NOx Reduction: Flue Gas Recirculation vs Selective Catalytic Reduction

Presented by Jason Jacobi

October 28, 2015

Agenda

- NOx Regulations
- What is NOx?
- NOx types
- How to control NOx?
- What is FGR?
- What is SCR?
- Pros/Cons
- CAPEX/OPEX

NOx Regulations

Federal Government

- EPA (US)
- CCME (Canada)

State/Provincial Government

- California (US)
- Alberta (Canada)

Local Jurisdictions

- San Joaquin Valley (US)
- Alberta Environment (Canada)

NOx Regulations
United States

BACT – Best Achievable Control Technology

BMACT – Boiler Maximum Achievable Control Technology

California & NOx Tolerance:

• 2 – 5 mmbtu	30 ppm
• 6 – 20 mmbtu	15 ppm
• 21 – 75 mmbtu	9 ppm
• 76+ mmbtu	5 ppm

San Joaquin Valley, CA

• 20+ mmbtu	5 ppm

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NOx Regulations
Canada

CCME – Canadian Council of Ministers of the Environment

Canada & NOx Tolerance:

- 40.0 g/GJ (76 ppm) current
- 13.0 g/GJ (25 ppm) proposed

Alberta Environment

Natural Gas (NG)

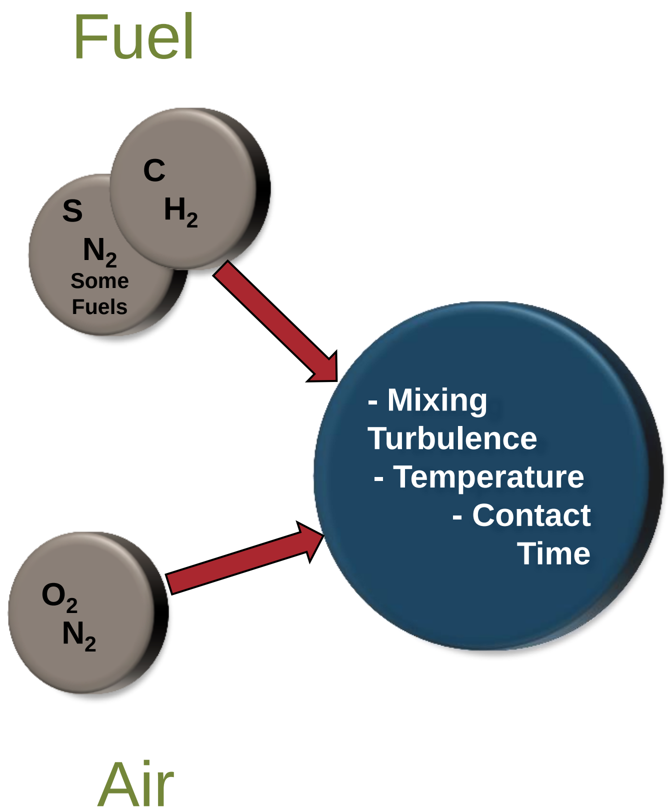
- 26.0 g/GJ (50 ppm) proposed limit
- 7.9 g/GJ (15 ppm) proposed target

Alternate Gaseous Fuel (AGF)

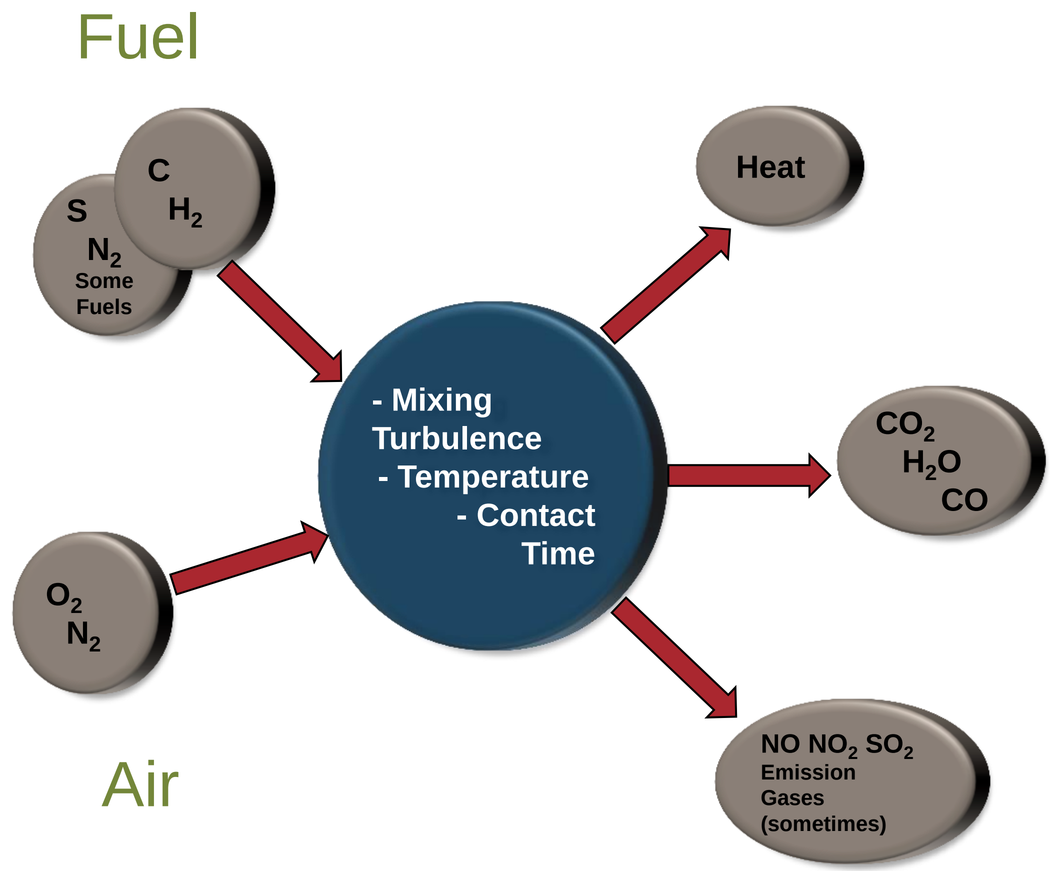
- 40.0 g/GJ (76 ppm) proposed limit
- 15.8 g/GJ (30 ppm) proposed target

What Is NOx?

Combustion


Fuel
C
H_2
S
N_2
Some Fuels
- Mixing Turbulence
- Temperature
- Contact Time
O_2
N_2
Air

Combustion



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NOx

Mono-Nitrogen Oxides, NO & NO_2

- NO (Nitric Oxide)
- NO_2 (Nitrogen Dioxide)
- Ambient = Equilibrium
- Heat = Endothermic Reaction
- NO = 80 – 90%

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NOx: A Precursor to Photochemical Smog

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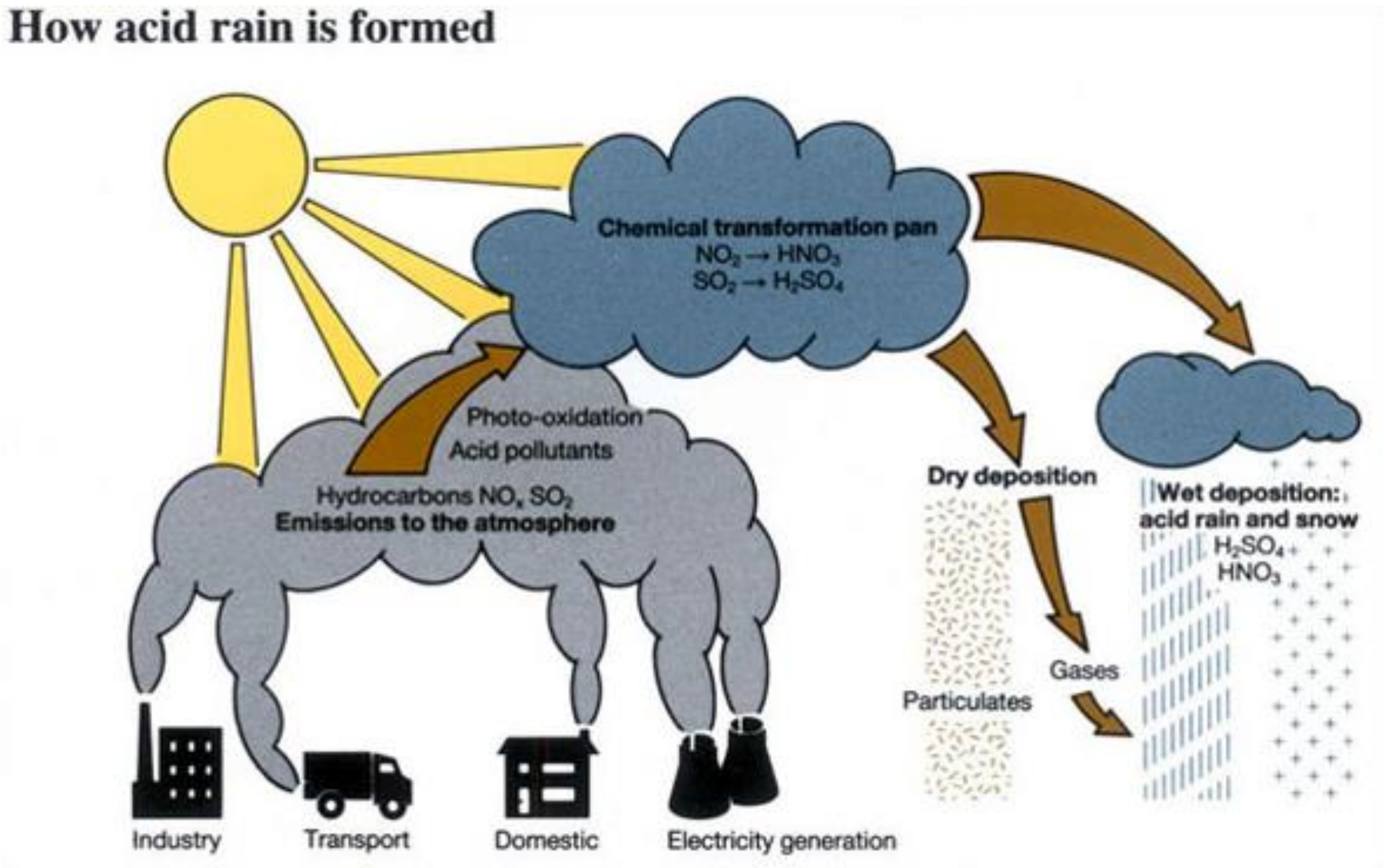
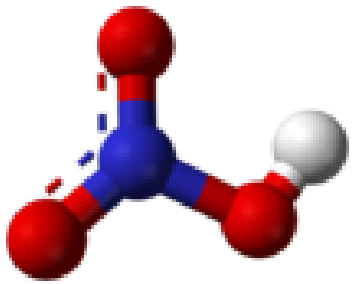
Acid Rain





Nitric Acid, HNO_3

Three Types of NOx

Fuel Bound

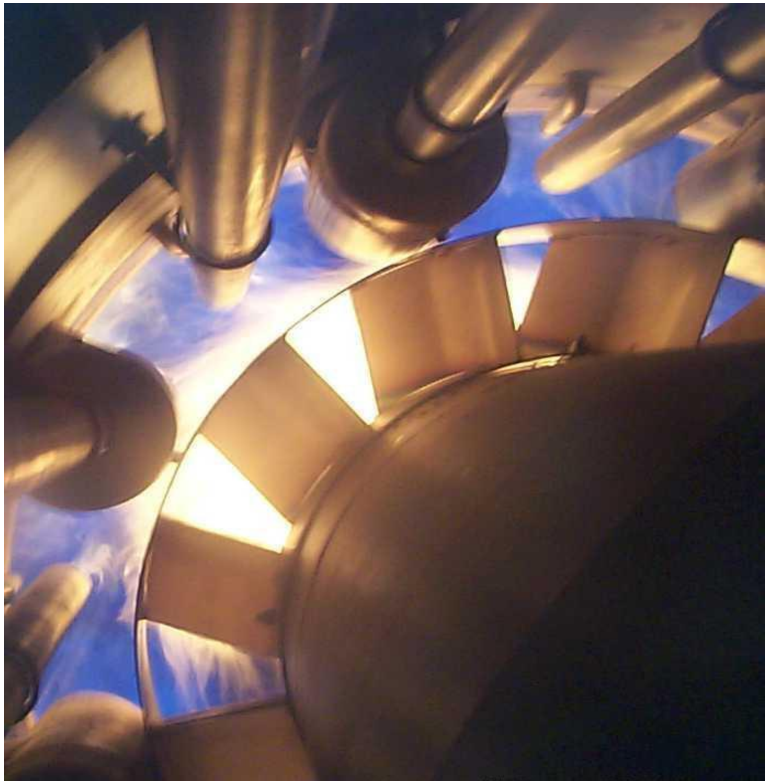
Prompt

Thermal

NOx Formation

Temperature

Duration



Total NOx

Result is Total NOx

Natural Gas:
- Approx. 120 ppm

#2 Oil:
- Approx. 180 ppm
- (Fuel Bound Nitrogen .015%)

#6 Oil:
- Approx. 425 ppm
- (Fuel Bound Nitrogen 0.300%)

Values are based on industrial watertube boilers >100 mmbtu/hr input
Smaller commercial boilers may be capable of lower values

Prompt NOx

- **Forms at lower temperatures (2200 – 2500^{O}F)**
- **Reacts with radicals such as Carbon (C) or Methylene (CH_2)**
- **Minor contributor to overall NOx production**

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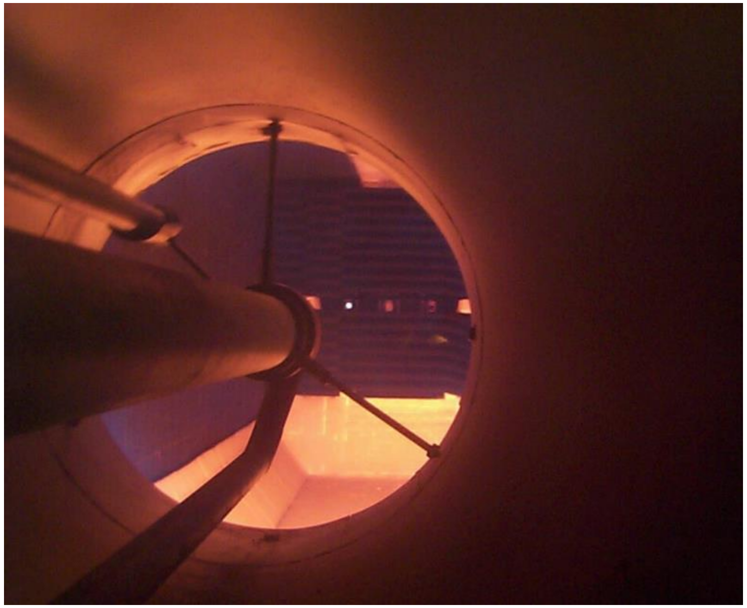
Thermal NOx

- **2900^{o} F…Nitrogen Oxides forming (NO & NO_2).**
- **Temperature and residence time.**
- **Major contributor to NOx production**



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Natural Gas

Primarily Methane CH_4

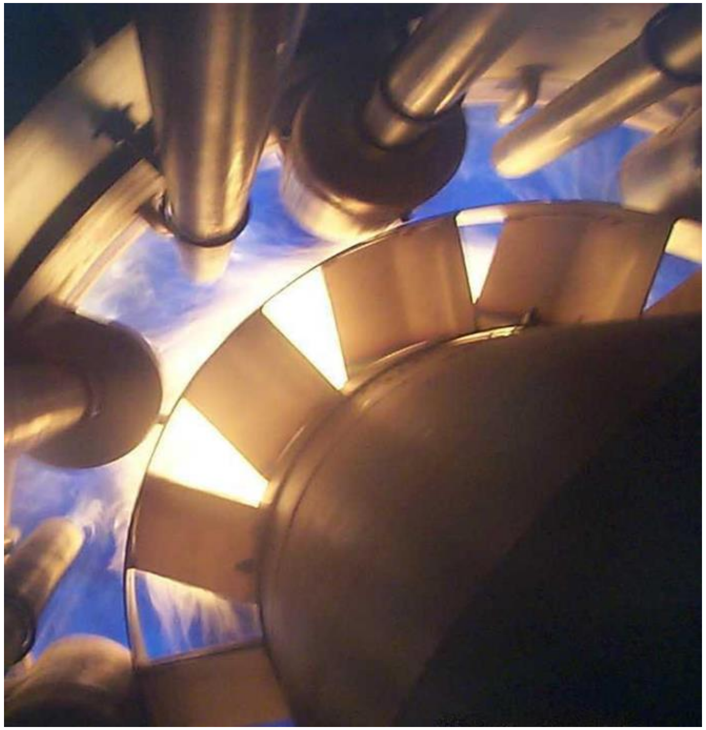
- Hydrocarbons
- Carbon Dioxide
- Nitrogen
- Hydrogen Sulfide

NOx & Natural Gas

How is it reduced?

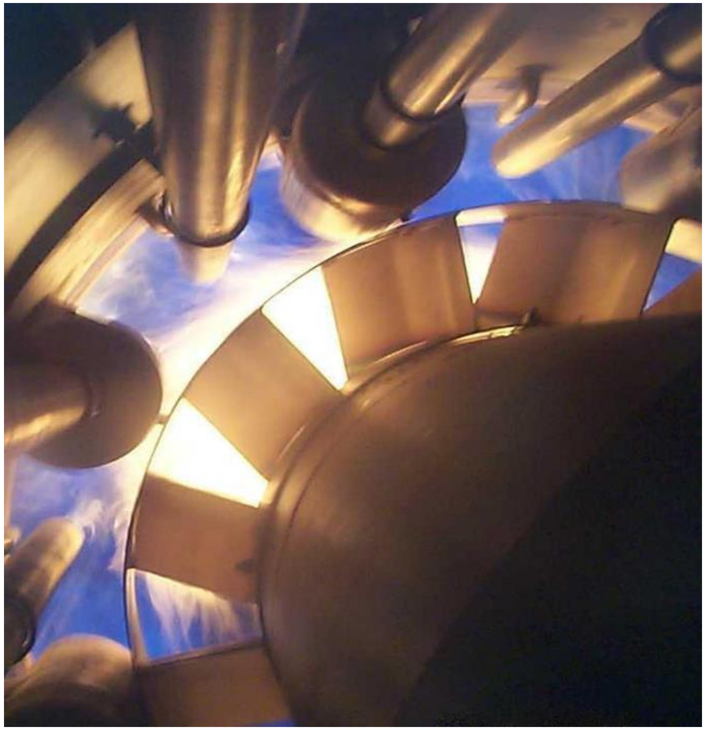
NOx Reduction

- **Low NOx Burners**
- **Flue Gas Recirculation (FGR)**
- **Selective Catalytic Reduction (SCR)**

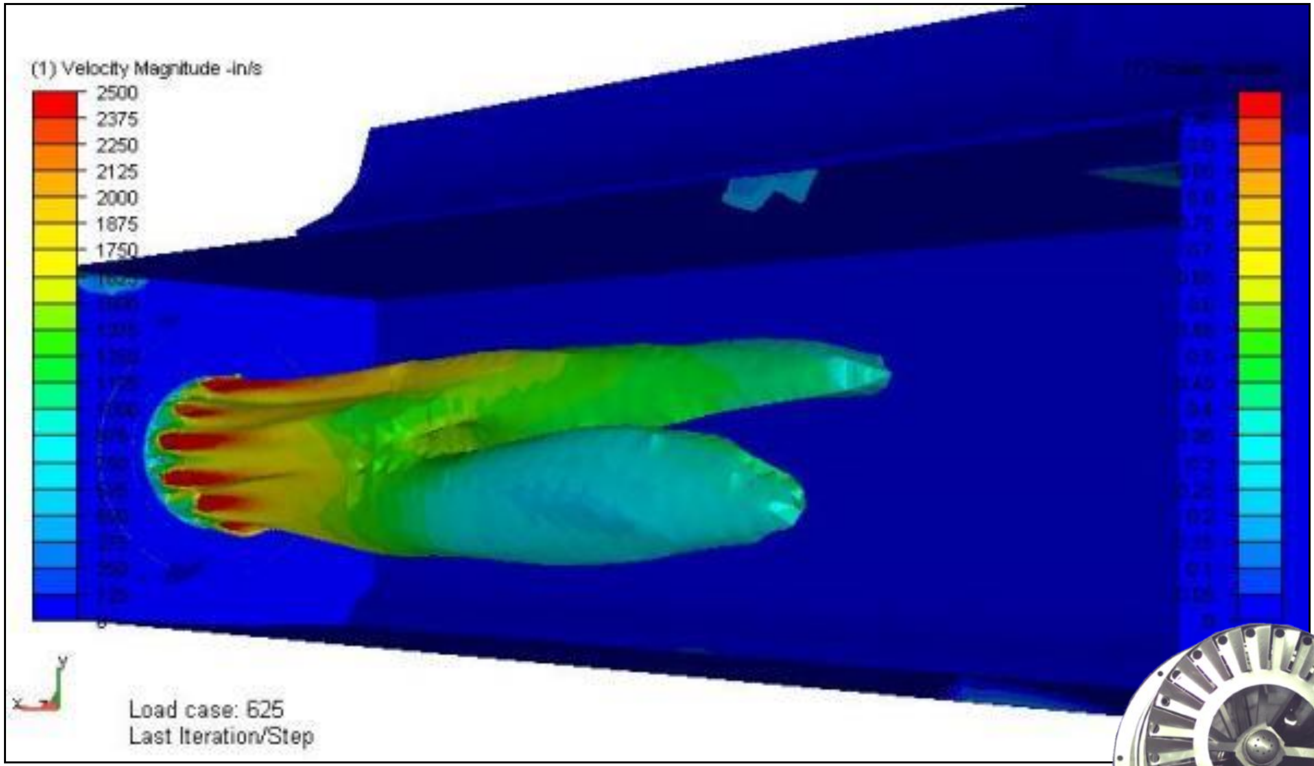


Low-NOx Burners

- **120 - 80 ppm**
- **80 - 9 ppm**
- **> 9 ppm**



Fitting the Burner to the Furnace



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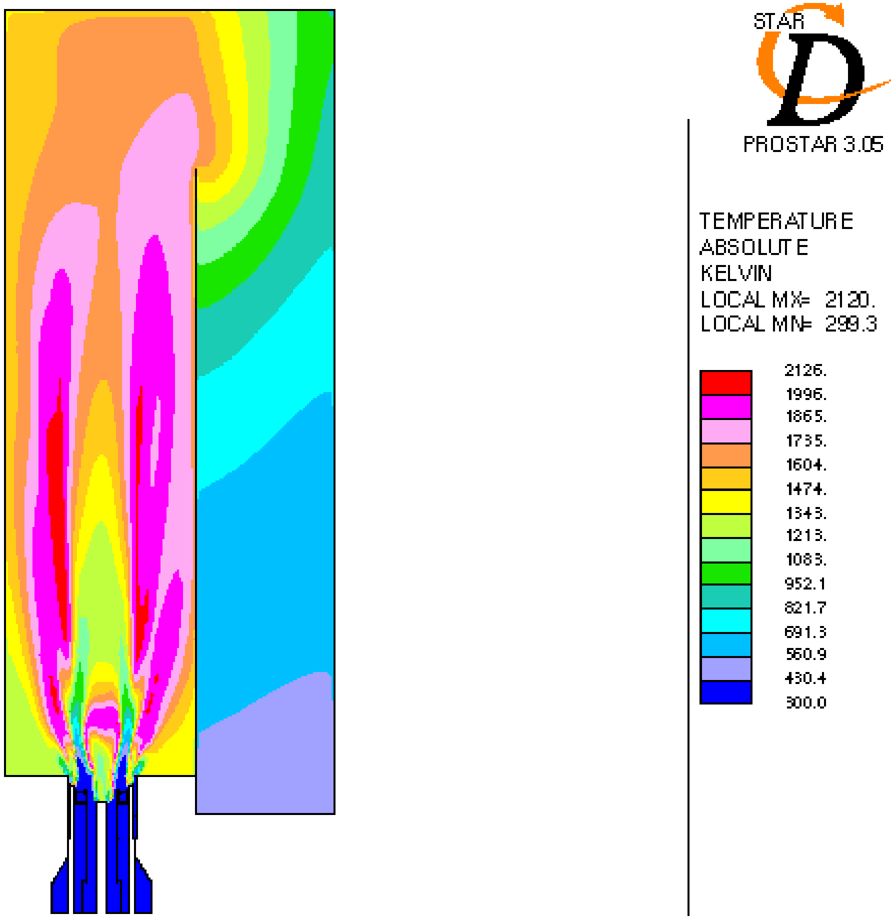
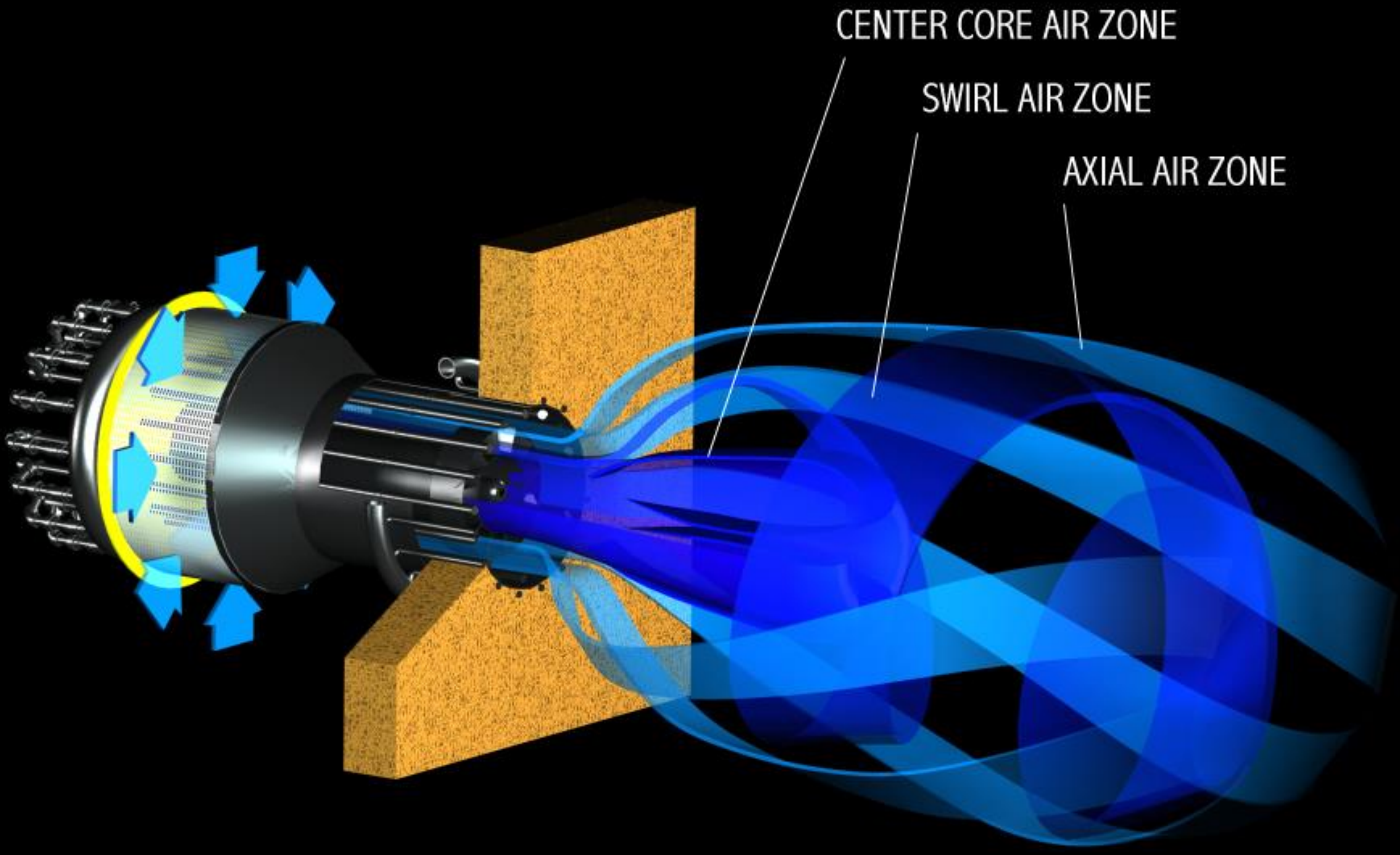
Furnace Geometry

Modern Industrial Watertube Furnace

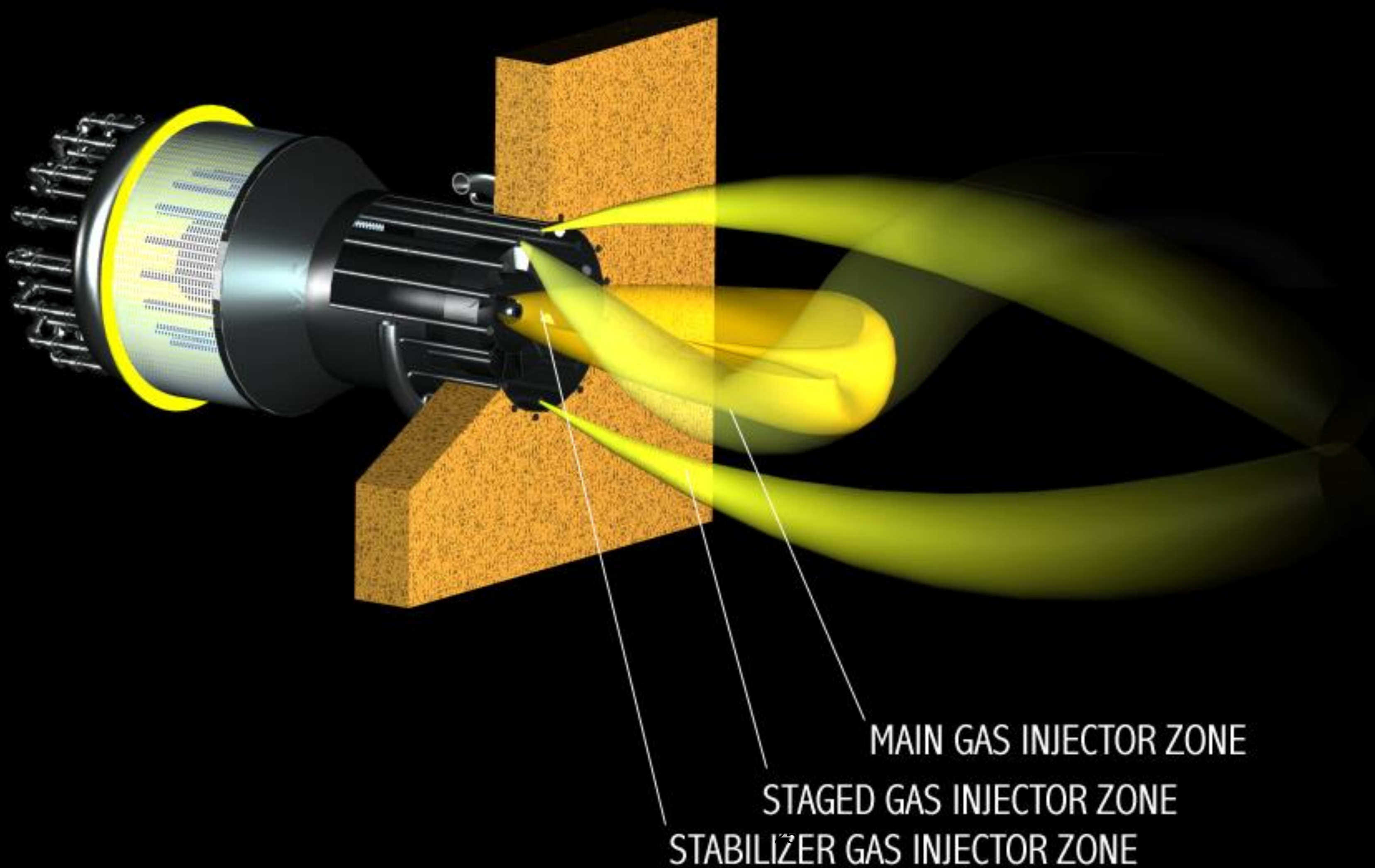
- **Provide the most generous volume possible for combustion**
- **Promote more uniform flame temperature**
- **Elimination of refractory that re-radiates heat back into furnace**

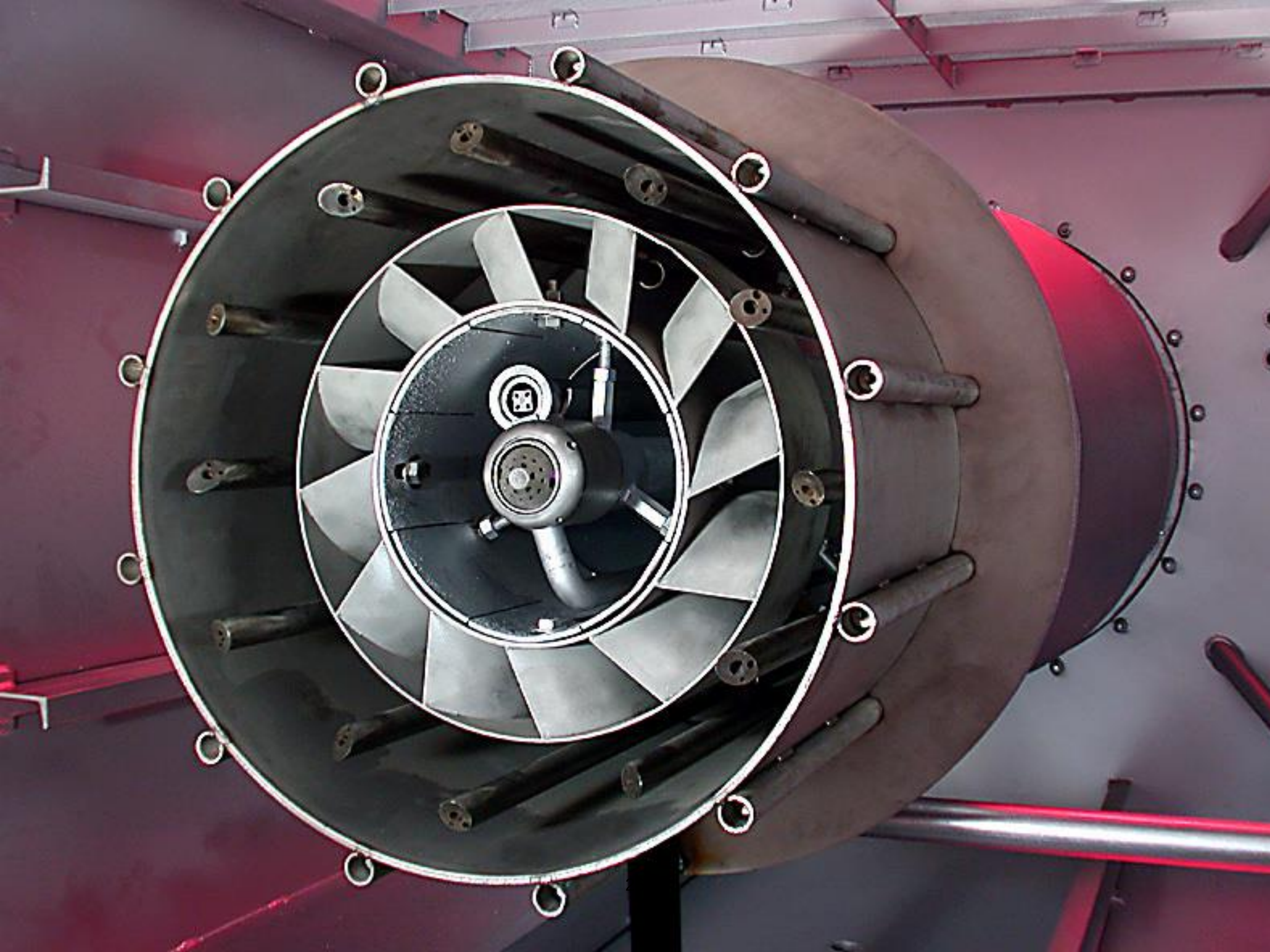
CFD- Furnace Temperature Profiling




CENTER CORE AIR ZONE
SWIRL AIR ZONE
AXIAL AIR ZONE

Gas Injection





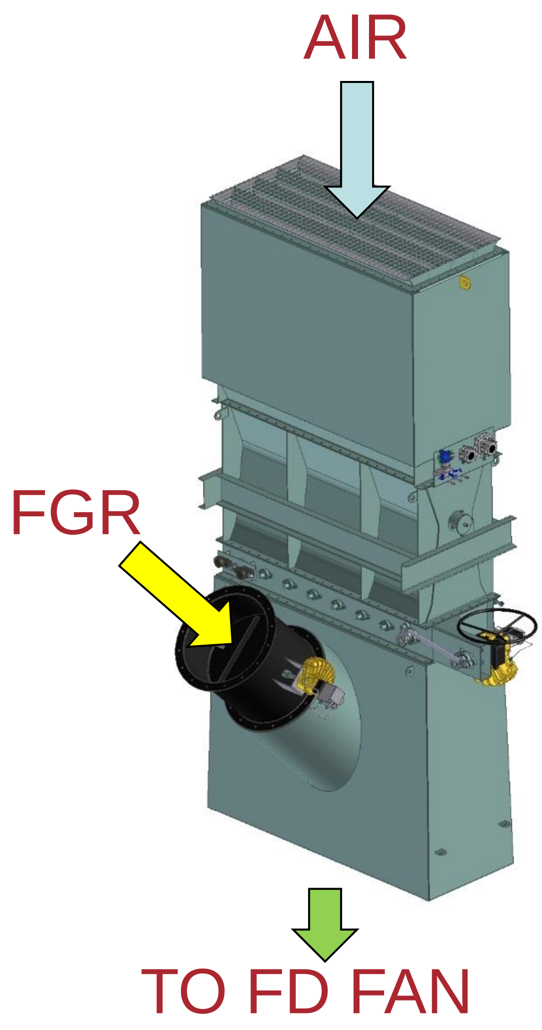
Flue Gas Recirculation

- 120 - 80 ppm
- **80 -   9 ppm**
- > 9 ppm

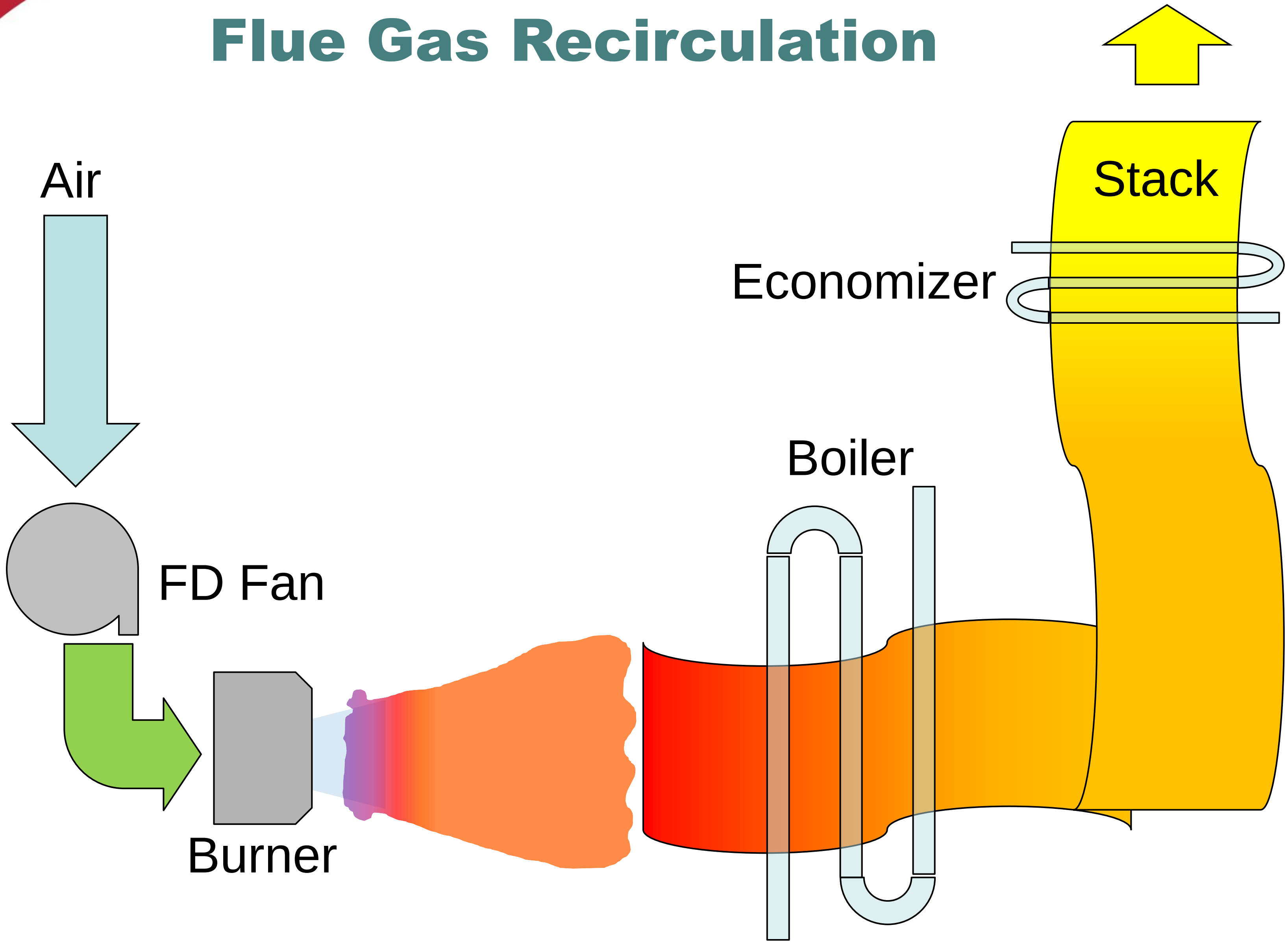
FGR

This is the most popular and efficient method of utilizing flue gas recirculation for NOx reduction.

Consists of “inducing” flue gases using the suction pressure at the inlet of the combustion air fan.



Flue Gas Recirculation



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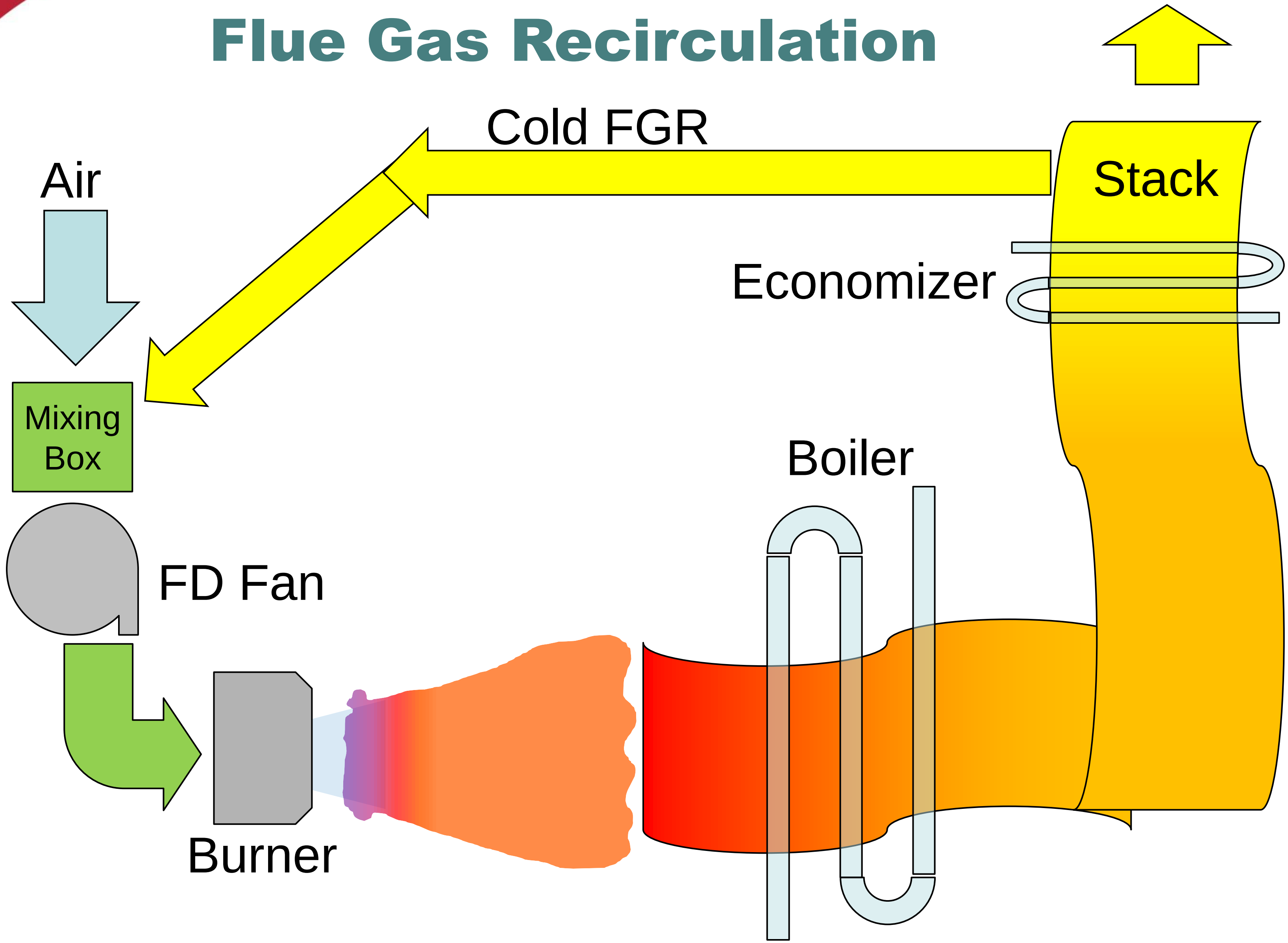
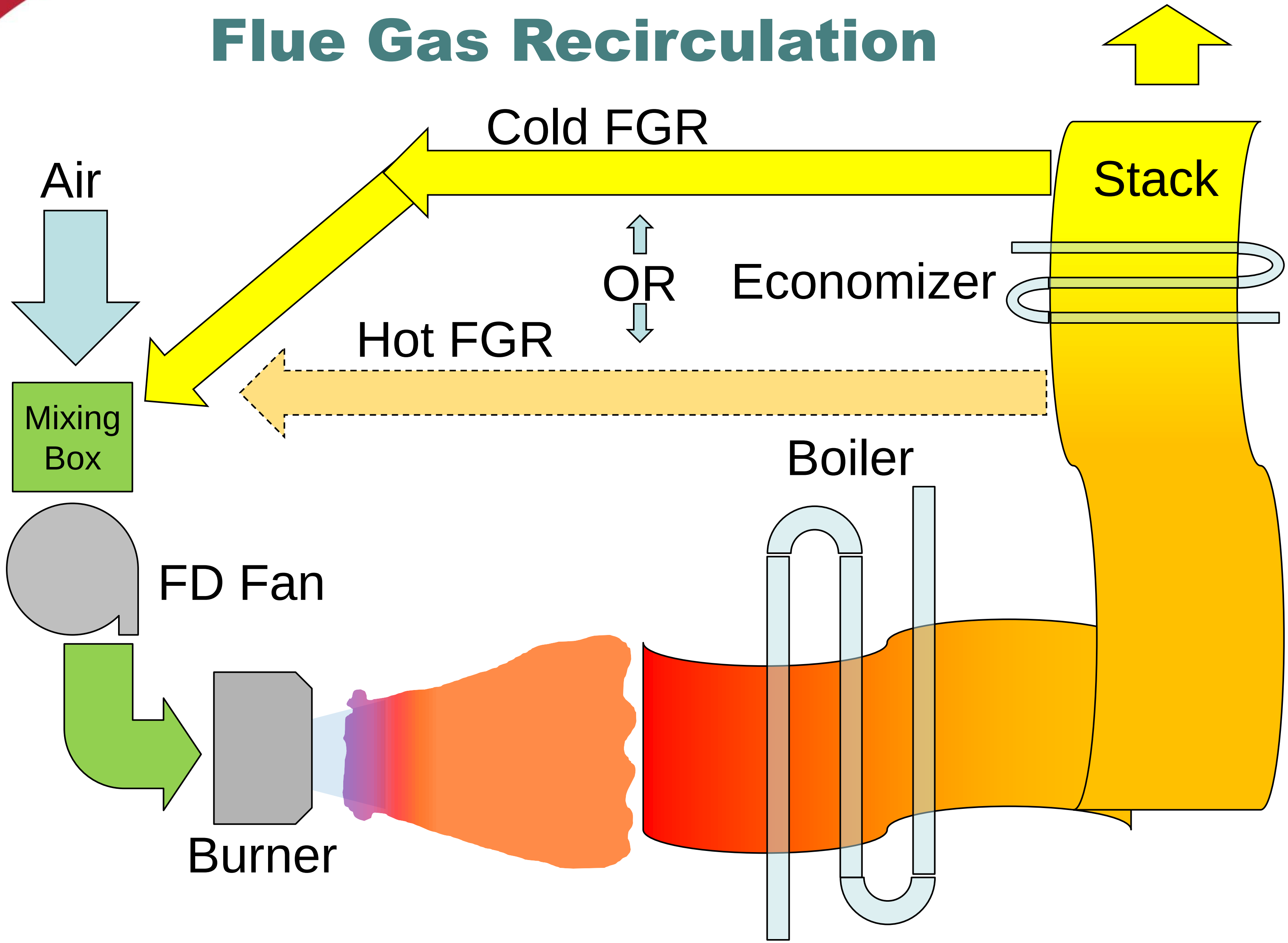
Flue Gas Recirculation



Flue Gas Recirculation



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FGR System Components

Ductwork

- From stack to fan suction

Damper

- To control % of flue gas recirculation

Air Inlet Mixing Box

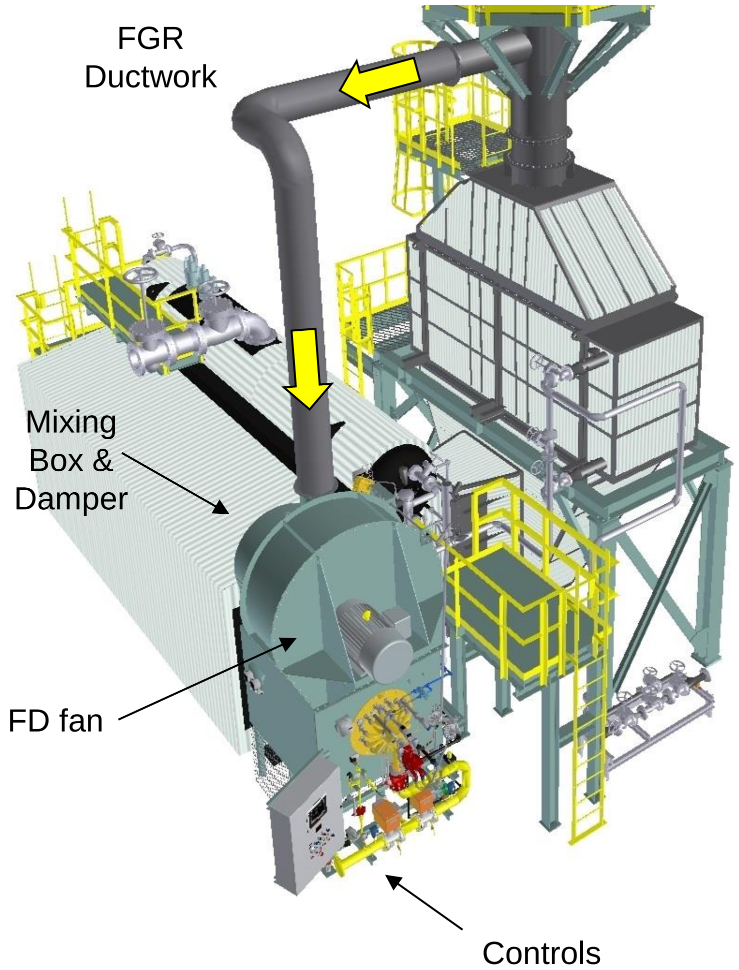
- To provide a chamber for fresh air to mix with flue gases prior to burner

Larger Fan

- To handle increased mass flow and higher mixture temperature

Control Upgrade

- Additional programming, instrumentation (FGR flow), I/O



FGR

The mixing of cooled flue gases with combustion air effectively reduces combustion temperature thus reducing thermal NOx. Using conventional burner technology, reductions of up to 80% are possible.

Using a 100 MMBTU/hr natural gas register burner as a reference, typical emissions are as follows:

- **Uncontrolled: 120 ppm NOx**
- **Using FGR: 20-30 ppm NOx**

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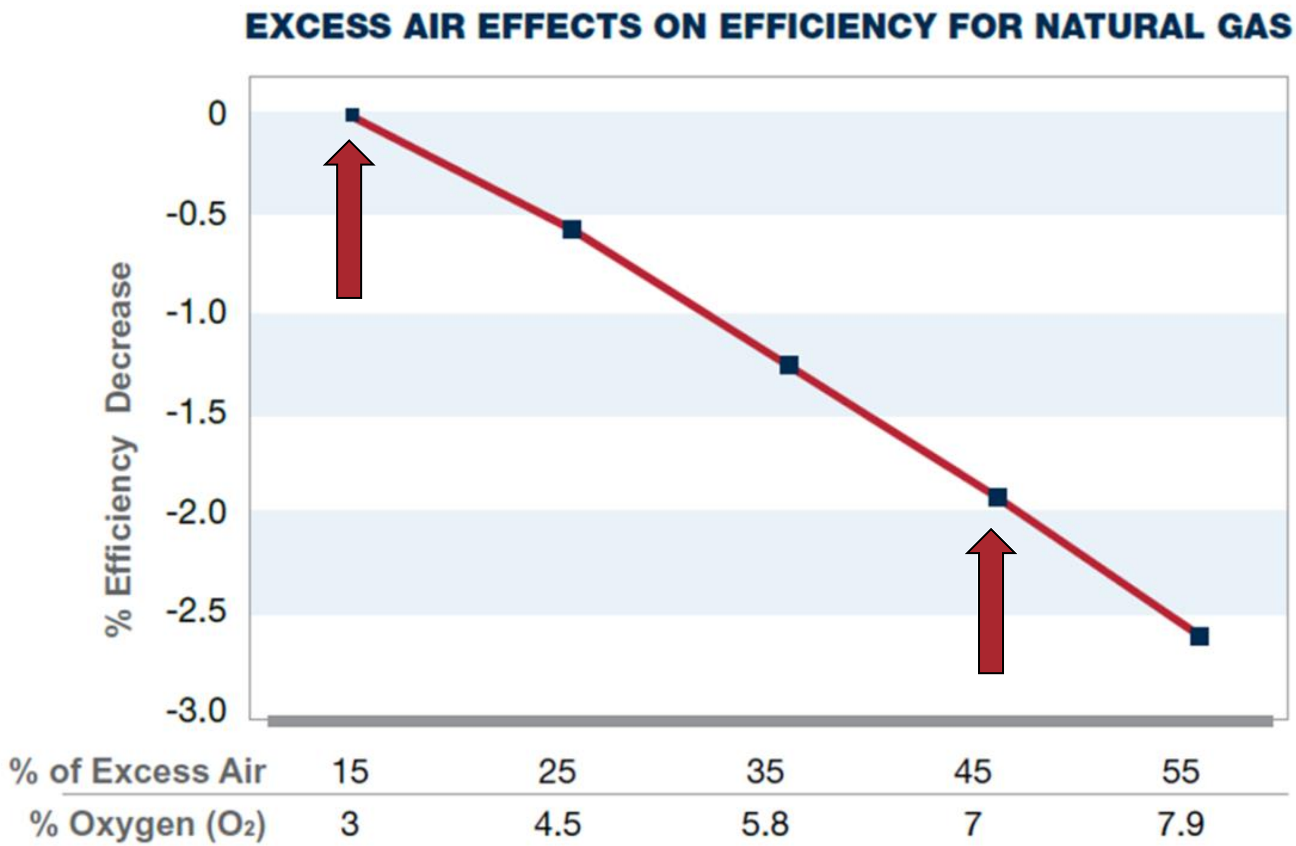
FGR + Excess Air

Sub 20 ppm NOx are possible using induced FGR, but to reach these levels, the formation of prompt NOx must also be addressed. This can be accomplished by premixing the fuel and air/FGR mixture prior to ignition thus minimizing fuel rich zones which are susceptible to forming prompt NOx.

Using high FGR rates and premixing of fuel and air/FGR, NOx reductions of 90% are possible thus allowing to reach 9ppm NOx levels.

These are commonly called "Ultra Low-NOx" burners.

As Excess Air Increases, Efficiency Decreases



Ultra Low NOx

Selective Catalytic Reduction

- **120 - 80 ppm**
- **80 - 9 ppm**
- **> 9 ppm**

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Post Combustion NOx Reduction

$NH_3 + NOx = N_2 + H_2O$

SNCR – Selective Non-Catalytic Reduction

- Spontaneous @ approx. 1800° F.
- Ammonia injected directly into furnace
- Large furnace, adequate residence time
- Not practical for packaged boilers

SCR – Selective Catalytic Reduction

- Lower temperatures @ 600-800° F
- Ammonia injected at boiler flue gas outlet
- Catalyst required
- Common on packaged boilers

SCR Performance

$NH_3 + NOx = N_2 + H_2O$

Source testing measurements of NOx & NH_3 slip

Usually 90-93% NOx reduction is achieved on units firing NG and #2 oil.

"Rule of Thumb" : NOx after the Catalyst will be 10% of the upstream NOx

Ammonia slip is measure at the stack and corresponds to the amount of NH_3 that didn't react with NOx.

Typically NH_3 slip levels are of 5 ppm or 10 ppm.

SCR Reagent Types

$NH_3 + NOx = N_2 + H_2O$

Anhydrous NH_3

- Pure Ammonia liquefied under pressure
- Low capital & operating cost
- Perceived as high risk
- Can be difficult to permit

Aqueous NH_3

- Ammonia in 20-30% water
- Higher capital & operating cost
- Perceived as low risk
- Permit normally easy to obtain

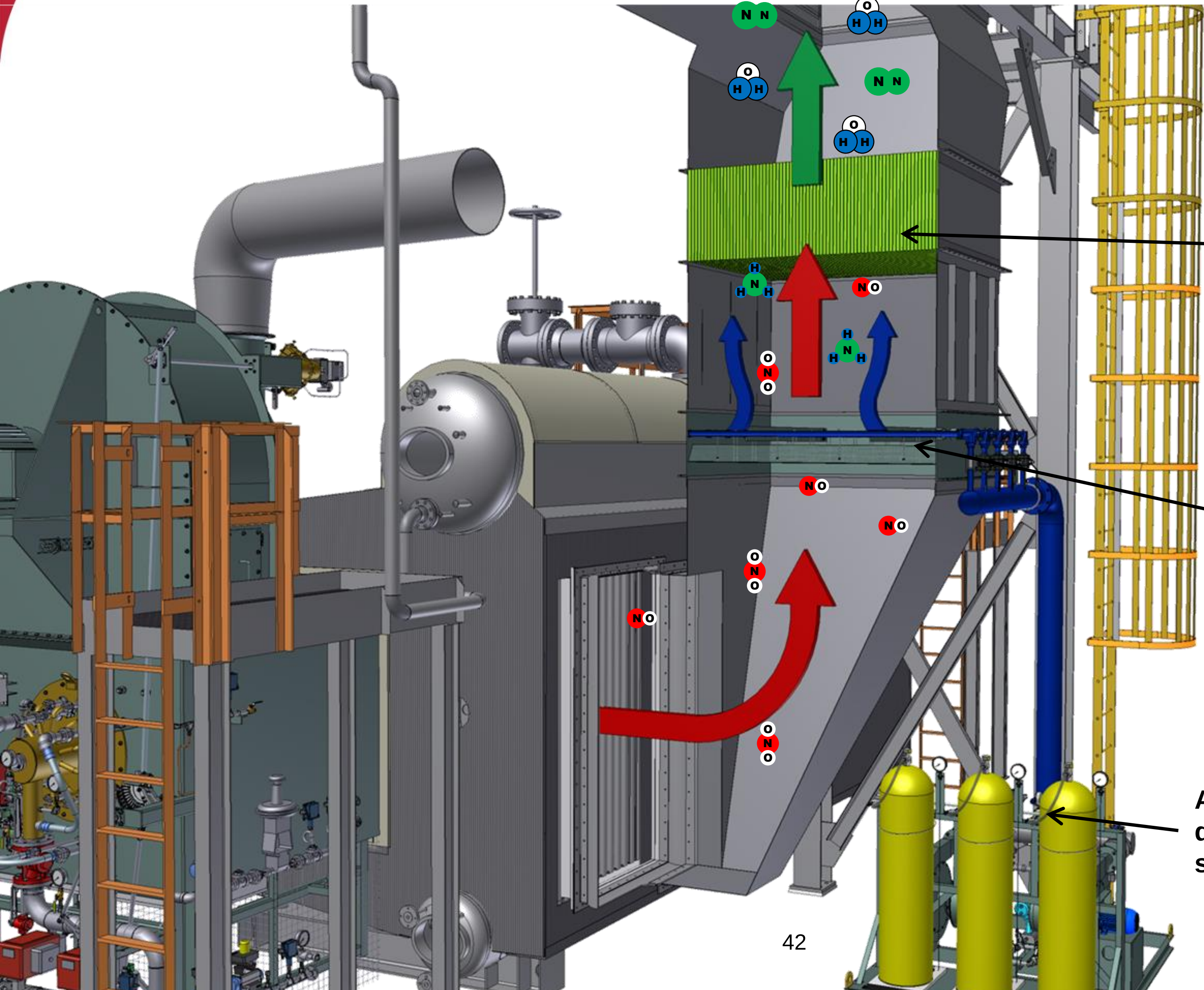
Urea

- Highest capital & operating cost
- Perceived as minimal risk
- Permit easy to obtain

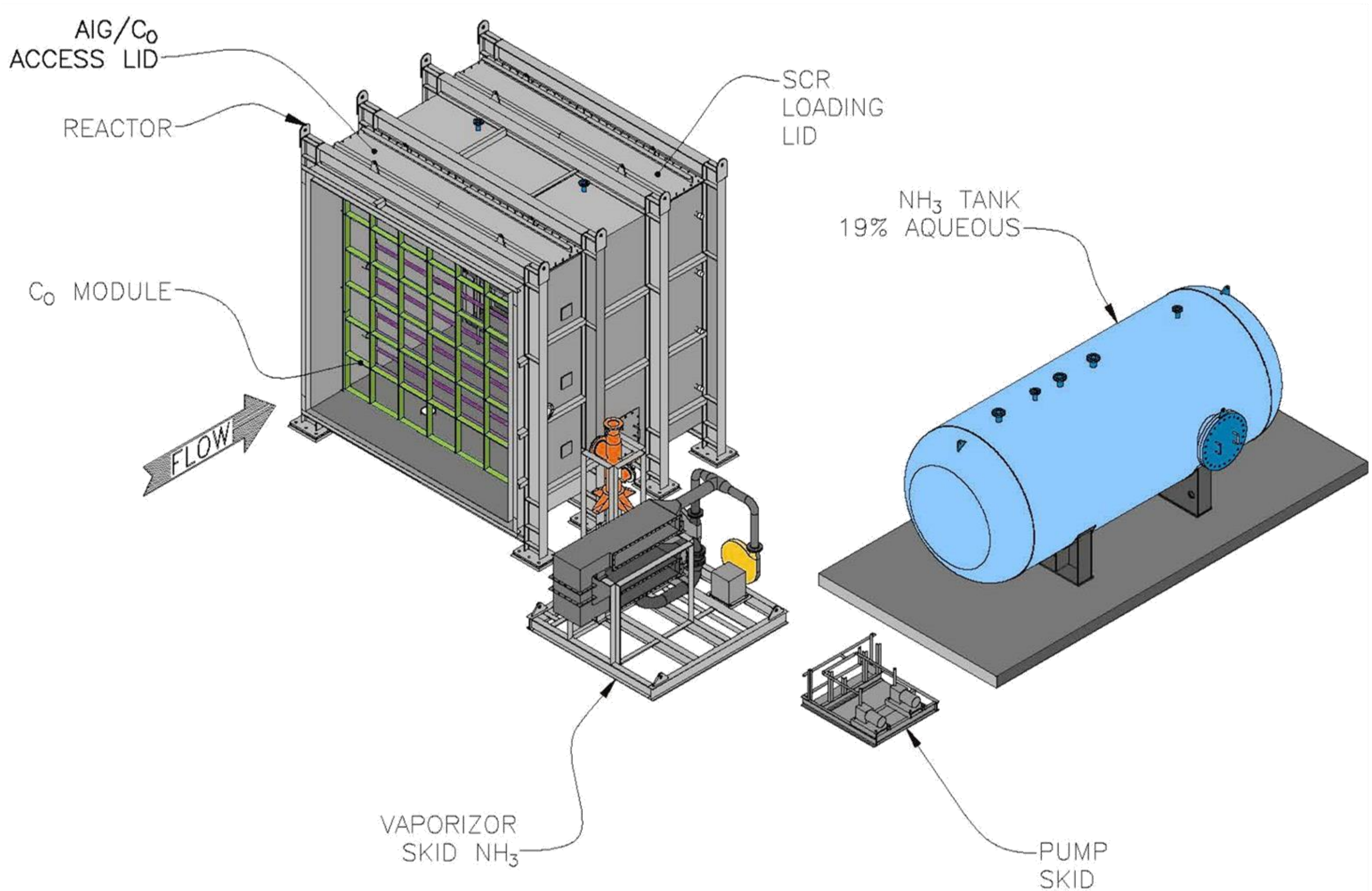
SCR System Components

- **Reagent Processing Skid**
  - Anhydrous Ammonia – Anhydrous Bottles For Storage, AFCU
  - Aqueous Ammonia – Ammonia Storage Tank, Forwarding Pump Skid, AFCU c/w Vaporizors
  - Urea – Urea Storage Tank, Urea Conversion Skid, AFCU
- **Catalyst**
  - NOx Catalyst
- **Ammonia Injection Grid (AIG)**
  - To inject ammonia
- **Reactor Housing**
  - Contains precious metal catalyst to assist reaction
- **System Control Upgrade**
  - Additional programming, instrumentation, I/O

System Components



Selective Catalytic Reduction (SCR)



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Selective Catalytic Reduction (SCR)

Ammonia Injection Grid

Selective Catalytic Reduction (SCR)

SCR Reactor Housing

Catalyst

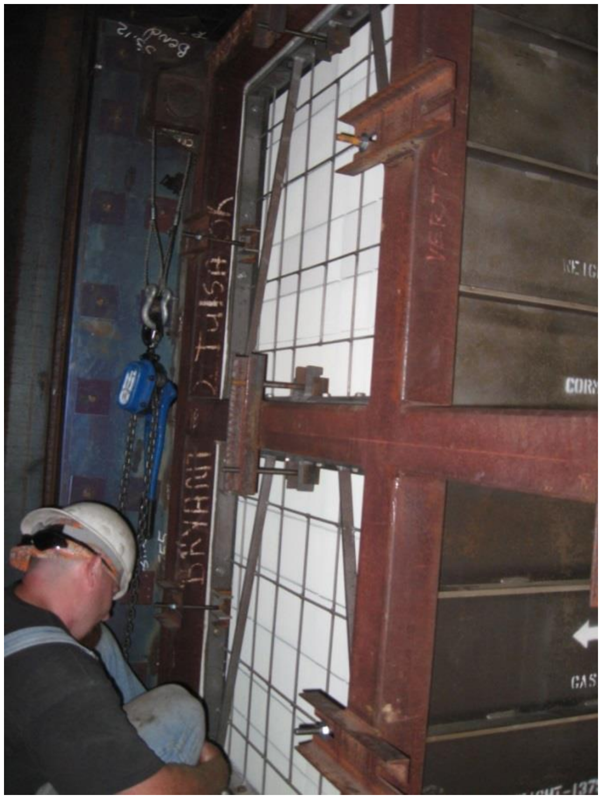
Corrugated Type Catalyst

Topsoe (DNX)
- Composite
- Hybrid

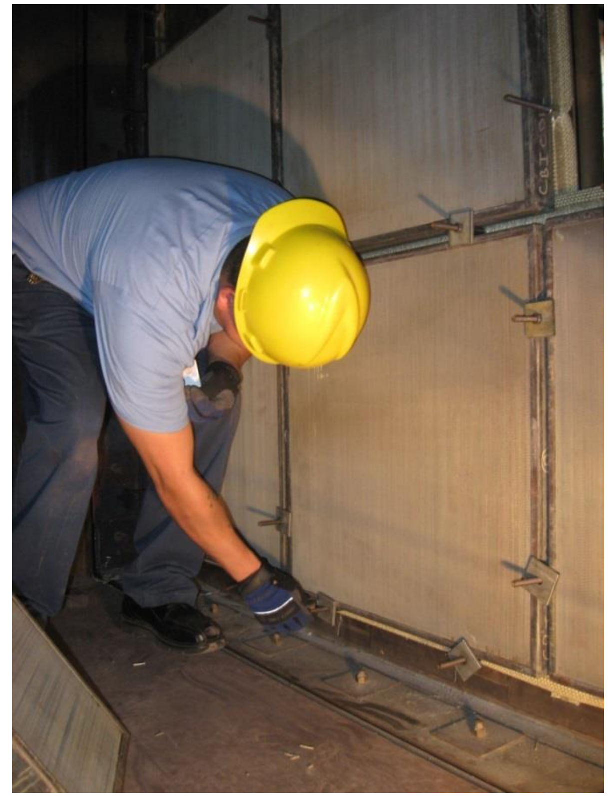
Single Catalyst Element

Inside the reactor, catalyst elements are stacked to form the catalyst bed.

Selective Catalytic Reduction (SCR)

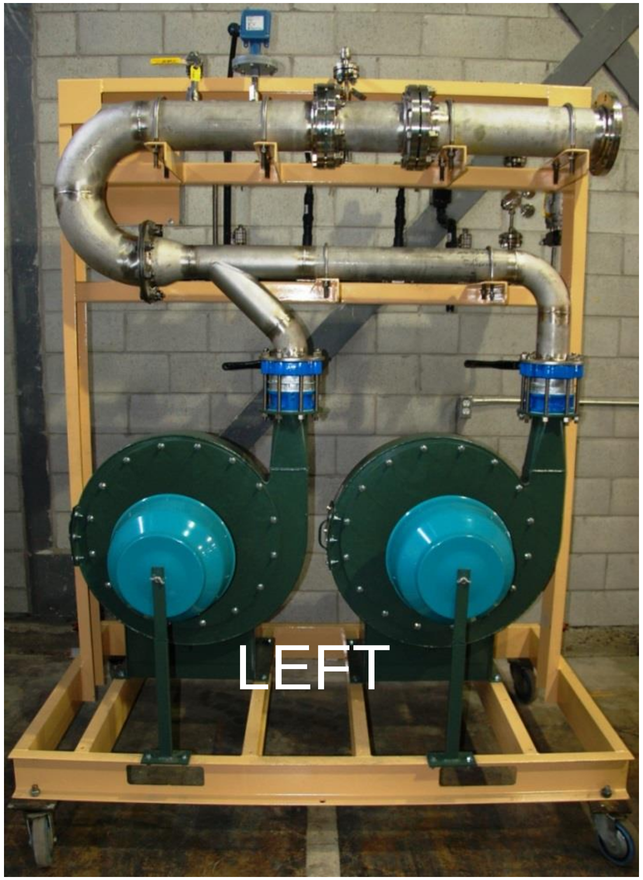


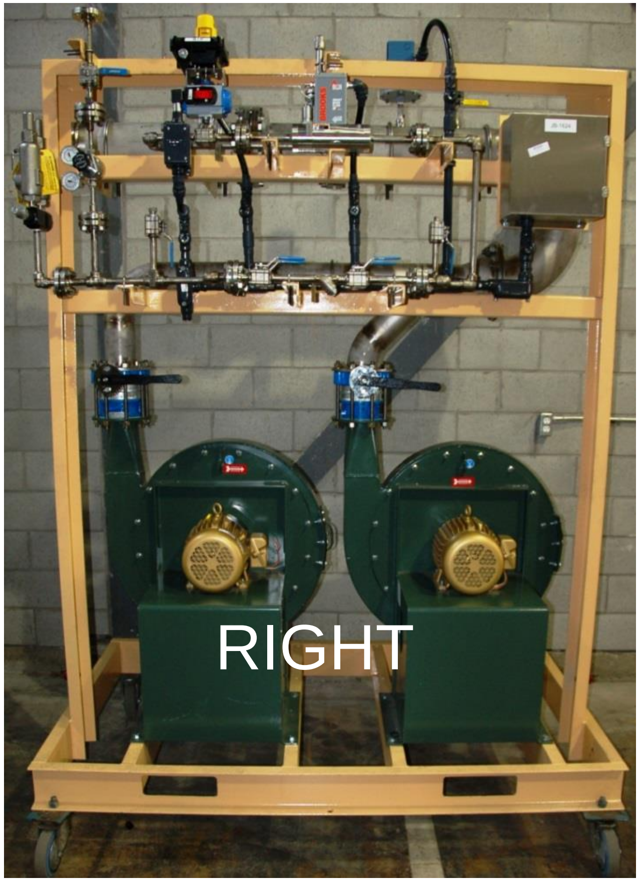
NOx Catalyst



CO Catalyst

Selective Catalytic Reduction (SCR)





Anhydrous Ammonia Metering & Dilution Air Skid

Selective Catalytic Reduction (SCR)

Aqueous Forwarding Pump Skid

Selective Catalytic Reduction (SCR)

Aqueous Ammonia Vaporization Skid

Ultra Low-NOx Burners

PROS

- On-site storage of ammonia is NOT required
- No SCR equipment and associated maintenance

CONS

- Technology is limited to < 200 mmbtu/hr in a single burner
- Burner cost is higher than standard units
- Large furnace volumes are required, often resulting in costly modularized or field-erected boilers at larger heat inputs
- Burner turndown is limited (typical 6:1)
- High excess air reduces thermal efficiency
- High FGR rates increase fan size and power consumption
- Complex metered combustion control systems are required
- Burner ramp rates are slower than standard systems
- Inlet air preheat temps are limited (reduced efficiency)

Selective Catalytic Reduction

PROS

- Single-digit NOx levels can be achieved
- Low cost standard burners can be utilized
- Boiler furnace sizing is unaffected
- No impact on burner turndown (10:1 typical)
- Low excess air does not reduce efficiency
- No significant impact on FD Fan power consumption
- Burner ramp rates are in excess of 20% / minute
- High-temp inlet air preheat systems increase efficiency
- More forgiving of fuels with changing compositions

CONS

- On-site ammonia storage required.
- Increased footprint or height for ductwork
- Additional pressure drop across catalyst increases fan hp, but not significant when compared to ultra low-NOx burners
- Catalyst maintenance/replacement required every 3-5 years

CAPEX

80,000 lb/hr watertube @ 9 ppm NOx

Item	FGR	SCR
Standard Boiler	$ 960,000	$ 960,000
Add FGR	$ 52,000	
Add SCR		$ 385,000
TOTAL	$ 1,012,000	$ 1,345,000
$/lb steam	$ 12.65	$ 16.81
		33%

CAPEX

80,000 lb/hr watertube @ 9 ppm NOx

Item	FGR	SCR
Standard Boiler	$ 960,000	$ 960,000
Add FGR	$ 52,000	
Add SCR		$ 385,000
TOTAL	$ 1,012,000	$ 1,345,000
$/lb steam	$ 12.65	$ 16.81
		33%

SCR costs additional 30%, so FGR is most economical

CAPEX

425,000 lb/hr watertube @ 9 ppm NOx

Item	FGR		SCR	
Standard Boiler	$	5,750,000	$	5,750,000
Add FGR	$	395,000		
Add SCR			$	675,000
TOTAL	$	6,145,000	$	6,425,000
$/lb steam	$	14.46	$	15.12
				5%

CAPEX

425,000 lb/hr watertube @ 9 ppm NOx

Item	FGR	SCR
Standard Boiler	$ 5,750,000	$ 5,750,000
Add FGR	$ 395,000	
Add SCR		$ 675,000
TOTAL	$ 6,145,000	$ 6,425,000
$/lb steam	$ 14.46	$ 15.12
		5%

This is interesting.

Cost of FGR vs. SCR is very close.

FGR is $280,000 less.

CAPEX

425,000 lb/hr watertube @ 9 ppm NOx

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Standard Boiler	$	5,750,000	$	5,750,000
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TOTAL	$	6,145,000	$	6,425,000
$/lb steam	$	14.46	$	15.12
				5%

This is interesting.

Cost of FGR vs. SCR is very close.

FGR is $280,000 less.

We need to take a closer look at OPEX.

OPEX

425,000 lb/hr watertube @ 9 ppm NOx

Item	FGR	SCR	
Increase Fan HP	$ 315,539.10	$ 18,254.33	$/yr
Increase NG	$ 322,599.70	0	$/yr
Add ammonia		$ 235,872.00	$/yr
TOTAL	$ 638,138.81	$ 254,126.33	

<u>$USD Assumptions</u>:
Electricity: 5₵/kWh
Fuel Gas: $3/mmbtu
Ammonia: $3/lb (anhydrous)

OPEX

425,000 lb/hr watertube @ 9 ppm NOx

Item	FGR	SCR	
Increase Fan HP	$ 315,539.10	$ 18,254.33	$/yr
Increase NG	$ 322,599.70	0	$/yr
Add ammonia		$ 235,872.00	$/yr
TOTAL	$ 638,138.81	$ 254,126.33	

SCR clearly costs less to operate than FGR.

$384,000 savings per year!

Today's Take-A-Ways

1. Our environment is finite and fragile…
2. Fuels we burn also finite
3. Efficiency are compromised for ultra low-NOx levels with FGR
4. KWh may also be impacted along with turndown with FGR
5. SCR will not normally impact fuel efficiency
6. Consider ALL options for NOx reduction.

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