Interpretation of Raw Data

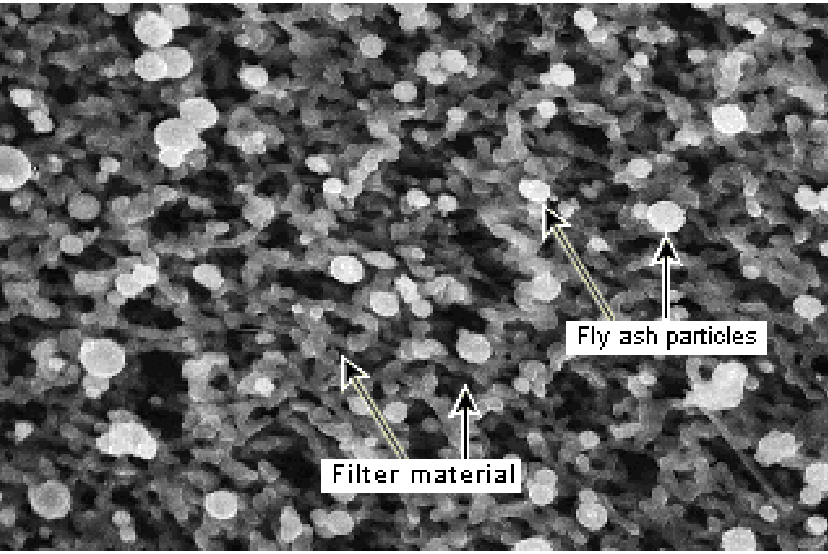
- Particulate emissions from both manmade and natural sources do not consist of particles of any one size. Instead, they are composed of particles over a relatively wide size range.
- It is often necessary to describe this size range. Particulate matter for size distribution evaluation is measured in a variety of ways:

  In the case of <u>cascade impactors</u>, particulate matter is separated into diameter size categories within the impactor head during sampling. The mass of particulate matter contained within each size range is recovered and determined gravimetrically.

  <u>Particle count</u> is another method of data interpretation for size distribution. Figure 1 is a photomicrograph of fly ash collected on a filter.

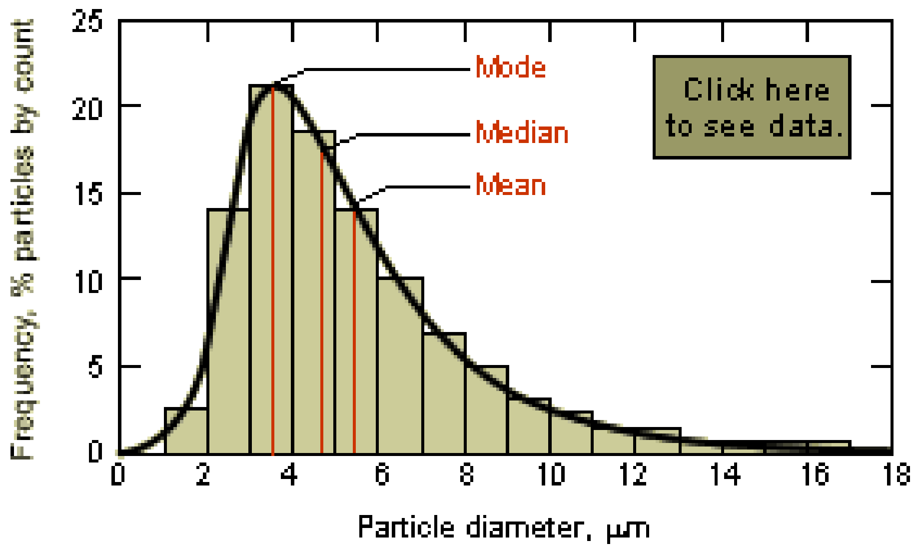
  The filter material shown is mixed cellulose ester (MCE).
- The particles shown here are in the 1-5 μm size range. From the photomicrograph, the number of particles in a predetermined size range is tabulated and the distribution can be plotted as shown in fig. 2.

Figure 1. Photomicrograph of Fly Ash Particles on an MCE Filter



Source: Courtesy of Air Control Techniques, P.C.

Figure 2. Histogram of a Particle Size Distribution

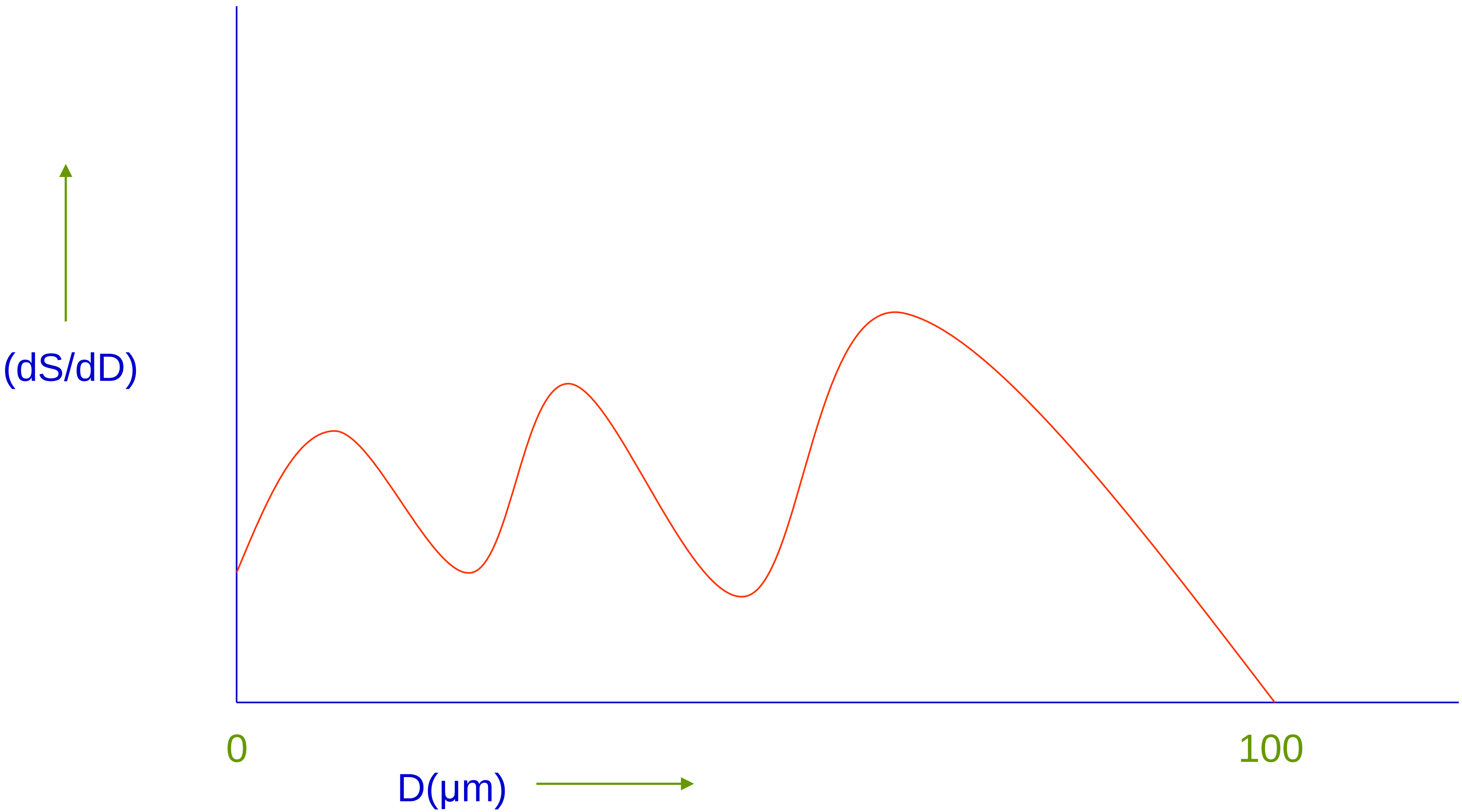


Source: *Particle Size Analysis in Industrial Hygiene*, Academic Press, 1971.

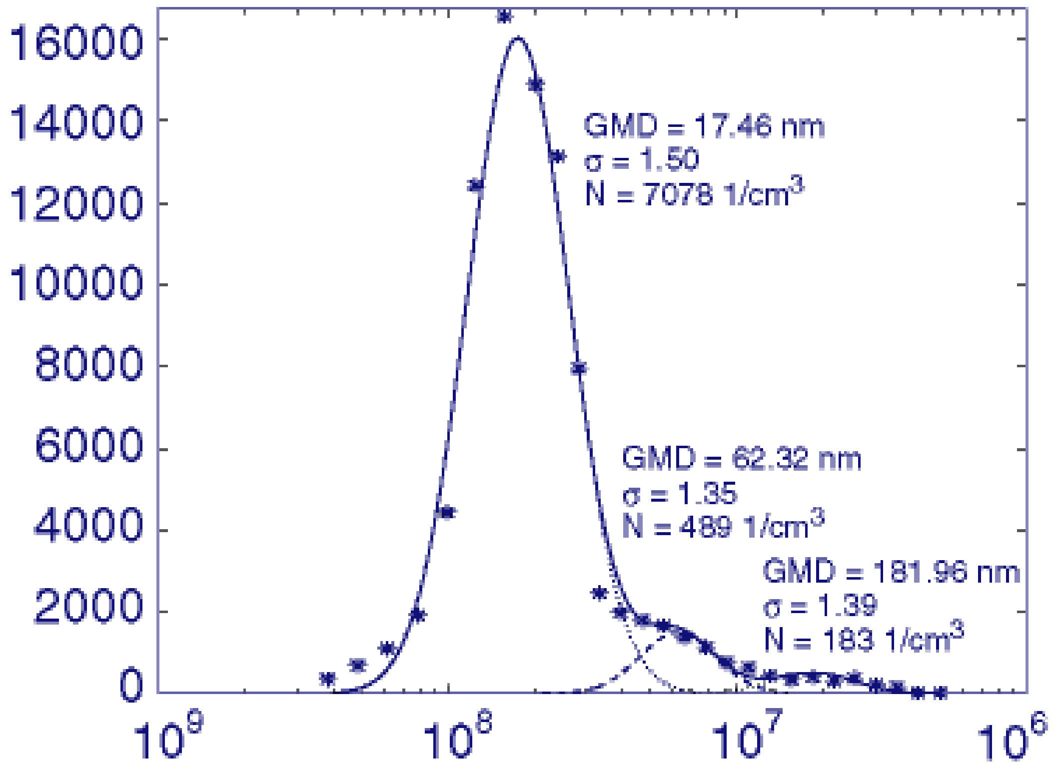
Size Distribution

- A histogram (shown in Figure 2) is one of the simplest ways to display a particle size distribution (frequency-distribution curve).
- Frequency can be plotted (on the Y-axis) by number count, surface area, volume or mass.
- The skewed distribution shown in Figure 2 is typically encountered in the field of air pollution control.
- The median, arithmetic mean, and mode help characterize the arithmetic mass distribution (see Figure 2).
- **mass median particle diameter** is the particle diameter that divides the frequency distribution in half.
- The **arithmetic mean diameter** is the arithmetic average particle diameter of the distribution.
- In particle size distributions, the mode is the particle diameter that occurs most frequently.

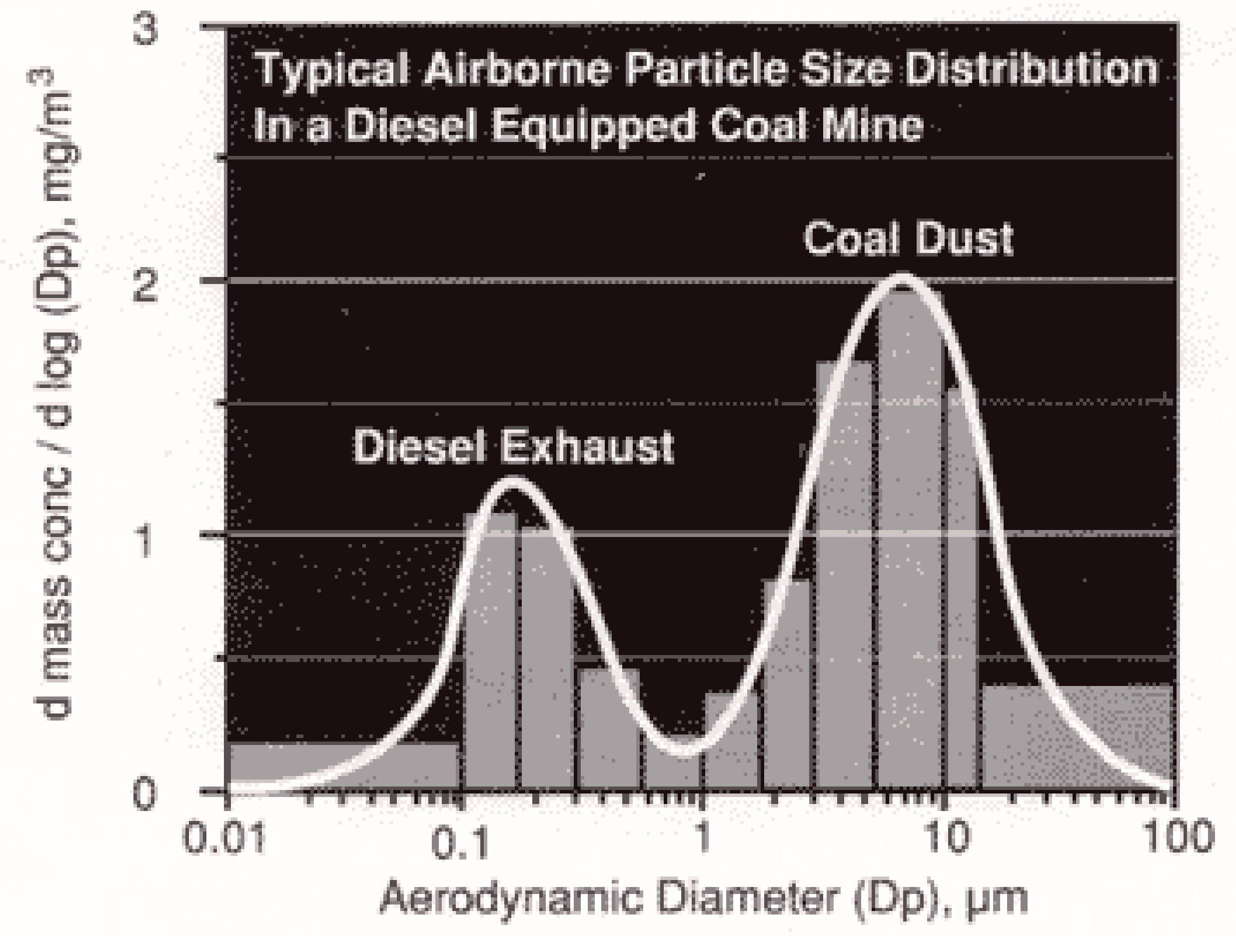
Frequency distribution curve on the basis of surface area



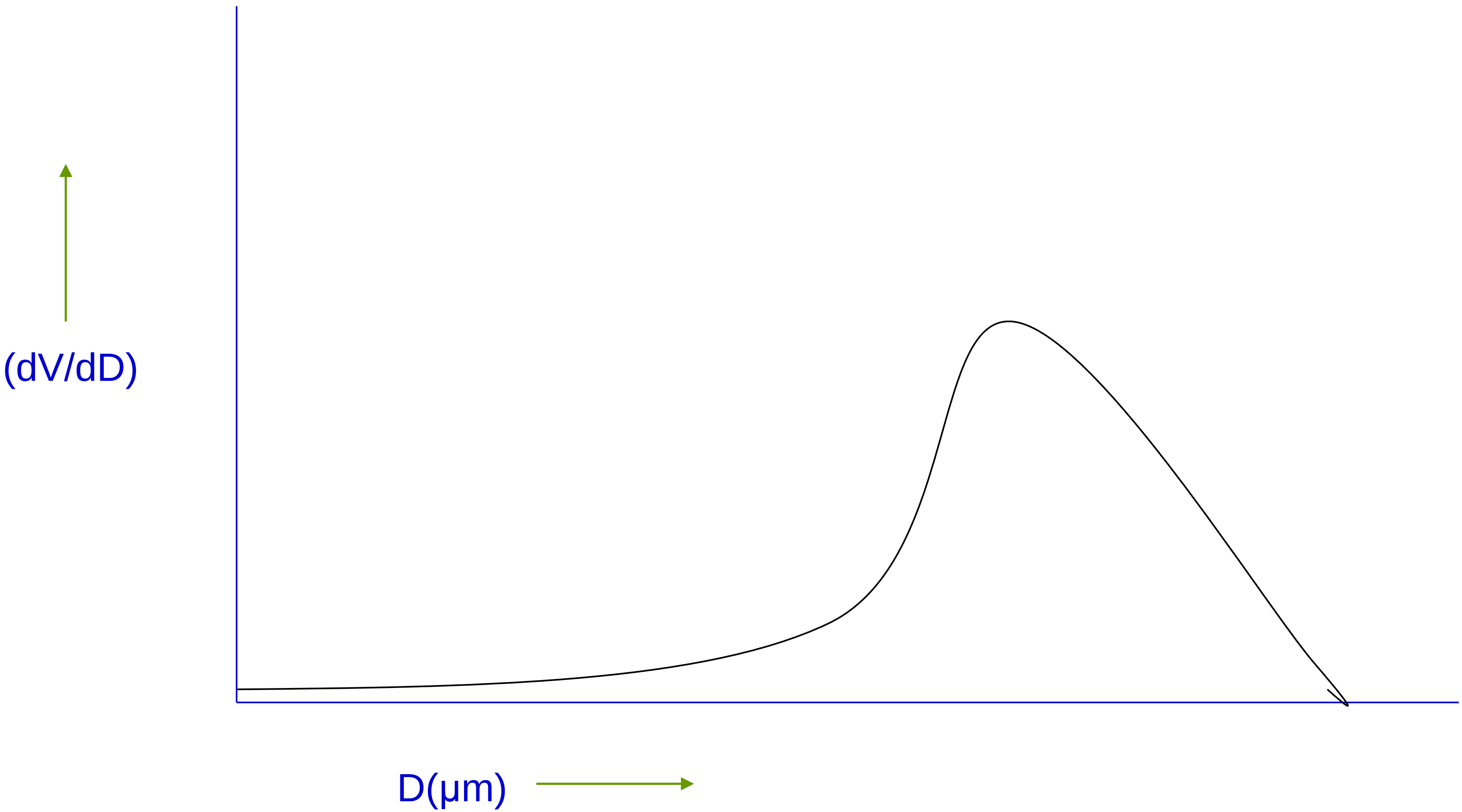
Frequency distribution curve on the basis of number concentration



Frequency distribution curve on the basis of mass concentration



Frequency distribution curve on the basis of volume



Nucleation: is the first step in the formation of either a new thermodynamic phase or a new structure via self-assembly or self-organization.

Ice crystallization, seeds help e,g. condensation nuclei

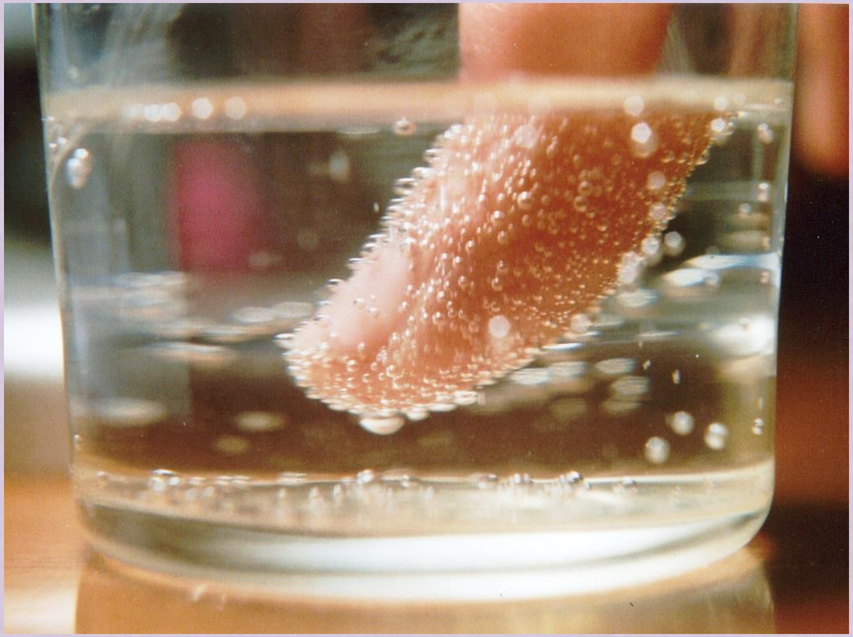
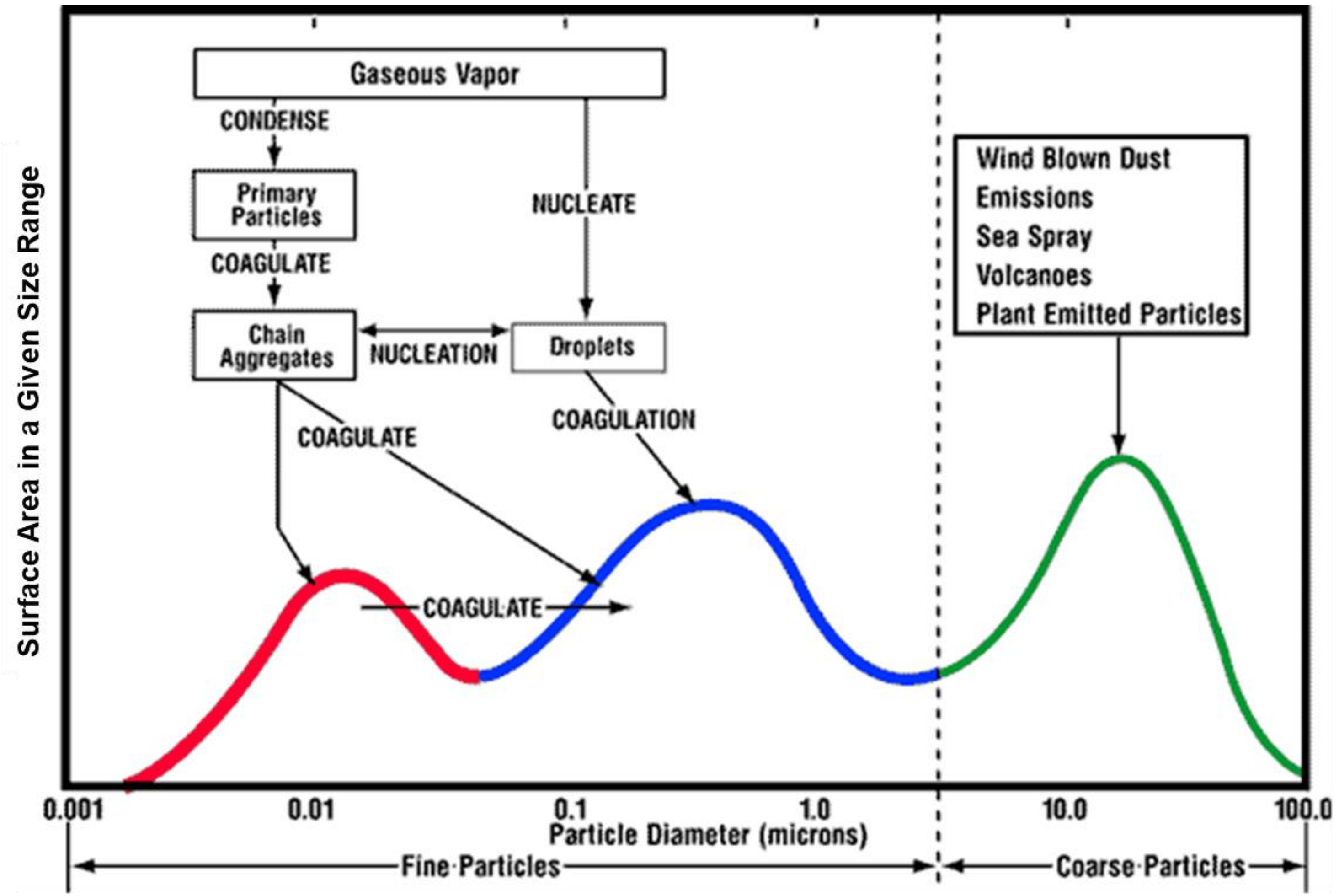


Table: Terms That Describe Airborne Particulate Matter Particulate

Particulate matter	Any material, except uncombined water, that exists in the solid or liquid state in the atmosphere or gas stream at standard conditions
Aerosol	A dispersion of microscopic solid or liquid particles in gaseous media
Dust	Solid particles larger than colloidal size capable of temporary suspension in air
Fly ash	Finely divided particles of ash entrained in flue gas. Particles may contain unburned fuel
Fume	Particles formed by condensation, sublimation, or chemical reaction, predominantly smaller than 1g (tobacco smoke)
Mist	Dispersion of small liquid droplets of sufficient size to fall from the air
Smoke	Small gasborne particles resulting from combustion
Particle	Discrete mass of solid or liquid matter
Fog	Visible aerosol
Soot	An agglomeration of carbon particles

How atmospheric aerosols are formed.



Nuclei mode: 0.005 to 0.1 micron m and Accumulation Mode: 0.1 to 1 micron m

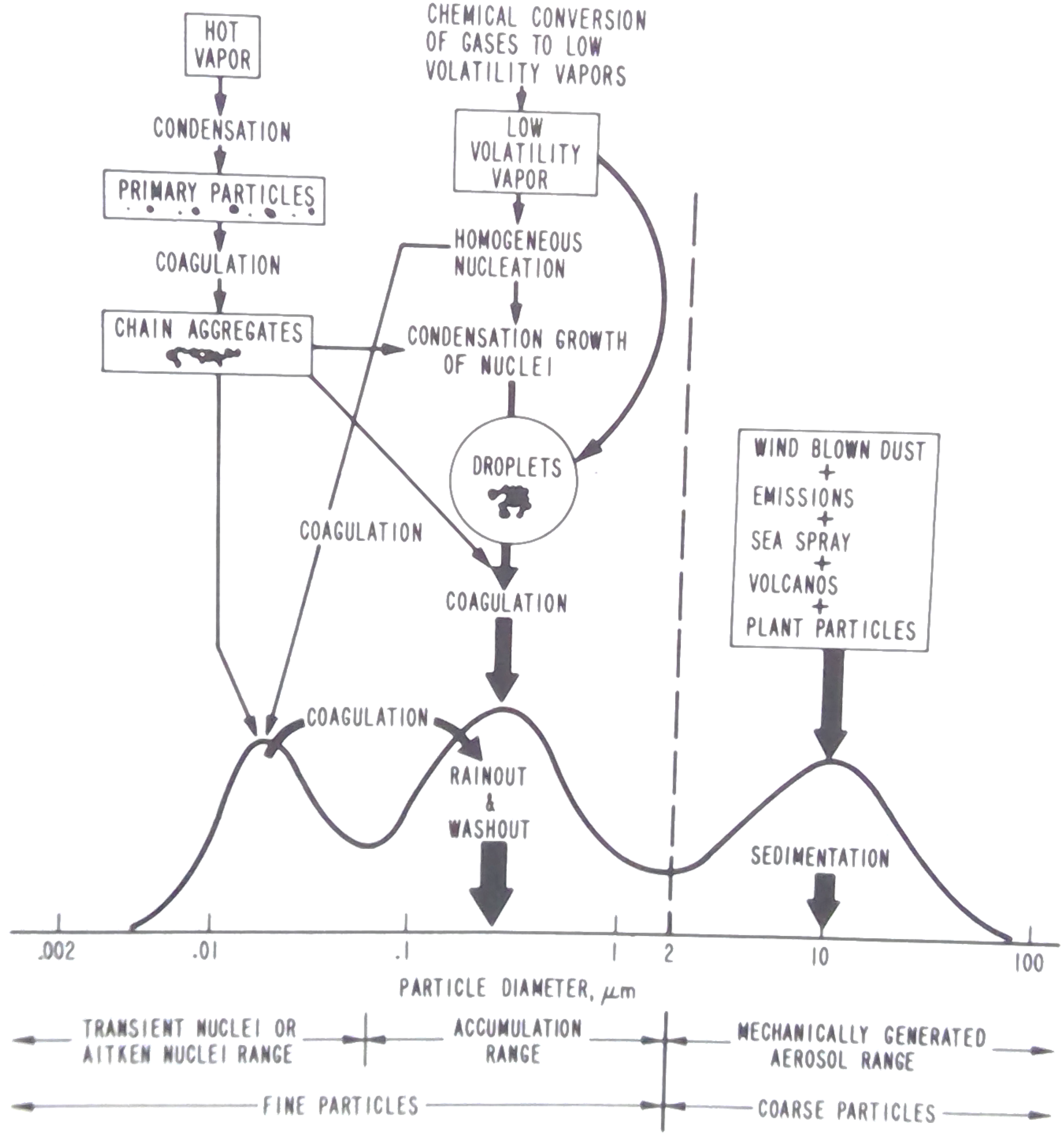


Figure 1.5. Idealized schematic of the distribution of particle surface area of an atmospheric aerosol (Whitby and Cantrell, 1976). The principal modes, sources, and

Figure 2. Ambient Particulate Matter Size Distributions

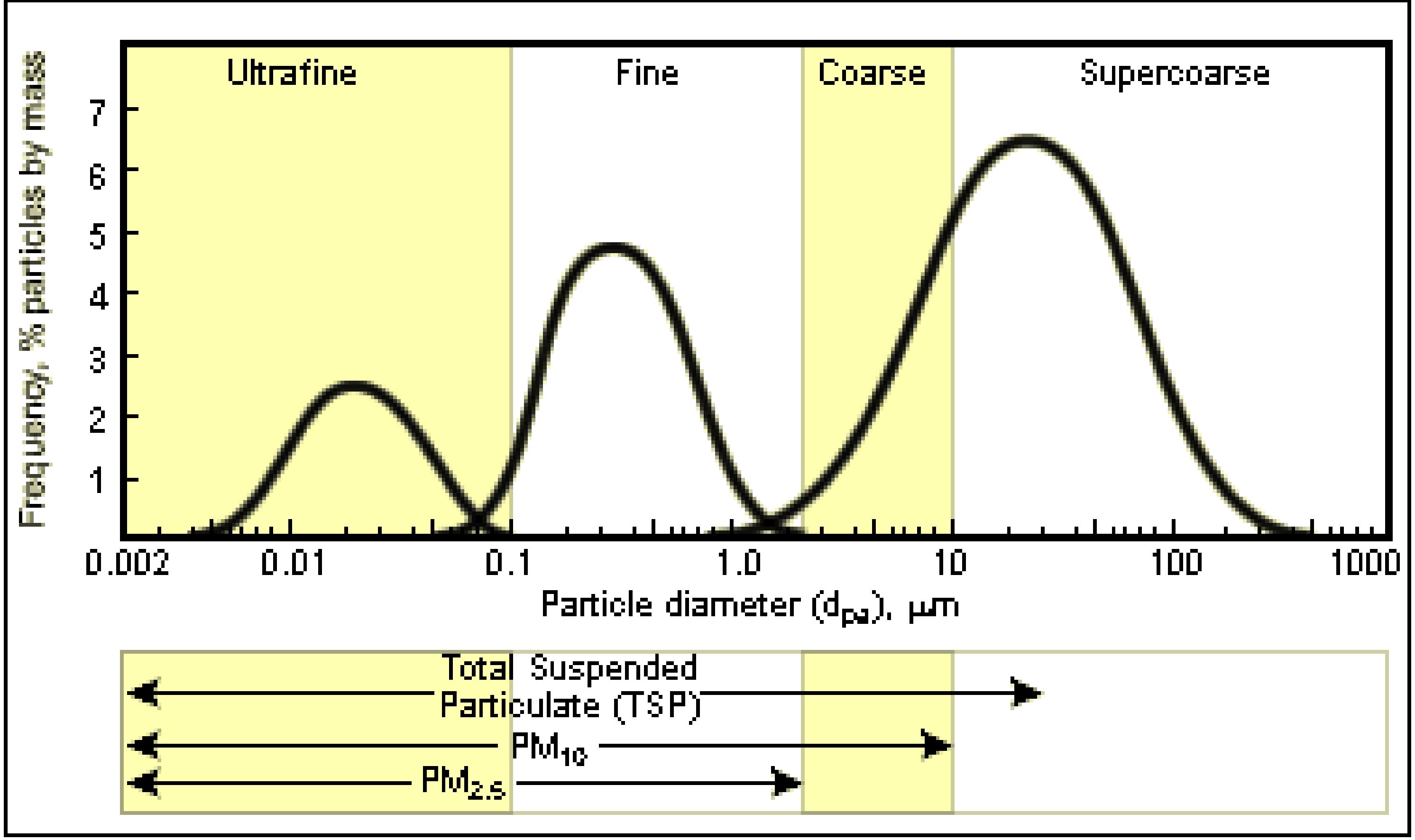
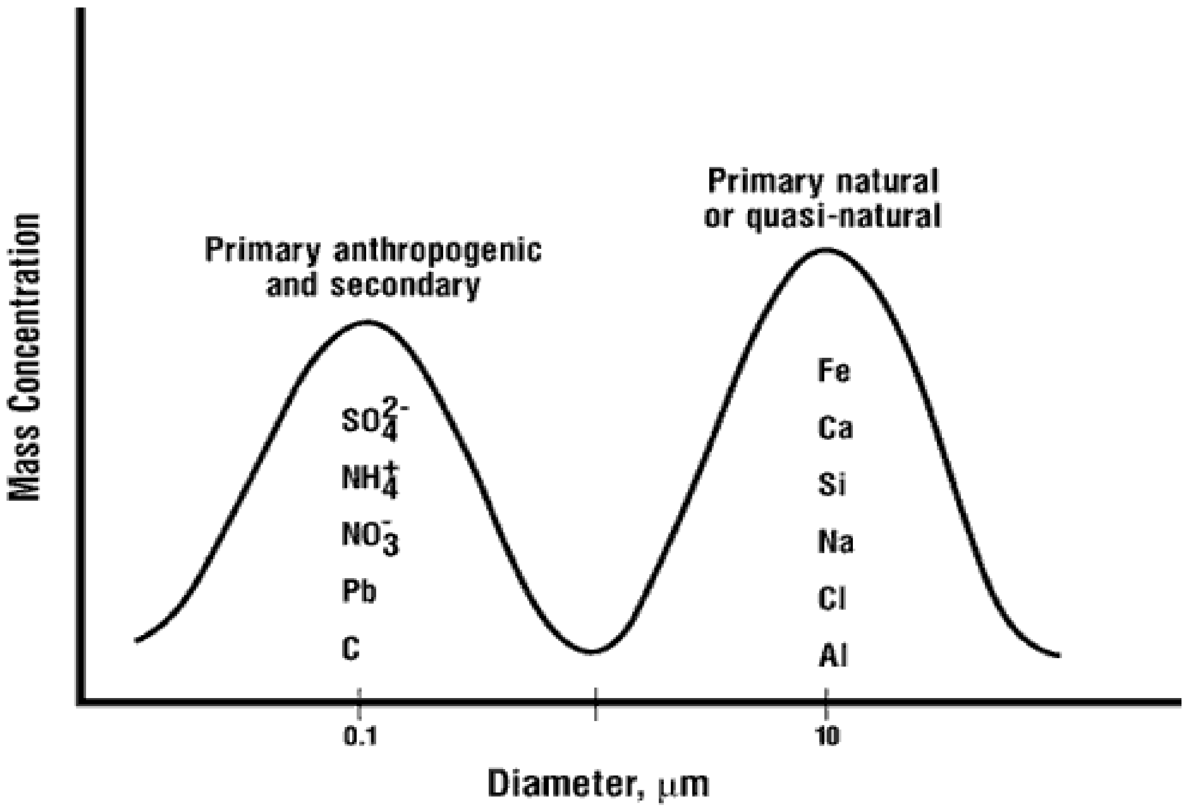


Figure: Bimodal size distribution observed for atmospheric particulate matter

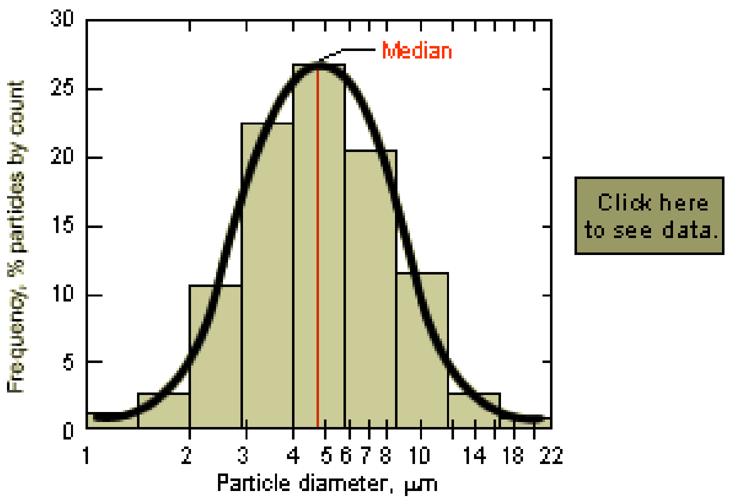


The size distribution of atmospheric aerosols is bimodal, with maximums at 10 microns and 0.1 microns. Particles larger than 2.5 microns are called coarse particles and particles with diameters less than 2.5 microns are called fine particles. Coarse particles originate from entrainment of wind-blown particles, while fine particles result from either high temperature combustion or secondary conversion of atmospheric gases.

Lognormal Size Distribution

When the particle diameters in Figure 2 are plotted on a logarithmic scale against the frequency of occurrence, a bell-shaped curve is generated. As shown in Figure 3 the particle size categories are altered to produce equidistant ranges when plotted on a logarithmic basis. This bell-shaped histogram is called a **lognormal curve.**

Figure 3. Histogram of a Lognormal Particle Size Distribution



Source: *Particle Size Analysis in Industrial Hygiene*, Academic Press, 1971.

- For many manmade sources, the observed particulate matter distribution approximates a lognormal distribution. Therefore, it is often beneficial to work with particle size distributions on a logarithmic basis.
- The terms, **geometric mean diameter** and **geometric standard deviation**, are substituted for arithmetic mean diameter and standard deviation when incorporating logarithms of numbers.
- When the frequency of the particle size distribution is based on mass, the more specific term **geometric mass mean diameter** is used.
- The geometric mass mean diameter is the diameter of a particle that has the logarithmic mean for the size distribution. It is the *n*th root of the product of *n* terms. The geometric mass mean diameter is expressed in eq(1) and eq(2).

$$\log d_g = \frac{\log d_{pa(1)} + \log d_{pa(2)} + \log d_{pa(3)} + \cdots + \log d_{pa(n)}}{n} \quad (1)$$

$$d_g = \sqrt[n]{d_{pa(1)} \times d_{pa(2)} \times d_{pa(3)} \times \ldots \times d_{pa(n)}} \quad (2)$$

Where

d_{pa} = Aerodynamic particle diameter, µm

d_g = Geometric mass mean diameter, µm

n = Number of particles in distribution

$$\sigma_g = \frac{d_{50}}{d_{15.78}} \qquad (3)$$

$$\sigma_g = \frac{d_{84.13}}{d_{50}} \qquad (4)$$

Where

σ_g	=	Geometric standard deviation of particle mass distribution
d_{50}	=	Mass median particle diameter, µm
$d_{15.78}$	=	Diameter of particle that is equal to or less than 15.78% of the mass of particles present, µm
$d_{84.13}$	=	Diameter of particle that is equal to or less than 84.13% of the mass of particles present, µm

Example 1.

Calculate the Mass Median Particle Diameter and the Geometric Standard Deviation for a Particle Distribution

Calculate both the mass median particle diameter and the geometric standard deviation for the following lognormal distribution data.

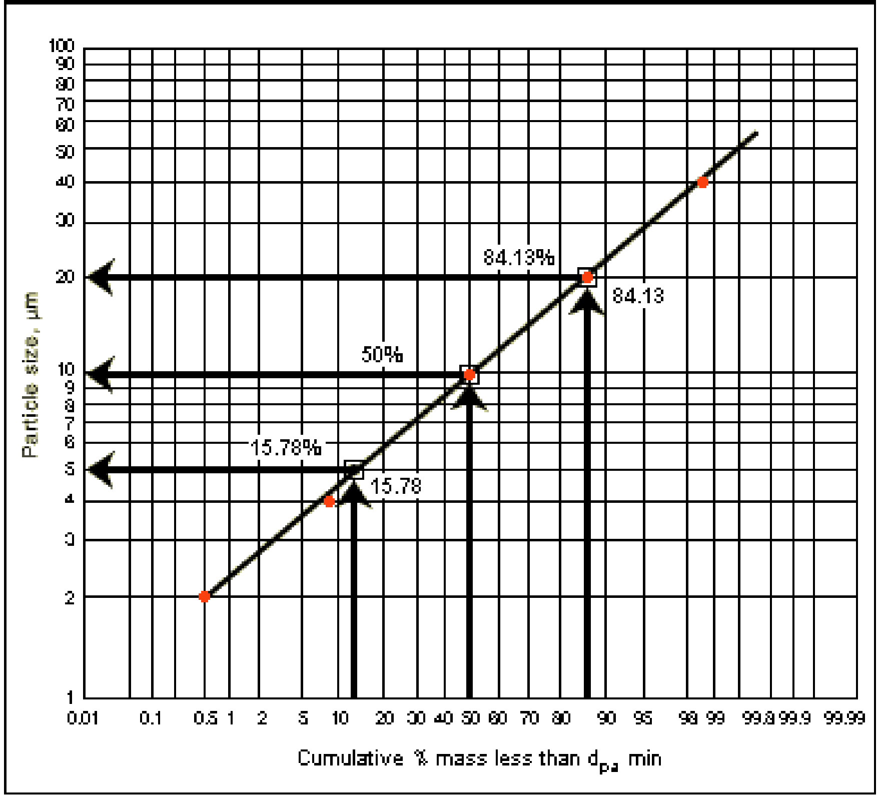
Table 1. Particle Size Data for Example Problem 1

Size Range (µm)	d_{pa} min (µm)	Concentration (µg/m^3)	% Mass in Size Range	Cum. % Mass < d_{pa} min
0 - 2	-	1.0	0.5	-
2 - 4	2	14.5	7.25	0.5
4 - 6	4	24.7	12.35	7.75
6 - 10	6	59.8	29.90	20.1
10 - 20	10	68.3	34.15	50.0
20 - 40	20	28.9	14.45	84.13
> 40	40	2.8	1.4	98.6
		Total = 200.0		100.0

Solution:

Step 1. Plot the distribution data from Table 1 on log-probability paper.

Figure 4. Size Distribution (Log-Probability Plot)



Contd….

- The straight line indicates that the particle size data set is lognormal.
- **Step 2**. Using the graph, determine the approximate particle size at 15.78, 50, and 84.13 percent probability.
- **Step 3**. Determine the mass median particle diameter.

$$\text{Mass median particle diameter} = d_{50} = 10\ \mu m$$

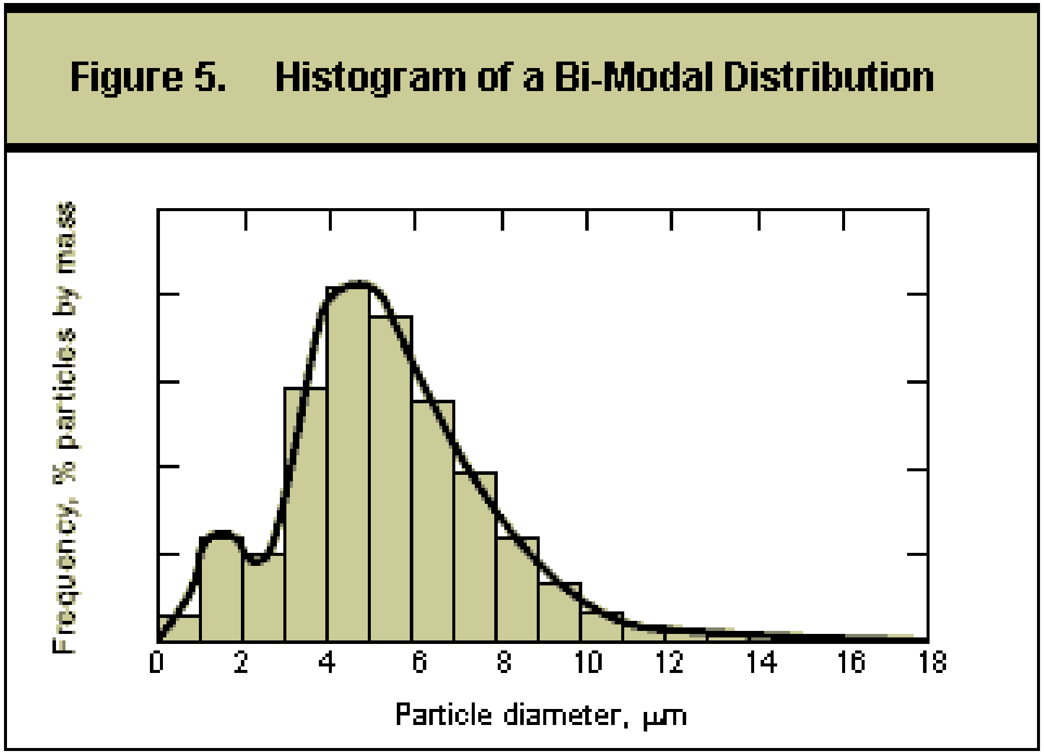
Step 4. Determine the geometric standard deviation of the particle mass distribution.

$$\sigma_g = \frac{d_{50}}{d_{15.78}} = \frac{10\ \mu m}{5\ \mu m} = 2.0$$

Or

$$\sigma_g = \frac{d_{84.13}}{d_{50}} = \frac{20\ \mu m}{10\ \mu m} = 2.0$$

Particle size distributions resulting from complex particle formation mechanisms or several simultaneous formation mechanisms may not be lognormal. As shown in Figure 5, these distributions may exhibit more than one peak (multi-modal).



In these cases, plots of the data on log-probability paper will not yield a straight line. In order to characterize this type of particle size data, it may be necessary to treat the data as two separate lognormal distributions.

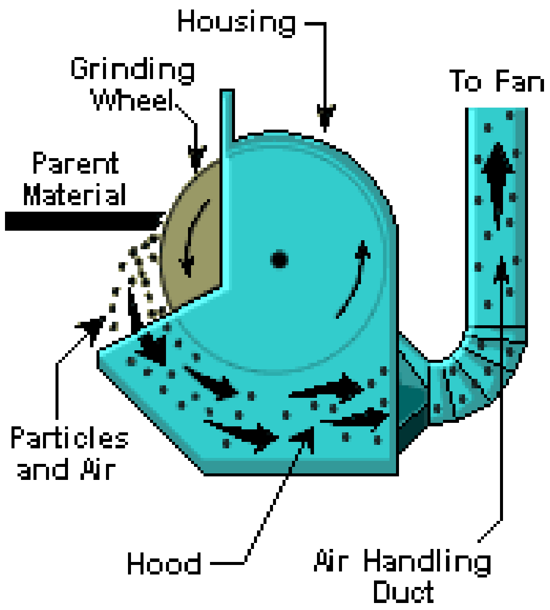
Particle Formation

The range of particle sizes formed in a process is largely dependent on the types of particle formation mechanisms present. The general size range of particles can be estimated by simply recognizing which particle formation mechanisms are most important in the process being evaluated. The most important particle formation mechanisms in air pollution sources include the following:

- Physical attrition/mechanical dispersion
- Combustion particle burnout
- Homogeneous and heterogeneous nucleation
- Droplet evaporation

Physical attrition occurs when two surfaces rub together. For example, the grinding of a metal rod on a grinding wheel yields small particles that break off from both surfaces (Figure 1). The compositions and densities of these particles are identical to the parent materials.

Figure 1. Grinding Wheel

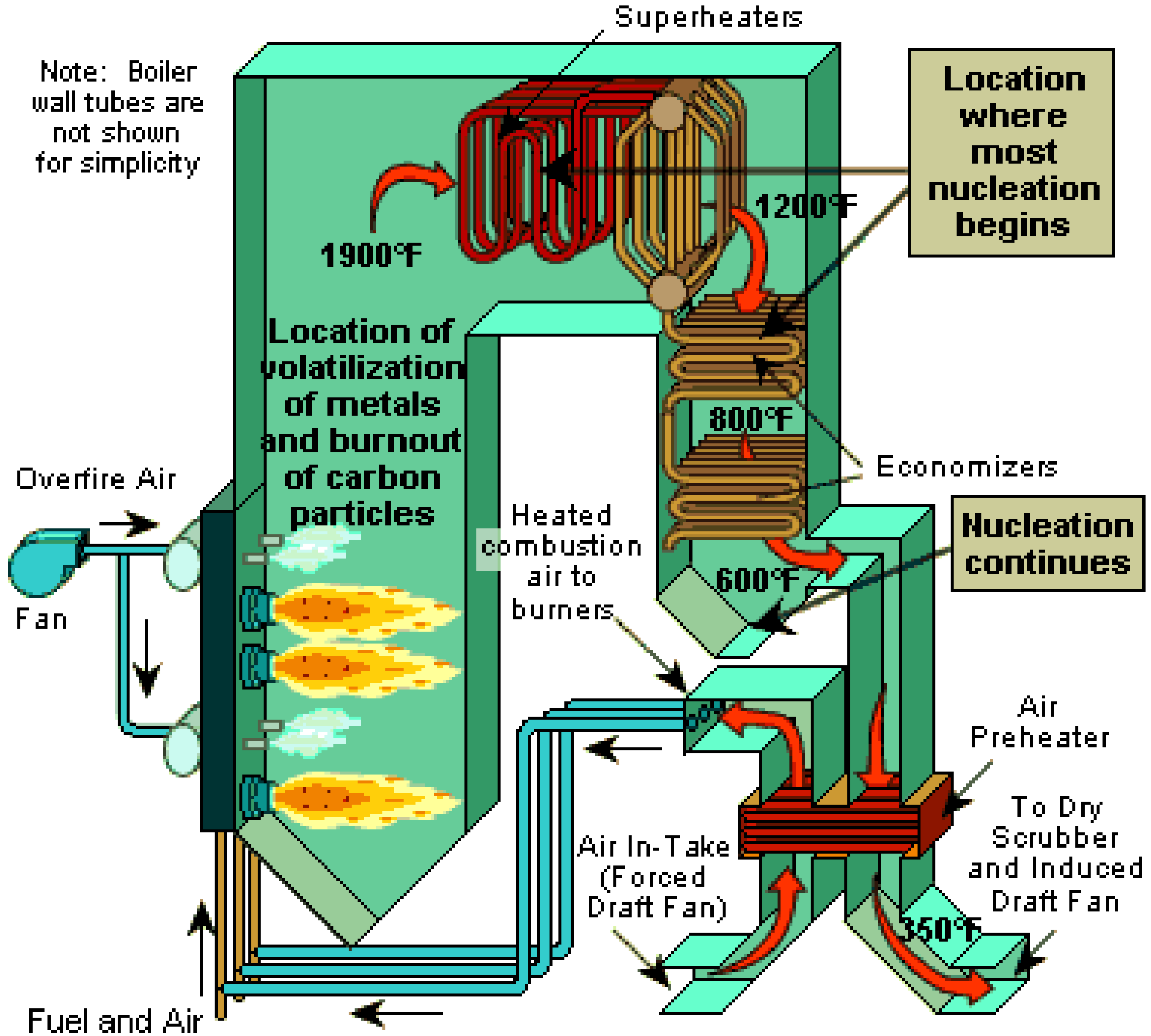


Combustion Particle Burnout

- When fuel particles are injected into the hot furnace area of the combustion process, such as in fossil-fuel-fired boilers (Figure 3), most of the organic compounds in the fuel are vaporized and oxidized in the gas stream. Fuel particles become smaller as the volatile matter leaves and they are quickly reduced to only the incombustible matter (ash) and the slow burning char composed of organic compounds. Eventually, most of the char will also burn leaving primarily the incombustible material.

- As combustion progresses, the fuel particles, which started as 10- to 1000-micrometer particles, are reduced to ash and char particles that are primarily in the 1 to 100 micrometer range. This mechanism for particle formation can be termed combustion particle burnout. Figure 3 shows where both **combustion particle burnout** and nucleation occur in a fossil-fuel-fired boiler. Nucleation is discussed in the next section.

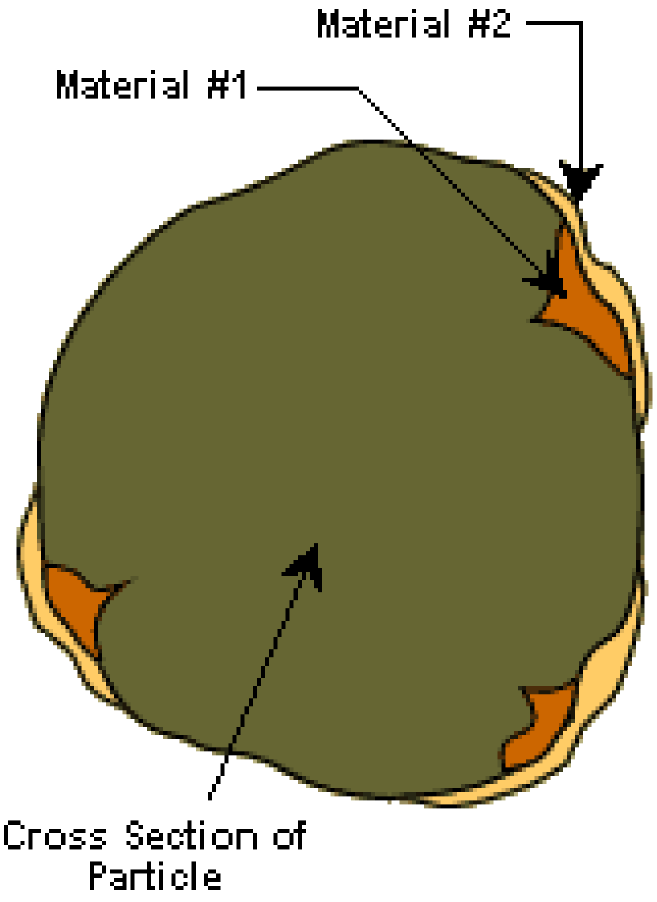
Figure 3. Fossil-Fuel-Fired Boiler



Homogeneous and Heterogeneous Nucleation

- Homogeneous nucleation and heterogeneous nucleation involve the conversion of vapor phase materials to a particulate form. In both cases, the vapor-containing gas streams must cool to the temperature at which nucleation can occur, which is the dew point. Each vapor phase element and compound has a different dew point. Therefore, some materials **nucleate** in relatively hot gas zones while others remain as vapor until the gas stream is cold.
- **Homogeneous nucleation** is the formation of new particles composed almost entirely of the vapor phase material. The formation of particles by homogeneous nucleation involves only one compound.
- **Heterogeneous nucleation** is the accumulation of material on the surfaces of existing particles (see Figure 4). In the case of heterogeneous nucleation, the resulting particle consists of more than one compound.
- There are two main categories of vapor phase material that can nucleate in air pollution source gas streams: (1) organic compounds, and (2) inorganic metals and metal compounds. In a waste incinerator, waste that volatilizes to organic vapor is generally oxidized completely to carbon dioxide and water.

Figure 4. Heterogeneous Nucleation



Droplet Evaporation

- Some air pollution control systems use solids-containing water recycled from wet scrubbers to cool the gas streams.
- This practice inadvertently creates another particle formation mechanism that is very similar to fuel burnout. The water streams are atomized during injection into the hot gas streams.
- As these small droplets evaporate to dryness, the suspended and dissolved solids are released as small particles.
- The particle size range created by this mechanism has not been extensively studied. However, it probably creates particles that range in size from 0.1 to 20 micrometers.
- All of these particles must then be collected in the downstream air pollution control systems.