CAE 553 Measurements and Instrumentation in Architectural Engineering

Fall 2018

November 13, 2018

IAQ: Particulate matter

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Why measure indoor air?

- We spend most of our time indoors
  - Nearly 90% of the time, on average in the developed world
  - Approximately 18 hours indoors for every 1 hour outdoors
- We bring materials, furnishings, appliances, and activities into buildings, most of which emit/release a variety of substances
  - Some harmful, some not
- Buildings also exchange air without the outdoors
  - Outdoor air pollution becomes indoor air pollution
  - Indoor pollution becomes outdoor pollution
- Indoor air is a dominant environmental exposure
  - More than half of the body's intake of air is done so inside homes
  - 80-90% inhaled in buildings generally

Some important classes of indoor pollutants

- Particulate matter
  - Size, shape, mass, constituents (e.g., elemental, chemical, metals)
- Inorganic gases
  - CO, NO_2, O_3, NH_3, H_2S, SO_2
- Organic gases (may partition to solids, binding to particles)
  - Volatile organic compounds (hundreds of these)
  - Semi-volatile organic compounds (SVOCs)
  - Carbonyls
  - Acids
  - Radicals
- Radioactive gases and particles (e.g. radon)
- Microbiological particles
  - Bacteria, viruses, fungi, allergens

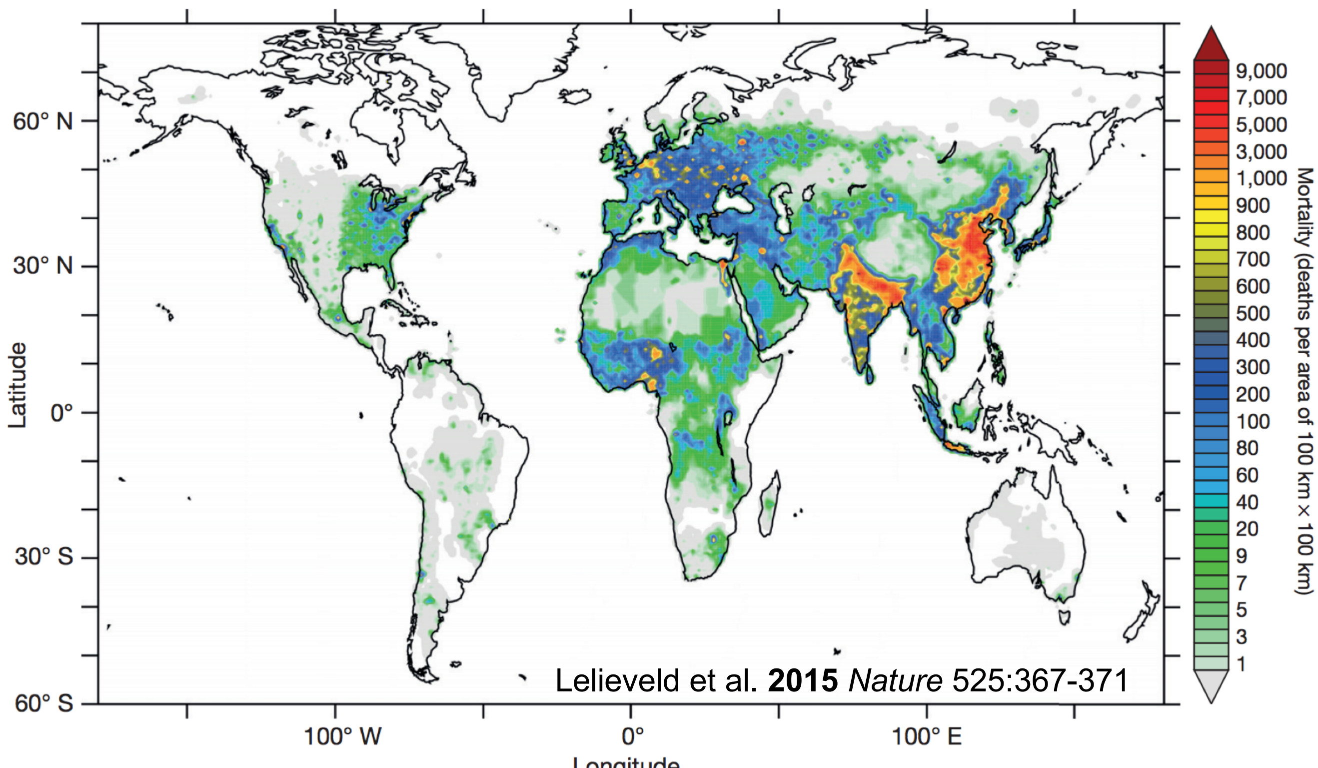
Types of indoor emission sources

- Building materials (VOC/SVOC)
  - Wood and composite wood
  - Gypsum wallboard
  - Concrete
  - Carpet
  - Vinyl flooring
- Furnishings (VOC/SVOC)
  - Bedding
  - Tables
  - Couches/chairs
  - Drapes
- Architectural coatings (VOC/SVOC)
  - Paints
  - Stains
  - Varnishes
- Outdoor-to-indoor transport (all)
- Consumer products (VOC/SVOC)
  - Cleaners
  - Fragrances
  - Personal care products
- Combustion (VOC/PM/SVOC/other)
  - Cigarettes, cigars, pipes
  - Gas stoves
  - Space heaters
  - Candles
  - Incense
- Electronics (PM/VOC/SVOC/other)
  - Laser printers
  - Computers
  - Photocopiers
- Volatilization from water (VOC)
- Soil vapor intrusion (VOC/radon)
- People, pets, insects (biological)

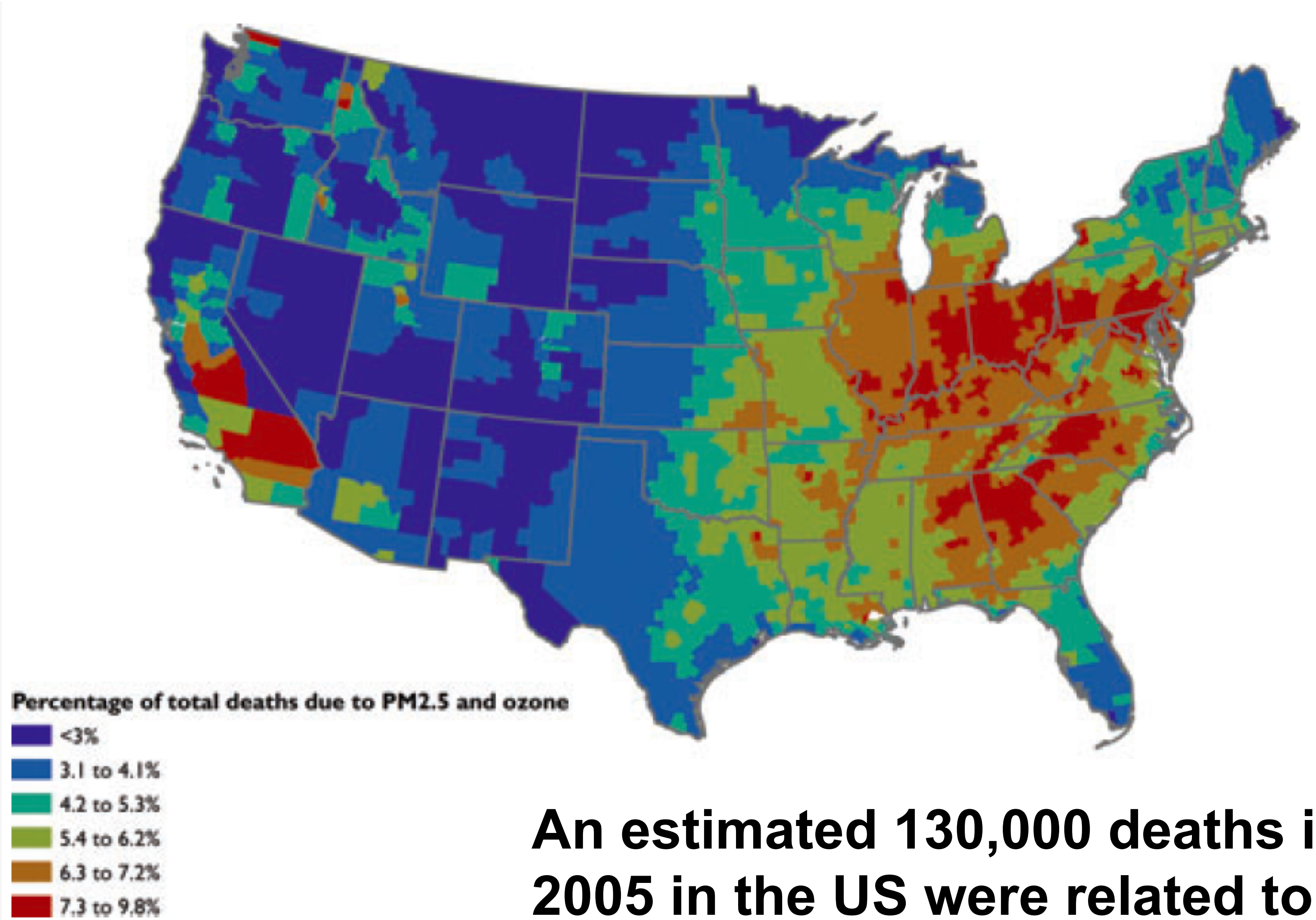
Outdoor air pollution and health

- Documented health effects include:
  - Stroke
  - Heart disease
  - Lung cancer
  - Chronic & acute respiratory diseases (including asthma)
  - Mortality

Outdoor air
3.3 million premature deaths globally in 2010



Outdoor air pollution and health



An estimated 130,000 deaths in 2005 in the US were related to outdoor $PM_{2.5}$ (and 4,700 w/ O_3)

Fann et al., **2012** *Risk Analysis*

Indoor air pollution sources and health

Association between gas cooking and respiratory disease in children

Melia et al., *British Medical Journal* **1977**, 2, 149-152

Indoor Air Pollution and Asthma

Ostro et al., *Am. J. Respir. Crit. Care. Med.* **1994**, 149, 1400-1406

Respiratory Symptoms in Children and Indoor Exposure to Nitrogen Dioxide and Gas Stoves

Garrett et al., *Am. J. Respir. Crit. Care. Med.* **1998**, 158, 891-895

Pollutant Exposures from Natural Gas Cooking Burners

Logue et al., *Environ Health Perspect.* **2014**, 122, 43-50

Association of domestic exposure to volatile organic compounds with asthma in young children

Rumchev et al., *Thorax* **2004**, 59, 746-751

Indoor air pollution sources and health

Cleaning products and air fresheners: exposure to primary and secondary air pollutants

Nazaroff and Weschler, *Atmos Environ.* **2004**, 38, 2841-2865

Frequent use of chemical household products is associated with persistent wheezing in pre-school age children

Sherriff et al., *Thorax* **2005**, 60, 45-49

The Use of Household Cleaning Sprays and Adult Asthma

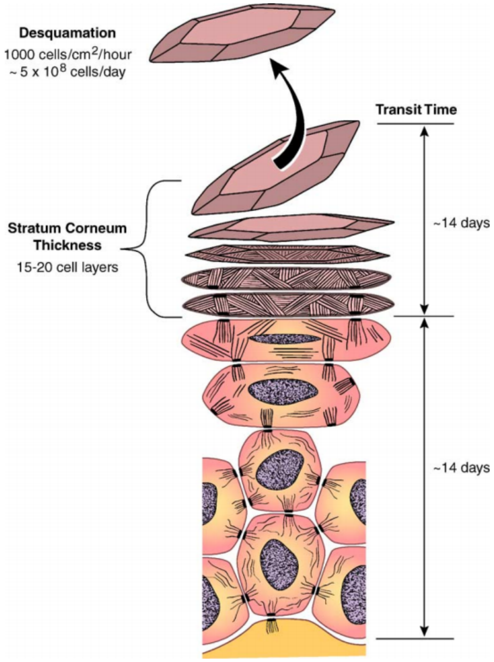
Zock et al., *Am. J. Respir. Crit. Care. Med.* **2007**, 176, 735-741

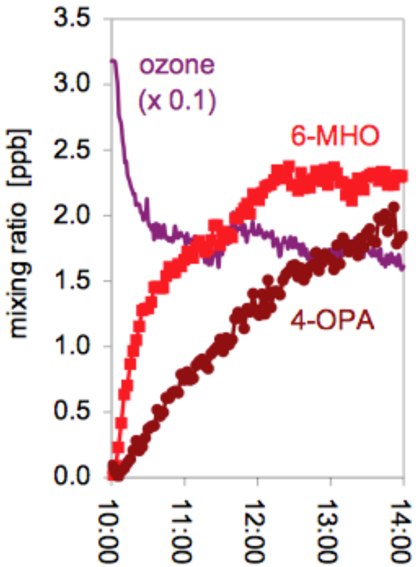
Indoor air pollution sources and health

Epidermal desquamation

Milstone, *J. Dermatol. Sci.* **2004**, 36, 131-140

We shed our entire outer layer of skin every 2-4 weeks





Reactions of ozone with human skin lipids: Sources of carbonyls, dicarbonyls, and hydroxycarbonyls in indoor air

Wisthaler and Weschler, *Proc Nat Acad Sci.* **2010**, 107, 6568-6575

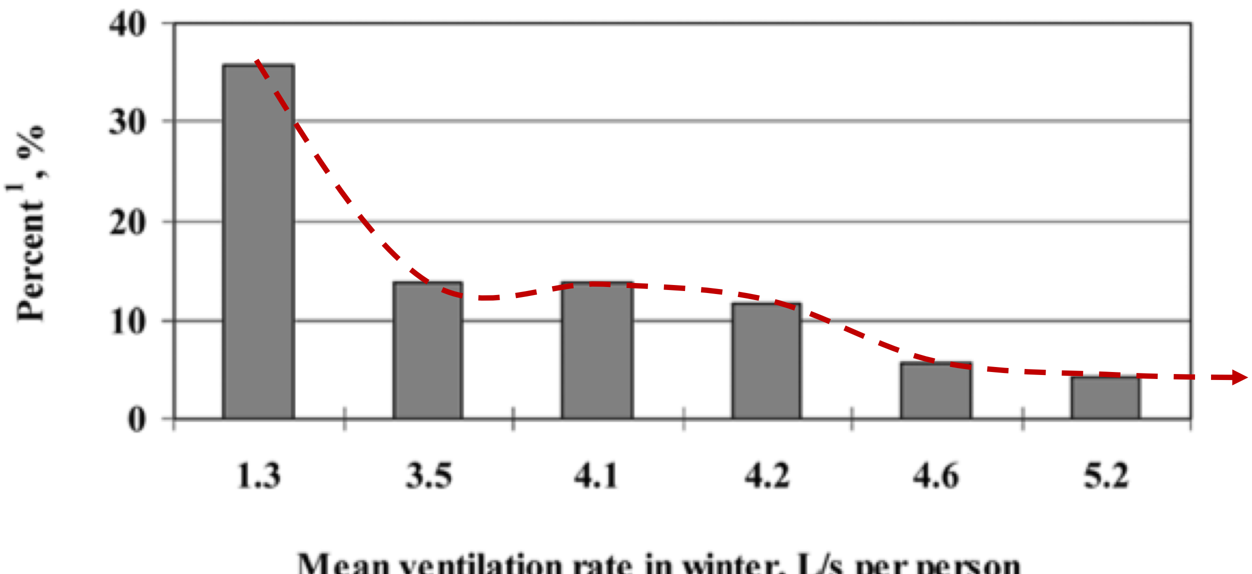
Indoor air pollution sources and health

Evidence of Airborne Transmission of the Severe Acute Respiratory Syndrome Virus

Yu et al., *New Engl. J. Med* **2004**, 350, 1731-1739

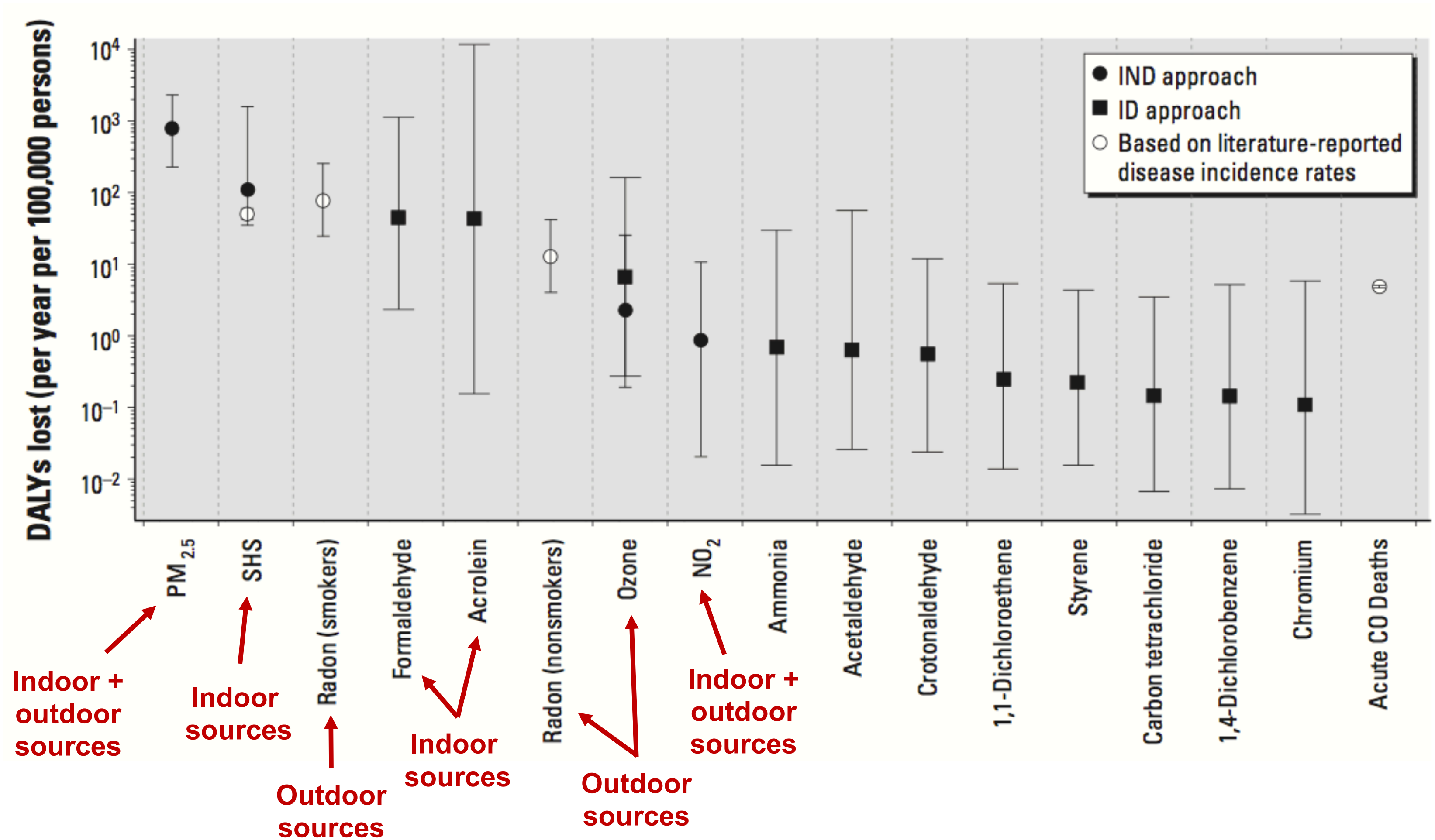
In China, Students in Crowded Dormitories with a Low Ventilation Rate Have More Common Colds: Evidence for Airborne Transmission

Sun et al. **2011** *PLoS ONE* 6:e27140



Indoor air pollution and health (in homes)

The **most harmful indoor air pollutants** inside residences:



Logue et al. **2012** *Environ Health Perspect* 120:216-222

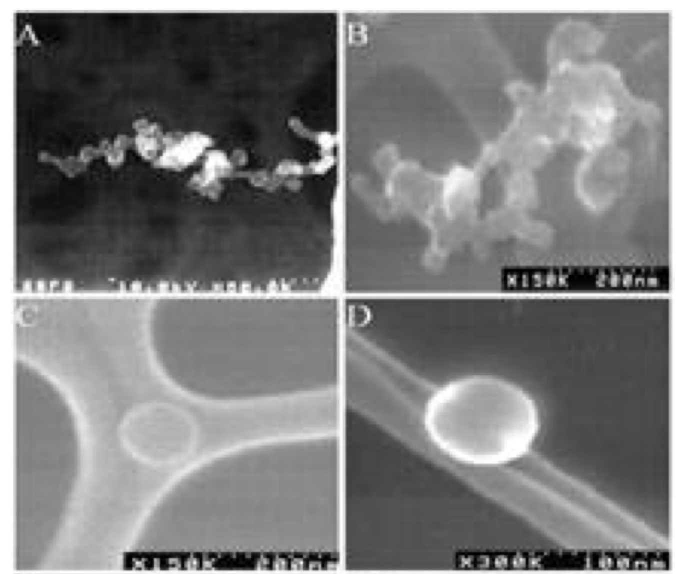
AIRBORNE PARTICULATE MATTER

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

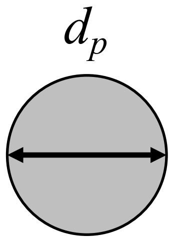
- Visibility effects outdoors



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

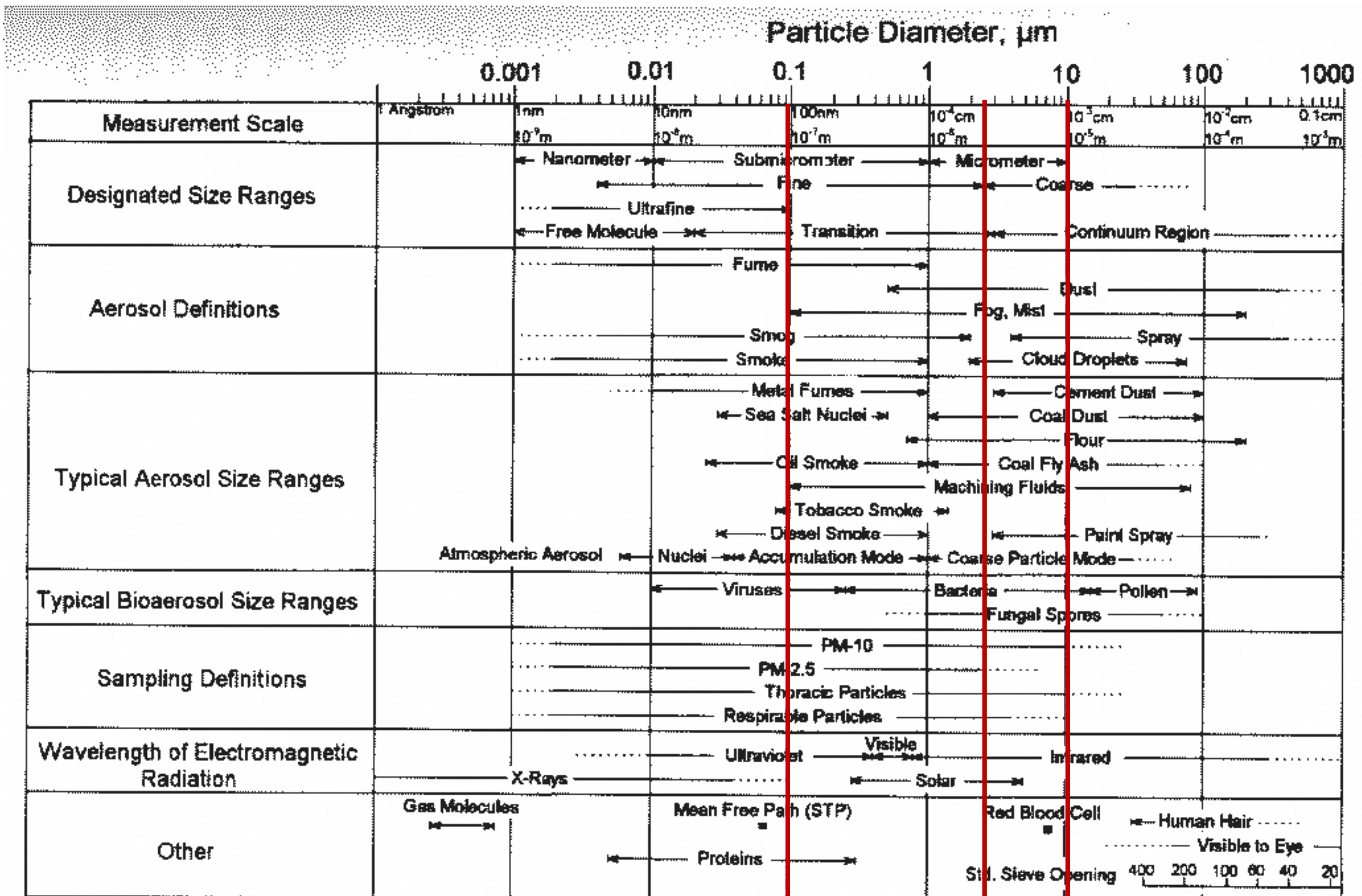


FIGURE 1.6 Particle size ranges and definitions for aerosols.

← UFP ← $PM_{2.5}$ ← PM_{10}

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}
  - $PM_{2.5\text{-}10}$
  - TSP
  - RSP

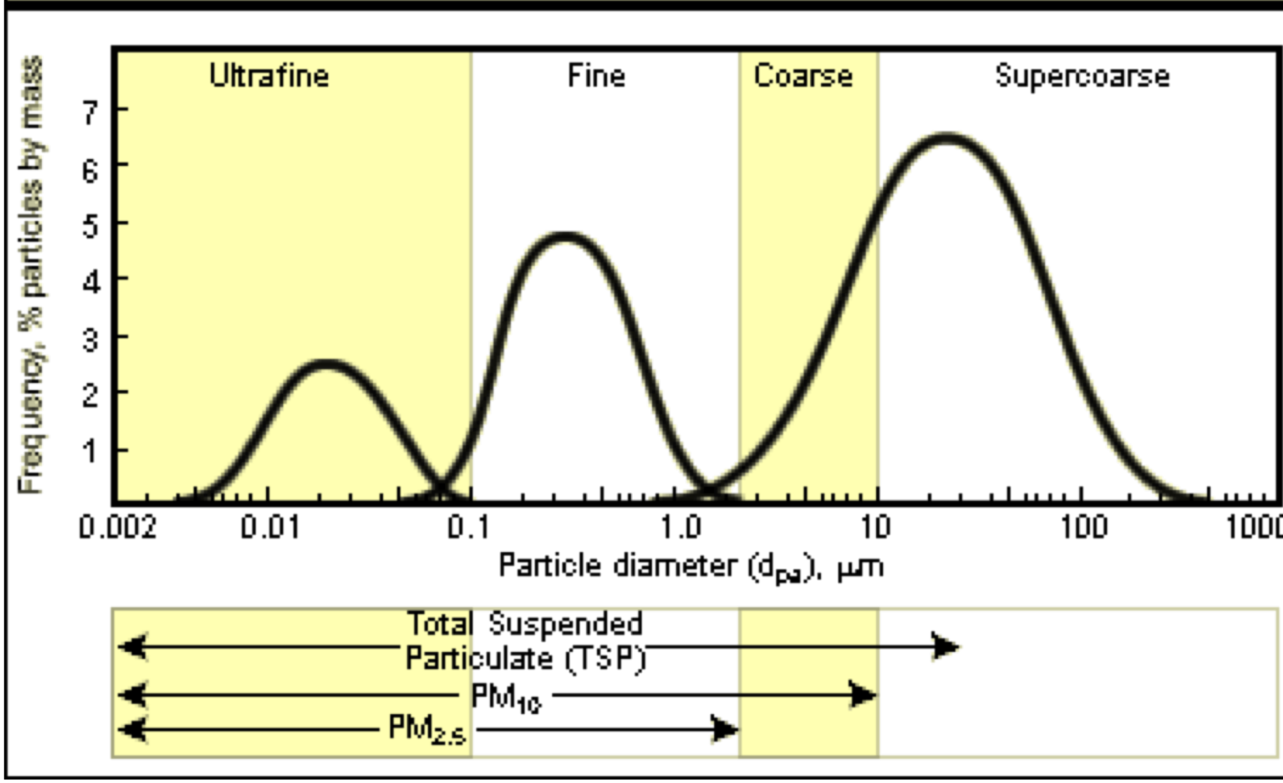
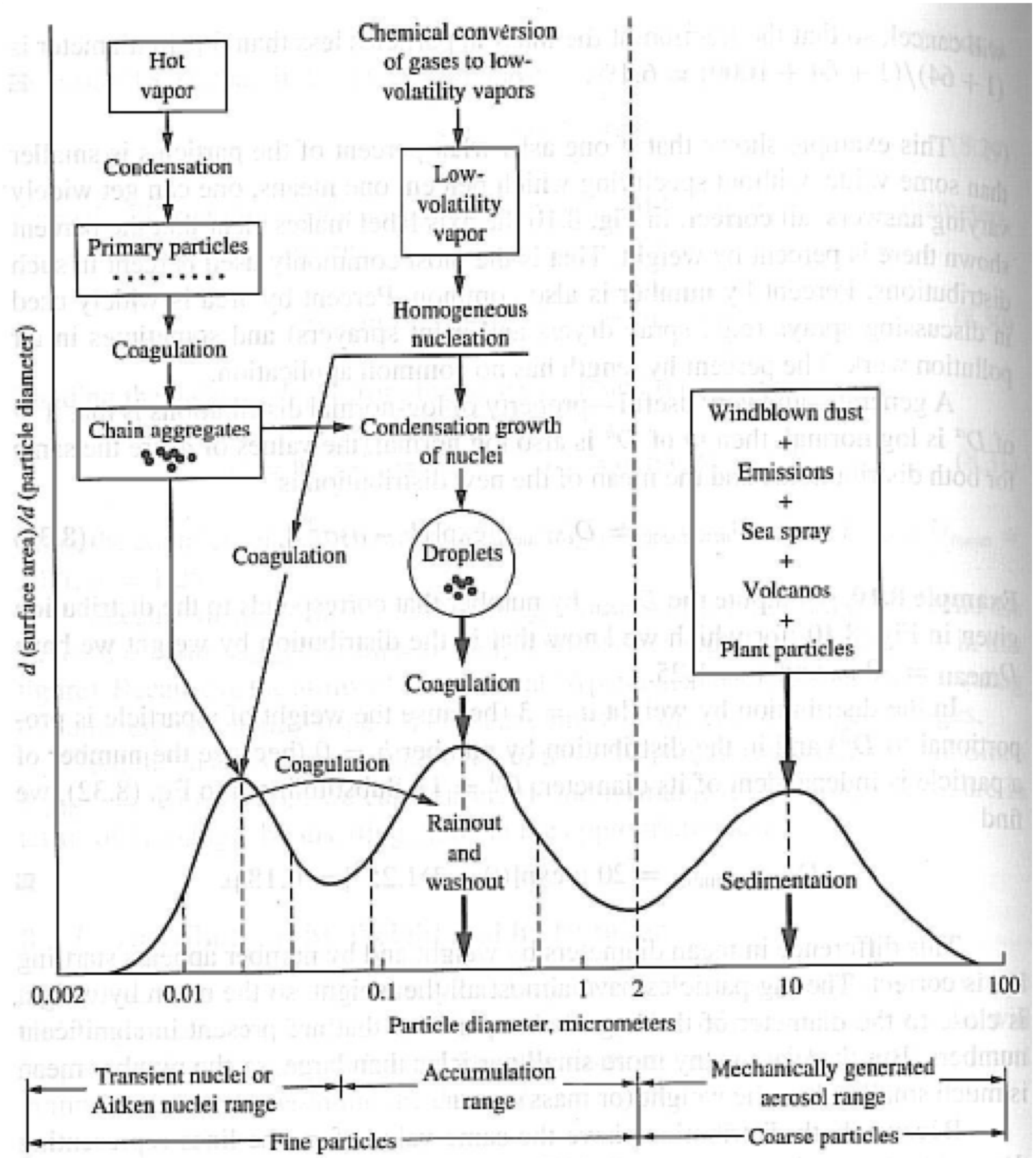


Figure 2. Ambient Particulate Matter Size Distributions

Particle formation mechanisms, surface area, and size

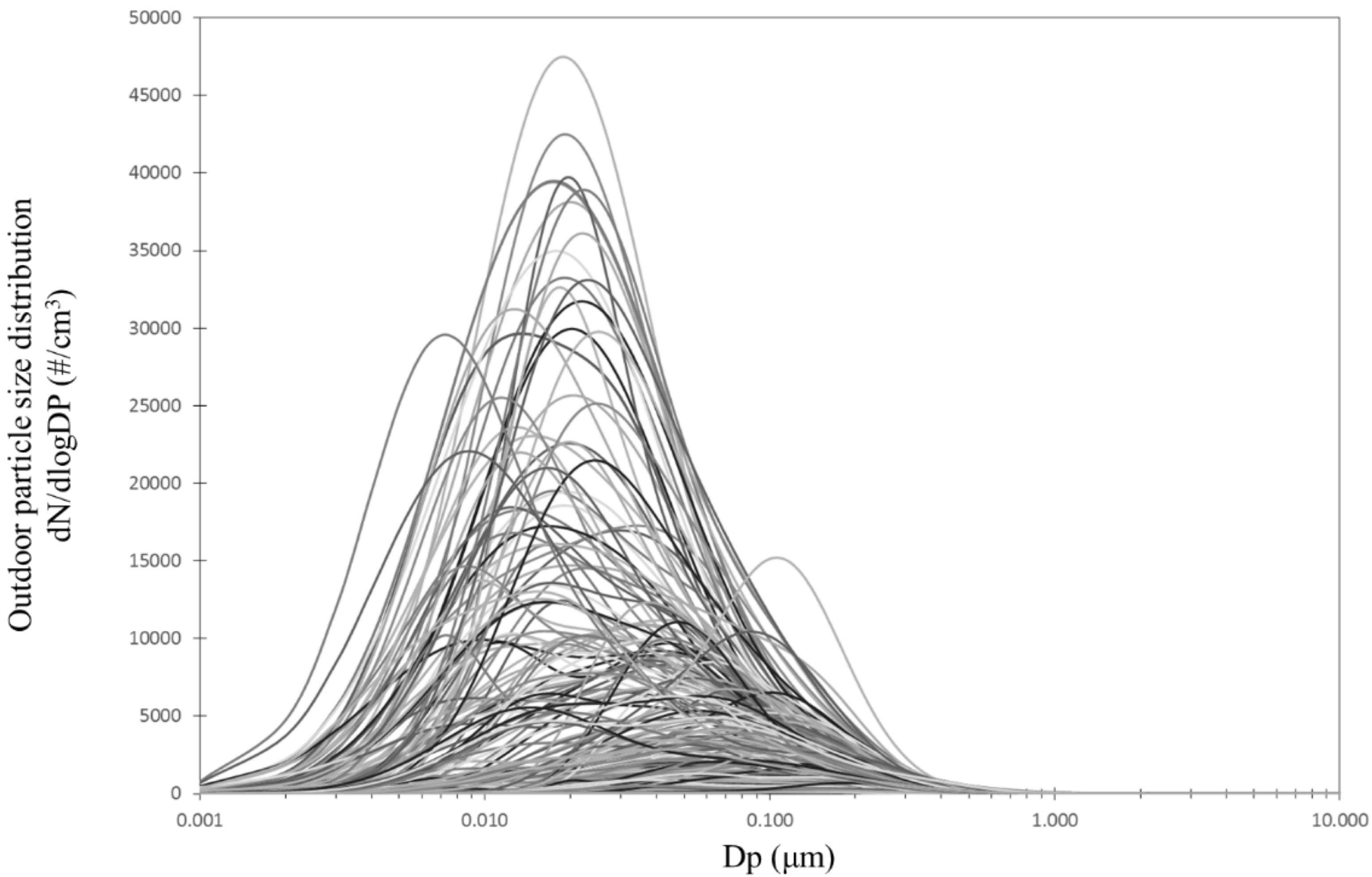


Seinfeld and Pandis, 2006

What do outdoor aerosol distributions look like?

Outdoor particle size distributions

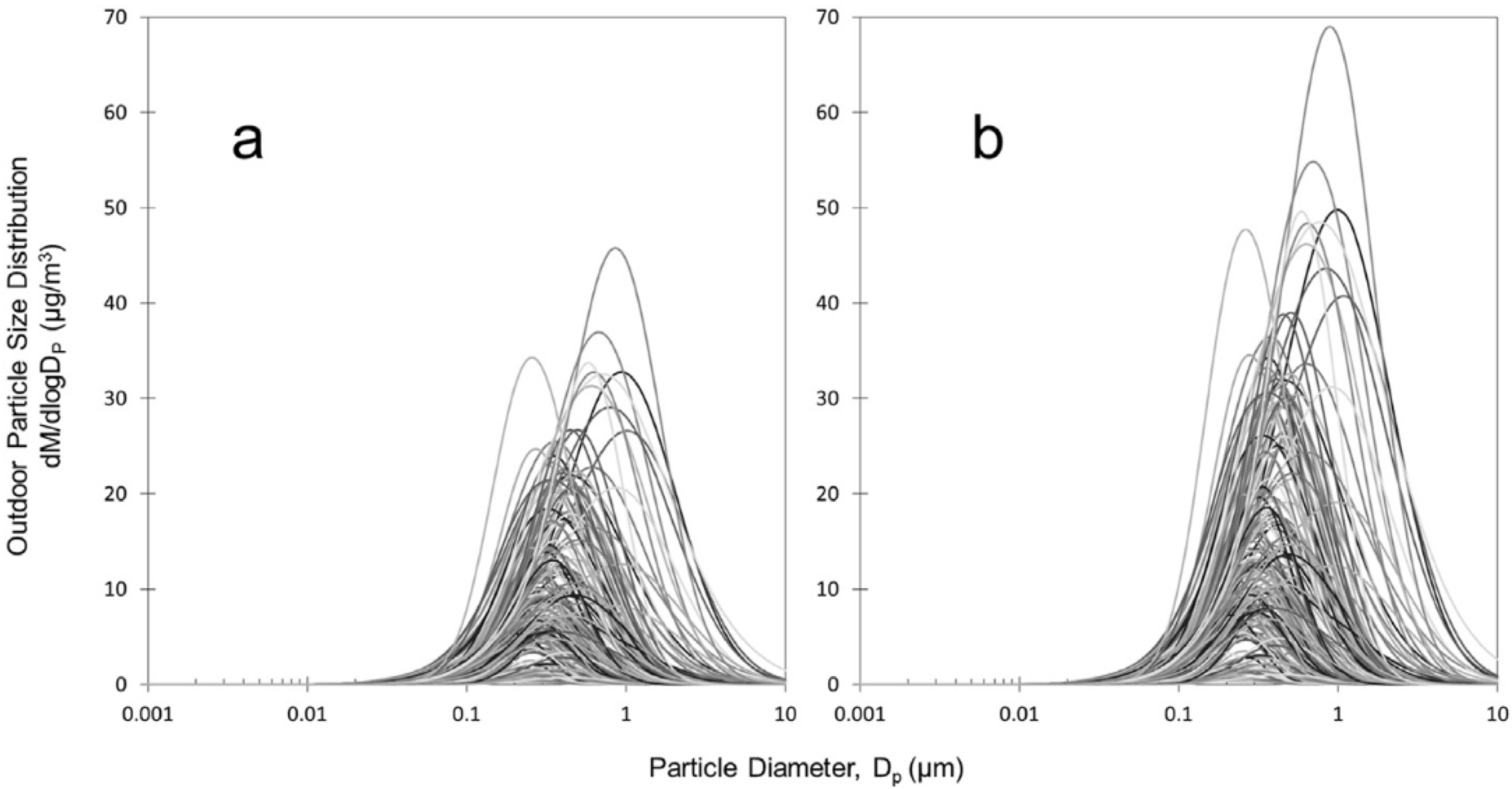
Almost all PM (by number) is <0.3 μm



Azimi et al., **2014** *Atmos Environ*

Outdoor particle size distributions

Almost all PM (by mass) is <10 μm



Azimi et al., **2014** *Atmos Environ*

What do indoor aerosol distributions look like?

Indoor particle sources

- Combustion processes
  - Incense smoke, candle burning, cigarette smoke, etc.
- Cooking
  - Both gas and electric stoves, toaster ovens, etc.
- Cleaning activities
  - Resuspension from cleaning, walking, etc.
- Other indoor sources
  - Aerosolization from tap water in humidifiers
  - Office appliances (e.g., printers, copiers, etc.)
- Transport from outdoors
  - Infiltration through leaks
  - Delivery via mechanical ventilation

Indoor particle sources

- Indoor particle sources vary in size and composition

Table 1 Attributes of particle size modes

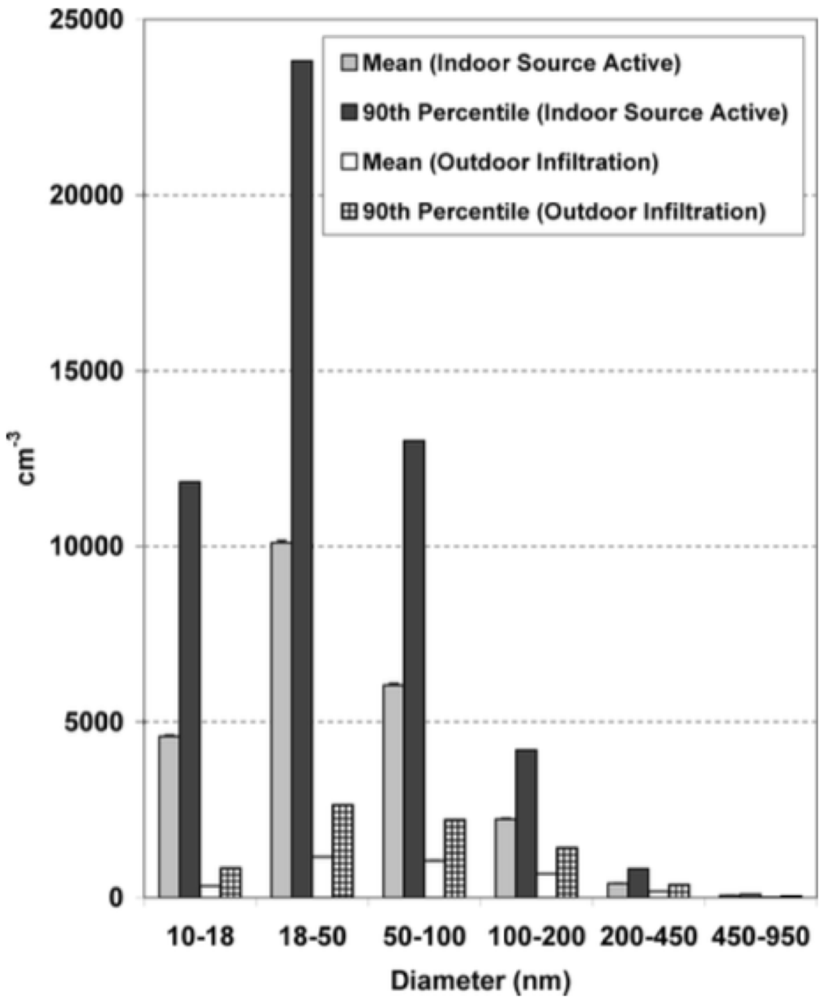
mode	diameter	indoor source	example composition
ultrafine	$\leq$ 0.1 μm	gas cooking	soot
accumulation	0.1-2 μm	tobacco smoke	organic liquids
coarse	> 2 μm	cleaning	crystal solids

- Indoor emission sources are typically <u>episodic</u>
  - 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 size distributions

Almost all PM (by number) is <0.2 μm



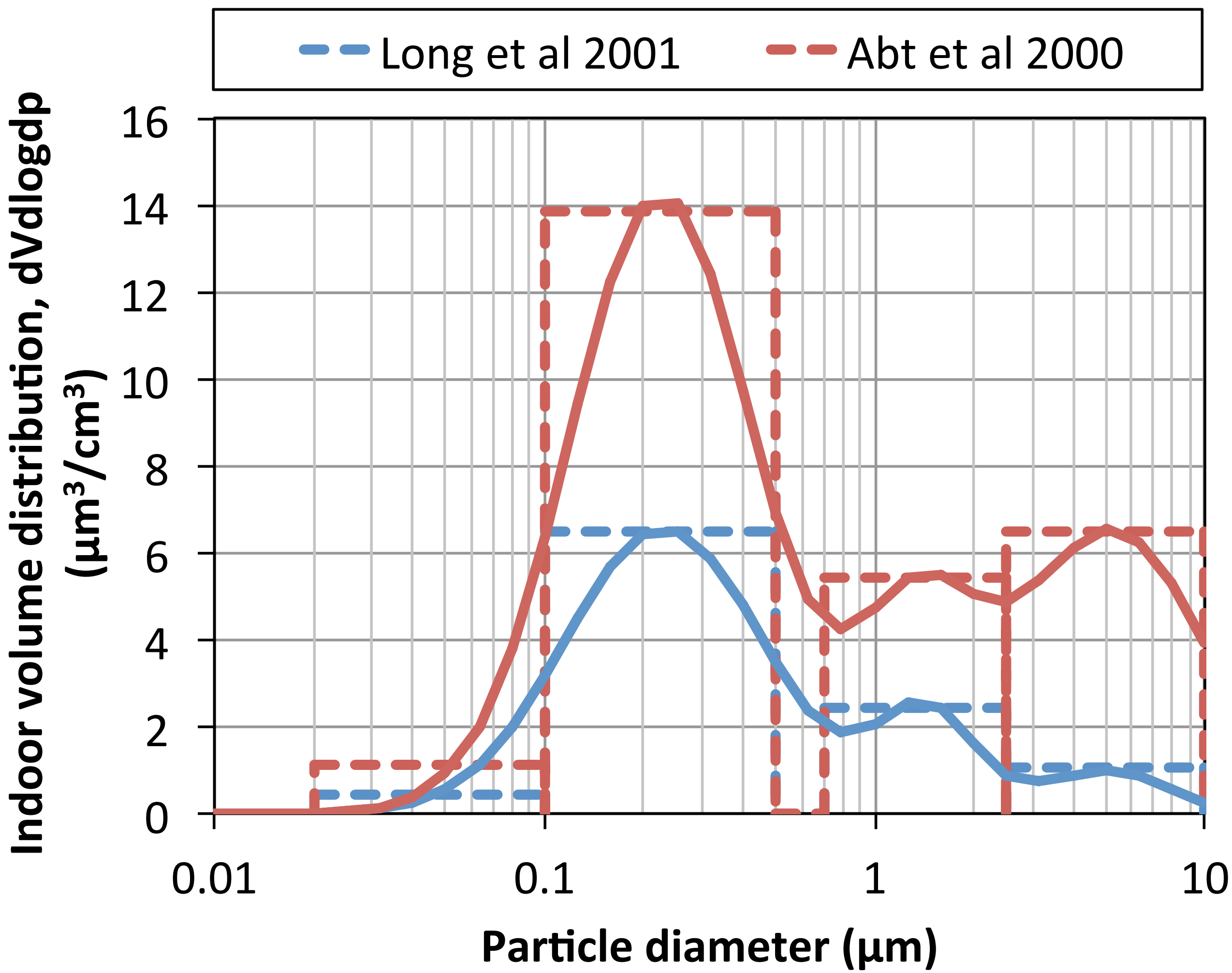
Wallace **2006** *Aerosol Sci Technol*

Appliance	Event	*N*	Mean emission rate ($\times 10^{12}$) (particles/min^{1})
Gas stove and toaster oven	Cooking	23	5.11
Gas clothes dryer	Drying clothes	6	4.40
Air popper	Popping corn	4	4.26
Electric toaster	Toasting	1	3.8
Match	Lighting candles	3	3.65
Spray cleaner	Housecleaning	6	2.60
Electric toaster oven	Cooking	54	2.11
Gas stove	Cooking	95	1.89
Electric stove	Cooking	21	1.25
Cigarette	Smoking	13	0.48
Electric mixer	Preparing food	5	0.57
Candles	Burning candles	10	0.56
Curling irons	Grooming	3	0.29
Steam iron	Ironing	6	0.24
Hair dryers	Grooming	8	0.23
Space heater	Heating	3	0.13
Hair straightener	Grooming	1	0.11
Laser printer	Printing 10 pages	3	0.06
Vacuums	Housecleaning	2	0.06
Fireplace	Fire lit	1	0.003

Wallace and Ott **2011** *J Expo Sci Environ Epidem*

Indoor particle size distributions

Almost all PM (by mass) is also <10 μm



Stephens **2018** *Atmosphere*

What is a typical indoor $PM_{2.5}$ mass concentration?

Indoor $PM_{2.5}$ concentrations

Table 1. Indoor, outdoor and personal $PM_{2.5}$ mass concentrations ($\mu g/m^3$) and air exchange rates (AER; h^{-1}).

Group	Category	Sample size	Mean	Median	STD
Overall study	Indoor	326	17.6	14.4	12.6
	Outdoor	334	18.1	15.5	10.7
	Personal	307	37.6	31.4	24.6
	AER	349	1.06	0.78	0.89

Meng et al. **2005** *Journal of Exposure Analysis and Environmental Epidemiology*

Indoor vs. outdoor $PM_{2.5}$ concentrations

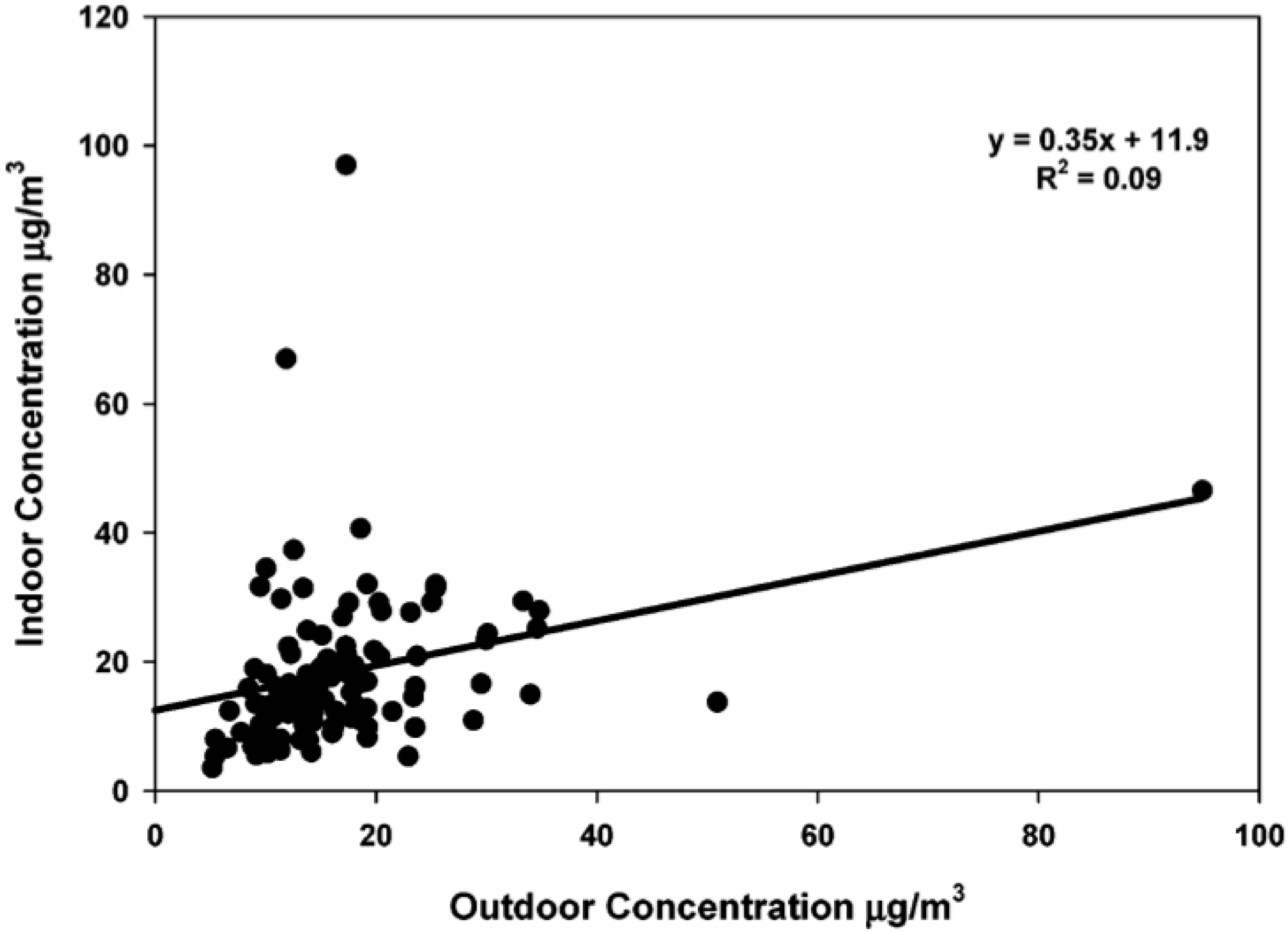


FIGURE 1. Indoor and outdoor $PM_{2.5}$ mass concentrations from 114 RIOPA homes. Line is the linear least squares regression line.

Meng et al. **2005** *Environ Sci Technol*

PARTICULATE MATTER MEASUREMENTS

Measuring particulate matter

- Sampling methods distinguish between:
  - Particle counting
    - No sizing
  - Particle sizing
    - Count + size information
  - Particle mass
  - Particle composition

  For biological particles:
  - Viable and non-viable bioaerosols

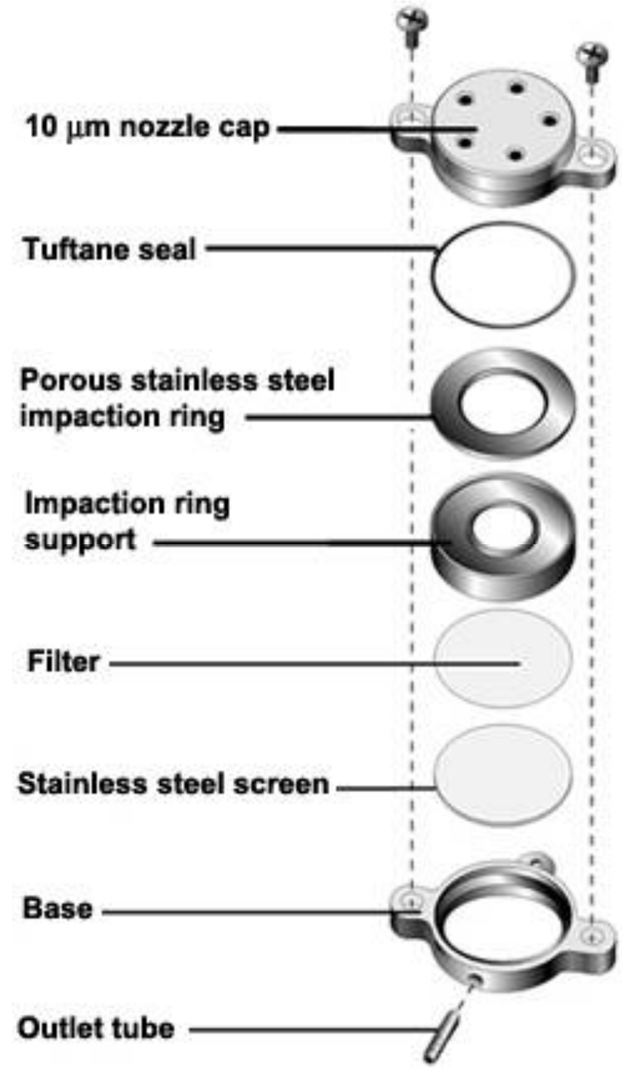
Gravimetric (mass-based) particle sampling

- Particles have very low masses
- Need to collect many particles to have measureable mass
- Most mass-based techniques are integrated samples
  - Sample onto filters at known airflow rate for known period of time
  - Weigh filters before and after
  - Calculate concentration
  - Correct for RH

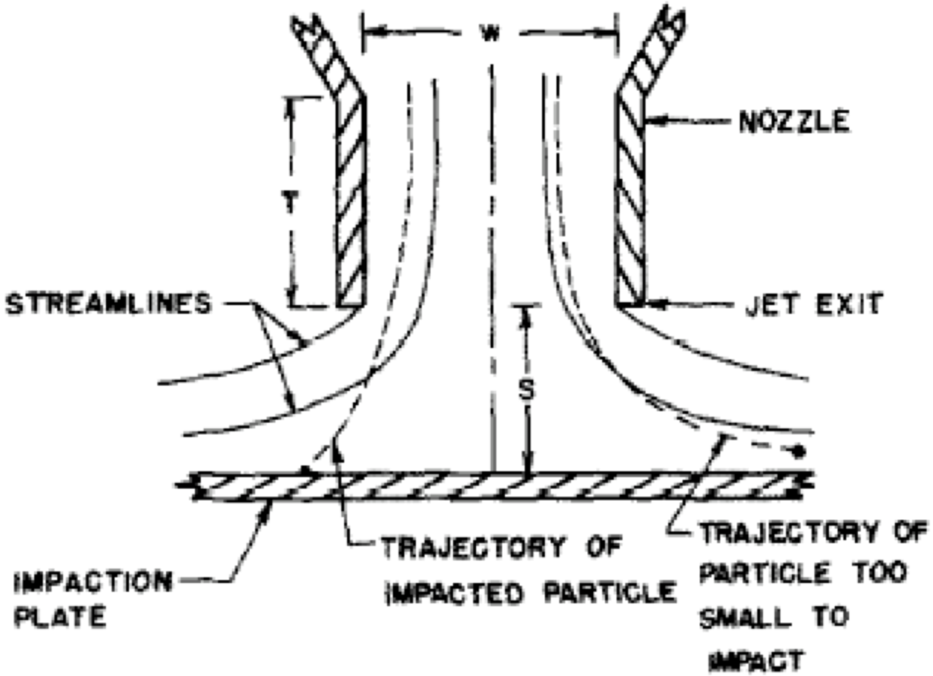
Particle Diameter [μm]	Particle Mass [g]
0.01	$5 \cdot 10^{-19}$
0.1	$5 \cdot 10^{-16}$
1	$5 \cdot 10^{-13}$
10	$5 \cdot 10^{-10}$

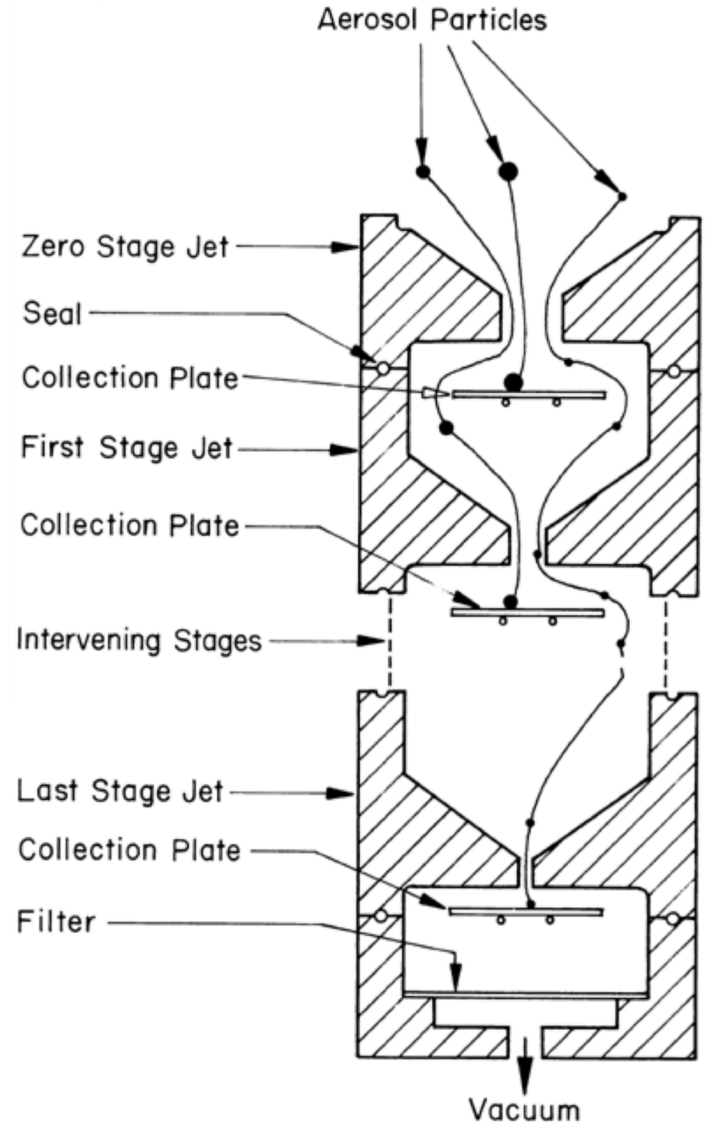
Gravimetric (mass-based) particle sampling

SKC PEM sampler: $PM_{2.5}$ or PM_{10} Impactor

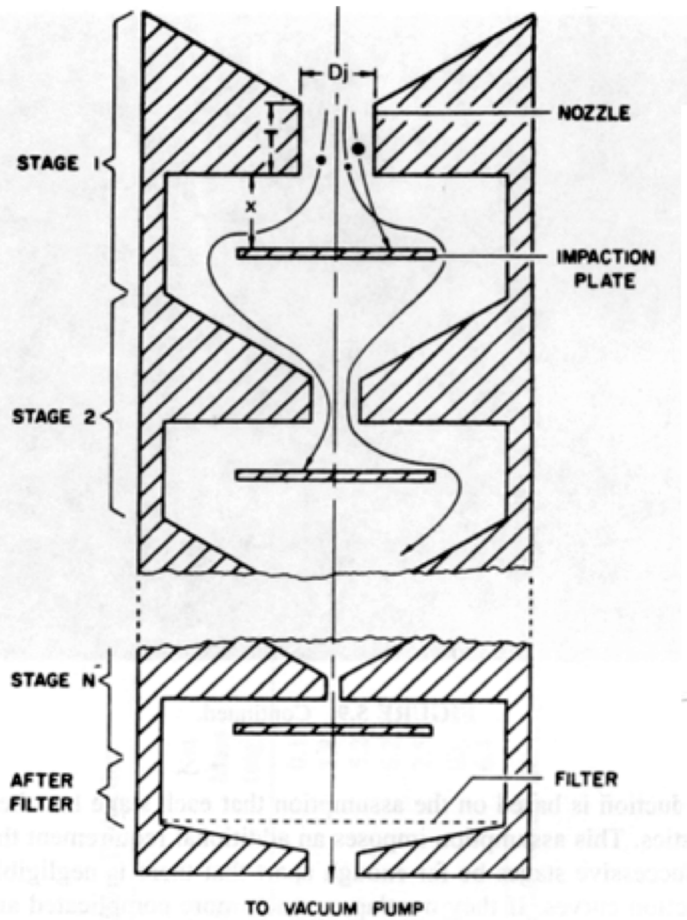


Gravimetric particle sampling: Cascade impactor

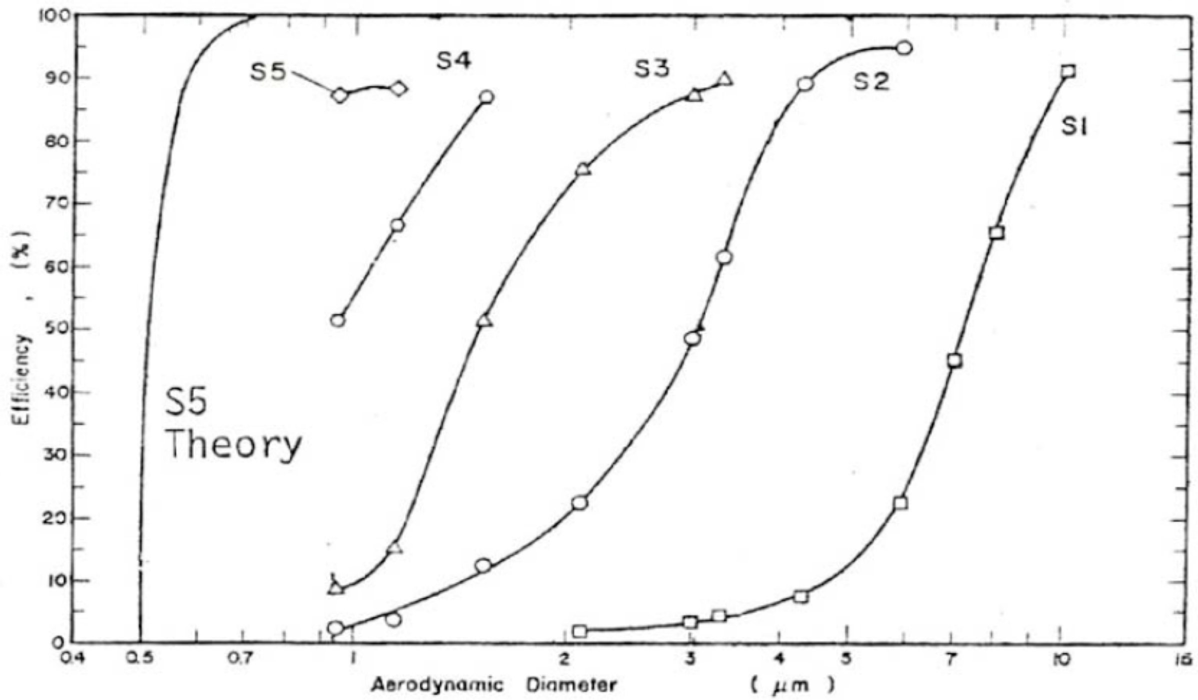




Gravimetric particle sampling: Cascade impactor



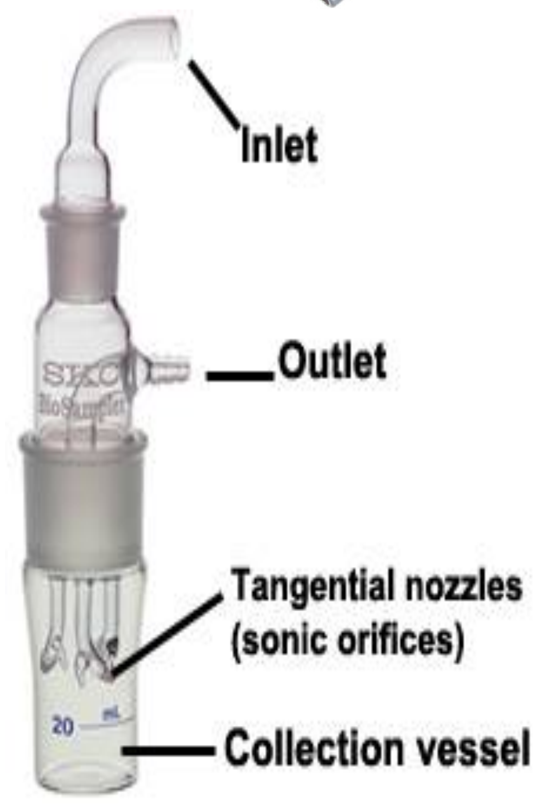
(a)



Bioaerosol sampling

- Impactors
  - Collect on filter, extract DNA from filter
  - Advantages and disadvantages of various filters

- Impingers
  - Collect aerosol in liquid suspension



Optical particulate matter measurements

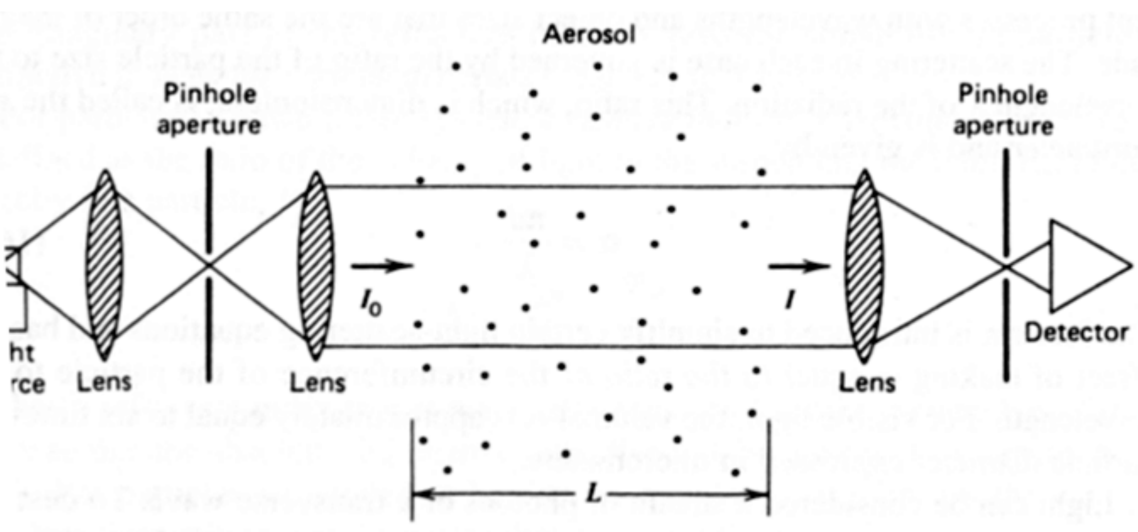
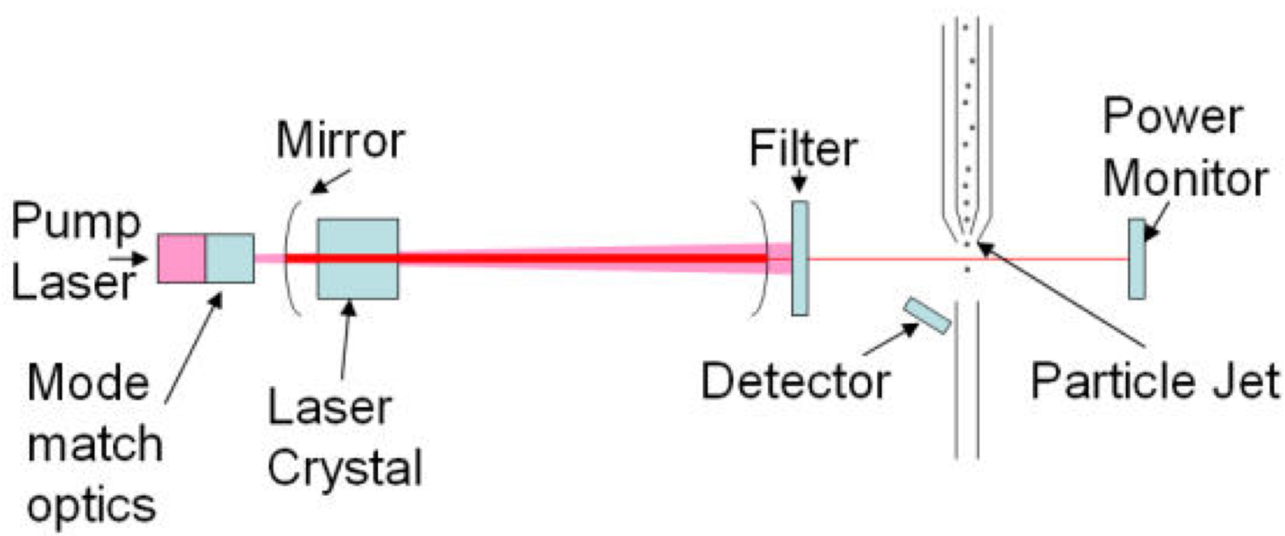


FIGURE 16.1 Schematic diagram of an extinction-measuring apparatus.

Extinction:

$$\frac{I}{I_0} = e^{-\sigma_e L}$$



Optical measurements: Mie/Rayleigh Theory for Scattering

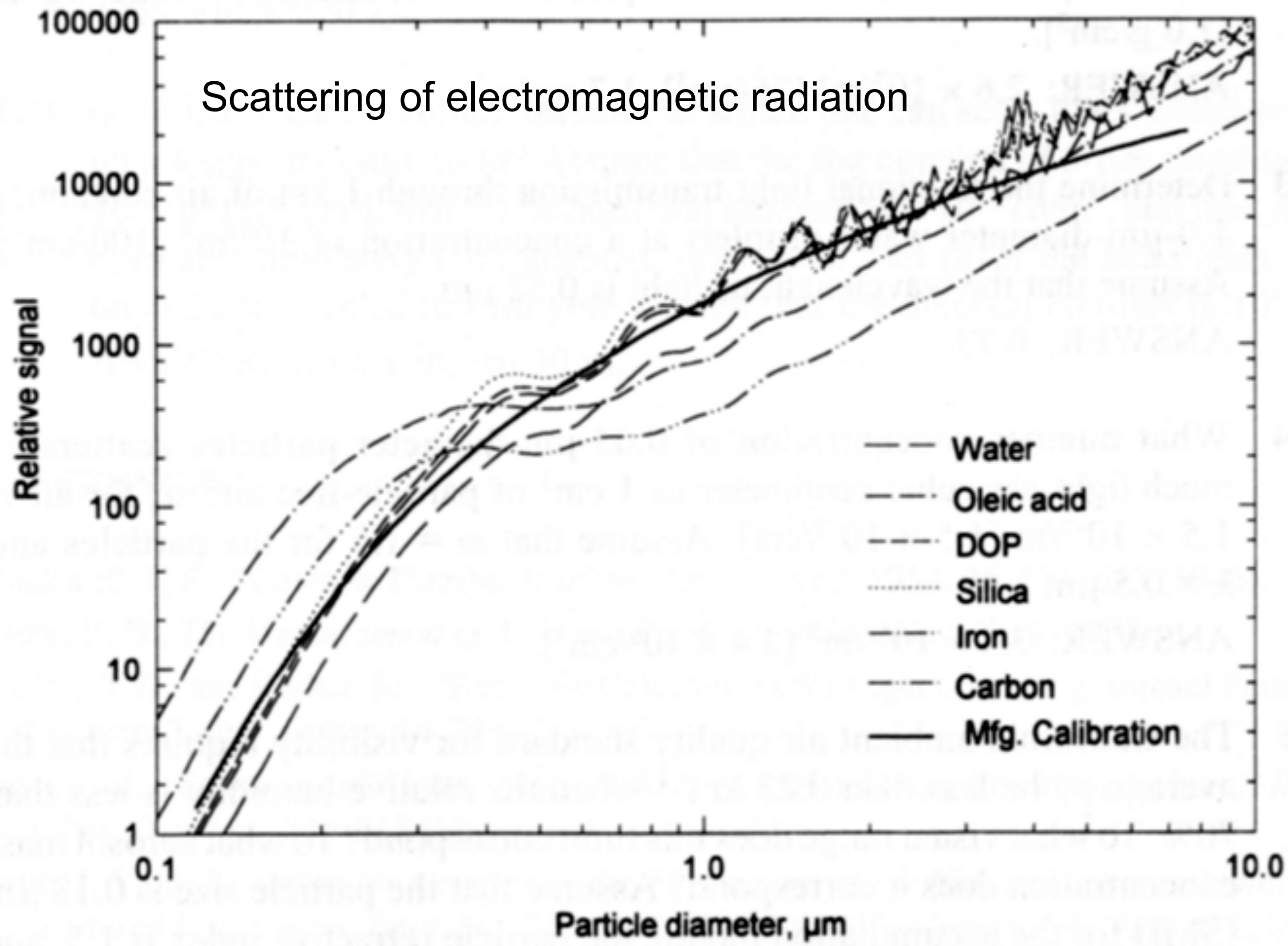
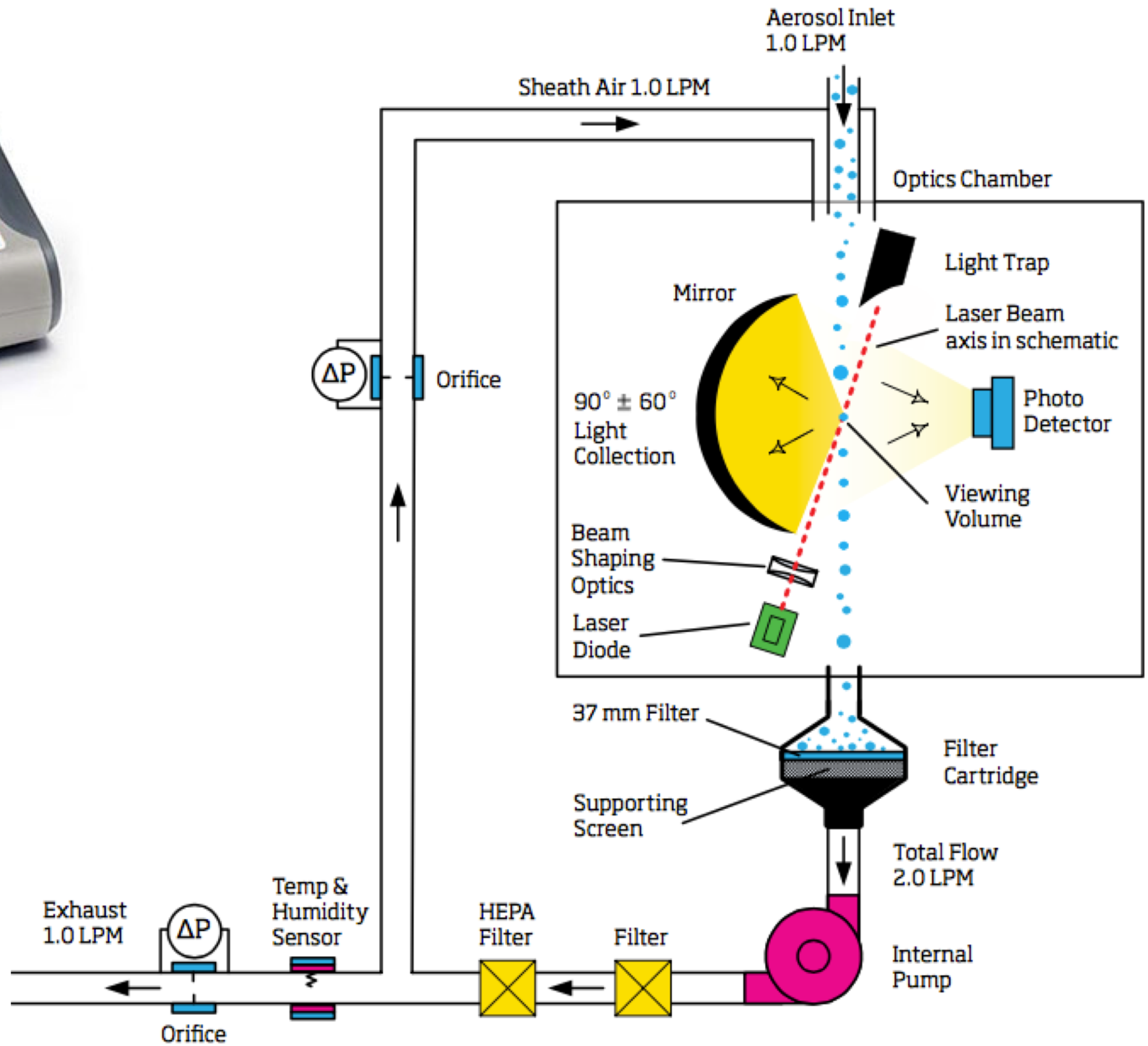


FIGURE 16.16 Calculated response curves for six materials and manufacturer's calibration curve for model LAS-X® (PMS, Inc., Boulder, CO) optical particle counter.

TSI Optical Particle Sizer



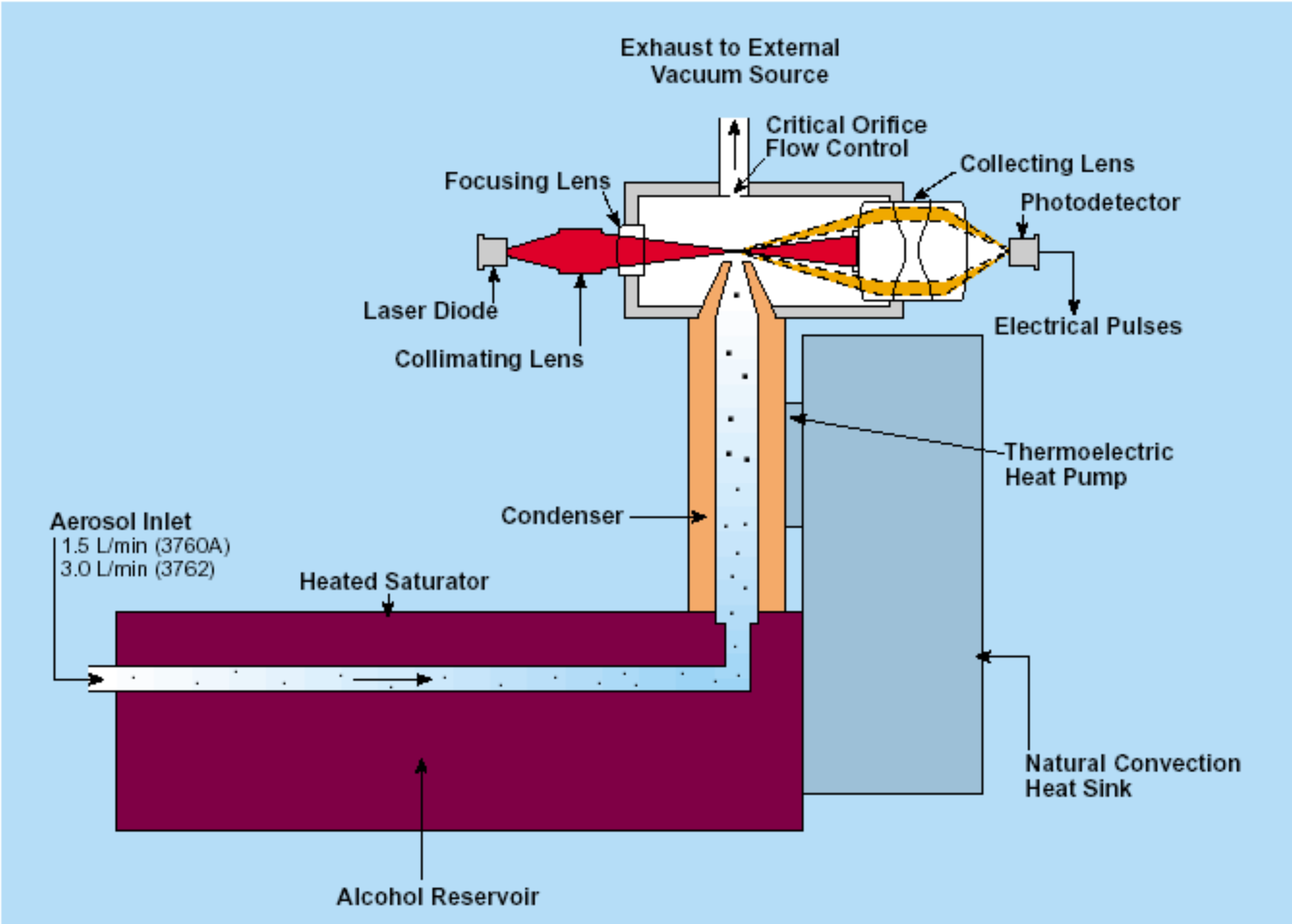
Measuring particle "mass" optically

- Photometers and nephelometers
  - Usually report $PM_{2.5}$, PM_{10}, etc.
  - Measure scattering for aerosol sample (~1L) over wide range of angles (θ)
    - Particle density is function of the light reflected into the detector
      - Scattered light depends on properties of the particles such as their shape, color, and reflectivity
  - Estimates mass concentration assuming aerosol density
  - Can be calibrated with gravimetric samples

Condensation particle counter (CPC)

- Particles are passed through a wick and grown with either water or butanol
  - Aerosol stream saturated and temperature equilibrated
  - Heterogeneous condensation on condensation nuclei (the particles)
  - Grown to 2 to 3 micrometers
  - Individual particles passed through light beam and scatter light onto a photodetector

Condensation nuclei counter (CNC)



Aerodynamic particle sizer (APS)

- A **time-of-flight** instrument
  - Two laser beams separated by known distance
  - Particle is accelerated between beams
  - Time between beams being broken is calibrated to a test aerosol
  - Particles exiting the jet have a velocity related to their aerodynamic diameter (assume spherical particles and unit density)
- Measures ~0.5 - 20 μm

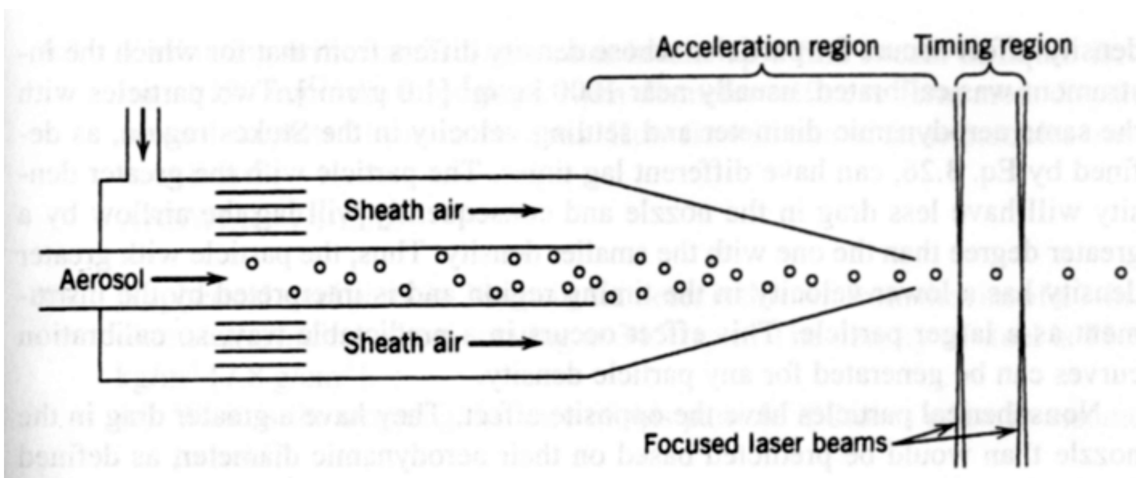
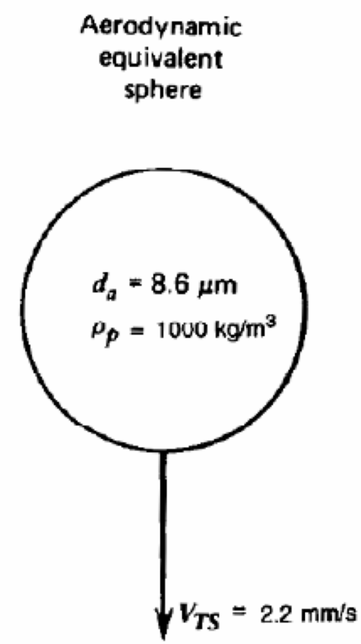


FIGURE 5.13 Schematic diagram of time-of-flight instrument.



Particle "mobility" analyzer: small particles

- Particles entering the system are neutralized using a radioactive source
  - Yields equilibrium charge distribution
- Particles then enter a Differential Mobility Analyzer (DMA) where the aerosol is classified according to **electrical mobility**
  - Only particles of a narrow range of mobility exit through the output slit.
- This monodisperse distribution then goes to a Condensation Particle Counter which determines the particle concentration at that size
- Measures 0.001 – 1 µm
  - 0.002 – 0.4 µm most accurate

Electrical mobility: Ability of charged particles to move through medium in response to electric field (inversely proportional to diameter)

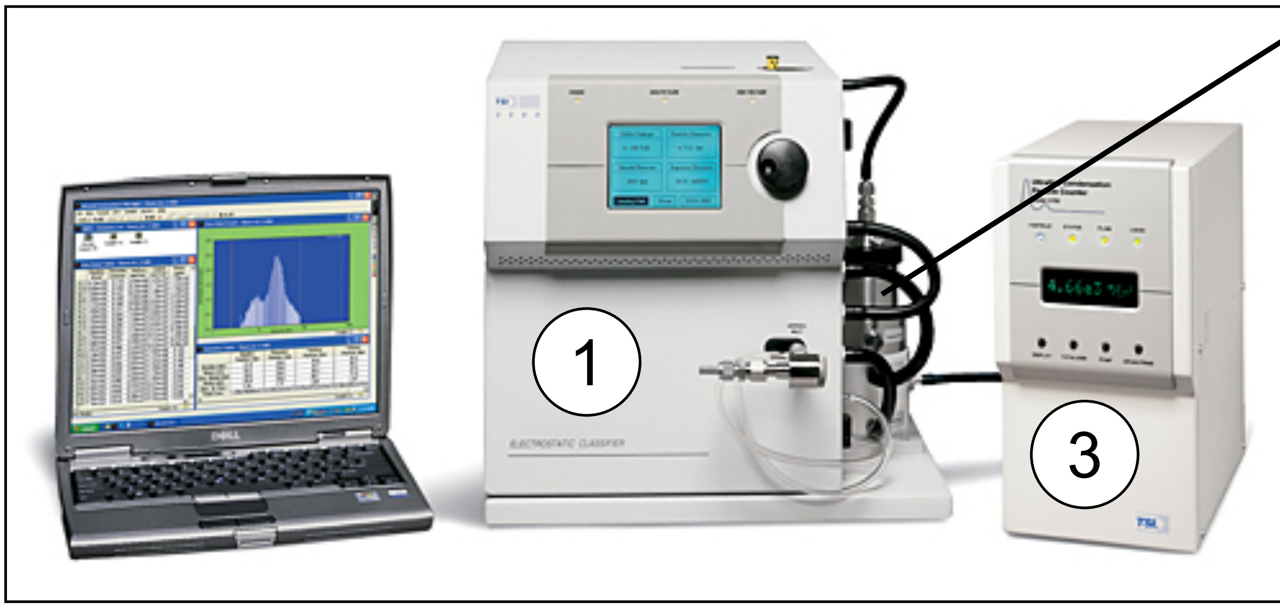
Particle mobility and charge distributions

TABLE 15.4 Distribution of Charge on Aerosol Particles at Boltzmann Equilibrium

Particle Diameter (μm)	Average Number of Charges	Percentage of Particles Carrying the Indicated Number of Charges								
		< –3	–3	–2	–1	0	+1	+2	+3	>+3
0.01	0.007				0.3	99.3	0.3			
0.02	0.104				5.2	89.6	5.2			
0.05	0.411			0.6	19.3	60.2	19.3	0.6		
0.1	0.672		0.3	4.4	24.1	42.6	24.1	4.4	0.3	
0.2	1.00	0.3	2.3	9.6	22.6	30.1	22.6	9.6	2.3	0.3
0.5	1.64	4.6	6.8	12.1	17.0	19.0	17.0	12.1	6.8	4.6
1.0	2.34	11.8	8.1	10.7	12.7	13.5	12.7	10.7	8.1	11.8
2.0	3.33	20.1	7.4	8.5	9.3	9.5	9.3	8.5	7.4	20.1
5.0	5.28	29.8	5.4	5.8	6.0	6.0	6.0	5.8	5.4	29.8
10.0	7.47	35.4	4.0	4.2	4.2	4.3	4.2	4.2	4.0	35.4

Scanning Mobility Particle Sizer (SMPS)

1. Electrostatic classifier (EC)
2. Differential mobility analyzer (DMA)
3. Condensation particle counter (CPC)



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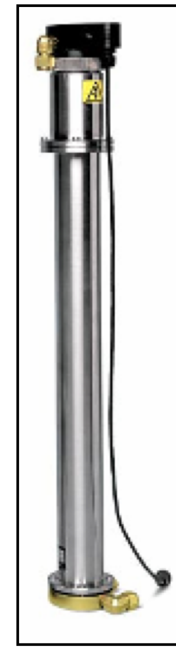
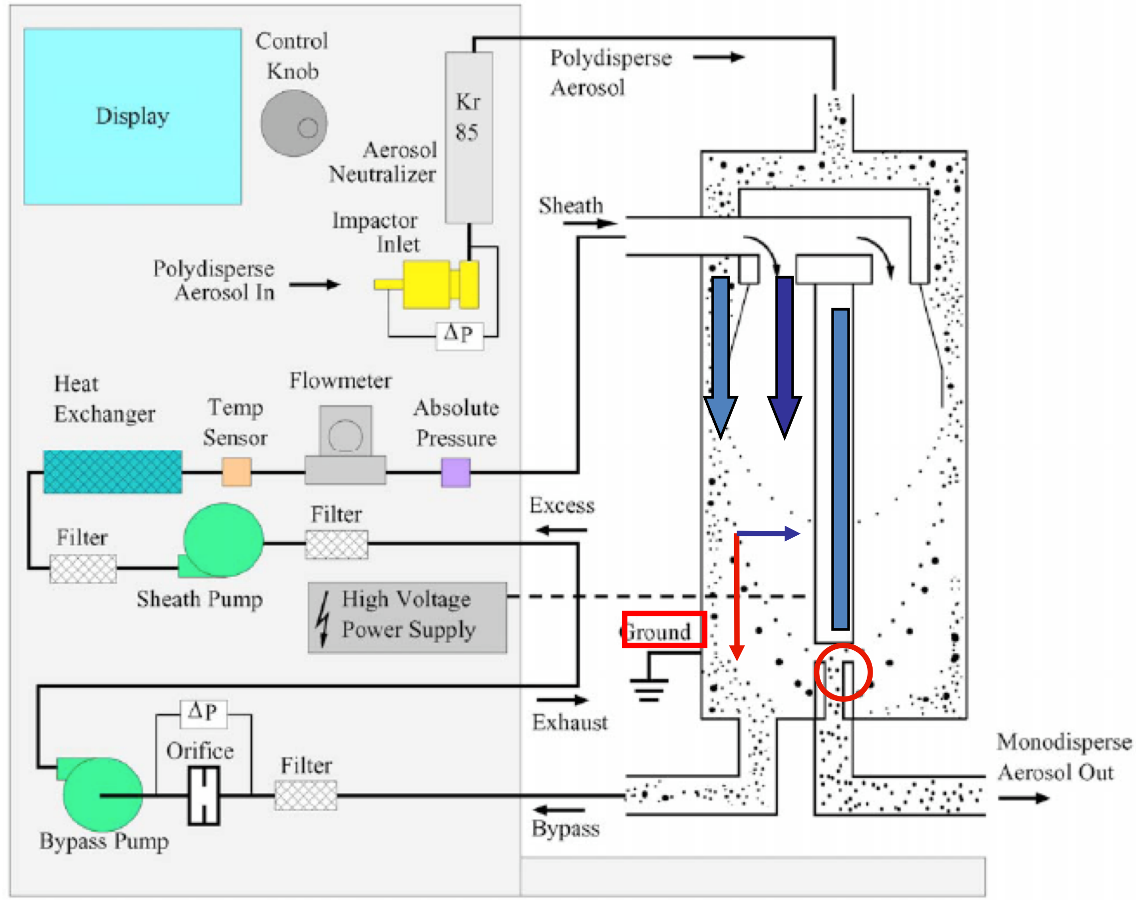


SMPS: EC and DMA



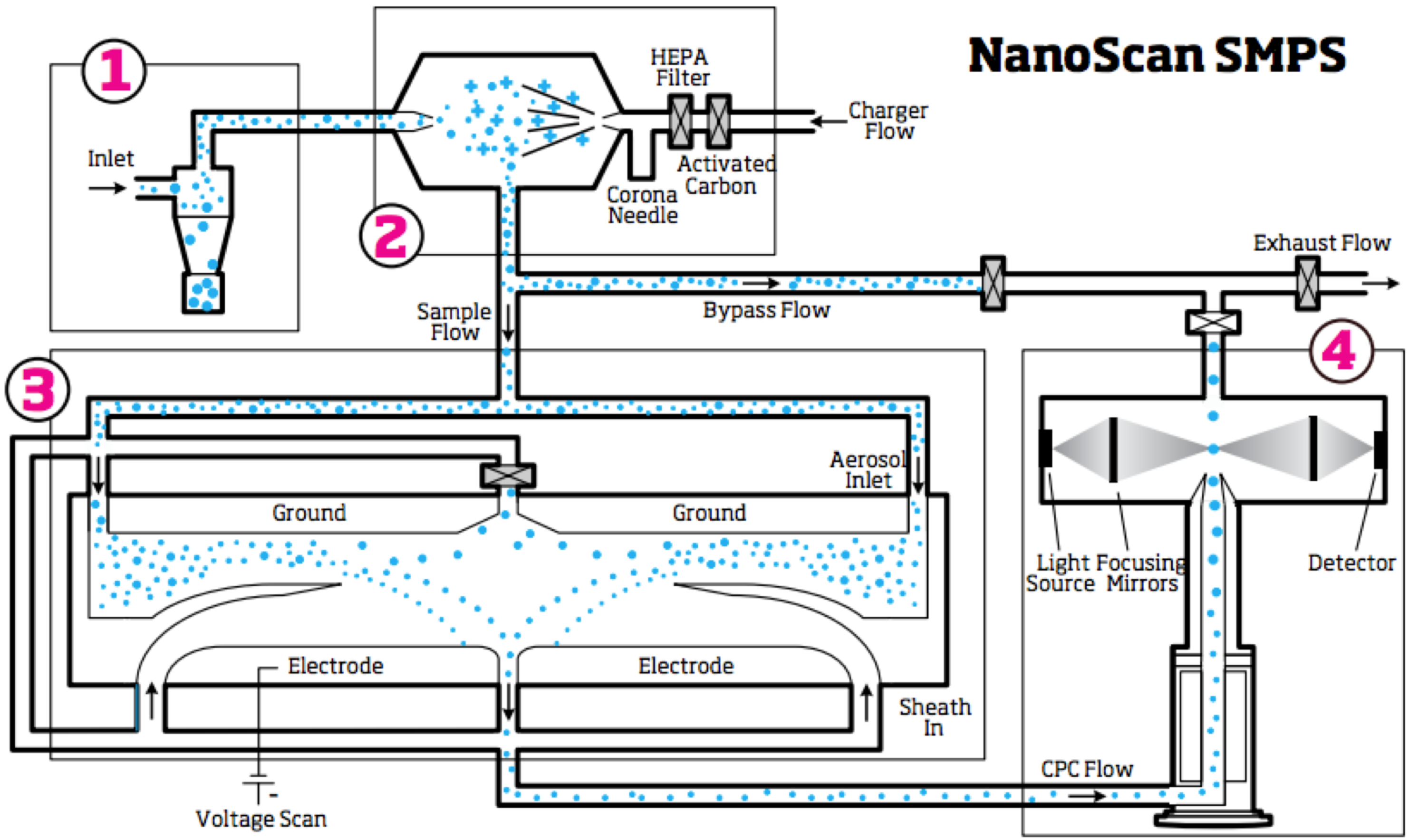
EC

- Kr-85 bipolar charger

DMA

- 2 laminar flows
  - Sheath and aerosol
- 2 concentric cylinders
  - Center negative voltage
  - Electric field
- **Positive** particles attracted through sheath air
- Location depends on electrical mobility, flow rate, and geometry
  - Cycles through different voltages to capture different size particles

TSI NanoScan SMPS



NanoScan SMPS operating principal

1. Pre-conditioner
2. Particle charger
3. Radial DMA (sizer)
4. CPC (counter)

Cost of particle sensors

- Relatively inexpensive
  - Gravimetric for particle mass
  - Light scattering for large particle mass
  - Condensation nucleus counter (CNC) for counting small particles
  - Cascade impactor for size-resolved mass
- Mid-range
  - Optical particle counters
- Expensive
  - Aerodynamic particle sizing for large particles
  - Differential mobility analyzer for small particles

Other issues with particle measurements

- Sampling line losses
  - Generally an issue for large (>1 μm) and small (< 0.05 μm) particles
- Sampling particles in moving air stream
  - Isokinetic and non-isokinetic sampling
- Particle composition
  - Collect sample of particles on filter
    - Analyze as you would for liquid or solid compounds
  - SMPS or APS w/ mass spec
    - Very expensive
- Bioaerosol sampling
  - Fungi, bacteria, viruses
  - Quantitative or presence/absence
  - Culturable, viable, DNA-based
  - Inhibitors

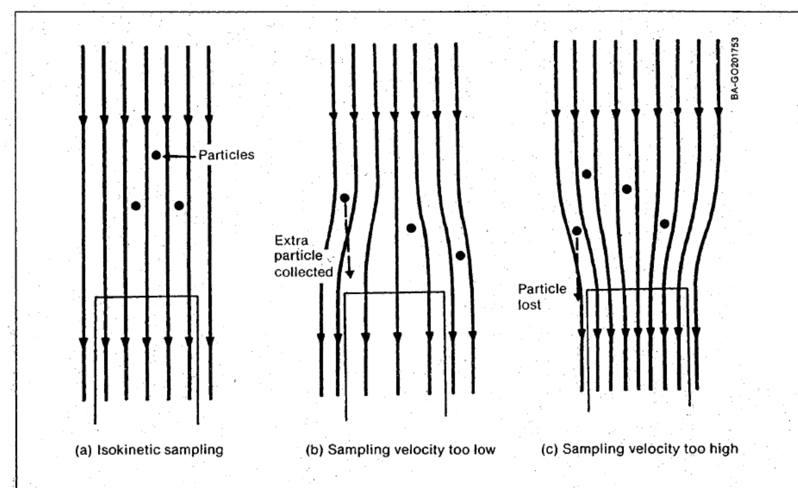


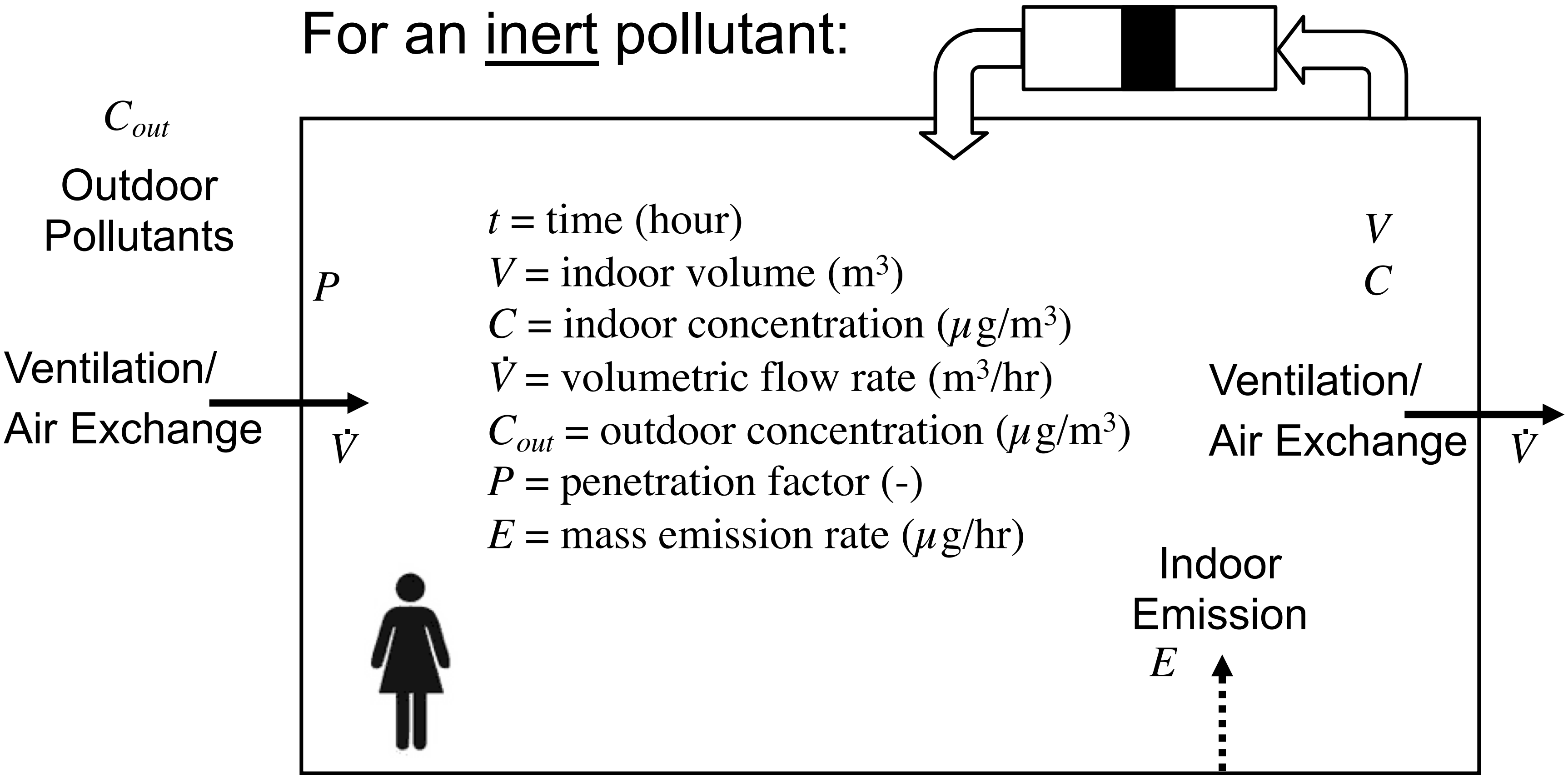
Fig. 7-10. Gas stream lines at the entrance to sampling probes (Source: Adapted from Strauss 1975, Fig. 2.12. © 1975. Used with permission of Pergamon Press)

Summary of particle measurements

- Wide variety of instruments available for particle measurement
  - What size of aerosol are you interested in?
  - Do you need sizing or is counting sufficient?
  - Do you need real-time data or integrated samples?
  - What type of aerosol are you trying to measure?
  - How much accuracy do you need?
  - How much money do you have?

Mass/number balance for an inert pollutant

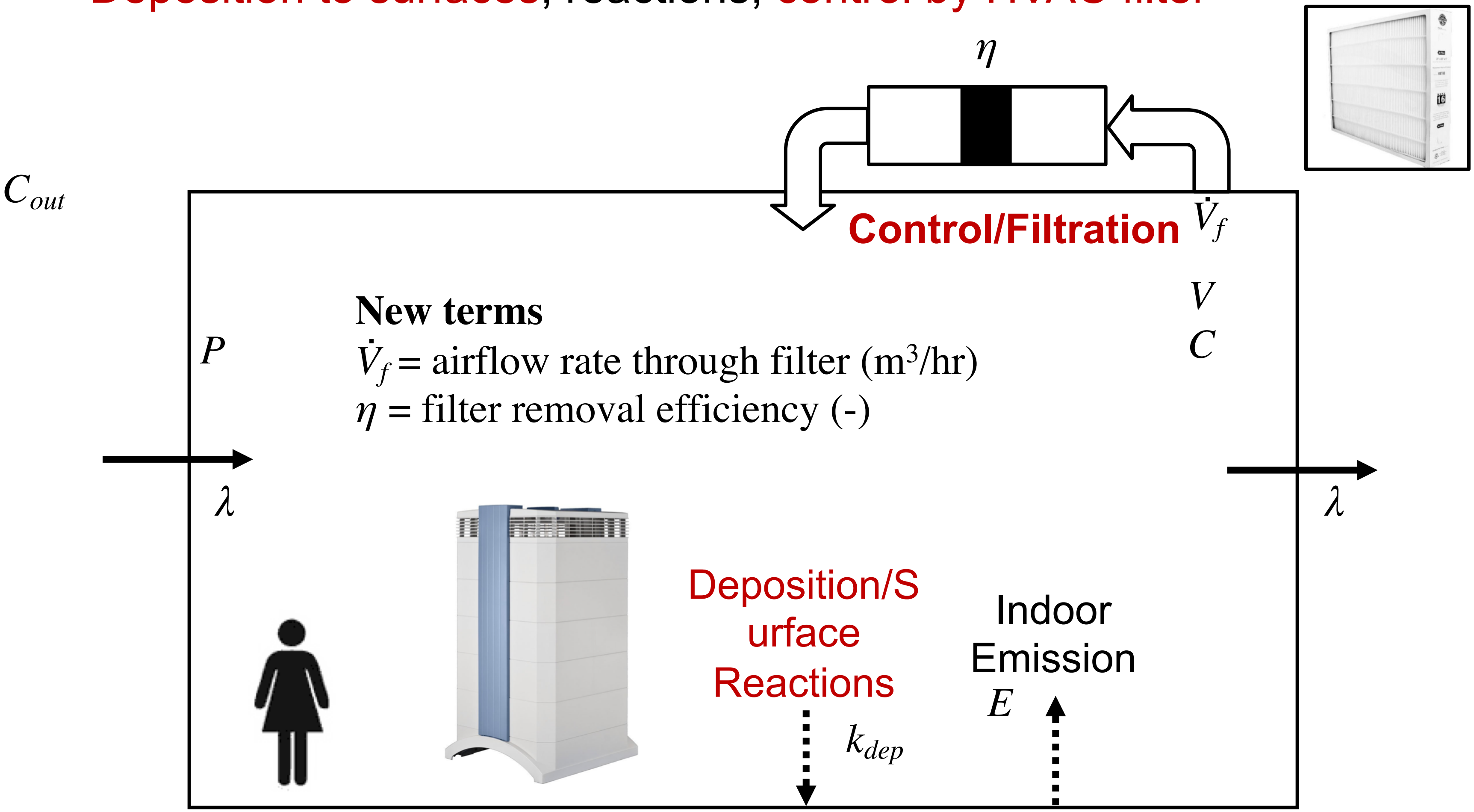
For an <u>inert</u> pollutant:



$$\frac{dC}{dt} = P\lambda C_{out} - \lambda C + \frac{E}{V} \qquad C_{ss} = PC_{out} + \frac{E}{\lambda V} \qquad \lambda = \frac{\dot{V}}{V} = \text{air exchange rate } \left(\frac{1}{\text{hr}}\right)$$

Mass/number balances for PM

- Other loss mechanisms are important to the mass balance
  - Deposition to surfaces, reactions, control by HVAC filter



Mass balance with filtration and deposition

- New term to mass balance (derive on the board):

$$V\frac{dC}{dt} = P\dot{V}C_{out} - \dot{V}C + E - \eta\dot{V}_f C - k_{dep}VC$$

$$\cancelto{0}{\frac{dC}{dt}} = P\lambda C_{out} - \lambda C + \frac{E}{V} - \frac{\eta\dot{V}_f}{V}C - k_{dep}C$$

- Assume steady state for now, divide by λ, and solve for C:

$$C_{ss} = \frac{P\lambda C_{out} + \frac{E}{V}}{\lambda + \frac{\eta\dot{V}_f}{V} + k_{dep}}$$

- CADR = Clear Air Delivery Rate ⟶ $CADR = \eta\dot{V}_f$

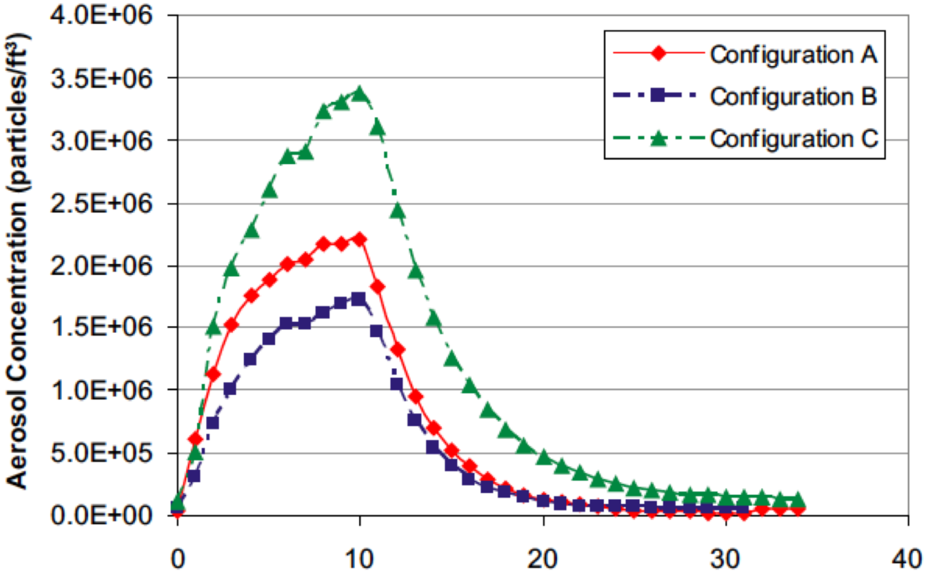
Units of flow (e.g., CFM or m^3/s)

Clean air delivery rate (CADR)

- Procedure dates back to 1985 Offermann et al., *Atmos Environ*
- Basic procedure involves elevating aerosol concentrations
  - Measuring subsequent decay with and without air cleaner operating

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

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



CLASS ACTIVITY

Class Activity

- Instruments:
  - TSI CPC
  - TSI Optical Particle Sizer (OPS)
  - TSI NanoScan SMPS
  - TSI DustTrak (photometer)

- Activity:
  - CADR test with an air cleaner in the class room / conference room