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COMPANIES

Stationary Engine Emission Controls & A/F Controllers / Remote Control

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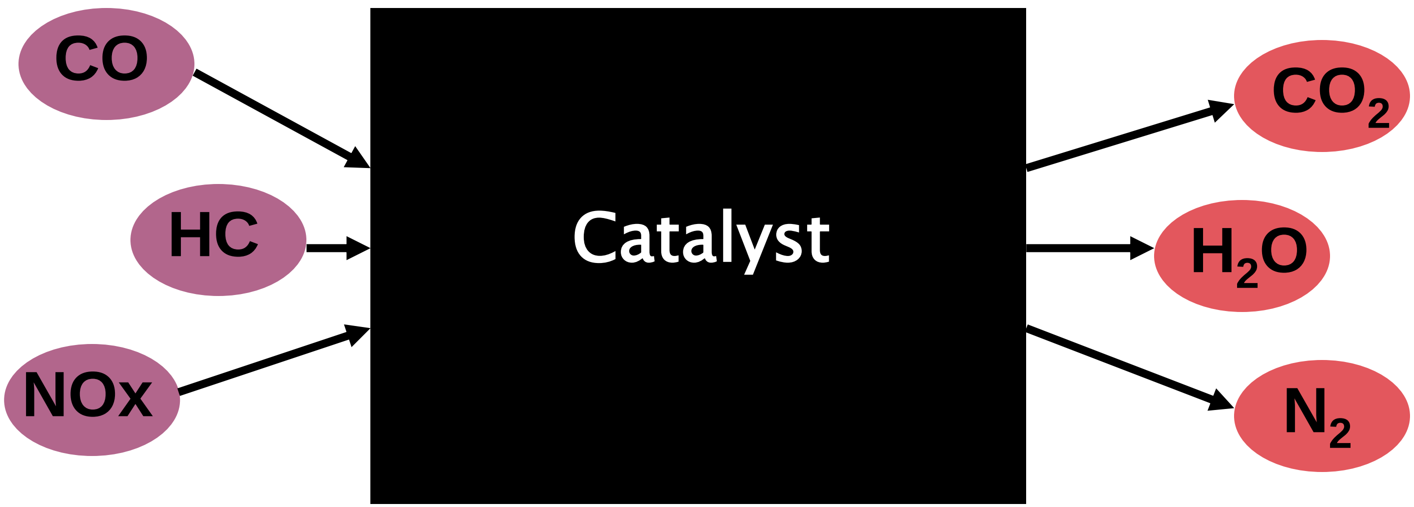
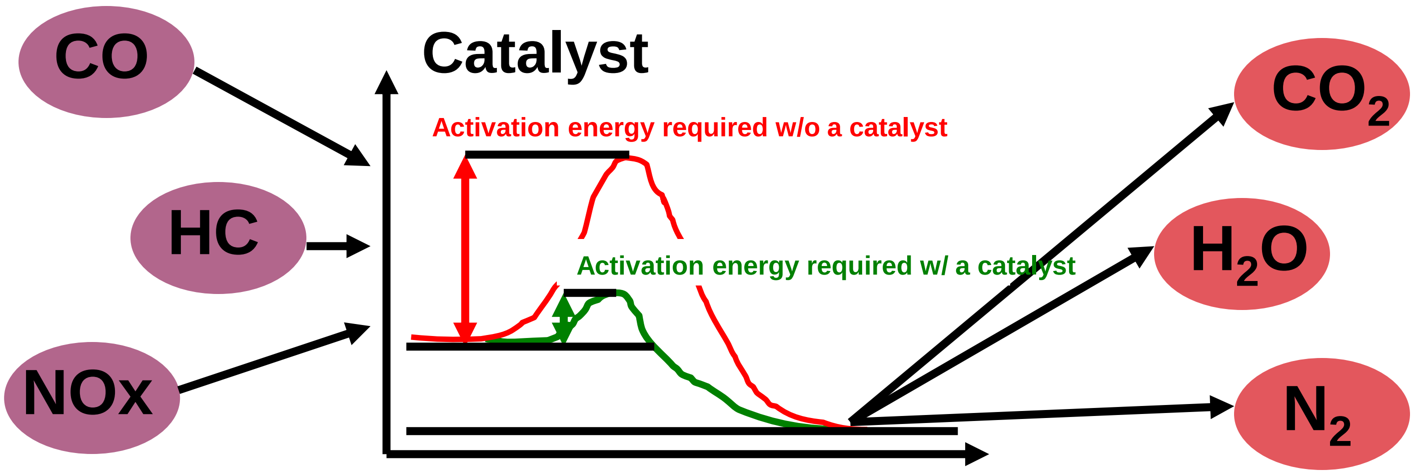
Outline

- What is a catalyst?
- How does it work?
  - Three Way Catalyst (aka NSCR or TWC) for Rich Burn Engines
    - Catalyst Components and Operation
    - Air-Fuel Ratio Controllers
    - Summary
  - Two Way Catalyst (aka Oxidation) for Lean Burn Engines
    - Catalyst Operation
    - Summary
  - Selective Catalytic Reduction Systems (aka SCR) for Lean Burn Engines
    - What is SCR? / How it is Different from Two Way and Three Way?

What is a catalyst?
Is it a black box???

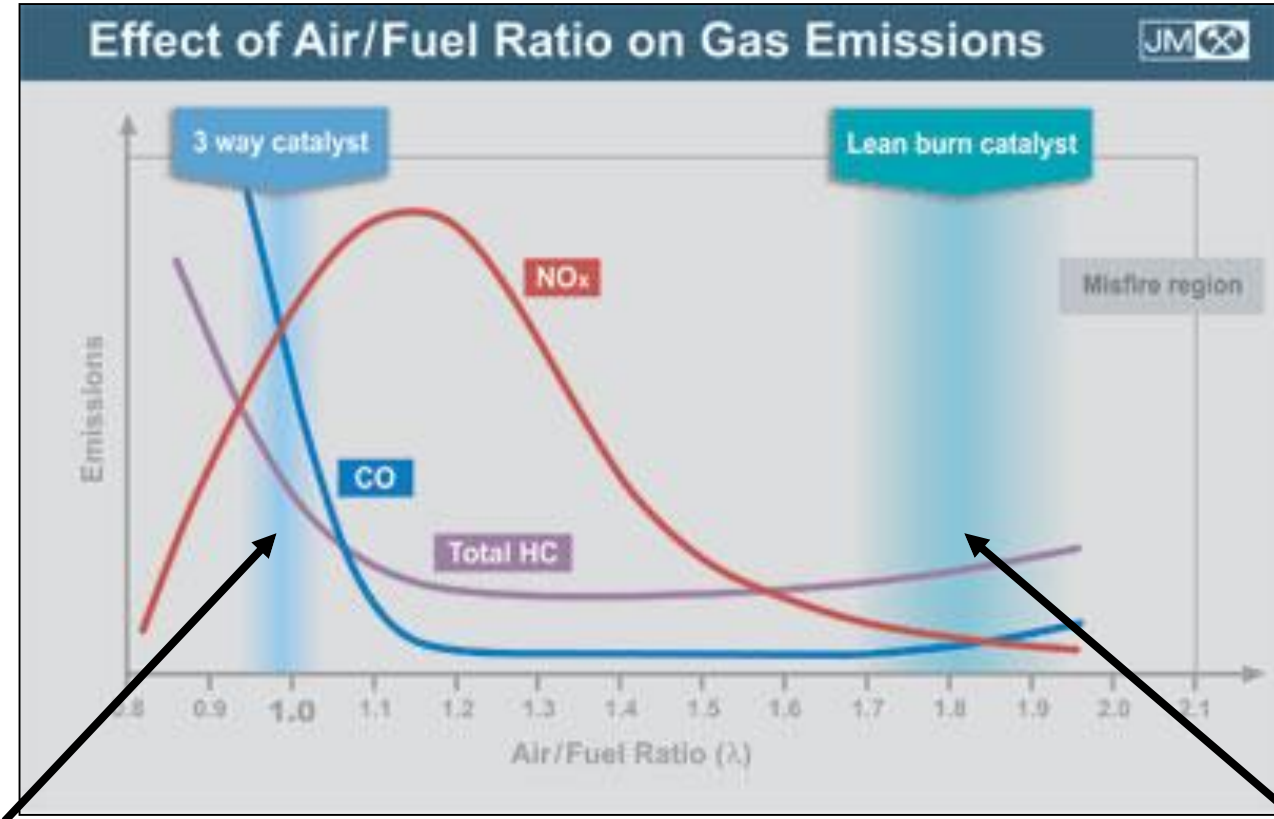


A catalyst is NOT a black box!
It is a substance that accelerates a chemical reaction



- A catalyst is a material that increases the rate of a chemical reaction while not undergoing any permanent change.
- This results in the chemical reaction occurring at a lower temperature and more quickly.
- Catalysts do not perform miracles, the reactions they perform have to be “allowed” chemically.
- Catalysts are designed to speed up the desired reactions, but not the undesired ones.

How does it work?
Different applications require different catalysts

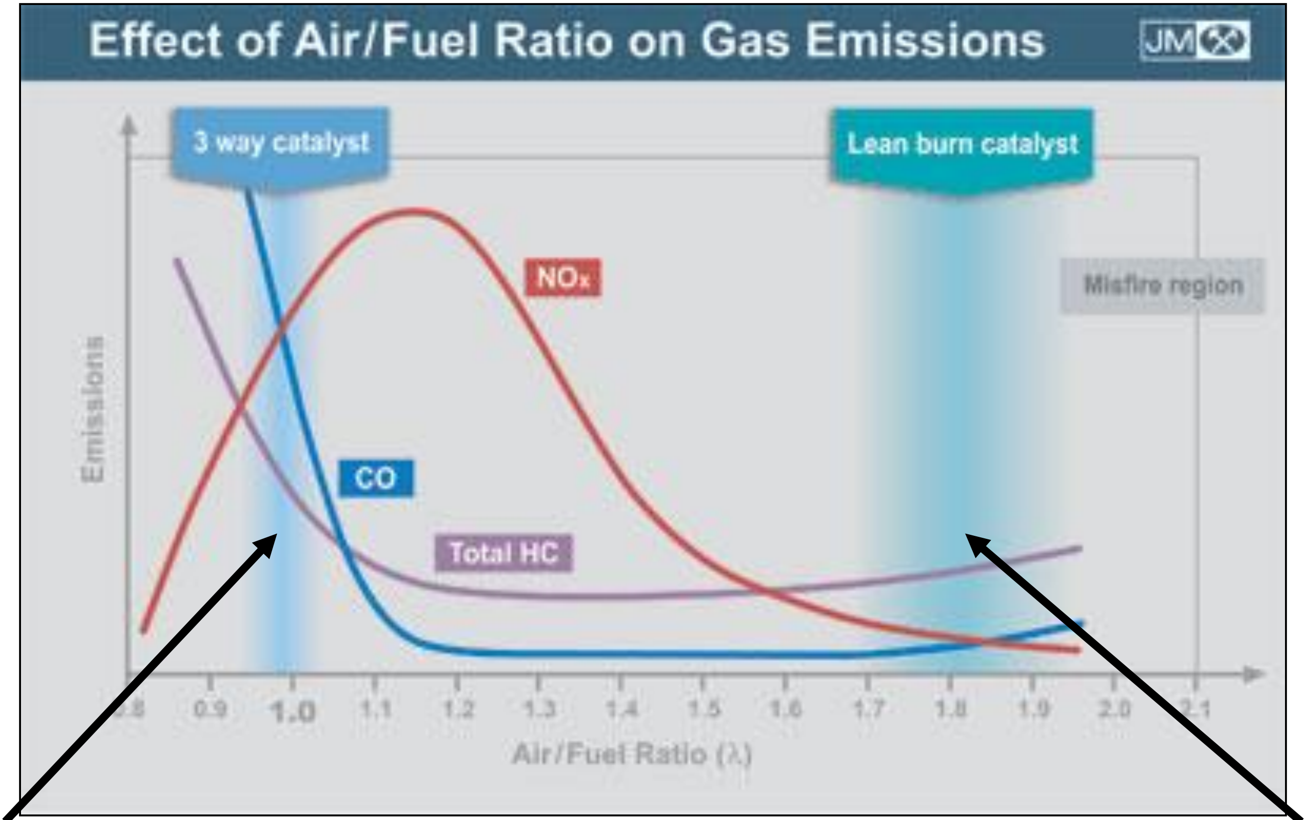


Section 1: Three way catalysts

Section 2: Two way catalysts

Section 3: SCR systems

How does it work?
Different applications require different catalysts



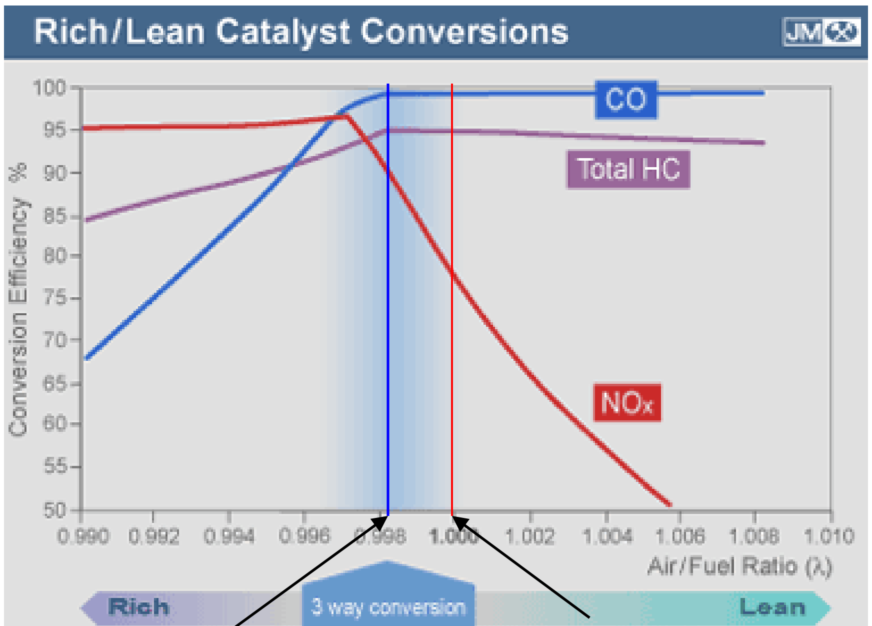
Section 1: Three way catalysts

Section 2: Two way catalysts

Section 3: SCR systems

Three way – NSCR – TWC catalyst – Rich burn

The A/Fuel ratio (Lambda) is critical, as the area of operation is with excess reductants (HC, CO). Exhaust composition is extremely important to the proper catalyst for the application



- **Oxidation Reactions**
- $CO + 1/2O_2 \longrightarrow CO_2$
- $CH_4 + 2O_2 \longrightarrow CO_2 + 2H_2O$

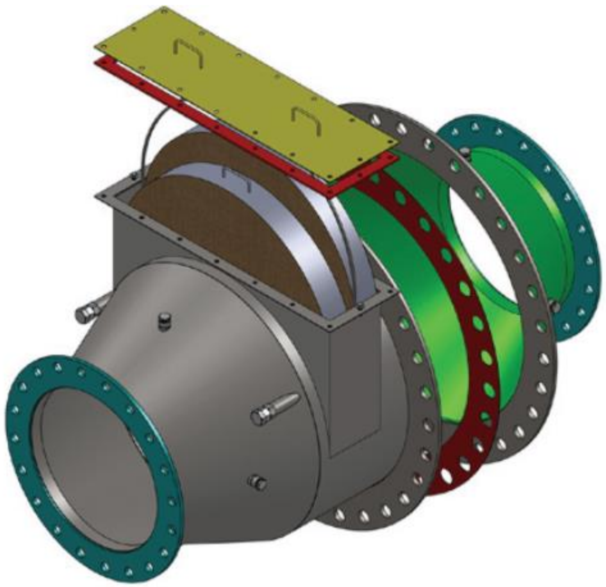
- **Reduction Reactions**
- $2NO + 2CO \longrightarrow N_2 + 2CO_2$
- $4NO + CH_4 \longrightarrow 2N_2 + CO_2 + 2H_2O$

Rich (Exhaust O_2 0.3% – 0.5%) Stoic (Reductants not in excess)

Both oxidation reactions and reduction reactions are taking place in TWC

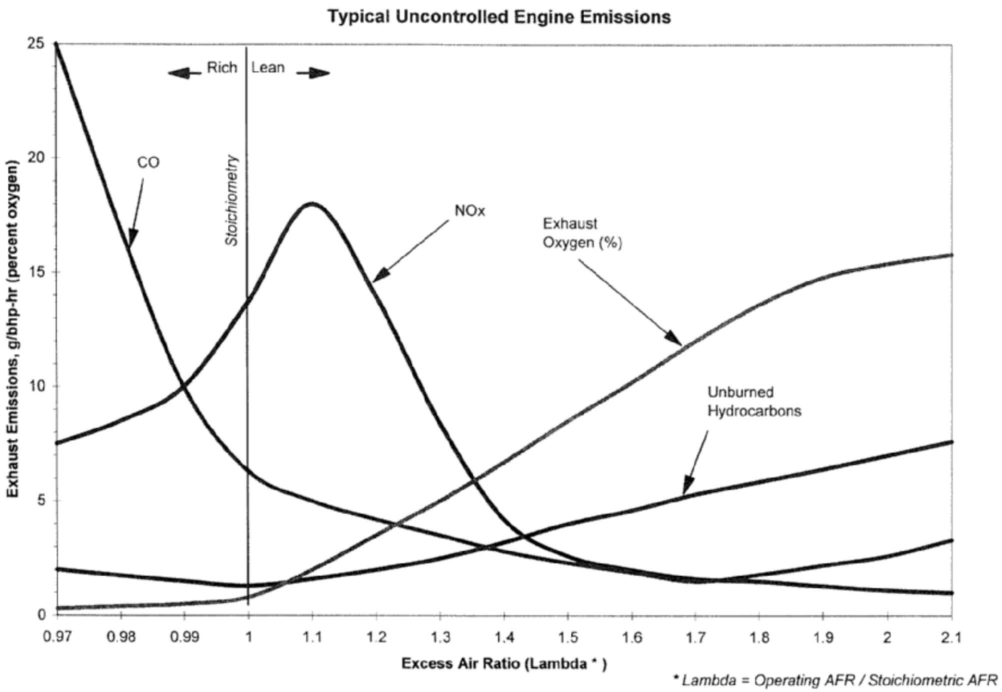
Three Way – Rich Burn Catalyst Components

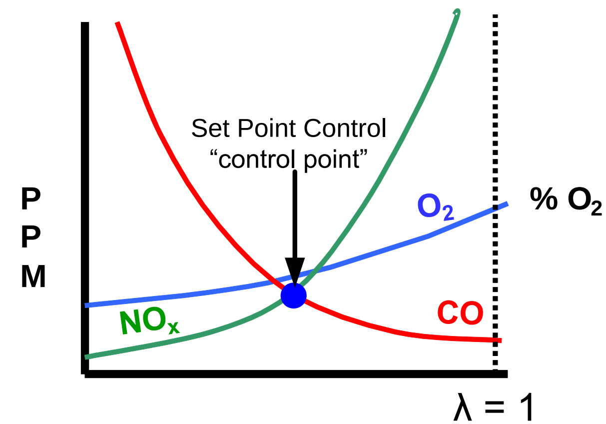
- **Substrate** – A high geometric surface area support for the washcoat.
- **Washcoat** – High surface area support for the catalyst, strong adhesion to the substrate.
- **Promoters** – Stabilise washcoat, modify sulphur chemistry.
- **Oxygen Storage Component** – Improve operating window, OBD.
- **Platinum Group Metal (PGM): Pt, Pd, Rh** – Active sites, have correct electronic structures to interact with HC, CO, NOx and O_2.



Rich Burn Engines Run Around λ = 1

- CO and NOx levels are related to the amount of exhaust O_2



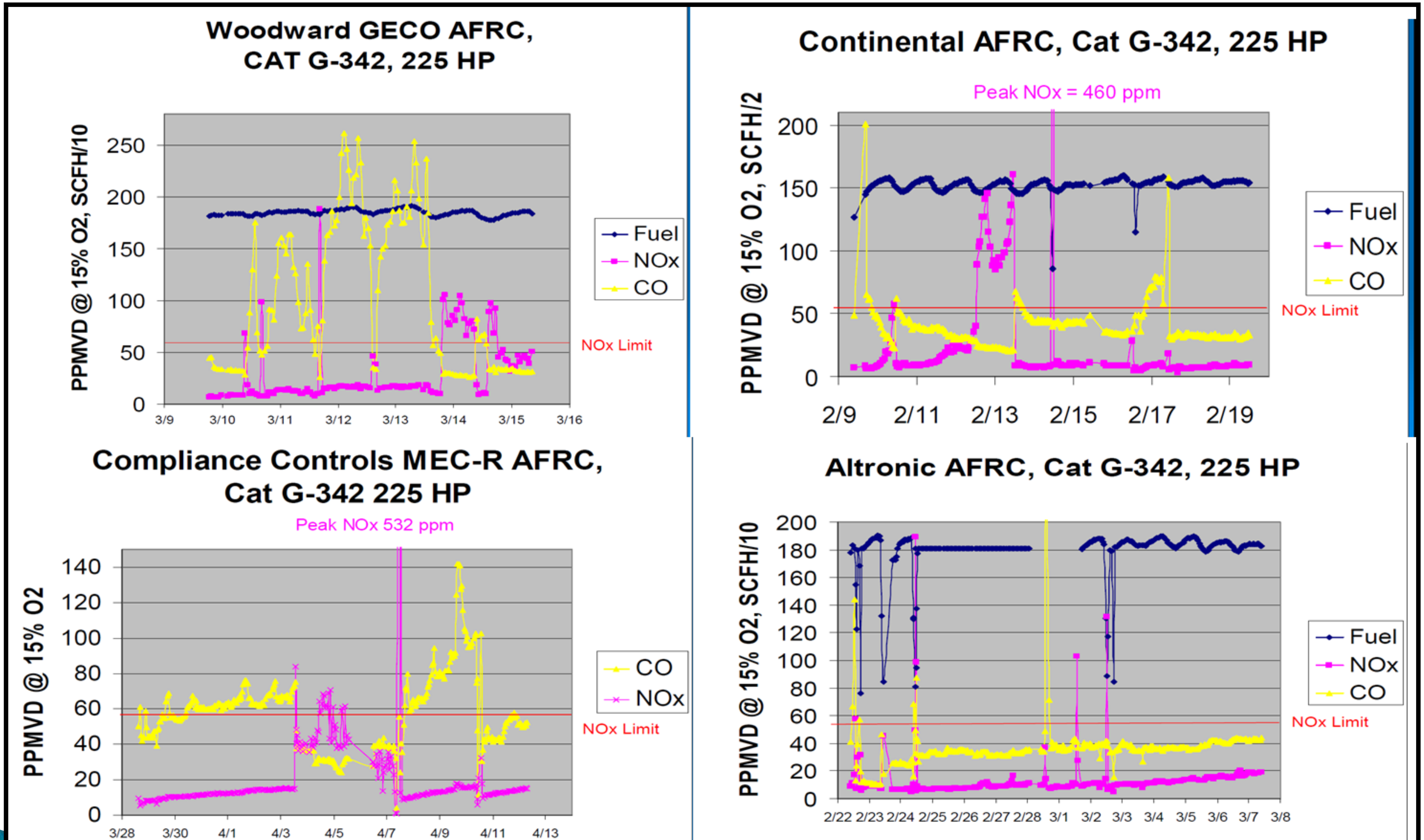


- AFR control relies on O_2 levels
  - Conventional controls uses "set point" control
  - Tries to control at a very narrow set point

Courtesy of WOODWARD

Conventional Set Point Controls

Fail to Stay in Compliance Over Time



*Actual data from South Coast Air Quality Management District testing

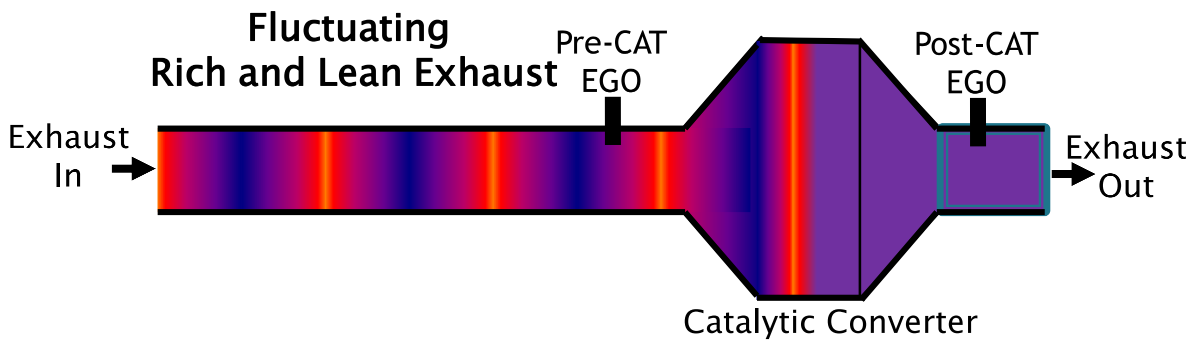
Current Control State

- Automotive approach (in use for decades)
  - Uses upstream and downstream heated O2 sensors (HEGO)
  - Highly advanced model-based automotive AFR Controls use dithering and dual HEGOs to measure oxygen storage capacity and determine excess emissions
  - Wider air-to fuel ratio window with gasoline
  - Rare to see Natural Gas automobiles
- Conventional Stationary Natural Gas Engine Approach
  - Often only use a Pre-Catalyst, unheated EGO sensor
  - No dithering, most industrial stationary AFR controls try to maintain a fixed Pre-Catalyst EGO set point
  - Very narrow AFR window with natural gas
  - Have been using ordinary gasoline engine EGOs
  - These EGOs are sensitive to natural gas causing shifts in the reading

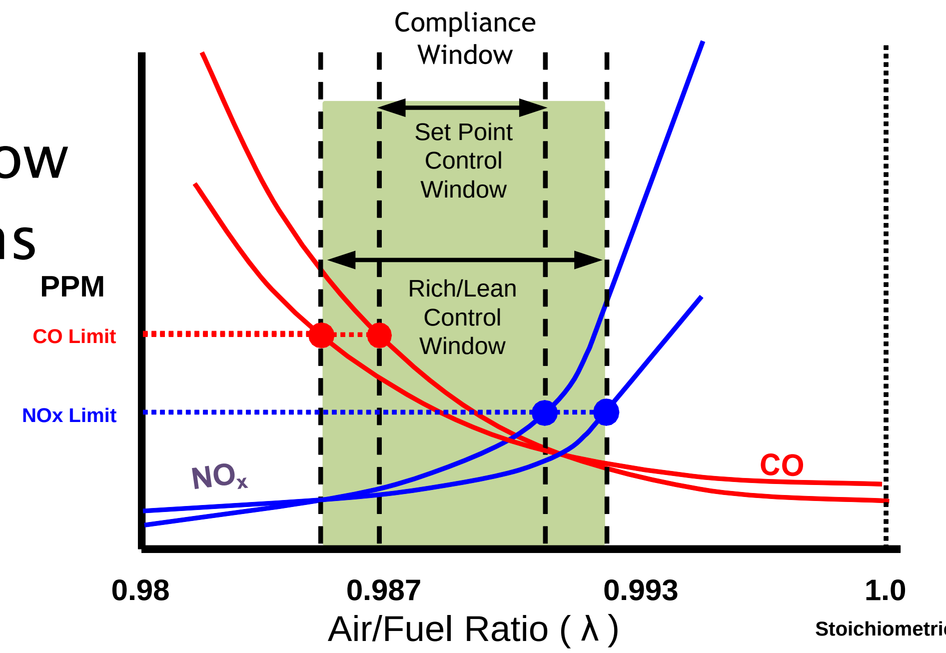
Courtesy of WOODWARD

Dithering Control

- Dithered operation allows the catalyst to operate properly



- Widens the compliance window tolerating hanging conditions



Courtesy of WOODWARD

Remote Monitoring and Control

The Good News

- AFRCs with Modbus TC/IP or Ethernet capabilities can be paired with ancillary equipment to allow for "dial in" remote monitoring and data storage
- AFRCs manufactures could develop software to remotely control AFRC setting when out of compliance
- New software developments could allow for remote alarms in the event of compliance or engine issues.
- OEM certified engines make use of direct connection to OBD and engine controls so they tend to be very effective in most cases but, due to proprietary nature of these systems, it is unknown whether remote monitoring or control is possible as of today

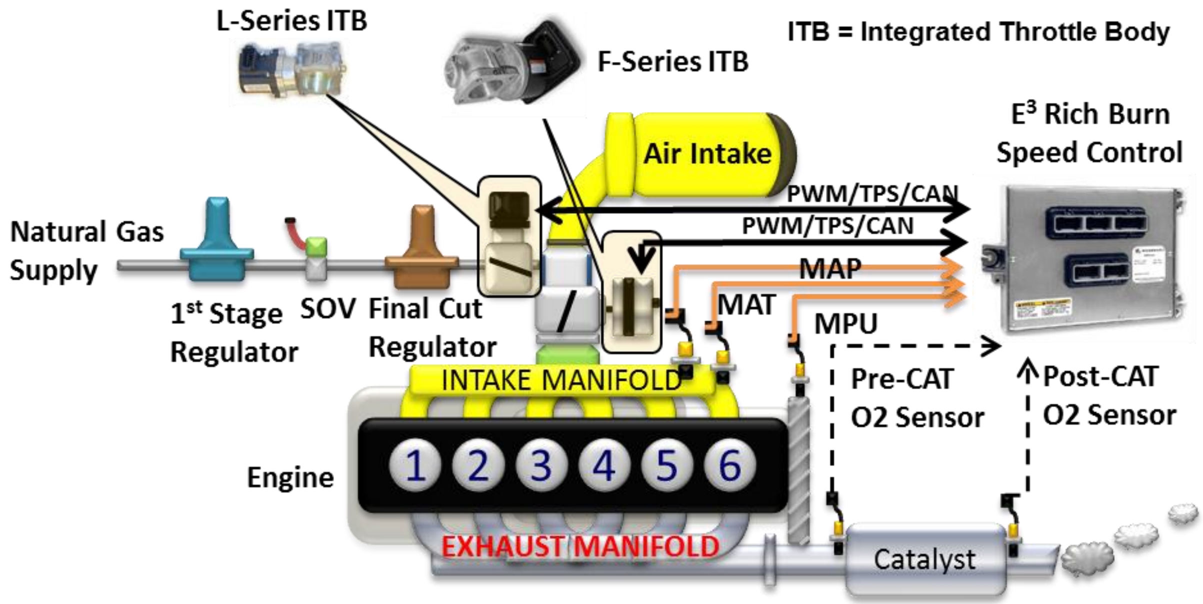
The Not So Good News

- Very basic AFRCs are not likely capable of remote monitoring without significant effort
- As of today, connections of AFRCs to SCADA systems at power plants have been done but industry experts have found this to be limited.
- Monitoring of remote AFRCs is nearly never done, if at all.
- No examples of "dial in" control capabilities of remote AFRCs have been found.

Not just AFR control – TOTAL engine control

System control approach – not just a component approach

- Misfire detection to reduce catalyst and engine damage
- Cylinder bank balancing for better engine performance
- Fuel limiting for better starting
- More information for better engine protection
- Data trending
- On-Board Diagnostics
- Speed/load control
- Interfaces and adjusts
  - Ignition timing
  - Generator controls

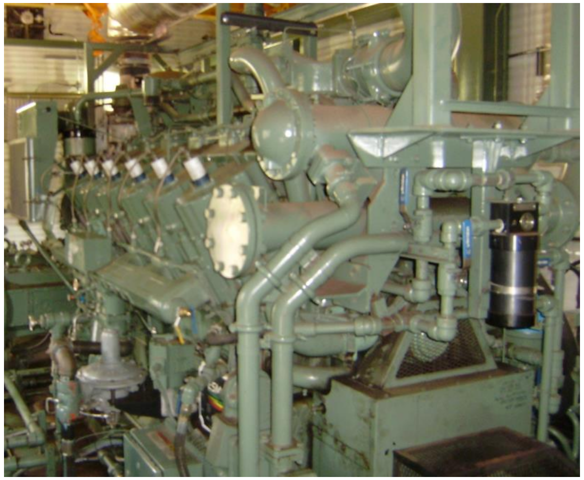


Courtesy of WOODWARD

Proven in the field to reduce cost

- California
  - CATERPILLAR 3412
  - Water Pump application
  - Highly variable load
  - In compliance over 8000hrs with no tweaking

- Wyoming
  - Waukesha 7044
  - Gas compressor application
  - In compliance over 6000 hours with no tweaking

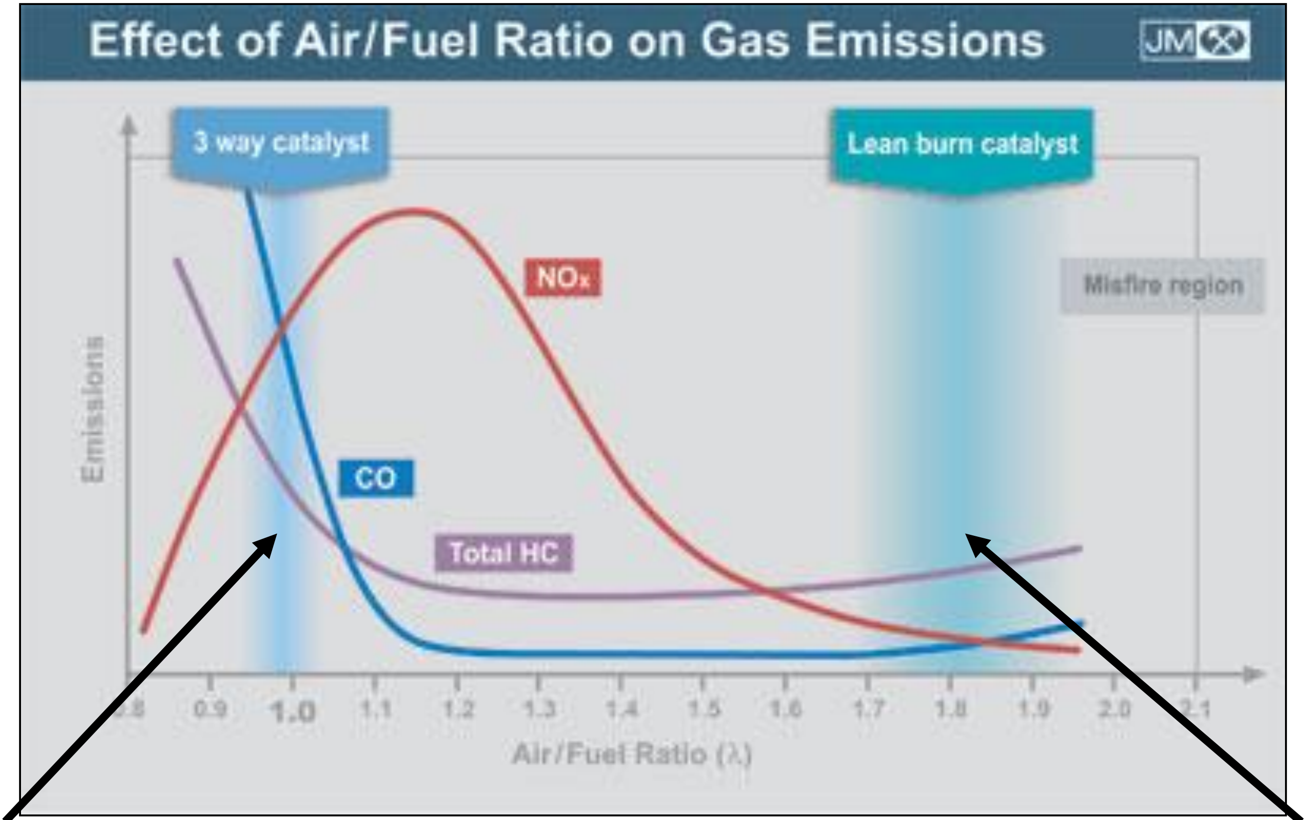


Courtesy of WOODWARD

Three Way – Rich Burn
Summary

- Three way catalyst effectiveness if very dependent on exhaust chemistry (lambda)
- Dithering or total engine control systems are much more effective than setpoint control
- Remote monitoring is still in its infancy and is not adopted in very many cases
- Remote control capabilities are nearly nonexistent
- The addition of ancillary equipment and software enhancements to “more advanced” AFRCs can allow for monitoring and control

How does it work?
Different applications require different catalysts



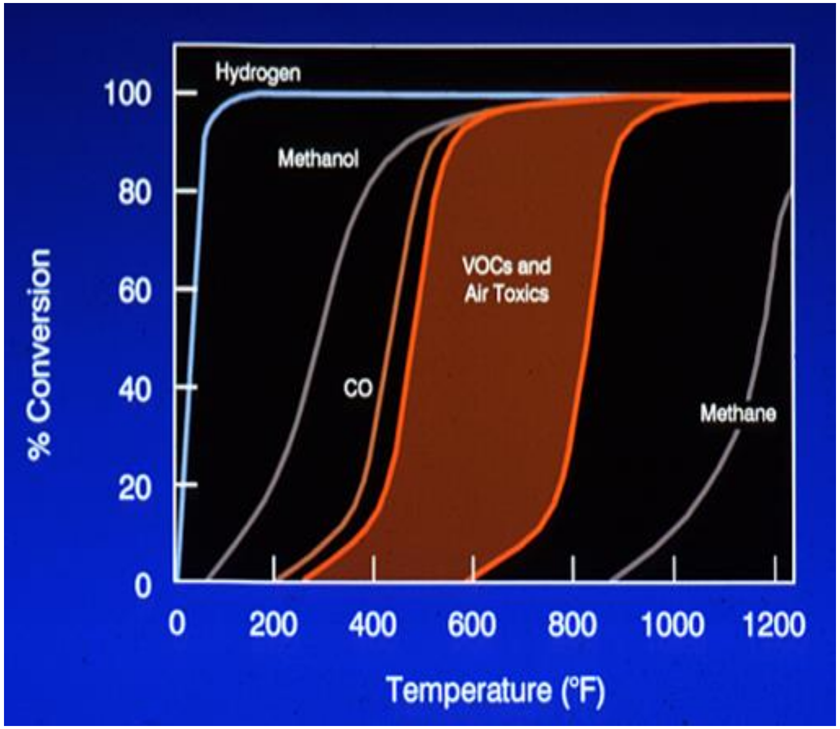
Section 1: Three way catalysts

Section 2: Two way catalysts

Section 3: SCR systems

Two Way – Lean Burn

The Air Fuel ratio (Lambda) is not as critical as the area of operation is with excessive O_2. The type of hydrocarbon (HC) being oxidized is extremely important in selecting the proper catalyst

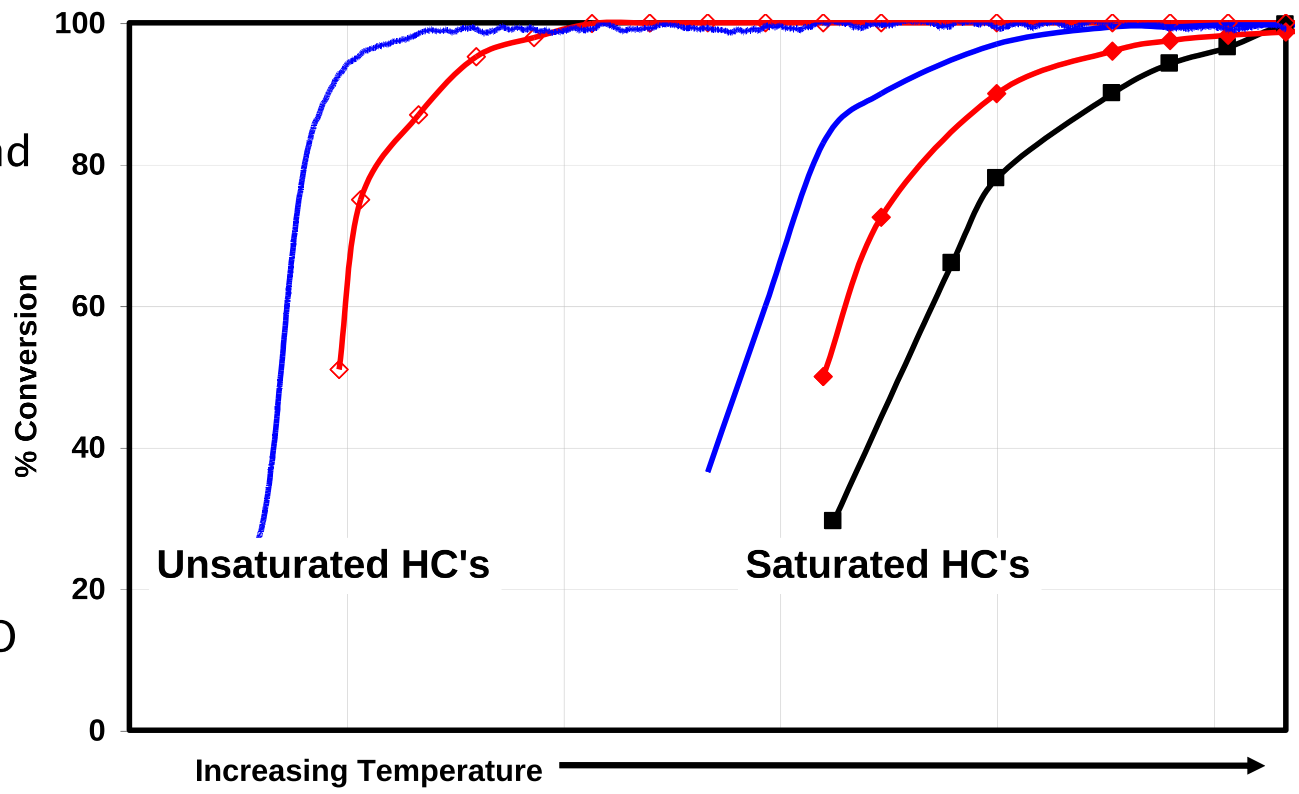


- **Oxidation Reactions**
- $CO + 1/2O_2 \longrightarrow CO_2$
- $HC + O_2 \longrightarrow CO_2 + H_2O$
  - *In this case HC is "any" HC, HAP, VOC*

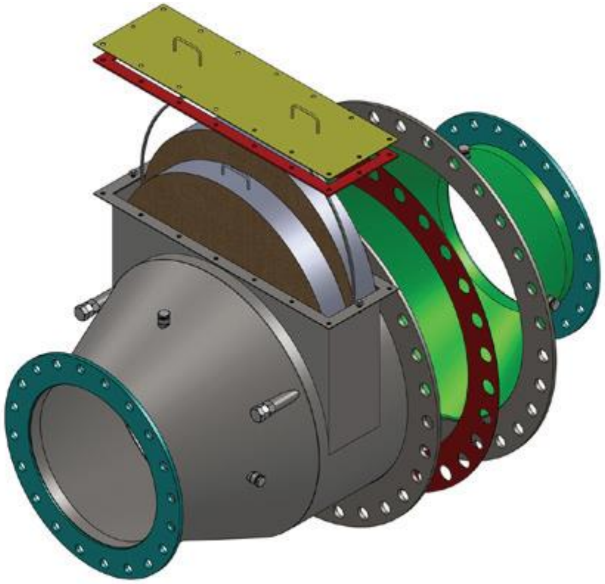
Only oxidation reactions are taking place

Two Way – Lean Burn
Hydrocarbon Oxidation

- Hydrocarbon oxidation across a catalyst is dependent on the hydrocarbon species and varies between easy to difficult.
- Order of difficulty
  - Methane > ethane > propane > butane
  - Saturated HC > Unsaturated HC
  - Unsaturated HC > CO
- Different catalysts are needed for different hydrocarbons



Two Way – Lean Burn Catalyst Components

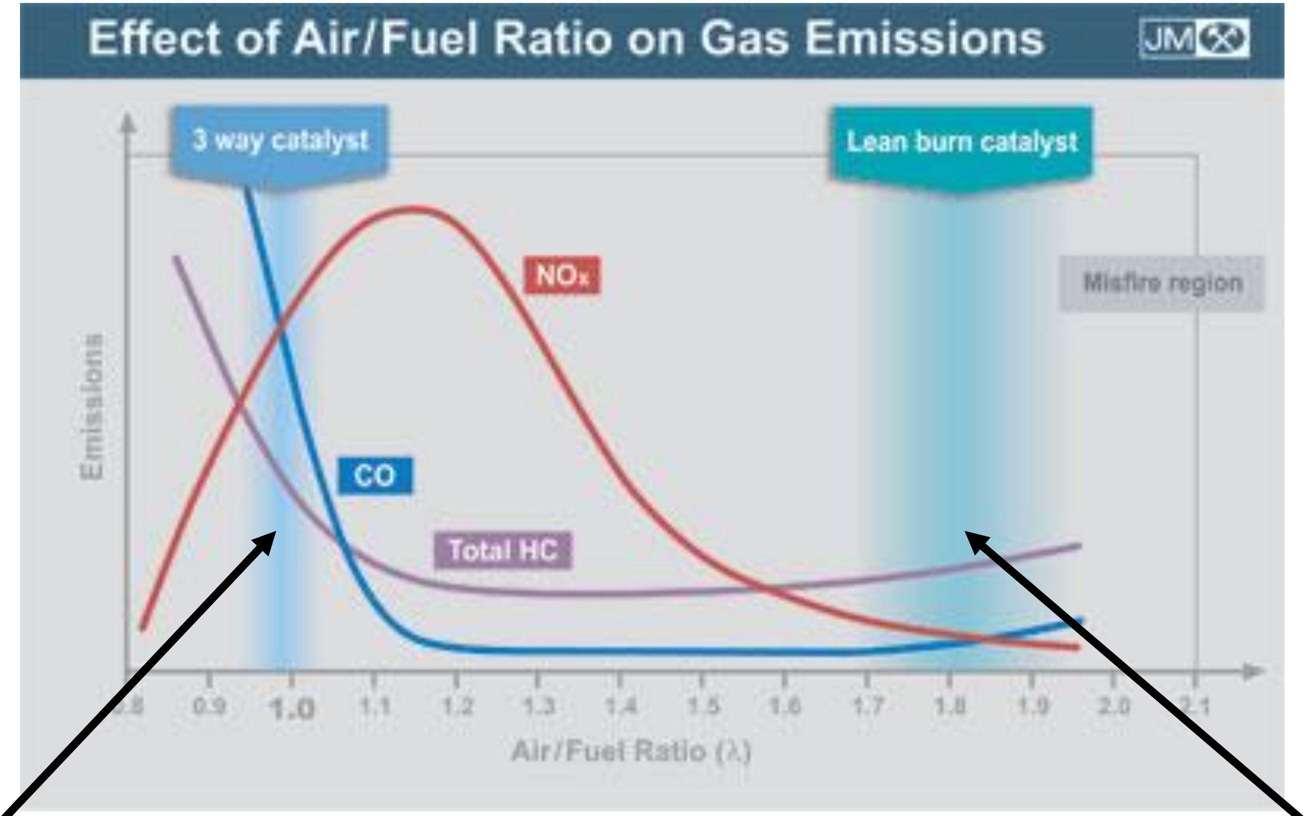


- **Substrate** – A high geometric surface area support for the washcoat.
- **Washcoat** – High surface area support for the catalyst, strong adhesion to the substrate.
- **Promoters** – Stabilise washcoat, modify sulphur chemistry.
- **Platinum Group Metal (PGM): Pt, Pd** – Active sites, have correct electronic structures to interact with HC, CO, and O_2.

Two Way – Lean Burn
Summary

- Oxidation catalyst selection is very dependent on hydrocarbon species
  - Catalyst activity is a combination of design materials as well as the optimizing for operating parameters
- Oxidation catalyst deactivation is similar to TWC catalyst
  - Deactivation of the catalyst is a result of the operating environment
    - Temperature, poisons, and masking
  - Thermal deactivation is irreversible
  - Chemical washing can restore significant amount of activity due to “typical” poisons

How does it work?
Different applications require different catalysts



Section 1: Three way catalysts

Section 2: Two way catalysts

Section 3: SCR systems

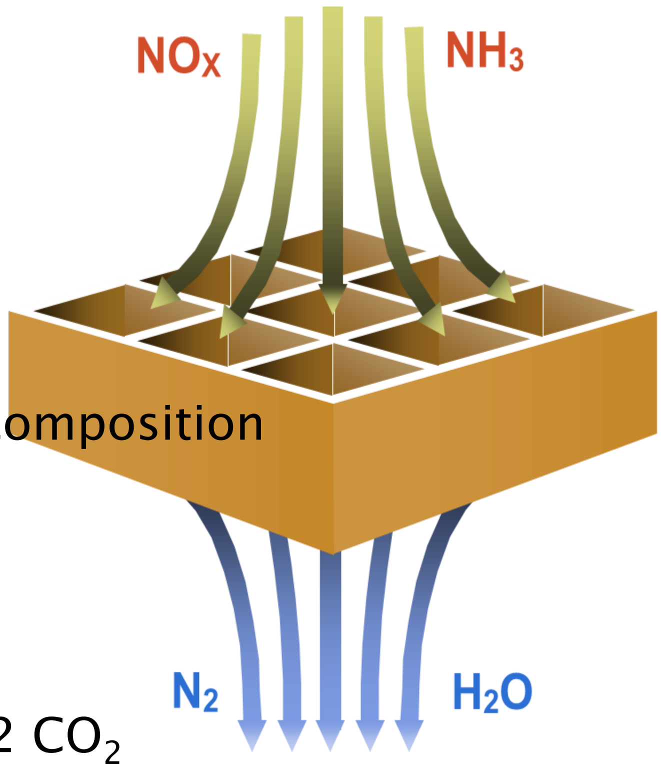
In typical stationary lean burn emission O_2 concentration is ~1000x of NOx. Most of the reducing agents react faster with oxygen than NOx:

$$2H_2 + O_2 \rightarrow 2H_2O$$
$$2CO + O_2 \rightarrow 2CO_2$$
$$(HC) + O_2 \rightarrow CO_2 + H_2O$$
$$NH_3 + O_2 \rightarrow NO + H_2O$$

NH_3 can be an exception if a selective catalytic reduction (SCR) catalyst is present.

Stoichiometric reaction of NOx molecules at the catalytically active surface with reducing agent Ammonia:

- $4\ NO + 4\ NH_3 + O_2 \rightarrow 4\ N_2 + 6\ H_2O$
- $NO_2 + 4\ NH_3 + O_2 \rightarrow 3\ N_2 + 6\ H_2O$
- $NO + NO_2 + 2\ NH_3 \rightarrow 2\ N_2 + 3\ H_2O$



Ammonia source is typically urea

- $(NH_2)_2CO \rightarrow NH_3 + HNCO$ decomposition
- $HNCO + H_2O \rightarrow NH_3 + CO_2$ hydrolysis
- $(NH_2)_2CO + H_2O \rightarrow 2NH_3 + CO_2$

One urea yields two NH_3

- $4\ NO + 2(NH_2)_2CO + O_2 \rightarrow 4\ N_2 + 4\ H_2O + 2\ CO_2$

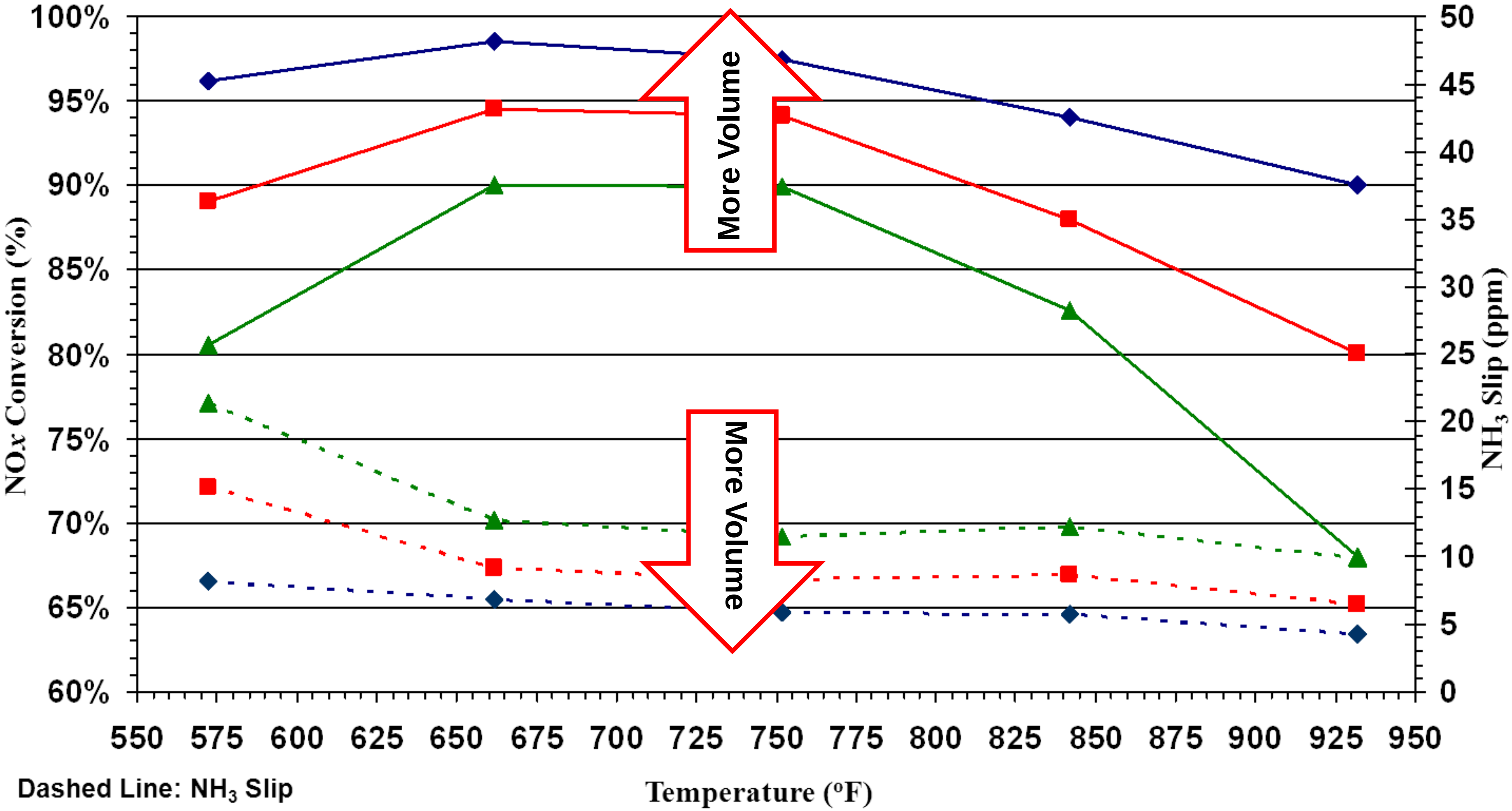
SCR – Lean Burn
Catalyst Composition

V_xO_y (0.3 to 5%) Analyzed as vanadium(V) oxide commonly known as vanadium pentoxide, is the most important compound of vanadium. In addition, binding and plastifier materials.

WO_3 / MoO_3 Tungsten(III) oxide (WO_3) is a compound of tungsten and oxygen

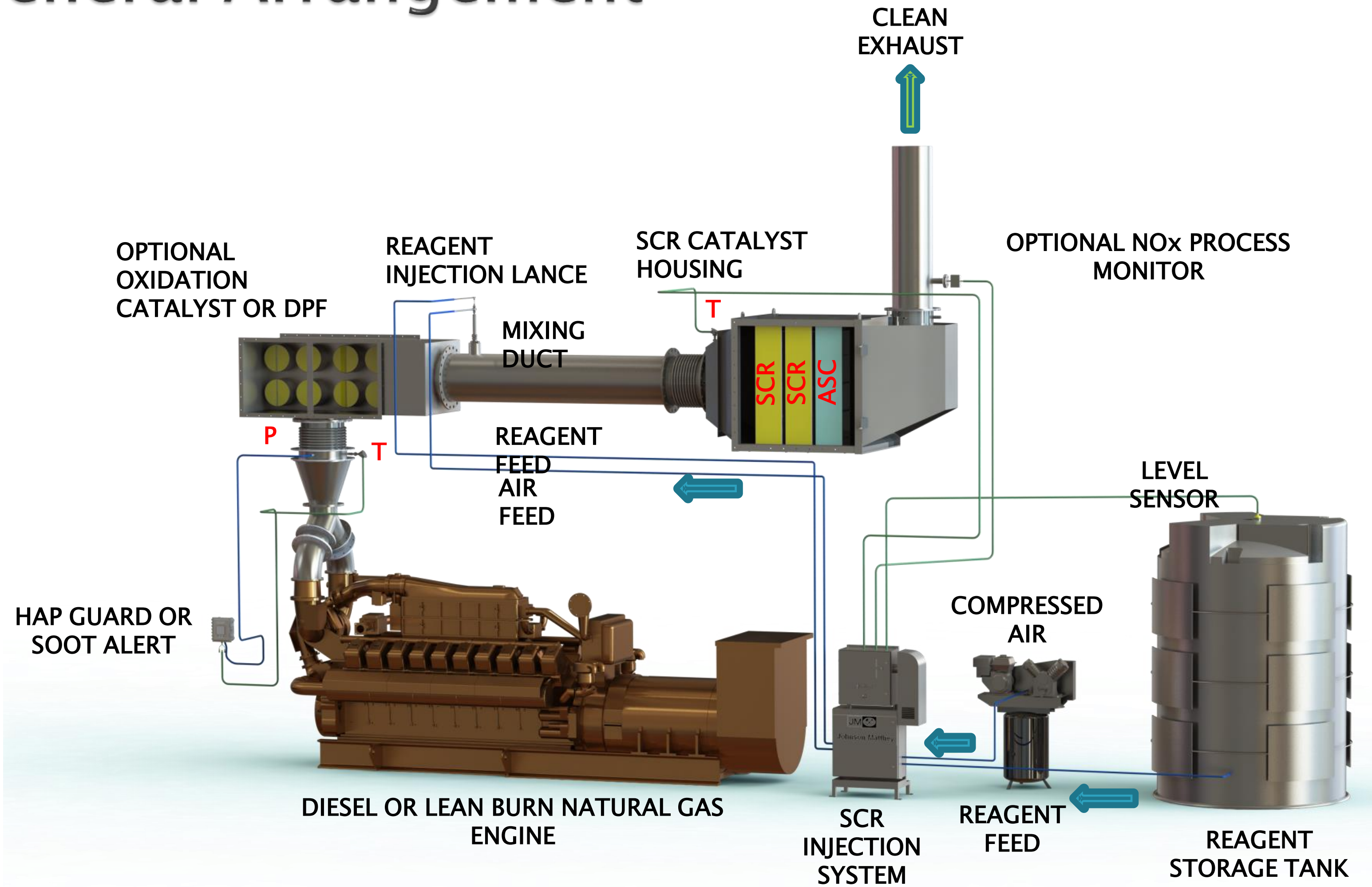
TiO2 - Titanium dioxide, also known as titanium(IV) oxide or titania, is the naturally occurring oxide of titanium, chemical formula TiO_2. When used as a pigment, it is called titanium white, Pigment White 6, or CI 77891.

SCR – Lean Burn
NOx Reduction and Temperature



Dashed Line: NH_3 Slip

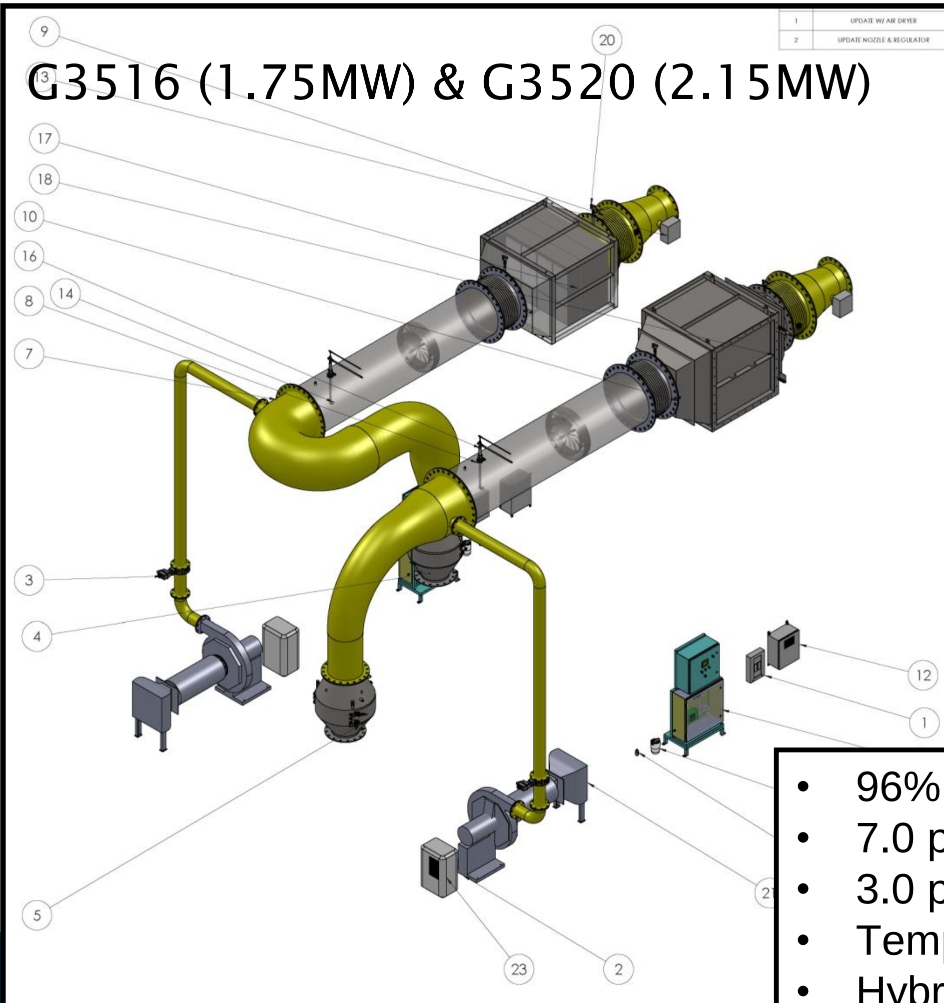
SCR – Lean Burn
General Arrangement



SCR – Lean burn

Real World Examples

G3516 (1.75MW) & G3520 (2.15MW)



- 96% NOx / 80% CO / 70% VOC Reduction
- 7.0 ppmvdc NOx Maximum
- 3.0 ppmvdc NOx Achieved
- Tempering Blowers to Limit SCR Temperature
- Hybrid Urea Injection Control w/NOx Sensor

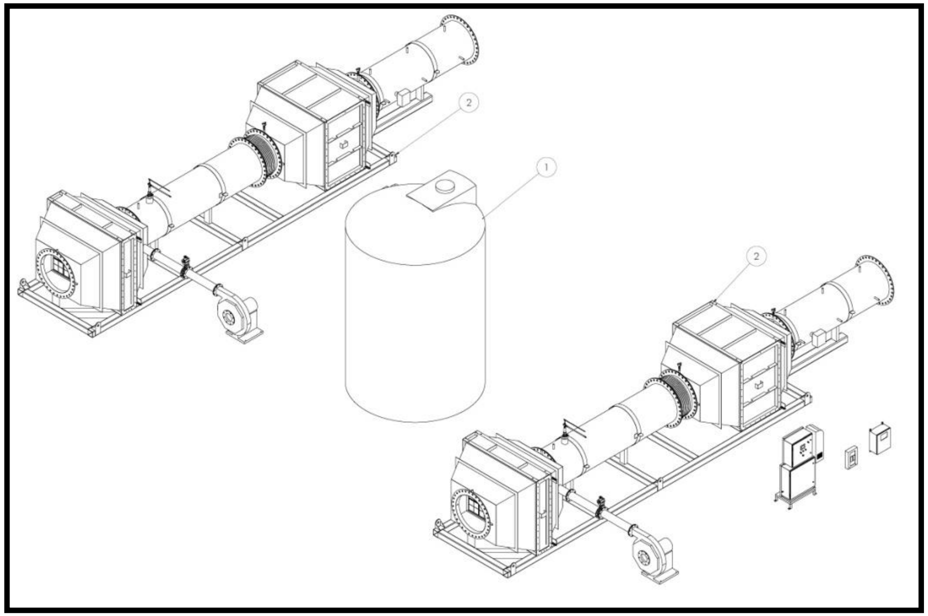
SCR – Lean burn

Real World Examples

- 96% NOx Reduction
- 93% CO Reduction
- 60% VOC Reduction
- 3.7 ppmvdc NOx Max
- 3.0 ppmvdc NOx Achieved
- Hybrid Injection w/CEMS

SCR – Lean burn

Real World Examples

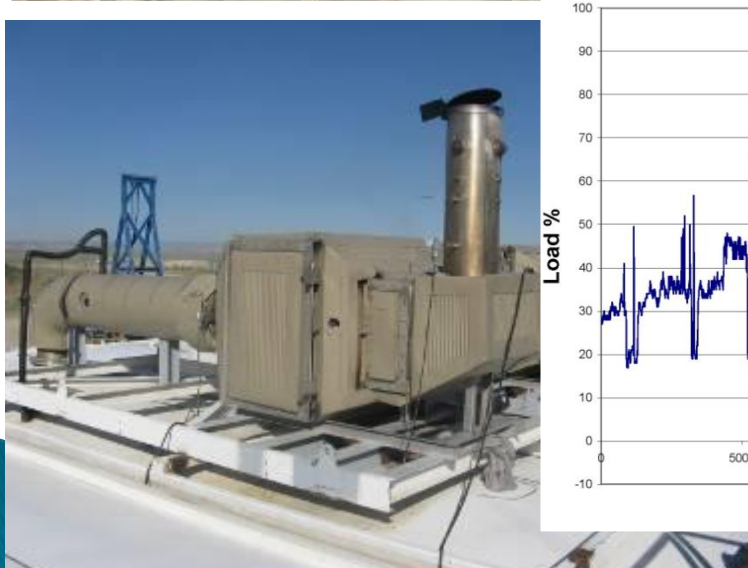


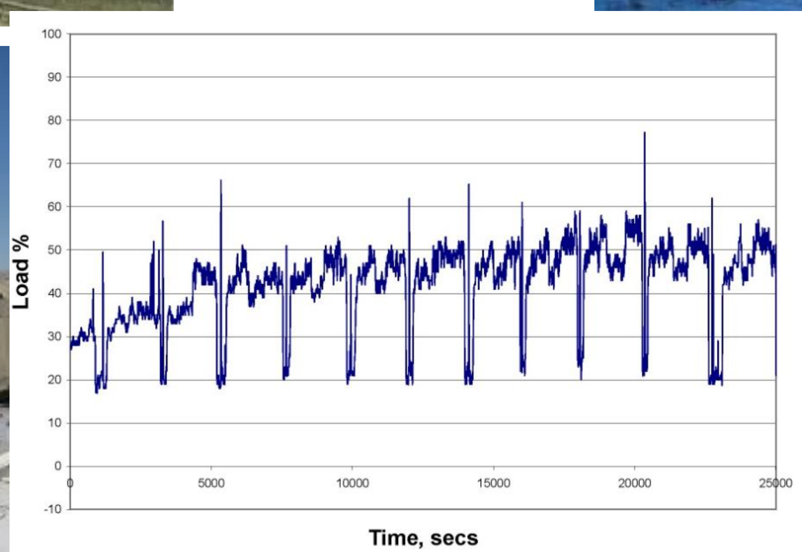
- 2 x G3616LE (4,735 hp) Prime Gas Compression
- 75% NOx / 95% CO / 72.2% VOC Reduction
- Tempering Blowers to Limit SCR Temperature
- Hybrid Urea Injection Control w/NOx Sensor
- ~5 inH_2O Total System Backpressure

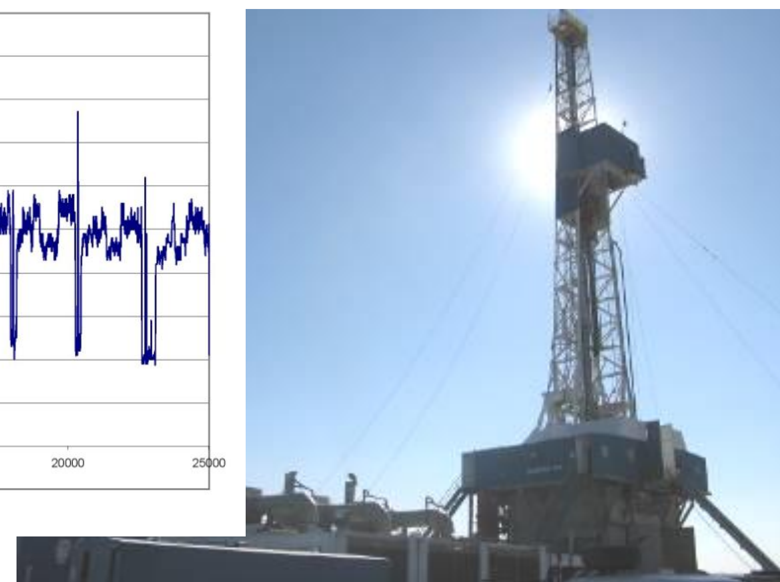
SCR – Lean burn

Real World Examples

- CAT 3512 Engines
- 3 Rig Engines Load Share
- 24 SCR Systems Total
- 90% NOx Reduction
- Skid Mounted
- Remote Locations



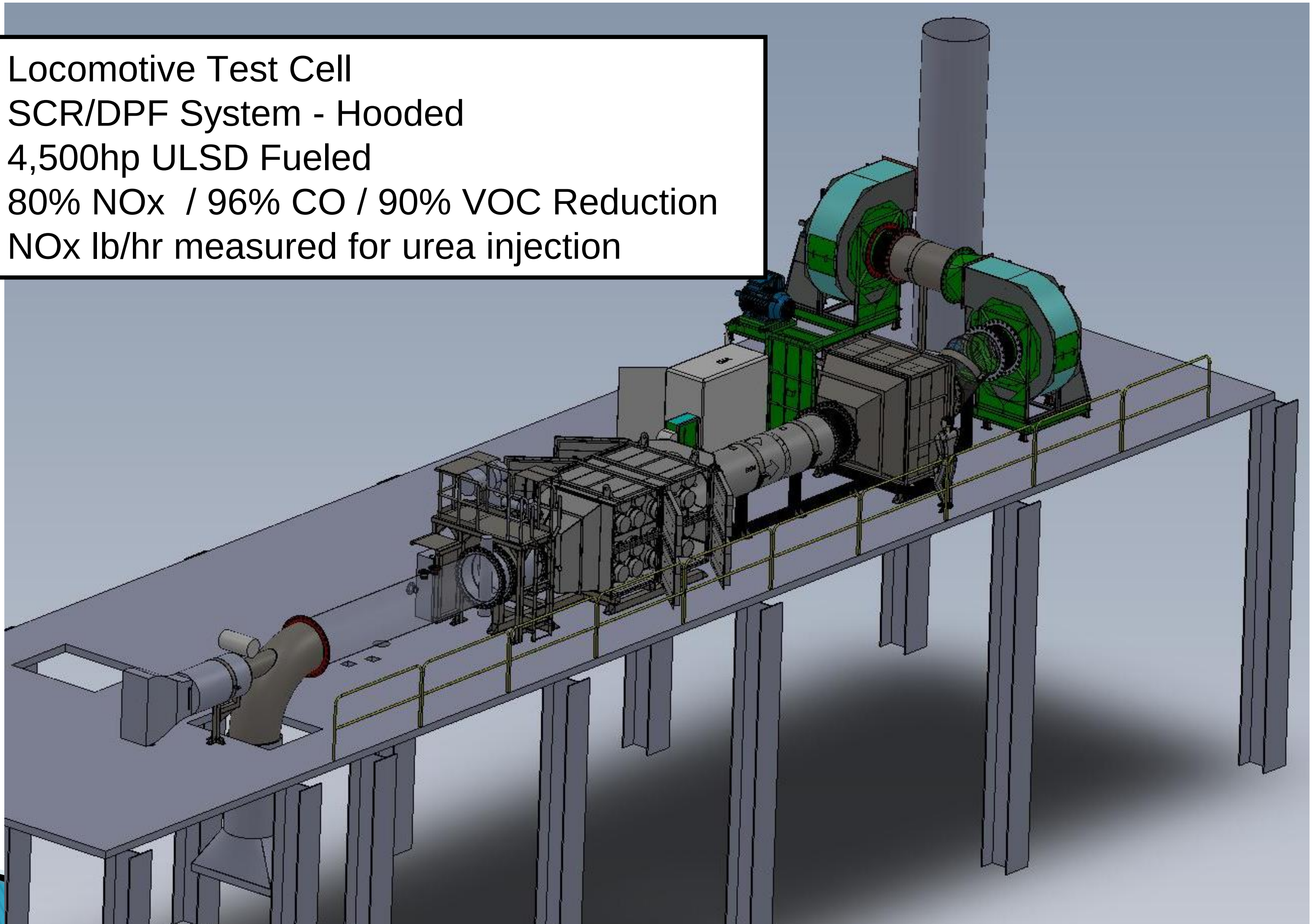




SCR – Lean burn

Real World Examples

- Locomotive Test Cell
- SCR/DPF System - Hooded
- 4,500hp ULSD Fueled
- 80% NOx / 96% CO / 90% VOC Reduction
- NOx lb/hr measured for urea injection

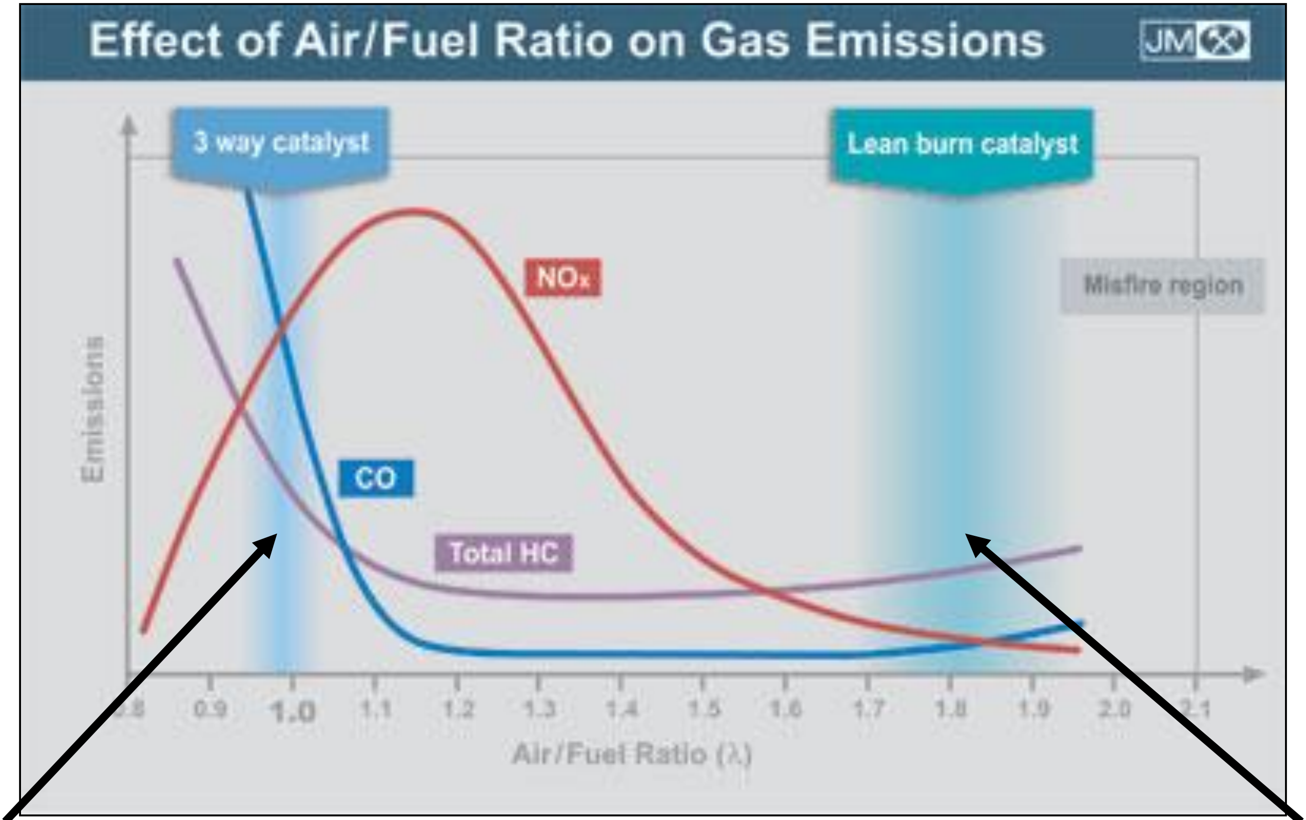


SCR Systems – Lean Burn

Summary

- Base metal catalyst with no Platinum Group Metals (PGM)
- Not a passive catalyst system; requires a reductant
- Customized to customer specifications and footprint
- Equipment scope is more than catalyst and a housing:
  - Reductant injection system, Mixing Duct, Reductant Tank, etc.
- Reductant injection system must be robust
  - Dosing too low = low NOx reduction
  - Dosing too high = excessive NH_3 slip
- Different operating temps than Two Way and Three Way
  - Two Way and Three Way must operate at <1250ºF
  - Urea-based SCR must operate at 575ºF – 950ºF

JM provides a wide range of catalysts



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Section 2: Two way catalysts

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Thank You!

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