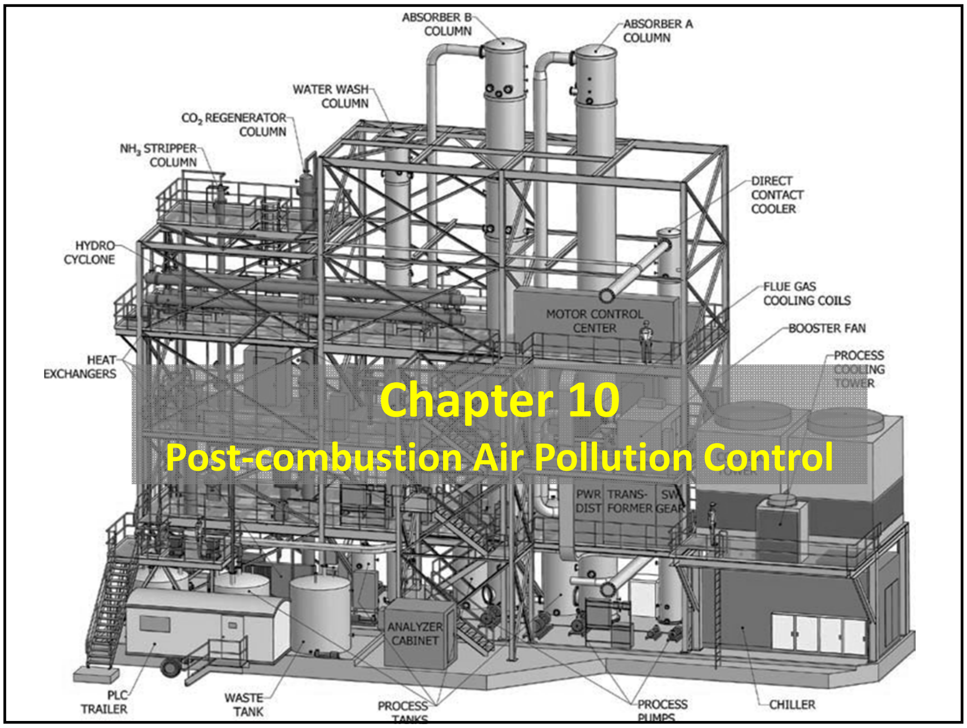
Chapter 10
Post-combustion Air Pollution Control



Introduction

- **Flue gas** is the gas exiting to the atmosphere via a flue, which is a pipe or channel for conveying exhaust gases from a combustion system
- More often, flue gas refers to the combustion exhaust gas produced at power plants.
- Engine exhaust

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Post Combustion Air Cleaning

- Regardless of the success of air emission control by pre- and in- combustion technologies, there are always various pollutants remaining in the flue gas.
  - NOx by low temperature combustion (about 50%)
  - SOx by sorbent injection (about 50%)
  - Particulates added
- Their concentrations have to be further reduced to certain levels to meet the existing air quality and air emission standards.

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Post Combustion Control Approaches

1. **Separation (capture) from the gas stream**
   - Separation of gases from air stream
   - Separation of particles from air stream
   - Condensation of gases to liquid
   - Absorption/Adsorption
2. **Conversion**
   - Catalytic conversion
   - Incineration
3. **Dilution** by ambient air, which is the last step through which the air pollutants enter the atmosphere (Chapter 11).

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Particulate Matter Emission Control

- Cyclone
- Filters
- Electrostatic precipitators
- Wet scrubbers

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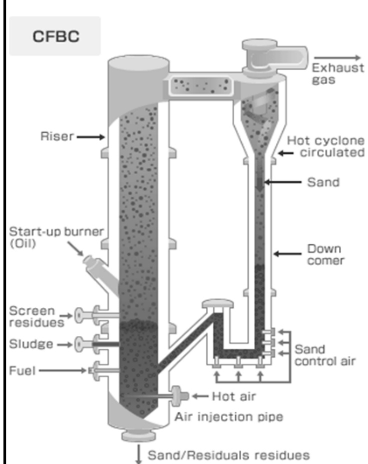
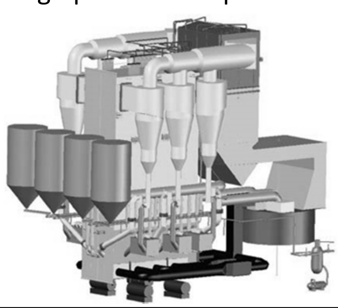
Cyclone



- Often for circulating system
- Ideal pre-cleaner for downstream PM control devices
- Advantages:
  - o **Non-contact** separation
  - o High flow rate
  - o Hot side, high temperature (>1000 ^{o}C)
  - o Low cost and great longevity
- Disadvantages:
  - o Works only for coarse particles (> 5 um)
  - o High pressure drop

Multiple units for high efficiency or greater flow through



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Industrial Electrostatic Precipitators

ESPs can collect dry particles, sticky or tarry particles, and wet mists, they are used by many different industries.

- Fossil fuel-fired boilers
- Cement plants
- Steel mills
- Petroleum refineries
- Municipal waste incinerators,
- Hazardous waste incinerators,
- Kraft pulp and paper mills, and
- lead, zinc, and copper smelters.

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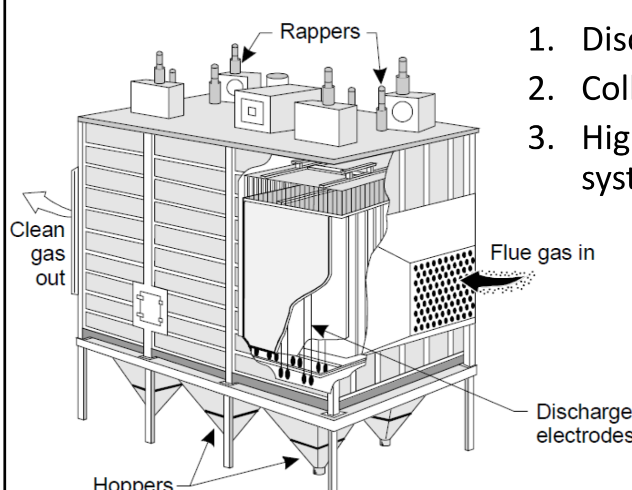
A Typical ESP

- All ESPs, regardless of their particular designs, contain the following essential components:



1. Discharge electrodes
2. Collection electrodes
3. High voltage electrical systems
4. Rappers
5. Hoppers
6. Shell

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- **Discharge electrodes** create a strong electrical field that ionizes flue gas, and this ionization **charges particles** in the gas.
  - Metal wires or a rigid electrode made from a single piece of metal.
- **Collection electrodes** **collect charged particles**, either flat plates or tubes with a charge opposite that of the discharge electrodes
- **High voltage equipment** **provides the electric field** between the discharge and collection electrodes used to charge particles.
- **Rappers** impart a vibration, or shock, to the electrodes, **removing the collected dust** that has accumulated on both collection electrodes and discharge electrodes.
  - Occasionally, water sprays are used to remove dust from collection electrodes.
- **Hoppers** are located at the bottom of the precipitator for temporary **storage of the dust**.
- The **shell** provides the base to support the ESP components and to enclose the unit.

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Types of Electrostatic Precipitators

ESPs can be grouped, or classified, according to a number of distinguishing features in their design. These features include the following:

- The structural design and operation of the discharge electrodes (**rigid-frame, wires or plate**) and collection electrodes (**tubular or plate**)
- The method of charging (**single-stage or two-stage**)
- The temperature of operation (**cold-side or hot-side**)
- The method of particle removal from collection surfaces (**wet or dry**)

These categories are not mutually exclusive. For example, an ESP can be a rigid-frame, single-stage, cold-side, plate-type ESP as described below.

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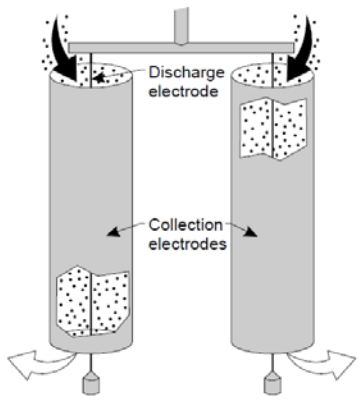
Tubular ESPs



- A tubular ESP is tightly sealed to minimize leaks of collected material.
- Tube diameters typically vary from 0.15 to 0.31 m, with lengths usually varying from 1.85 to 4.0 m.
- 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.

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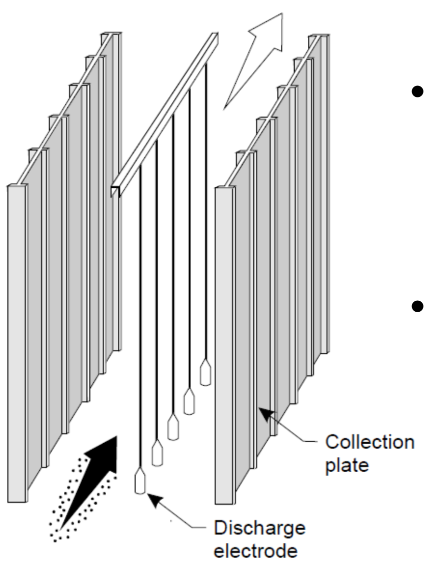
Plate ESPs



- Primarily collect **dry particles** and are used more often than tubular precipitators.
- collecting fly ash from industrial and utility boilers, cement kilns, glass plants, and pulp and paper mills.

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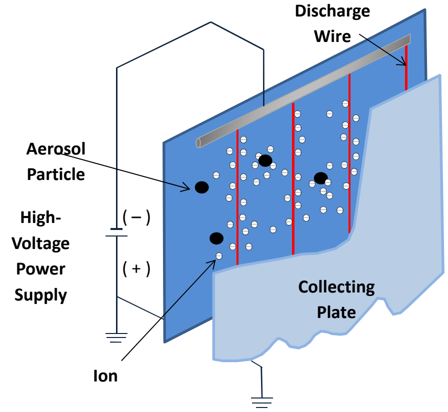
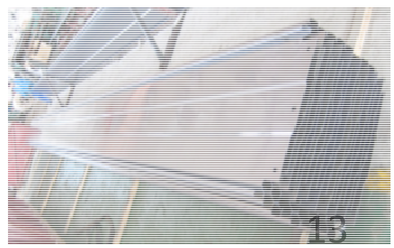
- Plate ESPs can have wire, rigid-frame, or occasionally, plate discharge electrodes.
- Discharge wire electrodes are approximately 0.13 to 0.38 cm in diameter.
- For ESPs with wire discharge electrodes, the plates are usually spaced from 15 to 30 cm apart.



- Collection plates are usually between 6 and 12 m high.
- For ESPs with rigid-frame or plate discharge electrodes, plates are typically spaced 30 to 38 cm apart and 8 to 12 m in height.



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- Most ESPs that reduce particulate emissions from boilers and other industrial processes are **single-stage** ESPs.
- After being charged, particles move in a direction perpendicular to the gas flow through the ESP, and migrate to an oppositely charged collection surface, usually a plate or tube.

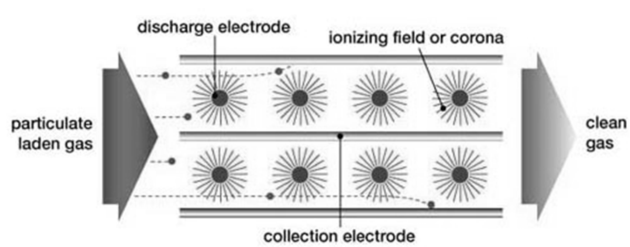

Diagram courtesy of http://www.zet.com/techrefs_overview_fr.html

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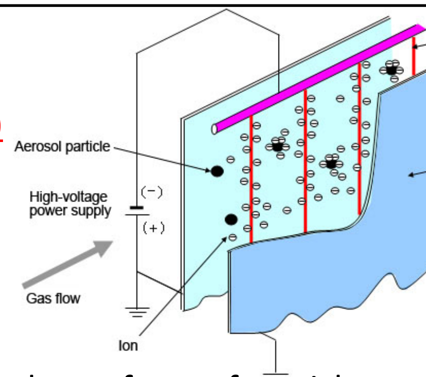
A **single-stage** precipitator uses high voltage **(50 to 70 kV)** to charge the particles, which are then collected within the same chamber on collection surfaces of opposite charge.



- The gas-phase ions arriving on the surfaces of particles and arriving as uncaptured ions must pass through the dust layers on the collection plates.
- At the metal surface of the collection plate, the voltage is zero, since the plate is electrically grounded.

Why ground the collection electrode?

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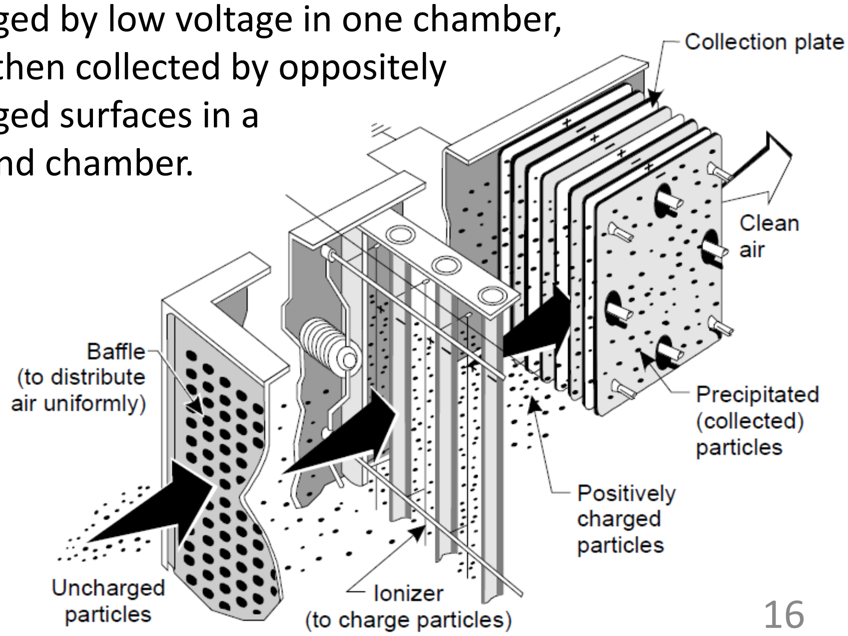
In a **two-stage** precipitator, particles are charged by low voltage in one chamber, and then collected by oppositely charged surfaces in a second chamber.



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- The second stage consists of parallel metal plates **<2.5 cm** apart.
- The particles receive a **positive charge** in the ionizer stage and are collected at the negative plates in the second stage.
- Two-stage precipitators were originally designed for air purification in conjunction with air conditioning systems. (They are also referred to as **electrostatic air filters**).
- Two stage ESPs are used primarily for the control of finely divided **liquid** particles. They have limited use for PM control.
- Meat smokehouses, pipe-coating machines, asphalt paper saturators, high speed grinding machines, welding machines, and metal-coating operations.

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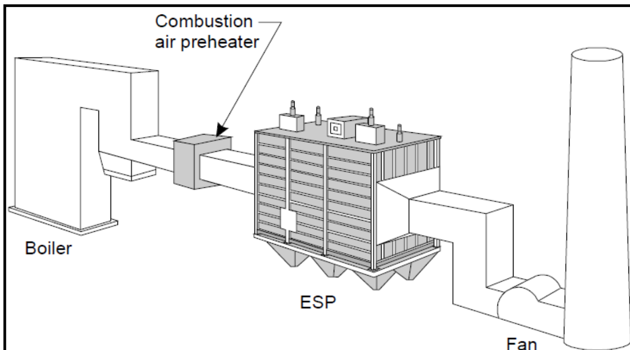
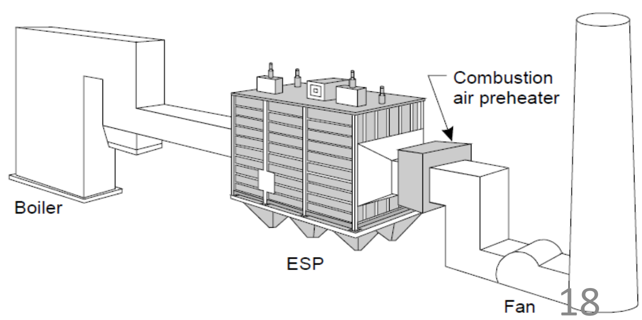


Cold-side ESPs have been used for over 50 years with industrial and utility boilers, where the flue gas temperature is relatively low (<204°C).

A **hot-side ESP** is located before the combustion air preheater in a boiler. The flue gas temperature 320-420 °C.



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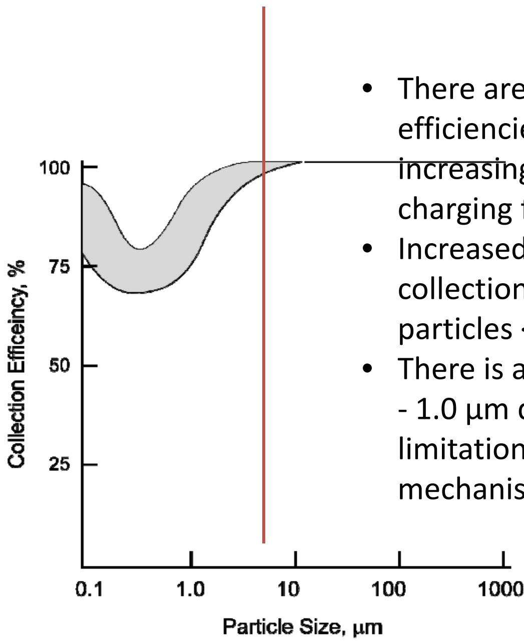
Typical Efficiency Curve (ESP)



- There are very high collection efficiencies > 1.0 µm due to the increasing effectiveness of field charging for large particles.
- Increased diffusion charging causes collection efficiency to increase for particles < 0.1 µm.
- There is a difficult-to-control range 0.1 - 1.0 µm due to the size dependent limitations of both of these charging mechanisms.

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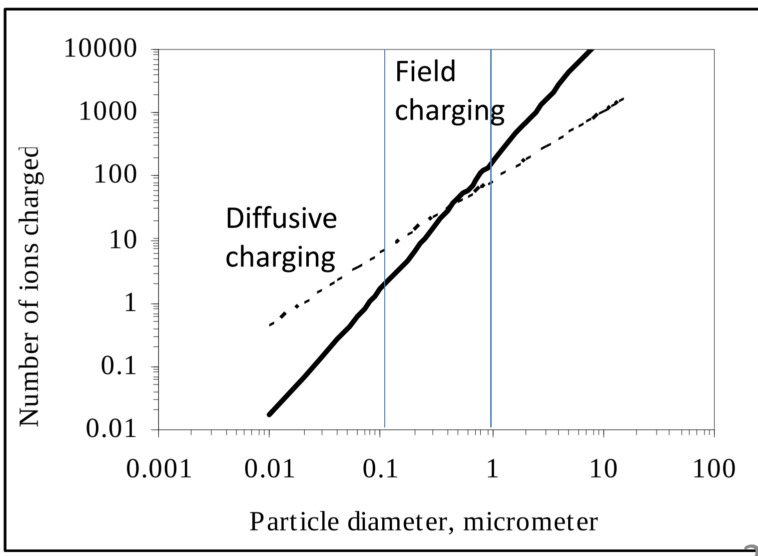
Recall Charging

$$n = \frac{d_p kT}{2K_E e^2} \ln\left[1 + \left(\frac{N_0 c_i \pi d_p K_E e^2}{2kT}\right)t\right] + \frac{E d_p^2}{4K_E e}\left(\frac{3\varepsilon_r}{\varepsilon_r + 2}\right)\left(\frac{t}{t+\tau}\right)$$



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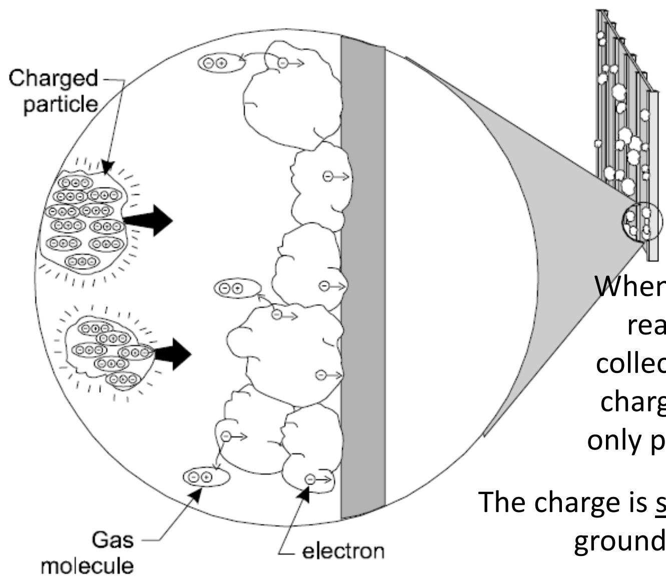
Dust Cake on Collection Electrode



When a charged particle reaches the grounded collection electrode, the charge on the particle is only partially discharged.

The charge is slowly leaked to the grounded collection plate.

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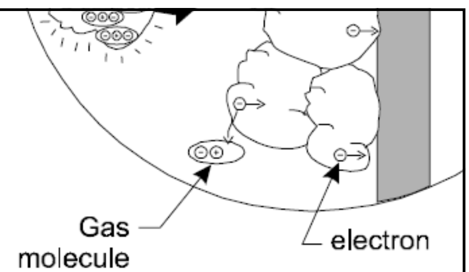

- A portion of the charge is retained and contributes to the inter-molecular adhesive and cohesive forces that hold the particles onto the plates.
- Adhesive forces cause the particles to physically hold on to each other because of their dissimilar surfaces.
- Newly arrived particles are held to the collected particles by cohesive forces; particles are attracted and held to each other molecularly.
- The dust layer is allowed to build up on the plate to a desired thickness and then the particle removal cycle is initiated.

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Dust Layer Resistivity

- At the metal surface of the electrically grounded collection plate, the voltage is zero.
- When new particles and ions are arriving, the electrostatic voltage caused by the gas ions can be quite high.
  - The strength of this electric field depends on the resistivity and thickness of the dust layer.
  - Voltages can be >10kV.

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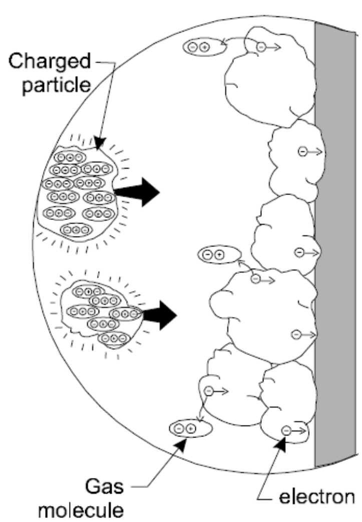
How static electric field is created?



- In high resistivity dust layers, the dust is not sufficiently conductive, so electrical charges have difficulty moving through the dust layer. Consequently, electrical charges accumulate on and beneath the dust layer surface, creating a strong electric field.

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Effect of Low Resistivity on Efficiency

- In **low resistivity** dust layers, the corona current is readily passed to the grounded collection electrode.
- Therefore, a relatively weak electric field, of several thousand volts, is maintained across the dust layer.
- Collected dust particles with low resistivity do not adhere strongly enough to the collection plate. They are easily dislodged and become **re-entrained** in the gas stream.
- Particles with very low resistivity may lose their charges rapidly to water in the gas or other particles.

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Back corona caused by ions build-up

- When the potential drop across the dust layer is so great that corona discharges begin to appear in the gas that is trapped within the dust layer. Positive gas ions are generated within the dust layer reduce some of the negative charges on the dust layer and neutralize some of the negative ions on the "charged particles" heading toward the collection electrode.
- Disruptions of the normal corona process greatly reduce the ESP's collection efficiency, which in severe cases, may fall below 50% (White 1974).

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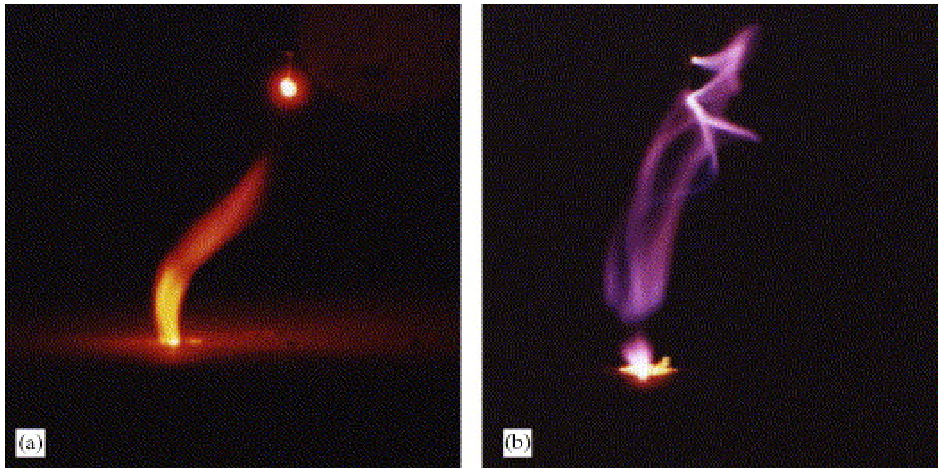

Fig. 8 Photographs of back-arc discharge from fly ash layer. The plate is at the bottom and the discharge electrode is above...

A. Jaworek , T. Czech , E. Rajch , M. Lackowski **Laboratory studies of back-discharge in fly ash**
Journal of Electrostatics Volume 64, Issue 5 2006 326 - 337

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Other Effects of High Resistivity on Efficiency

- **Reduced charging effectiveness:** Particles with too high a resistivity cannot be charged effectively.
- **Reduced electrical field intensity:** As the dust layer builds up, and the electrical charges accumulate on the surface of the dust layer. The migration velocities of small particles are especially affected by the reduced electric field strength.
- Back corona reduced efficiency

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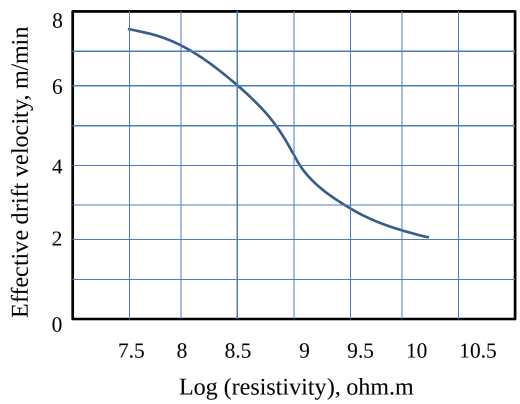
Effect of resistivity on Efficiency

- For an effective separation of particles using an ESP, the resistivity of the particles is preferably in the range of 10^7-10^{12} ohm·m.



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High resistivity causes operating challenges

- It may also cause unwanted electrical spark due to the static electric voltage build up!
- Dust particles with **high resistivity** are held too strongly to the plate, making them difficult to remove and causing rapping problems.

High resistivity can generally be reduced by

- Adjusting the temperature
- Increasing moisture content
- Adding conditioning agents to the gas stream
- Increasing the collection surface area

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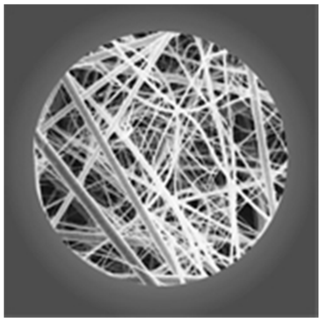
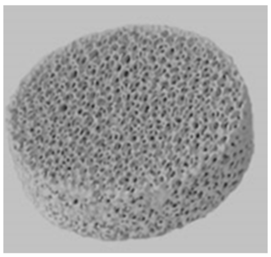
Industrial Filtration

Cotton may be used for the temperatures below 80 °C



Teflon and **glass** fiber work perfectly up to 260 °C.

For applications up to 450 °C **stainless steel** can be used under unfriendly **corrosive** environments.



At higher temperatures, **ceramic** materials are the best choice.

Filter Media

Filter Configuration

- Fiber, annular, box, etc.
- **Bag filters** made of fabric fiber materials, textile, plastics, ceramic
- Rigid barrier filters made of metal or sintered ceramic, powder or fibres.
- For applications at high temperatures, more rigid **"candle" filter elements** can be used; although the same principle applies. Typical filter media includes, but are not limited to
- **Granular bed filters** based on a layer of granular solids

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Fabric Filters for Stationary Sources

Fabric filtration is one of the most common air filtration techniques

1. Disposable filters are similar to those used I home HVAC system, including **mat** filters or **depth** filters.

- Mat filters are usually made using fiberglass
- Depth filters are generally constructed using fiberglass, glass fiber paper or some other **inert materials** such as fine steel fibers to form a deep mesh

2. Nondisposable filters are generally made of fabric material such as nylon, fiberglass or others. They are commonly used for industrial processes.

- Dust collected on the filter is removed by
  - shaking,
  - reversing air flow or
  - pulses of air.

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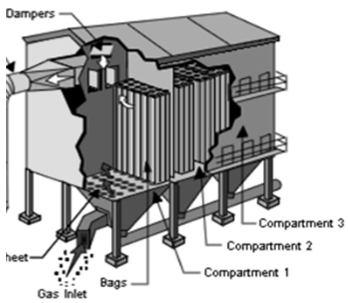


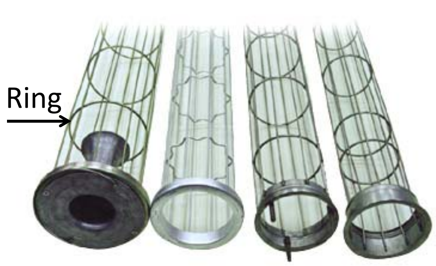
Bag-house

A fabric filter baghouse consists of

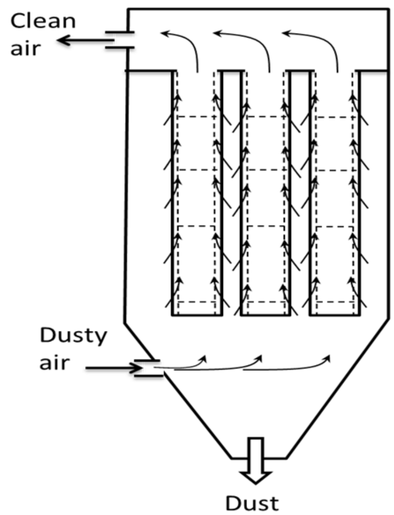
- Bags, fabric and support
- Housing or shell
- Collection hoppers
- Discharge devices
- Filter cleaning devices
- Fan

Bag Support (Metal cap and end cap not shown)

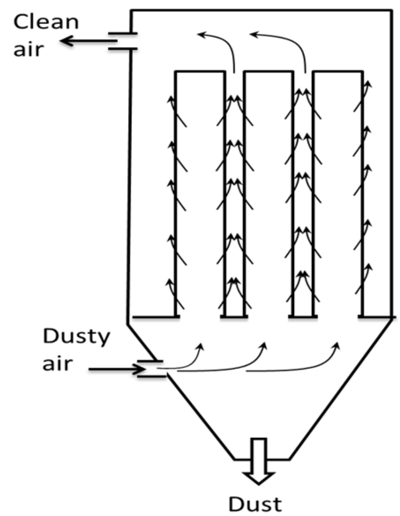
- **Anti-collapse rings** to keep it from completely collapsing during the cleaning cycle.
- **Rings** are usually made of 3/16 inch carbon steel. Depending on flue gas conditions, they can also be composed of cadmium-plated galvanized, or stainless steel.
- The rings are placed every 2 to 4 feet apart throughout the bag length depending on the length and diameter of the bag.
- Usually, the spacing between anti-collapse rings is larger at the top of the bag and is smaller near the bottom of the bag.



(Gas) Out-In model



(Gas) In-Out model



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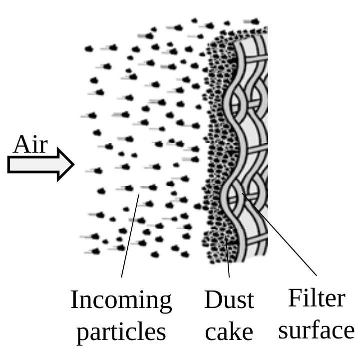
Dust Cake

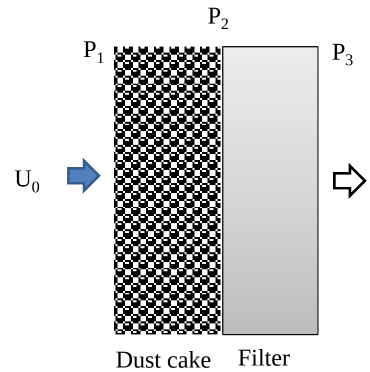


- During operation, gases are separated from dispersed particles by passing it through filter media.
- Captured particles will be retained on its surface, gradually forming the so-called "dust cake".
- This dust cake will increase the filter efficiency, but even more for a pressure drop.

Darcy's Law

$$U_0 = \frac{Q}{A} = \frac{\Delta P}{\mu}\frac{k}{\Delta x}$$

- where k is the permeability (m^2), and it is often determined experimentally,
- ΔP is the pressure drop across a porous media (a positive number),
- μ is the air viscosity, and
- Δx is the thickness of the porous media



$$U_0 = \frac{P_2 - P_3}{\mu}\left(\frac{k}{\Delta x}\right)_f$$

$$U_0 = \frac{P_1 - P_2}{\mu}\left(\frac{k}{\Delta x}\right)_{ck}$$

$$\Delta P = P_1 - P_3 = \mu U_0\left[\left(\frac{\Delta x}{k}\right)_{ck} + \left(\frac{\Delta x}{k}\right)_f\right]$$

Pressure Drop

- **ΔP** of a system (fabric filter) describes the resistance to airflow across the baghouse
- the higher the pressure drop,
  - the higher the resistance to air flow,
  - the higher energy consumption, and
  - possibly a larger fan
- **ΔP** is determined by measuring the difference in total pressure at two points, usually the inlet and outlet.
- The total **ΔP** can be related to the size of the fan that would be necessary to either push or pull the exhaust gas through the baghouse.
- Consider the pressure drop due to both a clean filter and dust layer

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Example 10.1

- *A set of baghouse surface filters have an active area of 60 m^2. The pressure drop through a freshly cleaned baghouse is 125 Pa and the bag is expected to be cleaned to remove dust cake when the pressure drop reaches 500 Pa in one hour. The gas being cleaned has a flow rate of 300 m^3/min with a particle loading of 10 g/m^3. If the average mass filtration efficiency is 99%, and the dust cake has a solidity of 0.5. Assume the real dust material is 2,000 kg/m^3.*
- *Estimate*
  - *a) the thickness of the cake when the filter is ready for cleaning*
  - *b) the permeability of the dust cake when it is due to be removed.*

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Solution

- *The mass of dust collected on the surface of the working filters in one hour is*

$$m = cQt\eta = 0.01\frac{\text{kg}}{\text{m}^3} \times \frac{300\text{m}^3}{\text{min}} \times 60\text{ min} \times 0.99 = 178.2\text{ kg}$$

- *a) The thickness of the cake collected in one hour is*

$$\Delta x_{ck} = \frac{m}{\rho_{ck} A\alpha} = \frac{178.2\text{ kg}}{2000\frac{\text{kg}}{\text{m}^3} \times 60\text{ m}^2 \times 0.5} = 0.003\text{ m or 3 mm}$$

- *When the dust cake is to be removed, the pressure drop cross the dust cake is*

$$(\Delta P)_{ck} = P_1 - P_2 = \Delta P - (\Delta P)_f = 500 - 125 = 375\ Pa$$

- *The face speed of velocity the gas flow is*

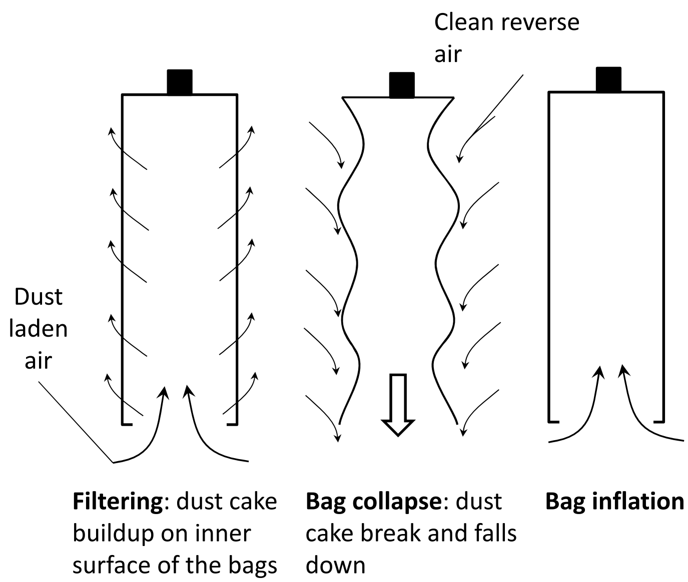
$$U_0 = \frac{Q}{A} = \frac{(300\text{ m}^3/\text{min}) \times (1\text{ min}/60\text{s})}{60\text{ m}^2} = 0.083\text{ m/s}$$

- *b) The dust cake permeability can be derived from Eq.* (10-3)

$$k_{ck} = \frac{\mu U_0 (\Delta x)_{ck}}{P_1 - P_2} = \frac{1.81\times10^{-5}\text{ Pa.s} \times 0.0083\text{ m/s} \times 0.003\text{ m}}{375\text{ Pa}} = 1.19 \times 10^{-12}\text{ m}^2$$

- *This value is close to that of permeable sandstone*

Dust Cake Removal



Reverse-Air Baghouse

- Reverse-air baghouses use very **<u>large bags</u>** (compared to shaker or pulse-jet baghouses) ranging from 8 to 18 inches in diameter and from 20 to 40 feet in length.
- Reverse-air cleaning baghouses are compartmentalized to permit a section to be **<u>off-line for cleaning</u>**.
- Cleaning air is supplied by a <u>separate fan</u> which is normally much <u>smaller</u> than the main system fan
- One compartment is cleaned at a time.
- The cleaning action is very gentle, allowing the use of less abrasion resistant fabrics such as fiberglass.
- Air flow direction is controlled by inlet/outlet gas dampers.

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- Reverse-air cleaning is generally used for cleaning woven fabrics.
- Cleaning frequency = 30 minutes to several hours
- Cleaning duration = 10-30 seconds to minutes
  - Total time is 1 to 2 minutes including time for valve opening and closing, and dust settling.
- Typical design parameters for reverse-air cleaning are

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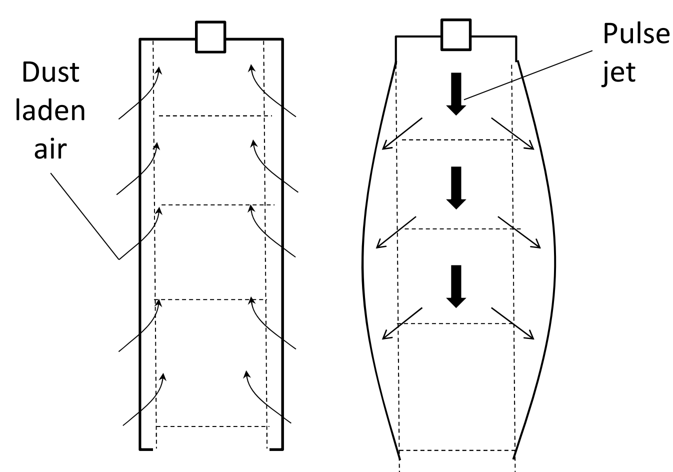
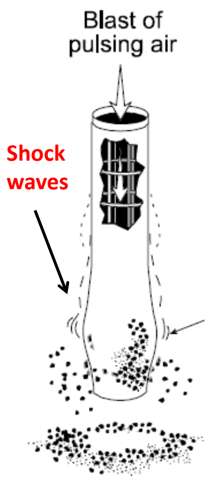


Filtering: dust cake buildup on outer surface of the bag

Pulsing: dust cake break and falls down

Pulse Jet Baghouse



- The **most commonly used** cleaning method is the pulse-jet or pressure-jet cleaning.
- Used for cleaning bags in an exterior filtration system (dust cake on outside surface of the bags)
- Dust is removed from the bag by a blast of compressed air injected into the top of the bag.
- **During pulse-jet cleaning, the flow of dirty air into the baghouse compartment is NOT stopped.**
- The air blast develops into a standing or shock wave that causes the bag to flex or expand as the shock wave travels down the bag tube.
- As the bag flexes, the cake fractures, and deposited particles are discharged from the bag.
- The shock wave travels down and back up the tube in approximately 0.5 seconds.

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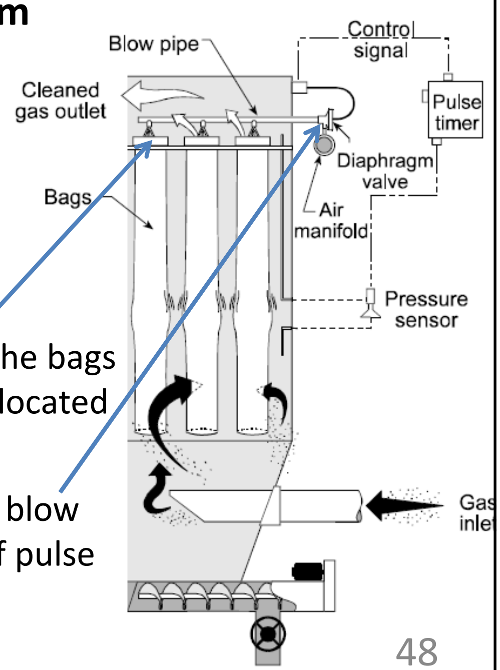
Pulse Jet Cleaning System

- The blast of compressed air must be strong enough for the shock wave to travel the length of the bag and shatter or crack the dust cake.
- Pulsing air is directed into the bags through nozzles or orifices located on the blow pipe.
- A diaphragm valve on each blow pipe provides the very brief pulse of compressed air.



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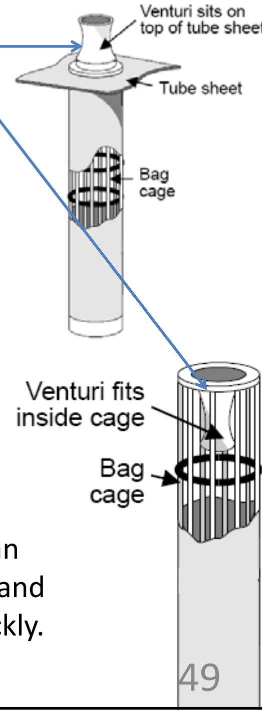
Venturi Pulse Jet Cleaning



- In some baghouse designs, a venturi sealed at the top or just inside the top of each bag is used to create a large enough pulse to travel down and up the bag.
- Vendors claim that the venturis can help increase the cleaning pressure, and thereby improve bag cleaning.
- In other pulse-jet designs, venturis are not used, but the bags are still cleaned effectively.
- The importance of the venturis is debatable.
- The use of venturis has in some cases directed an increased air flow to a specific spot on the bag, and actually caused the bag to wear a hole very quickly.

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NOTE

- Pulse-jet units are usually operated in a "non-dust cake" mode.
- Bags are pulsed frequently to prevent the formation of a thick cake and to keep the unit from having a high pressure drop across the dust cake and felted filter.
- However, sometimes a dust cake is desired in cases where woven bags are used in a pulse-jet baghouse.
- Pulse jet frequency: 0.3 to 0.5 seconds.
- The pressures = 60 -100 psig (414 kPa and 689 kPa).
  - Some vendors have developed systems to use a lower pressure pulsing air (40 psi).
- Typical design parameters for pulse-jet cleaning are

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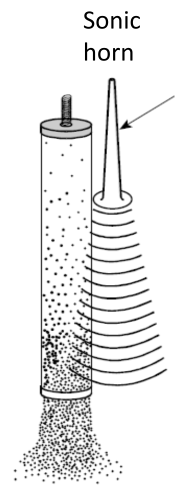
Optional Sonic Vibration

- In a few systems, shaking is accomplished by sonic vibration
- A sound generator is used to produce a low frequency sound that causes the bags to vibrate.
- The noise level produced by the generator is barely discernible outside the baghouse.
- Sonic cleaning is generally used along with one of the other cleaning techniques to help thoroughly clean dirty bags.



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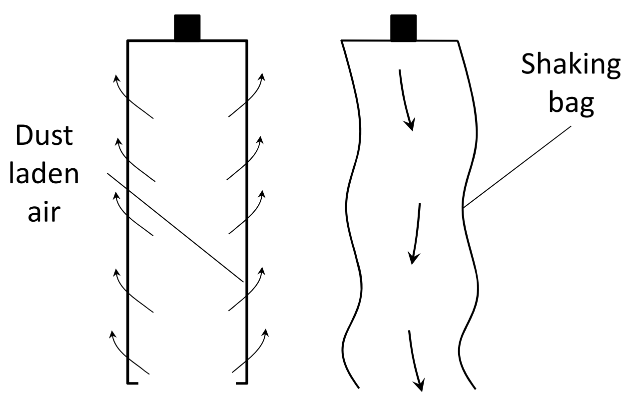

Filtering: dust cake buildup on inner surface of the bags

Shaking dust cake break and falls down

Filter Baghouse Design

- Careful design will reduce the number of operating problems and possible air pollution violations.
- Baghouses are designed by considering **pressure drop, filter drag, air-to-cloth ratio,** and **collection efficiency**.
- Previous vendor experience with the same or similar process to be controlled will generally be adequate for design purposes.

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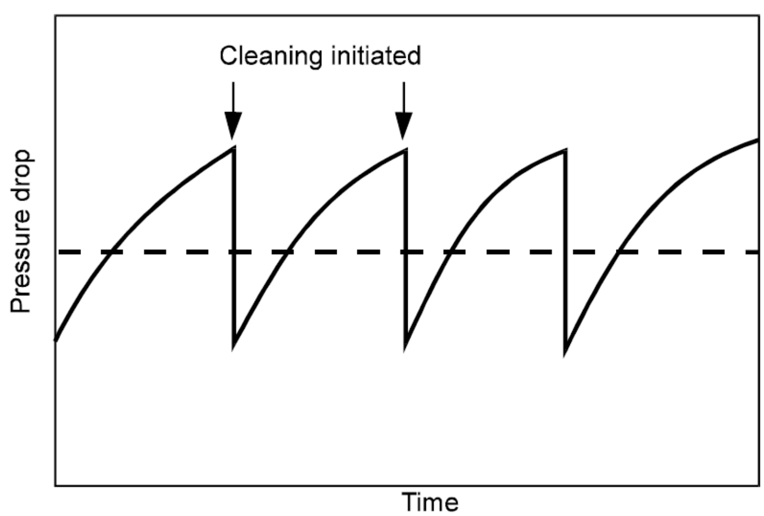
Overall Pressure Drop of a Multi-compartment Baghouse



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Advantages and Disadvantages of Fabric Filters

- Fabric filters are used in a wide variety of applications where high efficiency particulate collection is needed. The control efficiencies usually range from 99% to greater than 99.5% depending on the characteristics of the particulate matter and the fabric filter design.
- The performance of fabric filters is usually independent of the chemical composition of the particulate matter. However, they are not used when the gas stream generated by the process equipment includes corrosive materials that could chemically attack the filter media.
- Fabric filters are also not used when there are sticky or wet particles in the gas stream. These materials accumulate on the filter media surface and block gas movement.
- Fabric filters must be designed carefully if there are potentially combustible or explosive particulate matter, gases, or vapors in the gas stream being treated. If these conditions are severe, alternative control techniques, such as wet scrubbers, are often used.

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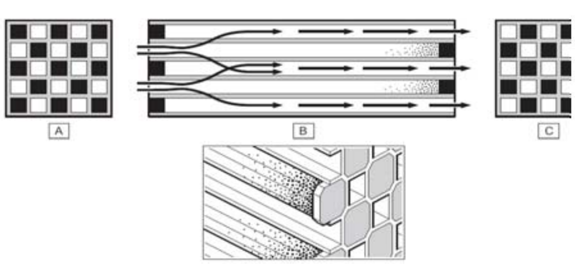
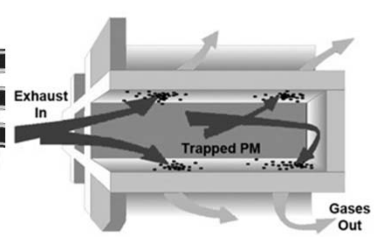
Diesel Particulate Filter (DPF)

- Diesel particulate are typically soot particles with adherent hydrocarbons, sulphate and other condensed compounds.
- Legally a particulate is anything in the exhaust stream that can be captured on a filter paper at 52 ^{o}C.





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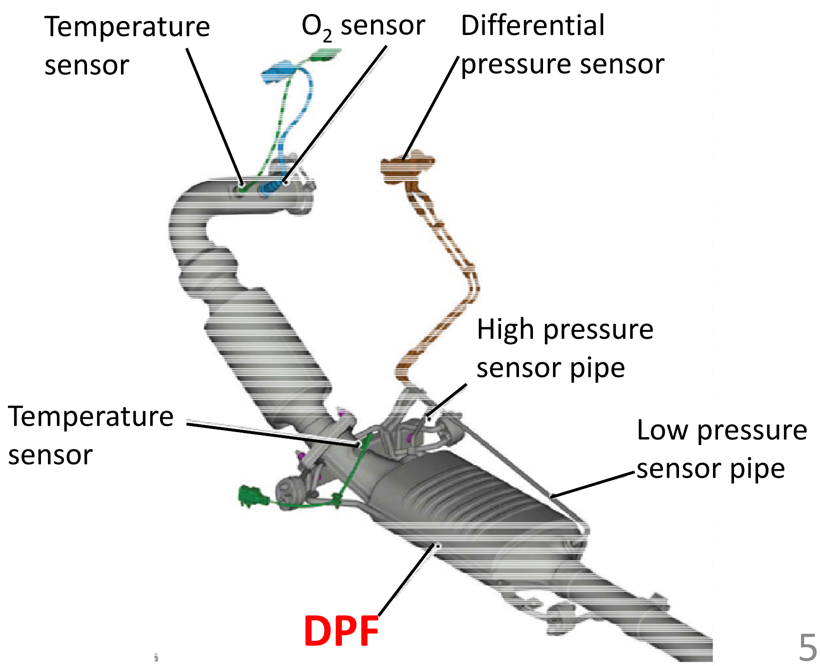

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DPF Generation Strategy

- To prevent DPF becoming blocked or even destroyed completely, regeneration must be initiated before a critical saturation point is reached.
- Regeneration is the burning of particulate collected DPF).
- Exhaust gas temperature must be at least 600 °C for the soot particles to burn; temperature is detected by the DPF exhaust gas temperature sensor

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Wet Scrubbers

- Wet scrubbers remove air pollutants by inertial of diffusional impaction, reaction with a sorbent or reagent slurry, or absorption into a liquid solvent.
- These types of scrubbers can be used to control Particulate Matter, hazardous air pollutants (HAP); inorganic fumes, vapors, and gases (e.g., chromic acid, hydrogen sulfide, ammonia, chlorides, fluorides, and SO_2).
- These types of scrubbers may also occasionally be used to control volatile organic compounds (VOC).

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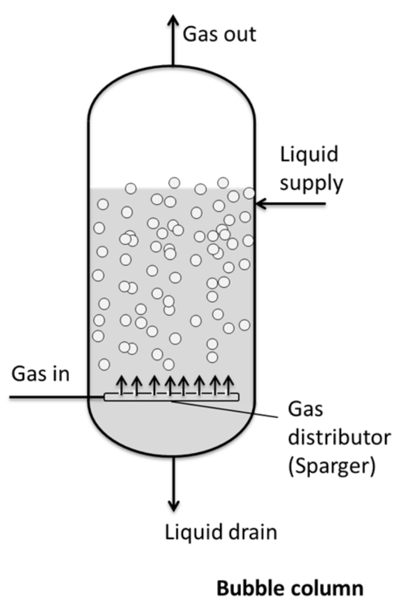

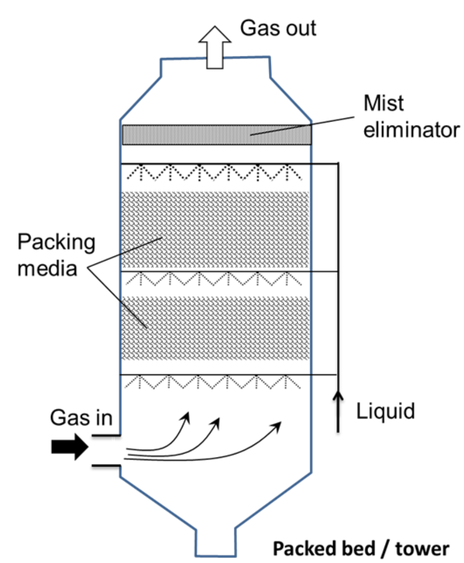

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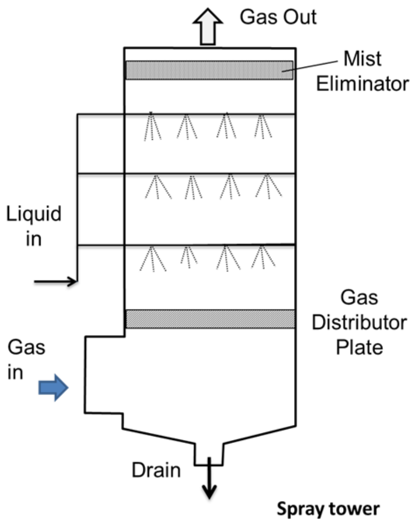

Gravity Spray Tower

- Countercurrent vertical tower
- **Droplets** sufficiently **large** so that the settling velocity is greater than the upward gas velocity
- Droplet size controlled to optimize particle contact and to provide easy droplet separation

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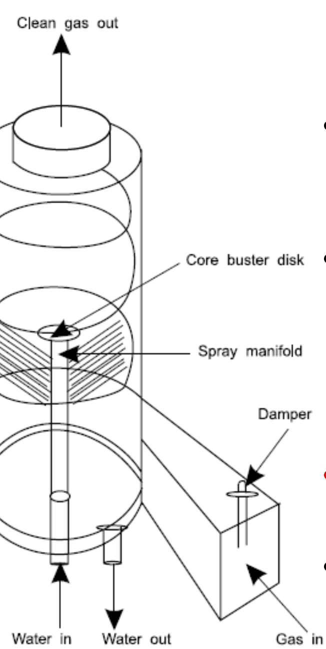

Cyclonic Spray Tower

- Increases the forces of collision and relative velocity of the droplets and gas stream
- Well designed cyclonic spray towers greatly increase the collection of particles smaller than 10 µm when compared to simple countercurrent spray towers
- Droplets produced by spray nozzles and collected by centrifugal force
- Two types: (1) Tangential inlet, (2) Vane - induced

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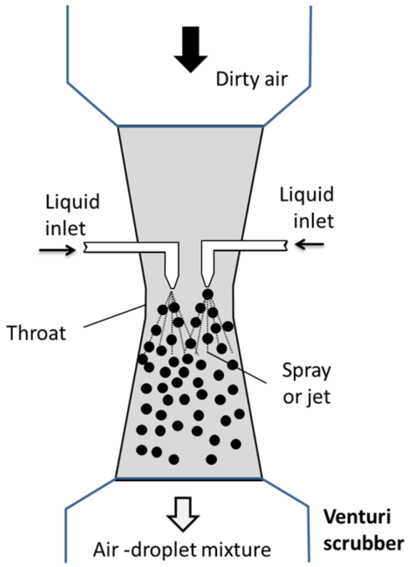

Venturi scrubber

- Gas accelerated at throat (Then what happens?)
- Atomized water droplets added at throat as a spray or jet collect particles
- Can be combined with a cyclonic collector to separate water droplets from air stream
- Has a large pressure drop

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Applications to Particulate Capture

Particle Size Collection Efficiency of Various Wet Scrubbers[4-6]

Type of Scrubber	Pressure Drop in Pa	Minimum Collectible Particle Diameter[a] in μm
Gravity spray towers	125–375	10
Cyclonic spray towers	500–2500	2–6
Impingement scrubbers	500–4000	1–5
Packed and moving bed scrubbers	500–4000	1–5
Plate and slot scrubbers	1200–4000	1–3
Fiber bed scrubbers	1000–4000	0.8–1
Water jet scrubbers	—	0.8–2
Dynamic	—	1–3
Venturi	2500–18,000	0.5–1

[a] Minimum particle size collected with approximately 85% efficiency.

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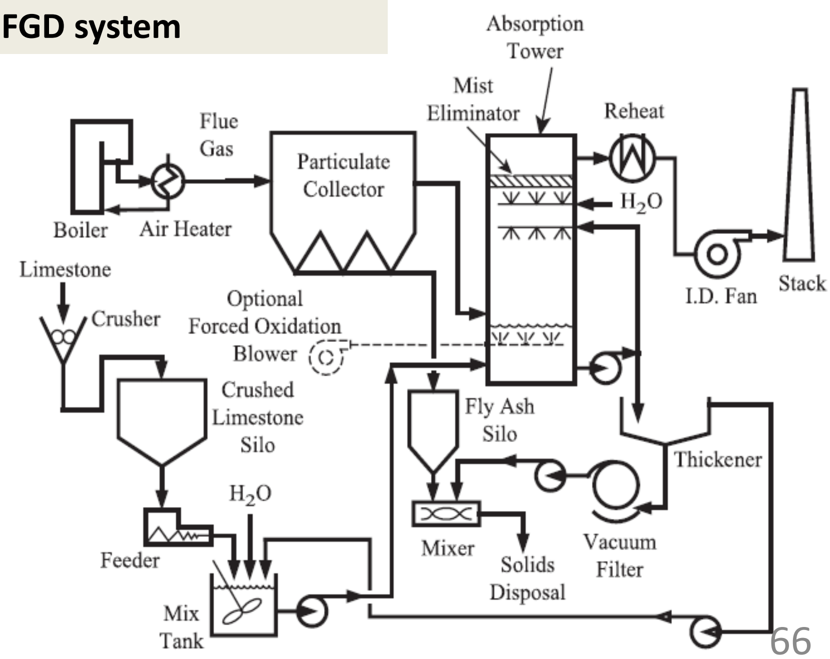
Wet Scrubber for SO2 Absorption

A typical process flow for lime FGD system



Types of FGD Sorbent and Byproducts

Process	Sorbent	End/By – Product
Wet scrubbers	Lime / Limestone Lime / Fly ash	Gypsum, Calcium sulphate/sulphite Calcium sulphate/sulphite/fly ash
Spray-dry scrubbers	Lime	Calcium sulphate/sulphite
Dual - alkali	Primary: sodium hydroxide Secondary: lime	Calcium sulphate/sulphite
Seawater	Primary: seawater Secondary: lime	Waste seawater
Walther	Ammonia	Ammonia sulphate

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Typical Operating Challenges

- **Scale buildup and plugging** of absorber internals and associated equipment were prominent problems.
  - Scale buildup ($CaSO_4$) on spray nozzles and entrainment separators was particularly troublesome.
  - New spray nozzle designs and careful control of the recirculating slurry have reduced internal scrubber scaling (EPA 1975). Problems with the entrainment separators have also been reduced by careful separator design, installing adequate wash sprays, and monitoring the pressure drop across them.
- High **liquid-to-gas ratios** can reduce scaling problems because the absorber outlet slurry is more dilute, containing less calcium sulfates and calcium sulfites that cause scaling.

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- Stack gas reheater: . Stack gas is reheated to avoid condensation on and corrosion of the ductwork and stack, and to enhance plume rise and pollutant dispersion.
  – Reheater failures were caused by acid attack to reheater components.
- **Corrosion** of scrubber internals, fans and ductwork, and stack linings have been reduced by using special materials such as rubber- or plastic-coated steel and by carefully controlling slurry pH with monitors.

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Post Combustion Control Approaches

1. **Separation (capture) from the gas stream**
   – Separation of gases from air stream
   – Separation of particles from air stream
   – Condensation of gases to liquid
   – Absorption/Adsorption
2. **Conversion**
   – Catalytic conversion
   – Incineration
3. **Dilution** by atmospheric air, which is the last step through which the air pollutants enter the atmosphere.

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SNCR and SCR

- **SNCR** = Selective Noncatalytic Reduction (SNCR)
- **SCR** = Selective Catalytic Reduction
- They are post-combustion control technologies based on the chemical reduction of nitrogen oxides by

  $NOx + ? \rightarrow N_2$ and H_2O

- The primary difference between the two technologies is that SCR utilizes a catalyst to increase the NOx removal efficiency, which allows the process to occur at lower temperatures.

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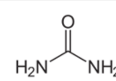
Reagents



- Both ammonia and urea have been successfully employed as reagents.
- Ammonia is generally less expensive than urea. However, the choice of reagent is based not only on cost but on physical properties and operational considerations.
- Urea is a nontoxic, less volatile liquid that can be stored and handled more safely than ammonia.
- Urea solution droplets can penetrate farther into the flue gas when injected into the boiler. This enhances mixing with the flue gas which is difficult on large boilers.
- Because of these advantages, urea is more commonly used than ammonia in large boiler applications of SNCR systems.

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SNCR

1. **Selective Non-catalytic Reduction (SNCR)** uses ammonia (NH_3) or urea (H_2NCONH_2) to reduce NOx to N2 and water. Overall reactions:

$$2NH_3 + 2NO + \frac{1}{2}O_2 \leftrightarrow 2N_2 + 3H_2O \qquad 870\text{-}1000\ ^oC$$

$$2NH_3 + 2NO + O_2 + H_2 \leftrightarrow 2N_2 + 4H_2O \qquad 700\text{-}1000\ ^oC$$

- The key to this process is operating within the narrow temperature window.
- No catalyst is required for this process; good mixing of the reactants at the right temperature and some residence time.

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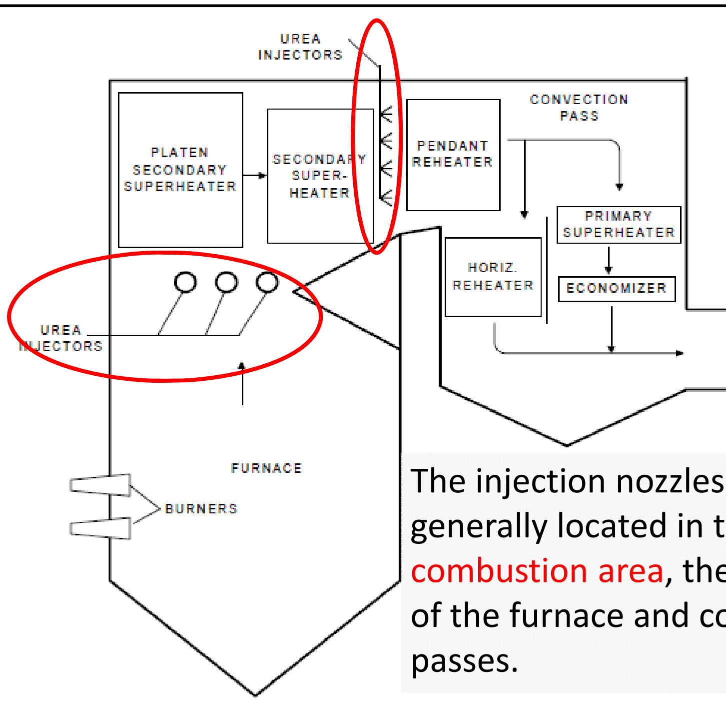
SNCR



The injection nozzles are generally located in the post-combustion area, the upper area of the furnace and convective passes.

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Factors to Consider

- The hardware associated with an SNCR installation is relatively simple and readily available. Installation of SNCR equipment requires minimum downtime.
- Consequently, SNCR applications tend to have low capital costs compared to SCR.
- Though simple in concept, it is challenging in practice to design an SNCR system that is reliable, economical, simple to control, and meets other technical, environmental, and regulatory criteria.
- Practical application of SNCR is limited by the boiler design and operating conditions.

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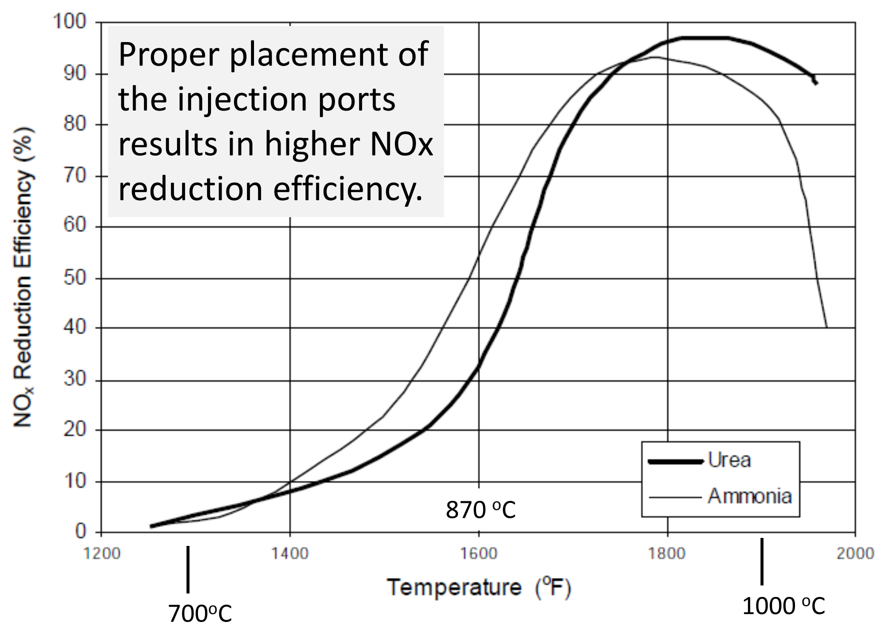
Proper placement of the injection ports results in higher NOx reduction efficiency.



Selective Noncatalytic Reduction for NOx Control on Coal-fired Boilers, Draft Report, prepared for the U.S. Environmental Protection Agency by The Cadmus Group, Inc., Bechtel Power Corporation, and Science Applications International Corporation. May 1998.

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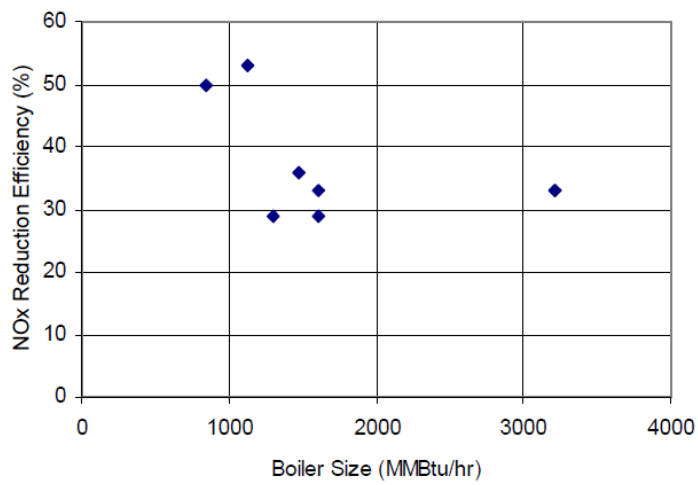
Real Efficiency vs. Boiler Size



Northeast States for Coordinated Air Use Management (NESCAUM). Status Report on NOx Control Technologies and Cost Effectiveness for Utility Boilers. June 1998.

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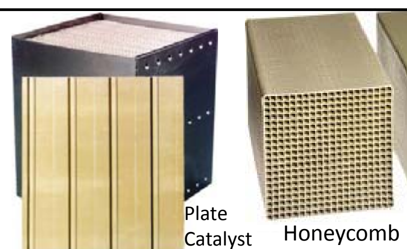
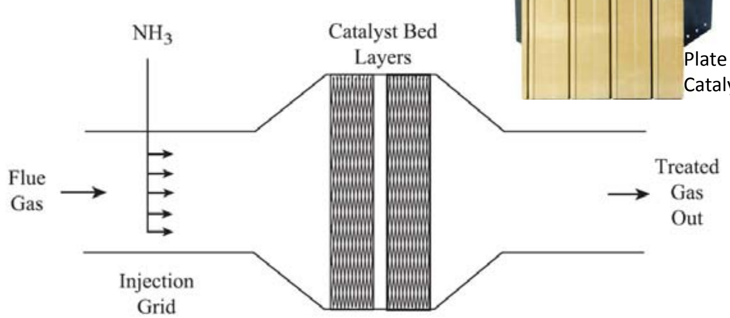
Selective Catalytic Reduction (SCR)





$$4NO + 4NH_3 + O_2 \rightarrow 4N_2 + 6H_2O$$

$$6NO + 4NH_3 \rightarrow 5N_2 + 6H_2O$$

$$2NO_2 + 4NH_3 + O_2 \rightarrow 3N_2 + 6H_2O$$

$$6NO_2 + 8NH_3 \rightarrow 7N_2 + 12H_2O$$

$$NO + NO_2 + 2NH_3 \rightarrow 2N_2 + 3H_2O$$

A variety of catalysts are developed for SCR.

- Precious metals are used in the low temperature ranges of 175 to 290°C.
- Vanadium pentoxide supported on titanium dioxide is a common catalyst for the temperature range of 260 to 425 °C.
- Zeolites, which are various alumino silicates, are used as high temperature catalysts in the range of 450 to 595 °C.

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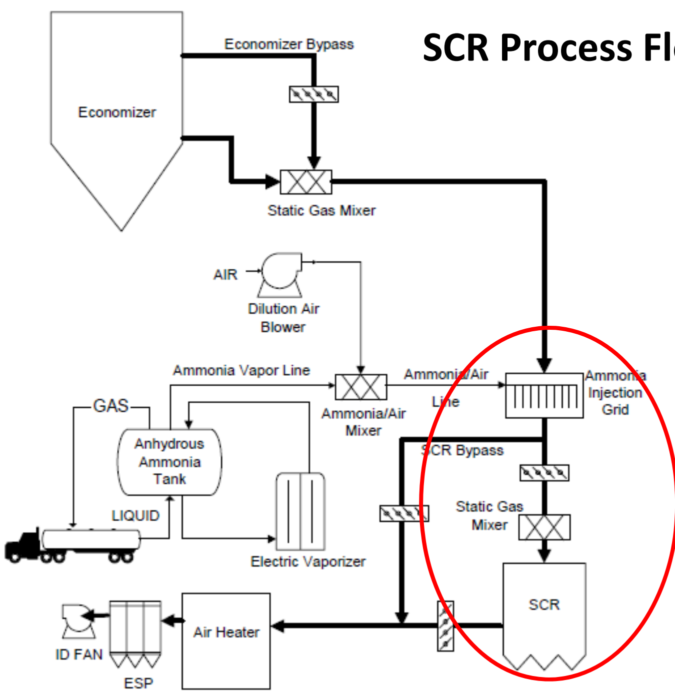
SCR Process Flow Diagram



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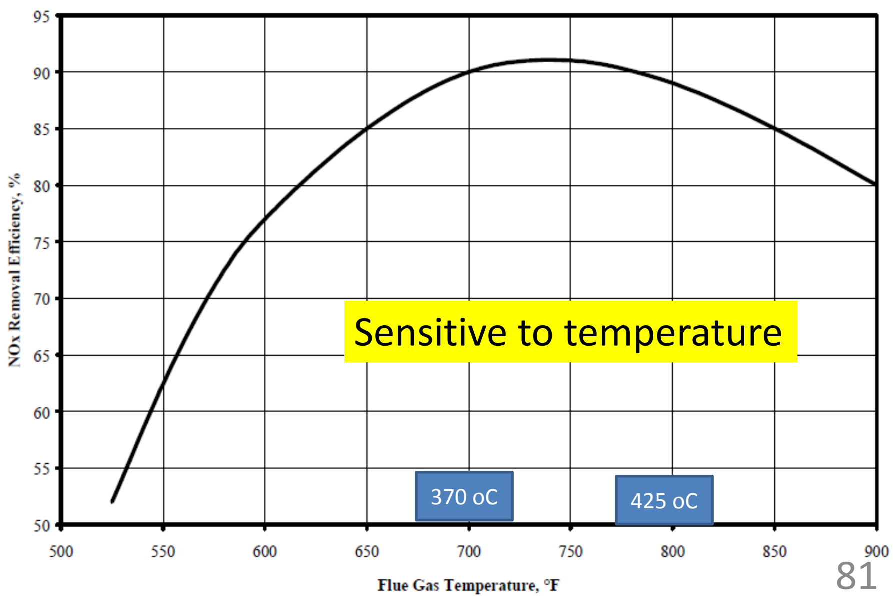
For a typical metal oxide-type catalyst



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Operating Considerations

- **Ammonia storage and handling:**
  - A small amount of ammonia, about 5 to 20 ppm, will pass, or "slip," through the catalyst, which creates an emission of a small amount of a hazardous air pollutant in exchange for reducing NOx.
- **Sulfuric acid:** Besides temperature, another catalyst issue is oxidation of SO_2 to SO_3 in flue gases from fuels that contain sulfur.
  - SO_3 results in sulfuric acid mist emissions, which can create opacity that is expensive to control.
  - Tungsten trioxide and molybdenum trioxide are catalysts that may minimize sulfur oxidation.

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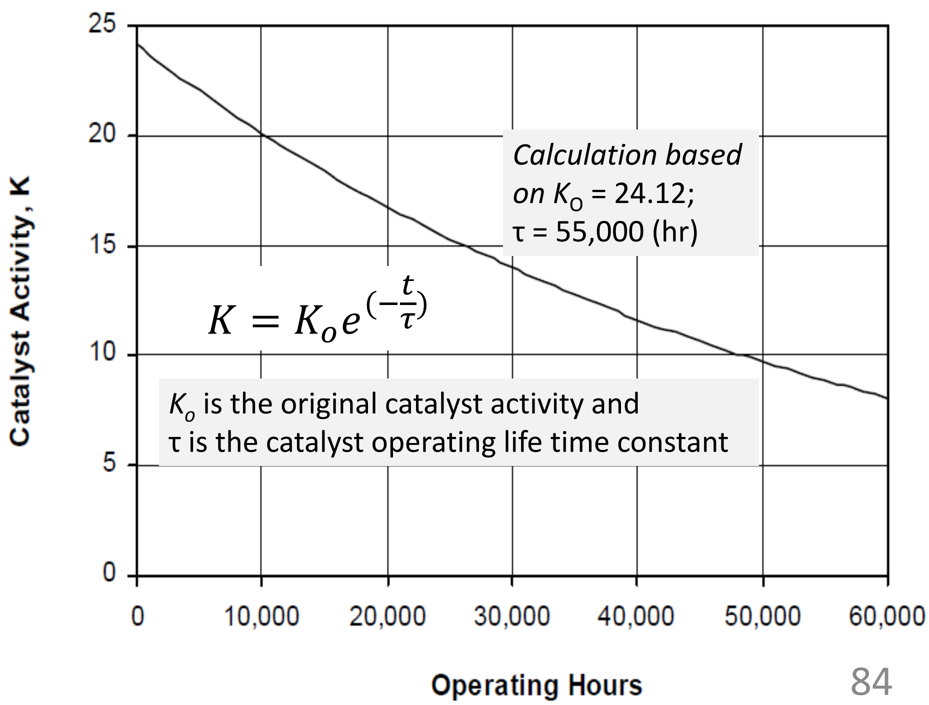
Operating Considerations (Cont…)

- **Catalyst fouling:**
  - Dust loading and catalyst fouling is a problem when there is a significant amount of particulate in the gas stream.
  - SCR systems currently are being retrofit into some coal-fired power plants as a result of stringent NOx control regulations.
  - The catalysts are configured into structured grids to minimize dust accumulation.
  - Some catalyst beds are fit with steam-operated soot blowers to remove dust.

- Catalyst accounts for 30-40% of the process
- Replaced 2-3 years



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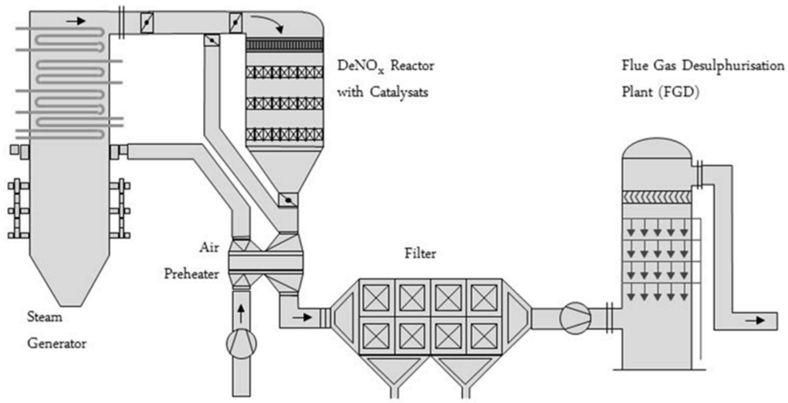
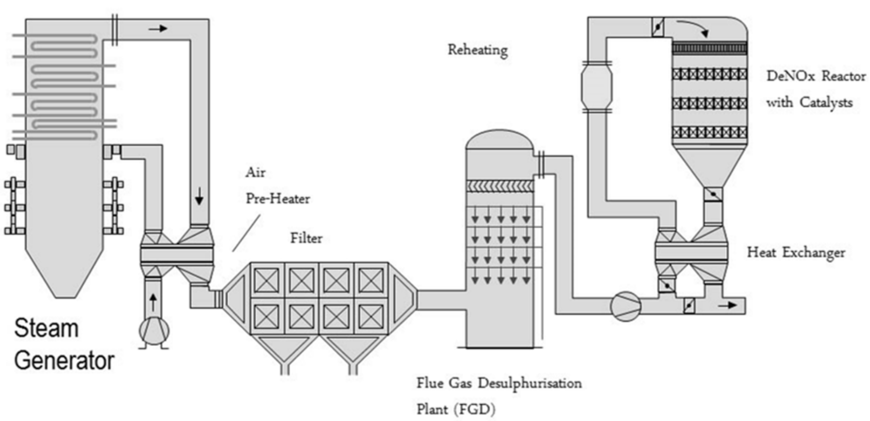
High dust SCR



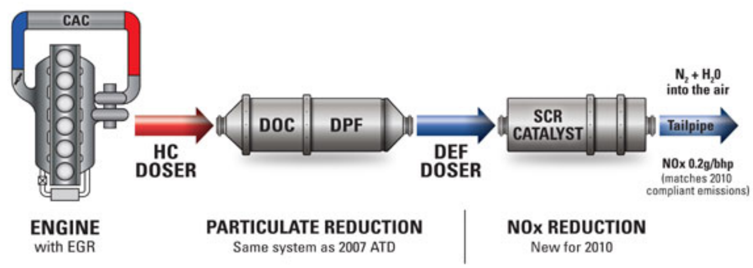
- The flue gas temperature in this location is usually within the optimum temperature window
- the flue gas contains particulates when it enters the SCR reactor.

Low dust SCR



- The disadvantage of low dust SCR is the temperature drop of the flue gas as it flows through the ESP
- More expensive catalyst

SCR for Mobile Sources



- SCR systems are common in stationary sources and are also used on a few mobile sources in Europe.
- In this system, the reductant is injected into the exhaust upstream of the catalyst .
- As the exhaust gases, along with the reductant, pass over a catalyst applied to either a ceramic or metallic substrate,

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SCR Effectiveness

- NOx emissions can be reduced by more than 70%.
- PM emissions could be reduced by 25% and
- HC emissions by 50-90% in SCR systems.
- SCR retrofit systems are available.
  - In USA/Canada it has to pass the government certification

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Incineration of VOC and residual fuels

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Post Combustion Control Approaches

1. **Separation (capture) from the gas stream**
   – Separation of gases from air stream
   – Separation of particles from air stream
   – Condensation of gases to liquid
   – Absorption/Adsorption
2. **Conversion**
   – **Catalytic conversion of NO**
   – **Incineration of VOC and HC**
3. **Dilution** by atmospheric air, which is the last step through which the air pollutants enter the atmosphere.

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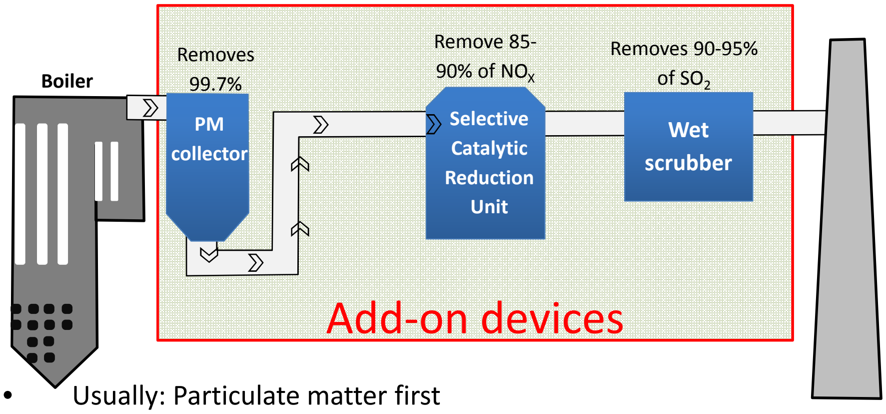
Schematic diagram of a flue-gas treatment process



- Usually: Particulate matter first
- Then a selective catalytic reduction (SCR) unit is employed for NO_x control at 350-400 ^oC, it is better to put the ESP upstream of the SCR.
  - This is because after the ESPs, fly ash particles are removed and will improve SCR catalyst lifetime while reducing SCR operation and maintenance problems.
- Wet scrubber for acidic gases and others

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Three Types of Incineration

1. **Flares** are usually used for gas streams that have an organic vapor concentration greater than 2-3 times the lower explosive limit (LEL)
   - **LEL, is the level of organic vapor concentration at which oxidation will be self-supporting if a source of ignition is provided.**
2. **Thermal oxidizers** are used for contaminated gas streams that have an organic vapor concentration 25%-50% of the LEL.
3. **Catalytic oxidizers** are used for gas streams that have concentrations <25% of the LEL.

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Design Factors

1. **Properties of gas stream**
   - Flow rate;
   - Gas composition;
   - Gas temperature;
   - Gas pressure available;
   - Utility costs and availability;
2. **Regulatory mandates**
   - Safety requirements;
   - Environmental requirements;
   - Social requirements.

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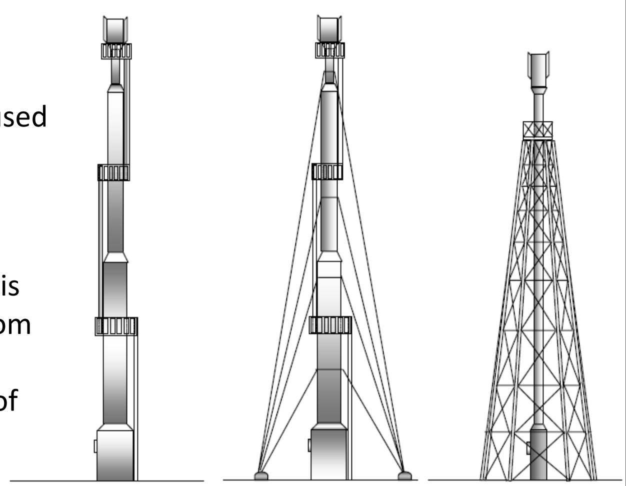
• Flare Type

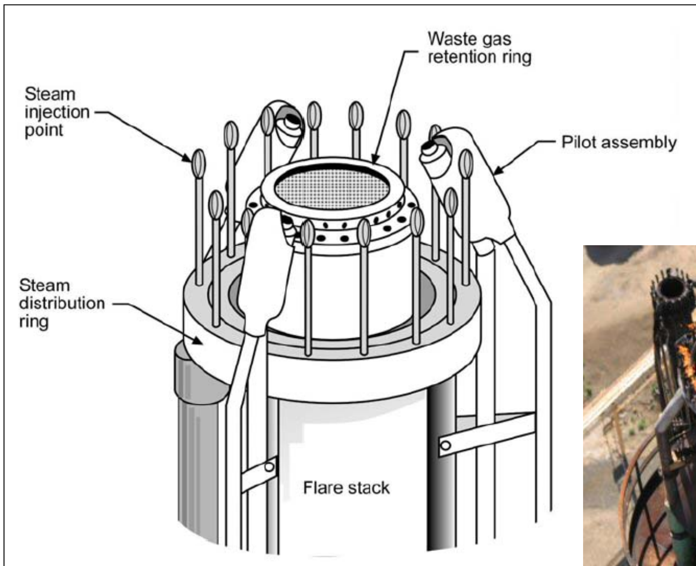
Elevated Flare **Ground Flare**

- **Elevated flare:**
- The most commonly used type in refineries and chemical plants.
- Large capacities.
- The waste gas stream is fed through a stack from 32-320 ft tall and is combusted at the tip of the stack.



(a) Self-Supported (b) Guy-wire Supported (c) Derrick Supported

94



Steam Assisted Elevated Flare System

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Elevated Flare

- The elevated flare, can be
  - steam assisted,
  - air assisted or
  - non-assisted.
- **Advantages**
  - Steam / air injection promote **smokeless** combustion
  - adequately elevated flare has the best dispersion characteristics for malodorous and toxic combustion products
- **Disadvantage**
  - steam injection/air injection cause **noise** pollution.
  - Capital costs are relatively high and large footprint

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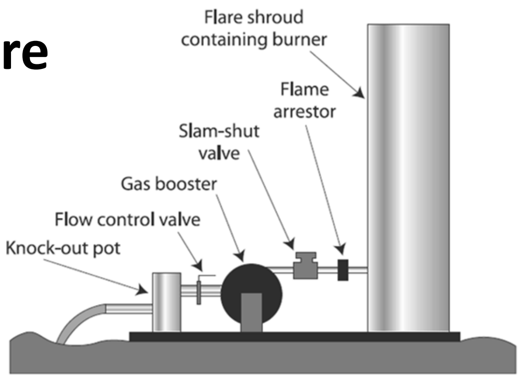
Ground Flare



- Smokeless operation with essentially no noise
- Poor dispersion of combustion product because it stack is near to ground,
- this may result in severe air pollution or hazard if the combustion products are toxic or in the event of flame-out.
- Multijet flare to increased capacity

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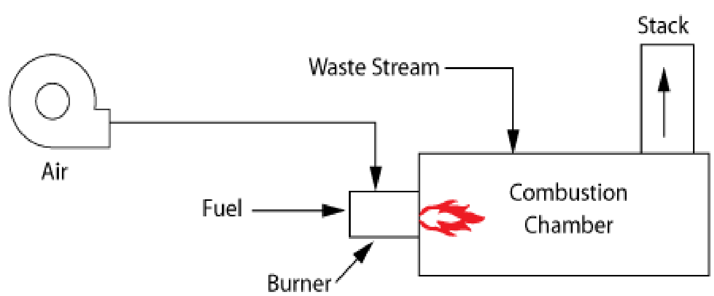
2. Thermal Oxidizers



- A thermal oxidizer burns VOC-containing gas streams in an enclosed refractory-lined chamber that contains one or more burners.
- The incoming waste hydrocarbon vapor can be co-fired with natural gas or propane to maintain consistently high oxidation temperatures.
- Heat recovery may be achieved with recuperative heat exchangers, with a regenerative design that employs ceramic beds, or by heating process fluids or generating steam.

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- The contaminated gas stream does not usually pass through the burner itself, unless a portion of the gas stream is used to provide the oxygen needed to support combustion of the fuel.
- Instead, the burners are used to heat the gas stream to the temperature necessary to oxidize the organic contaminants.
- Most thermal oxidizers operate at temperatures of 700-1,000°C.
- Typical residence times are 0.3 to 0.5 seconds, but may exceed 1 second.

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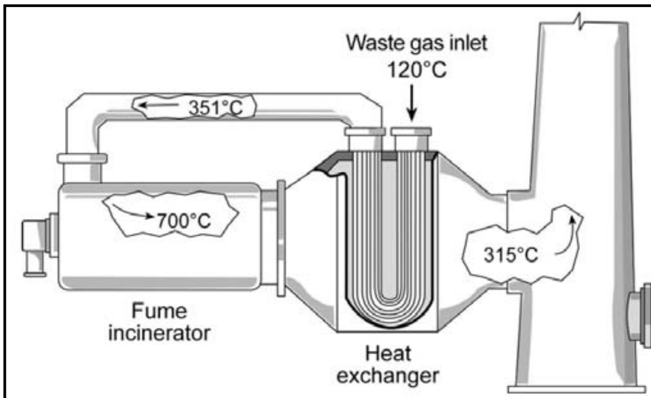

Recuperative Thermal Oxidizer

- A recuperative thermal oxidizer uses a shell-and-tube type heat exchanger to recover heat from the exhaust gas and preheat the incoming process gas, thereby reducing supplemental fuel consumption.
- Recuperative heat exchangers with a thermal energy recovery efficiency of up to 80%, mostly 50-60%, are in common commercial use.

100

- Because of the presence of the heat exchanger, particulate concentrations in the inlet gas stream must be minimized.
- Particulate matter can foul the inside surfaces of the tubes, reducing the thermal efficiency.
- PM can also increase the resistance to flow through the heat exchanger, reducing the fan's ability to move volume through the system, potentially causing fugitive emissions at the source.
- Some recuperative units include clean-out ports and access hatches to facilitate cleaning.

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Regenerative Thermal Oxidizer

- A regenerative thermal oxidizer uses **ceramic** **beds** to absorb heat from the exhaust gas and uses the captured heat to preheat the incoming process gas stream.
- Destruction of VOCs is accomplished in the combustion chamber, which is always fired and kept hot by a separate burner.
- This system provides very high heat recovery of up to 98%, and can operate with very lean process gas streams because supplemental heat requirements are kept to a minimum with the high heat recovery.
- The gas steam may contain less than 0.5% VOC, and have a low heat value.

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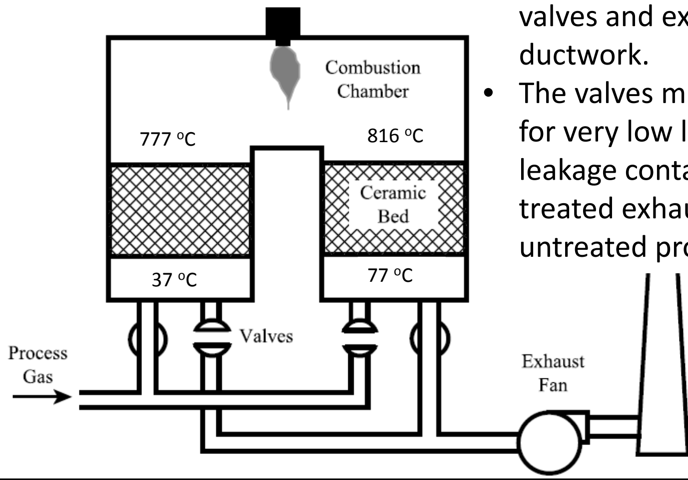
Two-chamber Regenerative Thermal Oxidizers

- Valves switch the direction of flow so that the incoming gas passes through the freshly warmed bed.
- Cycling valve every 30 to 120 sec
- T<70° C
- Requires large, rapid-cycling valves and extensive ductwork.
- The valves must be designed for very low leakage since any leakage contaminates the treated exhaust gases with untreated process gas.



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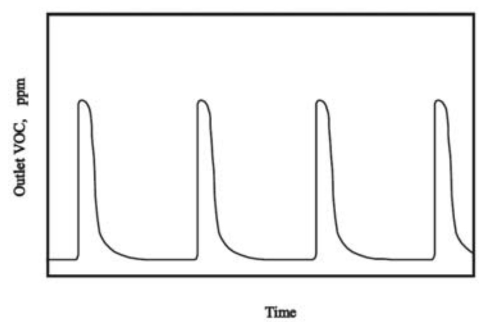
- Critical high-efficiency systems use zero-leakage valves with an air purge between double-seal surfaces.
- If the VOC emissions from a two-chamber bed are measured, the concentration would vary as shown Figure.
- Intermittent spikes in the VOC concentration would occur each time the valves switch the direction of flow,



- Untreated gas present in the inlet bed when it is suddenly switched to the outlet.

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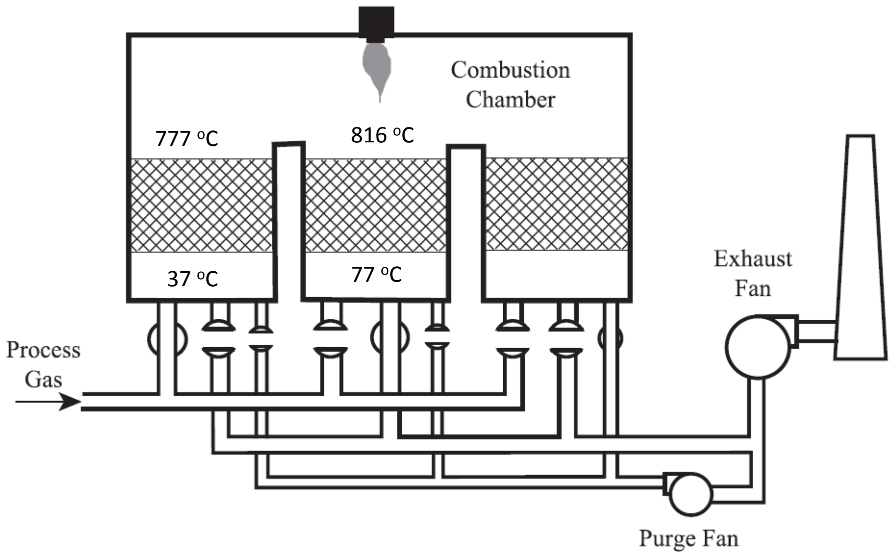

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Advantages of Thermal Oxidizers

- An **advantage** of thermal oxidation in an incinerator is the **high destruction efficiency** that can be obtained by proper control of the combustion chamber design and operation.
- If temperatures are maintained above 980°C, greater than 99% hydrocarbon destruction is routinely achievable.
- This efficiency depends on residence time, temperature, and mixing
  - or the three Ts: (Time, Temperature, and Turbulence) in the combustion chamber.

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Challenges to Thermal Oxidizers

- Thermal oxidizers can be costly to install because of required support equipment, including
  - high pressure fuel supplies (for example, natural gas),
  - substantial process-control and monitoring equipment.
- In addition, public perception of a new "incinerator" can make it difficult to locate and permit a new unit.

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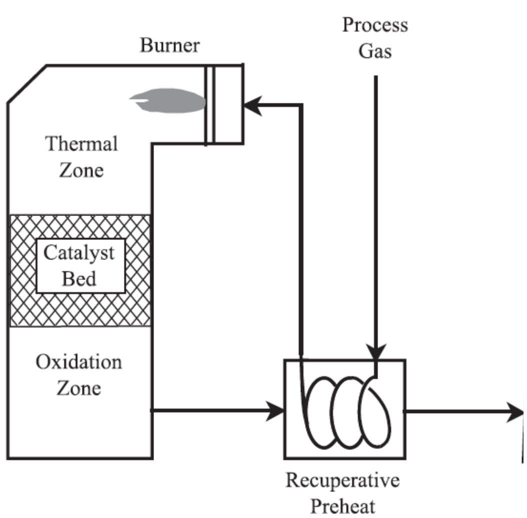
Catalytic Oxidation System



- Catalytic oxidizers are designed with both recuperative and regenerative heat exchangers.
- The catalyst causes the oxidation reaction to occur at much lower temperatures than thermal oxidation.

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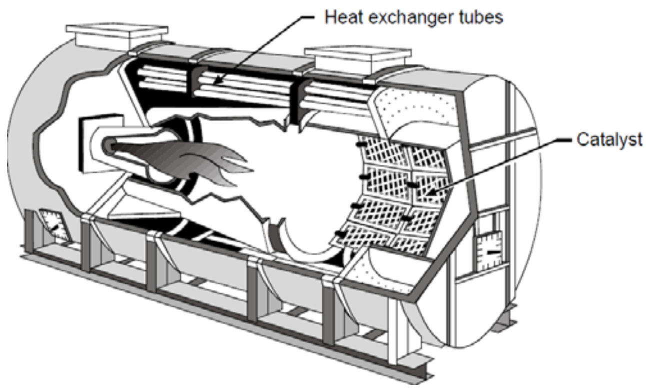
- The support structure of catalysts is arranged in a matrix that provides high geometric surface area, low pressure drop and uniform flow.



- Structures providing these characteristics include honeycombs, grids and mesh pads.

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Catalytic Oxidation System

- A typical minimum inlet temperature = 260- 315°C.
- For each 1% LEL *(The lower explosive limit)*concentration that is oxidized in the catalyst bed, the gas stream temperature will increase about 15°C.
- Catalytic oxidizers are usually used only on gas streams with an organic vapor concentration <25% of the LEL.
- Extremely high temperature will damage the catalysts
- High cost of the catalyst
- Performance problems related to physical and chemical deterioration of the catalyst material.

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Catalyst Fouling

- Catalytic oxidizers usually cannot be used effectively on waste gas streams with high concentrations of liquid or solid particles.
- These particles deposit on the catalyst surface, blocking access for the organic compounds.
- When low concentrations of particles are present, periodically cleaning the catalyst can restore more than 90% of its activity.

Catalyst Poisoning

- Certain metals can react or alloy with the catalyst, permanently deactivating it.
- Fast acting poisons include mercury, phosphorus, arsenic, antimony and bismuth.
- Slow acting poisons include lead, zinc and tin.
- At temperatures above about 535 °C, even copper and iron are capable of alloying with platinum, reducing its activity.

Catalyst Masking

- Some materials, principally sulfur and halogen compounds, have a high adsorptive affinity for some catalytic surfaces, reducing the active sites available to the organic compounds.