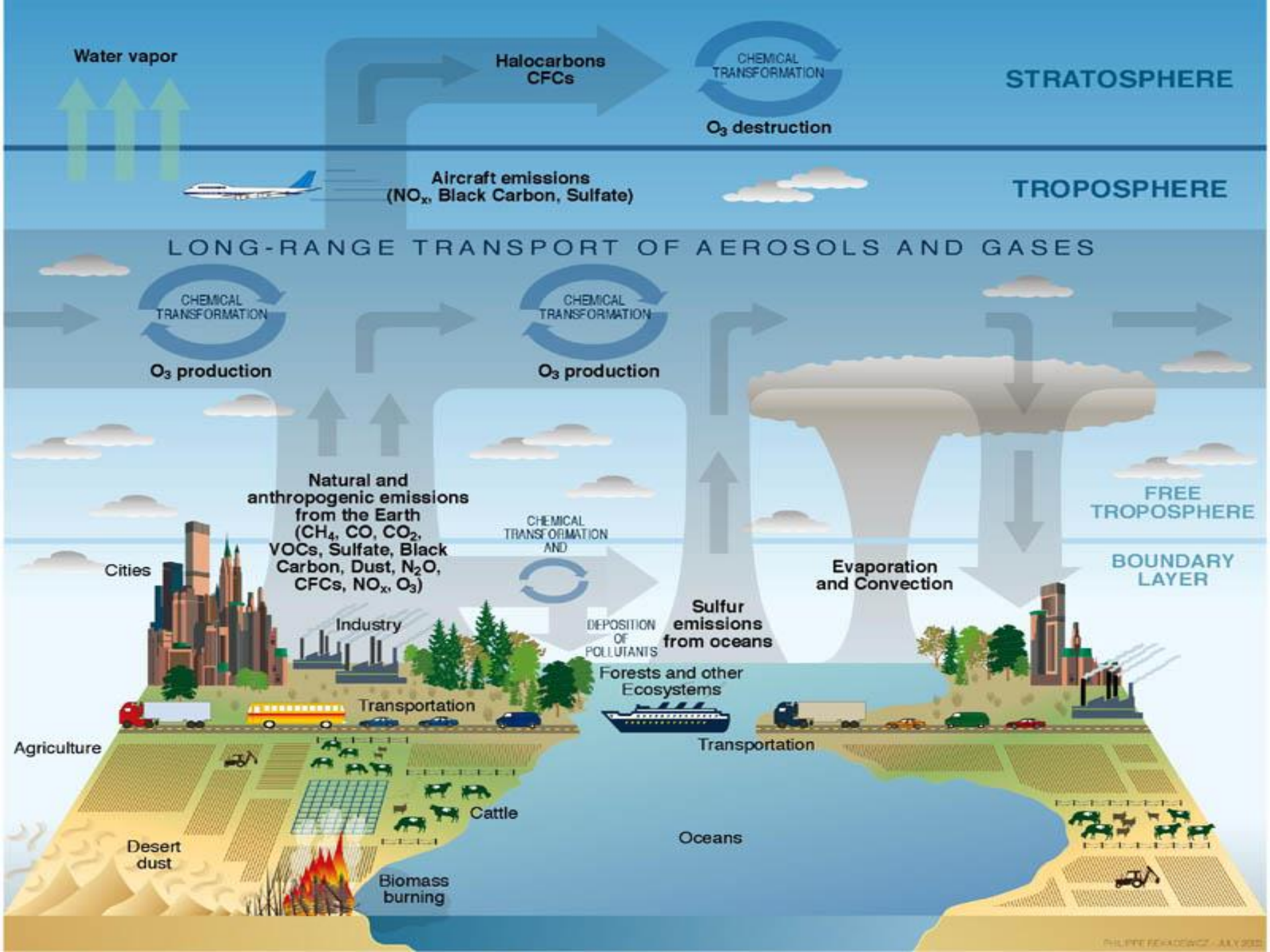
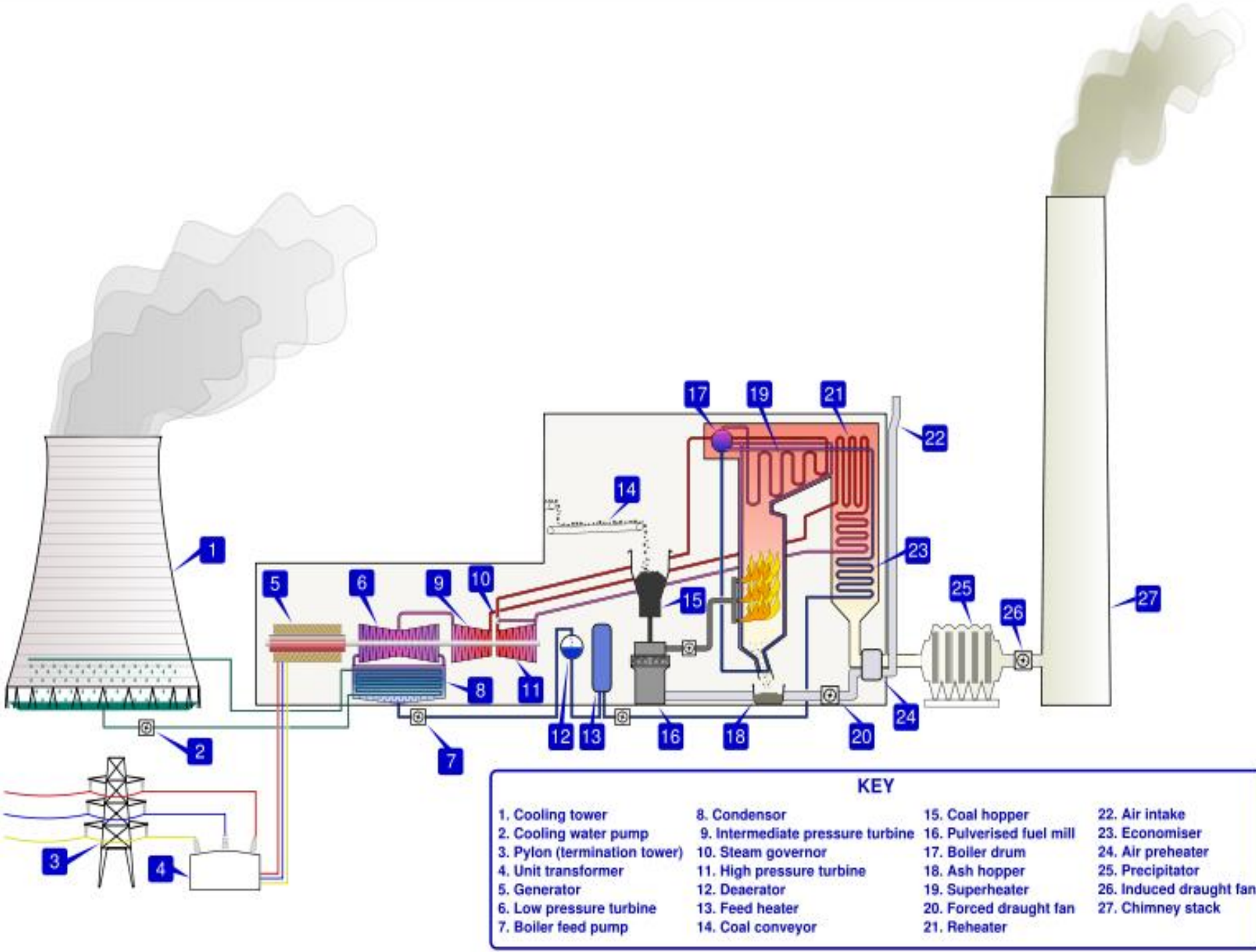

Water vapor
Halocarbons
CFCs
CHEMICAL TRANSFORMATION
O_3 destruction
STRATOSPHERE
Aircraft emissions
(NO_x, Black Carbon, Sulfate)
TROPOSPHERE
LONG-RANGE TRANSPORT OF AEROSOLS AND GASES
CHEMICAL TRANSFORMATION
O_3 production
CHEMICAL TRANSFORMATION
O_3 production
Natural and anthropogenic emissions from the Earth (CH_4, CO, CO_2, VOCs, Sulfate, Black Carbon, Dust, N_2O, CFCs, NO_x, O_3)
CHEMICAL TRANSFORMATION AND
FREE TROPOSPHERE
BOUNDARY LAYER
Cities
Industry
Evaporation and Convection
DEPOSITION OF POLLUTANTS
Sulfur emissions from oceans
Forests and other Ecosystems
Transportation
Transportation
Agriculture
Cattle
Oceans
Desert dust
Biomass burning

EEM606 AIR POLLUTION AND ITS CONTROL

Electric Power Plants


KEY
1. Cooling tower
2. Cooling water pump
3. Pylon (termination tower)
4. Unit transformer
5. Generator
6. Low pressure turbine
7. Boiler feed pump
8. Condensor
9. Intermediate pressure turbine
10. Steam governor
11. High pressure turbine
12. Deaerator
13. Feed heater
14. Coal conveyor
15. Coal hopper
16. Pulverised fuel mill
17. Boiler drum
18. Ash hopper
19. Superheater
20. Forced draught fan
21. Reheater
22. Air intake
23. Economiser
24. Air preheater
25. Precipitator
26. Induced draught fan
27. Chimney stack

Controls

ESP

SCR

Hg trap

SO_3 injection

Scrubber (dry and wet)

Use of calcium carbonate to trap sulfur dioxide to form calcium sulfate (gypsum). Again gypsum is used for cement manufacture.

Particulate control devices

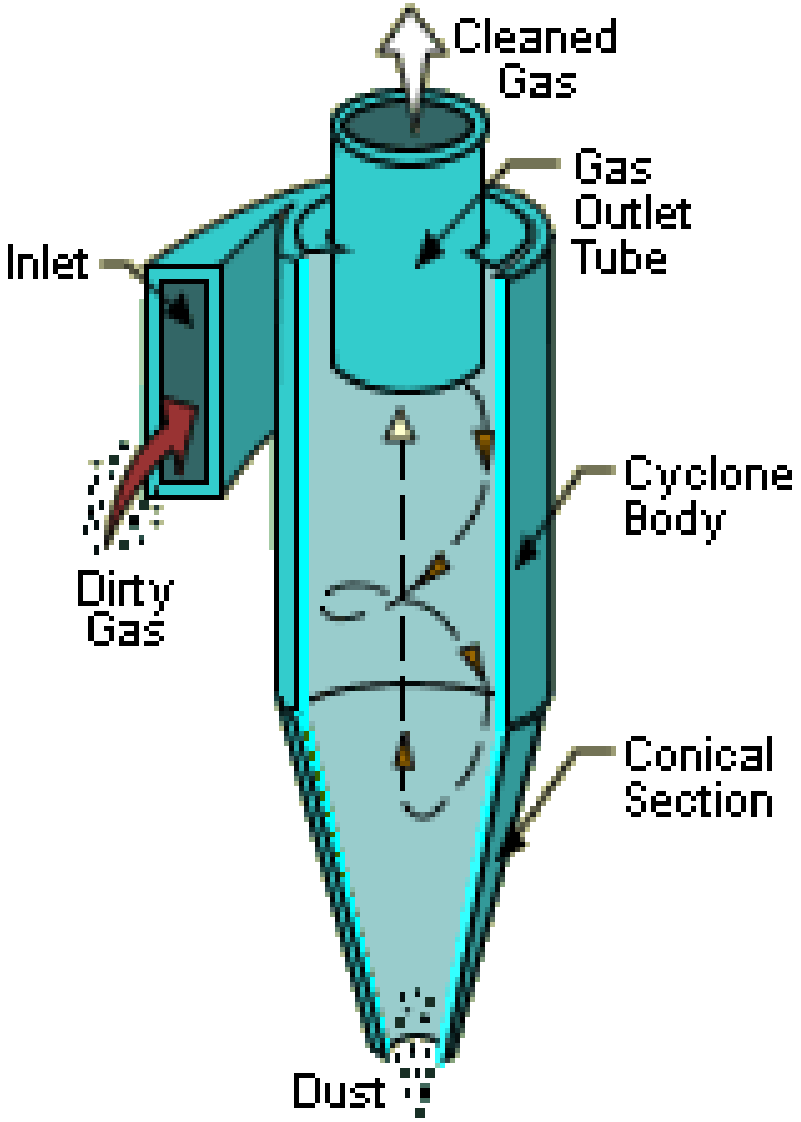
Prefilters like gravitational settling chambers are used for removing very coarse particles generally greater than 20 to 50 micron particles. Gravitational Settling chamber separates particles from a gas stream by gravity, especially for particles greater than 20 micron, under low effluent velocities.

Settling chambers are inexpensive to build and operate, but they are effective only on very large particles. In most practical circumstances, airflow rates are large. Consequently, only short residence times (seconds) are possible, greatly limiting the effectiveness of a gravitational settler for airborne particle removal.

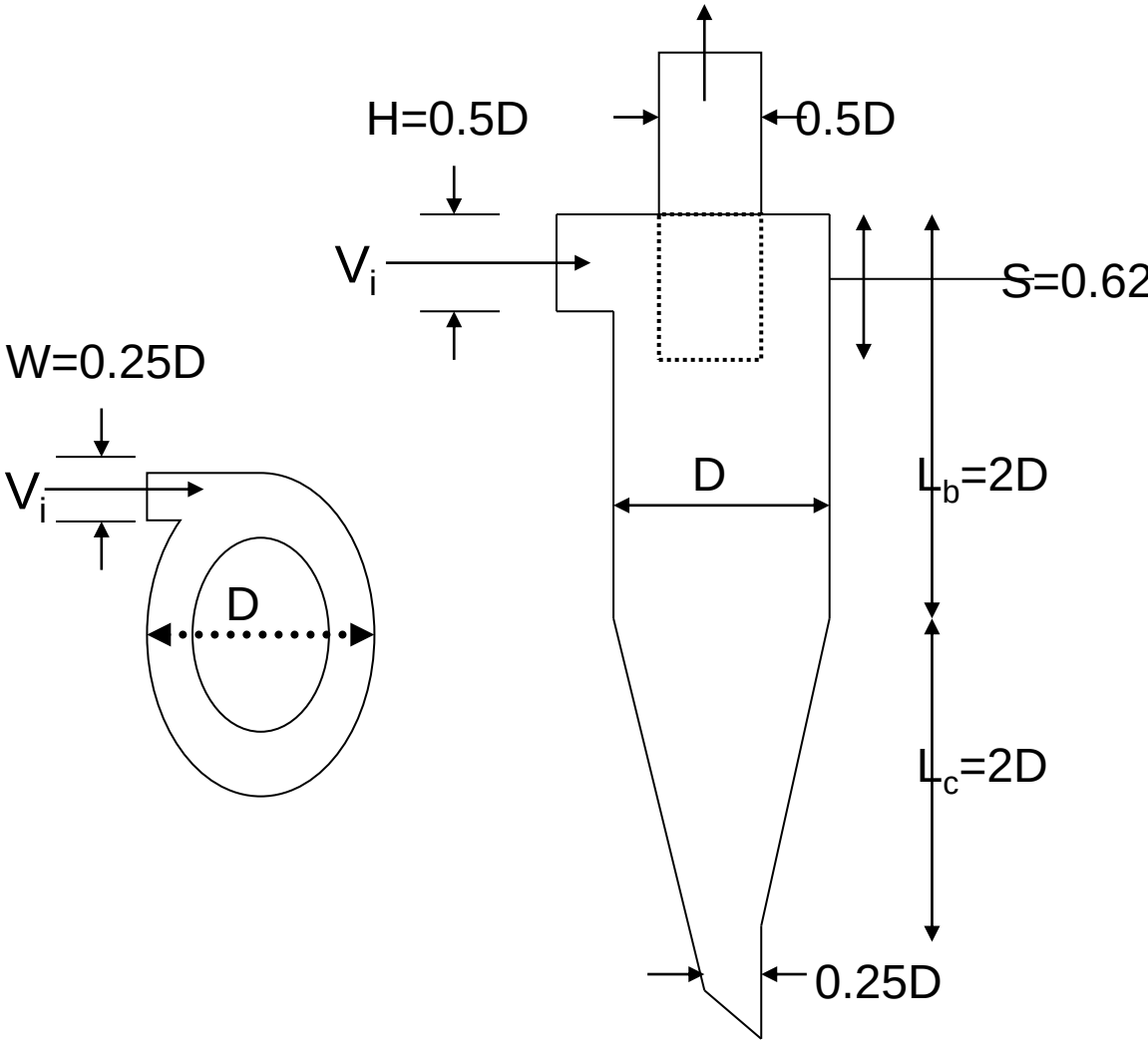
Cyclone separates particles by inertia in a vortex flow, common treatment before and ESP or fabric filter. Cyclones are widely used to remove coarse particles from gas streams. They exploit the inertia of particles to separate them from air. Relative to gravity settlers, cyclones achieve much better collection efficiencies for small coarse particles (down to about 2 μm) with smaller device volumes. Cyclones are often used upstream of fine-particle control devices, such as electrostatic precipitators or fabric filters.

The strengths of a cyclone include simple design and maintenance, a small floor area requirement, low to moderate pressure drop (typically 500-2500 Pa), and the ability to handle high particle loading rates. The key limitations are their **ineffectiveness against small particles** and the sensitivity of performance to airflow rate.

Figure 1. Top-Inlet Large-Diameter Cyclone



In a Cyclone, air introduced at the top, with a velocity V_i, swirls in an outer vortex around the perimeter and downward into the cone, then in an inner vortex up and out the top port. Inertia causes particles to drift toward the outer walls of the cyclone. This inertial drift is opposed by the drag exerted by air on the particles. Particles that reach the near vicinity of the outer wall settle under the influence of gravity and are collected at the bottom.



v_r is the radial drift velocity of the particle, and m is the particle mass. The tangential velocity in the vortex is approximated by the inlet velocity, V_i. The radial distance of the particle from the cyclone axis is R = D/2,
also $m = \rho_p(\pi/6)d_p^3$

Therefore, $F_d \sim (mV_i^2)/R$

$$3\pi\eta d_p v_r = 2(\rho_p(\pi/6)d_p^3)(V_i^2)/D$$

Upon rearranging the drift velocity is given by,

$$v_r = (V_i^2\rho_p d_p^2)/(9\eta D)$$

In order to get effectively removed, particles have to travel a radial distance ~W/2 (W is the width of the outer vortex) during their residence time (ɵ) in

the outer vortex. This condition provides a basis for estimating the cut-point diameter:

$$v_r = (V_i^2 \rho_p d_{50}^2)/(9\eta D) = W/2\theta = (W/2)\{ V_i/(\pi DN)\}$$

$$d_{50} = [(9\eta W)/(2\pi\rho_p N V_i)]^{0.5}$$

The number of turns in the outer vortex is estimated as

$$N \sim (1/H)(L_b + L_c/2)$$

Where the geometric parameters H, L_b, and L_c are, respectively, the height of the inlet, the length of the body, and the length of the cone region.

Given d_{50} for a particular particle size and cyclone design, the efficiency for other particle sizes is well described by the following empirical equation:

$$\eta = (d_p/d_{50})^2 / [1 + (d_p/d_{50})^2]$$

ESP (electrostatic precipitators) creates electrostatic charge on particles so they can be removed by an electric field, high-efficiency device that is used to treat stack gases in industries.

ESPs remove particles from gas streams in a two step process. First, the particles are electrically charged. Then, an electric field is applied to the gas in the direction normal to the airflow. Charged particles are forced by this electric field to drift across the air stream, toward collection plates, to which they adhere. The collected particles are occasionally removed from the ESP by mechanically rapping the plates, causing the accumulated particles to fall into a hopper for disposal.

In many commercial ESPs, the particle charging and removal steps occur within a single stage.

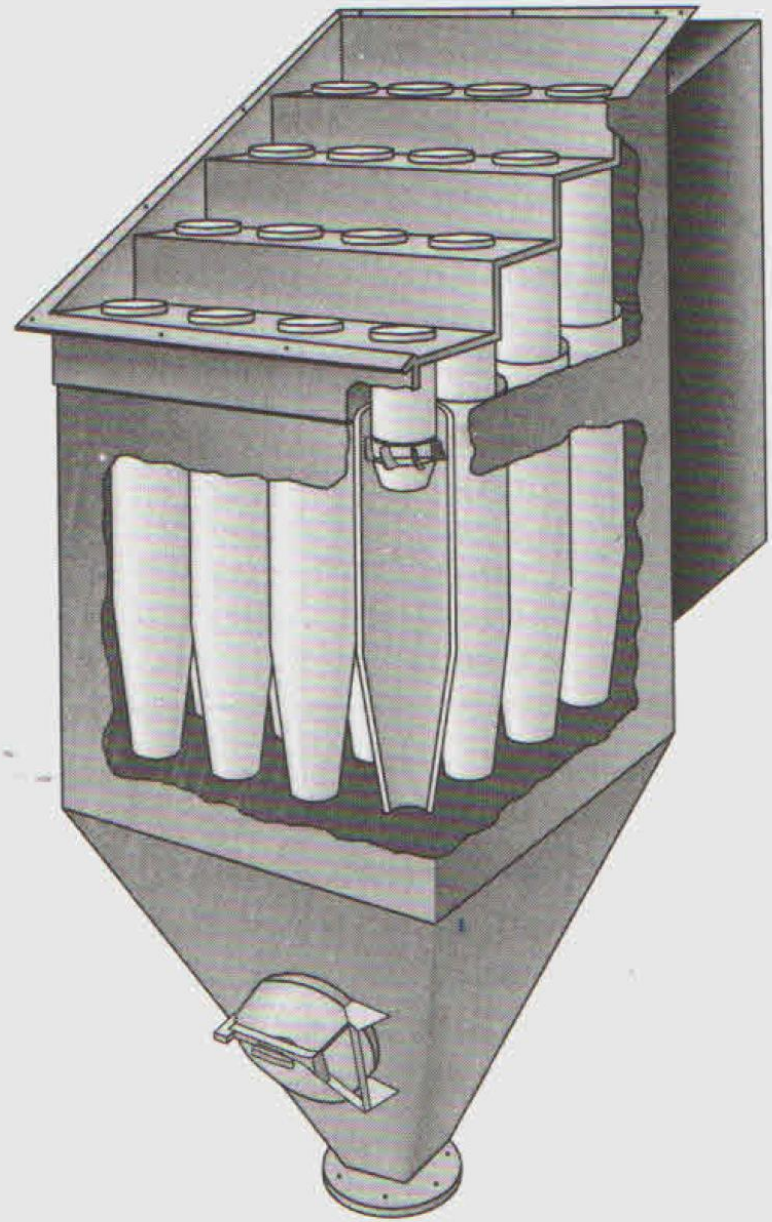
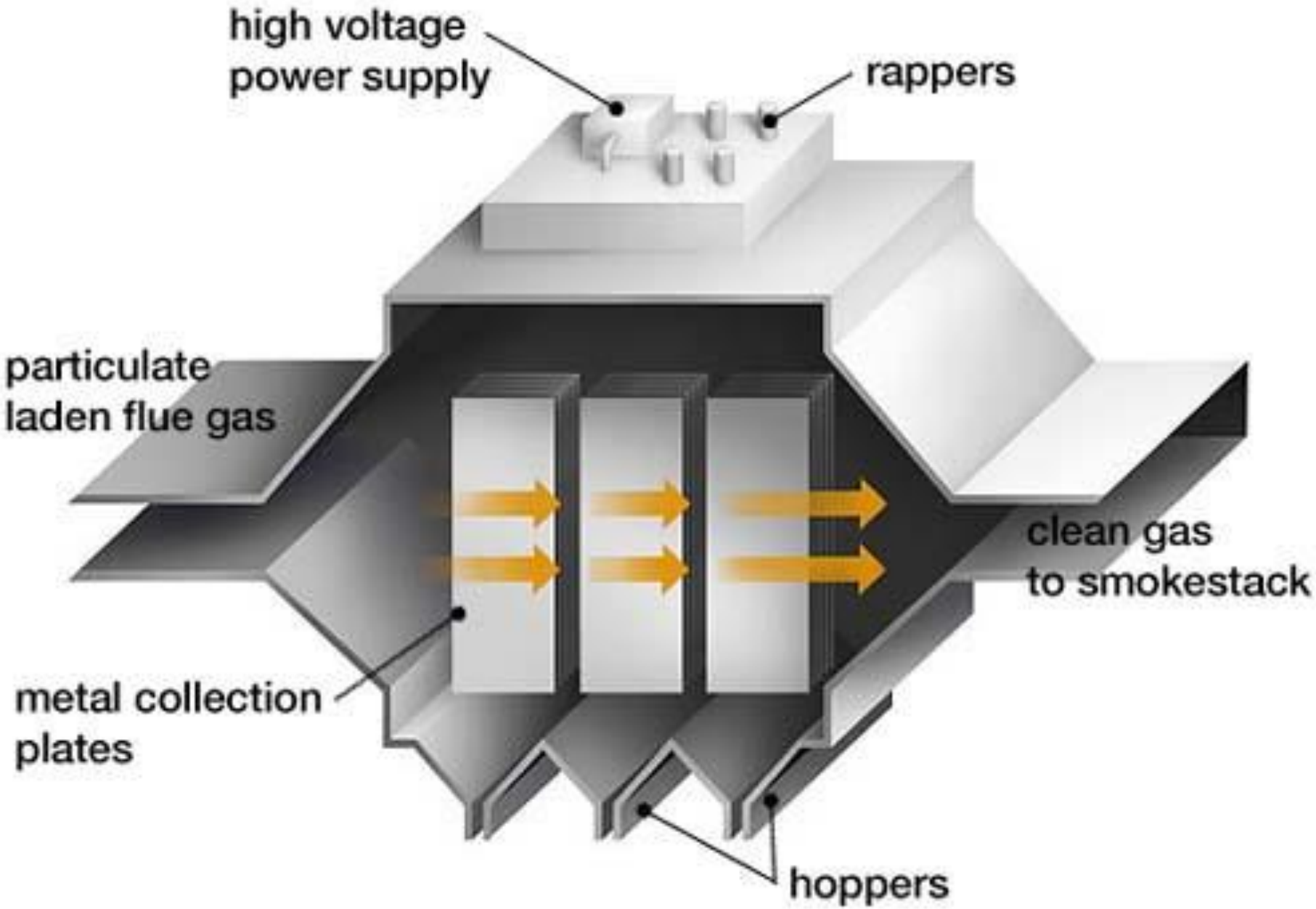
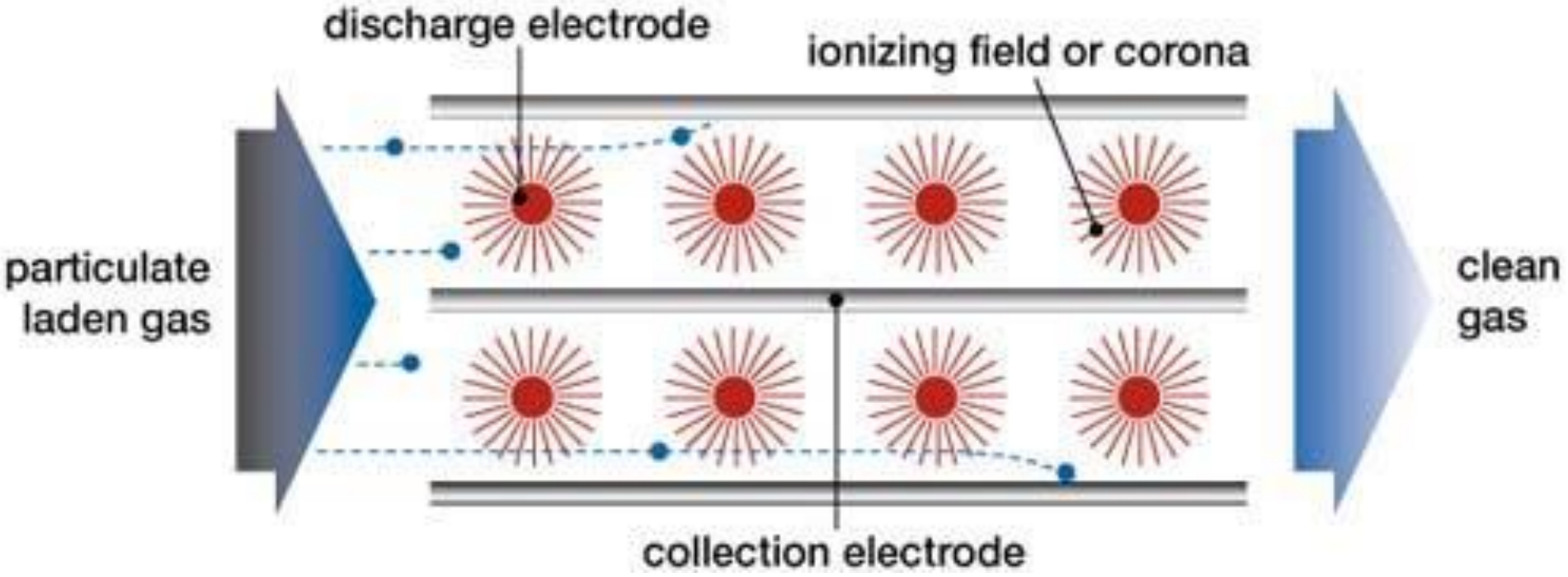
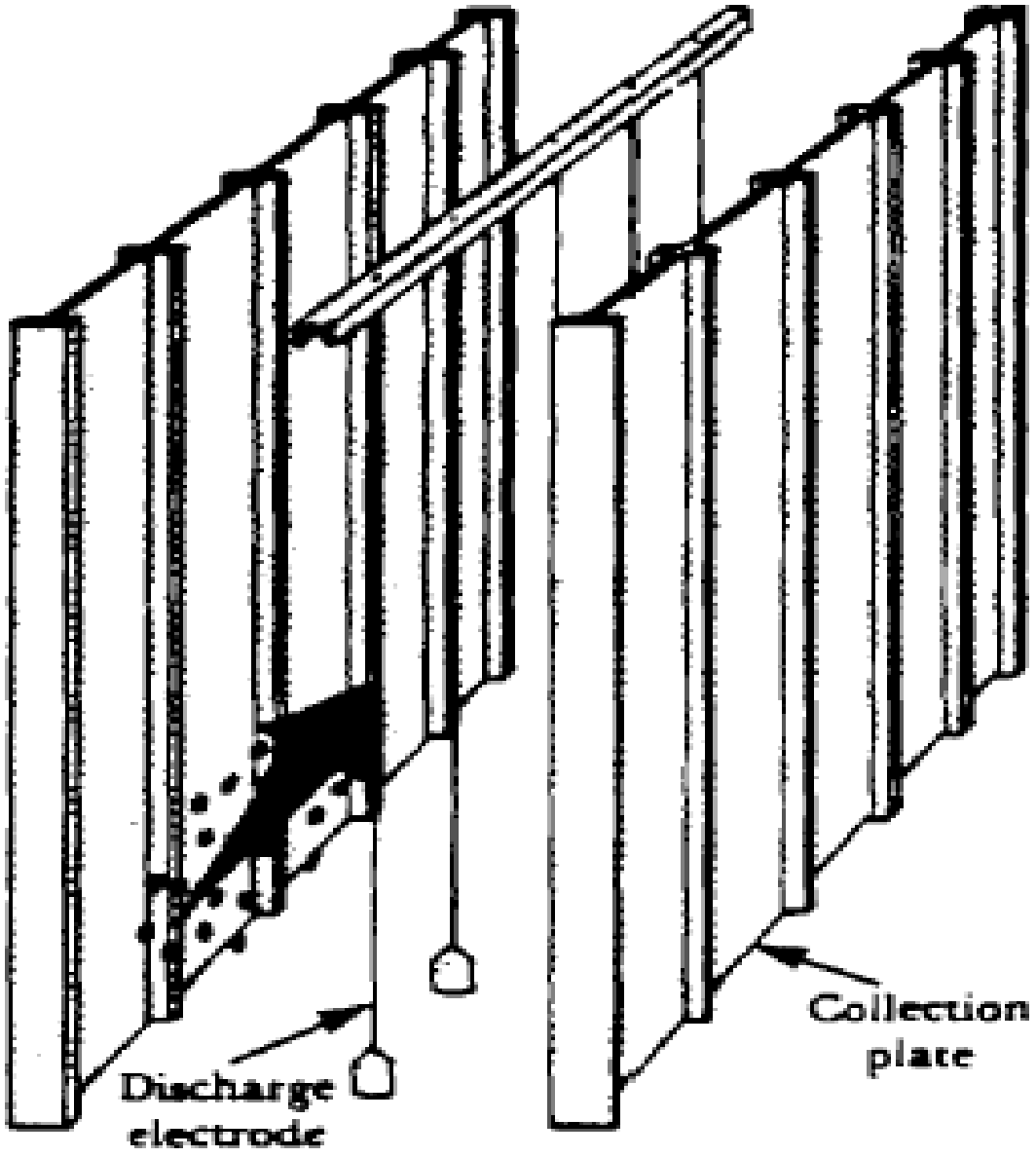


FIGURE 9.5
A multiclone, which places a large number of small cyclones in parallel. The dirty gas flows through an entrance duct, the edge of which is shown in the sketch at the rear, into the chamber shown in the cutaway, then flows downward into the individual tubes, getting its spiral motion from the turning vanes shown. The cleaned gas flows up the central tubes and out through the top of the device (through an outlet flue, not shown, which bolts to the slanting top of the device). The collected particles fall to the conical bottom. (Courtesy of Joy Environmental.)


high voltage
power supply
rappers
particulate
laden flue gas
clean gas
to smokestack
metal collection
plates
hoppers



The flue gas laden with fly ash is sent through pipes having negatively charged plates which give the particles a negative charge. The particles are then routed past positively charged plates, or grounded plates, which attract the now negatively-charged ash particles. The particles stick to the positive plates until they are collected. The air that leaves the plates is then clean from harmful pollutants.


Discharge
electrode
Collection
plate

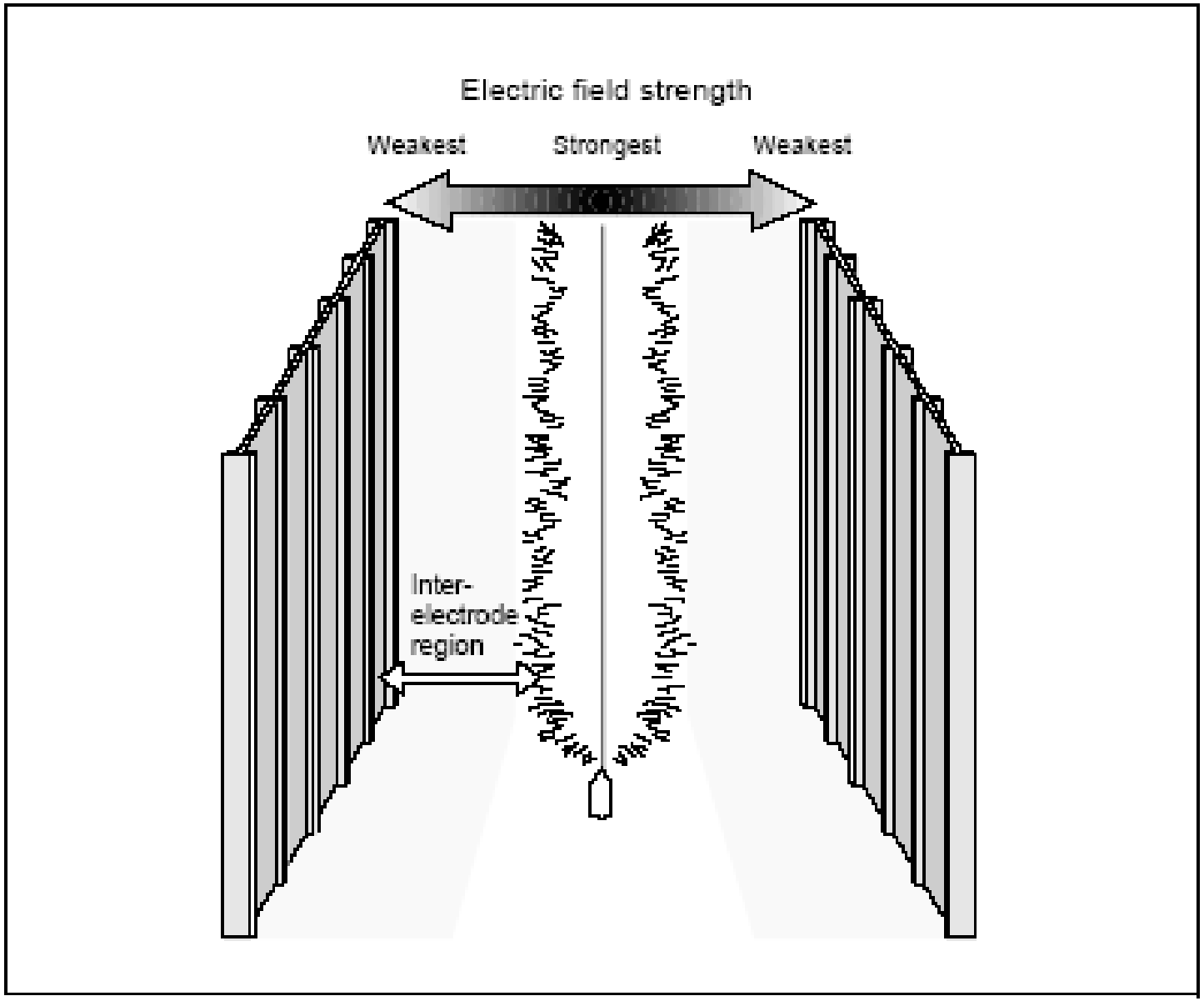
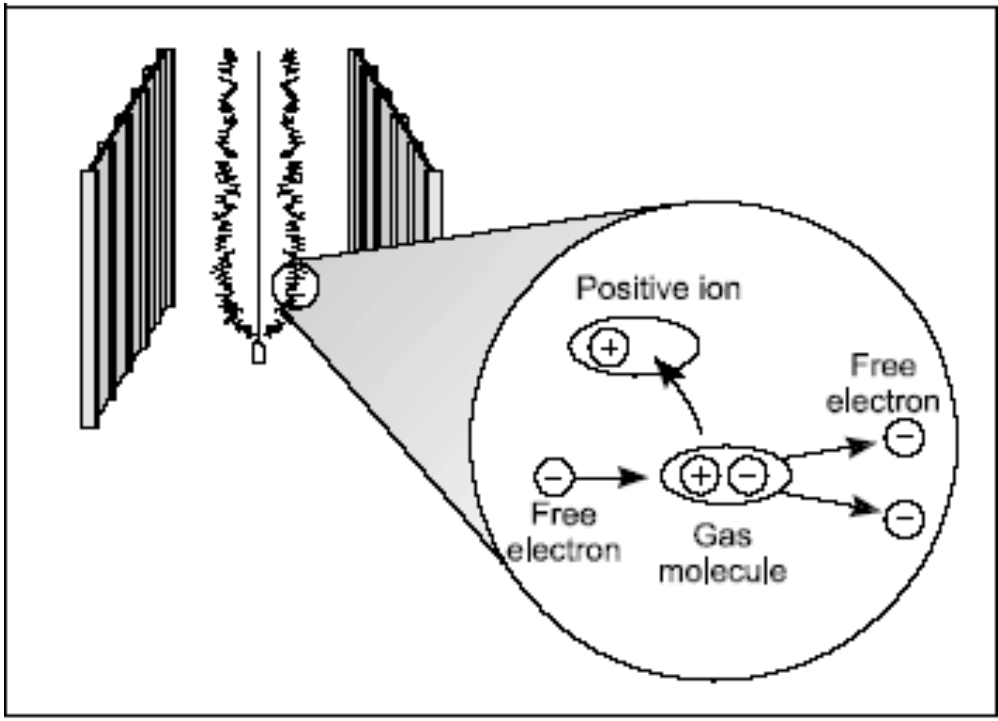


Figure 1-2. ESP electric field

Several things happen very rapidly (in a matter of a millisecond) in the small area around the discharge electrode. The applied voltage is Increased (~40 kV) until it produces a **corona discharge**, which can be seen as a luminous blue glow around the discharge electrode. The free electrons created by the corona are rapidly fleeing the negative electric field, which repulses them. They move faster and faster away from the discharge electrode. This acceleration causes them to literally crash into gas molecules, bumping off electrons in the molecules. As a result of losing an electron (which is negative), the gas molecules become positively charged, that is, they become positive ions.



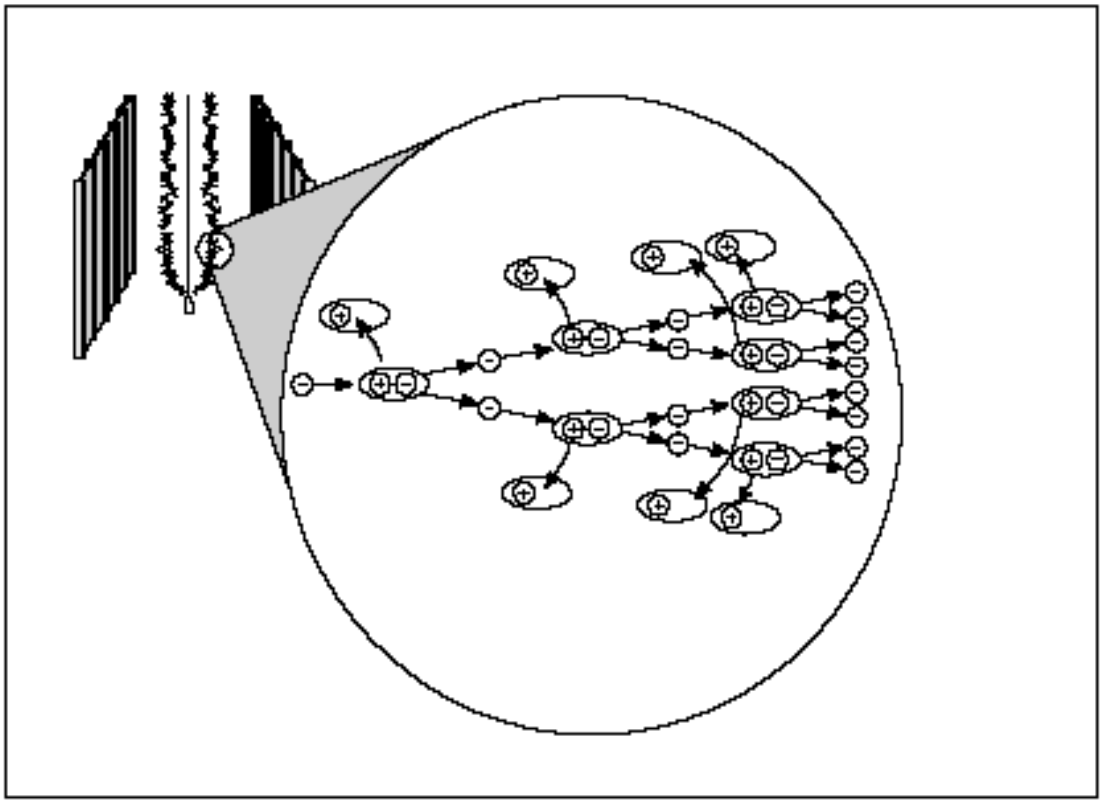


Figure 1-4. Avalanche multiplication of gas molecules

So, this is the first thing that happens—gas molecules are ionized, and electrons are liberated. All this activity occurs very close to the discharge electrode. This process continues, creating more and more free electrons and more positive ions. The name for all this electron generation activity is **avalanche multiplication.**

Particle Charging Mechanisms

Particles are charged by negative gas ions moving toward the collection plate by one of these two mechanisms: field charging or diffusion charging. In field charging, particles capture negatively charged gas ions as the ions move toward the grounded collection plate. Diffusion charging, as its name implies, depends on the random motion of the gas ions to charge particles.

In **Field charging**, as particles enter the electric field, they cause a local dislocation of the field. Negative gas ions traveling along the electric field lines collide with the suspended particles and impart a charge to them. The ions will continue to bombard a particle until the charge on that particle is sufficient to divert the electric lines away from it. This prevents new ions from colliding with the charged dust particle. When a particle no longer receives an ion charge, it is said to be saturated. Saturated charged particles then migrate to the collection electrode and are collected.

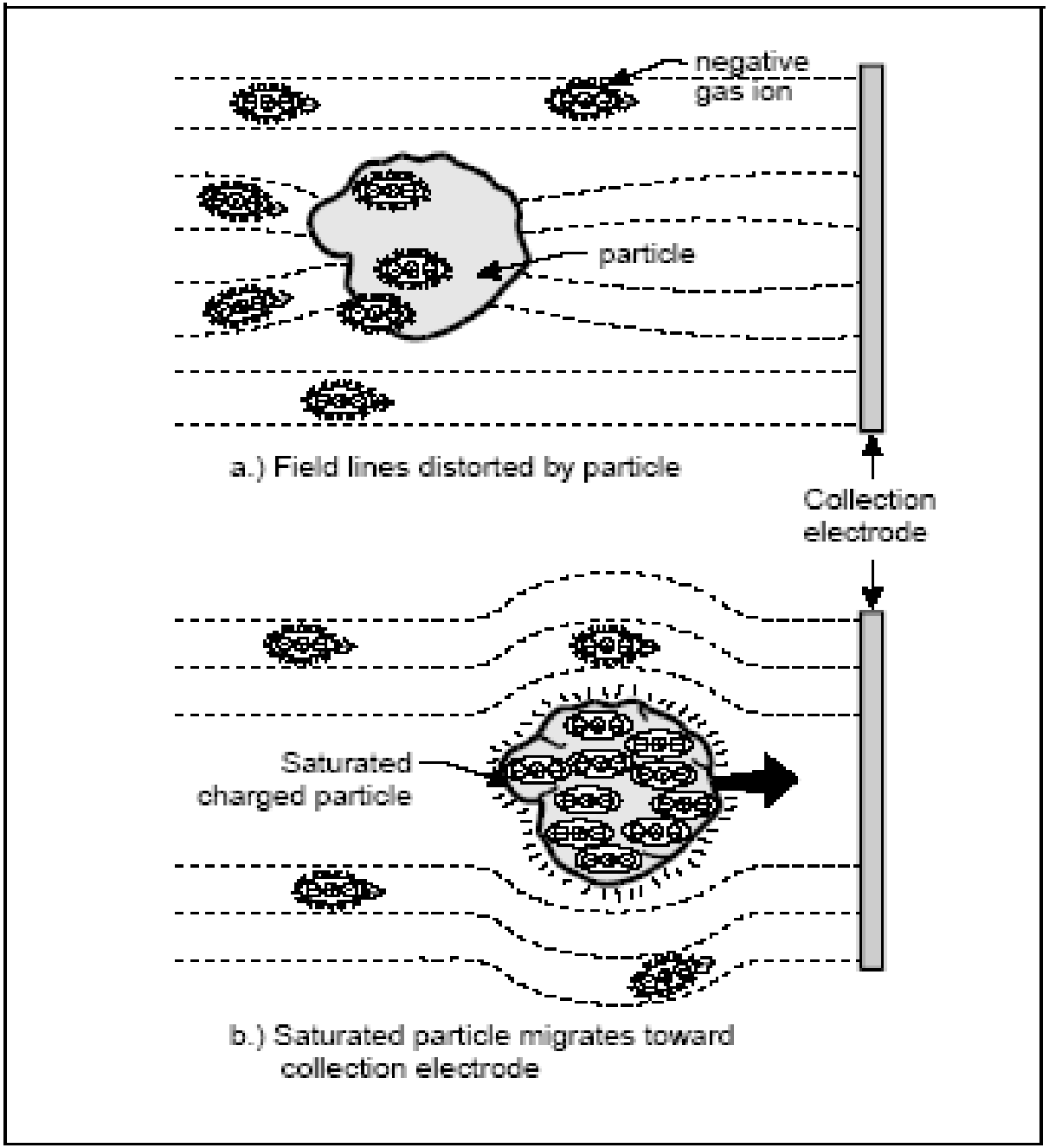


Figure 1-7. Field charging

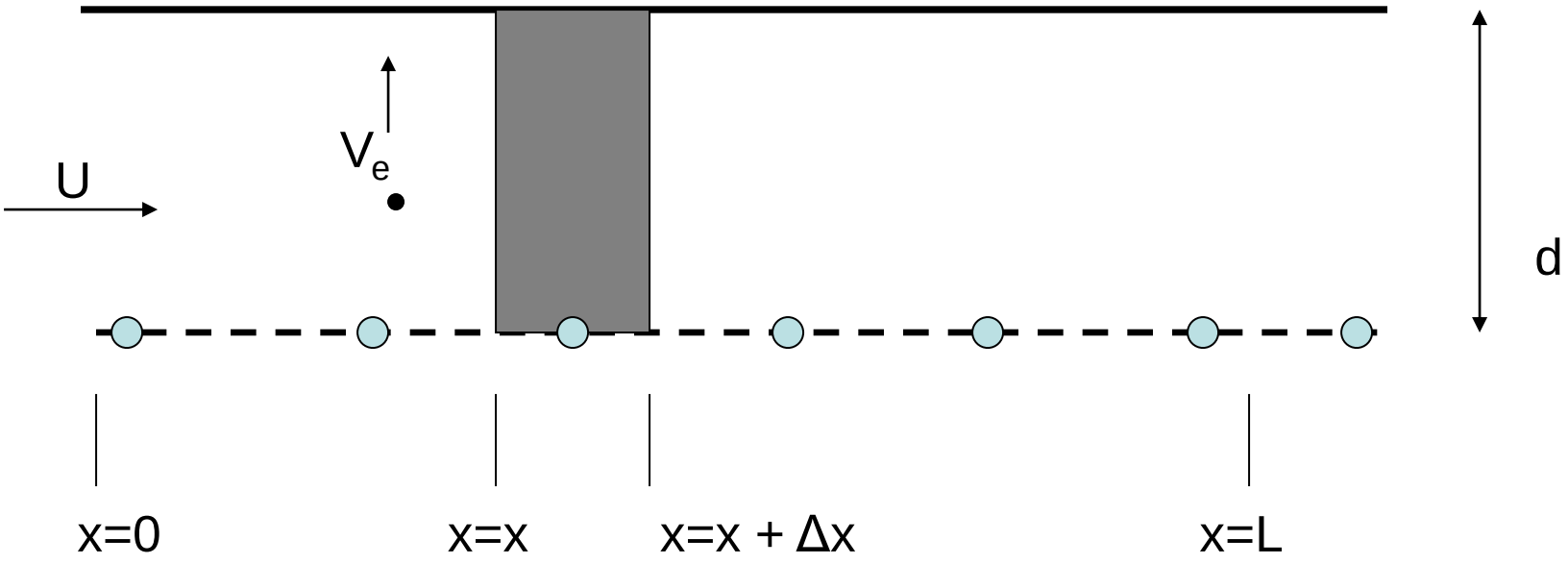
Diffusion charging is associated with the random Brownian motion of the negative gas ions. The random motion is related to the velocity of the gas ions due to thermal effects: the higher the temperature, the more movement. Negative gas ions collide with the particles because of their random thermal motion and impart a charge on the particles. Because the particles are very small (submicrometer), they do not cause the electric field to be dislocated, as in field charging. Thus, diffusion charging is the only mechanism by which these very small particles become charged. The charged particles then migrate to the collection electrode. Each of these two charging mechanisms occurs to some extent, with one dominating depending on particle size.

Field charging dominates for particles with a diameter >1.0 micrometer because particles must be large enough to capture gas ions. Diffusion charging dominates for particles with a diameter less than 0.1 micrometer. A combination of these two charging mechanisms occurs for particles ranging between 0.2 and 1.0 micrometer in diameter.

A third type of charging mechanism, which is responsible for very little particle charging is **electron charging**. With this type of charging, fast-moving free electrons that have not combined with gas ions hit the particle and impart a charge.

Large particles are removed efficiently because they become highly charged. Smaller particles do not acquire a large charge, but their electrostatic drift velocity remains high because the drag on them is small.

In the figure shown below, consider a slice Δx.



A steady state material balance applied to particles in the slice between x and x + Δx produces following equation:

$$(UWd)\,C(x) = (UWd)\,C(x + \Delta x) + (V_e W\,\Delta x)\,C(x + \Delta x/2)$$

Where W is the width of the collector plate, normal to the flow, and C is the particle concentration. The term on the left accounts for advective flow of particles into the slice. The 2 terms on the right account for, respectively, advective flow and electrostatic drift out of the slice. The electrostatic drift

Velocity, V_e, can be estimated by balancing the electrostatic force on a charged particle with the drag force on it.

$$F_e = F_d$$

$$qE = 3\pi\eta d_p C_c V_e$$ q is particle's charge,

Hence, $$V_e = (qEC_c)/(3\pi\eta d_p)$$ E is electric field strength

For simplicity lets assume that V_e is the same for all particles and rearrange the following equation:

$$(UWd)\, C(x) = (UWd)\, C(x + \Delta x) + (V_e W \Delta x)\, C(x + \Delta x/2)$$

$$[C(x + \Delta x) - C(x)]/\Delta x = -[V_e/(Ud)][C(x + \Delta x/2)]$$

Taking the limit as Δx tends to zero, we get

$$dC/dx = -[V_e/(Ud)]C$$ where C is a function of x

Using initial condition $C = C(0)$ at $x = 0$, we get

$$C(x) = C(0)\exp\{-(V_e x)/(Ud)\}$$

Using final condition C = C(L) at x = L and rearranging to get the efficiency, we get:

$$\eta = 1 - C(L)/C(0)$$

$$\eta = 1 - \exp\{-(LV_e)/(Ud)\}$$

(LW)/(UdW) is the **specific collector area, SCA** (ratio of collector plate area to volumetric flow rate, in units of inverse velocity).

Therefore, $\eta = 1 - \exp\{-(SCA)(V_e)\}$

This equation is also known as the **“Deutsch-Anderson”** equation.

Table 4-2. Equations used to estimate collection efficiency and collection area

Calculation	Deutsch-Anderson	Matts-Ohnfeldt
Collection efficiency	$\eta = 1 - e^{-w(A/Q)}$	$\eta = 1 - e^{-w_k(A/Q)^k}$
Collection area (to meet a required efficiency)	$A = \frac{-Q}{w}[\ln(1-\eta)]$	$A = \left[-\left(\frac{Q}{w_k}\right)^k [\ln(1-\eta)]\right]^{1/k}$
Where:	η = collection efficiency A = collection area w = migration velocity Q = gas flow rate ln = natural logarithm	η = collection efficiency A = collection area w_k = average migration velocity k = constant (usually 0.5) ln = natural logarithm

The **specific collection area (SCA)** is defined as the ratio of the collection surface area to the gas flow rate into the ESP. It is expressed in m^2 per 1000 m^3/h, of flue gas through the precipitator. Increasing the surface area for a given flue gas rate will generally increase the overall efficiency of the ESP. The typical range for SCA is between 11 and 45 m^2 per 1000 m^3/h. The SCA must be large enough to efficiently collect particles (99.5% collection efficiency), but not so large that the cost of the ESP is too high. If the dust has a high resistivity, the ESP is designed with a higher SCA [usually greater than 22 m^2 per 1000 m^3/h] to help reduce resistivity problems.

Given a drift velocity of 1 cm/s, good removal efficiency for 0.3 micron particles would require a specific collector area greater than about 1 s/cm. In practice, design values are usually in the range 0.2-2 s/cm. Common designs have channel widths of 15-40 cm and gas velocities, U ~ 1.2-2.5 m/s. Operating expenses for ESPs are dominated by the electrical power requirements needed to operate the corona discharge and to maintain the strong electric field.

Table 4-1. Typical ranges of design parameters for fly ash precipitators

Parameter	Range (metric units)	Range (English units)
Distance between plates (duct width)	20-30 cm (20-23 cm optimum)	8-12 in. (8-9 in. optimum)
Gas velocity in ESP	1.2-2.4 m/s (1.5-1.8 m/s optimum)	4-8 ft/sec (5-6 ft/sec optimum)
SCA	11-45 m^2/1000 m^3/h (16.5-22.0 m^2/1000 m^3/h optimum)	200-800 ft^2/1000 cfm (300-400 ft^2/1000 cfm optimum)
Aspect ratio (L/H)	1-1.5 (keep plate height less than 9 m for high efficiency)	1-1.5 (keep plate height less than 30 ft for high efficiency)
Particle migration velocity	3.05-15.2 cm/s	0.1-0.5 ft/sec
Number of fields	4-8	4-8
Corona power/flue gas volume	59-295 watts/1000 m^3/h	100-500 watts/1000 cfm
Corona current/ft^2 plate area	107-860 microamps/m^2	10-80 microamps/ft^2
Plate area per electrical (T-R) set	465-7430 m^2/T-R set (930-2790 m^2/T-R set optimum)	5000-80,000 ft^2/T-R set (10,000-30,000 ft^2/T-R set optimum)

Resistivity

Particle resistivity is a condition of the particle in the flue gas that can drastically affect ESP collection efficiency. Resistivity describes the resistance of the collected dust layer (on the plates) to the flow of electric current. Particles that have high resistivity are more difficult to collect than those having normal resistivity. This is because the collected dust layer tends to break down the flow of electric current from the discharge electrode to the collection electrode. Particles that have high resistivity do not leak their charge to ground upon arrival at the collection plate. Consequently, ESP performance is reduced. High resistivity problems occur most frequently when low sulfur coal is burned in boilers. The collection efficiency of some ESPs has been reduced as much as 50% due to resistivity problems (White, 1974).

Resistivity is a function of the chemical composition of the dust, the flue gas temperature and moisture concentration. For fly ash generated from coal-fired boilers, the resistivity depends on the temperature and moisture content of the flue gas and on the sulfur content of the coal burned; the lower the sulfur content, the higher the resistivity, and vice versa. If a boiler burns
low-sulfur coal, the ESP must be designed to deal with potential resistivity problems. High resistivity can be reduced by spraying water, SO_3 or some
other conditioning agent into the flue gas before it enters the ESP.

High resistivity can be reduced by adjusting the temperature and moisture content of the flue gas flowing into the ESP. Particle resistivity can be decreased by increasing the gas temperature above 260 °C (500 °F) or by reducing it below 150 °C (300 °F). Hot-side precipitators have frequently been used to combat resistivity problems, where the flue gas temperature into the ESP is greater than 260 °C. However, it has been reported that the efficiency of hot-side ESPs is quite sensitive to the composition of fly ash, and since the composition of fly ash is highly variable, reliable operation can be difficult.

Increasing the moisture content of the flue gas also lowers resistivity. This can be accomplished by spraying water or injecting steam into the duct work preceding the ESP. In both temperature adjustment and moisture conditioning, the flue gas must be above the dew point to prevent corrosion problems to the precipitator.

Other conditioning agents such as sulfuric acid, sulfur trioxide, ammonia, sodium chloride, and soda ash have also been used to reduce particle resistivity (White, 1974). For coal fly ash, the resistivity can be lowered by injecting approximately 10 to 30 ppm sulfur trioxide into the flue gas ducts preceding the ESP.

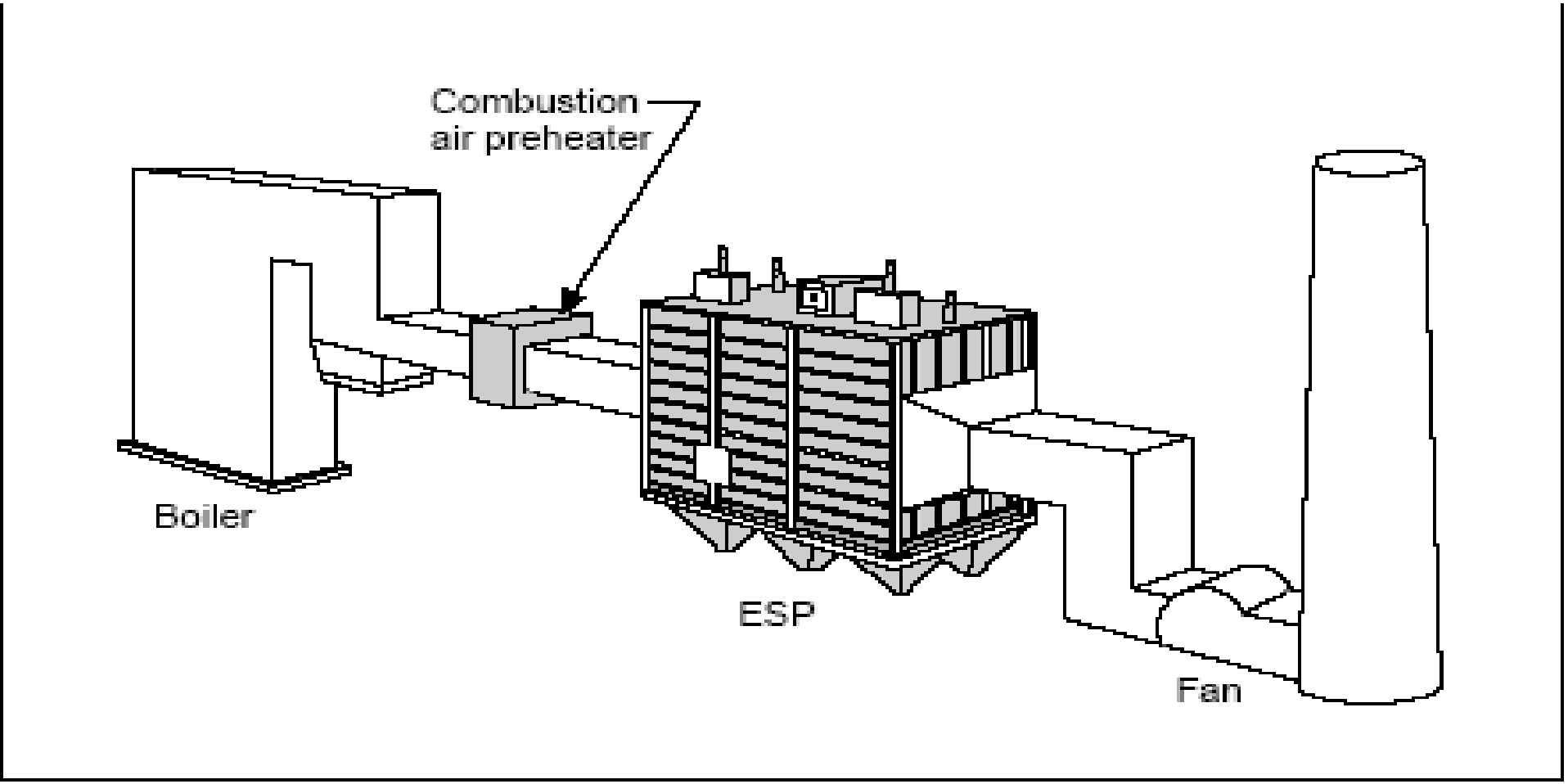
Other challenges with ESP operation:

Particles build up on the collection plates and form a layer (~1 cm). The layer does not collapse, thanks to electrostatic pressure (given from layer resistivity, electric field, and current flowing in the collected layer).

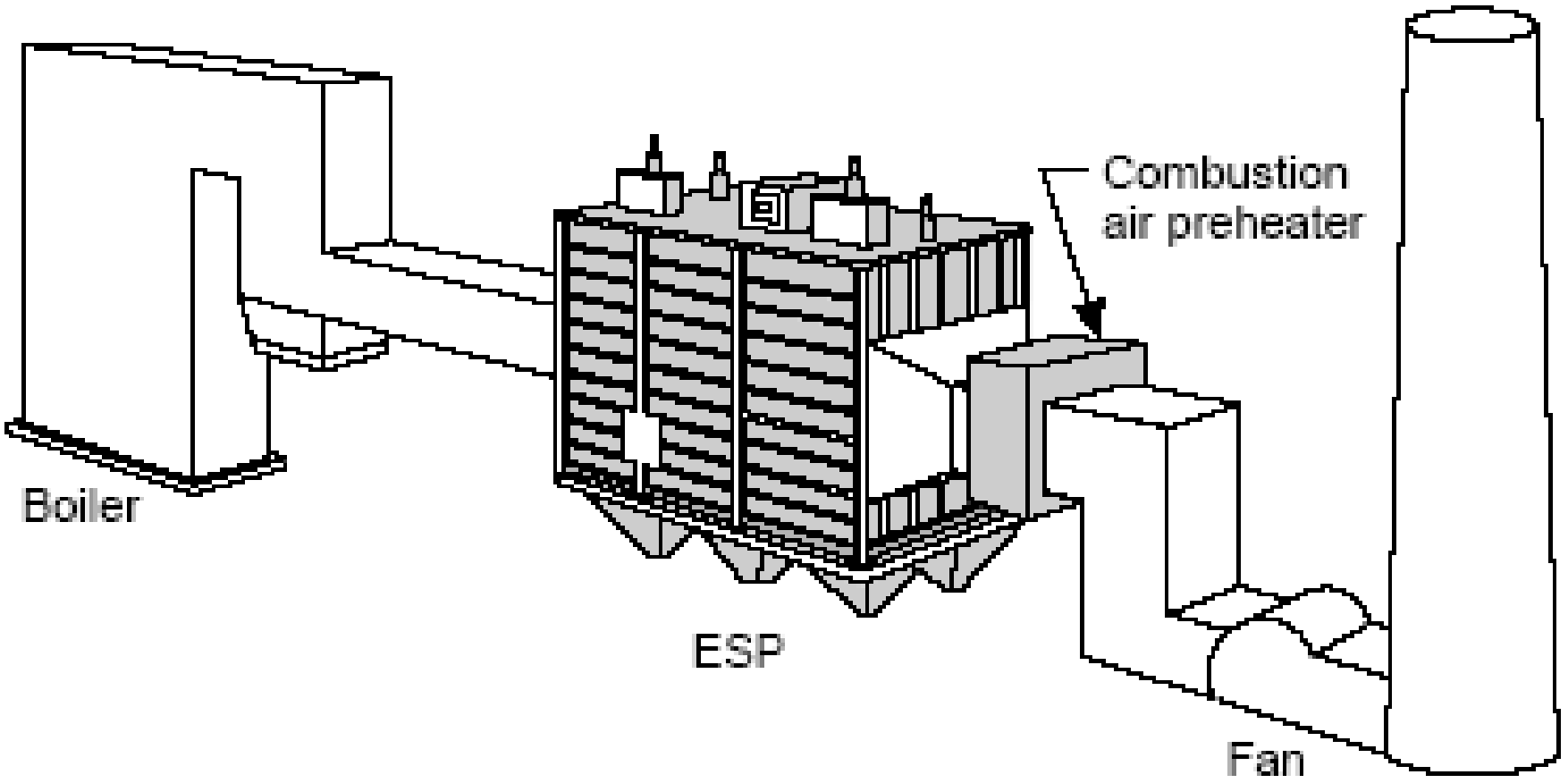
Physical and chemical properties of the dust such as dust type, size of the dust particles, and average and maximum concentrations in the gas stream are important ESP design considerations. For example, a dry ESP should not be used to collect explosive dust. In this case, it might be a better idea to use a baghouse or scrubber. Particle size is important; small particles are more difficult to collect and become reentrained more easily than larger particles. If the dust concentration is too high, the automatic voltage controller may respond by totally suppressing the current in the inlet fields.

Electrostatic precipitators are also grouped according to the temperature of the flue gas that enters the ESP: **cold-side** ESPs are used for flue gas having temperatures of approximately 204°C (400°F) or less; **hot-side** ESPs are used for flue gas having temperatures greater than 300°C (572°F).

A cold-side ESP is located *behind* the air preheater, whereas a hot-side ESP is located *in front* of the air preheater. The air preheater is a tube section that preheats the combustion air used for burning fuel in a boiler. When hot flue gas from an industrial process passes through an air preheater, a heat exchange process occurs whereby heat from the flue gas is transferred to the combustion air stream. The flue gas is therefore "cooled" as it passes through the combustion air preheater. The warmed combustion air is sent to burners, where it is used to burn gas, oil, coal, or other fuel including garbage.



Cold-side ESPs can be used to remove fly ash from boilers that burn high sulfur coal. Because these ESPs are operated at lower temperatures than hot-side ESPs, the volume of flue gas that is handled is less. Therefore, the overall size of the unit is smaller, making it less costly.

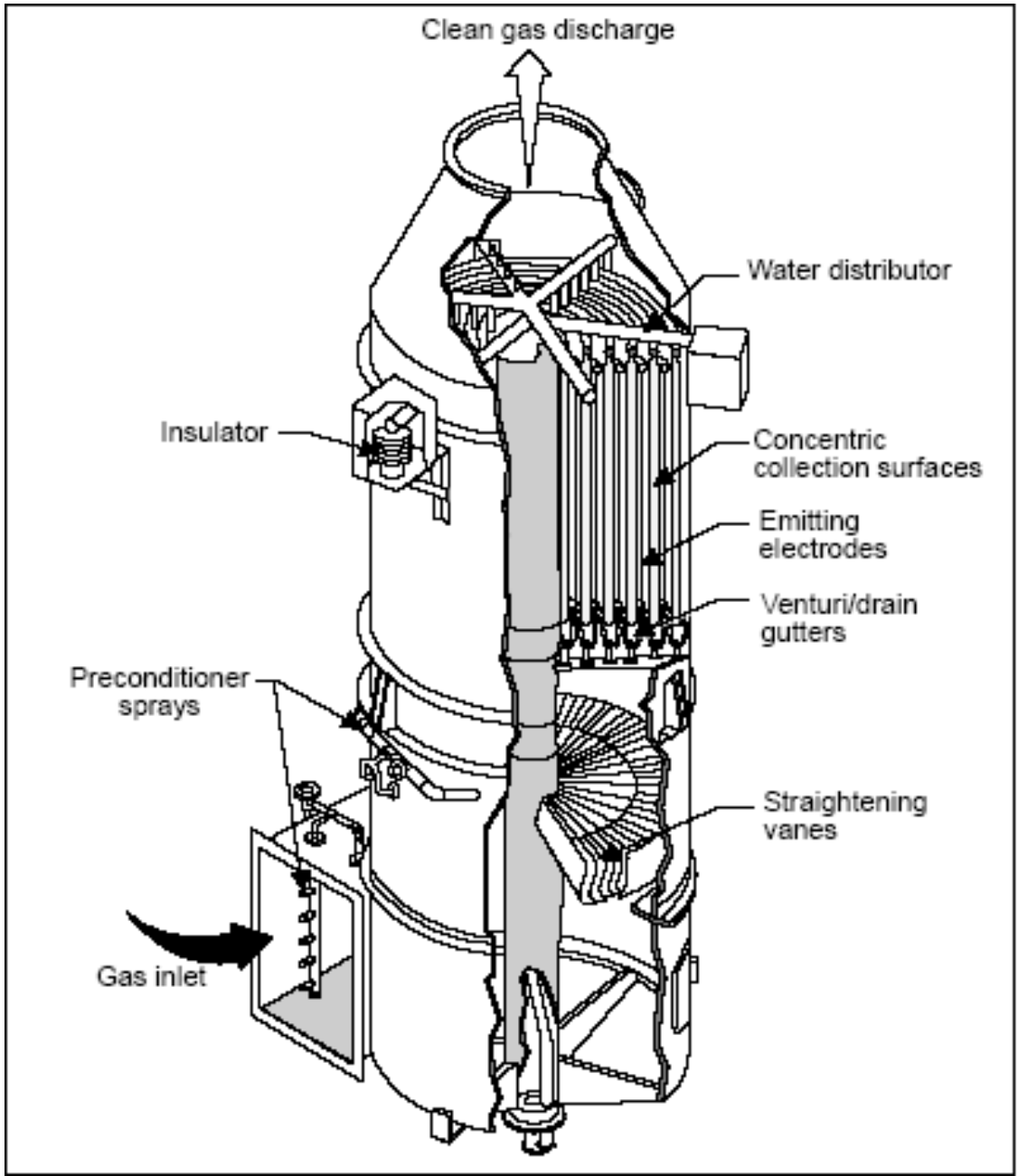


Fly ash produced from low sulfur coal-fired boilers has high resistivity, making it difficult to collect. High temperatures can lower resistivity. Consequently, **hot-side ESPs** became very popular during the 1970s for removing ash from coal-fired boilers burning low sulfur coal.

Electrostatic precipitators are not only used in utility applications but also other industries (for other exhaust gas particles) such as cement (dust), pulp & paper (salt cake & lime dust), petrochemicals (sulfuric acid mist), and steel (dust & fumes).

Electrostatic precipitation is typically a dry process, but spraying moisture to the incoming air flow helps collect the exceptionally fine particulates, and helps reduce the electrical resistance of the incoming dry material to make the process more effective. A **wet electrostatic precipitator** (**WESP**) merges the operational methods of a wet scrubber with an electrostatic precipitator to make a self-washing, self-cleaning yet still high-voltage device.

Wet ESPs are used for industrial applications where the potential for explosion is high (such as collecting dust from a closed-hood Basic Oxygen Furnace in the steel industry), or when dust is very sticky, corrosive, or has very high resistivity. The water flow may be applied continuously or intermittently to wash the collected particles from the collection electrodes into a sump (a basin used to collect liquid). The advantage of using a wet ESP is that it does not have problems with rapping re-entrainment or with back corona.



Tubular precipitators are generally used for collecting mists or fogs, and are most commonly used when collecting particles that are wet or sticky. Tubular ESPs have been used to control particulate emissions from sulfuric acid plants, coke oven byproduct gas cleaning (tar removal), and iron and steel sinter plants.

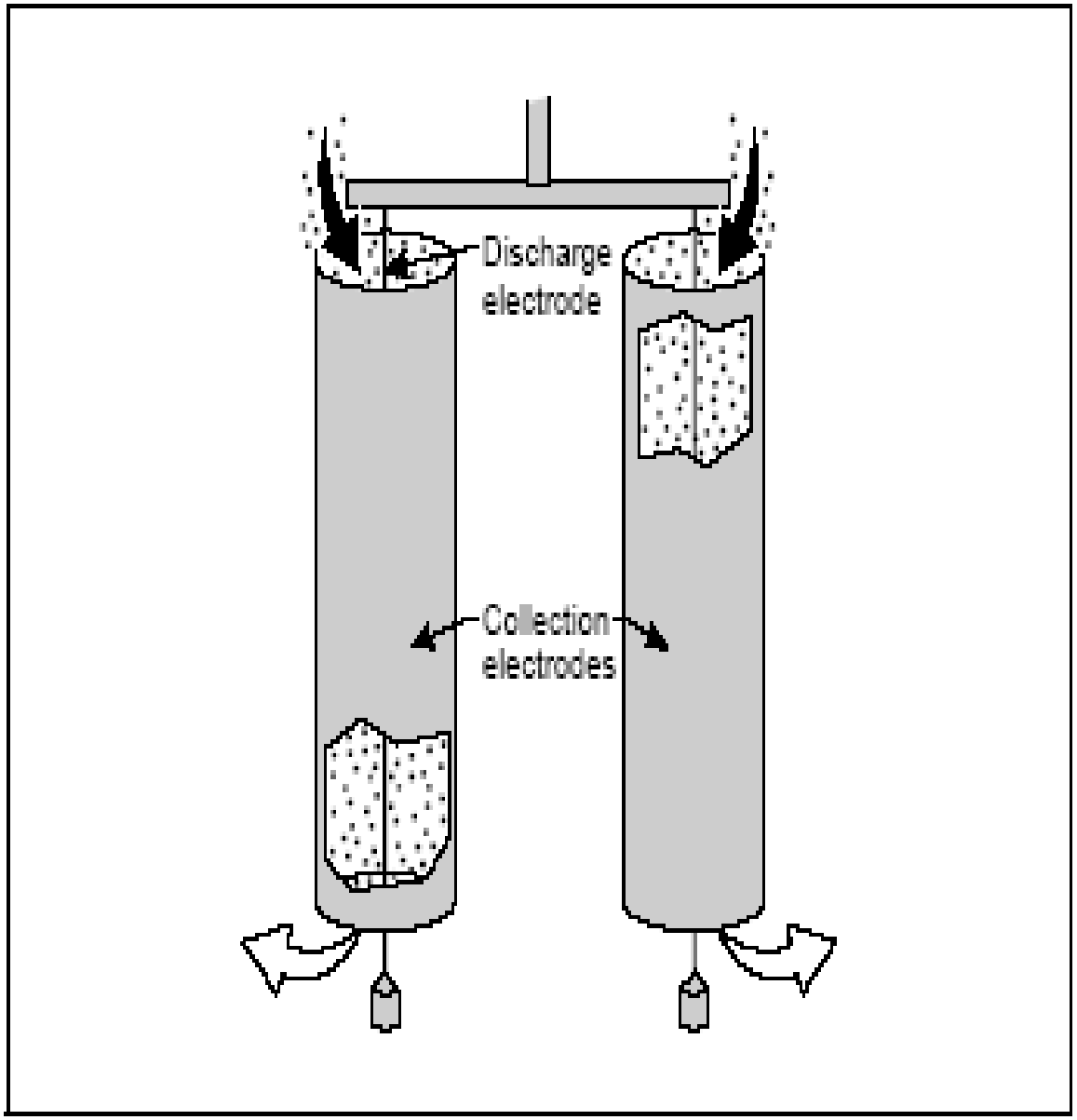


Figure 1-10. Gas flow through a tubular precipitator

ESPs compete with fabric filters in large-scale industrial air-cleaning processes. Both technologies can achieve very high removal efficiencies, even for submicron particles. Relative to fabric filters, ESPs have small pressure drops (~100 Pa), which reduces operating costs, and ESPs can be used to treat high-temperature gases.

Disadvantages include high initial cost, performance degradation when used on particles with low electrical conductivity, and potential safety hazards from high voltages.