

## Chapter 9

### **Combustion Processes and In Combustion Air Emission Control**

## Combustion Systems

- Stationary
  - Pulverized coal combustor
  - Fluidized bed combustor
  - ...
- Mobile (Engines)
  - Diesel engines
  - Gasoline engines
  - ...

**Stationary Combustor Systems**

Coal, oil and gas combustion to generator steam (electricity, process steam, etc.)

**Dryers and ovens**  
(Bricks, food, coated surfaces)

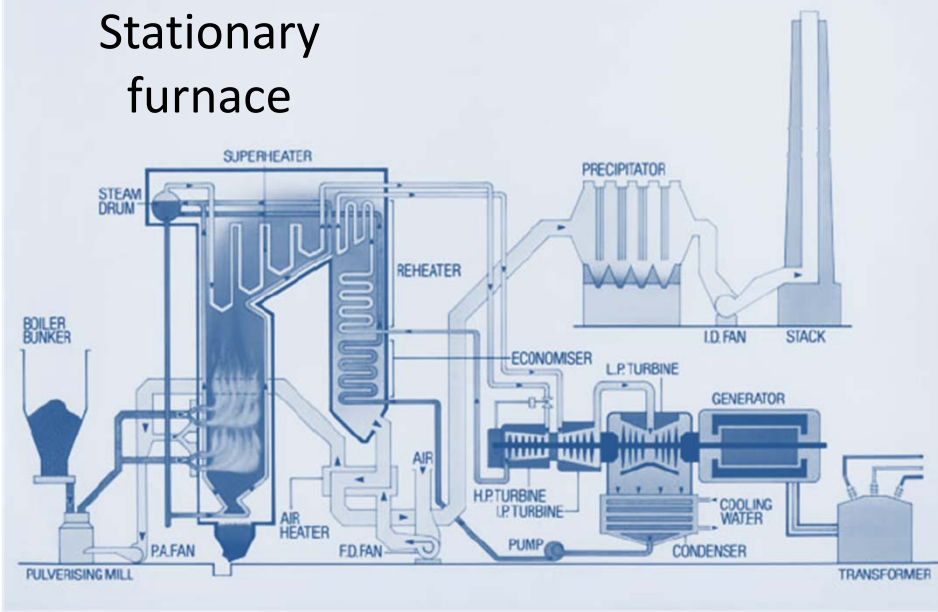


**Flaring**

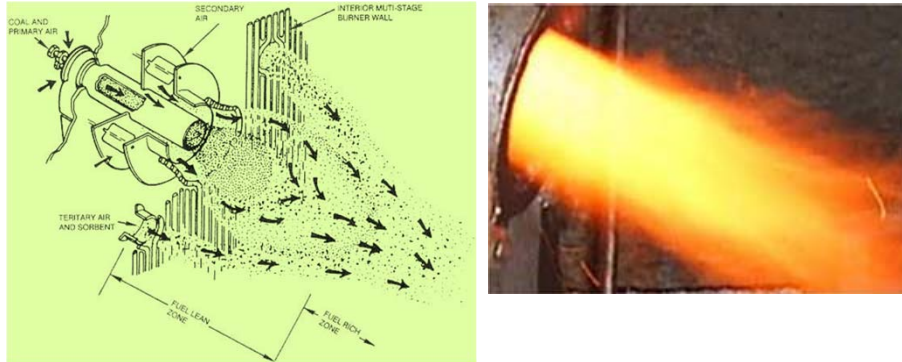


**Waste incinerator**

**Stationary furnace**



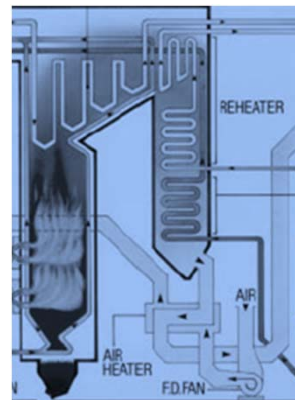
## 1. Pulverized Wood/Coal Burner



Coal is ground to fine particles (normally ranging from 2 mm to 50 mm) separated using a mesh screen before being fed to the burner.

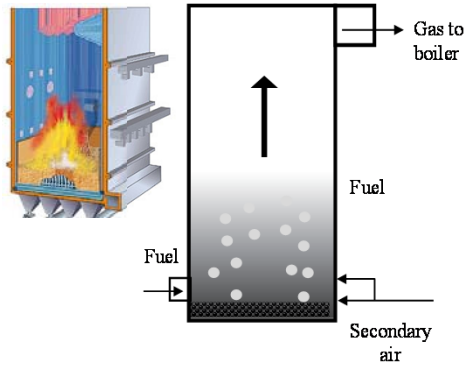
## 1. Pulverized Coal Burner

- The coarse ash particles fall down to the bottom of the furnace as a solid waste, which is referred to as bottom ash or slag;
- while the rest of the fine ash particles are carried along the combustion process with flue gas.
- In general, the ash particles formed during a pulverized coal combustion process is very fine and approximately 65 to 85% of the ash is fly ash.

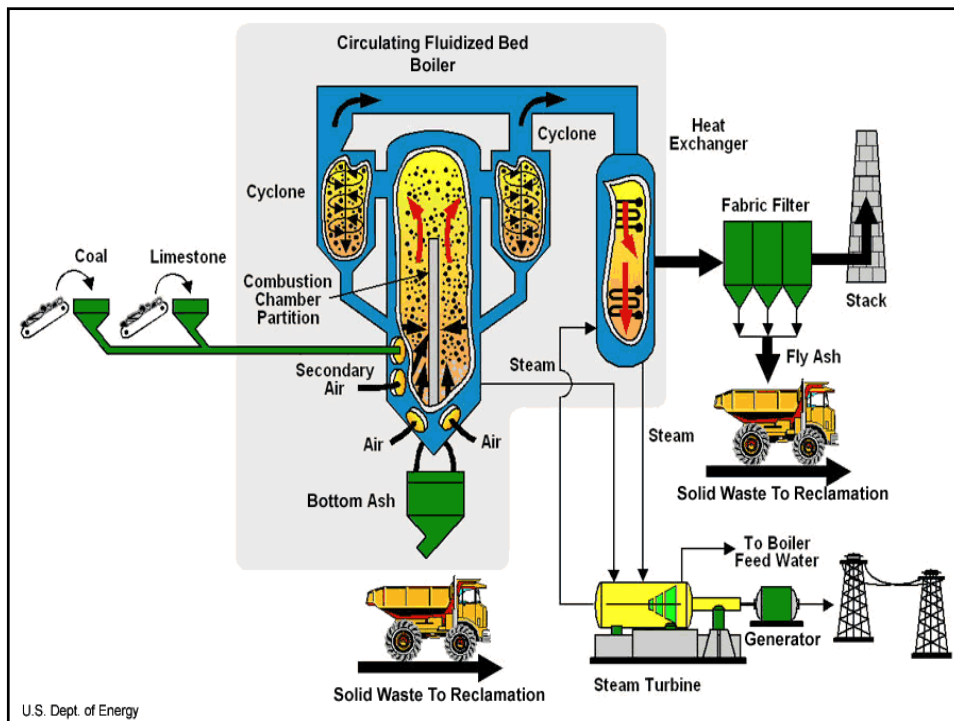
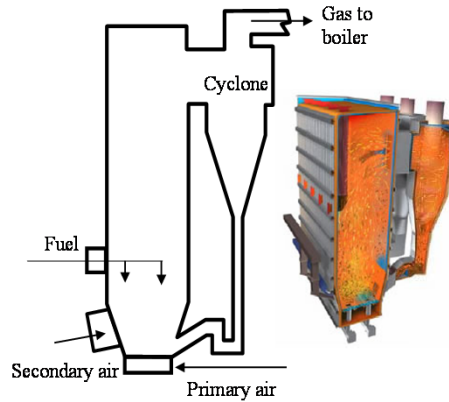


## 2. Fluidized Bed Combustion

### 1. Bubbling fluidized bed



### 2. Circulating fluidized bed



## Particle Dynamics in A Fluidized Bed

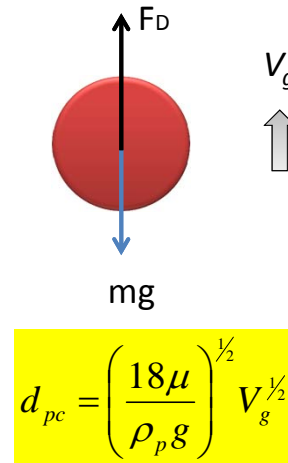
- Consider a spherical particle of  $d_{pc}$  suspended in a gas moving upward

$$mg = F_D$$

$$mg = 3\pi\mu d_{pc} V_g$$

$$\left( \frac{\rho_p \pi d_{pc}^3}{6} \right) g = 3\pi\mu d_{pc} V_g$$

$$d_{pc}^2 = \frac{18\mu}{\rho_p g} V_g$$



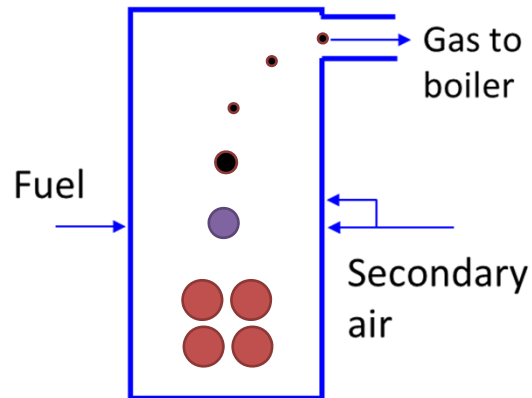
## In a Bubbling Fluidized Bed

- In bubbling fluidized bed combustion (BFBC) the bed particles behave like a boiling fluid but remain in the bed while the gas flows upward at a velocity of 1 to 3 m/s.
- We can estimate the particle size suspended in the bed using particle dynamics

Say,  $V_g = 1$  m/s, ignore  $C_c$  use air viscosity of  $4.5 \times 10^{-5}$  at 1000 K and 1 atm.

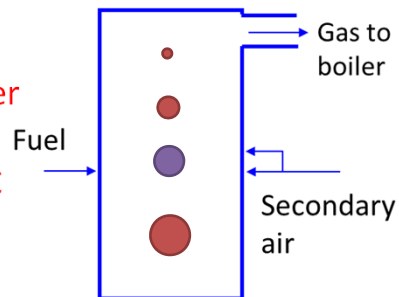
$$\begin{aligned} d_{pc} &= \left( \frac{18\mu}{\rho_p g C_c} \right)^{1/2} V_g^{1/2} = \left( \frac{18 \times 4.5 \times 10^{-5}}{1000 \times 9.81} \right)^{1/2} \\ &= 2.87 \times 10^{-4} \text{ m} \\ &= 287 \mu\text{m} = 0.287 \text{ mm} \end{aligned}$$

- What happens to smaller particles
- What happens to large particles

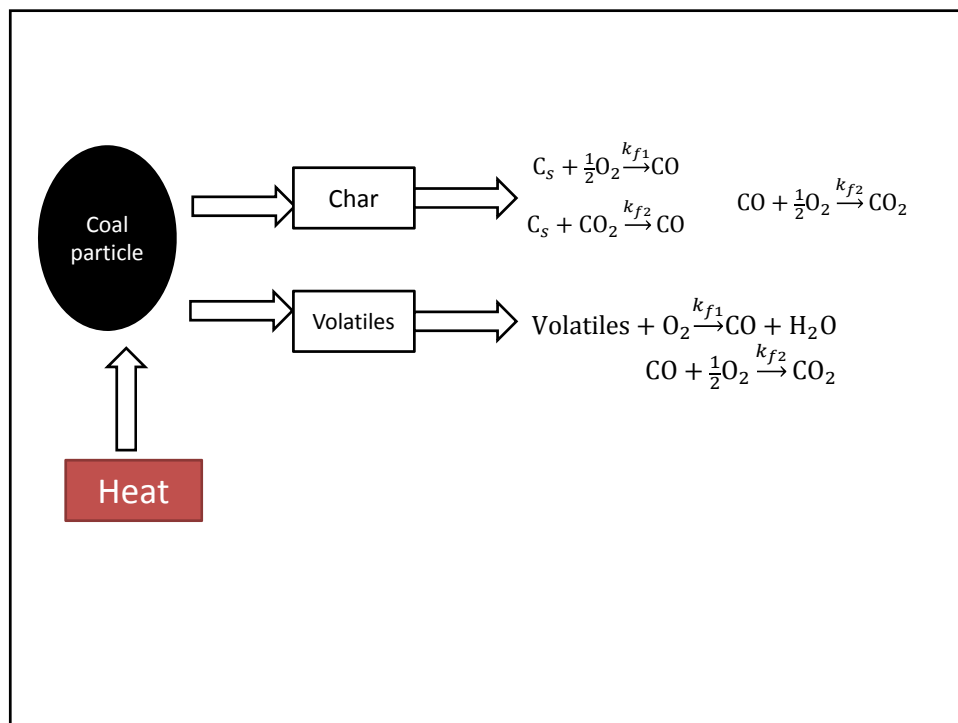
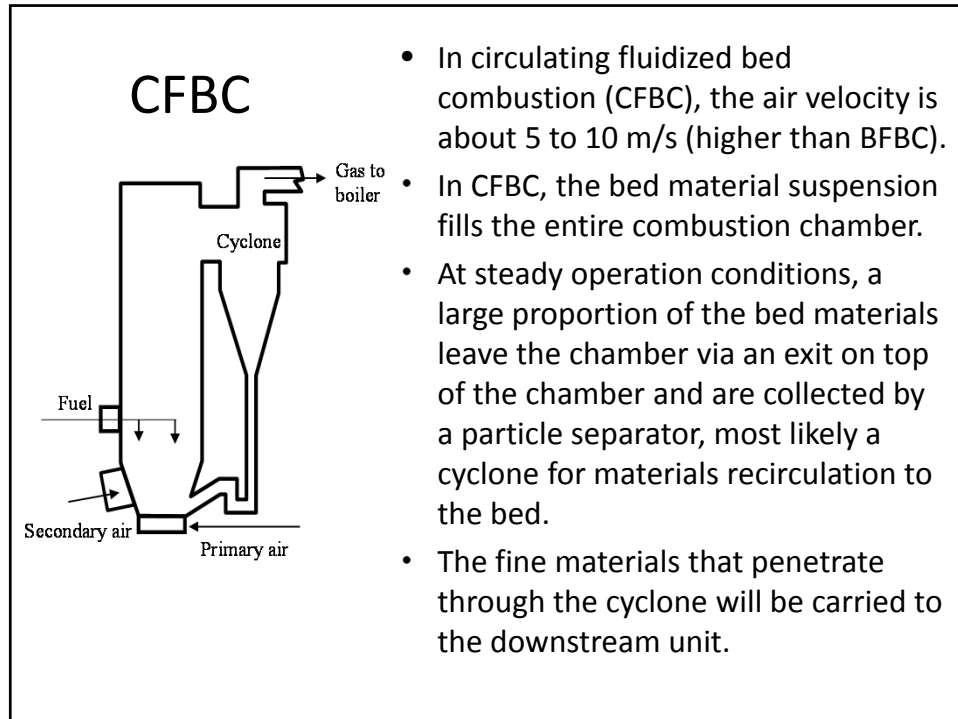


### Bubbling Fluidized Bed

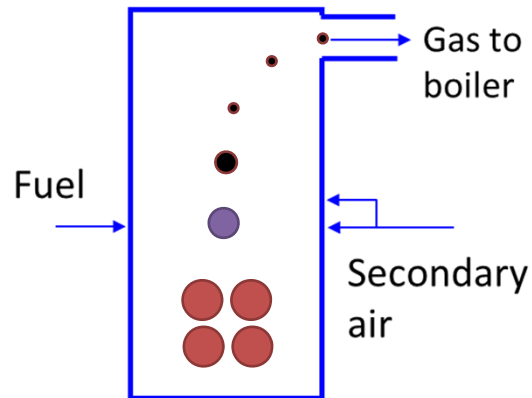
- The fuel particle size is larger while the furnace temperature is lower in FBC (800 - 950 °C) compared to pulverized coal combustion (>1000 °C).



- Due to the relatively low combustion temperature, FBC can handle low-grade fuels such as wet sludges or waste solid fuels with a relatively low NO<sub>x</sub> emission.
- On the other hand, the emissions of N<sub>2</sub>O may sometimes be high.

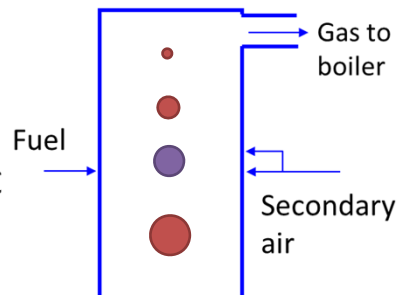


- What happens to smaller particles
- What happens to large particles



### Bubbling Fluidized Bed

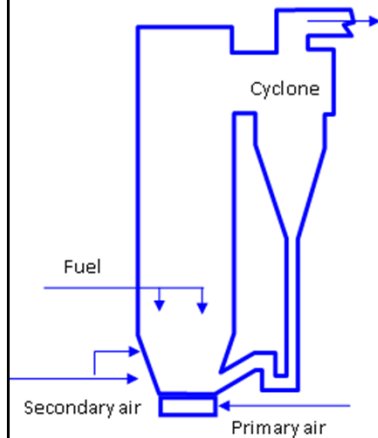
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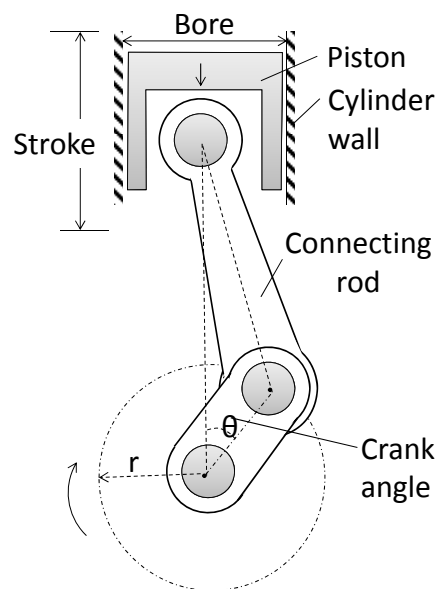


## CFBC



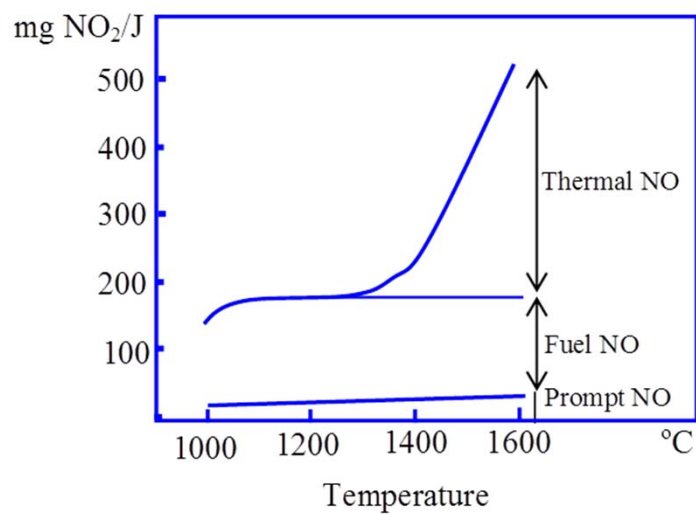
- In circulating fluidized bed combustion (CFBC), the air velocity is about 5 to 10 m/s (higher than BFBC).
- In CFBC, the bed material suspension fills the entire combustion chamber.
- At steady operation conditions, a large proportion of the bed materials leave the chamber via an exit on top of the chamber and are collected by a particle separator, most likely a cyclone for materials recirculation to the bed.
- The fine materials that penetrate through the cyclone will be carried to the downstream unit.

## Internal Combustion Engines



## NO<sub>x</sub> Control in Stationary Combustion Systems

### Recall: NO<sub>x</sub> Formation Mechanisms



## **NO<sub>x</sub> Control in Combustion**

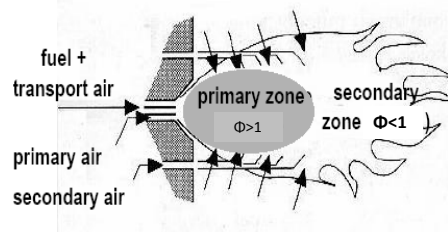
- Removal of nitrogen oxides during combustion process is much more favorable than post-combustion by flue gas cleaning.
- With the recent advances in NO<sub>x</sub> control during the combustion stage, conditions in the boiler furnaces now are no longer the same as those in the 1980s.
- The NO<sub>x</sub> emissions are dramatically reduced with the development of entirely new combustion techniques, such as fluidized bed combustion, where the combustion temperatures are low.

## **Typical Approaches**

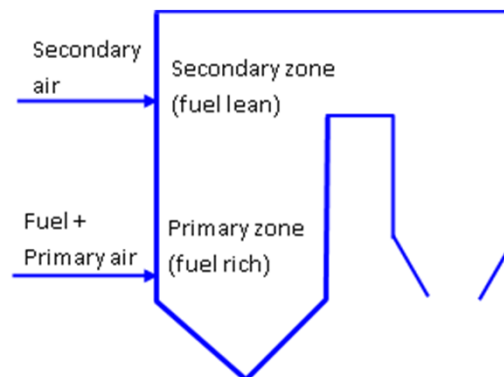
- Air staging
- Fuel staging
- Flue/Exhaust gas recirculation
- Reducing temperature of preheated combustion air
- Reducing the flame temperature by a long flame, and Reducing the excess air.

## Air staging low NO<sub>x</sub> burner mechanisms

- Primary air supplied as an oxidizer is introduced at the root of the flame, where **fuel rich combustion** takes place and most of the HCN and NH<sub>3</sub> are oxidized to molecular nitrogen.
- The remaining air needed for combustion is supplied to the flame from the flame periphery, where little HCN and NH<sub>3</sub> are left to produce nitric oxide.
- As a result of this air staging, the peak flame temperatures in burners remain lower than conventional burners, and the formation of thermal NO is reduced.



## Air Staging In Furnace



- The primary air is supplied at lower rows of burners, where combustion is under the **fuel rich condition**.
- The remaining or secondary air or is supplied at the upper level of the furnace, in the middle or top of the furnace.

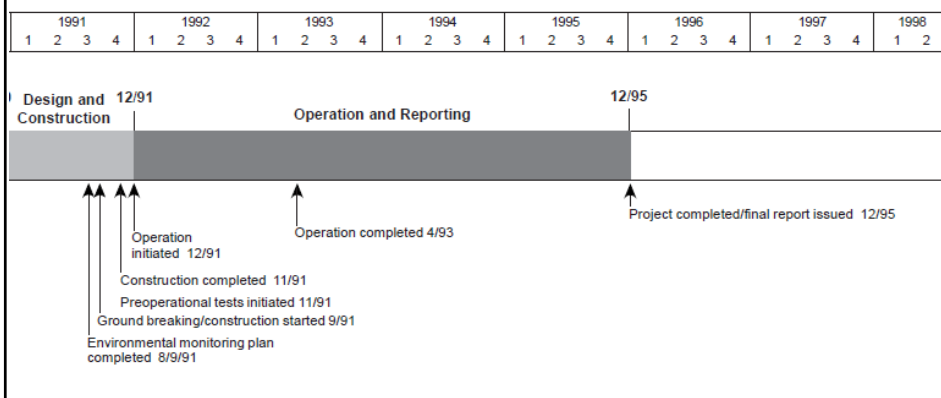
## Air Staging Effectiveness

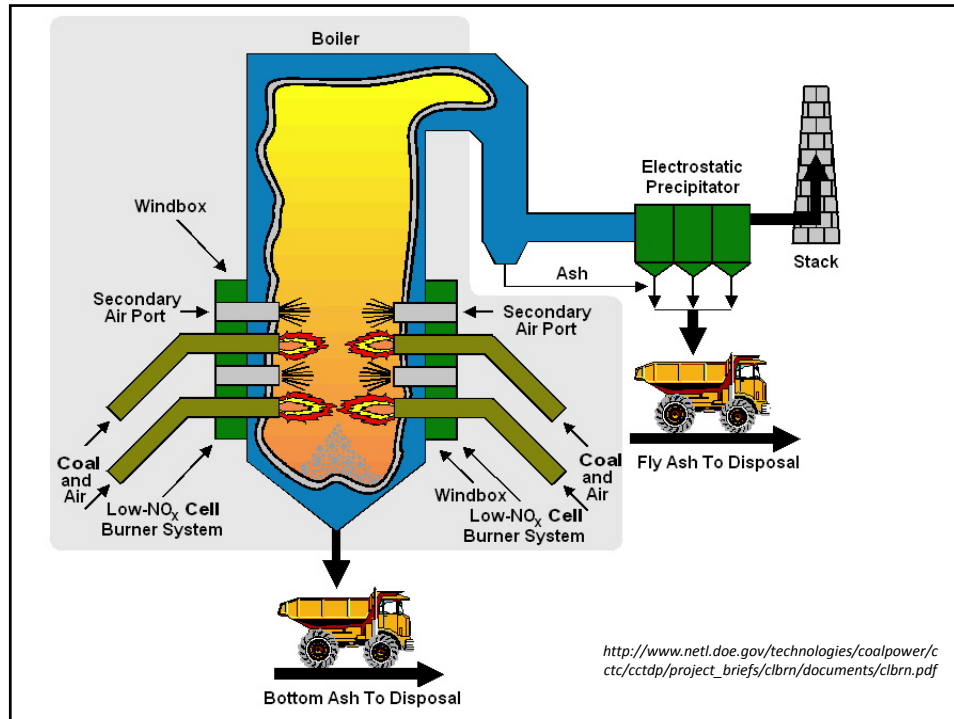
- The NO reduction by air staging varies from **10- 50%**, depending on the relative quantity of volatile compounds in the fuels.
  - For fuels with low volatiles, the fixed chars retain a considerable part of the fuel nitrogen. The nitrogen in char can form NO that cannot be effectively controlled by air staging.
  - The share of char nitrogen in the NO emission of air-staged combustion is actually higher than that from conventional pulverized coal combustion without air staging.
  - For pulverized coal combustion, the conversion rate of char nitrogen to NO varied from 20 to 80%, depending primarily on the property of the coal.
- While successful air staging reduces the NO<sub>x</sub> emission, one has to carefully monitor the possible **unburned emission components**, for example,
  - CO, C<sub>x</sub>H<sub>y</sub>, and unburned carbon in ash due to the fuel rich combustion in the primary zone.

### A Case Study

### Project Background

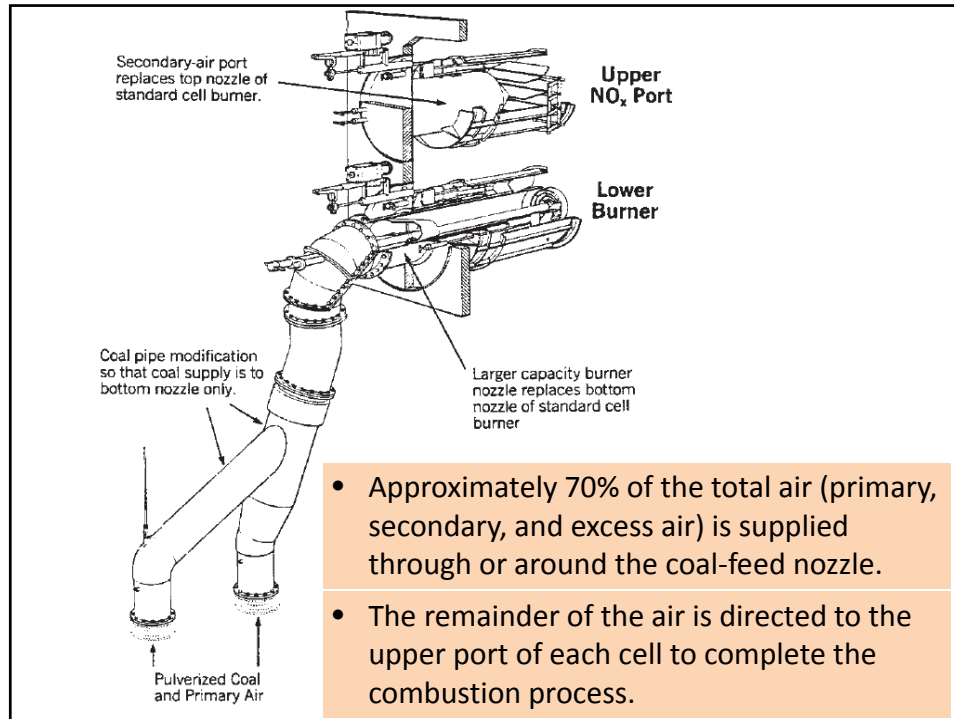
- Aberdeen, Ohio, USA
- Dayton Power and Light Company's J.M. Stuart Plant, Unit No. 4
- **Fuel:** Bituminous coal, 1.2% sulfur
- **Project Funding:** Total \$11,233,392





## Technology/Project Description

- The technology replaces the upper coal nozzle of the standard two-nozzle cell burner with a secondary air port.
- The lower burner coal nozzle is enlarged to the same fuel input capacity as the two standard coal nozzles.
- The technology operates on the principle of (*air*) staged combustion to reduce NO<sub>x</sub> emissions.
- Approximately 70% of the total air (primary, secondary, and excess air) is supplied through or around the coal-feed nozzle.
- The remainder of the air is directed to the upper port of each cell to complete the combustion process.
- The fuel-bound nitrogen compounds are converted to nitrogen gas, and the reduced flame temperature minimizes the formation of thermal NO<sub>x</sub>.



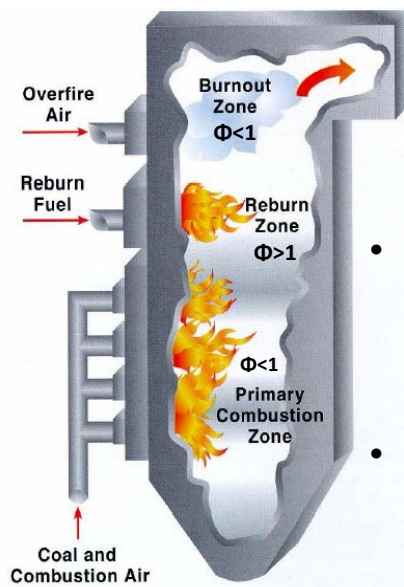
### Environmental Results Summary

- Short-term optimization testing (all mills in service) showed NO<sub>x</sub> reductions in the range of 53.0–55.5%, 52.5–54.7%, and 46.9–47.9% at loads of 605 MWe, 460 MWe, and 350 MWe, respectively.
- Long-term testing at full load (all mills in service) showed an average NO<sub>x</sub> reduction of 58% (over 8 months).
- Long-term testing at full load (one mill out of service) showed an average NO<sub>x</sub> reduction of 60% (over 8 months).
- Carbon monoxide (CO) emissions averaged 28–55 ppm at full load with LNCB<sup>®</sup> in service.
- *Fly ash increased, but downstream ESP performance remained virtually unchanged.*

## Operational and Economic Results

- Unit efficiency remained essentially unchanged.
- Unburned carbon losses (UBCL) increased by approximately 28% for all tests, but boiler efficiency loss was offset by a decrease in dry gas loss due to a lower boiler economizer outlet gas temperature.
- Boiler corrosion with LNCB<sup>®</sup> was roughly equivalent to boiler corrosion rates prior to retrofit.
- Capital cost for a 600 MWe plant in the Midwest, with a 1.2 lb/106 Btu initial NO<sub>x</sub> emission rate and 65% capacity factor, was \$9/kW (1994\$).
- Levelized cost (15-year) for the same 600 MWe plant was estimated at 0.284 mills/kWh and \$96.48/ton of NO<sub>x</sub> removed (constant 1994\$).

## Low NO<sub>x</sub> Burner by Fuel Staging



- In the third, burnout zone, the gases exiting the reburn zone undergo additional combustion with overfire air.
- A secondary fuel is injected or blown into the upper section of the furnace. This is a secondary sub-stoichiometric reburn zone without combustion air.
- Primary zone, coal is fired through conventional or low NO<sub>x</sub> burners generally in low excess-air conditions to reduce initial NO<sub>x</sub> formation.

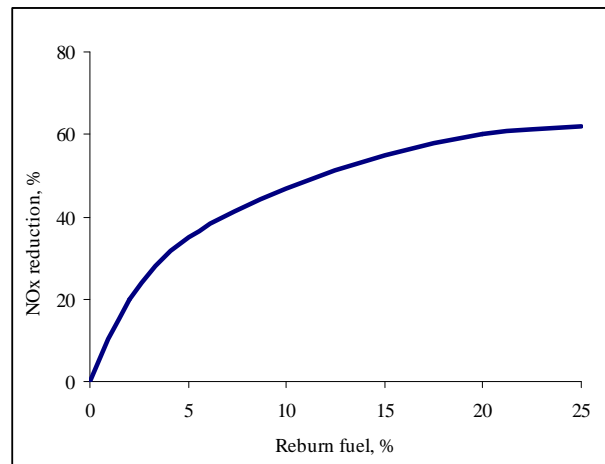
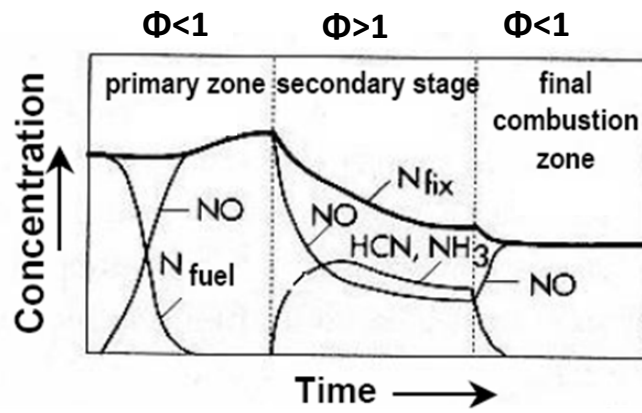


- **Secondary fuel supplied without combustion air.**
  - A primary function is to provide effective mixing of the natural gas with the bulk flue gas in the reburn zone.
  - Re-circulated flue gas is sometimes used as a carrier for the reburn fuel.
  - Currently natural gas is the most widely used secondary fuel although coal and oil are currently being demonstrated.
  - The secondary fuel breaks down at this stage to produce hydrocarbon fragments, which react with the NO<sub>x</sub> produced in the primary combustion zone and reduce it to atmospheric nitrogen.
  - In general, 10-30% of the total heat input can be used as the secondary fuel. The process creates fuel-rich oxygen-deficient reducing zone, which decomposes the NO<sub>x</sub>, formed in the primary combustion zone.
- **This final combustion stage is necessary to consume the carbon monoxide and unburnt hydrocarbons leaving the reburn zone.**

## Cost-effectiveness

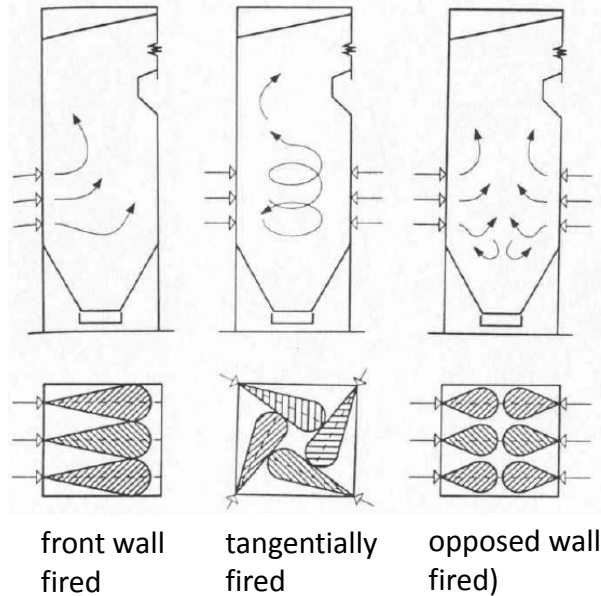
- The technology is capable of achieving relatively high NO<sub>x</sub> reduction (up to 70%).
- The cost of the secondary fuel influences the operating costs considerably.
- Hence reburning costs can be higher than other primary measures for NO<sub>x</sub> control.

## Fuel Staging Effectiveness



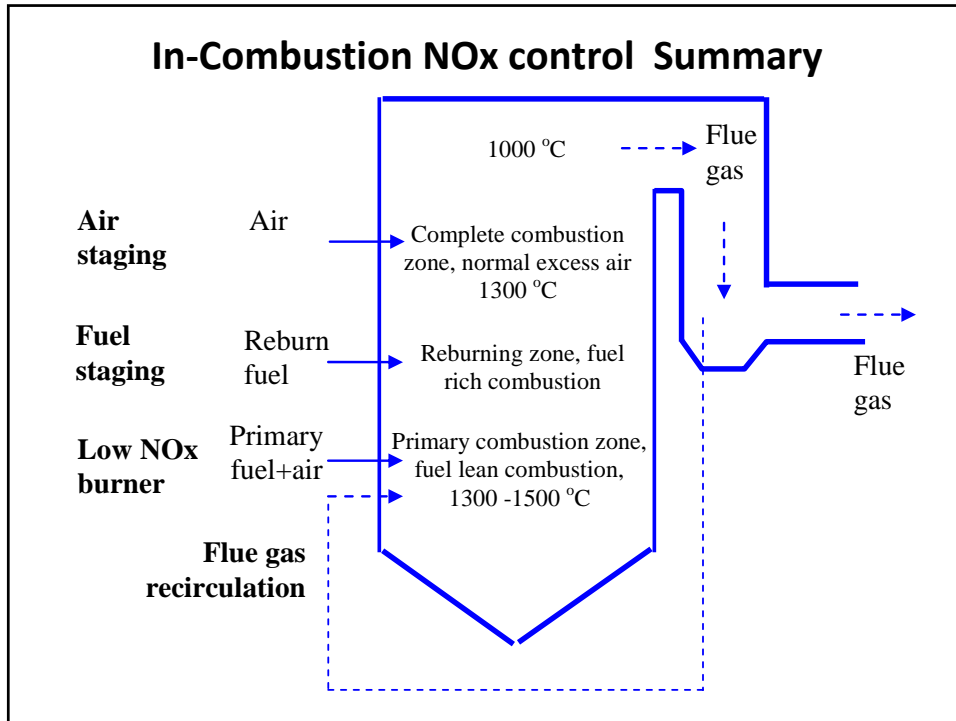
A typical efficiency curve for fuel staging  
(using micronized coal as reburn fuel)

### Combination Furnaces with low NO<sub>x</sub> burners



### Flue Gas Recirculation

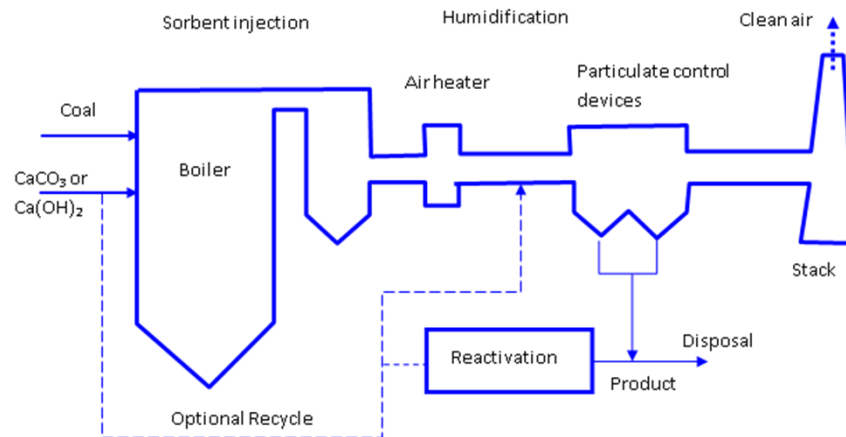
- Flue gas recirculation is used primarily for combustion of oil or gas fuels.
- Part of the flue gas is redirected to the primary combustion zone.
- The recirculated flue gas results in a lower temperature in the combustion zone and consequent low NO<sub>x</sub> emissions.



Technology	Advantageous	Problems
Low excess air		Fuel burnout decreases
Air staging	Always for NO <sub>x</sub> reduction	Limited effect, increased risk for corrosion, slagging
Low NO <sub>x</sub> burner	Always for NO <sub>x</sub> reduction	Minor decrease in fuel burn-out
Fuel staging in furnace	Always, especially for same fuels	Capital cost of system modification
Flue gas recirculation	Effective for high temperature oil or gas fired furnaces	Low efficiency if not combined with other methods

## In-combustion SO<sub>2</sub> Capture

### SO<sub>2</sub> Capture by Furnace Sorbent Injection Pulverized Coal Combustion

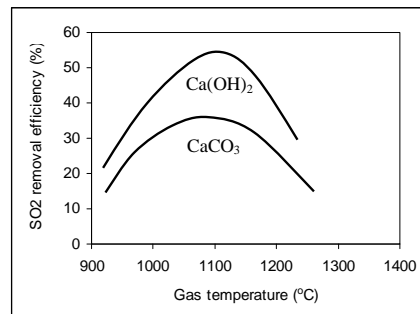


## SO<sub>2</sub> Capture by Furnace Sorbent Injection

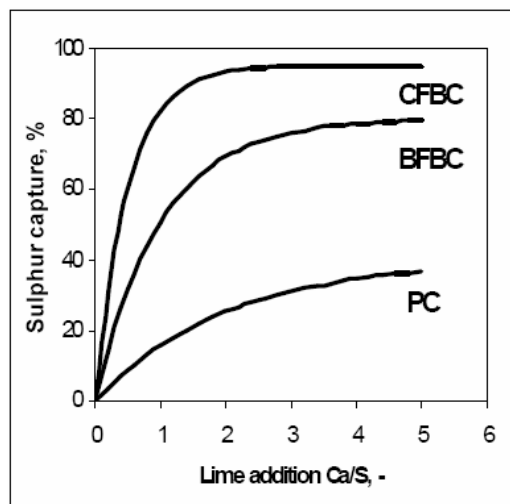
- During a combustion process before the hot combustion gases exit the combustion chamber, SO<sub>2</sub> can be captured by injection of a proper sorbent such as limestone or lime.
- The sorbent can be injected into the furnace or the hot part of the flue gas channel.
- This works well for older boilers with a relatively short remaining lifespan.
- As solid sorbent is injected into the gas furnace, more particles will join the fly ash and increase the load of downstream particulate control devices.
- In addition, an additional soot-blowing device is needed to remove solids accumulated on the inner surfaces of the furnaces, which is not a big technical problem.

## De-SO<sub>2</sub> Efficiency

- The efficiency of SO<sub>2</sub> removal by sorbent injection depends on the temperature where the sorbent is injected.
- When the sorbent is injected at a low temperature area, the SO<sub>2</sub> removal efficiencies can be in the range of 60-75 % with Ca and S molar ratios from 2-4.
- The concentration of SO<sub>2</sub> in typical flue gases from coal firing can be up to 5000 ppmv.



## *In-situ* capture in different furnaces



## Desulfurization Mechanisms

- **Decomposition of sorbent**

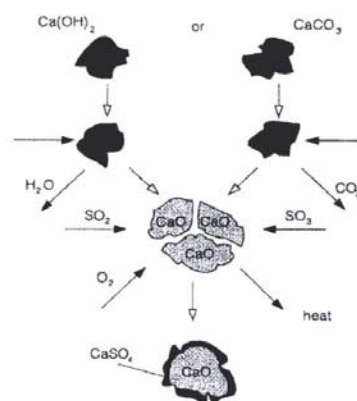
When exposed to high temperature gases, the sorbent first decomposes to CaO

- **Desulfurization reaction**

CaO then reacts with SO<sub>2</sub> and O<sub>2</sub> to form CaSO<sub>4</sub>.

- **Shell formation**

A white shell of CaSO<sub>4</sub> formed by desulphurization reactions surrounds the inner unreacted grayish portion, which slows down any further reaction as it is difficult for gas to penetrate through this shell.

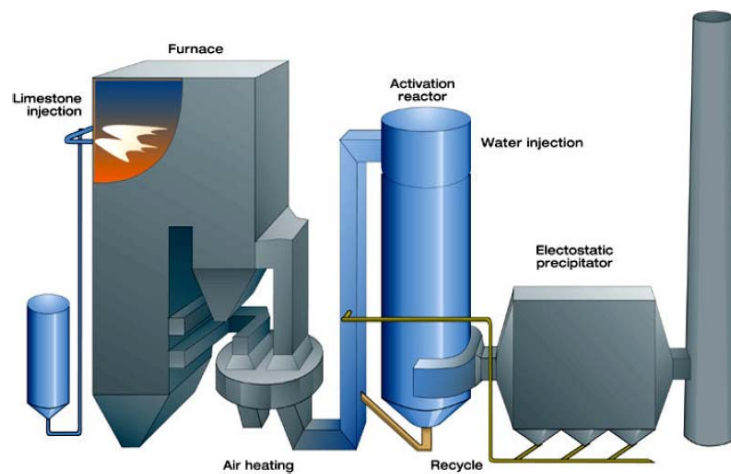


- The main solid product of the desulfurization reaction is CaSO<sub>4</sub> when temperature is below 1200 °C.

## Steam Reactivation of Partially Used Sorbent

- A large portion of the trapped CaO is unused and can be released for further reaction by the reactivation process.
- This efficiency can be further increased at a relatively higher cost by spraying water downstream into the flue gas duct before the particulate control devices in order to reactivate the spent sorbent to capture more SO<sub>2</sub>.

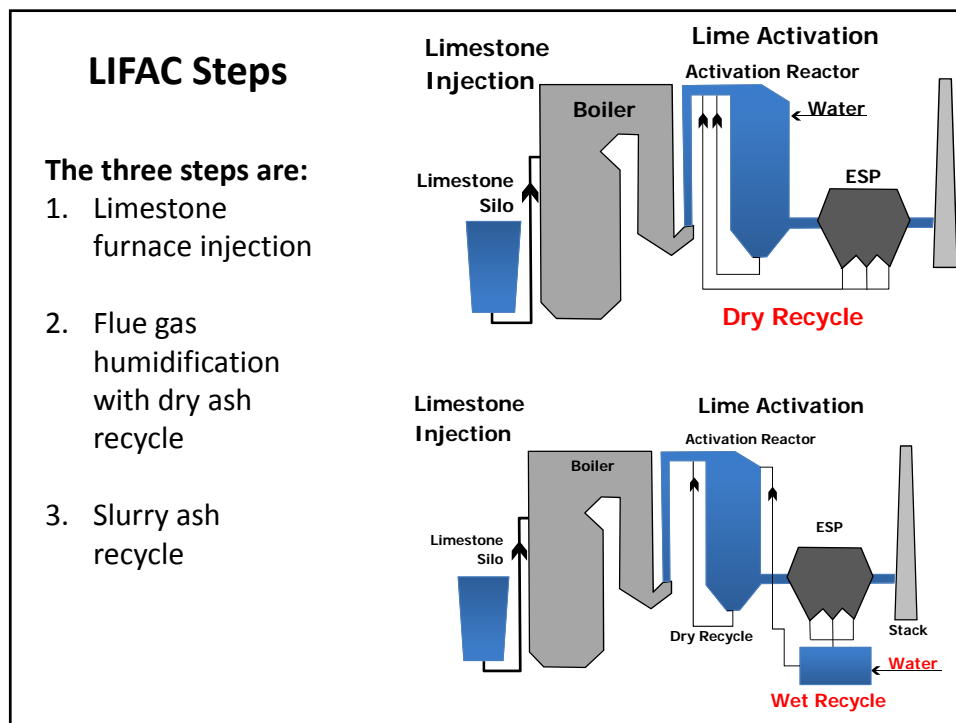
## Limestone Injection and Activation of Unreacted Calcium (LIFAC ) Process





- LIFAC process was developed by Kvaerner Pulping Power Division in Finland during the 1970s - 1980s.
- The desulfurization efficiencies were reported to be 65-85% at molar  $\text{Ca/S} = 2\text{-}2.5$ .
- In the LIFAC process, limestone is injected into the upper part of furnace near the superheater where it calcines into  $\text{CaO}$ 

$$\text{CaCO}_3 \rightarrow \text{CaO} + \text{CO}_2$$
- which then reacts with  $\text{SO}_2$  and  $\text{O}_2$  to form  $\text{CaSO}_4$ ,
 
$$\text{CaO} + \frac{1}{2}\text{O}_2 + \text{SO}_2 \rightarrow \text{CaSO}_4$$
- The spent sorbent is reactivated using water sprayed downstream in the activation reactor, where the temperature is about  $400^\circ\text{C}$ .
 
$$\text{CaO} + \text{H}_2\text{O} \rightarrow \text{Ca(OH)}_2$$
- The newly formed calcium hydroxide ( $\text{Ca(OH)}_2$ ) which is more reactive than  $\text{CaO}$ , captures with more  $\text{SO}_2$  from the flue gas stream by
 
$$\text{Ca(OH)}_2 + \text{SO}_2 \rightarrow \text{CaSO}_3 + \text{H}_2\text{O}$$
- At low temperatures the solid product is  $\text{CaSO}_3$  in the flue gas duct, which is collected together with fly ash in the downstream particulate control device, an electrostatic precipitator.



## LIFAC Cost-Effectiveness Analyses

- The first step provides 25 to 35 % SO<sub>2</sub> removal by injection of pulverized limestone into furnace.
- The investment cost is very modest, typically about 10% of the cost of the complete system.
- The activation reactor is the heart of the system. In Step 2 humidification of flue gas and recycle of dry ash increase the SO<sub>2</sub> removal up to 85 %.
- The investment cost of Step 2 is roughly 80 % of the cost of the complete system.
- The addition of Step 3 - slurry ash recycle – increases the SO<sub>2</sub> removal to 90 % with about 10 % of the total investment cost.

### SaskPower Company, Shand Power Station Shand, Saskatchewan, Canada

- Boiler capacity: 300 Mwe
- Fuel: :Lignite coal
- Sulphur content in coal as received: 0.5%
- Number of reactors: 1 reactor installed for half of the flue gas flow
- Operation started: 1992
- Slurry recycle system added



## **SO<sub>2</sub> Capture in Fluidized Bed Combustion**

- In fluidized bed combustion, SO<sub>2</sub> sorbent can be mixed with other bed materials for de-S.
- Since the temperature in the chamber is low (800 - 950 °C) , the CaSO<sub>4</sub> formed remains a stable compound.
- In addition to relatively low NO<sub>x</sub> emissions due to low combustion temperature, FBC can also capture any H<sub>2</sub>S, forming CaS that can be oxidized to CaSO<sub>4</sub> before it is oxidized into SO<sub>2</sub>.

## **Drawbacks**

- Increased downstream fly ash
- Increased erosion to the furnace walls.
- Fine particles are produced due to attrition and abrasion.

## Furnace Injection of Alkaline Sorbents for Sulfuric Acid Removal\*

Sulfuric acid controls are becoming of increased interest for coal-fired power generating units for a number of reasons.

- It is a Toxic Release Inventory substance
- It is a potential precursor to acid aerosol/condensable emissions from coal-fired boilers
- SO<sub>3</sub>/sulfuric acid in the flue gas can lead to power plant operating problems such as air heater plugging and fouling, back-end corrosion, and **plume opacity**.
- These issues will likely be exacerbated with the retrofit of selective catalytic reduction (SCR) for NO<sub>x</sub> control, as SCR catalysts are known to further oxidize a portion of the flue gas SO<sub>2</sub> to SO<sub>3</sub>.
- And sulfuric acid may also corrode the metal catalyst in the SCR

*\*Courtesy: Gary M. Blythe, URS Corporation, Austin, Texas, USA*

## Technical Background

- Sulfuric acid is present in most flue gases from coal combustion because a small percentage of the SO<sub>2</sub> produced from the sulfur in the coal (approximately 0.5 to 1.5%) is further oxidized to form SO<sub>3</sub>.
- The SO<sub>3</sub> combines with flue gas moisture to form vapor-phase or condensed sulfuric acid at temperatures below about 260°C.

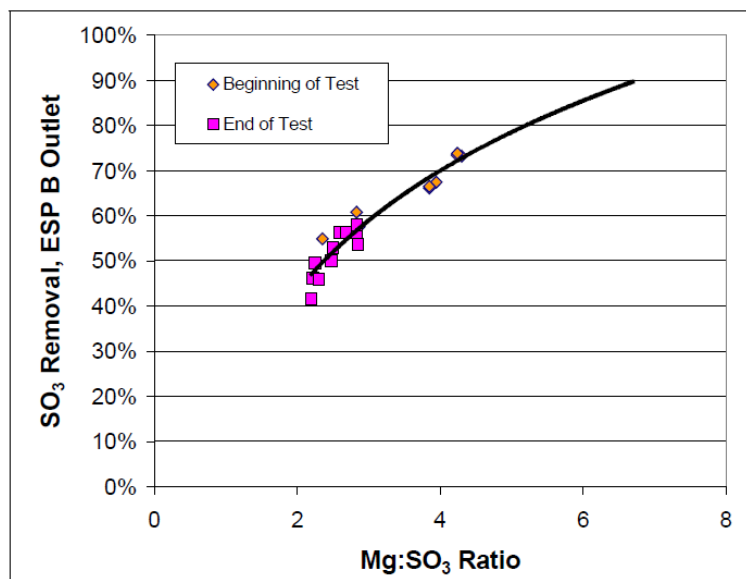
### Comparison of Furnace Injected Alkaline Sorbents for Sulfuric Acid Control (based on short-term test results)

Sorbent	Injection Mode	Injection Location	Estimated Molar Ratio to Achieve 60% Sulfuric Acid Removal	Estimated Molar Ratio to Achieve 90% Sulfuric Acid Removal
Dolomite	Dry Power	Top Front Row of Burners, Unit 2	30:1*	40:1*
Pressure-Hydrated Dolomitic Lime	Atomized Slurry	Across from Boiler Nose (11 <sup>th</sup> Floor), Unit 3	12:1*	Not Achieved
Commercial Magnesium Hydroxide	Atomized Slurry	Across from Boiler Nose (11 <sup>th</sup> Floor), Unit 3	4:1 – 5:1**	12:1**
Byproduct Magnesium Hydroxide	Atomized Slurry	Across from Pendant Superheat Tubes (14 <sup>th</sup> Floor), Unit 3	4:1**	7:1**

\*Molar ratio of calcium plus magnesium in reagent injected to SO<sub>3</sub> at the economizer outlet under baseline conditions

\*\*Molar ratio of magnesium in reagent injected to SO<sub>3</sub> at the economizer outlet under baseline conditions

### Long term performance using Mg



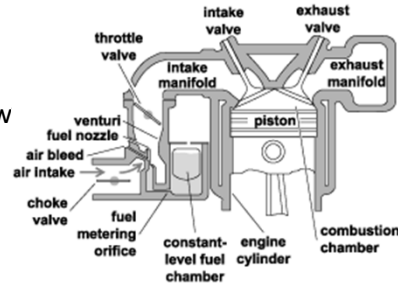
## Soot Reduction in Stationary Combustors

- Soot formation can be reduced by controlled turbulent mixing, which promotes more complete combustion.
- Additives to the fuels such as iron, nickel, manganese, or cobalt acting as catalysts can further improve the oxidation of soot.
- However, sometime these additives may also increase production of soot (uncertain)

## Air Emission Control for Internal Combustion Engines

## Carburetor

- The air and fuel are premixed in the carburetor, a device that controls the flow of air and fuel.
- The mixture is usually at an equivalence ratio of  $0.7 < \phi < 1.4$  to match the residence time for better air emission control.
- A cold engine is started with a fuel-rich mixture to secure successful ignition.
  - This results in highly incomplete combustion and high CO and HC emissions.
- Evaporation of the liquid fuel results in evaporative air emissions from the carburetor after the engine is turned off.
- Vapor recovery system and the adsorption-regeneration system can be employed to reduce the evaporative air emissions.
- Activated carbon is common adsorbent for the latter systems.



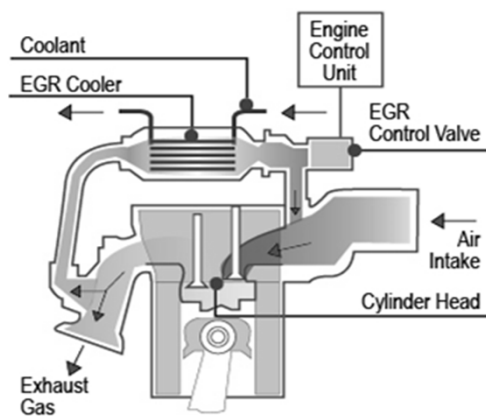
## Diesel Engines

- Diesel engines do not have carburetors for air-fuel premixing.
- Instead, air is drawn into the cylinder through the intake valve and diesel is injected directly into the cylinder of the engine.
- Diesel injection starts when it approaches the end of the compression stroke.
- At the moment, the high-temperature high pressure compressed air ignites the vapor of the diesel droplets.
- Diesel engines are usually run at fuel-lean conditions and the corresponding gaseous air pollutants such as CO and HC are reduced.
- However, the particulate matter (soot) emission is much higher than the gasoline engine because of the slower air-fuel mixing.

## Piston Engine Combustion Control

- NO<sub>x</sub> control approaches
  1. Control emission by adjusting fuel-air ratio upon demand to satisfy different performance requirements
    - Cold-start, acceleration, or part-load cruise
  2. Exhaust gas recirculation
  3. Piston design

## Engine Exhaust Gas Recirculation (EGR)



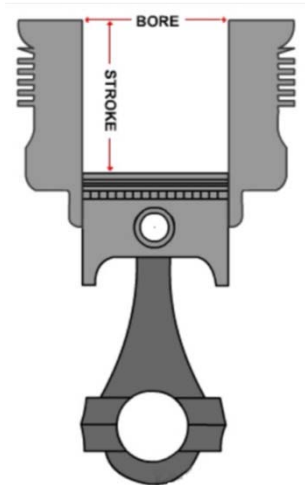


## EGR

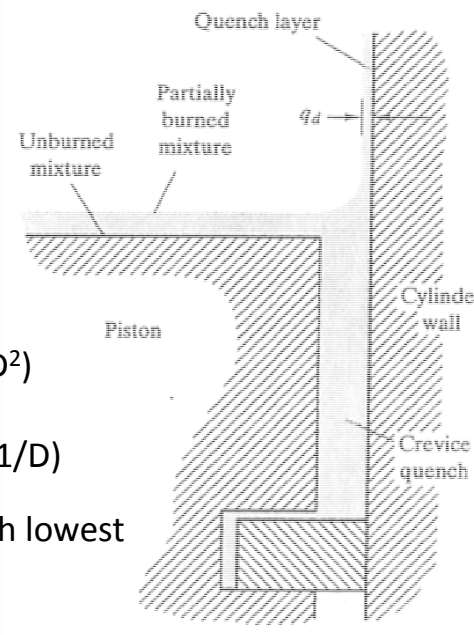
- Reduces peak gas temperature
- Reduces thermal NO
- Substantial decrease in NO can be achieved by 15-25% EGR, depending on the individual engine
- A properly designed EGR has minimal reductions in engine performance

### Engine Design: Stroke-Bore Ratio for low HC emission

- Bore = Diameter of the piston,  $D$
- Stroke = Max distance travelled by the piston,  $L$



- The larger the inside surface area of the cylinder, the greater the opportunity for unburned hydrocarbons to form.
- Inside wall area  $A \propto (DL+D^2)$
- Inside volume  $V \propto LD^2$
- $A/V = (DL+D^2)/LD^2 = (1/L+1/D)$
- Optimum design:  $L=D$ , with lowest HC emission



The diagram illustrates a cross-section of a combustion chamber. It shows a piston at the bottom and a cylinder wall on the right. The mixture is divided into three regions: 'Unburned mixture' on the left, 'Partially burned mixture' in the center, and a 'Quench layer' adjacent to the cylinder wall. A dimension line labeled '4d' indicates the thickness of the quench layer. A 'Crevice quench' is also shown at the bottom right corner where the piston meets the cylinder wall.

### Summary

#### In-combustion air pollution control

Primarily for NOX control by

- Air staging
- Fuel staging
- Flue/Exhaust gas recirculation
- Reducing temperature of preheated combustion air
- Reducing the flame temperature by a long flame, and Reducing the excess air.

Improved air-fuel mixing to reduce HC emissions

- EGR for engine emission control
- Engine designs for better combustion efficiency