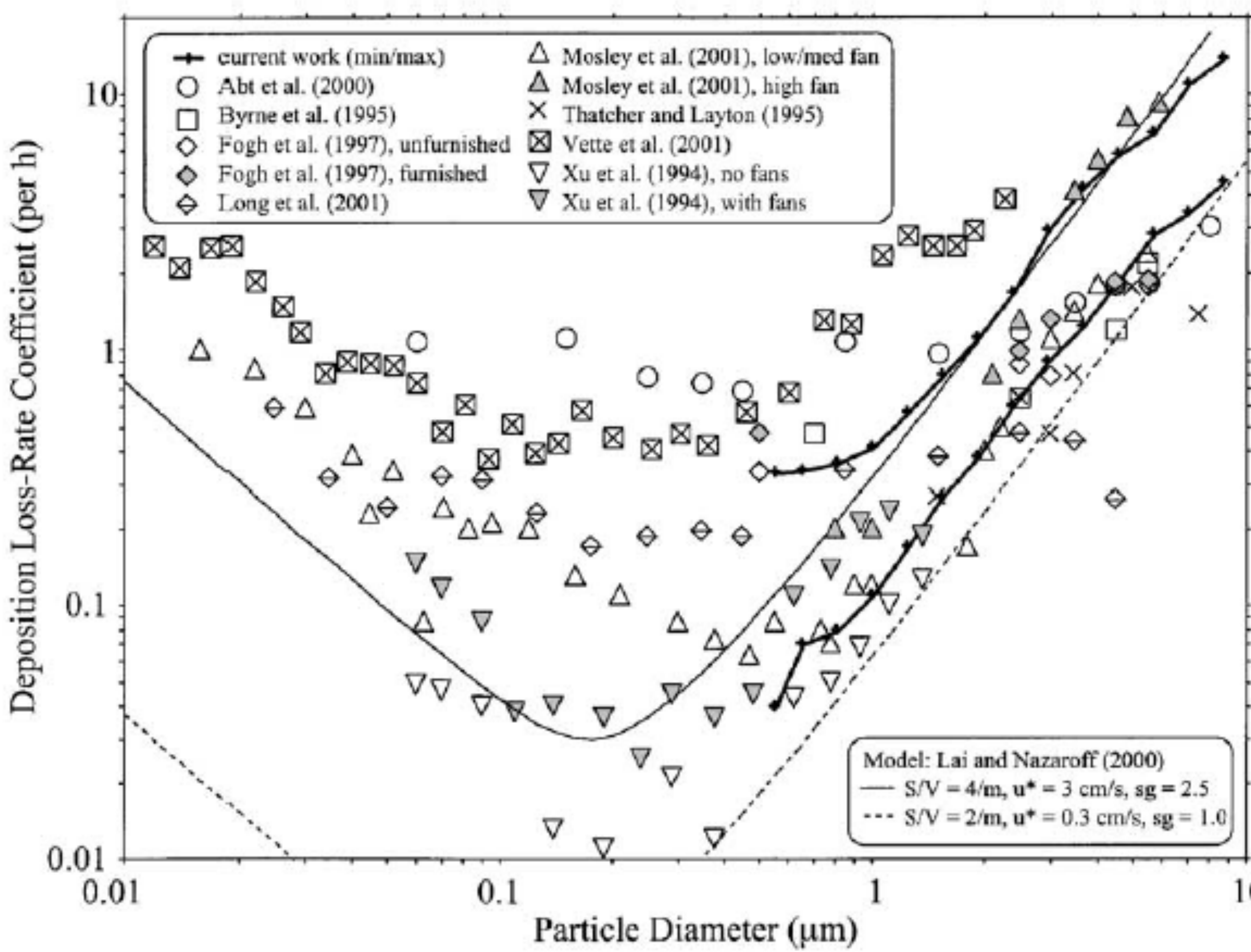
- Deposition in a chamber under different air speeds and furnishing conditions



Thatcher et al. 2002 *Atmos Environ*

Indoor losses: Deposition

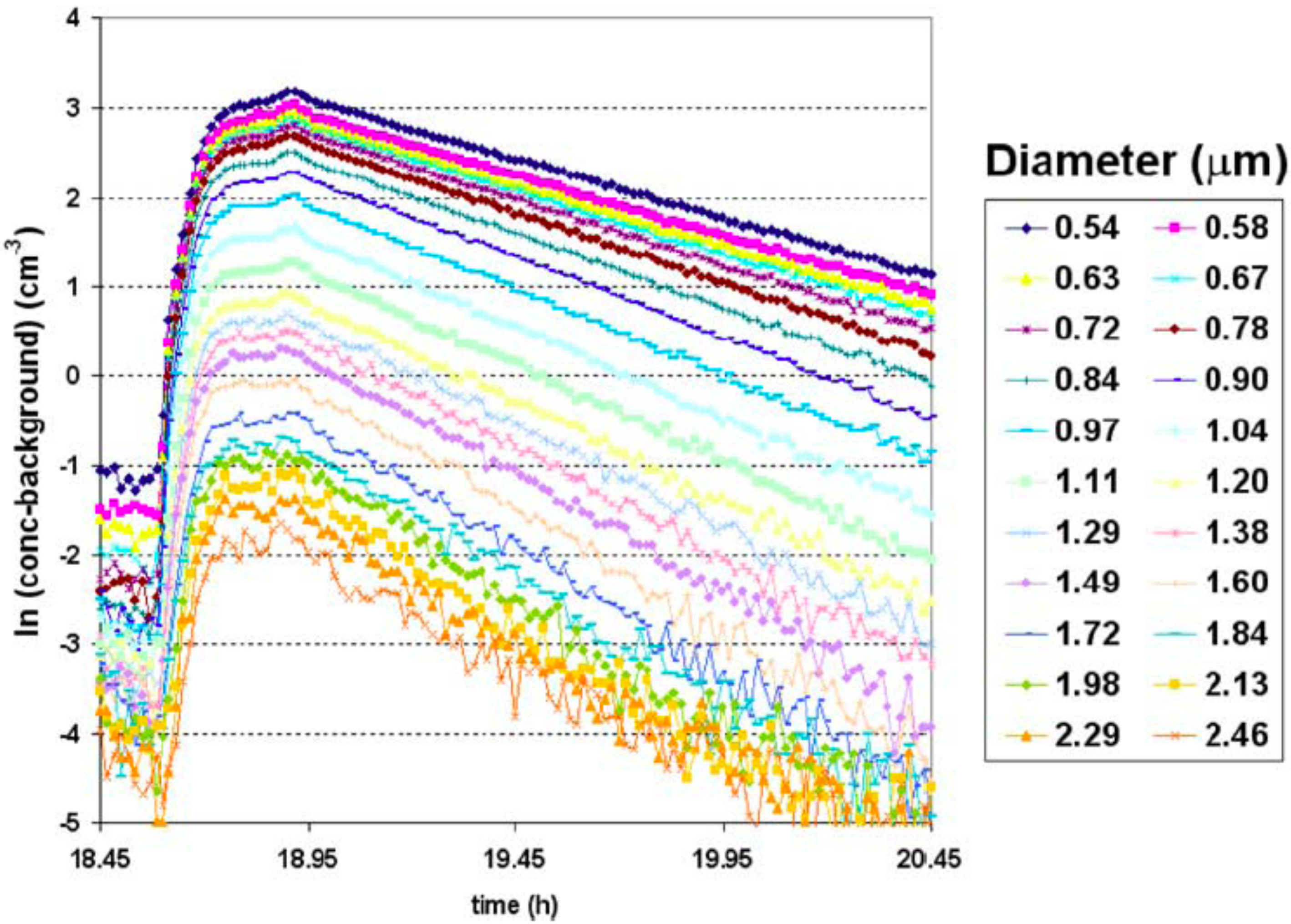
- Review of deposition in a chamber under different scenarios



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

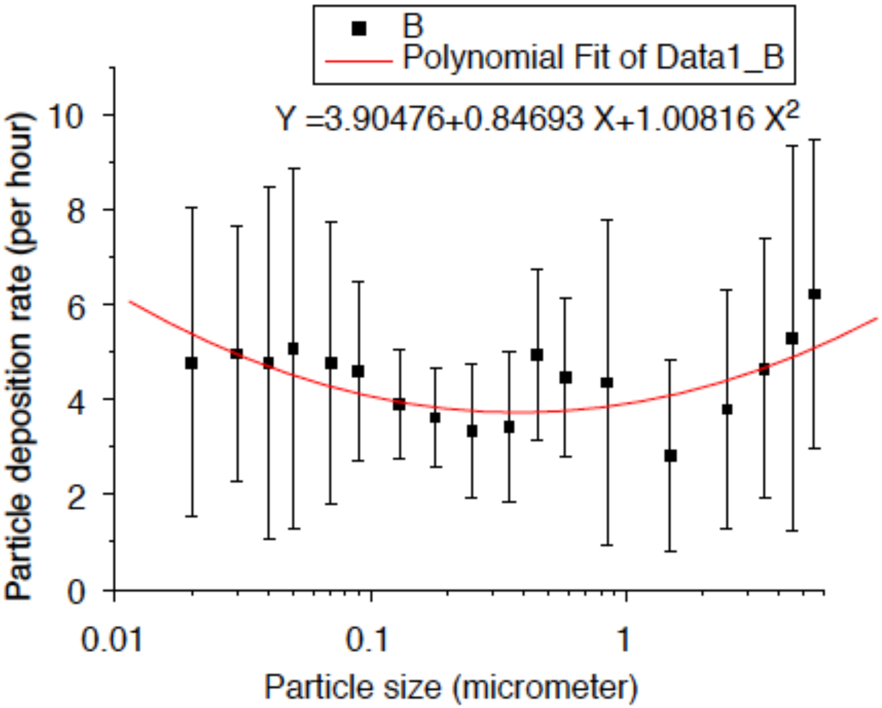


Fig. 3. The average of particle deposition rates for the 18 particle size intervals under normal ventilation conditions (Error bars represent one standard deviation). The polynomial fit line with the correlation coefficient ($R^2 = 0.33$).

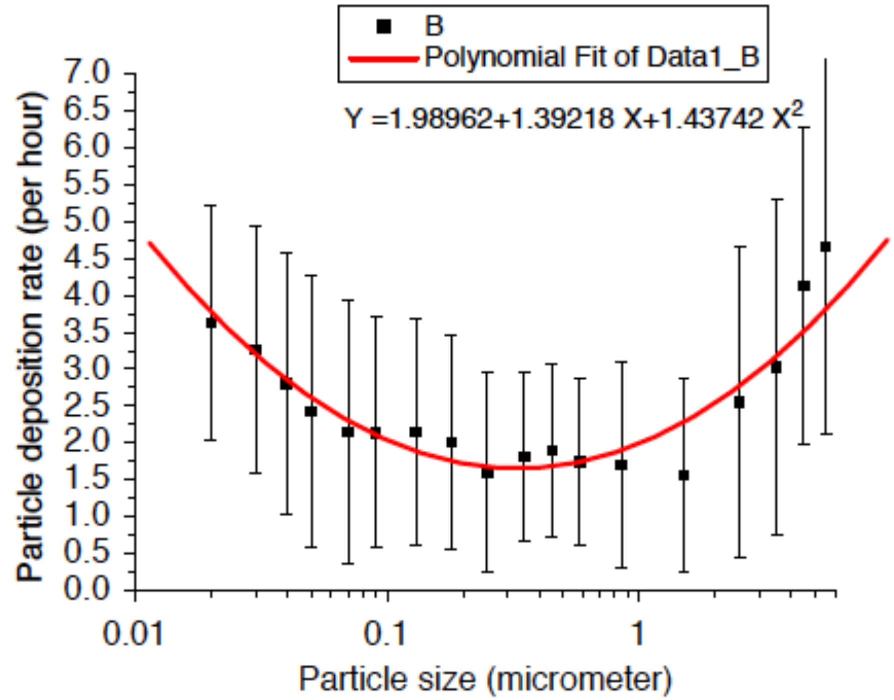
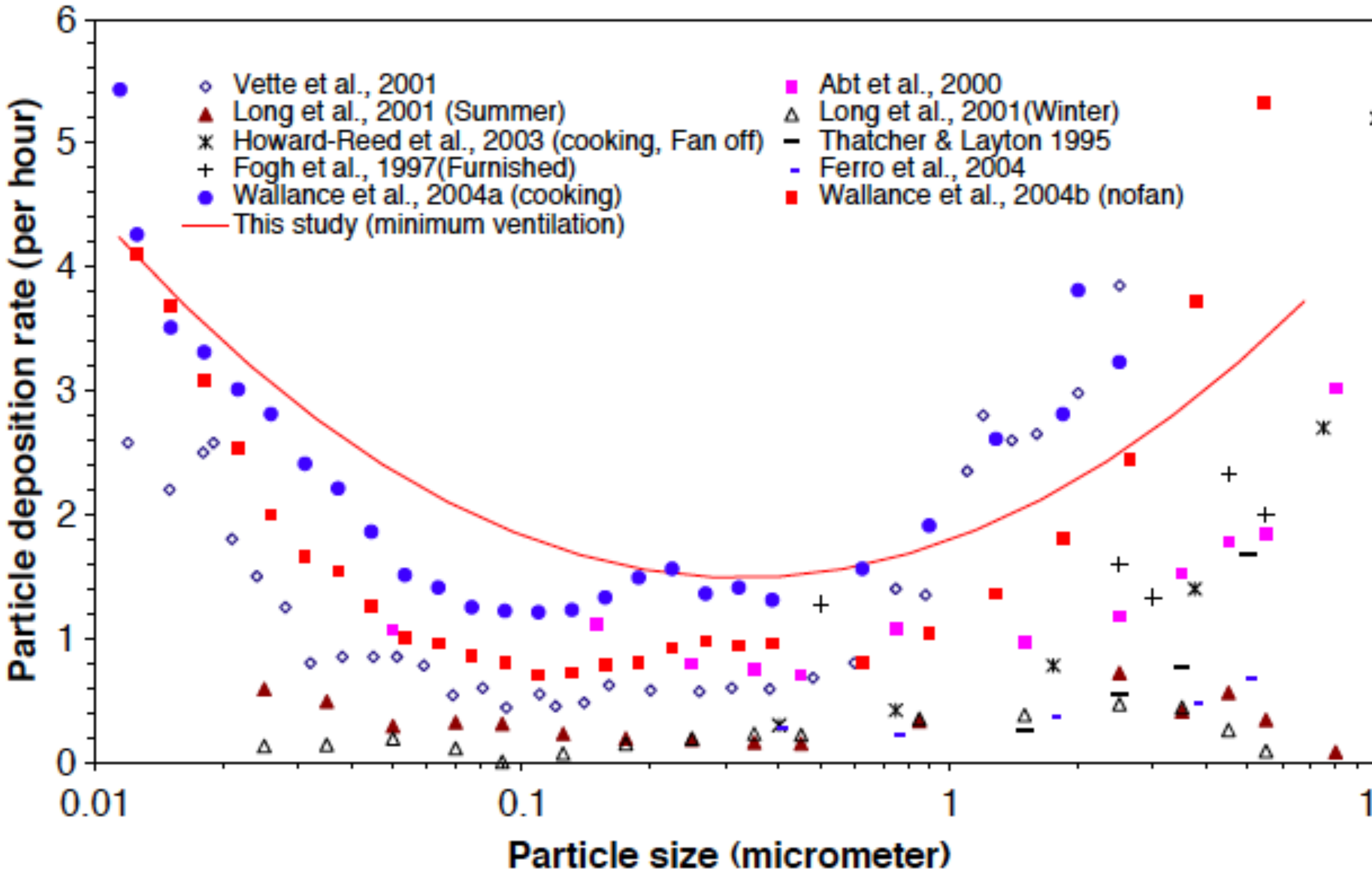


Fig. 4. The average of particle deposition rates for the 18 particle size intervals under minimum ventilation conditions (Error bars represent one standard deviation). The polynomial fit line with the correlation coefficient ($R^2 = 0.84$).

He et al. 2005 *Atmos Environ*

Indoor losses: Deposition

- Deposition in real homes



He et al. 2005 *Atmos Environ*

Indoor particles review

- What have we learned so far?
- We can describe particle concentrations by size (diameter)
- Particles of various sizes exist indoors
  - Smaller particles and the largest particles are typically indoor generated
  - Medium (fine) particles often infiltrated from outdoors
- Once indoors, particles of different sizes deposit on surfaces differently
  - 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 filtration
  - We will do this next week

Next time

- HW 4 assigned today
  - Different kind of assignment – reading assignment
  - On BB now with paper attached

- Next time:
  - Particle penetration and filtration (and air cleaners)