ENVE 576
Indoor Air Pollution
Fall 2016

Week 6: September 27, 2016
Particulate matter: physics, size distributions, respiratory deposition

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Built Environment Research @ IIT

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

Schedule updates

- HW #2 is due today
  - Emissions models and mass balances

- HW #3 will be assigned today
  - Reactive deposition and aerosol calculations

Project topics

- Topic selection suggestions
  - Your interest is the most important factor
    - Don’t shy away from big issues
  - Approach from a fundamental perspective
    - Think about Sources and Losses, Exposures and Doses
  - Consider data availability
  - Considerably more than glorified HW problem
  - Do a preliminary literature search to focus your efforts

Topic justification due

- Less than 1/2 page (a few sentences is fine)
- Describe topic in enough detail that I can provide feedback
- Include references to show that there is enough to get started on your project
- **Due October 4th to me via email**
- Criteria
  - Importance
  - Creativity
  - Justification
  - Reasonable scope

Lab instrumentation: T/RH and power/energy

Temperature/RH

Data logging

Temperature

Heat flux

IR camera

Solar radiation

Electric power

Lab instrumentation: HVAC diagnostics

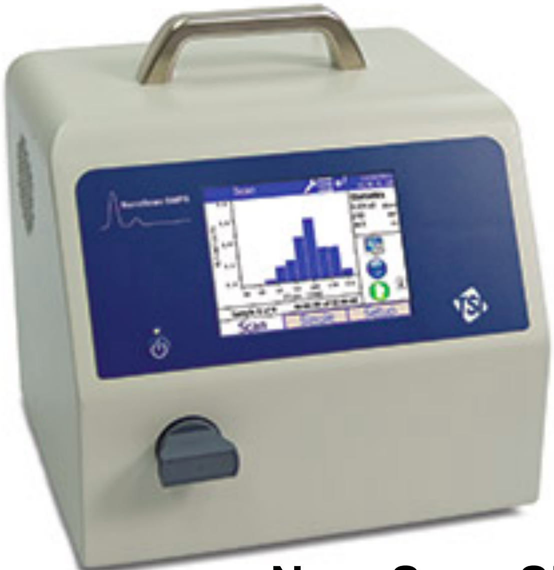
Blower door
(envelope leakage)

Duct blaster
(duct leakage
and airflow)

Pressure

TrueFlow
(HVAC airflow rates)

Lab instrumentation: Air quality (mostly PM)



NanoScan SMPS
10 to 500 nm

Optical particle sizer
0.3 to 10 μm

CO_2
(for AER)
CO

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

CPC
< 1 μm

CPC respirator fit tester
< 1 μm

Also BC, O_3, NO_2
and TVOC

Lab instrumentation: Air quality

- Cheaper instruments

Foobot IAQ monitor

Dylos particle counter

Lab facilities

Final project topics

Name	Project topic
Boyer, Jeffrey L.	Emissions from humidifying devices
Faramarzi, Afshin	
Liang, Dejun	
Liu, Xiaoqi	
Ma, Peiling	
Meng, Zhenyu	
Rice, Lindsey E.	Ventilation in Carman Hall
Shao, Zhihui (Kevin)	
Wang, Yintong	
Zeng, Yicheng	
Zhang, Peng (indoorenvir)	Radon control
Zhang, Xu	
Zhu, Guozhu	
Angulo Duato, Ana Claudia	

Remember:

- Teams of up to 2
- Project topic justification due October 4th

Tips on introduction and literature review

- Objectives
  - Grab reader and pull them into your story
  - Cite all relevant references
  - Establish gaps in existing research
  - Define parameters and make case for their importance
  - Organize and lay out rest of paper
- Start with a interesting fact about your topic
  - No need to be alarmist or over-the-top
  - Use a short sentence
  - Layer on more complicated ideas
- Conduct a comprehensive literature review
  - Use Web of Science and Google Scholar to find other sources
- Don’t need to cite all details about previous work
  - Just the central idea and most impactful previous findings

Tips on introduction and literature review

- Challenge is striking balance between accurately representing work of others and not going into too much detail
- Cite and define key parameters and emphasize why they are important
- After reading introduction, the reader should know the direction of the rest of the paper
- Keep it short (~3 paragraphs)
  - General motivation and importance
  - Previous work
  - Gaps in literature
  - Organizing principle of paper
  - Define and justify important parameters

Tips on introduction and literature review

- Avoid passive voice, be active
- It is acceptable to use "I" or "we"
- Vary your language:
  - Smith et al. (1972) measured …
  - Zhao and Stephens (2015) investigated…
  - Several studies report differences between… (Katz, 2004; Kinney et al., 2000; Allen and Collins, 1999)
- Follow the format for citations and references
- A good literature review:
  - Summarizes all important articles in the field
  - Cites high quality references
    - Also refers to lower quality references *if necessary*
  - States what is novel about the paper
    - Mentions what is missing in the literature
    - Does not denigrate others

Rest of your paper

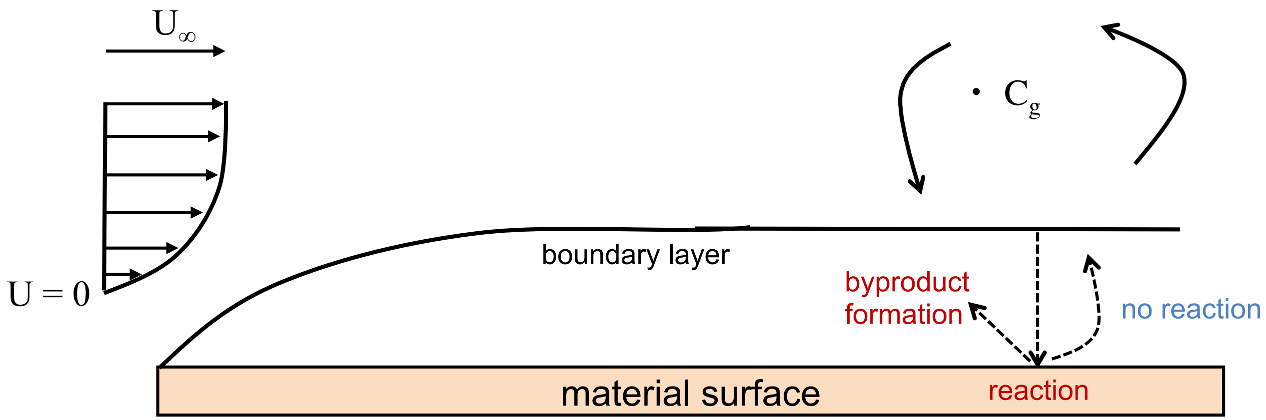
- Literature review is a key component
- So is the remaining methodology, results, discussion and conclusion
  - When in doubt, follow examples of previously published papers
    - e.g., just about anything from our suggested readings list
- Measurements are **not** required
  - No additional points for measurement vs. modeling study

Review from last time

- Last time we covered:
  - Reactions of gas-phase compounds
    - Heterogeneous (reactive deposition)
    - Homogeneous (gas-phase chemistry)

- Today we will begin ~3 weeks of lectures on particulate matter
  - Starting with:
    - Single particle physics
    - Particle size distributions
    - Respiratory deposition

Reactive deposition: summary



- For reactive gas-phase pollutants, we will have an additional loss rate to account for reactive losses to material surfaces

$$\frac{dC}{dt} = P\lambda C_{out} + \frac{E}{V} - \lambda C - \frac{v_d A}{V} C \qquad k_{dep} = \frac{v_d A}{V}$$

$$v_d = \frac{v_s v_t}{v_s + v_t}$$

$$\frac{1}{v_d} = \frac{1}{v_t} + \frac{1}{v_s} = \frac{1}{v_t} + \frac{4}{\gamma \langle v \rangle}$$

v_s = surface-limited deposition velocity (m/hr)
v_t = transport-limited deposition velocity (m/hr)
γ = reaction probability (-)
$\langle v \rangle$ = Boltzmann velocity (m/hr)

Reactive deposition: byproduct formation

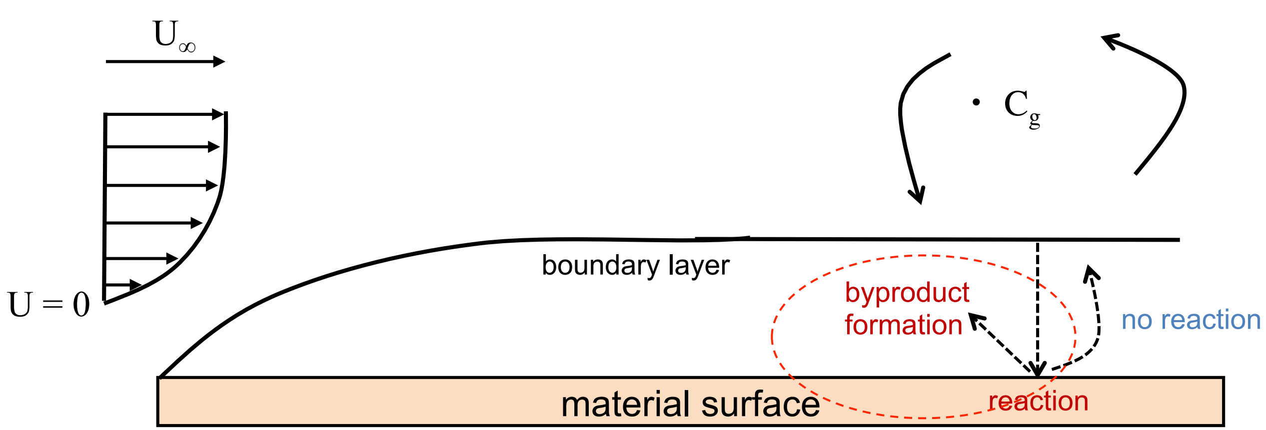
- Reactive deposition to surfaces removes indoor pollutants
  - Can also generate others in the form of reaction by-products

$$R_{byproduct} = (v_d A C) Y_i f_{conversion}$$

$R_{byproduct,i}$ = by-product i production rate (moles/hr)

Y_i = molar yield of i (moles i per moles of gas consumed)

$f_{conversion}$ = conversion factor (e.g., $\frac{10^{-6}}{MW}$ to convert from $\frac{\mu g}{m^3}$ to $\frac{moles}{hour}$)



Byproduct formation: mass balance

- Mass balance on reactive pollutant (e.g., ozone)

$$\frac{dC}{dt} = P\lambda C_{O_3,out} - \lambda C_{O_3} - \frac{v_d A}{V} C_{O_3}$$

- Mass balance on byproduct *i*

$$\frac{dC_i}{dt} = P\lambda C_{i,out} - \lambda C_i + Y_i \frac{v_{d,O_3} A}{V} f_{conversion} C_{O_3}$$

Tracking two species, need two mass balances…

Homogeneous chemistry

- Homogeneous reactions also occur in indoor environments
  - Gas *i* + Gas *j* → Byproduct *k*

$$R_{\text{homogeneous}} = -k_{ij} C_i C_j V$$

$R_{\text{homogeneous}}$ = loss rate due to homogenerous reactions between i and j (moles/hr or μg/hr)

k_{ij} = reaction rate constant (ppb^{-1} hr^{-1})

$k_{ij} C_j$ = reaction rate (1/hr)

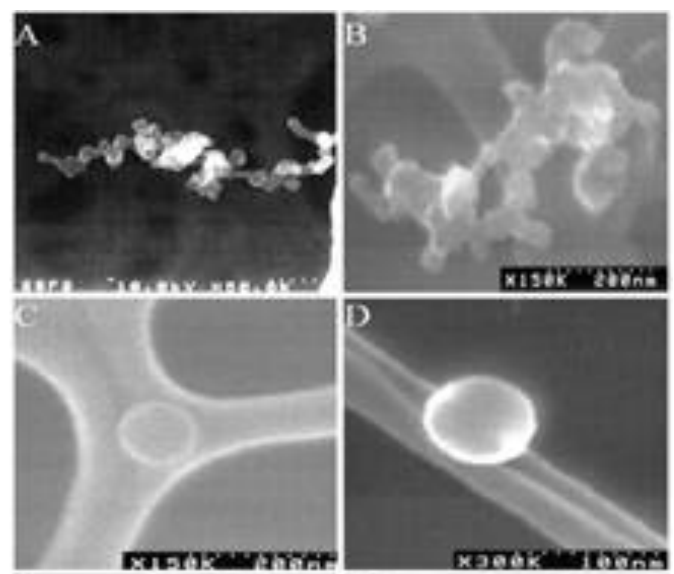
- Need at least 3 mass balances
  - Two reactants + product(s) $R_{byproduct,k} = (k_{ij} C_i C_j) Y_k f_{conversion}$
- For a reaction to be relevant indoors, it must occur on a relevant time scale
  - $k_j C_j$ (1/hr) needs to be on the same order as λ (1/hr)
    - Reaction must be reasonably fast

PARTICULATE MATTER

Overview, physics, size distributions, respiratory deposition

Particulate matter (PM)

- Particulate matter (PM) is its own class of pollutant
  - PM consists of a mixture of solid particles and liquid droplets suspended in air
  - Primary emissions are emitted directly by sources
    - Outdoors: Industry, construction, roads, smokestacks, fires, vehicles
    - Indoors: Smoking, cooking, resuspension of dust, transport from outdoors
  - Secondary emissions are formed in atmospheric reactions and some indoor reactions
- Health effects
  - Respiratory, cardiovascular, others
- Visibility effects outdoors

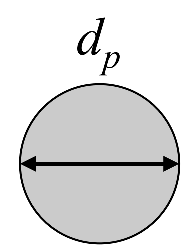


http://www.aerosols.wustl.edu/education/AerosolBasics/What%20is%20an%20aerosol.htm

Particle **sizes**

- Usually referring to a characteristic dimension
  - Diameter for sphere
  - Diameter for fibers (e.g. asbestos)
  - Equivalent diameter for non-spherical
- Micrometer (μm)
  - 1 μm = 10^{-6} m
- Nanometer (nm)
  - 1 nm = 10^{-9} m

- We usually treat particles as spherical:
  - Or 'equivalent' spheres



$$V = \frac{\pi}{6} d_p^3$$

Particle sizes

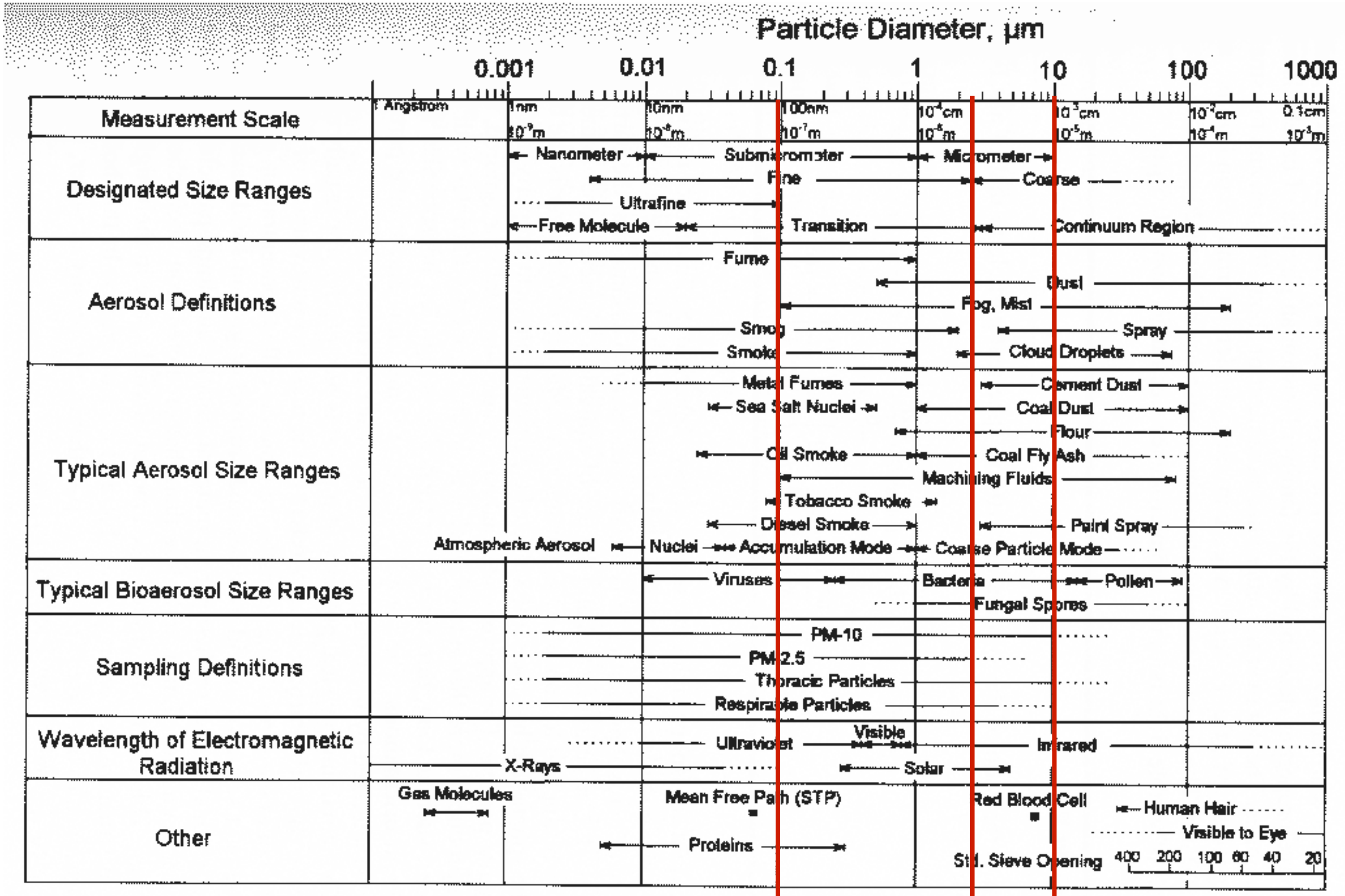
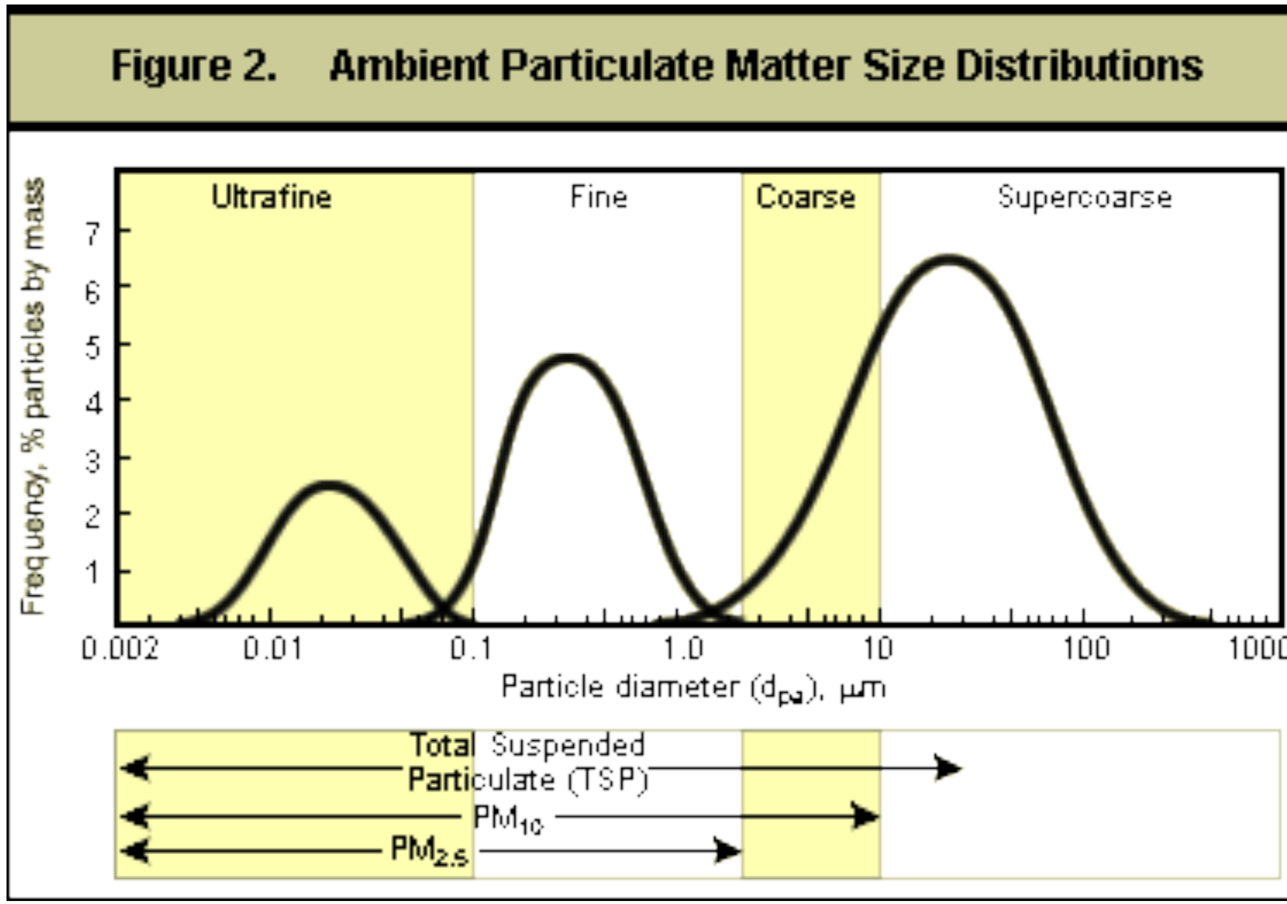


FIGURE 1.6 Particle size ranges and definitions for aerosols.

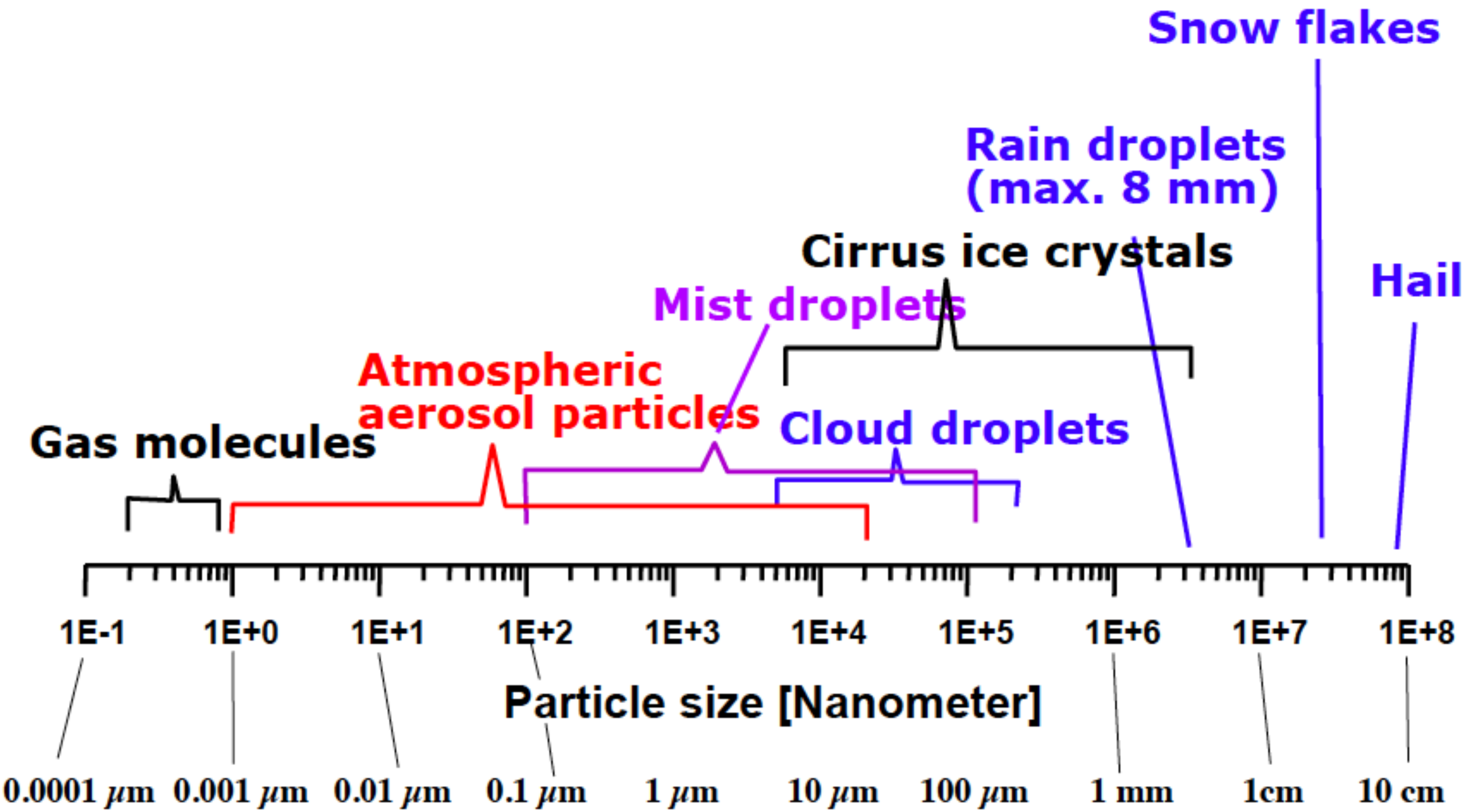
Hinds 1999

How are particle concentrations reported?

- Number
  - #/cm^3
  - UFP <100 nm
- Surface area
  - cm^2/cm^3
- Volume
  - m^3/m^3
- Mass
  - µg/m^3
  - $PM_{2.5}$
  - PM_{10}
  - $PM_{2.5-10}$
  - TSP
  - RSP

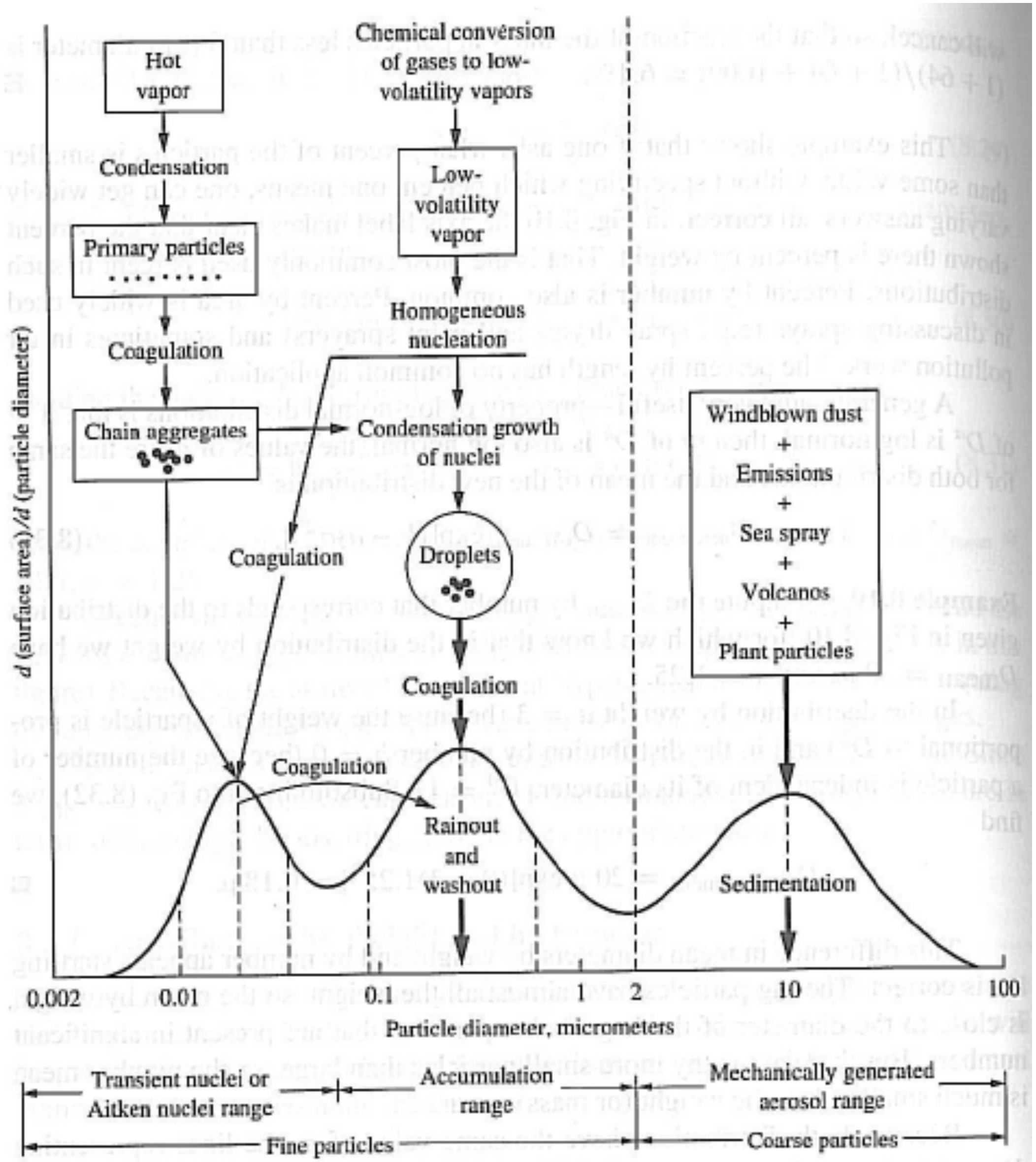


Particle sizes



Schneider, 2010

Particle formation mechanisms, surface area, and size



Seinfeld and Pandis, 2006

PARTICLE MOTION

What affects the movement of particles?

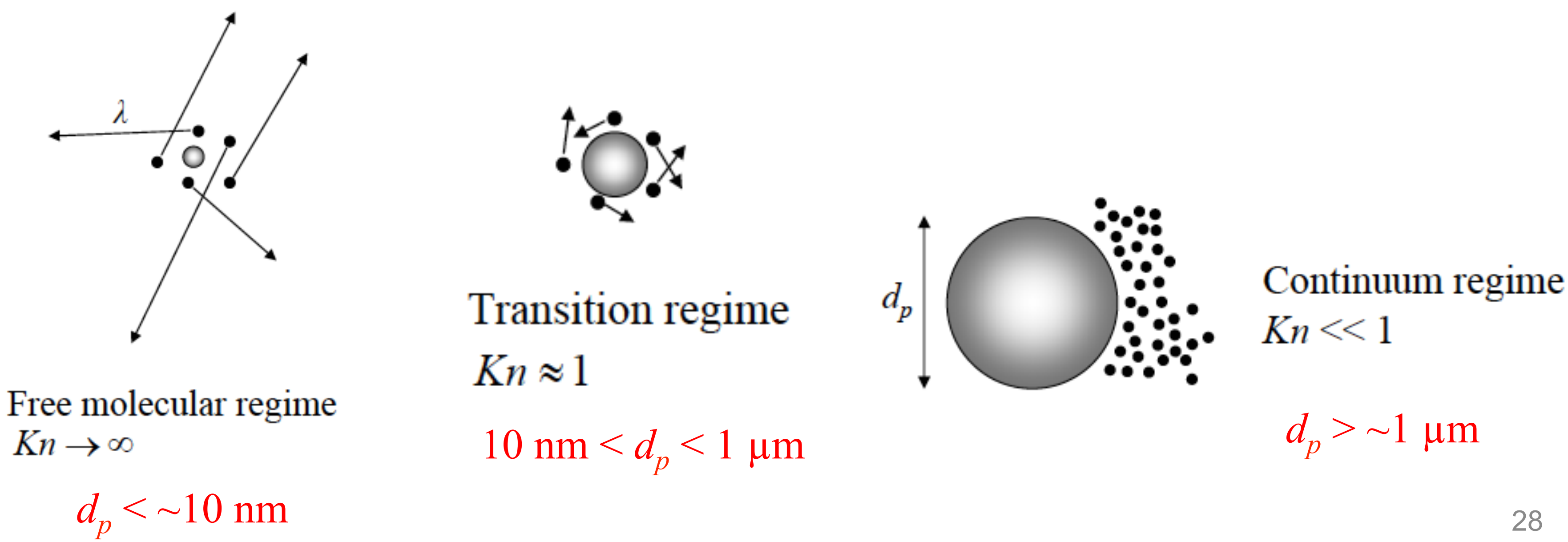
Particle motion in gases: Size regime

- Continuum regime and free molecular regime
  - Behavior of a particle in a gas is characterized by the ratio of the mean free path of the gas molecules to the diameter of the particle
  - Ratio is called the Knudsen number (*Kn*):

$$Kn = \frac{2\lambda}{d_p}$$

d_p = particle diameter (μm)

λ = mean free path of air (0.066 μm @ STP)



Seinfeld and Pandis, 2006; Schneider, 2010

Particle motion in gases: Flow regime

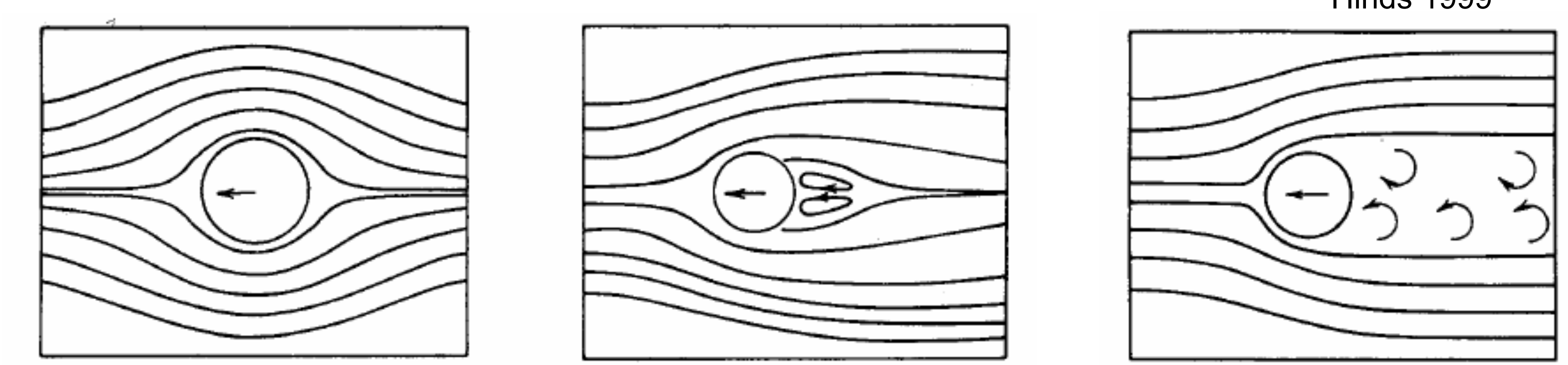
- Reynolds number:
  - Re is the ratio of inertial forces to frictional forces for fluid flow through a pipe or around an obstacle
  - For flow around a particle:

$$\mathrm{Re} = \frac{\rho_{air} V d_p}{\mu}$$

ρ_{air} = air density (kg/m^3)
V = relative velocity between particle and air (m/s)
μ = dynamic viscosity of air (1.8×10^{-5} kg/(m-s) at STP)

  - For flow around a particle:
    - Re < 1: laminar flow (frictional forces dominate)
    - Re > 1: turbulent flow (inertial forces dominate)

Hinds 1999



Re = 0.1 (a) Re = 2 (b) Re = 250 (c)

Particle motion in gases: Drag forces (large d_p)

- Newton's resistance law
  - Newton derived an equation for the force resisting the motion of a sphere passing through a gas:

$$F_D = C_D \frac{\pi}{8} \rho_{air} d_p^2 V^2$$

F_D = drag force (kg-m/s^2)
C_D = drag coefficient (-)

  - Assumes only inertia of air is important (not friction forces)
  - Therefore, this assumption is only valid for high Re (Re > 1000)
  - For smaller Re, the molecular viscous (friction) forces have to be considered
    - Under laminar flow conditions (Re < 1), viscous forces dominate and inertial forces can be neglected
    - In this case, we use **Stokes' Law**

Particle motion in gases: Drag forces (small d_p)

- Stokes' law states that: $$F_D = 3\pi\mu V d_p$$

  $$V = \text{particle velocity (m/s)}$$

  – Valid for laminar flow around a solid sphere

- Comparing Newton's and Stokes' laws:

$$F_D = C_D \frac{\pi}{8} \rho_{air} d_p^2 V^2 = 3\pi\mu V d_p$$

$$C_D = \frac{24\mu}{\rho_{air} V d_p} = \frac{24}{\text{Re}}$$

  – Therefore, in the Stokes' regime (Re < 1) the drag coefficient is 24/Re

Particle motion in gases

- Drag coefficient, C_D:

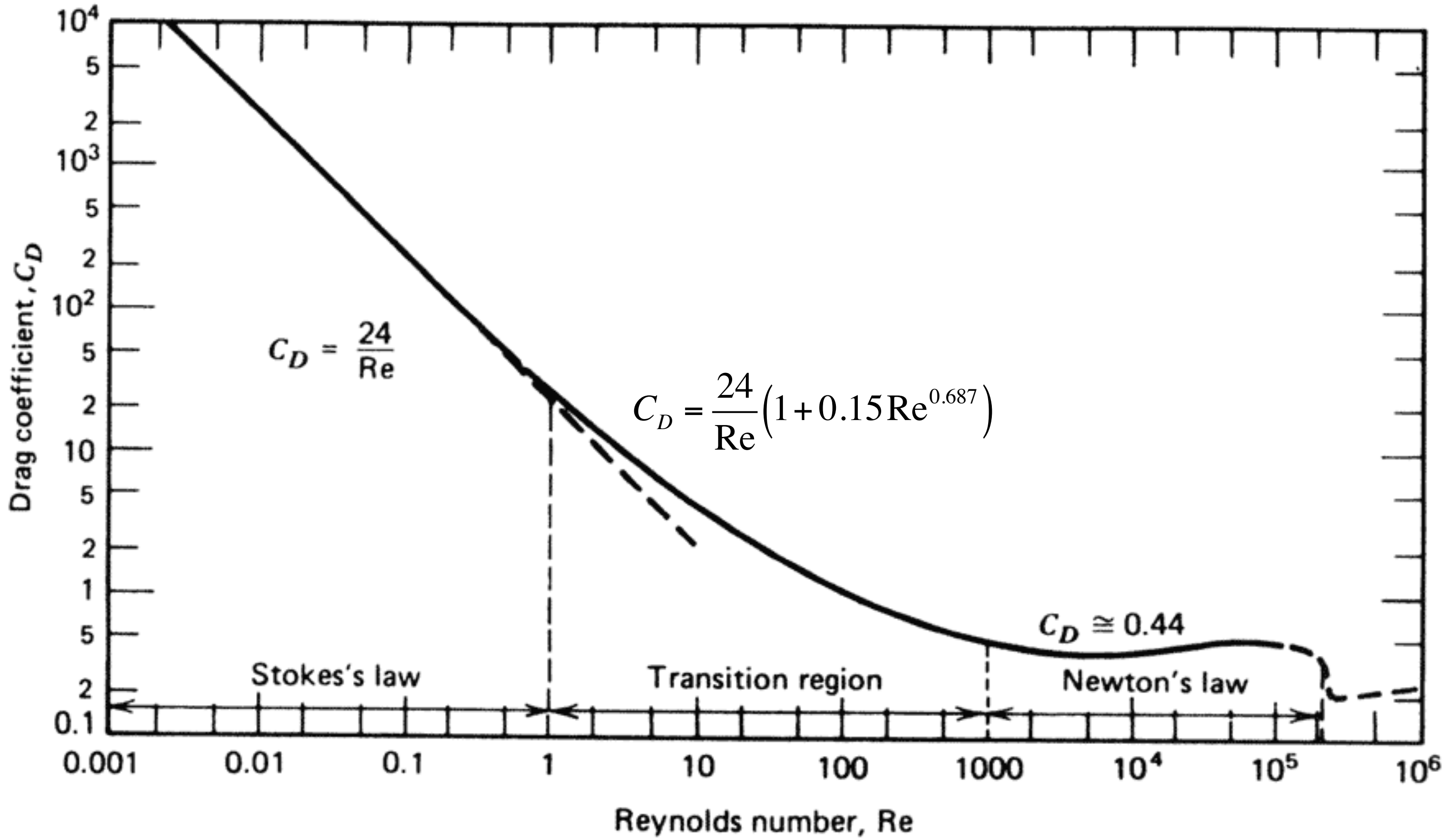


FIGURE 3.1 Drag coefficient versus Reynolds number for spheres.

Hinds 1999

Particle motion in gases: Typical Re values

- Re for various particle diameters at STP:
  - Reynolds numbers for particles in air falling at their terminal settling velocities at 298 K

Diameter (μm)	*Re*
0.1	7×10^{-9}
1	2.8×10^{-6}
10	2.5×10^{-3}
20	0.02
60	0.4
100	2
300	20

  - Almost all atmospheric aerosols are in the <u>Stokes' regime</u> and Stokes' law can be applied (i.e., d_p < ~80 μm)

Hinds 1999

Particle motion in gases: Stokes' regime

- Drag coefficient, C_D:

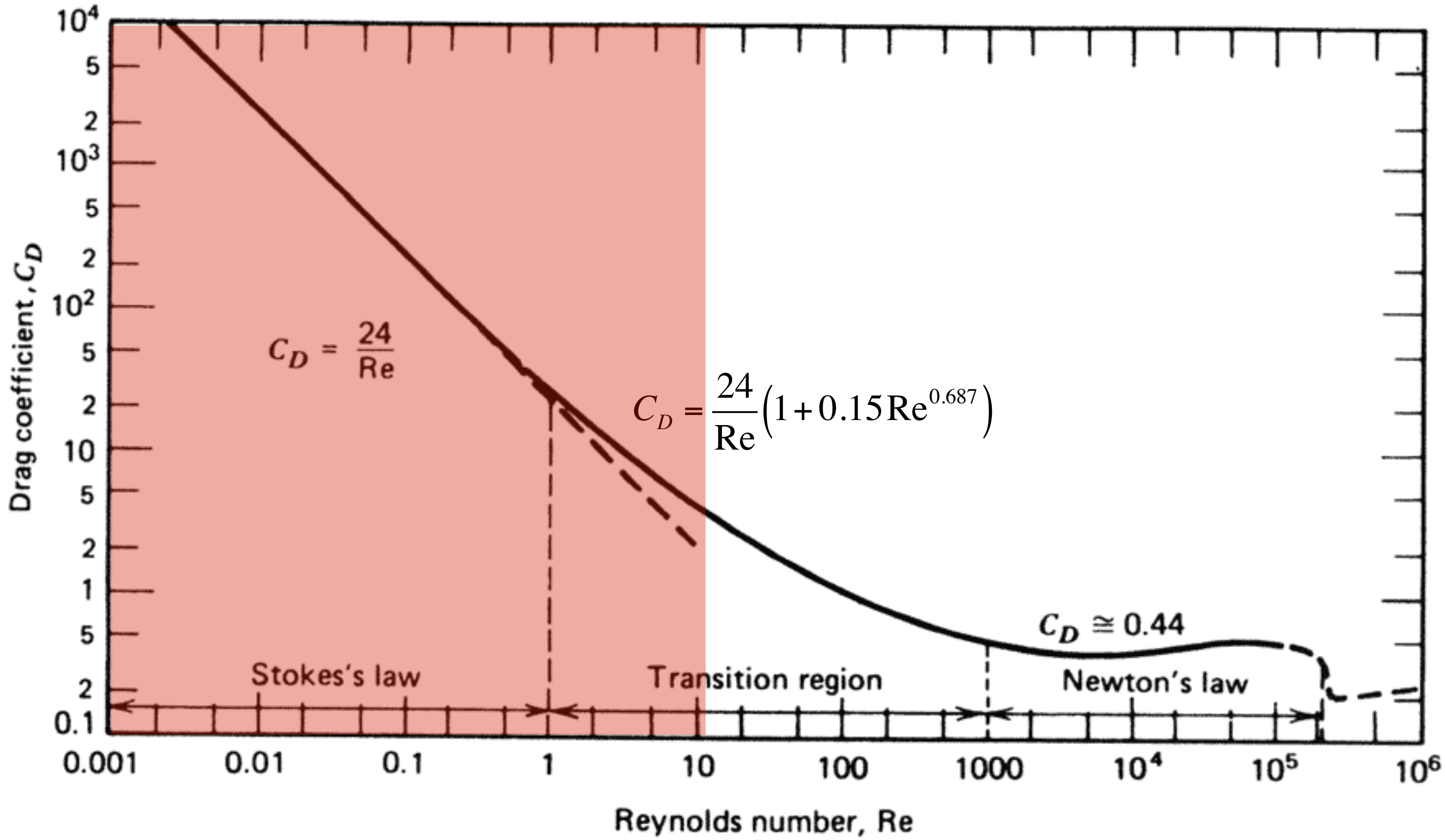


FIGURE 3.1 Drag coefficient versus Reynolds number for spheres.

Hinds 1999

Particle motion in gases: Newton's and Stokes' Laws

- When a particle is released into the air, it quickly reaches its "**terminal settling velocity**," V_{TS}
  - V_{TS} is a condition of constant velocity wherein the drag force of the air on the particle F_D is exactly equal but opposite to the force of gravity F_G

$$F_G = mg = \frac{\pi}{6}\rho_p d_p^3 g \qquad F_D = 3\pi\mu V d_p$$

$$\frac{\pi}{6}\rho_p d_p^3 g = 3\pi\mu V d_p$$

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

Particle motion in gases

- In the derivation of Stokes' law, it is assumed that the relative velocity of the gas (air) at the surface of the particle is zero
- This doesn't hold for small particles whose size approaches the mean free path of air (Kn ≤ 1)
  - Particles less than about 1 μm
- Stokes' law has to be corrected for "slip" conditions:
  - Cunningham slip correction factor, C_C:

$$F_D = \frac{3\pi\mu V d_p}{C_C}$$

$$C_C = 1 + \frac{\lambda}{d_p}\left(2.34 + 1.05 e^{-0.39\frac{d_p}{\lambda}}\right)$$

Based on Kn → lets you use Stokes' law for all regimes

Particle motion in gases: V_{TS} with slip correction

$$F_G = mg = \frac{\pi}{6}\rho_p d_p^3 g \qquad F_D = \frac{3\pi\mu V d_p}{C_C}$$

$$\frac{\pi}{6}\rho_p d_p^3 g = \frac{3\pi\mu V d_p}{C_C}$$

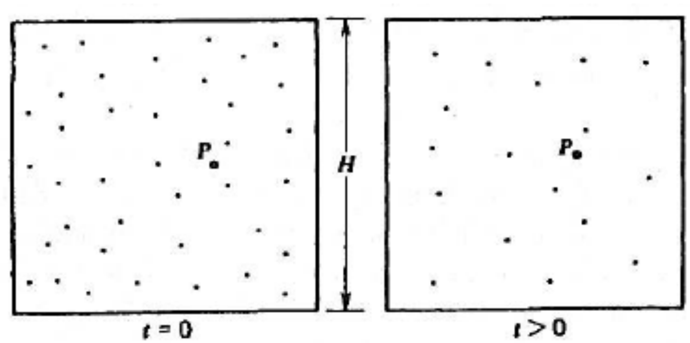
$$V_{TS} = \frac{\rho_p d_p^2 g C_C}{18\mu}$$

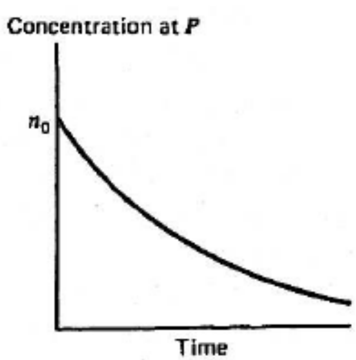
For Re < 1, which is true for most d_p < 100 µm

Particle motion in gases

- Terminal settling velocity for particles at STP

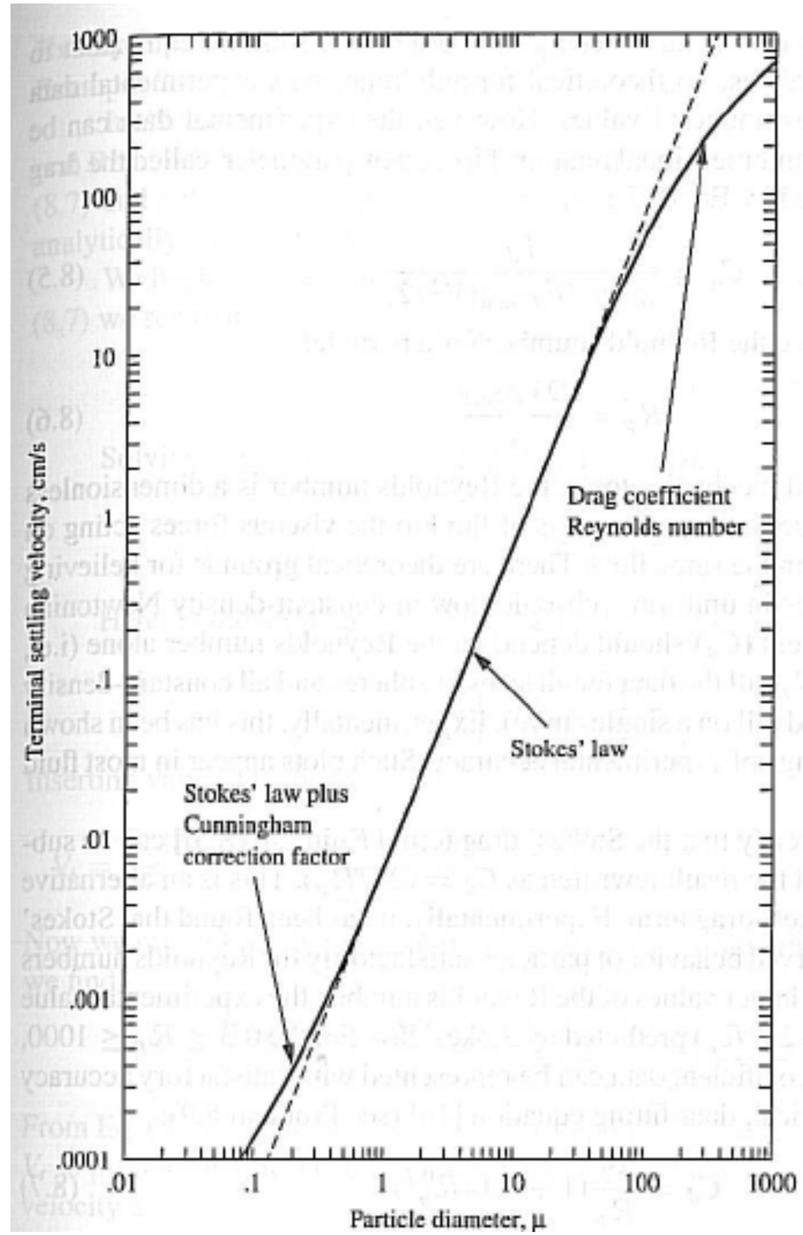
- What can we use V_{TS} for?
- Imagine "stirred settling"





$$N(t) = N_{t=0}e^{-\frac{V_{TS}}{H}t}$$

Larger particles settle out of the air faster



Particle motion in gases

- A couple of other important particle properties also exist
  - Equivalent diameters
  - Aerodynamic diameters
  - Stokes diameters

Non-spherical particles: equivalent diameters

- Many aerosol particles are not spherical
  - For example, soot particles, mineral dust, sea salt
- We can account for the effect of shape on particle motion by introducing a dynamic shape factor, χ:

Shape	Dynamic Shape Factor,[a] χ	Axial Ratio 2	Axial Ratio 5	Axial Ratio 10
Geometric Shapes				
Sphere	1.00			
Cube[b]	1.08			
Cylinder[b]				
Vertical axis		1.01	1.06	1.20
Horizontal axis		1.14	1.34	1.58
Orientation averaged		1.09	1.23	1.43
Straight chain[c]		1.10	1.35	1.68
Compact cluster				
Three spheres	1.15			
Four spheres	1.17			
Dusts				
Bituminous coal[d]	1.05–1.11			
Quartz[d]	1.36			
Sand[d]	1.57			
Talc[e]	1.88			

$$F_D = \frac{3\pi\mu V d_e}{C_C}\chi$$

d_e = volume equivalent diameter, or the diameter of a sphere having the same volume and density as the nonspherical particle

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

χ = ratio of the actual resisting force of the nonspherical particle to the resisting force a sphere of the same volume and density would have

Aerodynamic and Stokes diameters

Two other equivalent diameters are commonly used:

- The aerodynamic diameter (d_a) is the diameter of a spherical particle having the density of water (1 g/cm^3) and having the same settling velocity as the particle in question
- The Stokes diameter (d_s) is the diameter of a spherical particle having the same density and settling velocity as the particle in question

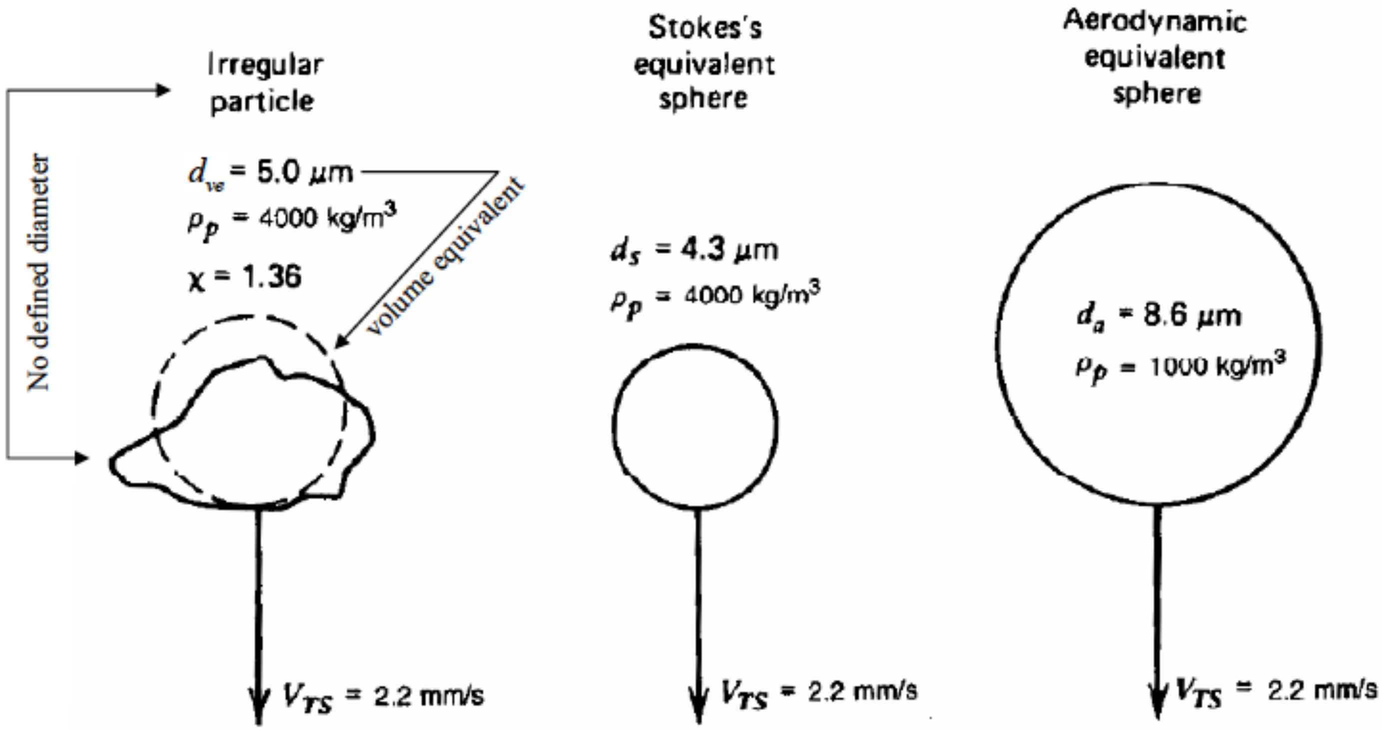
$$V_{TS} = \frac{\rho_p g C_C(d_e) d_e^2}{18\mu\chi} = \frac{\rho_0 g C_C(d_a) d_a^2}{18\mu} = \frac{\rho_p g C_C(d_s) d_s^2}{18\mu}$$

  – Note that C_C has to be calculated as a function of the diameter you're using

Aerodynamic and Stokes diameters

- For particles with d_p > 1 µm we can assume C_C = 1:

$$\frac{\rho_p d_{ve}^2}{\chi} = \rho_p d_S^2 = \rho_0 d_a^2$$



Non-spherical particle and its equivalent diameters

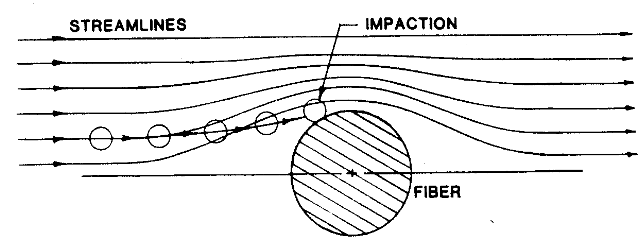
Other forces

- Other forces governing particle motion
  - Gravity (already covered)
  - Inertial impaction
  - Brownian diffusion
  - Electrophoretic
  - Thermophoretic

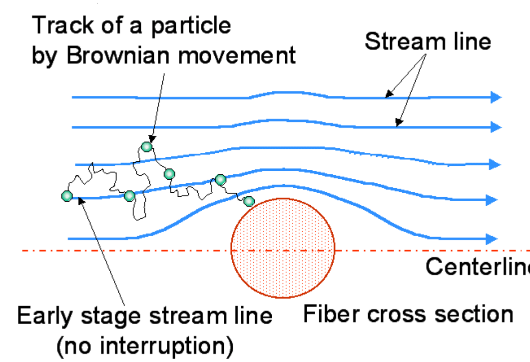
- We don't have time to cover these in full detail
  - But I will provide basic concepts and equations so we can understand what forces act to remove particles of various d_p from air

Other important forces

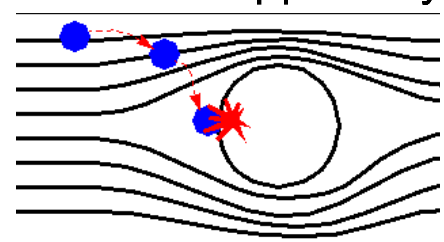
- **Inertial impaction**
  - Inertial transfer of particles onto surfaces
  - Important for larger particles: scales with d_p^2



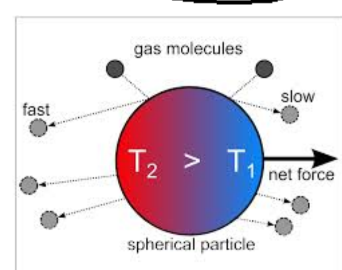
- **Brownian diffusion**
  - Movement by random molecular motion across a concentration gradient
  - Important for smaller particles: scales with $1/d_p$



- **Electrophoretic/electrostatic forces**
  - Particles can and do acquire charges and can be attracted to oppositely charged surfaces
  - Important for smaller particles: scales with $1/d_p$



- **Thermophoretic forces**
  - Particle movement driven by a temperature gradient
  - Weak function of d_p (but nearly constant for all d_p)



All forces combine to impact particle deposition

- More on this later, but these effects combine to influence particle deposition rates and rate constants
  - Particle deposition rate coefficient onto surfaces (1/hr): $k_{dep} = \frac{v_d A}{V}$

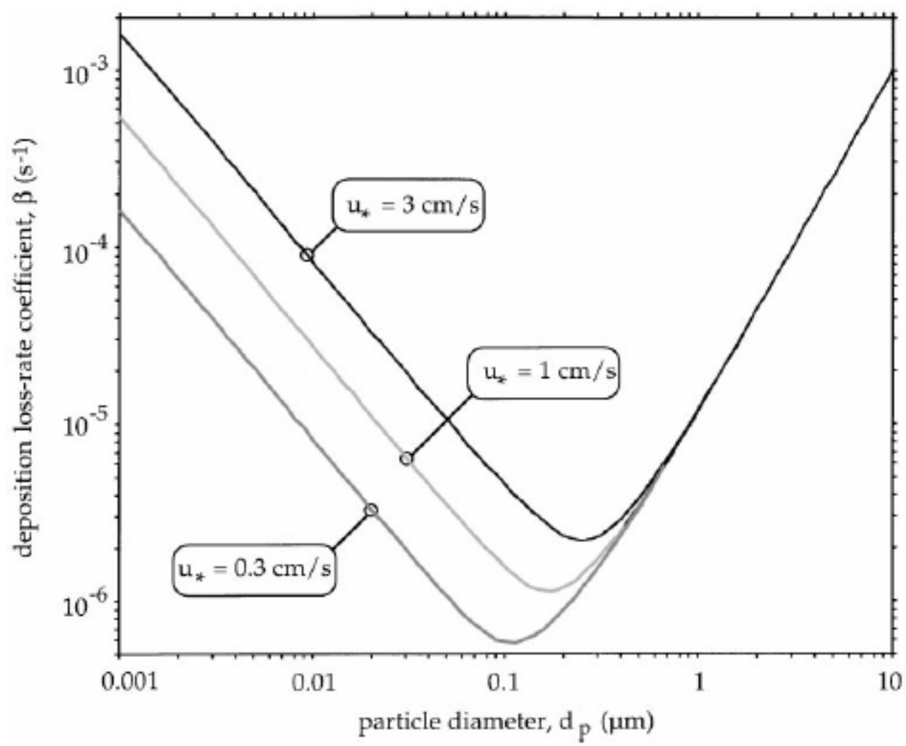


Fig. 5. Particle deposition loss-rate coefficient, β, for typical room dimensions (3 m high × 4 m × 5 m) according to the current model. Friction velocities of 0.3–3 cm s^{-1} approximately span the range expected for mechanically ventilated indoor spaces. Predictions assume air pressure is 1 atm, temperature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

*Note that 'friction velocity' is a function of the ratio of shear stress at a surface to air density

Lai and Nazaroff 2000 *J Aerosol Sci*

PARTICLE SIZE DISTRIBUTIONS

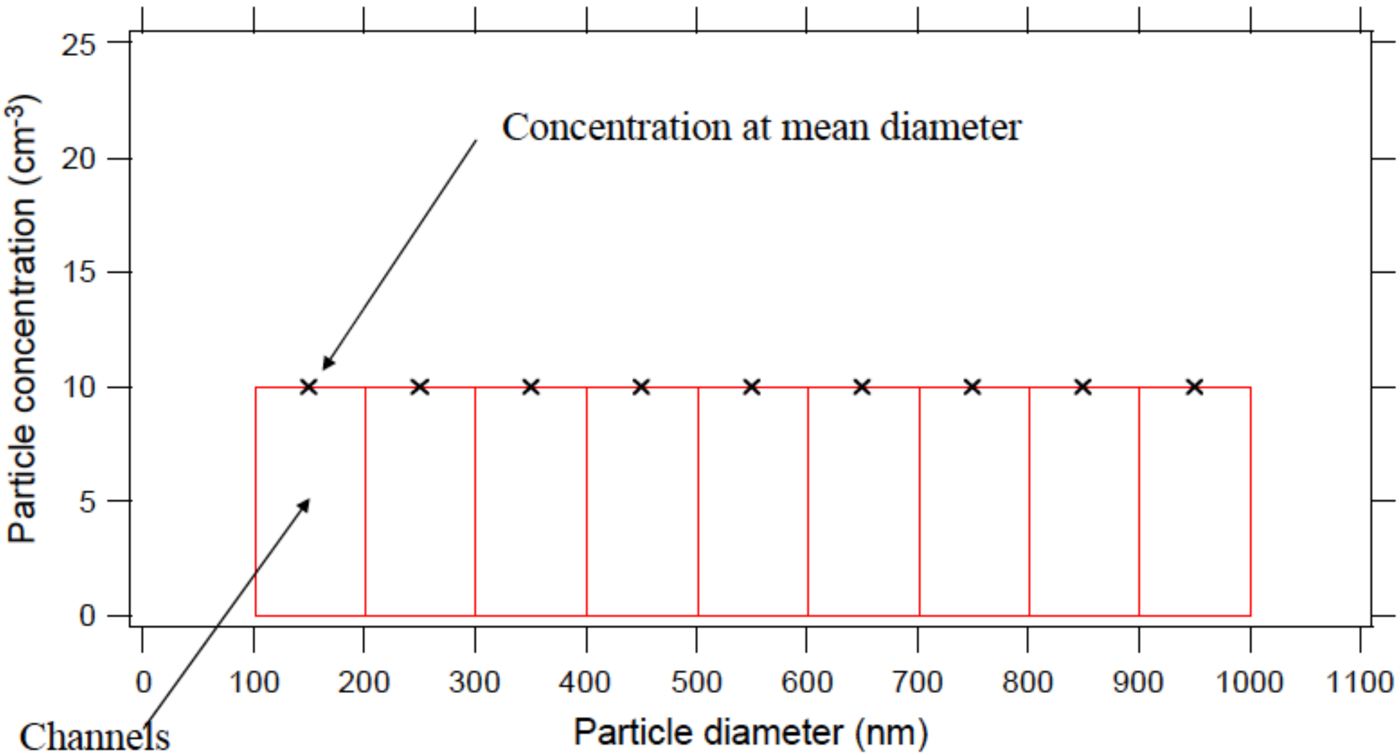
Size distributions

- 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 particle size distribution (PSD), 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

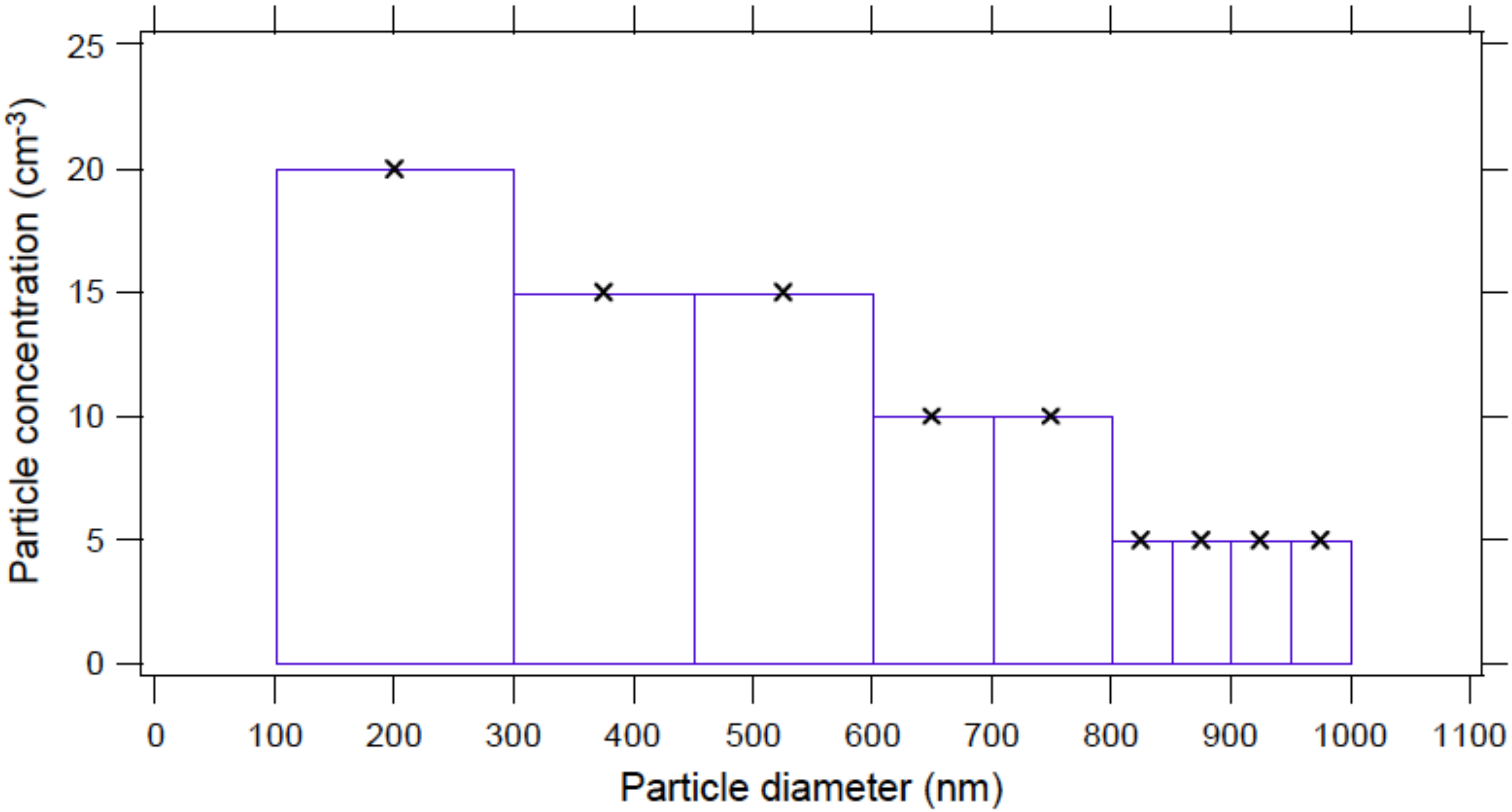
- Example instrument: 9 size channels, width of 100 nm each, each with 10 particles per cm^3
- We consider the measured concentration as $\mathrm{d}N$ in each channel



Schneider, 2010

Size distributions

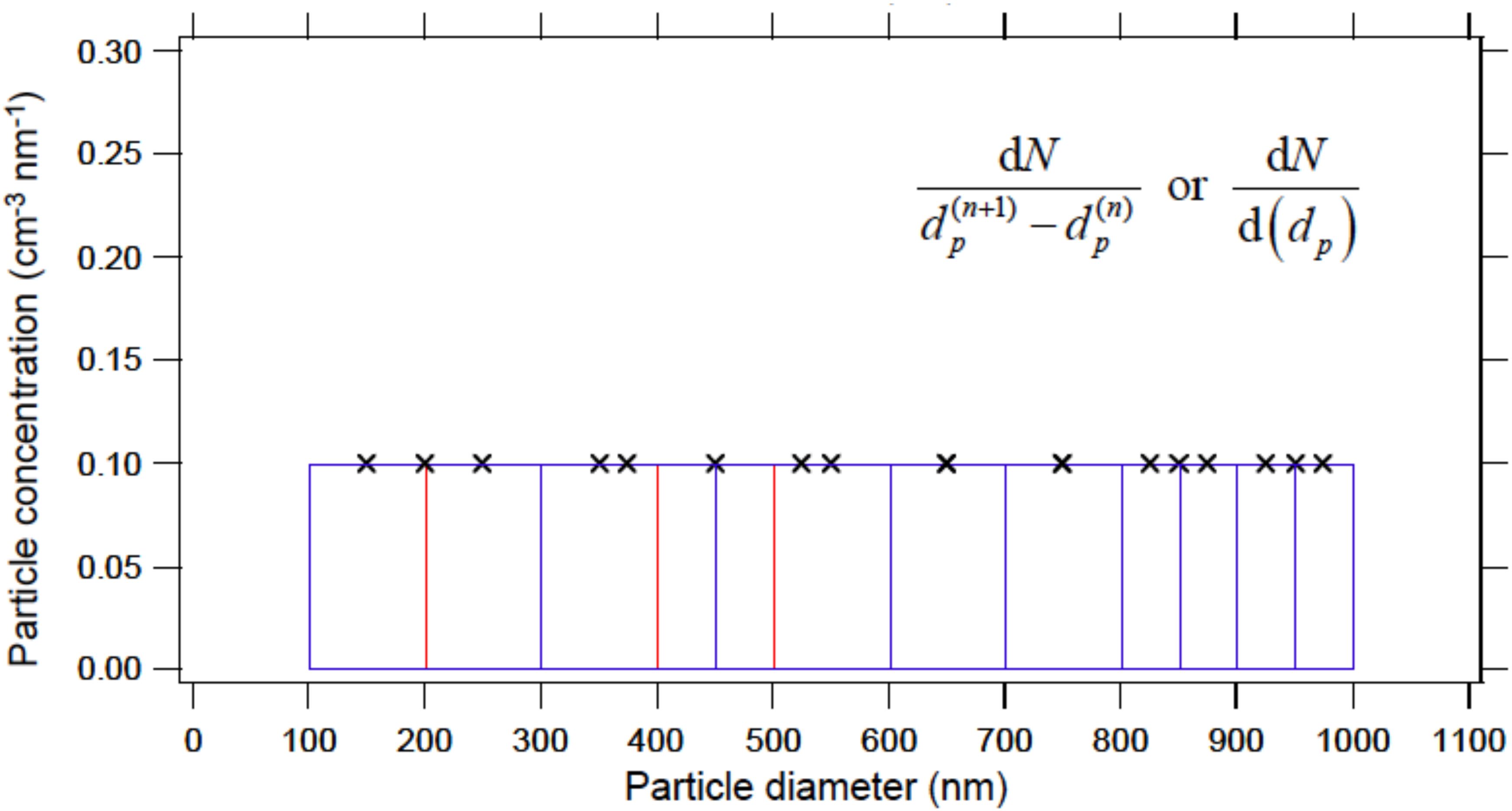
- If we use a different instrument with different channel widths, the shape of the distribution changes:



Schneider, 2010

Size distributions

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



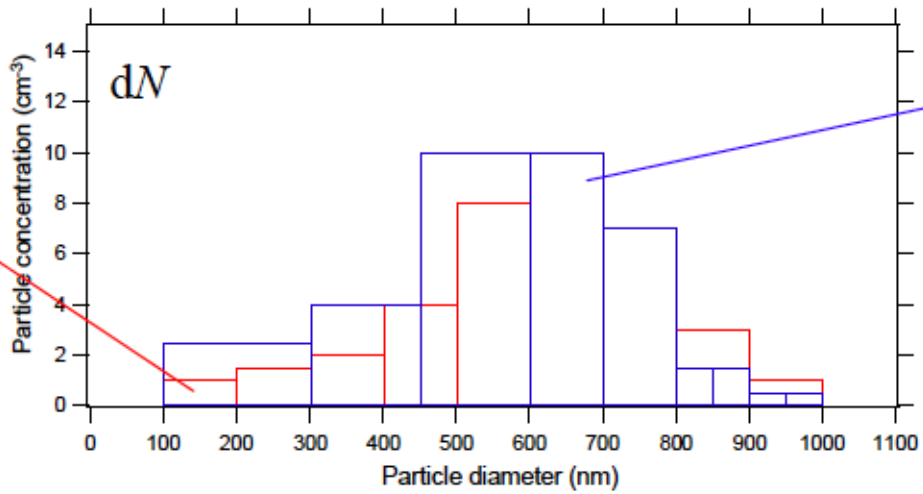
Schneider, 2010

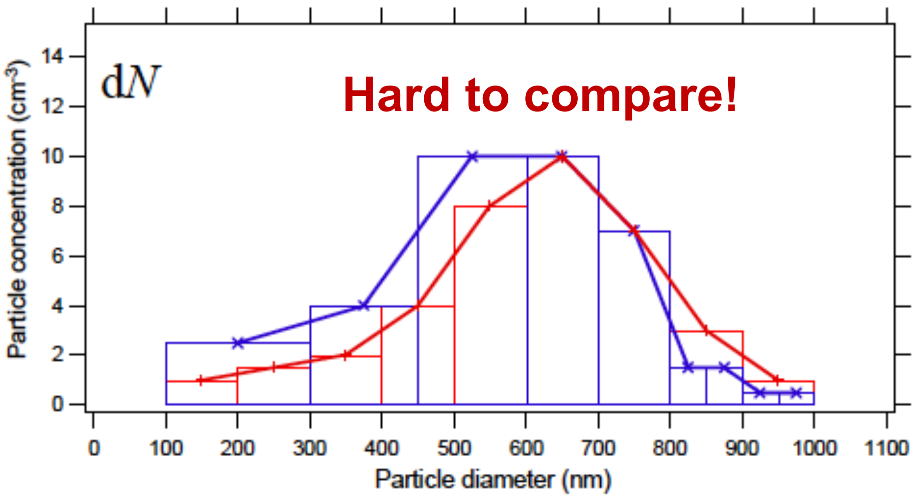
Size distributions

- 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





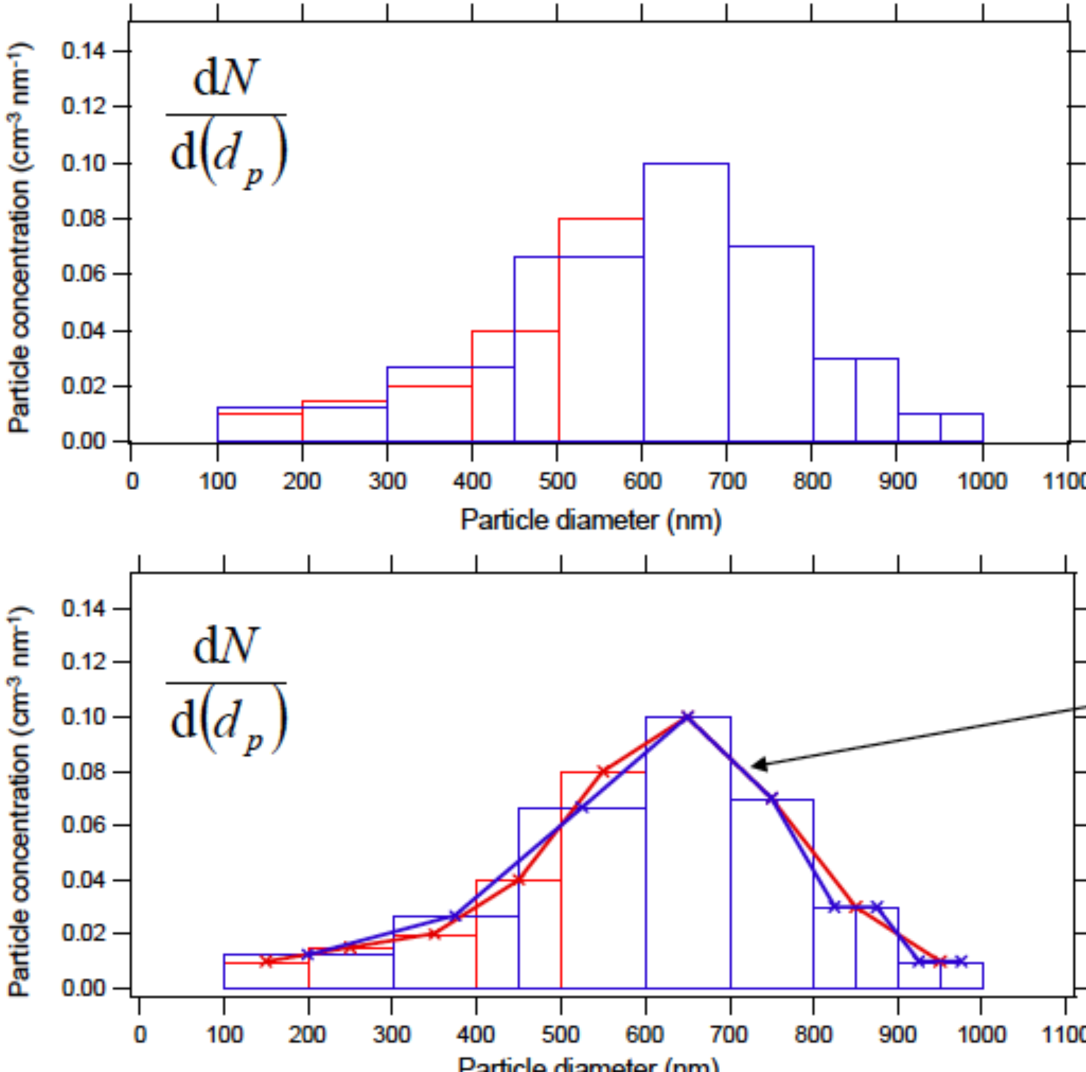
"Instrument 2"

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

- Divide by the channel widths… (better)



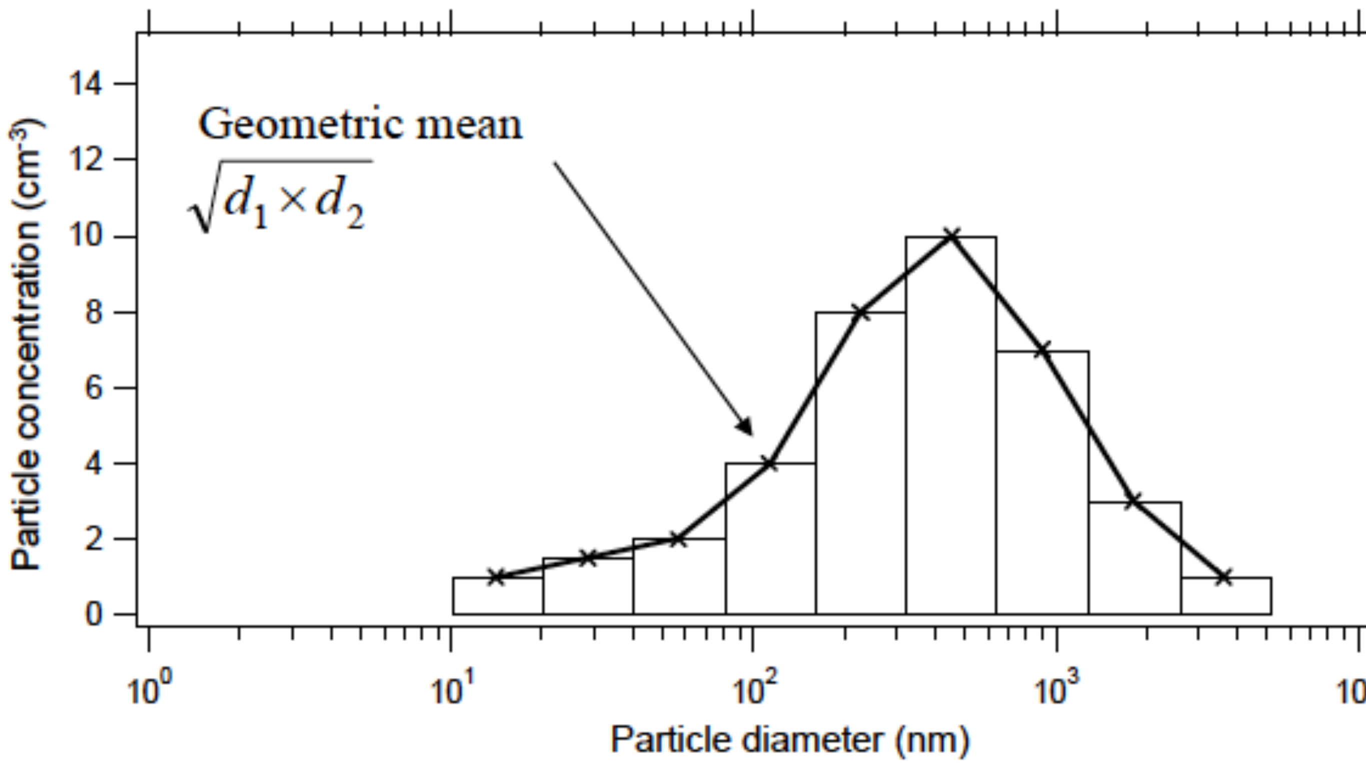
Almost the same distribution despite different measurement channels for the two instruments

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) and refer to particle size bins by their geometric mean diameter

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



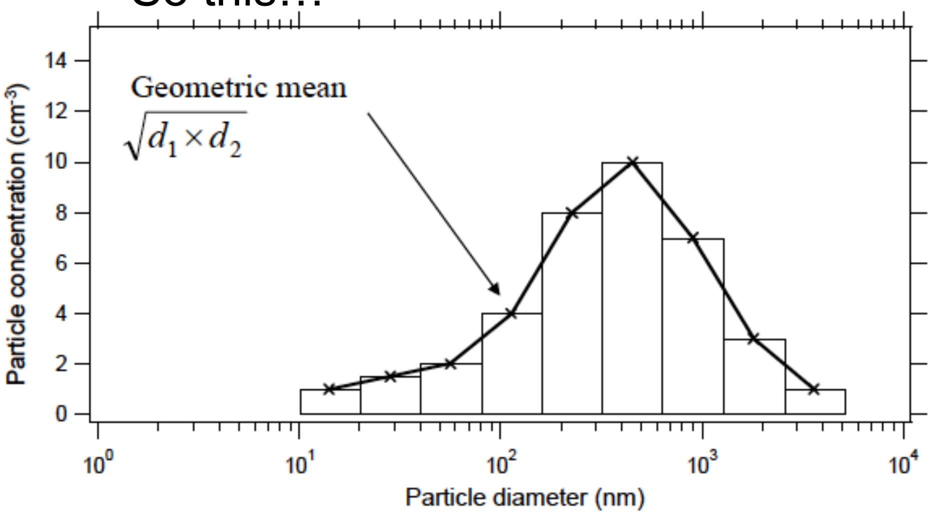
Schneider, 2010

Size distributions

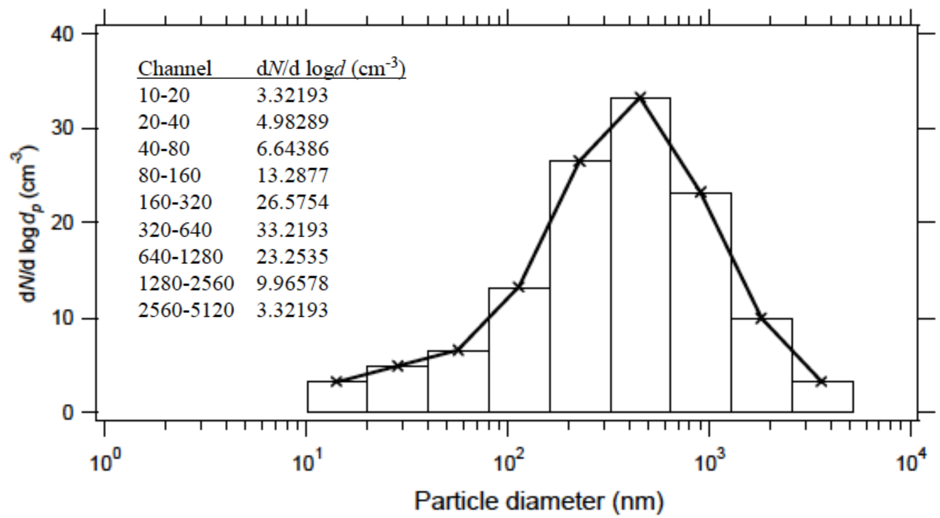
- For log scales we need to account for the channel width differently:

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

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

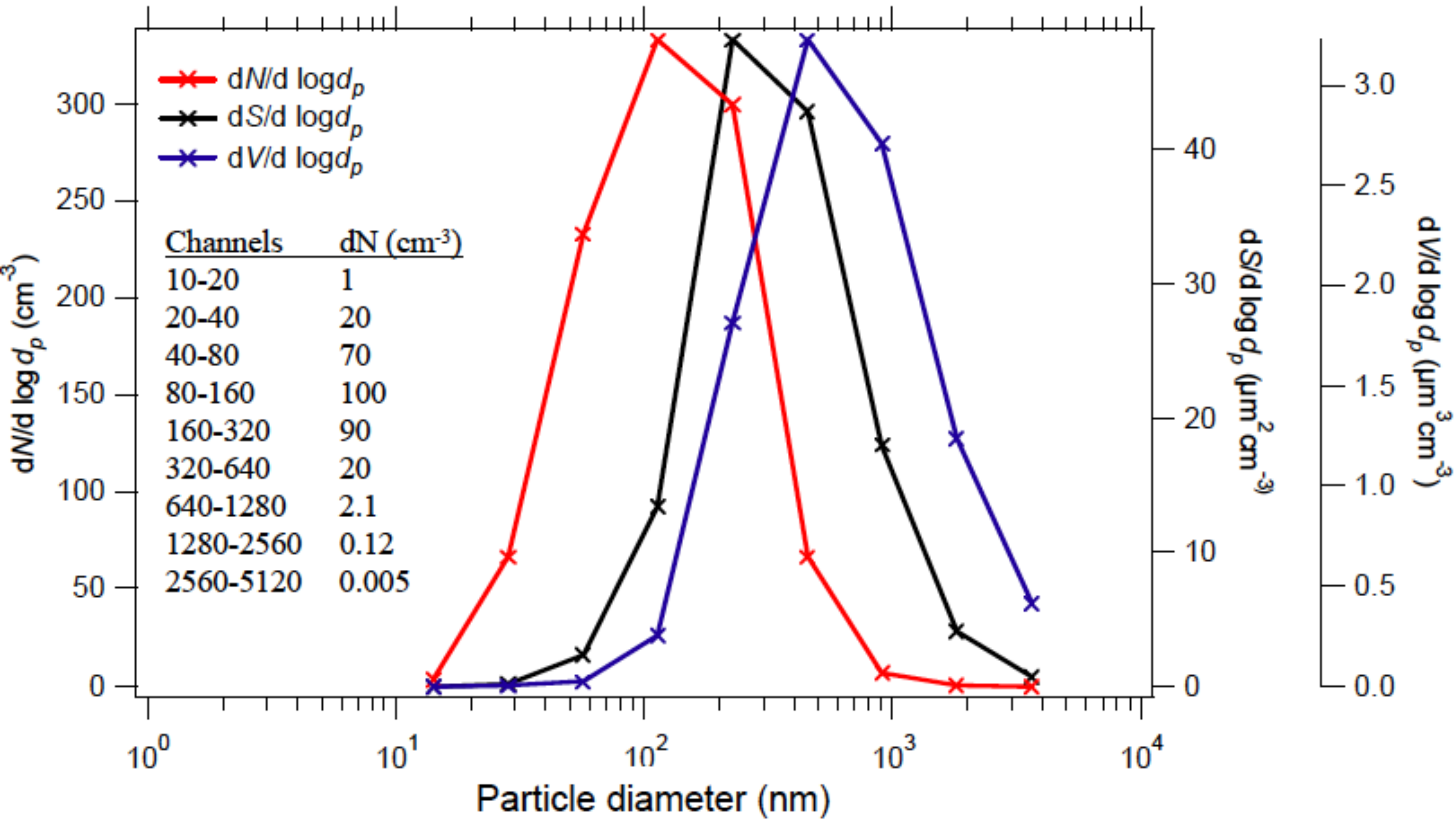
- Assuming spherical particles, the number concentration for each particle diameter can be converted to surface and volume concentrations:

- 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

- 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

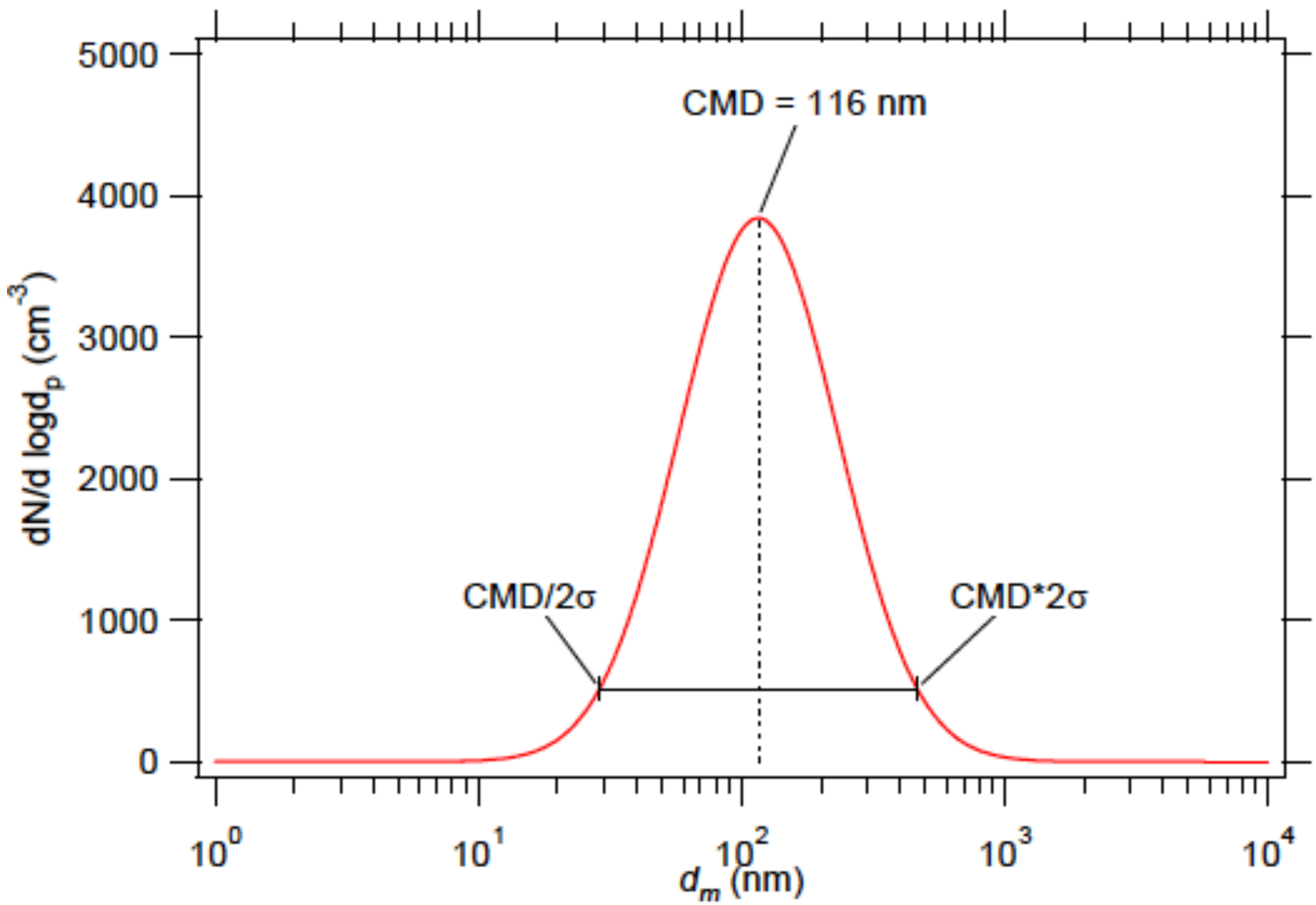
$\ln(d_g)$ or $\log(d_g)$ is dimensionless

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

Schneider, 2010

Lognormal distribution

- 95% of particles are in a size range given by: $e^{\ln \bar{d}_g \pm 2 \ln \sigma_g}$



Schneider, 2010

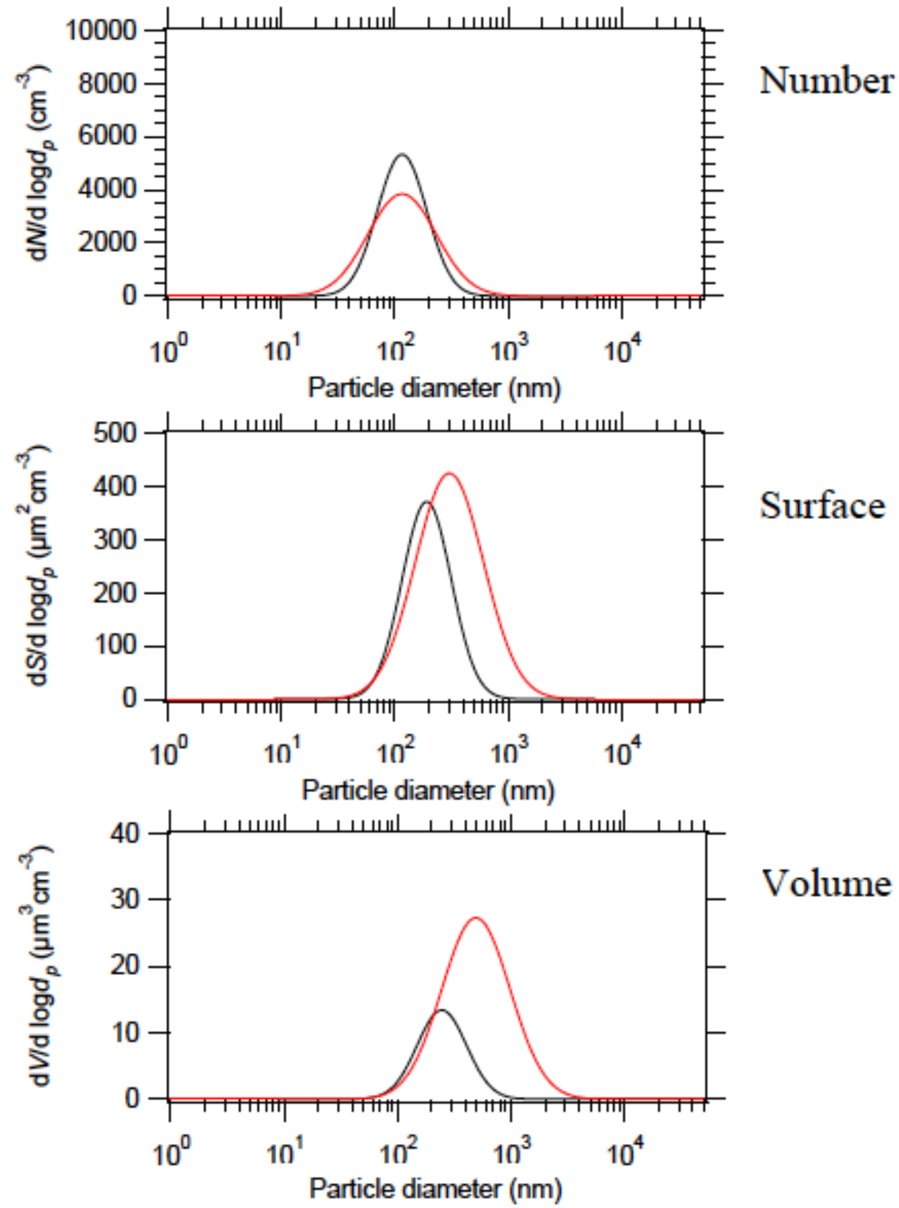
Lognormal distribution: dN, dS, and dV

- Example distribution for one 'mode':

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

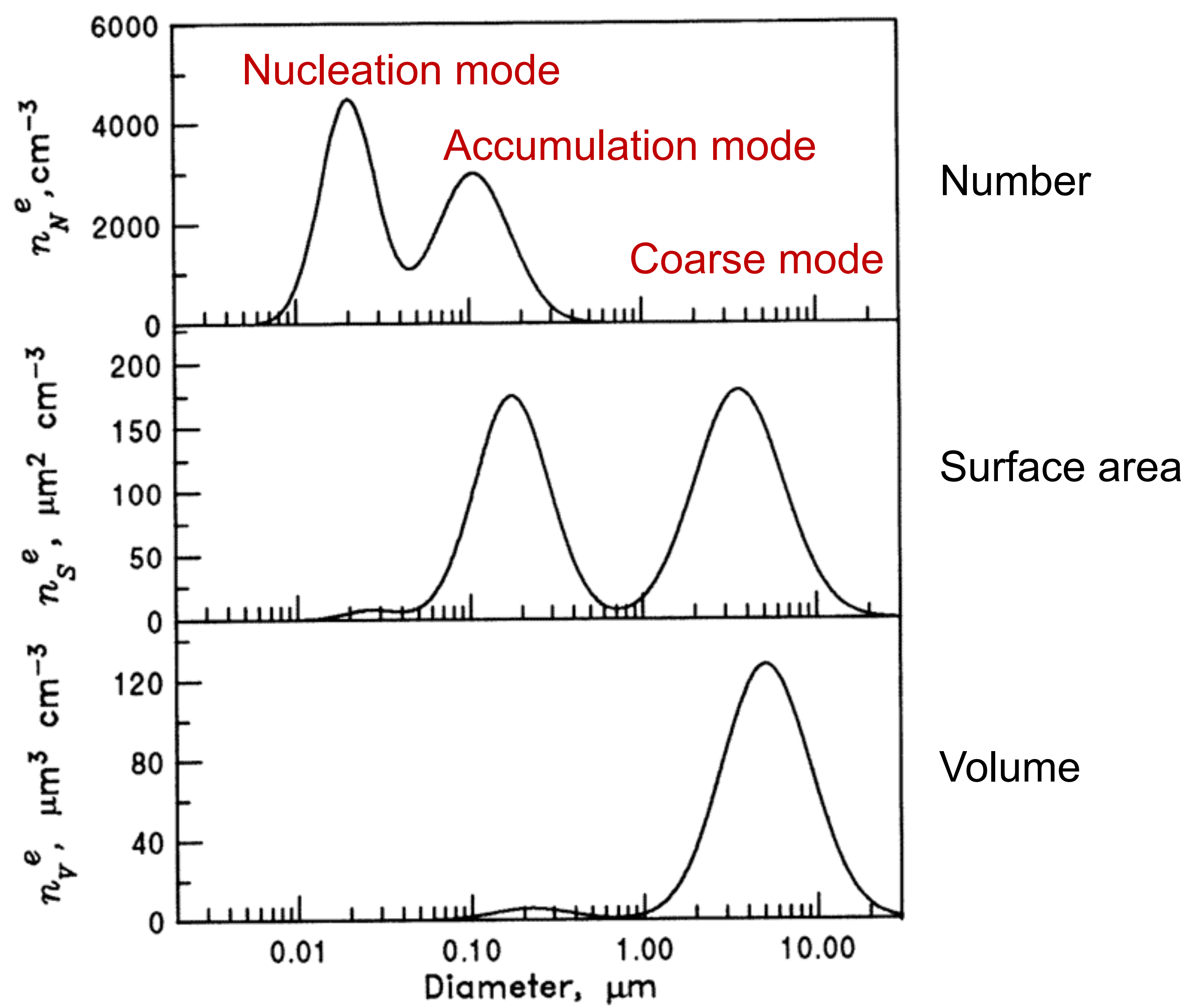
$$\sout{\sigma_g = 1.65}\quad \sigma_g = 2.0$$

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



Schneider, 2010

Typical aerosol distributions include multiple 'modes'



Lognormal distributions: Summing across modes

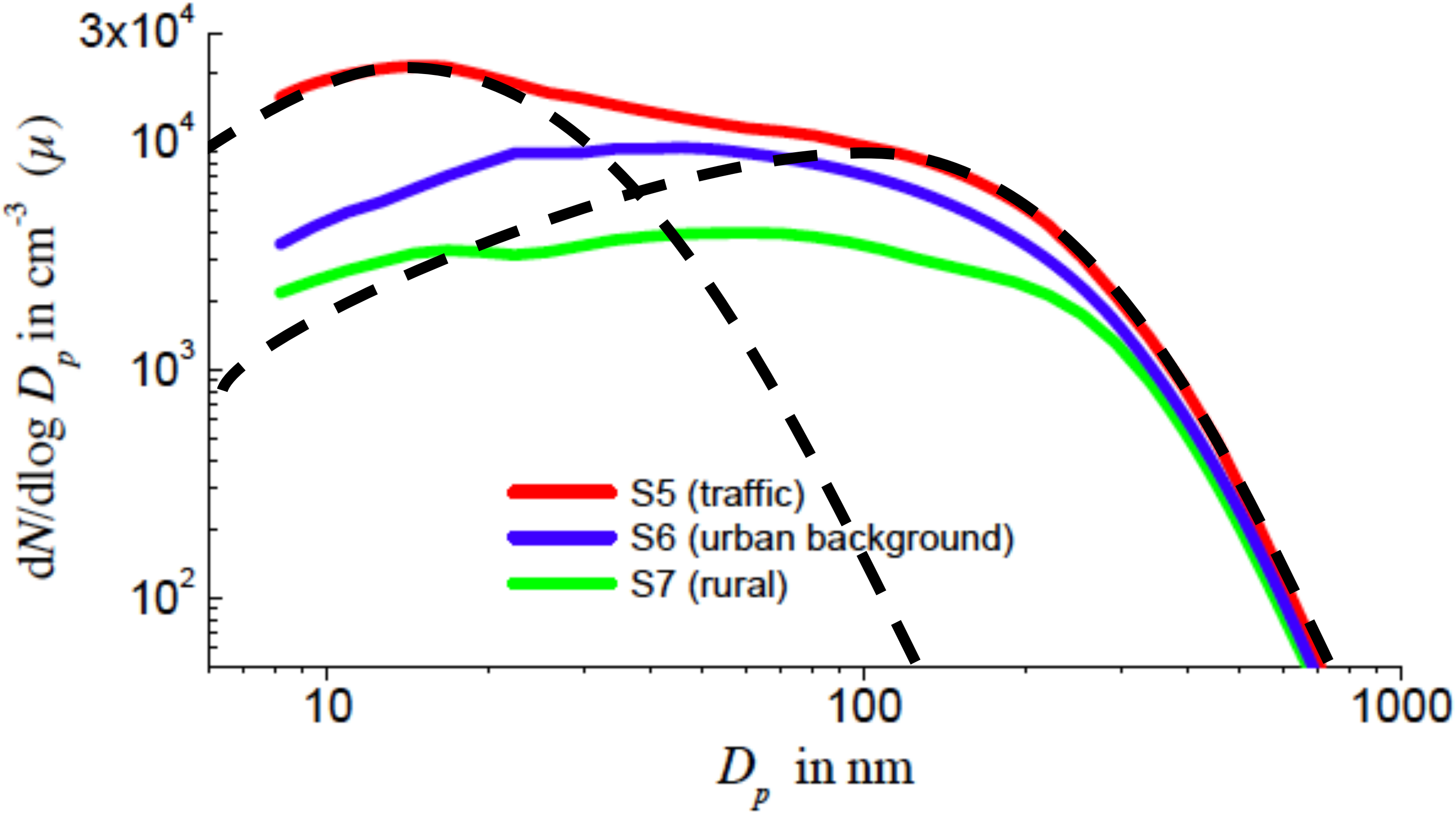
$$\frac{dN}{d\log d_p} = \sum_{i=1}^{n} \frac{N_i}{\sqrt{2\pi}\log\sigma_i} e^{\left(-\frac{(\log d_p - \log \bar{d}_{g,i})^2}{2(\log\sigma_i)^2}\right)}$$

	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).

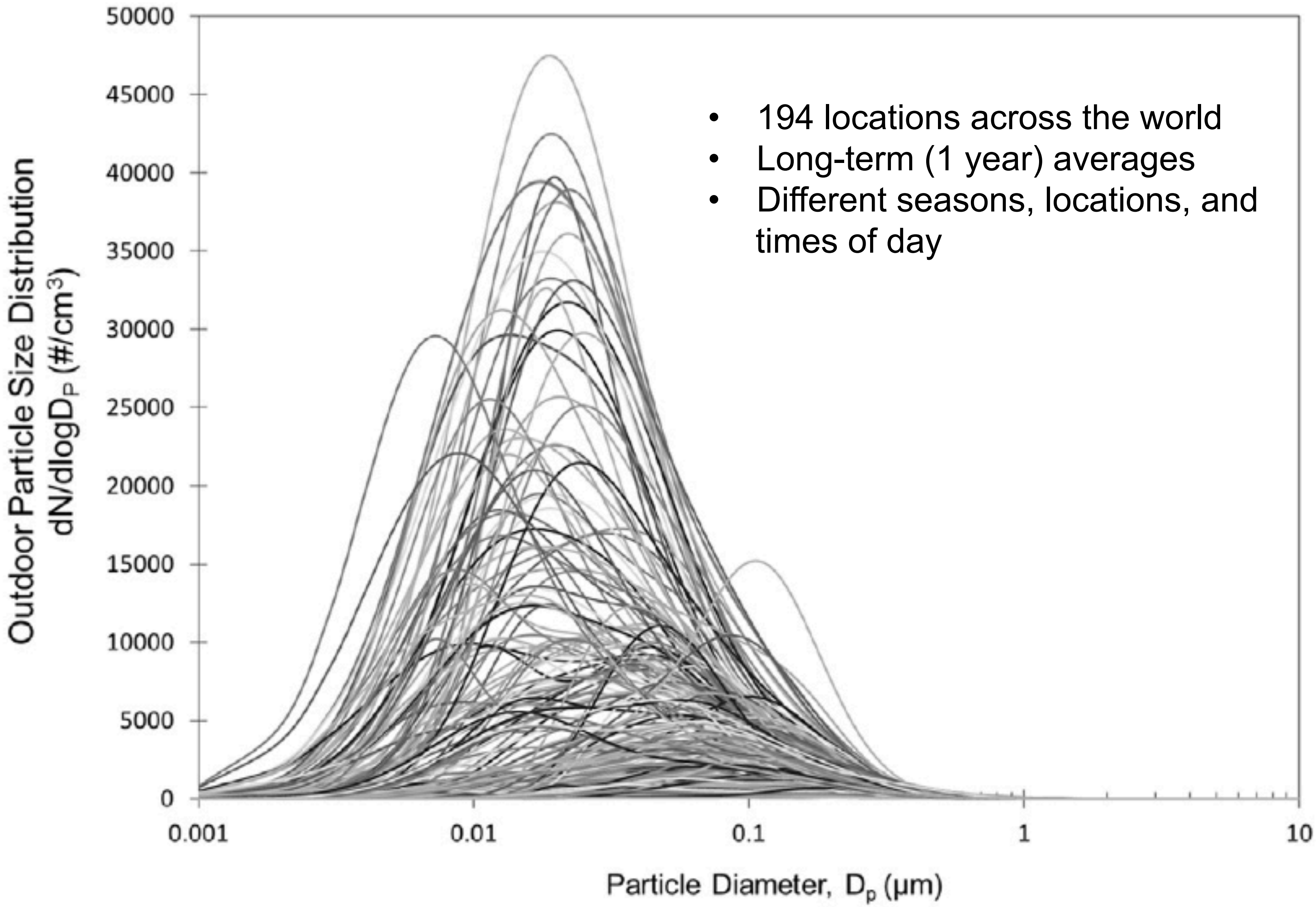
Typical outdoor PSDs

- Submicron particles outdoors in 3 locations in Germany



Costabile et al. 2009 *Atmos Chem Phys*

Typical outdoor PSDs



- 194 locations across the world
- Long-term (1 year) averages
- Different seasons, locations, and times of day

Azimi et al. 2014 *Atmos Environ*

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

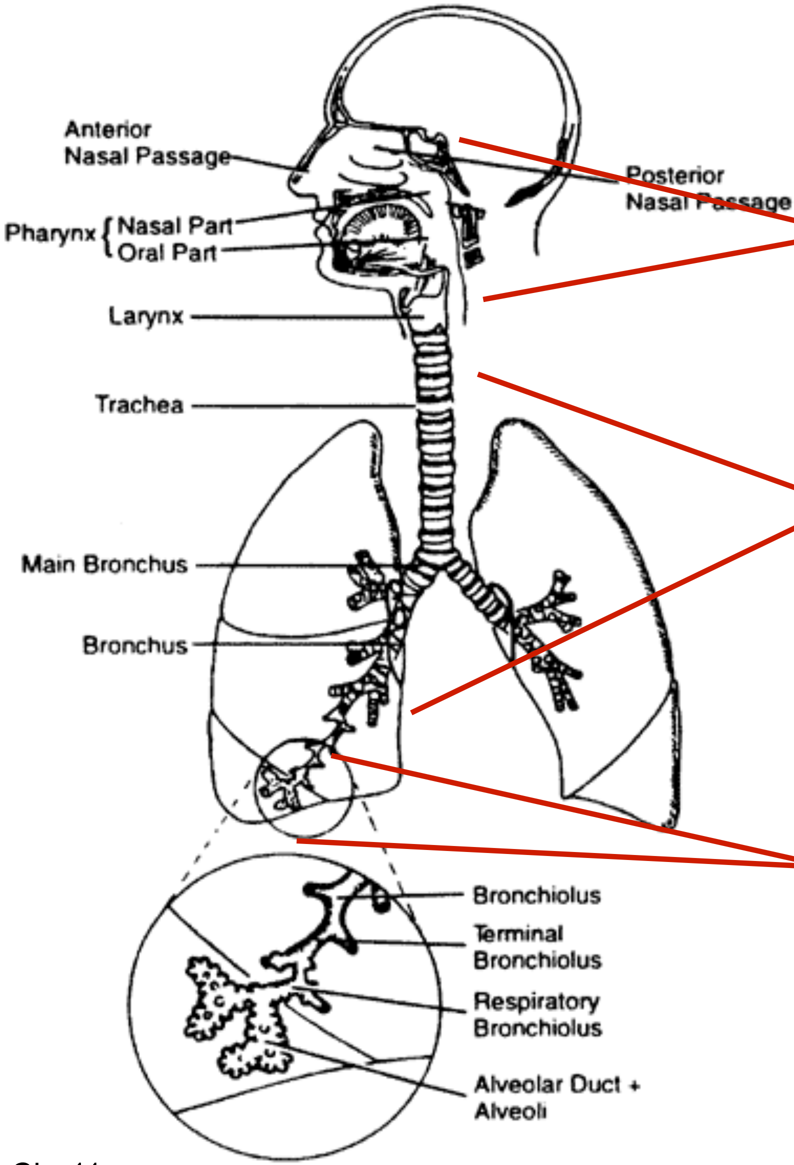
  ~0.5 L/breath at rest

  ~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



Nasopharyngeal

Tracheobronchial

(N&T regions “cleaned” by mucus)

Alveolar

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

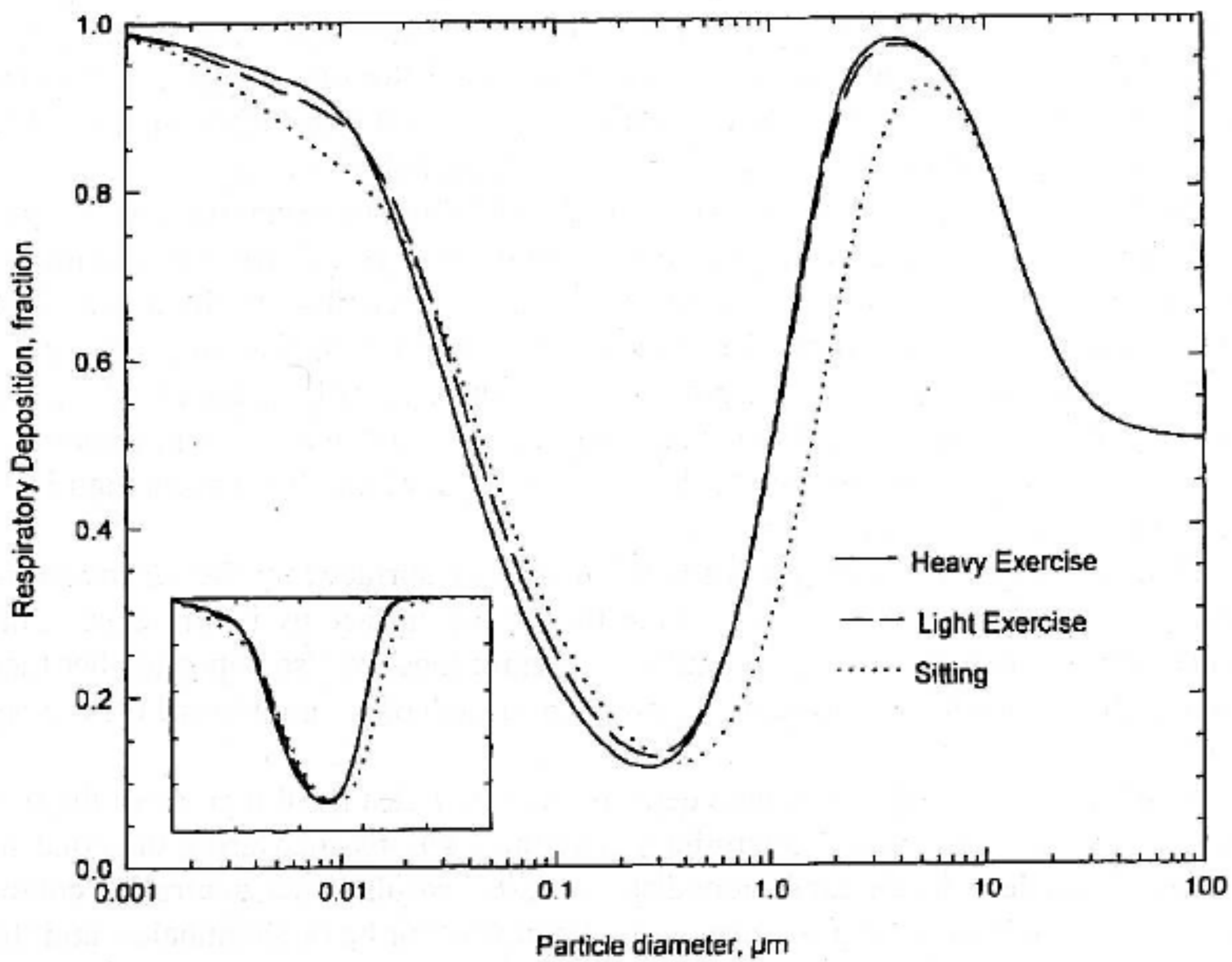
Particle deposition in lungs

- 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

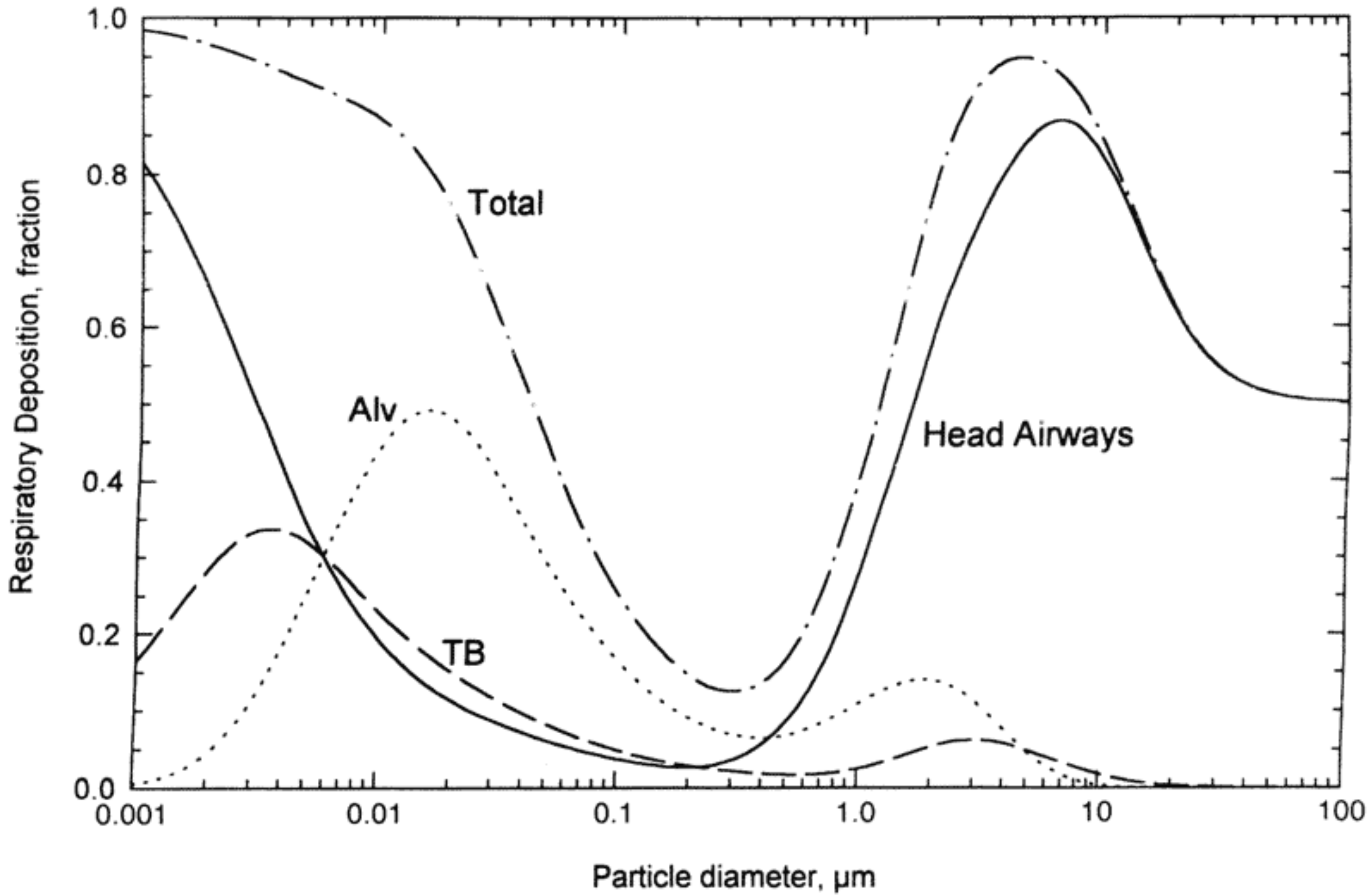
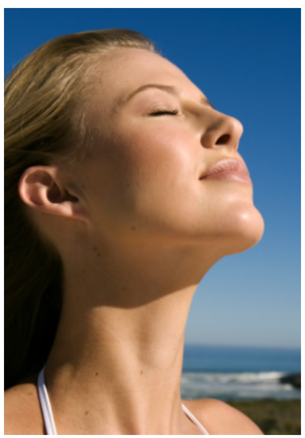


FIGURE 11.3 Predicted total and regional deposition for light exercise (nose breathing) based on ICRP deposition model. Average data for males and females.

Hinds, 1999 Ch. 11

Alveolar deposition by breathing type

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



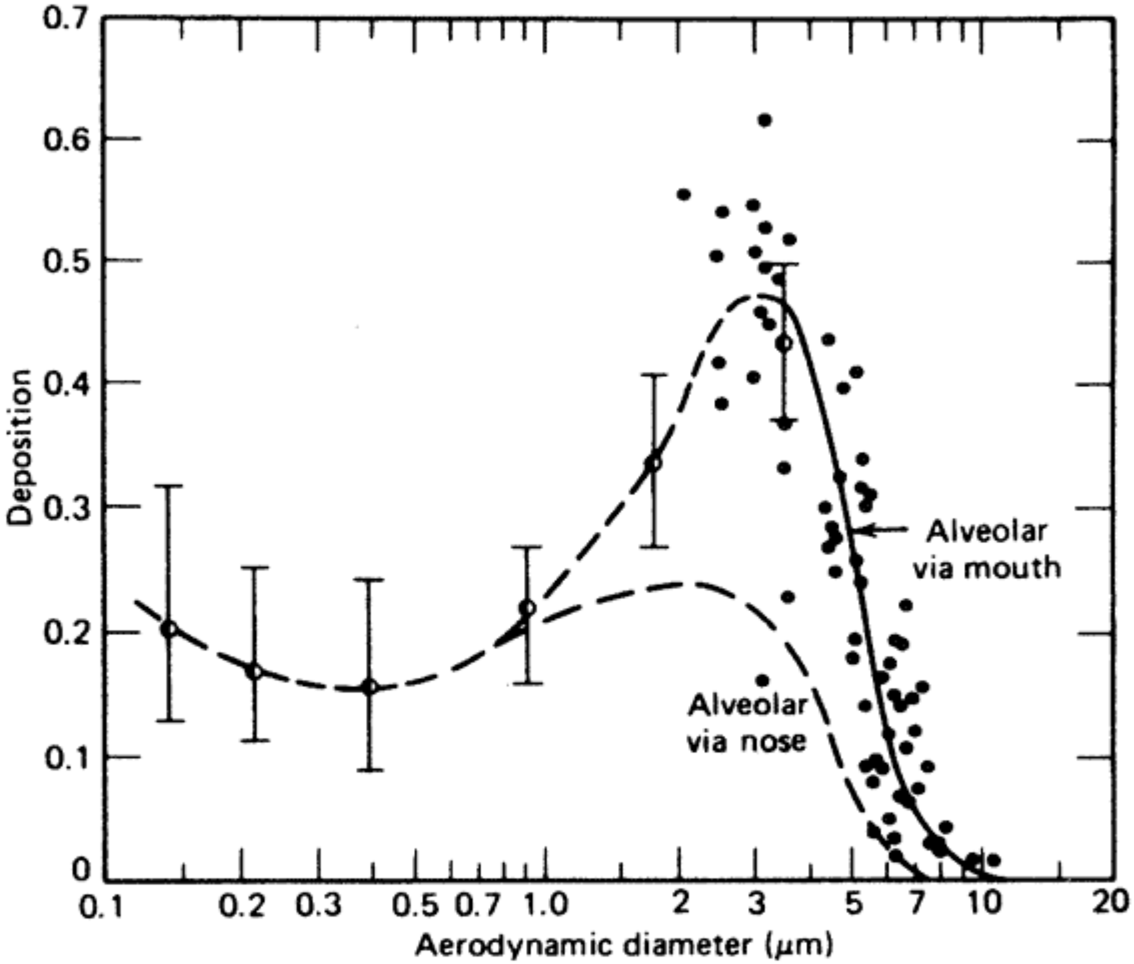


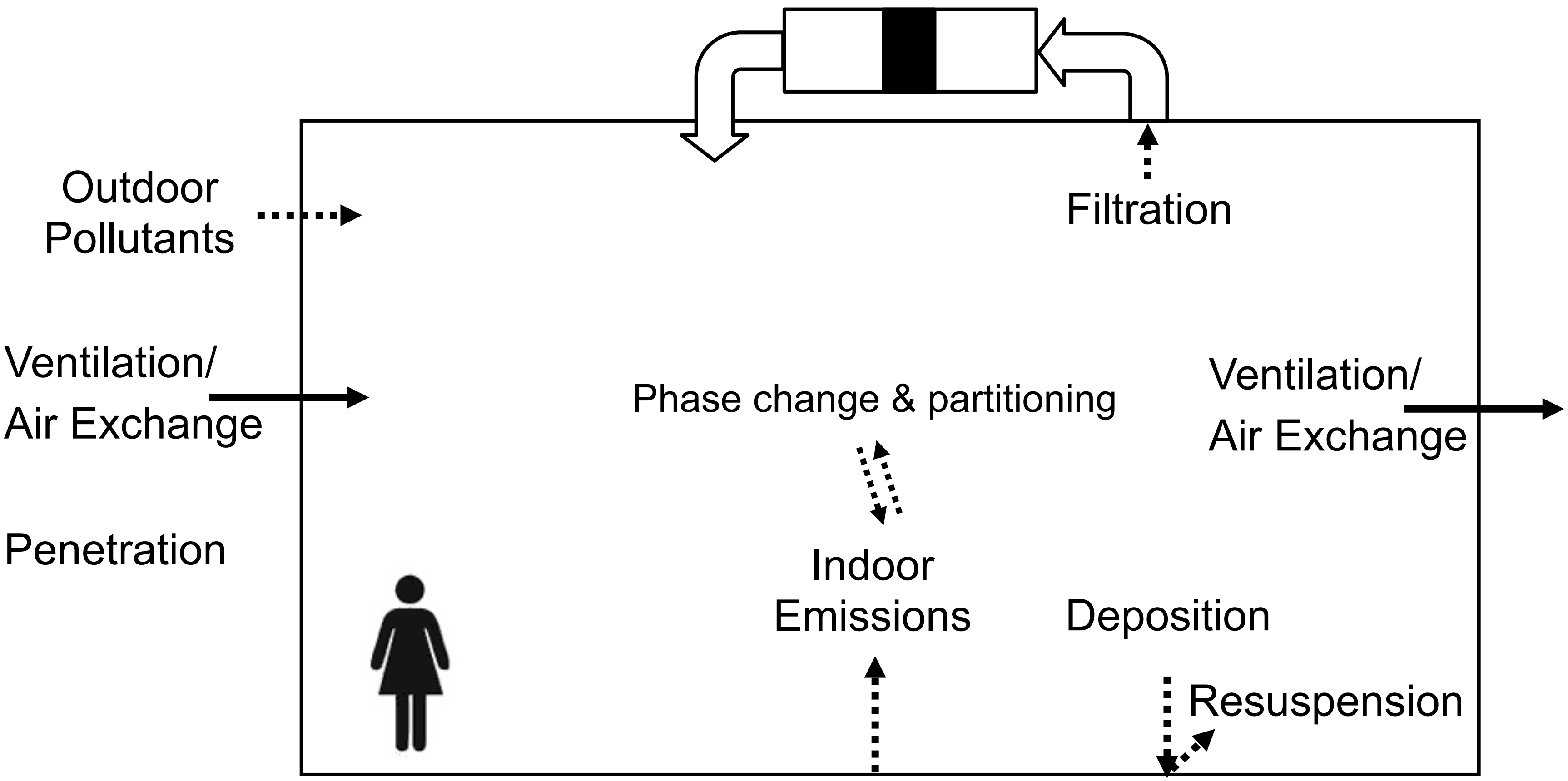
FIGURE 11.4 Experimental data for deposition in the alveolar region. Deposition is expressed as a fraction of mouthpiece inhalation versus aerodynamic diameter (geometric diameter used below 0.5 μm). Reprinted with permission from Lippmann (1977).

Hinds, 1999 Ch. 11

So what?

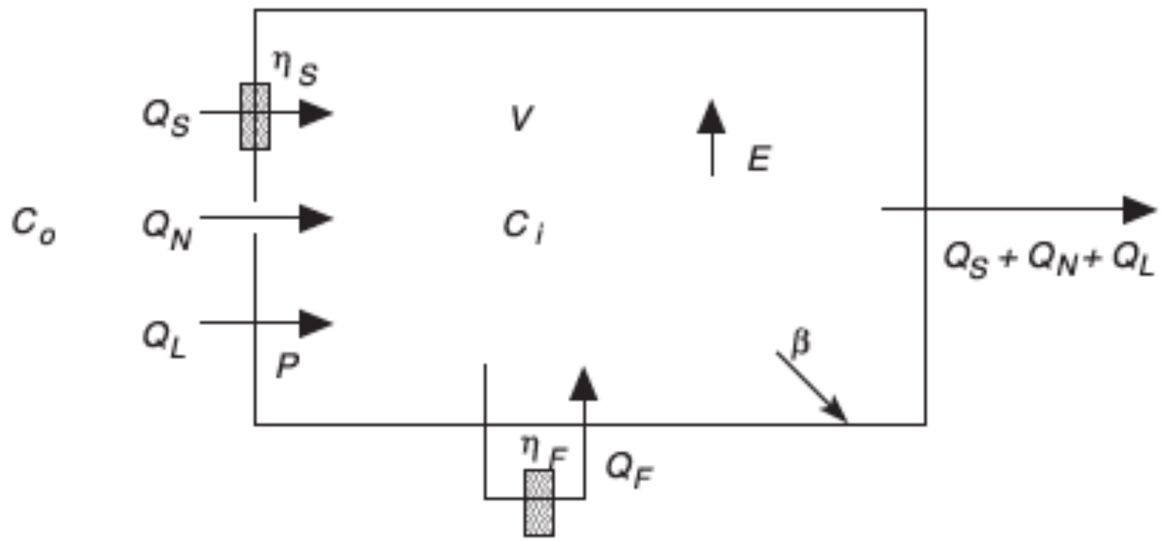
- We now understand more about particle sizes
  - And how different size particles deposit in different regions of our respiratory system
- We can examine different sources to determine their sizes
  - e.g., ETS or cooking particles
- And we can examine what particles will deposit in lungs?
  - And in 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

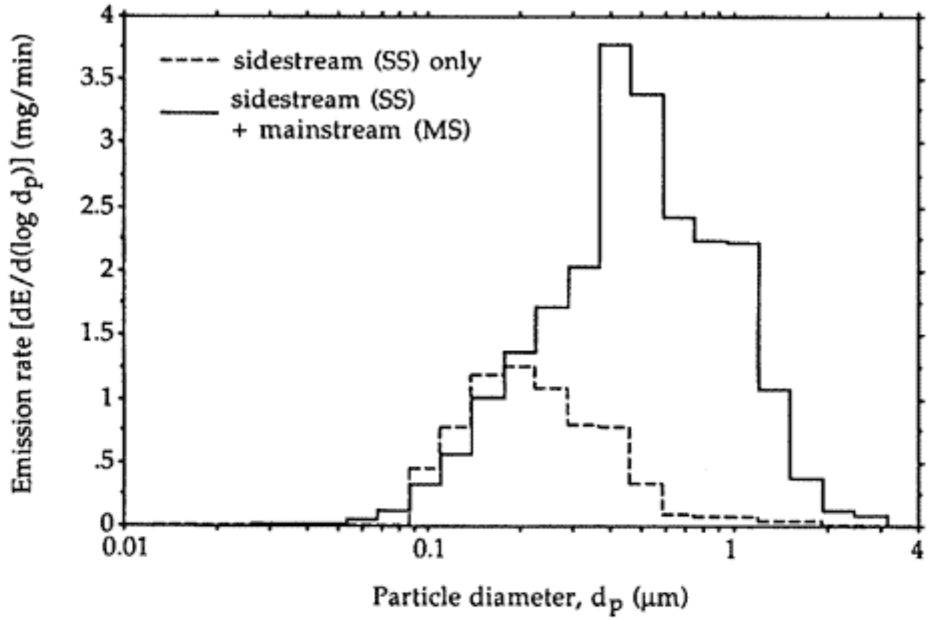
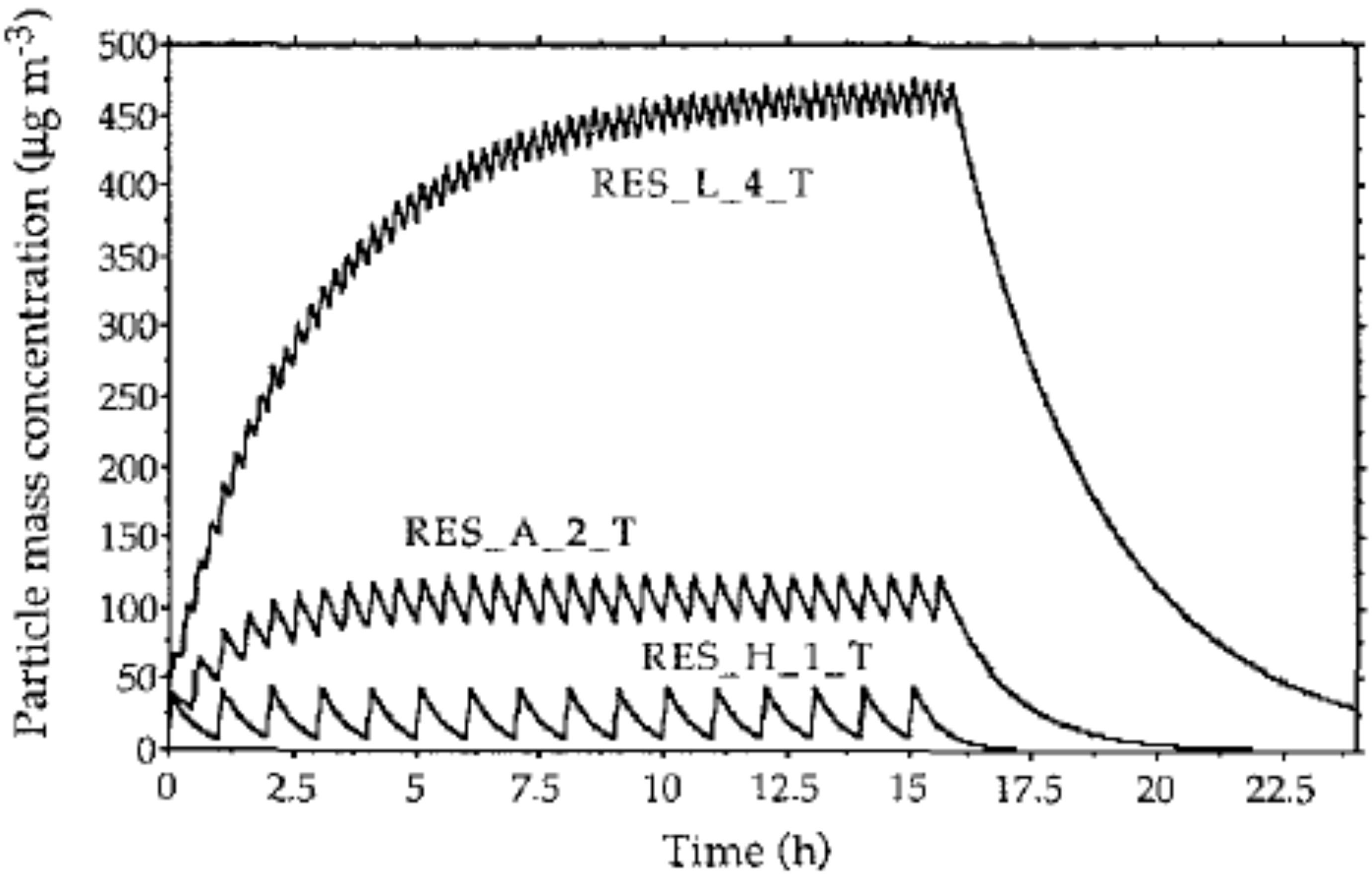


FIGURE 1. Effective particle emission rate from a burning cigarette as a function of particle diameter. The form of the figure is such that the area under a curve between two particle sizes is proportional to the mass emission rate of all particles within those size limits. These experiments were reported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

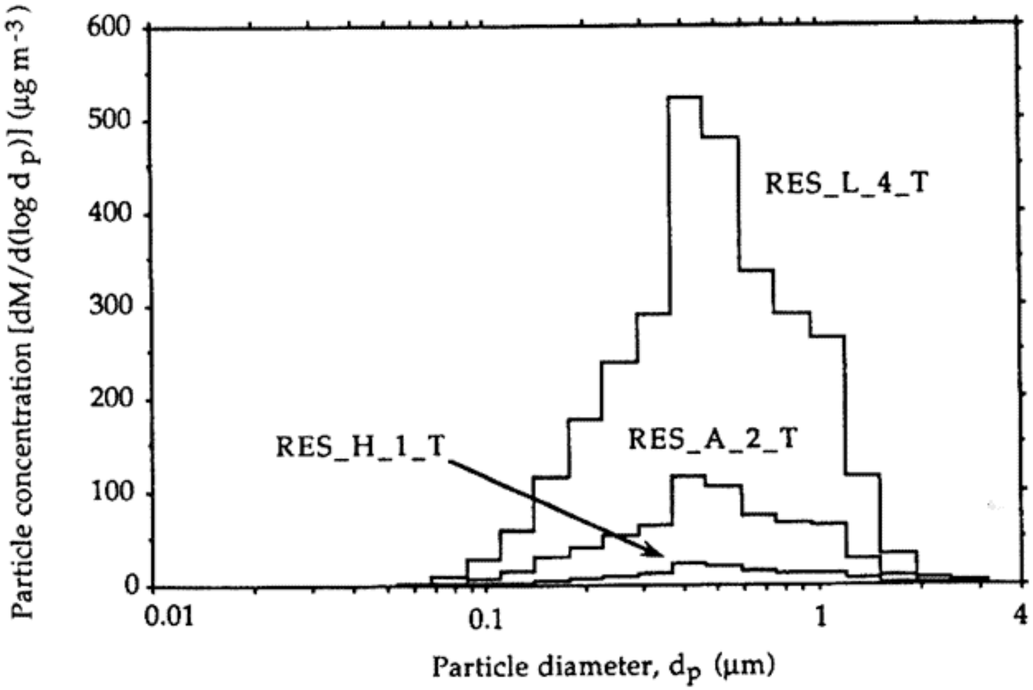


FIGURE 4. Average environmental tobacco smoke particle size distribution over 24-h period for three residential simulations corresponding

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**

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

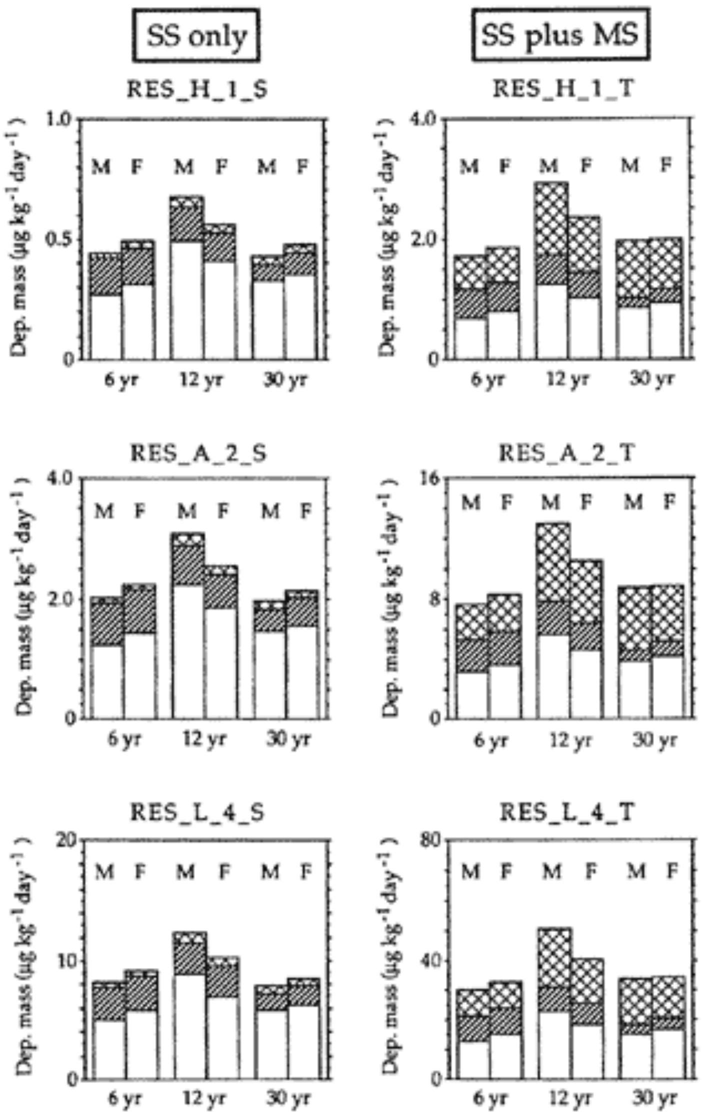
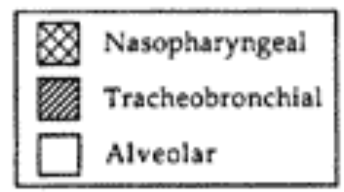
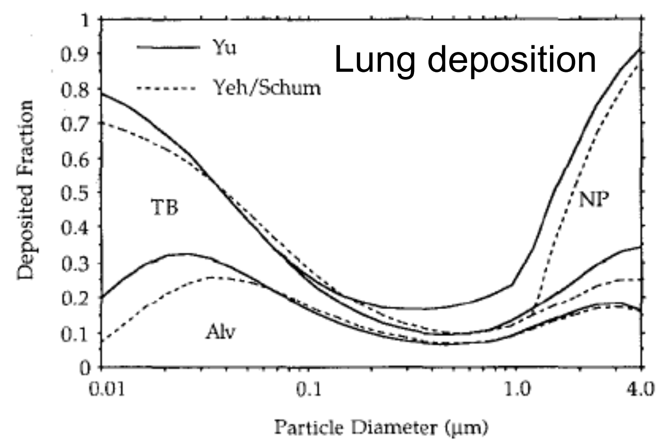


FIGURE 5. Regional lung deposition of environmental tobacco smoke particles from simulations of residential exposure. Each frame shows results for three age groups and each gender for one combination of smoking rate, particle emission profile, and building ventilation rate. The height of each bar gives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

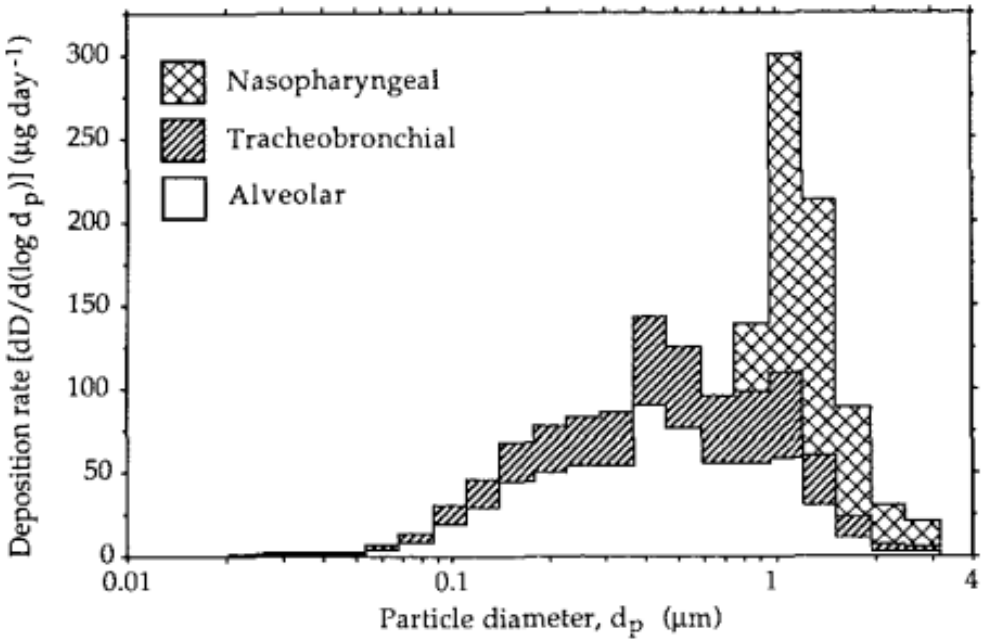
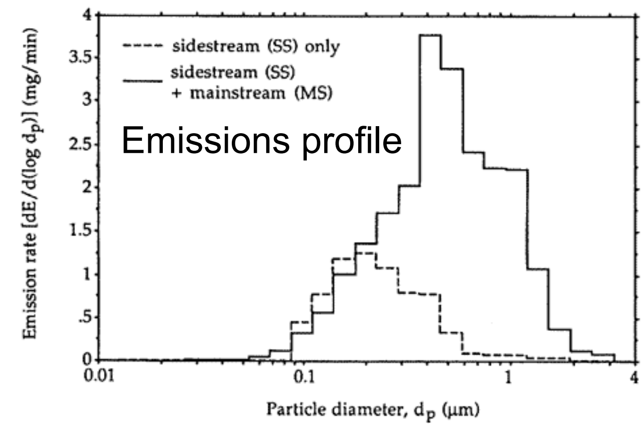
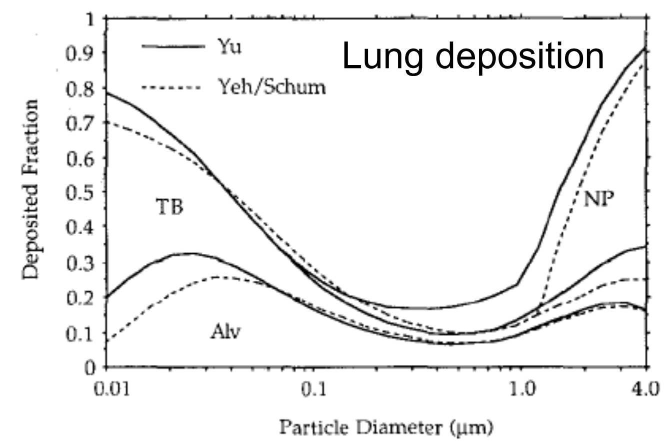


FIGURE 6. Size distribution of deposited mass of environmental tobacco smoke particles in 6-year-old boy for simulation RES_A_2_T. The form of the figure is such that the shaded area between two particle sizes is proportional to the average 24-h mass deposition rate of particles within those size limits.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





Nazaroff et al., 1993 *AS&T*

Next time

- Particle emission source characteristics, deposition, resuspension, and penetration through cracks