Air Quality Control

Dr. Motasem Saidan

m.saidan@gmail.com

Air Quality and Meteorology

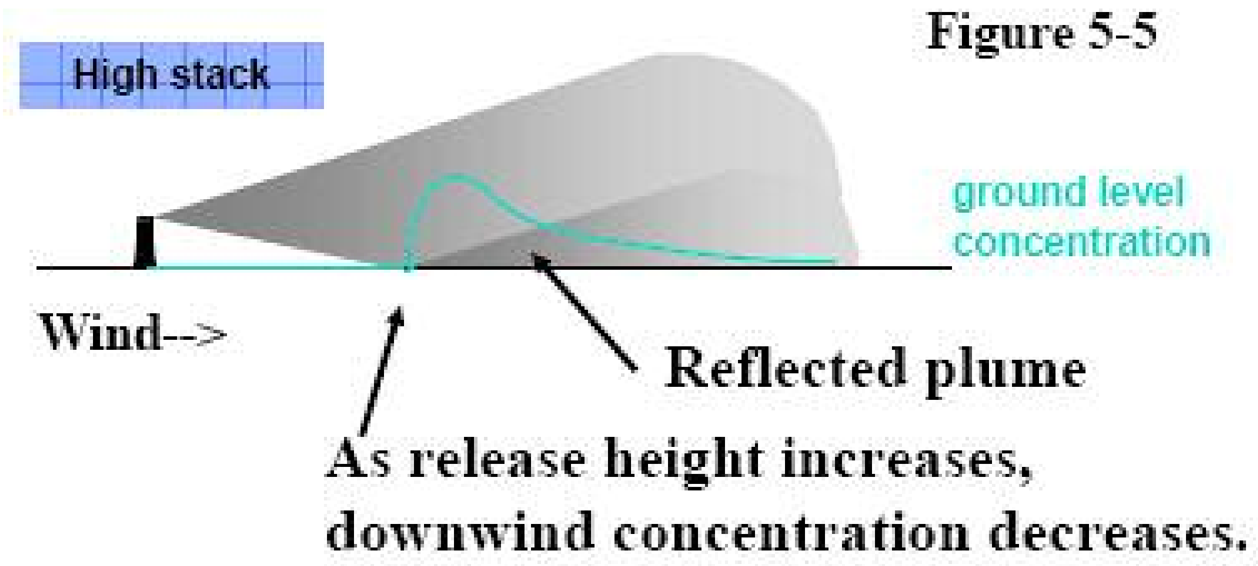
- Air quality depends on

  - wind
  - sunlight
  - temperature
  - precipitation and humidity
  - Energy from the sun and earth's rotation drives atmospheric circulation

- Circulation and the resulting interactions with water and temperature differences produce the climate and weather we observe

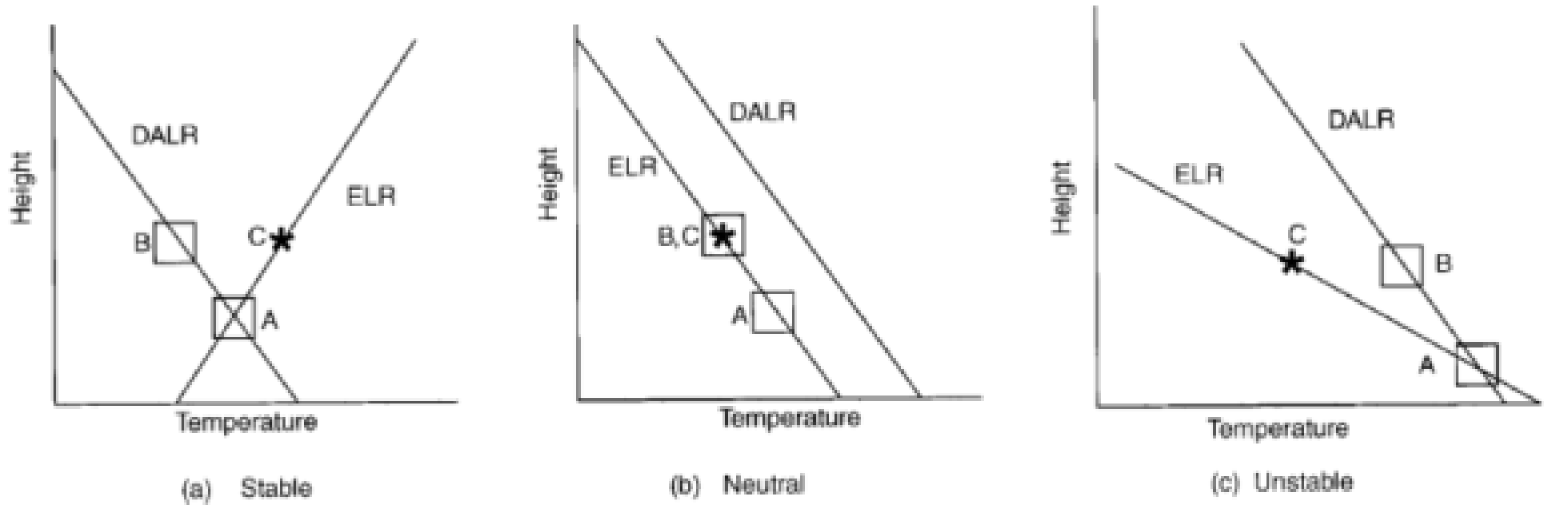
Plume types

The smoke trail or plume from a tall stack located on flat terrain has been found to exhibit a characteristic shape that is dependent on the stability of the atmosphere.



Atmospheric stability and temperature profile

- The adiabatic lapse rates (Γ) describe the temperature changes expected in a parcel of air when it is displaced vertically.
- This environmental lapse rate (ELR) is the vertical variation, or profile, of air temperature with height that exists at any particular time and place.
- The local balance between the two lapse rates gives an insight into the concept known as stability.



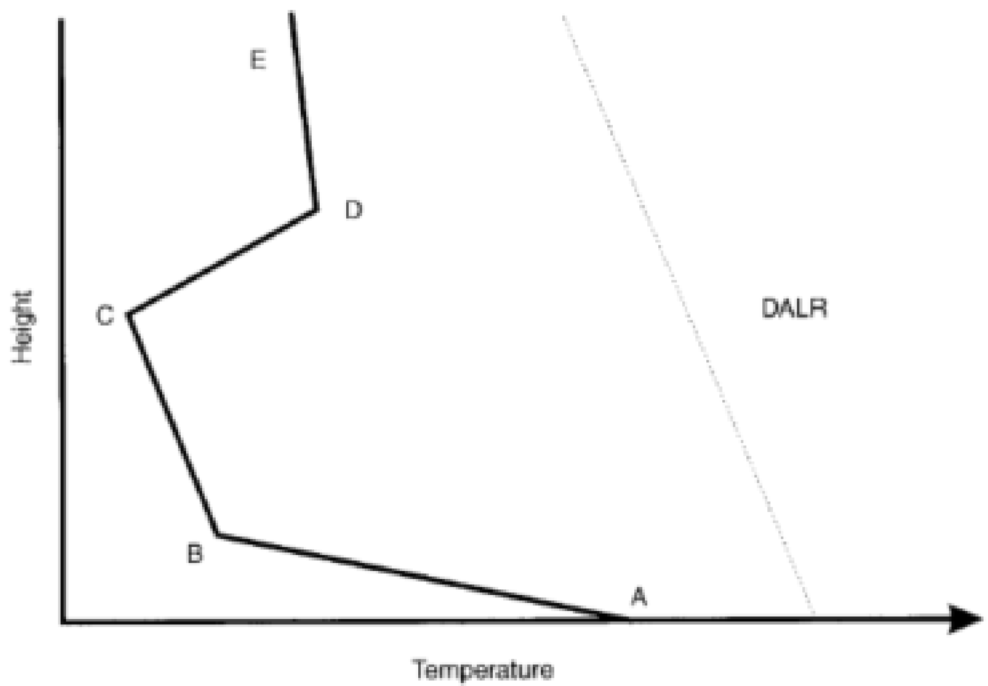
- In practice, real temperature profiles in the atmosphere often consist of a mixture of different ELRs, so that vertical dispersion will be different at different heights.

- Consider the ELR shown in the figure shown below:

  - Between A and B, strong solar heating of the ground has warmed the lowest layers of air;

  - the middle layer BC is close to DALR,

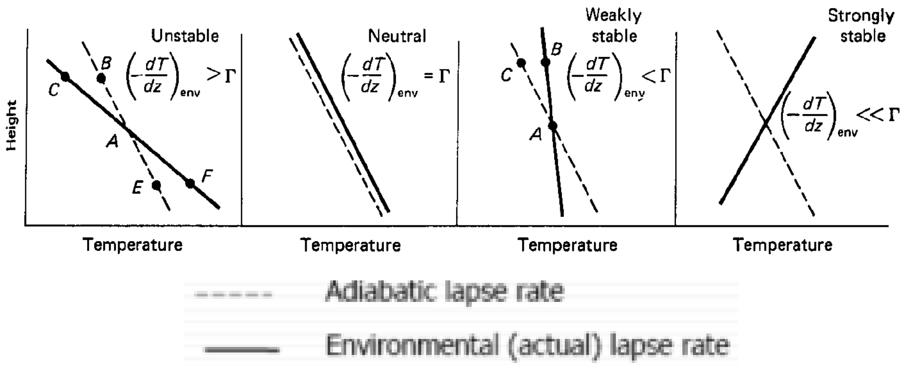
  - while the layer CD is showing an increase of temperature with height (this is known as an inversion of the temperature profile).

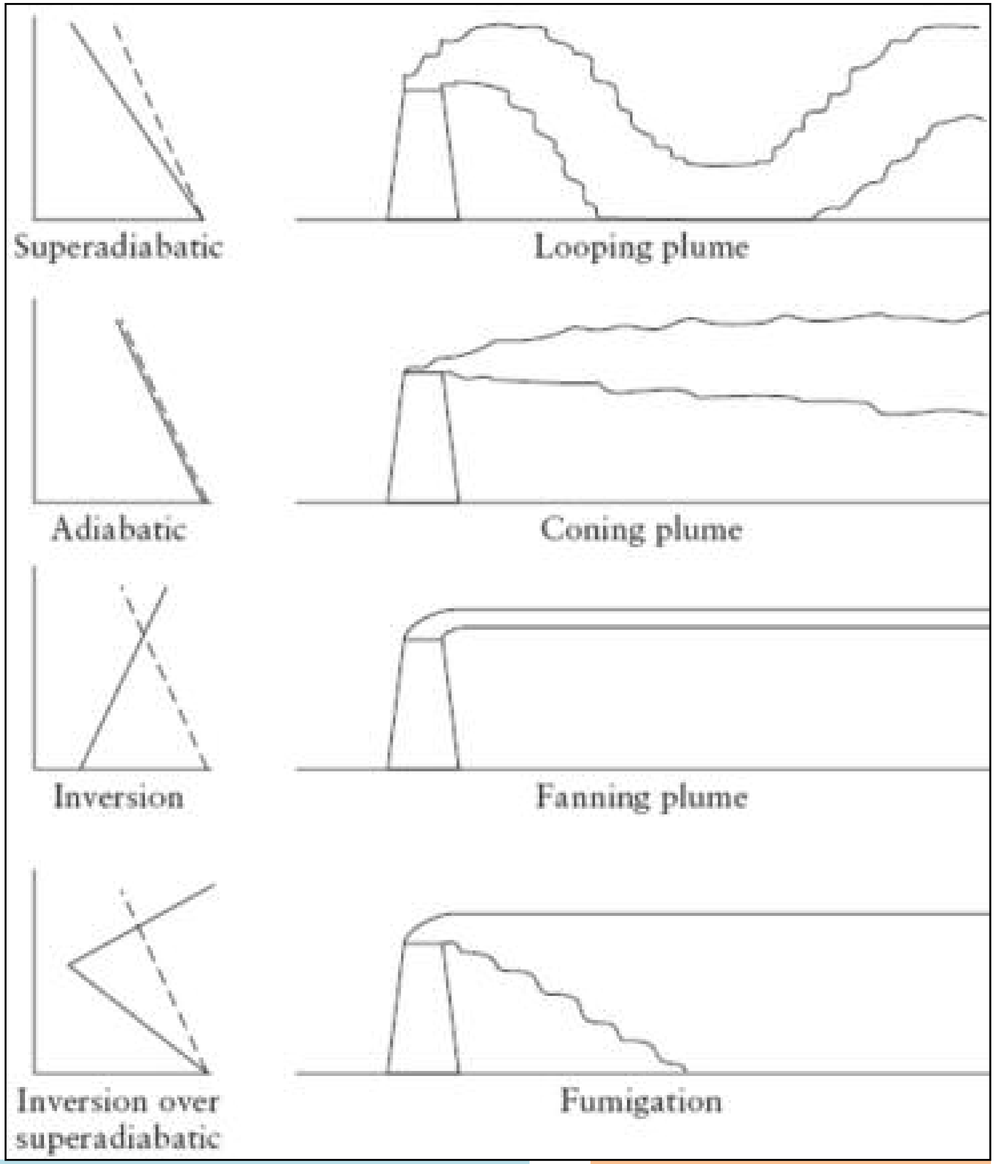


Stability Conditions

- In each case, the reference lapse rate is given as a broken line to allow comparison with the actual lapse rate, which is given as a solid line.

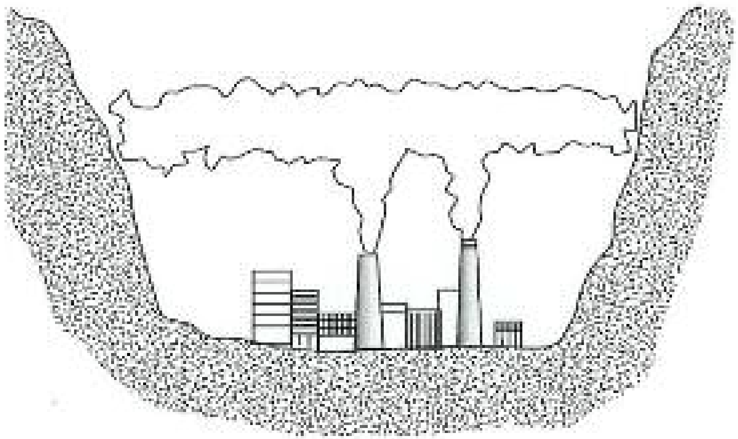
- In the bottom three cases, particular attention should be given to the location of the inflection point with respect to the top of the stack.





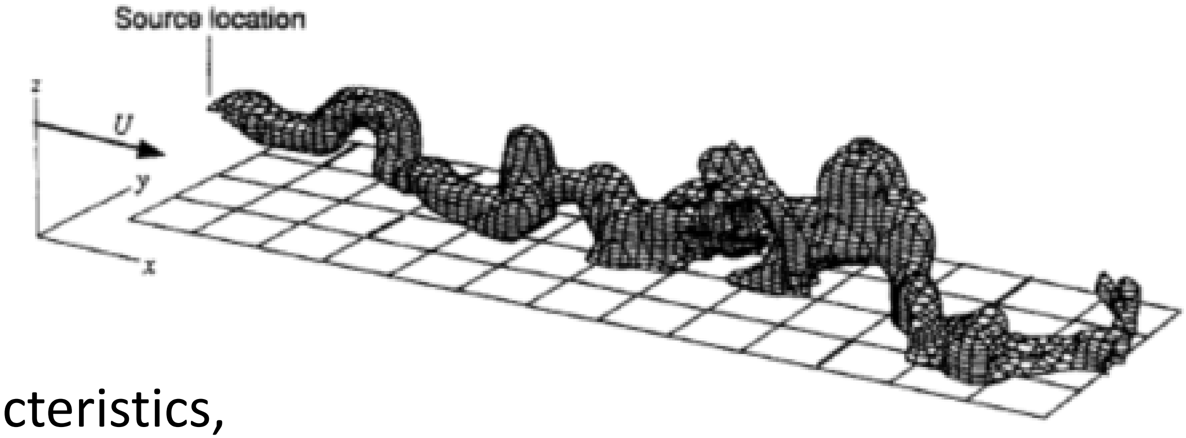
Inversions

- Result from radiational cooling of the ground
- Are intensified in river valleys
- Cause pollutants to be “trapped”



Atmospheric Dispersion

Factors Affecting Dispersion of Air Pollutants



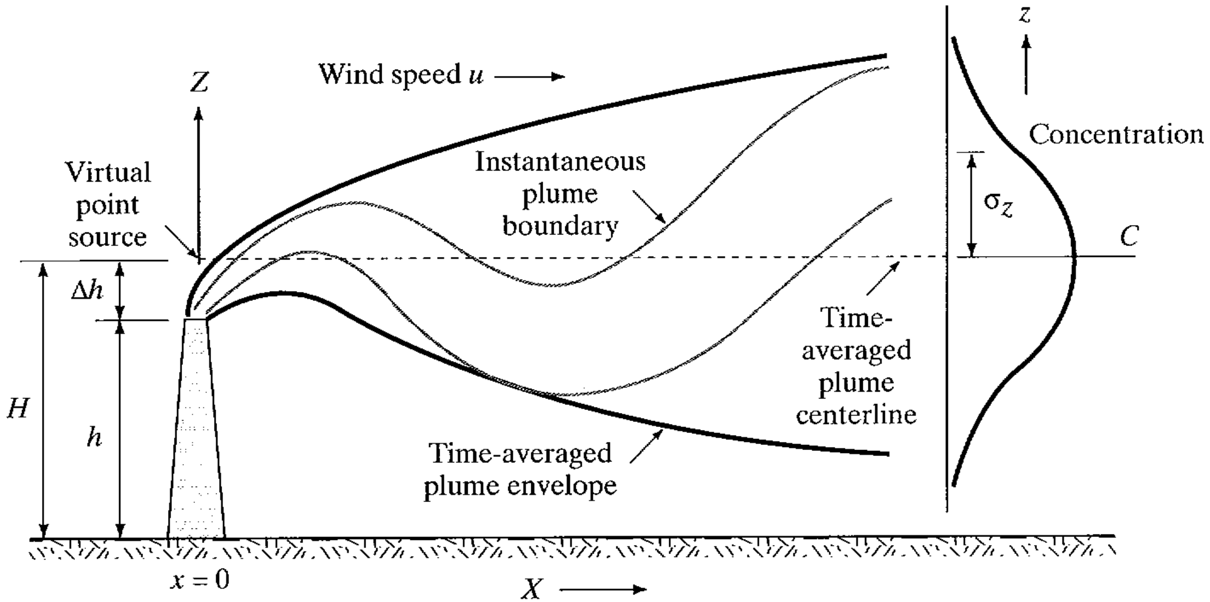
- the emission point characteristics,
- the nature of the pollutant material,
- meteorological conditions, and
- effects of terrain and anthropogenic structures.

Dispersion Modeling

- Dispersion is the process of spreading the emission over a large area, thereby reducing the concentration of the specific pollutants.
- The plume spread or dispersion is in two dimensions: horizontal and vertical.
- It is assumed that the greatest concentration of the pollutants is in the plume centerline, that is, in the direction of the prevailing wind.
- The spread of a plume in both directions is approximated by a Gaussian probability curve.
- A dispersion model is a mathematical description of the meteorological transport and dispersion process that is quantified in terms of source and meteorological parameters during a particular time.
- The resultant numerical calculations yield estimates of concentrations of the particular pollutant for specific locations and times.

Gaussian dispersion modeling assumptions

- Horizontal and vertical pollutant concentrations in the plume are normally distributed.
- Steady-state conditions (constant source emission strength)
- Wind speed, direction and diffusion characteristics of the plume are constant
- Conservation of mass, i.e. no chemical transformations take place



$$C_{(x,y,z)} = \frac{Q}{2\pi \bar{u} \sigma_y \sigma_z} \exp\left(-\frac{1}{2}\left[\left(\frac{y}{\sigma_y}\right)^2 + \left(\frac{z-H}{\sigma_z}\right)^2\right]\right)$$

The concentration of a pollutant at the ground level and at any distance *x* downwind from the source can be calculated as:

$$C_{(x,y,z)} = \frac{Q}{2\pi \bar{u} \sigma_y \sigma_z} \exp\left(-\frac{1}{2}\left[(y/\sigma_y)^2 + (z/\sigma_z)^2\right]\right)$$

where $C_{(x,y,z)}$ = concentration at some point in the coordinate space, kg/m^3
Q = source strength, or the emission rate, kg/s
$\bar{u}$ = average wind speed, m/s
σ_z and σ_y = standard deviation of the dispersion in the z and y directions
y = distance crosswind horizontally, m
z = distance vertically, m
H = effective height

Dispersion coefficients

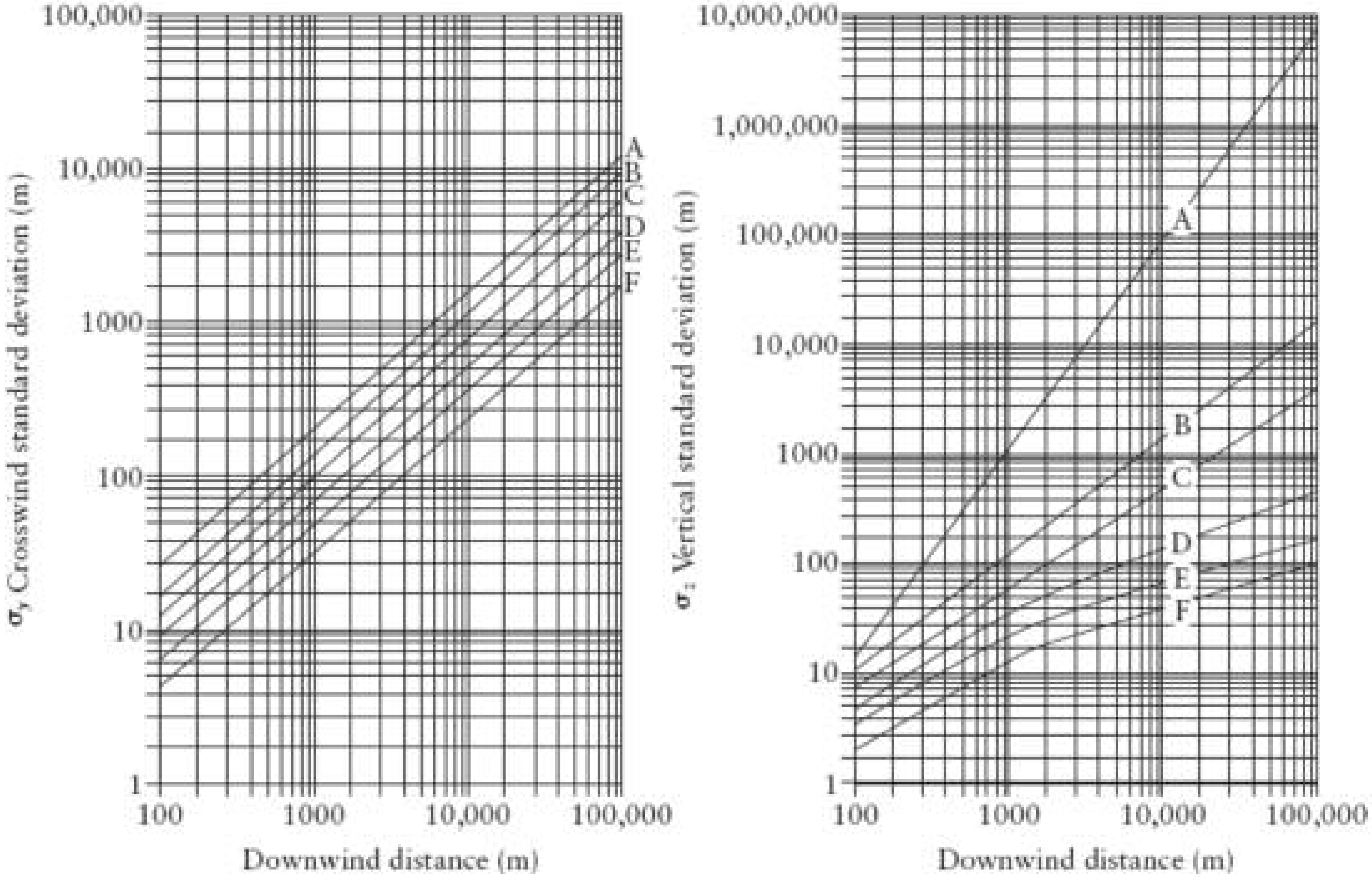


Figure 13.12 Dispersion coefficients. (After Turner, D.B. *Workbook of Atmospheric Dispersion Estimates*. U.S. Department of Health, Education and Welfare, Public Health Service, National Center for Air Pollution Control, Publication No. 999-Ap-28.)

Table 13.1 Atmospheric Stability Key for Figure 13.12

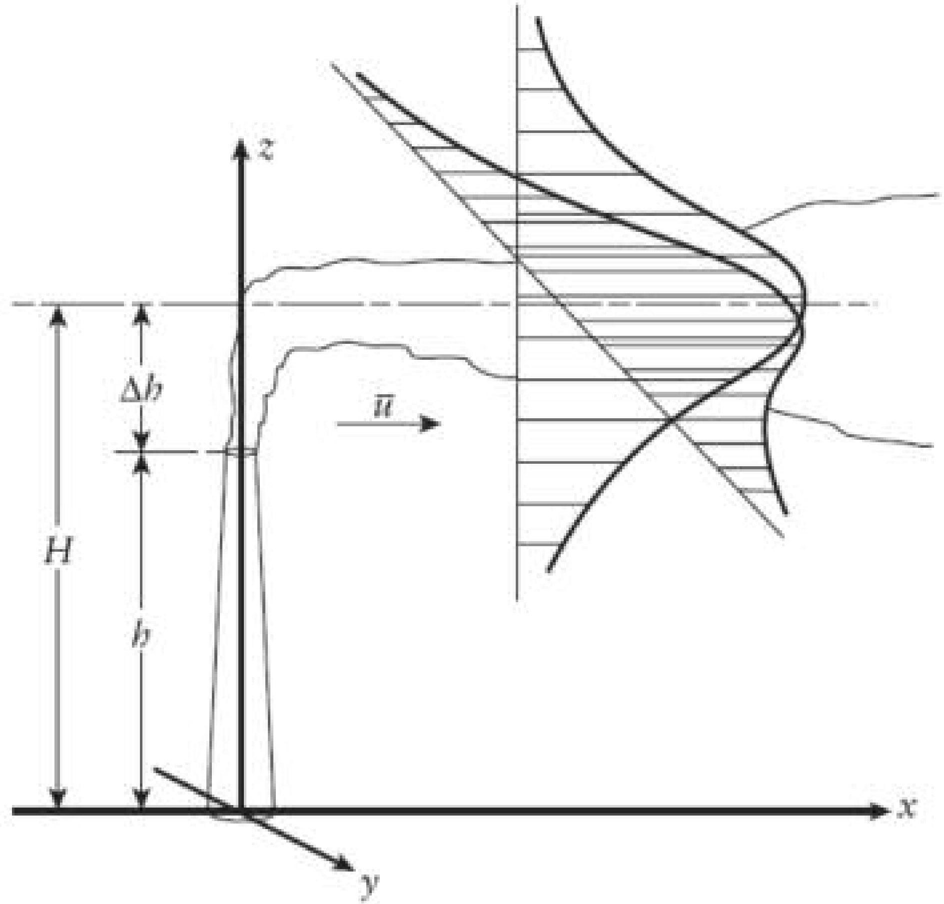
Surface Wind Speed (at 10 m) (m/s)	Day: Incoming Solar Radiation (Sunshine)			Night	
	Strong	Moderate	Slight	Mostly Overcast or ≥4/8 Cloud Cover	Mostly Clear or ≤3/8 Cloud Cover
<2	A	A–B	B	—	—
2–3	A–B	B	C	E	F
3–5	B	B–C	C	D*	E
5–6	C	C–D	D	D	D
>6	C	D	D	D	D

*The neutral category, D, should be assumed for overcast conditions day or night.
Source: Pasquill F. The estimation of the dispersion of windborne material, *The Meteorological Magazine*, Vol. 90, No. 1063, pp. 33–49. © British Crown Copyright 1961, the Met Office.

Effective Stack Height (H)

$$H = h + \Delta h$$

where:



H= effective stack height (m)

h= height of physical stack (m)

Δh= plume rise (m)

EXAMPLE 13.4

Problem Given a sunny summer afternoon with average wind, $\overline{u} = 4$ m/s, emission $Q = 0.01$ kg/s, and the effective stack height $H = 20$ m, find the ground level concentration at 200 m from the stack.

Solution From Table 13.1 the atmospheric stability is Type B for a wind speed of 4 m/s and strong sunshine. From Figure 13.12 at 200 m and stability B, $\sigma_y \cong 30$ m and $\sigma_z \cong 22$ m. Note that maximum concentrations occur on the plume centerline, at $y = 0$. Using Equation 13.2:

$$C_{(200,0,0)} = \frac{0.01\text{ kg/s}}{2(\pi)(4\text{ m/s})(30\text{ m})(22\text{ m})} \times \left\{\exp\left(-\frac{1}{2}(0/30\text{ m})^2\right) \times \left[\exp\left(-\frac{1}{2}[(0-20\text{ m})/22\text{ m}]^2\right) + \exp\left(-\frac{1}{2}[(0+20\text{ m})/22\text{ m}]^2\right)\right]\right\}$$

$$C_{(200,0,0)} = 8 \times 10^{-7}\text{ kg/m}^3$$

$$\text{or } C_{(200,0,0)} = 800\ \mu\text{g/m}^3$$

Control strategy development

How to determine the best approach to provide the emission reductions necessary to achieve the air quality goal.

Three primary considerations in designing an effective control strategy are:

(1) Environmental: factors such as equipment locations, ambient air quality conditions, adequate utilities (i.e., water for scrubbers), legal requirements, noise levels, and the contribution of the control system as a pollutant ؛

(2) Engineering: factors such as contaminant characteristics (abrasiveness, toxicity, etc.), gas stream characteristics, and performance characteristics of the control system; and

(3) Economic: factors such as capital cost, operating costs, equipment maintenance, and the lifetime of the equipment.

- **Pollution prevention should also be considered (eliminating pollution emissions at the source, substituting toxic raw materials, alternative processes, …)**

Air Pollution Control

- Control of Gaseous Pollutants
  - Absorption (Wet Scrubbing)
  - Adsorption
  - Combustion (Incineration)
  - FGD

- Control of Particulates Pollutants
  - Spray chamber
  - Cyclone
  - Bag house
  - Venturi
  - Electrostatic Precipitator (ESP)

Absorption

- Primary application: inorganic gases Example: SO_2
- Mass transfer from gas to liquid
- Contaminant is dissolved in liquid
- Liquid must be treated

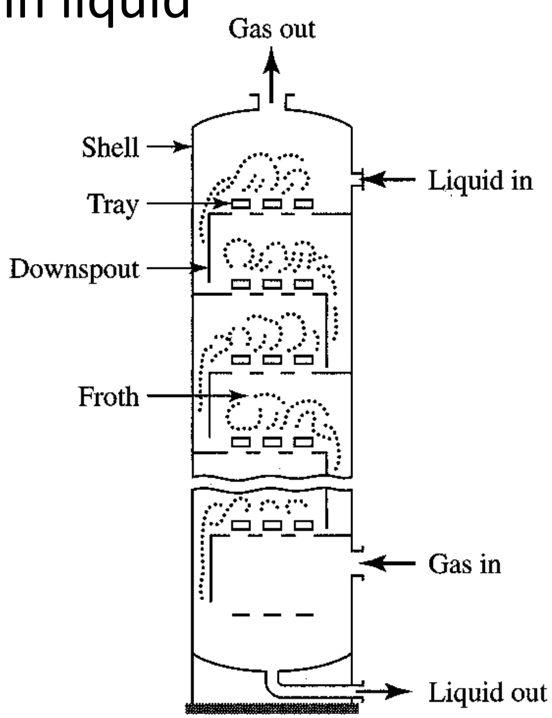
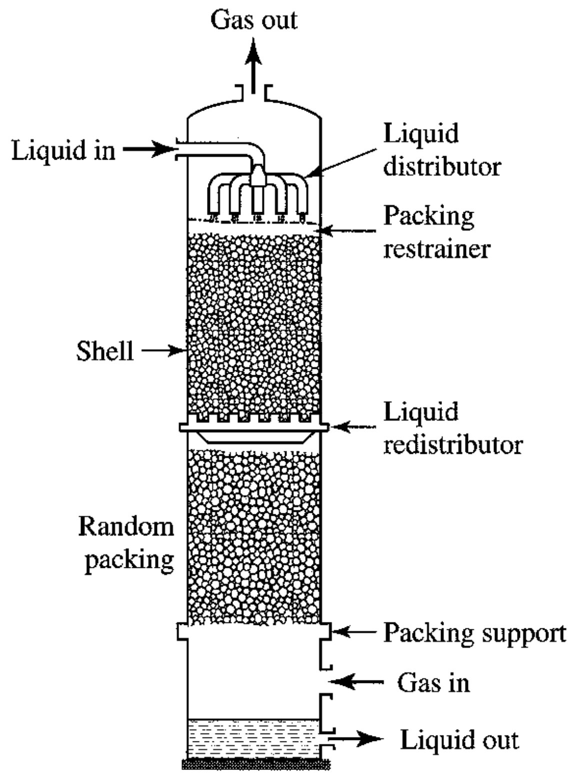


Plate tower



Packed tower

Packed Bed Scrubber

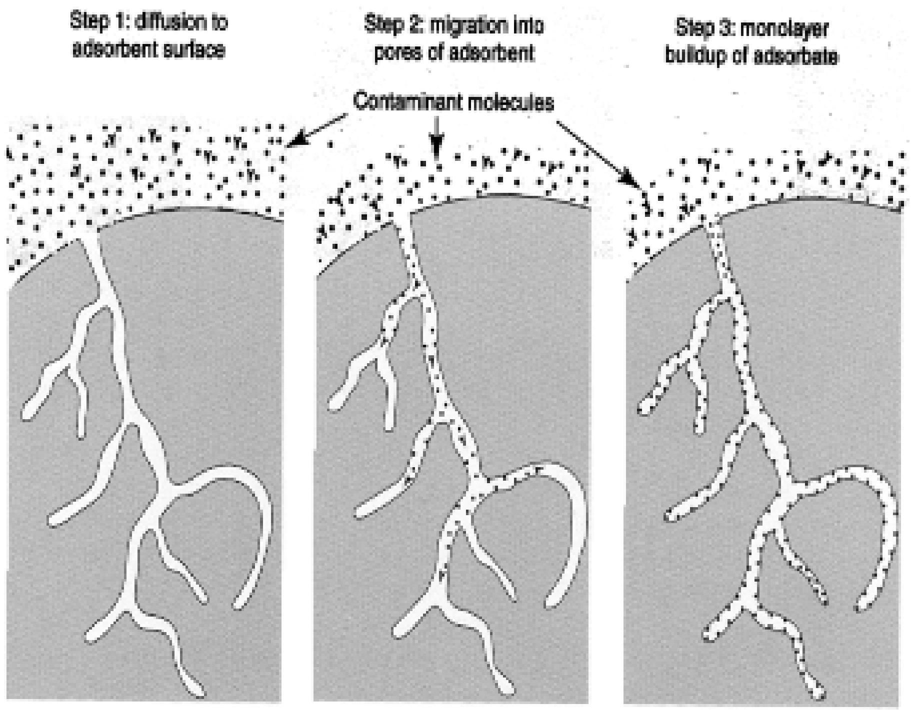
Vertical Venturi Scrubber

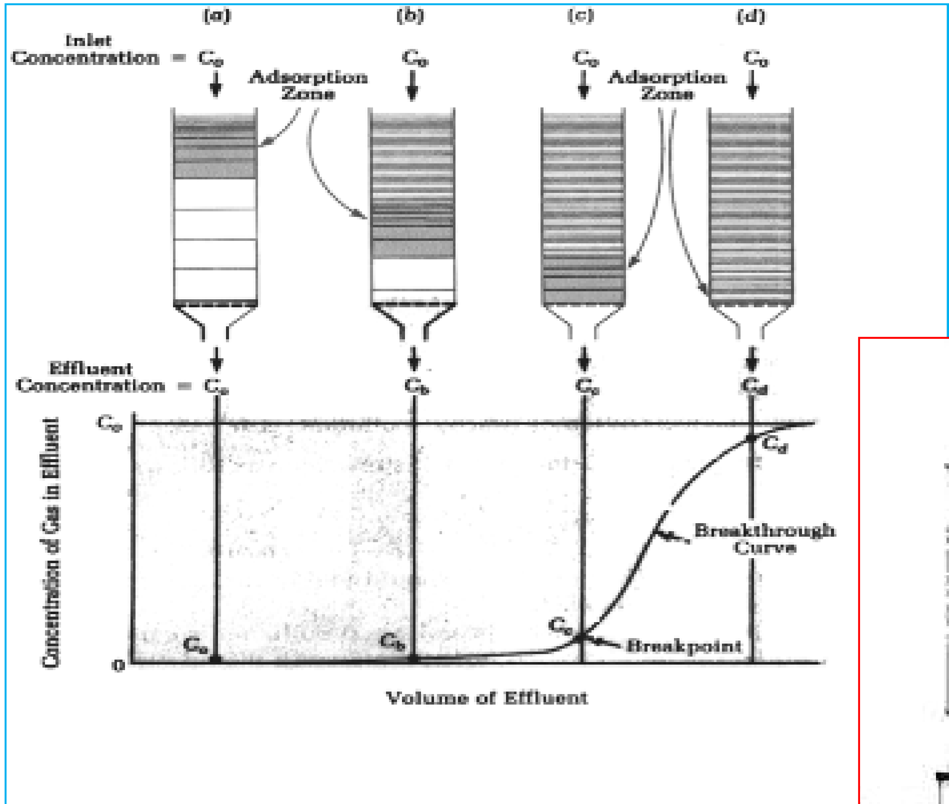
Adsorption

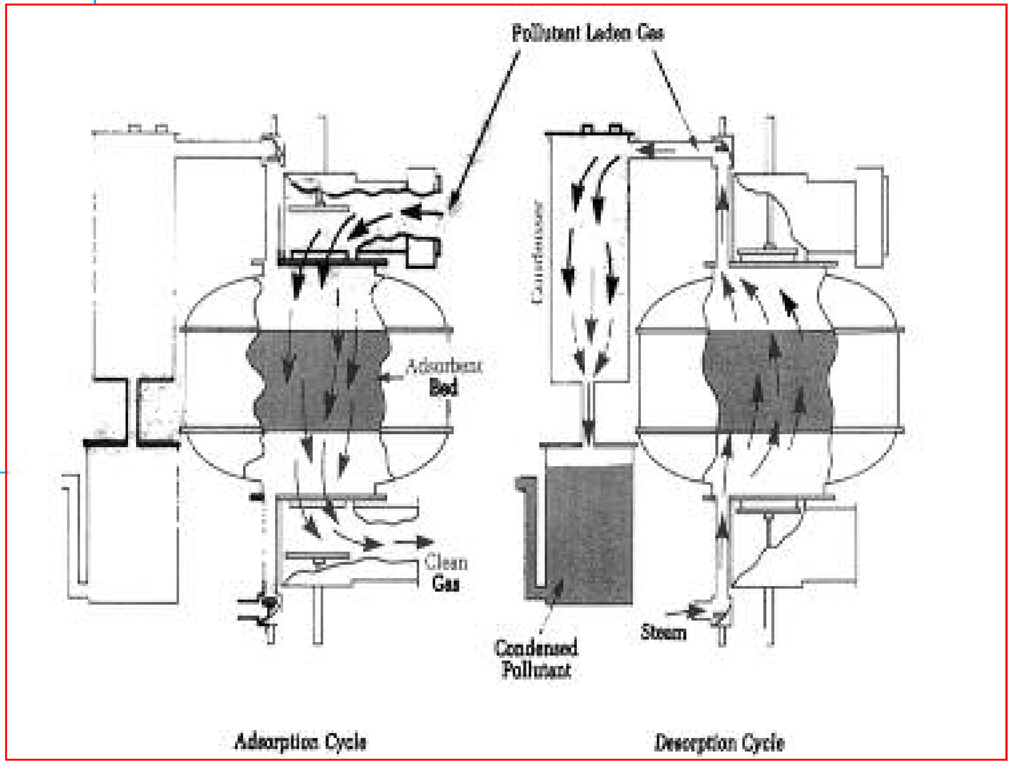
- Primary application: organic gases, Example: trichloroethylene
- Mass transfer from gas to solid
- Contaminant is ‘bound’ to solid
- Adsorbent may be regenerated

Common Adsorbents:

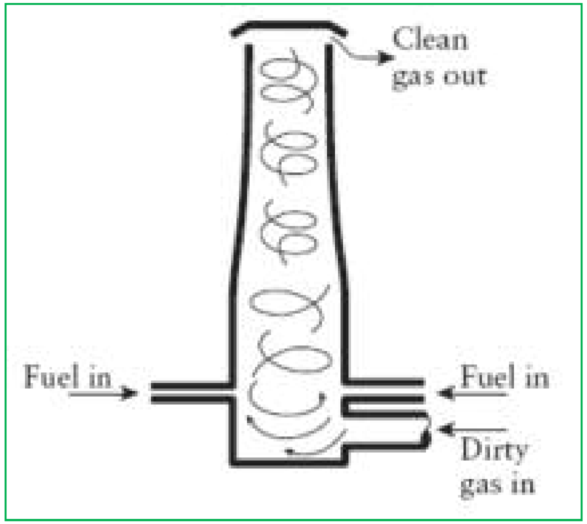
- Activated carbon
- Silica gel
- Activated alumina
- Zeolites (molecular sieves




(a)
(b)
(c)
(d)
Inlet Concentration = C_0
Adsorption Zone
Effluent Concentration = C_a
C_b
C_c
C_d
Concentration of Gas in Effluent
Breakthrough Curve
Breakpoint
Volume of Effluent


Pollutant Laden Gas
Adsorbent Bed
Clean Gas
Condenser
Condensed Pollutant
Steam
Adsorption Cycle
Desorption Cycle

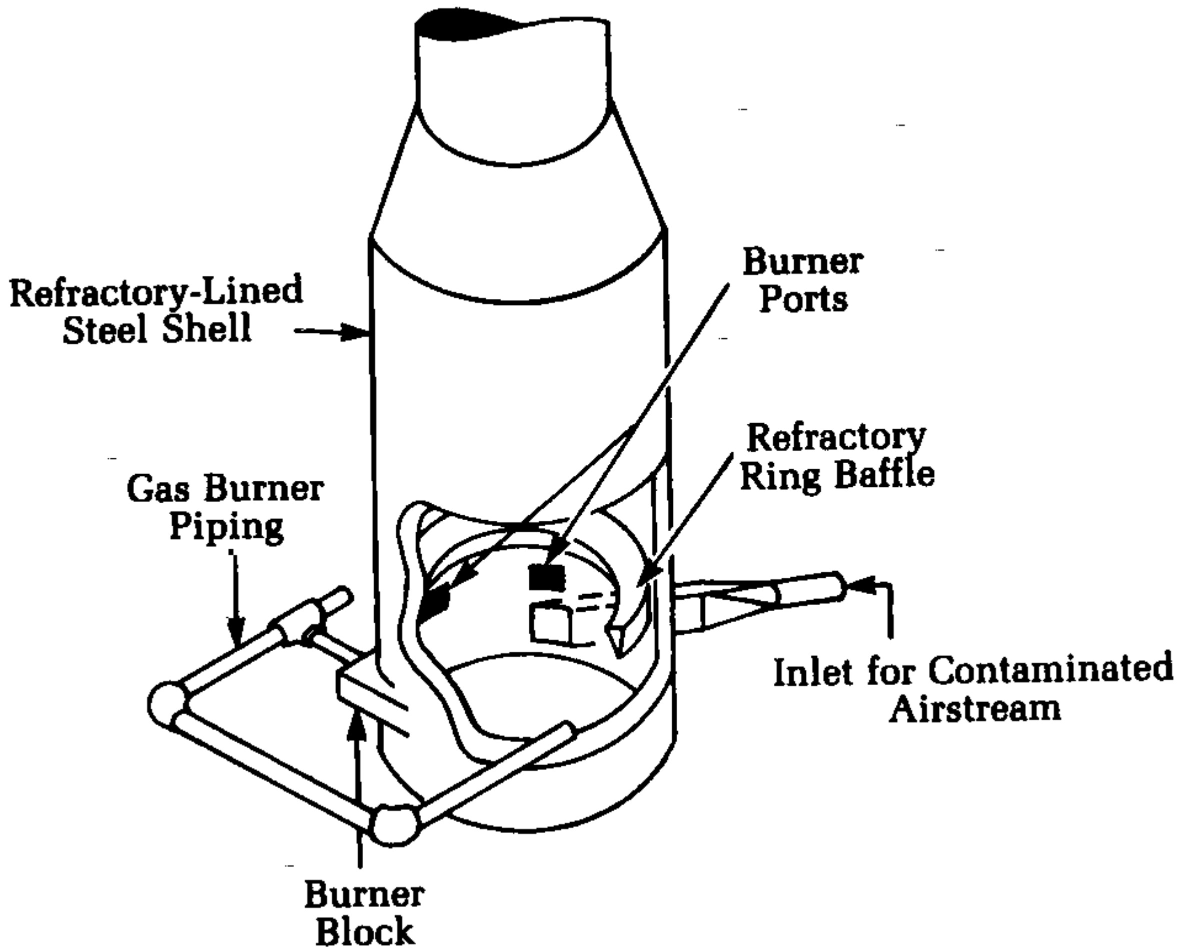
Incineration



Incineration or flaring used to oxidize:

- carbon monoxide
- organic air pollutants
- organics containing chlorine, sulfur, and nitrogen to carbon dioxide and water

Methods: direct flame combustion and catalytic combustion


Burner
Ports
Refractory-Lined
Steel Shell
Refractory
Ring Baffle
Gas Burner
Piping
Inlet for Contaminated
Airstream
Burner
Block

Flue Gas Desulfurization (FGD)

- **Non-regenerative:** non-recovery and reuse of chemical reagents
  - Chemicals: lime, limestone, caustic soda, soda ash, ammonia

$$SO_2 + CaCO_3 \text{--->} CaSO_3 + CO_2$$
$$SO_2 + Ca(OH)_2 \text{--->} CaSO_3 + H_2O$$
$$CaSO_3 + 1/2\ O_2 \text{--->} CaSO_4$$

  - Types: Wet and Dry

- **Regenerative:** recovery and reuse of chemical reagents

TABLE 6-6
Commercial non-regenerative FGD systems

System	% Capacity[a]
Limestone	47.3
Lime	23.8
Lime/flyash	9.2
Lime spray dry	3.8
Limestone/flyash	3.0
Dual alkali	2.4
Na_2CO_3 scrubbing	1.9
Lime/limestone	1.5
Na_2CO_3 spray dry	0.9

[a] % MW operating and committed, 1981.

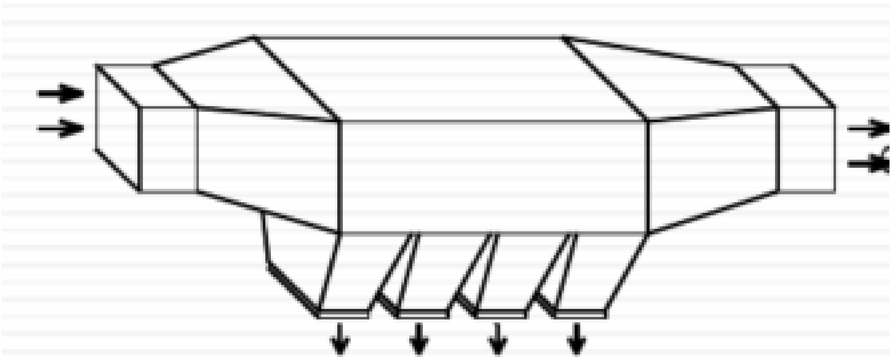
Source: C. E. Jahnig and H. Shaw, "A Comparative Assessment of Flue Gas Treatment Processes, Part I—Status and Design Basis," *Journal of the Air Pollution Control Association*, vol. 31, pp. 421–428, 1981.

Control of Particulate Pollutants

- Settling chambers
  - based on Stoke's Law
  - practical lower limit is 50-100 µm
- Cyclone
  - lower limit = 10 µm
- Bag house filter
  - removes very small particles
- Liquid scrubbing
- Electrostatic precipitation (ESP)

Settling Chambers

- Relies on the terminal velocity of a particle to settle out of a gas stream: Stoke's law

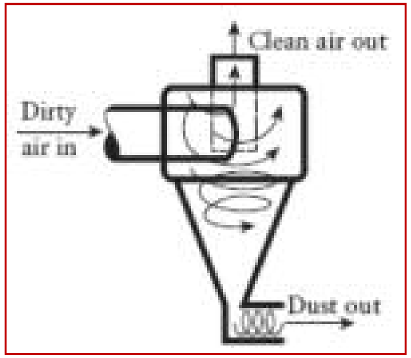


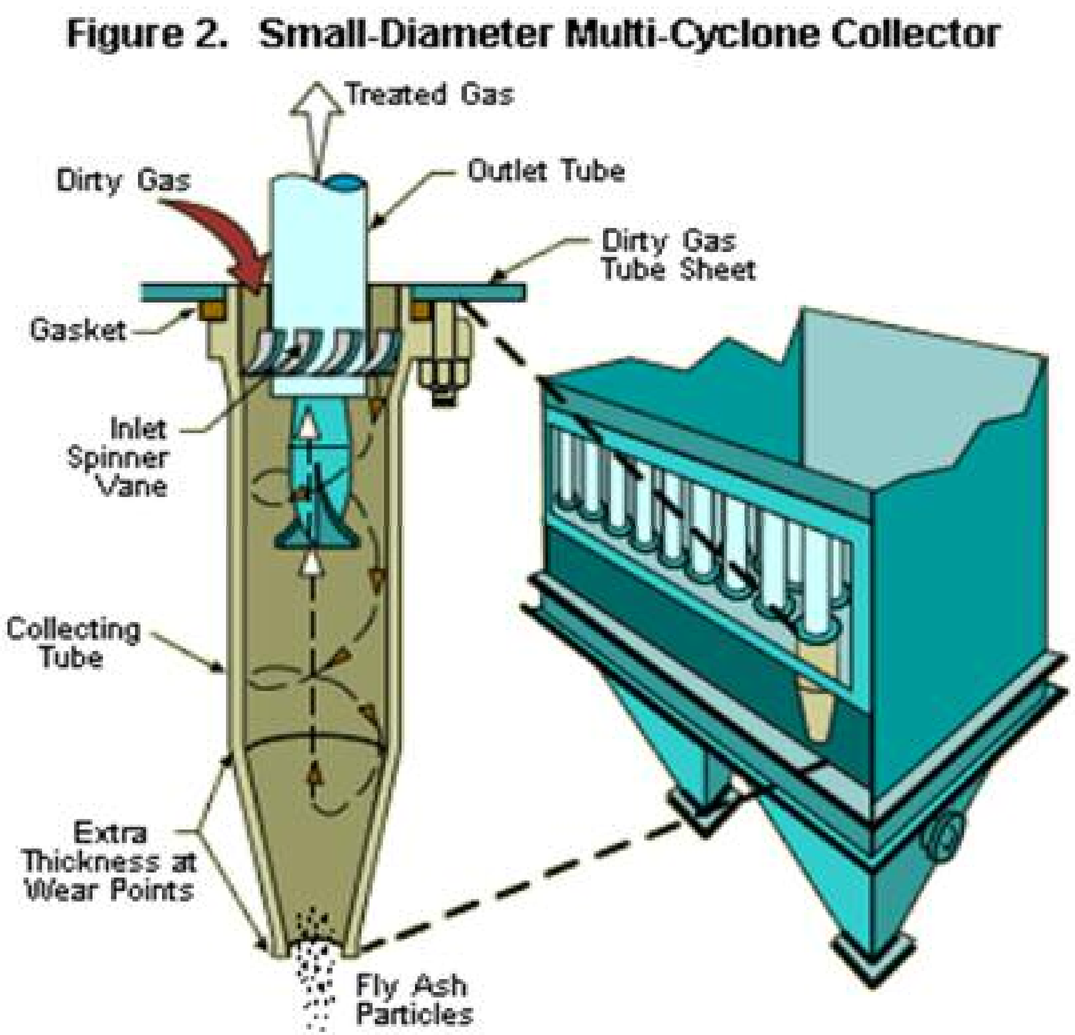
- wide places in the exhaust flue where larger particles can settle, usually with a baffle to slow the emission stream. Obviously, only very large particulates (>100 μ) can be efficiently removed in settling chambers.

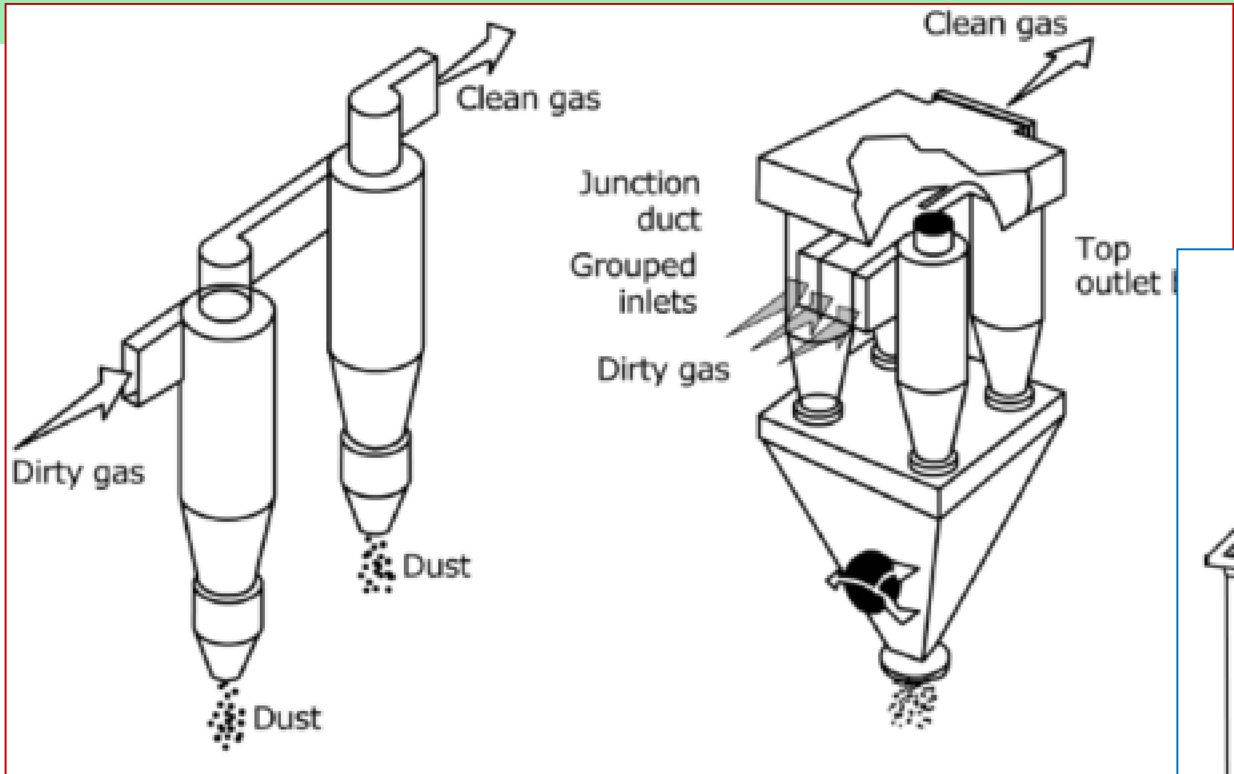
- A conventional design based on flow cross section expansion and dust collection hoppers.

Cyclones

- ✓ can be used for 50-100 μm size particles
- ✓ simple economical unit:
  - no moving parts
  - relies on inertial effects







A. two cyclones in series

B. Four cyclones in parallel

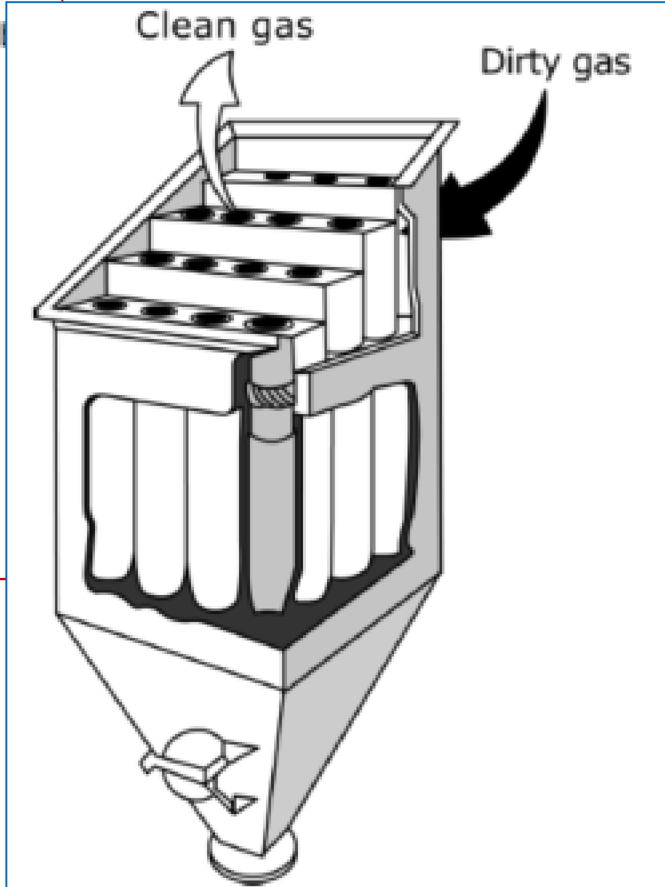


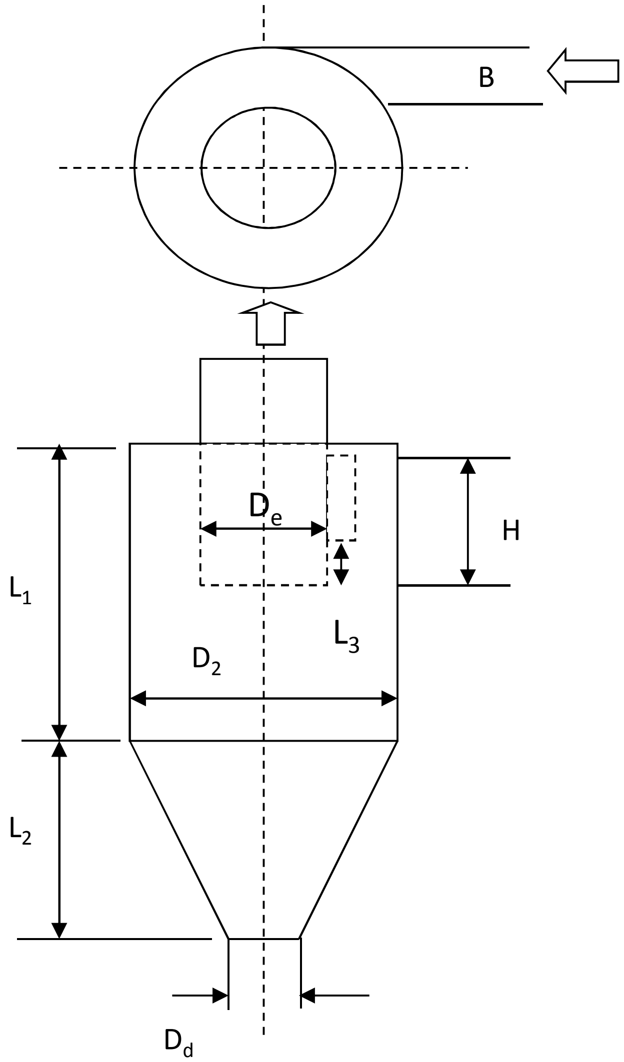
Figure 6-7. Multi-cyclone collector

For particle sizes greater than about 10 µm in diameter, the collector of choice is the cyclone

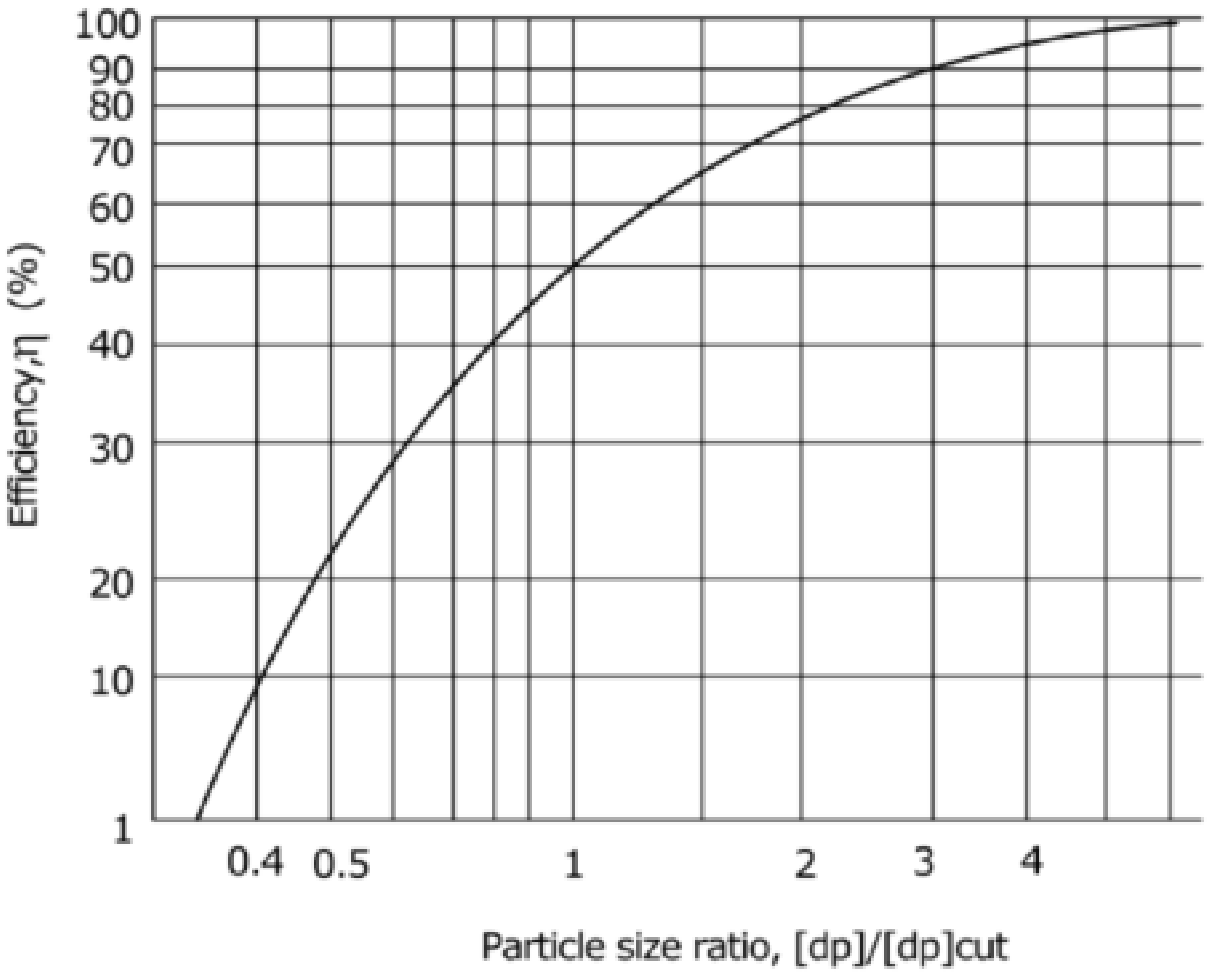
The particle size collected with 50% efficiency, termed the cut diameter:

$$d_{0.5} = \left[\frac{9 \mu B^2 H}{\rho_p Q_g \theta} \right]^{1/2}$$

$$\theta = \frac{\pi}{H} \left(2L_1 + L_2 \right)$$



$d_{0.5}$ = cut diameter at 50% removal
μ = dynamic viscosity of gas, Pa-s
B = width, m
H = height, m
ρ_p = particle density, kg/m3
Q_g = gas flow rate, m3/s
θ = effective number of turns


100
90
80
70
60
50
40
30
20
10
1
Efficiency,η (%)
0.4
0.5
1
2
3
4
Particle size ratio, [dp]/[dp]cut

Example

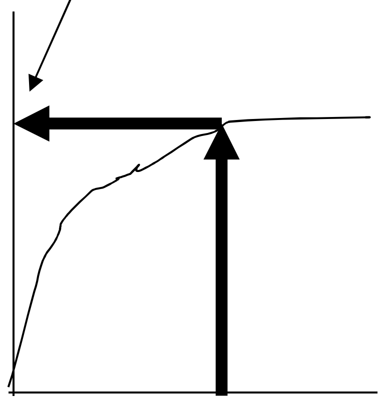
Given:
$D_2 = 0.5$ m
$Q_g = 4\ m^3/s$
T = 25 °C
$\rho_p = 800\ kg/m^3$

For standard Cyclone:
$B = 0.25\ D_2 = 0.13$ m
$H = 0.5\ D_2 = 0.25$ m
$L_1 = L_2 = 2\ D_2 = 1$ m

$$\theta = \frac{\pi}{0.25}\left(2(1)+1\right) = 37.7$$

Q = What is the removal efficiency for particles with ave diameter of 10 μm?

$\eta = 0.95$



$$d_{0.5} = \left[\frac{9(18.5x10^{-6})(0.13)^2(0.25)}{(800)(4)(37.7)}\right]^{0.5} = 2.41x10^{-6}$$

$$= 2.41(\mu m)$$

@ d =10 μm

$$\frac{d}{d_{0.5}} = \frac{10}{2.41} = 4.15$$

Baghouse Filter

- similar to conventional home vacuum cleaner
- Efficiency:

  >99.5% for <1 μm diameter

  >99.8% for >5 μm diameter

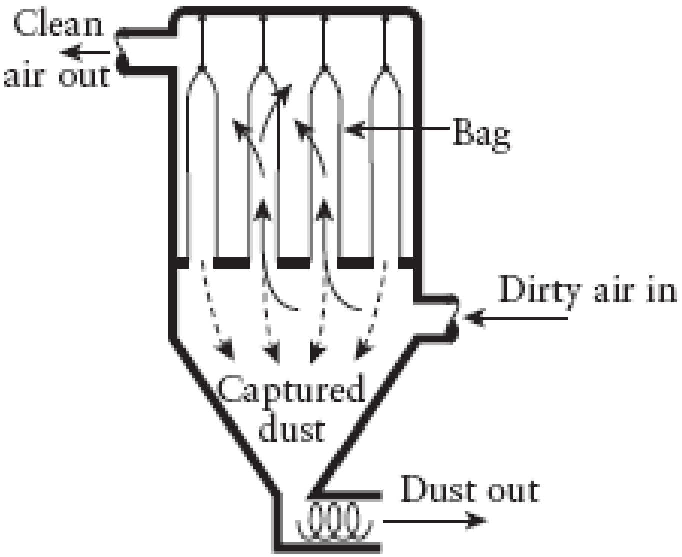
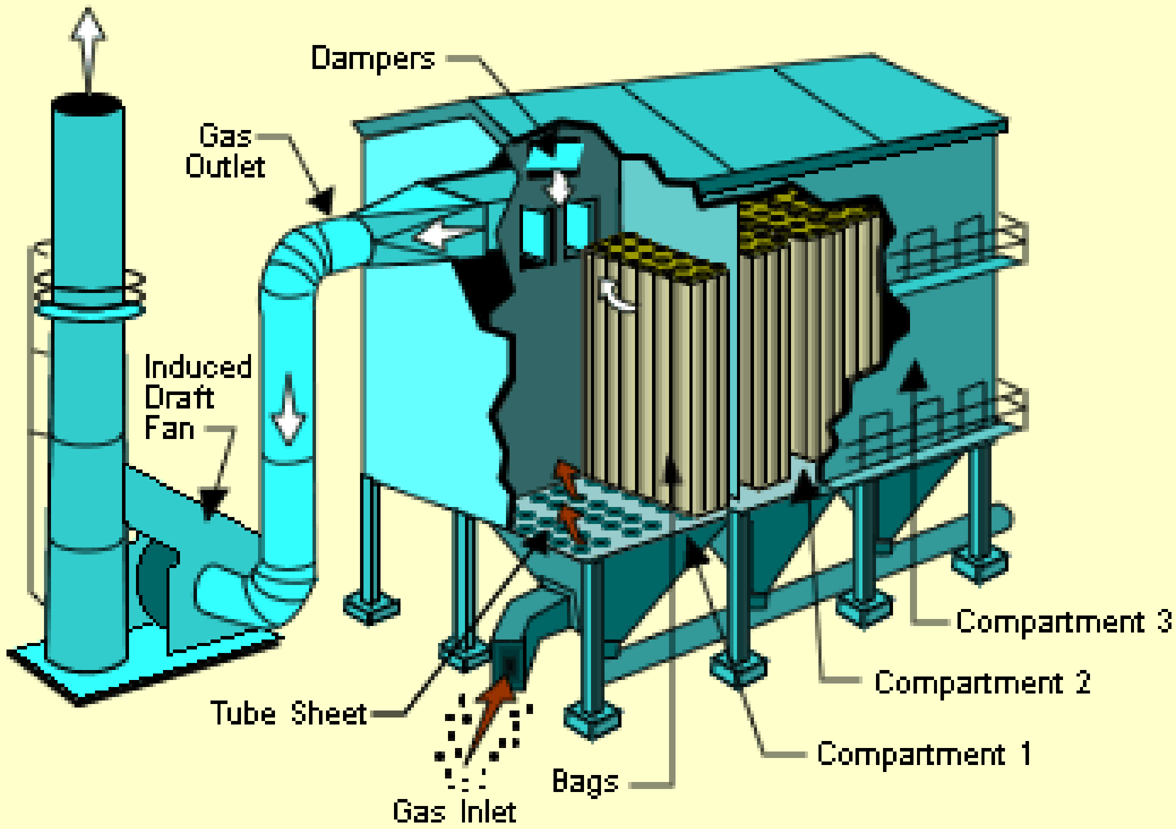


Figure 13. Reverse Air Fabric Filter



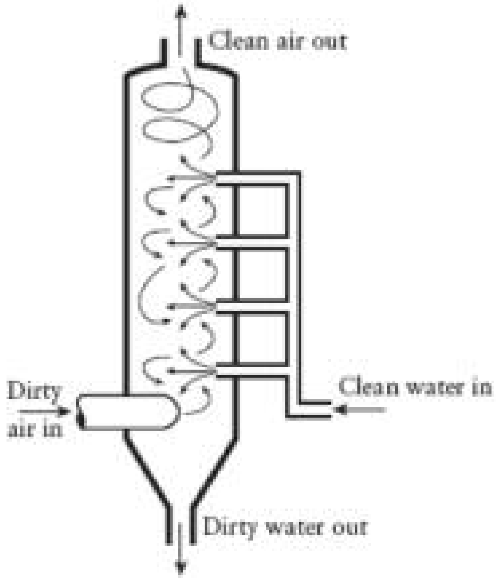
- Fabric filter materials:
  1. Natural fibers (cotton & wool)
     Temperature limit: 80 ^oC
  2. Synthetics (acetates, acrylics, etc.)
     Temperature limit: 90 ^oC
  3. Fiberglass
     Temperature limit: 260 ^oC

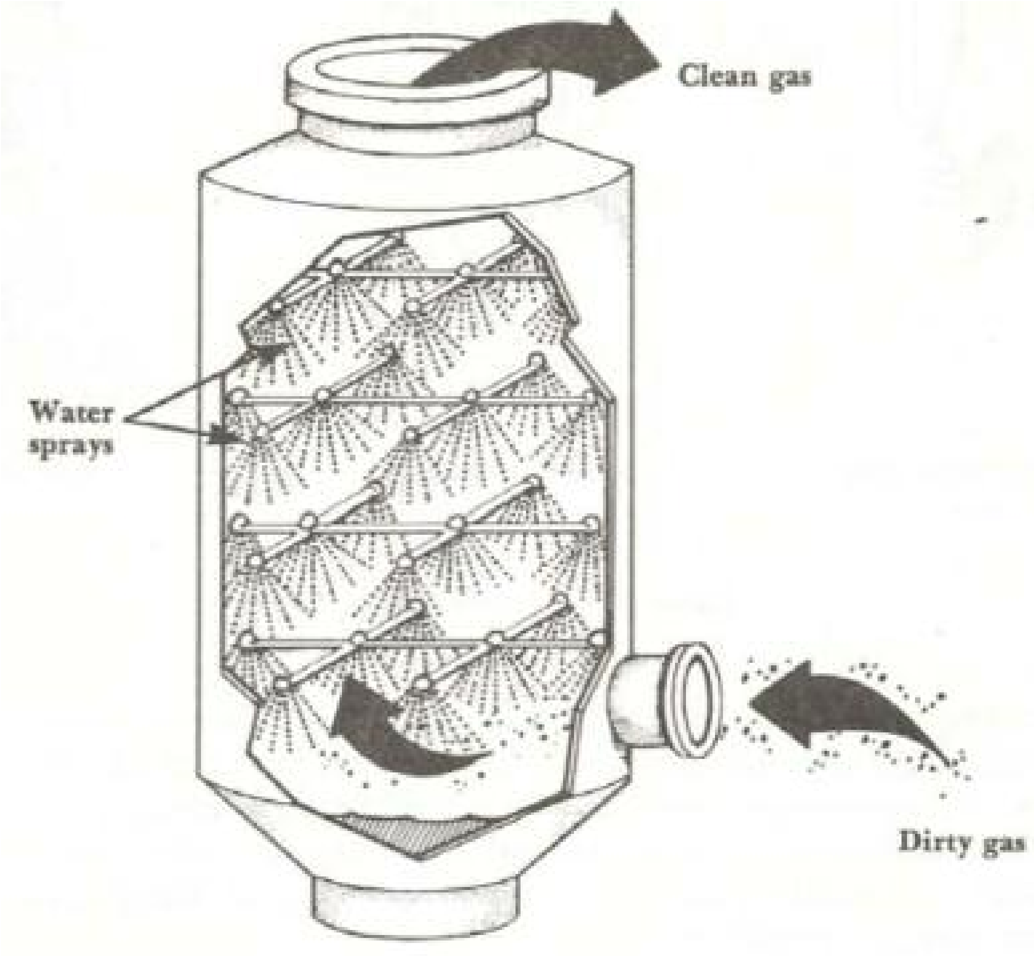
- Cannot be used for
  - wet air systems
  - corrosive gases
  - gases above 260oC

- Cleaning:
  1. Shaker
  2. Reverse air
  3. Pulse jet

Wet Scrubber

- can be used where
  - ✓ air is wet
  - ✓ corrosive
  - ✓ hot
  - ✓ where baghouses can not be used
  - ✓ for even higher efficiencies, a combination of a venturi scrubber and cyclone and can be used




Clean gas
Water
sprays
Dirty gas

Electrostatic Precipitator (ESP)

- high efficiency, dry collector of particulates
- high electrical direct current potential (30-75 kV)

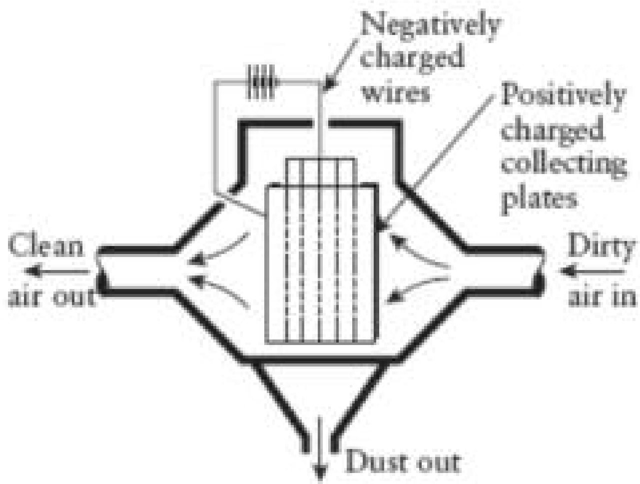
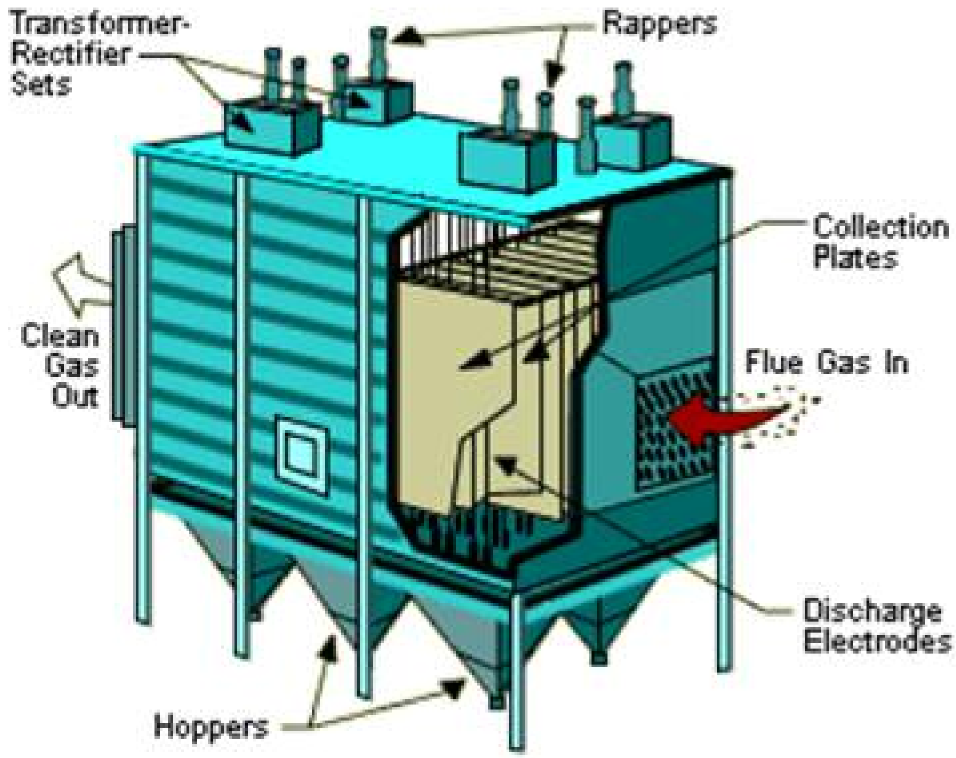
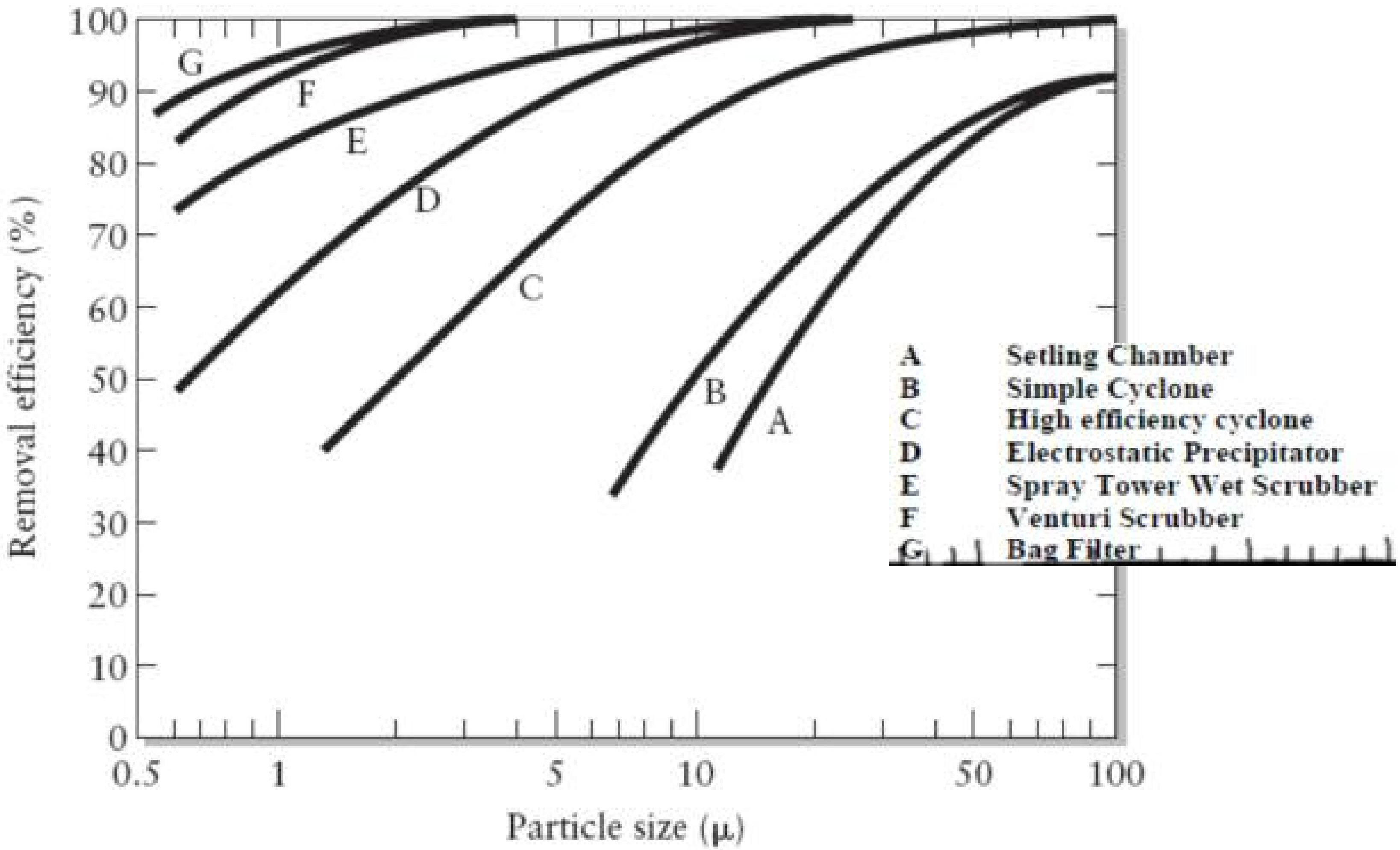


Figure 9. Conventional Electrostatic Precipitator



Comparison of Air Pollution Control Devices



Effectiveness of Air Pollution Control Devices