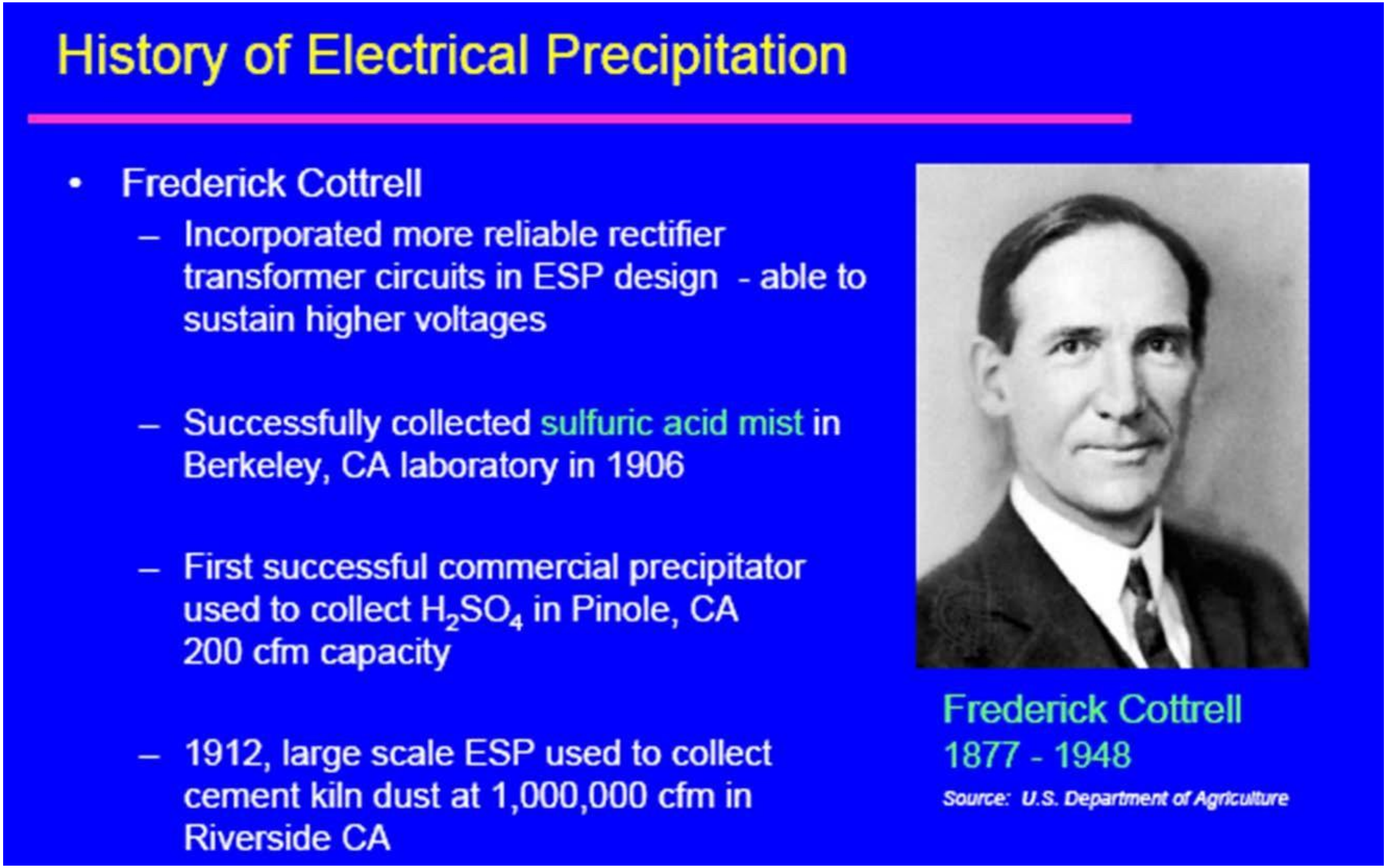
ELECTROSTATIC PRECIPITATORS

Operating principles



History of Electrical Precipitation

- Frederick Cottrell
  - Incorporated more reliable rectifier transformer circuits in ESP design - able to sustain higher voltages
  - Successfully collected sulfuric acid mist in Berkeley, CA laboratory in 1906
  - First successful commercial precipitator used to collect H_2SO_4 in Pinole, CA 200 cfm capacity
  - 1912, large scale ESP used to collect cement kiln dust at 1,000,000 cfm in Riverside CA

Frederick Cottrell
1877 - 1948

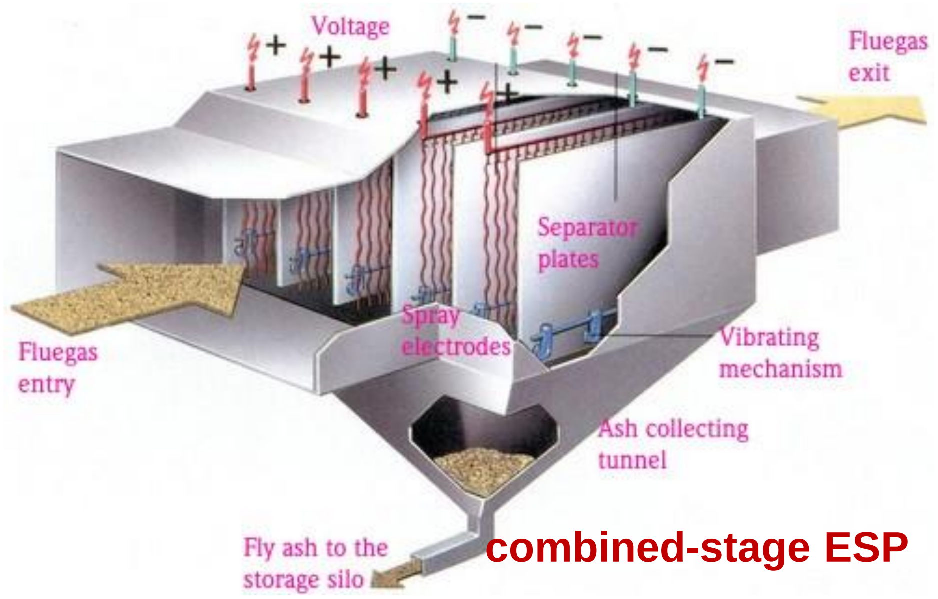
Source: U.S. Department of Agriculture

Principle

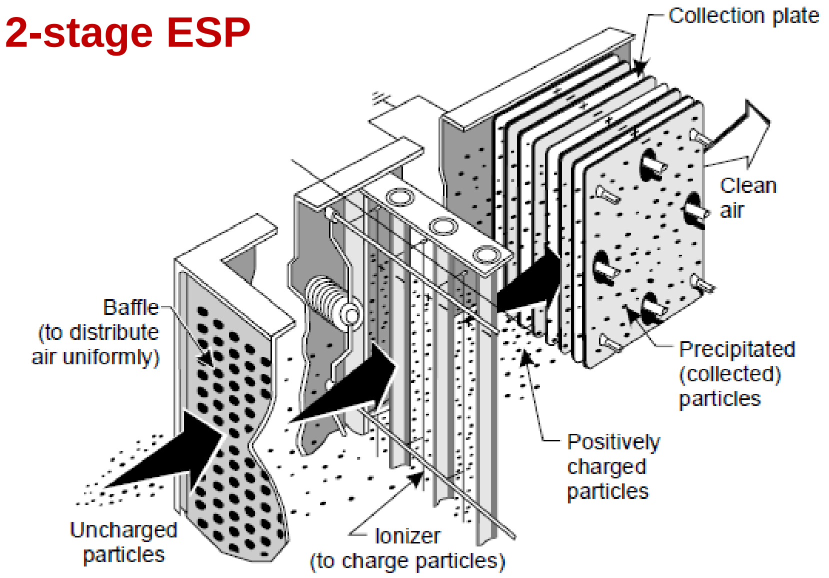
The basic idea of ESPs is to:
give the particles an **electrostatic charge** by ionization of the carrying gas and then put them in an electrostatic field that drives them to a collecting wall, from where they are removed.

ESPs are the unique among APC devices in that ***the forces of collection*** act **only** on the particles and not on the entire air stream.

- For most industrial applications, this two steps of charging and collecting particles are carried out simultaneously in the same part of the ESP.
- In electronic air filters used in air conditioners, charging and collecting are carried out in separated parts of the device (Two stages ESP).



combined-stage ESP



2-stage ESP

General field of applications

- **Advantages**
  - high removal efficiencies (>99%) also for finer particulates
  - high flow rates application also for extreme T and P flue gas conditions
  - applicable over a wide range of operating temperatures
  - high resistence to corrosive environmental conditions
  - dry captured particulates discharge
  - contained pressure drops with respect to alternative technologies with similar collection capacities
- **Drawbacks**
  - high capital costs
  - collection efficiency strongly dependent on flue gas flow rates, temperature and moisture content
  - very dependent on ash resistivity
  - explosion and fire risks from high tension supply
  - space requirements
  - complex operating requirements; not very flexible, once installed, to changes in operating conditions

Resisting force VS Driving force

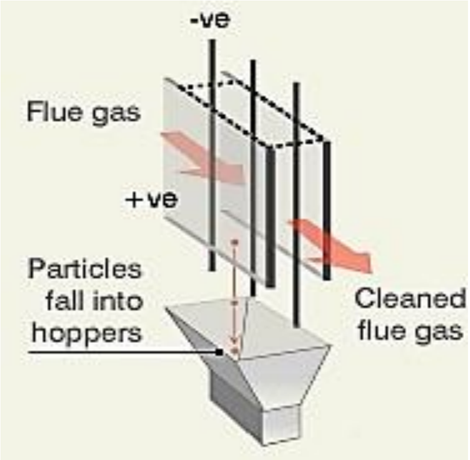
Gravity settlers and centrifugal separator are devices that drive particles against a solid wall (WALL collection devices). Even if centrifugal forces are more effective than gravity forces, both devices present very low efficiency for PM<5 micrometer.

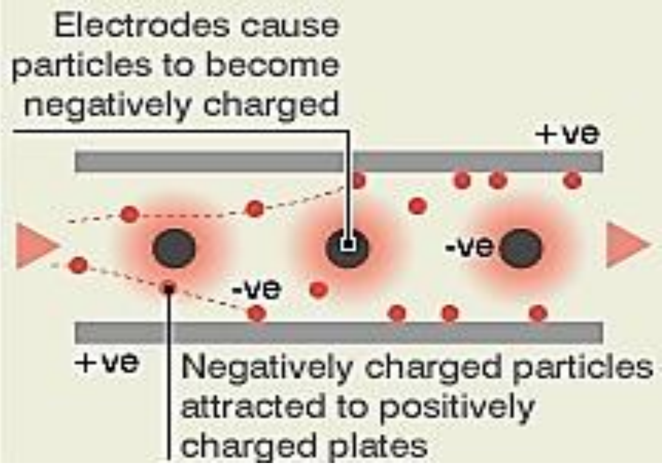
For wall collection devices to work on smaller particles, a force more powerful than gravity/centrifugal force must be exerted. This is the case of Electrostatic forces, employed within ESPs.

	Resisting Force Drag force	Driving Force External force	Driving Force Resisting Force	
Gravity settlers; Cyclones	Proportional to Particle diameter $F_A = 3\pi\mu_f \mathbf{d_p} v$	Proportional to Particle mass → diameter cubed $F_E = \rho_p (\pi \mathbf{d_p}^3 / 6)\, g$ $F_E = \rho_p (\pi \mathbf{d_p}^3 / 6)\, v^2 / r$	Proportional to diameter squared $F_E/F_A \propto \mathbf{d_p}^2$	This ratio falls rapidly when d_p decreases
Electrostatic Precipitators	Proportional to Particle diameter $F_A = 3\pi\mu_f \mathbf{d_p} v$	Proportional to particle surface → diameter squared $F_E = 3\pi \mathbf{d_p}^2 K\, E\, D/(D+2)\, E$	Proportional to diameter $F_E/F_A \propto \mathbf{d_p}$	This ratio falls when d_p decreases, but less rapidly

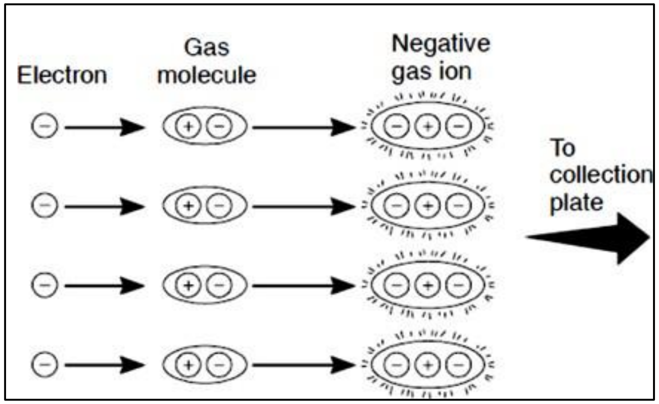
Operating principles

- Separation of particles through external electrical forces generated inside the device by high voltage application (30-100 kV) between two electrodes
  - discharge electrode → long wire
  - collecting electrode → plate or cylindrical
- Elementary processes
  - particle charging by ions generated by flue gas ionization in proximity of discharge electrode (**corona effect**);
  - particle migration towards collecting electrodes where they are captured on its surface, forming a “cake”
  - cake dust removal from collecting electrodes through dry mechanical systems (rapping, vibration) or wet systems (water)



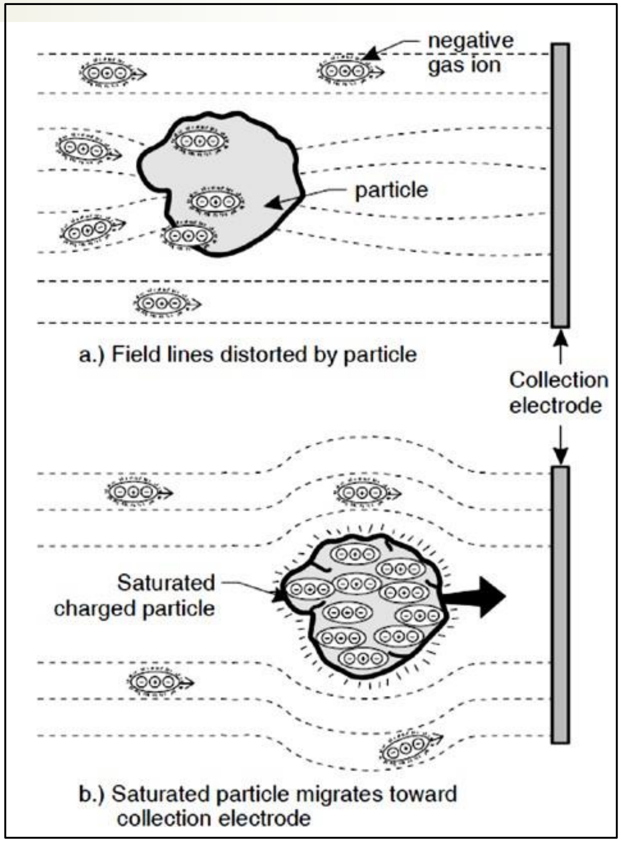


Operating principles - elementary processes



Gas ionization

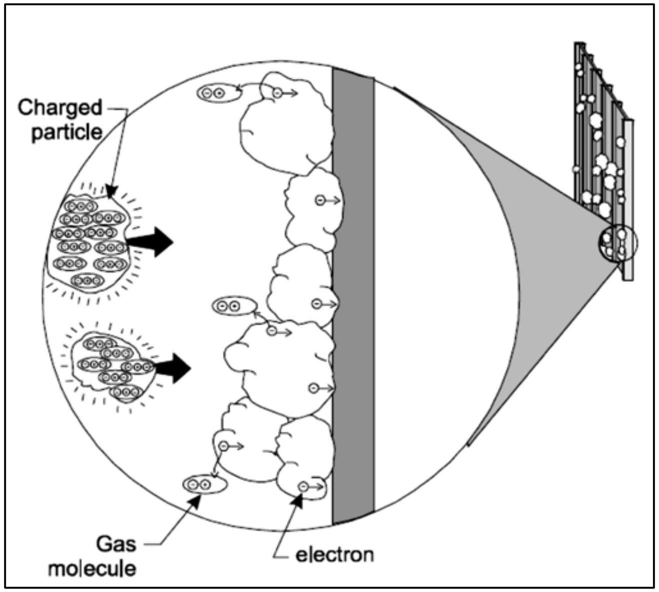
Particle charging



a.) Field lines distorted by particle

b.) Saturated particle migrates toward collection electrode

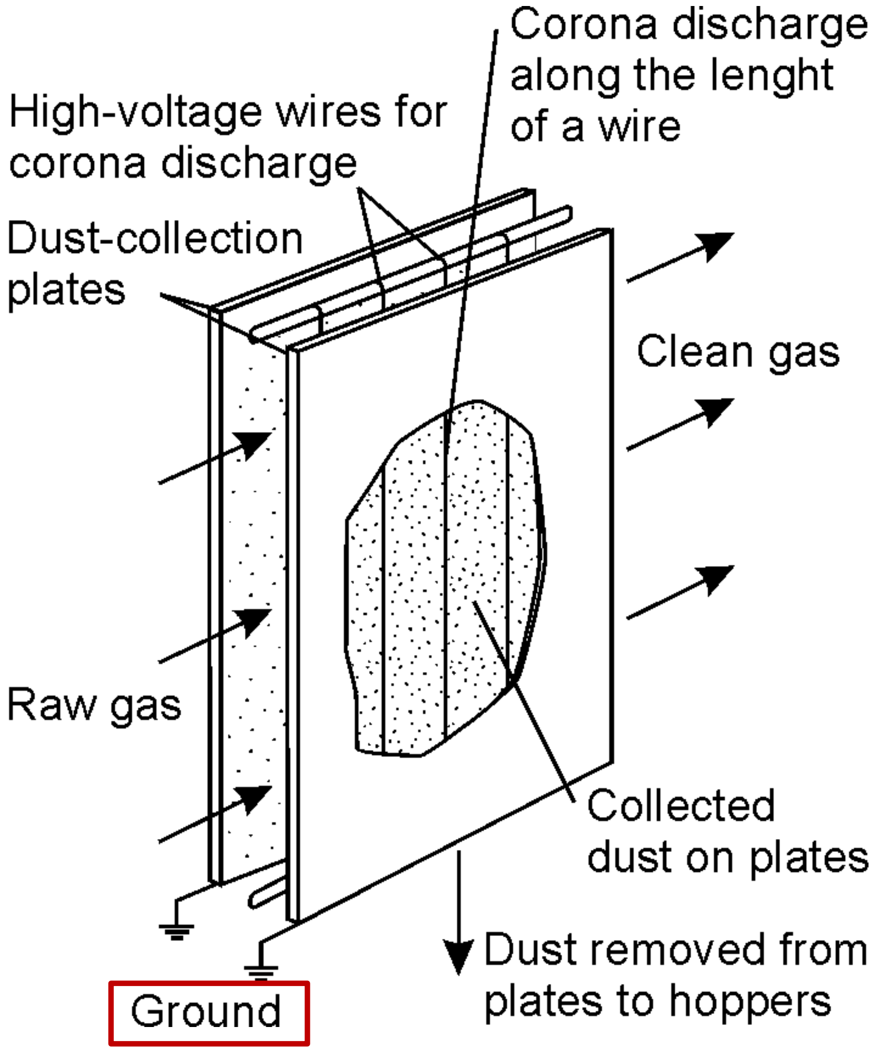
Particle migration

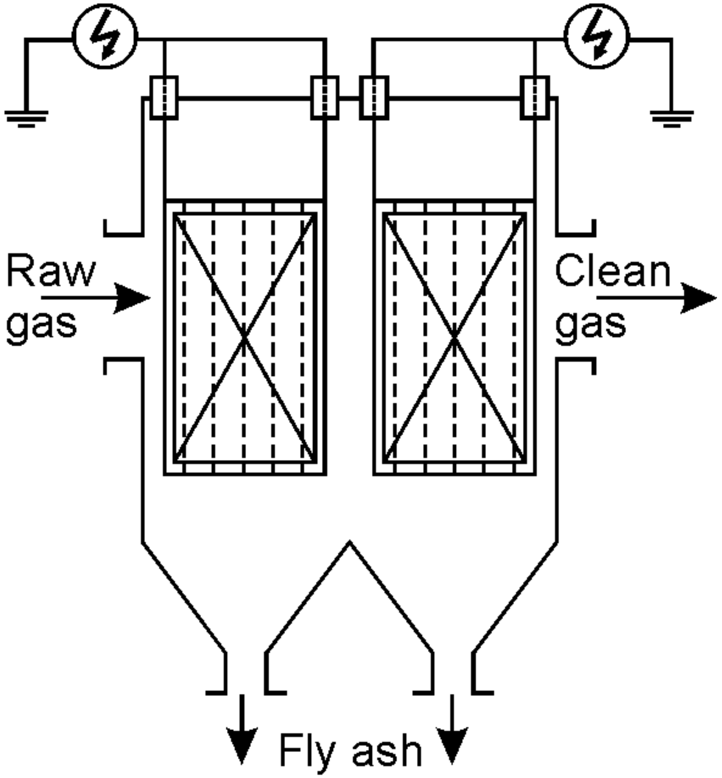


Once particles have migrated to a plate, they are considered to be collected. However, collected particles can be re-entrained into the gas, thus lowering the net ESP efficiency.

Once collected, particles begin to lose their charge to the plate. This transfer of charge completes the electrical circuits, produces current flows and allows maintenance of the voltage drop between the wires and the plates.

Operating principles

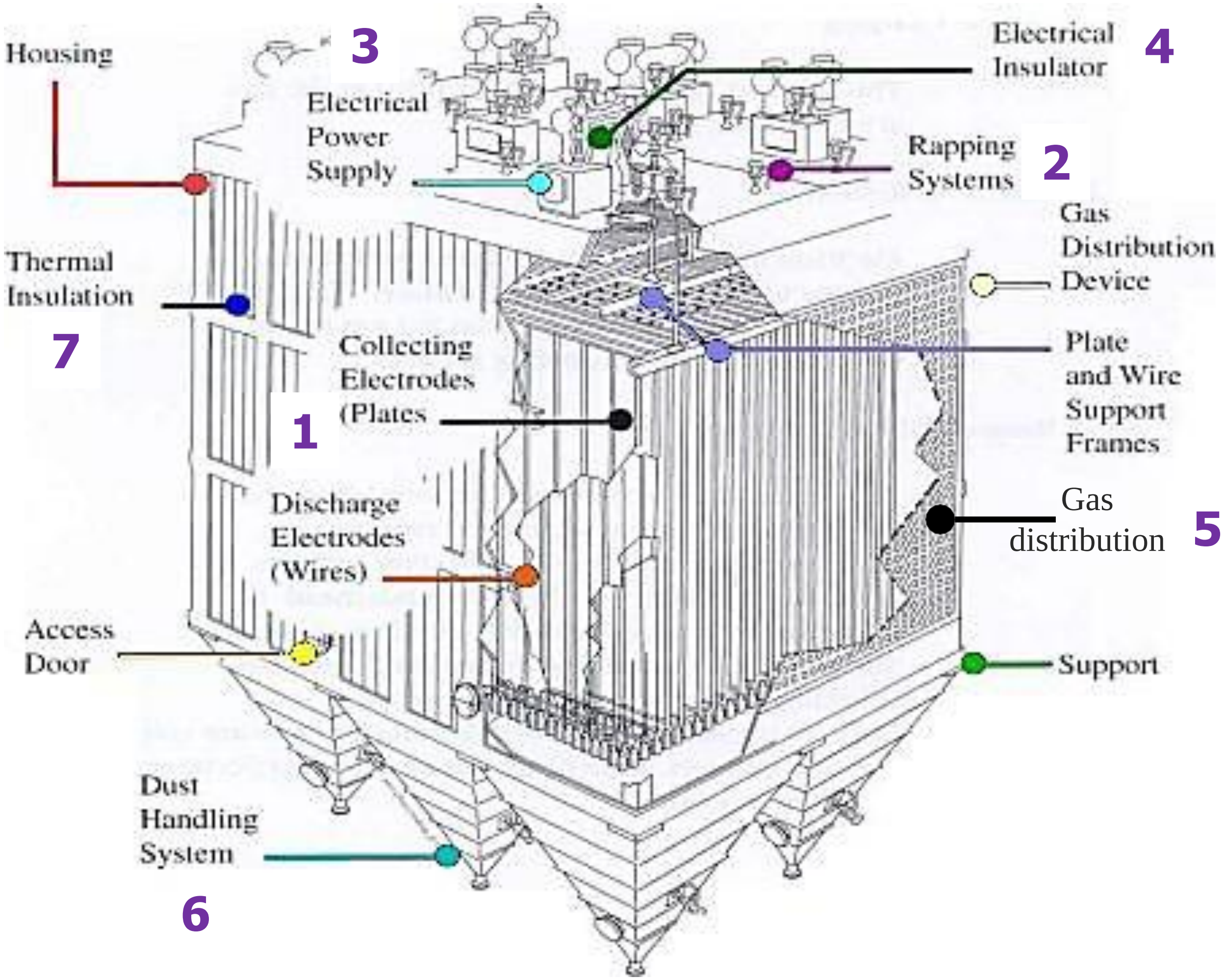




Design configuration

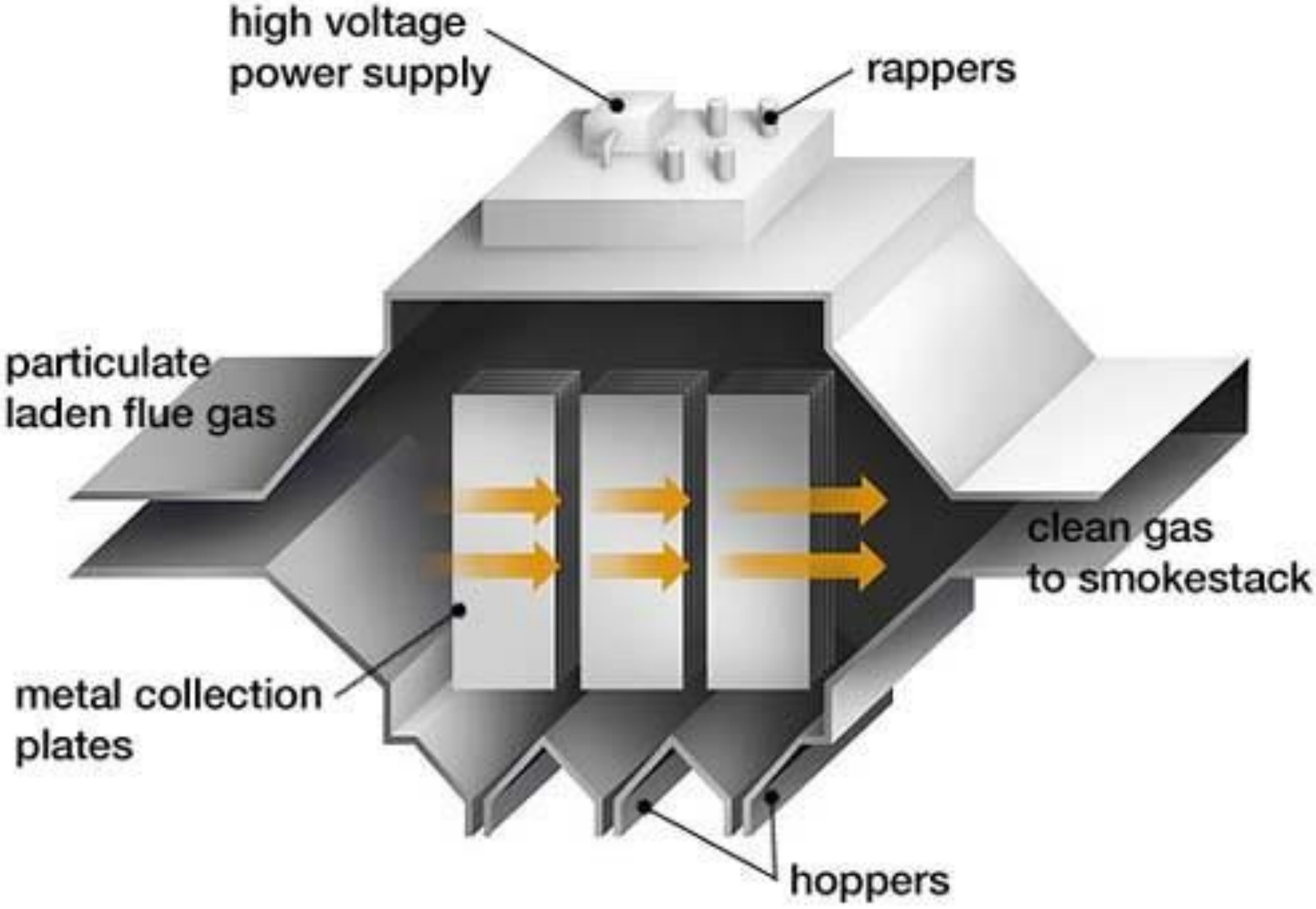
Main elements

1. electrodes
2. plate rapping system
3. power supply transformers-rectifying devices
4. high voltage electrode insulators
5. inlet gas distribution plates
6. particle collection hoppers
7. thermal insulation

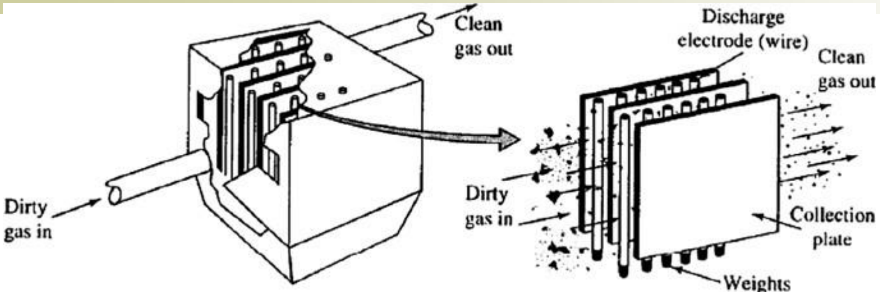


Design configuration

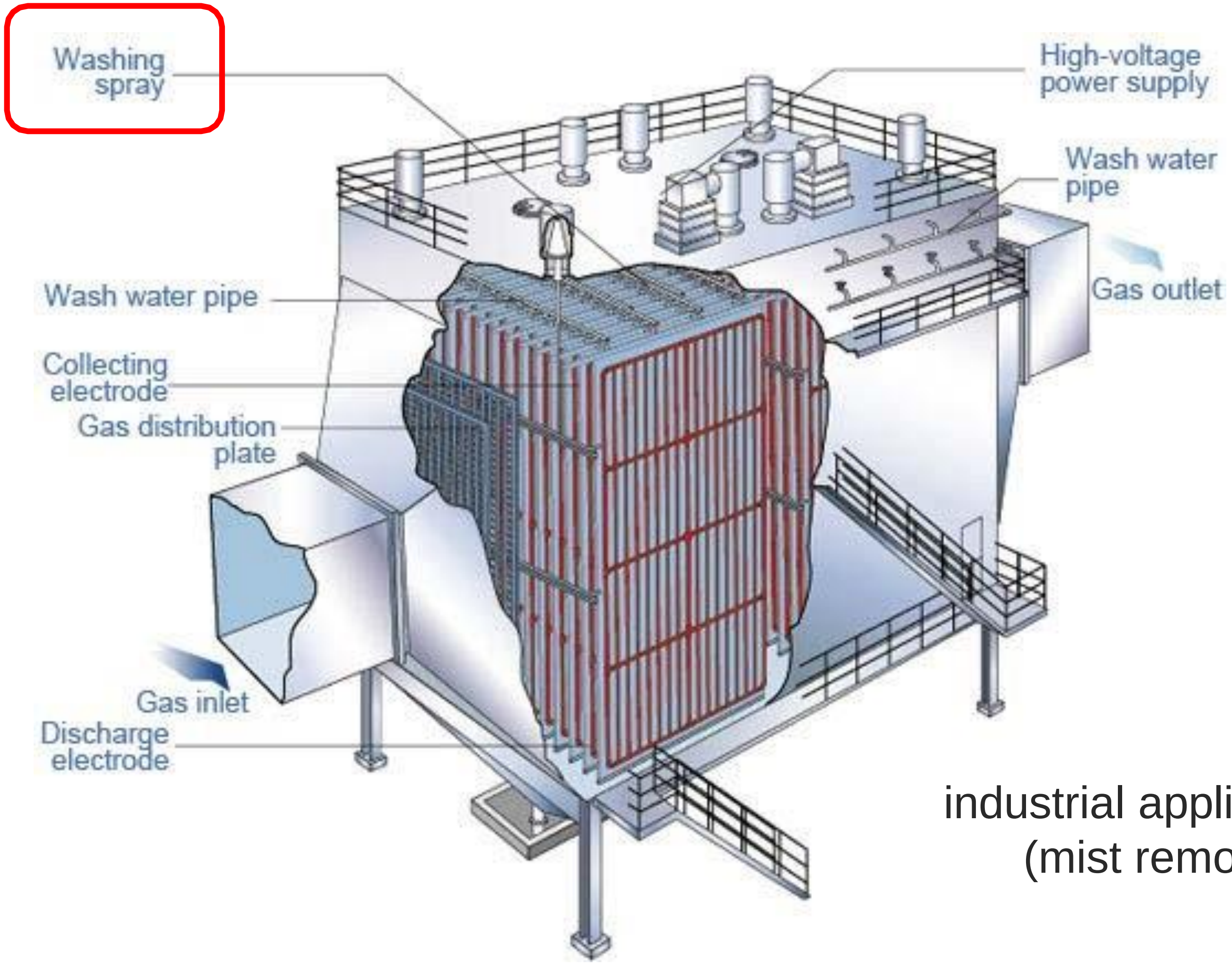
Design configuration: wire/plate precipitators



Operating principles

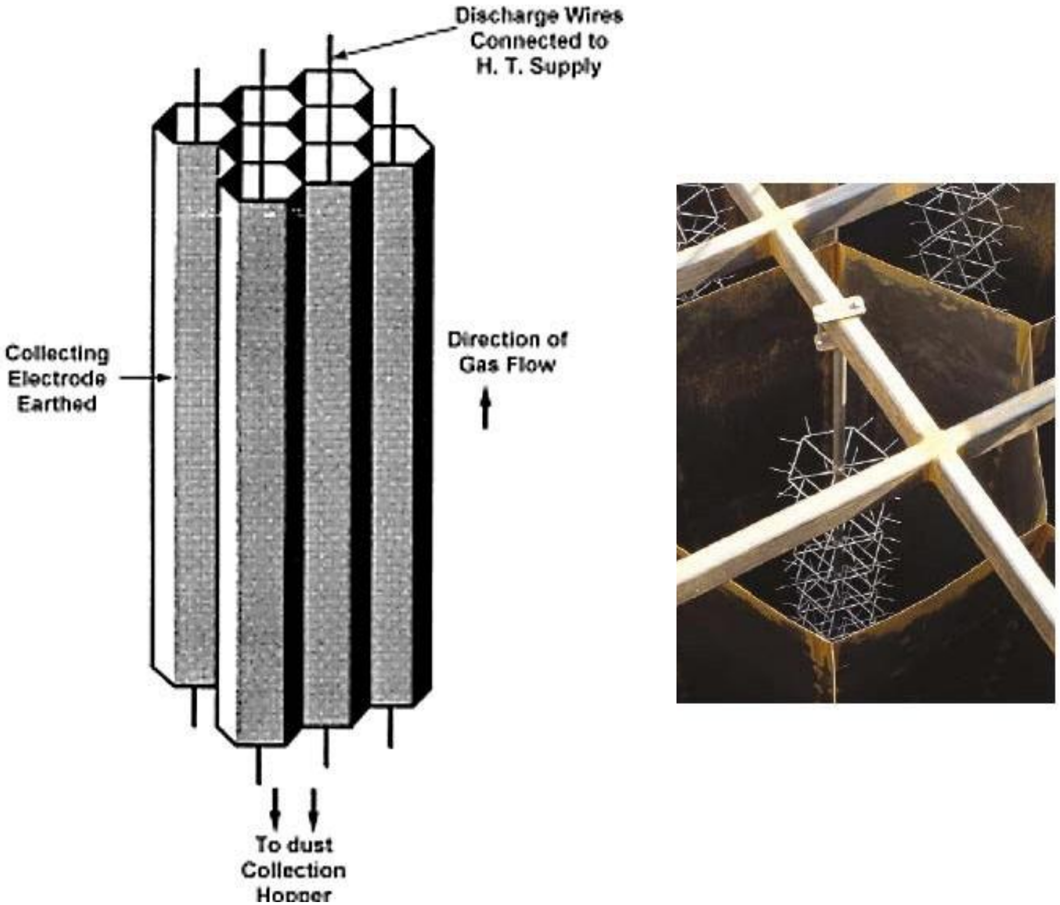


Design configuration: wet type precipitators

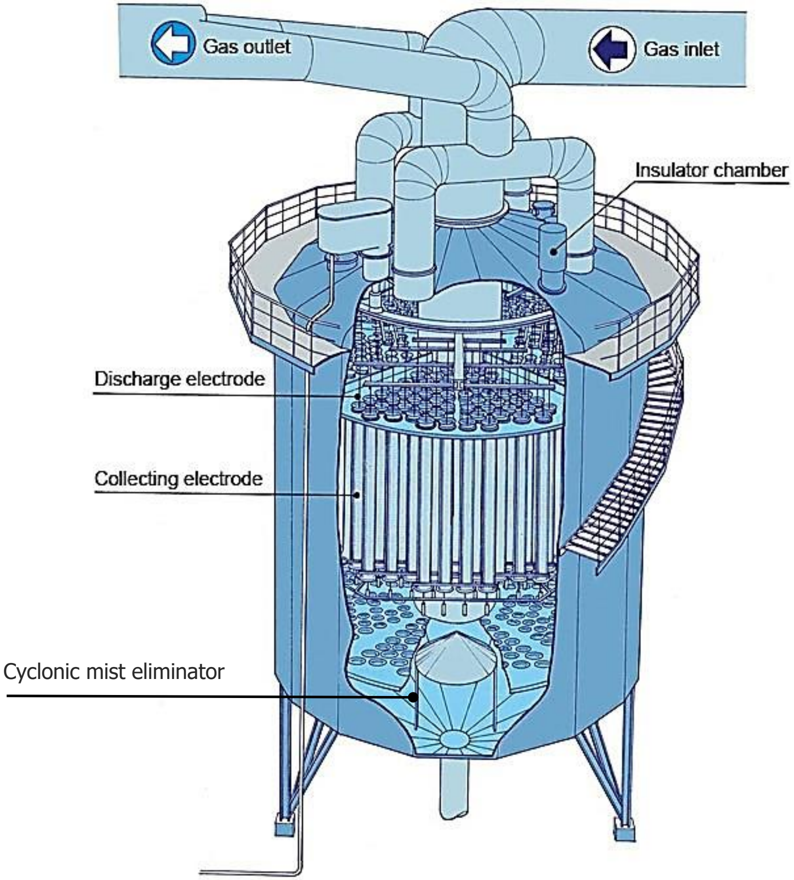


industrial applications
(mist removal)

Design configuration: tubular precipitators



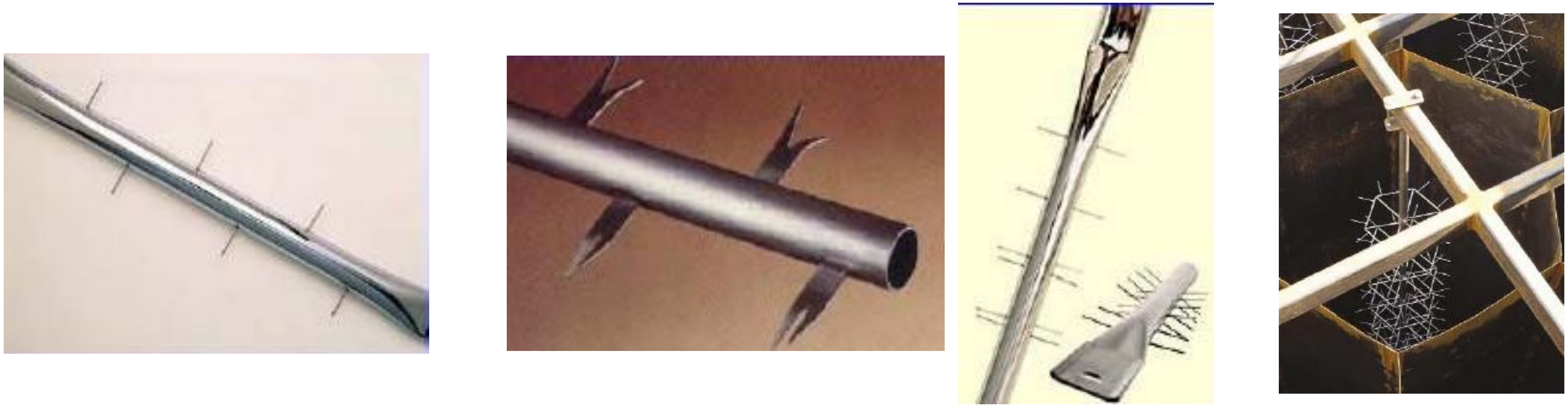
Dry type



Wet type

Design configuration: electrodes

- Discharge: wires with different shapes: circular or squared cross section, spiral ring, with or without pins of various forms



- Collection: parallel rectangular plates (most common) or tubular plates with cylindrical or polygonal cross section
- Industrial applications general design: discharge electrodes connected to negative polarity of power supply, collection plates grounded
  - maximum voltage and electric field intensity with stable operation and reduced sparking phenomena

Design configuration: voltage supply and dust removal system

Voltage supply

- transformer/rectifier set (TR) for providing, from grid Alternating Current (AC) supply, pulsating Direct Current (DC) at high voltage required for correct operation (30 – 100kV)
  - higher voltage and current attainable with Direct Current pulsating waveforms with respect to pure Dirrect Current
- sectionalization: whole device subdivided into discrete sections (fields), each being energized separately by single TR sets and independently controlled
  - number of fields ranging between 1 and 8, with higher values for high quality design configurations

Dust removal system

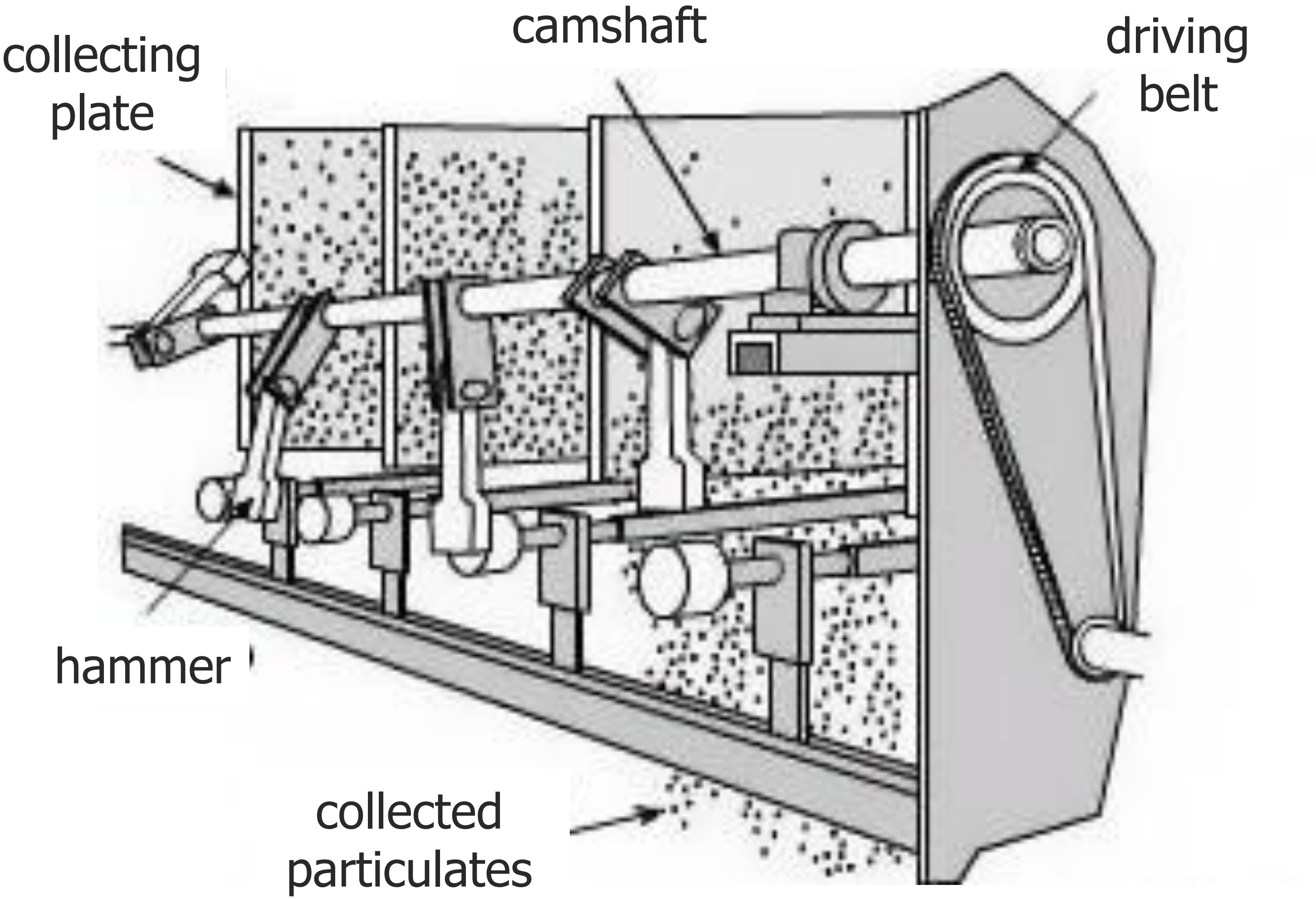
- Dry systems: most generally adopted
  - percussion of collecting electrodes with swinging hammers actuated mechanically or drop hammers actuated electromagnetically
  - vibration of electrodes with mechanically, pneumatically or electromagnetically actuated systems (typical for discharge electrodes cleaning)
- Wet systems
  - dust removal with thin films of water flowing down collecting surface (plate type) or water sprays located above tubes (tubular type)

Design configuration: dust removal system («rapping»)

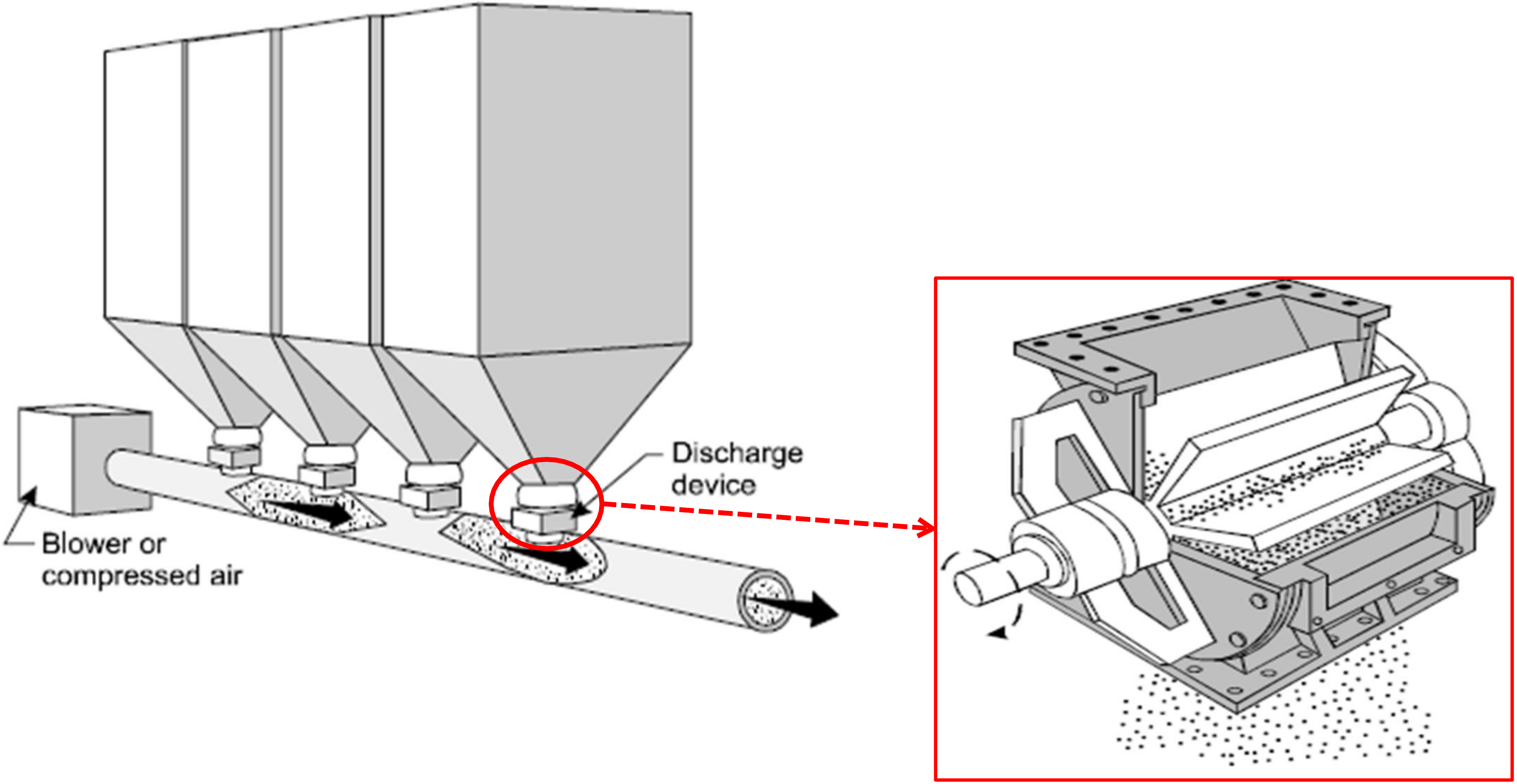
Electrode rapping

Collecting plate rapping

Design configuration: dust removal system («rapping»)

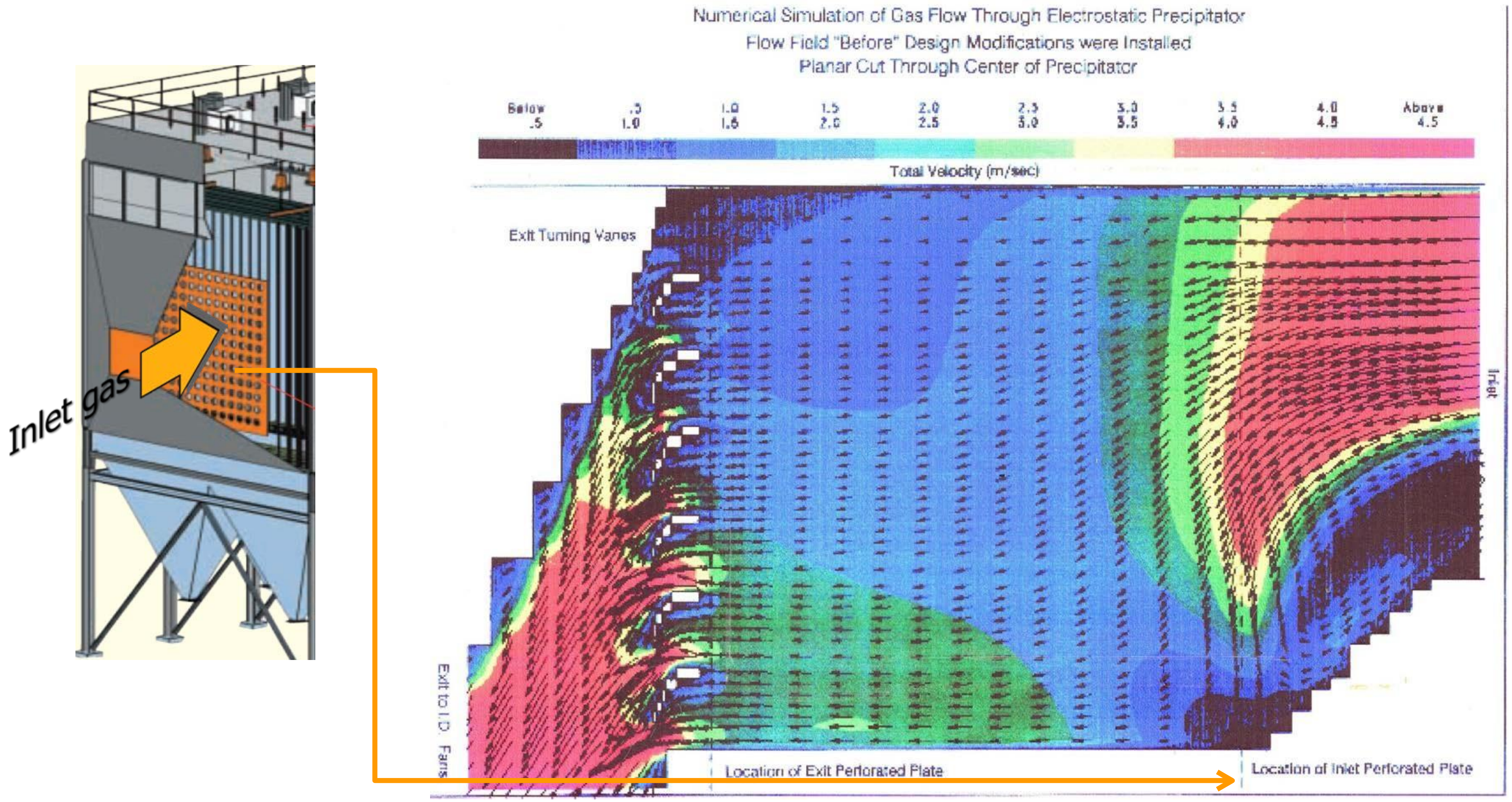


Design configuration: Hoopers



Design configuration: Inlet gas distribution

Perforated plates for uniform inlet/outlet gas flows



Design configuration: Plate sizing

- The plates in an ESP are typically taller (H) than they are long (Lp) and are placed in parallel and grouped in sections
- Sections in the direction of gas flow are called **mechanical fields** and each mechanical field can be subdivised into several **bus sections**.
- A bus section is the smallest number of plates energized by one transformer-rectifier set

- Consider one mechanical field of n plates in parallel across the entire width of the ESP. The gas flows through the «ducts» (space between the plates), so the n-2 interior plates all have both sides collecting dusts (active), while the two exterior plates each only utilized one side. Thus there are n-1 active plates in this mechanical field.

$$\mathbf{A=A_p\,(n-1)\,N_s=A_p\,(N-N_s)}$$

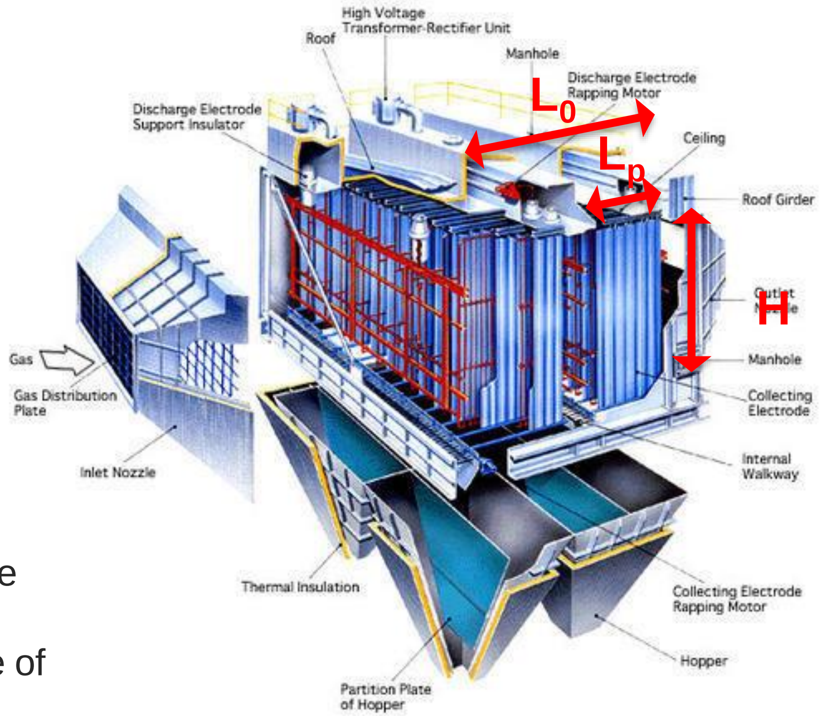
Where:

A_p= two-sided plate area (=2HLp)

n = number of plates <u>in parallel across </u>the width of the ESP

Ns= number of sections in the direction of flow (range of values: 2-6)

N= total number of plates in the ESP

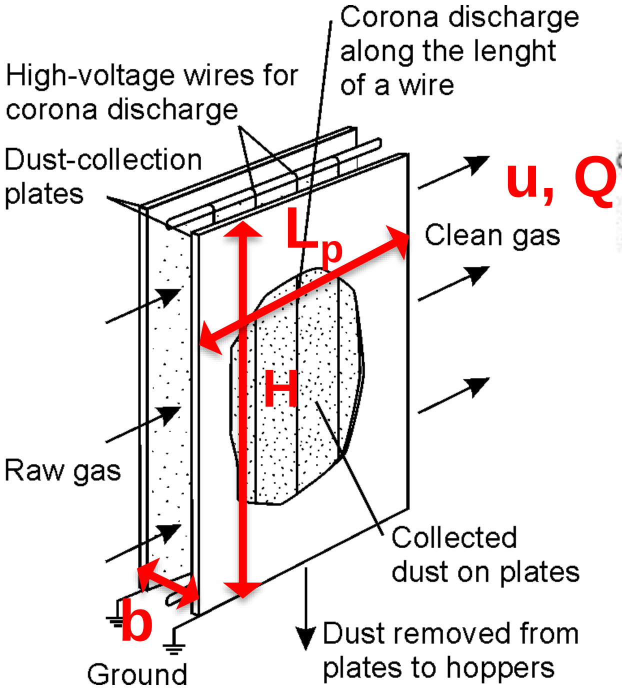


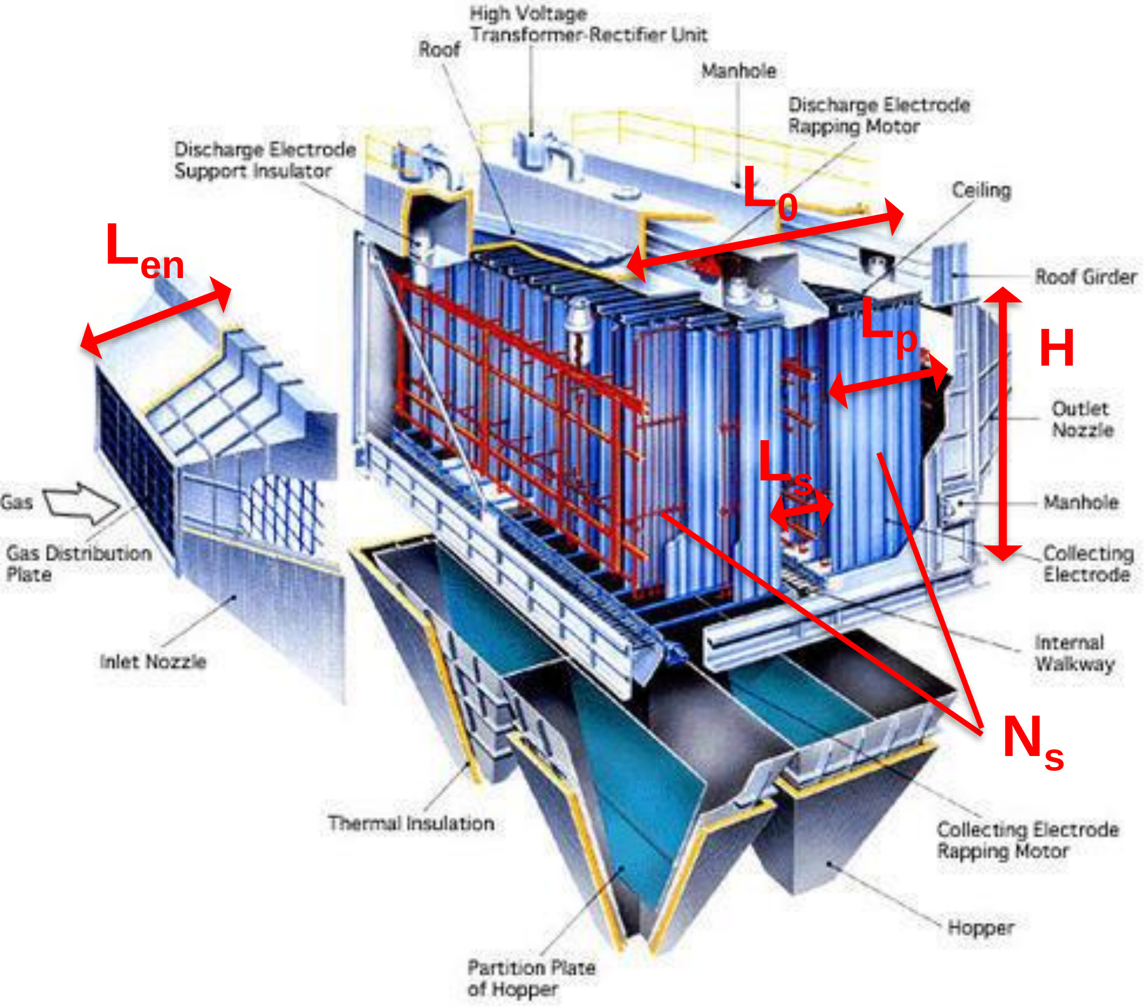
Example of two sections

Design configuration: Plate sizing

Determination of:

- A= total collection area
- N_d= number of ducts
- L_0= overall lenght
- Aa= actual collection area





Example of two sections

Design configuration: Internal configuration

- ☐ The overall width of ESP is virtually equal to the number of ducts for gas flow times the duct (channel width), increased by a little extra for width of the plates themselves and for the gaps between the outside plates and the walls

  N_d=Q/(u*b*H)
  Where:
  N_d= number of ducts
  Q= total volumetric gas flow rate m^3/min
  u= linear gas velocity in the ESP, m/min (range of values: 70-150 m/min)
  b= channel width (plate separation), m (0.15 – 0.40 m)
  H = plate height, m (range of values: 6-12 m)

- ☐ The overall lenght (L_0) of ESP is given by:

  $L_0=N_sL_p+(N_s-1)L_s+L_{en}+L_{ex}$
  Where:
  N_s= number of sections or mechanical fields
  L_p= plate lenght, m (range of values: 1-4 m)
  L_s= spacing between electrical sections, m (range of values: 0.5-1 m)
  L_{en}= entrance section lenght, m
  L_{ex}= exit section lenght, m

Design configuration: Internal configuration

- When the numbers of ducts and sections have been specified, the actual collection area (A_a) can be calculated as:

  $\mathbf{A_a=2*H*L_p*N_s*N_d}$

  Where:

  H = plate height, m (range of values: 6-12 m)

  L_p= plate lenght, m (range of values: 1-4 m)

  N_s= number of sections or mechanical fields

  N_d= number of ducts

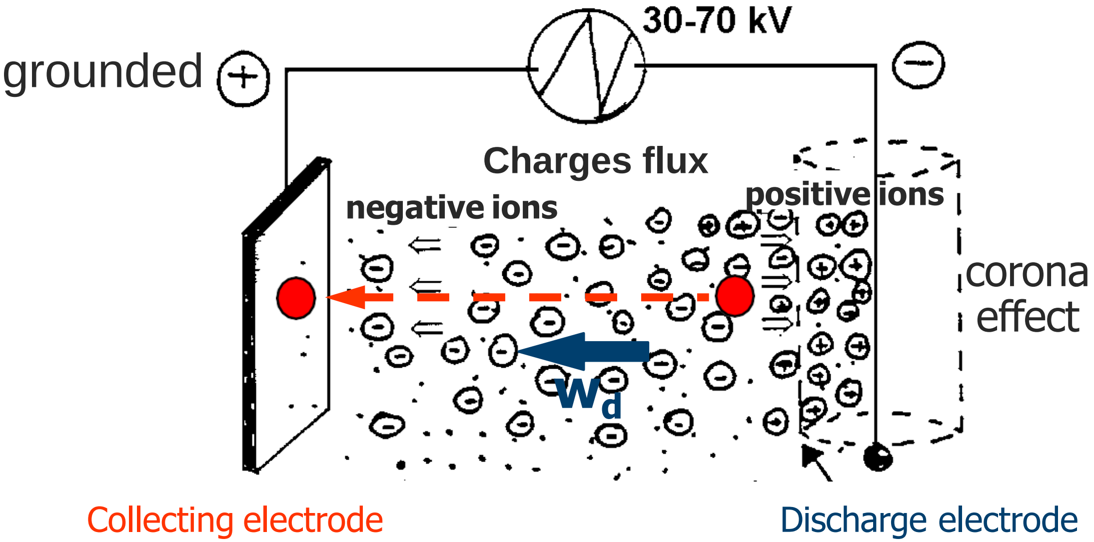
During the design process, several plate sizes and numbers of ducts are tried until one combination is found such that A_a is equal to (or slightly greater than) the required collection area A.

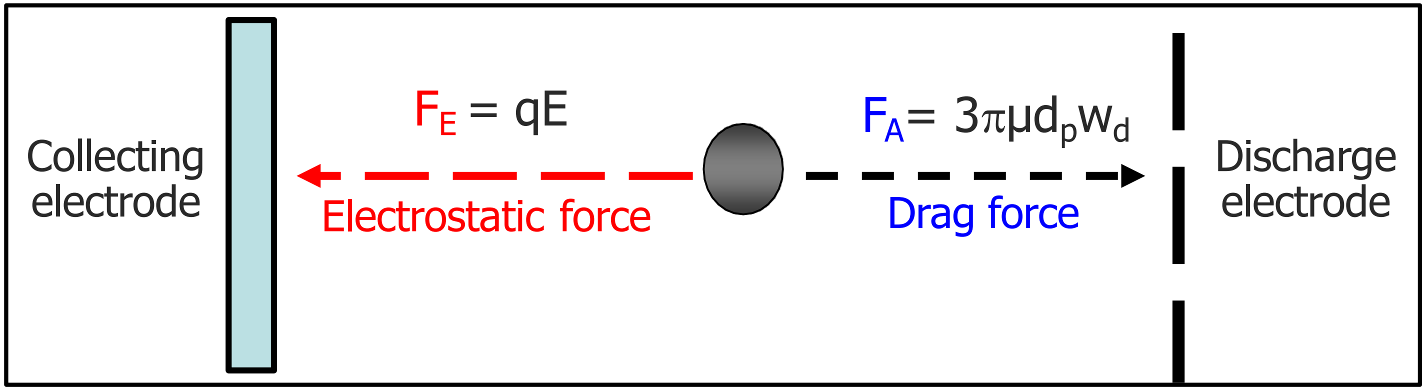
Design configuration: Housing frame

- Rectangular cross section box with hoppers in the lower part and inlet distribution plates at inward and outward upper sections
- Walls generally **insulated for preventing moisture condensation and corrosions**
- Ancillary equipment for proper electrodes alignment

Operating principles: particles motion

Particles motion: migration (drift) velocity w_d





Operating principles: particles motion

- Particles charge q (in Coulombs) → field charging (ions captured by particles through collisions)

$$q = 3\pi d_p^2 K_0 E_c D/(D+2)$$

With:
E_c = charging field strength (V/m) (Field strength at the time of charging)
K_0 = dielectric constant of free space (vacuum)[$8.85\cdot10^{-12}$ C(V·m)]
D = dielectric constant for the particle relative to free space

- External force = electrostatic force

$$F_E = q\,E$$

E = collecting field strength (V/m);

Operating principles: particles motion

Momentum balance

Stoke's law

$$m_p \cdot dw_d/dt = \Sigma_i F_i = qE - 3\pi\mu d_p w_d$$

Steady state: $dw_d/dt = 0$ → time for charging << residence time in precipitator (very good approximation)

$$w_d = qE/(3\pi d_p \mu)$$

Introducing q and rewriting for w_d:

$$w_d = \frac{K_0 E^2 d_p}{\mu} \frac{D}{(D+2)}$$

where $E \approx E_c$ (good approx. for single stage configuration) is the applied voltage/electrodes distance

Operating principles: particles motion

- Particle velocity in approaching collecting surface

electrofilters: $$w_d = \frac{K_0 E^2 d_p}{\mu} \frac{D}{(D+2)}$$

cyclones: $$v_t = d_p^2 \rho_p v_c / 18\mu r$$

- smoothed decrease of collection velocity with **particles diameter**, with greater efficiencies for finer particles
- migration velocity not dependent on flue gas velocity: no need to increase gas velocity for enhancing particle collection velocity, thus decreasing gas residence time → ESP large enough to obtain adequate residence time without affecting w_d

- Electric field strength E: higher E, higher drift
  - high E, increase in sparking frequency
    - cake disruption (particle reentrainment)
    - damage to transformers
  - low E
    - no sparks
    - removal efficiency too low
  - optimum values (50-100 sparks/minute) → pulsating DC supply + sectionalization

Operating principles: electric field strenght

Electric field strength E → pulsating DC supply

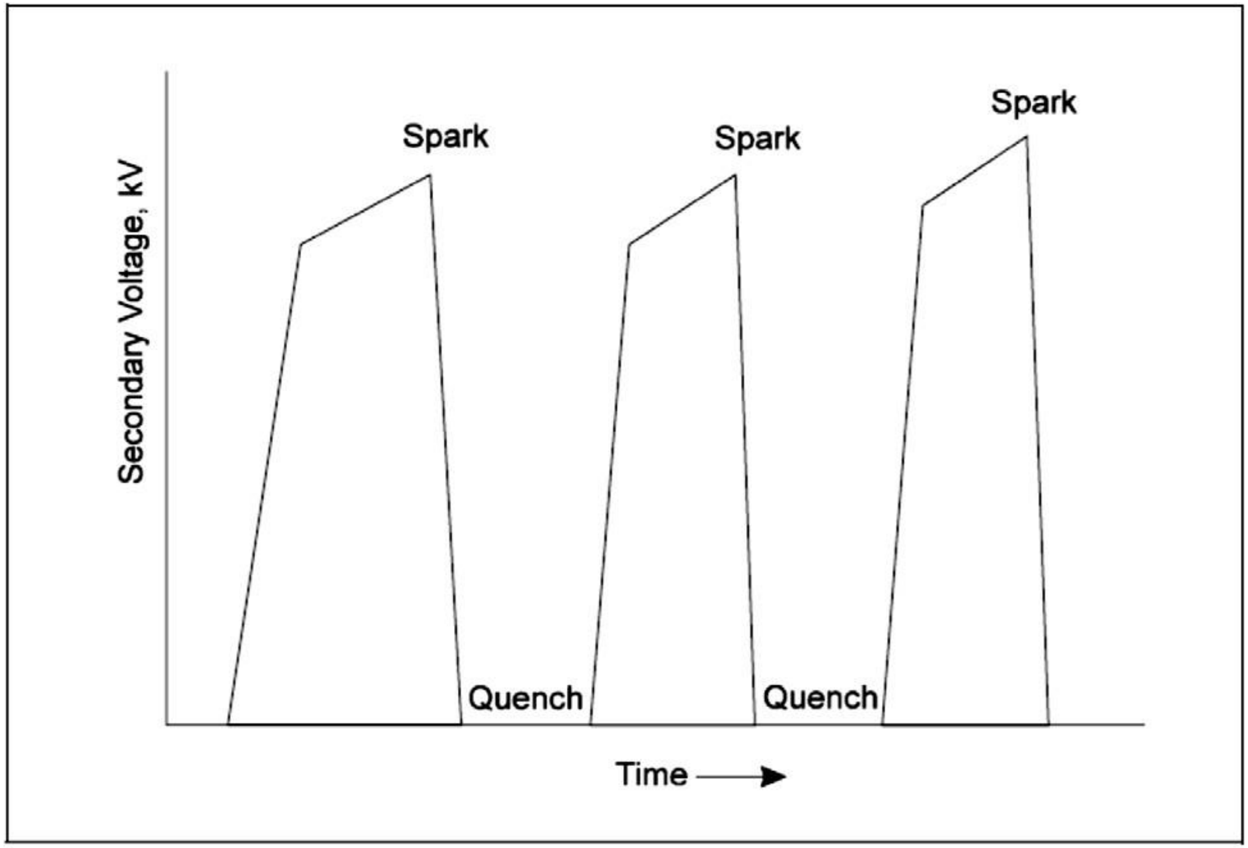


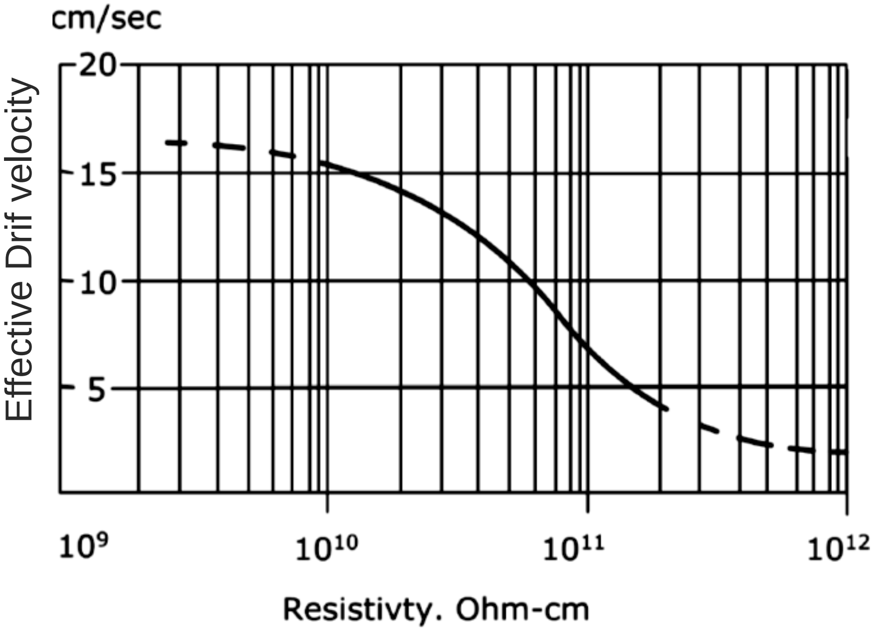
Figure 1-8. Spark generation profile

Operating principles: particle resistivity

- The resistivity of fly ash is a measure of its **resistance** to electrical conduction

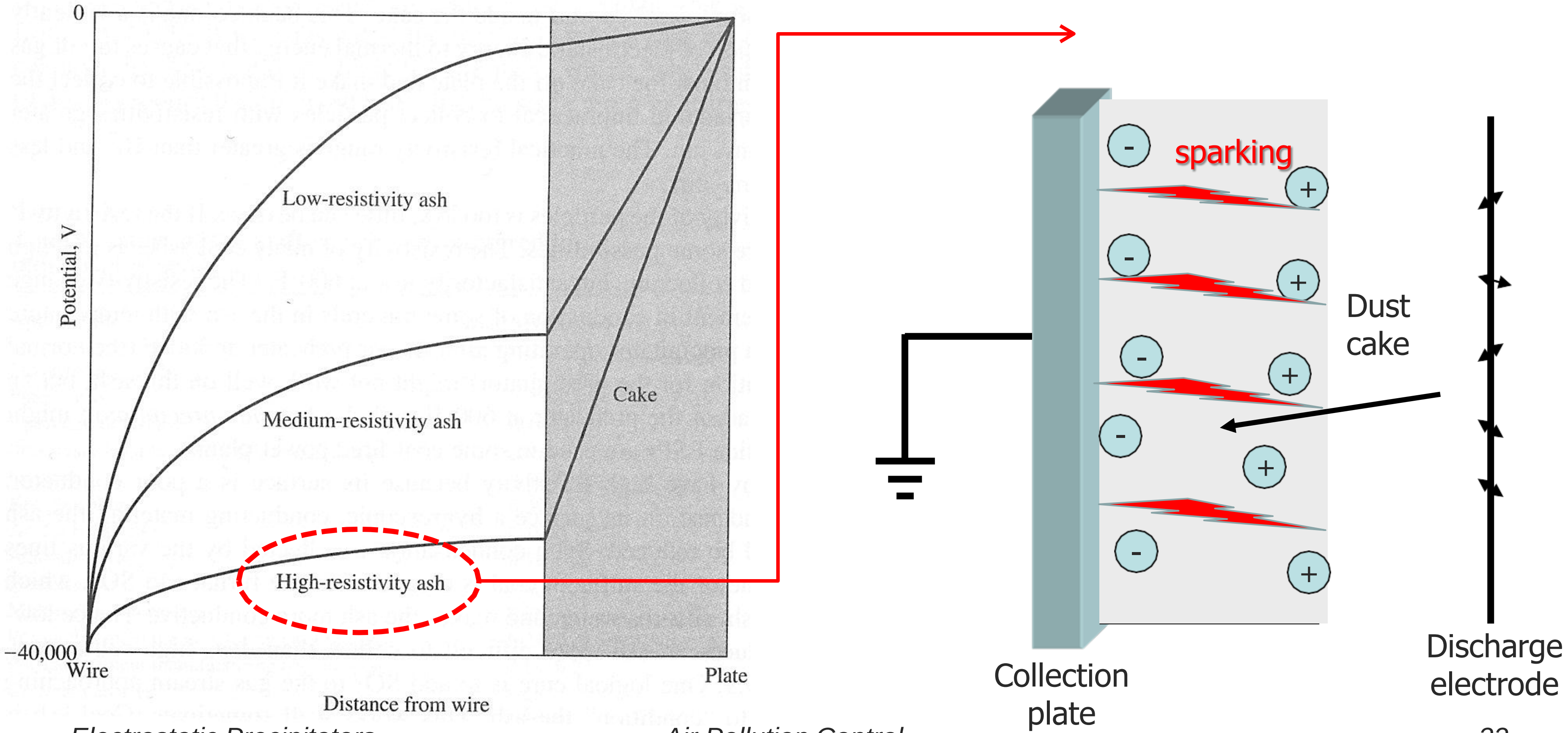
- Dust resistance to charge acquisition/loosing
  - low resistivity: easier charging/discharging
  - high resistivity: harder charging/discharging

- Range of values for optimal performance: 10^7 - 10^{10} ohm·cm
  - low resistivity particles (< 10^7 ohm·cm): separated dust at collecting electrode easily removed as single particle or few particles agglomerates → reentrainment
  - high resistivity particles (> 10^{10} ohm·cm)
    - decrease in voltage drop between electrodes → difficult dust charging



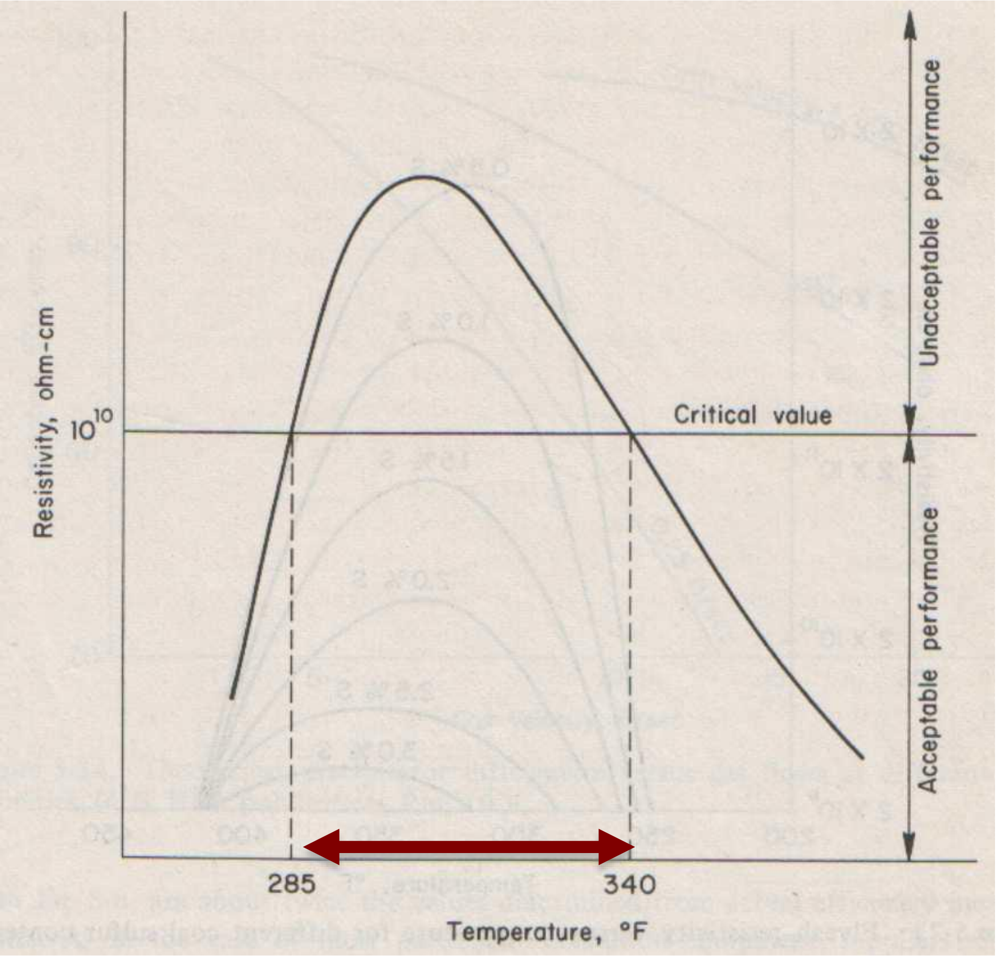
Operating principles: particle resistivity

- high resistivity particles, dust is a good insulator (> 10^{10} ohm·cm)
  - **increase** in voltage gradient **inside collected cake** → sparking inside dust cake (**back corona** effect) with **particles blow off**, **voltage supply perturbations** and particles' charge losses
  - **harder cake dislodging** from plate → increased rapping frequency, with rapid mechanical failure and/or plate misalignment



Operating principles: particle resistivity

Particulates resistivity Effect of temperature



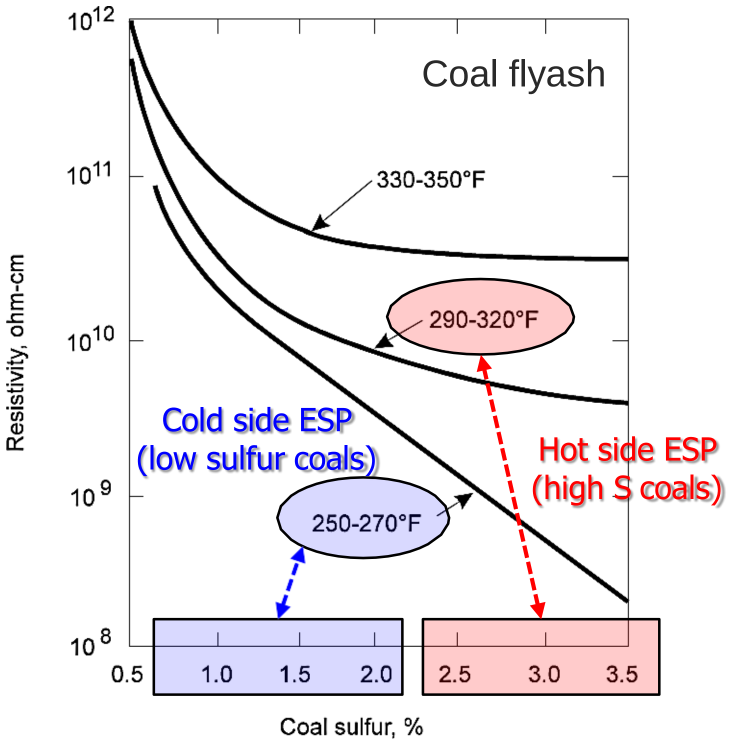
Resistivity varies with temperature, showing a maximum value at T=250-350°F.
(**120-170 °C**)

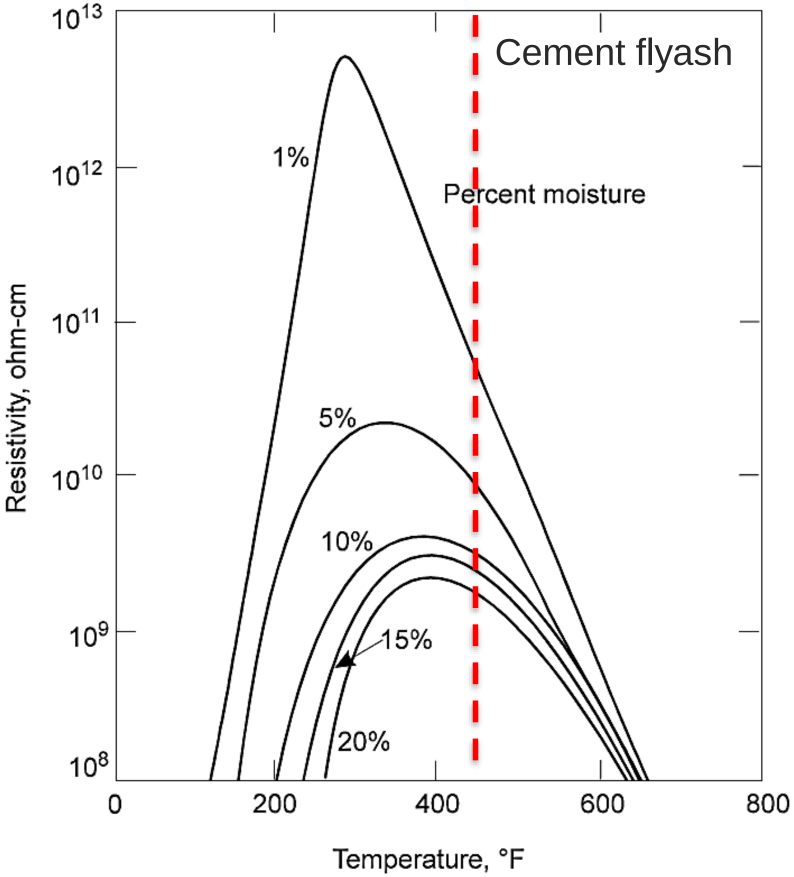
Unfortunately this is the temperature of flue gas from boilers. Lowering it increases **the risk of condensation** of sulfuric acid on cold surfaces, whilst increasing it above 350°F would result in heat loss out of the stack.

→Flue gas conditioning can be conveniently applied in these cases

Operating principles: particle resistivity

- Dependence with conductive characteristics of dust:
  - particles type and composition
  - flue gas moisture (higher conduction from water vapor adsorbed on particles)
  - flue gas temperature (higher surface retention of conductive compounds for lower T).
  - flue gas content of conductive compounds (f.i. SO_2)

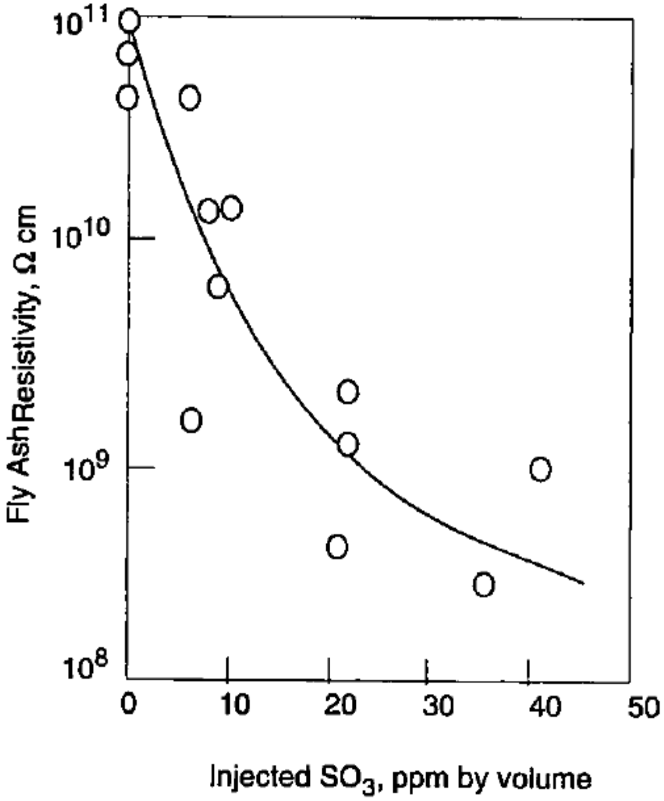




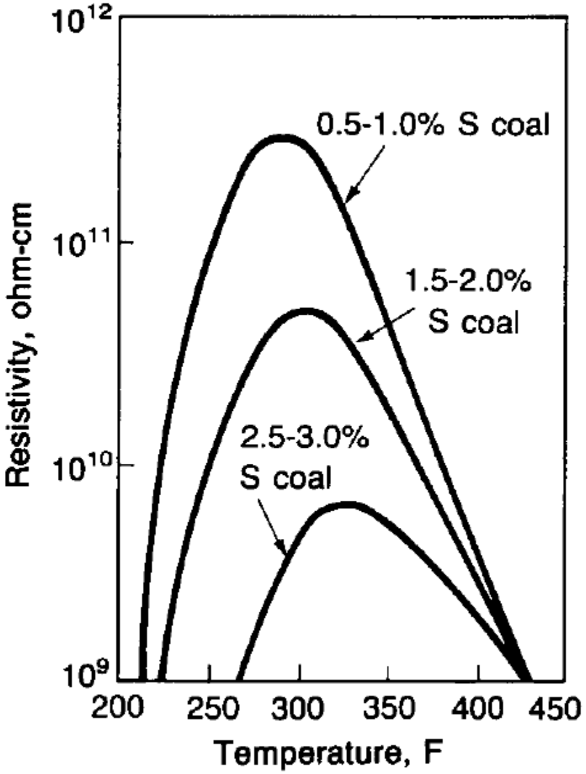
Operating principles: particle resistivity

Particulates resistivity: Effect of Flue gas conditioning

Use of SO_3



Resistivity of coal fly ash as a function of temperature and S content in coal

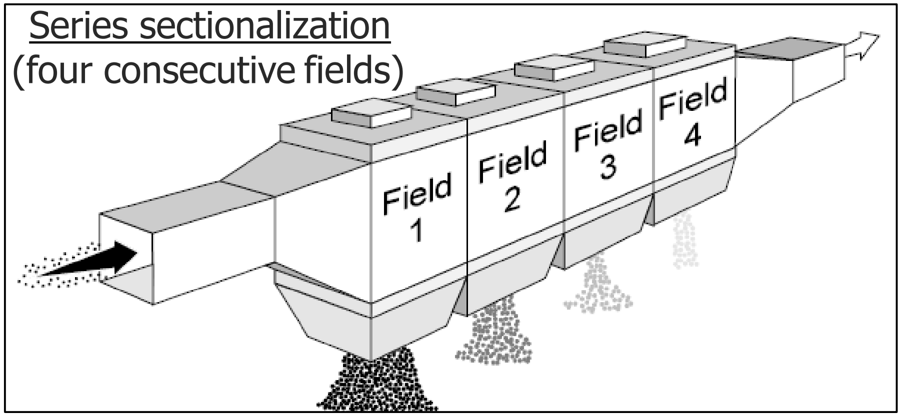


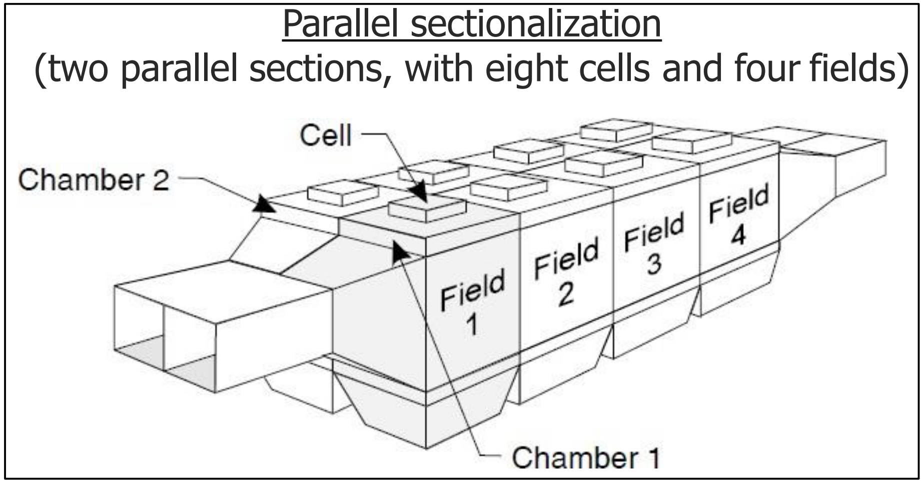
the electrical resistivity of the fly ash generally increases as the sulfur-to-ash content in the coal decreases, resulting in very low efficiency of ESPs

Operating principles: particle resistivity

- Potential interventions for high resistivity particles (most common situation of non optimal conditions)
  - gas conditioning for T and/or moisture correction
    - optimum T range: hot/cold side precipitators, cooling/heating requirements
    - moisture increases surface conduction, thus lowering resistivity
  - preliminary addition of chemical conditioners (SO_3, NH_3, proprietary mixtures)
  - apply separate stage design (sectionalization) + DC pulsating supply

    → optimization of sparking control systems

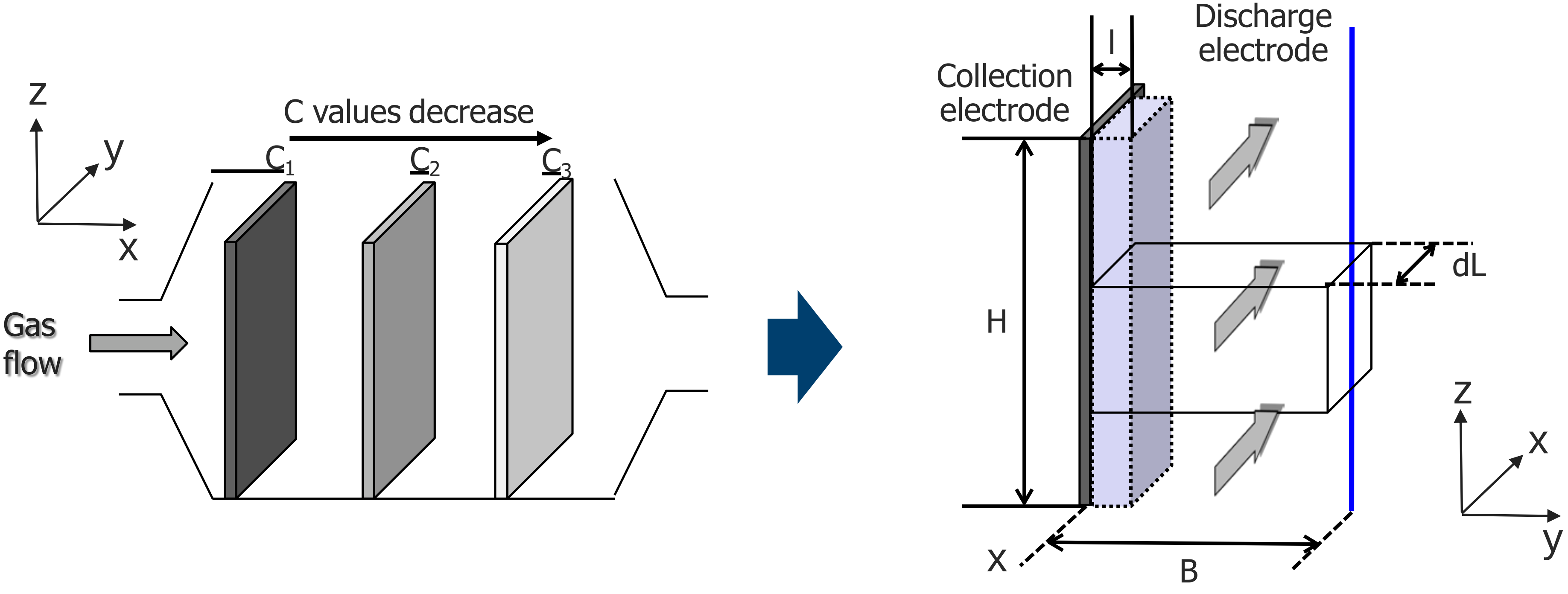

Series sectionalization
(four consecutive fields)


Parallel sectionalization
(two parallel sections, with eight cells and four fields)

Collection efficiency: lateral mixing model

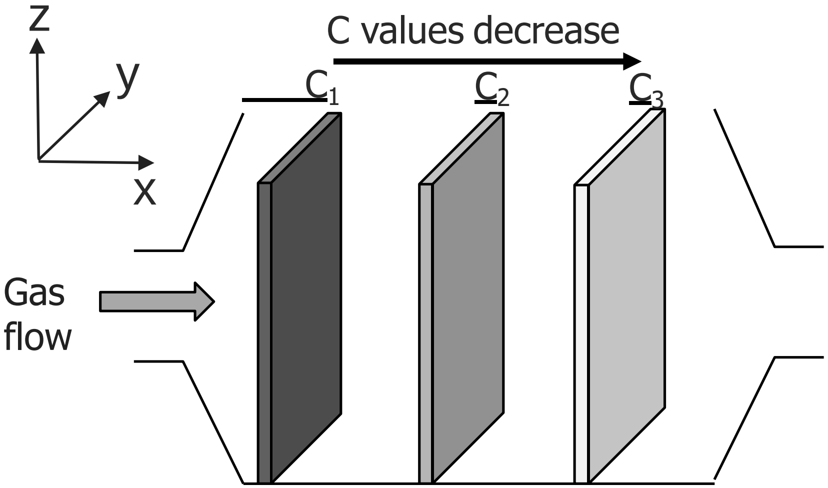
ASSUMPTIONS:

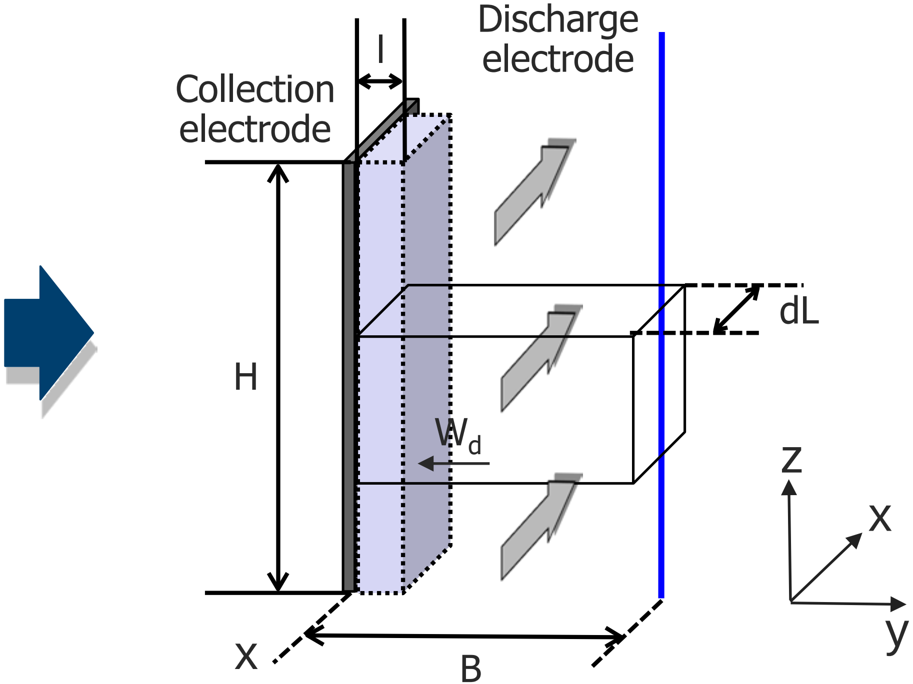
- Gases (and particles) move in the x direction at constant velocity «v», with no longitudinal mixing;
- The particles are uniformly distributed in the y and z direction at every x location
- The charging and collecting fields are constant and uniform; the particles quickly attain terminal velocity «w» in the y direction
- Re-entrainment of collected particles is negligible



Collection efficiency: lateral mixing model

Complete lateral mixing → uniform concentration of particulates in any cross section perpendicular to gas flow (C constant within plates)





In time interval dt:

- flue gas flow travels a distance dL along main direction;
- simultaneously, particles within a certain distance l from collection plate are removed
- within l, laminar flow (Stoke’s regime) conditions prevail, with particle velocity = w_d

Collection efficiency: lateral mixing model

Mass balance over dt

- total mass of particles present within dL over dt:

$m = C \cdot B \cdot H \cdot dL$

- mass M of particles removed over dt:

$M = C \cdot [B \cdot H \cdot dL - (B-l) \cdot H \cdot dL] = m_t - m_{t+dt} = -\,dm$

with $l = w_d dt$

Fraction of particles removed in time dt:

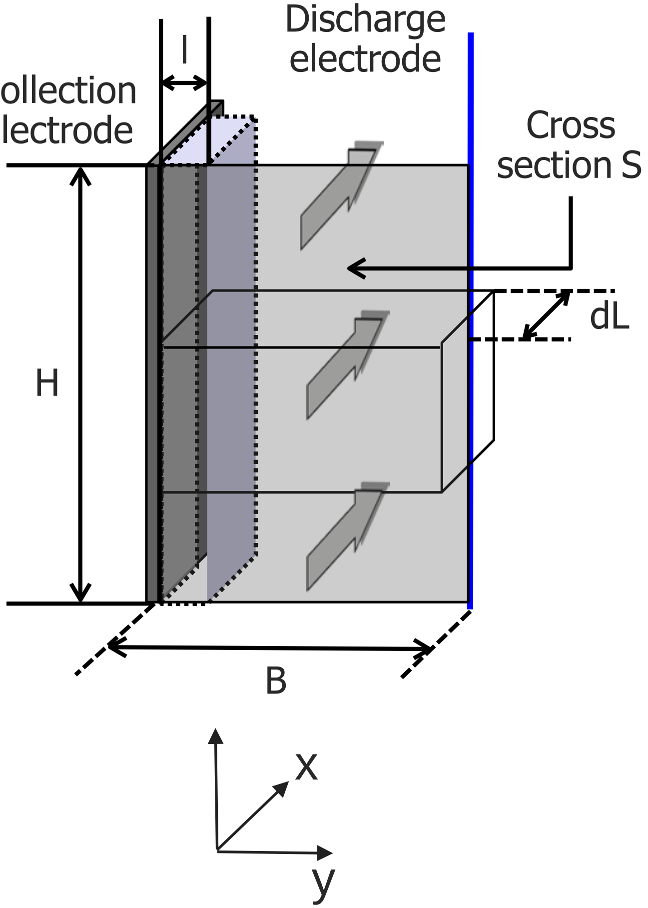
$$\frac{dm}{m} = -\frac{C \cdot l \cdot H \cdot dL}{C \cdot B \cdot H \cdot dL} = -\frac{l}{B}$$

Since $l = w_d dt$ and $dt = dL/v$, with v = flue gas velocity:

$$\frac{dm}{m} = -\frac{w_d dL}{v \cdot B} = -\frac{w_d dL}{Q} \cdot \frac{S}{B} = -\frac{w_d}{Q} \cdot dL \cdot H = -\frac{w_d}{Q} \cdot dA$$

where S = perpendicular cross section

dA = differential area of collecting plate



Collection efficiency: lateral mixing model

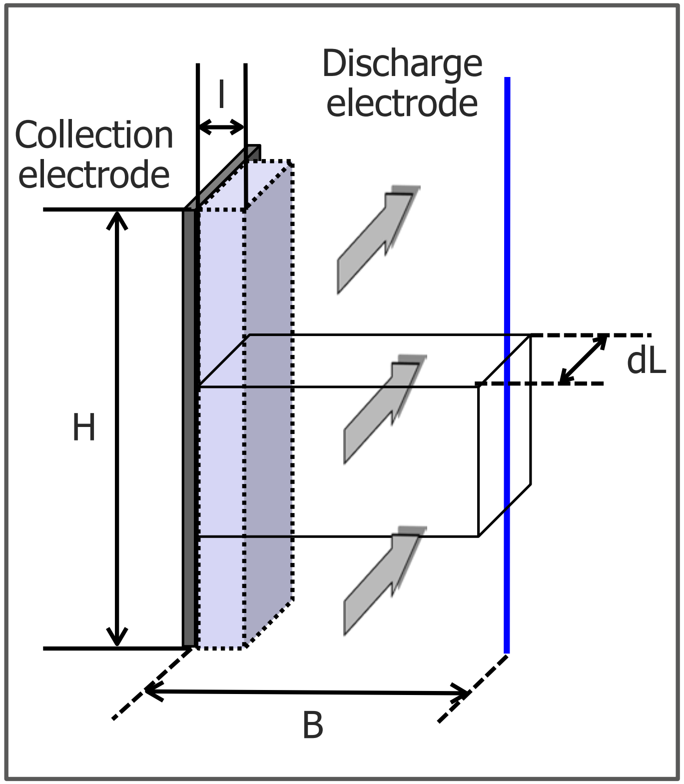
Mass balance over dt

- Integrating from inlet ($m=m_0$, $A=0$) to generic A:

$$\int_{m_0}^{m}\frac{dm}{m} = -\frac{w_d}{Q}\cdot\int_0^A dA \Rightarrow \frac{m}{m_0} = \exp\left(-\frac{w_d}{Q}\cdot A\right)$$

$$\text{Since } E(d_p) = \frac{m_0 - m}{m_0} = 1 - \frac{m}{m_0},$$

$$\boxed{E(d_p) = 1 - \exp - \left(\frac{w_d}{Q}\cdot A\right)}$$



Deutsch-Anderson Equation

Q = flue gas volume flow rate

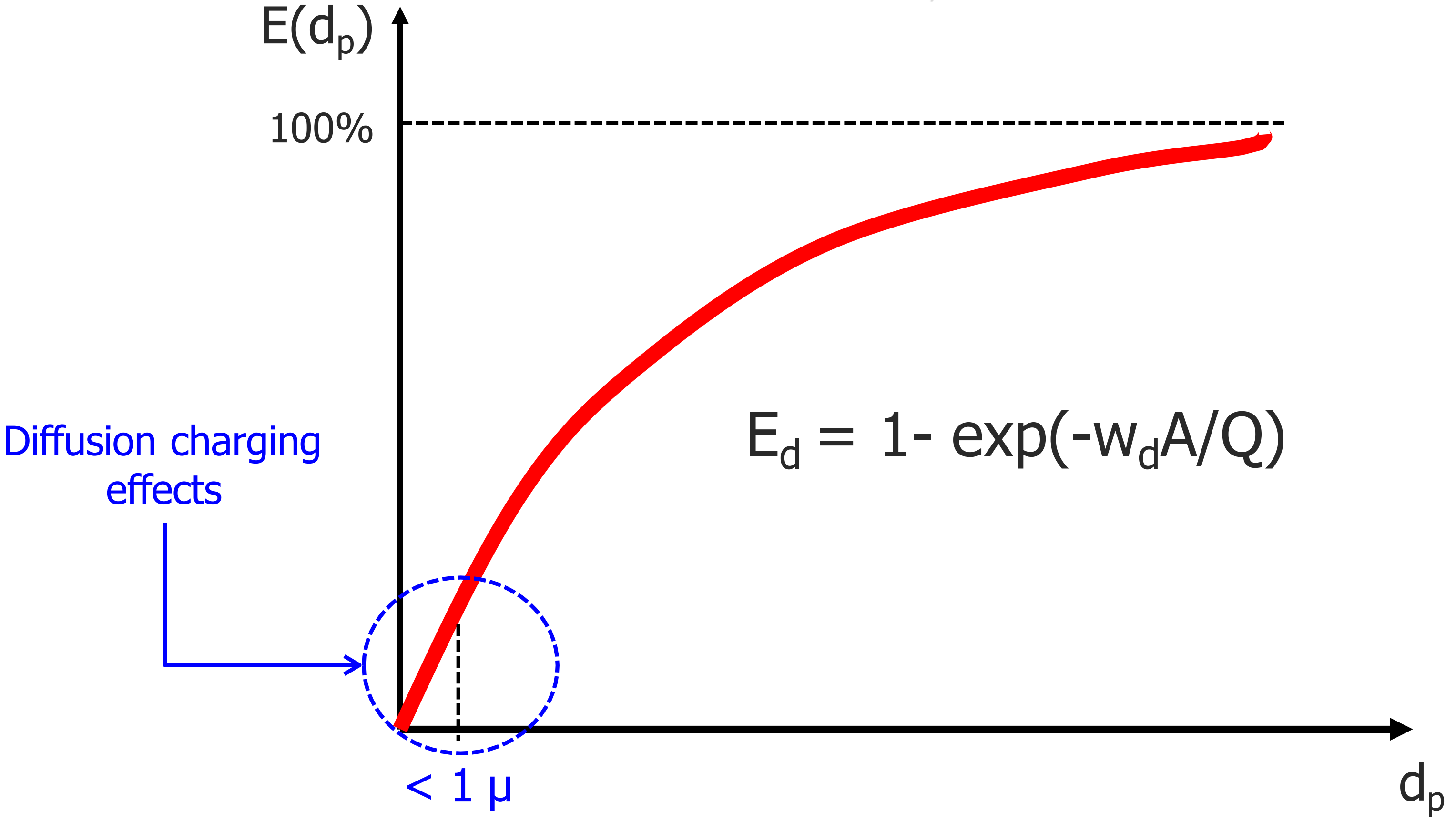
A = surface collecting area

w_d= migration velocity

Collection efficiency: lateral mixing model

Through substitution of w_d, the following dependence with d_p is worked out

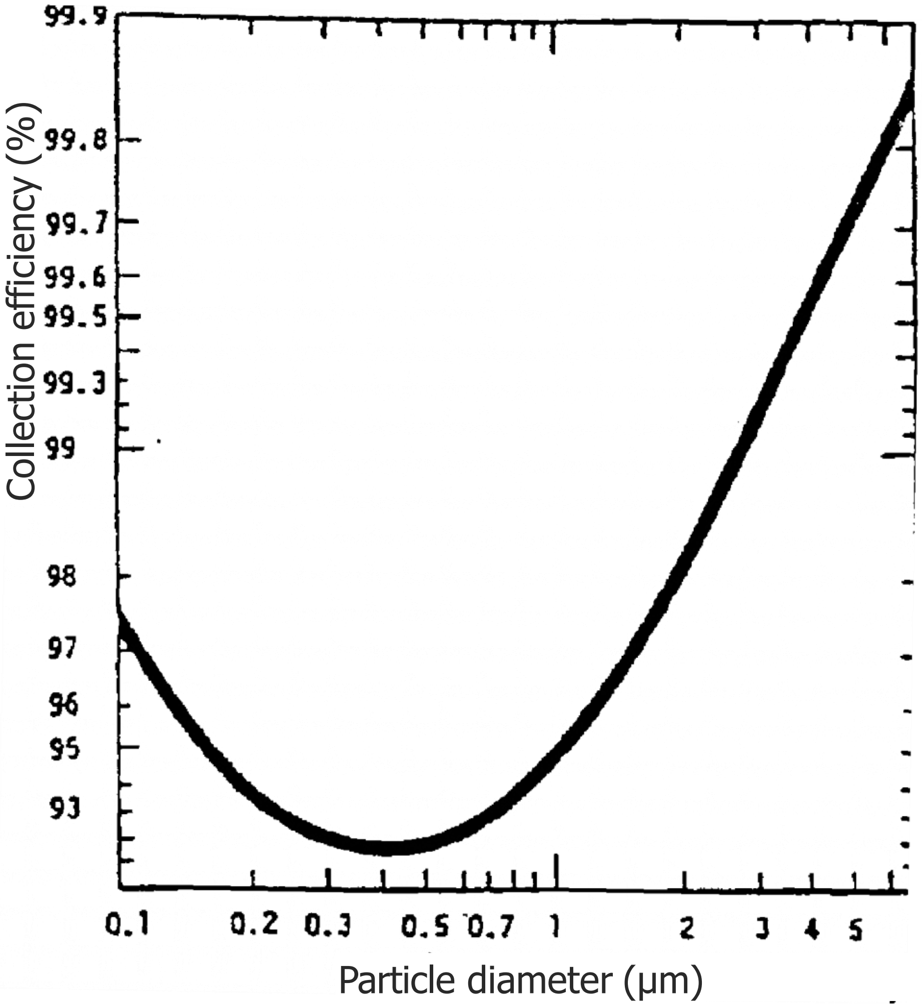
$$E(d_p) = 1 - \exp - \left(\frac{A}{Q} \cdot \frac{D}{D+2} \cdot \frac{K_0 E^2 d_p}{\mu} \right) \Rightarrow E(d_p) = 1 - \exp - \left(K \cdot d_p \right)$$



Collection efficiency

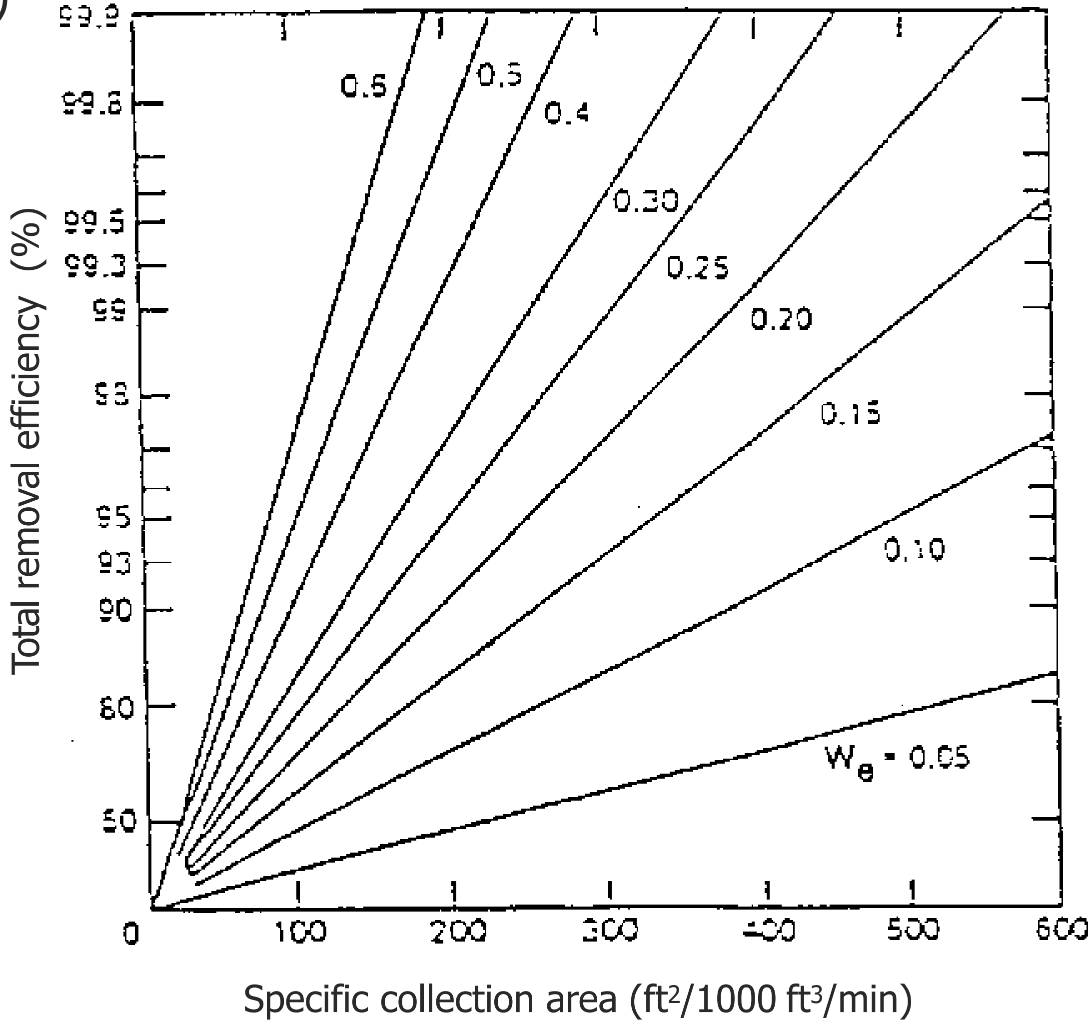
Diffusion charging: active for finer particles (less than ≈ 0.3-0.5 µm)

- brownian motions enhance charging, increasing particle collection efficiencies in sub micrometer size range



Collection efficiency: total collection efficiency (E_T)

$$E_T = \int_0^\infty \left[1 - \exp - \left(K \cdot d_p\right)\right] \cdot f(d_p) \cdot d(d_p)$$



Collection efficiency: total collection efficiency (E_T)

- Factors not considered (approximations of collection efficiency)
  - variability of temperature, concentrations, size distributions, particle charge and applied voltage along flue gas pathway;
  - non uniform flue gas velocity distributions in cross sections perpendicular to gas flow;
  - by-pass of collection zones, due to gas sneakage through hoppers and/or insulation space;
  - re-entrainment of collected particles

- Design approach alternatives
  1. numerical design codes: device length splitted in small sectors, where all parameters might be assumed to be constant
  2. adoption of correction coefficients to idealized collection efficiency model
  3. pilot plant experimental tests for deriving practical ranges of main design parameters

Collection efficiency - Empirical practical range of parameters

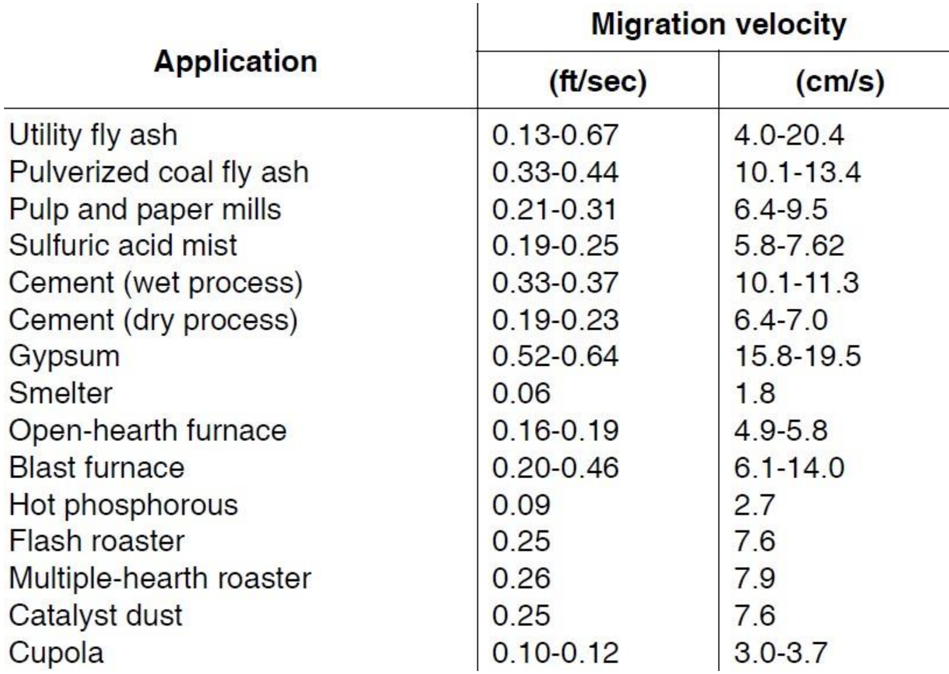
- Evaluation of **effective drift velocity** w_e for the whole particulates from pilot and/or full scale plants measurements of total collection efficiency E_T:

$$E_T = 1 - \exp(-w_e A/Q)$$

⬇

$$w_e = -\ln(1-E_T)\cdot Q/A$$

- Representative of the effective drift velocity of particles as a whole, including all the effects arising from deviations from ideal behavior and from size distribution type
  - “know-how” of commercial companies



Application	Migration velocity	
	(ft/sec)	(cm/s)
Utility fly ash	0.13-0.67	4.0-20.4
Pulverized coal fly ash	0.33-0.44	10.1-13.4
Pulp and paper mills	0.21-0.31	6.4-9.5
Sulfuric acid mist	0.19-0.25	5.8-7.62
Cement (wet process)	0.33-0.37	10.1-11.3
Cement (dry process)	0.19-0.23	6.4-7.0
Gypsum	0.52-0.64	15.8-19.5
Smelter	0.06	1.8
Open-hearth furnace	0.16-0.19	4.9-5.8
Blast furnace	0.20-0.46	6.1-14.0
Hot phosphorous	0.09	2.7
Flash roaster	0.25	7.6
Multiple-hearth roaster	0.26	7.9
Catalyst dust	0.25	7.6
Cupola	0.10-0.12	3.0-3.7

Empirical correction to ideal model

- Gas sneakage and dust re-entrainment

$$E_{eff}=1-[R+S+(1-S-R)(1-E_T)^{1/N}]^N \qquad \text{[Gooch-Francis]}$$

where

S = fractional amount of gas sneakage (-). With this term it is mean the situation where gases carrying dust bypass the active electrode system of an electrostatic precipitator

R = fractional amount of dust re-entrainment (-)

N = number of sections

E_T= total design collection efficiency

S, R = experimental evaluation from pilot and/or full scale plants

Example: 5% sneakage and 1% re-entrainment in a device with 4 sections and E_T = 99%

$$E_{eff}=1-[R+S+(1-S-R)(1-E_T)^{1/N}]^N=$$
$$=1-[0.01+0.05+(1-0.01-0.05)(1-0.99)^{1/4}]^4=$$
$$=0.984=98.4\%$$

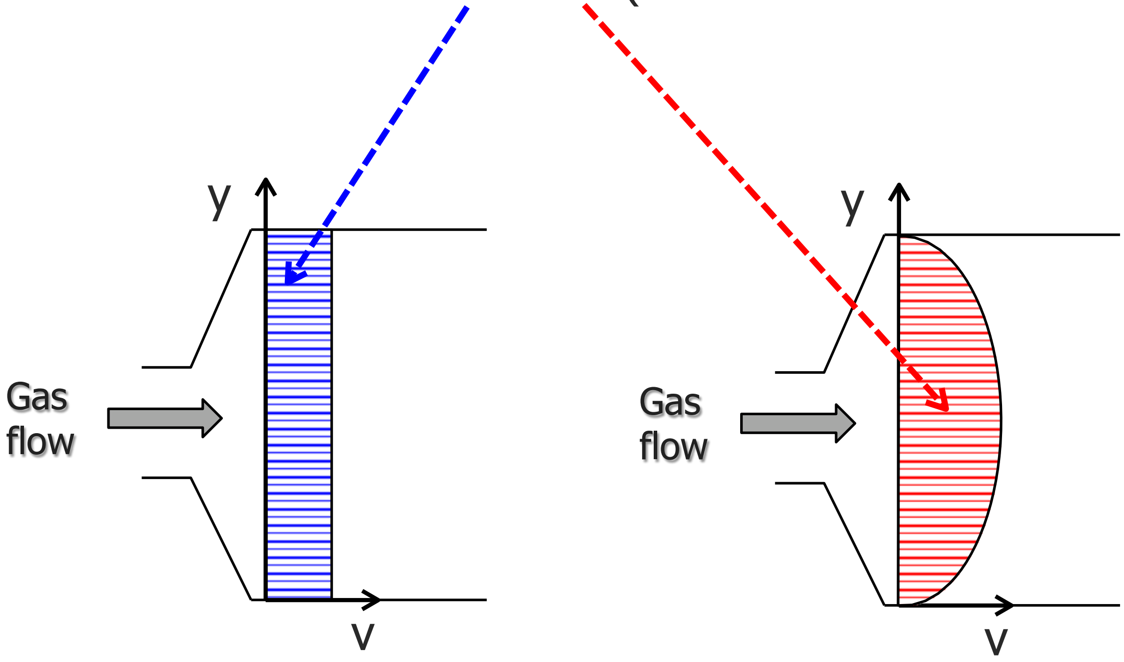
corresponding to an efficiency loss of 0.6% in absolute terms

Empirical correction to ideal model

- Non uniform gas velocity distributions
  - correction of drift velocity from Anderson Deutsch equation with an empirical quality factor F, depending on uniformity of flue gas velocity in cross section, to give an effective velocity w_{ef}

$$w_{ef} = -\ln(1-E_T)\cdot Q/(A\cdot F)$$

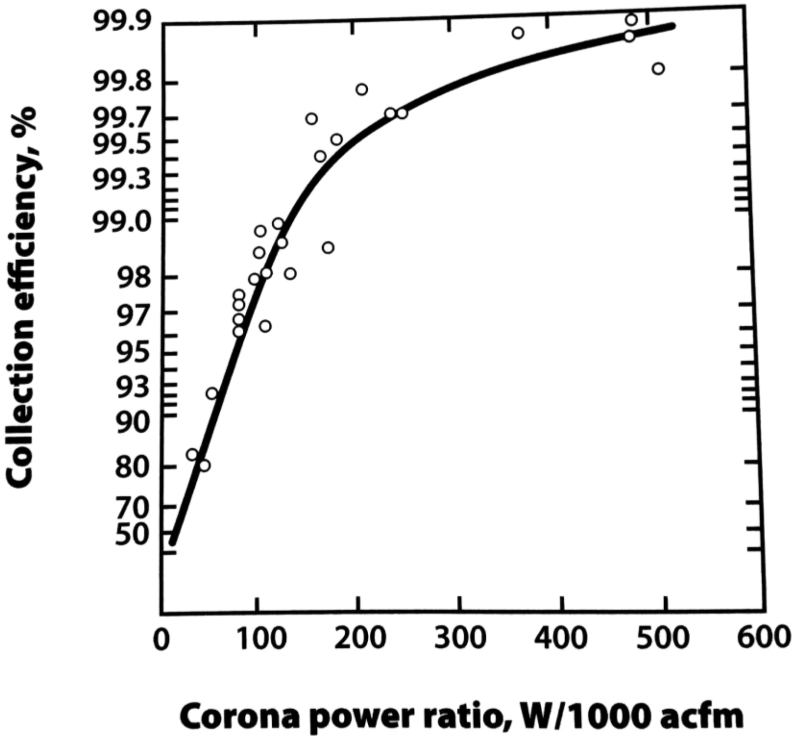
with F = 1.1 – 2 (uniform → non uniform)



Power consumption

There are two sources for operating power consumption in an ESP:

- **Pressure drop**. Even though the gas pressure is low (typically less than **2 cm of water**), the gas volume flow is high. Therefore, we must also consider the cost of fan power needed to pull the air through an ESP.
- **Corona power.** Even thugh voltages in ESPs are very high, the current flow due to gas ion migration is low, so the power consumption is not unreasonably high.



Actual cubic feet per minute (ACFM)

General field of applications

- Large utilization in metallurgical industry, cement kilns, coal and fuel oil fired power plants, petroleum refineries, waste incineration, paper industry, building materials manufacturing and non ferrous metal industry.
- Principal flue gas and particle effects on full scale applicability
  - particle size distribution: charging and separation;
  - particle resistivity: charging;
  - flue gas moisture and temperature: particles resistivity
- General performance and operating parameters

Parameter	Typical range
Gas volumetric flow rate (m^3/h)	$3·10^3 – 2.5·10^6$
Gas temperature (°C)	up to 1100
Inlet particulate concentration (g/m^3)	0.25 - 30
Particles resistivity (ohm·cm)	$10^3 - 10^{10}$
Pressure loss (kPa)	0.06 – 0.5
Flue gas velocity (m/sec)	0.5 - 3
Specific collection area [m^2/(m^3/h)]	0.02 – 0.5
Operating voltage (kV)	20 - 120
Energy consumption (kWh/1000 m^3)	0.1 - 3

Example: designing of electrostatic precipitator (1)

A ESP has to treat 20,000 m^3/min of air. The effective drif velocity has been estimated equal to 6.5 m/min (typical range = 1-10 m/min). The total efficiency is 99%.

A) Calculate the total collection area

B) Assuming the plates are 8 m high and 3 m long and that there are three sections in the direction of flow, calculate the number of plates required

C) Estimate the number of ducts (Nd) assuming a velocity of flue gas of 100 m/min and a channel width of 0.25 m

Example: designing of electrostatic precipitator (2)

1) Estimation of total collection area

$E_T = \quad 1 - \exp(- w_e A/Q)$

$A = - \ln(1-E_T)\cdot Q/w_e \approx 14{,}100$ mq

2) Estimation of the number of plates

$A=A_p\ (N-N_s)$ therefore $N= 300$ plates

3) Number of ducts

Nd=Q/(u*b*H) =100

REMEMBER WE HAVE TO VERIFY THE COLLECTION AREA DERIVED FROM GEOMETRY CONSIDERATIONS

Aa=2*H*Lp*Ns*Nd=14.400 mq…… it is verified!!