REINHOLD ENVIRONMENTAL Ltd.

2019 NOx-Combustion-CCR Round Table Presentation

February 11 & 12, 2019, in Salt Lake City, Utah / Hosted by PacifiCorp

4½ years of dual function catalyst performance at Wolf Hollow

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Agenda

1. Who are Umicore again?
2. US Regulation
3. System design challenges
4. Dual function catalyst and its layout
5. Wolf Hollow the story updated
6. Questions

Who are Umicore again?

Umicore Catalyst USA LLC

1. Late 2017 Umicore acquired Haldor Topsoe's Stationary and Automotive SCR businesses.
2. Umicore is a Belgian public traded company founded in 1989, but with roots dating back to 1805 in the mining industry.
3. Revenue of around 13.5 Billion USD and over 10,000 employees around the globe.
4. Three main business areas:
    1. Recycling
    2. Energy & Surface Technology
    3. Catalyst – this is where we are placed
5. Same good people, same good catalyst

US Regulation on turbine emissions

Tough, Tougher, “Future”

Regulations in the United States - “Tough”

Gas Turbine Emissions Standards (1995 – 2010)

- Average GT uncontrolled outlet NOx; 9 – 25 ppm
- NOx outlet range 2 – 8 ppm; 5 – >10 ppm NH3 slip
- Average DeNOx removal efficiency; 77% - 90%
- No emission compliance requirements during start up
- Required NH3 to NOx uniformity; 15% - 20% RMS
- Less than 1% gas bypass is acceptable
- Outlet CO emissions $\leq$ 2.0 ppm

Regulations in the United States - "Tougher"

Gas Turbine Emissions Standards (2010 – Current)

- Average GT outlet NOx; 20 – 35 ppm
- NOx outlet range 2 ppm; 2 – 5 ppm NH3 slip
- Average DeNOx removal efficiency; 90% - 94%
- Emission compliance begins with starting of the GT
- Currently suppling units 92% - 96% DeNOx with some 2 ppm NH_3 slip
- Outlet CO and VOC emissions 1.0ppm in some cases

Regulations in the United States – “Future”

- Anticipate “newer” generation GT’s with up to 50 ppm outlet NOx
- Anticipate more areas of the US to limit NH3 slip to 2 - 3 ppm
- 2 ppm NOx / 5 ppm NH3 slip or better will be the norm
- California is moving from RECLAIM to “command and control”
- Existing sources in CA will need to meet new lower limits
- California making 2 ppm NOx and <5 ppm slip std for all sources requiring (BARCT)
- CO & VOC emissions limited to 1ppm – 2ppm on most applications

System design challenges

Challenges OEM's Can't Ignore

Achieving >93% DeNOx and very low slip

- Ammonia to NOx uniformity
  - ✓ New and better AIG design & tuneability (1, 2 or 3 zones; mult. zone)
  - ✓ Supplemental firing / duct burners – may require (2) AIG's
  - ✓ Permanent sample / test grid
  - ✓ Use static mixers at the AIG to improve mixing
  - ✓ Liquid reagent injection (ammonia or urea)
- Compliance through start-up
- Flue gas bypass, you can have none
- Improved / faster ammonia control systems
- Stack measurement multiple point (CEMS)

Catalyst is not the limiting factor, near 100% DeNOx removal

Relationship of NH_3 to NOx Uniformity and NH_3 Slip

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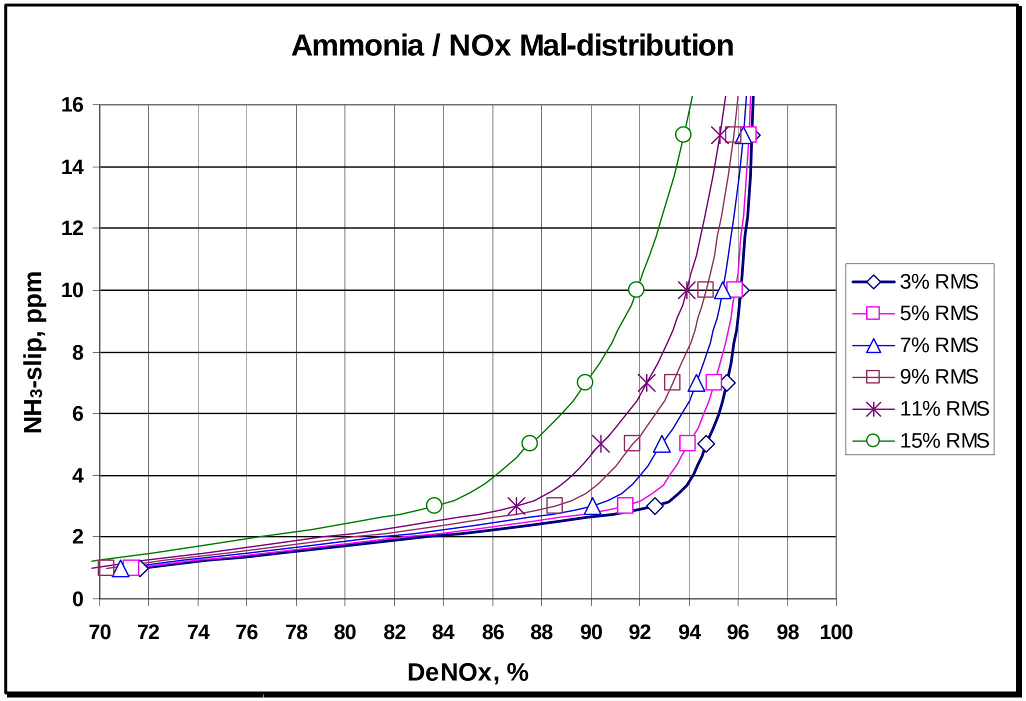
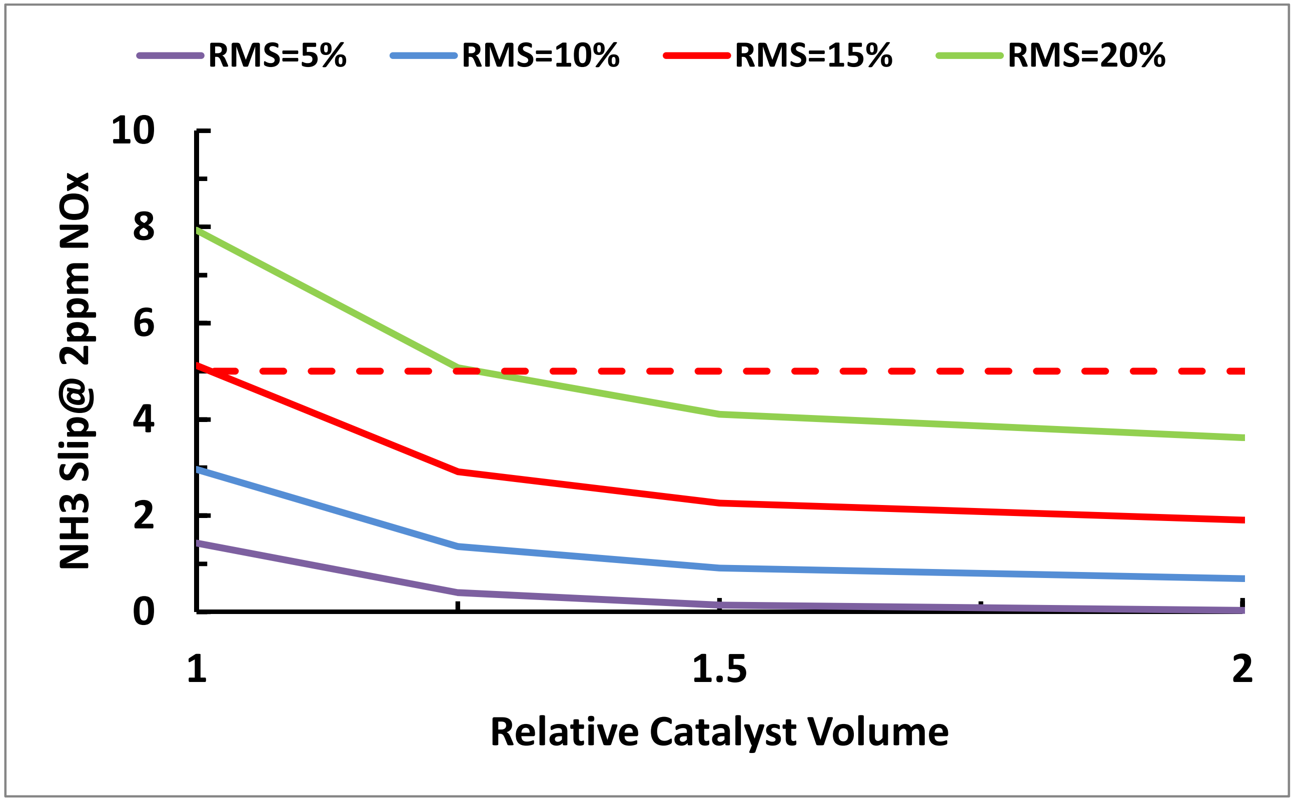
- Reagent Grade needed
- Ammonia slip given for end of guarantee period
- Ammonia slip will typically gradually increase over time due to loss of catalytic activity (except in high temp applications)
- Ammonia to NOx maldistribution is critical in high reduction low slip systems



Impact of Catalyst Volume on NH_3 Slip

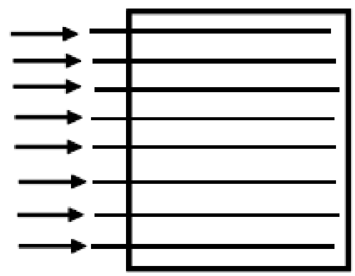
Based on 90% DeNOx design (20ppm-2ppm) & 5 ppm slip



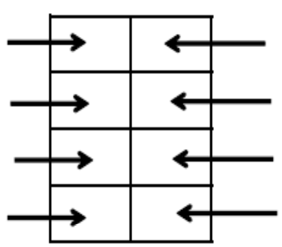
AIG Design and Tunability

AIG Must Have Adjustment Valves

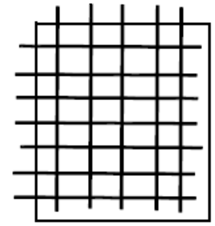
Single Zone - Common



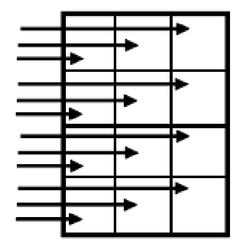
Double - Zone



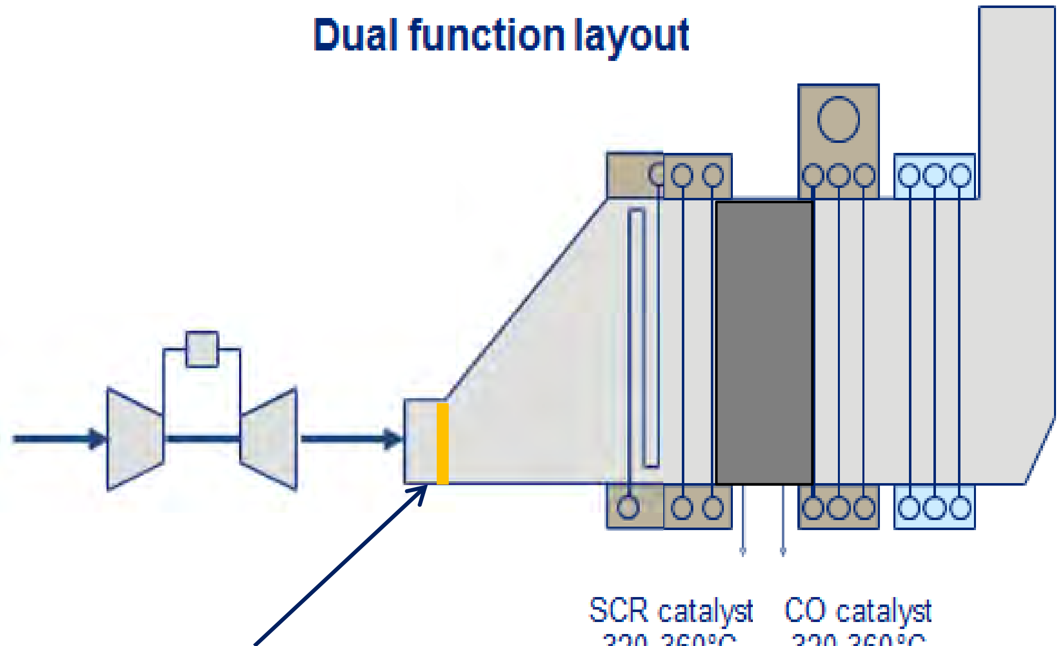
Multiple Zone



3 Zone – Vert. Adjustment



Liquid Reagent Injection - HRSG



Direct Injection of Aqueous Ammonia

or a Urea Solution

The Dual Function Catalyst

What makes a good one

What is a true dual function catalyst?

Beside NOx reduction it oxidize CO and VOC’s, in one and same catalyst

Based on our DNX catalyst with the active component being Pd

Allows for high SO_2 tolerance and low SO_2 oxidation

Have been used in excess of 160+ plants in a divers range of applications such as

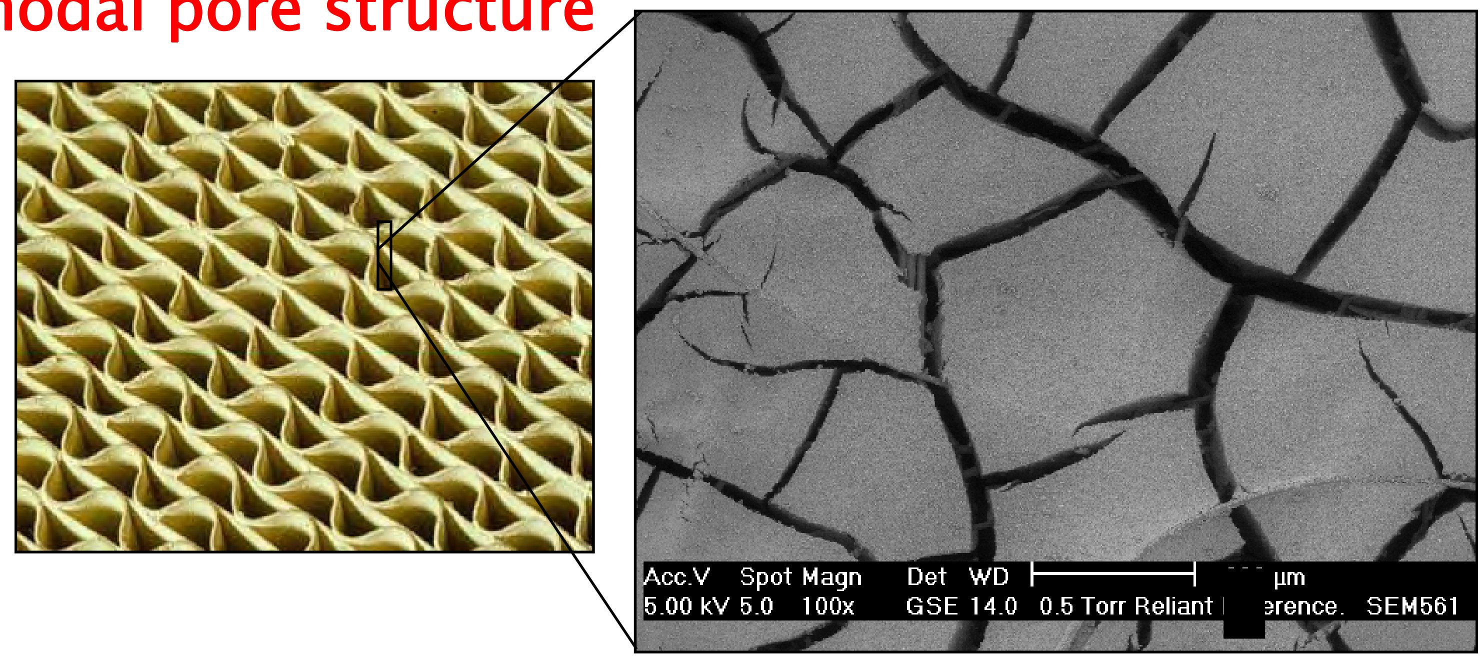
- Gas turbines
- Industrial plants
- Large NG fired Gas engines including landfill gas with siloxanes
- Diesel engines
- Chemical processing plants
- Refinery units

Typical CCGT Catalyst Module

Accessibility of active sites

DeNOx reaction is “Diffusion Limited”
more highways = higher diffusion rate = higher activity

Tri-modal pore structure



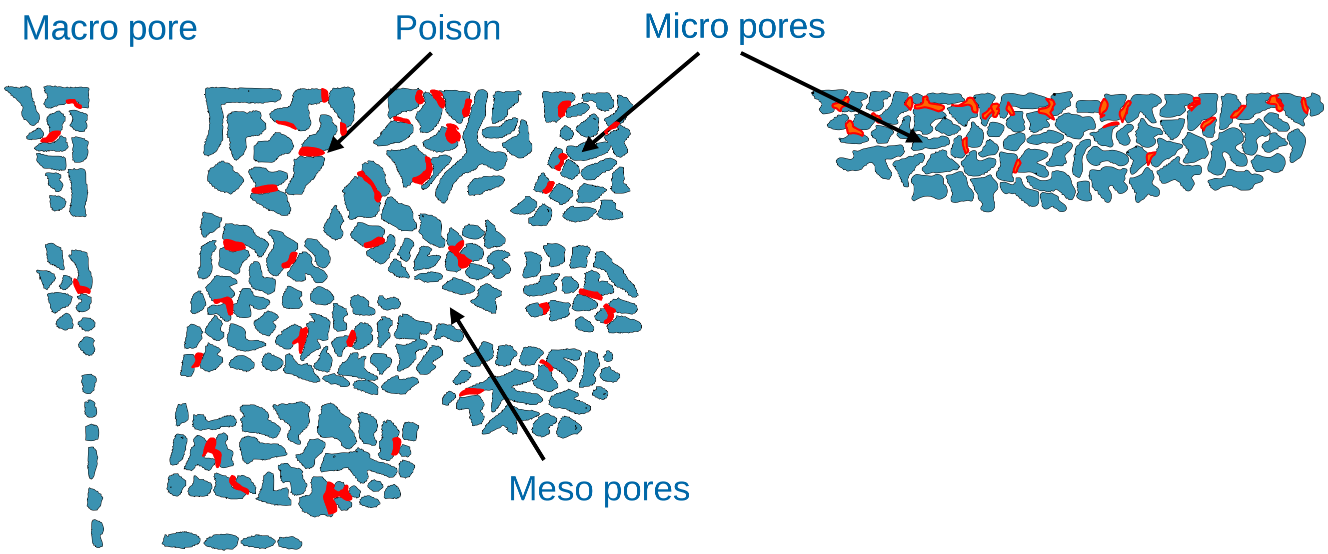
Pore structures is key to fight catalyst poisons

DNX® type catalyst

- Trimodal pore structure

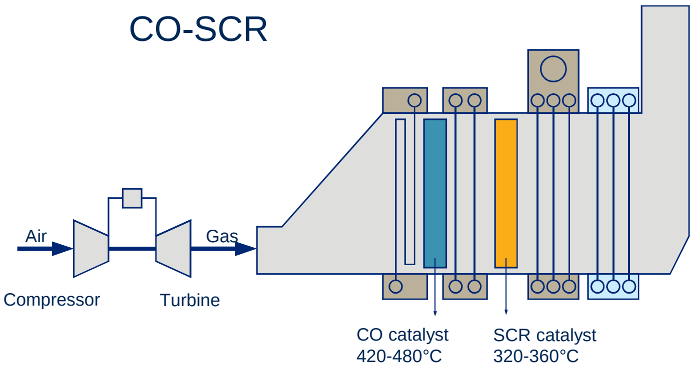
Extruded & plate type catalyst

- Homogenous micro pore structure

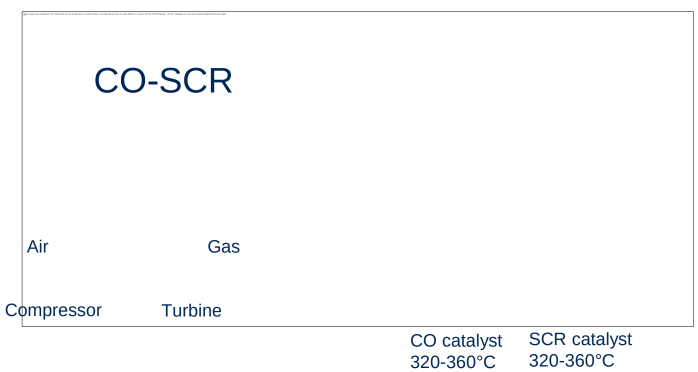


Basic HRSG Layouts

CO-SCR

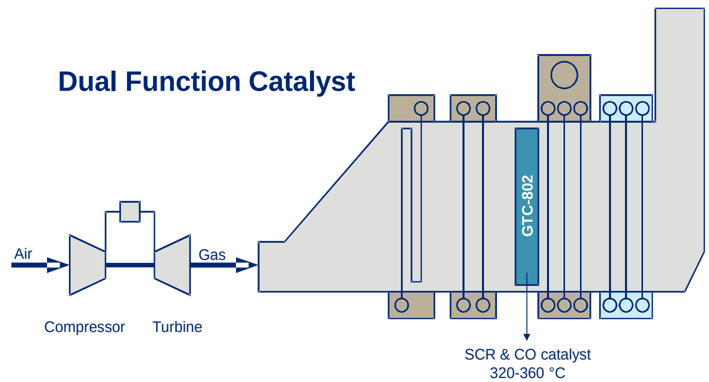


CO-SCR

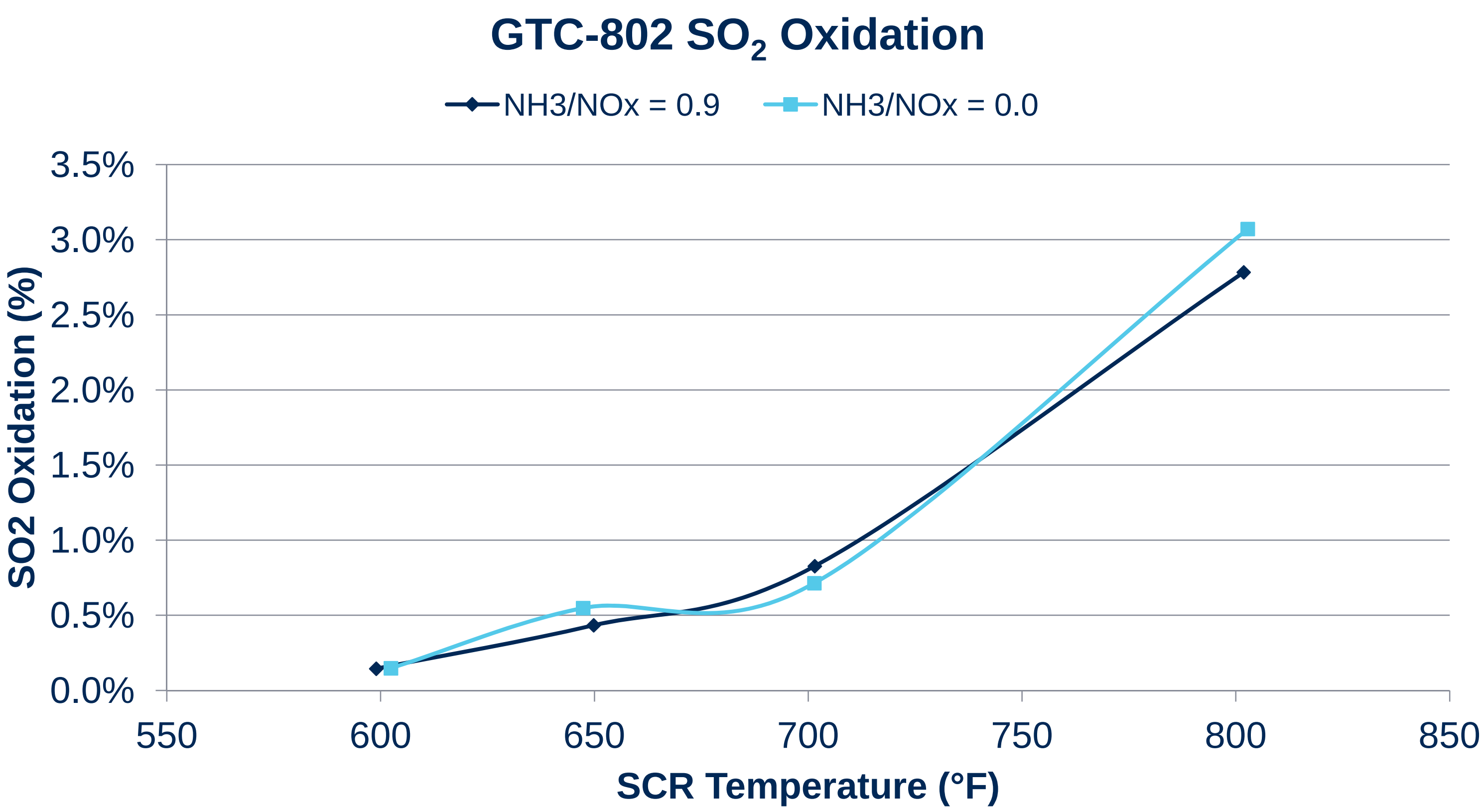


SCR-CO

Dual Function Catalyst



SO2 to SO3 Oxidation Rate
10 - 30 times lower than Pt based oxidation catalyst



SO_2 tolerance

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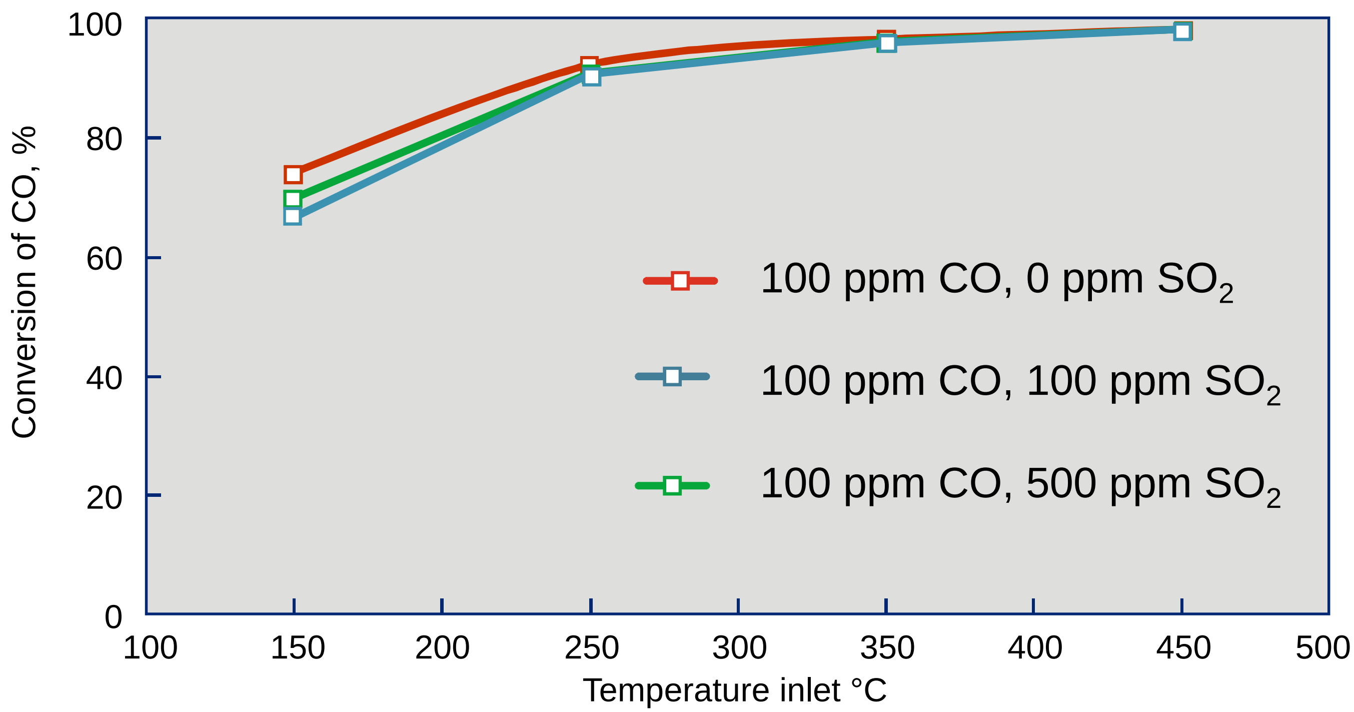
In operation since the mid 90'ies



Development of a Dual Function Catalyst

Performance Characteristics

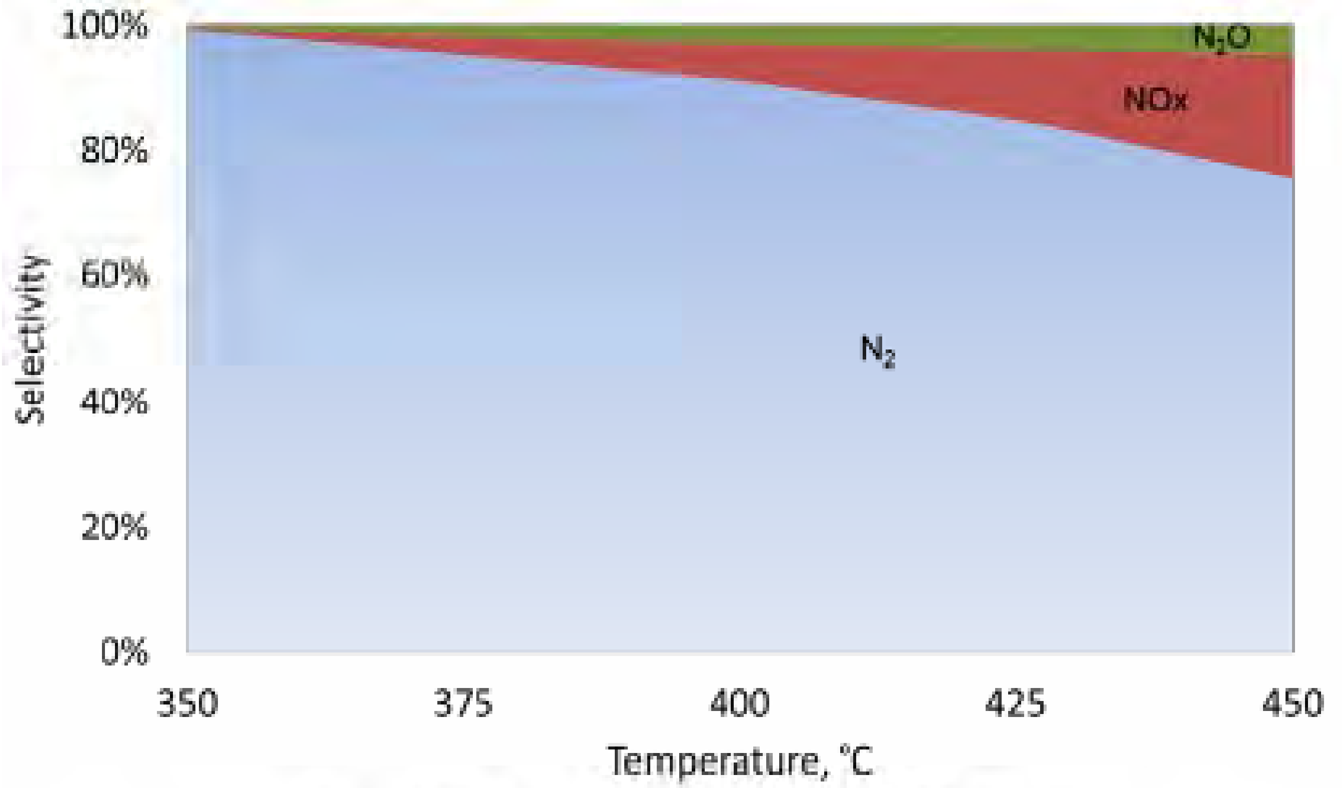
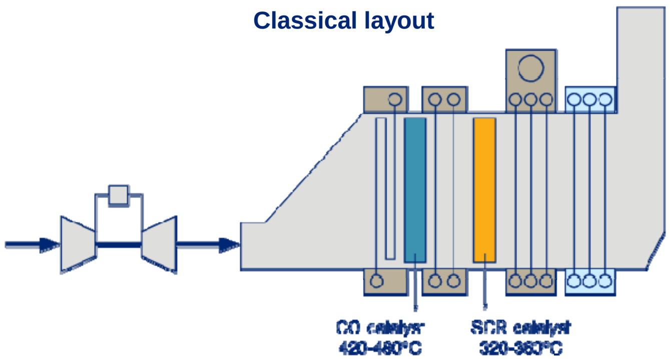
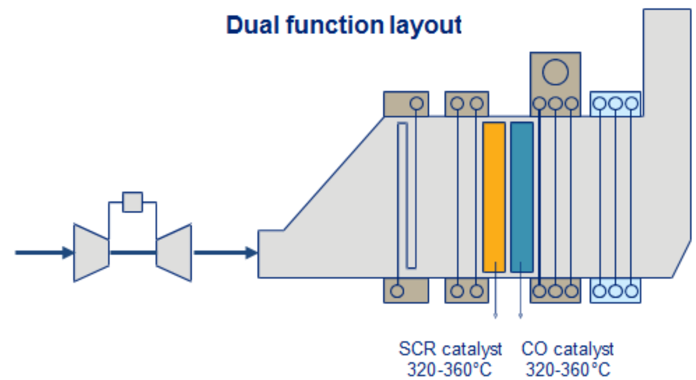


Figure 6 NH_3 oxidation selectivity on DNX® GTC-802

Performance Comparison

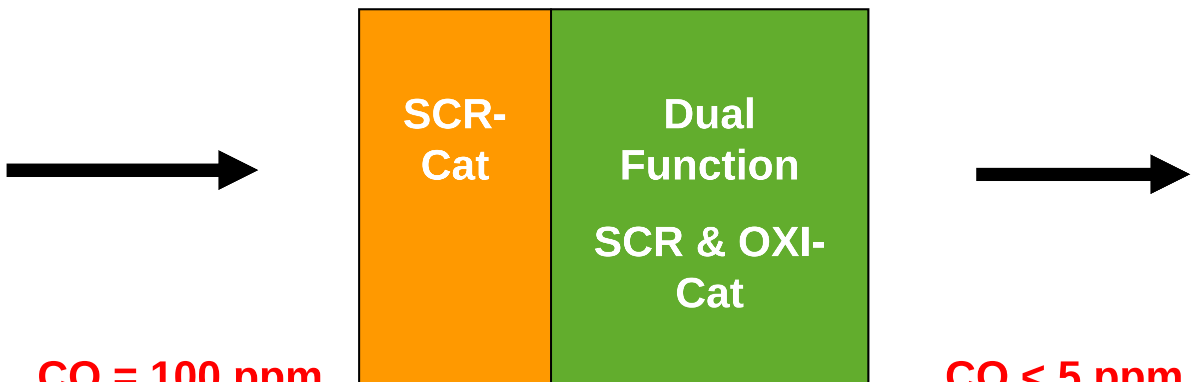
Advantages of a Pd based Dual Function Catalyst in a HRSG





Classical Layout	Dual Function Layout
Lower CO-catalyst volumes	Lower specific pressure drop
Higher HC oxidation	Lower SO_2 oxidation
Can't be exposed to NH_3	Not impacted by SO_2
Very high SO_2 oxidation	Easier installation
CO catalyst impacted by SO_2	Liquid ammonia injection

The Dual Function Catalyst – Basic Principle



CO = 100 ppm

NOx = 50 ppm

NH_3 = 50 ppm

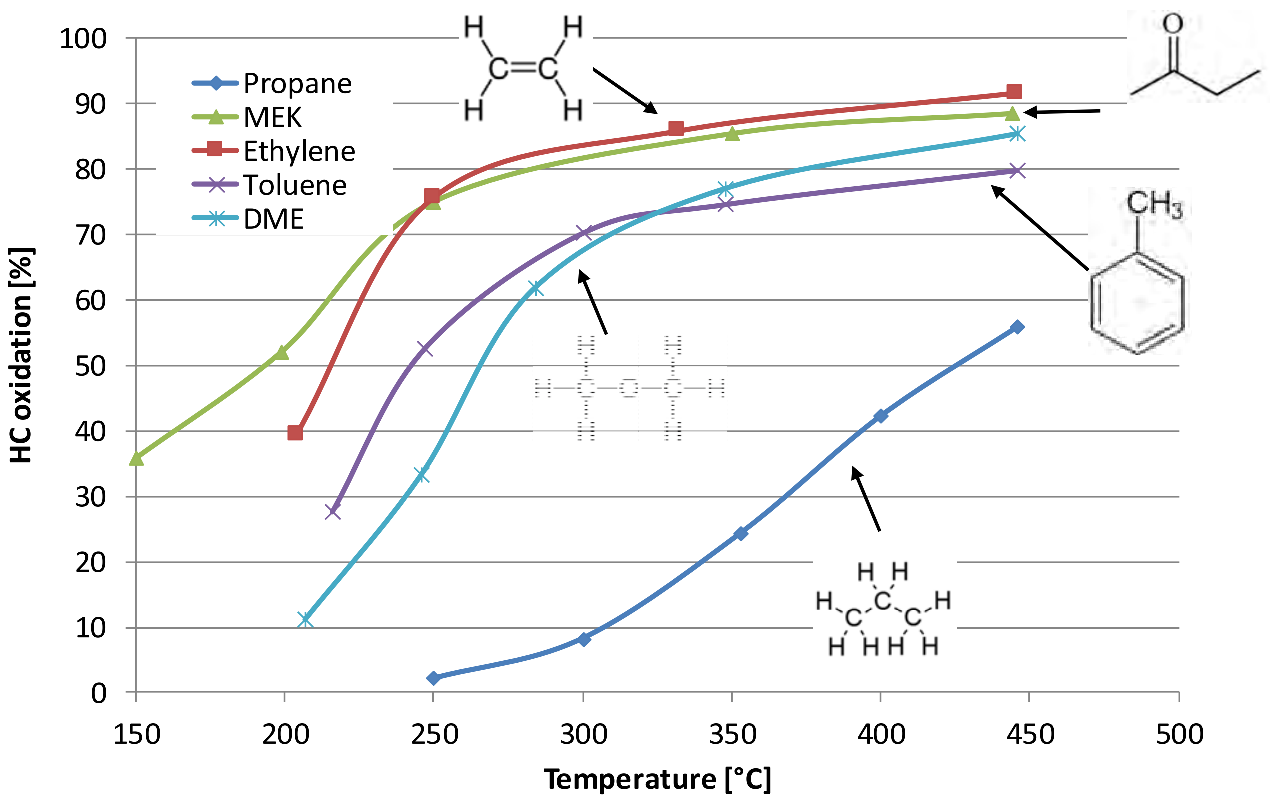
CO < 5 ppm

NOx < 5 ppm

NH_3 < 5 ppm

The VOCs

Propane, Ethylene, Toluene, MEK, DME



Wolf Hollow

Performance update

Story: Exelon, Wolf Hollow Plant

Left to Right:

Exelon Generation,

Wolf Hollow Unit 2 & 1

725 MWe

Background

2013-2014

1. In 2013 Umicore installed GT-201 at Wolf Hollow unit 1 & 2.
2. The plant operates under a CO emission permit.
3. Renewable energy causes the plant to sit at low load.
4. CO emission increases dramatically.
5. At this point in time Umicores dual function catalyst haven't been utilized at a plant this size.
6. 3 options:
   1. Shut down the plant
   2. Insert a spool piece upstream the AIG for conventional CO catalyst
   3. Install Umicores Dual Function catalyst

So what was done?

1. In October 2014 the nearly brand new SCR catalyst were replaced with a similar volume of GTC-802 dual function catalyst in both units.
2. Performance test at SOR were carried out
3. Test samples been send to the same 3rd party laboratory for testing.
4. Latest sample were taken out November 2018

Operating Performance - Wolf Hollow START-UP (Before vs. After)

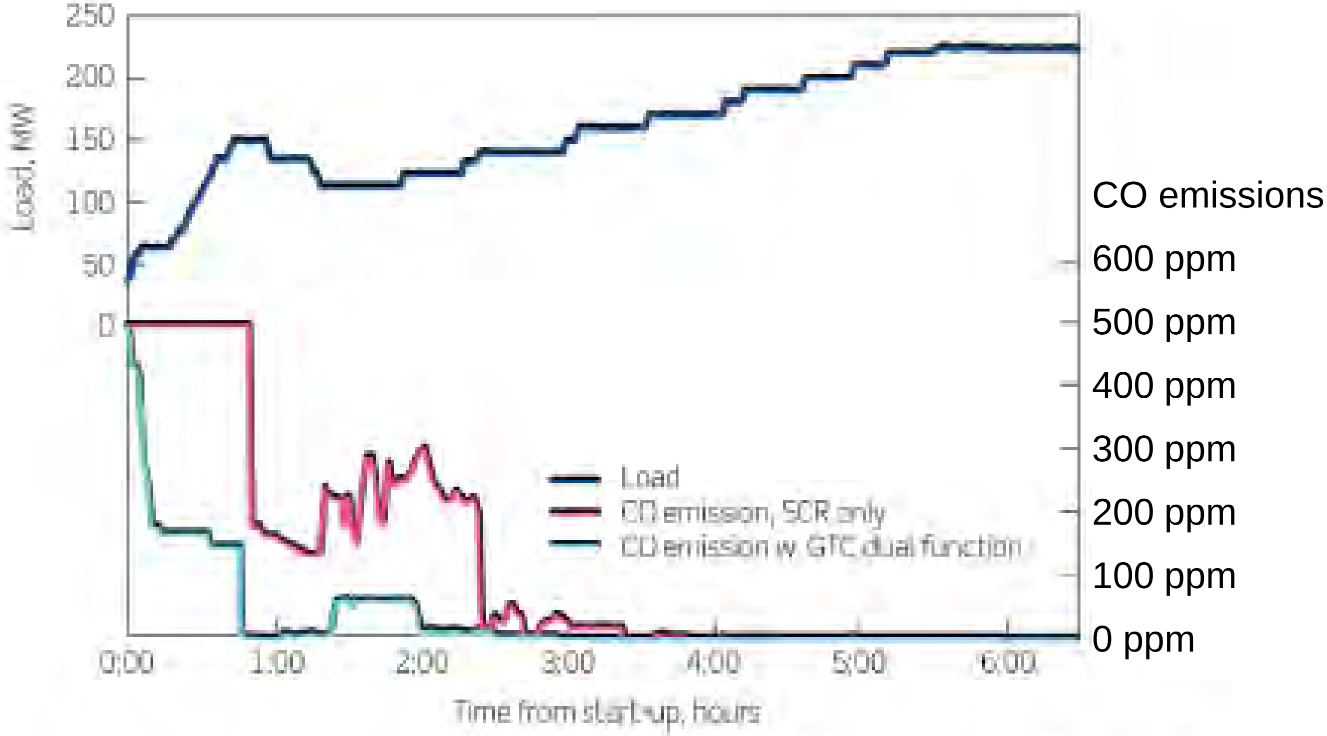


Figure 10 Comparison of performance between DNX® GTC-802 and DNX-929 SCR-only catalysts

Operating Performance – SOR until May 2017

DeNOx Performance @ 662F / 350C & 0 ppm CO

Testing Performed on Bench Scale Reactor

Exelon, Wolf Hollow Units 1&2

Testing Performed by Same Third Party Lab

Sample Tested	Hours	Sample Length	Gas velocity Nm/s	NH3/NOx ratio	Relative k/k_0
SOR, Oct. 2014	0	250mm	2.5	1.2	1.0
April 2015	4,000	500mm	2.5	1.2	1.0
March 2016	11,000	500mm	2.5	1.2	1.0
May 2017	20,000	500mm	2.5	1.2	0.98
November 2018	25.000	500mm	2.5	1.2	1.0

Operating Performance – SOR until May 2017

- CO Oxidation Performance, with 70 ppm ammonia injection
- Testing Performed on Bench Scale Reactor
- Exelon, Wolf Hollow Units 1&2
- Testing Performed by Same Third Party Lab

Sample Tested	Hours	Sample Length	Gas Temperature F / C	Gas velocity Nm/s	NH3/NOx ratio	CO Oxidation %
SOR, Oct. 2014	0	500mm	700 / 371	3.2	1.0	98.7
April 2015	4,000	500mm	700 / 371	2.7	1.0	99.2
March 2016	11,000	500mm	700 / 371	2.7	1.0	99.6
May 2017	20,000	500mm	700 / 371	2.5	1.0	99.6
November 2018	25.000	500mm	700/ 371	2.5	1.0	99.5

Thank you for your attention

Any questions (left)?

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