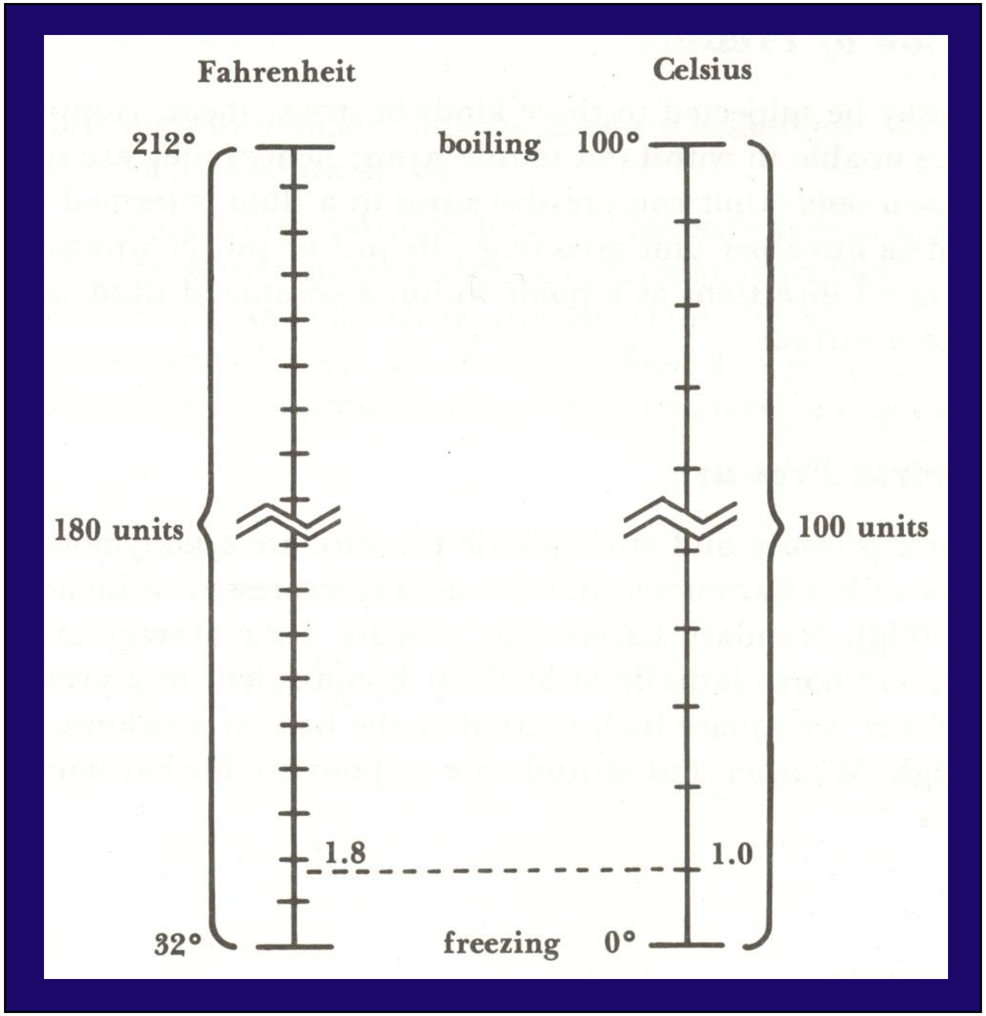
Chapter 1

Basic Concepts

Topics Covered

- Gas temperature
- Gas pressure
- Molecular weight and the mole
- Equation of state
- Viscosity
- Reynolds Number

Gas Temperature



Conversion Equations

$$°F = 1.8°C + 32$$

$$°C = \frac{°F - 32}{1.8}$$

Absolute Temperature

- Kelvin

$$K = °C + 273$$

- Rankine

$$°R = °F + 460$$

Standard Temperature

Group	T_{std}
USEPA (General)	68°F (20°C)
USEPA (Air monitoring)	77°F (25°C)
Industrial hygiene	70°F (21.1°C)
Combustion	60°F (15.6°C)
Science	32°F (0°C)

Example 1-1

The gas temperature in the stack of a wet scrubber system is 130°F. What is the absolute temperature in Rankine and Kelvin?

$$\text{Absolute Temp. } ^\circ\text{R} = 460^\circ\text{R} + 130^\circ\text{F} = 590^\circ\text{R}$$

$$\text{Absolute Temp. K} = \frac{590^\circ\text{R}}{1.8} = 327.8\text{K}$$

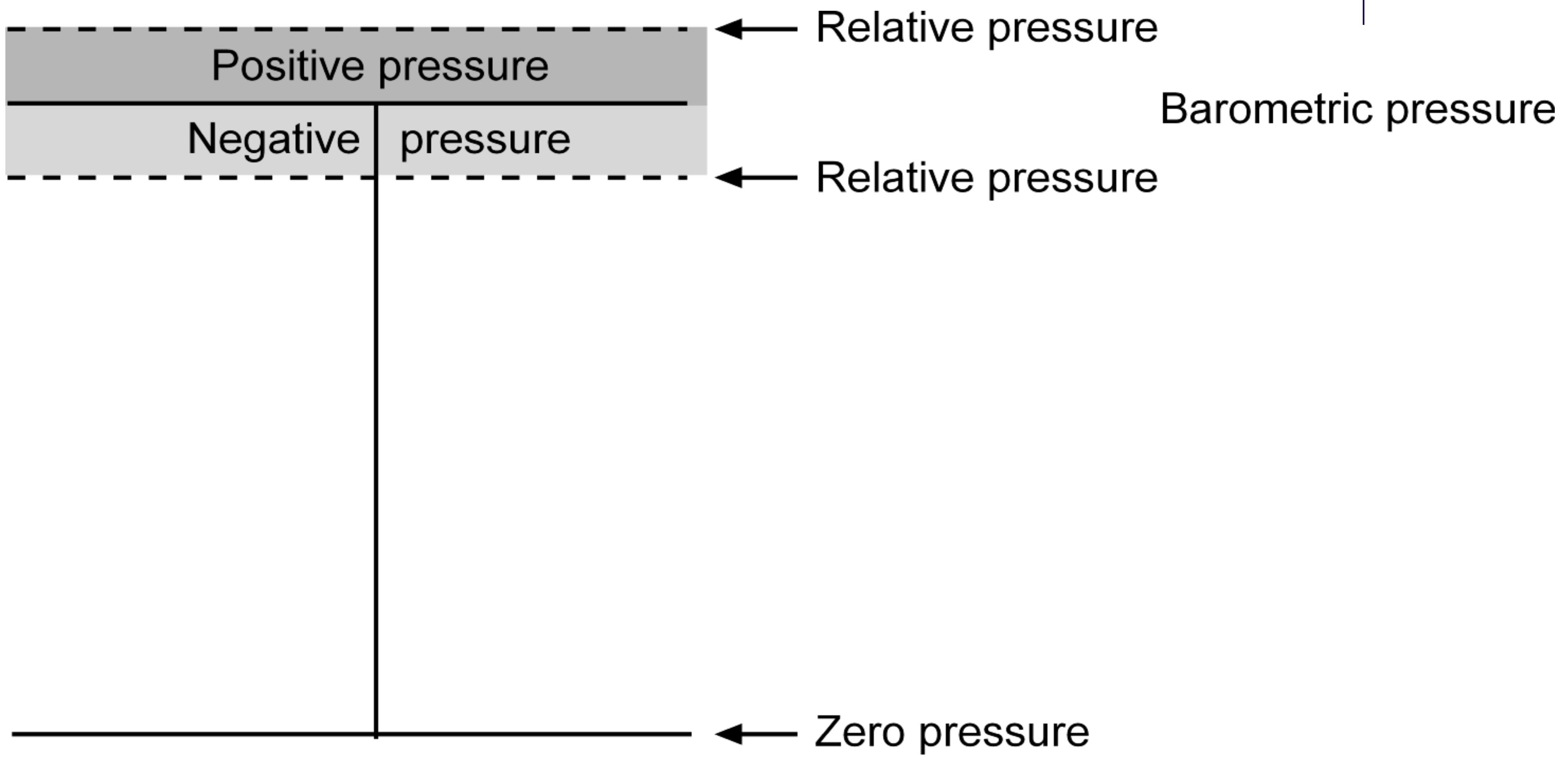
Gas Pressure

- Barometric pressure
- Gauge pressure
- Absolute pressure

Standard Pressure

Units	Value
Atmosphere (atm)	1
Pounds force per square inch (psi)	14.70
Inches of mercury (in Hg)	29.92
Millimeters of mercury (mm Hg)	760
Feet of water column (ft WC)	33.92
Inches of water column (in WC)	407
Kilopascals (kPa)	101.3
Millibars (mb)	1013

Gauge Pressure



Absolute Pressure

$$P = P_b + P_g$$

where

P = absolute pressure
P_b = barometric pressure
P_g = gauge pressure

Example 1-2

An air pollution control device has an inlet static pressure of -25 in WC.

What is the absolute static pressure at the inlet of the air pollution control device if the barometric pressure at the time is 29.85 in Hg?

Convert the barometric pressure units to inWC :

$$P_b = 29.85 \text{ in Hg} \left(\frac{407 \text{ in WC}}{29.92 \text{ in Hg}} \right) = 406 \text{ in WC}$$

Add the barometric and gauge (static) pressures :

$$P = 406 \text{ in WC} + (-25 \text{ in WC}) = 381 \text{ in WC}$$

Molecular Weight

Molecular weight is the sum of the atomic weights of all atoms in a molecule

$$MW_{mixture} = \sum_{i=1}^{n} \chi_i MW_i$$

χ_i = mole fraction of component I

MW_i = molecular weight of component i

The

erial that contains a
of molecules. It is
numerically equal to the molecular weight.

The gram-mole is the mass of material that contains Avogadro’s number of molecules.

It measures the amount of substance of a system and is defined as the amount of substance that contains as many elementary entities as there are atoms in exactly 0.012 kilogram of carbon-12. This quantity is known as Avogadro's number and is approximately 6.0221415×10^{23} (2002 CODATA value).

Equation of State

The ideal gas law:

$$PV = nRT$$

P = absolute pressure

V = gas volume

n = number of moles

R = constant

T = absolute temperature

Values for R

10.73 psia-ft^3/lb-mole-°R

0.73 atm-ft^3/lb-mole-°R

82.06 atm-cm^3/g-mole-K

8.31 x 10^3 kPa-m^3/kg-mole-K

Volume Correction

$$\frac{PV}{T} = nR = \text{CONSTANT} \, (\text{if } n = \text{CONSTANT})$$

$$\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2}$$

$$V_1 = V_2 \left(\frac{P_2}{P_1} \right) \left(\frac{T_1}{T_2} \right)$$

Example 1-3

A particulate control system consists of a hood, ductwork, fabric filter, fan, and stack. The total gas flow entering the fabric filter is 8,640 scfm. The gas temperature in the inlet duct is 320°F and the static pressure is -10 in WC. The barometric pressure is 28.30 in Hg.

If the inlet duct has inside dimensions of 3 feet by 4 feet, what is the velocity into the fabric filter?

Convert the static pressure to absolute pressure :

$$P = 28.30\,\text{in Hg}\left(\frac{407\,\text{in WC}}{29.92\,\text{in Hg}}\right) + (-10\,\text{in WC}) = 375\,\text{in WC}$$

Scfm = standard cubic feet per minute

acfm = actual cubic feet per minute

And then…

Convert the gas temperature to absolute temperature:

$$T_{actual} = 320°F + 460° = 780°R$$

Convert the inlet flow rate to actual conditions:

$$Q_{actual} = 8{,}640\,\text{scfm}\left(\frac{780°R}{528°R}\right)\left(\frac{407\,\text{in WC}}{375\,\text{in WC}}\right) = 13{,}853\,\text{acfm}$$

Calculate the velocity:

$$V = \frac{13{,}853\,{}^{\text{ft}^3}\!/_{\text{min}}}{3\text{ft}\cdot 4\text{ft}} = 1{,}154\,{}^{\text{ft}}\!/_{\text{min}}$$

Molar Volume

$$\frac{V}{n} = \frac{RT}{P}$$

At 68°F and 1 atm (EPA Standard conditions):

$$= \frac{\left(0.73\ \frac{atm - ft^3}{lb - mole \cdot {}^\circ R}\right)\left(528\ {}^\circ R\right)}{1\ atm} = 385.4\ \frac{ft^3}{lb - mole}$$

Example 1-4

What is the molar volume of an ideal gas at 200°F and 1 atm?

Solution…

$$\text{At } 200°\text{F and } 1 \text{ atm:}$$

$$\frac{V}{n} = \frac{RT}{P} = \frac{\left(0.73 \frac{\text{atm} \cdot \text{ft}^3}{\text{lb} - \text{mole}\,°\text{R}}\right)(660°\text{R})}{1\,\text{atm}} = 481.8\,\text{ft}^3 / \text{lb} \cdot \text{mole}$$

or

$$\frac{V}{n} = 385.4\left(\frac{660°\text{R}}{528°\text{R}}\right) = 481.8\,\text{ft}^3 / \text{lb} \cdot \text{mole}$$

Gas Density

$$PV = \left(\frac{m}{MW}\right)RT$$

$$\rho = \frac{m}{V} = \frac{P \cdot MW}{RT}$$

Example

Calculate the average molecular weight of air and the density of air at EPA standard conditions. Consider air to be composed of 21 mole% oxygen and 79 mole% nitrogen.

$$MW_{air} = 0.21\left(32 \, {}^{g}\!/\!_{mole}\right) + 0.79(28 \, {}^{g}\!/\!_{mole}) = 29 \, {}^{g}\!/\!_{mole}$$

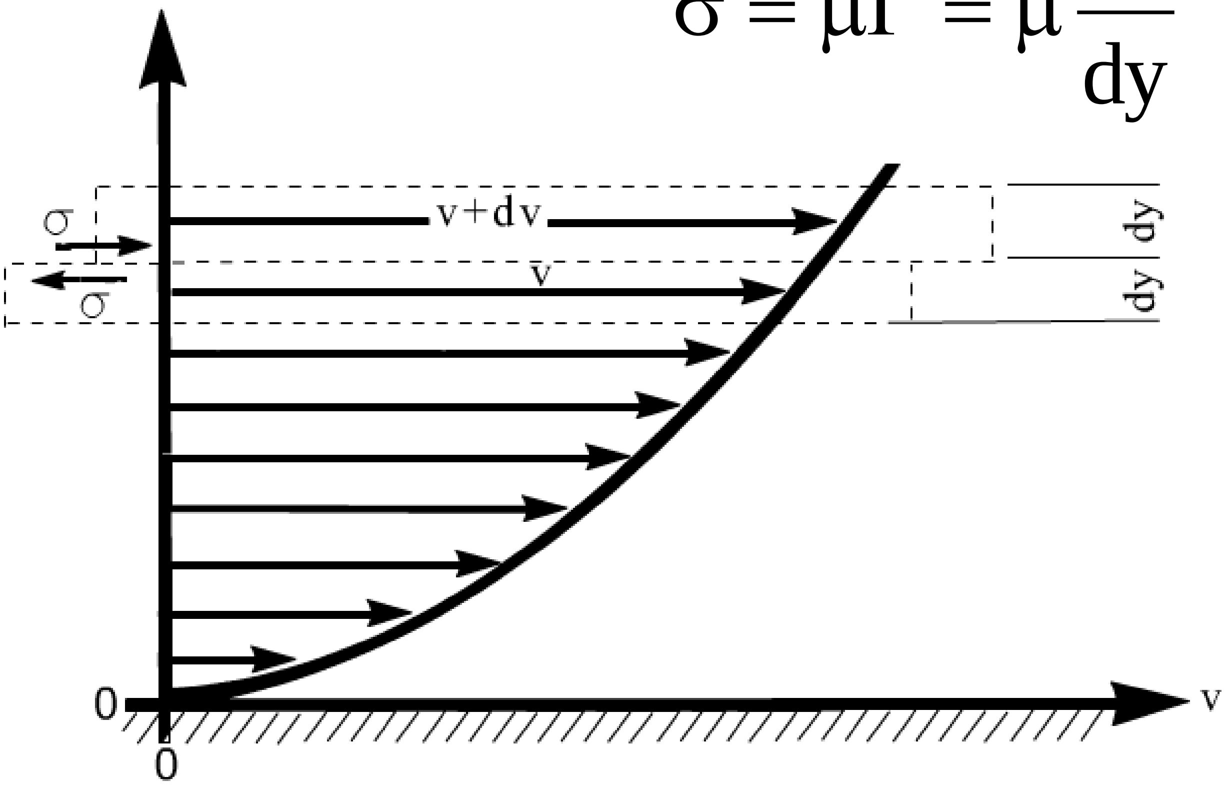
MW = 29 g/mole

Density = 0.0075 lb/ft^3

Viscosity

Figure 1-3

$$\sigma = \mu\Gamma = \mu \frac{dv}{dy}$$



Shearing stress in a moving fluid

Viscosity

Intermolecular Cohesive Forces

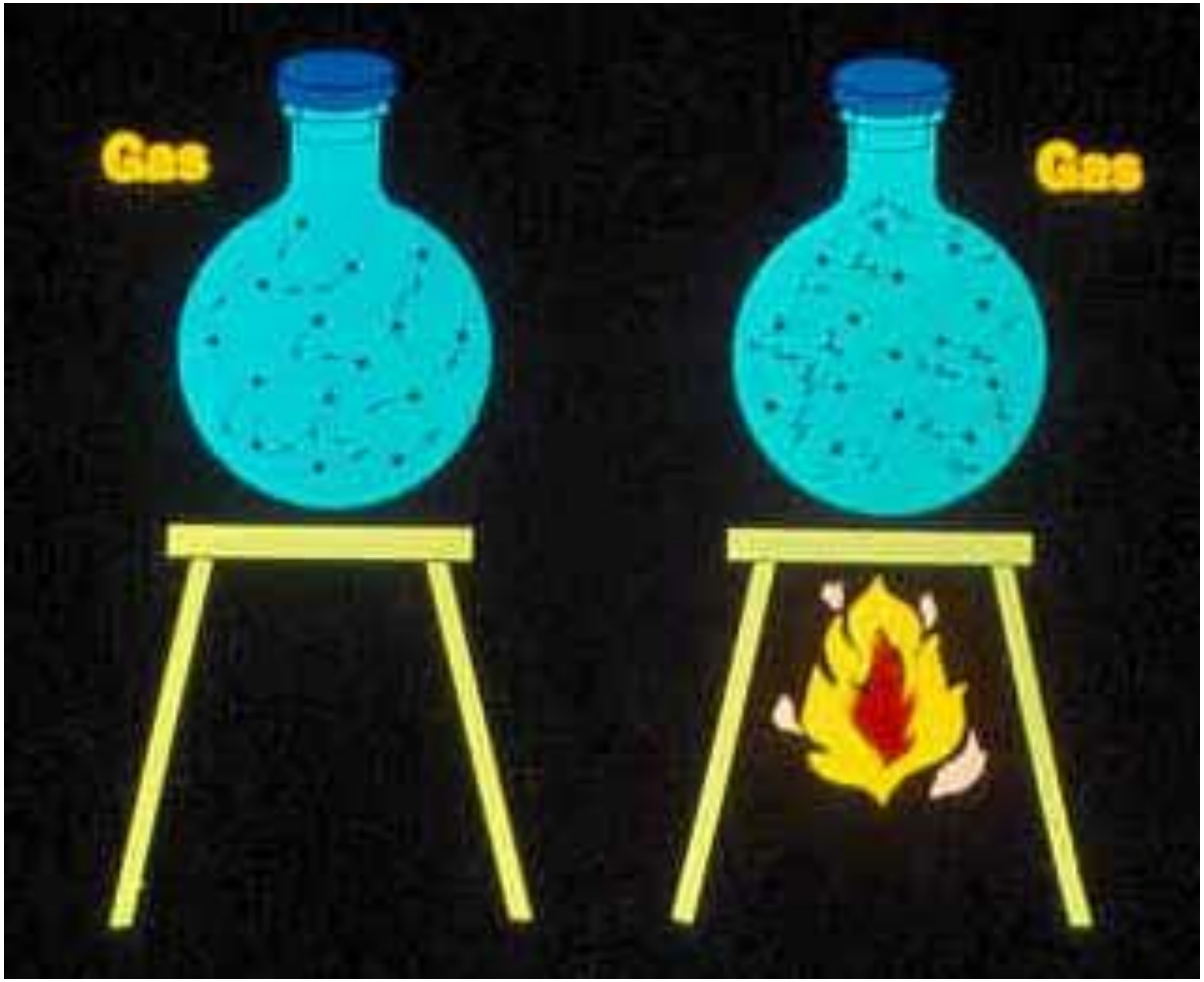
Momentum Transfer Between the Layers of Fluid

Heated Liquid = Lower Viscosity

Viscosity

Intermolecular Cohesive Forces

Momentum Transfer Between the Layers of Fluid



Heated Gas = Higher Viscosity

Estimating Gas Viscosity

$$\frac{\mu}{\mu_{ref}} = \left(\frac{T}{T_{ref}}\right)^{0.768}$$

Viscosity of air at 68°F is 1.21 x 10^{-5} lb_m/ft-sec

Kinematic Viscosity

$$\nu = \frac{\mu}{\rho}$$

where

ν = kinematic viscosity

μ = absolute viscosity

ρ = density

Reynolds Number

$$\mathrm{Re} = \frac{Lv\rho}{\mu}$$

where

Re = Reynolds Number

L = characteristic system dimension

v = fluid velocity

ρ = fluid density

μ = fluid viscosity

Flow Reynolds Number

$$Re = \frac{Dv\rho}{\mu}$$

Where for a circular duct

D = duct diameter

Particle Reynolds Number

$$Re_p = \frac{d_p v_p \rho}{\mu}$$

Where

d_p = particle diameter

v_p = relative particle to gas velocity

Most particle motion in air pollution control devices occurs in the Stokes and Transitional Regions

Flow Regime

Three flow regimes:

Rep < 1 laminar or Stokes flow

1 < Rep < 1000 transition flow

Rep > 1000 turbulent flow

Example 1-5

Calculate the Particle Reynolds Number for a 2μm diameter particle moving through 10°C still air at a velocity of 6 m/sec.

From Appendix B, the density of air at 20°C is 1.20 x 10-3 g/cm3 and the viscosity is 1.80 x 10-4 g/cm(sec)

Estimate the gas density at 10°C.

$$\rho = 1.20\text{x}10^{-3}\left(\frac{293\text{K}}{283\text{K}}\right) = 1.24\text{x}10^{-3}\ \text{g}/\text{cm}^3$$

Estimate the gas vicosity at 10°C.

$$\mu = 1.80\text{x}10^{-4}\left(\frac{293\text{K}}{283\text{K}}\right)^{0.768} = 1.75\text{x}10^{-4}\ \text{g}/\text{cm}\cdot\text{sec}$$

And then…

Calculate Particle Reynolds Number :

$$\mathrm{Re}_p = \frac{d_p v_p \rho}{\mu} = \frac{(2x10^{-4}\,\mathrm{cm})\left(6x10^{2}\,{}^{\mathrm{cm}}\!/\!_{\mathrm{sec}}\right)\left(1.24x10^{-3}\,{}^{\mathrm{g}}\!/\!_{\mathrm{cm}^3}\right)}{1.75x10^{-4}\,{}^{\mathrm{g}}\!/\!_{\mathrm{cm}\cdot\mathrm{sec}}}$$

Example 1-6

Calculate the Particle Reynolds Number for a gas stream moving through a 200 cm diameter duct at a velocity of 1,500 cm/sec.

- Assume that the particles are moving at the same velocity as the gas stream and are not settling due to gravity.
- Assume a gas temperature of 20°C and standard pressure.

Since there is no difference in velocity between the gas stream and the particle, the Particle Reynolds Number is zero.

The Flow Reynolds Number is:

$$Re = \frac{Dv\rho}{\mu}$$

$$\frac{(200\text{cm})\left(1{,}500\ \text{cm}/\text{sec}\right)\left(1.20\text{x}10^{-3}\ \text{g}/\text{cm}^{3}\right)}{1.80\text{x}10^{-4}\ \text{g}/\text{cm}\cdot\text{sec}} = 2.00\text{x}10^{6}$$

Example 1-7:

The mol fraction of water in the stack gas from a combustion process contains 14 mol% water vapor. What is the dew point temperature if the total pressure is 1 atm? The Antoine constants for water are:

A = 8.10765 B = 1750.286 C = 235.000

Solution:

At the dew point temperature:

$$P^* = P_i = y_i P = 0.14\ (1) = 0.14 \text{ atm or } 106.4 \text{ mmHg}$$

From the Antoine equation:

$$\log_{10} 106.4 = 8.10765 - \frac{1750.286}{T + 235.000}$$

Solve for T to obtain: T = 53°C

Review Questions:

1. How does the particle Reynolds number change when the gas temperature is increased? (see page 10)
   - Increases
   - Decreases
   - Remains unchanged

But it is fairly complicated…

An increase in T means an increase in viscosity, also a decrease in density, and an increase in velocity.

Review Questions:

2. How does the gas viscosity change as the temperature is increased? (see page 9)

- Increases
- Decreases
- Remains unchanged

Review Problems

1. The flows from Ducts A and B are combined into a single Duct C. The flow rate in Duct A is 5,000 scfm, the gas stream temperature is 350°F and the static pressure is -32 in WC. The flow rate in Duct B is 4,000 acfm, the gas stream temperature is 400°F and the static pressure is -35 in WC.

What is the flow rate in Duct C? Assume a barometric pressure of 29.15 in Hg. (see page 6)

Solution #1

Calculate the absolute pressure in Duct B :

$$P = 29.15\,\text{in Hg}\left(\frac{407\,\text{in WC}}{29.92\,\text{in Hg}}\right) + (-35\,\text{in WC}) = 361.5\,\text{in WC}$$

Convert the flow in Duct B to standard conditions :

$$Q_B = 4{,}000\,\text{acfm}\left(\frac{528°\text{R}}{860°\text{R}}\right)\left(\frac{361.5\,\text{in WC}}{407\,\text{in WC}}\right) = 2{,}181\,\text{scfm}$$

Combine flows :

$$Q_c = 5{,}000\,\text{scfm} + 2{,}181\,\text{scfm} = 7{,}181\,\text{scfm}$$

Review Problems

2. Calculate the Particle Reynolds Numbers for the following particles. Assume a gas temperature of 20°C and a pressure of 1 atm. (see page 10)

- 10 μm particle moving at 1 ft/sec relative to the gas stream
- 10 μm particle moving at 10 ft/sec relative to the gas stream
- 100 μm particle moving at 1 ft/sec relative to the gas stream
- 100 μm particle moving at 10 ft/sec relative to the gas stream

Solution #2 (a & b)

a. 10 μm particle moving at 1 ft/sec relative to the gas stream

$$\mathrm{Re}_p = \frac{d_p v_p \rho}{\mu} = \frac{(10x10^{-4}\,cm)\left[\left(1.0\ {}^{ft}\!/_{\sec}\right)\left(30.48\,{}^{cm}\!/_{ft}\right)\right]\left(1.20x10^{-3}\ {}^{g}\!/_{cm^3}\right)}{1.80x10^{-4}\ {}^{g}\!/_{cm\cdot\sec}} = 0.203$$

b. 10 μm particle moving at 10 ft/sec relative to the gas stream

$$\mathrm{Re}_p = \frac{d_p v_p \rho}{\mu} = \frac{(10x10^{-4}\,cm)\left[\left(10.0\ {}^{ft}\!/_{\sec}\right)\left(30.48\,{}^{cm}\!/_{ft}\right)\right]\left(1.20x10^{-3}\ {}^{g}\!/_{cm^3}\right)}{1.80x10^{-4}\ {}^{g}\!/_{cm\cdot\sec}} = 2.032$$

Solution #2 (c & d)

c. 100 μm particle moving at 1 ft/sec relative to the gas stream

$$\mathrm{Re}_p = \frac{d_p v_p \rho}{\mu} = \frac{\left(100x10^{-4}\,cm\right)\left[\left(1.0\ {}^{ft}\!/_{\sec}\right)\left(30.48\,{}^{cm}\!/_{ft}\right)\right]\left(1.20x10^{-3}\ {}^{g}\!/_{cm^3}\right)}{1.80x10^{-4}\ {}^{g}\!/_{cm\cdot\sec}} = 2.03$$

d. 100 μm particle moving at 10 ft/sec relative to the gas stream

$$\mathrm{Re}_p = \frac{d_p v_p \rho}{\mu} = \frac{\left(100x10^{-4}\,cm\right)\left[\left(10.0\ {}^{ft}\!/_{\sec}\right)\left(30.48\,{}^{cm}\!/_{ft}\right)\right]\left(1.20x10^{-3}\ {}^{g}\!/_{cm^3}\right)}{1.80x10^{-4}\ {}^{g}\!/_{cm\cdot\sec}} = 20.3$$

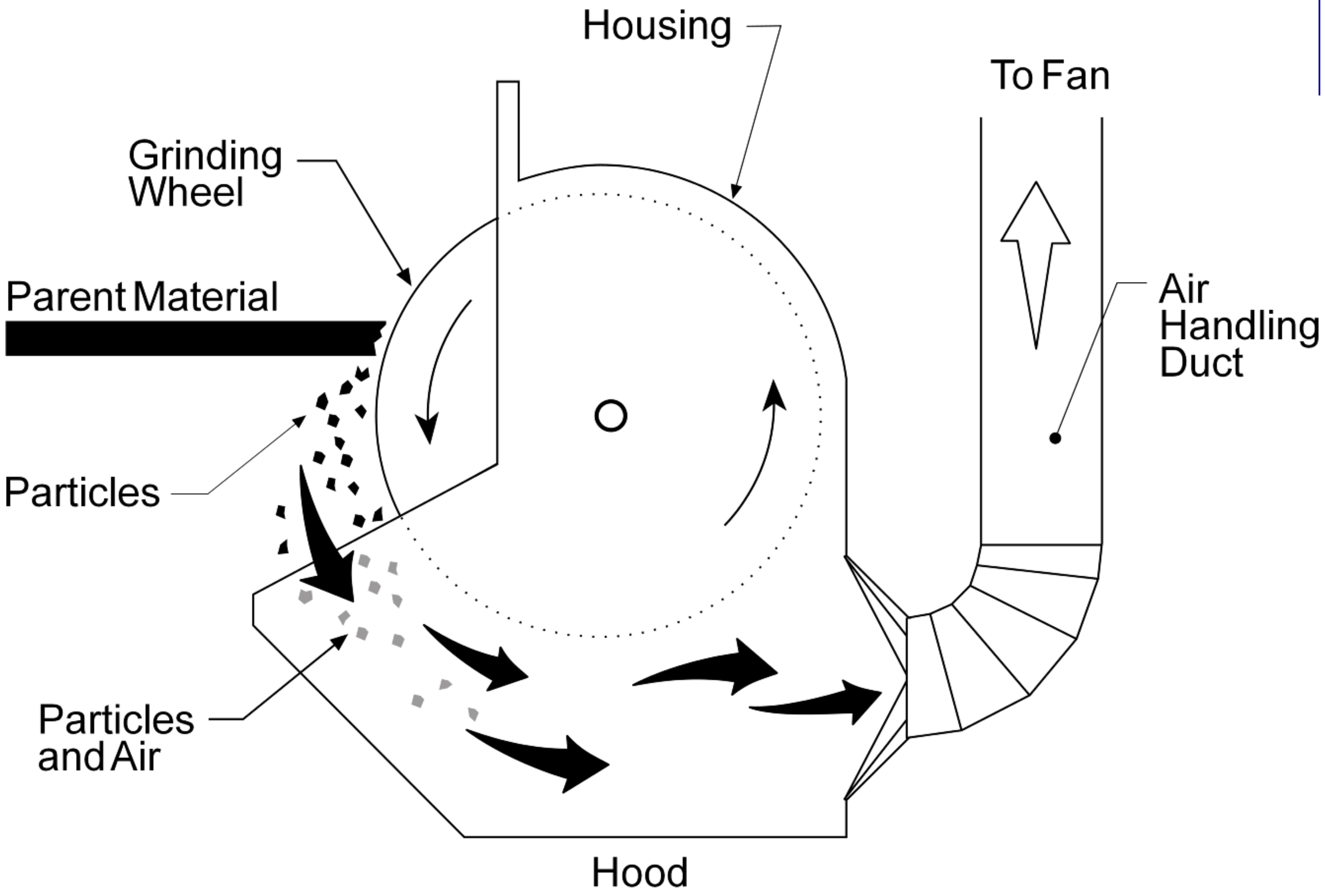
Chapter 2

Particulate Matter Formation and Regulation

Particle Formation Mechanisms

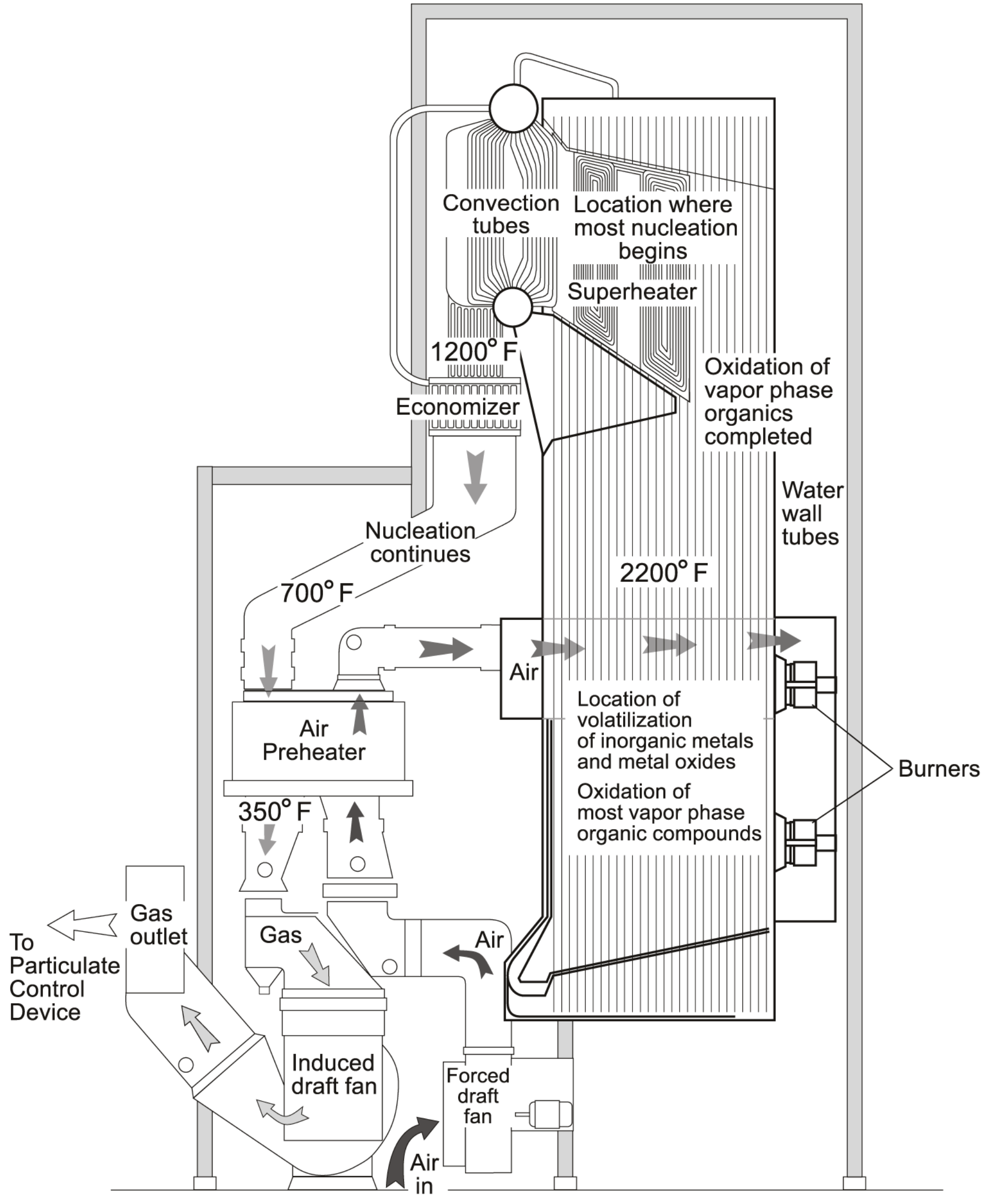
- Physical attrition/mechanical dispersion
- Combustion particle burnout
- Homogeneous condensation
- Heterogeneous nucleation
- Droplet evaporation

Grinding Wheel

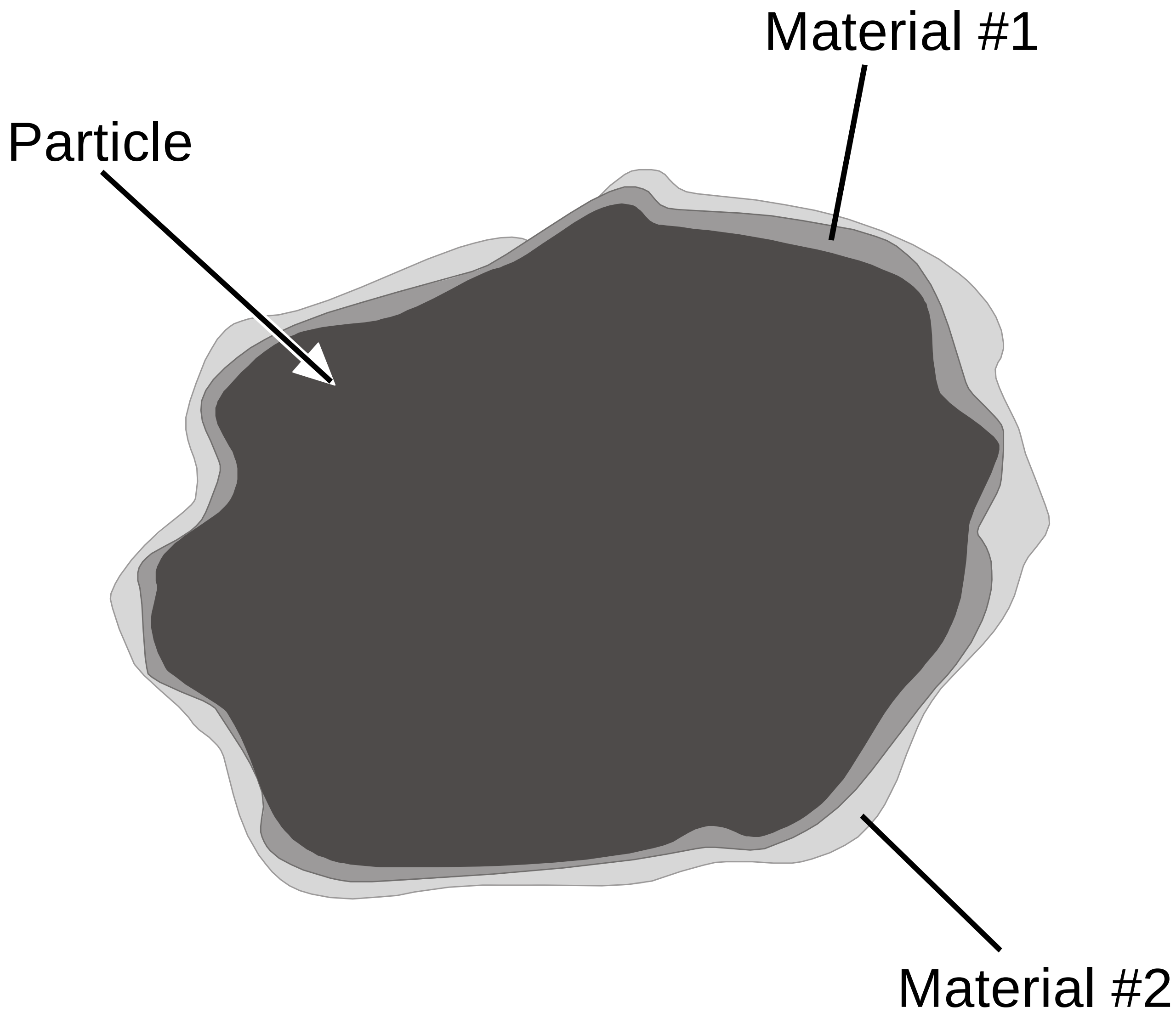


Tertiary Crusher

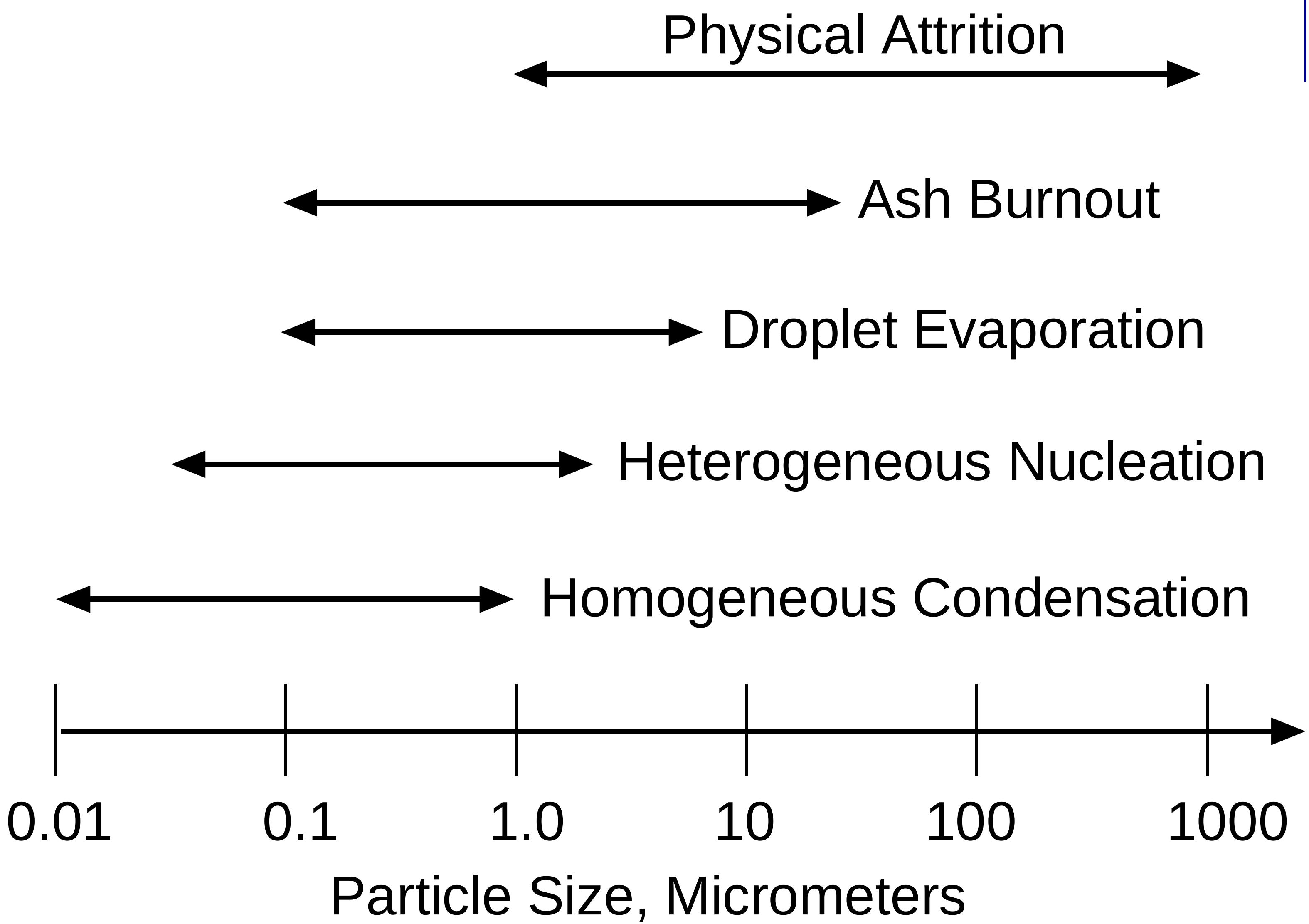
Combustion Process



Heterogeneous Nucleation



Summary of Formation Mechanisms

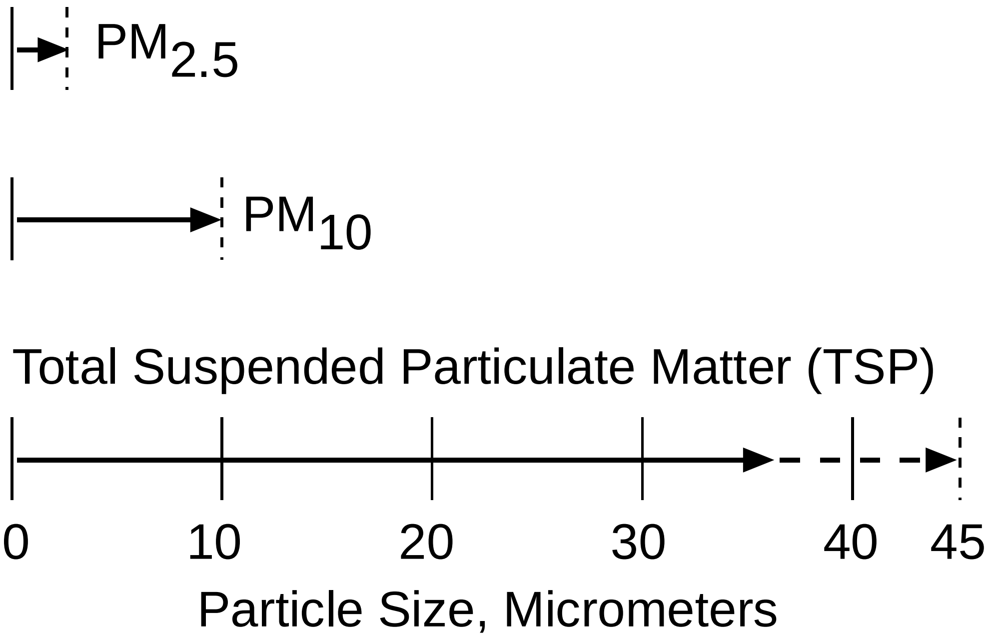


Sources of Particulate Matter

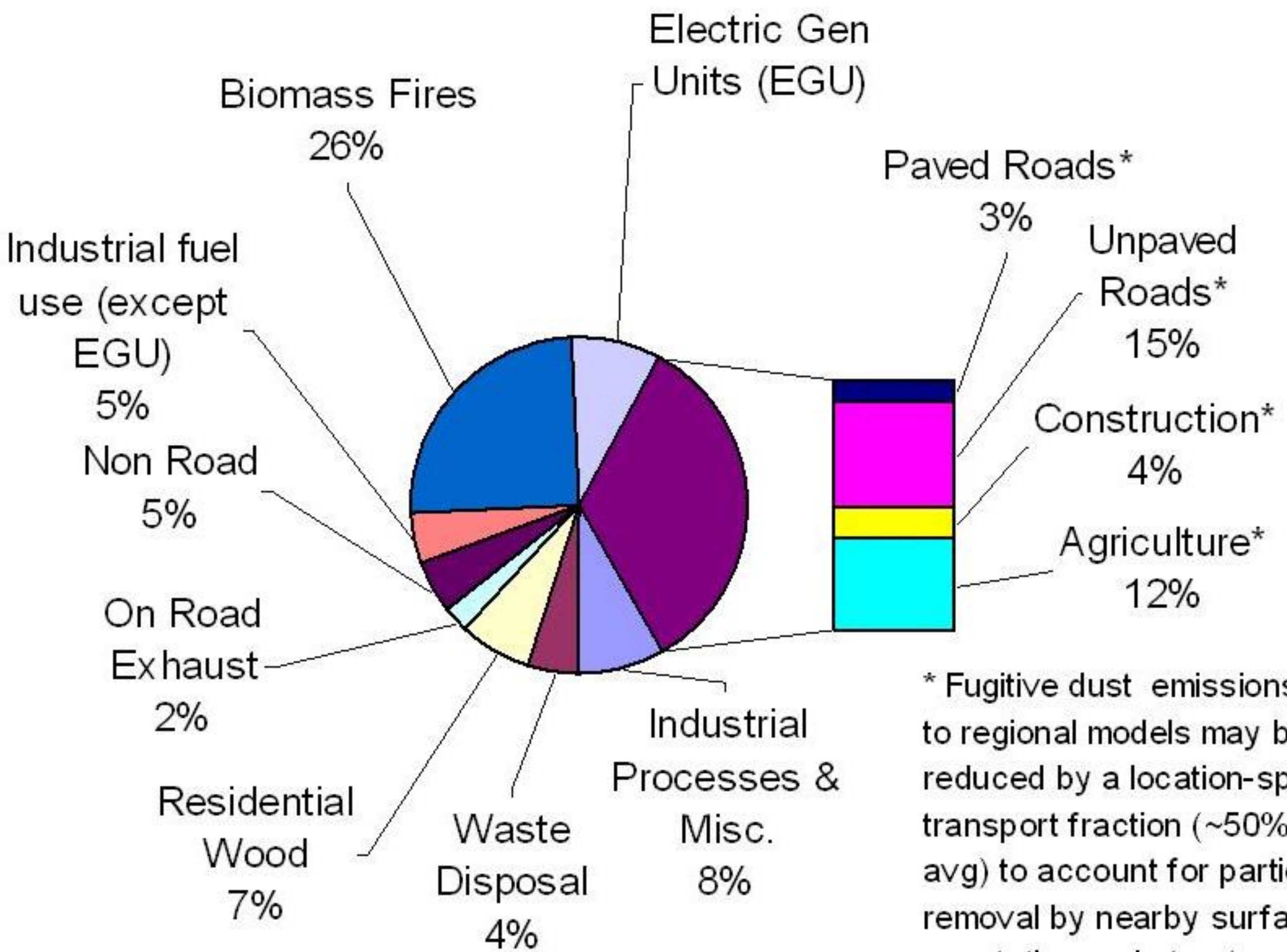
- Primary particulate matter
- Secondary particulate matter
  - Condensation particles
  - Reaction particles

Particulate Matter Size Range Definitions

Note:
Actual particle size range included as TSP varied from 35 to 45 micrometers due to ambient monitor differences.



PM2.5 Annual Emissions (by Sector)



* Fugitive dust emissions input to regional models may be reduced by a location-specific transport fraction (~50% nat'l avg) to account for particle removal by nearby surface vegetation and structures.

Particulate Matter Regulation

Particulate Matter Regulation

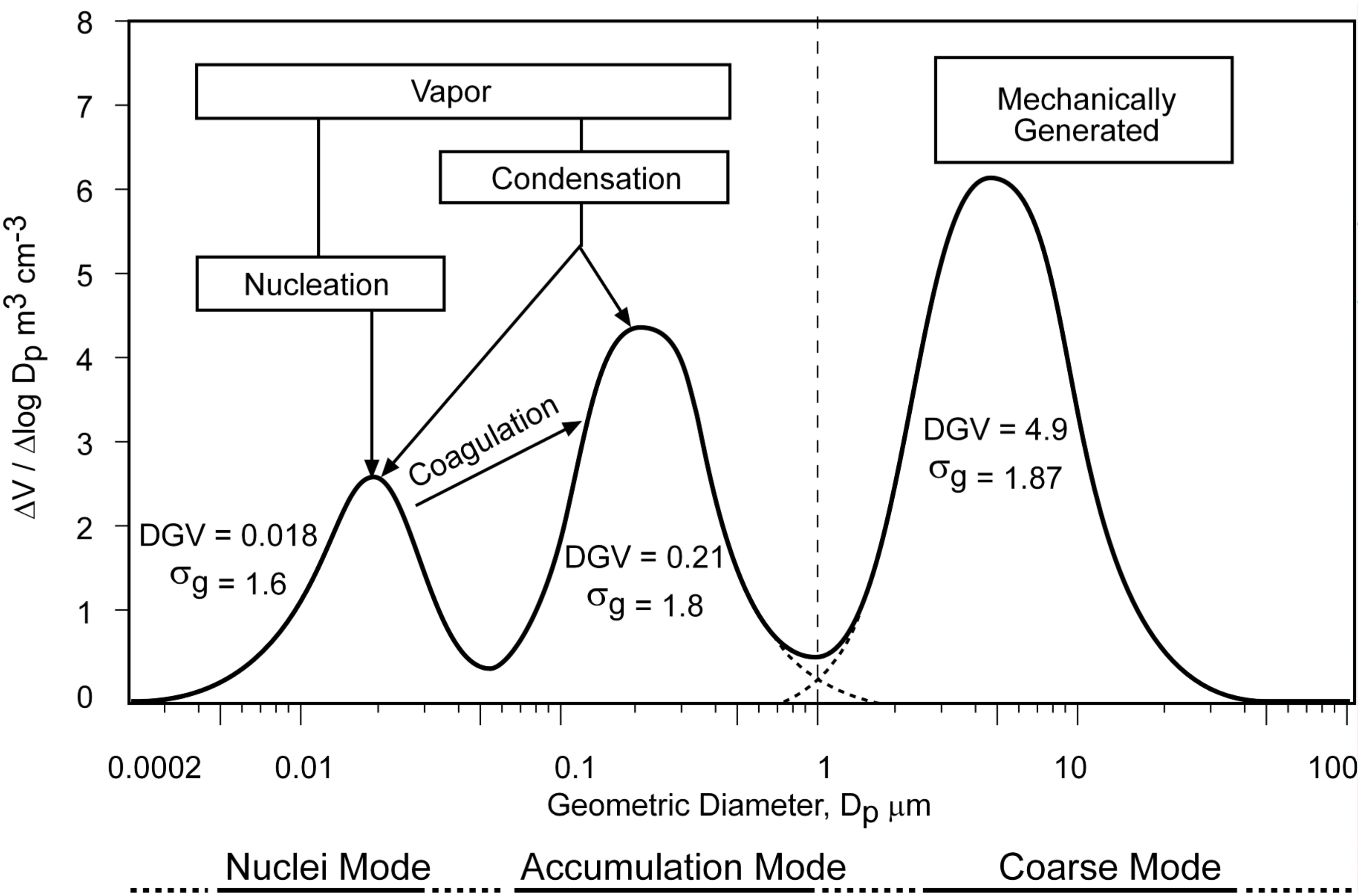
- Before the Clean Air Act
  - 1600s
  - 1950s
- Clean Air Act Amendments of 1970
  - NAAQS
  - SIPs
  - NSPS

Summary of NAAQS for PM_{10} and $PM_{2.5}$ (2006 revision of the 24-hour standard)

Pollutant	Health-based Standard	
	Type of Average	**Concentration**
PM_{10}	**Annual Arithmetic Mean**	**50 $\mu g/m^3$**
	24-hour[a]	**150 $\mu g/m^3$**
$PM_{2.5}$	**Annual Arithmetic Mean**	**15 $\mu g/m^3$ [b]**
	24-hour[c]	**35 $\mu g/m^3$**

a) not to be exceeded more than once per year on average over a three year period
b) three-year average of the annual average
c) determined from the 98th percentile, averaged over three years

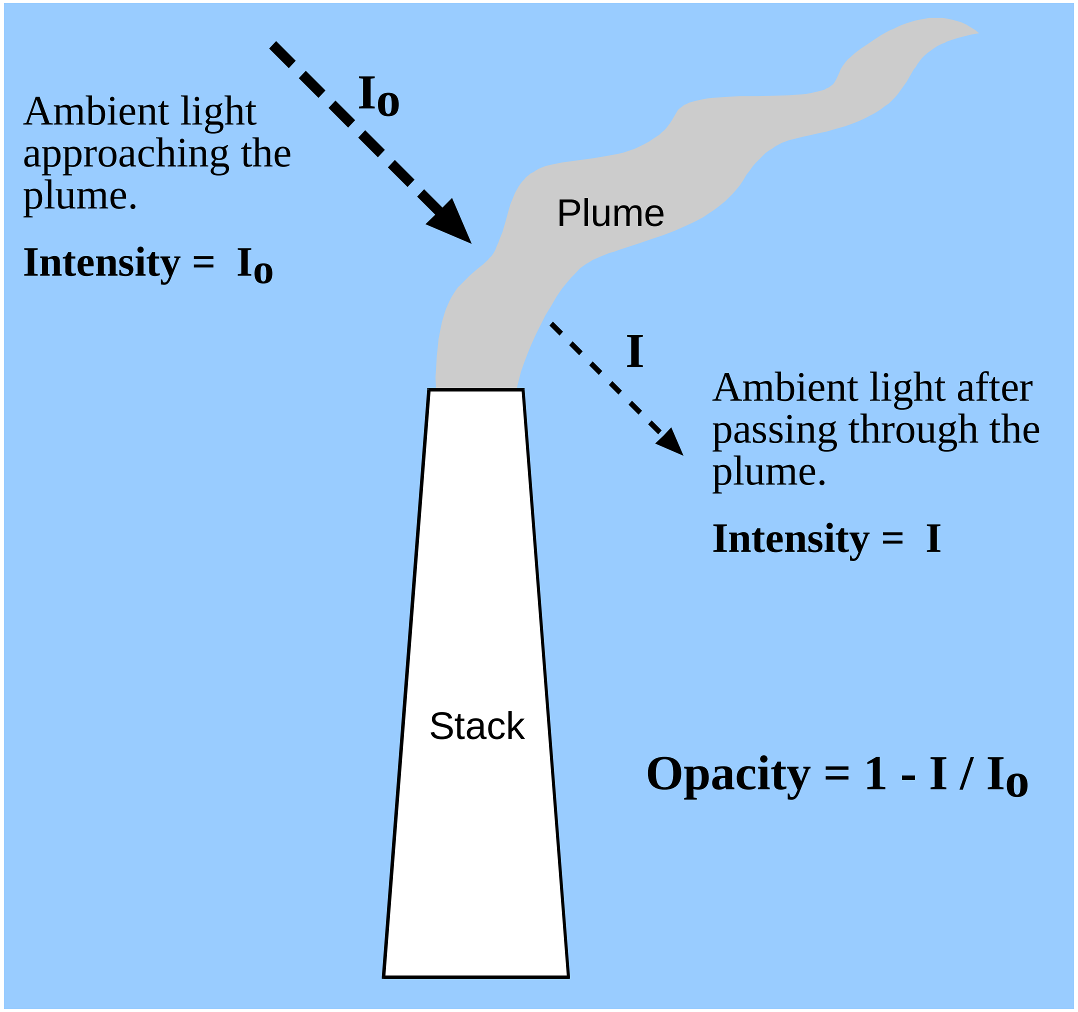
Typical Ambient Particle Size Distribution



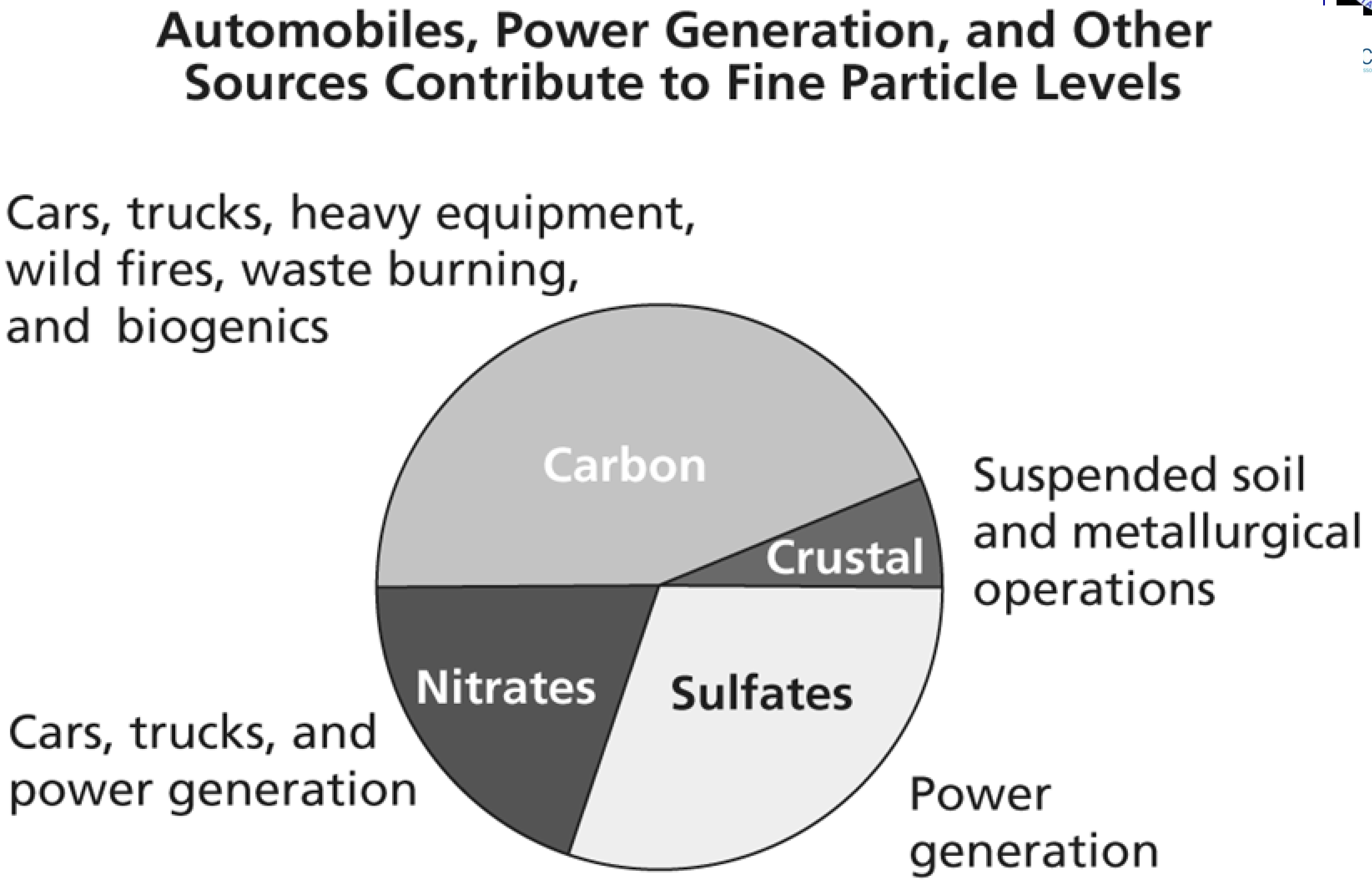
State Implementation Plans

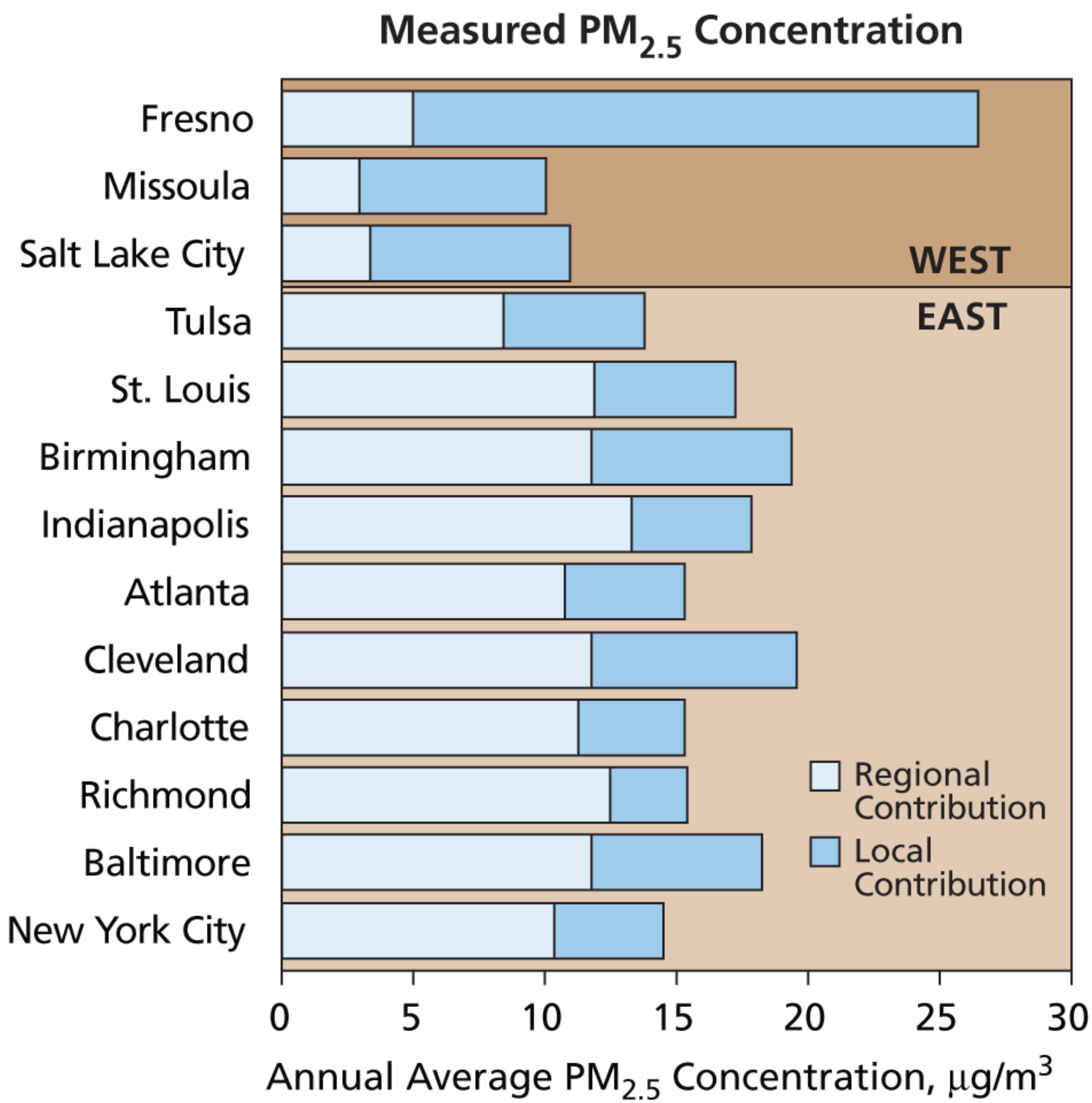
- Fuel burning regulations
- Process weight regulations
- Opacity limitations

Plume Opacity



Where does it all come from?





NACAA
national association of clean air agencies

Clean Air Act Amendments of 1977

- Case-by-Case Permit Reviews
- PSD and BACT
- NSR and LAER

Standards for Hazardous Air Pollutants

- Clean Air Act of 1970
- Clean Air Act of 1990
    - 189 hazardous pollutants
- NESHAPS vs NSPS/BACT/LAER
- MACT

Clean Air Act Amendments and Visibility

- Class I areas
- Regional Haze Rule
- BART
- Implementation plans
  - 2007
  - 10 year periodic plans

Title V Operating Permits

- What is Title V
- Title V and the public
- Title V requirements

Chapter 3

Particle Sizing

Topics Covered

- Measurement methods
- Data analysis

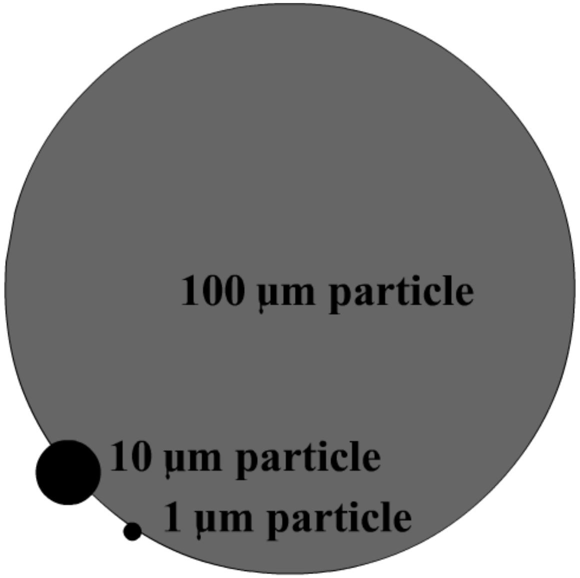
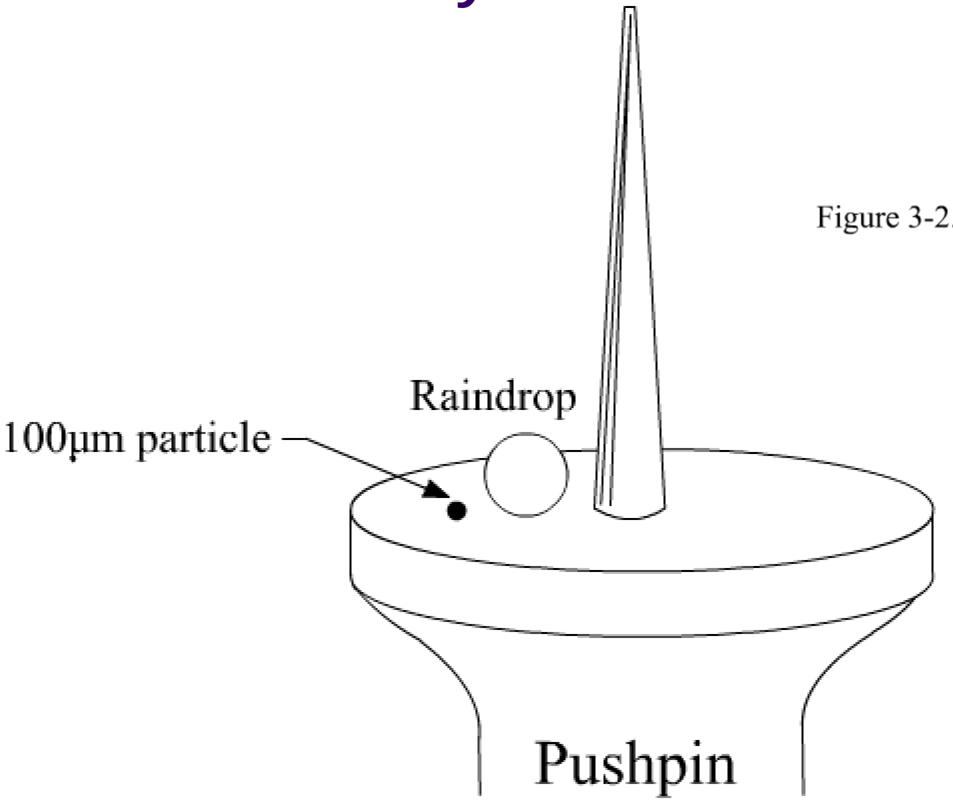
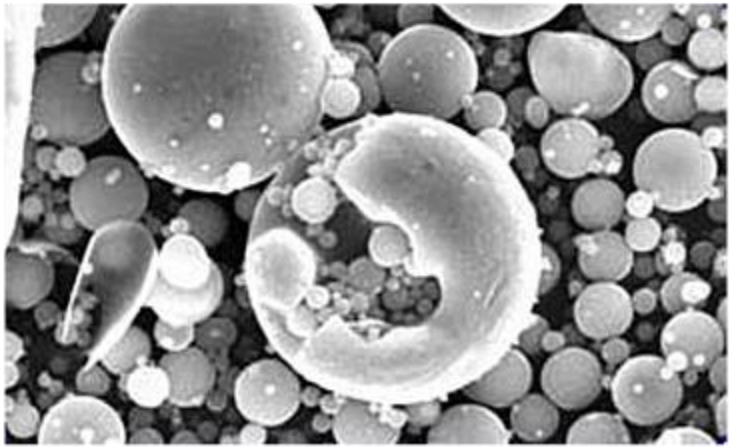


Figure 3-2. 1µm and 10µm particles compared to a 100µm particle.

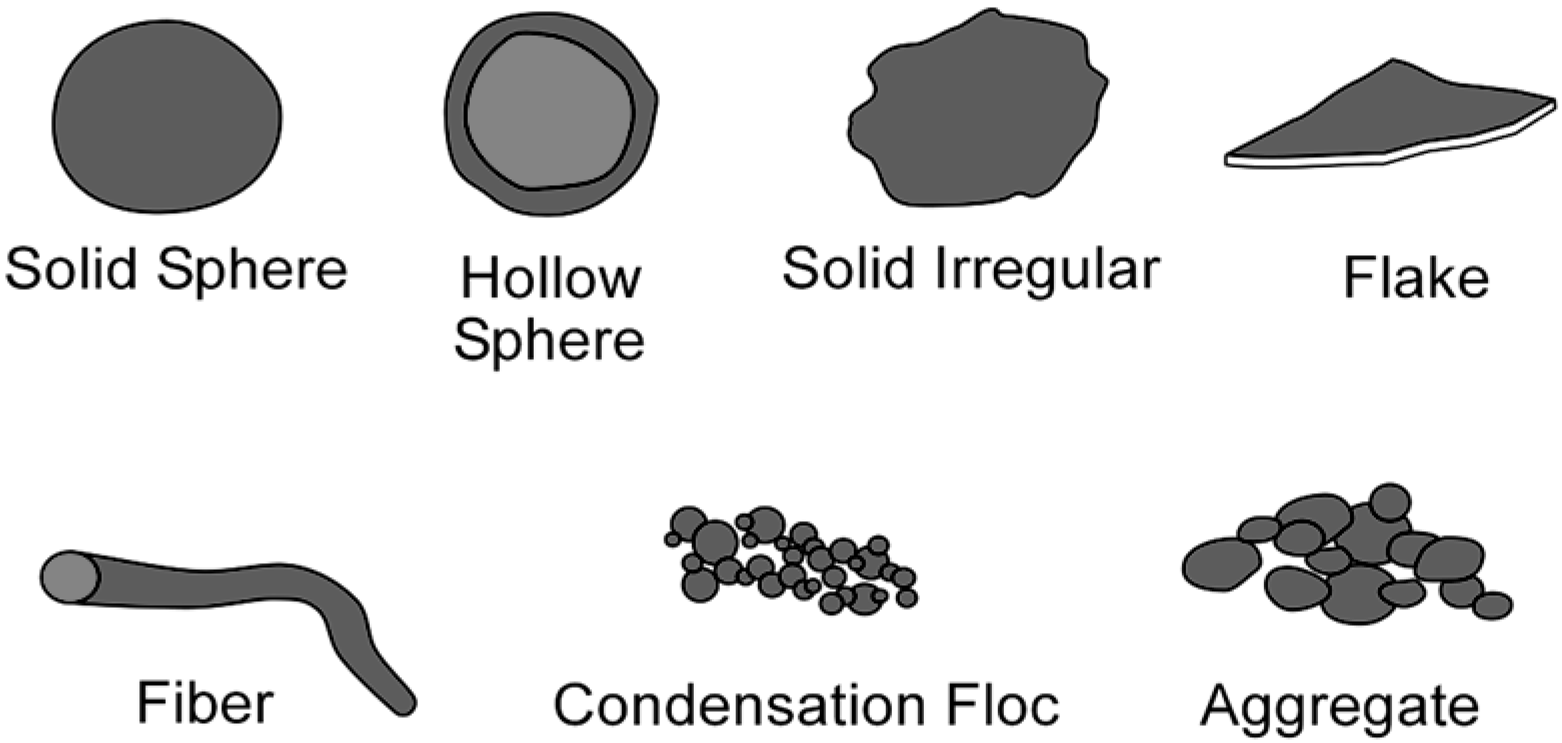




Particle Size and Air Pollution Control

Table 3-1. Spherical Particle Diamete, Volume, and Surface Area		
Diameter (m)	Volume (cm^3)	Area (cm^2)
0.1	5.23×10^{-16}	3.14×10^{-10}
1.0	5.23×10^{-13}	3.14×10^{-8}
10.0	5.23×10^{-10}	3.14×10^{-6}
100.0	5.23×10^{-7}	3.14×10^{-4}
1,000.0	5.23×10^{-4}	3.14×10^{-2}

Particle Size?



Aerodynamic Diameter

The diameter of a sphere with a density of 1 g/cm^3 that has the same falling velocity in air as the actual particle

$$d_p = d\sqrt{\rho_p C_c}$$

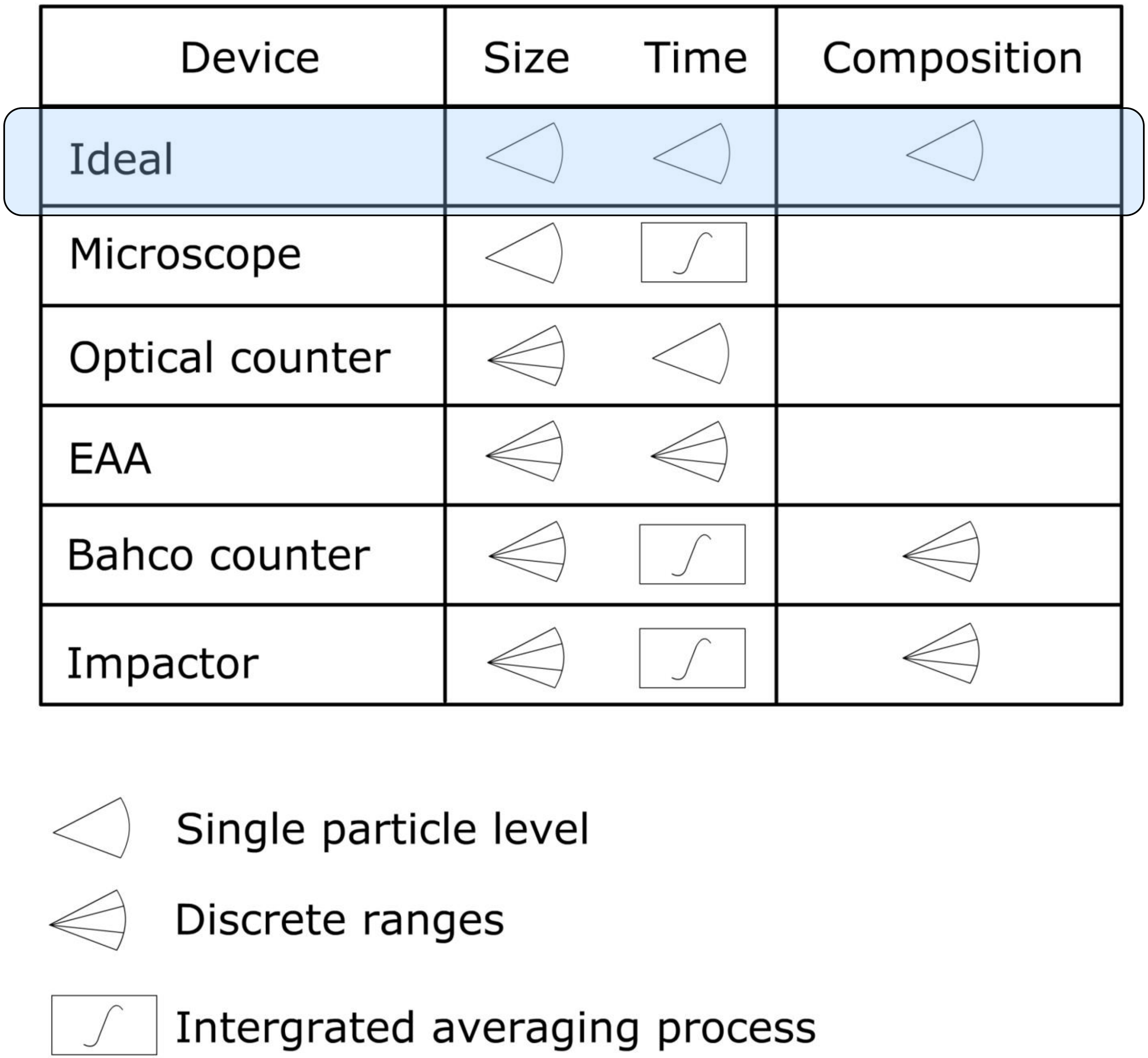
Measurement Methods

- Microscopy
- Optical counters
- Electrical aerosol analyzer
- Bahco analyzer
- Cascade impactors

Ideal Measuring Device

- Measure the exact size of each particle
- Determine the composition of each particle
- Report real-time data instantaneously

Figure 3-12. Comparison of particle sizing devices



Microscopy

Polarized Light Microscopy

Scanning Electron Microscopy

Energy Dispersive X-Ray Spectroscopy

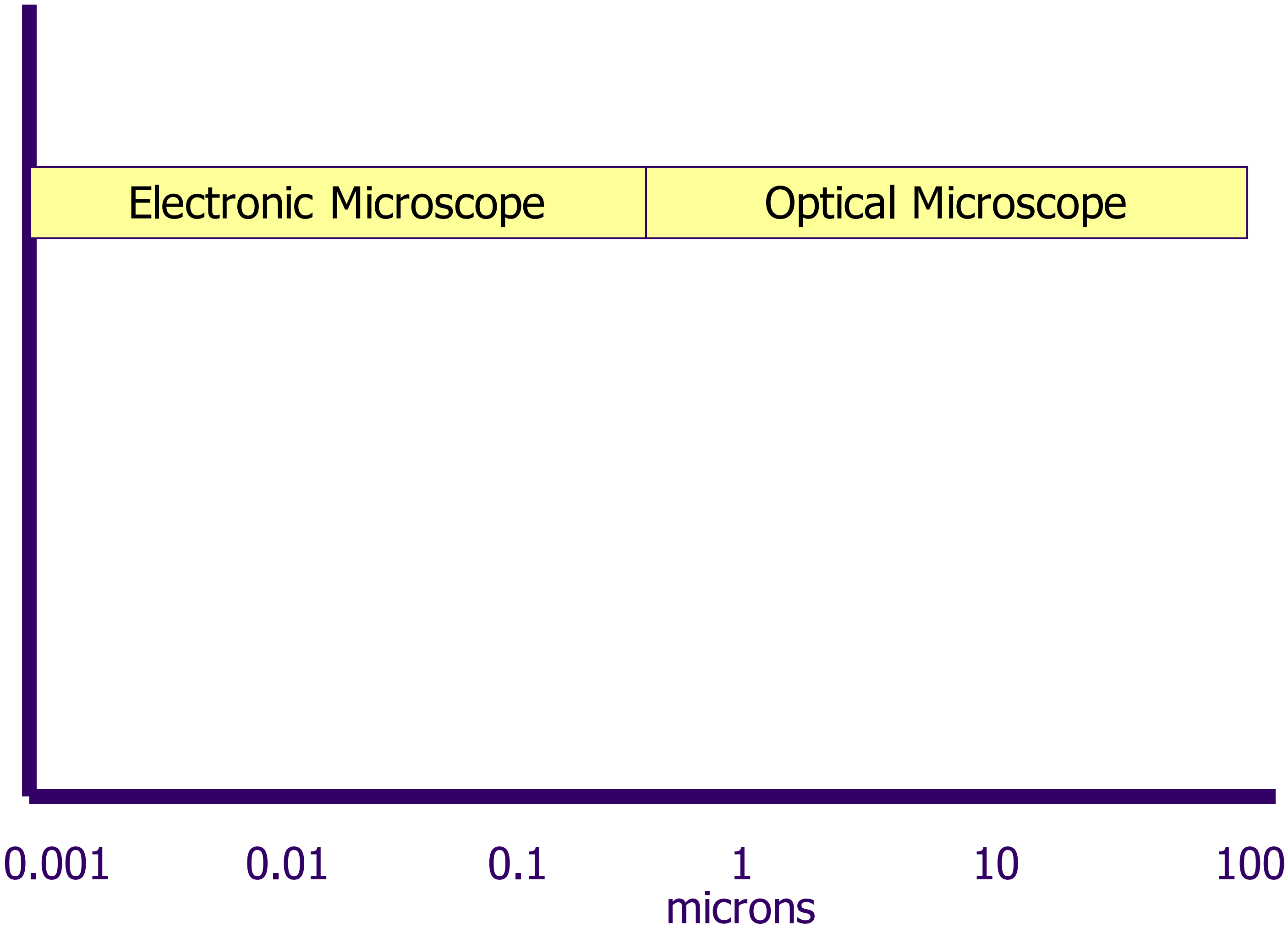
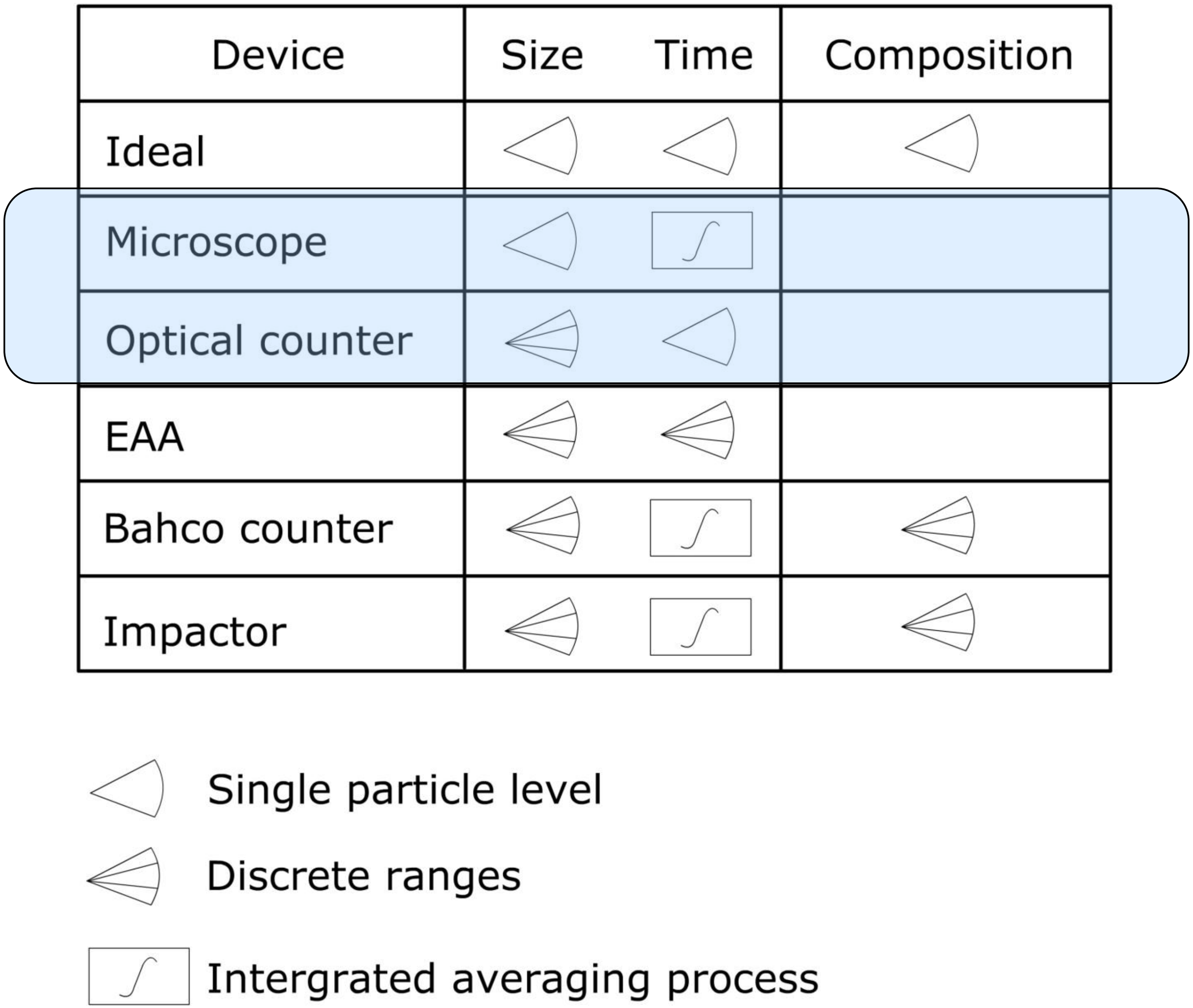
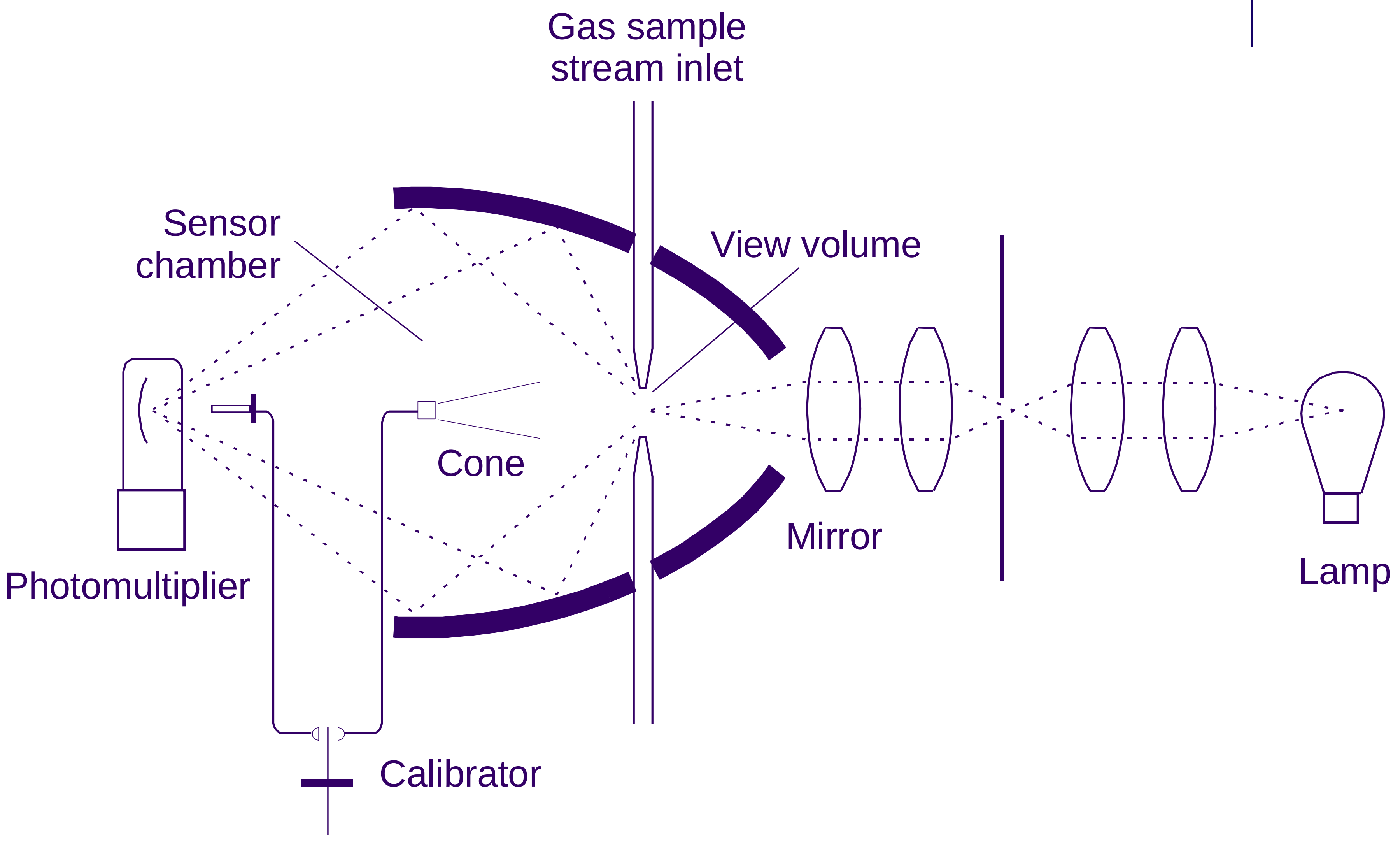

Electronic Microscope
Optical Microscope
0.001
0.01
0.1
1
10
100
microns

Figure 3-12. Comparison of particle sizing devices



Optical Particle Counter



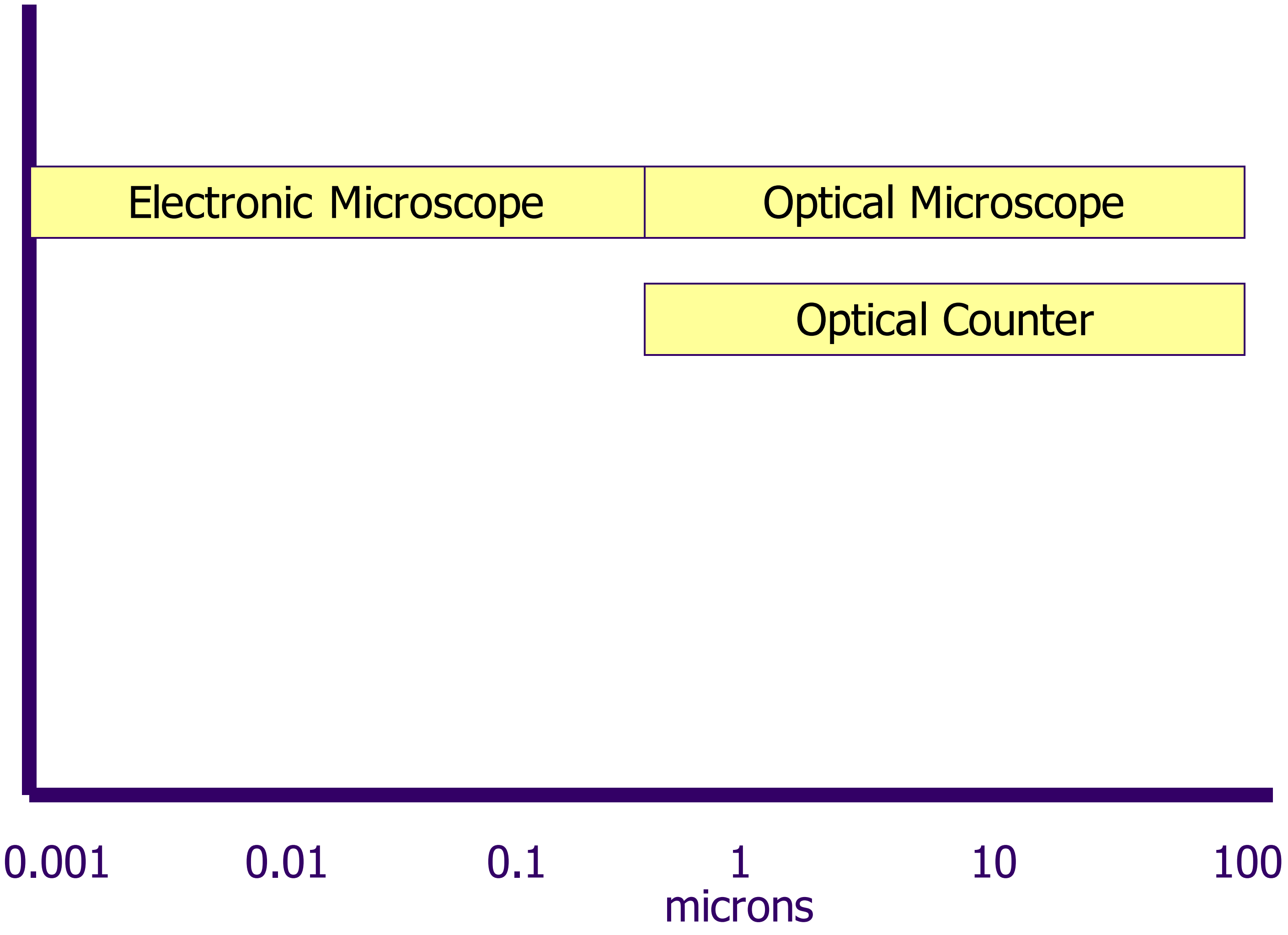
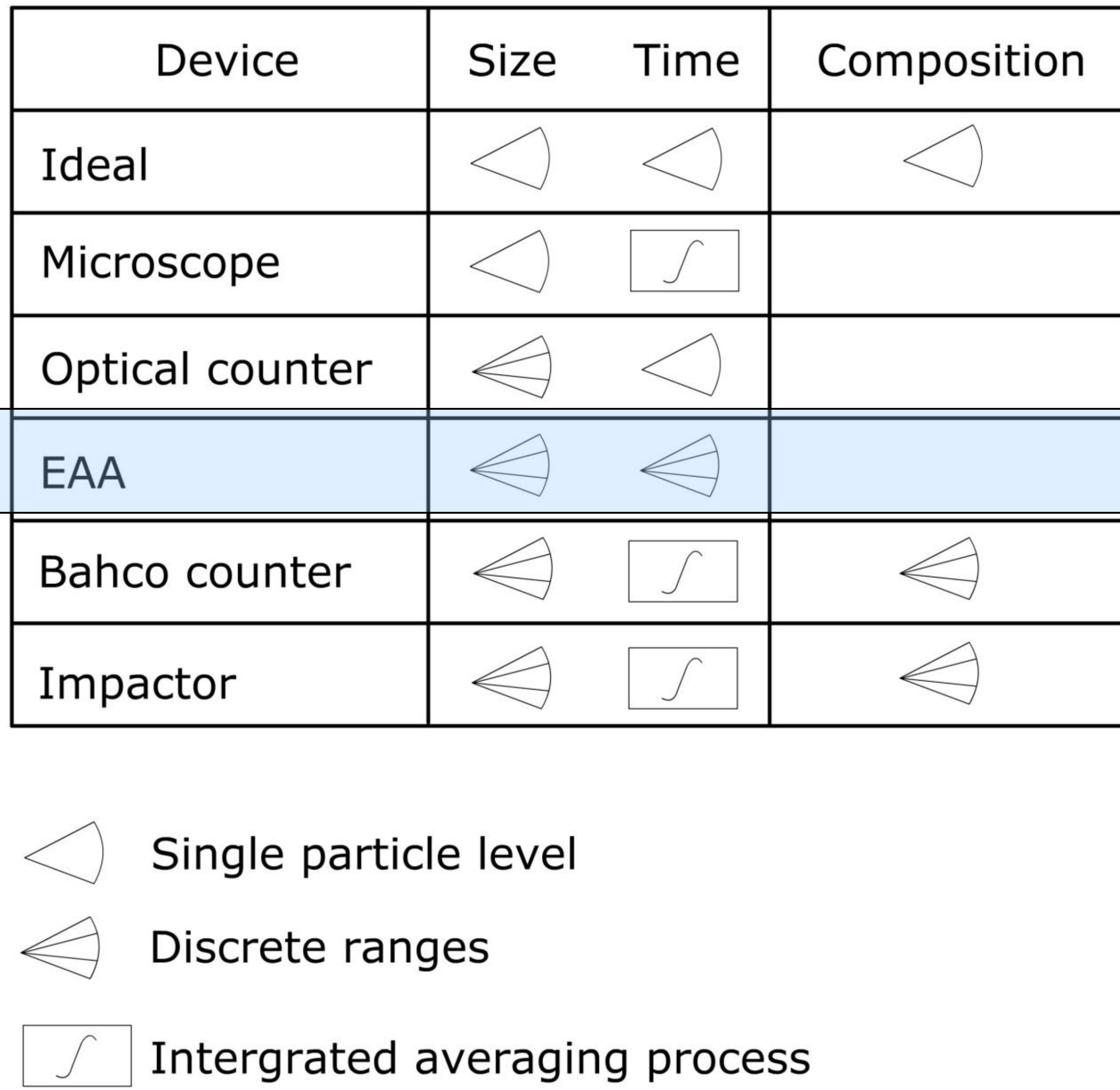
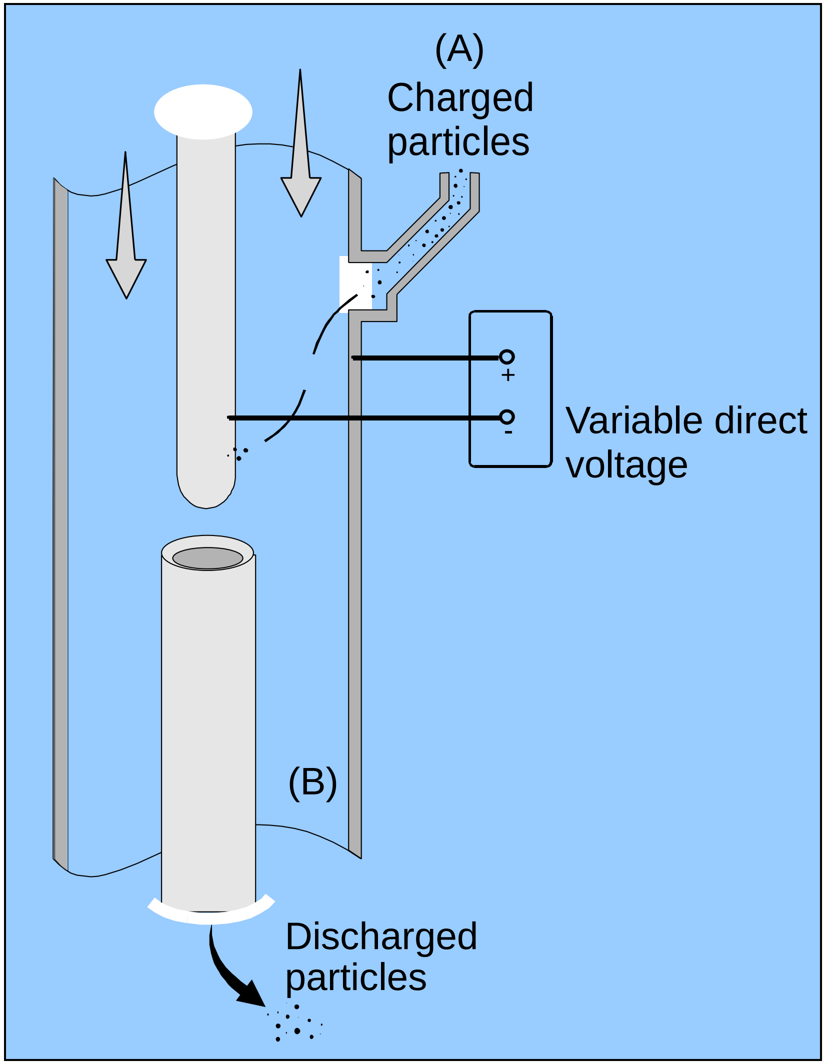

Electronic Microscope
Optical Microscope
Optical Counter
0.001
0.01
0.1
1
10
100
microns

Figure 3-12. Comparison of particle sizing devices



Electrical Aerosol Analyzer



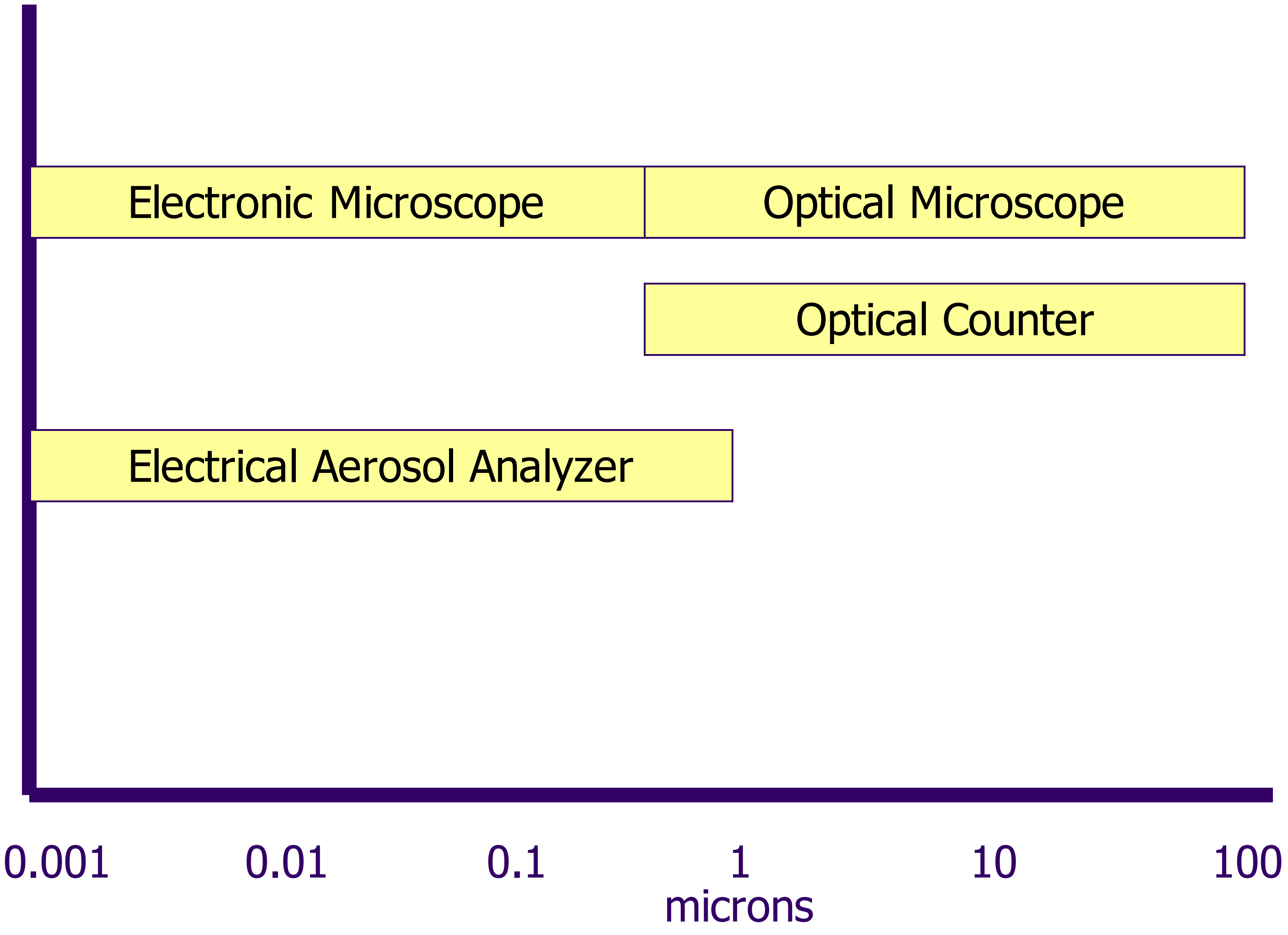
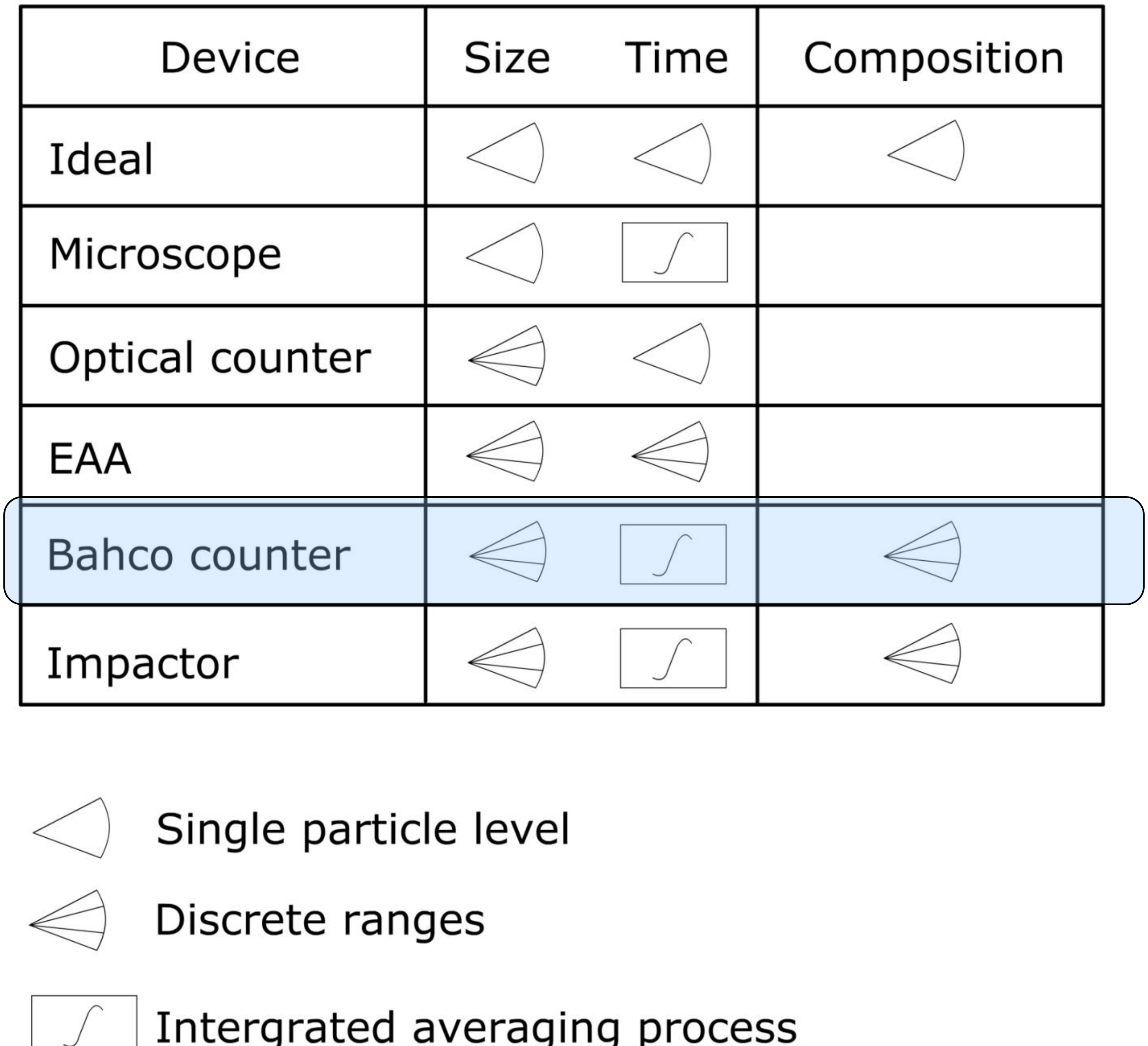
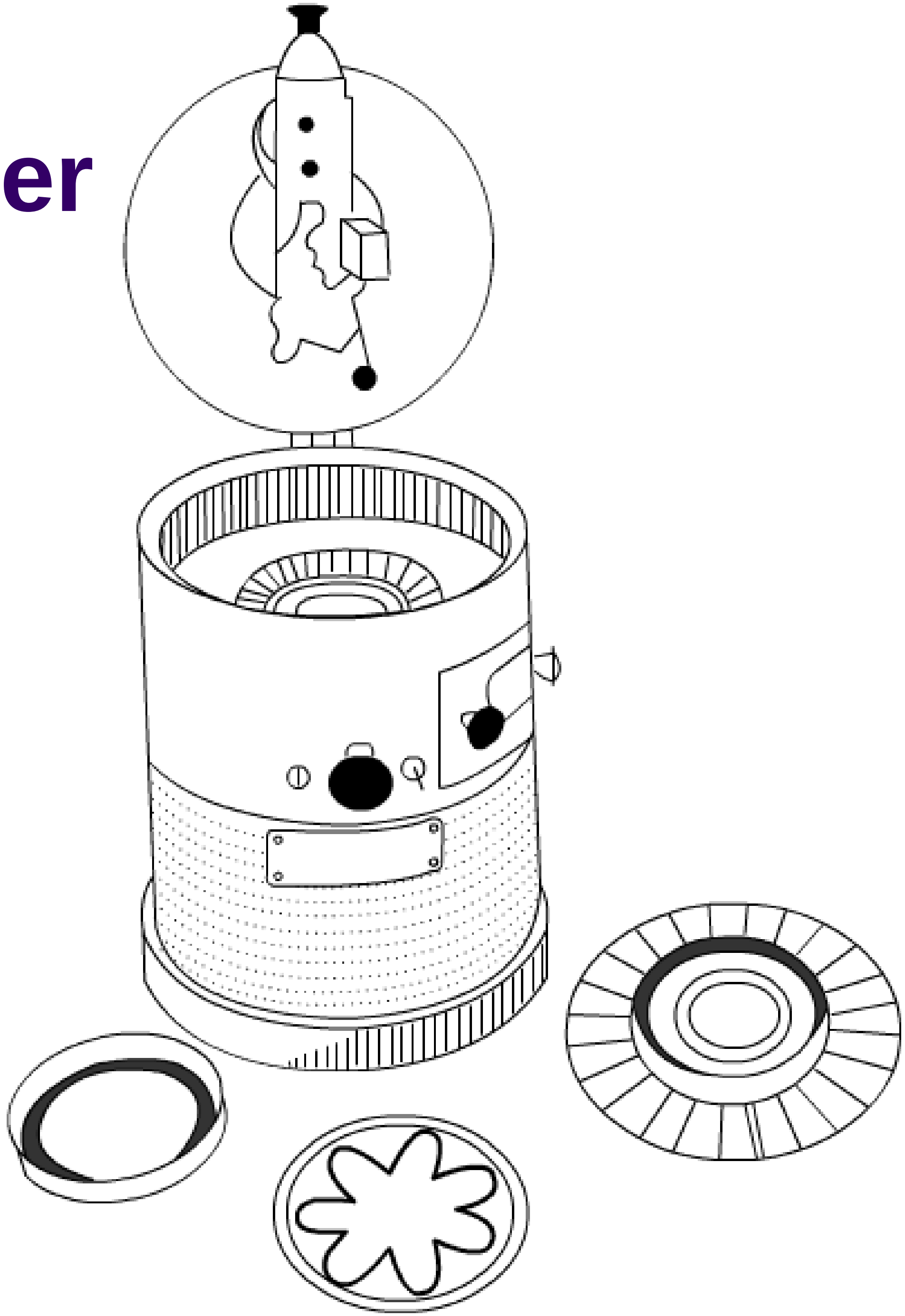

Electronic Microscope
Optical Microscope
Optical Counter
Electrical Aerosol Analyzer
0.001
0.01
0.1
1
10
100
microns

Figure 3-12. Comparison of particle sizing devices



Bahco Analyzer



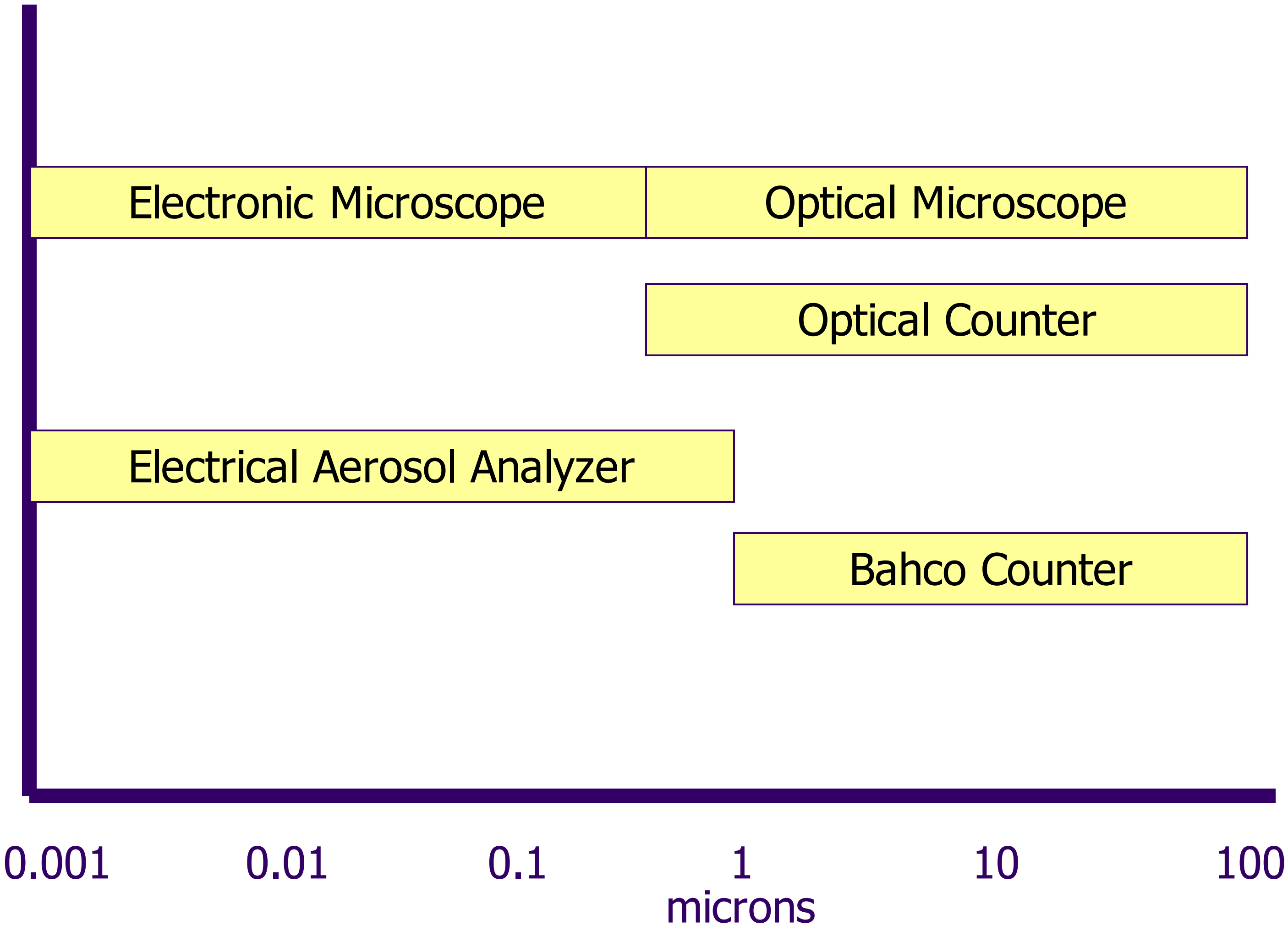
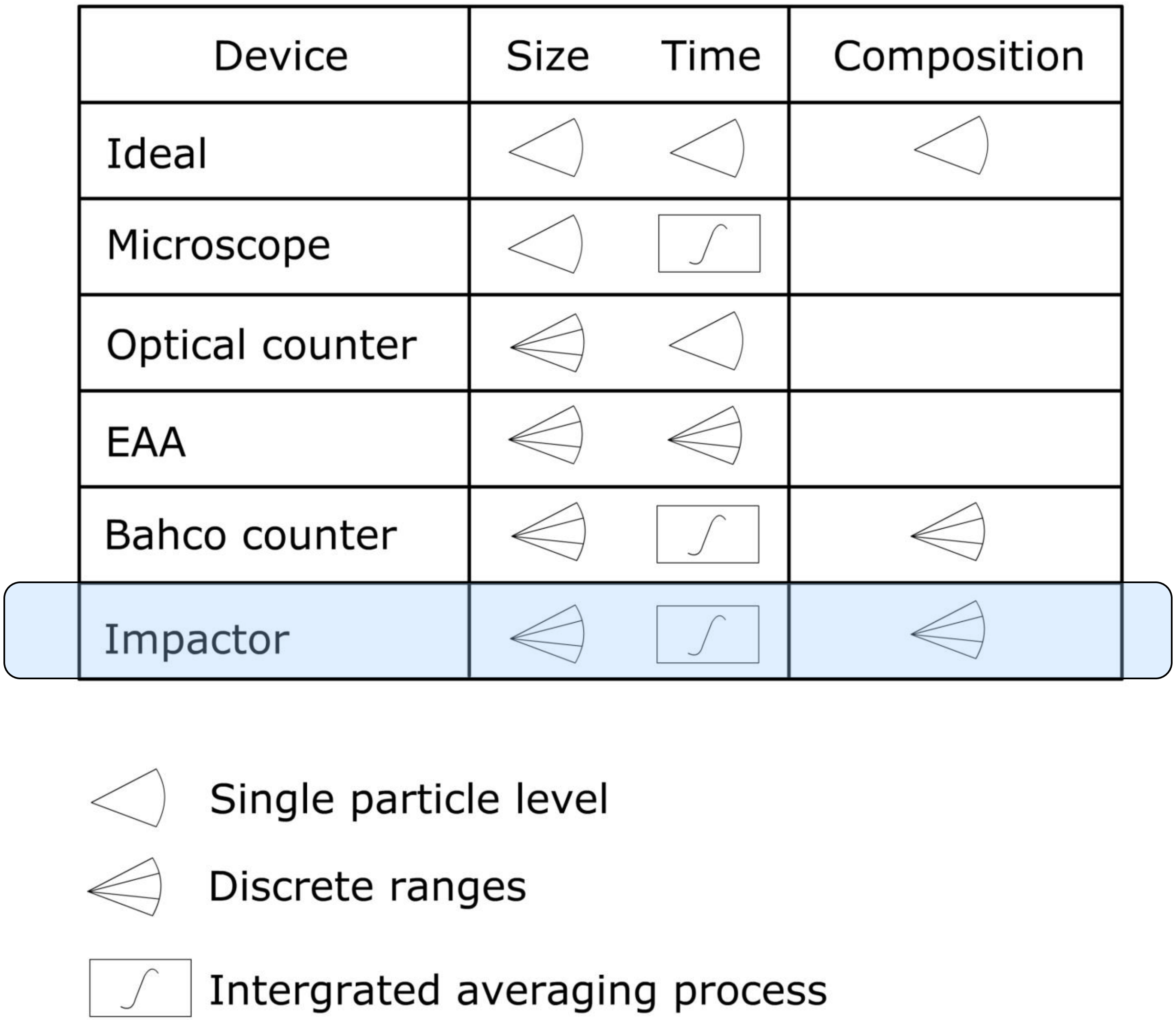
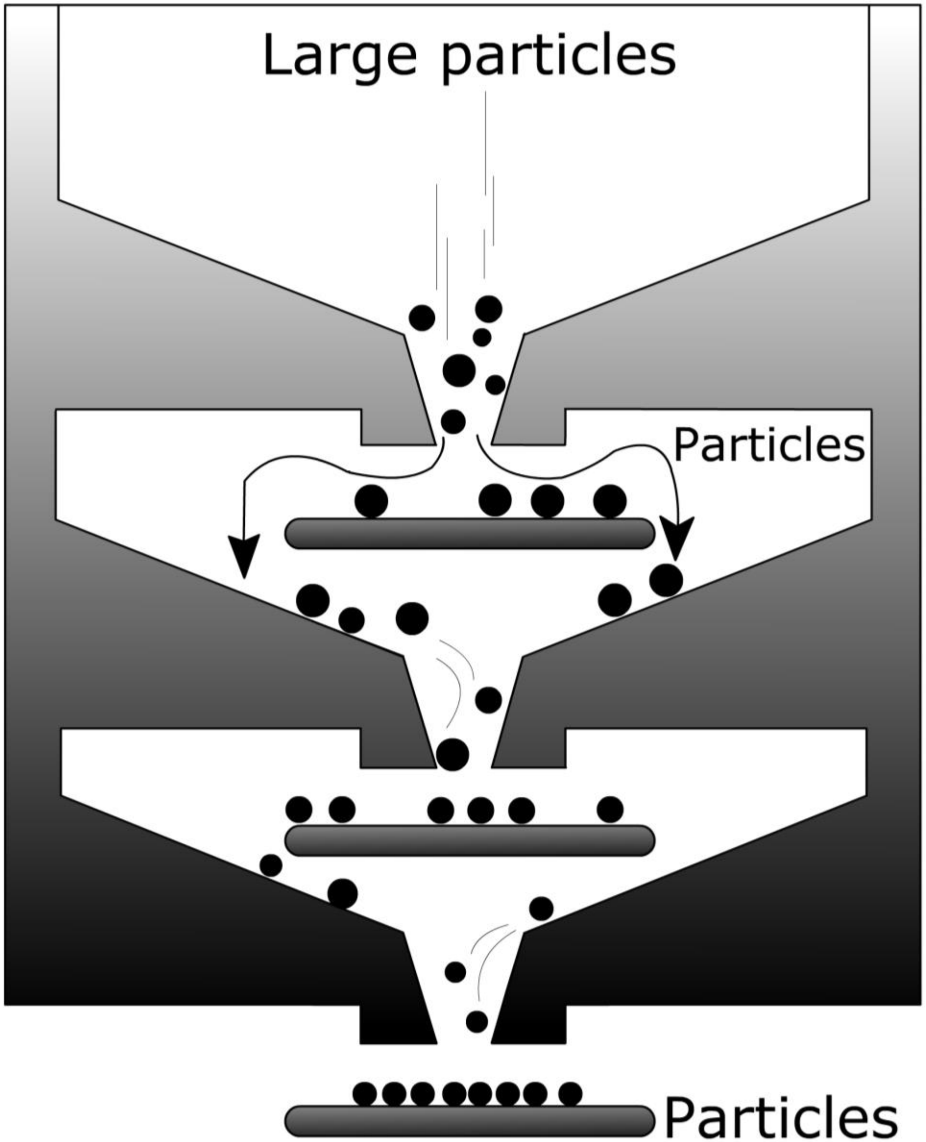

Electronic Microscope
Optical Microscope
Optical Counter
Electrical Aerosol Analyzer
Bahco Counter
0.001
0.01
0.1
1
10
100
microns

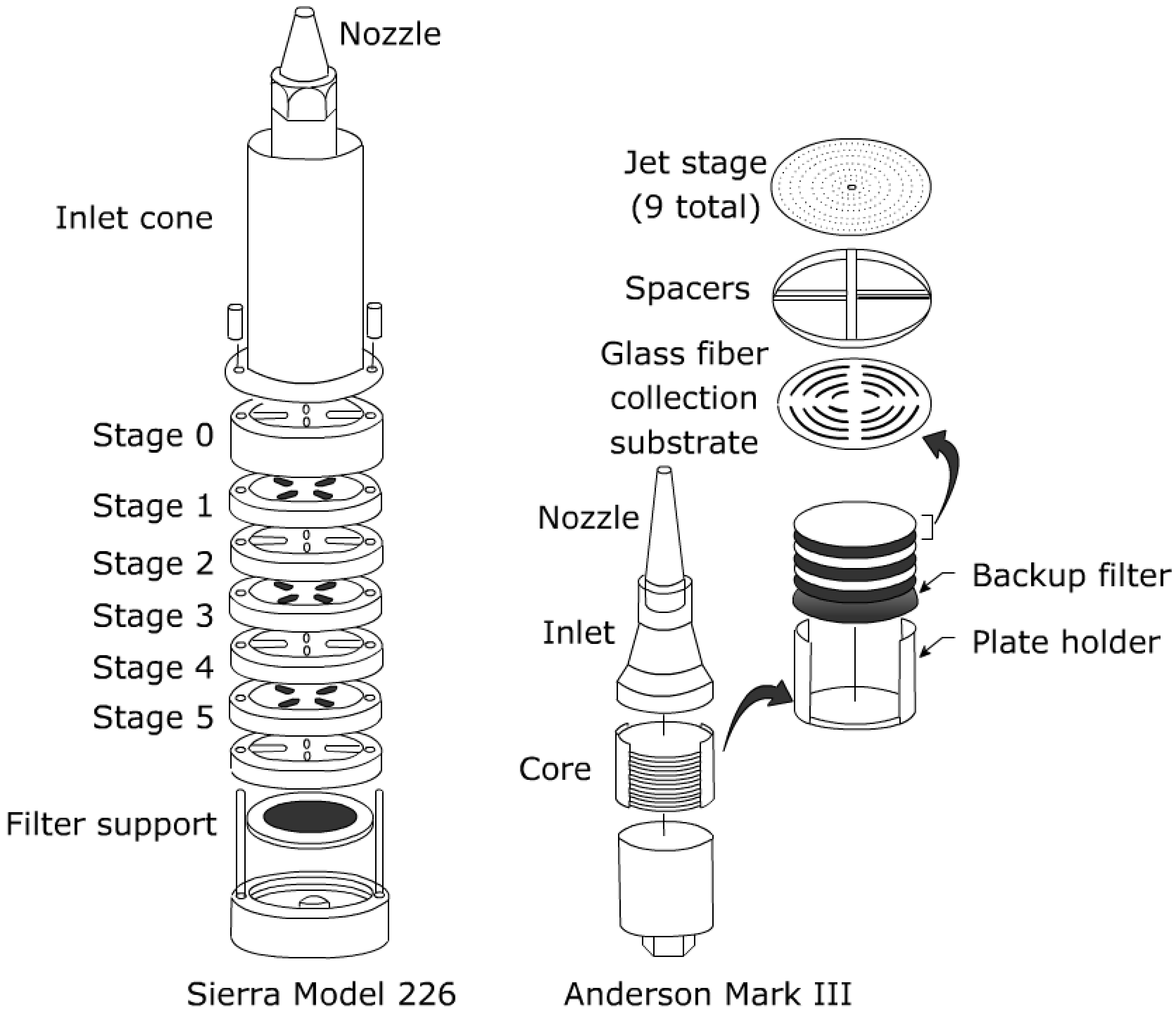
Figure 3-12. Comparison of particle sizing devices

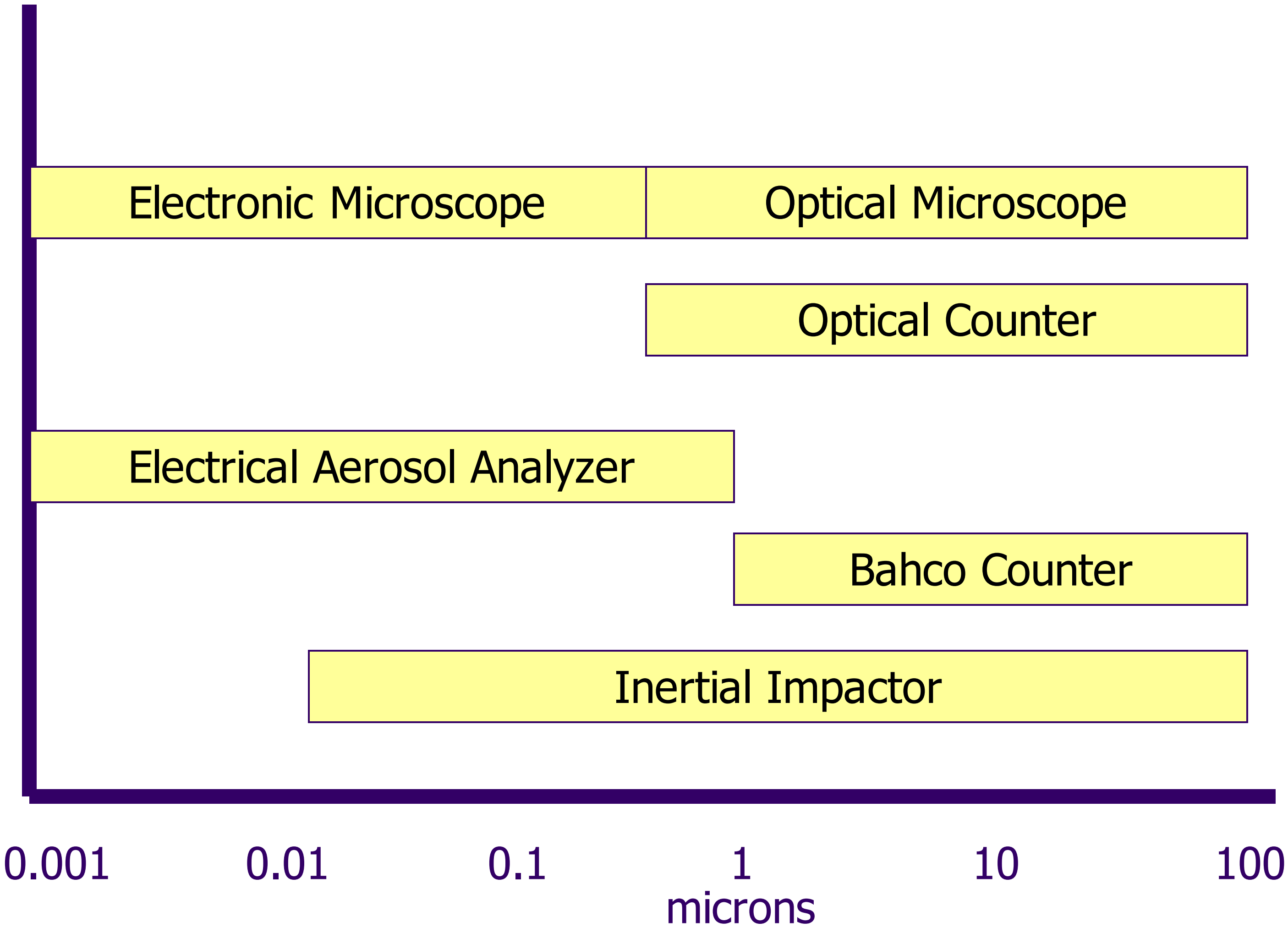


Cascade Impactor

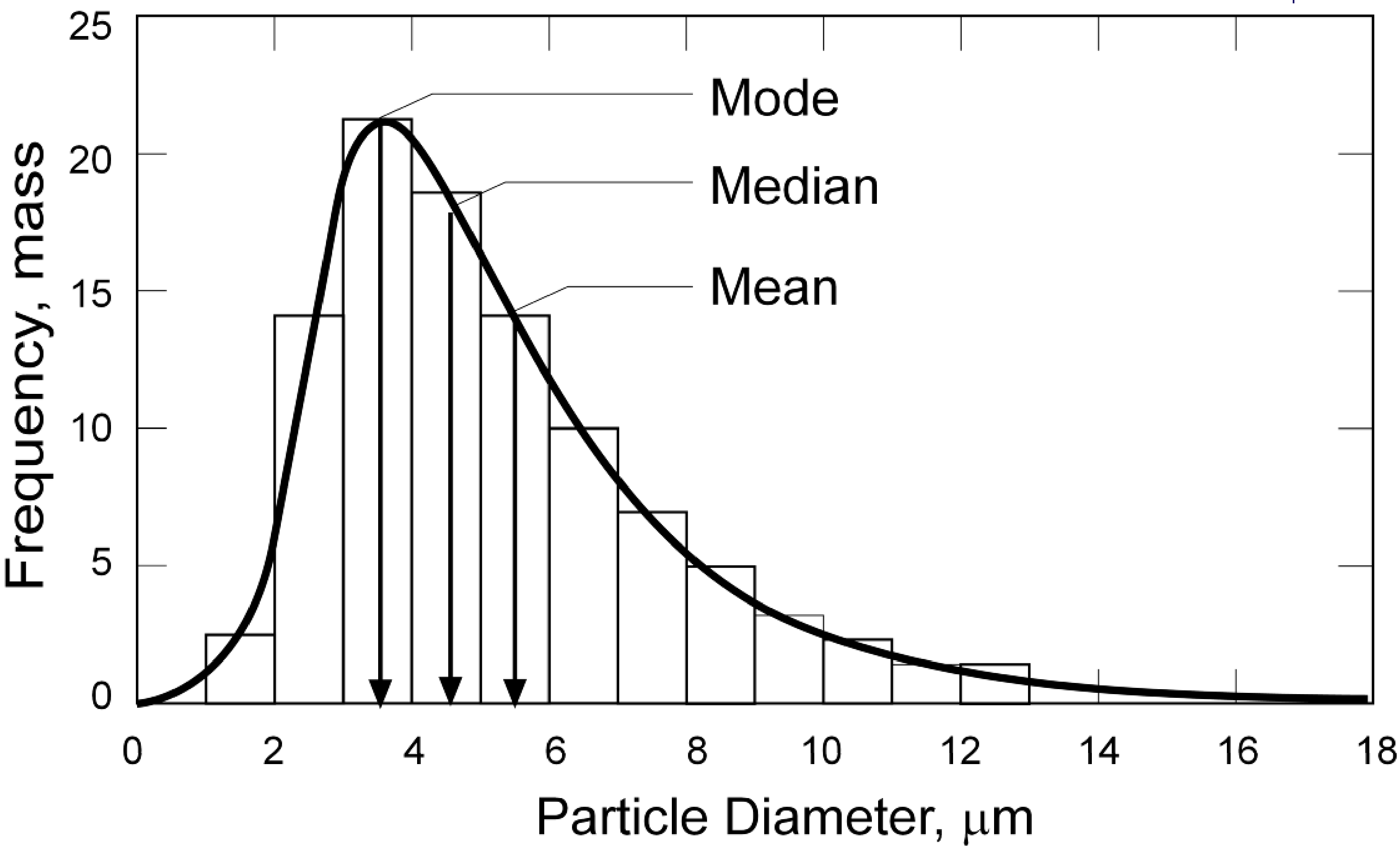


Cascade Impactors

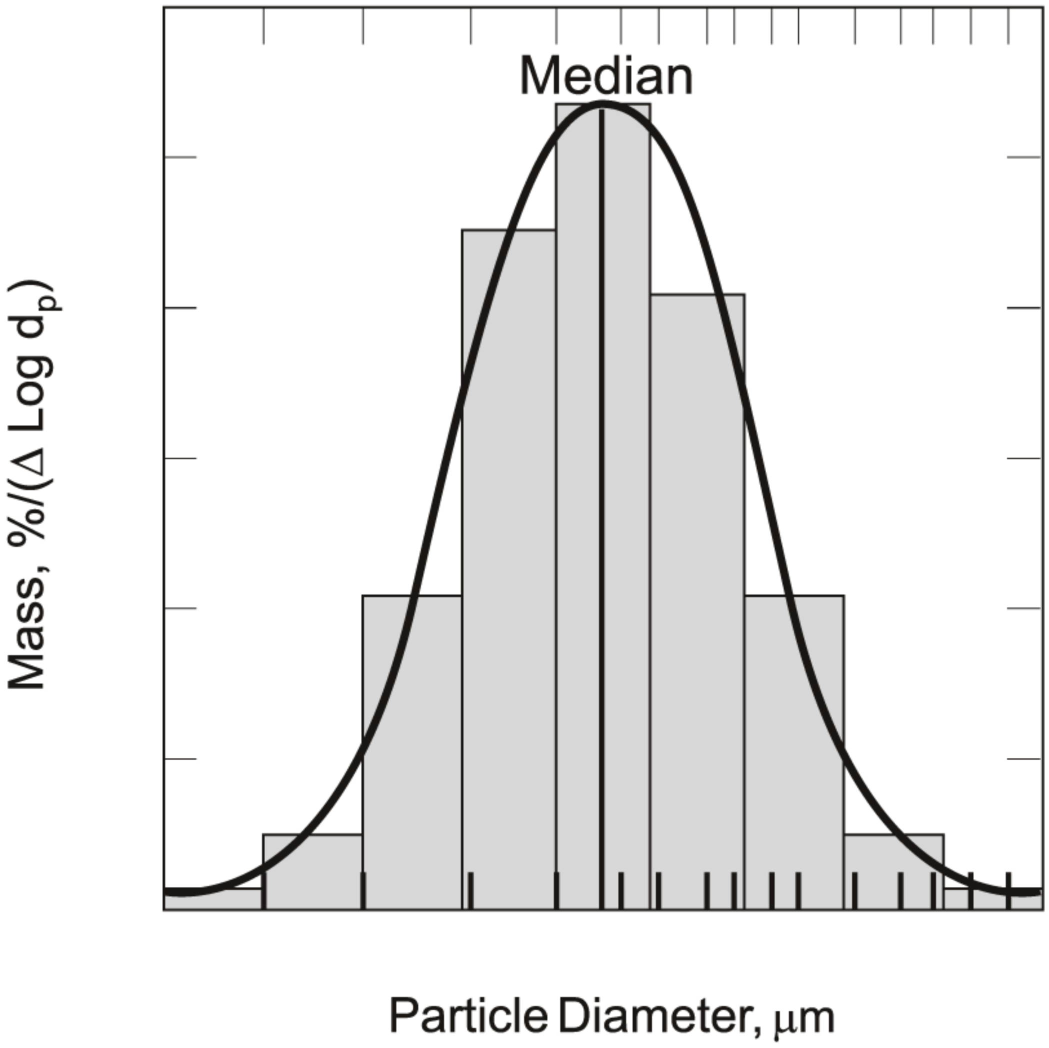



Electronic Microscope
Optical Microscope
Optical Counter
Electrical Aerosol Analyzer
Bahco Counter
Inertial Impactor
0.001
0.01
0.1
1
10
100
microns

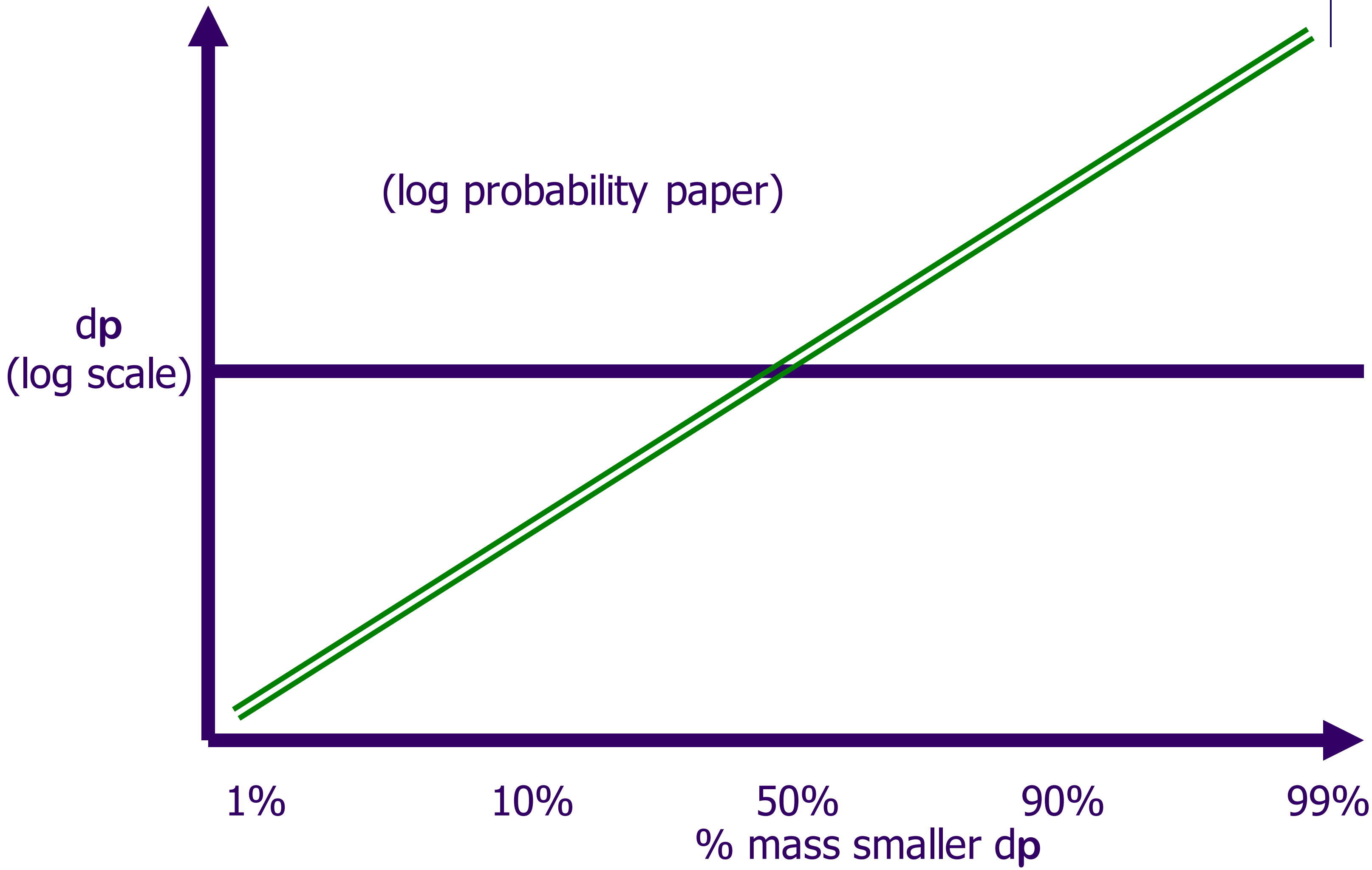
Data Analysis

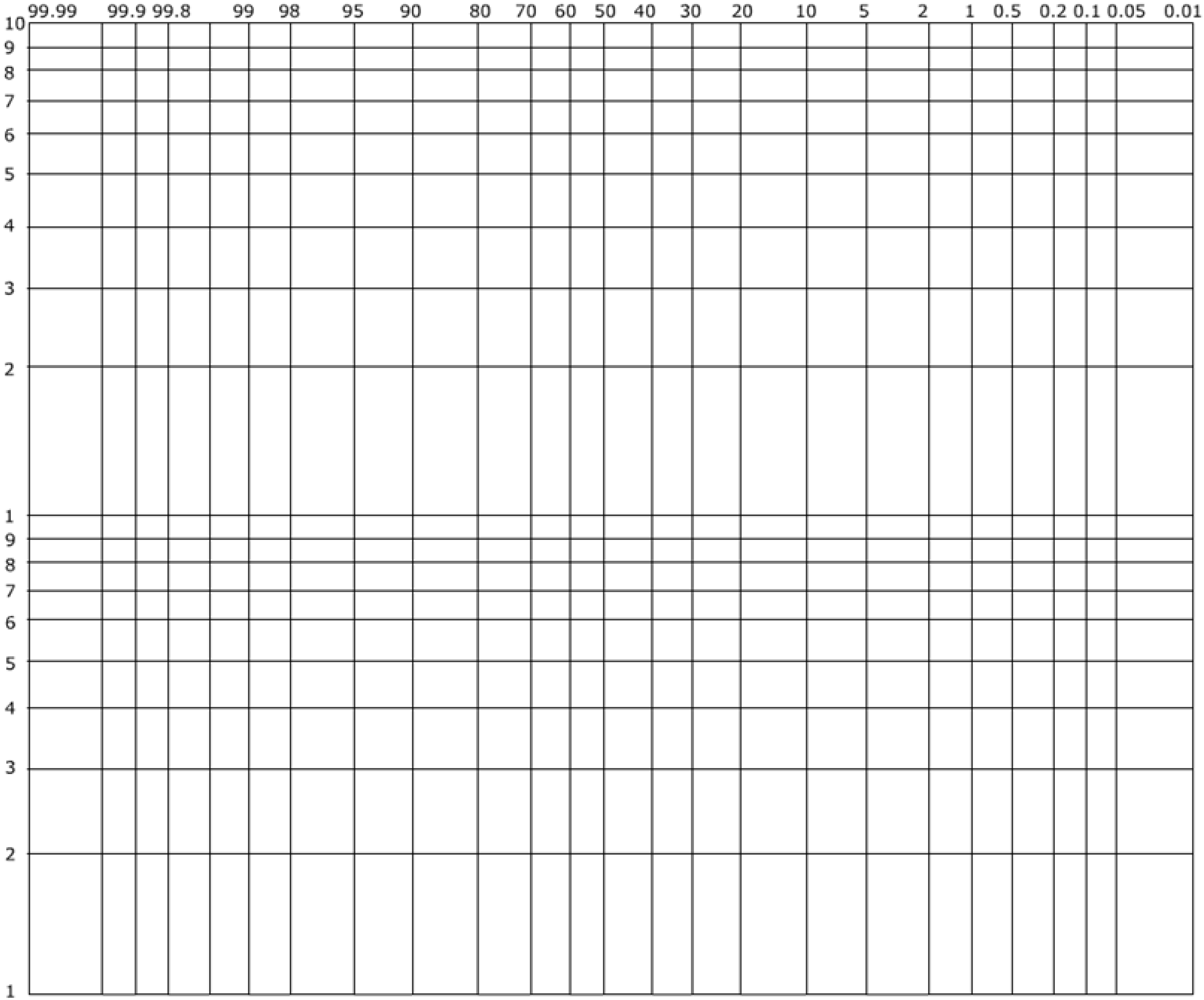


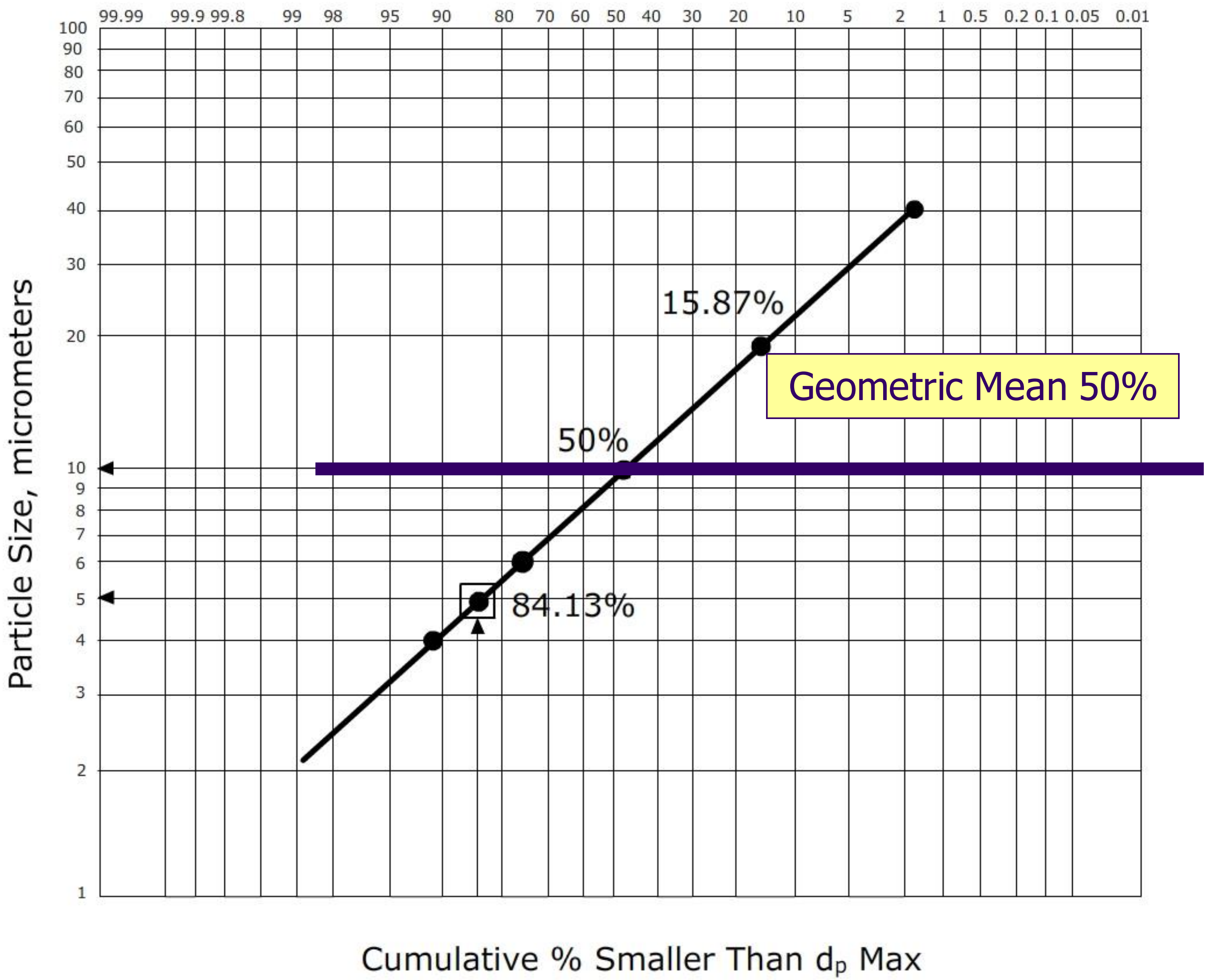
Log-Normal Distribution



Log-Probability Plots




99.99 99.9 99.8 99 98 95 90 80 70 60 50 40 30 20 10 5 2 1 0.5 0.2 0.1 0.05 0.01
10 9 8 7 6 5 4 3 2 1 9 8 7 6 5 4 3 2 1



99.99
99.9
99.8
99
98
95
90
80
70
60
50
40
30
20
10
5
2
1
0.5
0.2
0.1
0.05
0.01
100
90
80
70
60
50
40
30
20
10
9
8
7
6
5
4
3
2
1
Particle Size, micrometers
15.87%
Geometric Mean 50%
50%
84.13%
Cumulative % Smaller Than d_p Max

Geometric Standard Deviation

$$\sigma_g = \frac{d_{15.87}}{d_{50}}$$

or

$$\sigma_g = \frac{d_{50}}{d_{84.13}}$$

Example 3-1

Determine the mass mean diameter and the geometric standard deviation of the particle collection represented by the following distribution:

Size Range (gm)	Mass (mg)
<2	1.0
2 to 4	14.5
4 to 6	24.7
6 to 10	59.8
10 to 20	68.3
20 to 40	28.9
>40	2.8

Solution…

Refer to the table. Determine the total mass and calculate the percentage in each size range.

2. Starting with the size range for the smallest particles (<2 mm), subtract the percent mass in that range (0.50%) from 100.00 to determine the cumulative percent mass greater than 2 mm (99.50%).

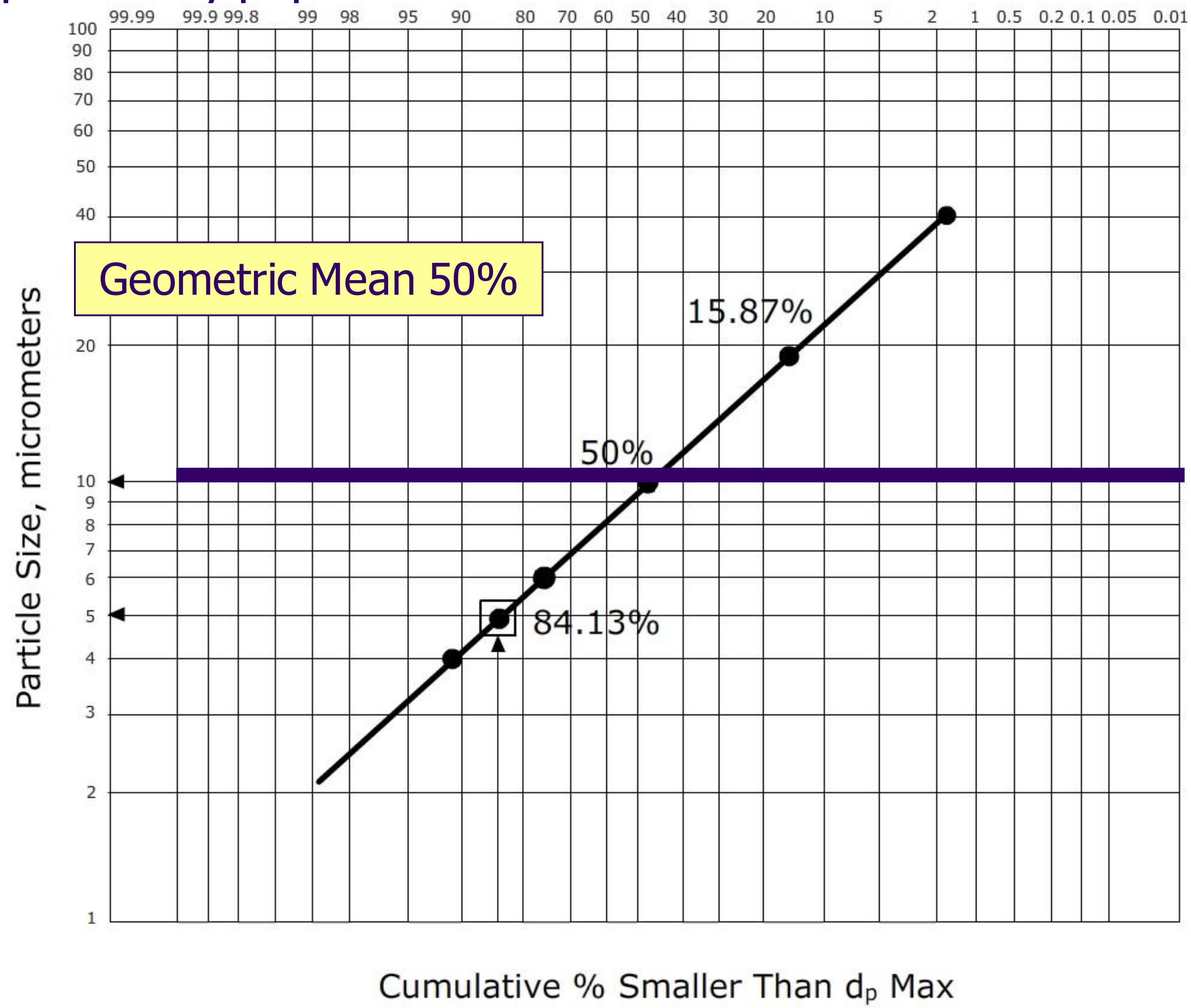
3. For each subsequent size range, subtract the percent mass in that range from the cumulative percent mass of the previous size range to determine the cumulative percent mass less than d_p max for that size range.

Example Particle Size Data			
Size Range (μm)	Mass (mg)	% Mass in Size Range	Cumulative % Mass Less Than dp max
<2	1.0	0.50	99.50
2 to 4	14.5	7.25	92.25
4 to 6	24.7	12.35	79.90
6 to 10	59.8	29.90	50.00
10 to 20	68.3	34.15	15.85
20 to 40	28.9	14.45	1.40
>40	2.8	1.40	---
TOTAL	200.0	100.0	

For example, for the 2-4 μm size range, 99.50% - 7.25% = 92.25%, the cumulative percent mass less than 4 mm.

And then…

Plot $d_p$max versus Cumulative Percent Mass Smaller Than $d_p$max on log-probability paper:



Finally…

The mass mean particle diameter is found at the 50th percentile and is 10 mm. The geometric standard deviation is calculated from:

$$\sigma_g = \frac{d^{15.87}}{d^{50}} = \frac{20\mu m}{10\mu m} = 2.0$$

or

$$\sigma_g = \frac{d^{50}}{d^{84.13}} = \frac{10\mu m}{5\mu m} = 2.0$$

Review Questions

1. Calculate the aerodynamic diameter of a spherical particle having a true diameter of 2 μm and a density of 2.7 g/cm^3.

Solution:

Assume that the Cunningham slip correction factor is 1.

$$d_p = d\sqrt{\rho_p C_c} = 2\sqrt{(2.7)(1.0)} = 3.29\mu m$$

Review Questions

2. Given the following distributions:

- Is either distribution lognormal?
- If yes, what is the geometric mass mean diameter and the geometric standard deviation?

Size Range (μm)	Sample A Mass (mg)	Sample B Mass (mg)
<0.6	25.50	8.50
0.6 to 1.0	33.15	11.05
1.0 to 1.2	17.85	7.65
1.2 to 3.0	102.00	40.80
3.0 to 8.0	63.75	15.30
8.0 to 10.0	5.10	1.69
>10.0	7.65	0.01

Solution #2 (a)

Size Range (gm)	Mass (mg)	Percent Mass in Size Range	Cumulative Percent Mass Less Than $d_p$max
<0.6	25.50	10	90
0.6 to 1.0	33.15	13	77
1.0 to 1.2	17.85	7	70
1.2 to 3.0	102.00	40	30
3.0 to 8.0	63.75	25	5
8.0 to 10.0	5.10	2	3
>10.0	7.65	3	---
TOTAL	255.0	1 00 . 0	

But wait there is more

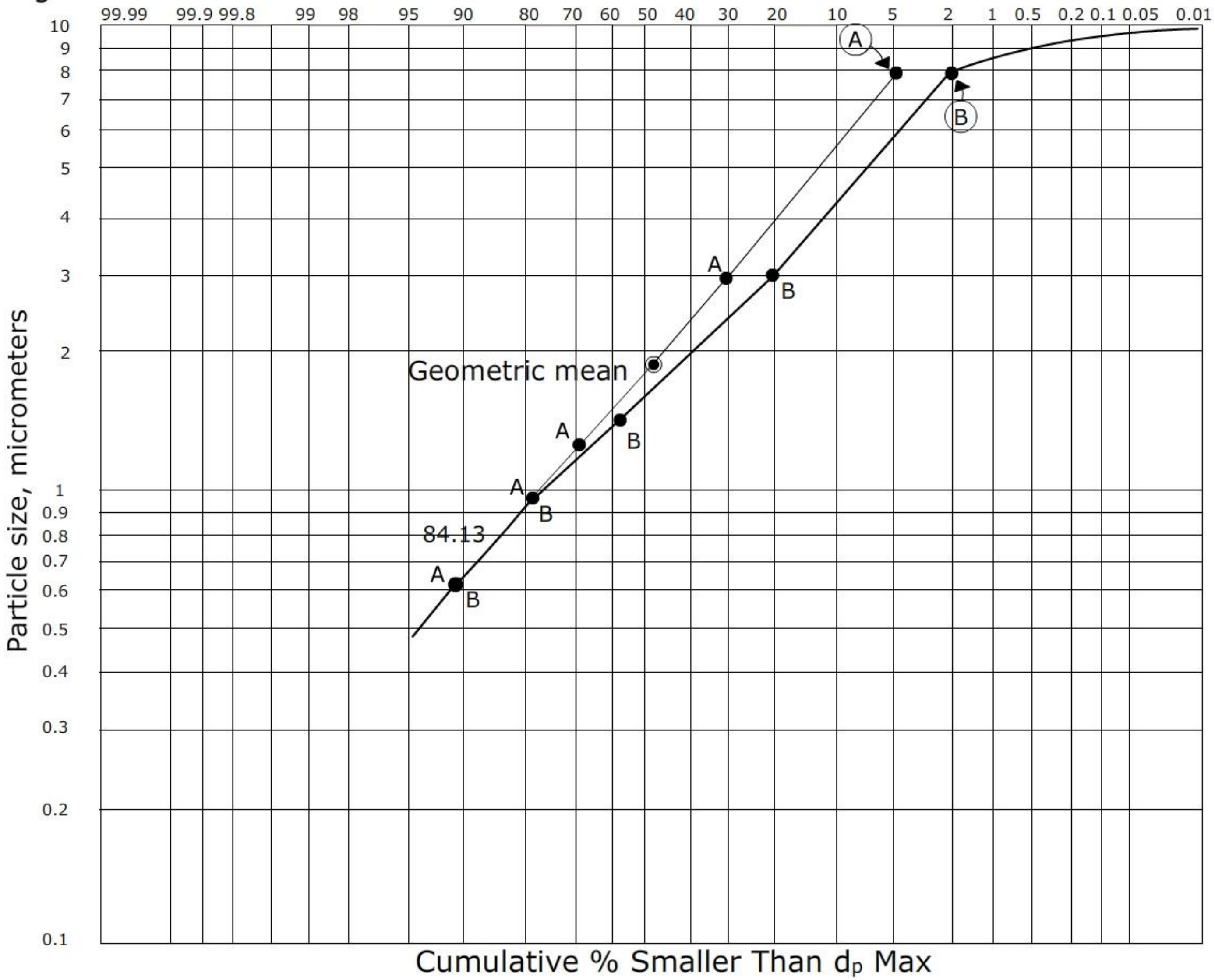
Solution #2 (b)

Size Range (gm)	Mass (mg)	Percent Mass in Size Range	Cumulative Percent Mass Less Than $d_p$max
<0.6	8.50	10	90
0.6 to 1.0	11.05	13	77
1.0 to 1.2	7.65	9	68
1.2 to 3.0	40.80	48	20
3.0 to 8.0	15.30	18	2
8.0 to 10.0	1.69	1.99	0.01
>10.0	0.01	0.01	---
TOTAL	85.0	100.0	

But wait there is more

Finally, Plot them

Figure 3-20.



A) Is lognormal

B) Is not lognormal

But wait there is more

And finally…

The geometric mass mean diameter and the geometric standard deviations for Sample A are:

$$d_{50} = 1.9\mu m$$

$$\sigma_g = \frac{d_{50} = 1.9\mu m}{d_{84.13} = 0.8\mu m} = 2.4$$

Chapter 4

Particle Collection Mechanisms

Collection Mechanisms

- Gravitational settling
- Centrifugal inertial force
- Inertial impaction
- Brownian motion
- Electrostatic attraction
- Thermophoresis
- Diffusiophoresis

Particle Motion

$$\Sigma F = m_p a_p = m_p \frac{dv_p}{dt}$$

where

ΣF = sum of all forces acting on the particle ($g \cdot cm/sec^2$)

m_p = mass of the particle (g)

a_p = acceleration of the particle (cm/sec^2)

v_p = velocity of the particle (cm/sec)

t = time (sec)

cgs units given, but any consistent set of units is ok

English System Units

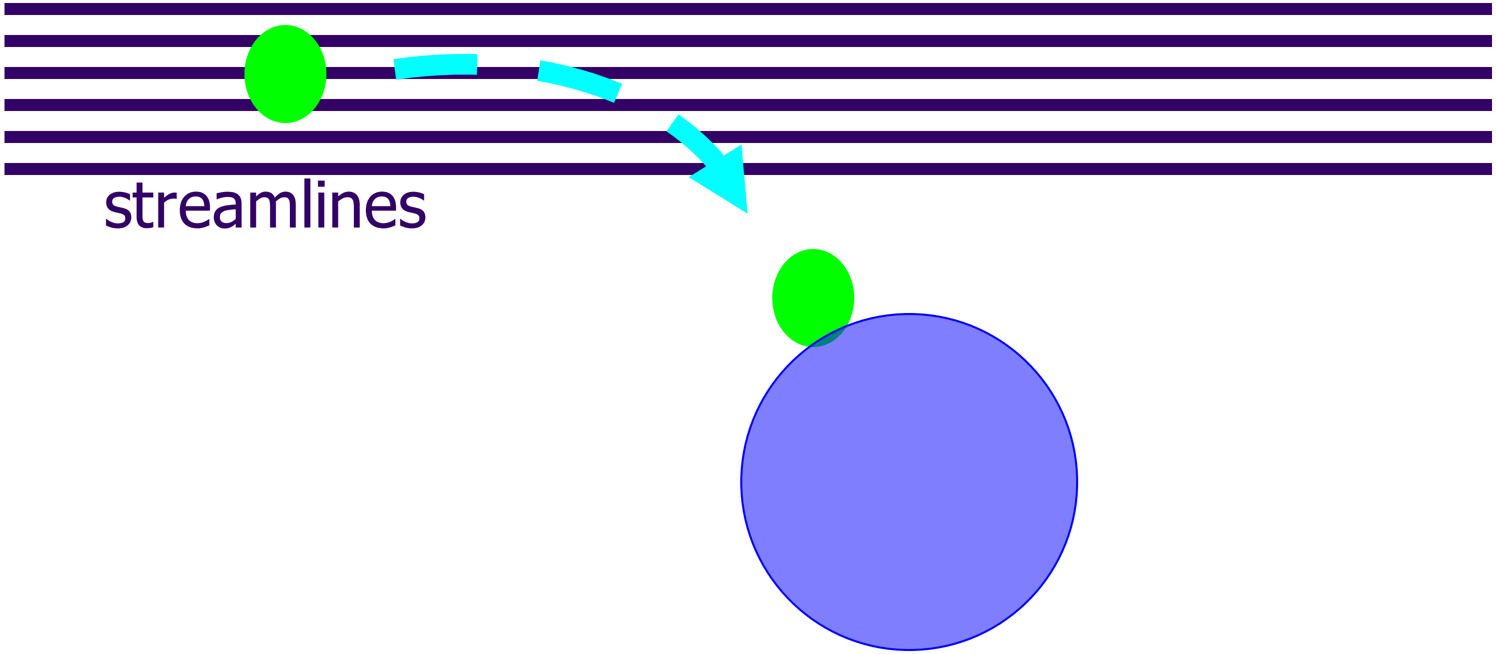
$$\Sigma F = \frac{m_p a_p}{g_c}$$

where

ΣF = sum of all forces acting on the particle (lb_f)
m_p = mass of the particle (lb_m)
a_p = acceleration of the particle (ft/sec^2)

$$g_c = 32.2 \frac{lb_m ft}{lb_f \, sec^2}$$

Gravitational Settling



Forces on a Particle

- Gravitational force
- Buoyant force
- Drag force

Gravitational Force

$$F_G = m_p g = \rho_p V_p g$$

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

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

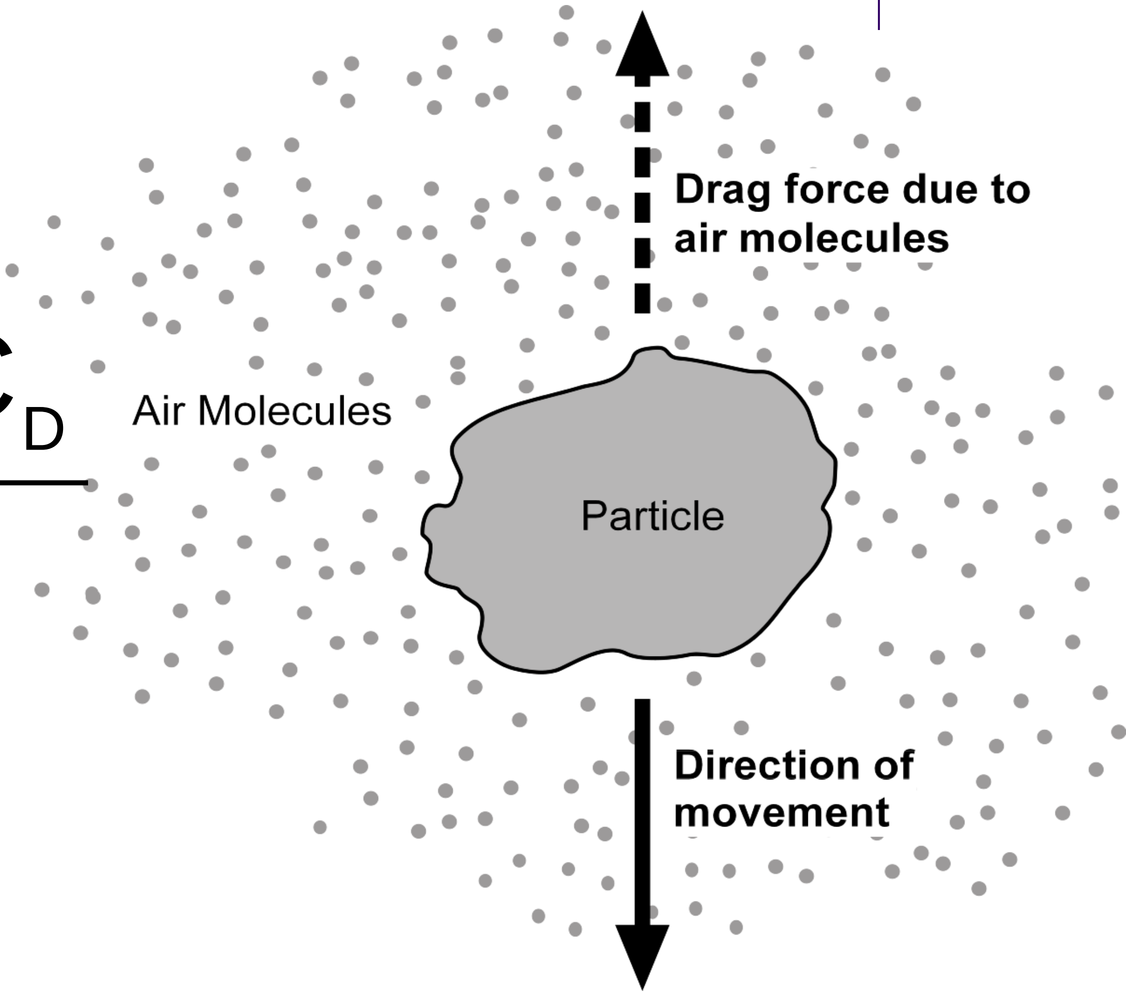
Buoyant Force

$$F_B = m_g g = \rho_g V_p g$$

$$F_B = \frac{\pi d_p^3 \rho_g g}{6}$$

Drag Force

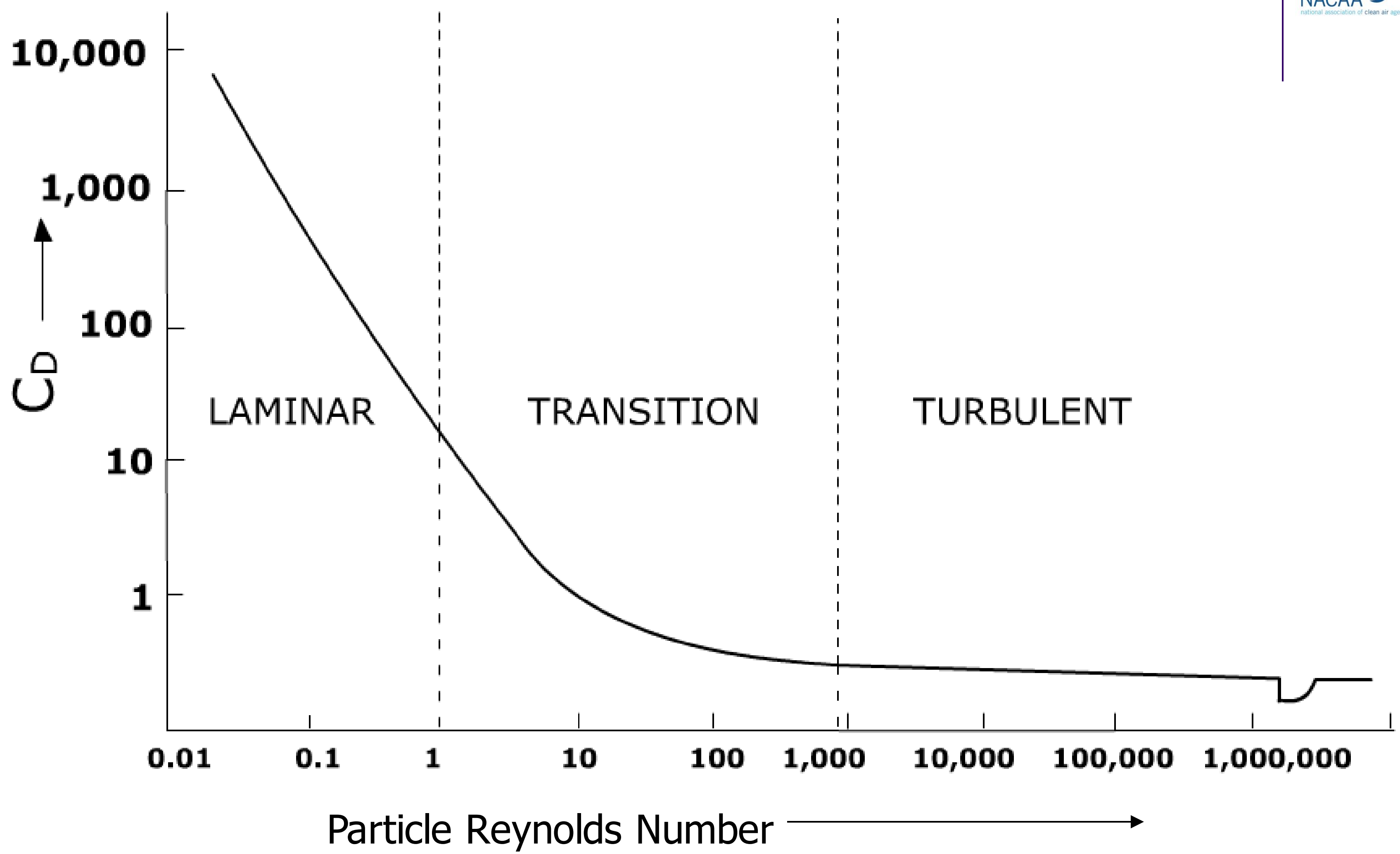
$$F_D = \frac{\pi d_p^2 \rho_g V_p^2 C_D}{8}$$



Drag Coefficient

C_D is a function of the particle Reynolds number

$$\mathrm{Re}_p = \frac{d_p v_p \rho_g}{\mu_g}$$



10,000
1,000
100
10
1
C_D
LAMINAR
TRANSITION
TURBULENT
0.01
0.1
1
10
100
1,000
10,000
100,000
1,000,000
Particle Reynolds Number

- Laminar ($Re_p<1$)

$$C_D = \frac{24}{Re_p}$$

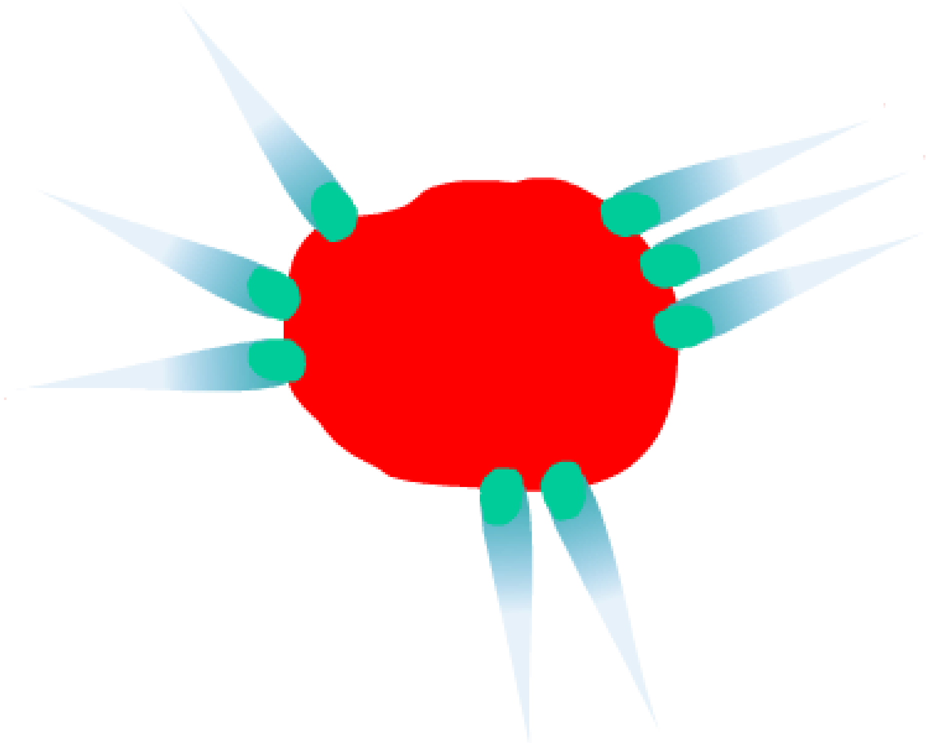
- Transition ($1<Re_p<1{,}000$)

$$C_D = \frac{18.5}{Re_p^{0.6}}$$

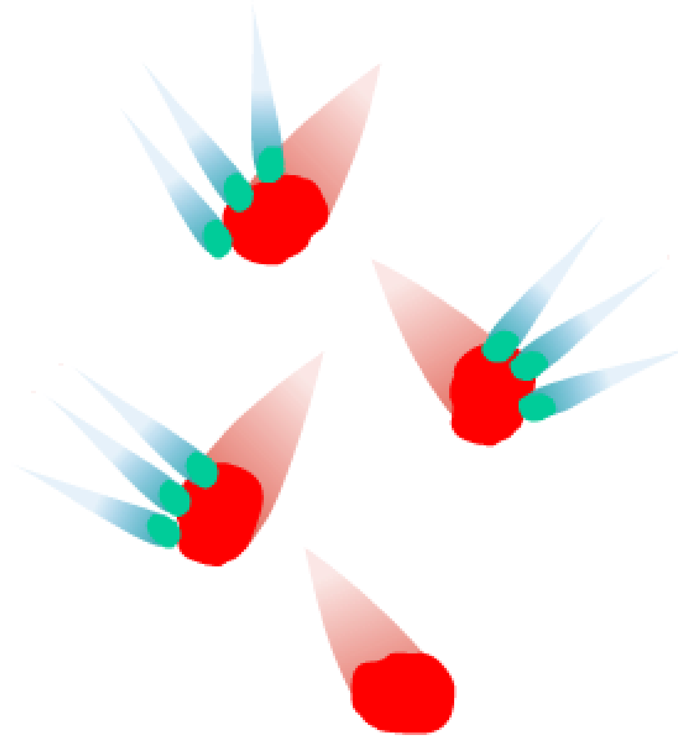
- Turbulent ($Re_p>1{,}000$)

$$C_D = 0.44$$

Laminar Regime



$d_p > 1 \mu m$

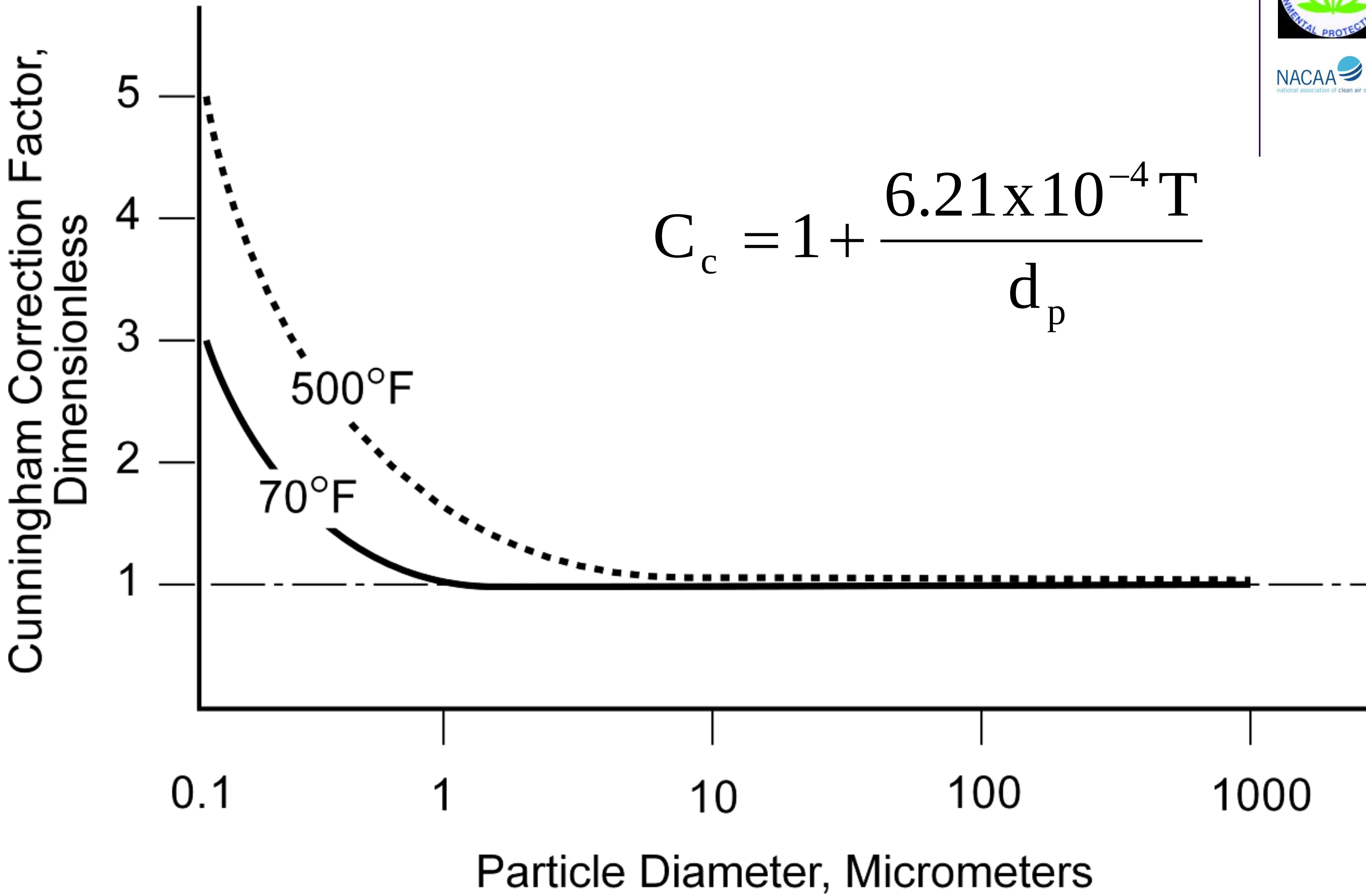


$d_p < 1 \mu m$

Laminar Regime Drag Coefficient

$$C_D = \frac{24}{Re_p\, C_c}$$

C_c is the Cunningham slip correction factor



$$C_c = 1 + \frac{6.21x10^{-4}T}{d_p}$$

- Laminar (Re_p<1)

$$F_D = \frac{3\pi\mu_g v_p d_p}{C_c}$$

- Transition (1<Re_p<1,000)

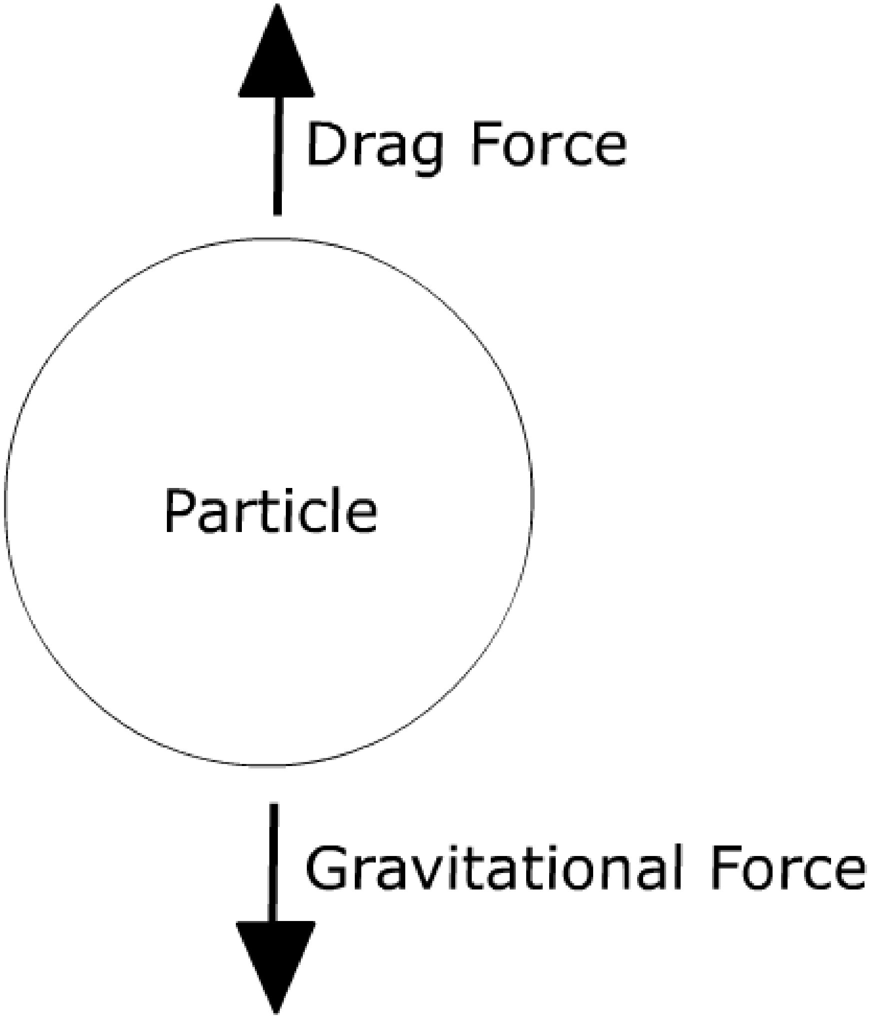
$$F_D = 2.31\pi(d_p v_p)^{1.4}\mu_g^{0.6}\rho_g^{0.4}$$

- Turbulent (Re_p>1,000)

$$F_D = 0.055\pi(d_p v_p)^2\rho_g$$

Terminal Settling Velocity

$$F_G - F_D = 0$$



Terminal Settling Velocity

Laminar Regime

$$v_t = \frac{g C_c \rho_p d_p^2}{18\mu_g}$$

Terminal Settling Velocity

Transition Regime

$$v_t = \frac{0.153\, g^{0.71} \rho_p^{0.71} d_p^{1.14}}{\mu_g^{0.43} \rho_g^{0.29}}$$

Terminal Settling Velocity

Turbulent Regime

$$v_t = 1.74\left(\frac{g\,\rho_p d_p}{\rho_g}\right)^{0.5}$$

Determination of Flow Regime

$$K = d_p \left(\frac{g \rho_p \rho_g}{\mu_g^2} \right)^{0.33}$$

where

g = acceleration of particle due to gravity (980 cm/sec^2)
ρ_p = particle density (g/cm3)
μ_g = gas viscosity (g/(cm·sec))
d_p = physical particle diameter (cm)
ρ_g = gas density (g/cm^3)

Don't get wrapped up in the units; any consistent set of units is ok.

K Values

Laminar region	K<2.62
Transitional region	2.62<K<69.12
Turbulent region	K>69.12

Terminal Settling Velocities of Unit Density Spheres at 25° C		
Particle Size (μm)	Terminal Settling Velocity at 25° C (cm/sec)	Flow Condition
0.1	0.000087	Laminar
1.0	0.0035	Laminar
10.0	0.304	Laminar
50.0	7.5	Laminar
80.0	19.3	Laminar
100	31.2	Transitional
200	68.8	Transitional
1,000	430.7	Transitional
10,000	1,583	Turbulent
100,000	5,004	Turbulent

Example 4-1

Calculate the terminal settling velocity in 20°C air of a 45 μm diameter particle with a density of 1 g/cm³.

Solution

Calculate K to determine the flow region :

$$K = d_\rho \left(\frac{g p_\rho p_g}{\mu_g^{\,2}} \right)^{0.33} = 45\text{x}10^{-4}\,\text{cm} \left[\frac{\left(980\,\text{cm}/\text{sec}^2\right)\left(1.0\,\text{g}/\text{cm}^3\right)\left(1.20\text{x}10^{-3}\,\text{g}/\text{cm}^3\right)}{\left(1.80\text{x}10^{-4}\,\text{g}/\text{cm}\cdot\text{sec}\right)^2} \right] = 1.35$$

Assume $C_c = 1.0$

$$v_t = \frac{g C_c p_\rho}{18\mu 8} = \frac{\left(980\,\text{cm}/\text{sec}^2\right)1.0\left(1.0\,\text{g}/\text{cm}^3\right)\left(45\text{x}10^{-3}\,\text{g}/\text{cm}^3\right)^2}{18\left(1.80\text{x}10^{-4}\,\text{g}/\text{cm}\cdot\text{sec}\right)} = 6.13\,\text{cm}/\text{sec}$$

Example 4-2

Calculate the terminal settling velocity in 20°C air of a 2 μm diameter particle with a density of 1 g/cm³.

Solution

Calculate K to determine the flow region :

$$K = d_{\rho}\left(\frac{gp_{\rho}p_{g}}{\mu_{g}^{2}}\right)^{0.33} = 2x10^{-4}\,cm\left[\frac{\left(980\,{}^{cm}\!/\!_{sec^2}\right)\left(1.0\,{}^{g}\!/\!_{cm^3}\right)\left(1.20x10^{-3}\,{}^{g}\!/\!_{cm^3}\right)}{\left(1.80x10^{-4}\,{}^{g}\!/\!_{cm\cdot sec}\right)^{2}}\right] = 0.06$$

$$C_c = 1 + \frac{6.21x10^{-4}T}{d_p} = 1 + \frac{6.21x10^{-4}\,(293K)}{2\mu m} = 1.09$$

Example 4-2

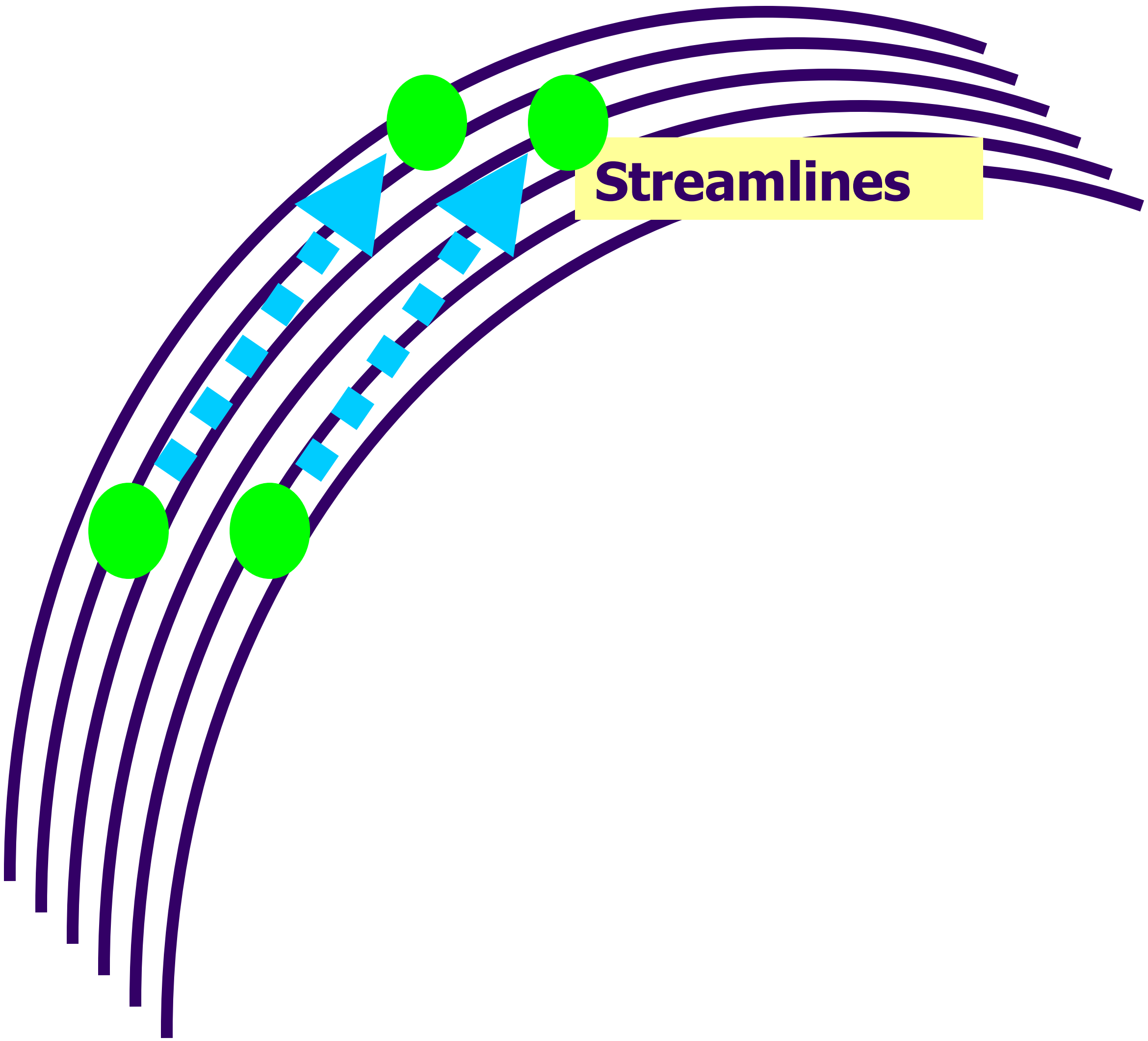
Calculate the terminal settling velocity in 20°C air of a 2 μm diameter particle with a density of 1 g/cm³.

Then…

Calculate K to determine the flow region :

$$v_t = \frac{gC_c p_\rho d_p}{18\mu_g} = \frac{\left(980\ \mathrm{cm}/\mathrm{sec}^2\right)1.09\left(1.0\ \mathrm{g}/\mathrm{cm}^3\right)\left(2\mathrm{x}10 - 4\mathrm{cm}\right)^2}{18\left(1.80\mathrm{x}10^{-4}\ \mathrm{g}/\mathrm{cm}\cdot\mathrm{sec}\right)} = 0.013\ cm/\mathrm{sec}$$

Centrifugal Inertial Force



Forces on a Particle

- Centrifugal force

$$F_C = \frac{\pi d_p^3 \rho_p u_T^2}{6R}$$

- Drag force

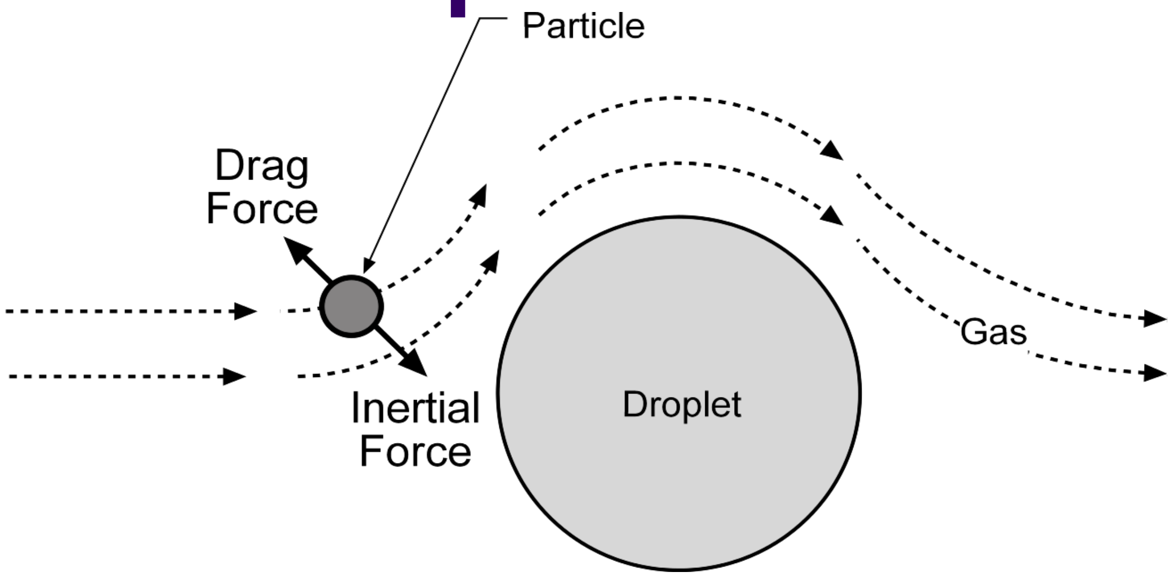
$$F_D = \frac{3\pi \mu_g v_p d_p}{C_c}$$

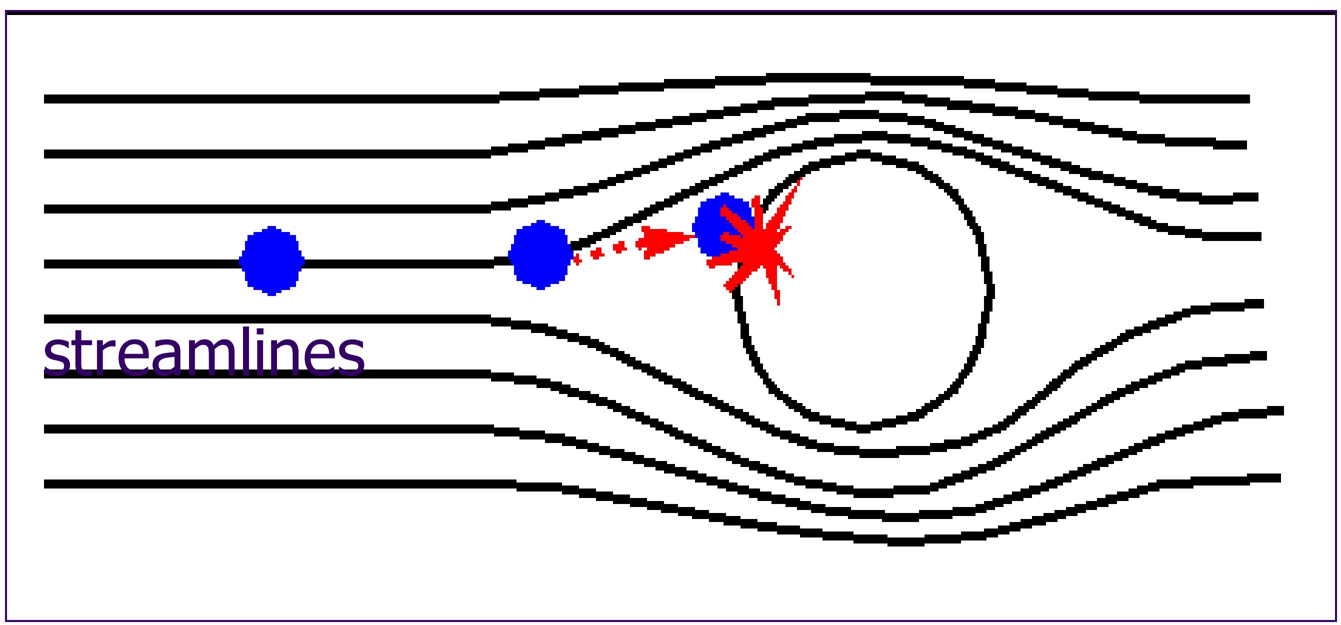
u_T = tangential velocity of the gas (cm/sec)
R = cylinder radius (cm)

Particle Radial Velocity

$$v_p = \frac{C_c d_p^2 \rho_p u_T^2}{18 \mu_g R}$$

Inertial Impaction





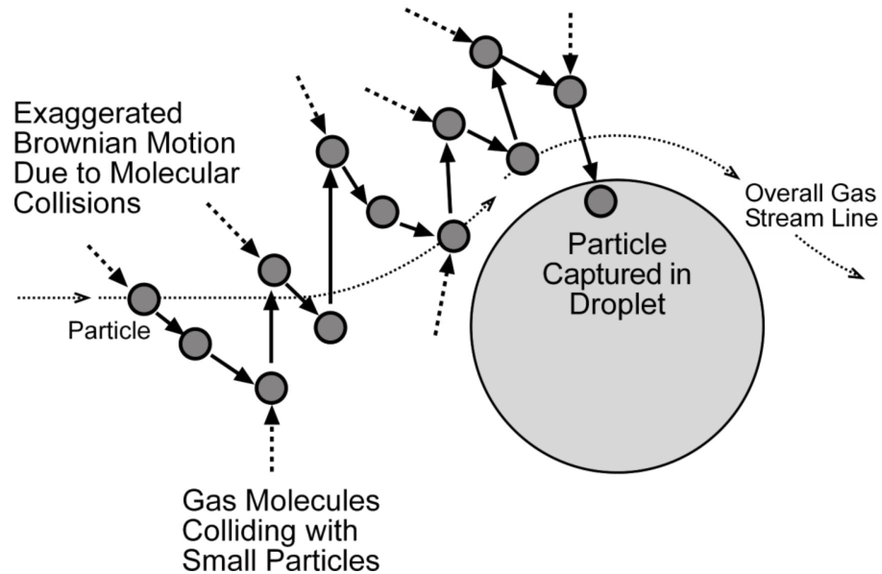
Inertial Impaction Parameter

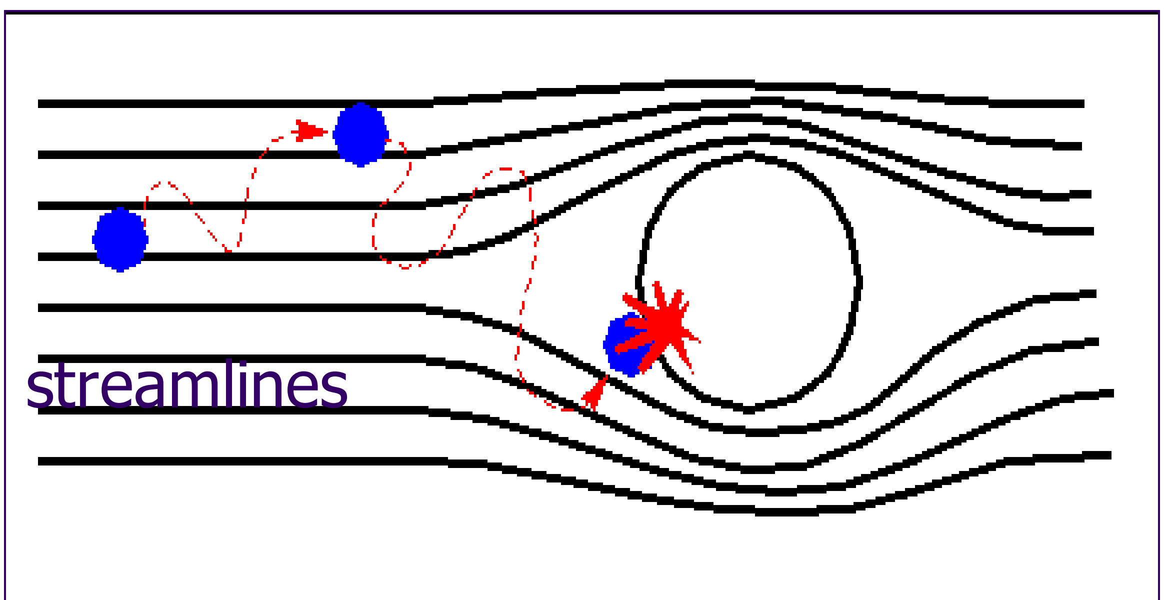
$$\psi_I = \frac{C_c d_p^2 v_p \rho_p}{18 \mu_g D_c}$$

Where

Ψ_I = inertial impaction parameter (dimensionless)
C_c = Cunningham slip correction factor (dimensionless)
d_p = physical particle diameter (cm)
v_p = difference in velocity between the particle and the target (cm/sec)
D_c = diameter of collection target (cm)
ρp = particle density (g/cm3)
μg = gas viscosity (g/(cm . sec))

Brownian Motion





Diffusional Collection Parameter

$$\psi_D = \frac{C_c k T}{3 \pi \mu_g d_p D_c v_p}$$

Where

k = Boltzmann constant (g . cm2/sec2 . K)

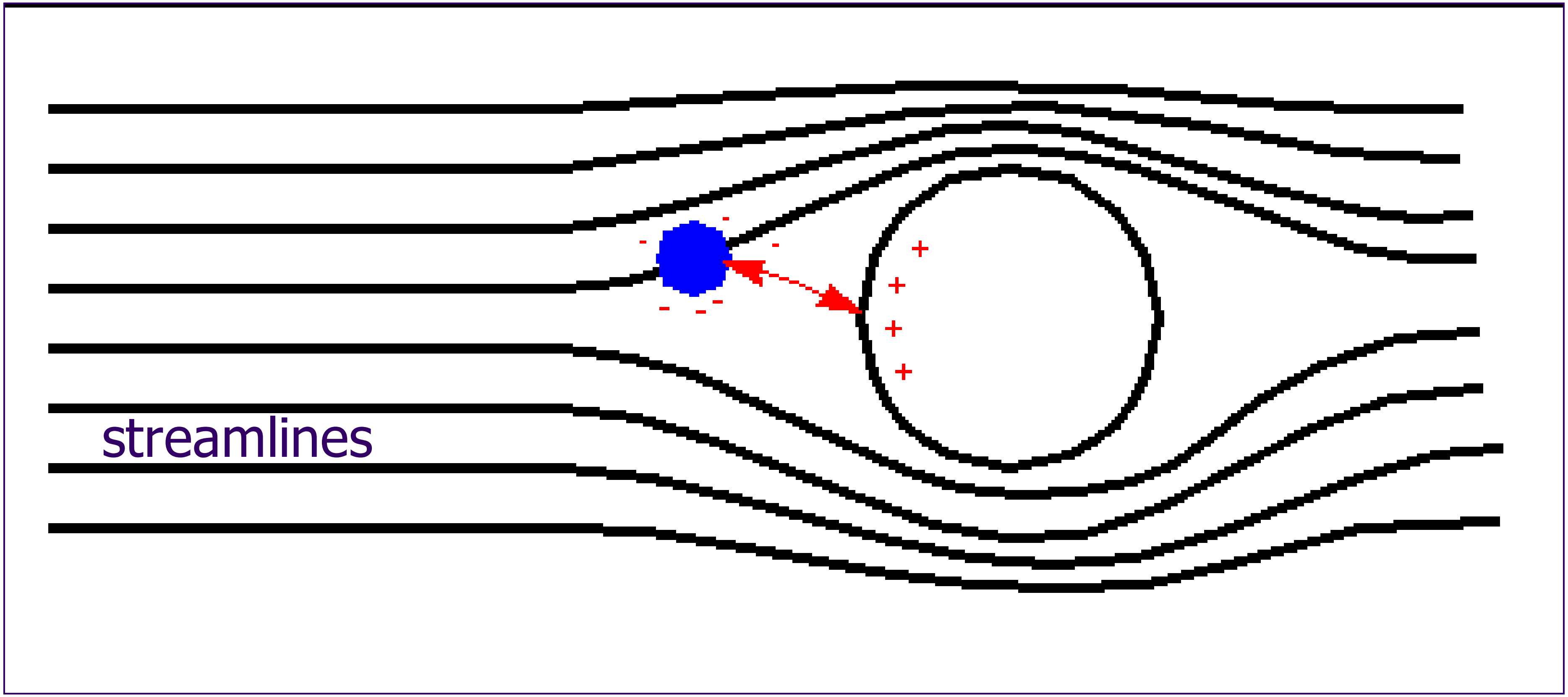
T = absolute temperature (K)

C_c = Cunningham slip correction factor (dimensionless)

μg = gas viscosity (g/cm .sec)

d_p = physical particle diameter (cm)

Electrostatic Attraction



Charging Mechanisms

- Field charging (large particles, >2μm)

$$n_f = \left(\frac{3\varepsilon}{\varepsilon+2}\right)\left(\frac{Ed_p^2}{4e}\right)$$

Where
n_d = number of charges deposited by diffusion charging
d_p = particle diameter (cm)
k = Boltzmann constant (k = 1.4 x 10-16g . cm^2/sec^2 . K)
T = absolute temperature (K)
c_i = ion velocity (c_i = 2.4 x 10^4 cm/sec)
e = charge of an electron (e = 4.8 x 10^{-10}statcoulomb)
t = time (sec)
N_i = ion concentration ($number/cm^3$)

Charging Mechanisms

- Diffusion charging (small particles, <0.4μm)

$$n_d = \frac{d_p kT}{2e^2} \ln\left(1 + \frac{\pi d_p c_i e^2 N_i t}{2kT}\right)$$

Where
n_d = number of charges deposited by diffusion charging
d_p = particle diameter (cm)
k = Boltzmann constant (k = 1.4 x 10-16g . cm^2/sec^2 . K)
T = absolute temperature (K)
c_i = ion velocity (c_i = 2.4 x 10^4 cm/sec)
e = charge of an electron (e = 4.8 x 10^{-10}statcoulomb)
t = time (sec)
N_i = ion concentration ($number/cm^3$)

Forces on a Particle

- Electrostatic force

$$F_E = neE$$

- Drag force

$$F_D = \frac{3\pi\mu_g v_p d_p}{C_c}$$

Particle Migration Velocity

$$v_p = \omega = \frac{neEC_c}{3\pi\mu_g d_p}$$

Example 4-3

Determine the migration velocity of a 2 μm unit-density particle carrying 800 units of charge in an electric field of 2kV/cm. Assume that the gas temperature is 20°C:

Solution:

To solve this problem, the following relationships are used:

300 volts = 1 statvolt

1 statvolt = 1 statcoulomb/cm

1 dyne = 1 $statcoulomb^2/cm^2$ = 1 $g.cm/sec^2$

C_C = 1.09 (as calculated in Example 4-2)

The electric field in centimeter-gram-second units is:

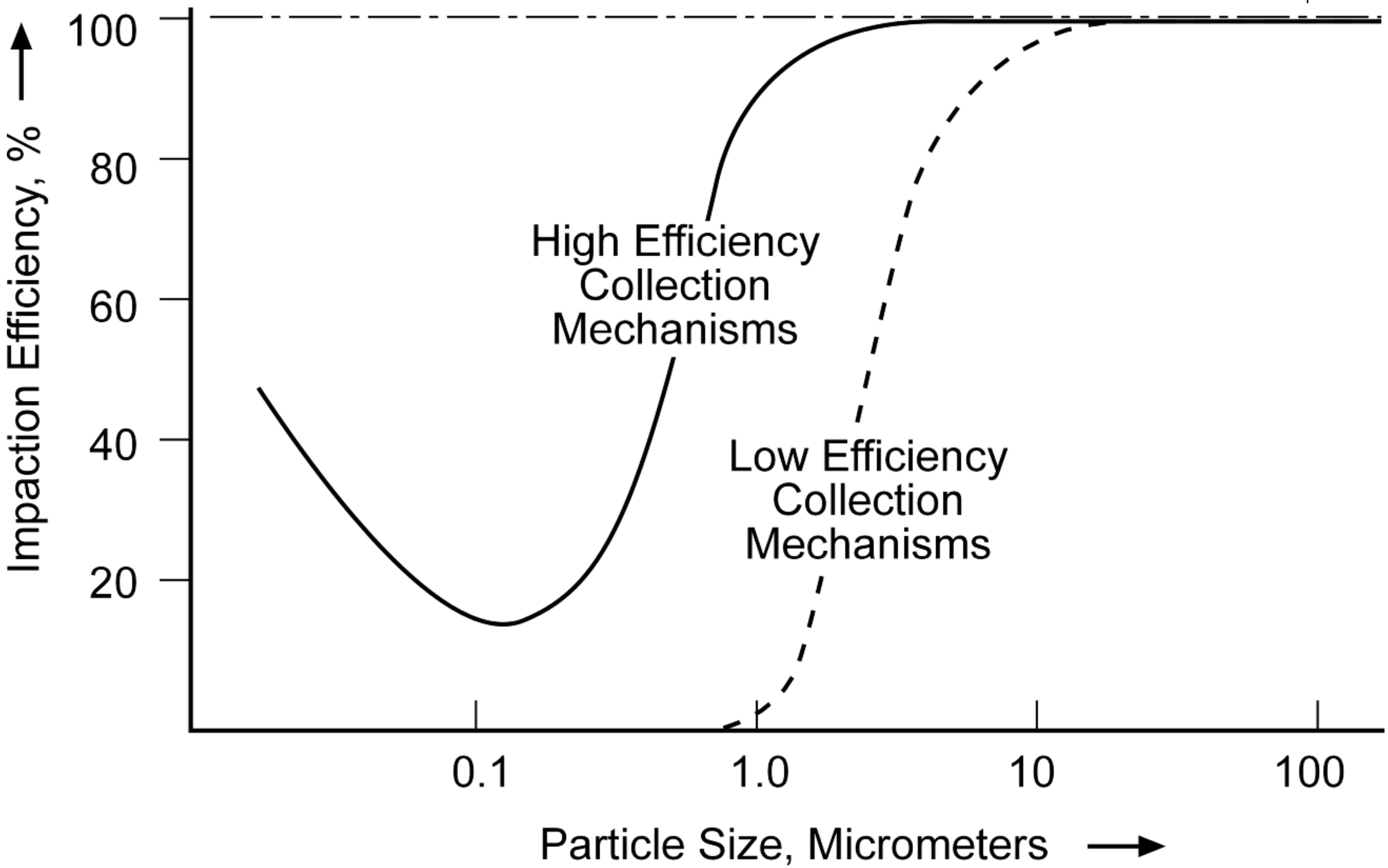
$$E = 2\,\frac{\text{kV}}{\text{cm}} = 2{,}000\,\frac{\text{V}}{\text{cm}}\left(\frac{\text{statvolt}}{300\ \text{volts}}\right) = 6.67\,\frac{\text{statvolts}}{\text{cm}} = 6.67\,\frac{\text{statcoulombs}}{\text{cm}^2}$$

$$\omega = \frac{neEC_c}{3\pi\mu_g d_p} = \frac{(800)(4.8\text{x}10^{-10}\ \text{statcoulombs})\left(6.67\,\frac{\text{statcoulombs}}{\text{cm}^2}\right)(1.09)}{3\pi\left(1.8\text{x}10^{-4}\,\frac{\text{g}}{\text{cm}\cdot\text{sec}}\right)(2\text{x}10^{-4}\text{cm})}$$

Phoretic Forces

- Thermophoresis
- Diffusiophoresis

Size-Efficiency Relationships



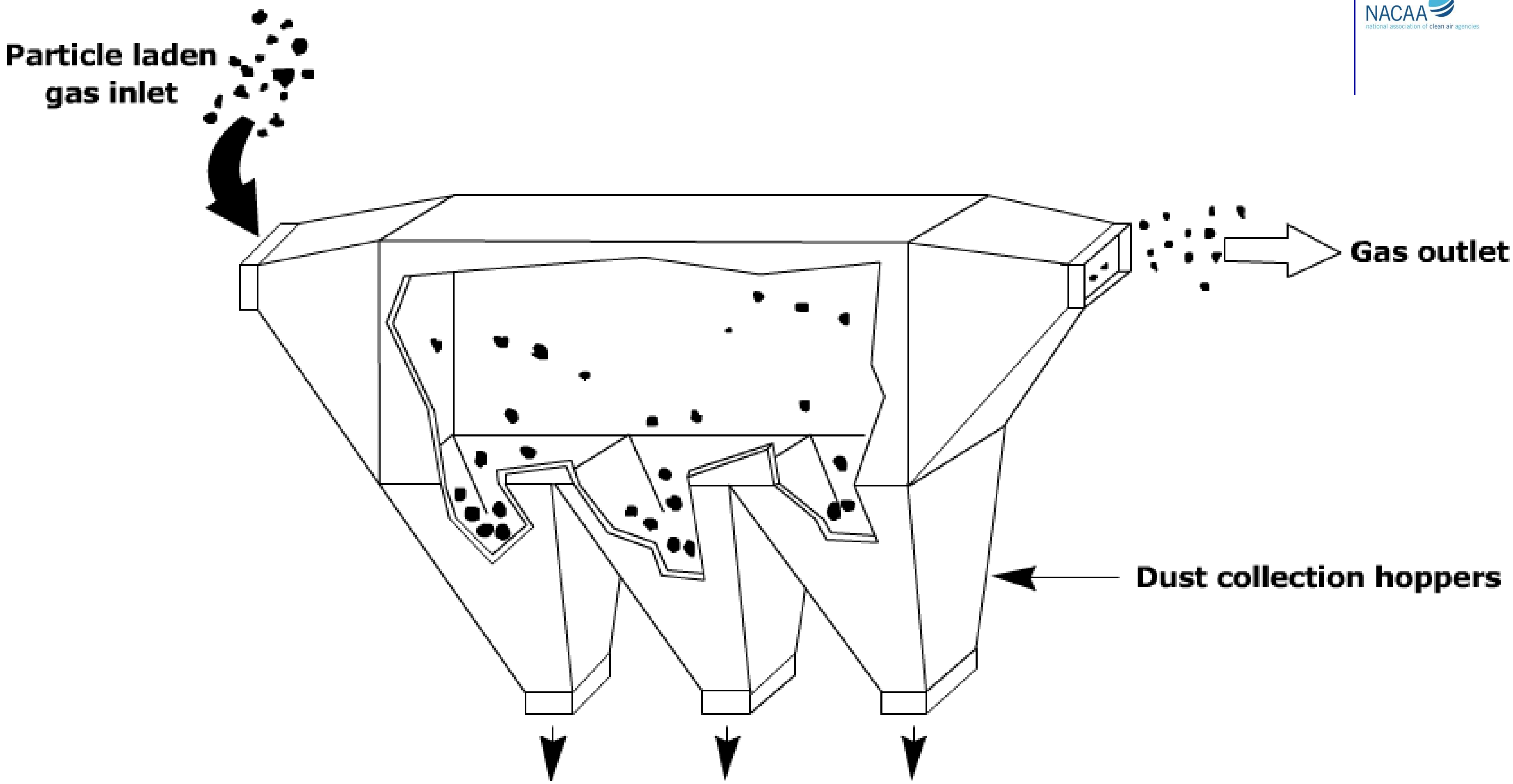
Chapter 5

Settling Chambers

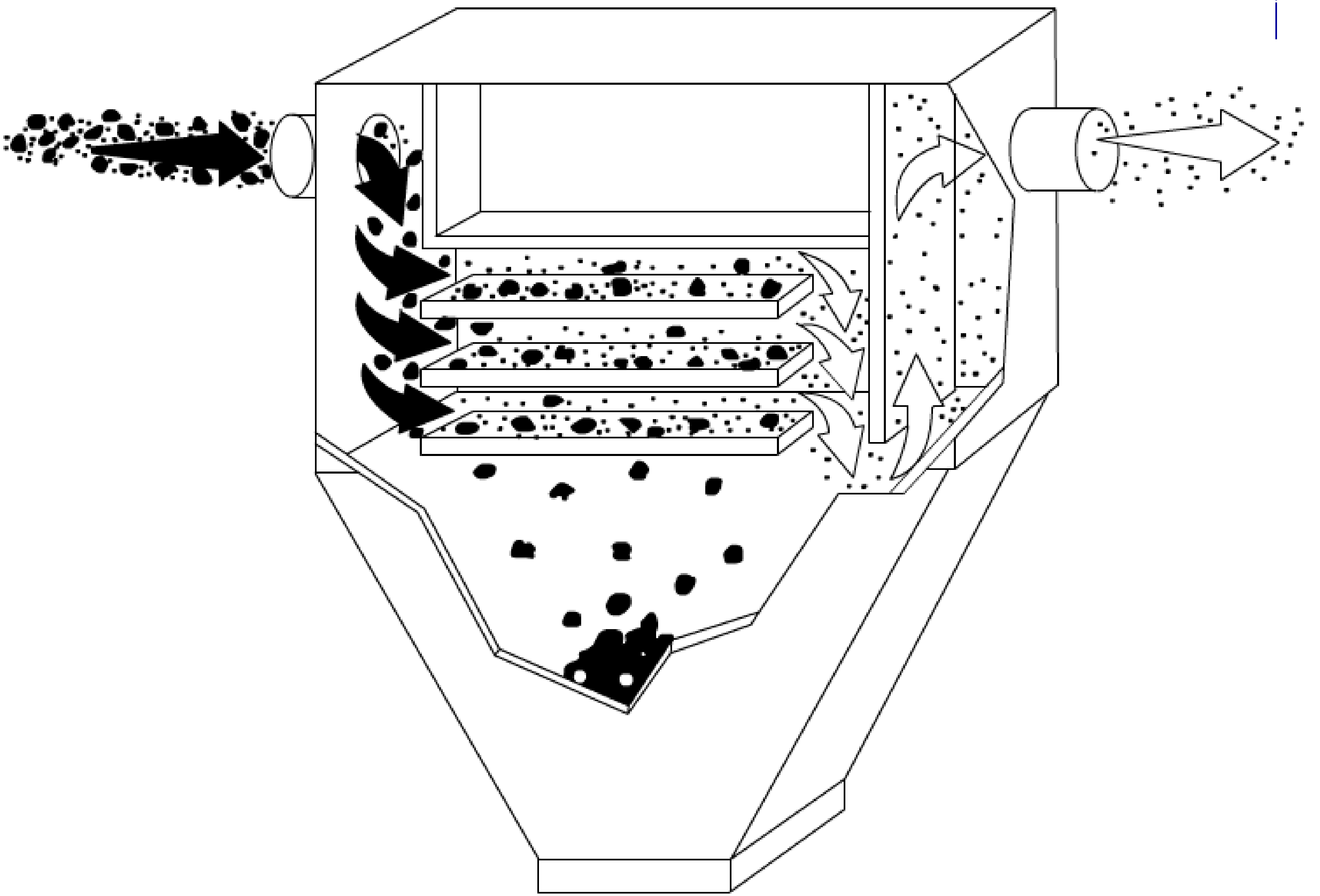
Collection Mechanisms

- Gravitational settling

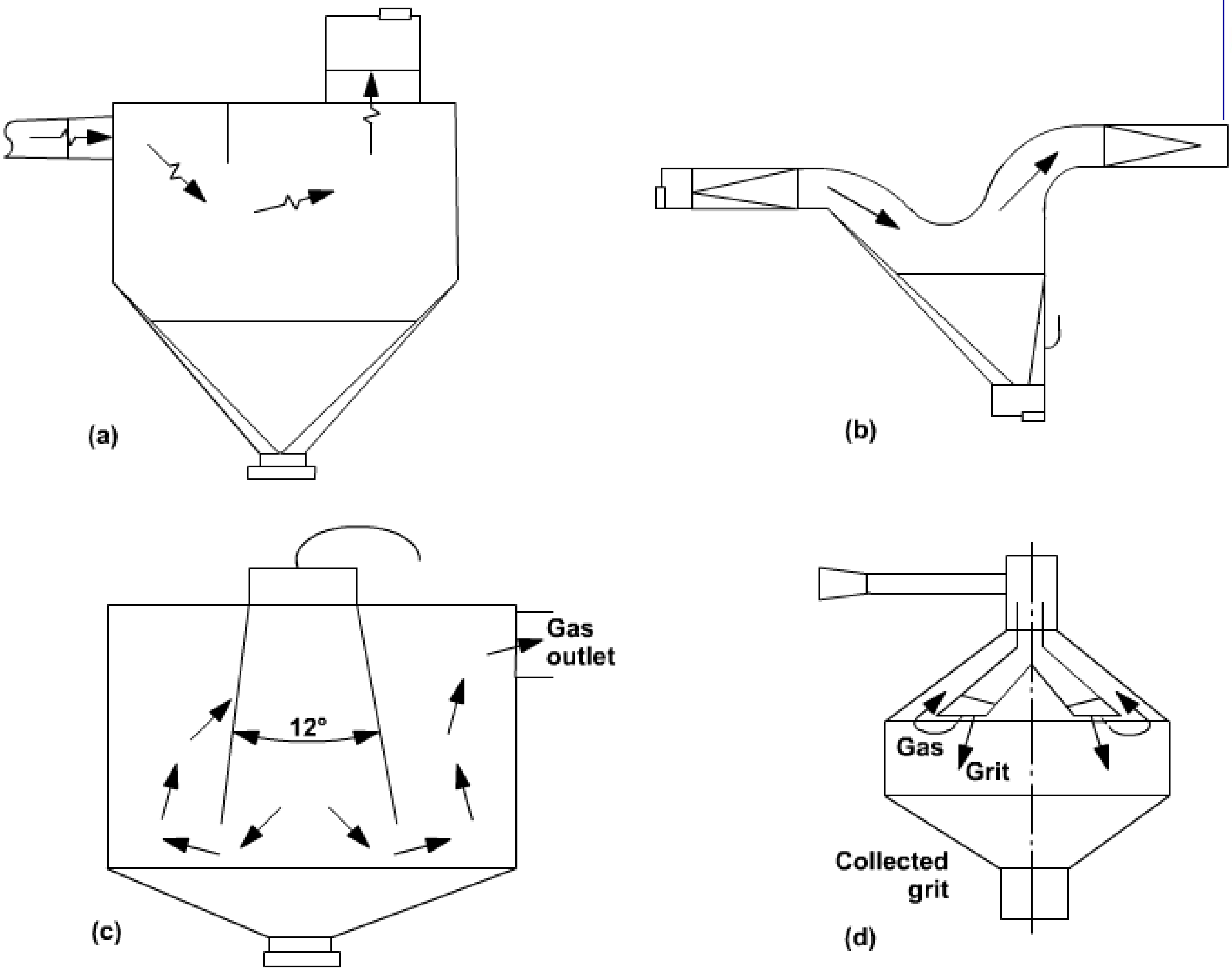
Simple Settling Chamber



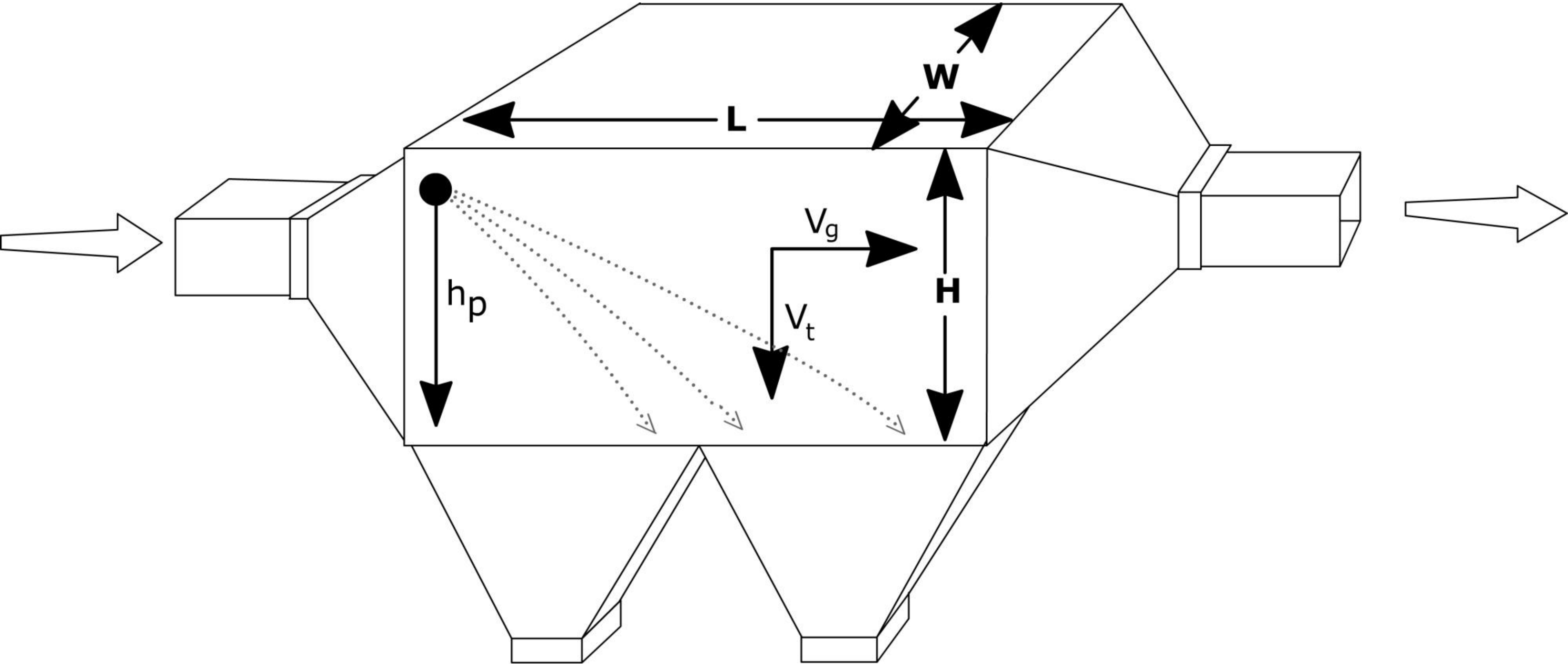
Multi-Tray Settling Chamber
Howard



Momentum Separators



Performance Evaluation



Collection Efficiency

$$\eta_i = 1 - e^{-x}$$

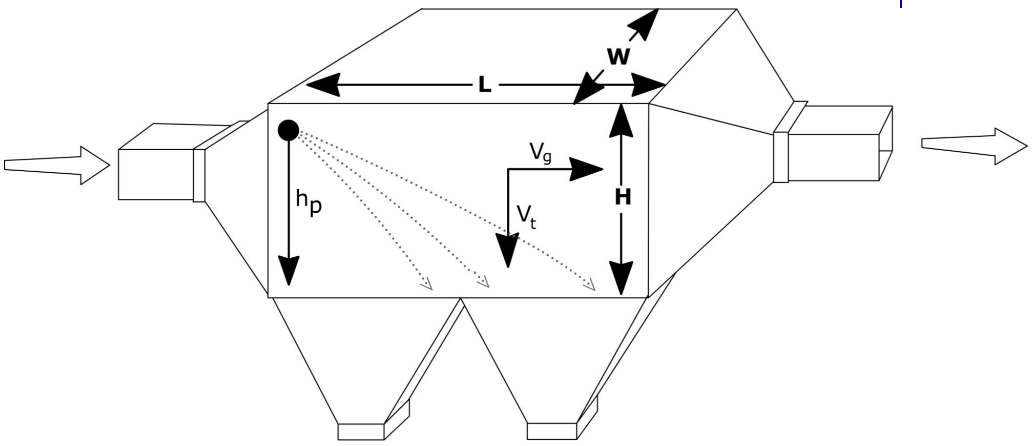
$$x_i = \frac{t_r}{t_s}$$

where

t_r = chamber residence time

t_{si} = particle settling time

$$t_r = \frac{L}{v_g}$$



$$v_g = \frac{Q}{WH}$$

$$t_r = \frac{LWH}{Q}$$

$$t_s = \frac{H}{v_t}$$

Collection Efficiency

$$\eta_i = 1 - e^{-\left(\frac{v_{ti} L W N_c}{Q}\right)}$$

where

v_t = particle terminal settling velocity (ft/sec)
L = chamber length (ft)
Q = gas flow rate (ft^3/sec)
W = chamber width (ft)
N_c = number of passages through chamber

Terminal Settling Velocity

Laminar Regime

$$v_{ti} = \frac{g\, C_c \rho_p d_{p_i}^2}{18\mu_g}$$

Collection Efficiency

Laminar Regime

$$\eta_i = 1 - e^{-\left(\frac{g\rho_p LWN_c}{18\mu_g Q}\right)d_{p_i}^2}$$

Chamber Velocity

Pickup Velocities of Various Materials

Material	Density (g/cm3)	Median Size (mm)	Pickup Velocity (ft/sec)
Aluminum chips	2.72	335	14.2
Asbestos	2.20	261	17.0
Nonferrous foundry dust	3.02	117	18.8
Lead oxide	8.26	15	25.0
Limestone	2.78	71	21.0
Starch	1.27	64	5.8
Steel shot	6.85	96	15.2
Wood chips	1.18	1,370	13.0
Sawdust	---	1,400	22.3

Example 5-1

Estimate the collection efficiency of a 75 μm diameter particle in a simple settling chamber 10 ft wide by 10 ft high by 30 ft long when the gas velocity through the chamber is 5 ft/sec.

Assume a particle density of 120 lb_m/ft^3 and gas stream conditions of 68°F and 1 atm.

Solution

Convert particle size to feet:

$$d_p = 75\mu m\left(\frac{ft}{0.3048x10^6\mu m}\right) = 2.46x10^{-4}\ ft$$

Example 5-2 continued…

Calculate volumetric flow rate:

$$Q = v_g W H = \left(5\,\frac{\text{ft}}{\text{sec}}\right)(10\text{ft})(10\text{ft}) = 500\,\frac{\text{ft}^3}{\text{sec}}$$

Calculate collection efficiency:

$$\eta = 1 - e^{-\left(\frac{g\rho_p L W N_c}{18\mu_g Q}\right) d_p^2} = 1 - e^{-\left[\frac{\left(32.17\frac{\text{ft}}{\text{sec}^2}\right)\left(120\frac{\text{lb}_m}{\text{ft}^3}\right)(30\text{ft})(10\text{ft})(1)}{18\left(1.21\text{x}10^{-5}\frac{\text{lb}_m}{\text{ft}\cdot\text{sec}}\right)\left(500\frac{\text{ft}^3}{\text{sec}}\right)}\right](2.46\text{x}10^{-4}\text{ft})^2} =$$

$$= 0.475 = 47.5\%$$

Advantages and Disadvantages

Advantages:

Low Capital Cost
Very Low Energy Cost
No Moving Parts
Few Maintenance Requirements
Low Operating Costs
Excellent Reliability
Low Pressure Drop
Device Not Subject to Abrasion
Provides Incidental Cooling of Gas Stream
Dry Collection and Disposal

Disadvantages:

Relatively Low PM Collection Efficiencies
Unable to Handle Sticky or Tacky Materials
Large Physical Size
Trays in Multiple-Tray Settling Chamber may Warp

Review Questions

Estimate the collection efficiency of a 50 μm diameter particle in a simple settling chamber 5 meters wide by 2 meters high by 10 meters long when the gas velocity is 0.3 m/sec.

Assume a particle density of 4.6 g/cm^3 and gas stream conditions of 20°C and 1 atm.

Review Solutions

Calculate the volumetric flow rate:

$$Q = v_g W H = \left(0.3\,\frac{m}{sec}\right)(5m)(2m) = 3.0\,\frac{m^3}{sec} = 3.0\times10^6\,\frac{cm^3}{sec}$$

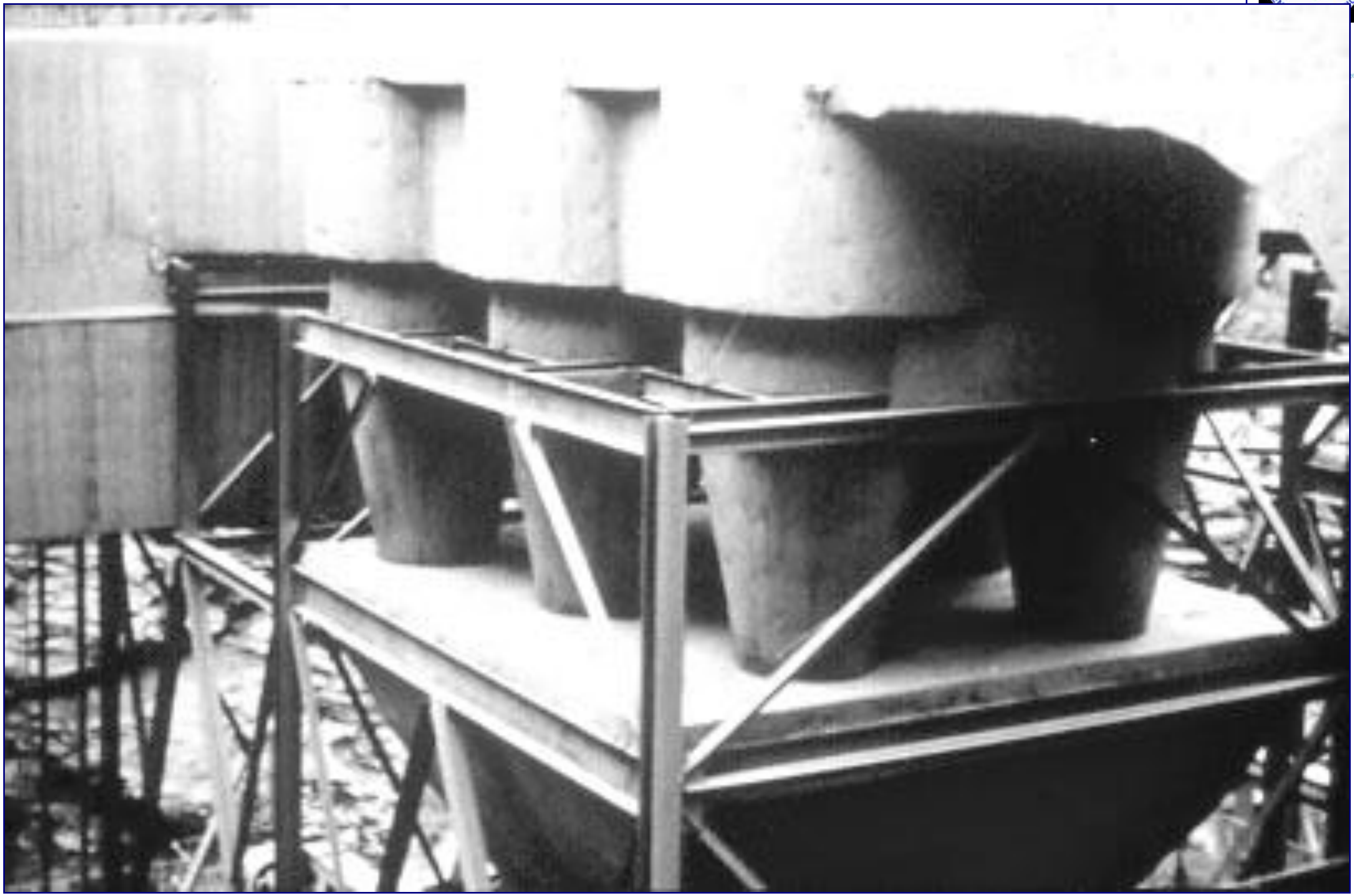
Calculate collection efficiency:

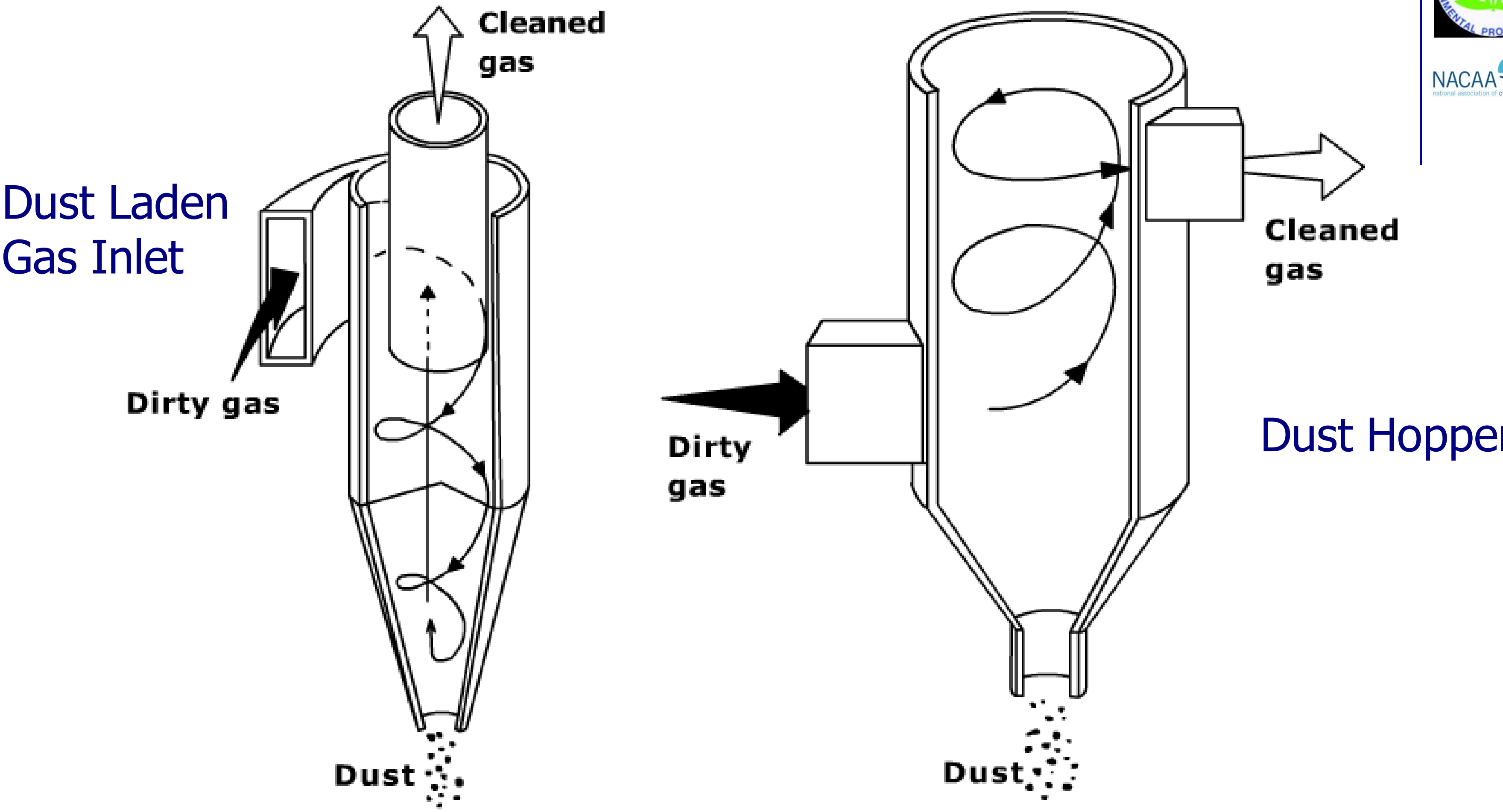
$$\eta = 1 - e^{-\left(\frac{g\rho_p L W N_c}{18\mu_g Q}\right) d_p^2}$$

$$= 1 - e^{-\left[\frac{\left(980\,\frac{cm}{sec^2}\right)\left(120\,\frac{g}{cm^3}\right)(1000cm)(500cm)(1)}{18\left(1.80\times10^{-4}\,\frac{g}{cm\bullet sec}\right)\left(3.0\times10^6\,\frac{cm^3}{sec}\right)}\right](50\times10^{-4}cm)^2} = 0.997 = 99.7\%$$

Chapter 6

Cyclones

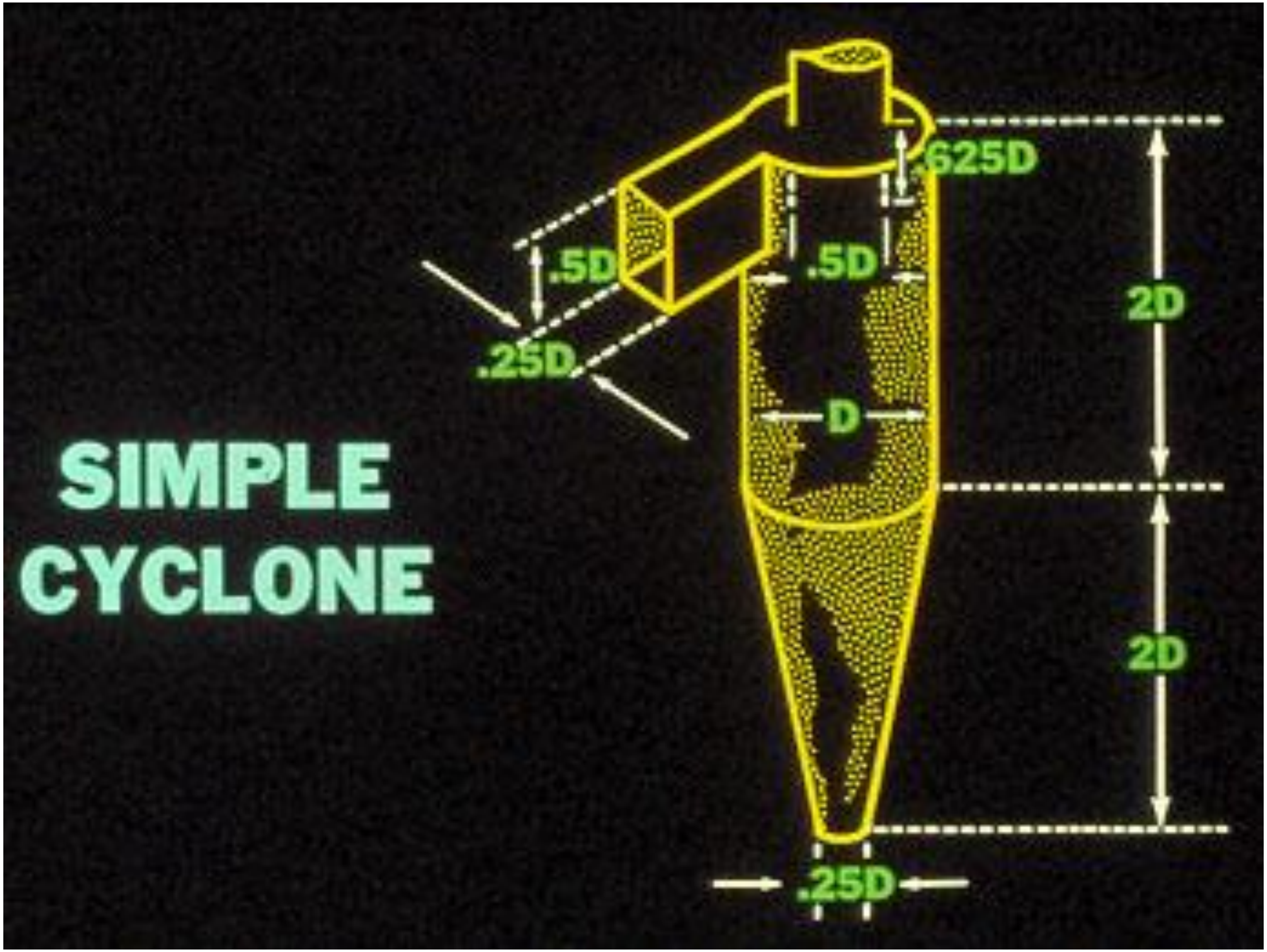




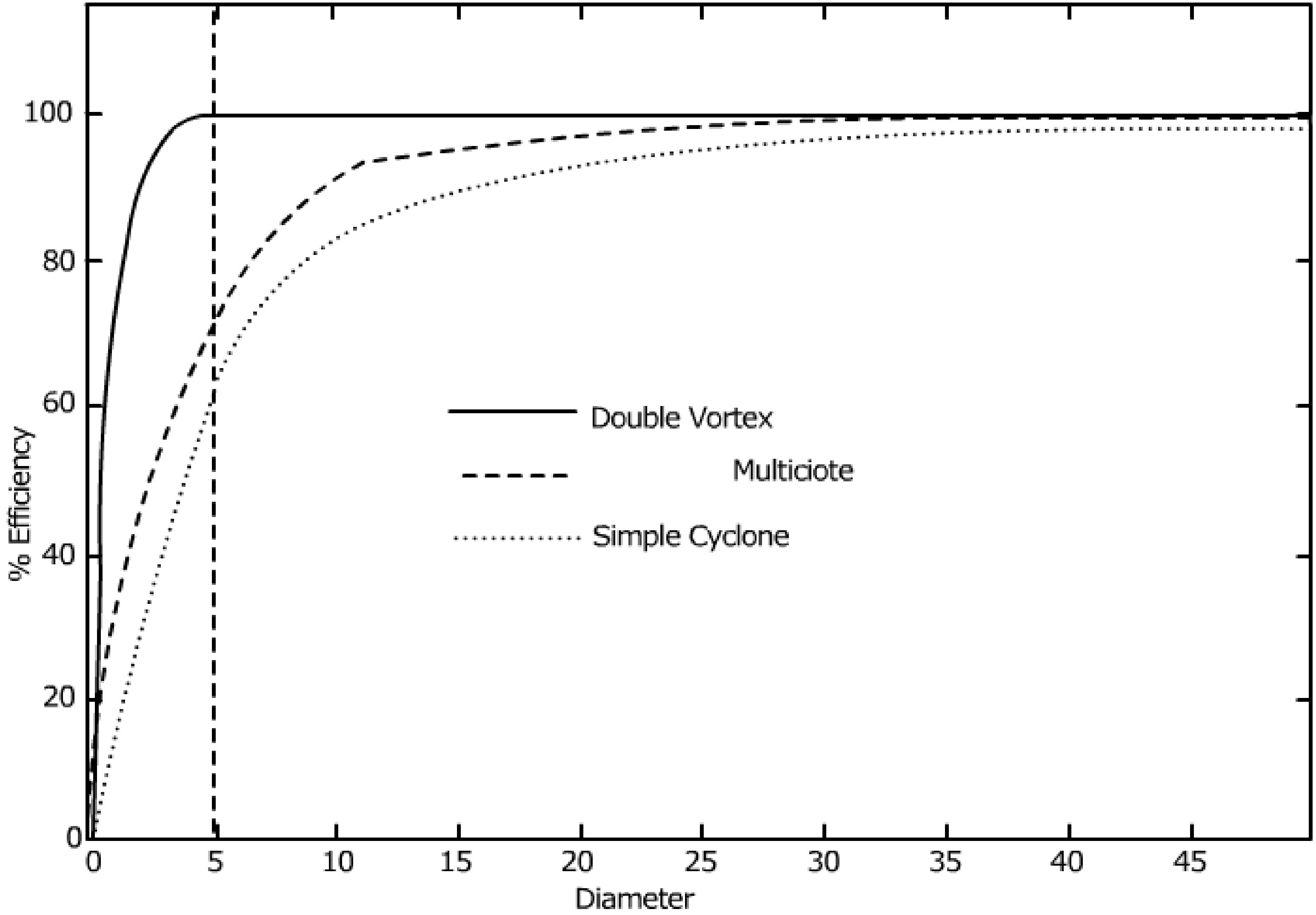
A. Top inlet B. Bottom inlet

Factors Affecting Performance

- Particle diameter: $H = f(d^2)$
- Gas flow rate: $H = f(Q^2)$
- Cyclone diameter
- Residence time

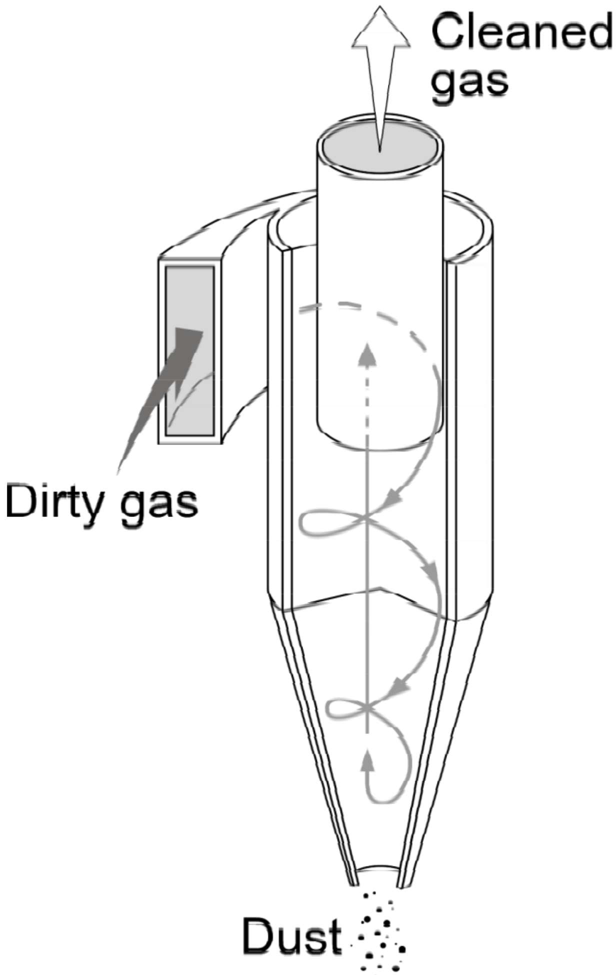

SIMPLE
CYCLONE
.625D
.5D
.5D
.25D
D
2D
2D
.25D

Size Efficiency Curves

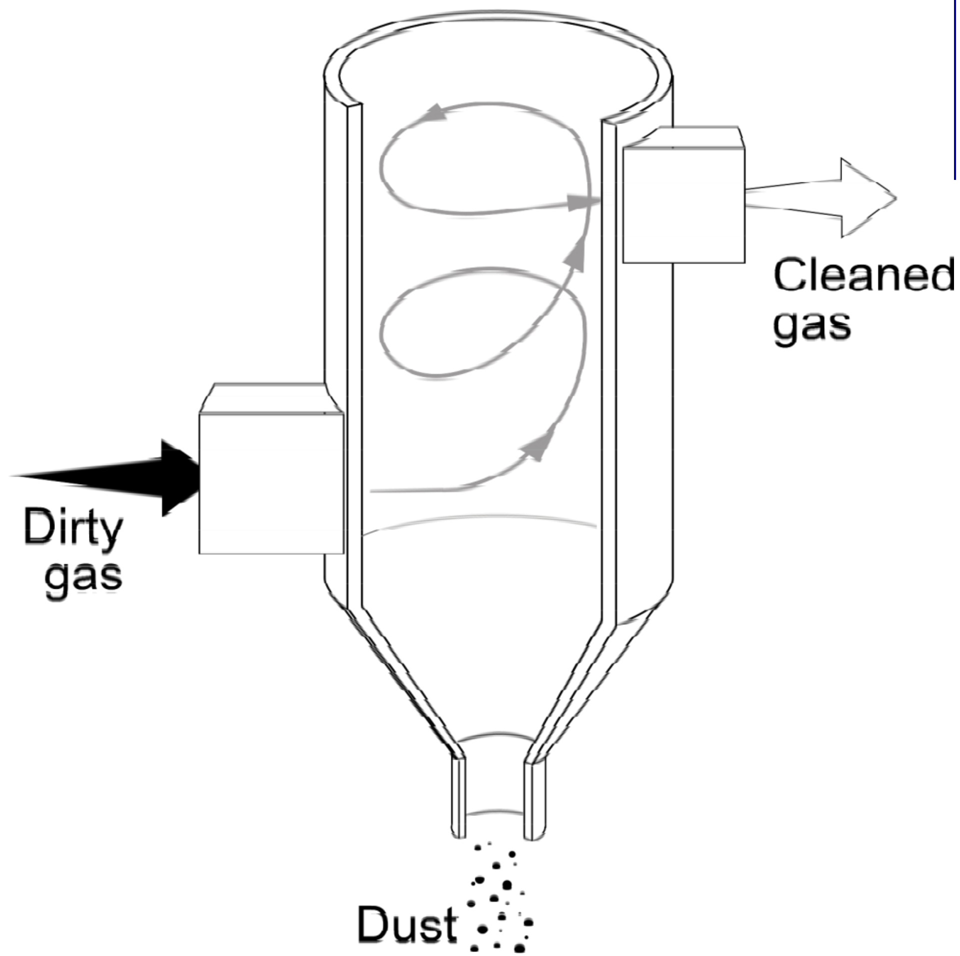


Cyclone Systems

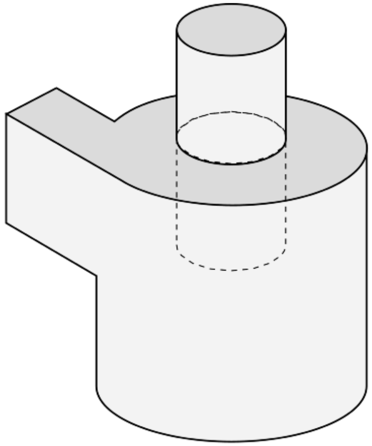
- Large diameter cyclones
- Small diameter multi-cyclones



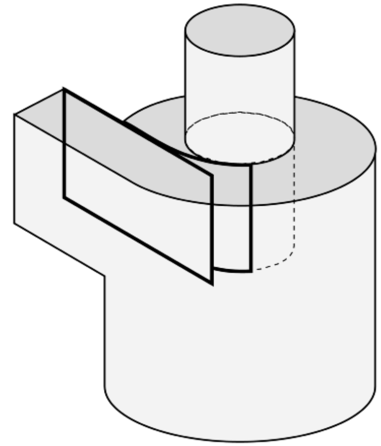
A. Top inlet



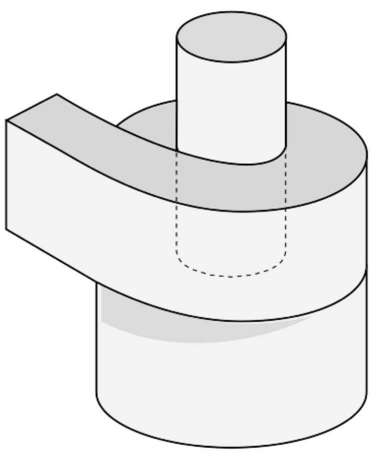
B. Bottom inlet



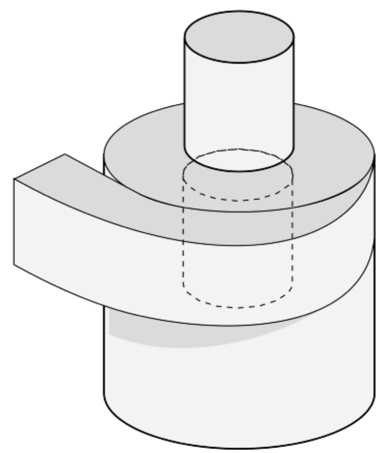
A. Tangential entry



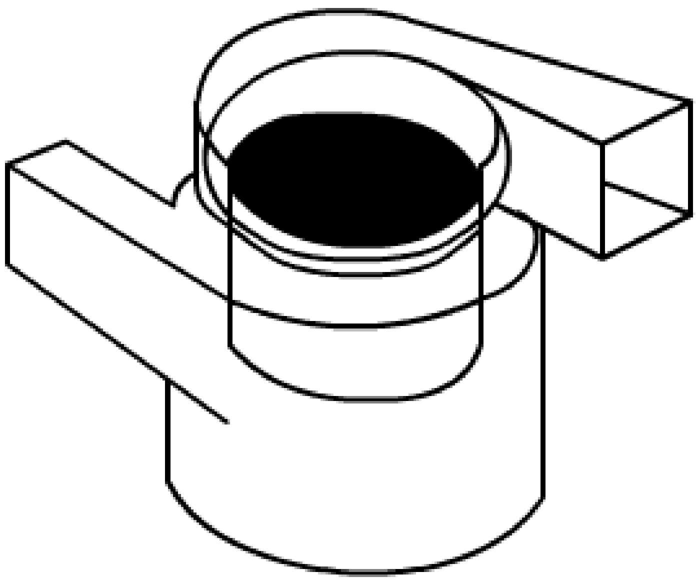
B. Tangential entry
with deflector vanes



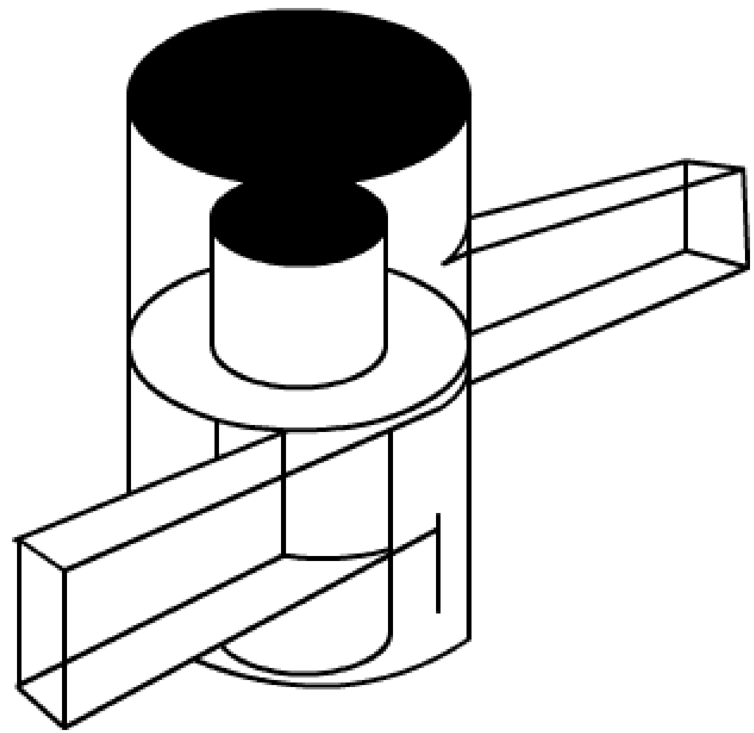
C. Helical entry



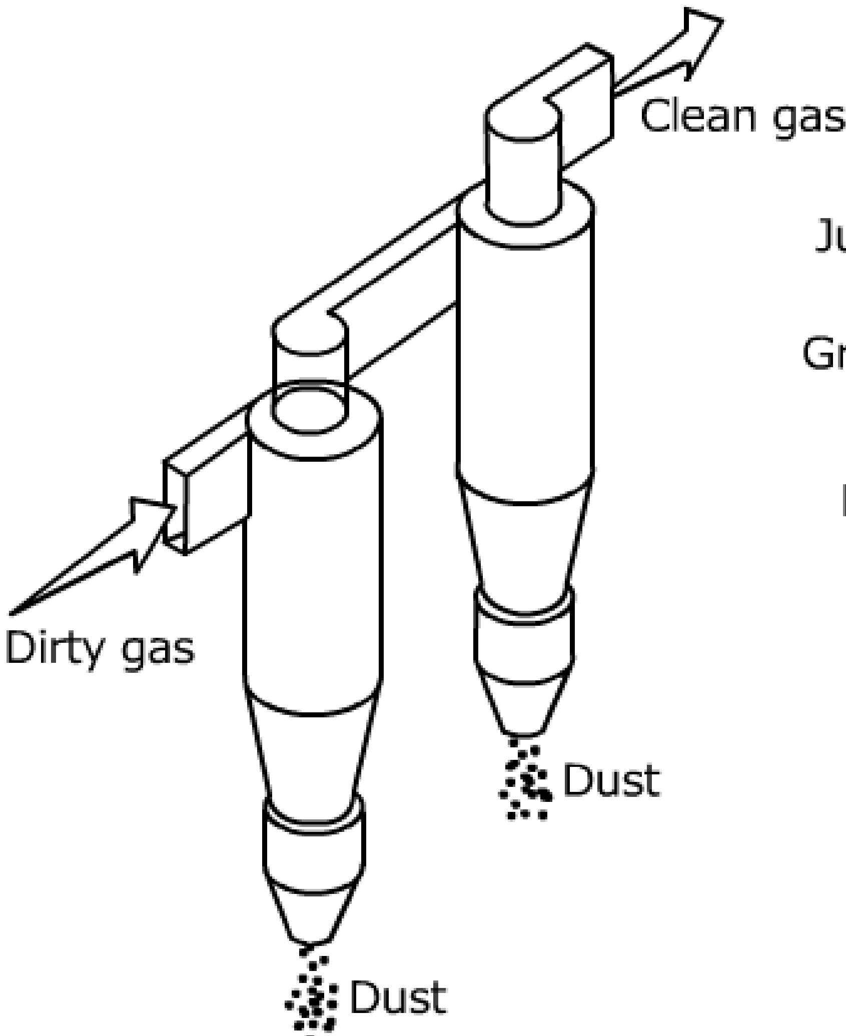
D. Involute entry



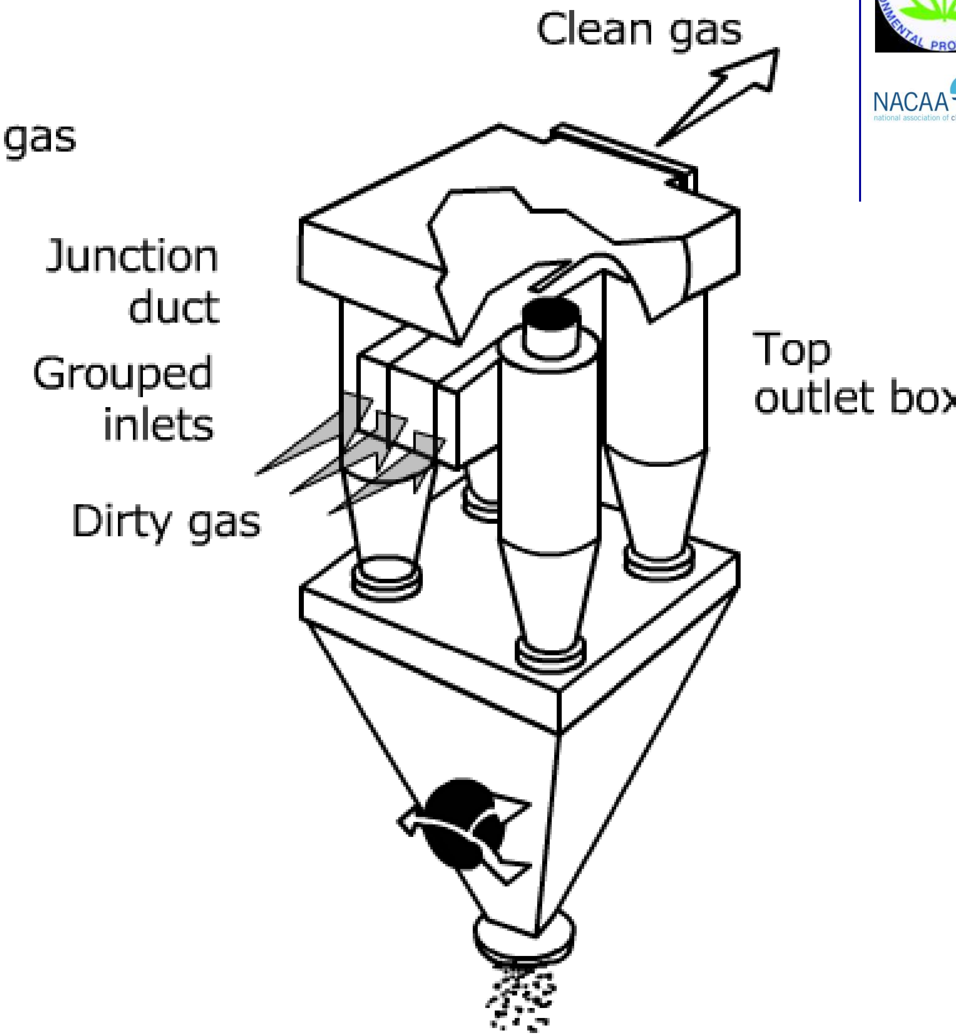
A. Involute scroll outlet



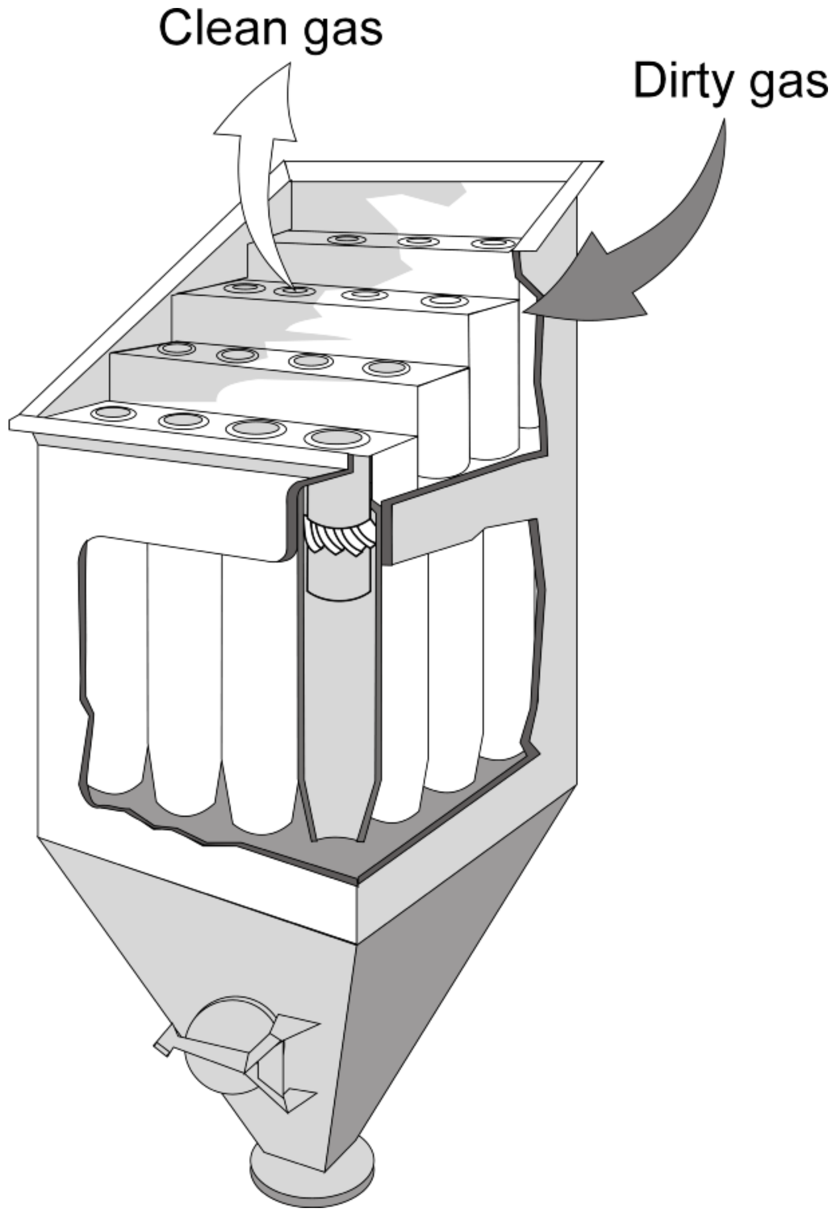
B. Outlet drum

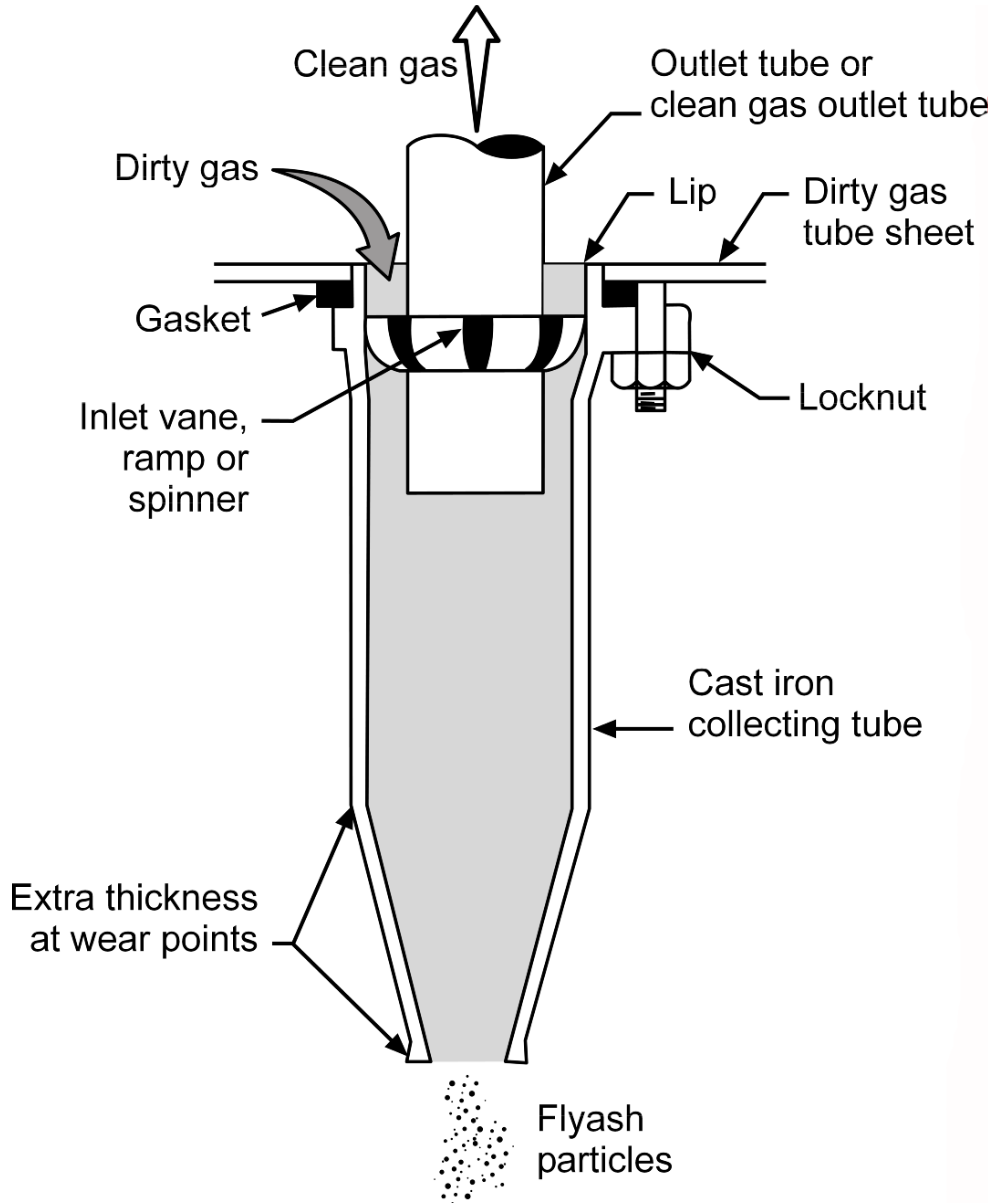


A. two cyclones in series

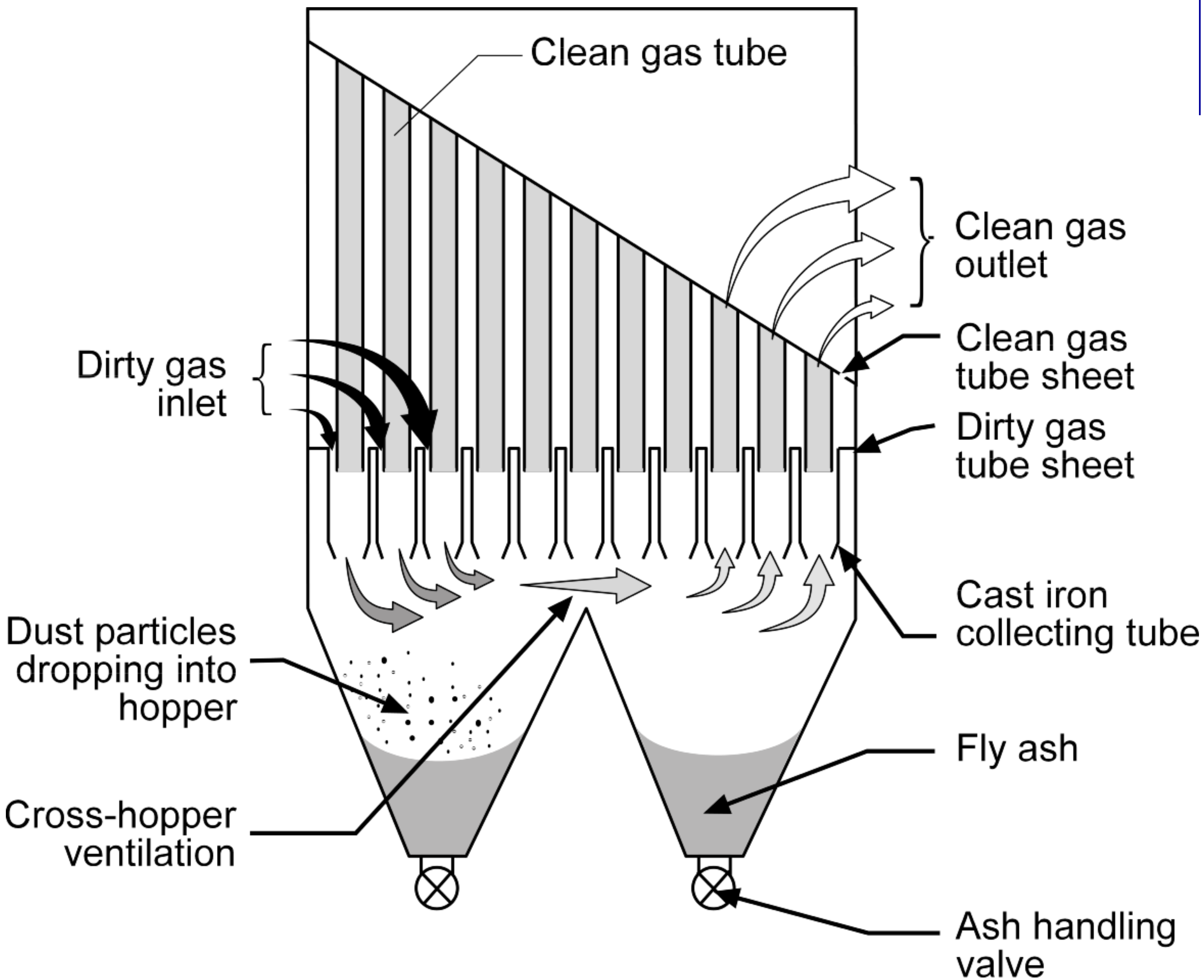


B. Four cyclones in parallel


Clean gas
Dirty gas


Clean gas
Outlet tube or
clean gas outlet tube
Dirty gas
Lip
Dirty gas
tube sheet
Gasket
Locknut
Inlet vane,
ramp or
spinner
Cast iron
collecting tube
Extra thickness
at wear points
Flyash
particles

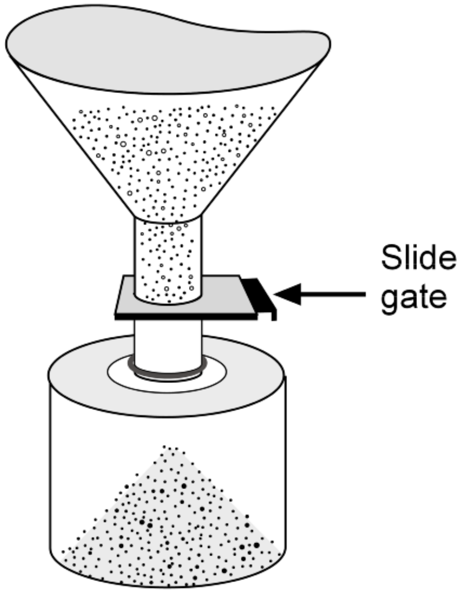
Cross Hopper Recirculation



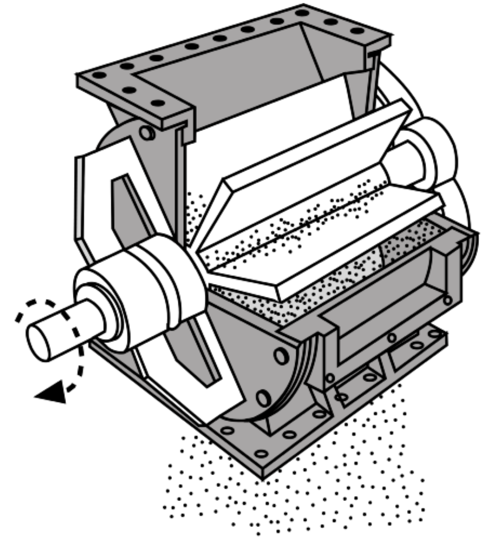
Hopper Design

- Properly sealing solids discharge valve
- Adequately sized hopper throat
- Adequately sloped hopper walls
- Strike plates or vibrators
- Thermal insulation

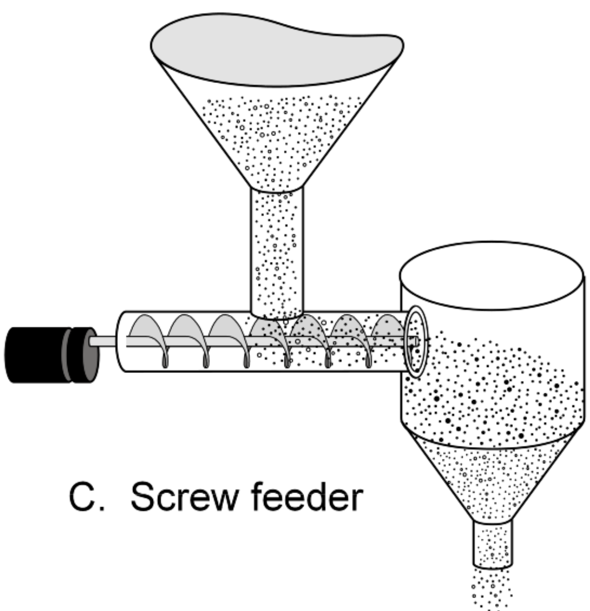
Solids Removal Valves



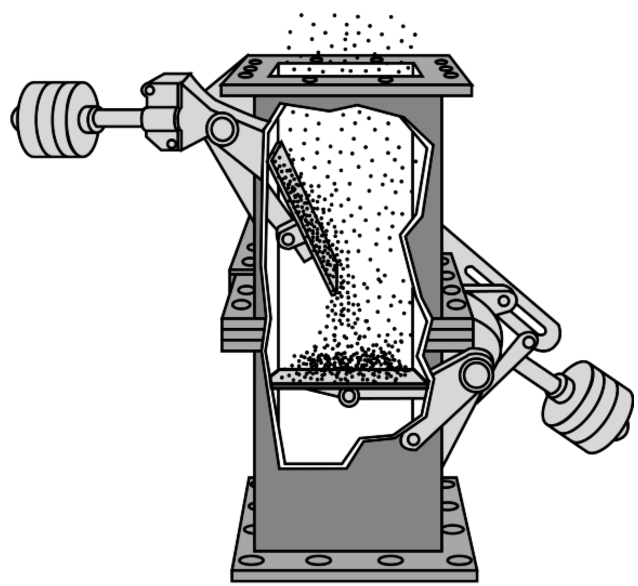
A. Simple manual slide gate



B. Rotary valve



C. Screw feeder



D. Double flap valve

Collection Efficiency

Lapple Technique

$$\left[d_p\right]_{cut} = \sqrt{\frac{9\mu_g B}{2\pi n_t v_i \rho_p}}$$

where

$[d_p]_{cut}$	= cut diameter (ft) (the particle size collected with 50% efficiency)
μ_g	= gas viscosity (lb_m/ft·sec)
v_i	= inlet gas velocity (ft/sec)
ρ_p	= particle density (lb_m/ft^3)
ρ_g	= gas density (lb_m/ft^3)
B_c	= cyclone inlet width (ft)
n_t	= number of turns

$$n_t = \frac{v_i t}{\pi D}$$

$$t = \frac{V_{cyclone} - V_{outlet\,core}}{Q}$$

where

v_i = inlet gas velocity (ft/sec)

t = residence time (sec)

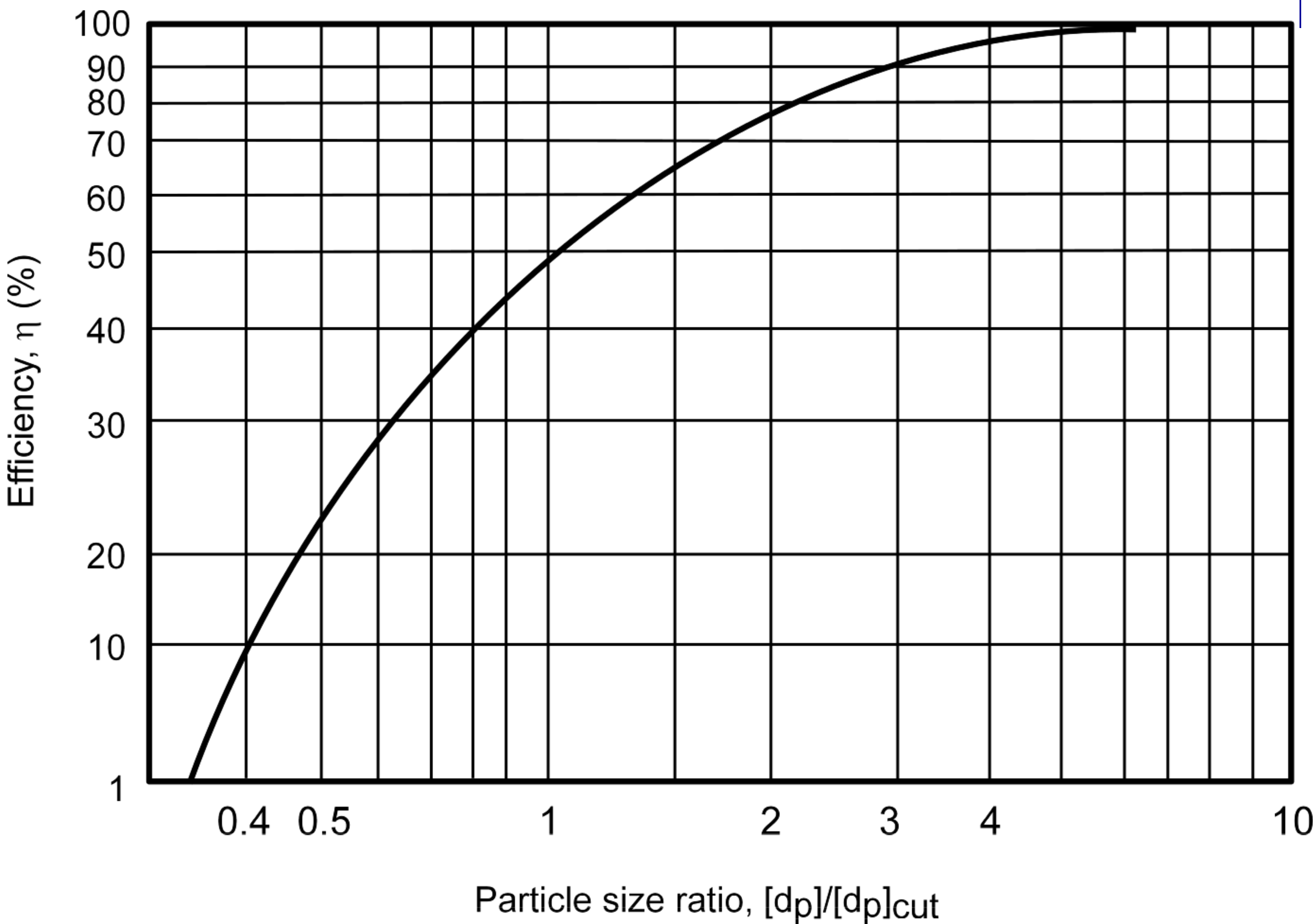
D = cyclone diameter (ft)

$V_{cyclone}$ = total volume of cyclone (ft^3)

$V_{outlet\ core}$ = volume of outlet core (ft^3)

Q = volumetric flow rate (ft^3/sec)

Lapple Efficiency Curve



Example 6-1

A large diameter cyclone is being used for the removal of grain dust in the range of 8 to 100 μm diameter.

What are collection efficiencies over this range if the cyclone has an inlet width of 1 ft, an inlet gas velocity of 50 ft/sec, and an operating temperature of 68°F?

Assume n_t = 1 and a particle density of 80 lb_m/ft^3.

$$[d_p]_{cut} = \sqrt{\frac{9\mu_g B_c}{2\pi\pi(1}} = \sqrt{\frac{9\left(1.21x10^{-5}\ lb_m/_{ft \cdot sec}\right)(1ft)}{2\pi\pi(1\left(50\ ft/_{sec}\right)\left(80\ lb_m/_{ft^3}\right)}} = 6.58x10^{-5}\ ft = 20\mu0$$

Example 6-1 continued…

Estimate efficiency of 8, 12, 20, 30, 50 and 100 μm diameter particles:

Example 6-1 Efficiency Estimates		
$[d_p]_i$ (mm)	$[d_p]_i/[d_p]_{cut}$	hi (%)
8	0.40	9
12	0.60	28
20	1.00	50
30	1.50	65
50	2.50	85
100	5.00	98

Collection Efficiency

Leith Technique

$$\eta_i = 1 - e^{-2(C\Psi)^{\frac{1}{2n+2}}}$$

where

η_i = efficiency for particle diameter i (dimensionless)
C = cyclone dimension factor (dimensionless)
Ψ = cyclone inertial impaction parameter (dimensionless)
n = vortex exponent (dimensionless)

The steps to achieve the answer to the above equation are covered in your text, pages 12 – 15 of Chapter 6.

Pressure Drop

$$\Delta P = 0.003 K_C \rho_g v_i^2 \left(\frac{ab}{D_e^2} \right)$$

where

ΔP = static pressure drop (in WC)

K_C = 16, for tangential inlet; 7.5, for inlet vane (dimensionless)

ρ_g = gas density (lbm/ft^3)

v_i = inlet velocity (ft/sec)

a = cyclone inlet height (ft)

b = cyclone inlet width (ft)

D_e = outlet pipe diameter (ft)

Pressure Drop

$$\Delta P = K_P \rho_g v_g^2$$

where

ΔP = static pressure drop (in WC)

K_P = 0.013 to 0.024 (dimensionless)

ρ_g = gas density (lb_m/ft^3)

v_g = inlet velocity (ft/sec)

Example 6-2

A single high efficiency cyclone has an inlet width of 2 ft, an inlet height of 5 ft and an outlet pipe diameter of 5 ft.

Estimate the pressure drop when the inlet velocity is 50 ft/sec and the gas temperature is 68°F.

Using Equation 6-13:

$$\Delta P = 0.003 K_c \rho_g V_g^2 \left[\frac{ab}{D_e^2} \right]$$

$$= 0.003(16)\left(0.075 \frac{lb_m}{ft^3} \right)\left(50 \frac{ft}{sec} \right)^2 \left[\frac{(5ft)(2ft)}{(5ft)^2} \right] = 3.6 \text{in WC}$$

And also…

Using Equation 6-14:

$$\Delta P = K_p \rho_g V_g^2 = 0.024 \left(0.075 \frac{lb_m}{ft^3}\right)\left(50 \frac{ft}{sec}\right) = 4.5 \text{ in WC}$$

Instrumentation

- Static pressure drop gauges
- Inlet and outlet temperature gauges

Advantages and Disadvantages

Advantages

- Low Capital Cost
- No Moving Parts
- Few Maintenance Problems
- Low Operating Cost
- Relatively Low Pressure Drop
- Dry Collection and Disposal
- Relatively Small Space Requirement

Disadvantages

- Relatively Low PM Collection Efficiencies
- Unable to Handle Sticky Materials
- High Efficiency Units Experience Higher Pressure Drop

Review Questions

1. What is the normal range of inlet gas stream velocity for large diameter cyclones? (page 3)
5 to 10 feet per second
20 to 50 feet per second
5 to 10 feet per minute
20 to 50 feet per minute

2. What is the purpose of using a solids discharge valve on the hoppers of cyclone collectors? Select all that apply. (page 6)
Minimize air infiltration into the cyclone
Minimize the risk of fires
Maintain solids flow out of the hopper

3. What design feature initiates the spinning gas flow in a large diameter cyclone? (page 4)
Turning vanes
Gravity
Tangential gas inlet
None of the above

Review Questions

4. Which type of cyclone collector has higher radial velocities? (page 2)
 Large diameter cyclones
 Multi-cyclones

5. What is the purpose of the clean side tube sheet in a multi-cyclone collector? (page 6)
Support the cyclone tubes
Separate the inlet gas stream from the outlet gas stream
Separate the outlet gas stream from the hopper
None of the above

6. What is the typical number of complete turns (360 degrees) achieved in a large diameter cyclone operating with a normal inlet gas velocity? (page 3)
 One-half to three
 Two to five
 Five to ten
 Greater than ten

Review Questions

7. What is the typical range in the diameters of multi-cyclone tubes? (page 6)
1 to 6 inches
6 to 12 inches
12 to 18 inches
18 to 24 inches

8. Must multi-cyclone tubes be oriented vertically (inlet at top, cyclone discharge at bottom) in order to operate properly? (page 6)
Yes
No

9. Why is it important to fabricate the outlet extension tubes of multi-cyclone collectors from abrasion resistant material? (page 3)
Minimize abrasion caused by the inlet gas stream
Minimize abrasion caused by the outlet gas stream
Minimize fracturing the inlet particulate matter
All of the above

Review Questions

10. The performance of a cyclone collector is related to the __ of the particle diameter.
First power
Second power
Third power
Performance is independent of particle size

11. The performance of a cyclone collector is related to the __ of the gas velocity.
First power
Second power
Third power
Performance is independent of radial gas velocity

12. Static pressure drop across a cyclone collector is related to the __ of the gas flow rate.
First power
Second power
Third power
Static pressure drop is independent of gas flow rate

Review Questions

13. Typical static pressure drops in a multi-cyclone collector are:

1 to 3 in WC
2 to 6 in WC
1 to 3 psig
2 to 6 psig

14. Multi-cyclone collectors are capable of effectively removing particles down to approximately _______ micrometers.

0.5 micrometers
3 micrometers
10 micrometers
20 micrometers
50 micrometers

Review Problem #1

1. What is the overall collection efficiency for a single cyclone collecting dust with the distribution given below?

The collector has a diameter of 1 ft, an inlet gas velocity of 50 ft/sec, and an operating temperature of 200°F?

The particle density is 70 lb_m/ft^3. Assume the gas stream spins two complete rotations within the cyclone. (page 10)

Size (μm)	10	20	30	40	50	60	70	80	100	
% of Mass	1	3	9	13	24	29	15	4	2	100%

Review solution

Solution

Estimate the gas viscosity at 200°F:

$$\mu = \mu_{ref}\left(\frac{T}{T_{ref}}\right)^{0.768} = 1.21x10^{-5}\ \frac{lb_m}{ft \cdot \sec}\left(\frac{660°R}{528°R}\right)^{0.768} = 1.44x10^{-5}\ \frac{lb_m}{ft \cdot \sec}$$

Calculate the cut diameter:

$$\left[d_p\right]_{cut} = \sqrt{\frac{9\mu_g B}{2\pi n_t v_i \rho_p}} = \sqrt{\frac{9\left(1.44x10^{-5}\ \frac{lb_m}{ft \cdot \sec}\right)1\ ft}{2\pi(2)\left(50\ \frac{ft}{\sec}\right)\left(70\ \frac{lb_m}{ft^3}\right)}} = 5.43x10^{-5}\ ft = 16.5\mu m$$

And then…

Calculate the fractional efficiencies:

Problem 6-1 Efficiency Estimates		
$[d_p]_i$ (μm)	$[d_p]_i/[d_p]_{cut}$	η_i (%)
10	0.6	28
20	1.2	55
30	1.8	74
40	2.4	83
50	3.0	90
60	3.6	94
70	4.2	97
80	4.8	98
100	6.1	100

And finally…

Calculate the overall efficiency:

Size (gm)	**% of Mass**	**η_i (%)**	**Mass collected (%)**
10	1	28	0.28
20	3	55	1.65
30	9	74	6.66
40	13	83	10.79
50	24	90	21.60
60	29	94	27.26
70	15	97	14.55
80	4	98	3.92
100	2	100	2.00
	100%		88.71%

Review problem #2

2. A single cyclone collector has the following fractional efficiency curve. Estimate the overall collection efficiency of a dust with a d_{50} of 50 μm and a σ_g of 1.67. (page 10)

Solution…

Plot cumulative distribution plot…

Divide into particle size ranges and determine the percent mass in each size range:

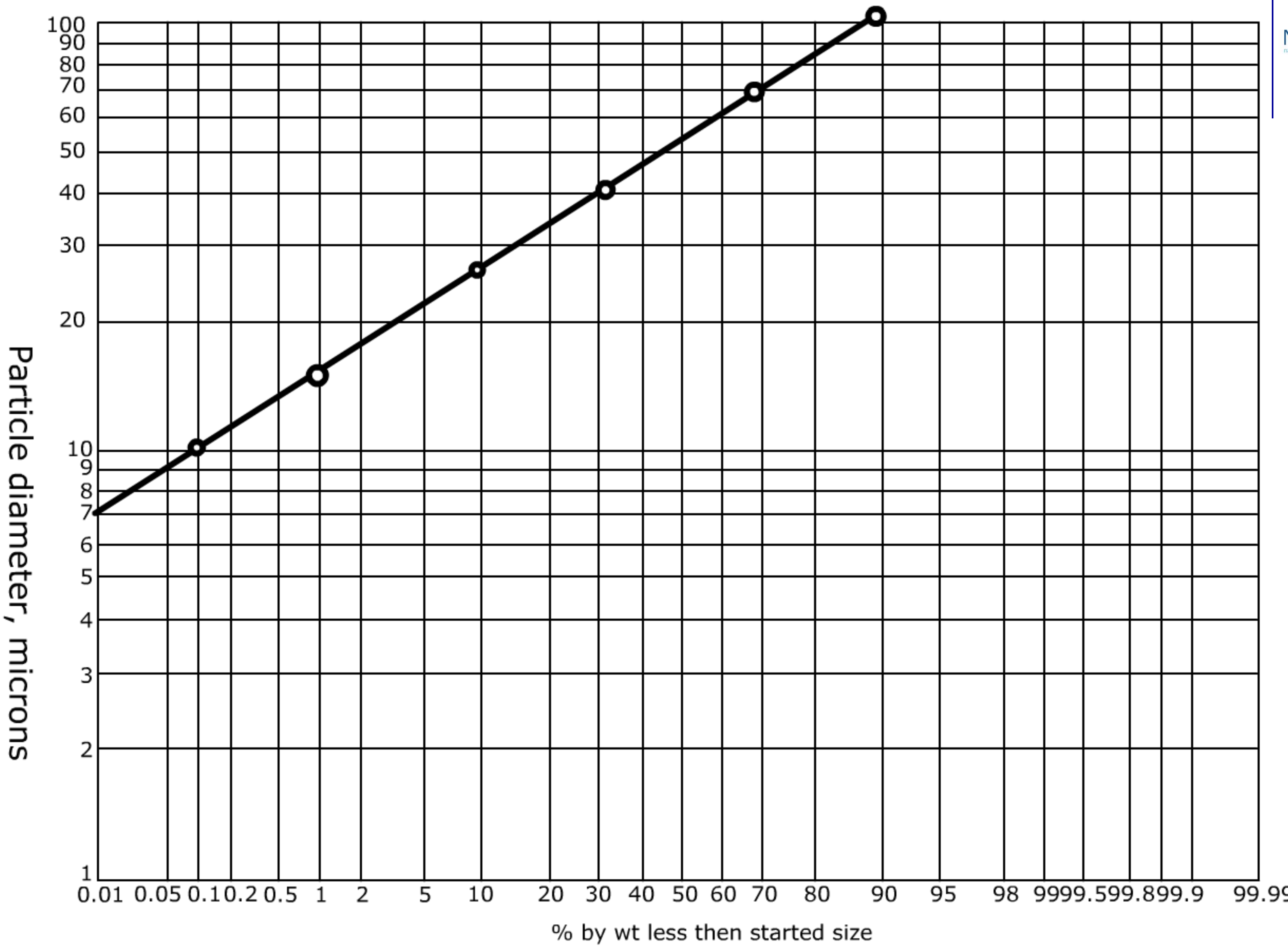
Size (gm)	% of Mass Less Than Size	Size Range (mm)	% of Mass
10	0.1	0 to 10	0.1
15	1.0	10 to 15	0.9
26	10.0	15 to 26	9.0
40	32.0	26 to 40	22.0
67	70.0	40 to 67	38.0
100	90.0	67 to 100	20.0
		>100	10.0

And then…

Calculate the overall efficiency:

Size Range (gm)	Avg Size (gm)	% of Mass	hi (%)	Mass Collected (%)
0 to 10	5.0	0.1	28	0.03
10 to 15	12.5	0.9	52	0.47
15 to 26	20.5	9.0	68	6.12
26 to 40	33.0	22.0	82	18.04
40 to 67	53.5	38.0	93	35.34
67 to 100	83.5	20.0	99	19.80
>100	100.0	10.0	99	9.90
		100%		89.70%

And plot…



100
90
80
70
60
50
40
30
20
10
9
8
7
6
5
4
3
2
1
Particle diameter, microns
0.01 0.05 0.1 0.2 0.5 1 2 5 10 20 30 40 50 60 70 80 90 95 98 99 99.5 99.8 99.9 99.99
% by wt less then started size

Chapter 7

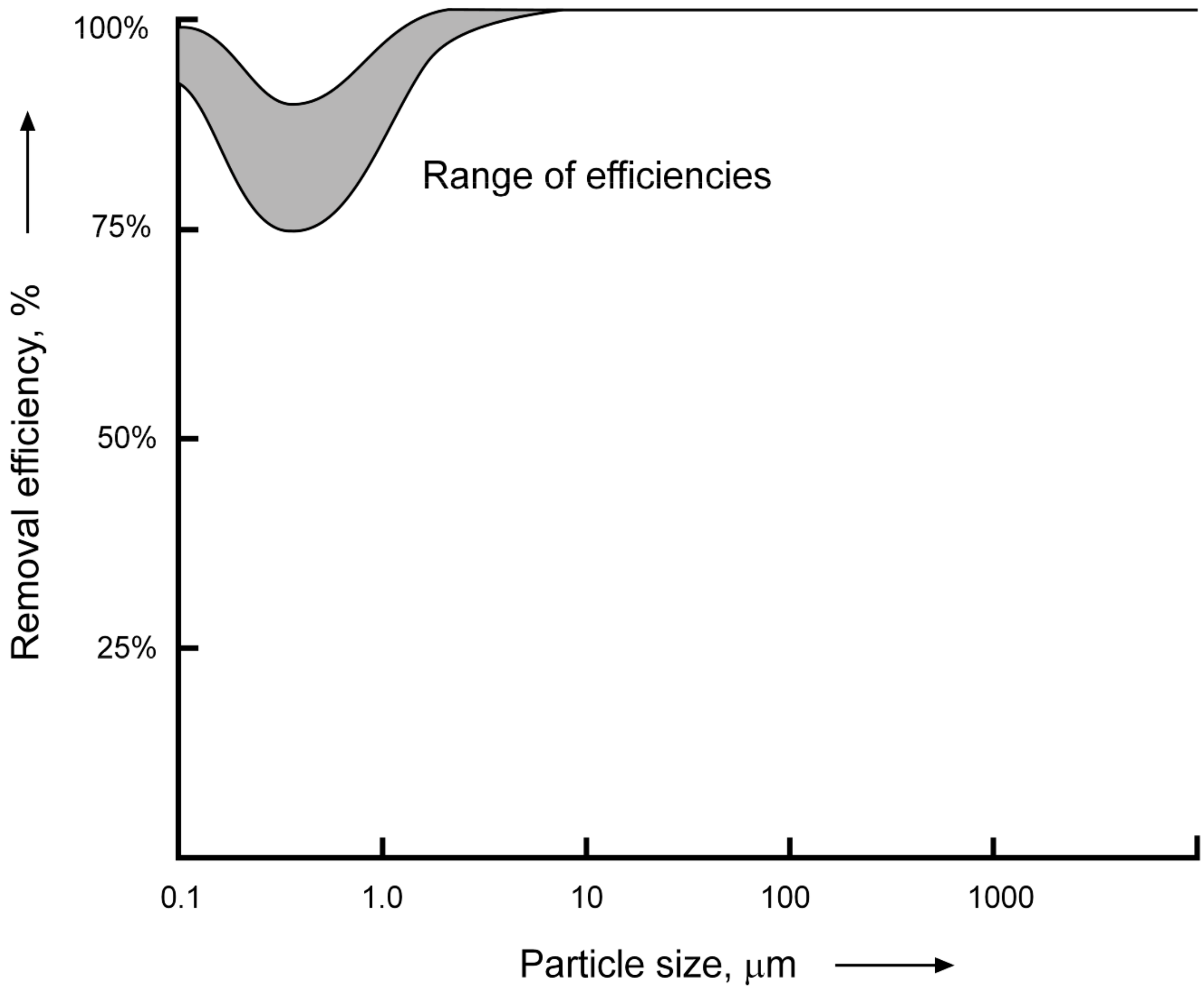
Fabric Filters

Particle Collection Steps

- Capture particulate matter using a filtration media
- Remove collected material from the filter surface
- Dispose of accumulated solids

Capture Mechanisms

- Inertial impaction
- Brownian motion
- Electrostatic attraction
- Gravitational settling
- Sieving

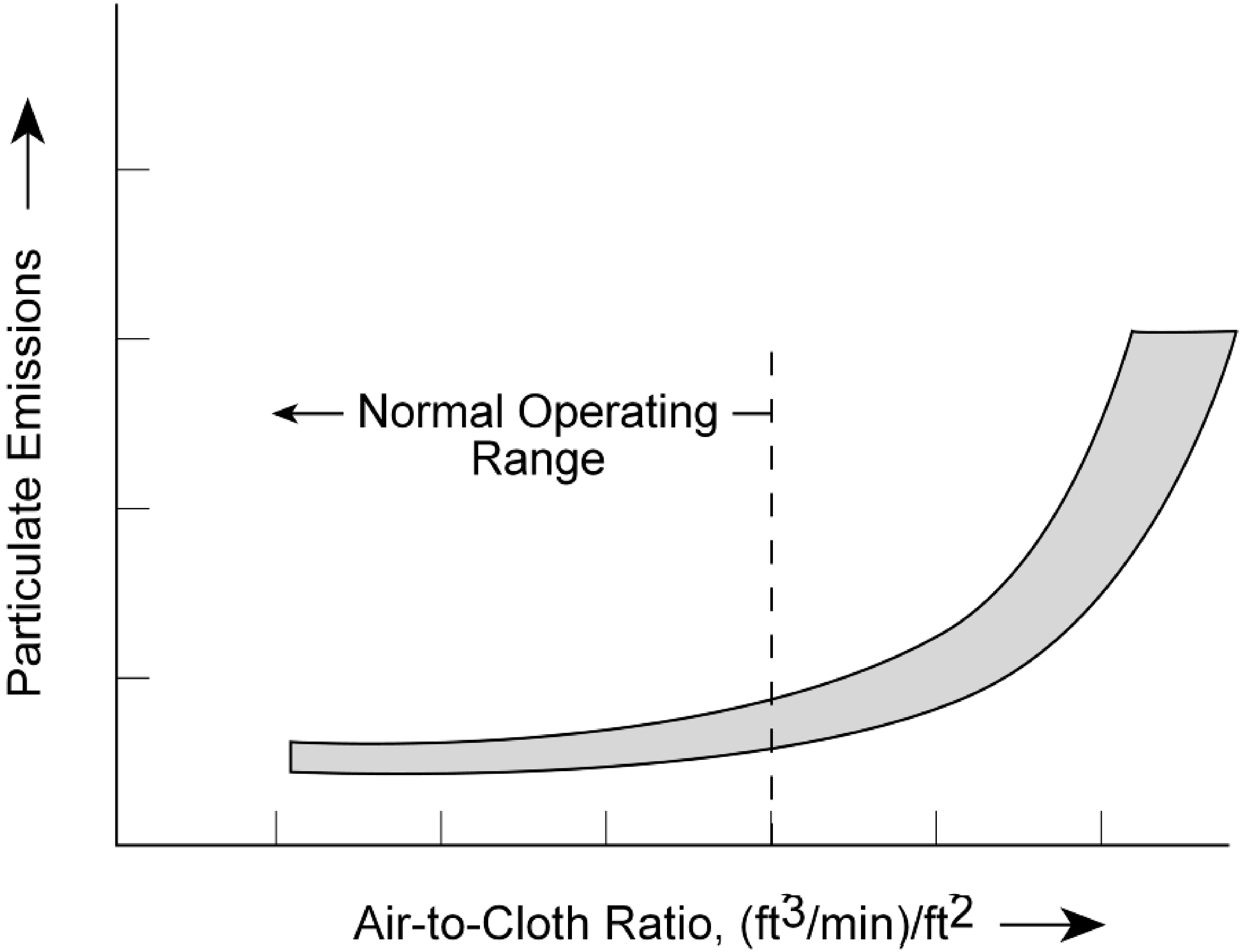

100%
75%
50%
25%
Removal efficiency, %
Range of efficiencies
0.1
1.0
10
100
1000
Particle size, μm

Factors Affecting Efficiency

- Air-to-cloth ratio
- Holes, tears and gaps
- Blinding and bag blockage

Air-to-Cloth Ratio

$$\text{A / C Ratio}\left(\frac{\text{ft}}{\text{min}}\right) = \frac{\text{Actual Gas Flow Rate}\left(\frac{\text{ft}^3}{\text{min}}\right)}{\text{Fabric Surface Area}\left(\text{ft}^2\right)}$$



Particulate Emissions
Normal Operating Range
Air-to-Cloth Ratio, (ft3/min)/ft2

Air-to-Cloth Ratios in Various Industrial Categories

Industry	Reverse Air	Pulse Jet
Basic Oxygen Furnaces	1.5 – 2.0	6 – 8
Brick Manufacturers	1.5 – 2.0	9 – 10
Coal-Fired Boilers	1.0 – 1.5	3 – 5
Electric Arcs	1.5 – 2.0	6 – 8
Feed Mills	-	10 – 15
Grey Iron Foundries	1.5 – 2.0	7 – 8
Lime Kilns	1.5 – 2.0	8 – 9
Municipal Incinerators	1.0 – 2.0	2.5 – 4.0
Phosphate Fertilizer	1.8 – 2.0	8 – 9
Portland Cement	1.2 – 1.5	7 - 10

Example 7-1

Calculate the gross and net air-to-cloth ratios for a reverse air baghouse with 20 compartments, 360 bags per compartment, a bag length of 30 ft, and a bag diameter of 11 inches.

Use an actual gas flow rate of 1.2 × 106 ft^3/min.

Assume that two compartments are out of service when calculating the net air-to-cloth ratio

Solution

Bag area = πDL

Area/bag = π (11 inches)(ft/12 in.) 30 ft =

86.35 ft^2/bag

The gross air-to-cloth ratio is calculated assuming that all the bags are in service.

Total number of bags =

(360 bags/compartment)(20 compartments) =

7,200 bags

Total fabric area = (7,200 bags)(86.35 ft^2/bag) =

621,720 ft^2

Solution (continued)

$$(A/C)_{gross} = \frac{1.2\,x10^6\ ft^3/min}{621{,}720\,ft^2} = 1.93\ (ft^3/min)/ft^2$$

The net air-to-cloth ratio is calculated by subtracting the compartments that are not in filtering service.

Total number of bags =
(360 bags/compartment)(18 compartments) = 6,480 bags

Total fabric area = (6,480 bags)(86.35 ft^2/bag) = 559,548 ft^2

$$(A/C)_{net} = \frac{1.2\,x10^6\ ft^3/min}{559{,}548\,ft^2} = 2.14\ (ft^3/min)/ft^2$$

Factors Affecting Efficiency

- Air-to-cloth ratio
- Holes, tears and gaps
- Blinding and bag blockage

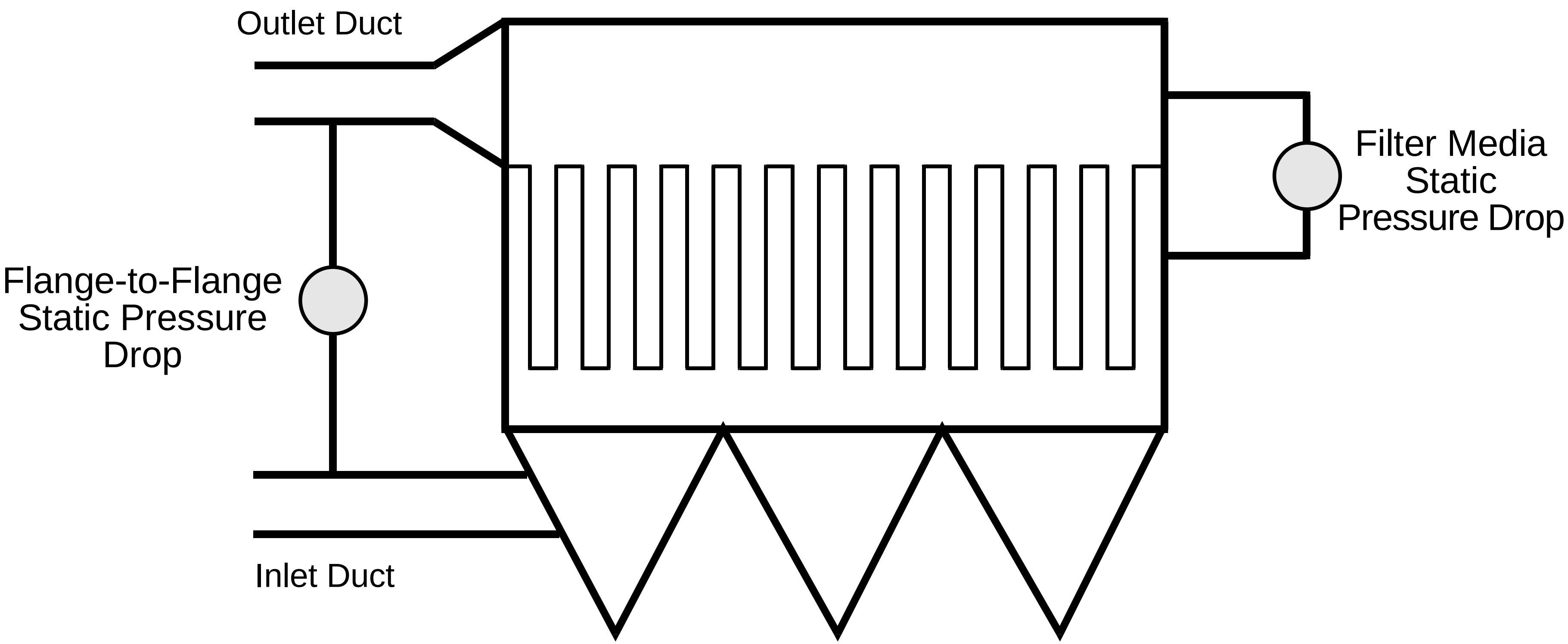
Factors Affecting Efficiency

- Air-to-cloth ratio
- Holes, tears and gaps
- Blinding and bag blockage
  - Water
  - Lubricating oil
  - Condensed organic
  - Submicrometer particles

Applicability Limitations

- Blinding
- Large particle abrasion
- Fire or explosion
- Gas temperature

Static Pressure Drop



Pressure Drop Modeling

$$\Delta P_t = \Delta P_f + \Delta P_c$$

where

ΔP_t = total pressure drop

ΔP_f = fabric pressure drop

ΔP_c = dust cake pressure drop

Fabric Pressure Drop

$$\Delta P_f = K_1 v_f$$

where

K_1 = fabric resistance factor

v_f = filtration velocity

Dust Cake Pressure Drop

$$\Delta P_c = K_2 c_i v_f^2 t$$

where

K_2 = dust cake resistance factor

c_i = inlet dust concentration

v_f = filtration velocity

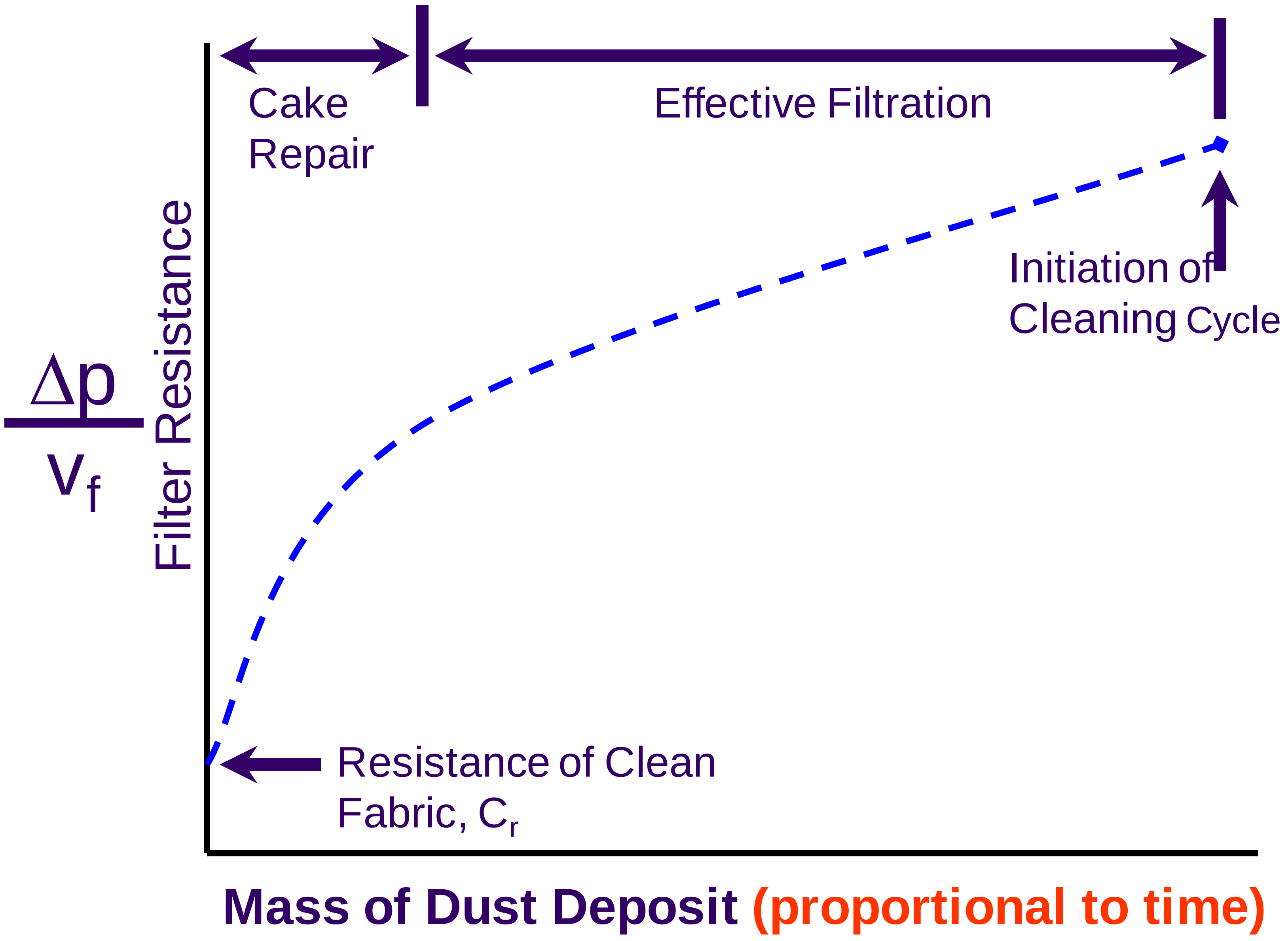
t = time

Total Pressure Drop

$$\Delta P_t = K_1 v_f + K_2 c_i v_f^2 t$$

$$S = \Delta P_t / v_f = K_1 + K_2 c_i v_f t$$

where S = filter drag



Cake Repair
Effective Filtration
Initiation of Cleaning Cycle
Filter Resistance
$\frac{\Delta p}{v_f}$
Resistance of Clean Fabric, C_r
Mass of Dust Deposit (proportional to time)

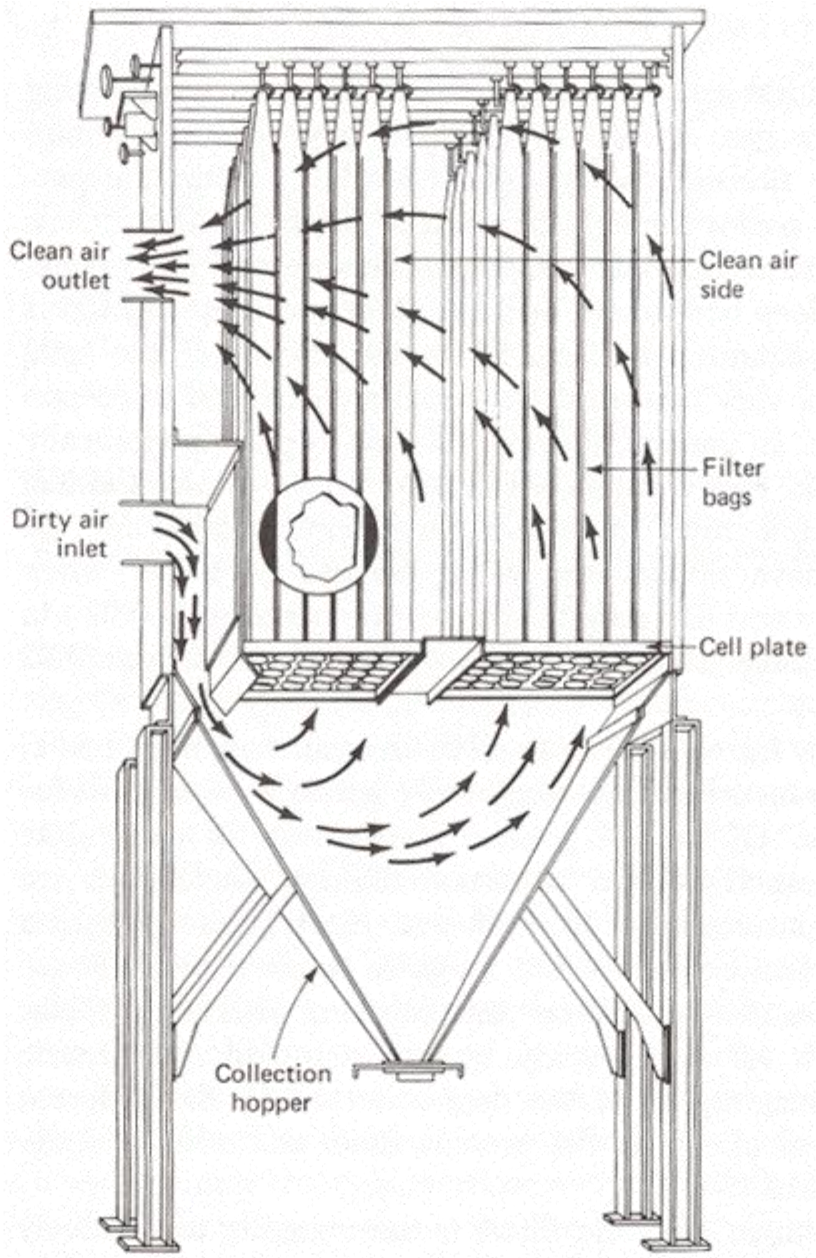
Cleaning Method

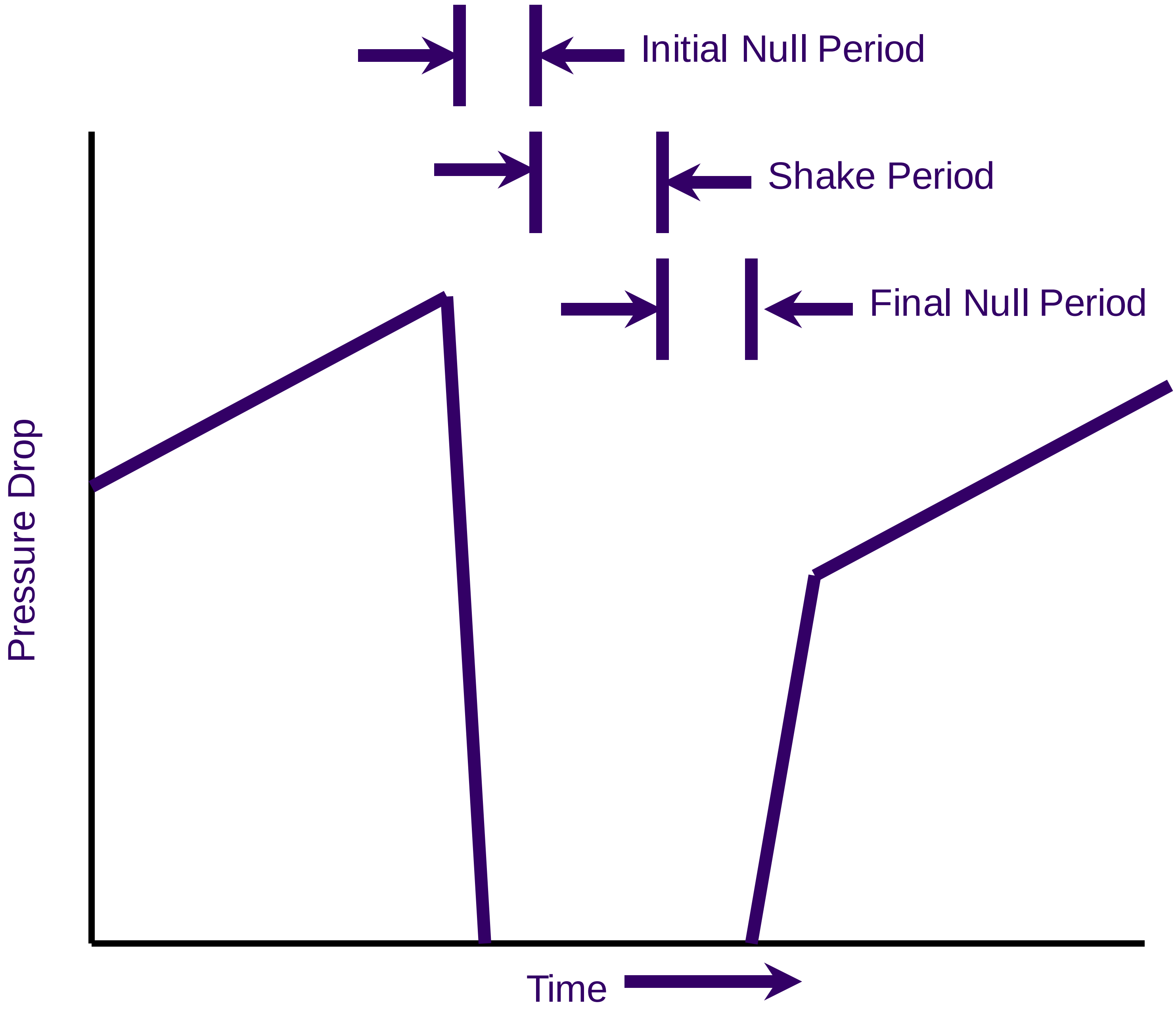
- Shaker
- Reverse air
- Pulse jet

Operating Mode

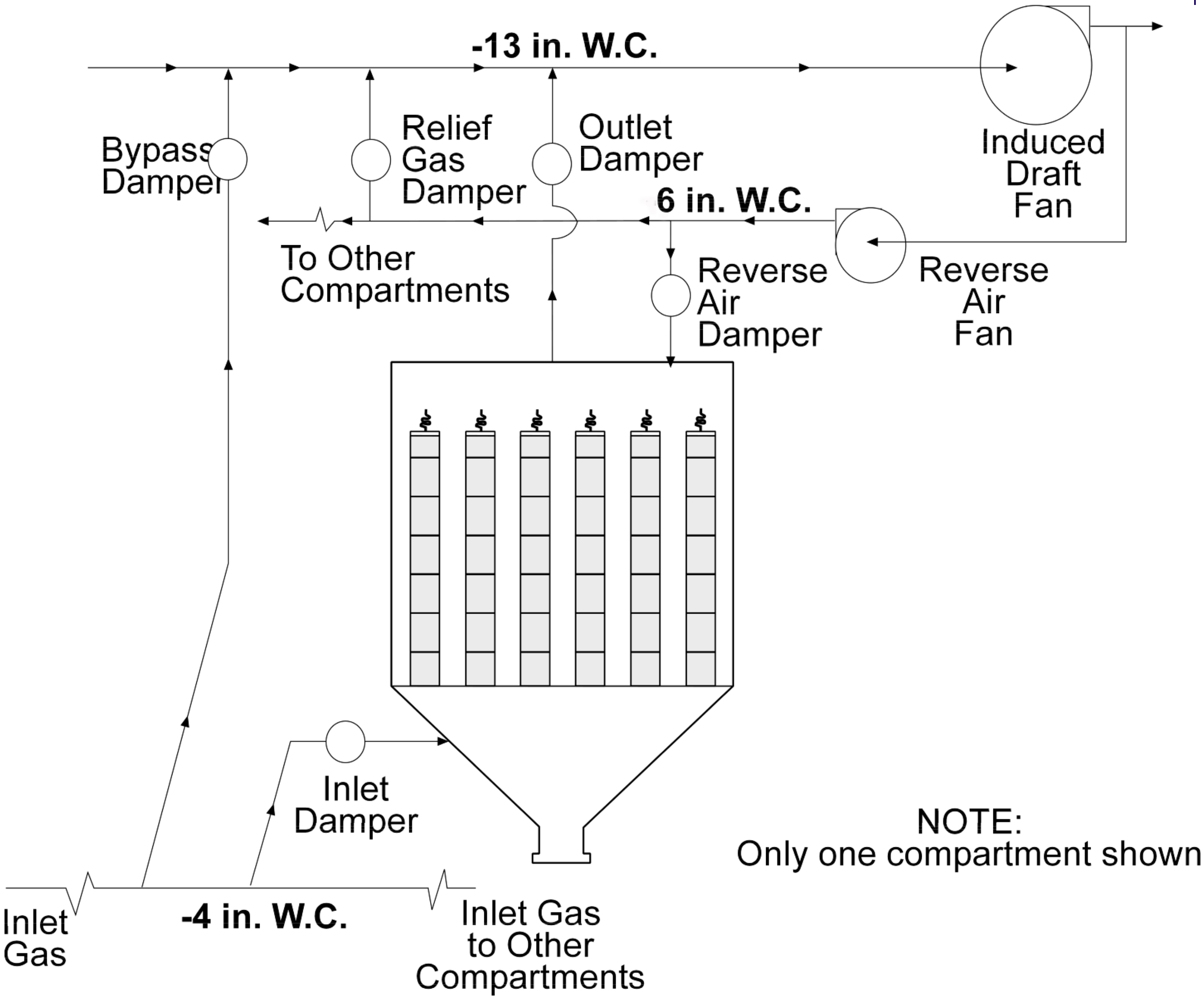
- Intermittent
- Periodic
- Continuous

Shaker Fabric Filter

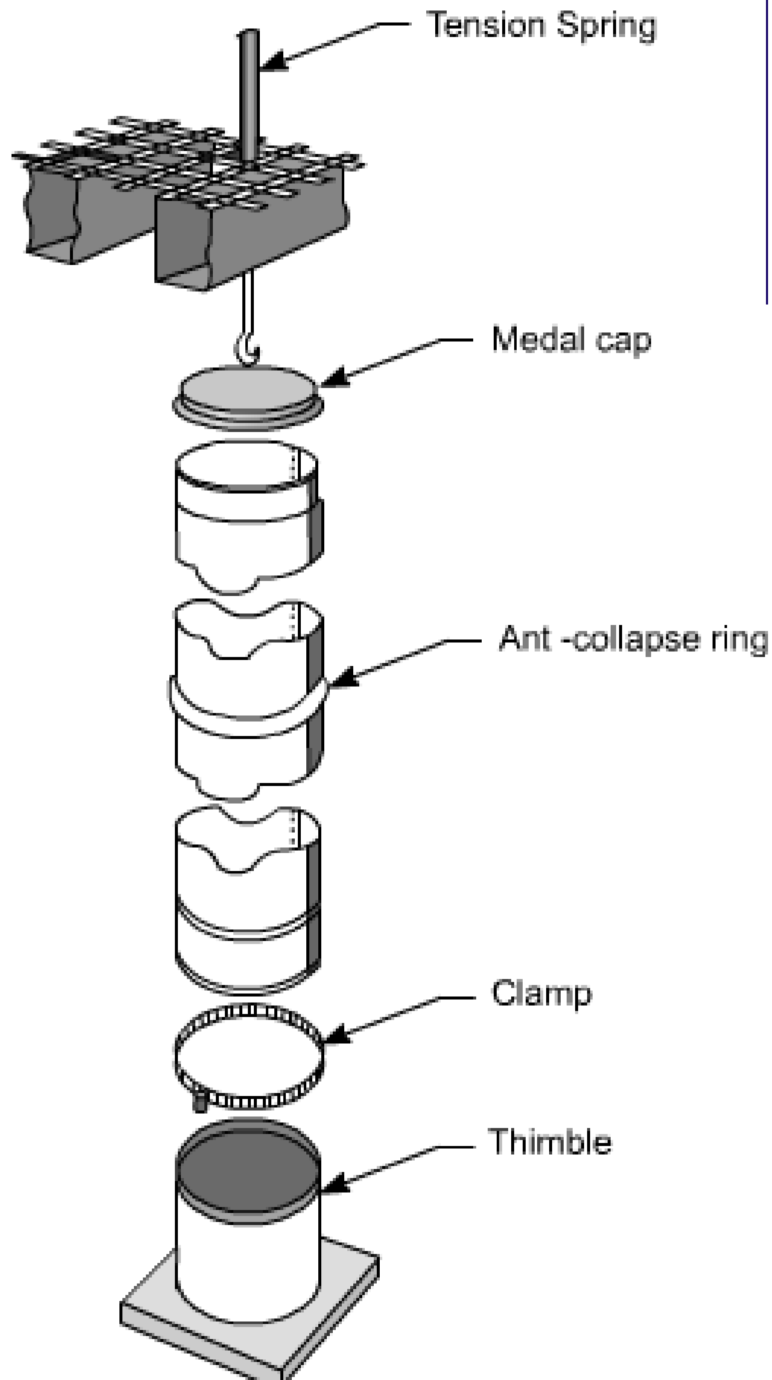


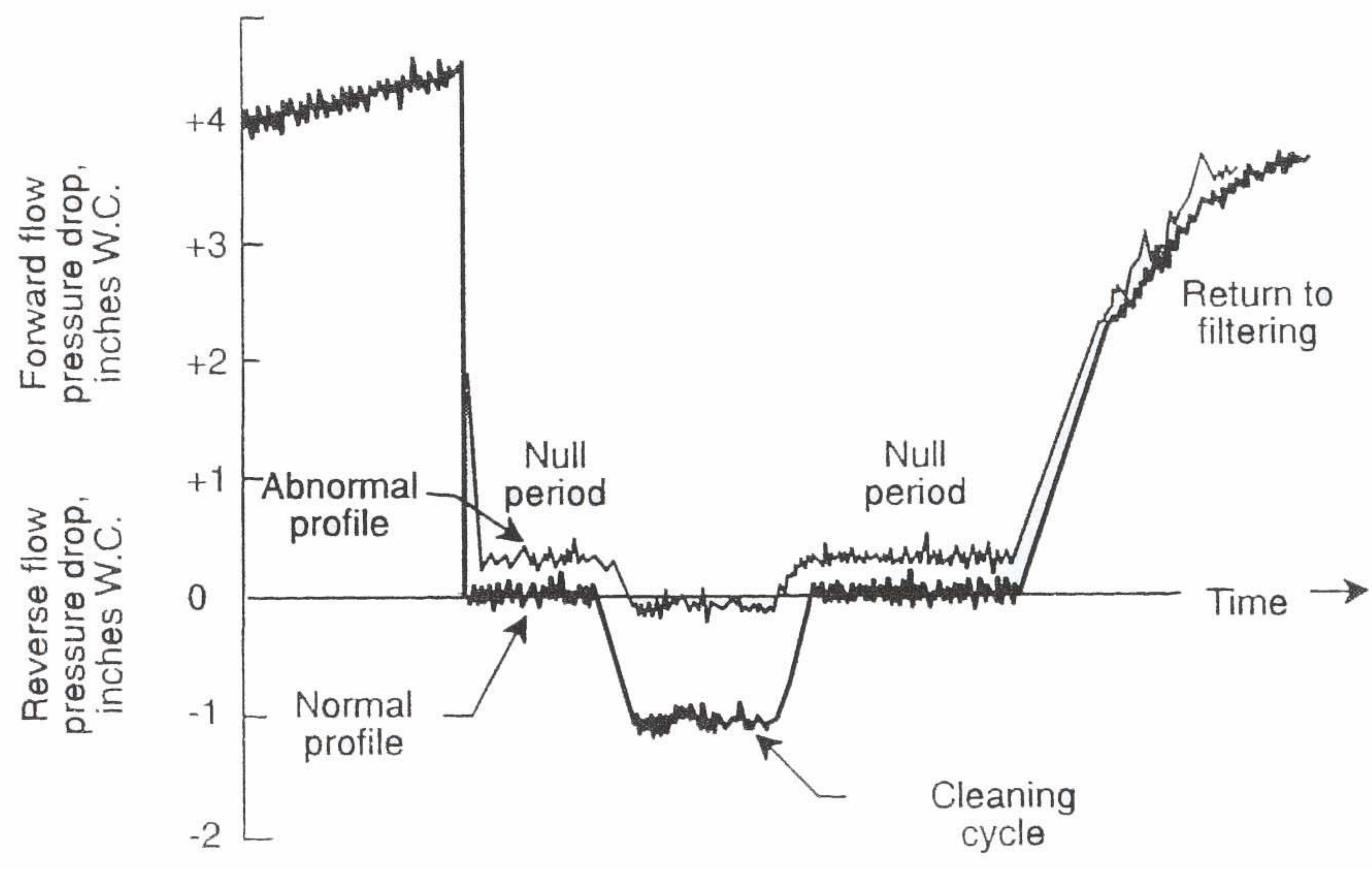

Initial Null Period
Shake Period
Final Null Period
Pressure Drop
Time

Reverse Air Fabric Filter



Bag Attachment

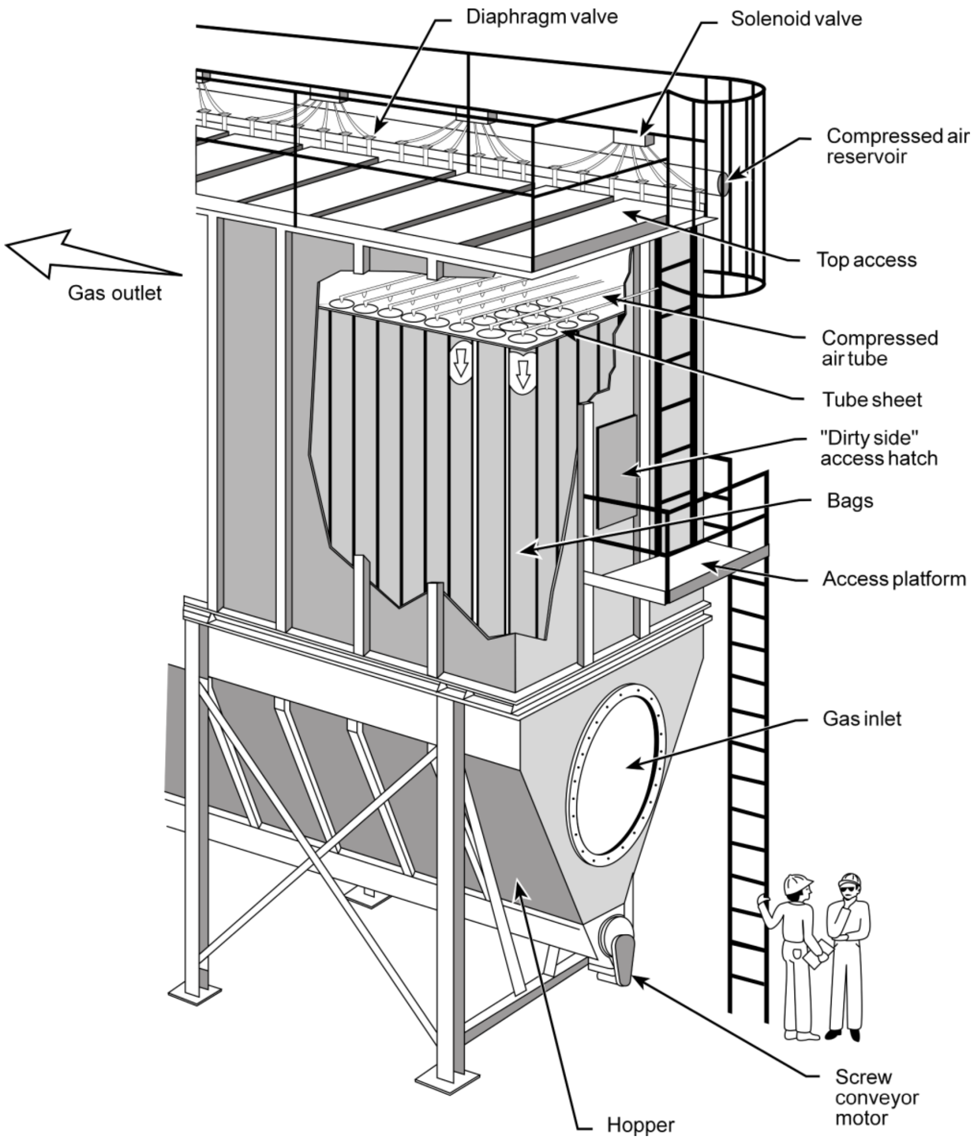


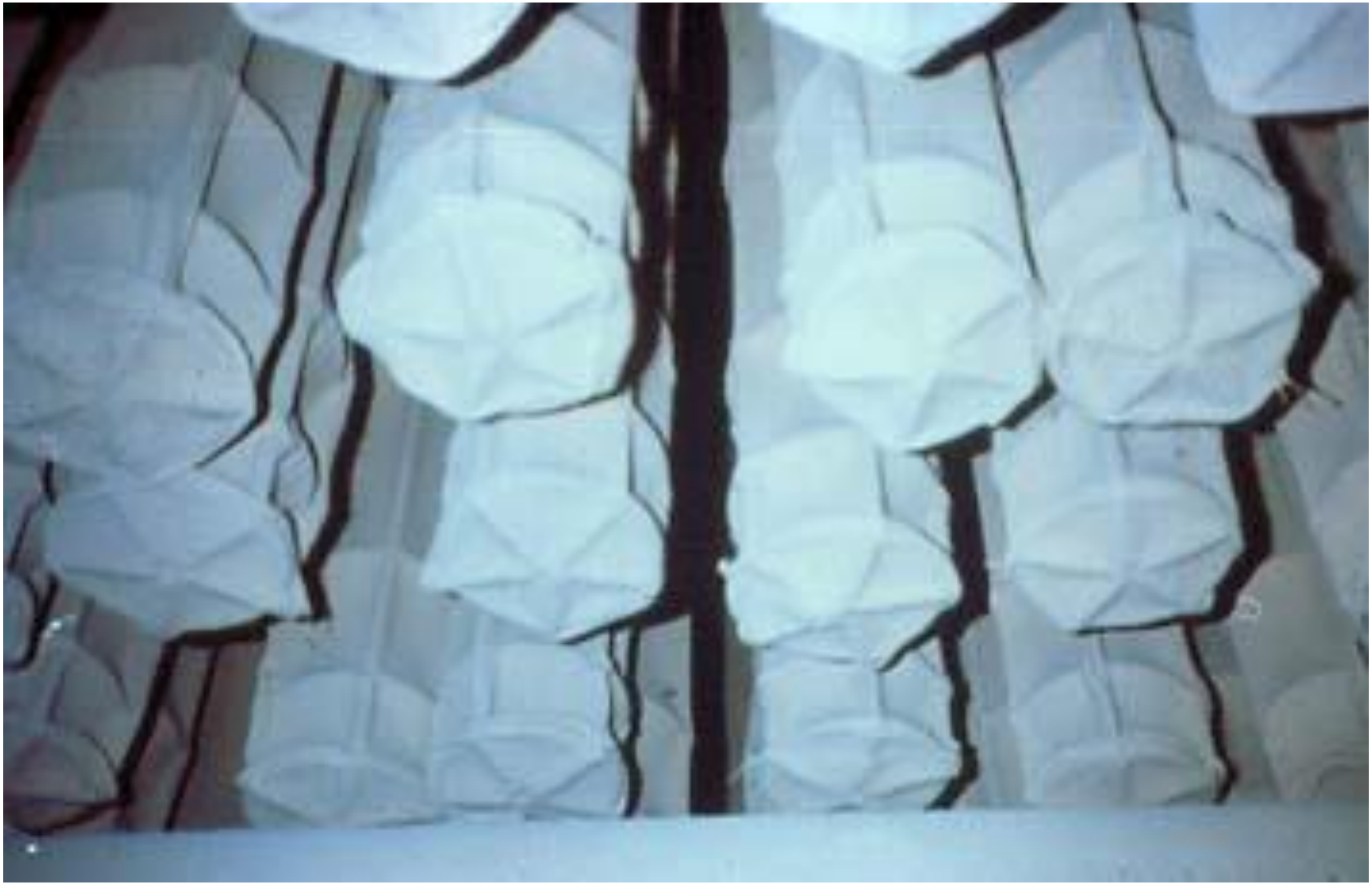


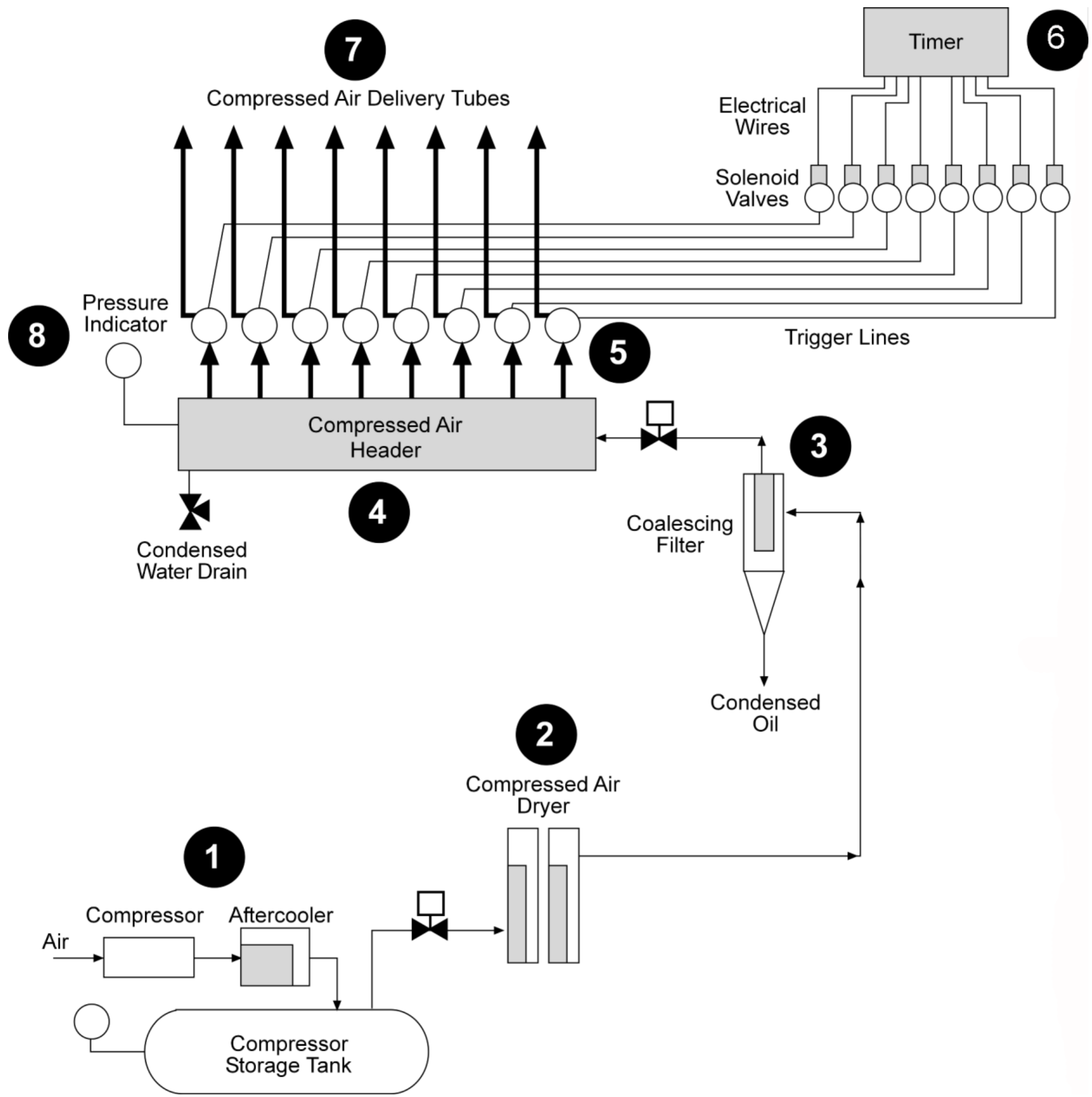
Forward flow pressure drop, inches W.C.
Reverse flow pressure drop, inches W.C.
+4
+3
+2
+1
0
-1
-2
Abnormal profile
Null period
Null period
Return to filtering
Time
Normal profile
Cleaning cycle

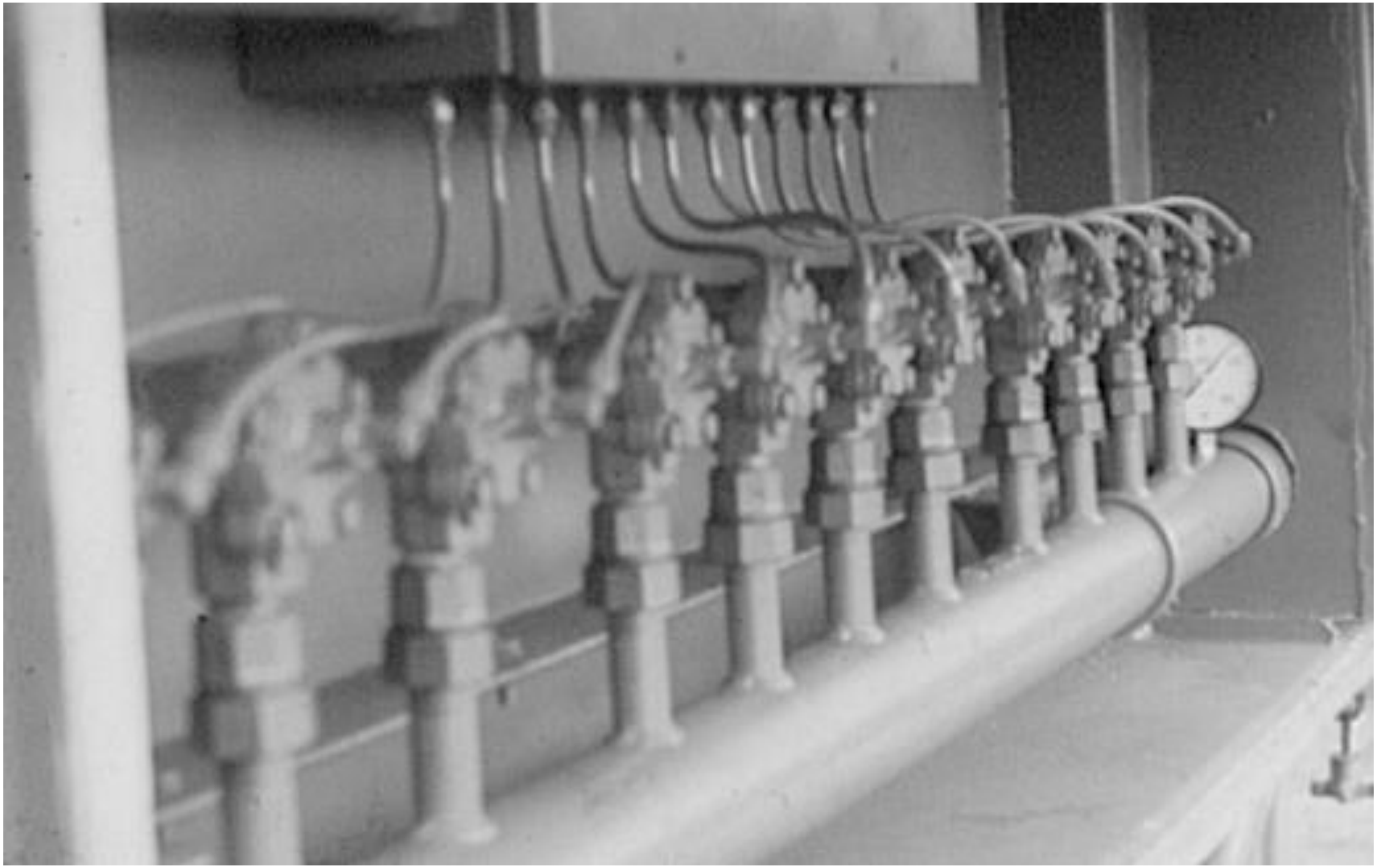
Pulse Jet Fabric Filter

Pulse Jet Fabric Filter





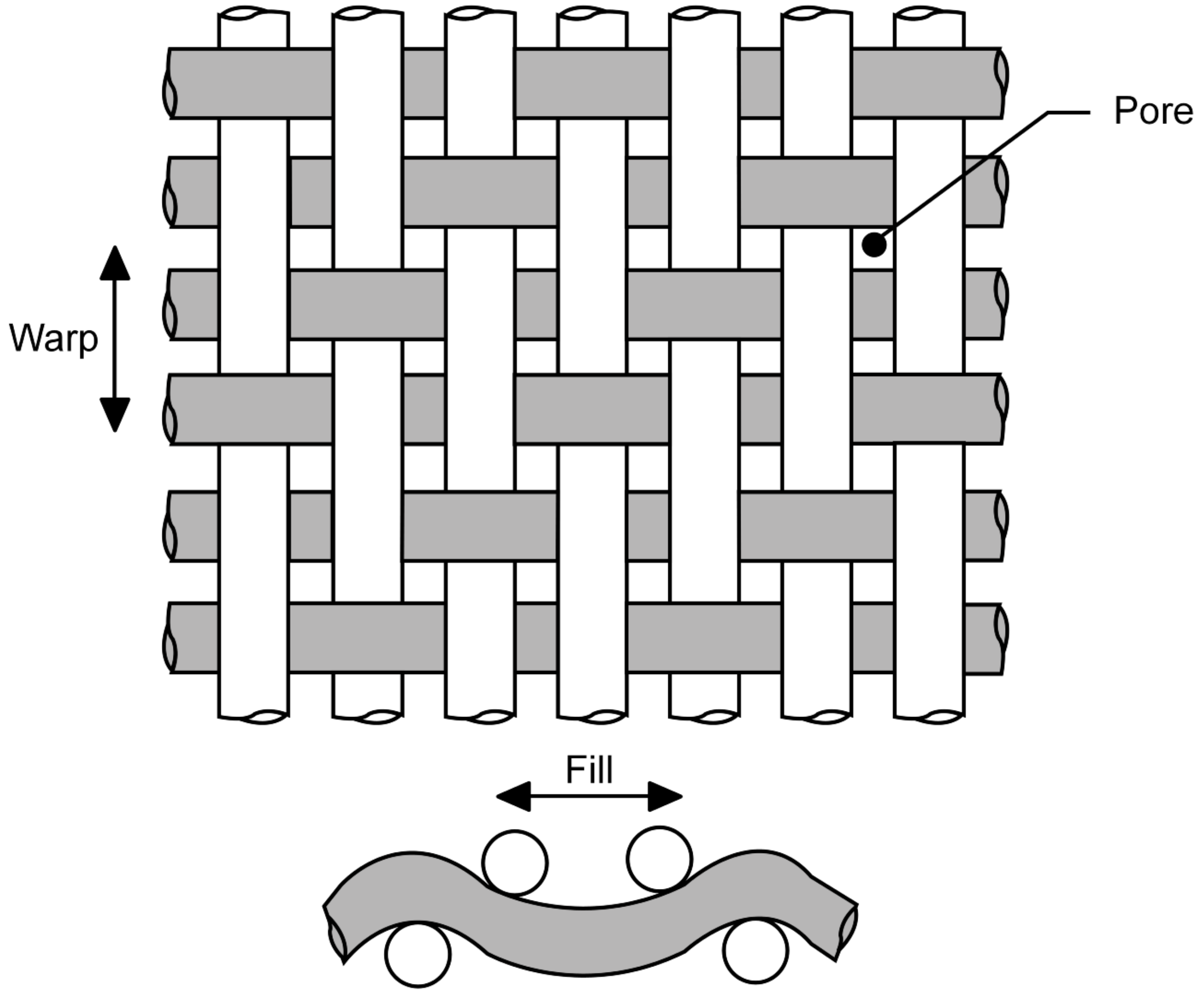

7
Compressed Air Delivery Tubes
Timer
6
Electrical
Wires
Solenoid
Valves
Pressure
Indicator
8
5
Trigger Lines
Compressed Air
Header
3
4
Condensed
Water Drain
Coalescing
Filter
Condensed
Oil
2
Compressed Air
Dryer
1
Compressor
Aftercooler
Air
Compressor
Storage Tank

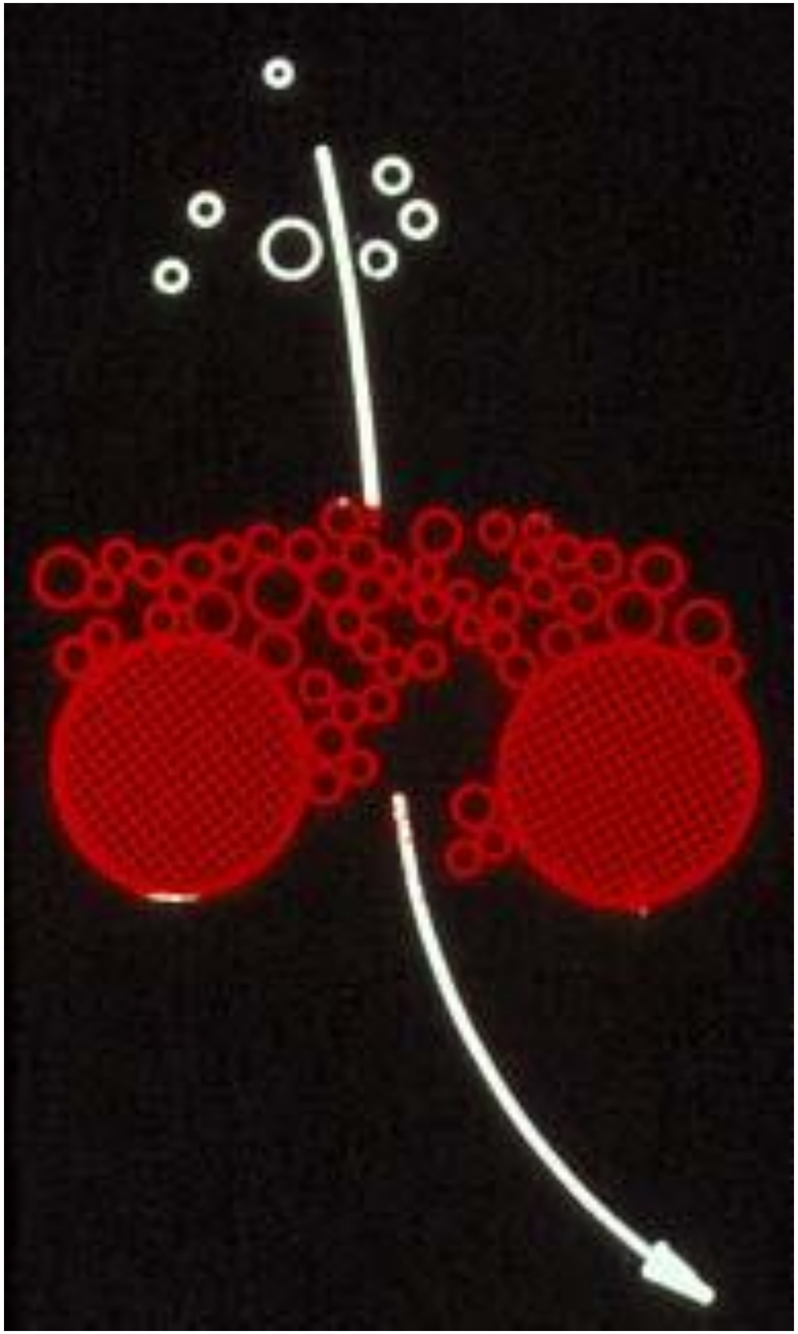


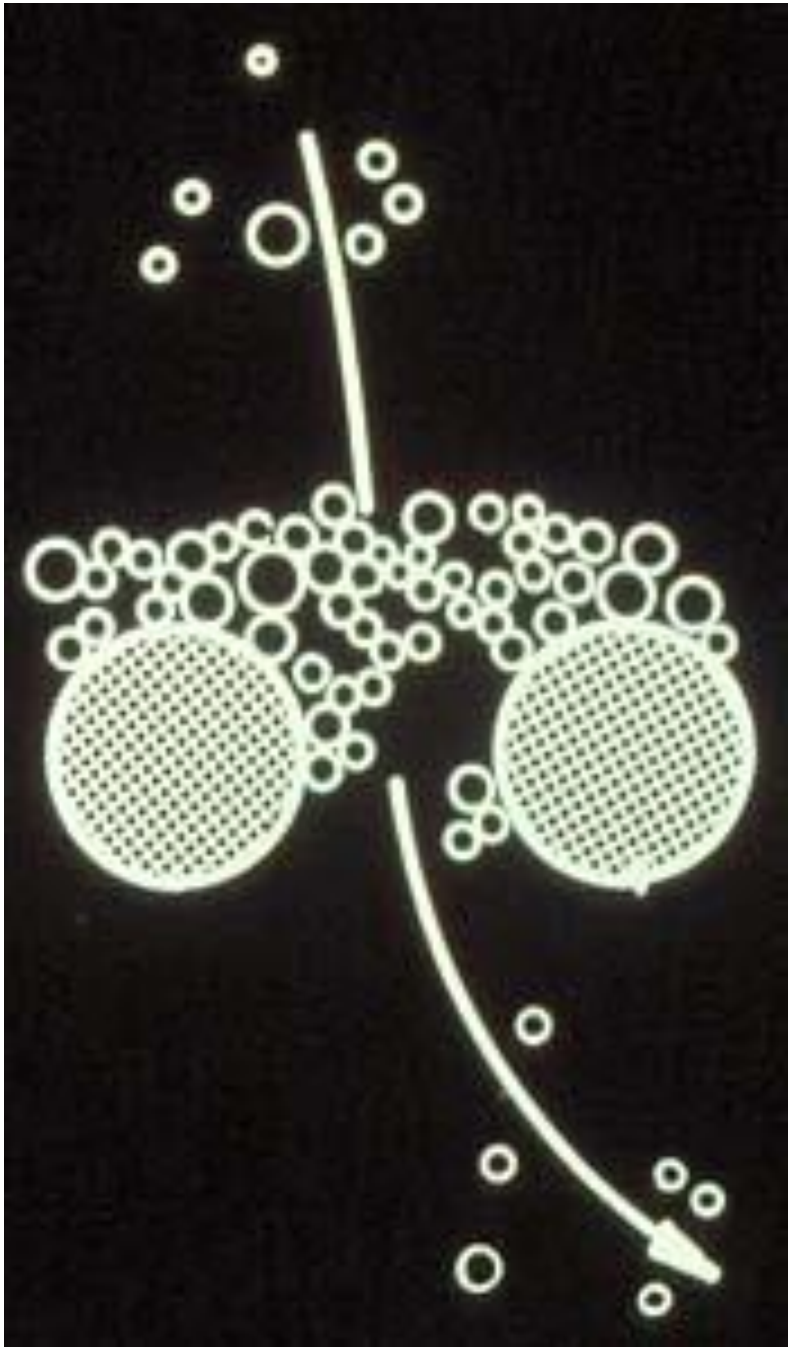
Filtration Media

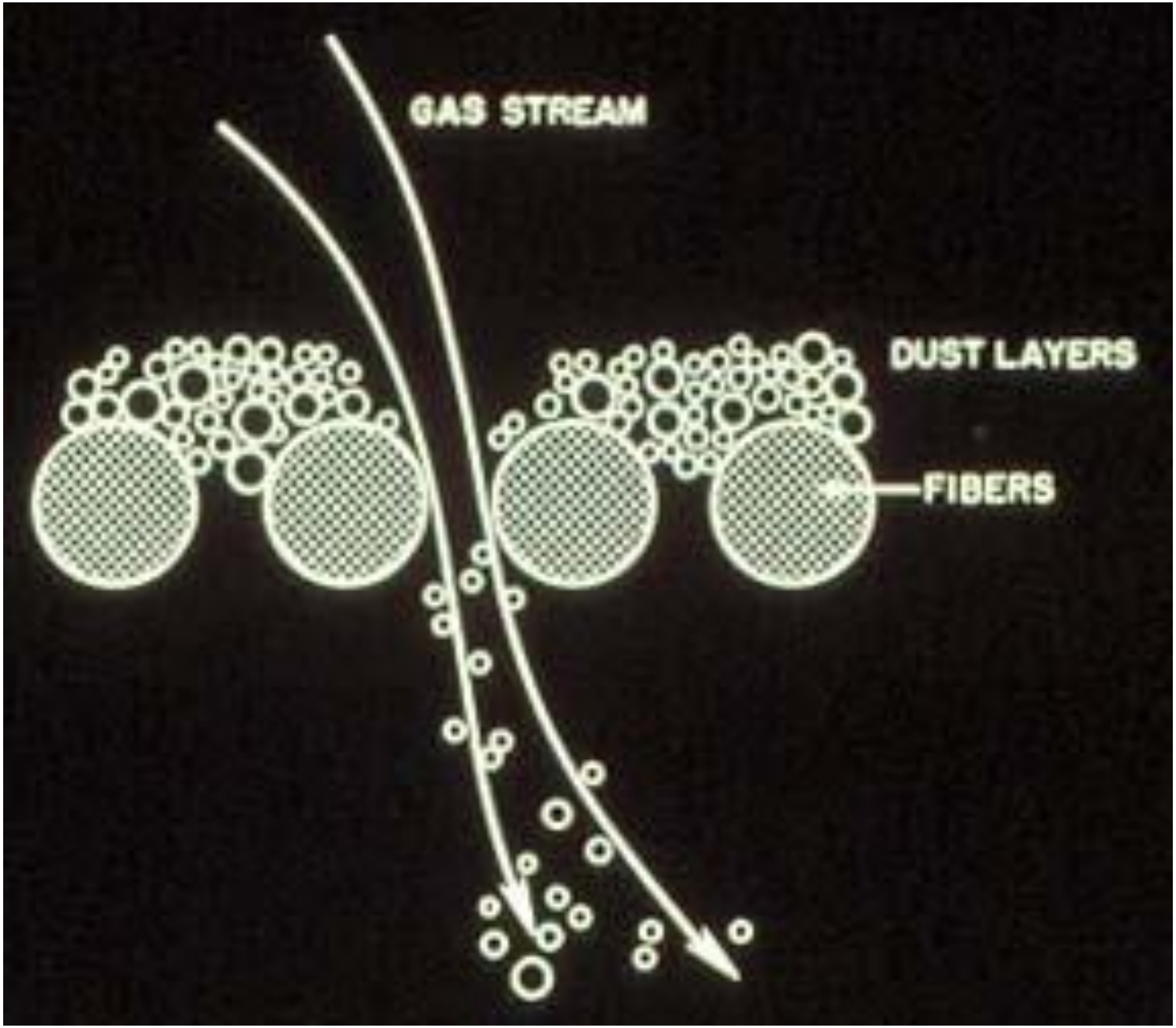
- Woven fabric
- Felted fabric
- Membrane fabric
- Sintered metal fiber
- Ceramic cartridge

Woven Fabrics

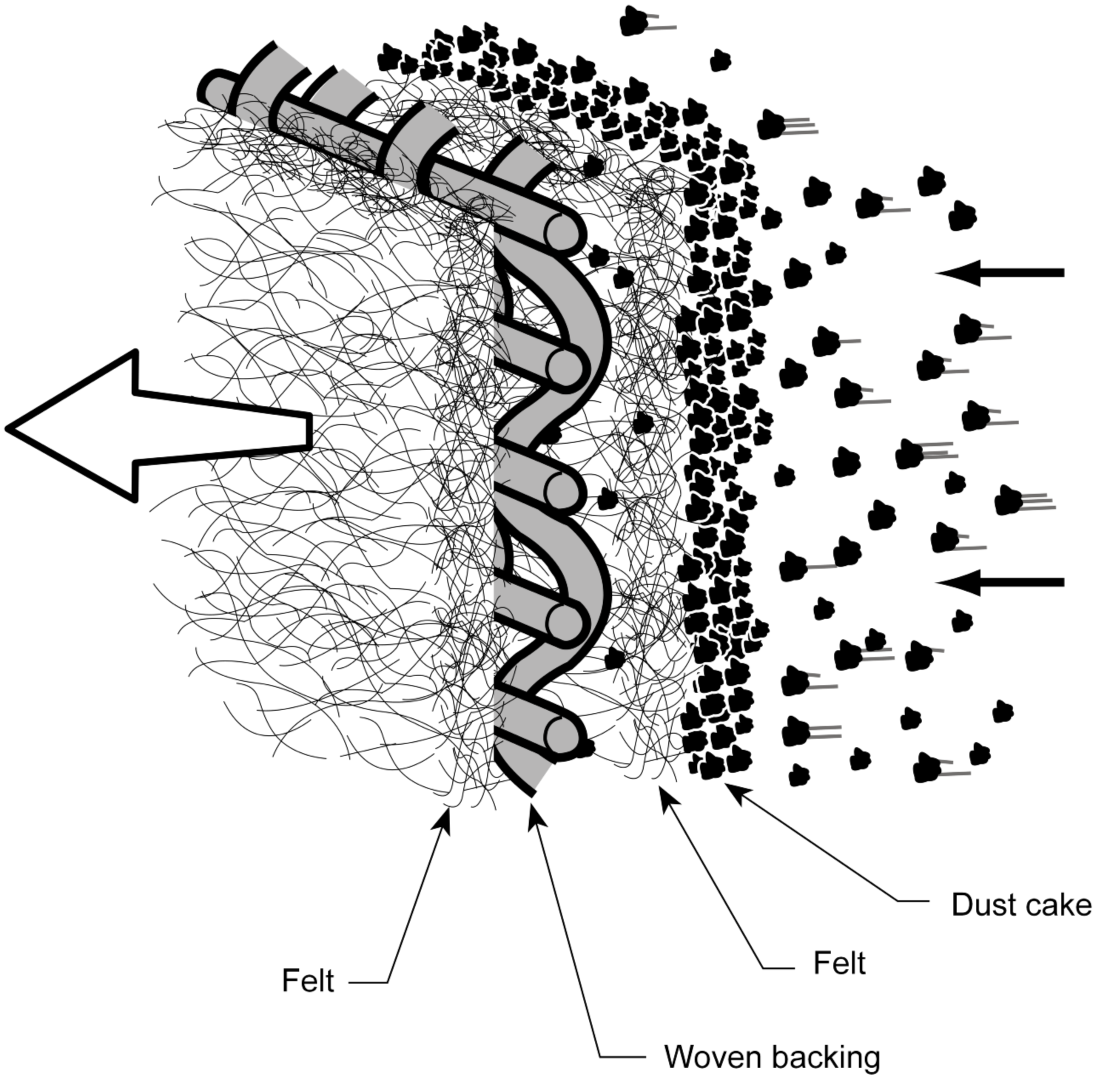


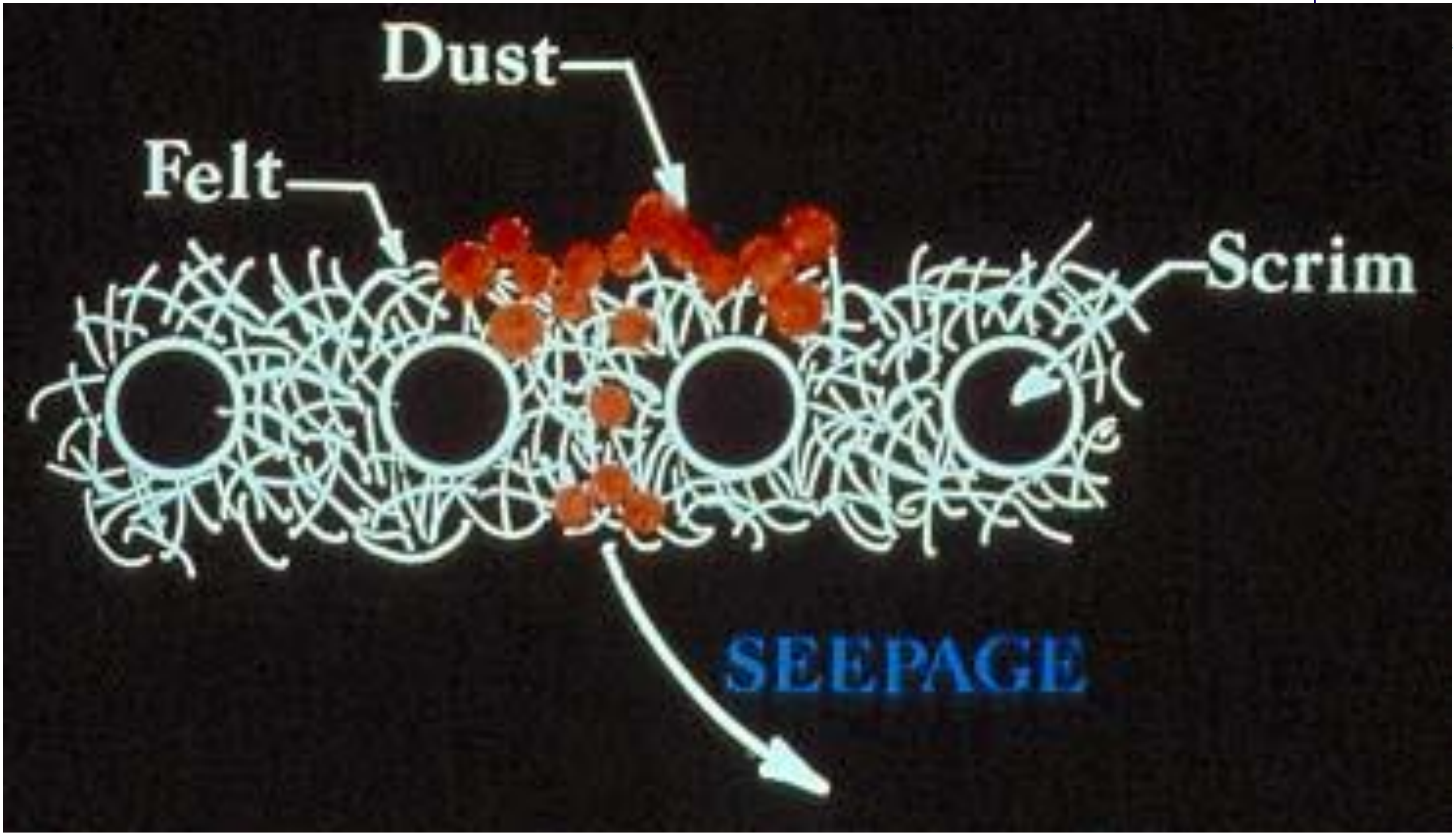





GAS STREAM
DUST LAYERS
FIBERS

Felted Fabrics




Dust
Felt
Scrim
SEEPAGE

Cartridge Filters

Cartridge Filters

Fabric Selection

- Maximum temperature of the gas stream
- Composition of the gas stream
- Physical abrasion
- Fabric flex conditions

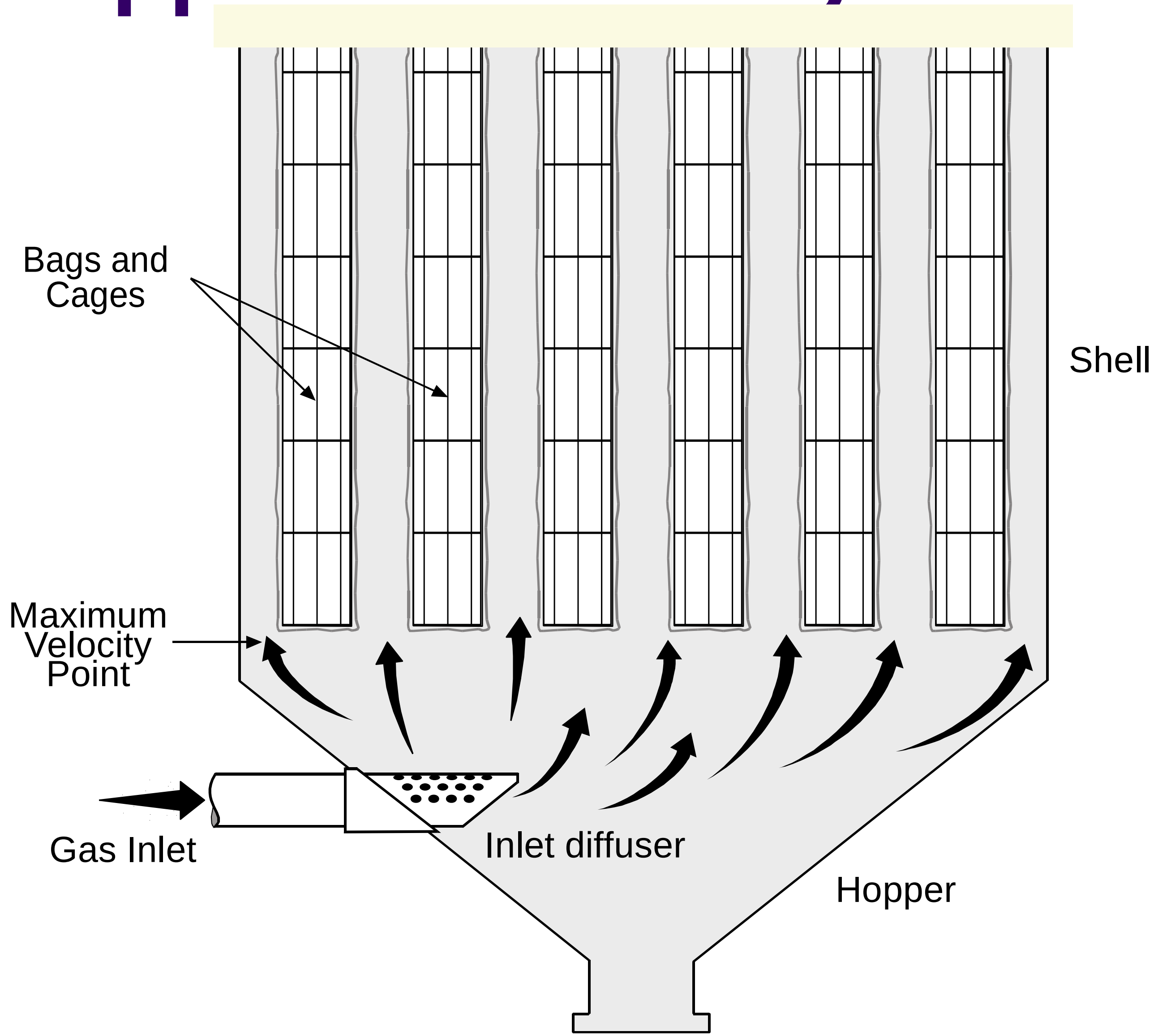
Temperature & Acid Resistance Characteristics				
Generic Name	**Common or Trade Name**	**Max. Temp. °F**		**Acid Resistance**
		Continuous	**Surges**	
Natural Fiber, Cellulose	Cotton	180	225	Poor
Polyolefin	Polyolefin	190	200	Good to Excellent
Polypropylene	Polypropylene	200	225	Excellent
Polyamide	Nylon®	200	225	Excellent
Acrylic	Orlon®	240	260	Good
Polyester	Dacron®	275	325	Good
Aromatic Polyamide	Nomex®	400	425	Fair
Polyphenylene Sulfide	Ryton®	400	425	Good
Polyimide	P-84®	400	425	Good
Fiberglass	Fiberglass	500	550	Fair
Fluorocarbon	Teflon®	400	500	Excellent
Stainless Steel	Stainless Steel	750	900	Good
Ceramic	Nextel®	1300	1400	Good

Fabric Resistance to Abrasion and Flex		
Generic Name	**Common or Trade Name**	**Resistance to Abrasion and Flex**
Natural Fiber, Cellulose	Cotton	Good
Polyolefin	Polyolefin	Excellent
Polypropylene	Polypropylene	Excellent
Polyamide	Nylon®	Excellent
Acrylic	Orlon®	Good
Polyester	Dacron®	Excellent
Aromatic Polyamide	Nomex®	Excellent
Polyphenylene Sulfide	Ryton®	Excellent
Polyimide	P-84®	Excellent
Fiberglass	Fiberglass	Fair
Fluorocarbon	Teflon®	Fair
Stainless Steel	Stainless Steel	Excellent
Ceramic	Nextel®	Fair

Fabric Utilization

- Gas approach velocity
- Bag spacing and length
- Bag reach and accessibility

Gas Approach Velocity



Example 7-3

What is the difference in gas approach velocities for two identical pulse jet fabric filters with the following design characteristics?

Characteristic	Unit A	Unit B
Compartment area, ft^2	130	130
Number of bags	300	300
Bag diameter, in.	6	6
Bag height, ft	10	10
Air-to-cloth ratio, $(ft^3/min)/ft^2$	5	8

Solution

The bag area for both units is identical. It is calculated using the circumference of the bag times the length.

Bag area = πDL = π(6 in.)(1 ft/12 in.)(10 ft) = 15.7 ft^2/bag

Total bag area = (300 bags)(15.7 ft^2/bag) = 4,710 ft^2

Total gas flow rate, Unit A =

$$\frac{5\left(ft^3/\min\right)}{ft^2}\left(4{,}710\ ft^2\right) = 23{,}550\ ft^3/\min$$

Total gas flow rate, Unit B =

$$\frac{8\left(ft^3/\min\right)}{ft^2}\left(4{,}710\ ft^2\right) = 37{,}680\ ft^3/\min$$

The area for gas flow at the bottom of the pulse jet bags is identical in both units.

Solution (continued)

Area for flow = total area – bag projected area

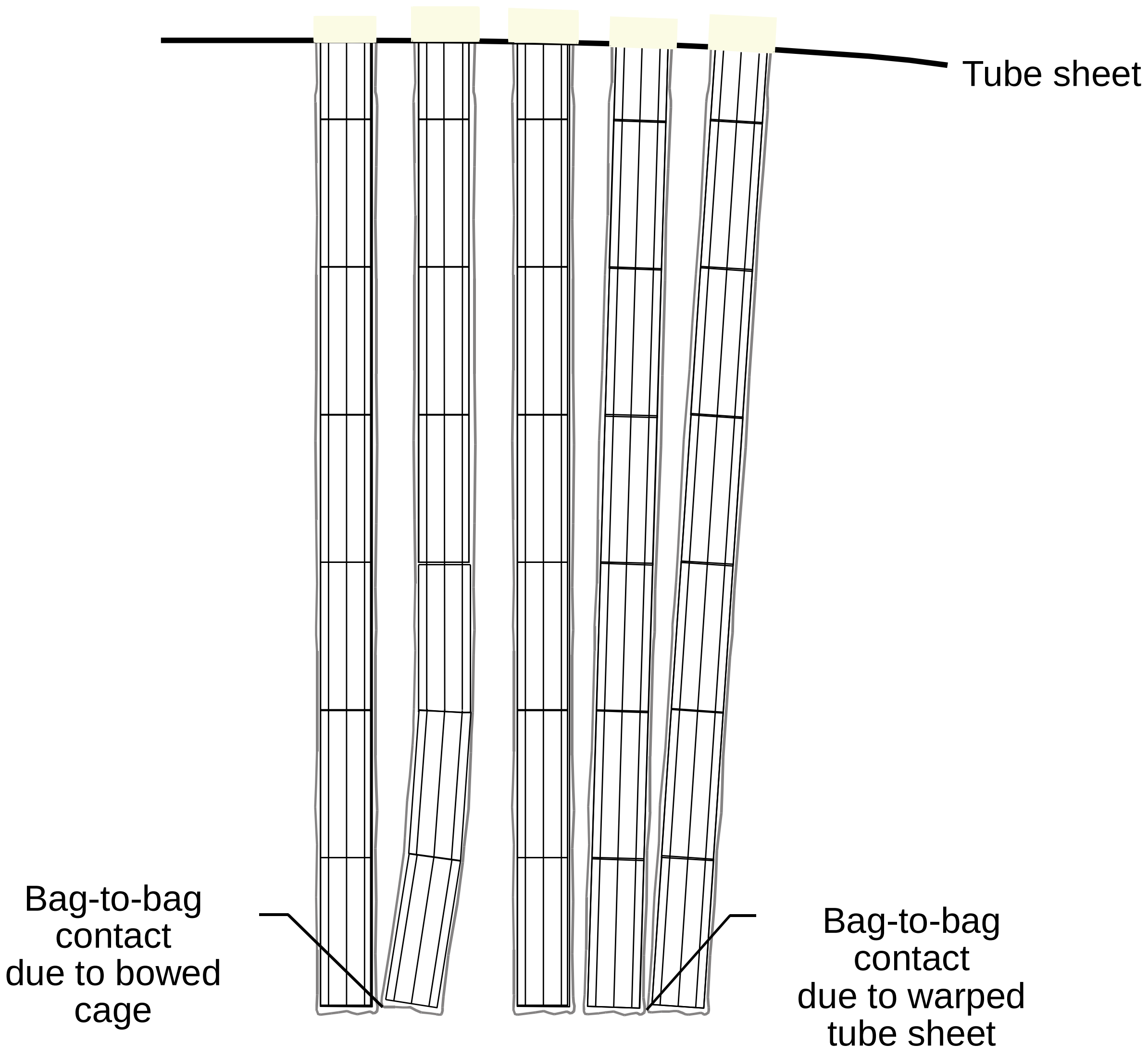
= total area – (number of bags)(circular area of bag at bottom)

$$= 130\ ft^2 - (300)(\pi D^2/4)$$
$$= 130\ ft^2 - 58.9\ ft^2$$
$$= 71.1\ ft^2$$

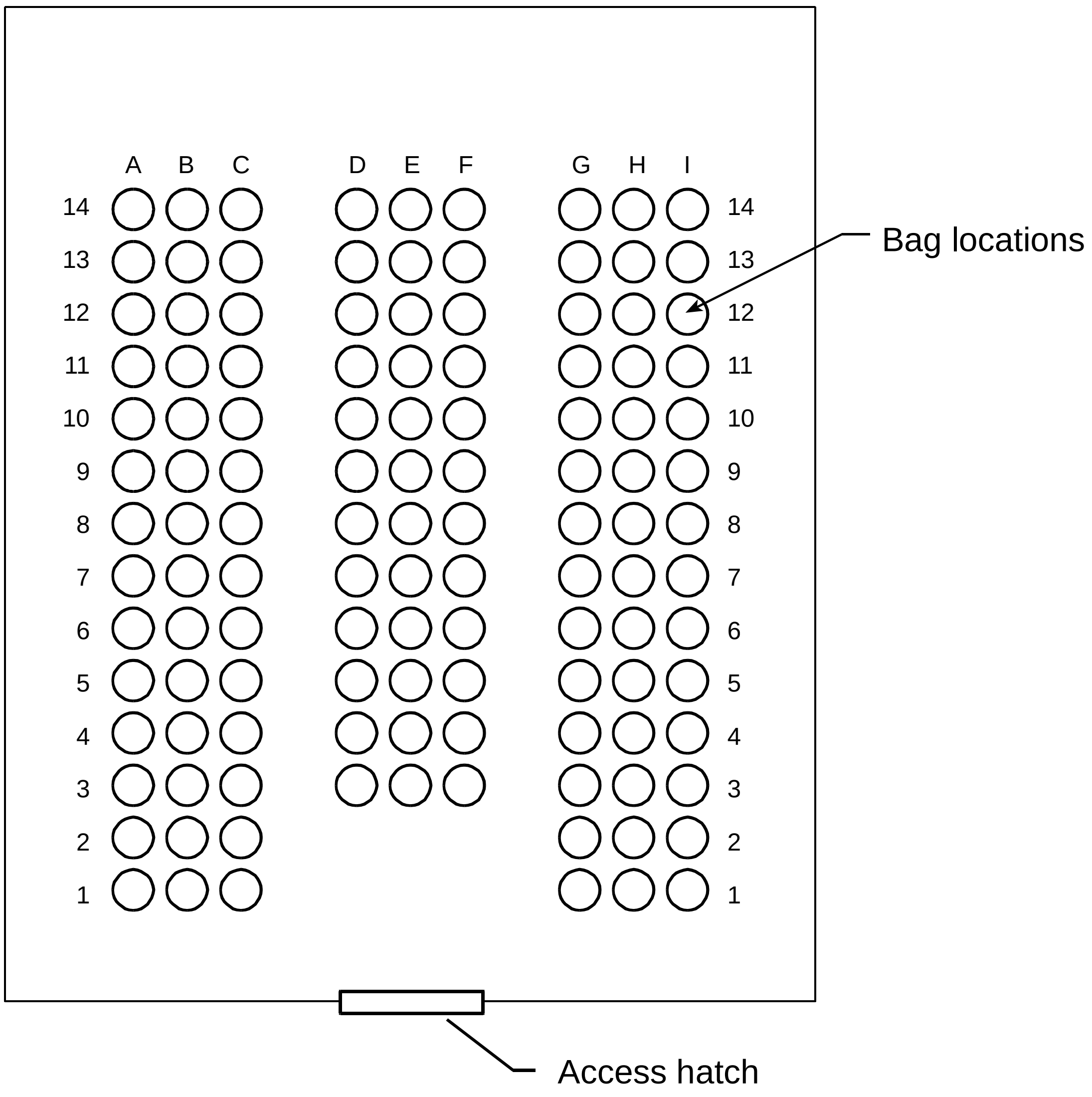
Gas approach velocity for Unit A = $\dfrac{23{,}550\ ft^3/\min}{71.1\ ft^2} = 331\ ft/\min$

Gas approach velocity for Unit B = $\dfrac{37{,}680\ ft^3/\min}{71.1\ ft^2} = 530\ ft/\min$

Bag Spacing and Length



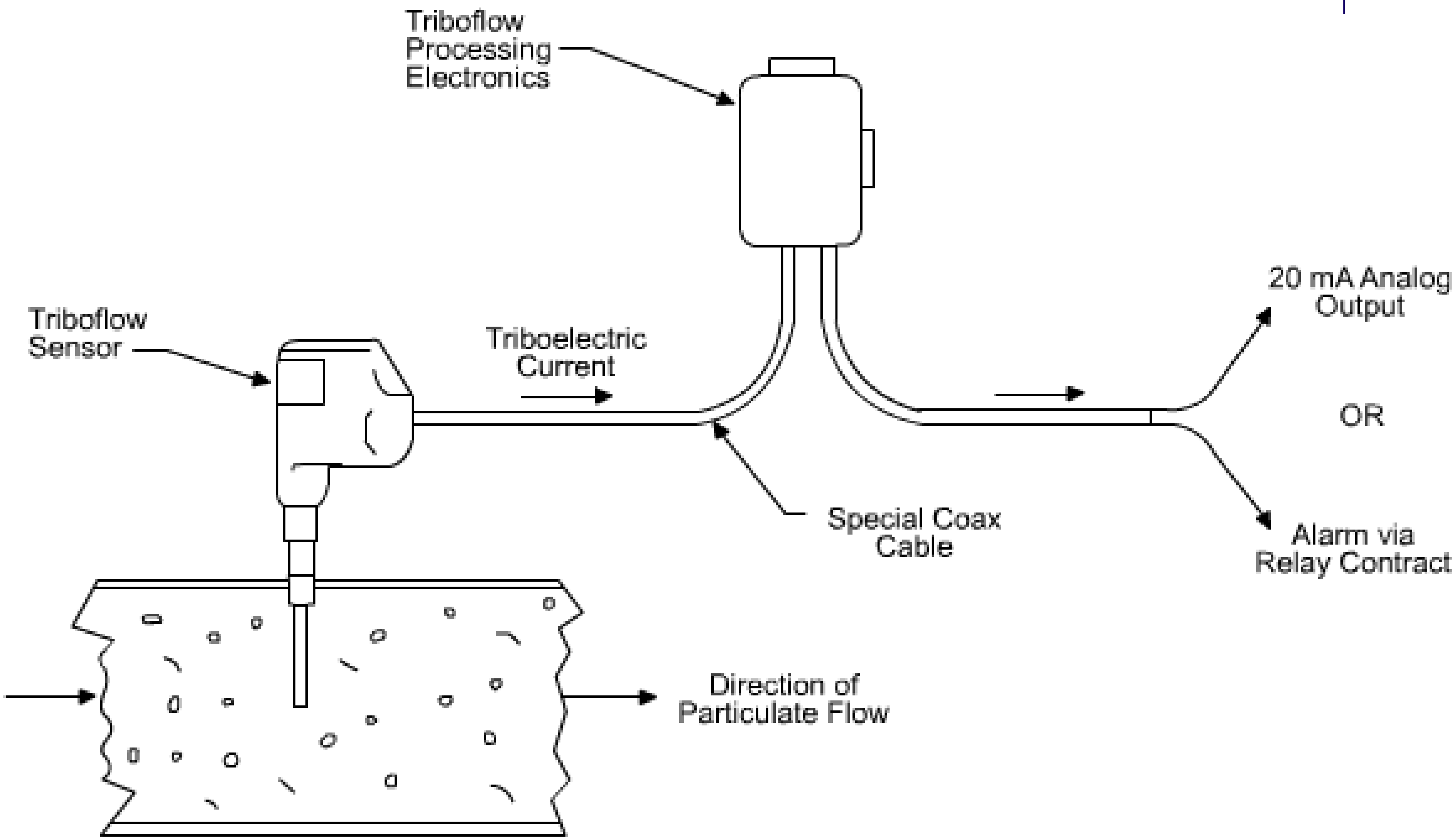
Bag Reach and Accessibility



Instrumentation

- Static pressure drop gauges
- Inlet and outlet gas temperature gauges
- Bag break detector
- Opacity monitor

Bag Break Detector



Advantages and Disadvantages

Advantages

- High Collection Efficiency (>99%)
- Effective for a Wide Range of Dust Types
- Modules Can be Factory Assembled
- Operates Over Wide Range of Gas Flow Rates
- Reasonably Low Pressure Drop
- Good Efficiency for Small Particles
- Dry Collection and Disposal

Disadvantages

- Large Footprint
- Temperature Limitations
- Requires Dry Environment
- Fire or Explosion Potential
- High Maintenance Cost

Review Problems

1. Calculate the net air-to-cloth ratio for a reverse air baghouse with 12 compartments containing 276 bags each.

The diameter of each bag is 11 in, and the bag height is 28 ft. One of the compartments is always off-line for cleaning, and another is off-line for maintenance.

Use a gas flow rate of 350,000 acfm.

Solution #1

$$\text{Individual bag area} = \pi \text{Dh} = \pi\left[11\,\text{in}\left(\frac{1\,\text{ft}}{12\,\text{in}}\right)\right](28\,\text{ft}) = 80.6\,\frac{\text{ft}^2}{\text{bag}}$$

$$\text{Total net bag area} = 80.6\,\frac{\text{ft}^2}{\text{bag}}\left(276\,\frac{\text{bags}}{\text{compartment}}\right)(10\,\text{compartments}) = 222{,}456\,\text{ft}^2$$

Net air-to-cloth ratio $= \dfrac{Q}{A} = \dfrac{350{,}000\,\dfrac{\text{ft}^3}{\text{min}}}{222{,}456\,\text{ft}^2} = 1.57\,\dfrac{\text{ft}}{\text{min}}$

Review Problems

2. Calculate the gas approach velocity for a pulse jet baghouse having a single compartment, 60 rows of bags with 10 bags each, and a bag diameter of 6 in.

Assume that the internal dimensions of the compartment are 6.5 ft x 40 ft.

Use a gas flow rate of 66,000 acfm.

Solution #2

Total baghouse shell area = (6.5 ft)(40 ft) = 260 ft^2

Bottom area of bag $= \frac{\pi D^2}{4} = \frac{\pi\left[6\,\text{in}\left(\frac{1\,\text{ft}}{12\,\text{in}}\right)\right]^2}{4} = 0.196\,\frac{\text{ft}^2}{\text{bag}}$

Total bottom area $= 0.196\,\frac{\text{ft}^2}{\text{bag}}\left(10\,\frac{\text{bags}}{\text{row}}\right)(60\,\text{rows}) = 118\,\text{ft}^2$

Open area = total shell area – total bottom area =

260 ft^2 – 118 ft^2 = 142 ft^2

Gas approach velocity $= \frac{Q}{A} = \frac{66{,}000\,\frac{\text{ft}^3}{\text{min}}}{142\,\text{ft}^2} = 465\,\frac{\text{ft}}{\text{min}} = 7.75\,\frac{\text{ft}}{\text{sec}}$

Review Problem #3

3. Would a 150 μm size particle or particle agglomerate successfully settle by gravity in the pulse jet baghouse described in Problem 2?

Assume a temperature of 20°C, a particle density of 1.0 g/cm^3, and that the transitional region terminal settling velocity equation is appropriate for this particle size.

Solution #3

$$v_t = \frac{0.153\, g^{0.71} \rho_p^{0.71} d_p^{1.14}}{\mu_g^{0.43} \rho_g^{0.29}} =$$

$$\frac{0.153\left(980\,\frac{cm}{sec^2}\right)^{0.71}\left(1\,\frac{g}{cm^3}\right)^{0.71}\left(150\,x\,10^{-4}\,cm\right)^{1.14}}{\left(1.8\,x\,10^{-4}\,\frac{g}{cm\cdot sec}\right)^{0.43}\left(1.2\,x\,10^{-3}\,\frac{g}{cm^3}\right)^{0.29}} = 48.58\,\frac{cm}{sec} = 1.59\,\frac{ft}{sec}$$

The 150 μm particle will not settle. The upward velocity of the gas stream is much higher than the terminal settling velocity.

Review Problem #4 & solution

4. Calculate the static pressure difference between the clean gas plenum of a top access type pulse jet baghouse and the ambient air.

Assume that the inlet static pressure to the baghouse is - 4 in WC and the static pressure drop across the baghouse is 5 in WC.

Solution

Static pressure in the clean gas plenum =

-4 in WC – (5 in WC) = -9 in WC

Since the ambient gauge pressure is 0 in WC, the static pressure difference between the clean gas plenum and the ambient air is 9 in WC.

Review Problem #5

5. It is proposed to install a pulse jet fabric filter with an air-to-cloth ratio of 2.5 ft/min to clean a 10,000 scfm air stream at 250°F.

Determine the filtering area required for this operation and, using the information below, choose an appropriate filter bag and determine how many will be needed.

Filter bag	A	B	C	D
Tensile strength	Excellent	Very good	Fair	Excellent
Maximum temperature (°F)	260	275	260	220
Relative cost per bag	2.6	3.8	1.0	2.0
Size	4¾” x 10’	6” x 10’	6” x 14’	6” x 14’

Solution #5

Calculate actual flow rate:

$$Q = 10{,}000\,\frac{ft^3}{min}\left(\frac{250°F + 460}{68°F + 460}\right) = 13{,}447\,\frac{ft^3}{min}$$

Calculate filtering area:

$$\text{Filter area} = \frac{Q}{A/C\,\text{Ratio}} = \frac{13{,}447\,\frac{ft^3}{min}}{2.5\,\frac{ft}{min}} = 5{,}379\,ft^2$$

Bag D can be eliminated because its maximum temperature is too low. Bag C can be eliminated because it has only fair tensile strength.

Only Bags A and B will be considered further.

Solution (continued)

For Bag A:

Bag Area $= \pi Dh = \pi\left[4.75\,\text{in}\left(\frac{1\,\text{ft}}{12\,\text{in}}\right)\right](10\,\text{ft}) = 12.44\frac{\text{ft}^2}{\text{bag}}$

Number of Bags $\dfrac{5{,}379\,\text{ft}^2}{12.44\frac{\text{ft}^2}{\text{bag}}} = 432\,\text{bags}$

Relative Cost $= \left(\frac{2.6}{\text{bag}}\right)432\text{bags} = 1{,}123$

For Bag B:

Bag Area $= \pi Dh = \pi\left[6\,\text{in}\left(\frac{1\,\text{ft}}{12\,\text{in}}\right)\right](10\,\text{ft}) = 15.71\frac{\text{ft}^2}{\text{bag}}$

Number of Bags $\dfrac{5{,}379\,\text{ft}^2}{15.71\frac{\text{ft}^2}{\text{bag}}} = 342\,\text{bags}$

Relative Cost $= \left(\frac{3.8}{\text{bag}}\right)342\text{bags} = 1{,}300$

Bag A should be chosen b/c of its lower relative cost.

Chapter 8

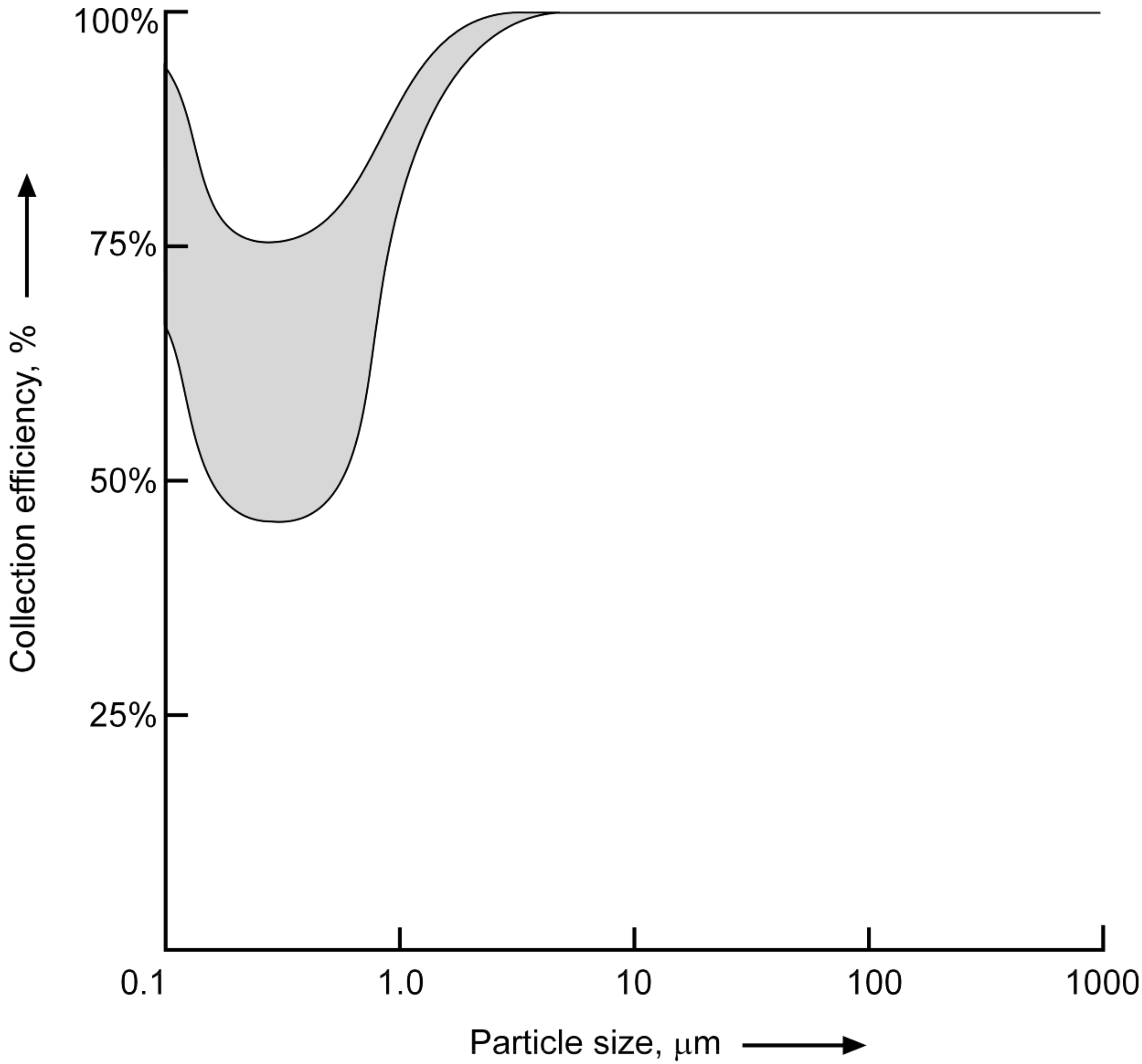
Wet Scrubbers

Particle Collection Steps

- Capture particulate matter in droplets, liquid sheets or liquid jets
- Capture droplets entrained in the gas stream
- Treat contaminated liquid prior to reuse or discharge

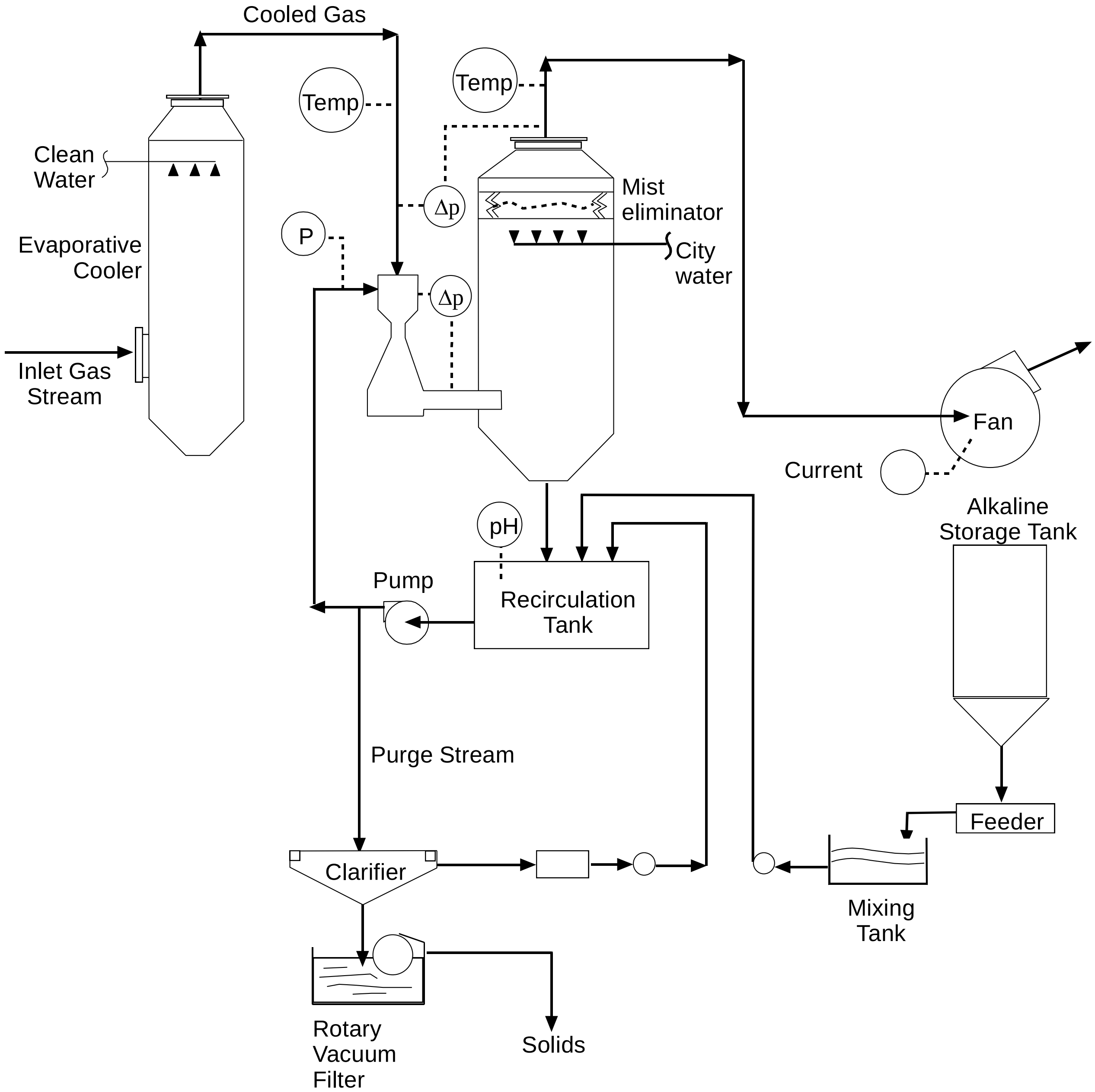
Collection Mechanisms

- Inertial impaction
- Brownian motion
- Electrostatic attraction



100%
75%
50%
25%
Collection efficiency, %
0.1
1.0
10
100
1000
Particle size, μm

Wet Scrubber System



Operational Issues

- Gas cooling
- Liquid to Gas Ratio
- Alkali addition
- Wastewater treatment and Liquid Recirculation

Operational Issues

- Gas cooling
- Liquid to Gas Ratio
- Alkali addition
- Wastewater treatment and Liquid Recirculation

Operational Issues

- Gas cooling
- Liquid to Gas Ratio
- Alkali addition
- Wastewater treatment and Liquid Recirculation

Liquid-to-Gas Ratio

$$\text{L / G Ratio}\left(\frac{\text{gal}}{10^3\,\text{acf}}\right) = \frac{\text{Liquid flow rate}\left(\frac{\text{gal}}{\text{min}}\right)}{\text{Gas flow rate}\left(\frac{10^3\,\text{acf}}{\text{min}}\right)}$$

Example 8-1

What is the design liquid-to-gas ratio for a scrubber system that has an outlet gas flow rate of 15,000 acfm, a pump discharge rate of 100 gpm, and a liquid purge rate of 10 gpm?

The purge stream is withdrawn from the pump discharge side.

$$\frac{L}{G} = \frac{Inlet\ liquid\ flow\,(gpm)}{Outlet\ gas\ flow\ rate\,(1{,}000\ acfm)}$$

Inlet liquid flow = 100 gpm – 10 gpm = 90 gpm

$$\frac{\mathrm{L}}{\mathrm{G}} = \frac{90\,\mathrm{gpm}}{15{,}000\ \mathrm{acfm}} = 0.006\,\frac{\mathrm{gal}}{\mathrm{acf}} = 6.0\,\frac{\mathrm{gal}}{1{,}000\,\mathrm{acf}}$$

Operational Issues

- Gas cooling
- Liquid to Gas Ratio
- Alkali addition
- Wastewater treatment and Liquid Recirculation

Alkali Requirements and Addition

$SO_3^{=} + Ca(OH)_2 \rightarrow CaSO_4 + H_2O$ Reaction 8-1

$2HCl + Ca(OH)_2 \rightarrow CaCl_2 + 2H_2O$ Reaction 8-2

$2HF + Ca(OH)_2 \rightarrow CaF_2 + 2H_2O$ Reaction 8-3

Example 8-3

Calculate the amount of calcium hydroxide (lime) needed to neutralize the HCl absorbed from a gas stream having 50 ppmv HCl and a flow rate of 10,000 scfm.

Assume an HCl removal efficiency of 95%.

Solution

Calculate HCl absorbed in the scrubbing liquid:

$$50\,\text{ppmv} = \frac{50\,\text{ft}^3\ \text{HCl}}{10^6\,\text{ft}^3\text{total}} = 0.00005\frac{\text{ft}^3\text{HCl}}{\text{ft}\ \ \text{total}} = 0.00005\frac{\text{lb}-\text{mole HCl}}{\text{lb}-\text{mole total}}$$

And then…

Solution (continued)

$$\text{HCl absorbed} = 10{,}000\,\text{scfm}\left(\frac{\text{lb}-\text{mole}}{385.4\,\text{scf}}\right)\left(0.00005\,\frac{\text{lb}-\text{mole HCl}}{\text{lb}-\text{mole total}}\right)(0.95)$$

$$= 0.00123\,\frac{\text{lb}-\text{mole}}{\text{min}}$$

$$Ca(OH)_2 \text{ required} = \left(\frac{1\text{ lb}-\text{mole } Ca(OH)_2}{2\text{ lb}-\text{mole HCl}}\right)\left(0.00123\,\frac{\text{lb}-\text{mole HCl}}{\text{min}}\right)$$

$$= 0.00062\,\frac{\text{lb}-\text{mole}}{\text{min}}\left(74\,\frac{\text{lb } Ca(OH)_2}{\text{lb}-\text{mole}}\right)\left(60\,\frac{\text{min}}{\text{hr}}\right)$$

$$= 2.75\,\frac{\text{lb}}{\text{hr}}$$

Operational Issues

- Gas cooling
- Liquid to Gas Ratio
- Alkali addition
- Wastewater treatment and Liquid Recirculation

Factors Affecting Liquid Purge Rate

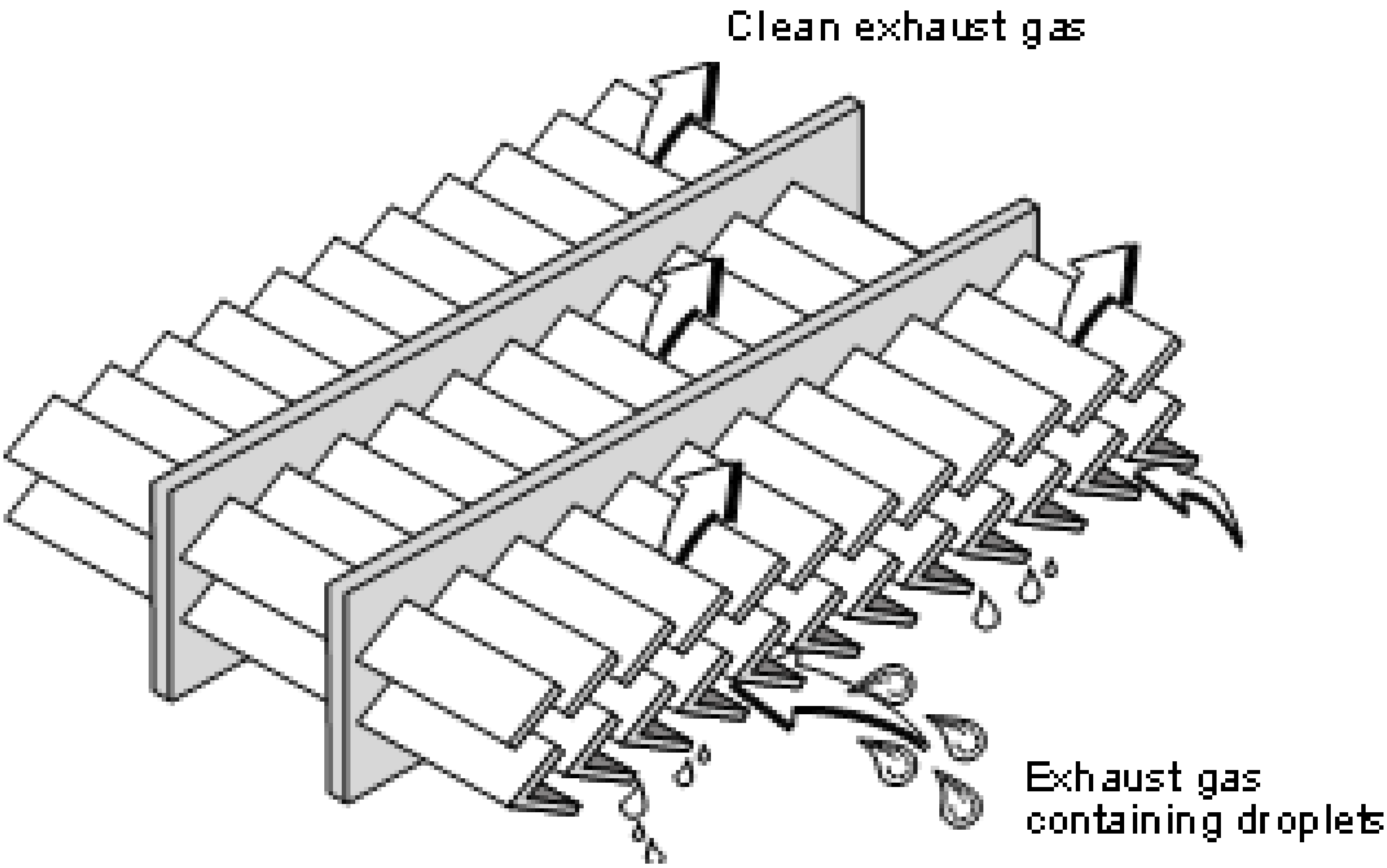
- Rate of particulate matter capture
- Maximum acceptable suspended solids concentration
- Rate of dissolved solids precipitation
- Rate of chlorine or fluorine accumulation

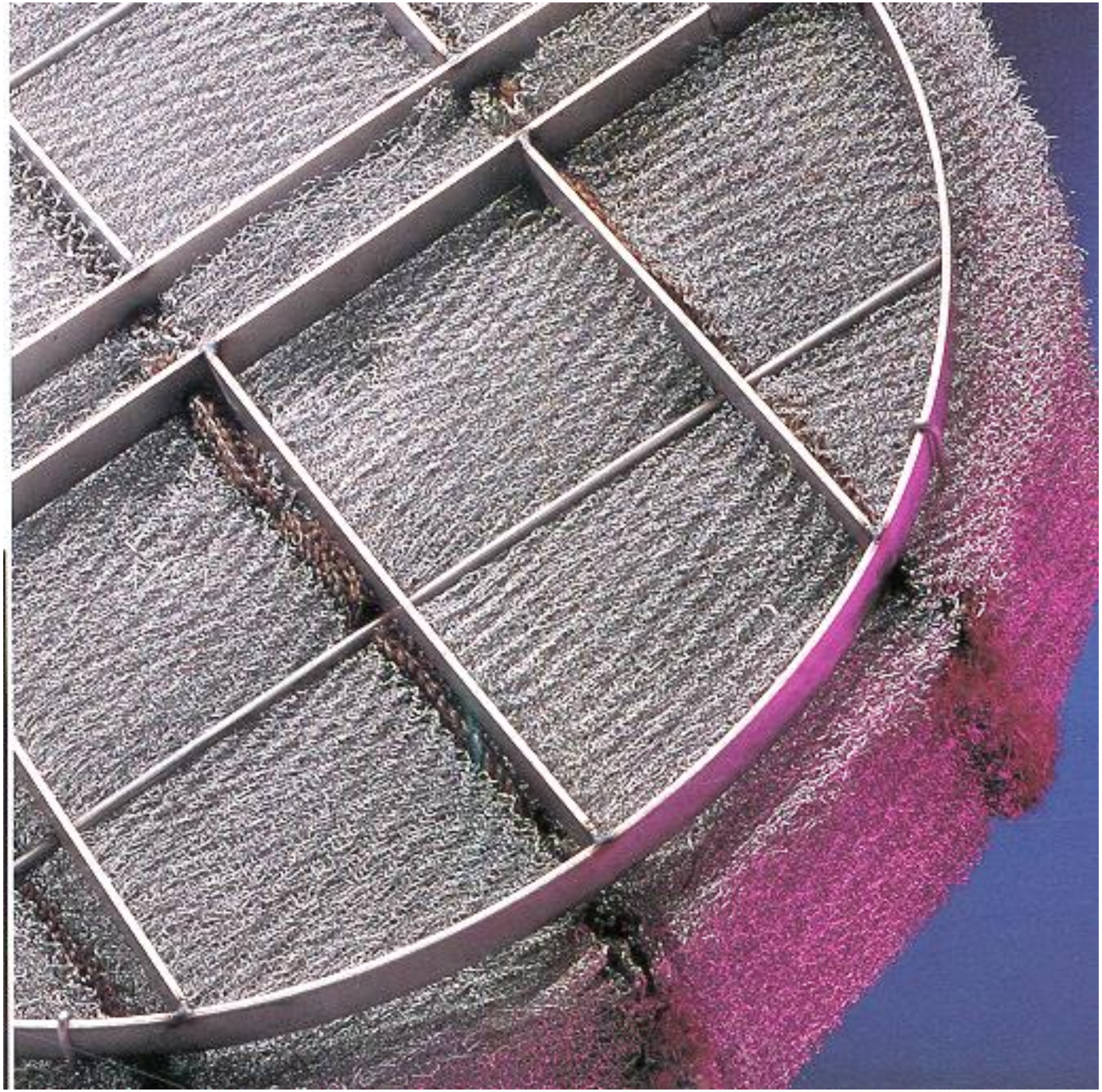
Applicability Limitations

- Particle size distribution
- Water availability
- Wastewater treatment
- Condensation plume

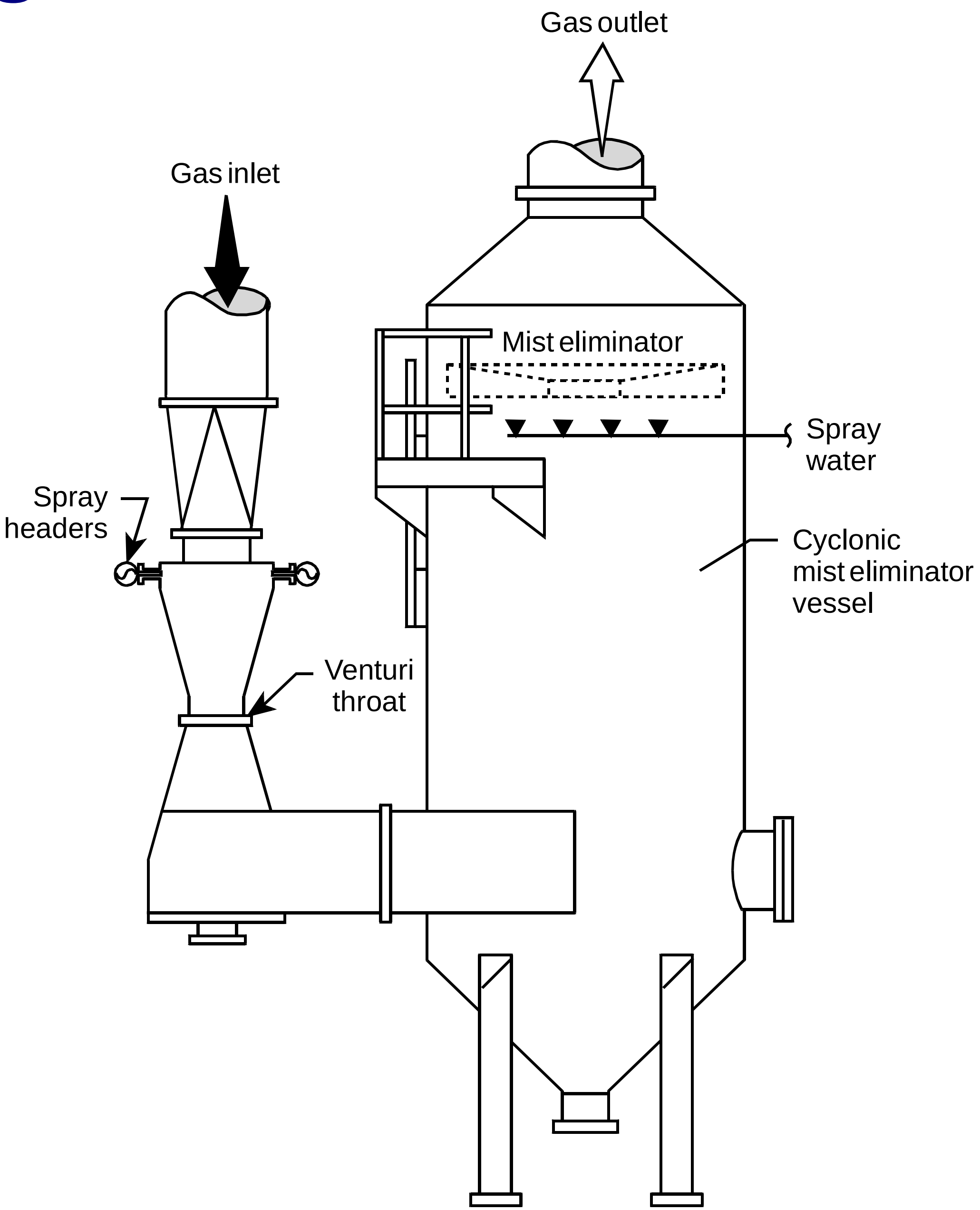
Types of Mist Eliminators

- Chevrons
- Mesh and woven pads
- Cyclones


Clean exhaust gas
Exhaust gas
containing droplets



Cyclones



Gas outlet
Gas inlet
Mist eliminator
Spray water
Spray headers
Cyclonic mist eliminator vessel
Venturi throat

Mist Eliminator Velocity

$$\text{Velocity} = \frac{\text{Gas flow rate (ACFM) (min/60 sec)}}{\text{Mist eliminator area (ft}^2\text{)}}$$

Maximum Velocities

Mist Eliminator Type	Orientation	Maximum Gas Velocity, ft/sec
Zigzag	Horizontal	15 – 20
Zigzag	Vertical	12 – 15
Mesh Pad	Horizontal	15 – 23
Mesh Pad	Vertical	10 – 12
Woven Pad	Vertical	8 – 15
Tube Bank	Horizontal	18 – 23
Tube Bank	Vertical	12 – 16

Example 8-4

Estimate the gas velocity through a mist eliminator having a diameter of 6.5 feet, an average gas flow rate of 4,000 dscfm*, and a peak gas flow rate of 4,760 dscfm.

The peak gas stream temperature is 130°F, the static pressure during peak flow in the vessel is –30 in. WC, and the barometric pressure is 29.4 in. Hg.

The moisture content of the gas stream is 6% by volume.

*dscfm = dry standard cubic feet per minute

Solution

The gas velocity should be evaluated under peak flow conditions because this is the time when reentrainment is most probable.

Convert the gas flow rate to actual conditions:

$$\text{scfm} = \frac{\text{dscfm}}{\left(\frac{100 - \%\text{H}_2\text{O}}{100}\right)} = \frac{4{,}760\,\text{dscfm}}{\left(\frac{100-6}{100}\right)} = 5{,}064\,\text{scfm}$$

Solution (continued)

$$\text{Absolute pressure} = 29.4\,\text{in. Hg} + \left[-30\,\text{in. WC}\left(\frac{1\,\text{in. Hg}}{13.6\,\text{in. WC}}\right)\right] = 27.19\,\text{in. Hg}$$

Absolute temperature = 130°F + 460° = 590°R

$$\text{acfm} = 5{,}064\left(\frac{590°\text{R}}{528°\text{R}}\right)\left(\frac{29.92\,\text{in. Hg}}{27.19\,\text{in. Hg}}\right) = 6{,}227\,\text{acfm}$$

$$\text{Area} = \frac{\pi d^2}{4} = \frac{\pi(6.5\,\text{ft})^2}{4} = 33.2\,\text{ft}^2$$

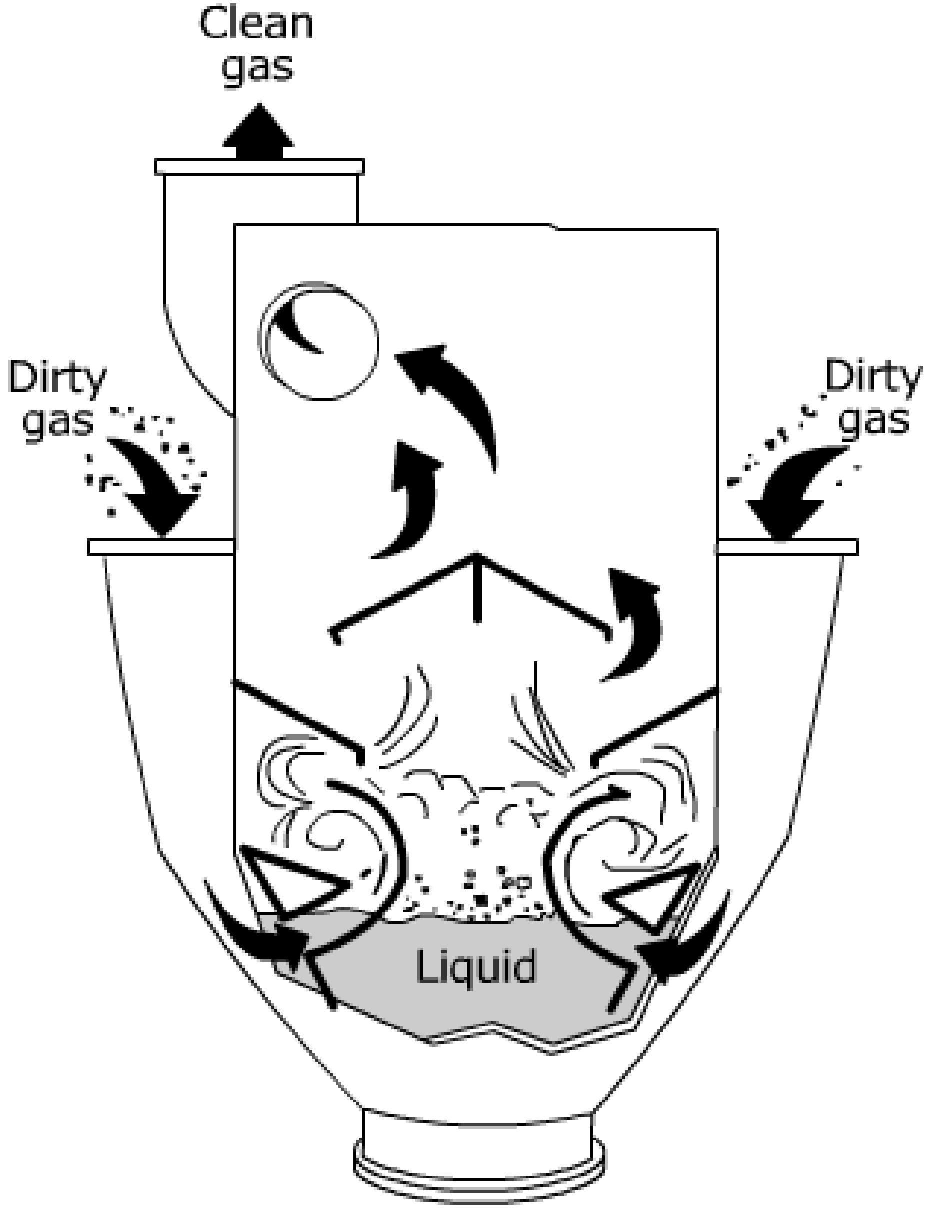
$$\text{Velocity} = \frac{6{,}227\,\frac{\text{ft}^3}{\text{min}}\left(\frac{\text{min}}{60\,\text{sec}}\right)}{33.2\,\text{ft}^2} = 3.13\,\text{sec}$$

Scrubber Systems

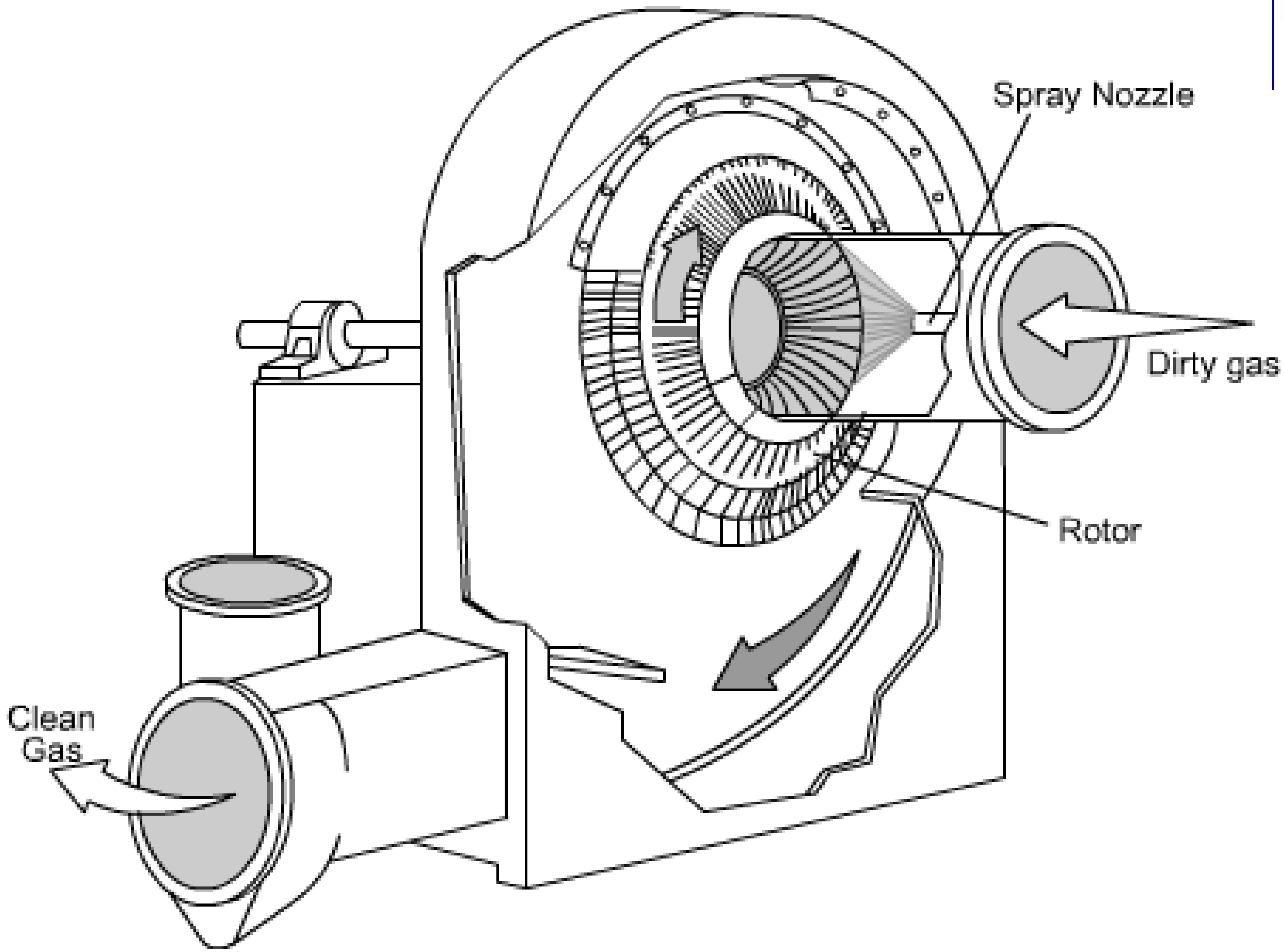
- Spray tower scrubbers
- Orifice scrubbers
- Mechanically aided scrubbers
- Packed bed scrubbers
- Ionizing wet scrubbers
- Tray or plate scrubbers
- Catenary grid scrubbers
- Venturi scrubbers
- Collision scrubbers

Spray Tower

Orifice Scrubber



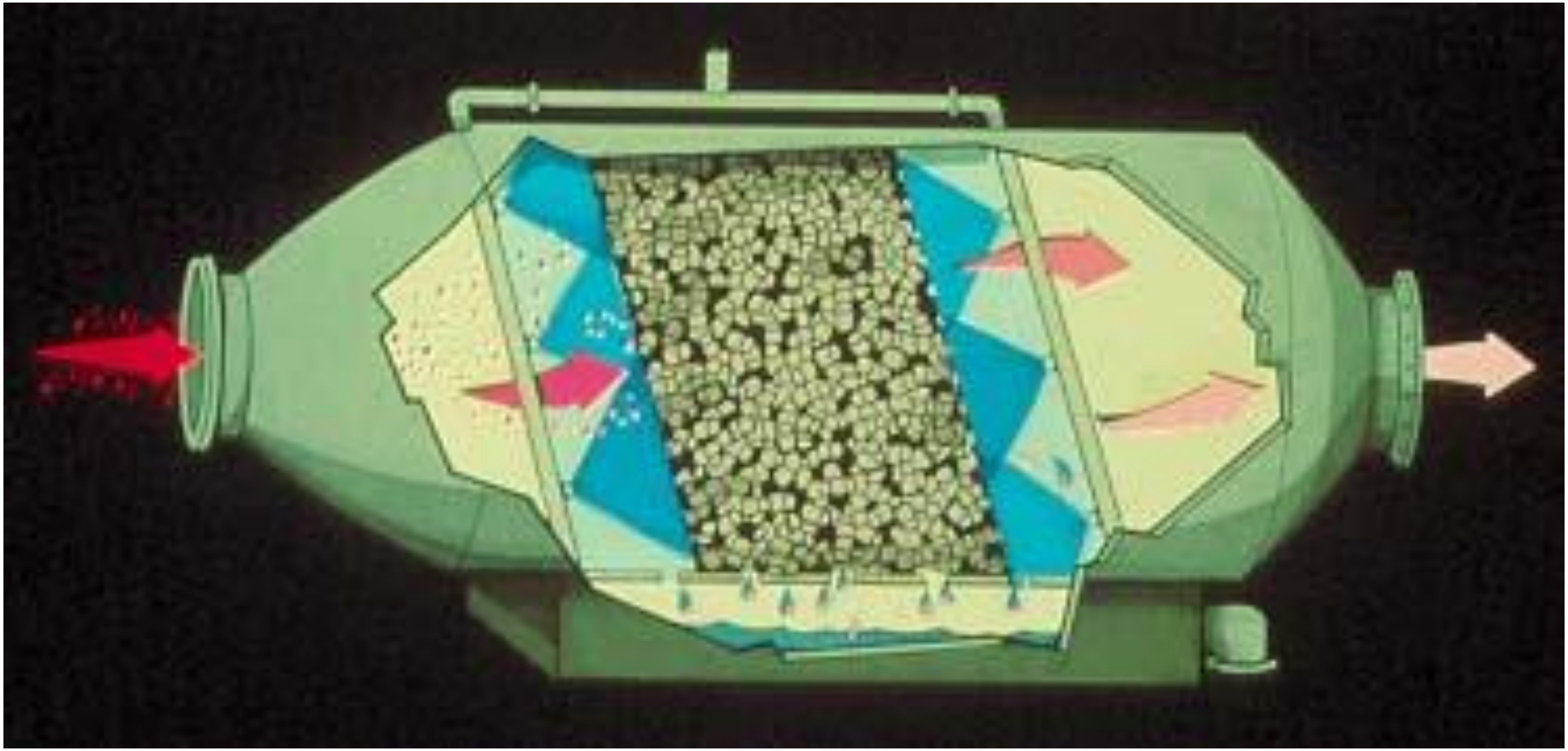
Mechanically Aided Scrubber

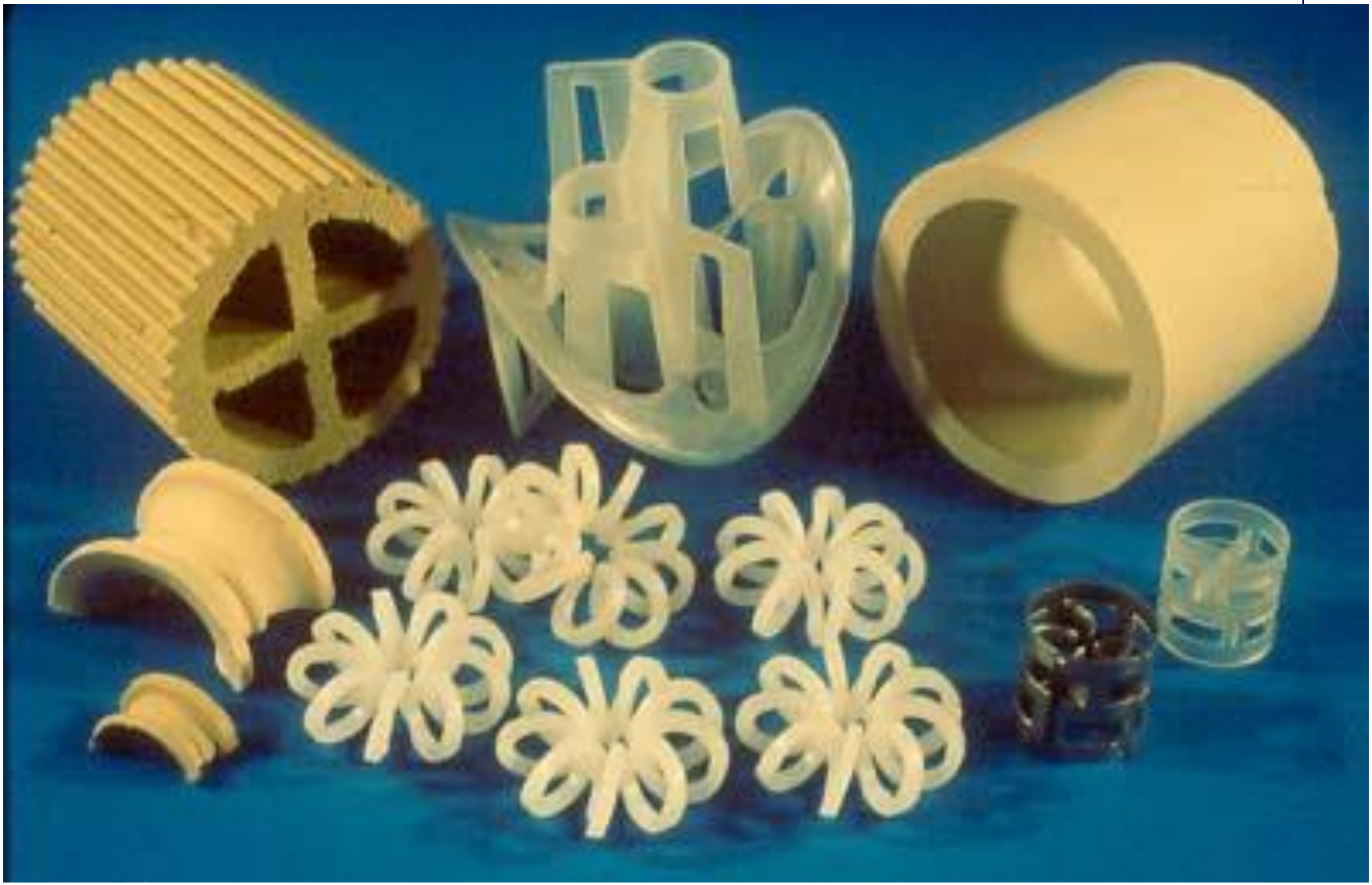



clean gas
mist eliminator
scrubber liquor
packing
feed gas
to drain

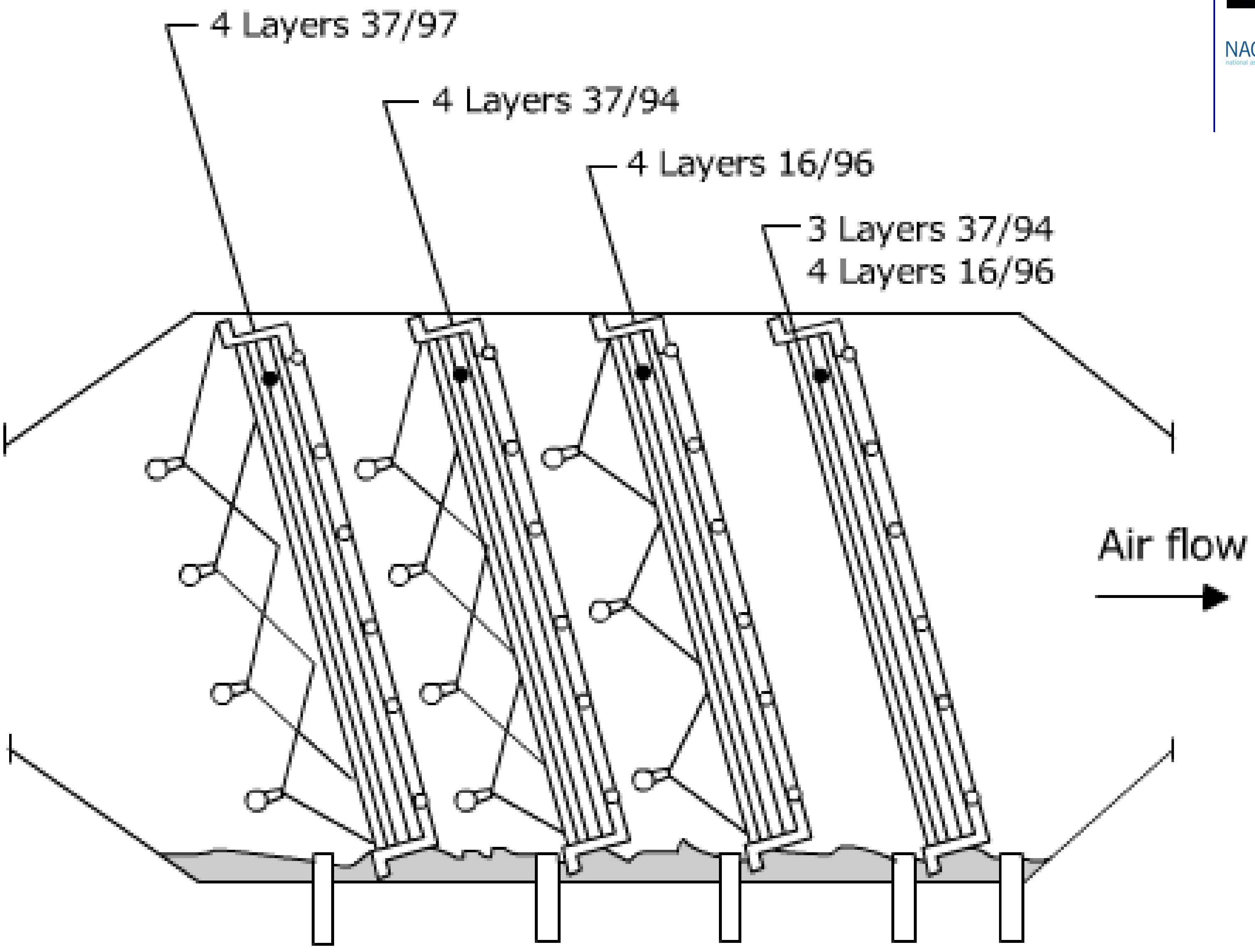
Packed Bed

Horizontal Packed Bed

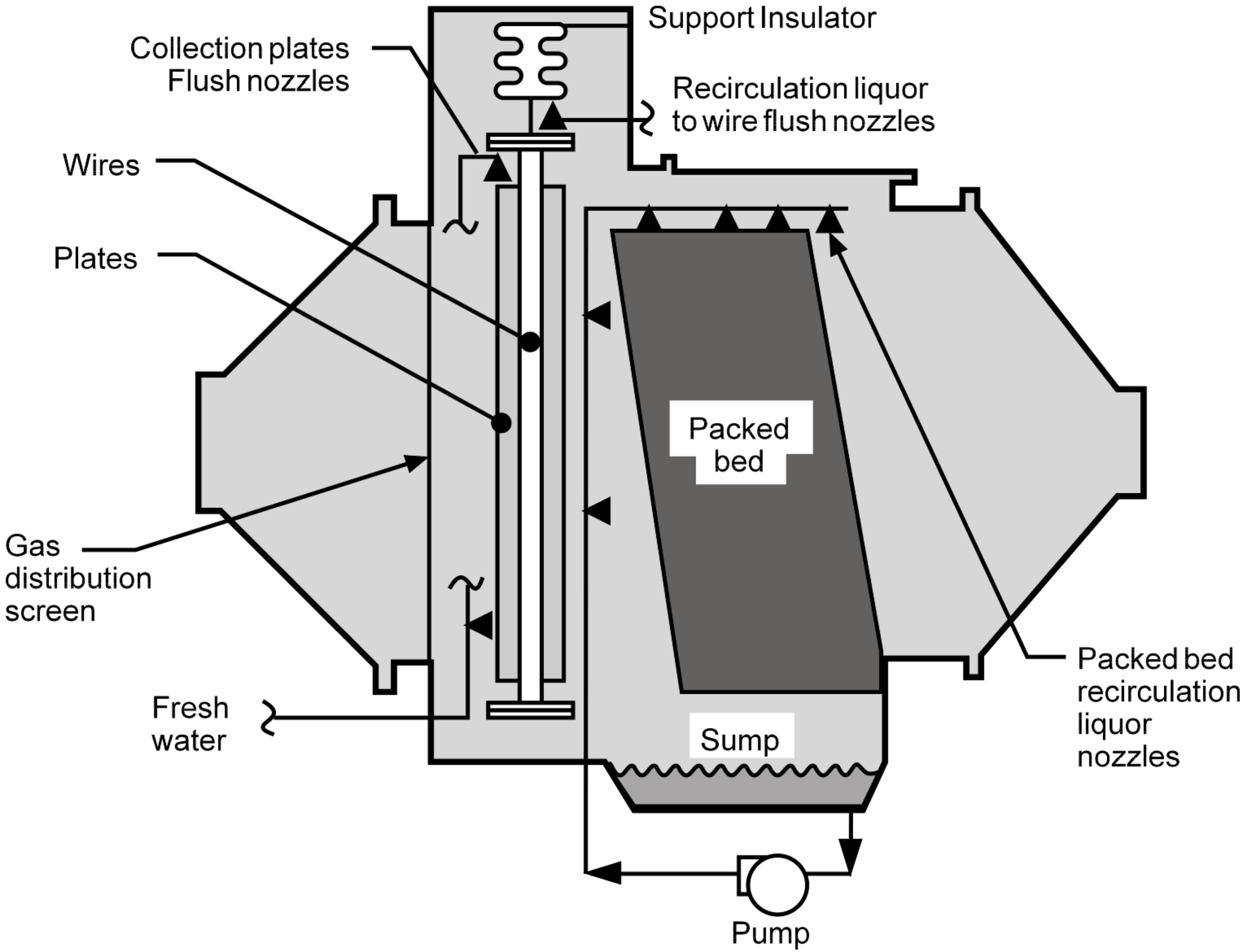


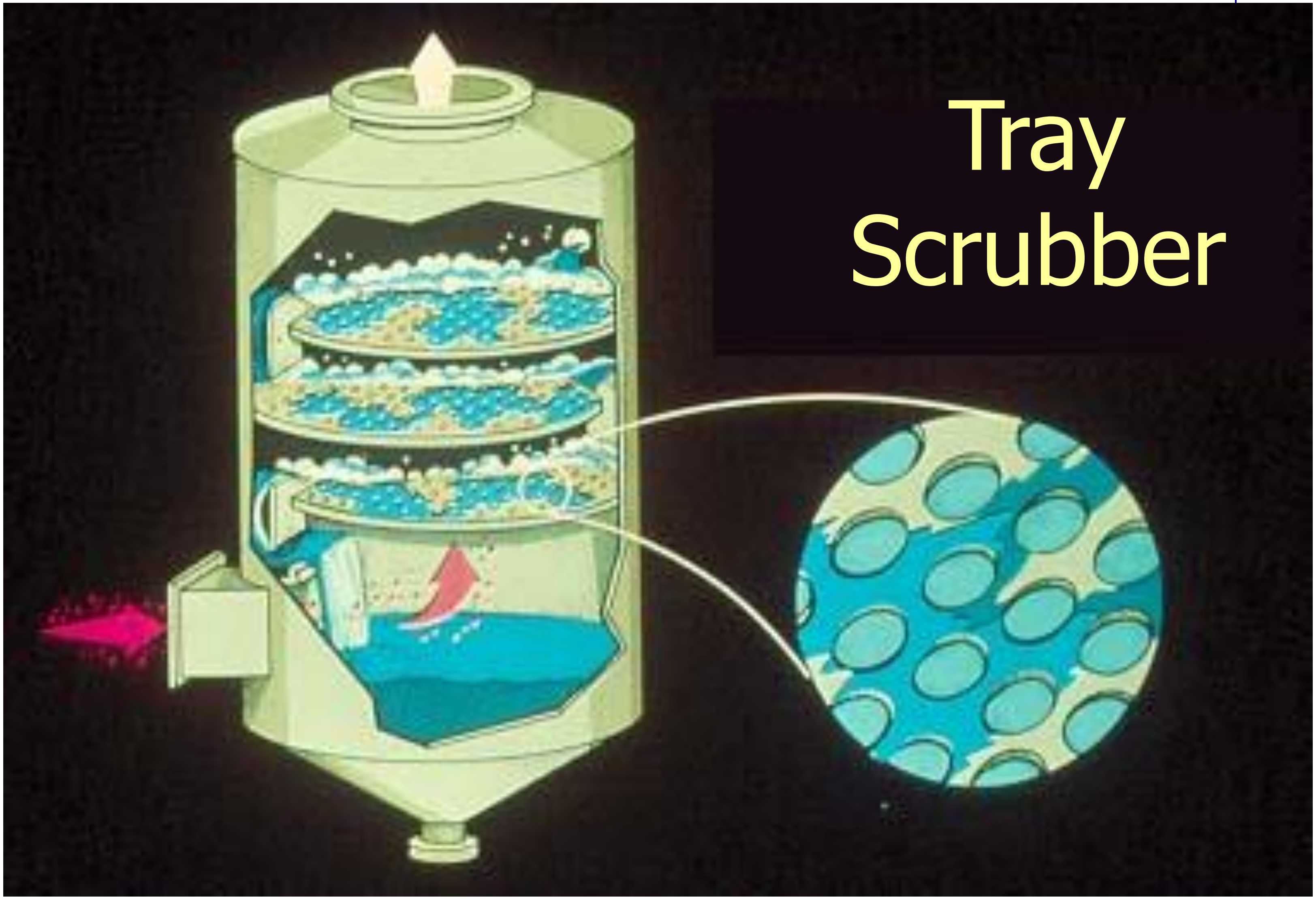


Fiber Bed Scrubber

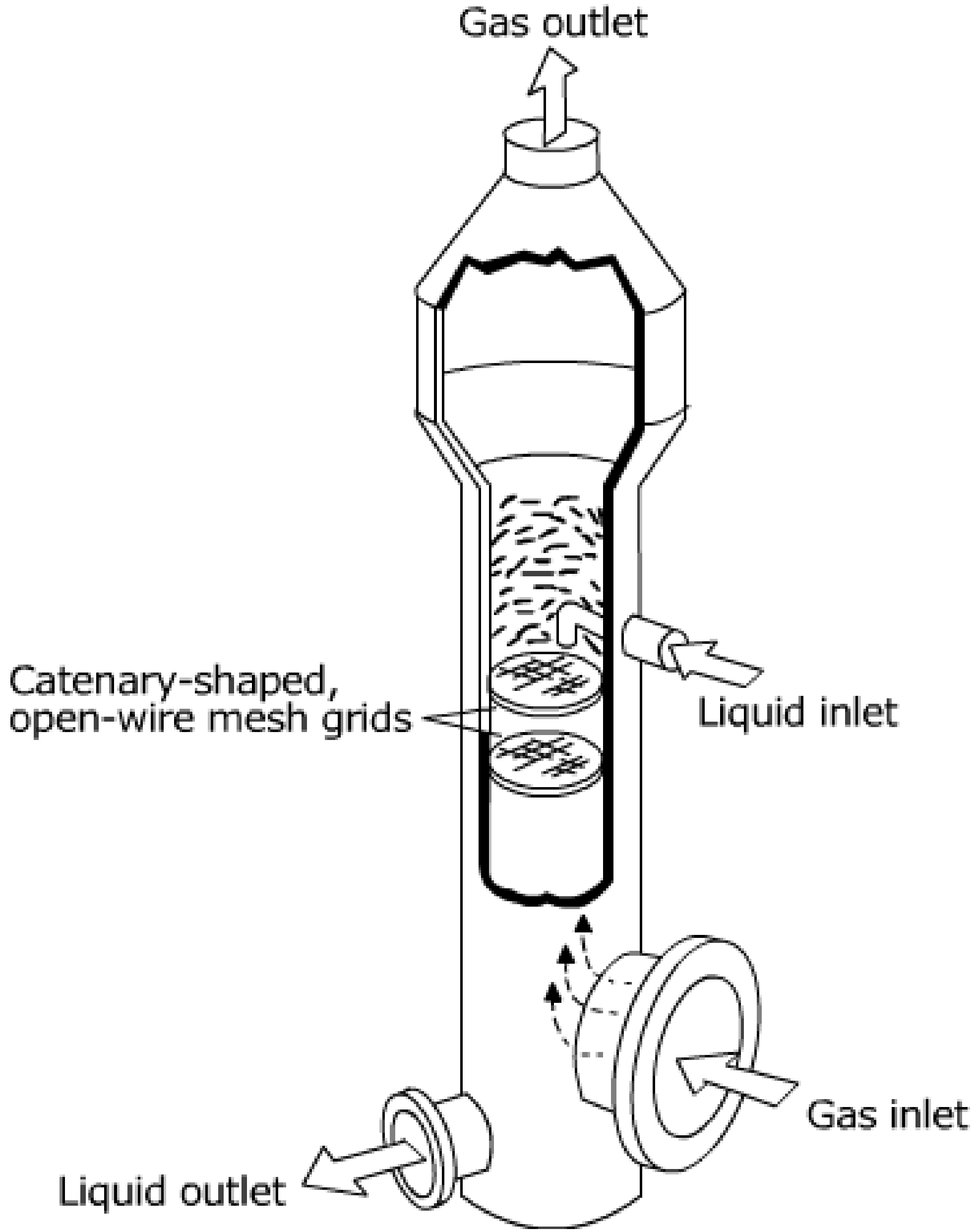


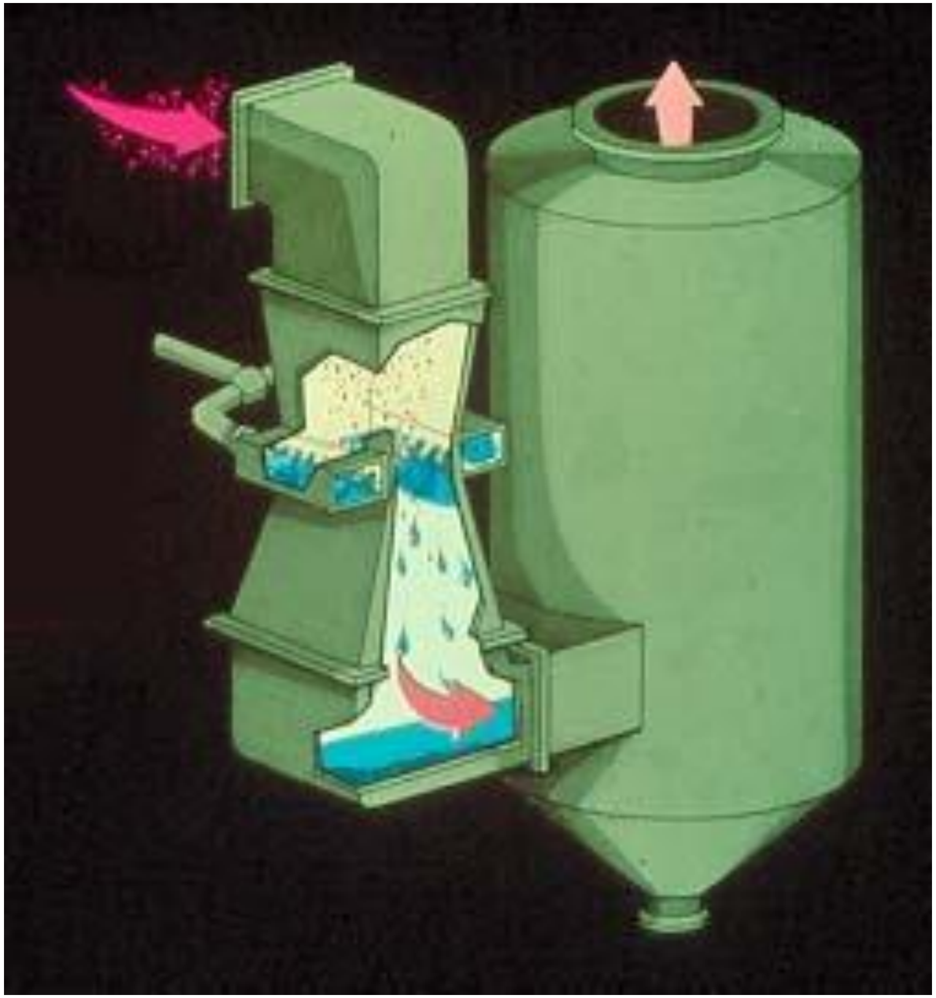
Ionizing Wet Scrubber




Tray
Scrubber

Catenary Grid Scrubber

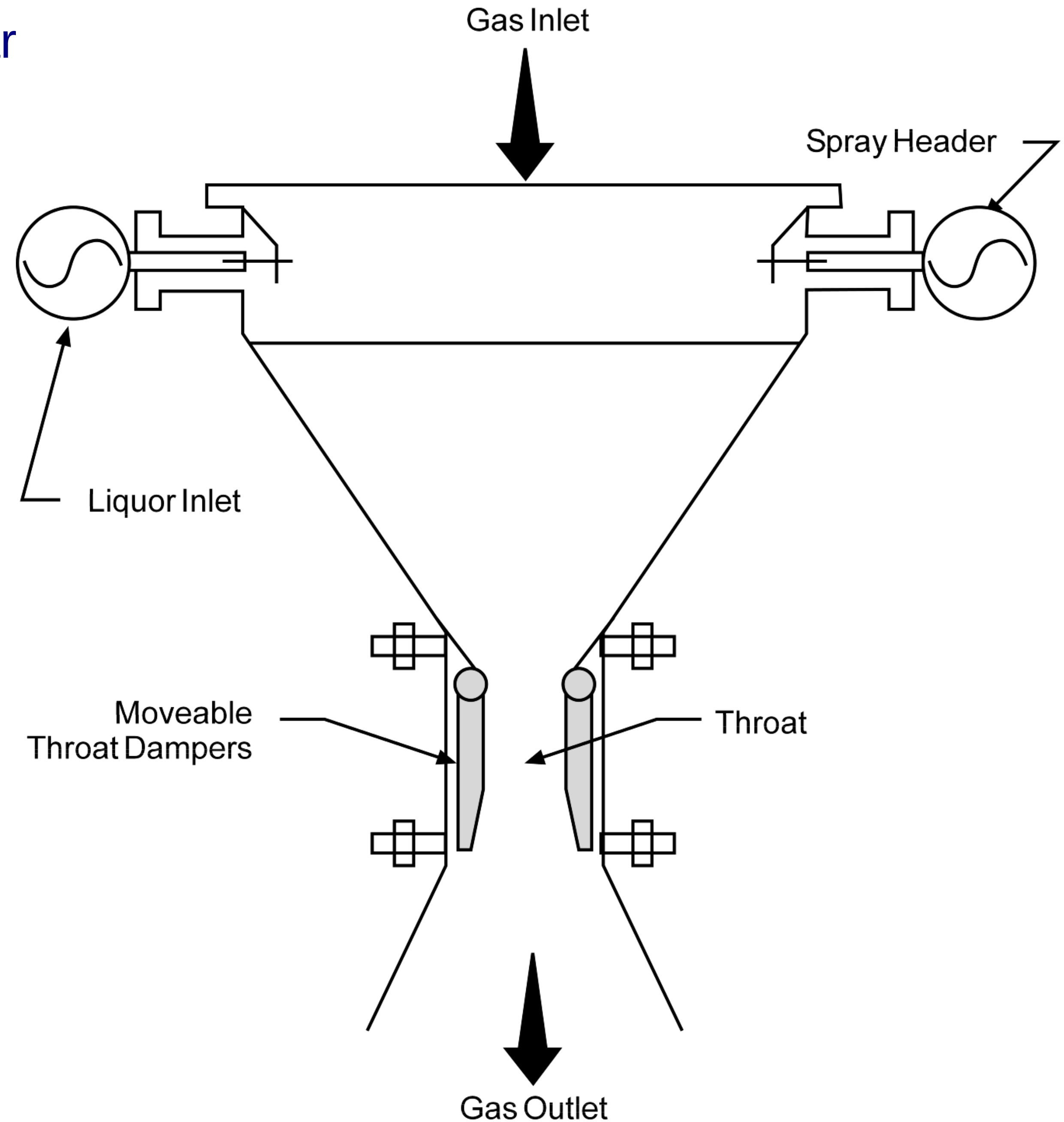




Venturi Scrubber

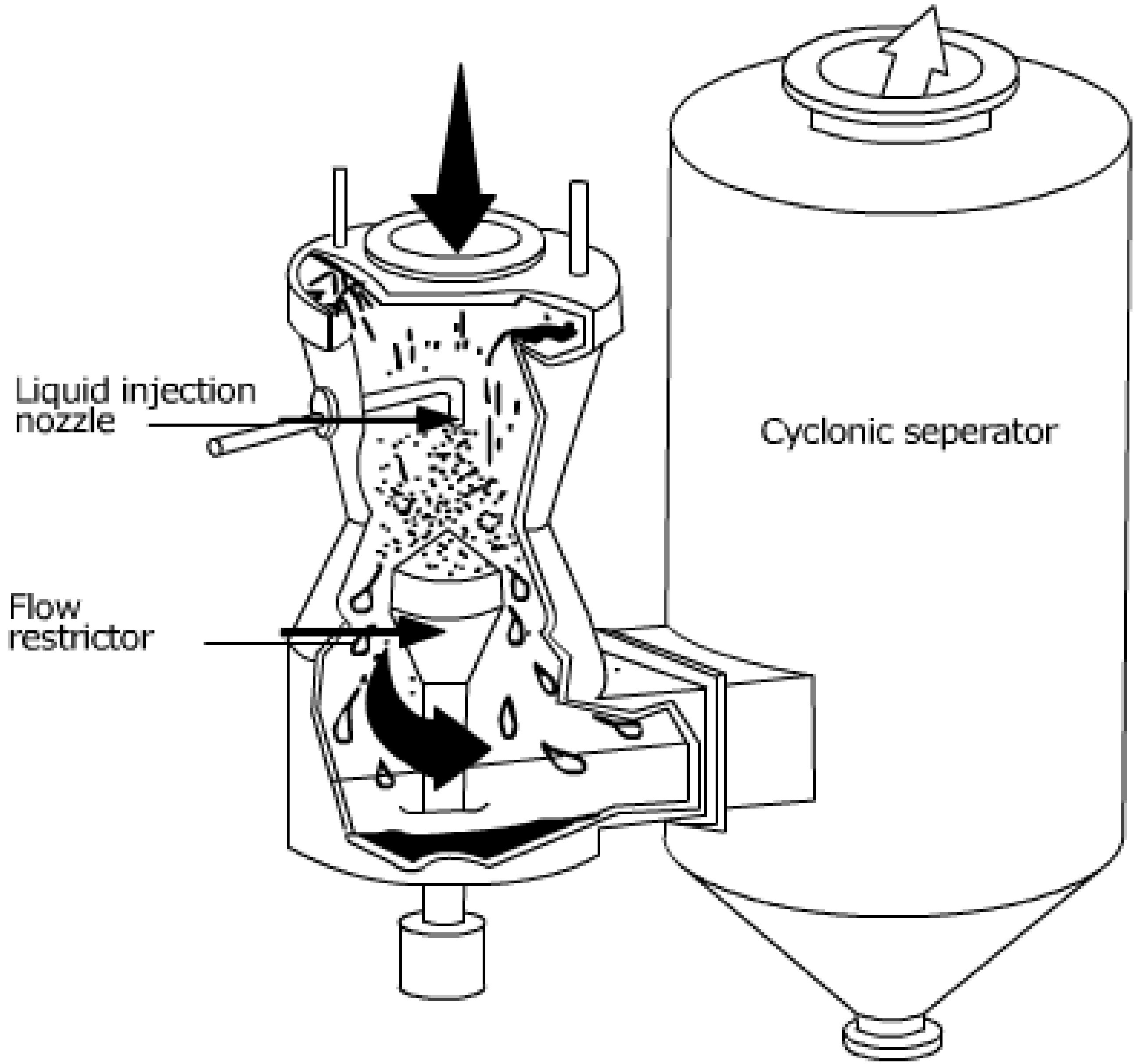
Adjustable Throat Venturi

Rectangular

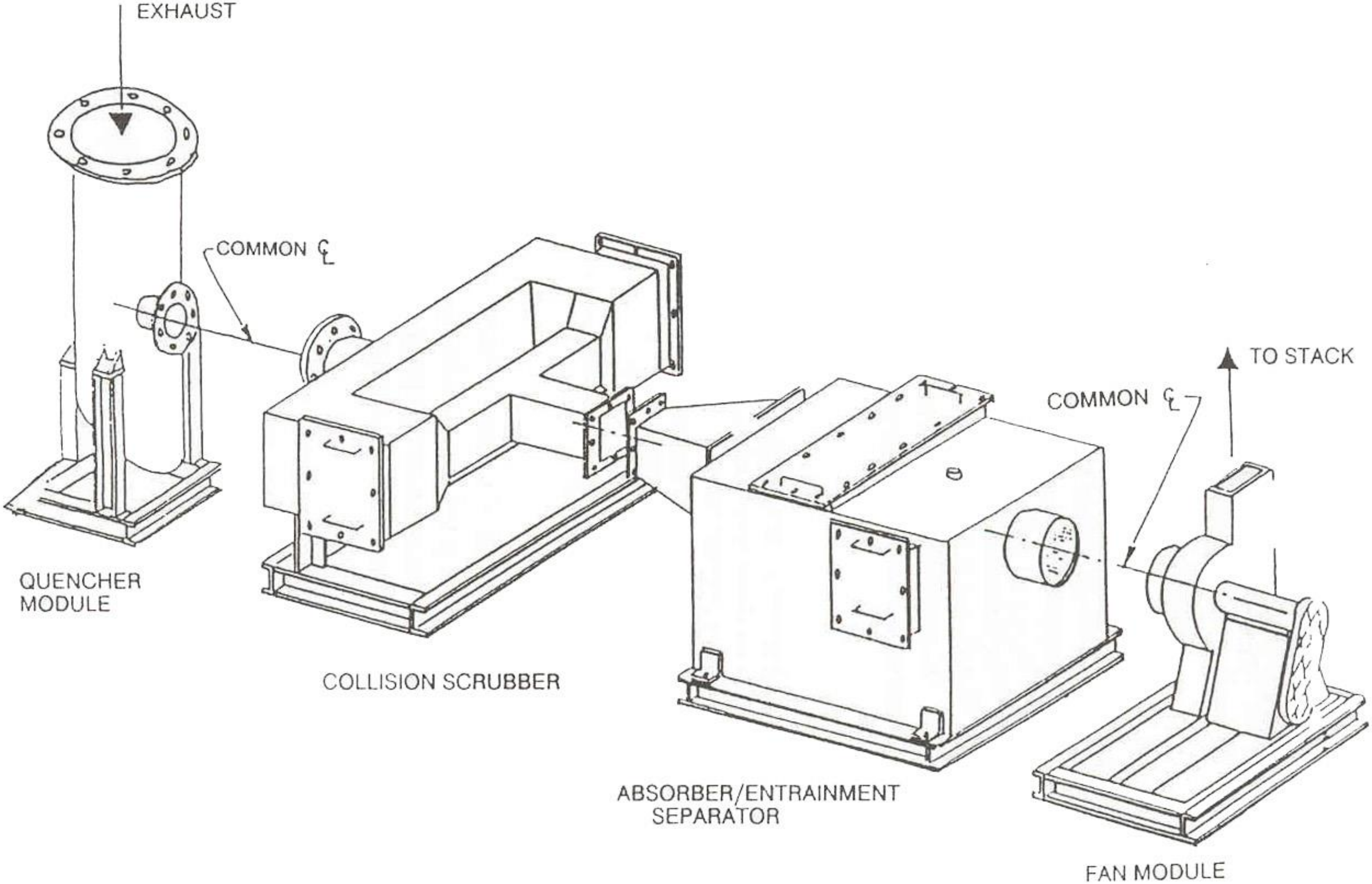


Adjustable Throat Venturi

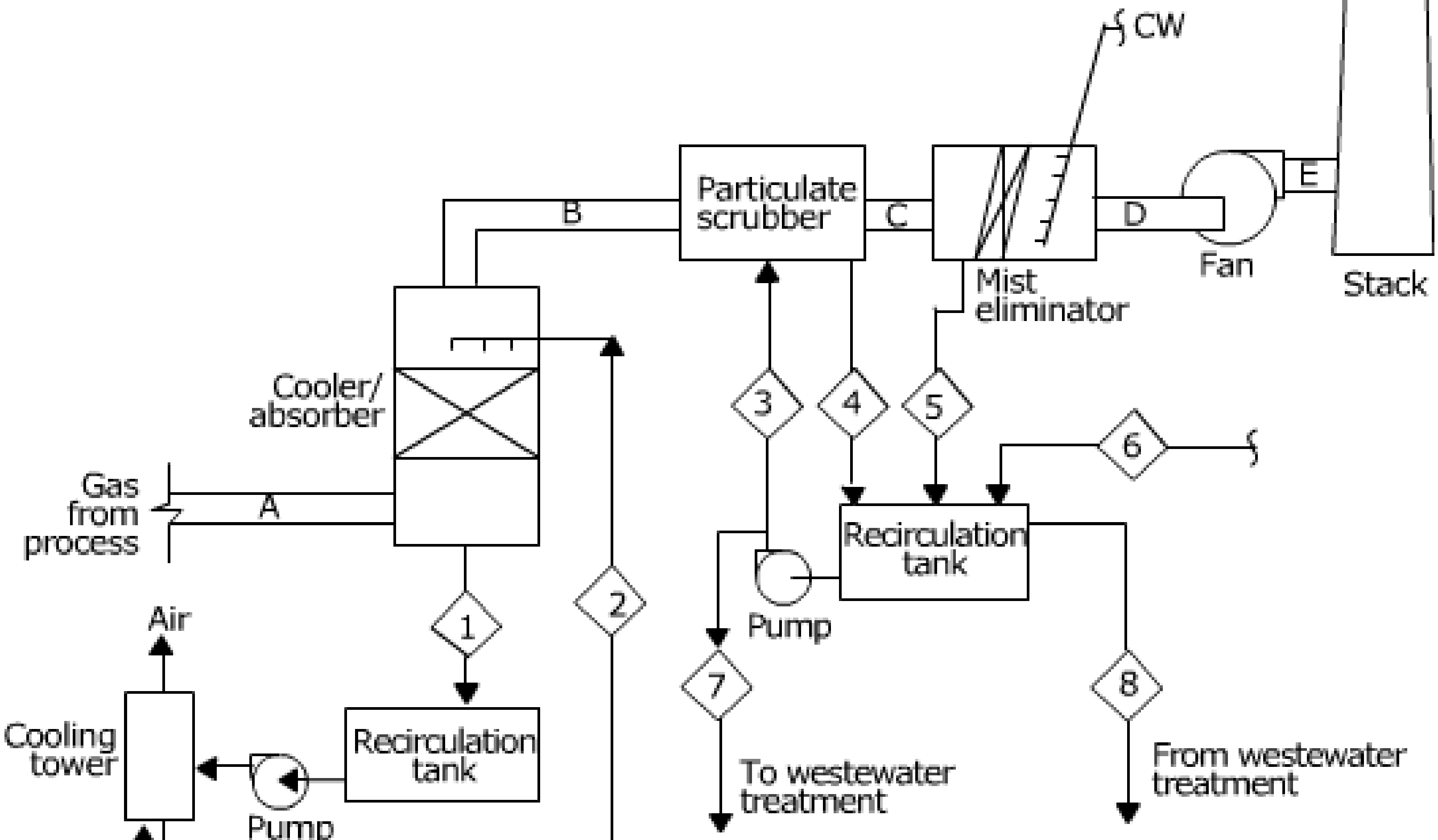
Circular



Collision Scrubber



Condensation Growth Scrubbers



Performance Evaluation

- Empirical evaluation
- Pilot scale tests
- Theoretical models

Inertial Impaction Parameter

$$\Psi = \frac{C_c d_p^{\,2} \rho_p V}{18 \mu_g D_c}$$

where

C_c = Cunningham slip correction factor

d_p = physical particle diameter, cm

ρ_p = particle density, gm/cm^3

V = difference in velocities of particle and target, cm/sec

D_c = target diameter, cm

μ_g = gas viscosity, gm/cm • sec

Yung et al. Venturi Scrubber Model

$$\eta_i = 1 - e^{-B\frac{4\Psi + 4.2 - 5.02\Psi^{0.5}\left(1+\frac{0.7}{\Psi}\right)\tan^{-1}\sqrt{\frac{\Psi}{0.7}}}{\Psi + 0.7}}$$

where η_i= penetration for particle size i
B = parameter defined below
Ψ = impaction parameter at throat entrance, dimensionless

$$B = \left(\frac{L}{G}\right)\frac{\rho_l}{\rho_g C_D}$$

where
L/G = liquid to gas ratio, dimensionless
$\rho_{1,}$ ρ_g= liquid and gas density, kg/m^3
C_D = drag coefficient (liquid at the throat)

$$\Psi = \frac{d^2 v_{gt} C_c \rho_p}{9\mu_g d_d}$$

d = particle physical diameter, cm
v_{gt} = gas velocity in throat, cm/sec
μ_g = gas viscosity, gm/cm·sec
d_d = droplet diameter, cm
C_c = Cunningham slip corr. factor
ρ_p = particle density (gm/cm^2)

Calvert Spray Tower Model

$$P_i = e^{-\left[\frac{0.75\, v_t \eta_i Z}{r_d (v_t - v_{G})}\right]\left[\frac{L}{G}\right]} \qquad \eta_i = \left[\frac{\Psi_i}{(\Psi_i + 0.7)}\right]^2$$

where

P_i	= penetration for particle size I (penetration = 1 – collection efficiency)
Ψ_i	= impaction parameter, dimensionless
v_t	= droplet terminal settling velocity, cm/sec.
η_i	= efficiency due to impaction parameter, dimensionless
Z	= scrubber height, cm
r_d	= droplet radius, cm
v_G	= gas superficial velocity, cm/sec
L/G	= liquid to gas ratio, dimensionless

Calvert Tray Tower Model

An equation for estimating the collection efficiency of a single size particle has been developed by Calvert et al for counter-current spray tower scrubbers:

$$\eta_i = 1 - e^{-\left[\frac{1.5 v_t \eta_I z}{d_d \left(v_t - v_g\right)}\right]\left(\frac{L}{G}\right)}$$

Where:

η_i = collection efficiency for particle size i
v_t = droplet terminal settling velocity (cm/sec)
η_I = single droplet collection efficiency due to impaction (dimensionless)
z = scrubber height (cm)
d_d = droplet diameter (cm)
v_g = gas velocity (cm/sec)
L/G = liquid to gas ratio (dimensionless; i.e., liters/min per liters/min)

Johnstone model for estimating the collection efficiency for a single size particle (Venturi Scrubber)

$$\eta_i = 1 - e^{-k\sqrt{\Psi_I}\frac{Q_l}{Q_g}}$$

Where:

η_i	= collection efficiency for particle size i
k	= constant (1,000 ft3/gal)
Ψ_I	= inertial impaction parameter (dimensionless)
Q_l/Q_g	= liquid to gas ratio (gal/1,000 ft^3)

In this relationship, the inertial impaction parameter is calculated using the gas velocity in the throat. The constant, k, is typically 0.1-0.2 1,000 ft^3/gal.

Instrumentation

- Inlet and outlet gas stream temperatures
- Inlet and purge liquid flow rates
- Recirculation pump discharge pressure
- Liquid distribution header pressure
- Inlet and outlet liquid pH
- Scrubber pressure drop
- Mist eliminator pressure drop

Advantages and Disadvantages

Venturi Scrubbers

Advantages

- High Collection Efficiency
- Capable of Handling Flammable and Explosive Dusts
- Can Handle Mists
- Low Maintenance
- Simple Design and Easy to Install
- Provides Cooling for Hot Gases
- Neutralizes Corrosive Gases and Dusts

Disadvantages

- Waste Water Must be Treated
- Collected Particulates are in Sludge Form
- High Corrosion Potential
- High Pressure Drop
- May Require Protection Against Freezing
- Final Exhaust Must be Reheated
- Sludge Disposal May be Expensive

Review Problems

1. Calculate the liquid-to-gas ratio for a scrubber system with a gas flow rate of 4,000 ft3/sec and a recirculation liquor flow rate of 2,000 gal/min.

Is this value in the normal range for a particulate matter wet scrubber?

Solution

Gas Flow Rate

$$\left(4{,}000\,\frac{\text{ft}^3}{\text{sec}}\right)\left(60\,\frac{\text{sec}}{\text{min}}\right) = 240{,}000\,\frac{\text{ft}^3}{\text{min}}$$

Liquid-to-gas ratio

$$\frac{2{,}000\,\frac{\text{gal}}{\text{min}}}{240\,\frac{1{,}000\ \text{ft}^3}{\text{min}}} = 8.33\,\frac{\text{gal}}{1{,}000\ \text{ft}^3}$$

This is within the normal range of 4-20 gal/1,000 acf

Review Problems

1. Estimate the liquid purge rate for a scrubber system treating a gas stream of 25,000 scfm with a particulate matter loading of 1.0 grains per scf.

Assume that the scrubber particulate matter removal efficiency is 97% and the maximum suspended solids level desirable in the scrubber is 3% by weight.

Solution

Calculate the inlet particulate mass:

$$\text{Inlet mass} = 25{,}000\,\frac{\text{ft}^3}{\text{min}}\left(\frac{1.0\,\text{grains}}{\text{ft}^3}\right)\left(\frac{\text{lb}}{7{,}000\,\text{grains}}\right) = 3.57\,\frac{\text{lb}}{\text{min}}$$

And then…

Solution #2 (continued)

Collected mass = 0.97 (Inlet mass) = $3.46 \dfrac{\text{lb}}{\text{min}}$

Purge solids of 3.46 lb/min are 3% of the total purge stream, therefore:

$$\text{Purge stream} = \frac{3.46 \dfrac{\text{lb}}{\text{min}}}{0.03} = 115.3 \frac{\text{lb}}{\text{min}}$$

And then…

Solution #2 (continued)

A stream with 3% suspended solids has a specific gravity of about 1.03, therefore:

$$\text{Purge stream density} = \left(8.34\,\frac{\text{lb water}}{\text{gal}}\right)(1.03) = 8.59\,\frac{\text{lb}}{\text{gal}}$$

$$\text{Purge stream flow rate} = \frac{115.3\,\frac{\text{lb}}{\text{min}}}{8.59\,\frac{\text{lb}}{\text{gal}}} = 13.4\,\frac{\text{gal}}{\text{min}}$$

Review Problem #3

3. A chevron mist eliminator is 8 ft in diameter. The gas flow rate through the scrubber system has been measured at 60,500 acfm.

a. What is the average velocity through the mist eliminator?

b. What is the average velocity if 40% of the mist eliminator is completely blocked due to solids accumulation? Is this velocity within the normal operating range of a vertically mounted chevron mist eliminator?

Solution for part a:

$$V = \frac{Q}{A}$$

$$A = \frac{\pi D^2}{4} = \frac{\pi (8\,ft)^2}{4} = 50.3\ ft^2$$

$$V = \frac{\left(60{,}500\,\frac{ft^3}{min}\right)\left(\frac{min}{60\,sec}\right)}{50.3\ ft^2} = 20.0\,\frac{ft}{sec}$$

Solution for part b:

$$A_{open} = 0.6A = 0.6(50.3) = 30.2\ ft^2$$

$$V = \frac{\left(60{,}500\,\frac{ft^3}{min}\right)\left(\frac{min}{60\,sec}\right)}{30.2\ ft^2} = 33.4\,\frac{ft}{sec}$$

This is not within normal operating range.

Review Problem #4

4. Estimate the collection efficiency of 5 μm diameter particles with a density of 2.0 g/cm^3 in a counter-current spray tower 2.5 meters high. The gas flow rate is 200 m^3/min, the water flow rate is 150 l/min, the gas velocity is 100 cm/sec, and the mean droplet diameter is 800 μm.

Assume a temperature of 20°C and a Cunningham correction of 1.0.

Solution #4

Calculate the droplet terminal settling velocity:

Determine the flow region:

$$K = d_p \left(\frac{g \rho_p \rho_g}{\mu_g^2} \right)^{0.33}$$

$$= 800 \times 10^{-4}\,\text{cm} \left[\frac{\left(980 \frac{\text{cm}}{\text{sec}^2}\right)\left(1.0 \frac{\text{g}}{\text{cm}^3}\right)\left(1.2 \times 10^{-3} \frac{\text{g}}{\text{cm}^3}\right)}{\left(1.8 \times 10^{-4} \frac{\text{g}}{\text{cm} \cdot \text{sec}}\right)^2} \right]^{0.33} = 25.0$$

Therefore, the flow region is transition.

And then…

Solution #4

$$v_t = \frac{0.153\, g^{0.71} \rho_p^{0.71} d_p^{1.14}}{\mu_g^{0.43} \rho_g^{0.29}}$$

$$= \frac{0.153\left(980\,\frac{cm}{sec}\right)^{0.71}\left(1.0\,\frac{g}{cm^3}\right)^{0.71}\left(800\,x\,10^{-4}\,cm\right)^{1.14}}{\left(1.8\,x\,10^{-4}\,\frac{g}{cm\cdot sec}\right)^{0.43}\left(1.2\,x\,10^{-3}\,\frac{g}{cm^3}\right)^{0.29}} = 327.5\,\frac{cm}{sec}$$

And then…

Calculate the inertial impaction parameter:

Solution #4

$$\Psi_I = \frac{(1.0)\left(5\,x\,10^{-4}\,cm\right)^2\left(2.0\,\frac{g}{cm^3}\right)\left(327.5\,\frac{cm}{sec} - 100\,\frac{cm}{sec}\right)}{18\left(1.8\,x\,10^{-4}\,\frac{g}{cm \cdot sec}\right)\left(800\,x\,10^{-4}\,cm\right)} = 0.439$$

And then…

Calculate the single droplet collection efficiency:

$$\eta_I = \left(\frac{0.439}{0.439 + 0.35}\right)^2 = 0.310$$

And then…

Solution #4

Calculate the particle collection efficiency:

$$\eta = 1 - e^{-\left[\frac{1.5\left(327.5\frac{cm}{\sec}\right)(0.310)(250\,cm)}{\left(800\,x10^{-4}\,cm\right)\left(327.5\frac{cm}{\sec}-100\frac{cm}{\sec}\right)}\right]\left[\frac{\left(150\frac{l}{\min}\right)\left(1x10-3\frac{m^3}{\min}\right)}{200\frac{m^3}{\min}}\right]}$$

$$= 0.792 = 79.2\%$$

Review Problem #5

5. Using the relationship of Johnstone et al, estimate the collection efficiency of a 0.5 μm diameter particle with a density of 1.5 g/cm^3 in a venturi scrubber having a throat gas velocity of 500 ft/sec and a liquid to gas ratio of 10.0 gal/1,000 ft^3.

Assume a temperature of 68°F and a k of 0.15 1,000 ft^3/gal.

Solution #5

Calculate the mean droplet diameter:

$$d_d = \frac{16,400}{500} + 1.45(10.0)^{1.5} = 78.7\,\mu m$$

Calculate the Cunningham correction factor:

$$C_c = 1 + \frac{6.21x10^{-4}\,T}{d_p} = 1 + \frac{6.21x10^{-4}(293K)}{0.5\,\mu m} = 1.36$$

And then…

Solution #5

Calculate the inertial impaction parameter:

$$\Psi_I = \frac{(1.36)(0.5 \text{ x } 10^{-4} \text{ cm})^2 \left(1.5 \frac{\text{g}}{\text{cm}^3}\right)\left(500 \frac{\text{ft}}{\text{sec}} \text{ x } 30.48 \frac{\text{cm}}{\text{ft}}\right)}{18\left(1.8 \text{ x } 10^{-4} \frac{\text{g}}{\text{cm} \cdot \text{sec}}\right)(78.7 \text{ x } 10^{-4} \text{ cm})} = 3.048$$

Calculate the particle collection efficiency:

$$\eta_i = 1 - e^{-0.15 \frac{1{,}000 \text{ ft}^3}{\text{gal}} \sqrt{3.048} \left(10.0 \frac{\text{gal}}{1{,}000 \text{ ft}^3}\right)} = 0.927 = 92.7\%$$

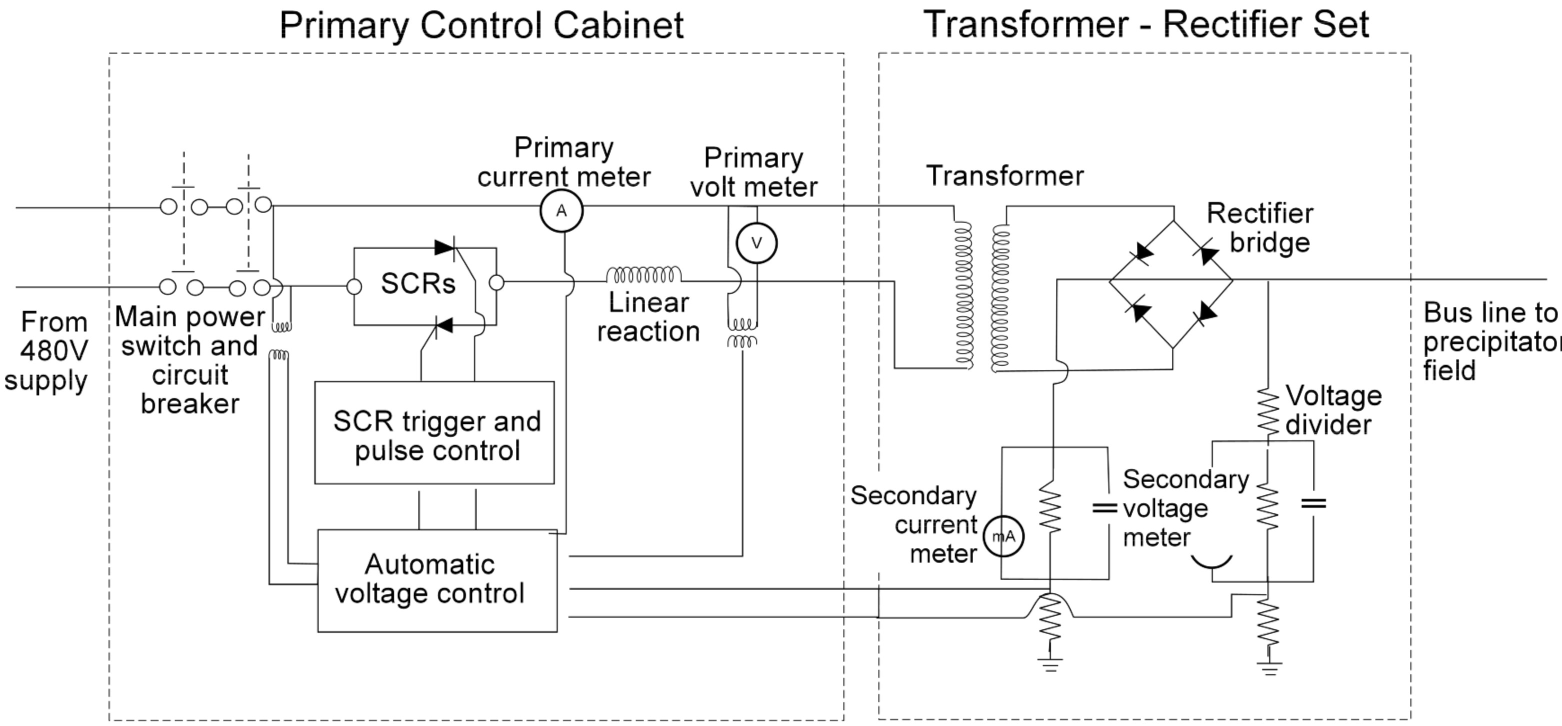
Chapter 9

Electrostatic Precipitators

Particle Collection Steps

- Capture particulate matter on vertical plates using electrostatic attraction
- Remove collected material from the plates
- Dispose of accumulated solids

Precipitator Energization

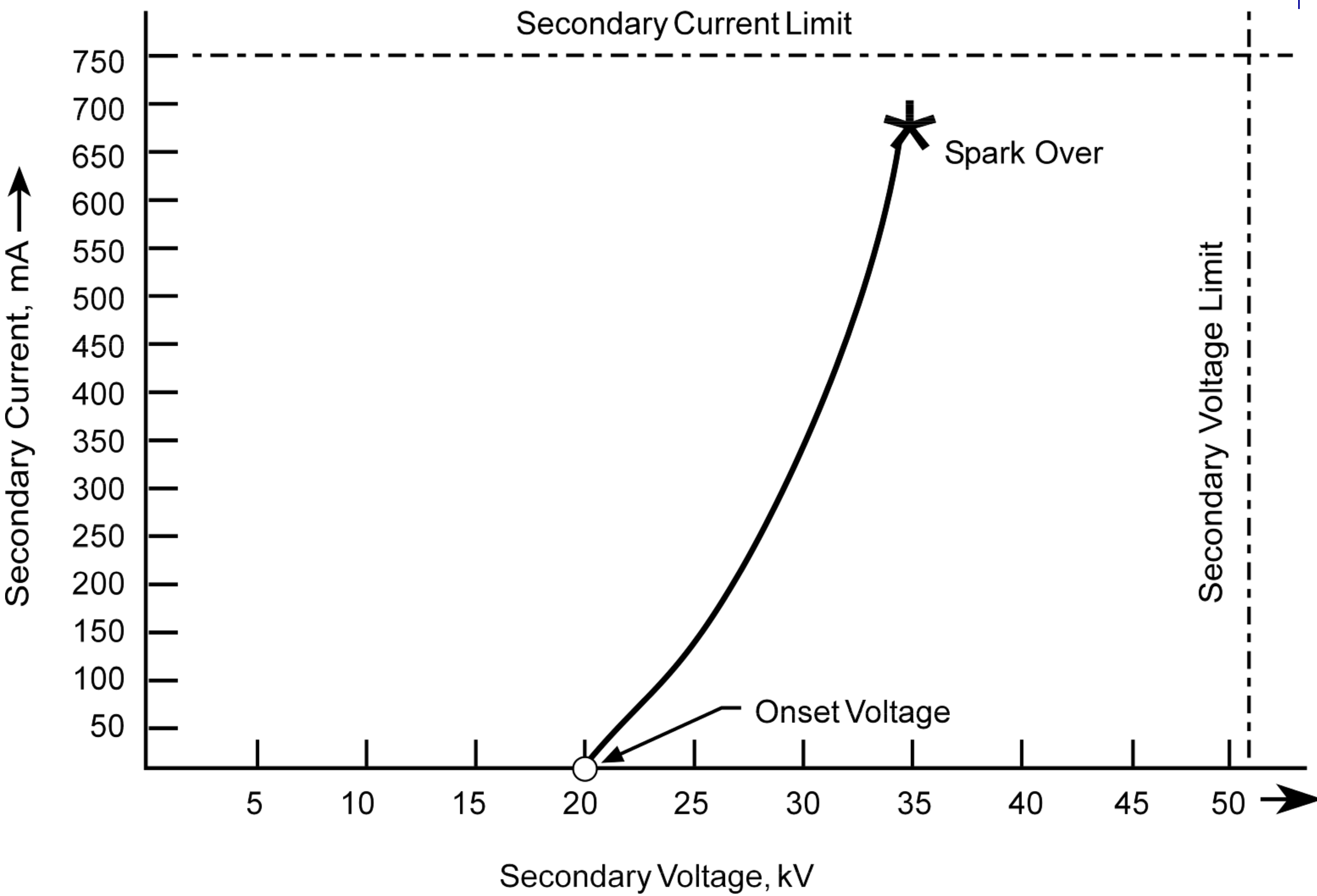


Basic Steps in Energizing a Precipitator Field

- Open/close 480 volt A.C. power supply to the primary control cabinet
- Control voltage and adjust voltage and current waveforms in primary line to the transformer
- Control current flow during sparking
- Increase voltage
- Convert electricity to direct current form

Components

- Main power switch and circuit breaker
- Automatic voltage controller, silicon controlled rectifiers (SCRs), trigger/pulse control for SCRs
- Linear reactor (located adjacent to primary control cabinet)
- Transformer
- Rectifier bridge

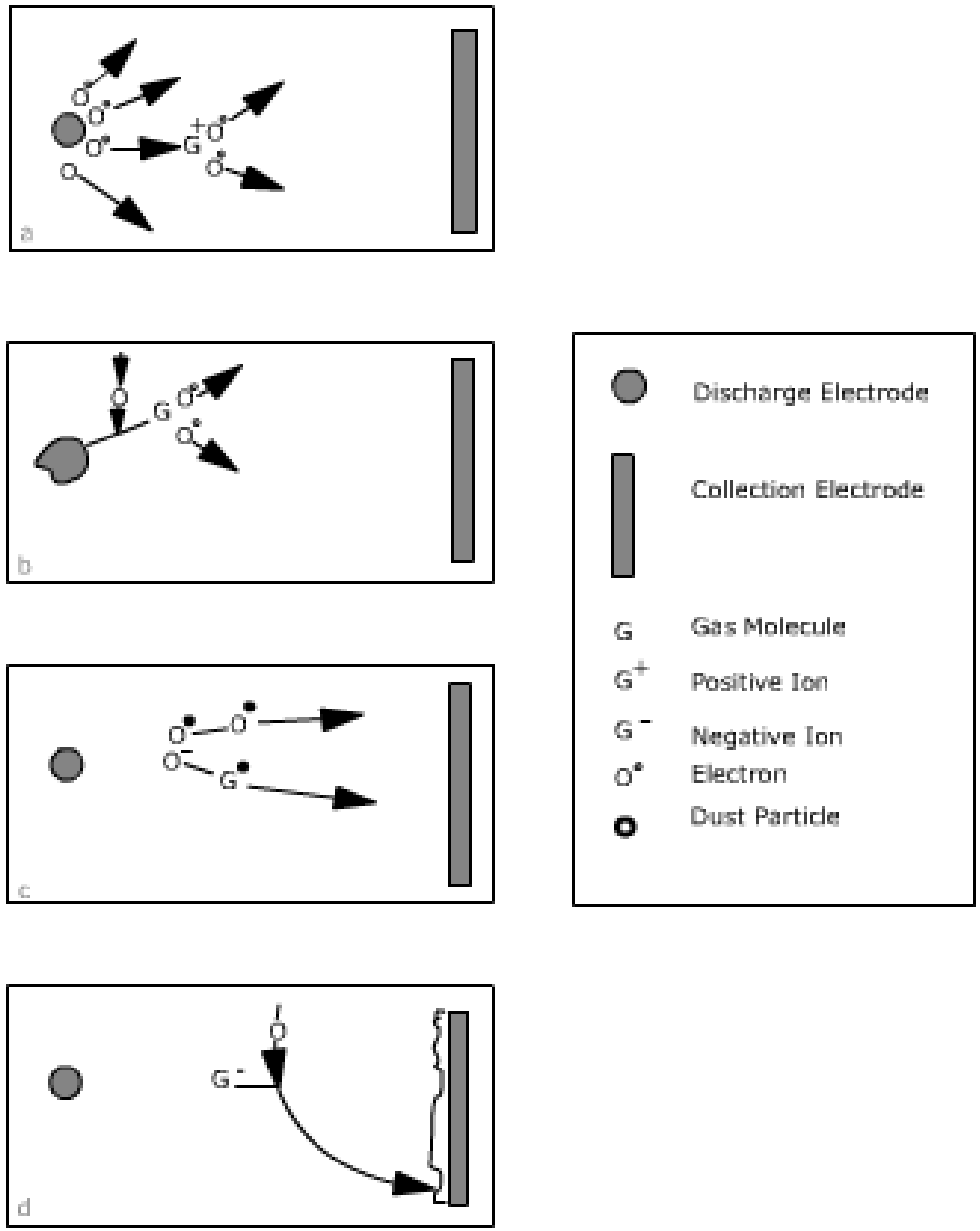


Secondary Current Limit
750
700
650
600
550
500
450
400
350
300
250
200
150
100
50
Secondary Current, mA
Spark Over
Onset Voltage
Secondary Voltage Limit
5
10
15
20
25
30
35
40
45
50
Secondary Voltage, kV

Voltage Limiting Factors

- Primary voltage limit
- Primary current limit
- Secondary voltage limit
- Secondary current limit
- Spark rate limit
- SCR conduction angle

Particle Charging and Migration

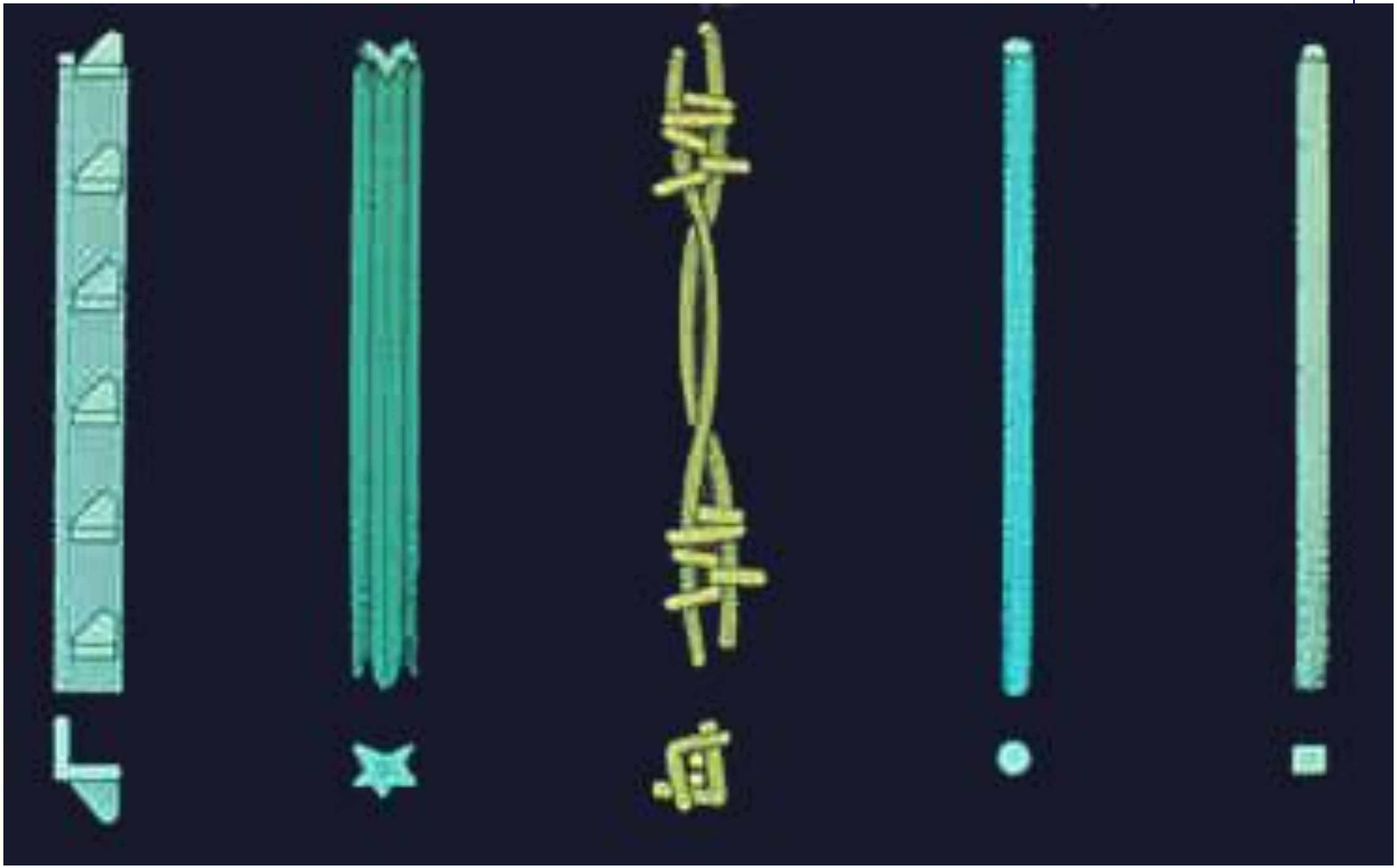


Particle Migration Velocity

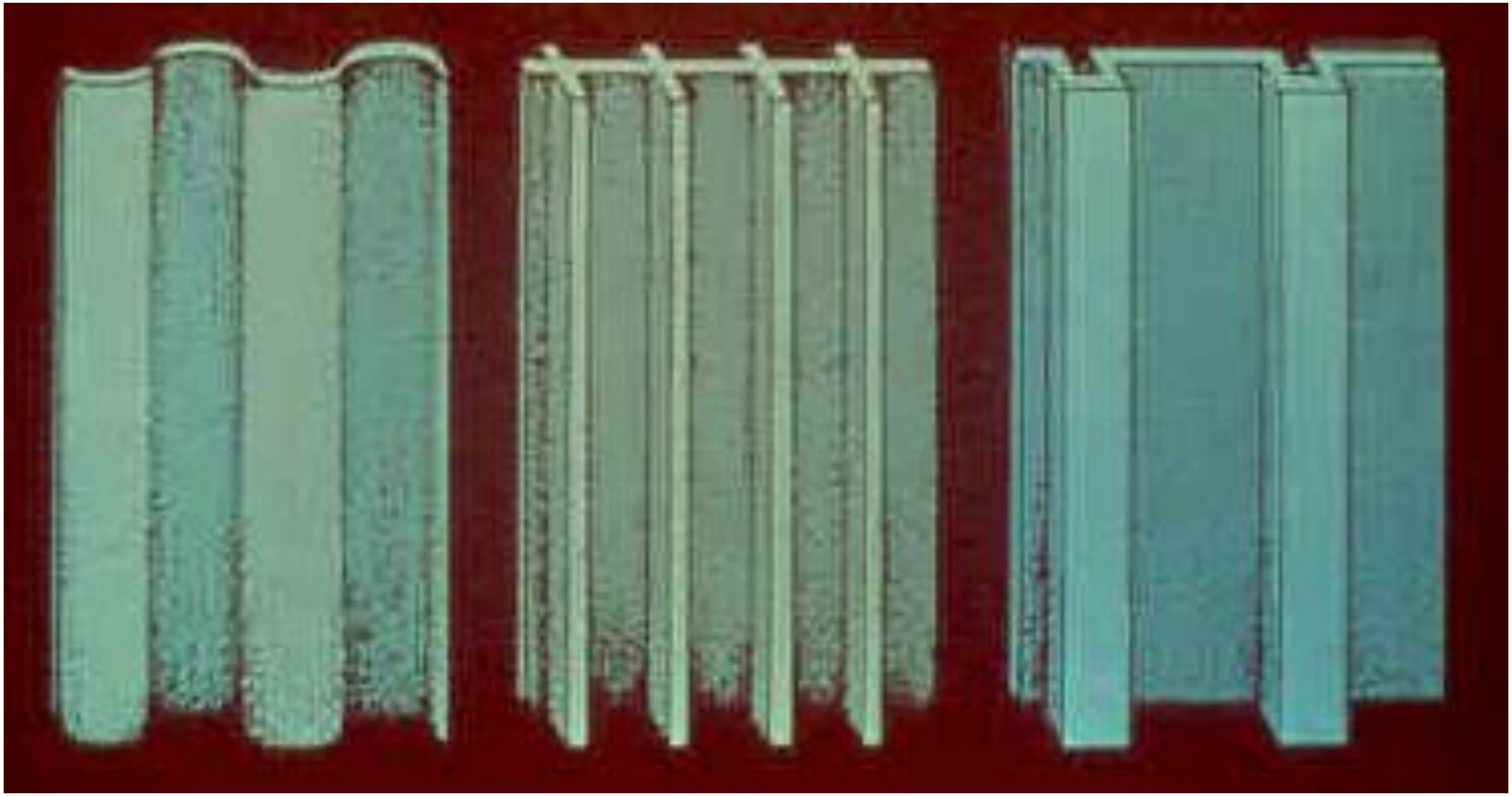
$$\omega = \frac{neEC_c}{3\pi\mu_g d_p}$$

High Voltage System

Discharge Electrodes

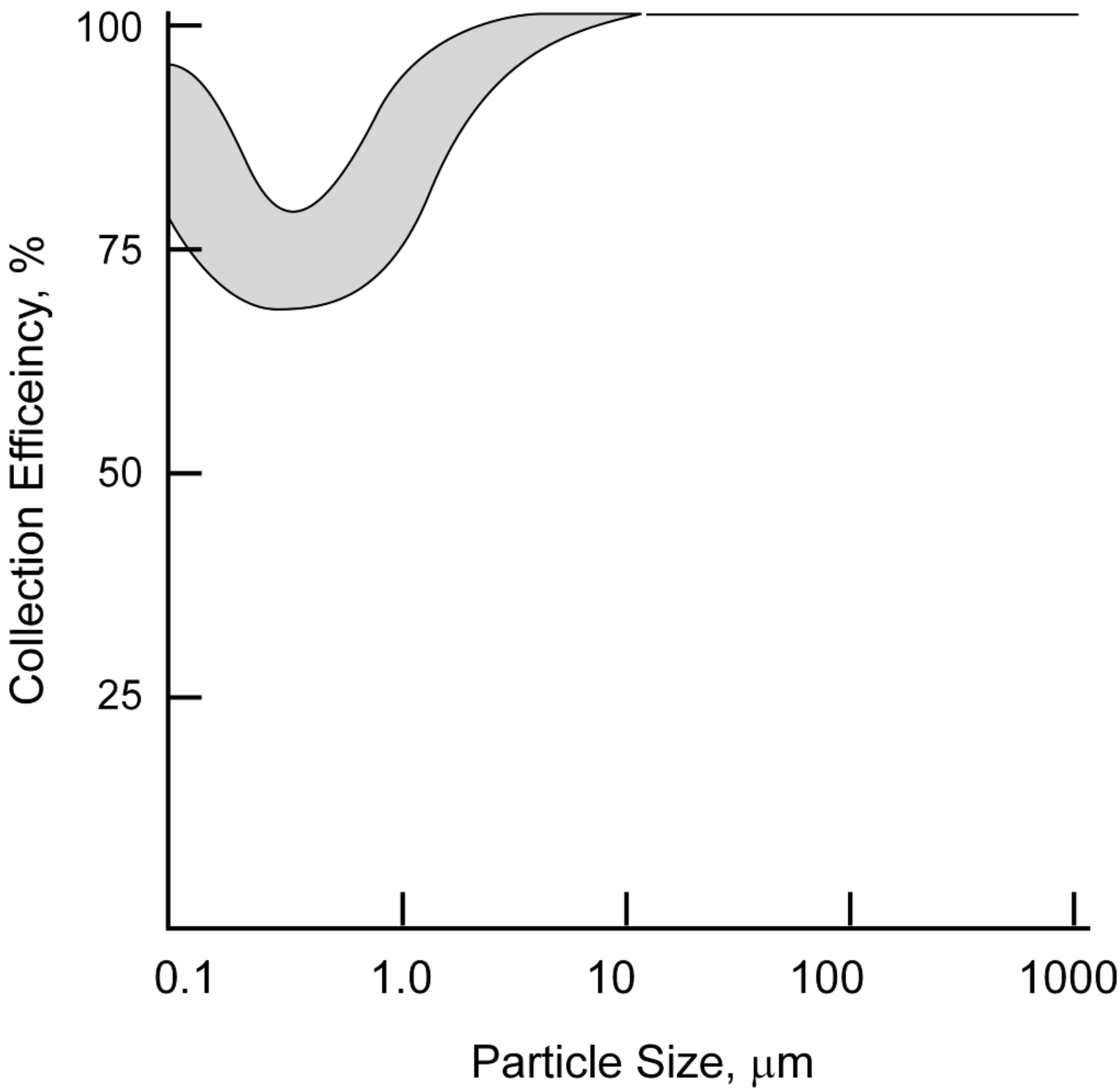


Collection Plates



Collection Mechanisms

- Electrostatic attraction
- Gravitational settling

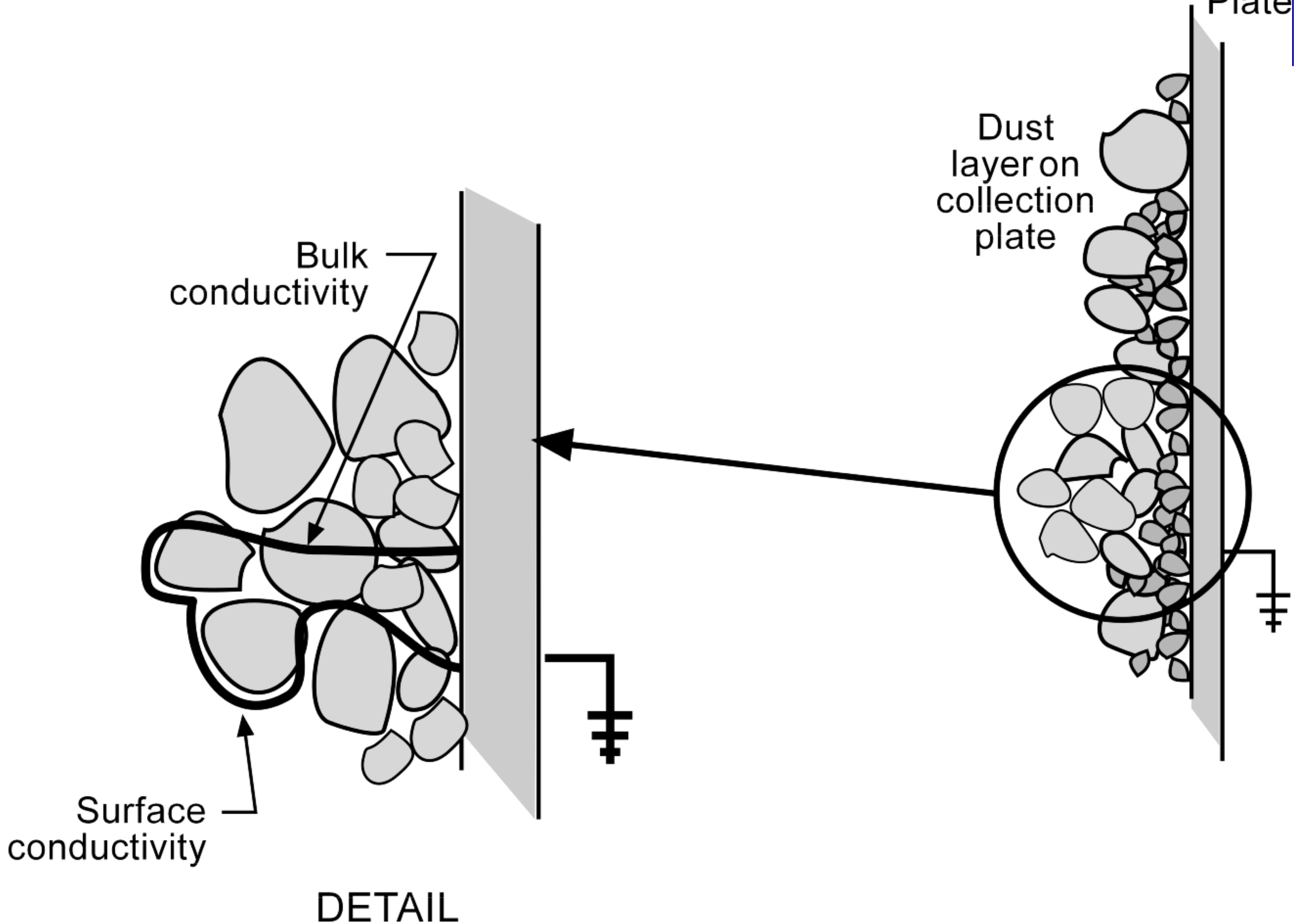


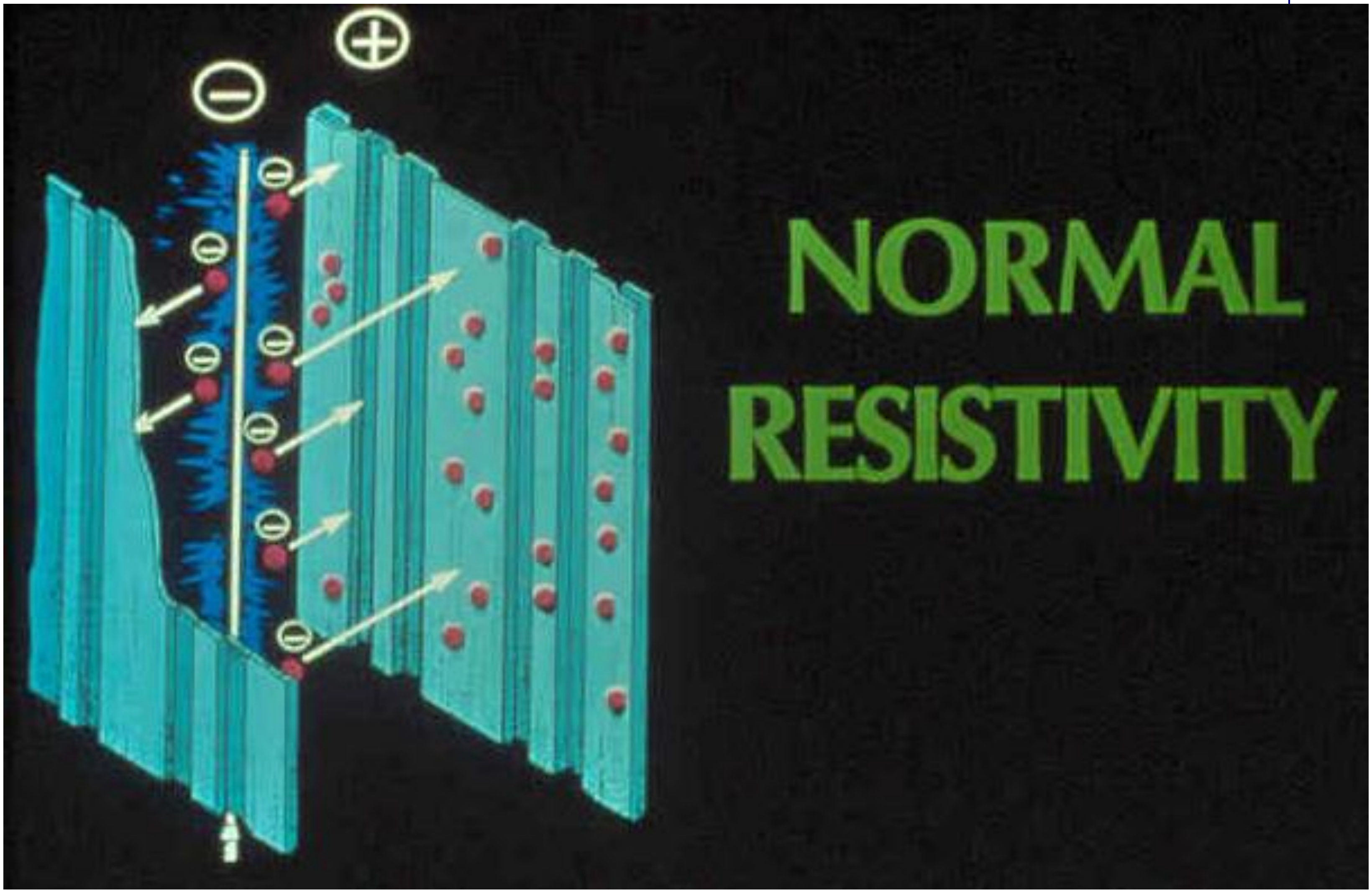
100
75
50
25
Collection Efficeincy, %
0.1
1.0
10
100
1000
Particle Size, μm

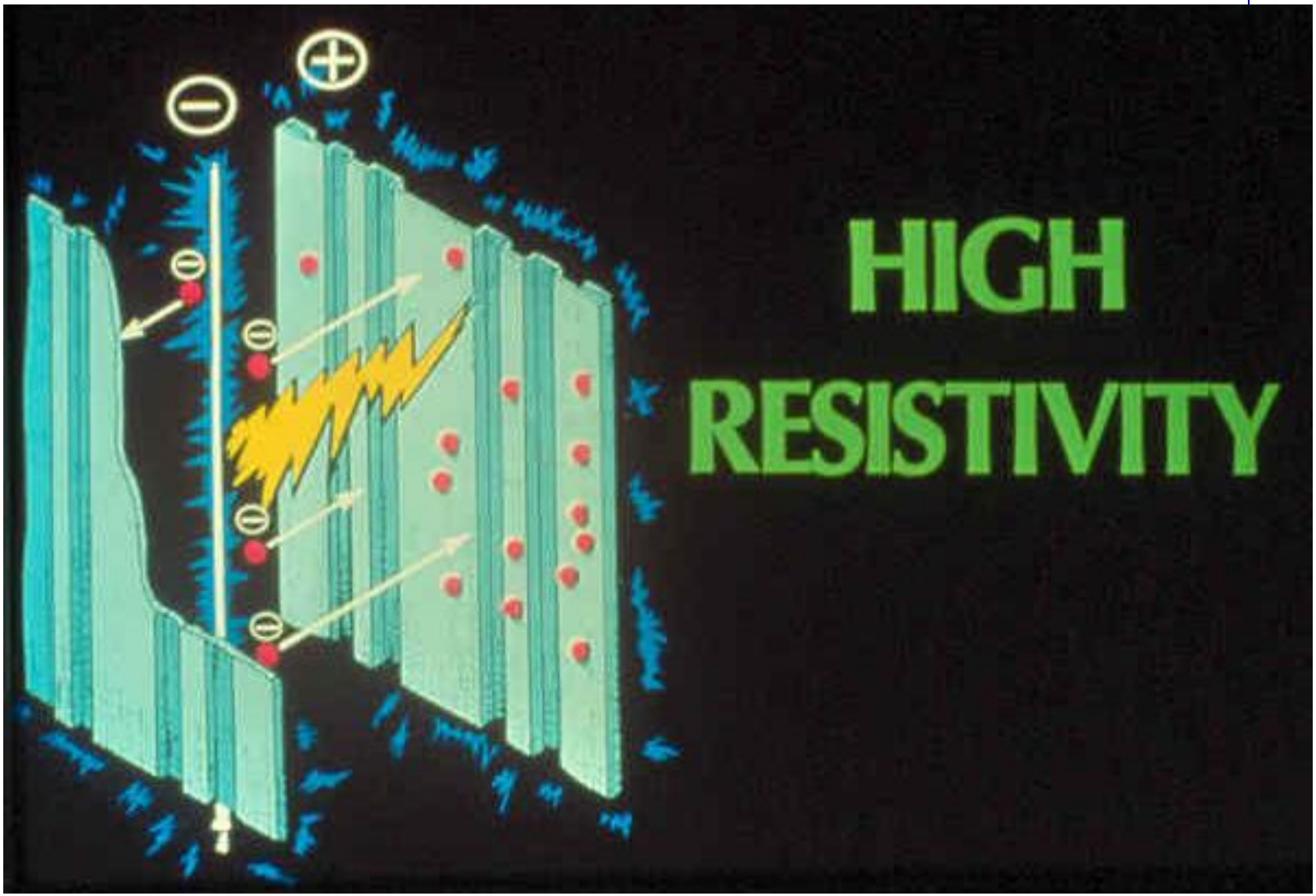
Resistivity

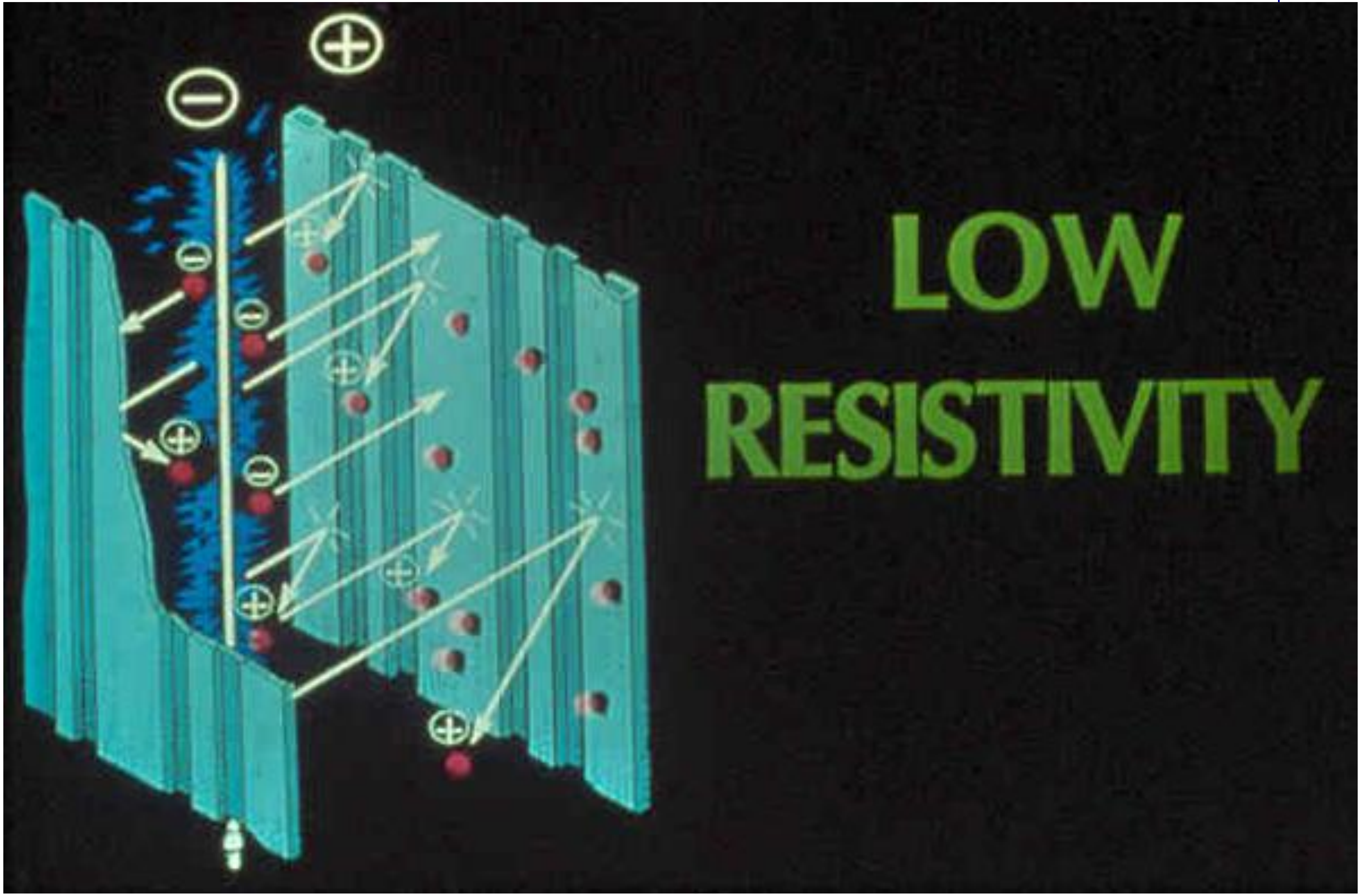
- Opposite of conductivity
- Controls deposition of particles onto plate

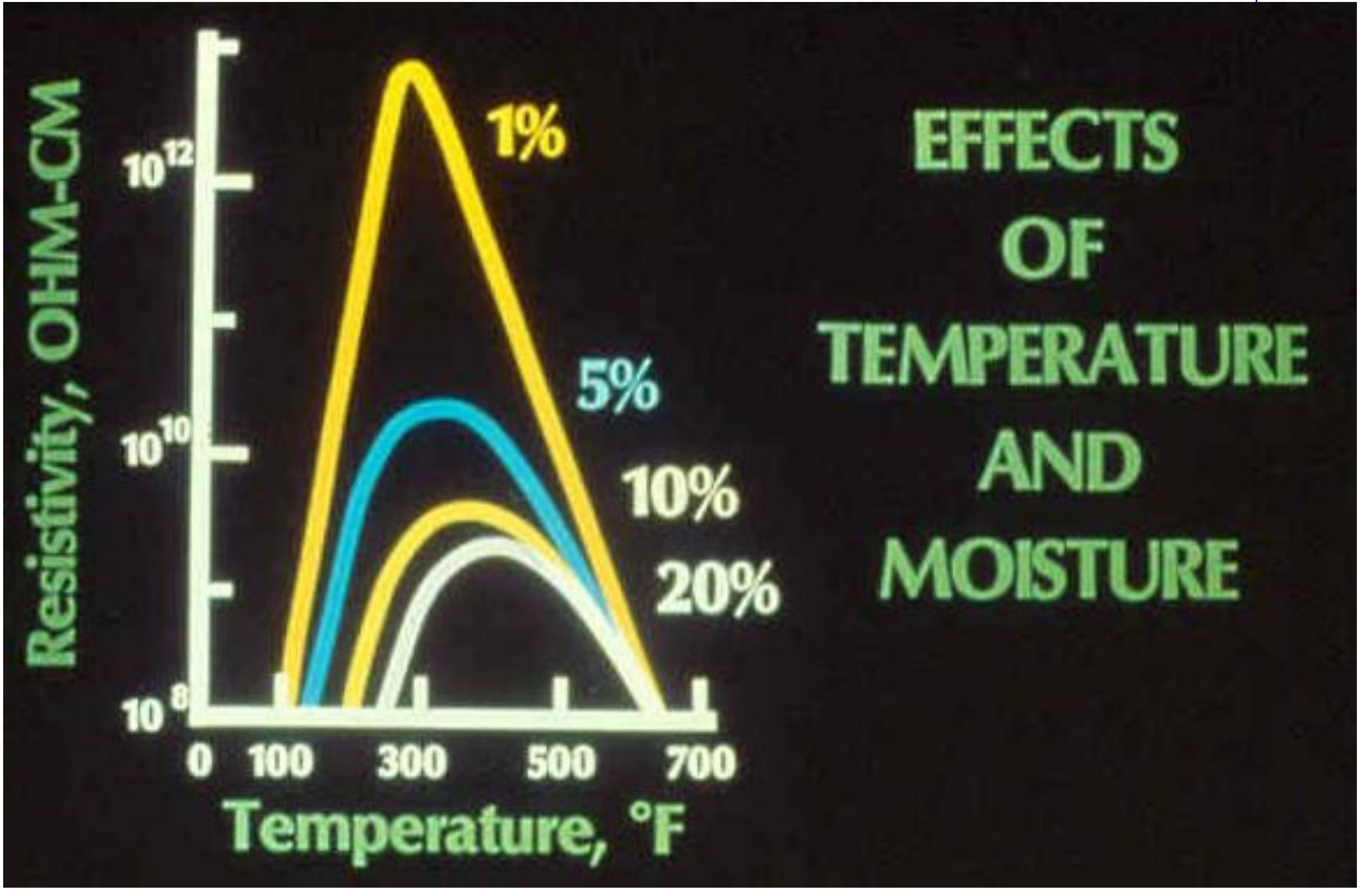
Conductivity Paths

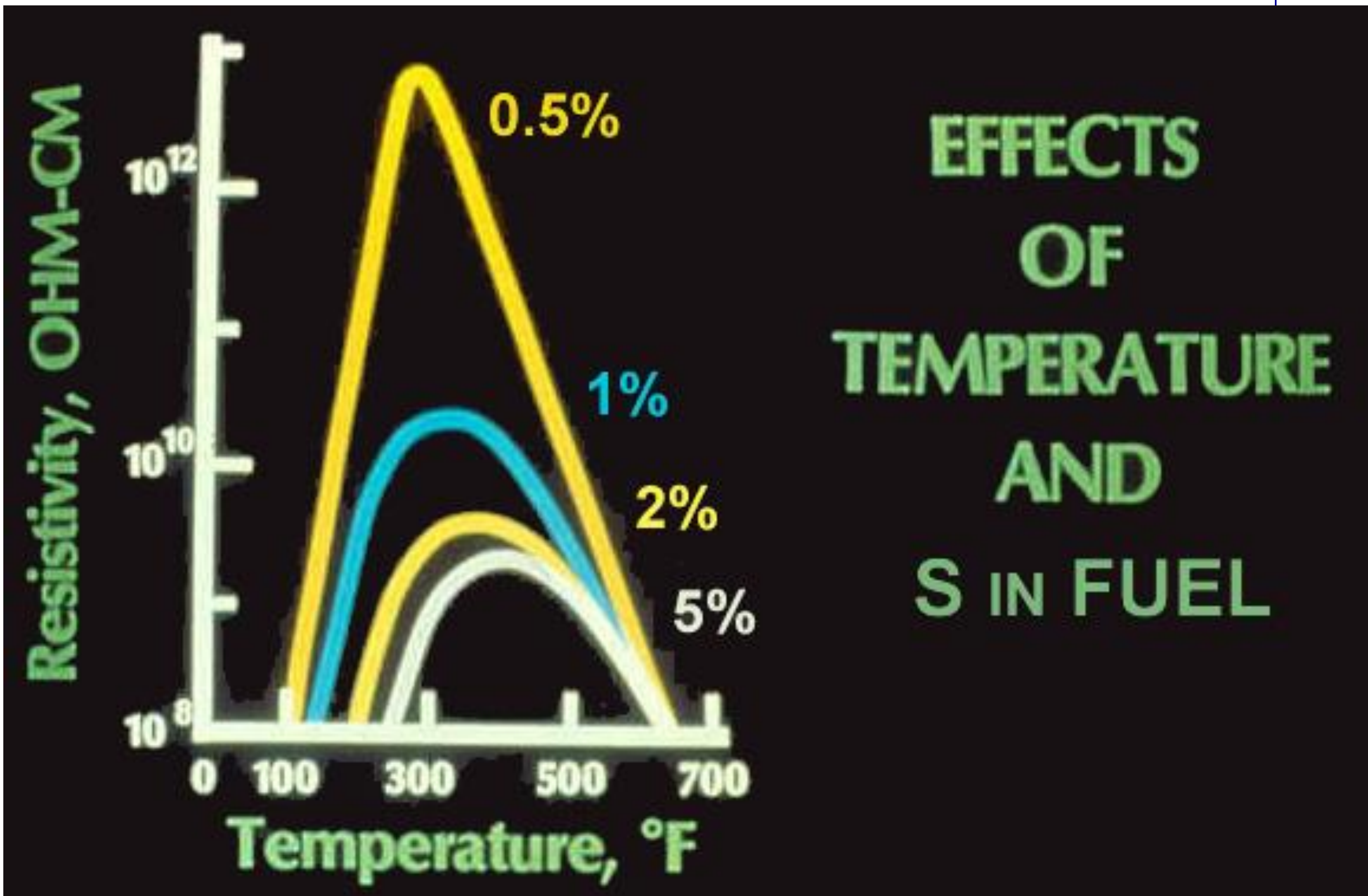



NORMAL
RESISTIVITY


HIGH
RESISTIVITY


LOW
RESISTIVITY


Resistivity, OHM-CM
10^12
10^10
10^8
0
100
300
500
700
Temperature, °F
1%
5%
10%
20%
EFFECTS
OF
TEMPERATURE
AND
MOISTURE



EFFECTS OF TEMPERATURE AND S IN FUEL
Resistivity, OHM-CM
10^{12}
10^{10}
10^{8}
0.5%
1%
2%
5%
0
100
300
500
700
Temperature, °F

Conditioning High Resistivity

- Adjust temperature
- Condition with additional substances (e.g., H_2O, SO_3, NH_3)

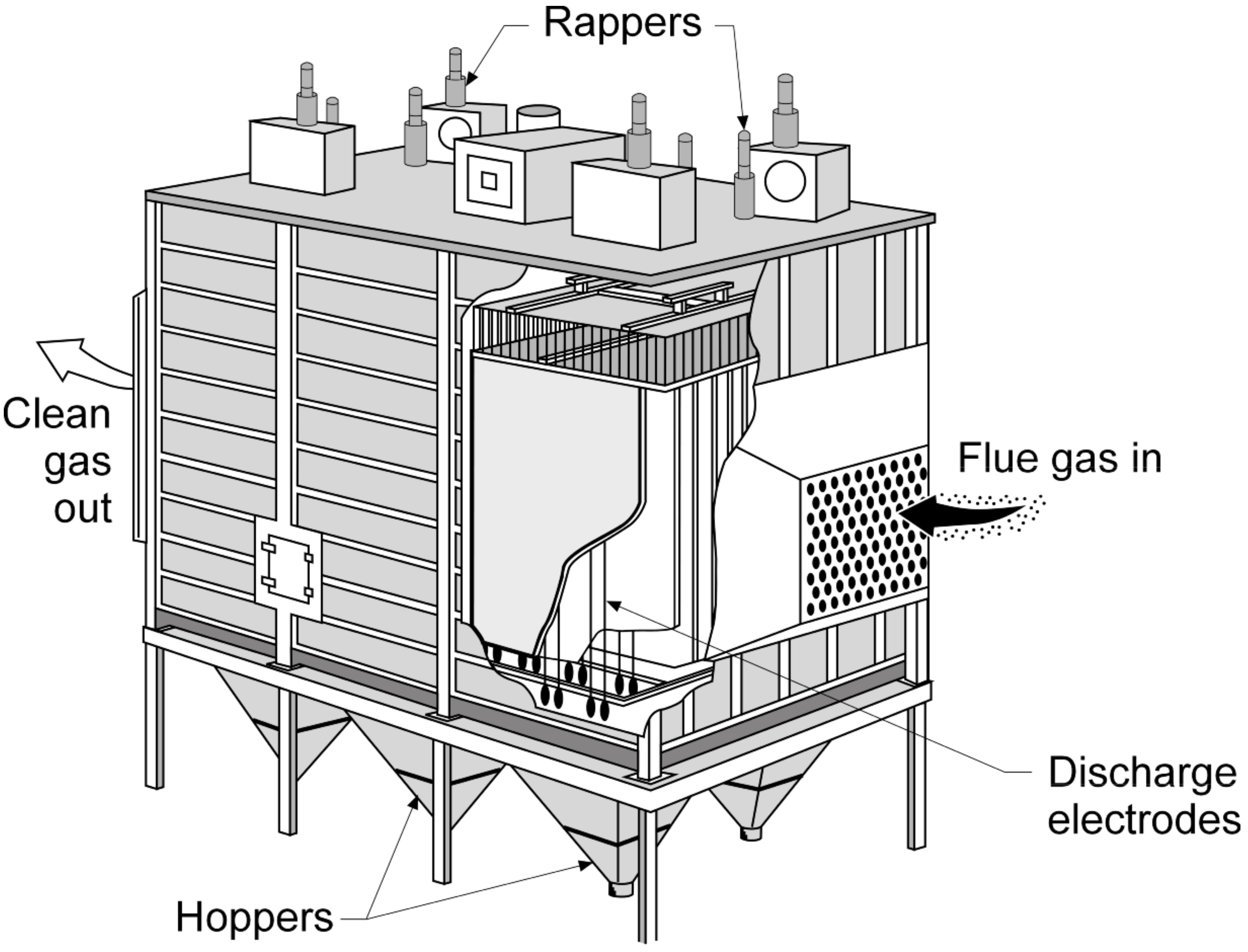
Common ESP Designs

- Negative corona, single stage, dry
- Negative corona, single stage, wet
- Positive corona, two stage, wet

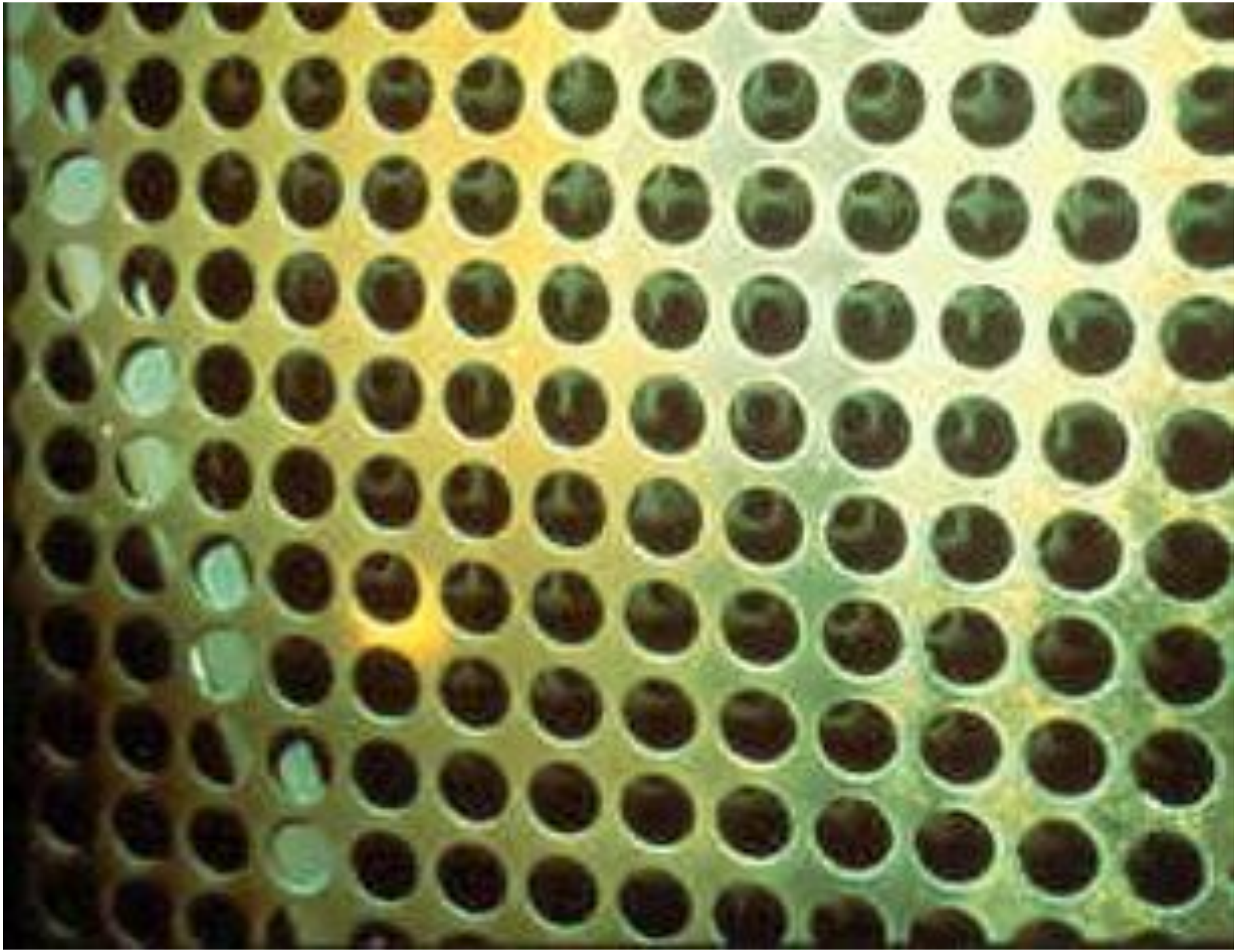
Design Options

- Negative corona or positive corona?

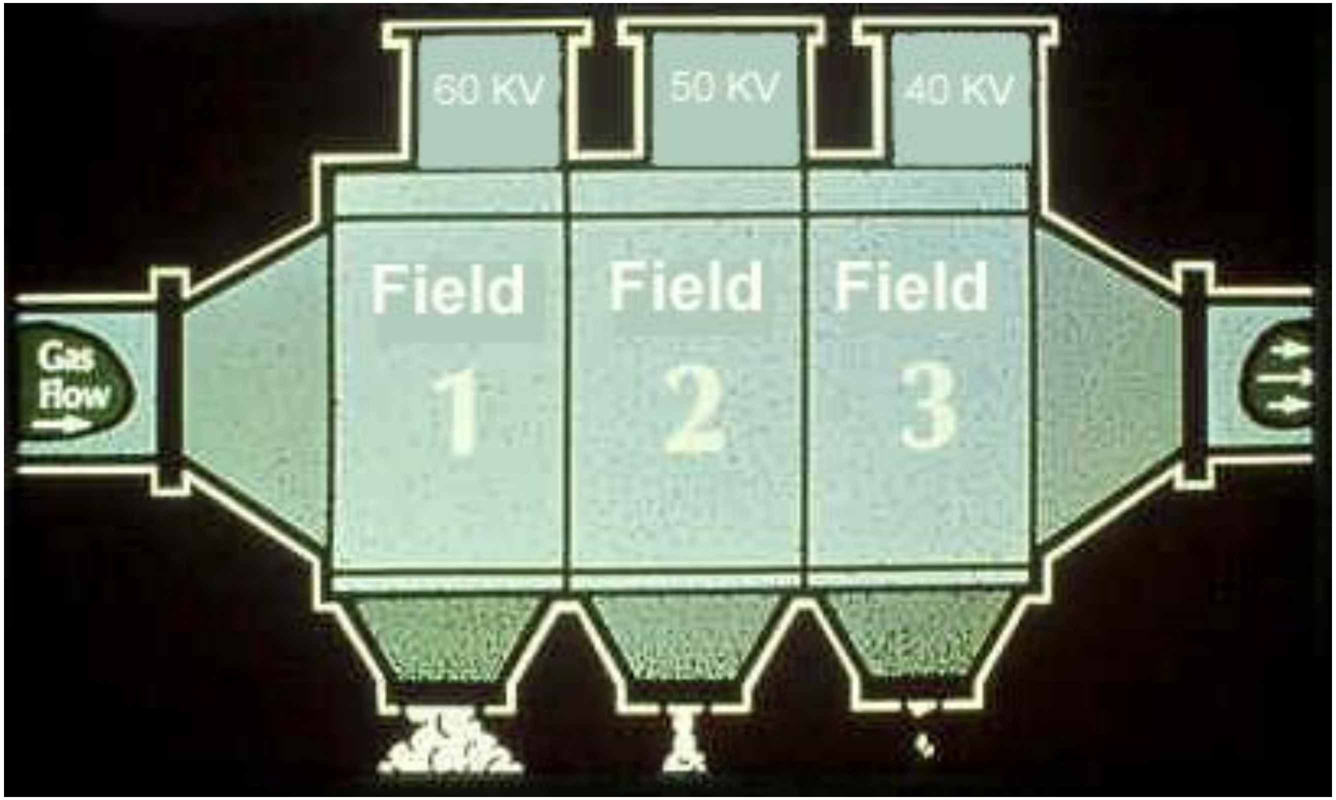
Negative Corona, Single Stage, Dry ESP



Gas Distributor

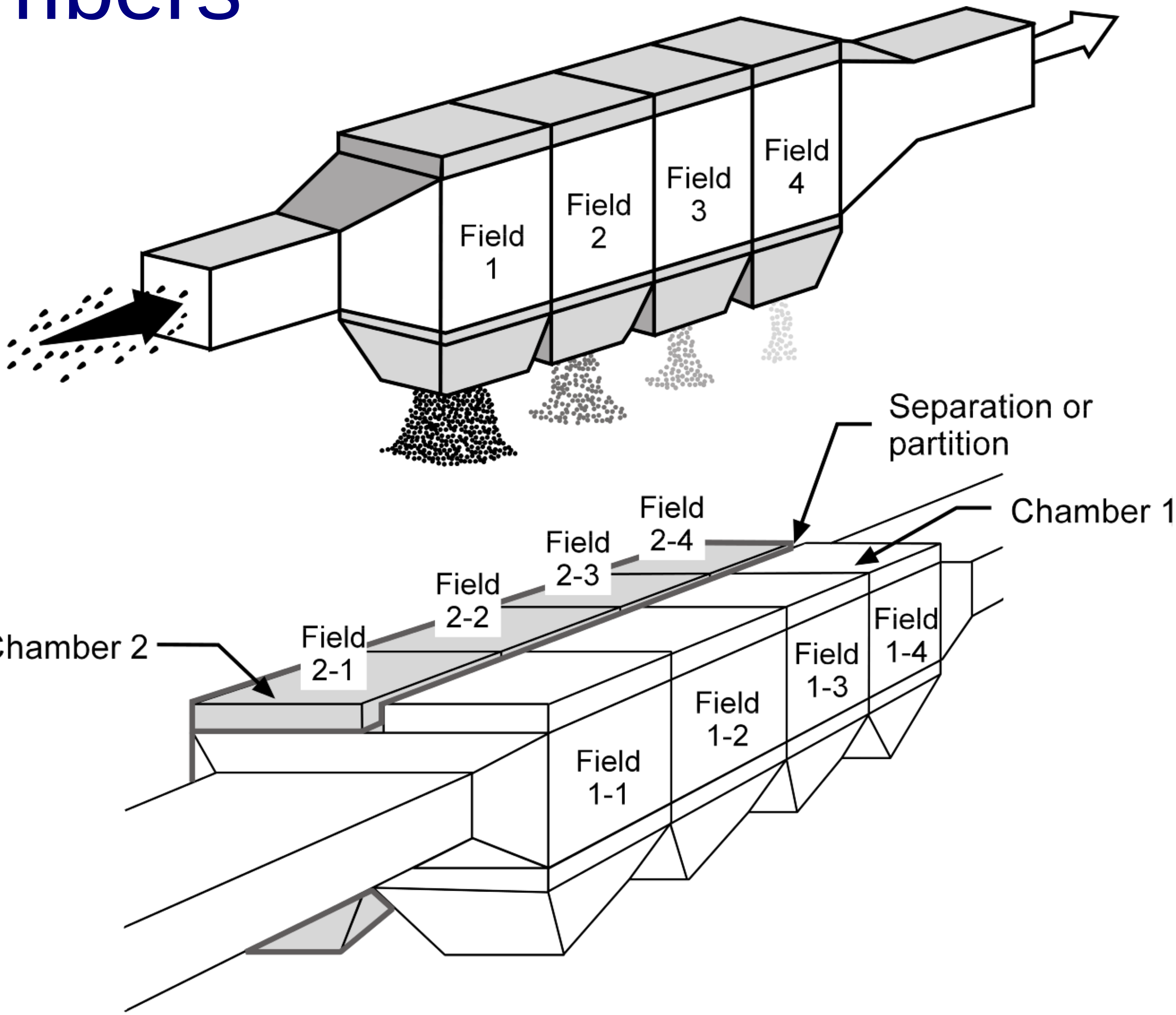


Field Construction

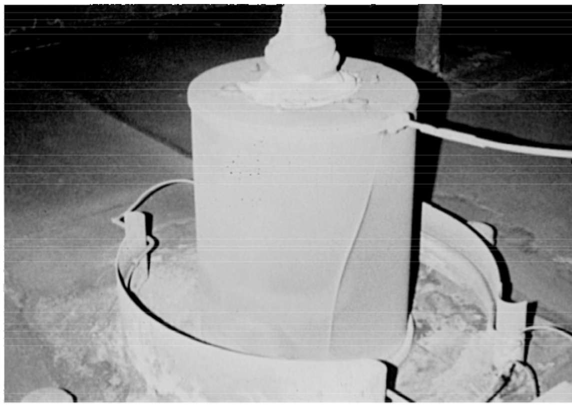


One advantage of this system is that if you only had one field and it went down, your whole operation would have to be shut down.

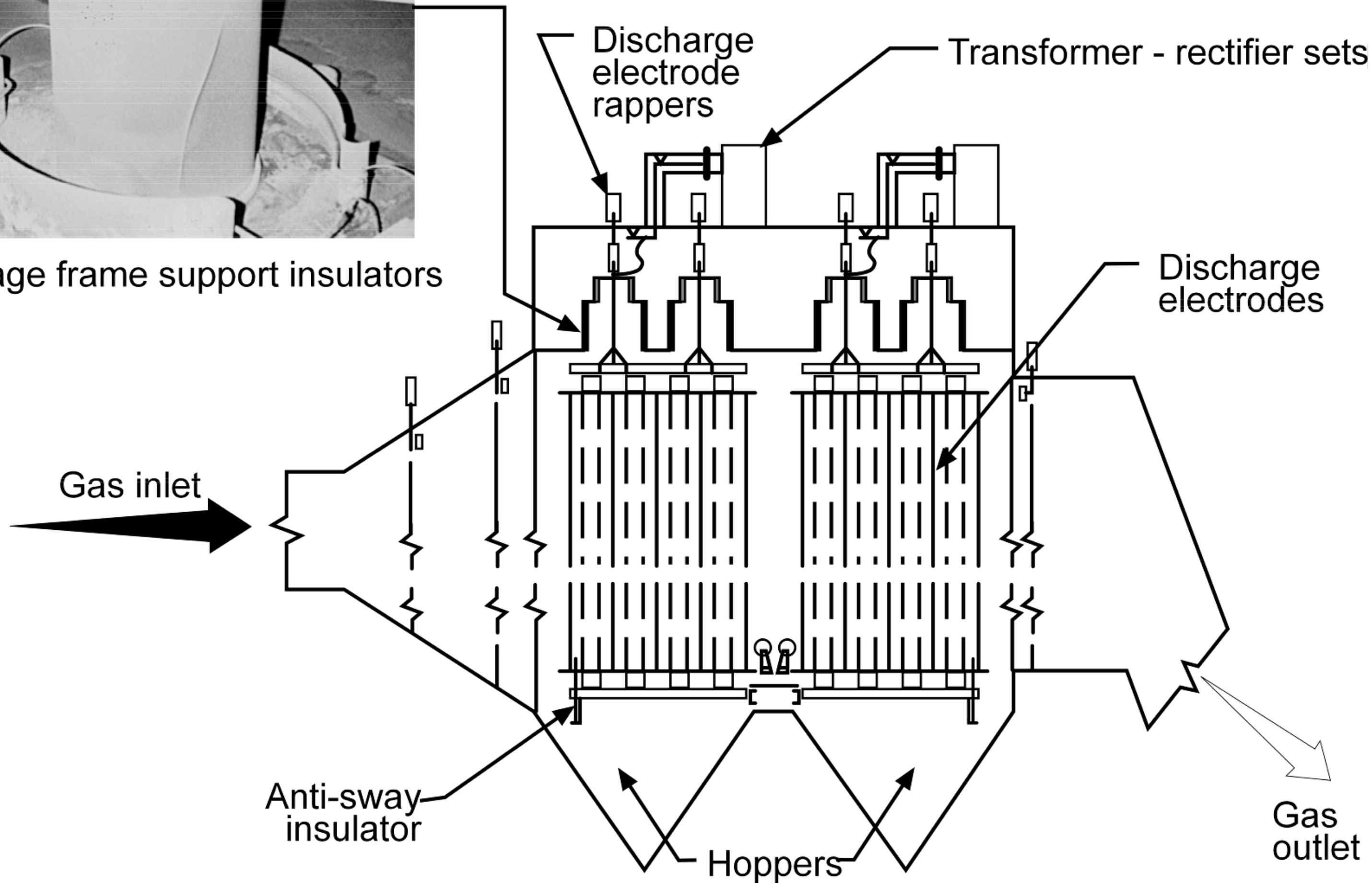
Arrangement of Fields and Chambers



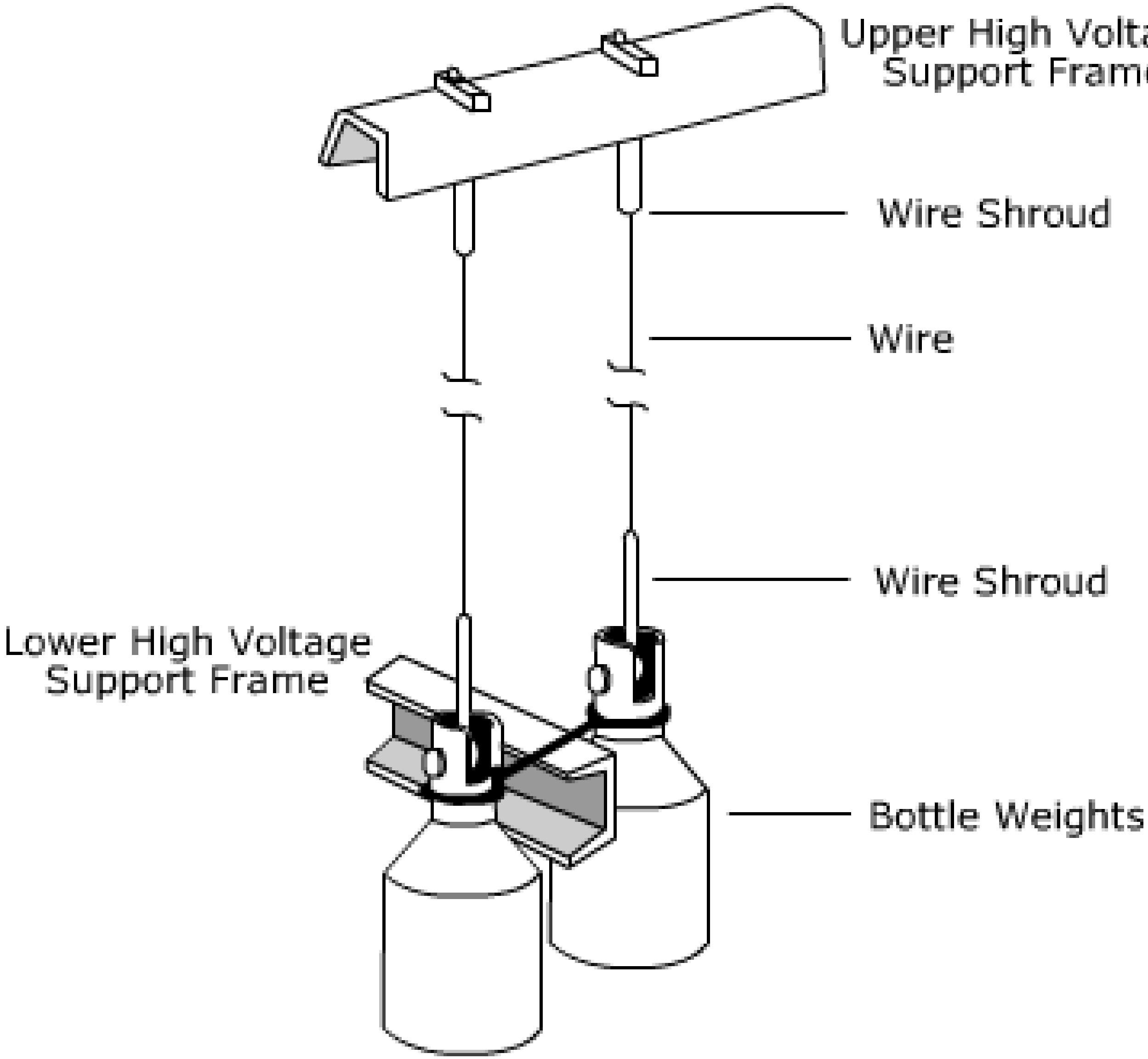
High Voltage Frame Support Insulators

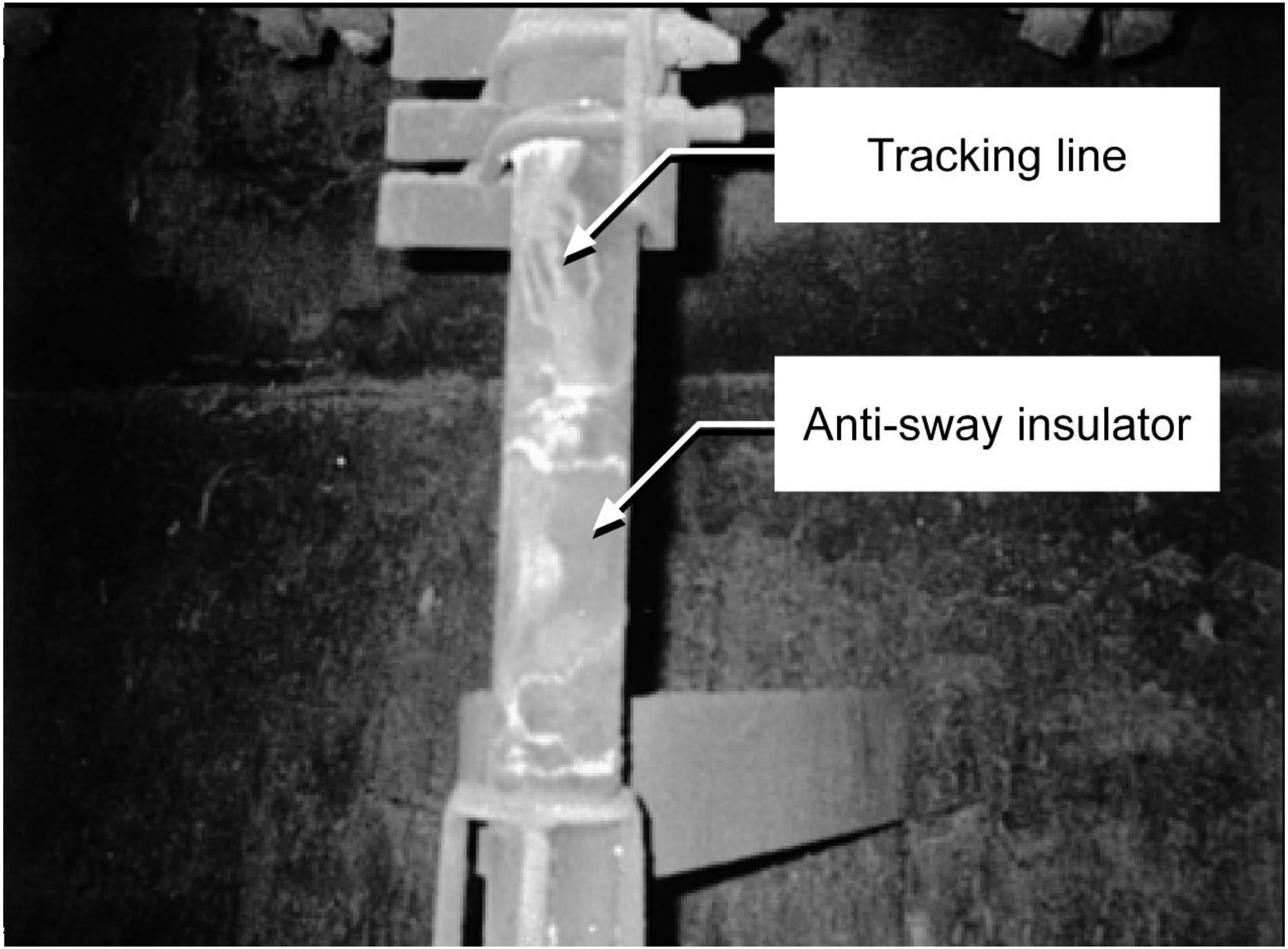


High voltage frame support insulators

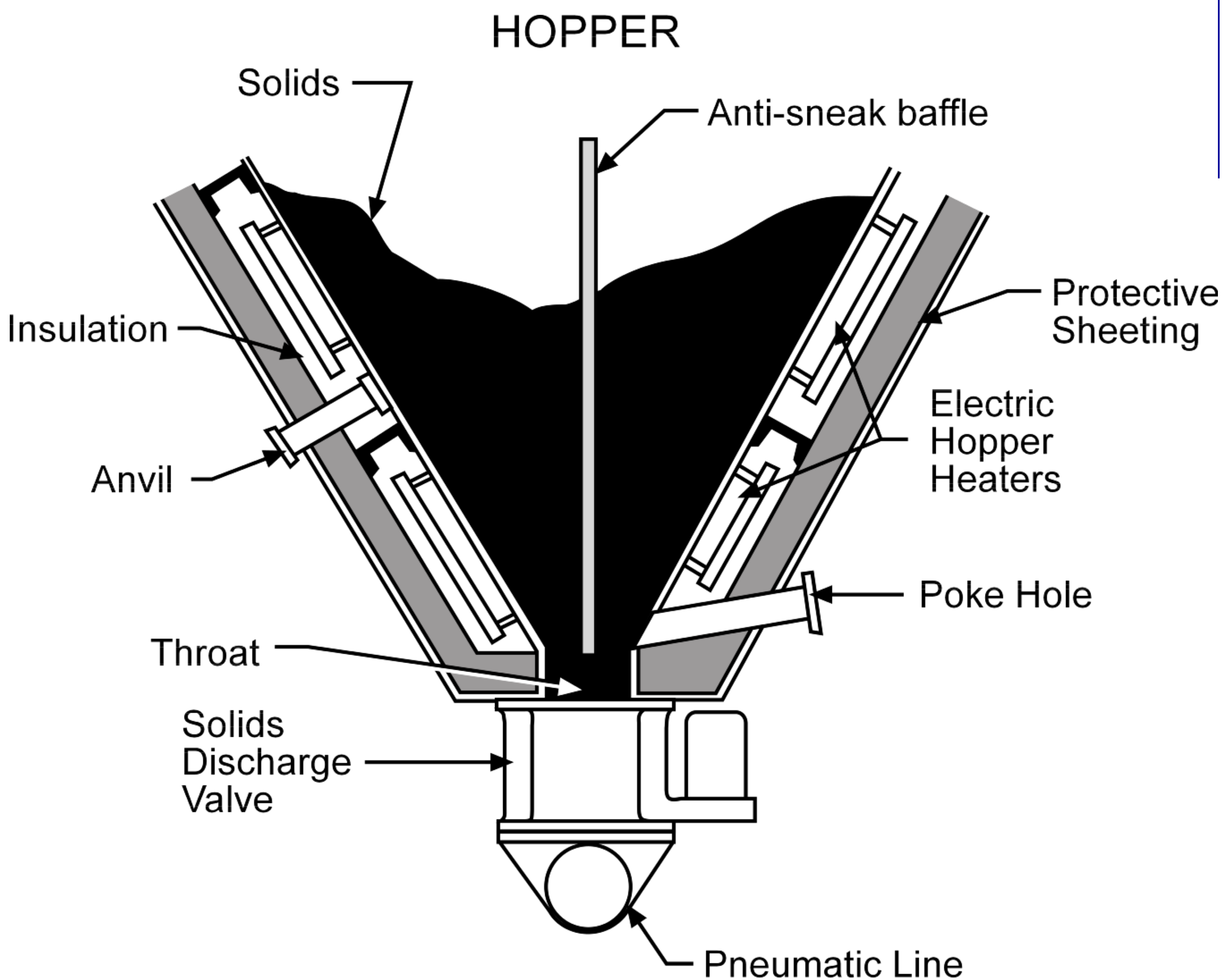


Wire Type Discharge Electrodes




Tracking line
Anti-sway insulator

Rappers


HOPPER
Solids
Anti-sneak baffle
Insulation
Protective
Sheeting
Electric
Hopper
Heaters
Anvil
Poke Hole
Throat
Solids
Discharge
Valve
Pneumatic Line

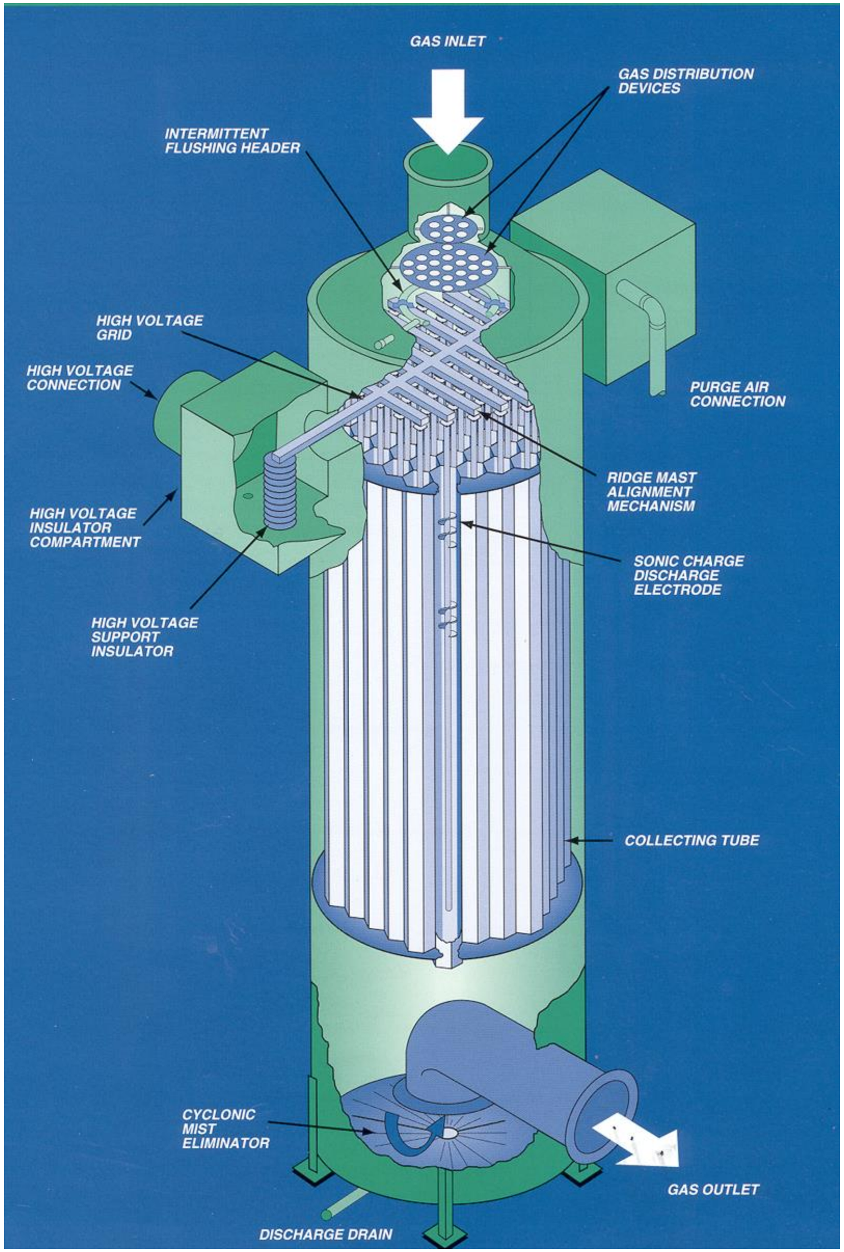
Design Options

- Negative corona or positive corona?
- Single stage or two stage?

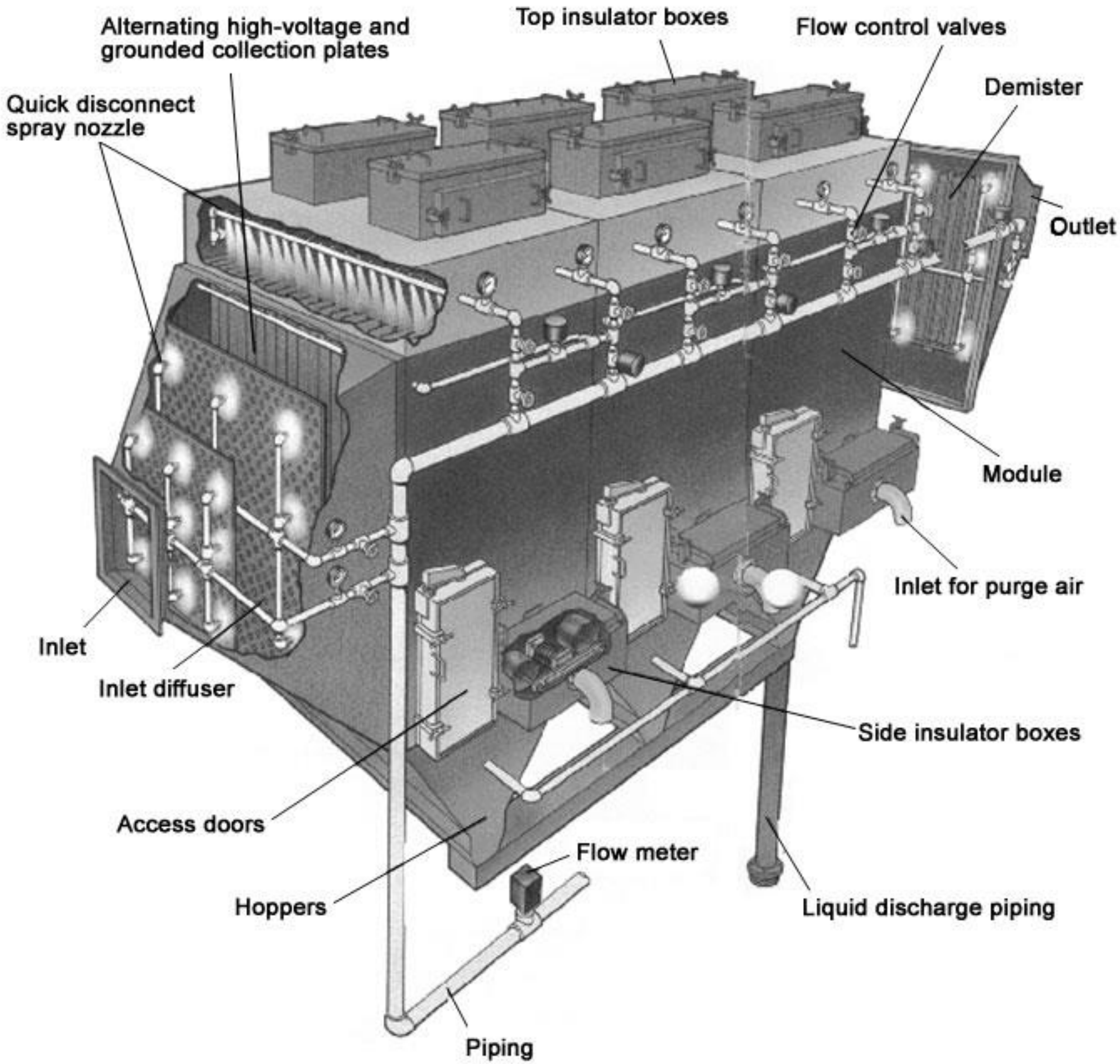
Design Options

- Negative corona or positive corona?
- Single stage or two stage?
- Wet or dry?

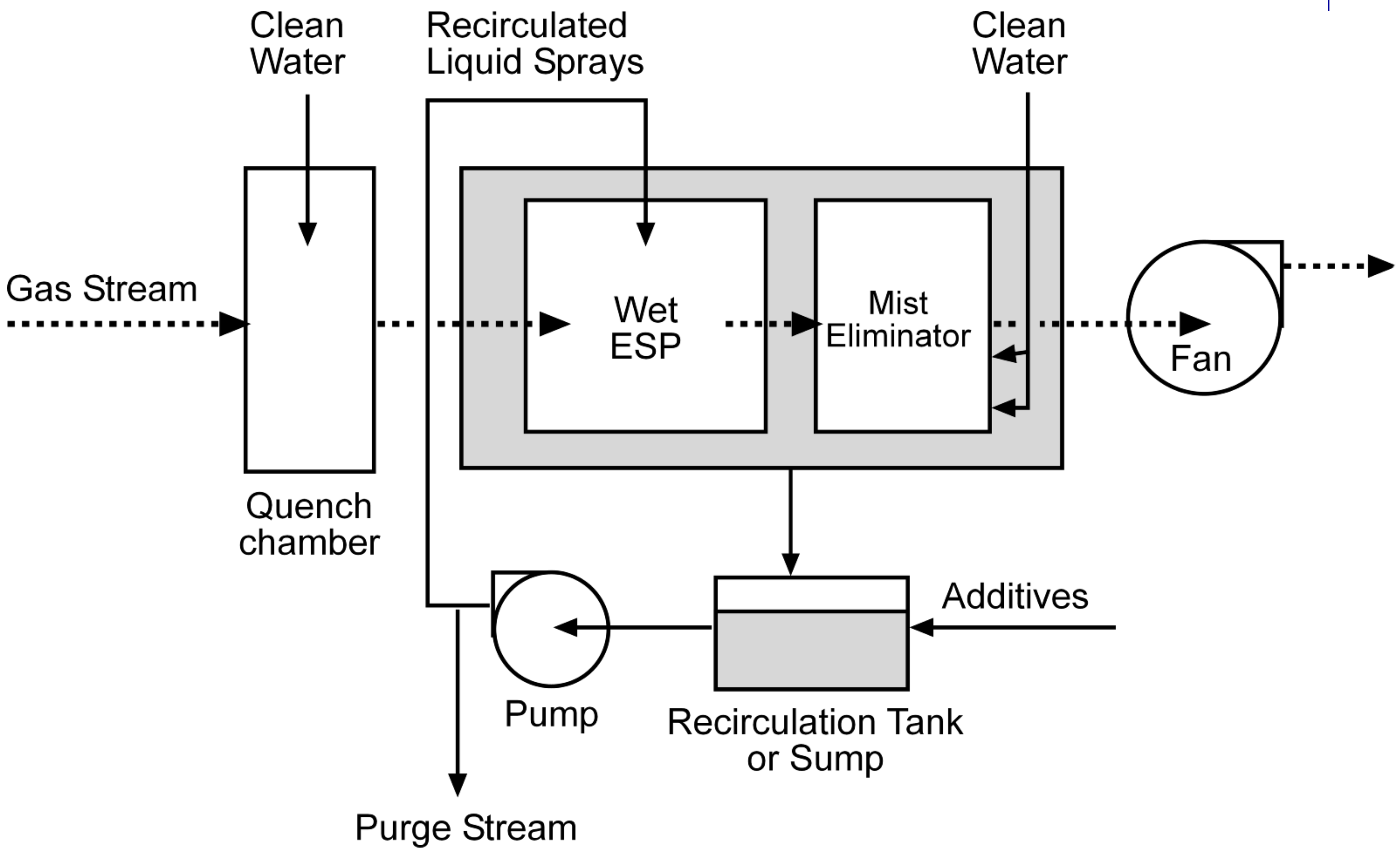
Vertical Flow Wet ESP



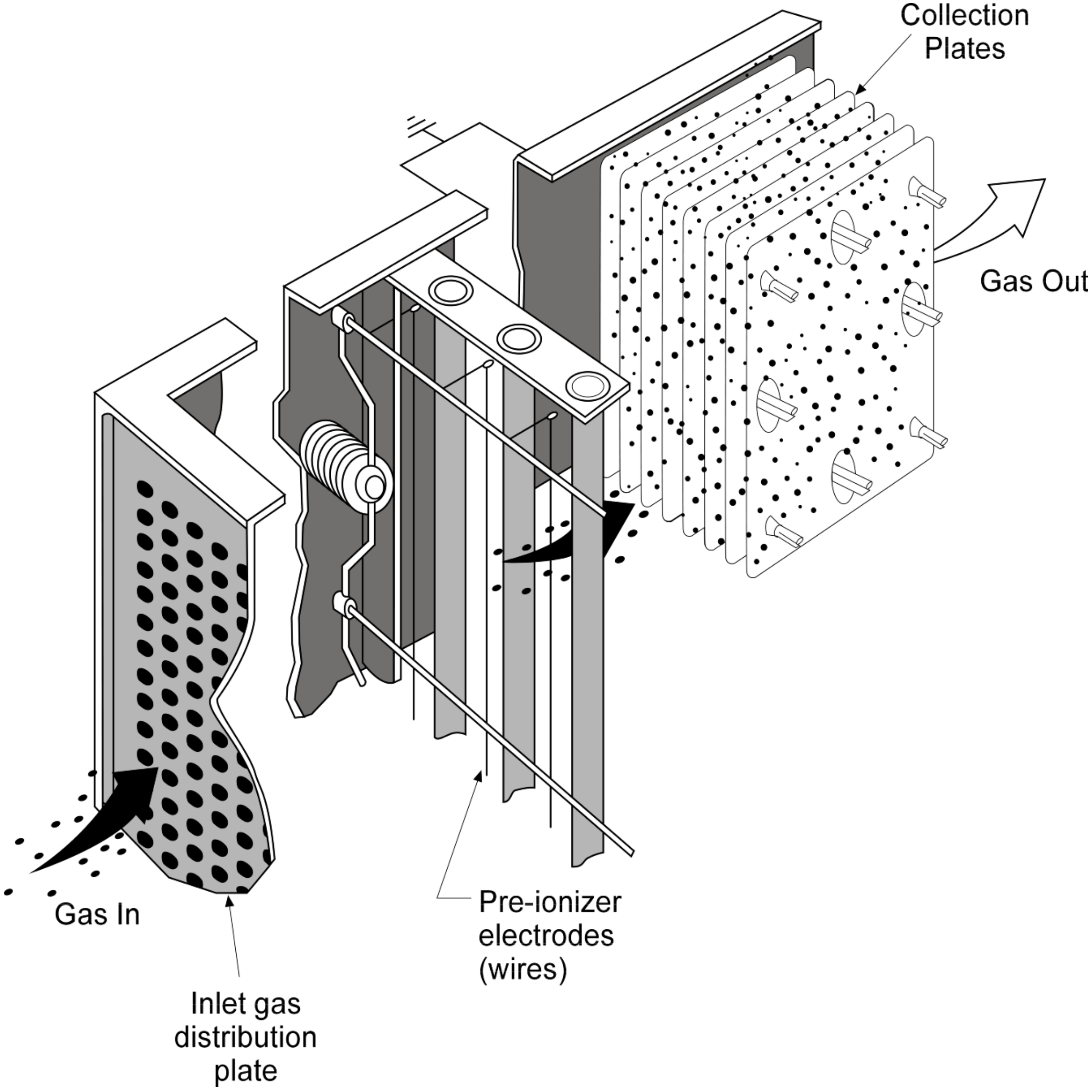
Horizontal Flow Wet ESP



Negative Corona, Single Stage, Wet ESP



Positive Corona, Two Stage, Wet ESP



Collection Efficiency

Deutsch-Anderson Equation

$$\eta = 1 - e^{-\omega \frac{A}{Q}}$$

where

η = efficiency (decimal form)

ω = migration velocity (ft/sec)

A = total collection plate area (ft^2)

Q = total gas flow rate (ft^3/sec)

e = base of natural logarithm = 2.718

Collection Efficiency

Matts-Ohnfield Equation

$$\eta = 1 - e^{-\left[\omega\left(\frac{A}{Q}\right)\right]^{k}}$$

where

k = dimensionless constant

Effective Migration Velocities for Various Industries

Application	Effective Migration Velocity	
	ft/sec	cm/sec
Utility Coal-Fired Boiler	0.13 - 0.67	4.0 - 20.4
Pulp & Paper Mill	0.21 - 0.31	6.4 - 9.5
Sulfuric Acid Mist	0.19 - 0.25	5.8 - 7.6
Cement (Wet Process)	0.33 - 0.37	10.1 - 11.3
Cement (Dry Process)	0.19 - 0.23	5.8 - 7.0
Gypsum	0.52 - 0.64	15.8 - 19.5
Open-Hearth Furnace	0.16 - 0.19	4.9 - 5.8
Blast Furnace	0.20 - 0.46	6.1 - 14.0

Specific Collecting Area

$$SCA = \frac{A}{Q}$$

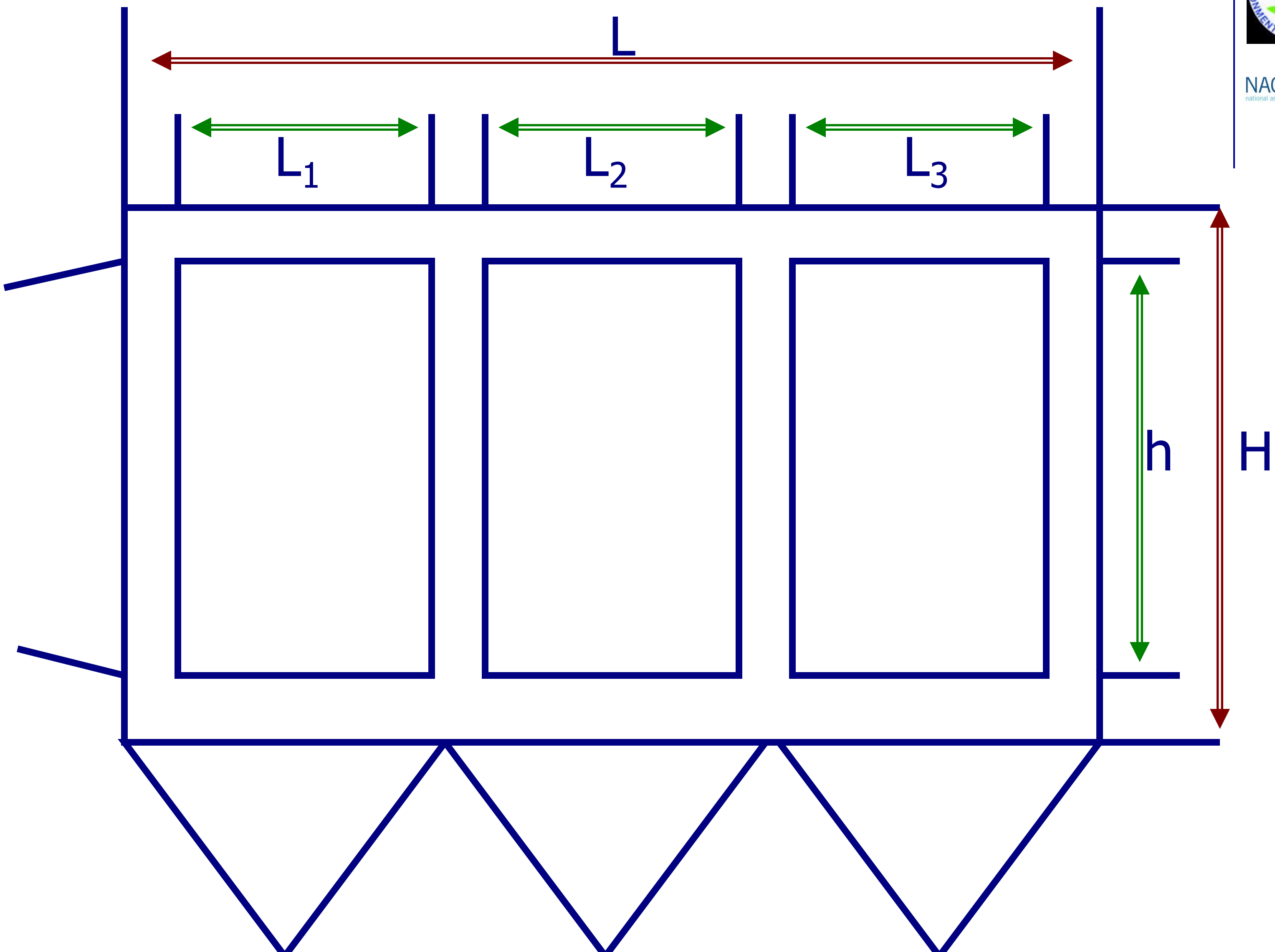
where

SCA = specification collection area, $ft^2/(1{,}000\ ACFM)$

A = total collection plate area, ft^2

Q = total gas flow rate, $ft^3/min \times 0.001$

Aspect Ratio



$\text{Aspect Ratio} = (L_1+L_2+L_3)/h$

$\text{Aspect Ratio} = L/H$

Aspect Ratio

$$AR = \frac{\sum_{i=1}^{n} L_i}{h}$$

where:

AR	= aspect ratio (dimensionless)
L_i	= length of plates in field i (ft)
h	= collection plate height (ft)
n	= number of fields in series

Example 9-3

An electrostatic precipitator serving a cement kiln has four fields in series. All of the fields have collection plates that are 24 feet high. The first two fields have collection plate lengths of 9 feet each. The last two fields have collection plate lengths of 6 feet.

What is the aspect ratio?

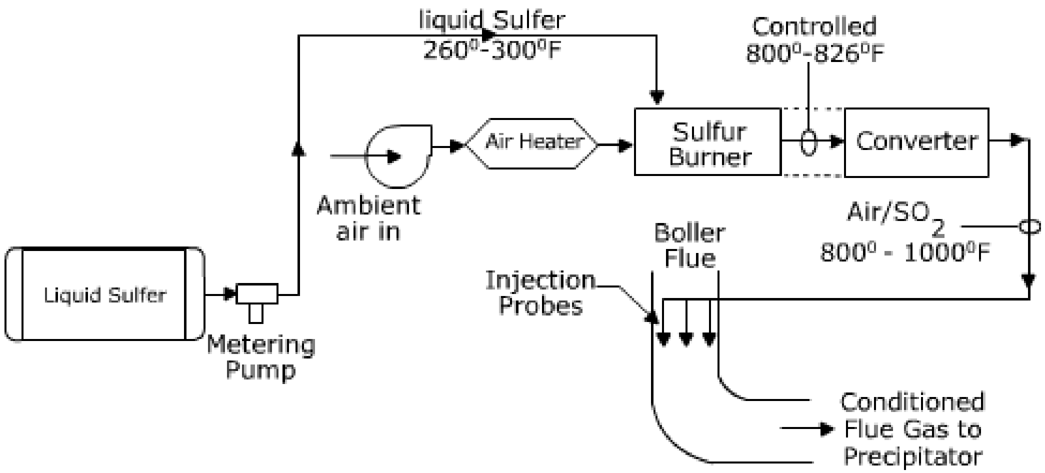
$$AR = \frac{\sum_{i=1}^{n} L_i}{h} = \frac{9+9+6+6}{24} = 1.25$$

Example 9-4

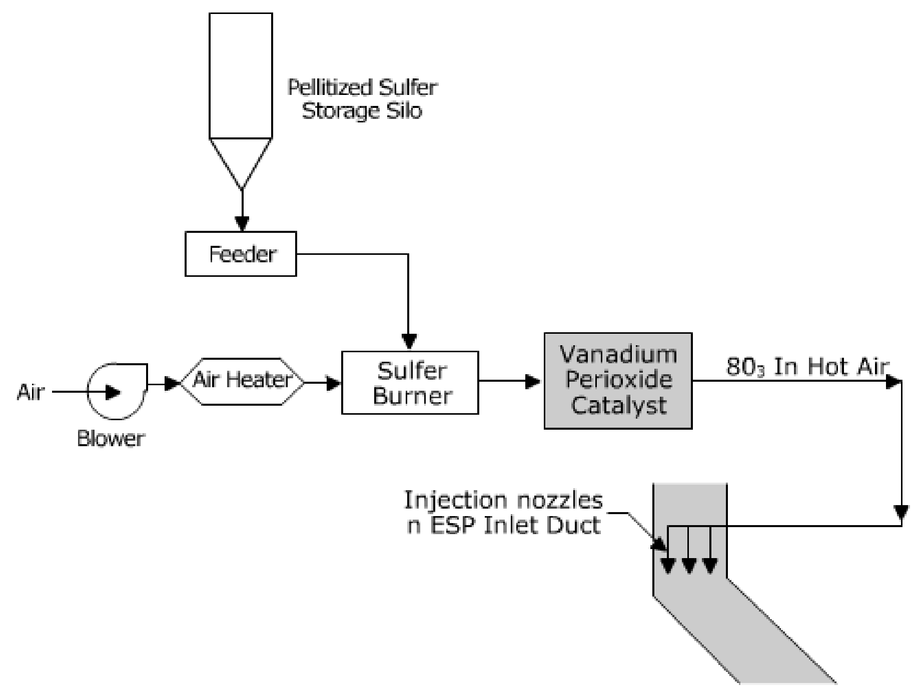
Estimate the quantities of dust in each field of a four-field electrostatic precipitator having efficiencies of 80%, 75%, 70%, and 65% respectively. Assume a gas flow rate of 250,000 ACFM and a particulate matter loading of 2 grains per actual cubic foot.

Field	Assumed Efficiency	Particulate Entering (lb_m/hr)	Particulate Leaving, (lb_m/hr)	Particulate Collected (lb_m/hr)
1 (inlet)	80	4,286	857	3,429
2 (middle)	75	857	214	643
3 (middle)	70	214	64	150
4 (outlet)	65	64	22	42

Sulfur Trioxide Conditioning Systems



Conventional system



Pelletized system

Example 9-5

A coal-fired utility boiler generates 5 ppm of sulfuric acid. Diagnostic tests have indicated that 17 ppm of sulfuric acid are needed in the gas stream to maintain the flyash resistivity in the moderate range.

Calculate the sulfur required to operate a sulfur trioxide conditioning system for a period of one year.

Assume that the boiler has a gas flow rate of 1.0×10^6 ACFM, the gas temperature is 310°F, the boiler operates 82% of the year, and the sulfur trioxide system is needed 85% of the operating time.

Example 9-5 Solution

Sulfur Trioxide System Operating Hours:

$$\text{Operating hours} = 8{,}760 \text{ total hours}\left(\frac{0.82 \text{ boiler hours}}{\text{total hours}}\right)\left(\frac{0.85 \text{ FGC hours}}{\text{boiler hours}}\right)$$

= 6,106 FGC hours

Sulfur Trioxide on Demand:

SO^3 needed = 17 ppm – 5 ppm = 12 ppm = 1.2×10^{-5} lb moles $S0^3$/lb mole flue gas

Example 9-5 continued

Sulfur Trioxide Injection Requirements:

$$SO_3\ needed =$$

$$\left(1x10^6 \frac{ft^3}{\min}\right)\left(\frac{528°R}{770°R}\right)\left(\frac{lb-mole}{385.4\,std\ ft^3}\right)\left(60\frac{\min}{hr}\right)\left(1.2\,x10^{-5}\frac{lb-mole\,SO_3}{lb-mole}\right)$$

= 1.28 lb-moles/hr

Example 9-5 continued

Sulfur Required:

Sulfur lb moles = SO_3 lb moles = 1.28 lb-moles/hr

$$\text{Sulfur required} =$$

$$\left(1.28\,\frac{\text{lb}-\text{moles}}{\text{hr}}\right)\left(6{,}106\,\frac{\text{hrs}}{\text{year}}\right)\left(32\,\frac{\text{lb S}}{\text{lb}-\text{mole}}\right)\left(\frac{\text{ton}}{2{,}000\,\text{lbs}}\right)$$

= 125 tons/year

Instrumentation

- Electrical parameters
- Rapper parameters
- Inlet and outlet gas temperature
- Inlet and outlet oxygen concentration

Instrumentation

- Electrical parameters
  - Primary voltage
  - Primary current
  - Secondary voltage
  - Secondary current
  - Spark rate
  - SCR conduction angle
  - Field limiting condition
  - Power input

Advantages and Disadvantages

Electrostatic Precipitators

Advantages

- High Collection Efficiency
- Dry Collection and Disposal
- Small Pressure Drop
- Capable of Handling Large Gas Flow Rates
- Low Electrical Power Requirements
- Low Maintenance

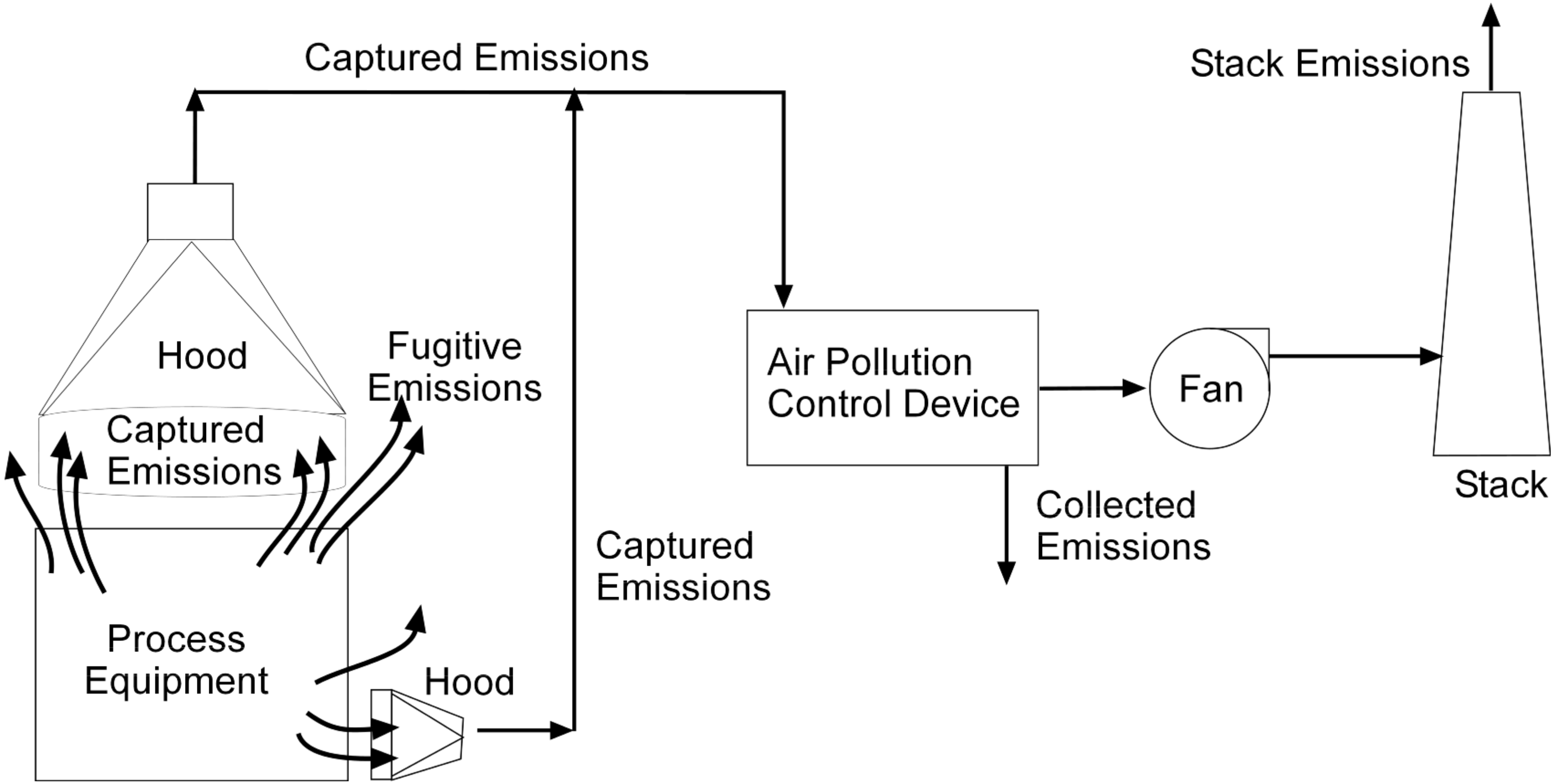
Disadvantages

- High Capital Cost
- Particle Resistivity Limitations
- May Require Injection of SO_3 or NH_3 to Control Resistivity
- Relatively Large Footprint
- Special Precautions for Safe Operating at High Voltage

Chapter 10

Hoods and Fans

Hoods
What Hoods do



Fugitive Emissions

- Escape capture by process equipment exhaust hoods
- Are emitted during material transfer
- Are emitted to the atmosphere from the source area
- Are emitted directly from process equipment

$$\text{Fugitive emissions} = \text{Total emissions} - \text{Emissions captured by hood}$$

$$\text{Stack emissions} = \text{Emissions captured by hood} \times \left(\frac{100 - \eta}{100} \right)$$

Example 10-1

Calculate the fugitive emissions and the stack emissions if the process equipment generates 100 lb_m/hr of particulate matter, the hood capture efficiency is 95%, and the collection efficiency of the air pollution control device is 95%.

Solution

calculate the fugitive emissions:

Fugitive emissions = Total emissions - Emissions captured by hood

$$100 \, \mathrm{lb_m/hr} - 95 \, \mathrm{lb_m/hr} = 5 \, \mathrm{lb_m/hr}$$

And then…

Calculate the stack emissions:

$$\text{Stack emissions} =$$

$$\text{Emissions captured by hood x}\left(\frac{100-\eta}{100}\right)$$

$$=\left(95\,{}^{\text{lb}_m}\!/_{\text{hr}}\right)\left(\frac{100-95}{100}\right)=4.75\,{}^{\text{lb}_m}\!/_{\text{hr}}$$

Example 10-2

Calculate the fugitive emissions and the stack emissions if the process equipment generates 100 lb_m/hr of particulate matter, the hood capture efficiency is 90%, and the collection efficiency of the air pollution control device is 95%.

Solution

calculate the fugitive emissions:

Fugitive emissions = Total emissions - Emissions captured by hood

$$100 \, {}^{lb_m}\!/_{hr} - 90 \, {}^{lb_m}\!/_{hr} = 10 \, {}^{lb_m}\!/_{hr}$$

And then…

Calculate the stack emissions:

$$\text{Stack emissions} =$$

$$\text{Emissions captured by hood x} \left(\frac{100 - \eta}{100} \right)$$

$$= \left(90 \, {}^{\text{lb}_m}\!/_{\text{hr}} \right) \left(\frac{100 - 95}{100} \right) = 4.5 \, {}^{\text{lb}_m}\!/_{\text{hr}}$$

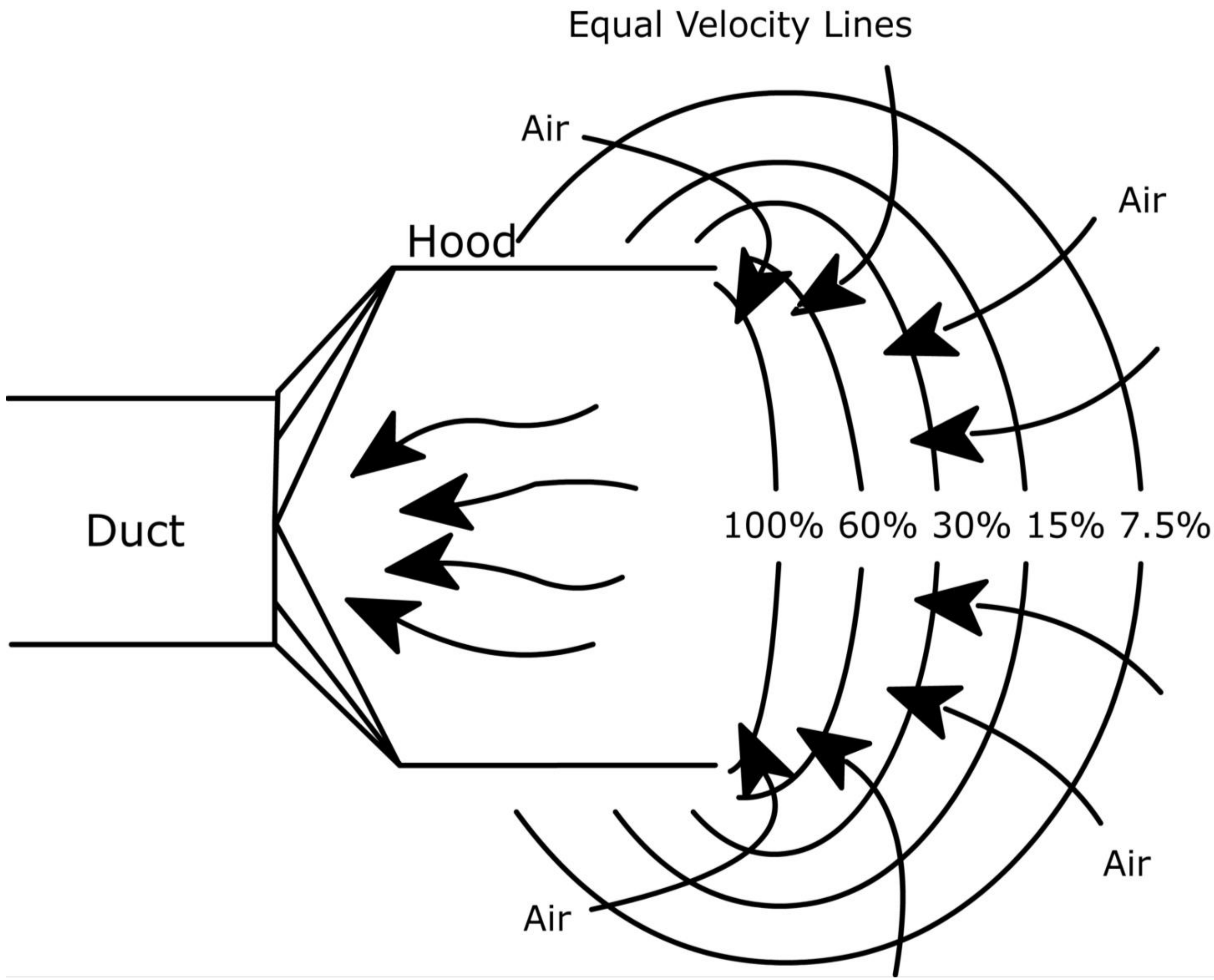
Slight changes in the ability of the hood to capture the pollutants can have a large impact on the total fugitive and stack emissions released into the atmosphere.

Can't Always see them…

- If there are many small fugitive sites
- If there is one major site that cannot be seen
- If the matter is not in the size range that causes light scattering

Hood Operating Principles

- Operate under negative pressure
- Hood must be close to emission source.
- Capture Velocity: the air velocity at any point in front of the hood that will overcome opposing air currents and capture contaminated air.


Equal Velocity Lines
Air
Air
Hood
Duct
100% 60% 30% 15% 7.5%
Air
Air

Capture Velocities Considerations

- The surrounding air currents
  - Minimal room air currents vs. disturbing room air currents
- The level of toxicity of the pollutant to be captured
  - Nuisance value only vs. high toxicity
- The amount of pollutant
  - Intermittent (low production) vs. high production (heavy use)
- Area of the hood opening
  - Large hood (large air mass in motion) vs. small hood (local control only)

Capture Velocities

Type of Material Release	Capture Velocity (ft/min)
With no velocity into quiet air	50-100
At low velocity into moderately still air	100-200
Active generation into zone of rapid air motion	200-500
With high velocity into zone of very rapid air motion	500-2,000

Example 10-3

The recommended capture velocity for a certain pollutant entering a 16-inch diameter hood is 300 ft/min.

What is the required volumetric flow rate for the following distances from the hood face (X)?

A. X = 12 in. (75% of hood diameter)
B. X = 24 in. (150% of hood diameter)

$$Q = v_h (10X^2 + A_h)$$

Example 10-3

The recommended capture velocity for a certain pollutant entering a 16-inch diameter hood is 300 ft/min.

What is the required volumetric flow rate for the following distances from the hood face (X)?

A. X = 12 in. (75% of hood diameter)
B. X = 24 in. (150% of hood diameter)

$$Q = v_h (10X^2 + A_h)$$

Solution for a: A. X = 12 in (75% of hood diameter)

Calculate the area of the hood opening:

$$A_h = \frac{\pi D^2}{4} = \frac{\pi\left[16\text{in}\left(\frac{1\text{ft}}{12\text{in}}\right)\right]^2}{4} = 1.40\text{ft}^2$$

Calculate the volumetric flow rate, Q, required obtaining the recommended capture velocity of 300 fpm at a distance of 12 inches from the hood:

Solution for a:

A. X = 12 in (75% of hood diameter)

A_h = 1.40 ft^2 and X = 12 inches

$$Q = v_h(10X^2 + A_h)$$

$$= 300 \,\text{ft}/\text{min}\left[10(1\text{ft})^2 + 1.40\text{ft}^2\right] = 3{,}420\,\text{ft}^3/\text{min}$$

The required volumetric flow rate for 300fpm at a distance of 12 inches is 3,420 ft^3/min

Solution for b:

B. X = 24 in (150% of hood diameter)

The hood opening remains the same:

$$A_h = \frac{\pi D^2}{4} = \frac{\pi\left[16\text{in}\left(\frac{1\text{ft}}{12\text{in}}\right)\right]^2}{4} = 1.40\text{ft}^2$$

Calculate the volumetric flow rate, Q, required obtaining the recommended capture velocity of 300 fpm at a distance of 24 inches from the hood:

Solution for B: B. X = 24 in (150% of hood diameter)

$A_h = 1.40\ ft^2$ and X = 24 inches

$$Q = v_h (10X^2 + A_h)$$

$$= 300\ {}^{ft}\!/_{min} \left[10(2ft)^2 + 1.40ft^2\right] = 3{,}420\ {}^{ft^3}\!/_{min}$$

The volumetric flow rate requirements increased approximately 4 times when the X was doubled

Hood Designs for Improved Performance

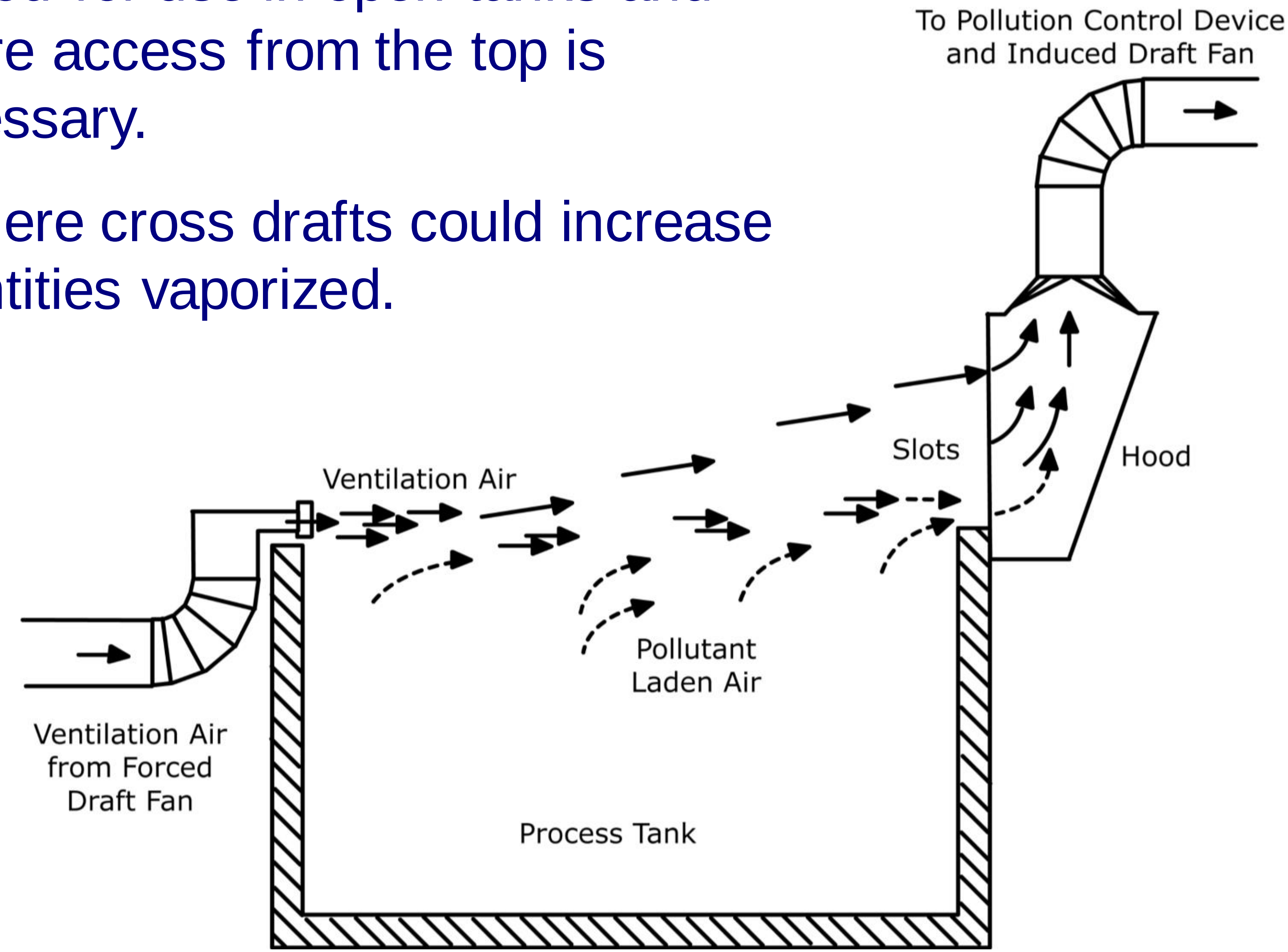
- Considerations for hot gas streams
- Use of Flanges
- Use of Side Baffles
- Other Designs

Added Side Baffles

Push Pull Hoods

+ good for use in open tanks and where access from the top is necessary.

- Where cross drafts could increase quantities vaporized.



Monitoring Hood Capture Effectiveness

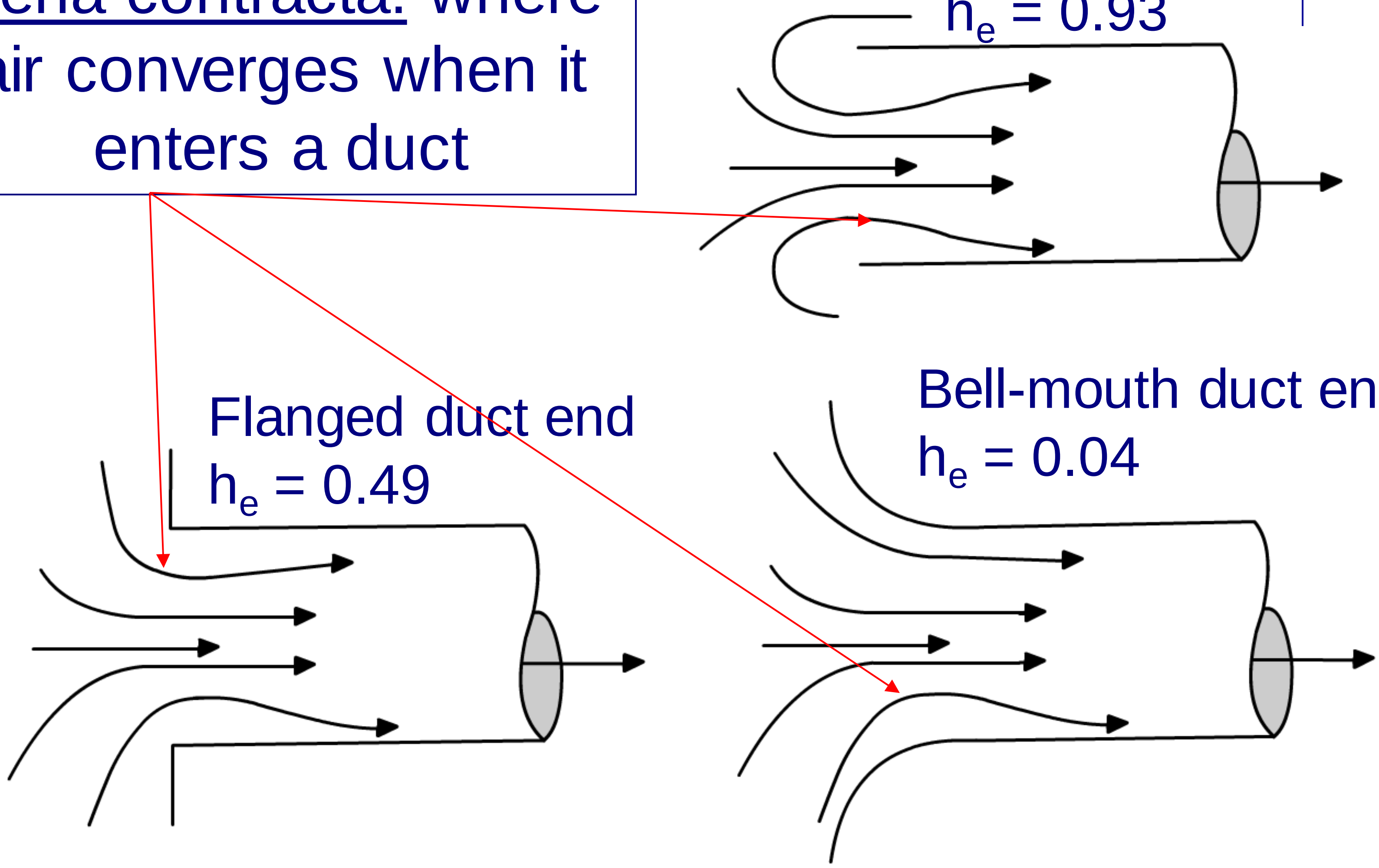
$$SP_h = VP_d + h_e$$

where

SP_h = hood static pressure
VP_d = velocity pressure in duct
h_e = hood entry loss
h_e = $F_h VP_d$
F_h = hood entry loss coefficient (dimensionless)

Duct shape affects airflow

<u>Vena contracta:</u> where air converges when it enters a duct



After the vena contract the airflow expands to fill the duct

Velocity Pressure

$$VP_d = \rho_g \left(\frac{v_d}{1{,}096.7} \right)^2$$

where
VP_d = duct velocity pressure (in WC)
v_d = duct gas velocity (ft/min)
ρ_g = gas density (lbm/ft^3)

- As gas flow rate increases the static pressure increases
- A decrease in static pressure indicates the gas flow rate has decreased from previous levels.

Example 10-4

A hood serving a paint dipping operation has a hood static pressure of 1.10 in WC. The baseline hood static pressure was 1.70 in WC.

Estimate the gas flow rate under the following two conditions:

A. At present operating conditions
B. At baseline levels

Use the data provided below:

- F_h = 0.93
- Temperature = 68°F
- Duct diameter 2 ft (inside diameter)

Example 10-4 solution

Calculate the velocity pressure in the duct:

$$SP_h = (1 + F_h)VP_d$$

$$VP_d = \frac{SP_h}{1 + F_h} = \frac{1.10 \text{ in WC}}{1 + 0.93} = 0.57 \text{ in WC}$$

F_h = 0.93

Temperature = 68°F

Duct diameter 2 ft (inside diameter)

Example 10-4 solution

Calculate the gas velocity in the duct:

$$VP_d = \rho_g \left(\frac{v_d}{1{,}096.7} \right)^2$$

$$v_d = 1{,}096.7 \sqrt{\frac{VP_d}{\rho_g}} = 1{,}096.7 \sqrt{\frac{0.57 \text{ in WC}}{0.0747 \, \text{lb}_m / \text{ft}^3}} = 3{,}029.5 \, \text{ft}/\text{min}$$

F_h = 0.93

Temperature = 68°F

Duct diameter 2 ft (inside diameter)

Example 10-4 solution

Calculate the gas flow rate:

$$Q = v_d A_d = v_d \left(\frac{\pi D^2}{4} \right)$$

$$= 3{,}029.5 \, \text{ft}/\text{min} \left[\frac{\pi (2\text{ft})^2}{4} \right] = 9{,}515.5 \, \text{ft}^3/\text{min}$$

$F_h = 0.93$
Temperature = 68°F
Duct diameter 2 ft (inside diameter)

The gas flow rate at present operating conditions is 9,515.5 ft^3/min

Example 10-4

A hood serving a paint dipping operation has a hood static pressure of 1.10 in WC. The baseline hood static pressure was 1.70 in WC.

Estimate the gas flow rate under the following two conditions:

A. At present operating conditions
B. At baseline levels

Use the data provided below:

- F_h = 0.93
- Temperature = 68°F
- Duct diameter 2 ft (inside diameter)

Example 10-4 solution (part b)

Calculate the velocity pressure in the duct:

$$SP_h = (1 + F_h)VP_d$$

$$VP_d = \frac{SP_h}{1 + F_h} = \frac{1.70 \text{ in WC}}{1 + 0.93} = 0.88 \text{ in WC}$$

F_h = 0.93
Temperature = 68°F
Duct diameter 2 ft (inside diameter)

Example 10-4 solution

Calculate the gas velocity in the duct:

$$VP_d = p_g \left(\frac{v_d}{1{,}096.7} \right)^2$$

$$v_d = 1{,}096.7 \sqrt{\frac{VP_d}{p_g}} = 1{,}096.7 \sqrt{\frac{0.88 \text{ in WC}}{0.0747 \, {}^{lb_m}/_{ft^3}}} = 3{,}764.2 \, {}^{ft}/_{min}$$

$F_h = 0.93$
Temperature = 68°F
Duct diameter 2 ft (inside diameter)

Example 10-4 solution

Calculate the gas flow rate:

$$Q = v_d A_d = v_d\left(\frac{\pi D^2}{4}\right) = 3{,}764.2\,{}^{\text{ft}}\!/_{\text{min}}\left[\frac{\pi(2\text{ft})^2}{4}\right] = 11{,}819.9\,{}^{\text{ft}^3}\!/_{\text{min}}$$

$F_h = 0.93$
Temperature = 68°F
Duct diameter 2 ft (inside diameter)

The decrease in WC from 1.7 in to 1.1 indicates a drop in the gas flow rate from 11,820 to 9.518 acfm. That's a 20% decrease.

Transport Velocities

Contaminant	Transport Velocity (ft/min)
Vapors, gasses, smoke	Any (usually 1000-2000)
Fumes	1400-2000
Very fine, light dust	2000-2500
Dry dust and powders	2500-3500
Average industrial dust	3500-4000
Heavy dusts	4000-4500
Heavy or moist	4500 and up

Calculating Duct Diameter

A duct system transporting a dry dust requires a minimum transport velocity of 2,800 ft/min. The volumetric flow rate for the system is 978 acfm.

What is the necessary duct diameter in inches for this section of ductwork to maintain the minimum transport velocity?

Solution

Calculate the Duct Area:

$$A_d = \frac{Q}{v_d} = \frac{978\,\text{ft}^3/\text{min}}{2{,}800\,\text{ft}/\text{min}} = 0.349\text{ft}^2$$

Calculate the Duct Diameter:

$$A_d = \frac{\pi D^2}{4}$$

$$D = \sqrt{\frac{4A_d}{\pi}} = \sqrt{\frac{4(0.349\text{ft}^2)}{\pi}} = 0.667\text{ft} = 8\text{in}$$

Fans

Types of Fans

- Axial
- Centrifugal
- Special

Figure 10-9. Axial fan

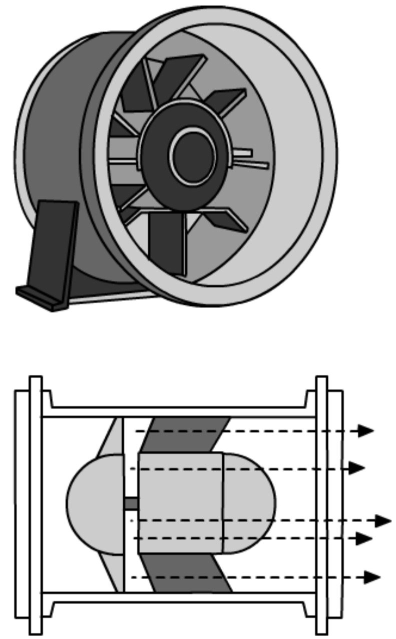
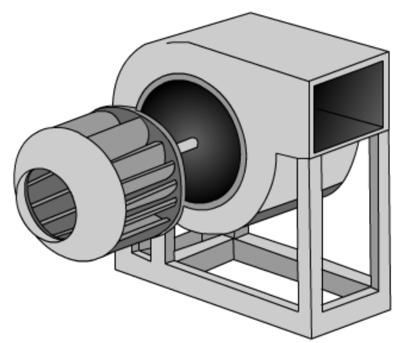


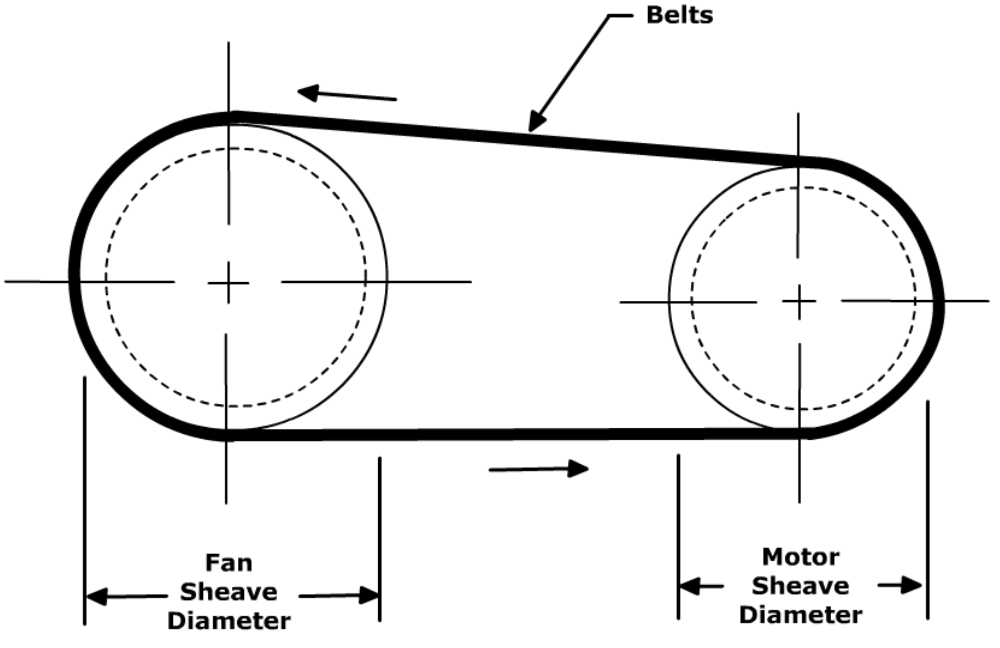
Figure 10-10. Centrifugal fan



Fan Components

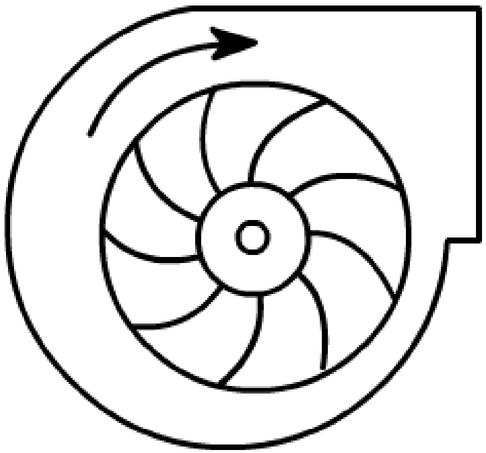
- Direct Drive
- Belt Drive
- Variable Drive

Figure 10-11. Centrifual fan motor sheaves



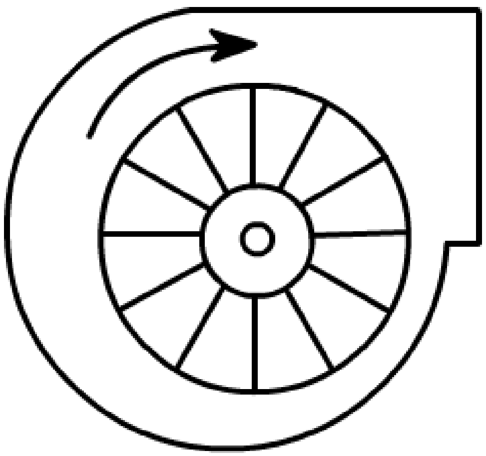
Centrifugal Fan Wheels

- Forward curved
- Radial
- Backward curved
  - Standard blade
  - Airfoil blade



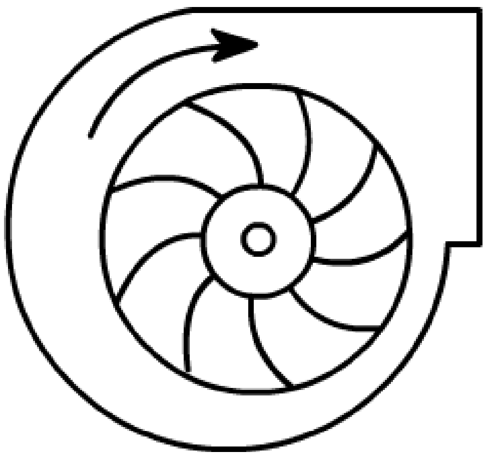
A. Forward curved

- Has 24-64 shallow blades
- Efficiency less than backward inclined
- Operates at lowest speed



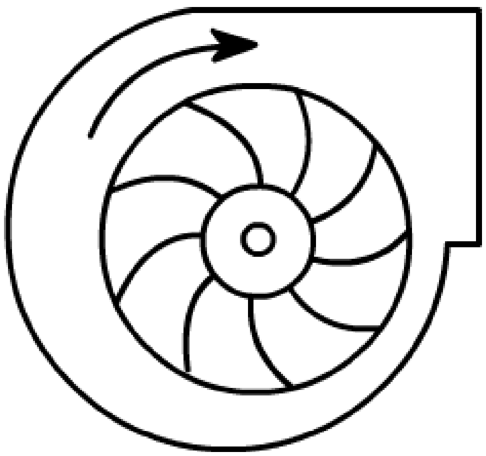
C. Radial

- Has 6-10 blades
- Efficiency less than backward inclined
- Operates at low speed



B. Backward curved

- Has 9-16 blades
- Efficiency only slightly less than airfoil
- Operates at high speed

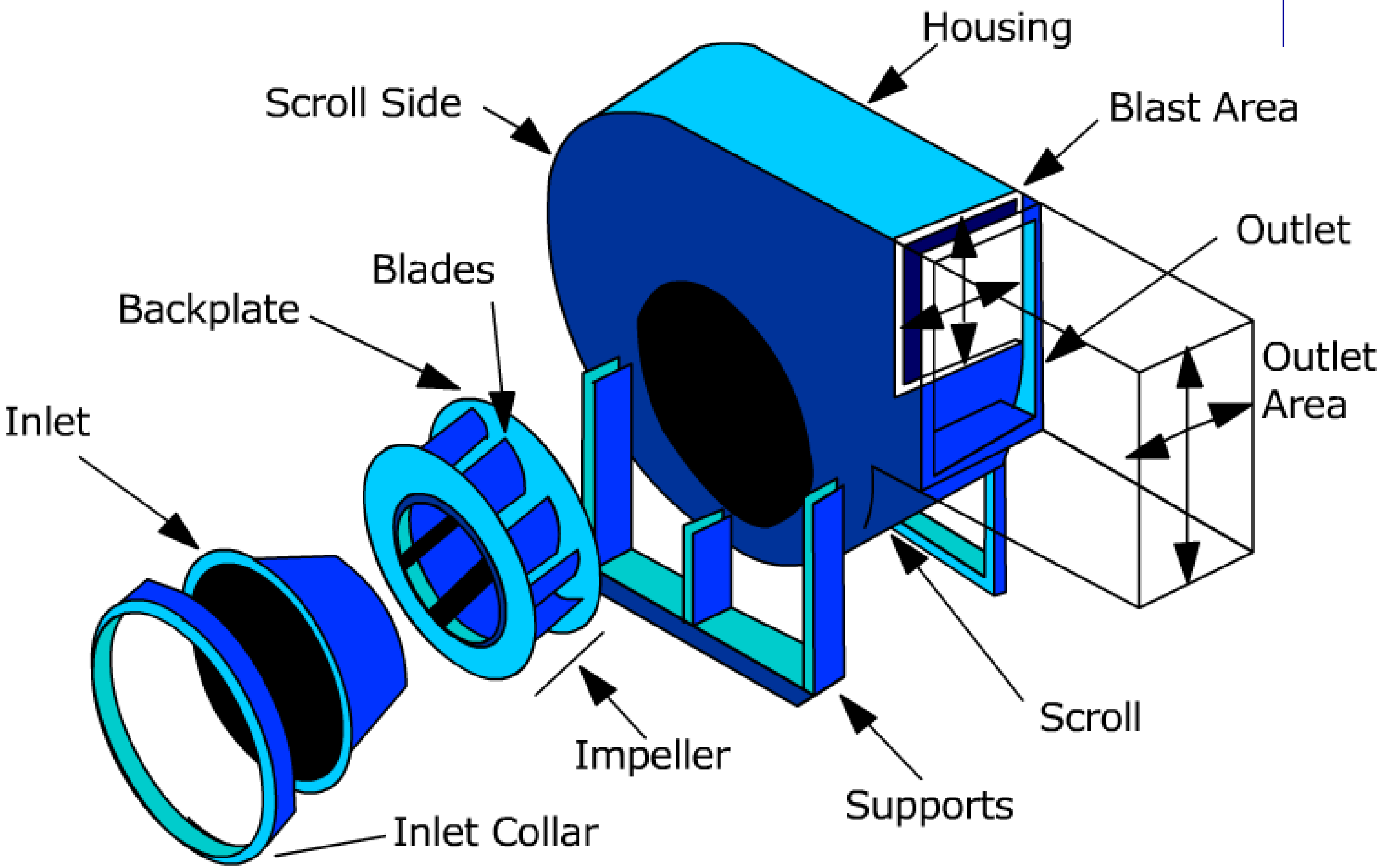


B. Backward curved

Backward Curved – but with Airfoil blade

- Has 9-16 blades
- Most efficiency
- Operates at highest speed

Centrifugal Fans



Centrifugal Fan Operating Principles

Fan Law #1:

the relationship of speed to gas flow rate

$$Q_2 = Q_1\left(\frac{RPM_2}{RPM_1}\right)$$

Where

Q_1 =baseline gas flow rate (acfm)
Q_2 = present gas flow rate (acfm)
RPM_1 = baseline fan wheel rotational speed (revolutions per minute)
RPM_2 = present fan wheel rotational speed (revolutions per minute)

Centrifugal Fan Operating Principles

Fan Laws:

Static pressure at the outlet is always higher than the SP at the inlet

$$\text{Fan SP} = Sp_{out} - Sp_{in} - VP_{in}$$

Centrifugal Fan Operating Principles

Fan Law #2:

Fan SP is related to the square of the fan speed

$$\text{Fan}\,\text{SP}_2 = \text{Fan}\,\text{SP}_1 \left(\frac{\text{RPM}_2}{\text{RPM}_1} \right)^2$$

Where

Fan SP_1 = baseline fan static pressure (in WC)
Fan SP_2 = present fan static pressure (in WC)
RPM_1 = baseline fan wheel rotational speed (revolutions per minute)
RPM_2 = present fan wheel rotational speed (revolutions per minute)

Centrifugal Fan Operating Principles

Fan Law #3:

The brake horsepower is also related to the cube of the fan speed

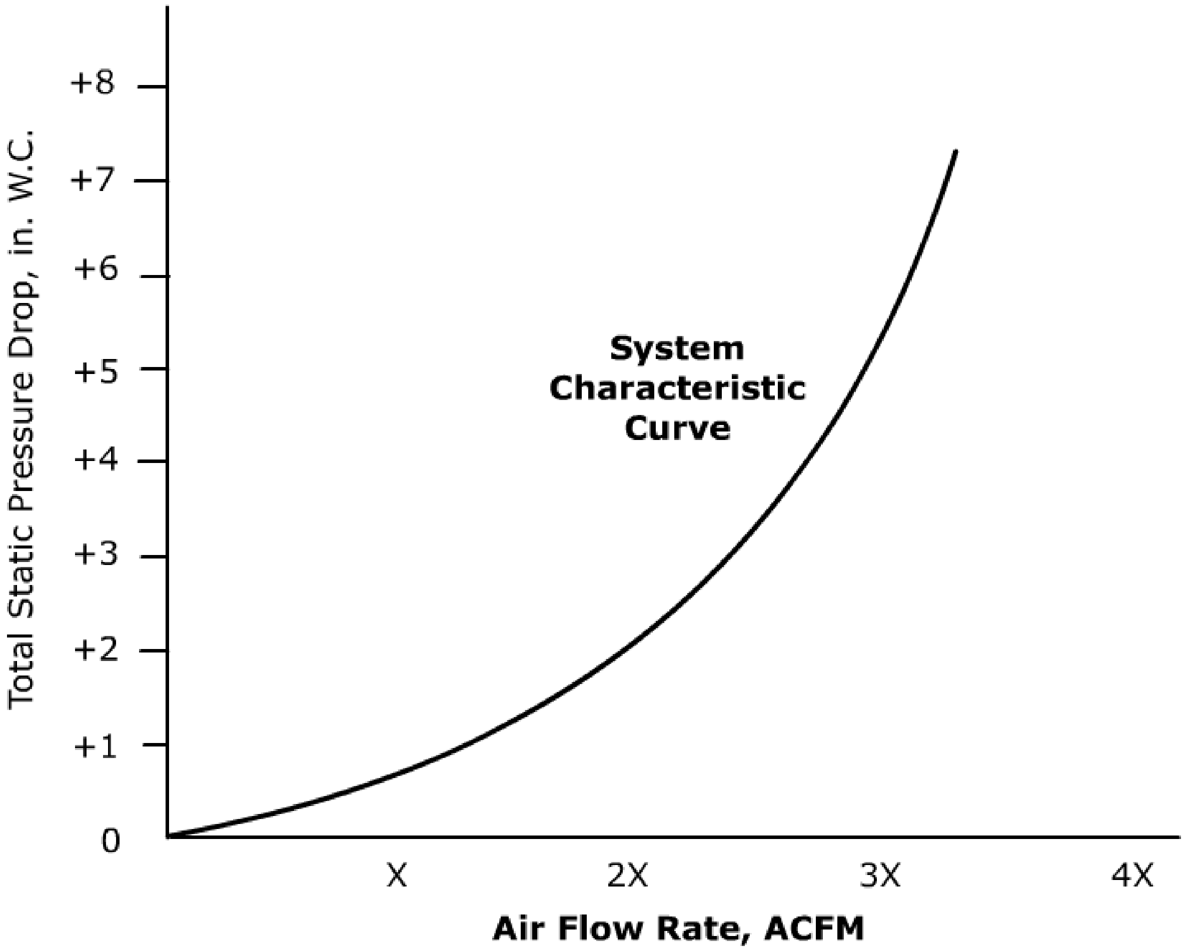
$$BHP_2 = BHP_1\left(\frac{RPM_2}{RPM_1}\right)^3$$

Where

- BHP_1 = baseline brake horsepower
- BHP_2 = present brake horsepower
- RPM_1 = baseline fan wheel rotational speed (revolutions per minute)
- RPM_2 = present fan wheel rotational speed (revolutions per minute)

System Characteristic Curve

Figure 10-14. System characteristic curve



Multi-Rating Table (sample)

194 LS

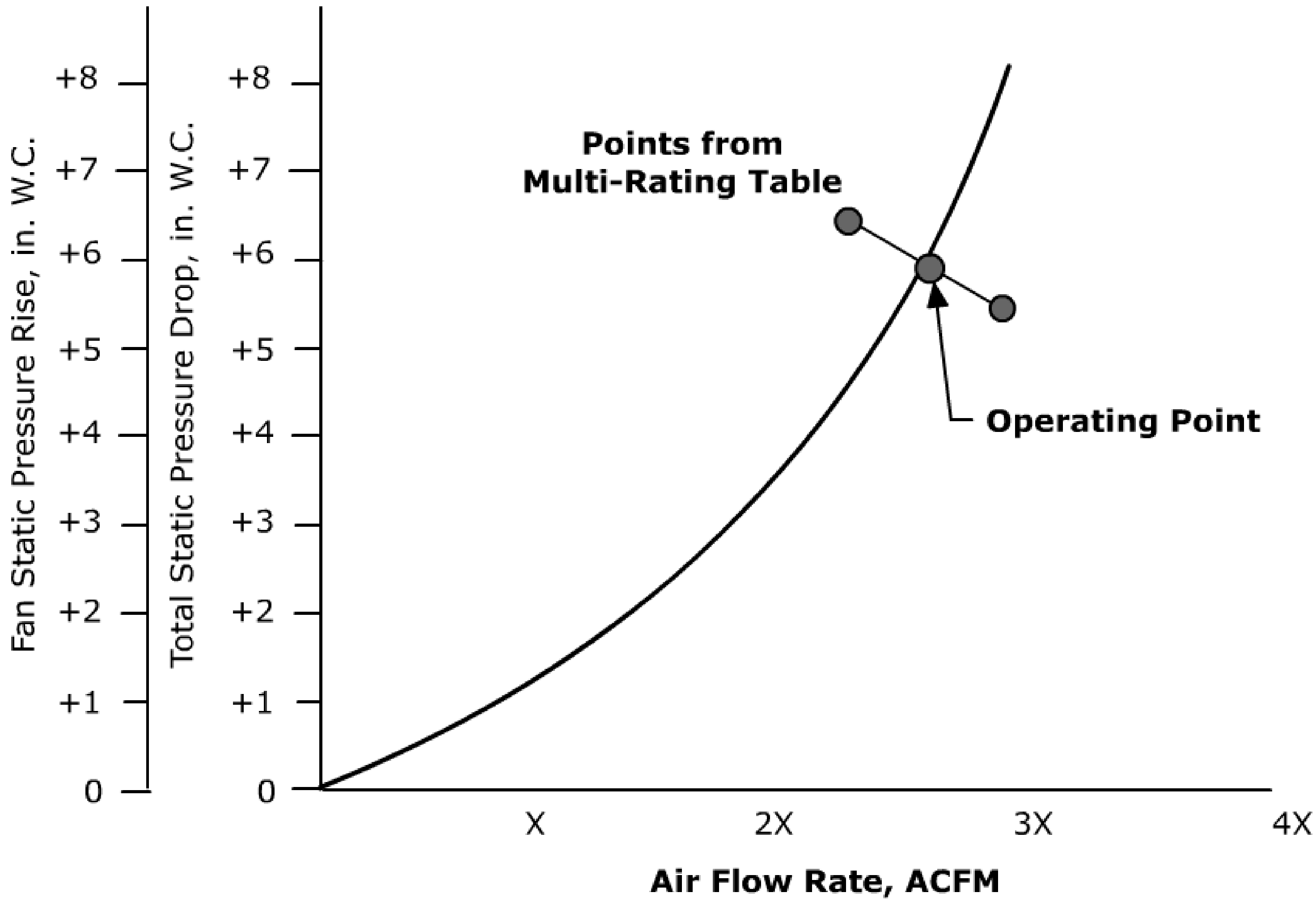
Inlet diameter: 11" O.D.
Outlet area: .660 sq. ft. inside
Wheel diameter: 19⅛"
Wheel circumference: 5.01 ft

CFM	OV	2"SP		4"SP		6"SP		8"SP		10"SP		12"SP		14"SP		16"SP		18"SP	
		RPM	BHP	RPM	BHP	RPM	BHP	RPM	BHP	RPM	BHP	RPM	BHP	RPM	BHP	RPM	BHP	RPM	BHP
660	1000	995	0.48	1392	1.01	1698	1.60	1960	2.27	2191	2.98	2399	3.74	2592	4.55	2769	5.38	2938	6.27
792	1200	1008	0.55	1398	1.11	1703	1.75	1962	2.45	2192	3.20	2398	3.99	2588	4.83	2767	5.71	2936	6.65
924	1400	1023	0.62	1405	1.23	1708	1.90	1965	2.64	2194	3.43	2401	4.27	2589	5.14	2766	6.05	2932	7.01
1056	1600	1042	0.71	1418	1.35	1716	2.07	1971	2.84	2197	3.67	2401	4.53	2593	5.46	2769	6.42	2935	7.41
1188	1800	1061	0.80	1431	1.49	1726	2.24	1980	3.06	2203	3.92	2407	4.83	2593	5.78	2771	6.79	2936	[illegible]
1320	2000	1084	0.90	1447	1.64	1739	2.44	1987	3.29	2209	4.19	2414	5.15	2600	6.13	2773	7.16	2940	[illegible]
1452	2200	1109	1.01	1466	1.80	1753	2.65	1999	3.54	2221	4.49	2422	5.47	2607	6.50	2778	7.55	2943	[illegible]
1584	2400	1136	1.13	1485	1.98	1769	2.87	2012	3.80	2229	4.78	2431	5.82	2612	6.87	2786	7.98	2949	[illegible]
1716	2600	1162	1.26	1505	2.16	1784	3.10	2025	4.03	2242	5.11	2441	6.18	2623	7.38	2791	8.40	2956	[illegible]
1980	3000	1223	1.56	1554	2.58	1824	3.62	2059	4.70	2272	5.82	2464	6.95	2644	8.14	2815	9.30	2973	[illegible]
2244	3400	1290	1.91	1606	3.04	1867	4.19	2098	5.38	2305	6.59	2495	7.83	2671	9.09	2838	10.4	2995	[illegible]
2508	3800	1361	2.33	1661	3.56	1917	4.84	2141	6.12	2345	7.44	2531	8.78	2703	10.1	2866	11.5	[illegible]	[illegible]
2772	4200	1439	2.83	1723	4.16	1968	5.54	2189	6.95	2387	8.37	2569	9.80	2740	11.3	2900	12.8		
3036	4600	1519	3.40	1788	4.84	2025	6.32	2239	7.85	2432	9.36	2611	10.9	2780	12.5	2937	14.1		
3300	5000	1603	4.07	1855	5.58	2086	7.20	2294	8.83	2483	10.5	2660	12.1	2825	13.8	2978	15.5		
3564	5400	1691	4.84	1929	6.45	2148	8.14	2350	9.88	2536	11.6	2708	13.4	2869	15.2	3024	17.0		
3828	5800	1781	5.73	2005	7.41	2214	9.18	2409	11.0	2591	12.9	2759	14.8	2917	16.7	3069	18[illegible]		

Figure 10-15. Portion of a typical multi-rating table (reprinted courtesy of The New York Blower Company)

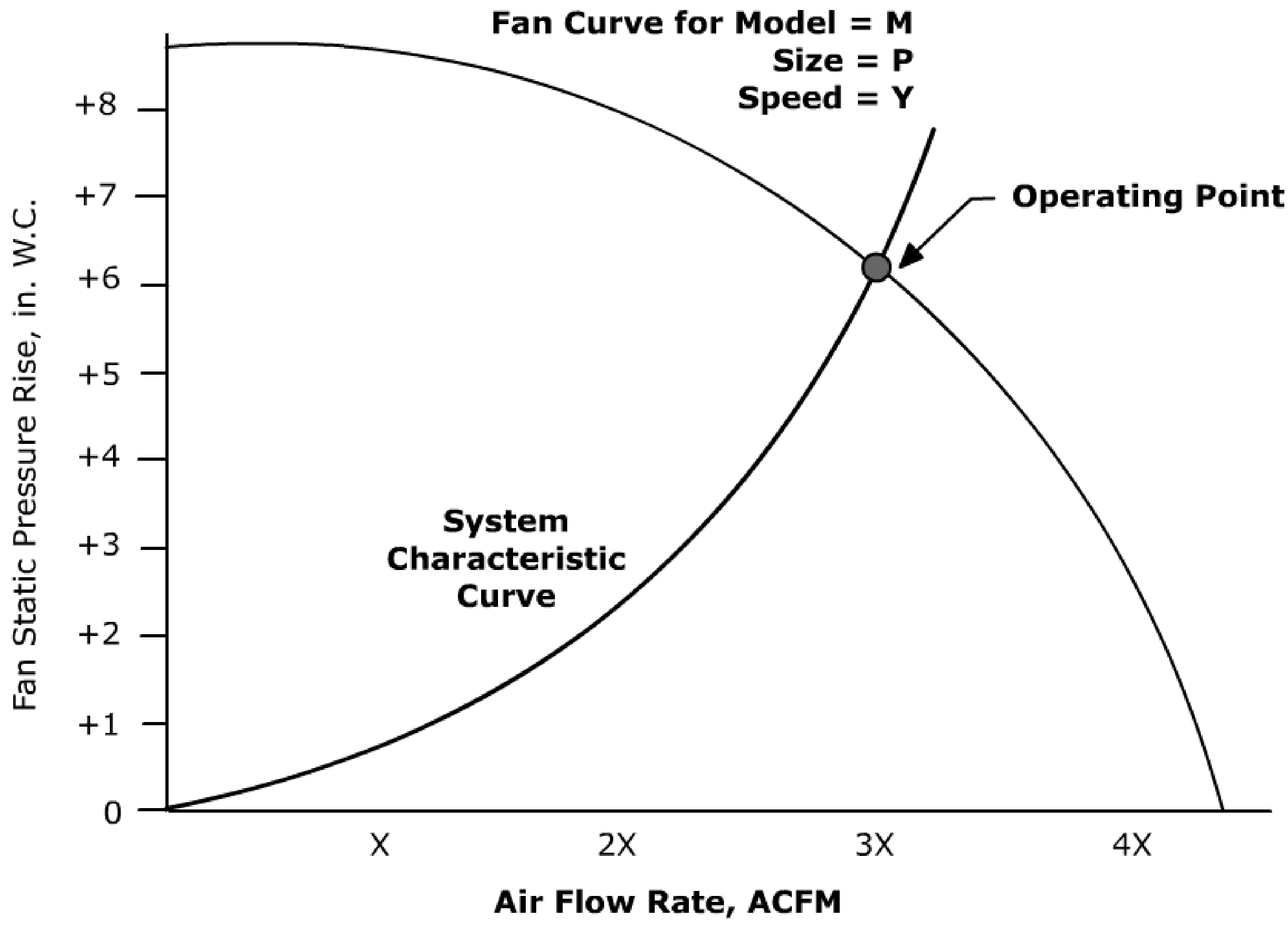
Operating Point

Figure 10-16. Operating Point



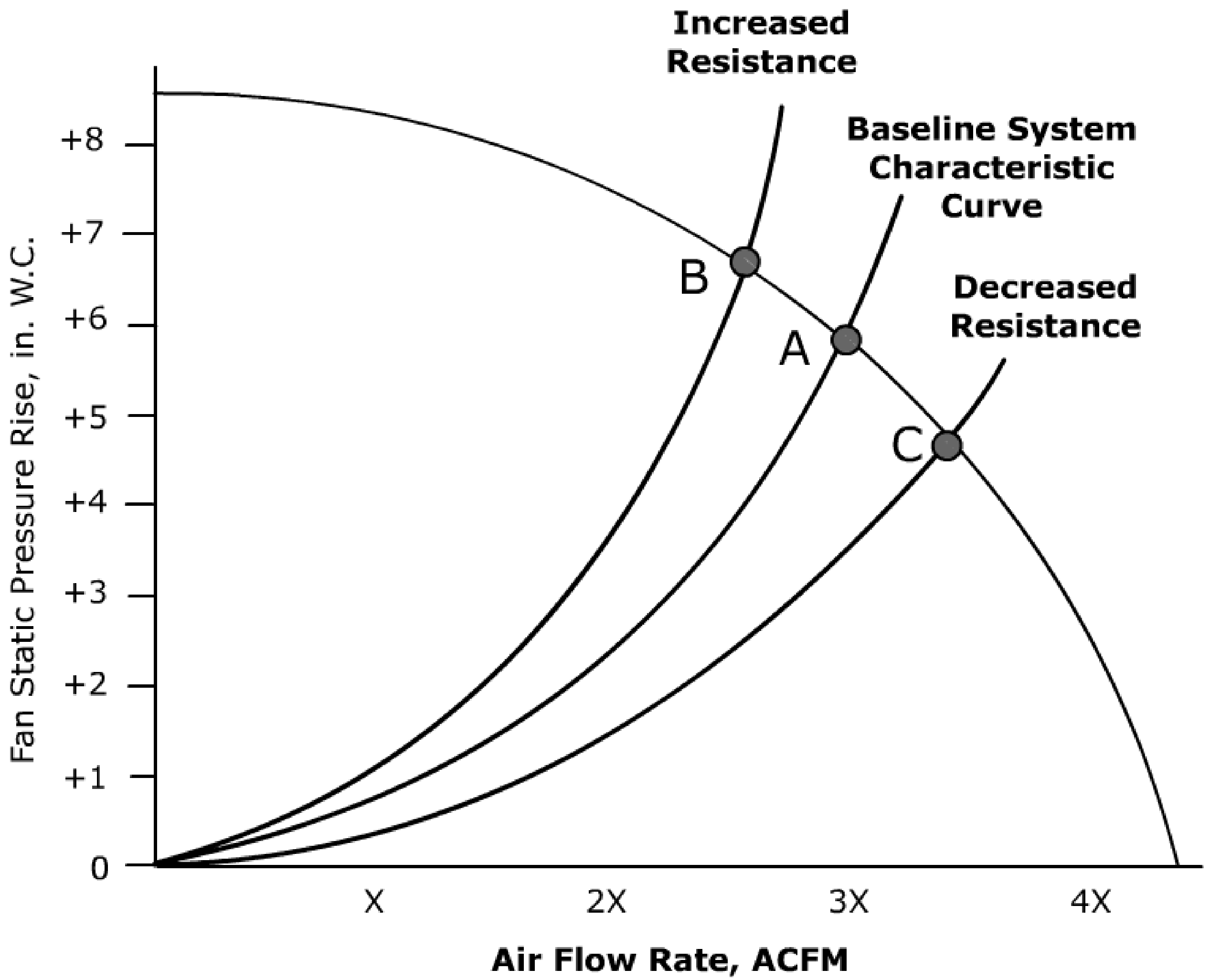
Fan Curve

Figure 10-17. Fan characteristic curve



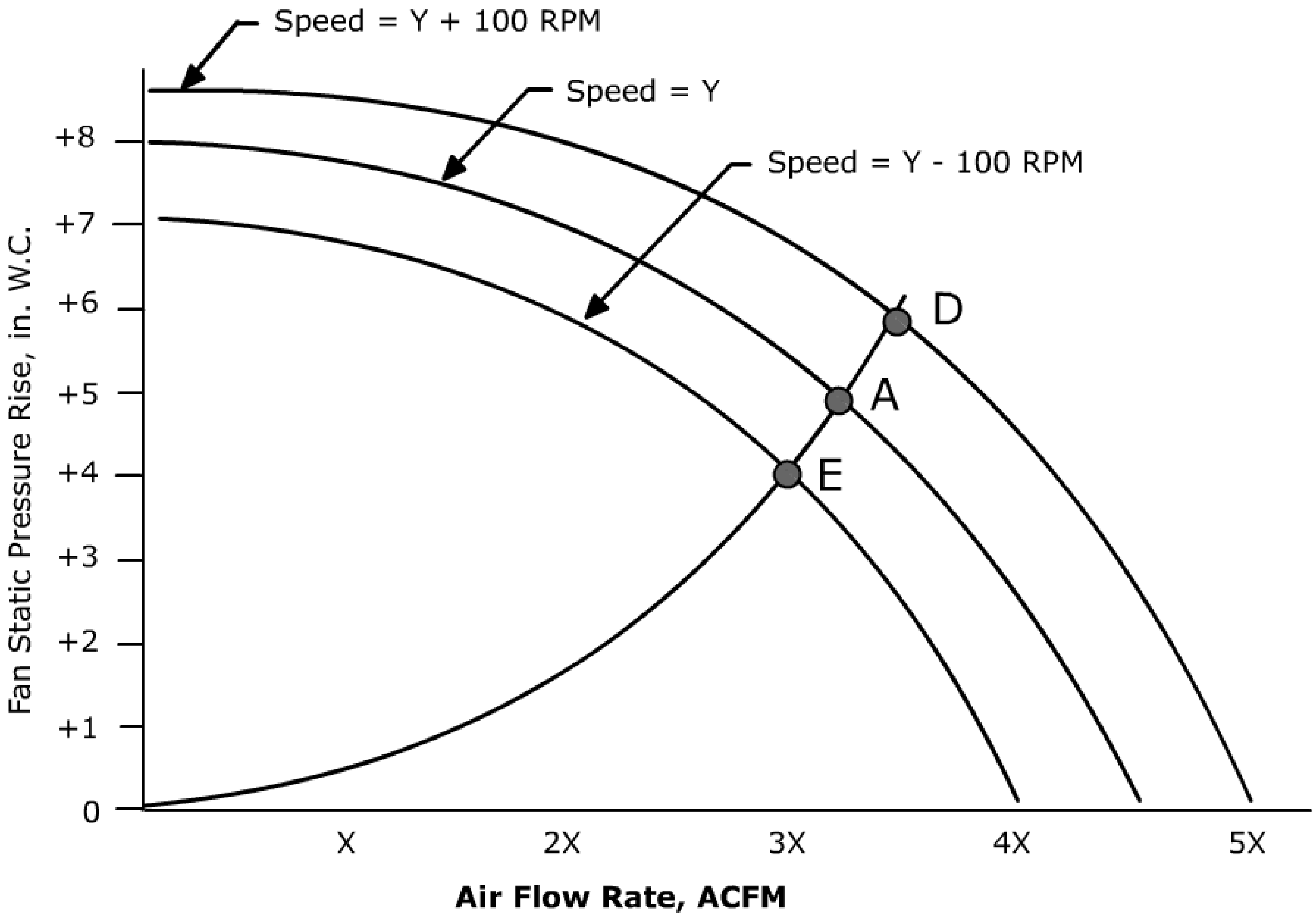
Changes in the System Resistance Curve

Figure 10-18. Changes in the system resistance curve



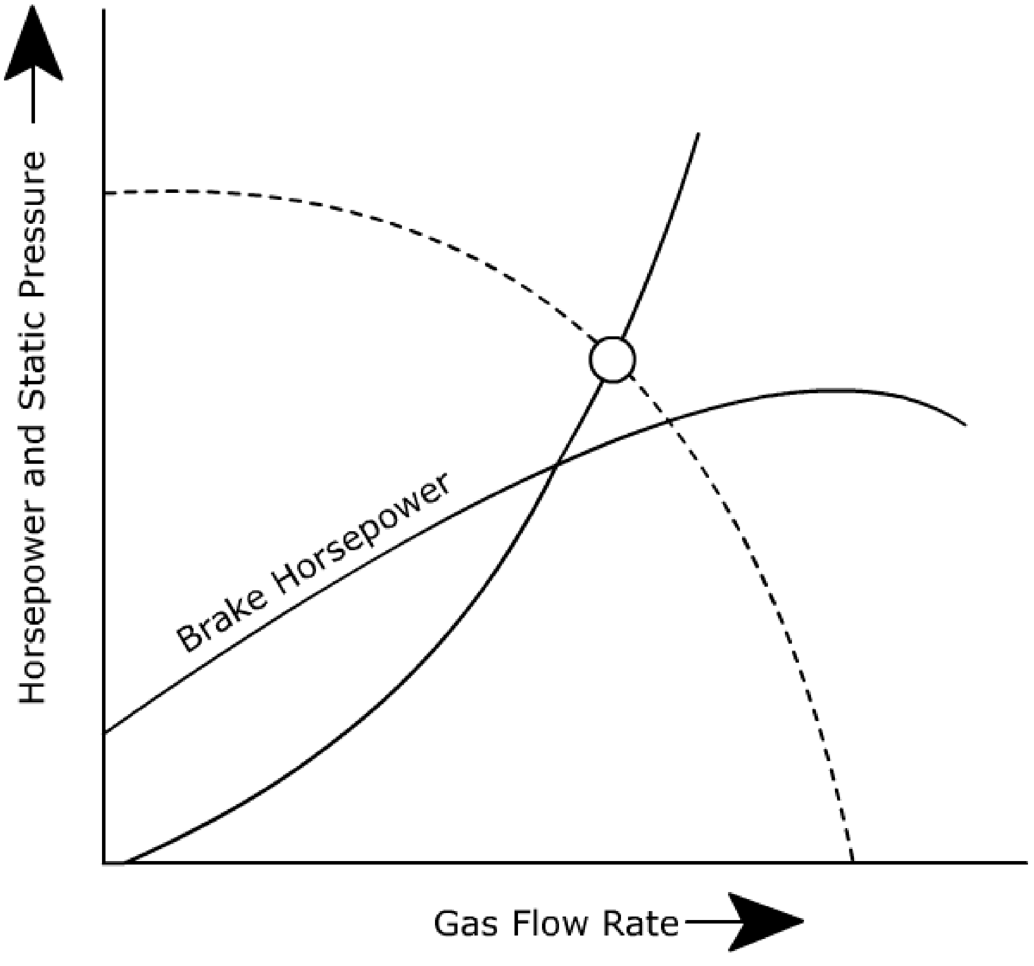
Changes in the Fan Speed

Figure 10-19. Changes in fan speed



Brake Horsepower Curve

Figure 10-20. Brake horsepower curve



Baseline System Characteristic

Evaluating the Entire Industrial Process

Why evaluate the whole process?

•Changes in the process equipment can have a major impact on the efficiency of the control device.

•Changes in the air pollution control device can affect the ability of the process hoods to capture the pollutants at the point of generation.

•The operating data from one unit in the system can be valuable in evaluating the operating conditions in another unit in the system.

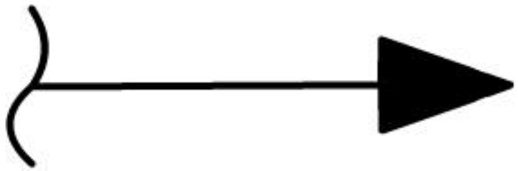
•Hoods and fans can influence the efficiency of the air pollution control equipment and the release of fugitive emissions from the process equipment.

Flowcharts

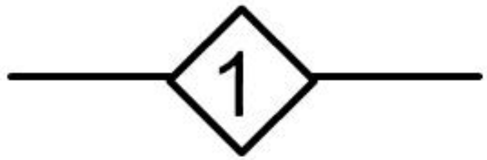
How are Flowcharts Useful?

- Evaluating process operating changes that are affecting control device performance
- Identifying instruments that are not working properly
- Identifying health and safety problems
- Communicating effectively

Flowchart Symbols



Utility Stream



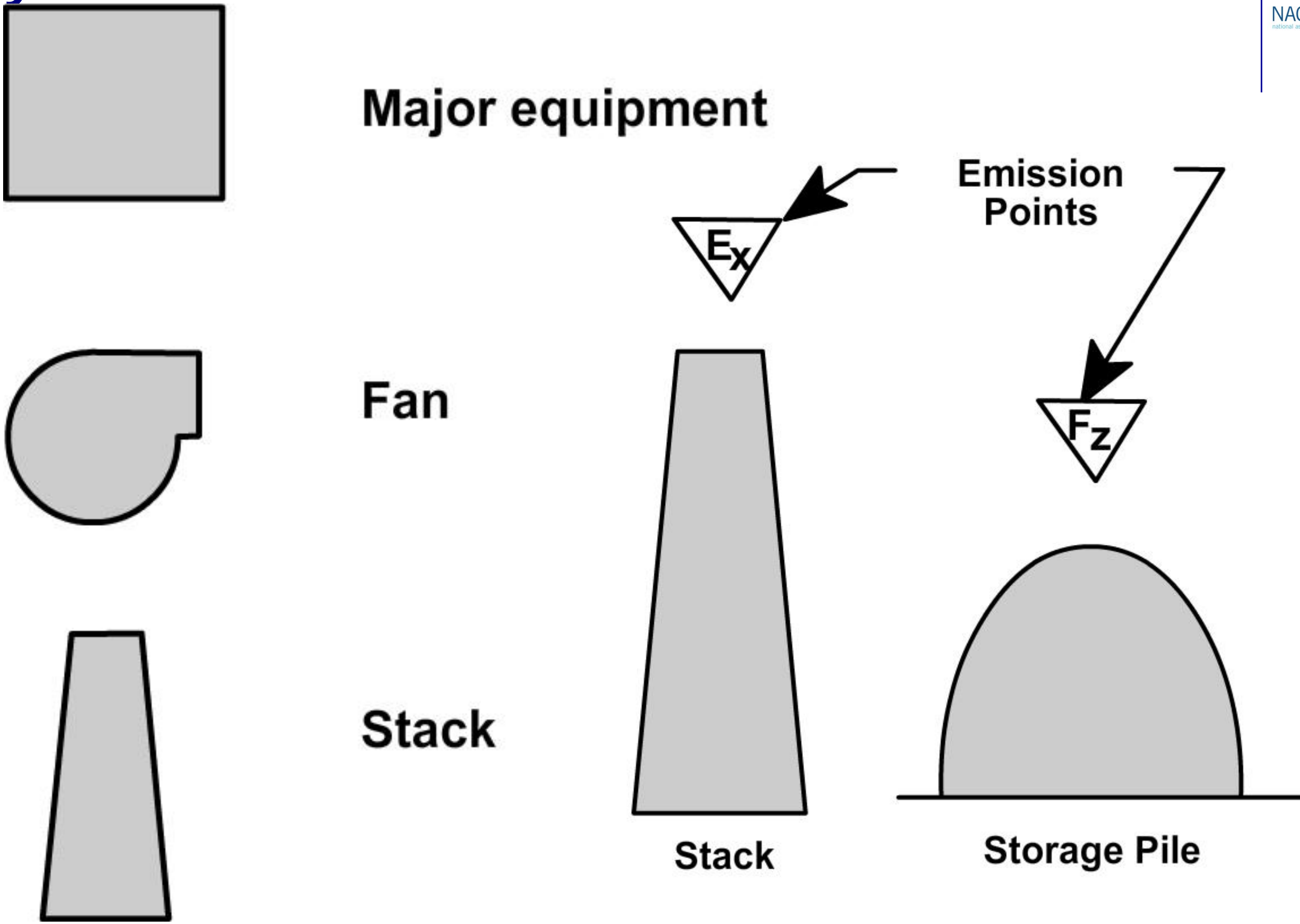
Solid or Liquid Stream

Gas Stream

Codes for Utility Streams

Cal	-compressed calibration gas	HS	-high pressure stream
CA	-compressed air	IA	-instrument air
CD	-condensate	LS	-low pressure steam
CW	-city (or plant) fresh water	Oil	-No. 2 or No. 6 oil
Gas	-natural gas		

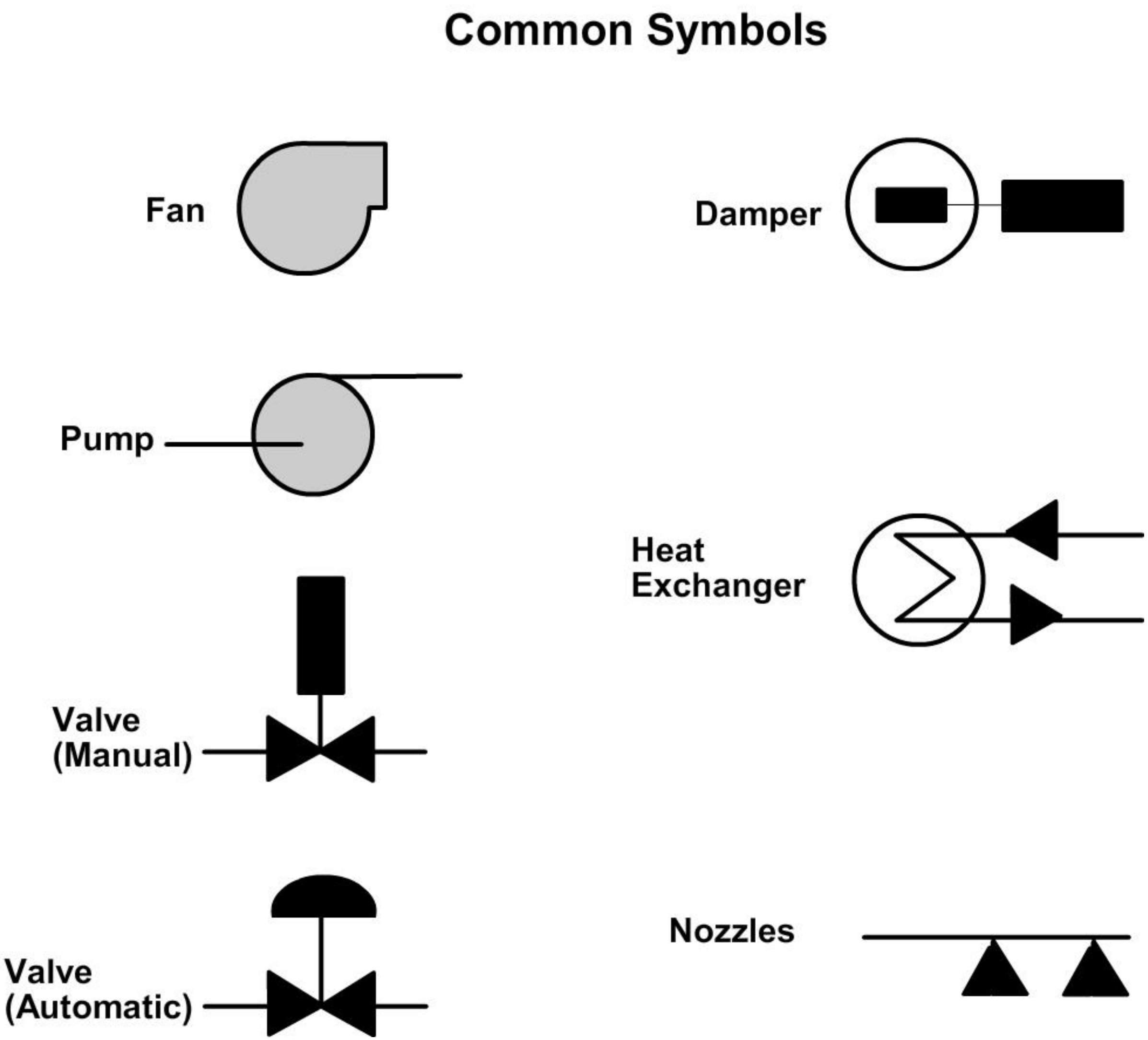
Major Equipment & Emission Point Symbols



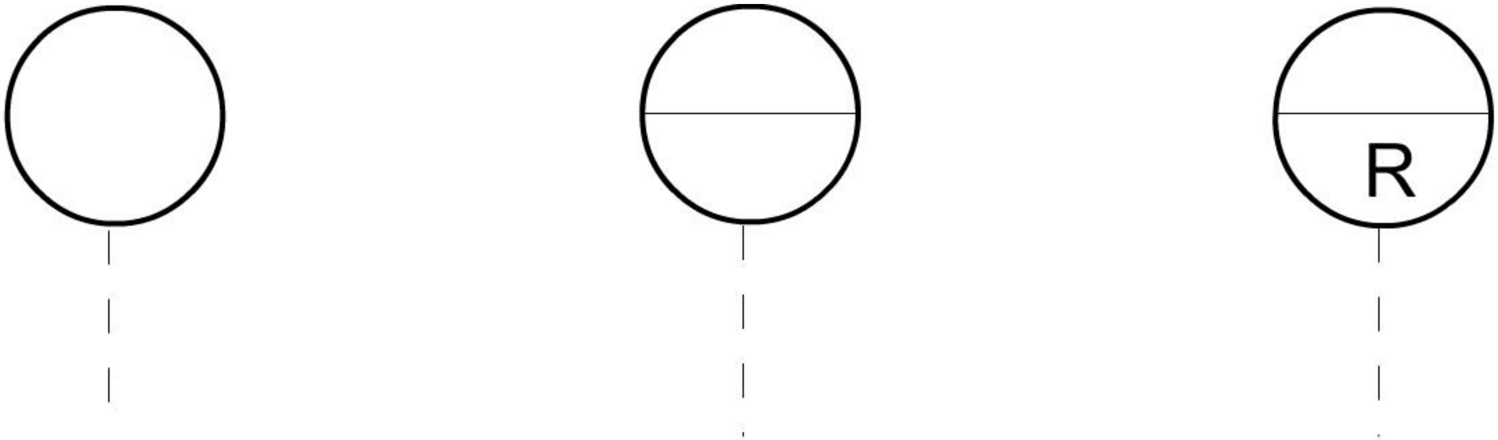
Minor Components of Systems

Fabric Filters	**Wet Scrubbers**
Bypass dampers	Pumps
Relief dampers	Nozzles
Outlet dampers	Manual valves
Reverse air fans	Automatic valves
Carbon Adsorbers and Oxidizers	
Indirect heat exchangers	
Fans	

Minor Component Symbols



Instruments



Direct Reading Instrument

Panel Mounted Instrument

Panel Mounted Instrument with Continuous Recorder

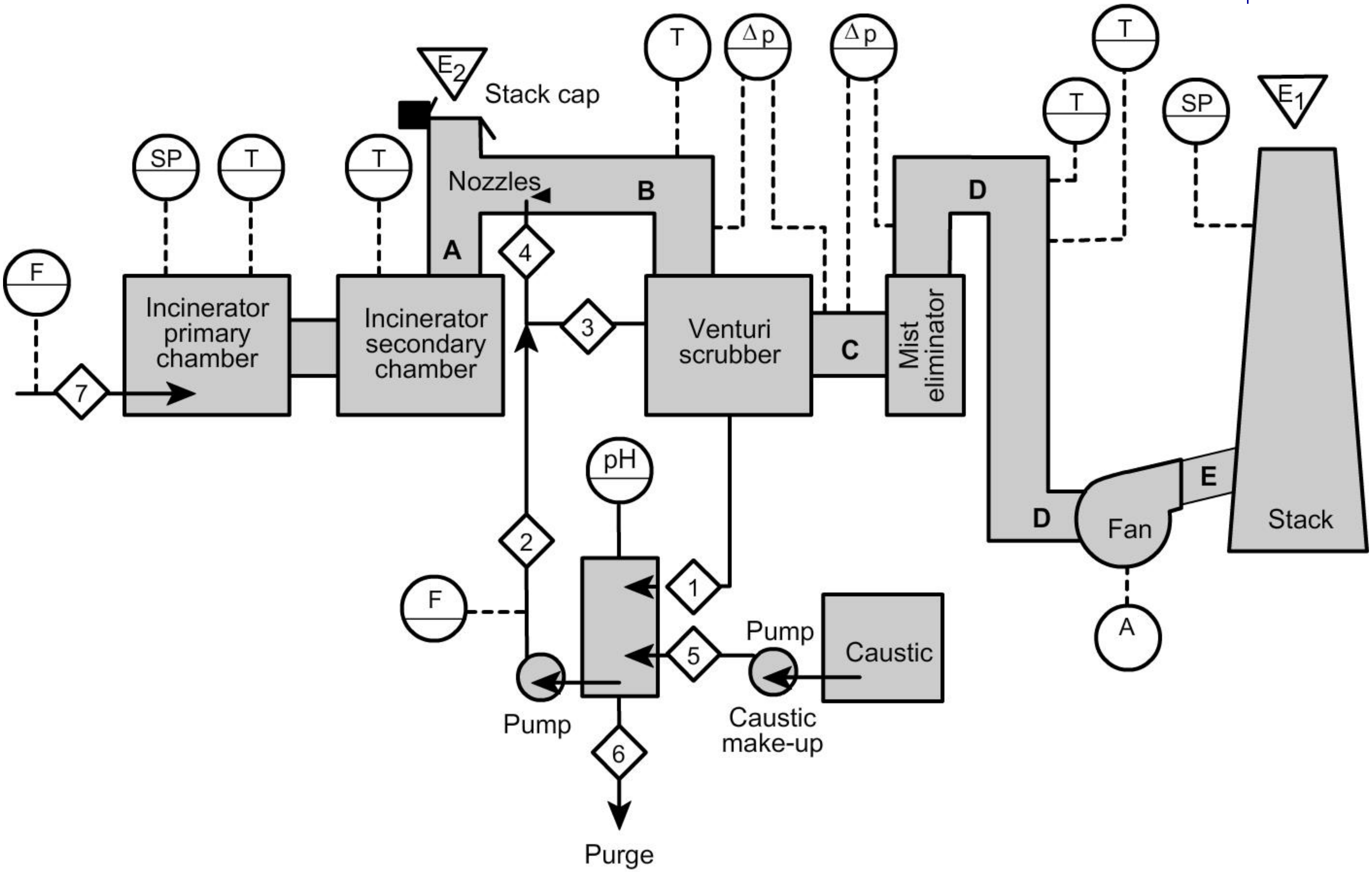
Instrument Codes

A	Motor current	pH	Liquid or slurry pH
CEM	Continuous emission monitor	Δp	Static pressure drop
Den	Density	SP	Gas static pressure
F	Flow	SSP	Stack sampling port
L	Liquid level	T	Temperature
LEL	Lower explosive limit	V	Vacuum gauge
MP	Measurement port	VOC	Low concentration VOC monitor
Op	Opacity	W	Weight
P	Gas or liquid pressure		

Materials of Construction

CS	Carbon Steel	RL	Rubber lined
FRP	Fiberglass reinforced plastic	SS	Stainless steel
N	Nickel alloy	WD	Wood

Diagrams



E_2
Stack cap
Nozzles
A
B
T
Δp
Δp
T
T
SP
E_1
SP
T
T
F
D
Incinerator primary chamber
Incinerator secondary chamber
4
3
Venturi scrubber
C
Mist eliminator
7
pH
2
1
F
5
Pump
Caustic
Pump
Caustic make-up
6
Purge
D
Fan
E
Stack
A

How diagrams help

1. Determine whether or not the operating data is consistent and logical.
2. Compare current data against site-specific baseline data.
3. Determine specific areas that may need emphasis during the inspection.
4. Determine potential health and safety problems that may be encountered during the inspection.

Examples 10-8 and 10-9

Please review in your text

Flowcharts Summary

- Identify changes in control device performance due to process changes
- Identify instruments that are not consistent with other similar instruments in the system
- Communicate effectively with other personnel
- Avoid potential health and safety hazards