Aerosols I & II

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Objectives

- Know aerosol terms
- Describe commonly used techniques for aerosol sampling and size analysis
- Select appropriate aerosol sampling devices
- Explain the size distribution concept

Introduction

- Particulate sampling is different compared to gas sampling. Particle sampling methods must consider physical as well as chemical properties
  - Particle behavior and toxicity depends on size, shape, and density, as well as chemical makeup
  - Often specific particle sizes must be collected
  - Particles are difficult to capture
- Aerosols
  - Solid or liquid particles dispersed in a gaseous medium
  - Classically, a 2 phase flow problem

Definitions

- Dusts
  - Dry particulate matter
    - < 1 μm to 1 mm
  - Formed by grinding, crushing, etc.
- Fumes
  - Fine solid aerosol particles
    - 0.01 μm primary particles to 1 μm agglomerates
  - Formed by condensation of vaporized solid material
    - Welding, smelting, etc.
- Mists
  - Spherical droplet aerosols
    - From a few microns to over 100 μm
  - Produced by mechanical processes like splashing, bubbling, spraying, etc.
- Fogs
  - Droplet aerosols, 1 to 10 μm
  - Produced condensation from vapor phase
- Smokes
  - Complex mixtures of solid and liquid aerosol particles, gases, and vapors
    - 0.01 to 1 μm in diameter, with larger agglomerates
  - Caused by incomplete combustion.
- Fibers
  - Elongated particles
    - length to width ratio > 3:1

- Polydispersed
  - Wide range of particle sizes
- Monodispersed
  - Narrow range of particle sizes

Particle formation mechanisms:

Primary particle formation ***results from mechanical disruption of the earth's surface.***

Direct generation of sand/dust aerosols

Sea-spray aerosols resulting from bursting bubbles of entrained air.

Secondary particle formation ***results from Gas-to-particle conversion***

----- Homogeneous nucleation

N **molecules form a stable cluster by diffusion induced collisions**

cluster continues to grow

Typically, a stable cluster is ~1 nm and contains 10's of molecules

Aqueous phase chemical reactions (oxidation of SO_2 to aerosol SO4)

----- Combustion particle formation

Results from the incomplete combustion of fuel (soot carbon etc)

Particle Composition

Primary aerosols: soil dust – iron, calcium, silicates; Sea-spray: sodium, chloride, calcium, sulfate, potassium, etc

Secondary aerosols: sulfates, nitrates, organics, halogens,

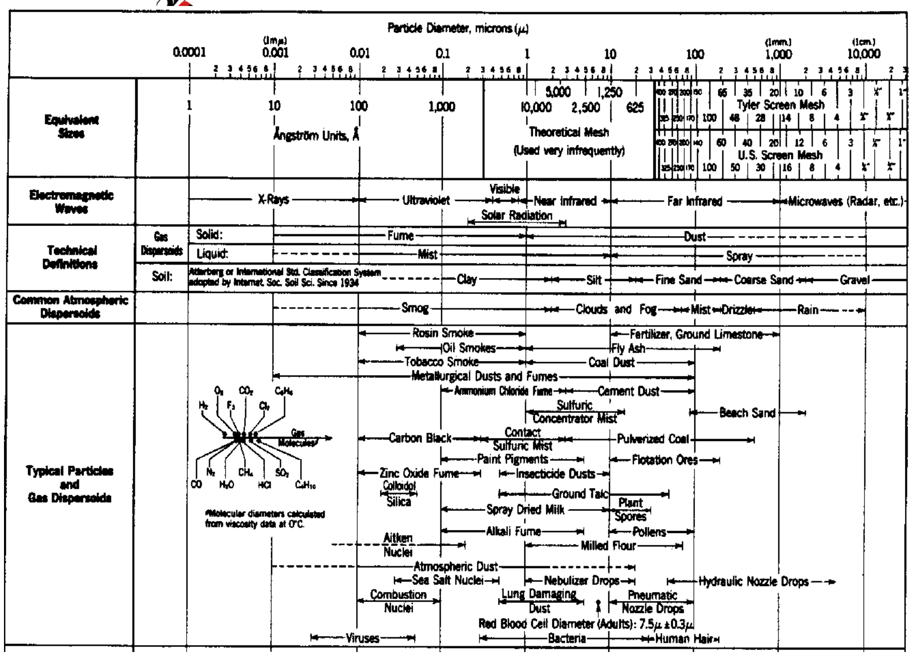
Combustion aerosol: sulfates, nitrates, elemental carbon, organic carbon, soot

Sulfates are derived from oxidation of SO_2

Nitrates are derived from oxidation of NOx

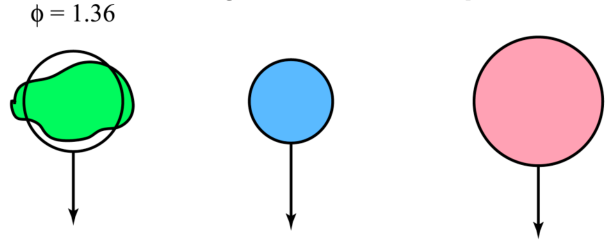
Organic (acids) derived from oxidation of VOC's from plants, cars, etc.

Size Characteristics of Particles



Particle Diameters

irregular particle	Stokes' equivalent sphere	Aerodynamic diameter
d_v = 5.0 μm	d_s = 4.3 μm	d_a = 8.6 μm
ρ_p = 4000 kg/m	ρ_p = 4000 kg/m	ρ_p = 1000 kg/m
ϕ = 1.36		



V_{TS} = 2.2 mm/sec	V_{TS} = 2.2 mm/sec	V_{TS} = 2.2 mm/sec

Comparison of equivalent volume diameter, Stokes diameter, and aerodynamic diameter.

Aerodynamic diameter

Aerodynamic diameter (d_a) is the diameter of a spherical particle of density ρ_0 = 1 g/cm^3 which has the same terminal settling velocity in air as the particle of interest.

$$d_a = d_p \left(\frac{\rho_p}{\rho_0} \right)^{1/2}$$

Stokes diameter (d_s) is the diameter of a spherical particle that has the same density and terminal settling velocity in air as the particle of interest.

$$d_a = d_s \left(\frac{\rho_b}{\rho_0} \right)^{1/2}$$

ρ_b is the bulk density

PM2.5 = particles with aerodynamic diameters < 2.5 microns

PM10 = particles with aerodynamic diameters < 10 microns

Motion of Airborne Particles

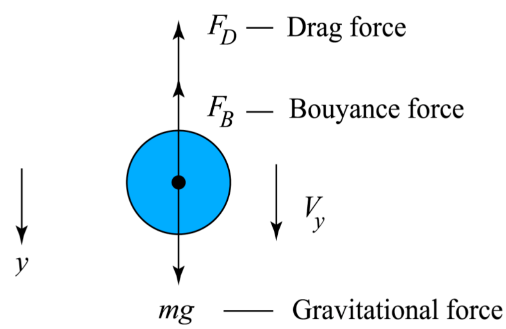
- Particles (aerosols) tend to remain suspended in the air until attractive forces act on them.
  - Settling velocity for small particles is less than ordinary air currents
  - Attractive forces cause particles to adhere to each other and to surfaces, causing them to be removed from the air
  - Smaller particles are more difficult to dislodge

Motion of Airborne Particles

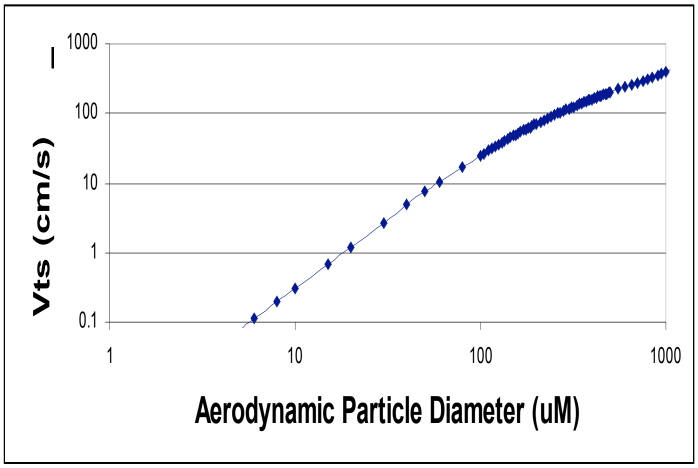
- Sampling methods capture particles by various aerosol deposition mechanisms
  - Sedimentation (gravity)
  - Impaction
  - Interception
  - Diffusion
  - Other
    - Electrostatic attraction
    - Thermal deposition
    - Etc.

Motion under gravity

$$F_D = \frac{3\pi\eta D_p u_\infty}{C_c}$$



Settling Velocity



$\ln(Vts) = -8.799E\text{-}03x^3 - 2.024E\text{-}02x^2 + 2.337x - 6.278$
where x= ln(diam) in microns; Vts in cm/s
Unit density spheres, sizes from 0.1 to 1000 um

Da (µm)	Vt (cm/s)
4	0.05
5	0.0776
6	0.111
8	0.196
10	0.306
15	0.684
20	1.21
30	2.72
40	4.84
50	7.55
60	10.28
80	17.2
100	25.1

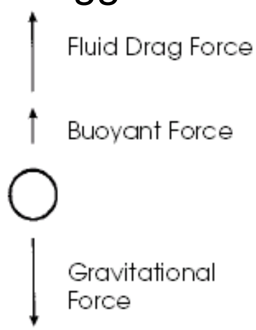
Particle Removal mechanisms

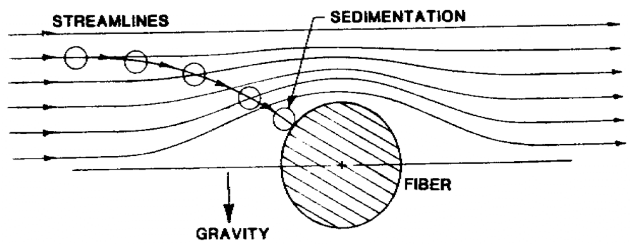
- Sedimentation
- Impaction
- Interception
- Diffusion
- Electrostatic

These mechanisms can act together and strongly depend on the particle size

Sedimentation

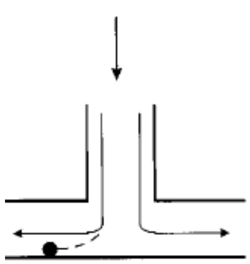
- Larger particles can be captured by sedimentation (gravity)
- Note, primary (smaller) particles form larger agglomerates, with much faster settling times

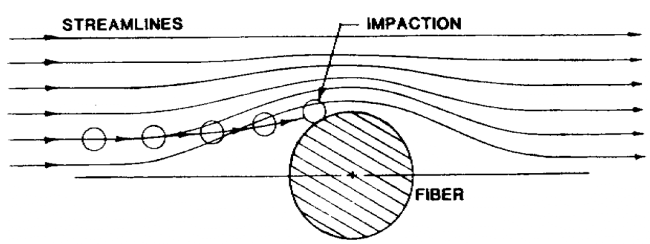




Impaction

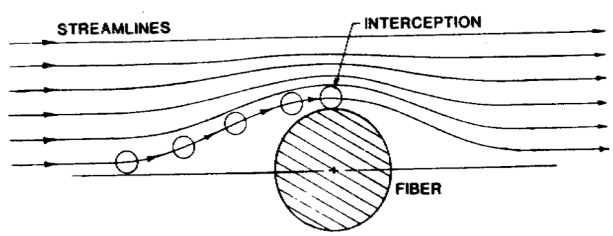
- Larger particles can be captured by impaction
  - Particle inertia carries it across flow streamlines





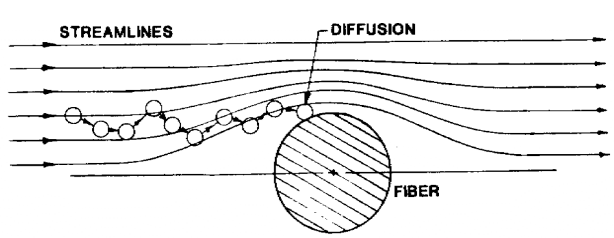
Interception

- Particles can be captured when the airstream carries them to within ½ diameter of a surface
  - For larger particles



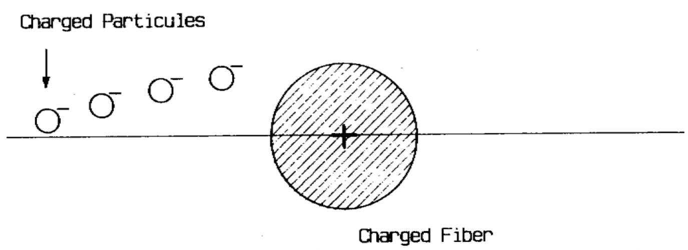
Diffusion

- Brownian motion causes particles to contact surfaces
  - Capture method for small particles



Electrostatic attraction

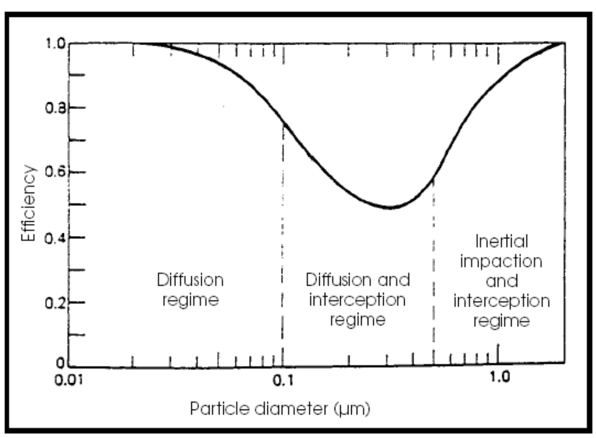
- Particles can be captured by electrical charge
  - Good for small particles



- Thermal deposition and other methods (magnetic attraction) also may be used

Particle capture by size

- The “most penetrating” particle (most difficult size to filter out) is ~0.3 micrometers in size:

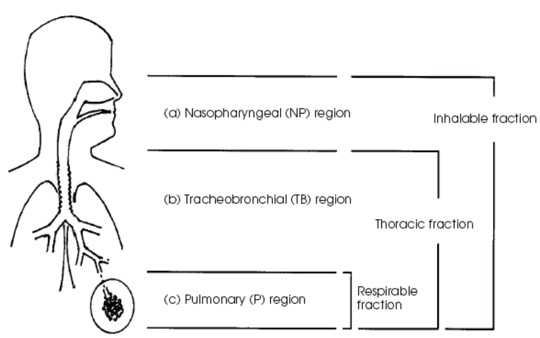


Particle retention on surfaces

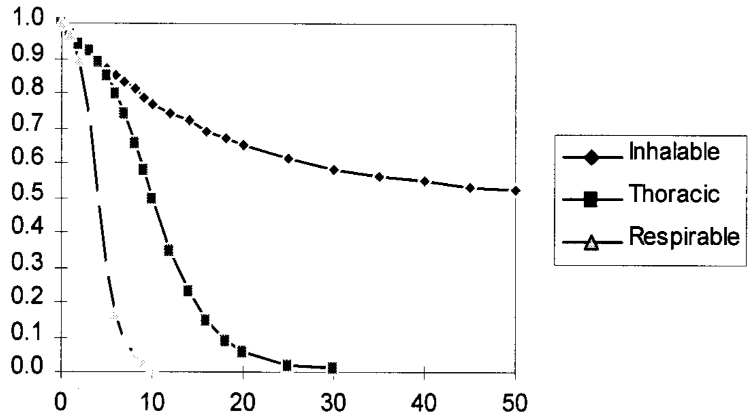
- Particles are strongly attracted to surfaces
  - van der Waals forces, electrostatic attraction, capillary forces, etc.
  - Smaller particles are more difficult to dislodge

Deposition of Inhaled Particles

- Size selective sampling relies on principles of particle physics to collect samples of different size particles.
- For industrial hygiene, particles are classified according to where they deposit in the respiratory tract:
  - Inhalable
    - Up to 50 μm
  - Thoracic
    - < 10 μm
  - Respirable
    - < 5 μm



Collection efficiency for particle aerodynamic diameter



END Part 1

- Questions?

- Part 2 covers aerosol sampling methods

Filter-Based Technologies

- Filtration is the most important method used to collect aerosol samples
  - Easy, inexpensive, widely used
  - Variety of filter media and sampling devices

Filter Media

- Fiber filters
  - Cellulose, glass, or quartz fibers
  - Low pressure drop, high loading capacity, inexpensive
  - May not be adequate for sub-micron particles
  - Water absorption problems may interfere with gravimetric analysis

Filter Media

- Porous membrane filters
  - Cellulose ester, PVC, PTFE, etc.
  - Porous mesh microstructure, convoluted flow path
  - Available in pore sizes of 0.1 to 10 µm
    - 5 µm pore size = 98% efficient for sub-micron particles
  - "Depth" filters
    - Particles are deposited within the filter structure, not just on the surface
  - Higher flow resistance, lower loading capacity

Filter Media

- Straight-through (capillary) membrane filters
  - Polycarbonate or polyester with uniform size pores
  - High-pressure drop, low loading capacity
  - Susceptible to static electricity and particle loss
  - Used for electron microscopic analysis

Filter Media

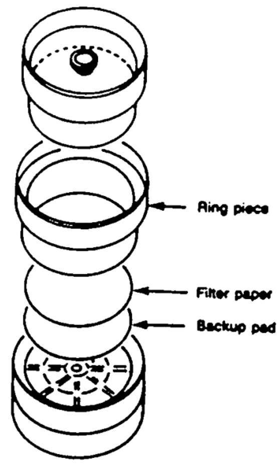
- Polyester foam
  - "Emerging technology"
  - Used for simultaneous sampling of multiple aerosol fractions
  - Foam plugs with final filter

Filter Media

Filter media	Examples
Mixed cellulose ester (MCE)	Metals, welding fumes, asbestos, etc
Polyvinyl chloride (PVC)	Total or nuisance dust, silica
Teflon (PTFE)	Paraquat, organic arsenic, PM mass, organics
Glass fiber	Polynuclear aromatic hydrocarbons, strychnine

Filtration-Based Techniques

- Basic 37 mm Filter Cassette
  - Plastic cassette w/plugs
    - Filter paper
    - Backup pad
    - Outlet has air-distribution channels ("wagon wheel")
  - 2- or 3-pieces
    - 3-piece unit can be used "open-faced", when an even distribution of particulate is needed
      - Chemically treated filters (i.e., glutaraldehyde, isocyanates)
      - Microscopic analysis (asbestos)



Filtration-Based Techniques

- Gravimetric analysis
  - Known volume of air drawn through a filter
  - Final weight - initial weight (tare) = mass of contaminant on filter
  - Concentration (exposure) = mass on filter / air volume = mg/m^3
  - Filters usually must be pre-weighed
    - Laboratories provide pre-weighed, numbered filters
    - The industrial hygienist can weigh filters
    - Requires analytical balance, drying chamber, and good lab technique

Filtration-Based Techniques

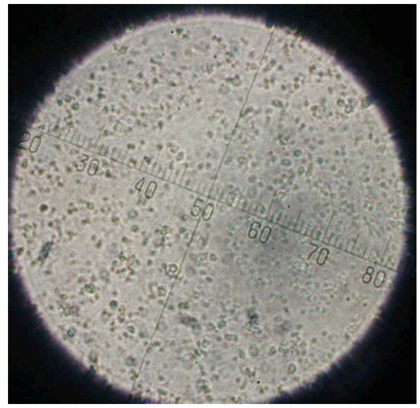
- Gravimetric analysis
  - "Matched weight" filters are convenient, as the need to pre-weigh is avoided
    - Two "matched weight" filters are placed into the cassette
    - The upper filter = final weight
    - The lower filter = tare weight
    - The less tolerance in the "match", the more the cost and the lower the detection limit

Filtration-Based Techniques

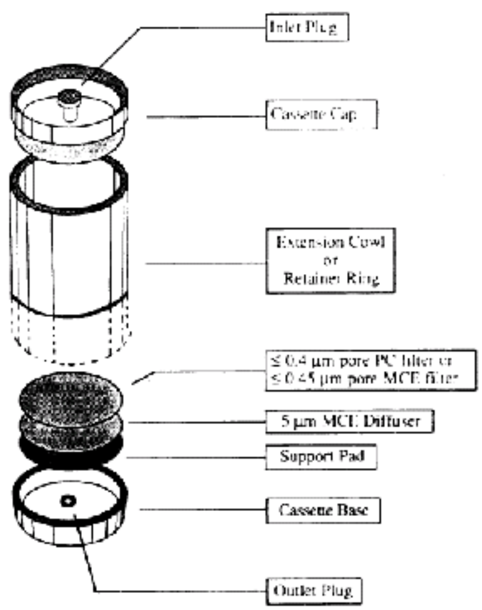
- Chemical analysis (various NIOSH and OSHA methods)
  - Known volume of air is drawn through the filter
  - For metals, the filter paper is dissolved, diluted, and analyzed (usually ICP or FAA)
  - For organics, the filter paper is extracted, concentrated, and analyzed (GC, HPLC, MS)
    - Contaminant mass is determined
    - Mass of contaminant/air volume = mg/m^3

Filtration-Based Techniques

- Microscopic analysis (asbestos)
  - Asbestos cassette is designed for fiber-counting accuracy
    - Conductive plastic minimizes static electricity
    - Cowl to promote even fiber distribution
    - 25 mm diameter improves fiber density on filter
    - “Plenum” back to avoid “wagon wheel” deposition pattern
    - Mixed cellulose ester (MCE) filter recommended (two filters for TEM
    - Sampling is “open face”, with the cassette pointed downward



25 mm cowled cassette, for asbestos



Filtration-Based Techniques

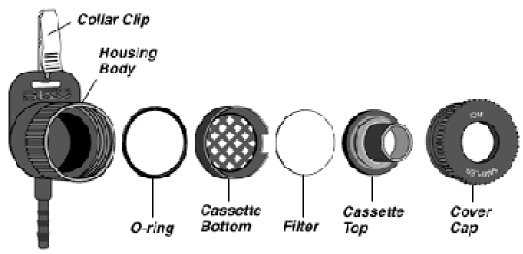
- Microscopic analysis (asbestos)
  - Phase Contrast Microscopy (PCM) analysis (NIOSH 7400)
    - Required for OSHA work
  - Transmission Electron Microscopy(TEM) required for "clearance sampling" in schools (EPA AHERA method, NIOSH 7402)
    - TEM is preferred by EPA
    - OSHA accepts NIOSH 7402 method

Filtration-Based Techniques

- Microscopic analysis (asbestos)
  - Transmission Electron Microscopy(TEM) required for "clearance sampling" in schools (EPA AHERA method, NIOSH 7402)
    - TEM is preferred by EPA
      - Fiber types identified
      - Smaller fibers can be seen
      - Unfortunately, there is no corresponding epidemiology, so the results cannot be interpreted properly
    - OSHA accepts NIOSH 7402 method
      - Fiber counting is by PCM
      - TEM is used to identify fibers for a more accurate count

Filtration-Based Techniques

- Inhalable samplers
  - "Traditional" cassettes under-represent the amount of inhalable particulate, especially for larger-sized particles (open-face collects more than closed-face)
  - Institute of Occupational Medicine samplers (IOM)



Filtration-Based Techniques

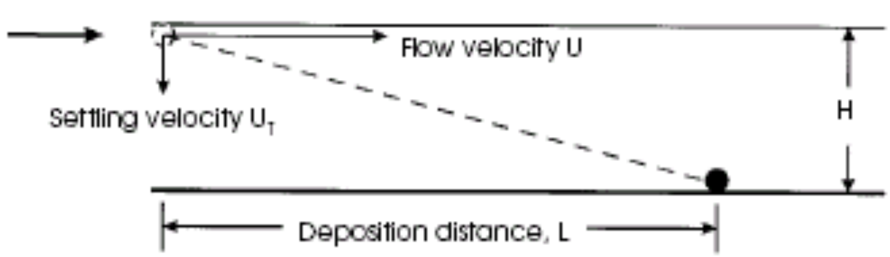
- Inhalable samplers
  - IOM sampler (cont.)
    - Designed for "inhalable" particulate
      - 2 lpm, 25 mm filter
      - Removable cassette and filter are weighed as a unit
      - Open-face calibration required
        - » No easy way to connect a calibration device
        - » "Pickle Jar" and other open-face calibration methods
  - Inhalable samplers adopted by TLV
    - Refer to Appendix D of TLV book
    - OSHA sampling should be traditional open-face

Sedimentation-Based Techniques

- Sedimentation = “settling out” by gravity
  - Particulate matter tends to remain suspended in air
    - Normal ventilation rates usually exceed settling velocity
  - Sedimentation devices
    - Elutriators (settling chambers)
      - Vertical elutriator
        - » Cotton dust sampling
      - Horizontal elutriator

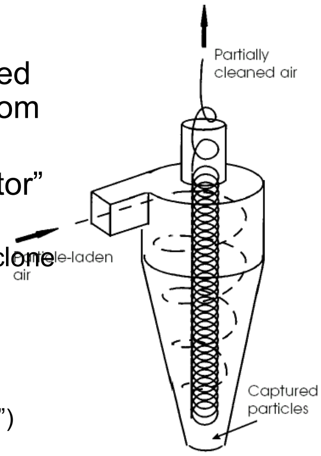
Elutriators

- Horizontal elutriator (cont).
  - BMRC sampler, intended to capture respirable size particles
    - 5 µm midpoint
    - Seldom used today

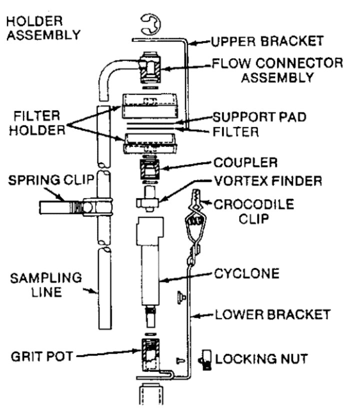


Inertial techniques: Cyclones

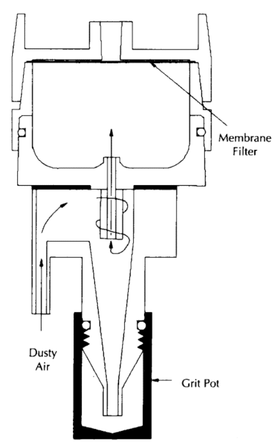
- Cyclones
  - Centrifugal forces cause larger sized particles to move to be removed from the air stream
  - The cyclone acts as a "pre-separator"
    - Large particles collect in the "grit pot"
    - Smaller particles pass through the cyclone and are collected on a filter
    - "Cut size" d_{50} (50% efficiency size)
      - 5 µm (old BMRC)
      - 4.5 µm (OSHA)
      - 4 µm (ACGIH, ISO/CEN, "Soderholm")



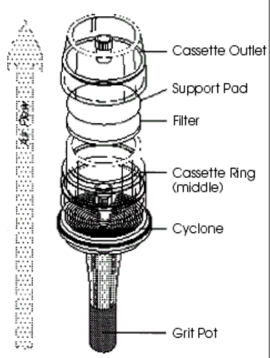
Cyclones



10 mm Dorr-Oliver Cyclone (OSHA)



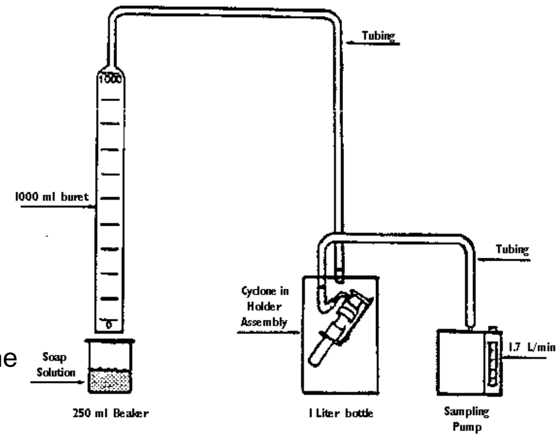
BGI metal cyclone



SKC aluminum cyclone

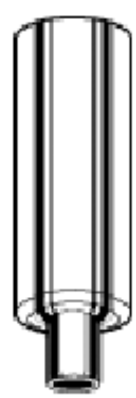
Cyclones

- Cyclone calibration
  - Often no direct way to connect calibrator
  - "Jar" method
    - Cyclone is placed into a "pickle jar"
    - Calibrator is connected to the jar inlet



Cyclones

- Cyclone calibration (cont)
  - Calibration adapters attach to the cyclone, providing a means to connect the calibrator
  - Calibrators can be attached directly to other cyclones, like the BGI metal cyclone



SKC calibration adapter

Cyclones

- Cyclone flow rates are critical to assure performance
  - 1.7 lpm (Dorr-Oliver) for 4.5 µm
  - 1.9 lpm (SKC) for 5 µm (old BMRC)
  - 2.5 lpm (SKC) for 4.0 µm
  - 2.2 lpm (BGI) for 4.0 µm

Cyclone Sampling

- Respirable Silica (NIOSH 7500)
  - Equipment
    - 10 mm nylon cyclone
    - Cassette w/5 µm PVC filter
    - 1.7 lpm
  - Collect a bulk sample of dust
  - Analysis
    - Filter is dissolved, and the suspension is re-filtered onto a silver membrane filter
      - Filter is analyzed by X-Ray Diffraction
  - Evaluation
    - PEL for dust mixture is based on % quartz, cristobalite, and tridymite (refer to OSHA guidance).

OSHA Silica Sampling

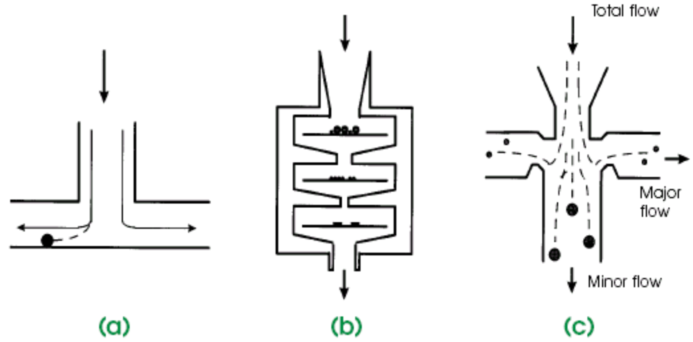
PEL for respirable silica

$$= \frac{10 \text{ mg/m}^3}{\% \text{ quartz} + 2(\% \text{ cristobalite}) + 2(\% \text{ tridymite}) + 2}$$

Impaction-Based Technologies

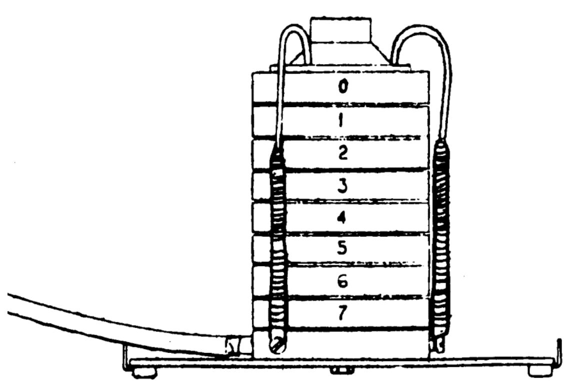
- Widely used to characterize aerosols
  - "Jet and Plate" impactors direct a stream of high-velocity air against a collection surface, characterized by the 50% cut size, d_{50}
    - Single-stage impactors often used as "preseparators"
    - "Cascade" impactors allow for simultaneous collection of multiple particle size fractions
      - "Anderson" sampler to characterize dust or biological sampling
      - "Marple" personal breathing zone sampler
  - "Virtual Impactor" separates particles into two streams ("dichotomous" samplers)
  - Konimeter (historic), dust impacted on glass plate, microscope counted

Impaction-Based Technologies



Inertial impactors: (a) conventional jet-to-pate impactor collecting a single size fraction (say all particles over 10 μm); (b) multistage or cascade impactor in which each stage collects a different size fraction; and (c) virtual impactor or dichotomous sampler in which size fractions are separated but not removed from the airstream.

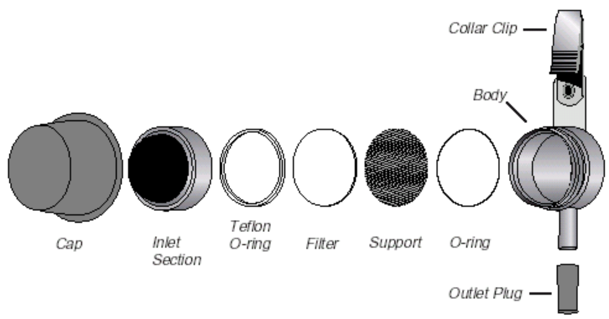
Impaction-Based Technologies



Anderson Cascade Impactor

SKC Button Aerosol Sampler for inhalable dust sampling

- ACGIH/ISO collection curve
- 4 lpm flowrate
- 25 mm filter



SKC Personal Environmental Monitor for PM10 and PM2.5

- US-EPA collection curve

  2, 4 or 10 lpm flowrate

  37 mm PTFE filter