REINHOLD ENVIRONMENTAL Ltd.

2018 NOx-Combustion Round Table & Expo Presentation

February 19-20, 2018, in St. Louis, MO / Hosted by Dynegy

UMICORE Catalyst USA, LLC.

Reinhold Environmental Conference

St. Louis, MO
February 20, 2018

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Agenda

- Introduction of Umicore Catalyst USA, LLC
- Umicore GT/GTC catalyst basics: What Makes It Different From The Rest
- What is Umicore “Dual Function” catalyst
  - Review of characteristics and attributes
- SCR/Dual function catalyst retrofits - Three case studies
  - CCGT replace SCR catalyst with dual function catalyst – Exelon Wolf Hollow
  - CCGT add SCR catalyst on unit with no catalyst & liquid NH_3 injection – Jingfeng, China
  - CCGT repl. SCONOx system with dual function catalyst & liquid urea – City of Redding
- Challenges that the OEM’s can’t ignore
- What’s on the horizon – CCGT emission system of the future

Umicore
In brief

- Established in 1805 when Napoleon Bonaparte granted control of the Vieille-Montague mine to Jean Dony
- Originally a mining company
- Sold all mines in the 1990's
- Purchased PMG in 2003, large auto catalyst company
- Currently company comprised of 4 business units

Over 10,000 employees

Turnover of $US13 billion in 2016

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Umicore

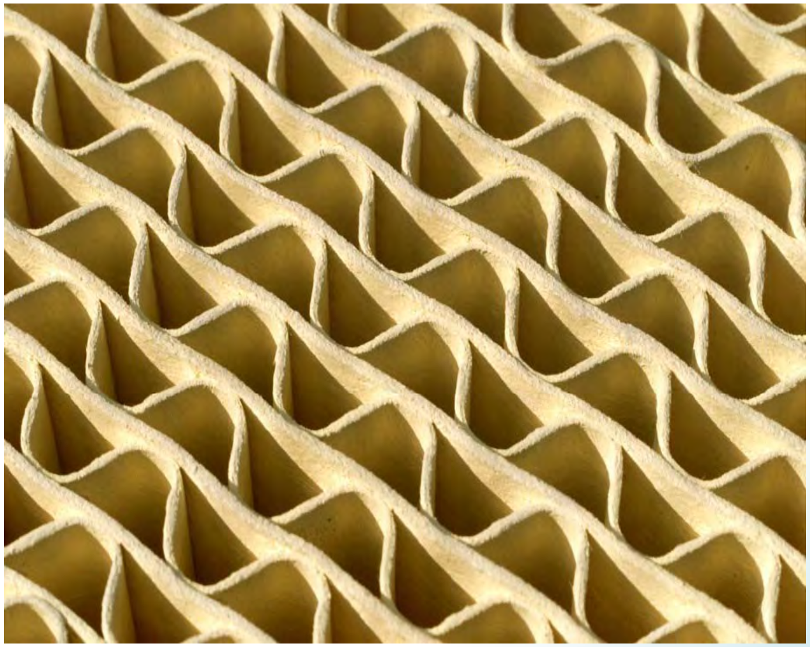
- Energy and Surface Technology
  - Rechargeable batteries – materials
  - Electro-optic materials
  - Thin film production
  - Electroplating
  - Cobalt and specialty metals
- Catalyst Business Unit
  - Auto – 8 unique types of catalyst
  - Stationary
  - Precious metals chemistry

Umicore

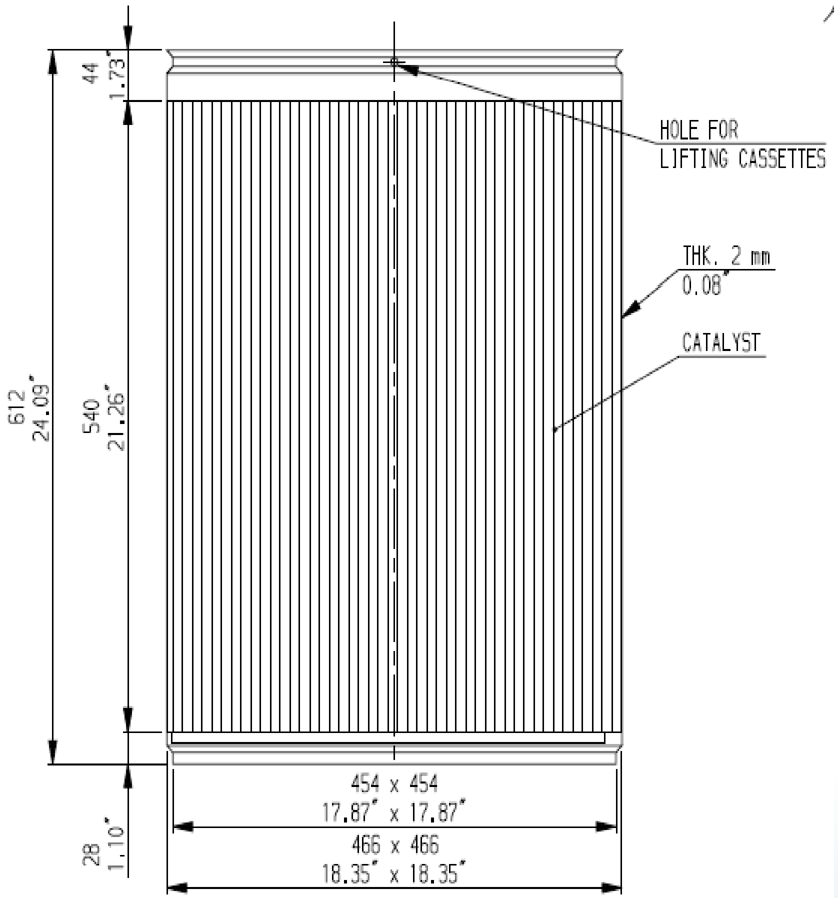
- Recycling
  - End of life rechargeable batteries
  - Precious metal refining
  - Mobile and stationary catalyst precious metals
  - Jewelry and industrial metals
  - Technical materials
- Umicore Marketing Services
  - Worldwide offices selling and distributing Umicore’s broad range of products and services

SCR BASICS
Catalyst 101 – GT (SCR ONLY) & GTC (DUAL FUNCTION)

Umicore Corrugated Catalyst Substrate



Typical Catalyst Element



Standard element shell lengths:

612mm – 540mm catalyst

572mm – 300, 340, 500mm

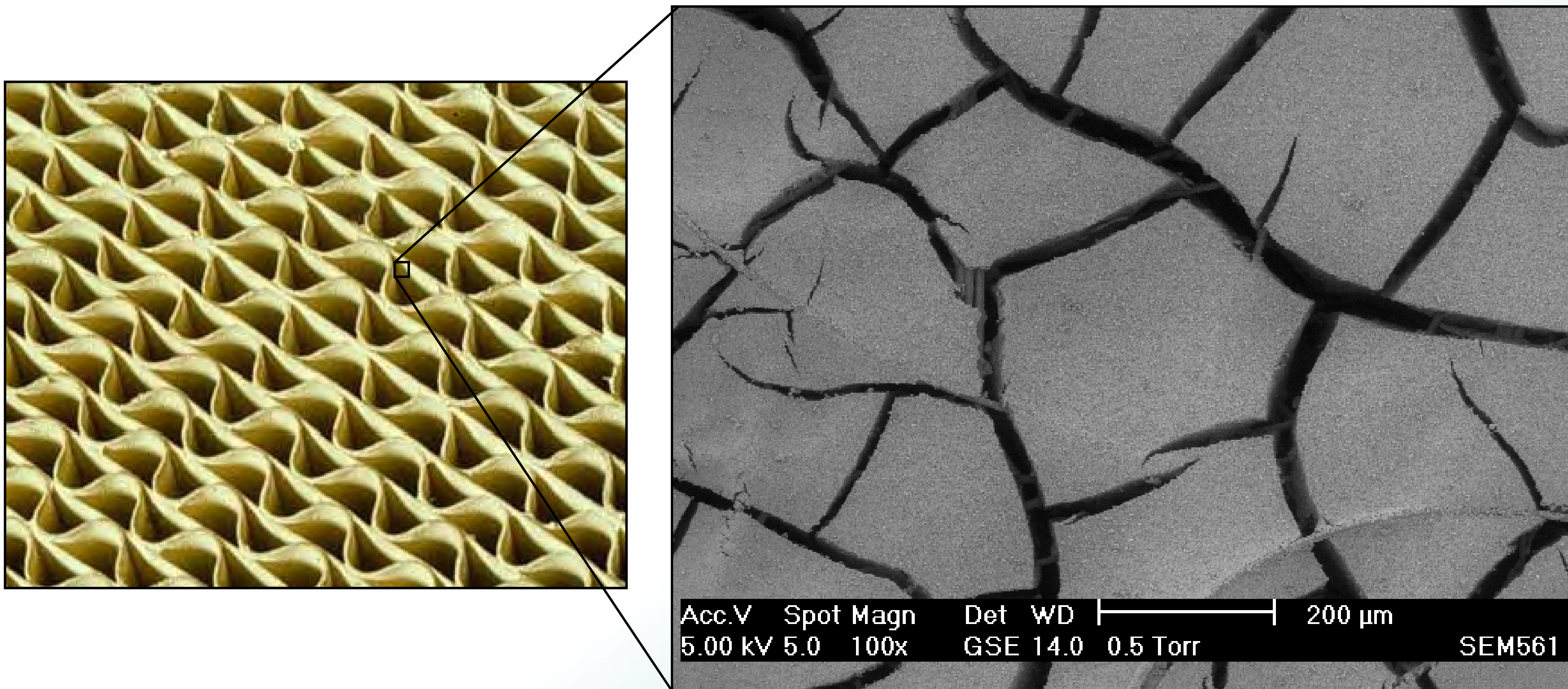
342mm – 270mm

322mm – 120, 130, 162, 175, 200, 250mm

Typical CCGT Catalyst Module

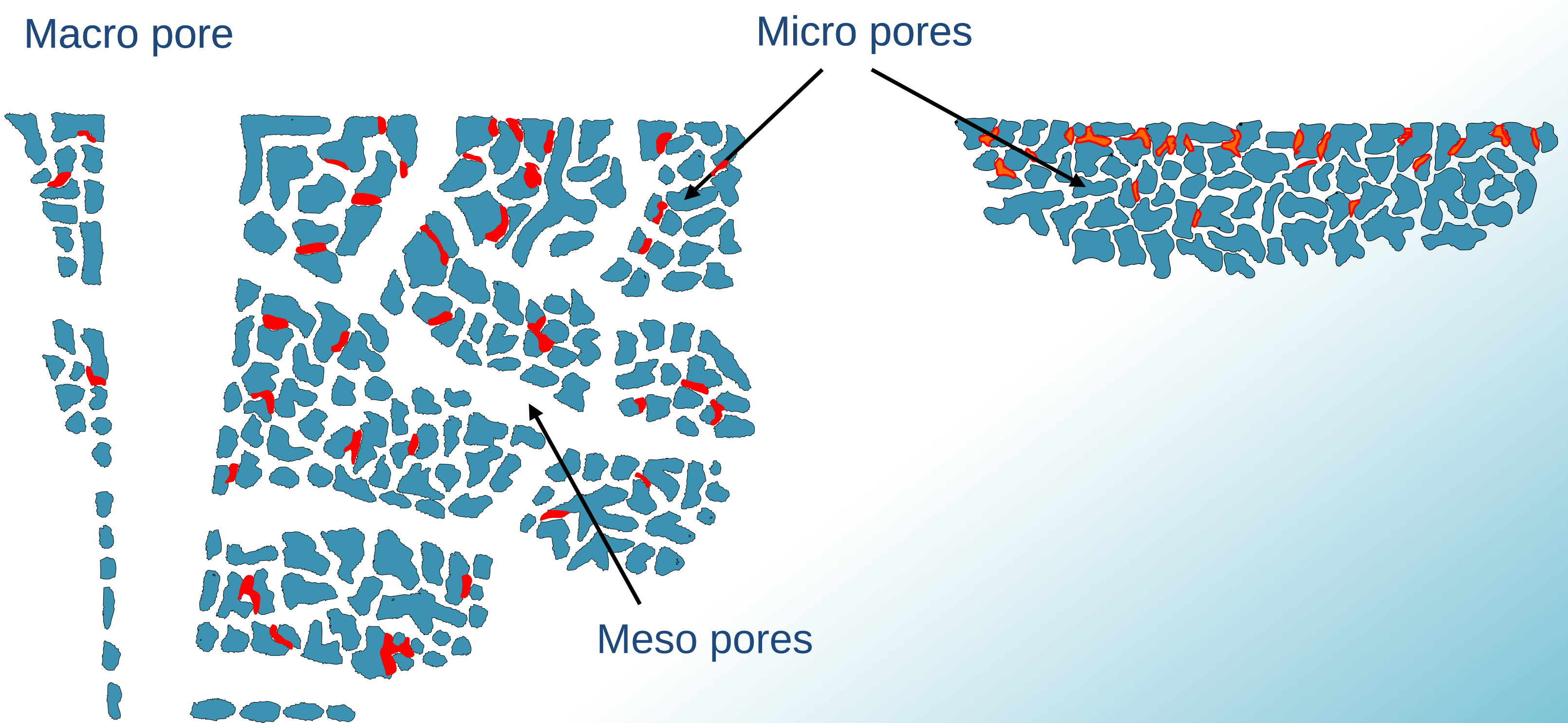
Advantages of DNX Catalyst – Surface Area

DeNOx reaction is "Diffusion Limited"
more highways = higher diffusion rate = higher activity
Tri-modal pore structure



Pore structures

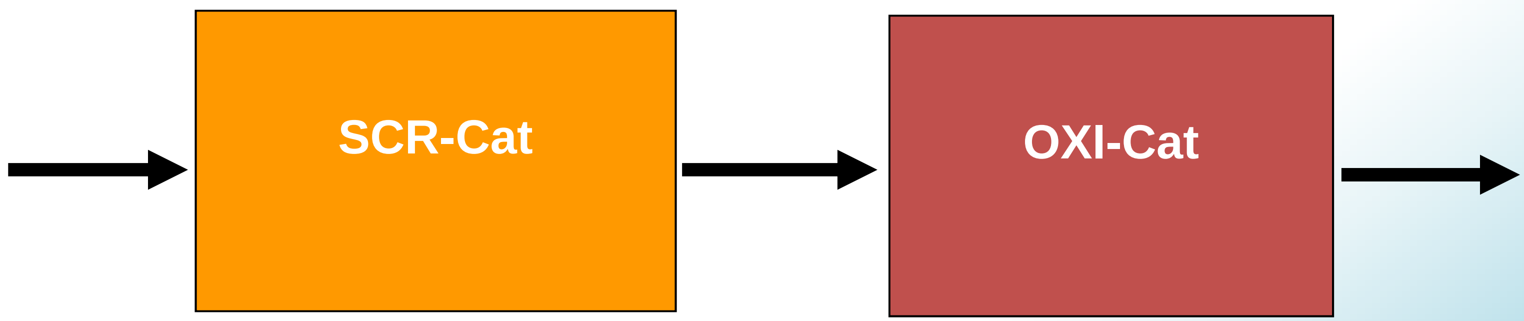
- Umicore DNX type catalyst
  - Trimodal pore structure
- Extruded & plate type catalyst
  - Homogenous micro pore structure



The Dual Function Position – Reactions

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

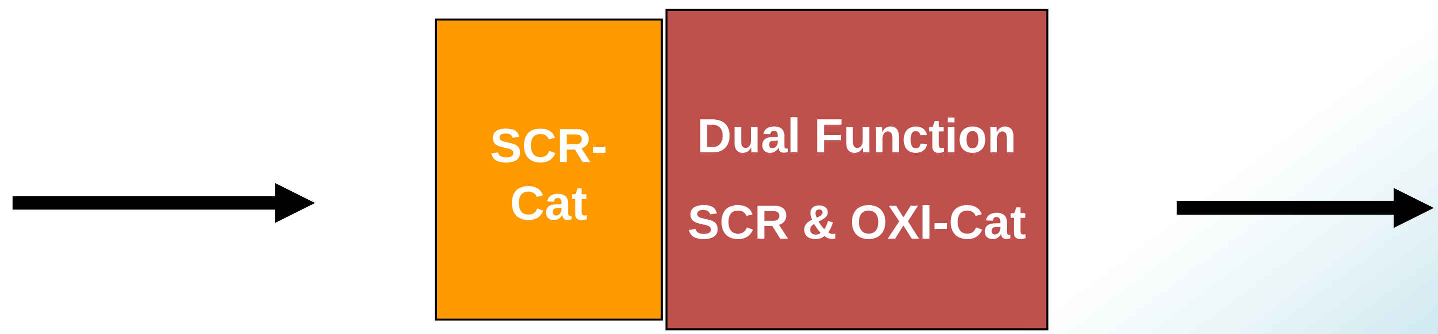
$$CO + \tfrac{1}{2}\ O_2 \rightarrow CO_2$$



CO = 100 ppm	**CO = 100 ppm**	**CO < 5 ppm**
NOx = 50 ppm	**NOx < 5 ppm**	**NOx < 5 ppm**
NH_3 = 50 ppm	**NH_3 < 5 ppm**	**NH_3 < 5 ppm**

The Dual Function Catalyst – Basic Principle

- Noble metal based
  - Palladium
- Supported on a DeNOx GT-201 catalyst
  - Vanadium & Tungsten on Titania (TiO_2)



CO = 100 ppm

NOx = 50 ppm

NH_3 = 50 ppm

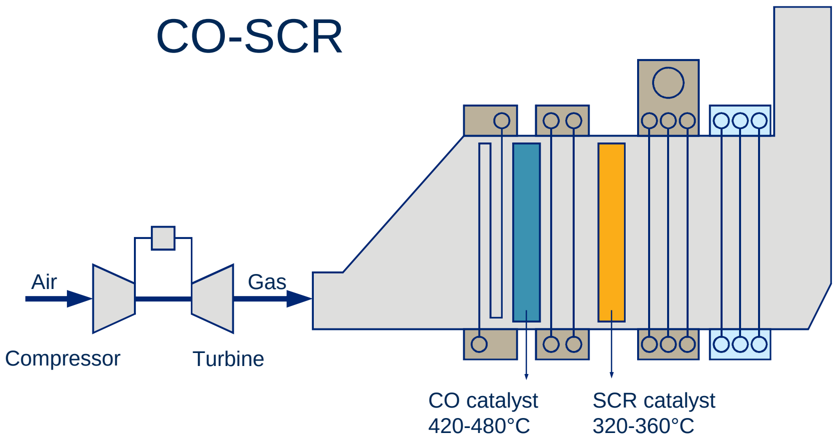
CO < 5 ppm

NOx < 5 ppm

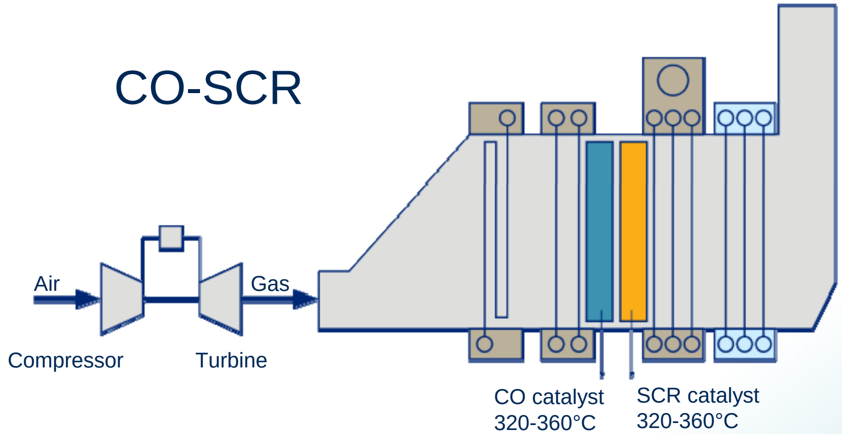
NH_3 < 5 ppm

Basic HRSG Layouts

CO-SCR

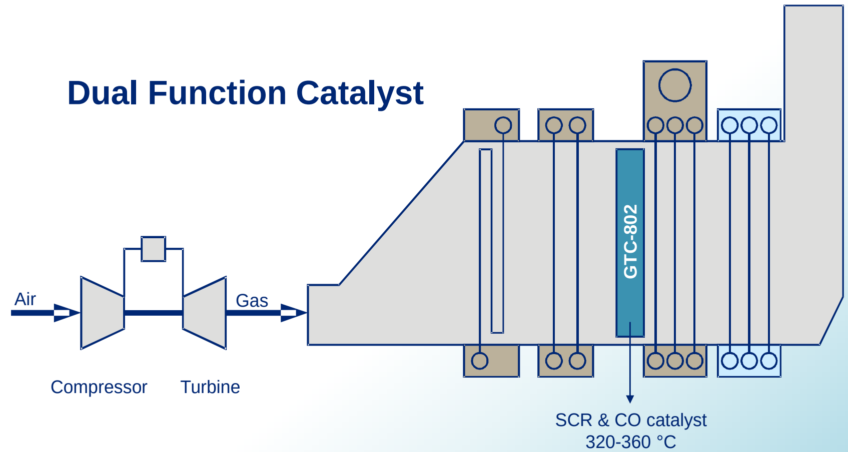


CO-SCR



SCR-CO

Dual Function Catalyst



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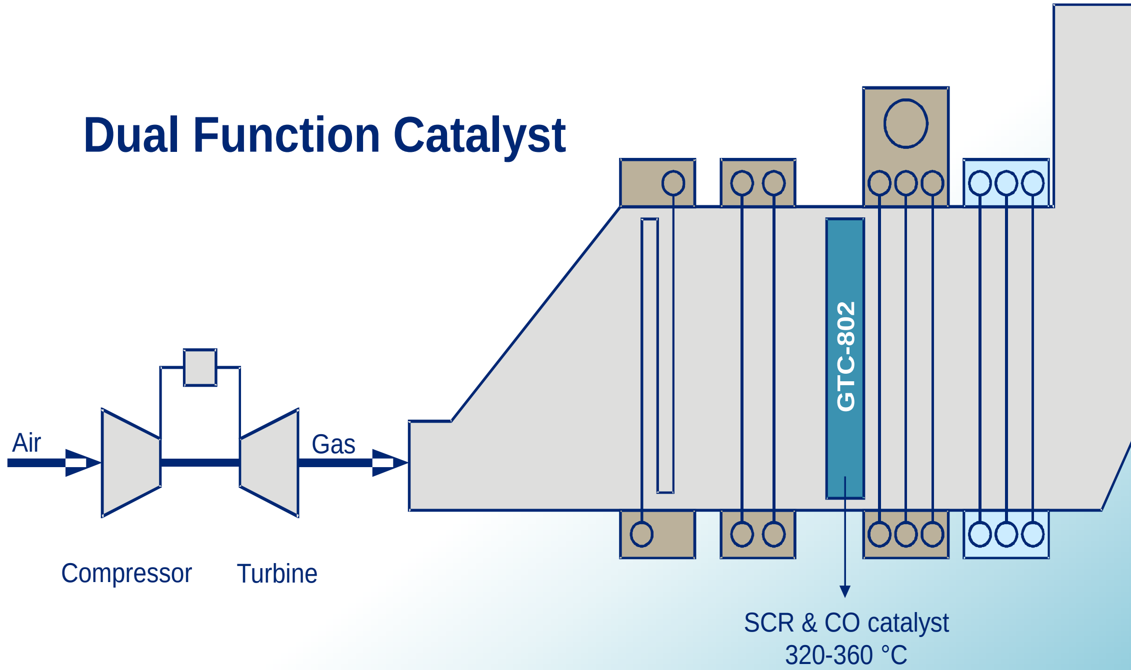
Performance

Advantages of Dual Function Catalyst in a HRSG

Optimized

Dual Function Arrangement

- Lowest specific system pressure drop
- Lowest SO_2 oxidation
- Lowest NO oxidation
- Easiest installation
- Lower NH_3 slip
- Can utilize frameless module design
- Liquid ammonia injection



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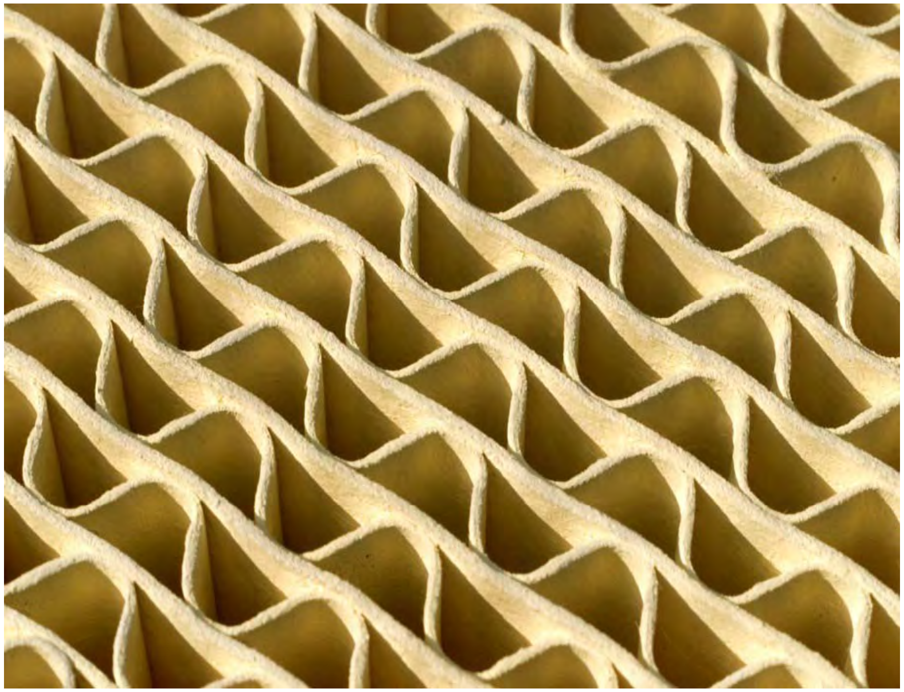
(Formaly Haldor Topsoe Inc.)

Total 82		Dual Function References (NO_x, CO, VOC)			
No. of Units	Location	User Type	Year Installed	Catalyst Type	Status
1	USA	Diesel Engine	2011	DNX-929 / DNO-2929	Running
4	ECUADOR	HRSG (Siemens STG - 100)	2012	DNX-929/ DNO-2929	Running
1	USA	Ethanol	2012	DNX-929/ DNO-2929	Running
1	USA	HRSG (GE LM - 6000)	2014	GT-201 /GTC-802	Running
2	USA	HRSG (Taurus 70)	2014	GT-301 / GTC-803	Running
7	USA	Large NG Engine	2015	DNX-929/ DNO-2929	Running
3	USA	Large NG Engine	2015	DNX-929/ DNO-2929	Running
2	USA	Large NG Engine	2015	DNX-929/ DNO-2929	Running
3	USA	Large NG Engine	2015	DNX-929/ DNO-2929	Running
2	USA	HRSG (MHPS M501G)	2014	GTC-802	Running
1	USA	Boiler	2016	DNX-929 / DNO-2929	Running
1	USA	Steam Methane Reformer (Methanol)	2016	DNX-929 / DNO-2929	Running
2	USA	Auxiliary Boilers	2016	DNX-929 / DNO -2929	Running
1	USA	Refinery FCC Unit (High Dust)	2016	DNX-FCC / DNO-2664	Running
1	USA	Cement Plant (After Baghouse)	2016	DNX-939 / DNO 2939	Running
1	USA	Carbon Black - Thermal Oxidizer	2016	DNX-929 / DNO -2929	Running
1	USA	Auxiliary Boiler	2016	DNO-1929	Running
2	USA	HRSG (MHPS M501GAC)	2018 (Expected)	GT-201 / GTC-802	On Order
1	USA	Auxiliary Boiler	2018 (Expected)	DNX-929 / DNO -2929	On Order
2	USA	Refinery Heater	2018 (Expected)	DNX-939 / DNO 2639	On Order
3	USA	Large NG Engine	2017	DNX-929/ DNO-2929	Running
1	USA	Chemical Plant Boiler	2018 (Expected)	DNX-929/ DNO-2929	On Order
1	USA	Steam Methane Reformer	2018 (Expected)	DNX-929/ DNO-2929	On Order

No. of Units	Location	User Type	Year Installed	Catalyst Type	Status
3	USA	NG Engine (GE Jenbacher JMS 420)	2017	DNX-929 / DNO-2929	Running
12	USA	Large NG Engine	2017	DNX-929 / DNO-2929	Running
1	USA	Cement Plant	2018 (Expected)	DNO-2949	On Order
2	USA	HRSG (Siemens SGT - 800)	2018 (Expected)	GT-201 / GTC-802	On Order
2	USA	Auxiliary Boiler	2017	DNX-929 / DNO-2929	Running
2	USA	NG Engine (CAT G3516H)	2017	DNO-2929	Running
1	USA	NG Engine (MTU 20V4000L33FN)	2017	DNO-2629	Running
1	USA	NG Engine (GE Jenbacher JMS 612)	2017	DNO-2929	Running
7	USA	Landfill Gas / NG Engine (Cat CG260)	2017	DNX-649 / DNO-2639	Running
2	USA	HRSG (MHPS M501GAC)	2020 (Expected)	GTC-802	On Order
1	USA	NG Engine (CAT CG170-16)	2017	DNX-629 / DNO-2929	Running
2	USA	HRSG (MHPS M501GAC)	2020 (Expected)	GTC-802	On Order
2	USA	Large Biomass	2018 (Expected)	DNX-949 / DNO-2929	On Order

SCR & Dual Function Catalyst Characteristics & Attributes



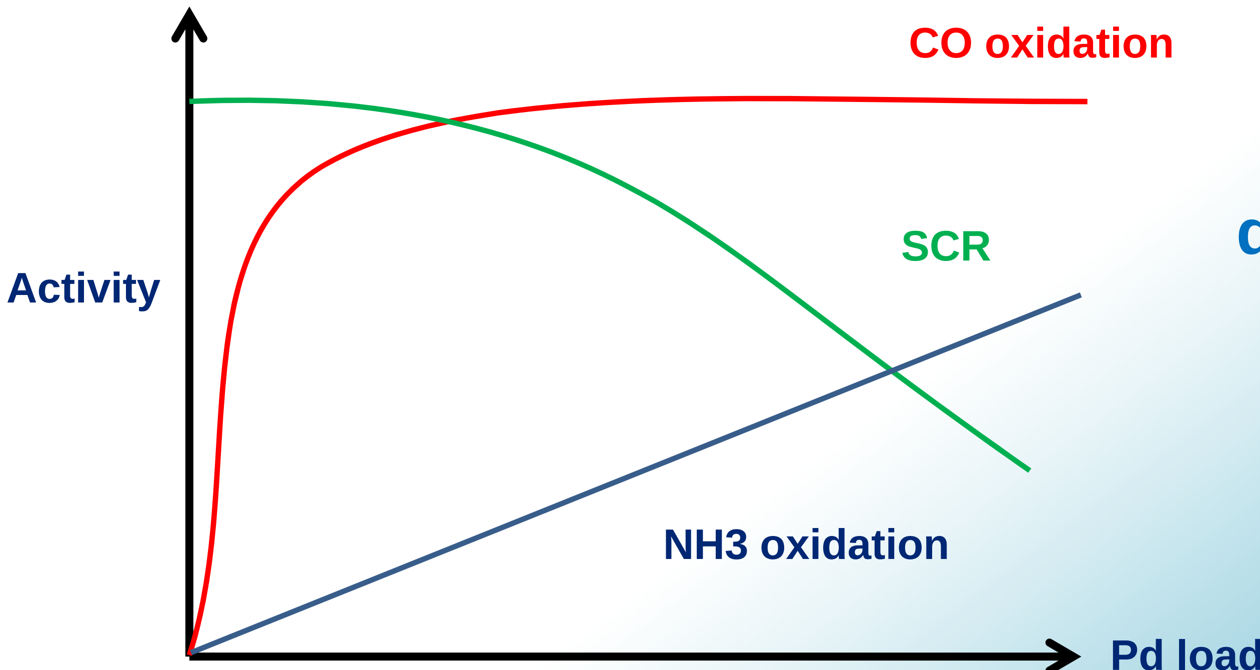
Operating Performance – GT/GTC Catalyst Comparison – New Catalyst

	Catalyst	DeNOx, %	DeCO, %	NH_3 slip, ppmv
SCR only	GT-201	93.5	0	5.7
Dual function (SCR and CO oxidation)	GTC-802	92.9	97.8	4.4

Test conditions: Gas inlet composition: 50 ppmv NOx, 55 ppmv NH_3, 100 ppmv CO, 15%vol O_2, 10 % vol H_2O, N_2 balance. Temperature: 350°C / 662°F

Development of a Dual Function Catalyst

- Pd loading
  - Optimal Pd-load to be found
    - CO oxidation vs. NH_3 oxidation
    - Cost



NB: Monolith activity. Temperature dependent.

Pd load and distribution is the key

Development of a Dual Function Catalyst

Performance Characteristics

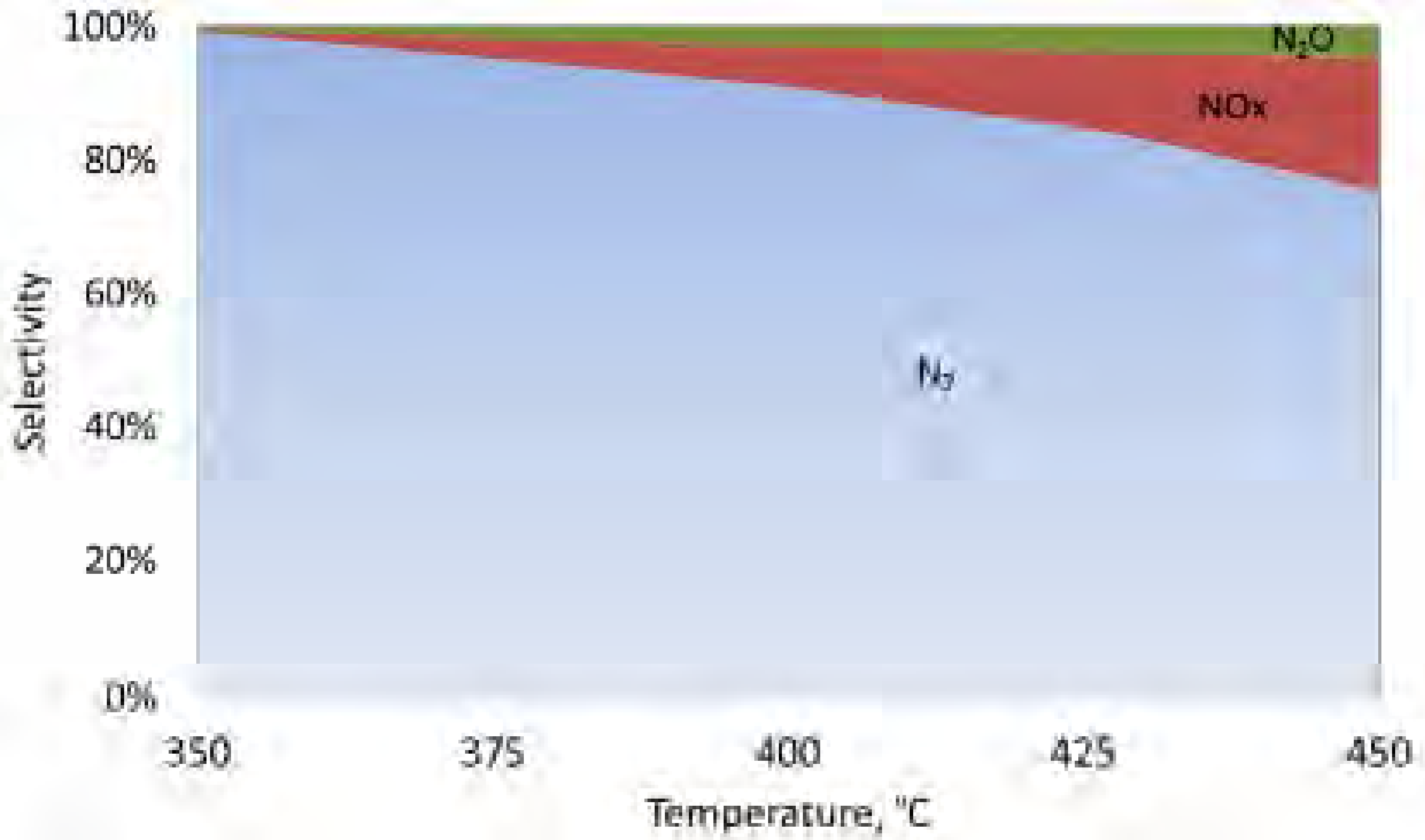
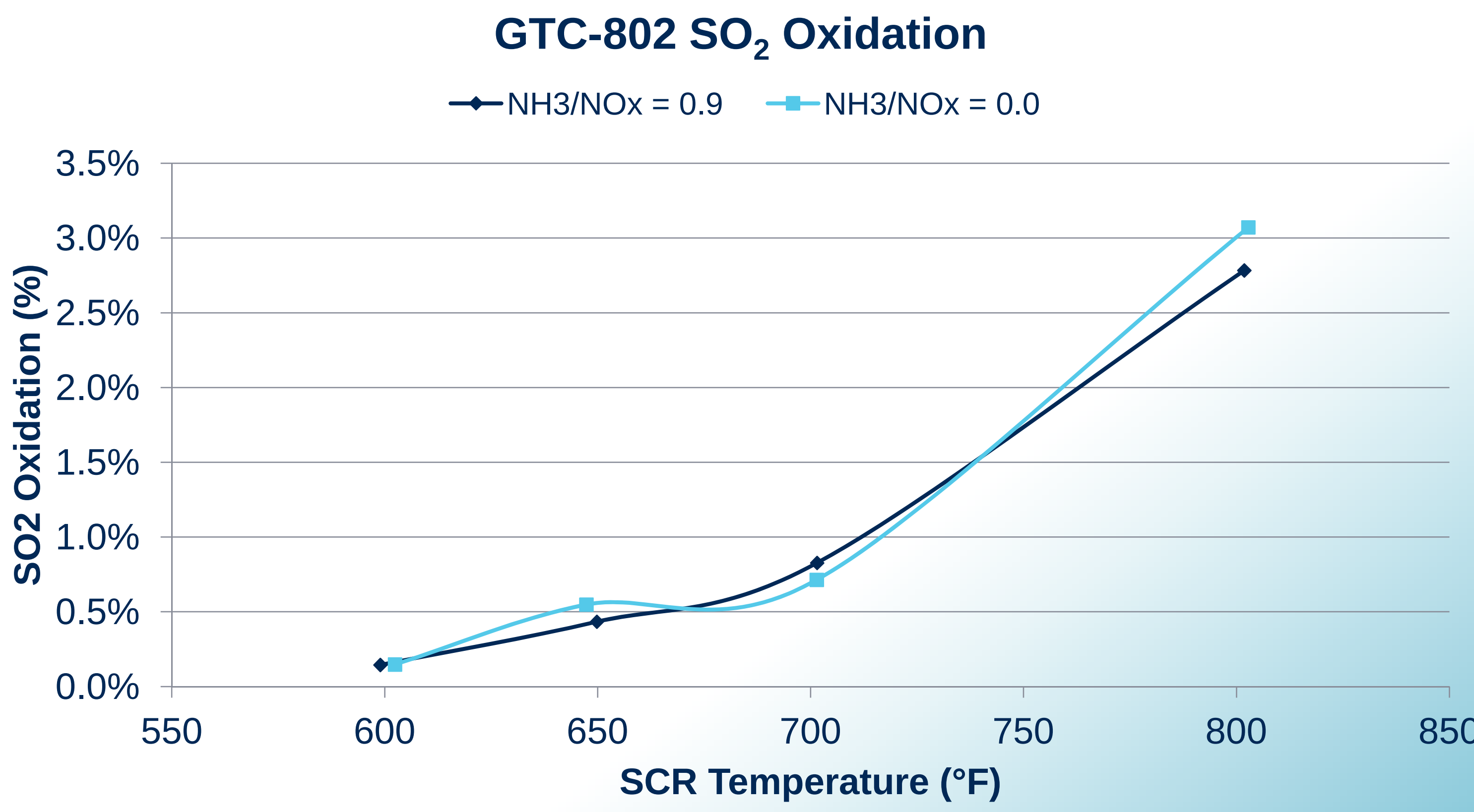


Figure 6 NH_3 oxidation selectivity on DNX® GTC-802

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



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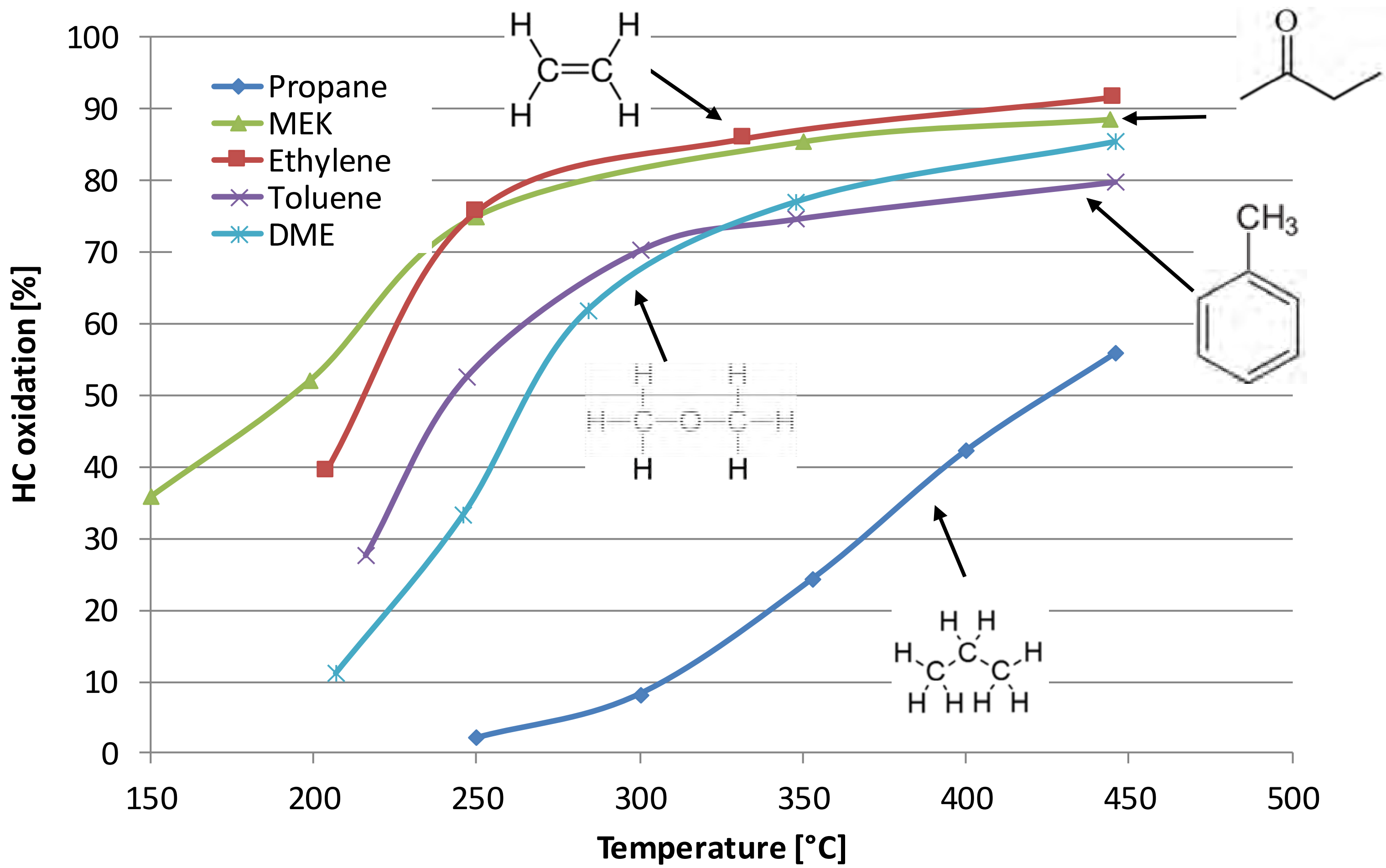
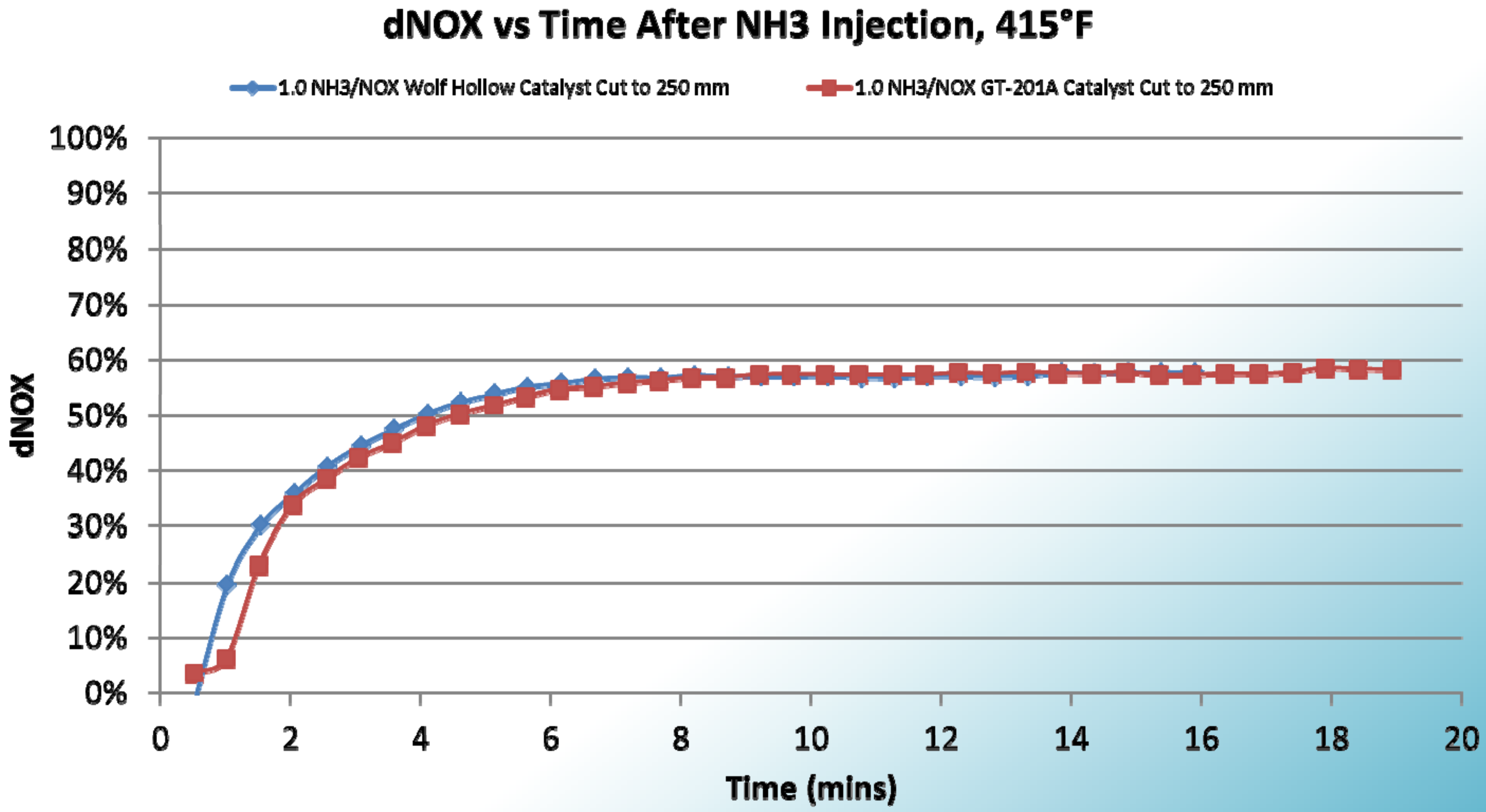
Propane, Ethylene, Toluene, MEK, DME
VOC Oxidation



Response Comparison GT vs GTC Catalyst

- 250 mm catalyst length



Case Study 1

Replace SCR catalyst with dual function catalyst

Exelon Wolf Hollow Units 1&2

40 months of operation

Story: Exelon, Wolf Hollow Plant

Left to Right:

Exelon Generation,

Wolf Hollow Unit 2 & 1

725 Mwe Gross

MHI 501G Turbine

Deltak HRSG

Story: DNX® GTC-802 Installation, Wolf Hollow Unit 2

DNX® GTC-802
Prior to installation in Unit 2 at Wolf Hollow

Story: GTC Catalyst Installation Wolf Hollow Unit 2

Operating Performance - Wolf Hollow

INITIAL START-UP

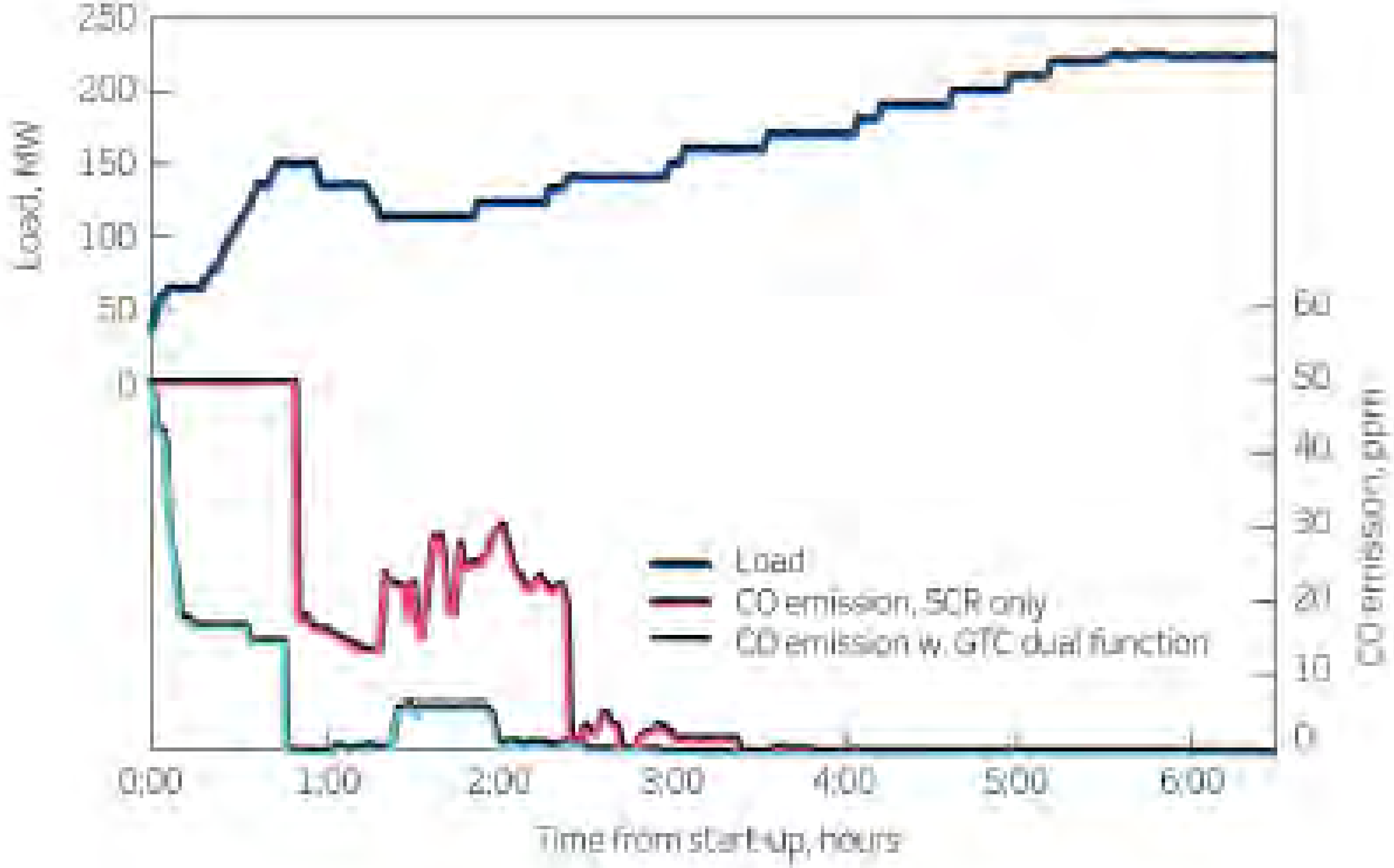


Figure 10 Comparison of performance between DNX® GTC-802 and DNX-929 SCR-only catalysts

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

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

Case Study 2

Install SCR catalyst in CCGT with no catalyst

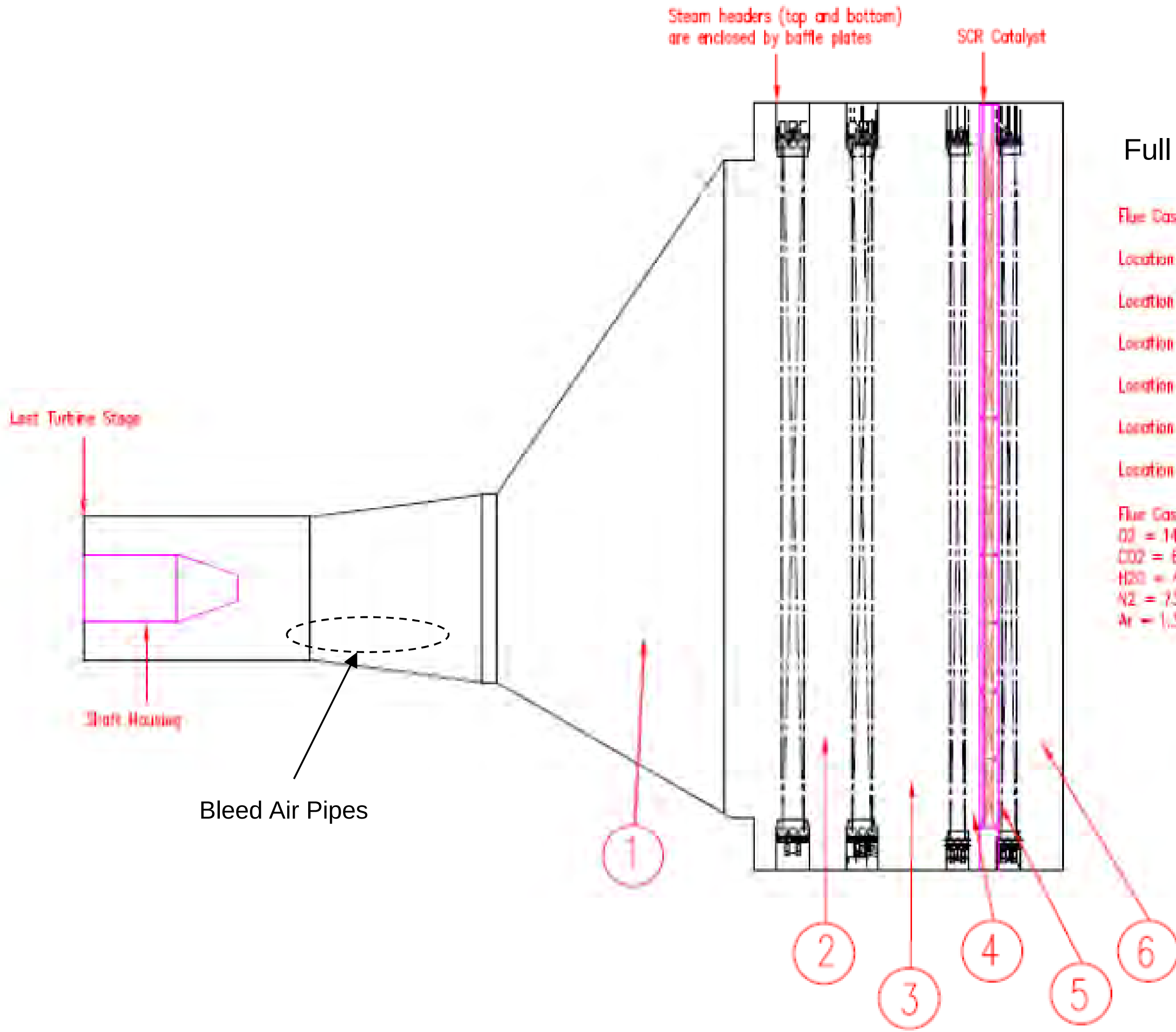
Liquid ammonia injection

MHI 701F

Jingfeng (Beijing Energy); Beijing, China

55 months of operation

Jingfeng SCR System Sketch



Full Scale Conditions

Flue Gas Flow = 2573.4 t/hr (5,673,376 lb/hr)

Location 1: T = 578 C, P = 3.44 kPa

Location 2: T = 559 C, P = 3.22 kPa

Location 3: T = 459 C, P = 2.85 kPa

Location 4: T = 393 C, P = 2.57 kPa

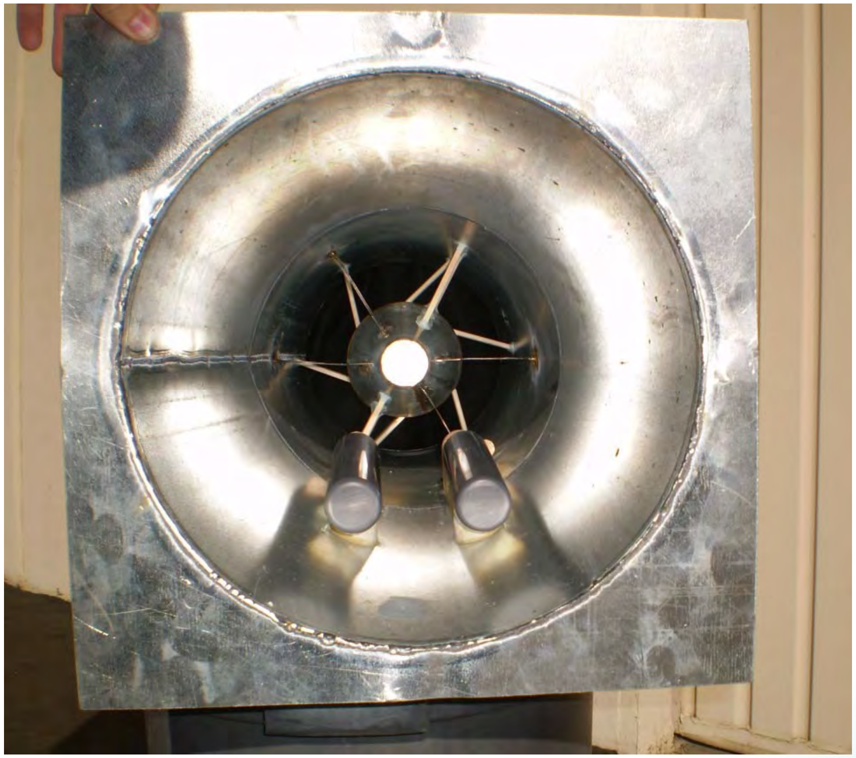
Location 5: T = 393 C, P = 2.33 kPa

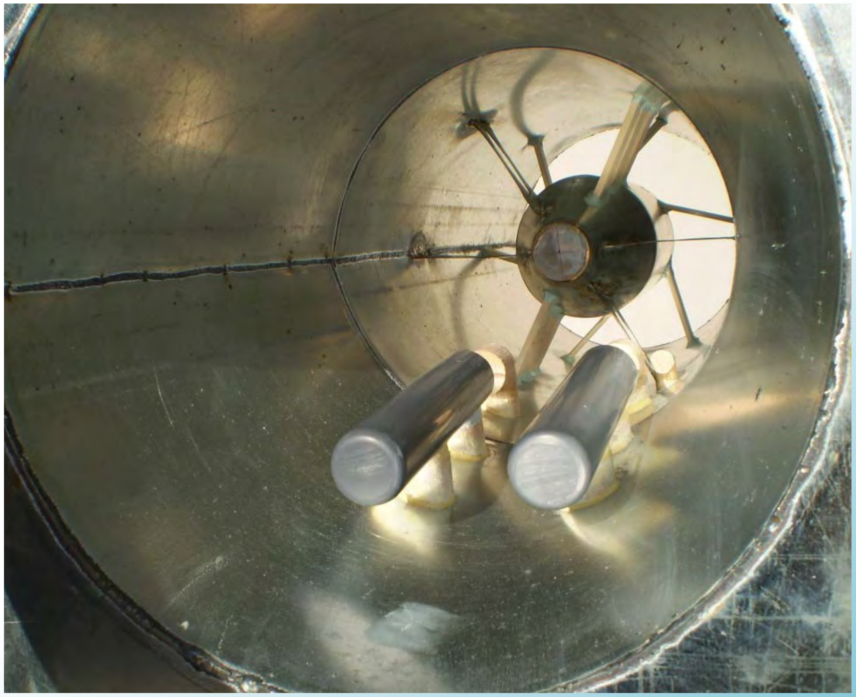
Location 6: T = 324 C, P = 2.06 kPa

Flue Gas Composition (weight %):
O_2 = 14.09
CO_2 = 6.04
H_2O = 4.9
N_2 = 73.65
Ar = 1.32

Jingfeng 1/16 scale model

Jingfeng 1/16 scale model





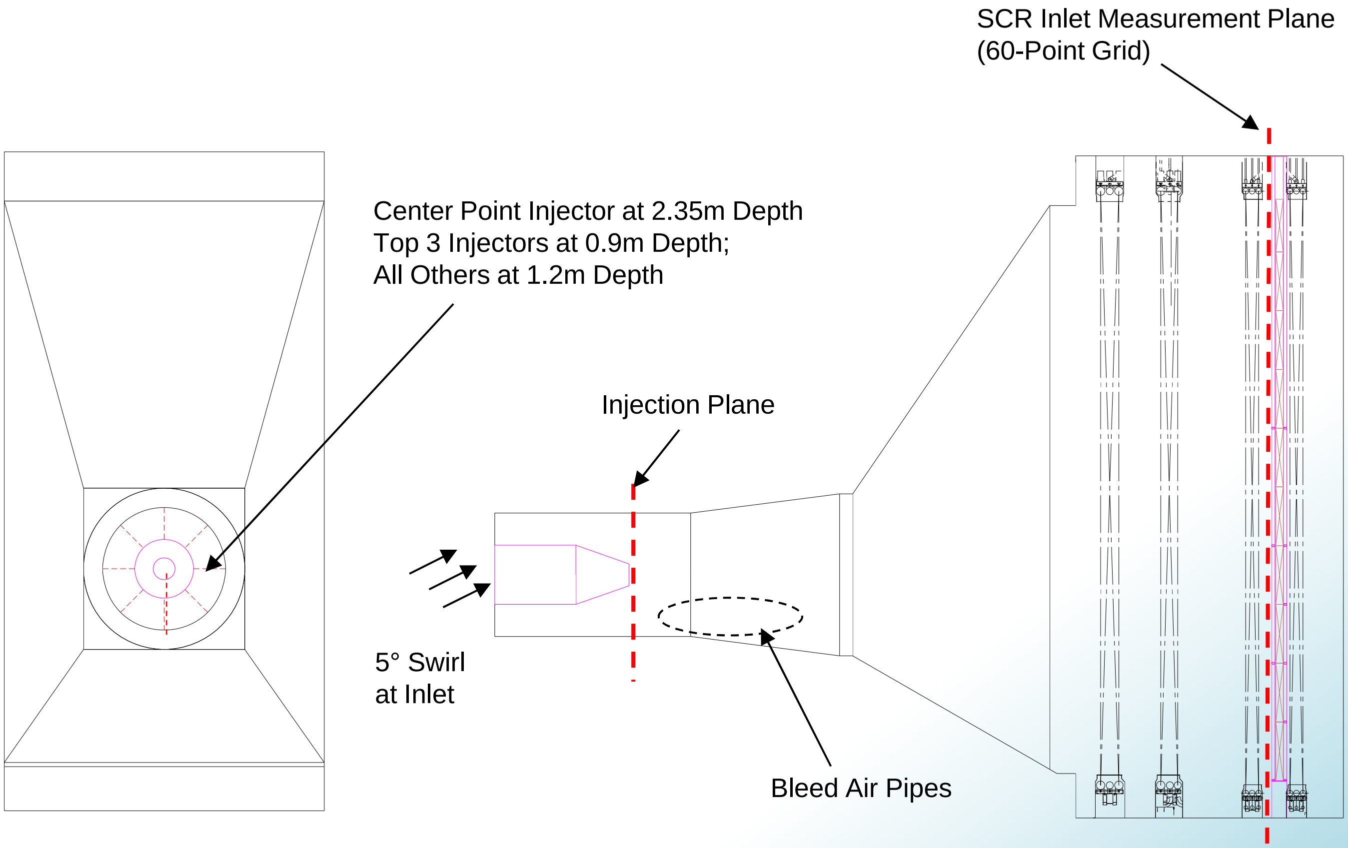
Physical Model Objectives

- NH_3 RMS at SCR catalyst inlet to be <10%

RMS% = 100% * (StdDev)/(Avg)

- Velocity RMS at SCR catalyst inlet <15%
- These criteria were targeted in the flow model study (ammonia was simulated in the physical model using propane tracer gas)

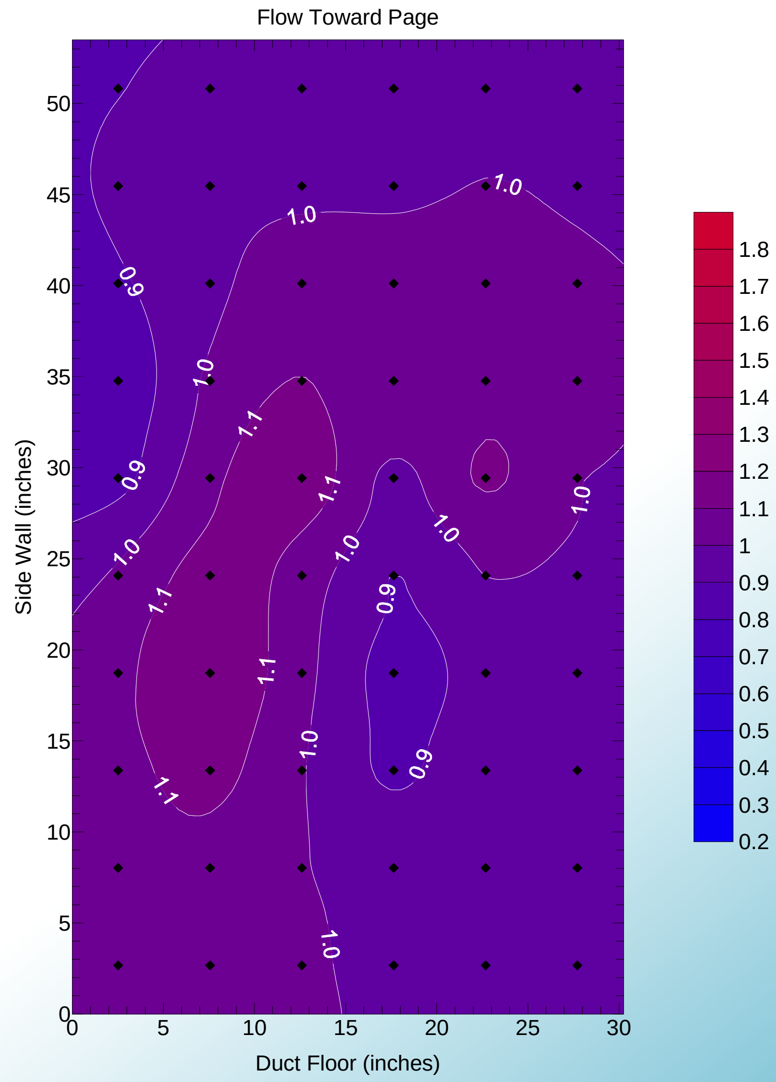
Case 6: Nine Injectors (Varying Depths, with 5° Swirl)



Case 6: Nine Injectors (Varying Depths, with 5° Swirl)

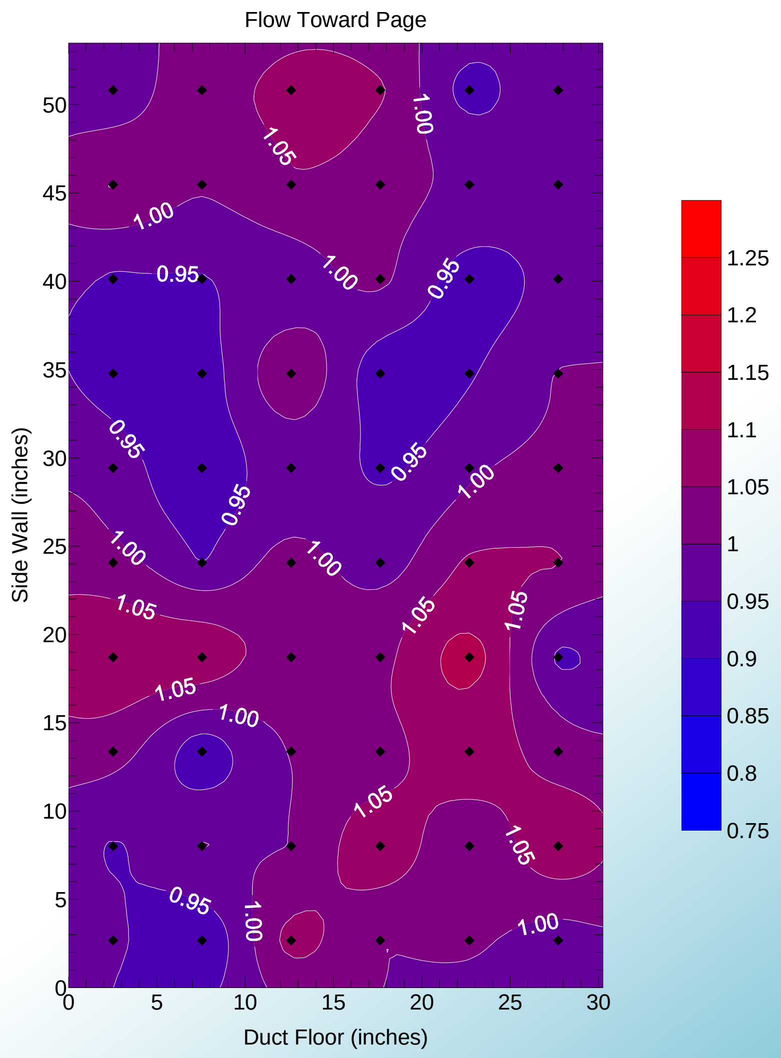
Normalized NH_3 Concentration at SCR Inlet; RMS = 7.8%

(Equal NH_3 flow to each injector)

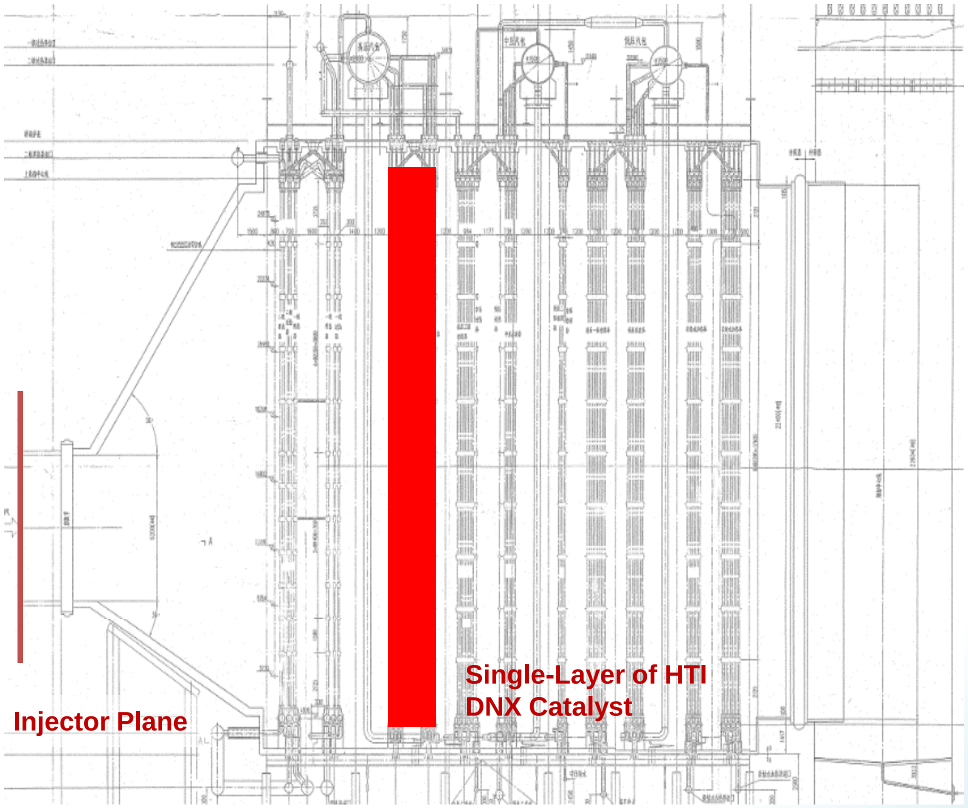


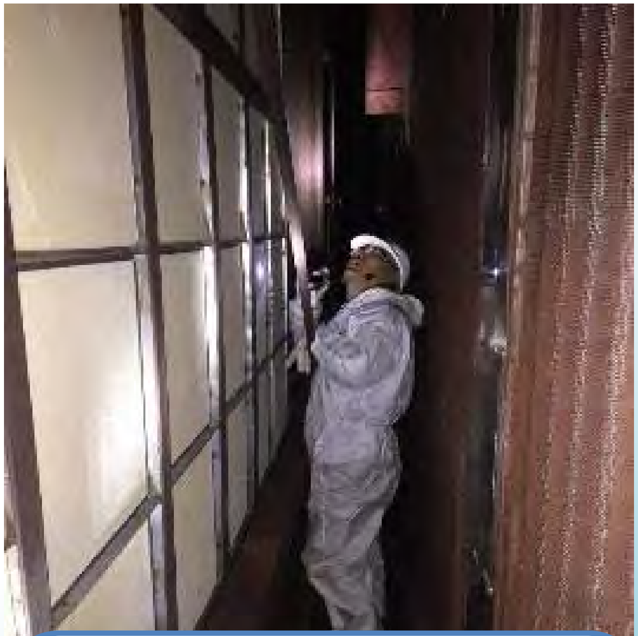
Velocity Profile at SCR Inlet

Normalized Velocity
at SCR Inlet; RMS = 5.6%



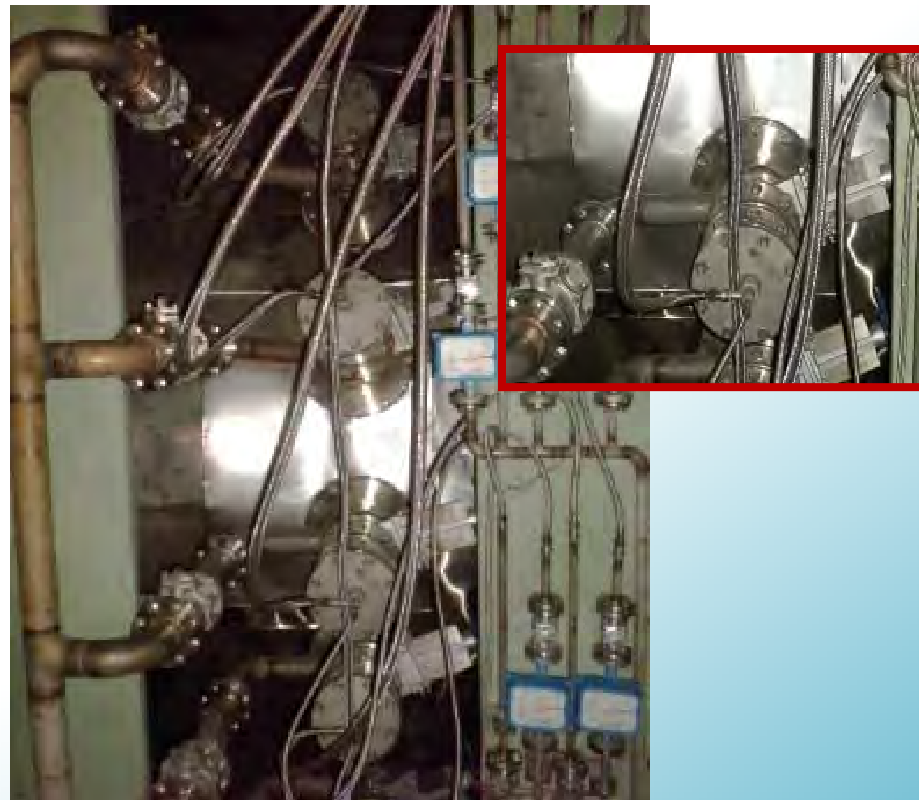
Jingfeng Catalyst Layout





Installed single catalyst layer (~22”** [560 mm] **frame depth) between HP EVAP sections (~35”** [914 mm] **clear distance)

AMMONIA TANK / PUMP AREA & INJECTOR LOCATION



9 Dual-Fluid Injectors
(8 arranged circumferentially, 1 center injector)

INSIDE THE CTG EXHAUST DUCT @ INJECTOR PLANE

Injector fatigue assessment
Removed injectors to check for any cracking on the sheath
(8 injectors visible in the picture above, #02 injector removed)

Nozzle close-up
No plugging of the nozzles had occurred, and there were no visible signs of overheating on any of the nozzles.

9 Dual-Fluid Injectors
(8 arranged circumferentially, 1 center injector)

Results following 2013 tuning

- **PERFORMANCE GUARANTEES**
- 80% NO_x reduction
- - Starting NO_x of 34 ppm (15% O_2)
- - Target NO_x emissions of 6.8 ppm
- Ammonia slip ≤ 3.5 ppm
- Pressure drop ≤ 1.6 iwcd
- NH_3:NO_x maldistribution ± 10% RMS

- **PERFORMANCE RESULTS**
- 82% NO_x reduction
  - NO_x emissions of 5.9 ppm
- Ammonia slip ≤ 0.9 ppm
- Pressure drop ≤ 1.0 iwcd
- NH_3:NO_x maldistribution ± 5% RMS

Case Study 3

Install dual function catalyst with liquid urea injection

Replaced expensive SCONOx system

CCGT with SGT 900

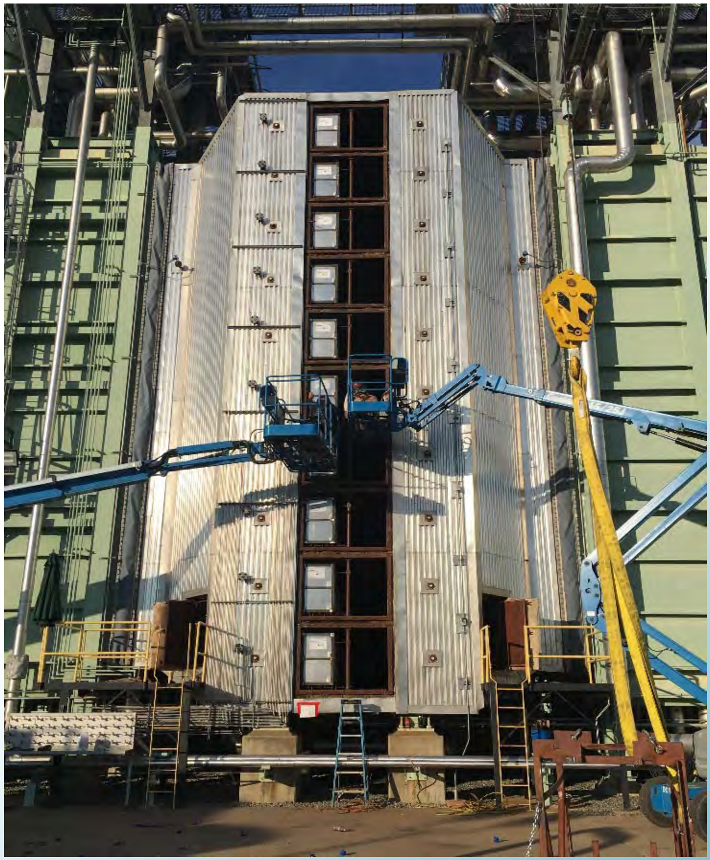
City of Redding, Units 5 & 6

Installed late 2017

City of Redding Unit 5

Four layers of catalyst

Single layer of catalyst



City of Redding Unit 5

Umicore dual function module

Use of module installation cart

City of Redding Unit 5

Dual function catalyst elevation

Liquid urea injection points

Initial performance, Unit 5

Parameter	Historical	New
Compressor inlet Temp ºF	40.5	40.1
CT MW	46.5	46.5
Fuel Flow (kscfh)	467	463
Steam MW	14.4	14.9
Stack flow (dscf/hr)	13,331,260	13,413,830
dP across catalyst	6.3	1.1
dP perf plate	NA	0.90
total dP (turbine to stack)	12.1	7.7
Percent dP change	NA	36.4%

Initial Performance, Unit 5

Parameter	Inlet NOx, ppmvdc	Inlet CO, ppmvdc	Outlet NOx ppmvdc	Outlet CO ppmvdc	NH3 slip ppmvdc
Design	18.0	5.0	2.0	4.0	< 5.0
Actual	16.0	5.0	1.5	0.0	< 2.0

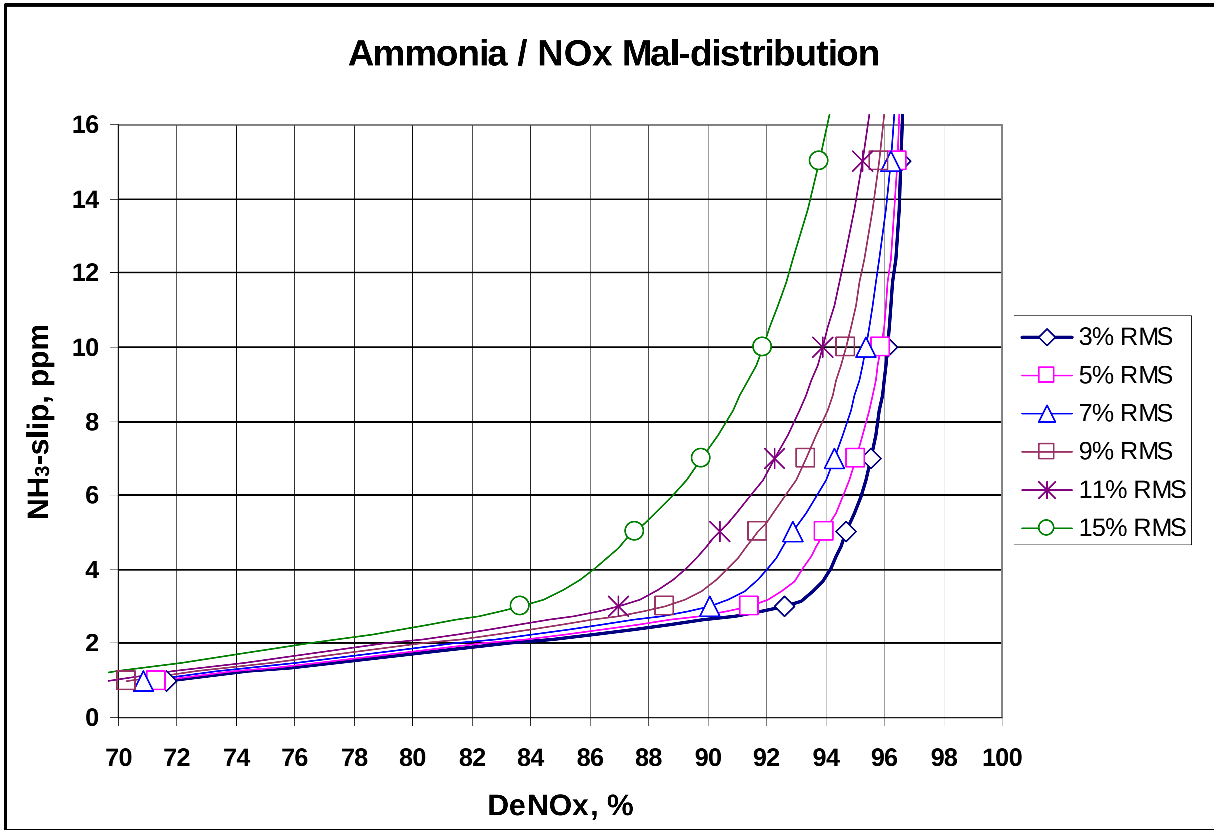
Challenges OEM's Can't Ignore

Achieving >93% DeNOx and very low slip

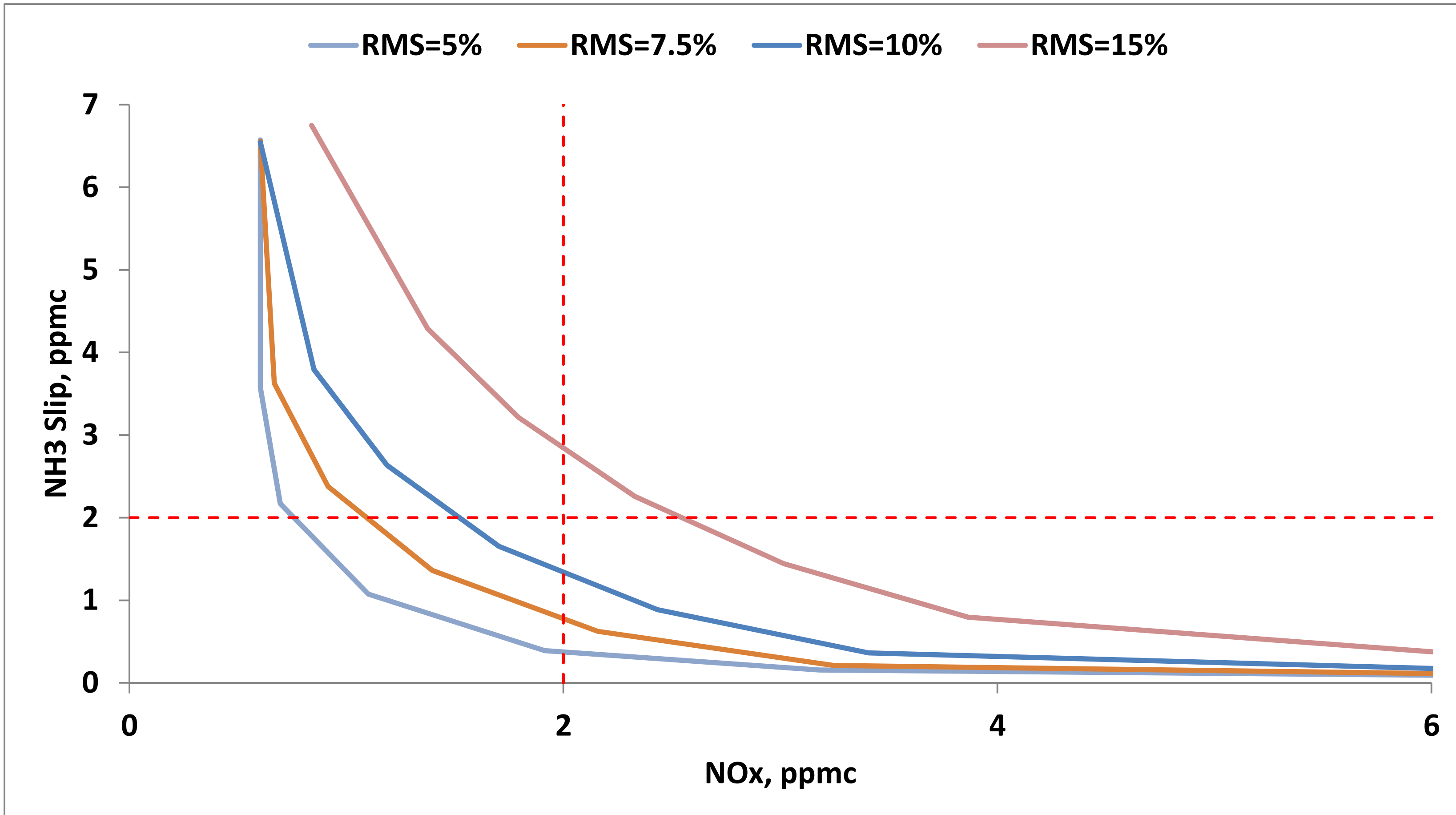
- Ammonia to NOx uniformity
  - ✓ AIG design & tuneability (1, 2 or 3 zones; mult. zone)
  - ✓ Supplemental firing / duct burners – may require (2) AIG's
  - ✓ Permanent sample / test grid
  - ✓ Liquid reagent injection (ammonia or urea)
- Compliance through start-up
- Flue gas bypass
- Optimized process control for reagent injection
- Stack measurement multiple point (CEMS)

Relationship of NH_3 to NOx Uniformity and NH_3 Slip

- 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

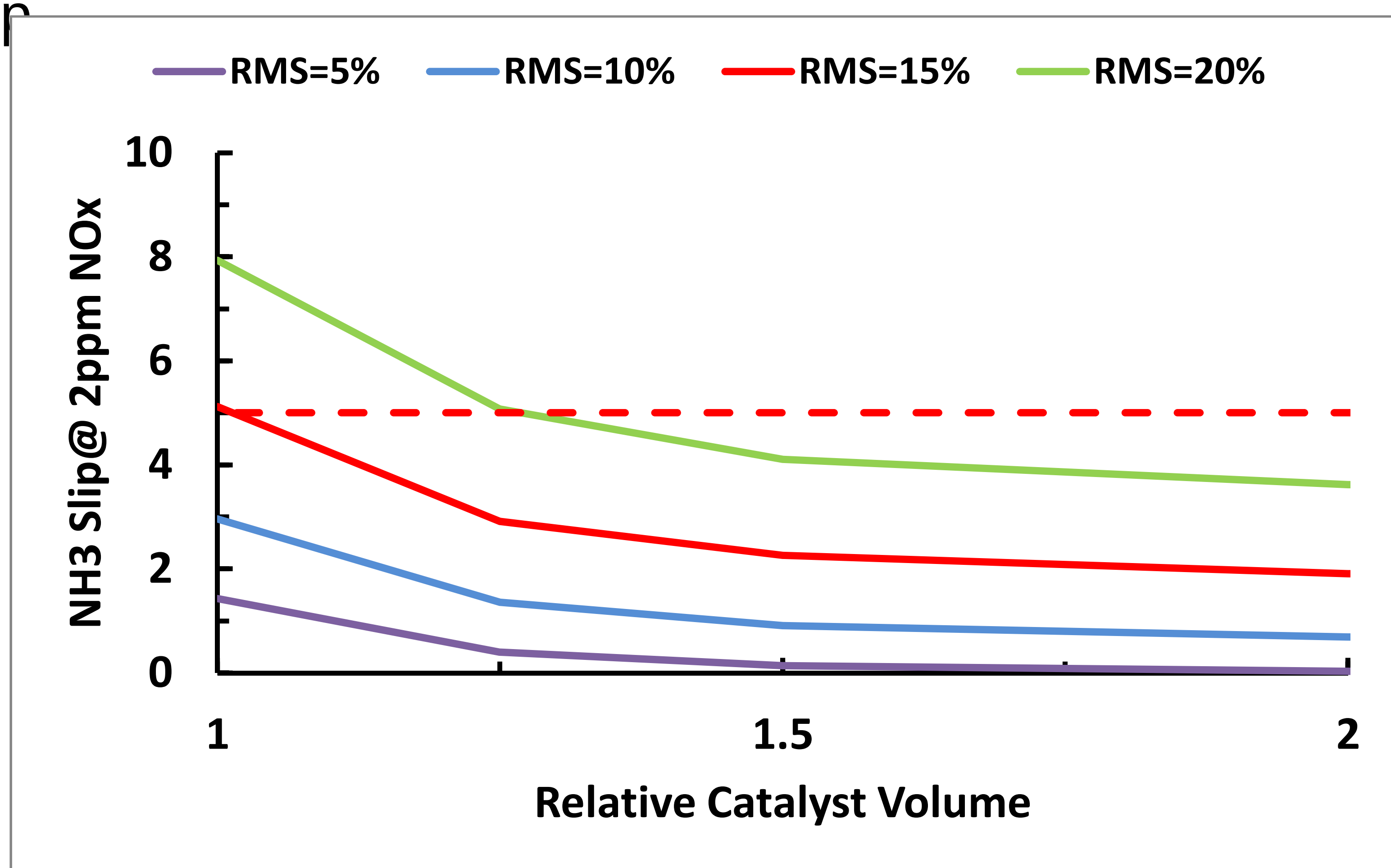


Achieving 2.0 ppm NOx and 2.0 ppm NH3 slip



Impact of Catalyst Volume on NH_3 Slip

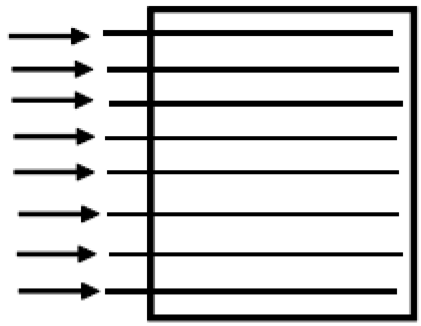
Based on 90% DeNOx design (20ppm-2ppm) & 5 ppm slip



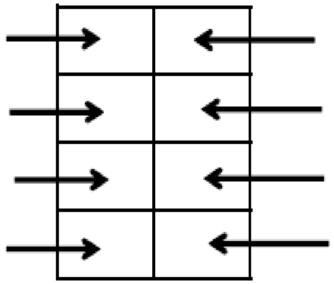
AIG Design and Tunability

AIG Must Have Adjustment Valves

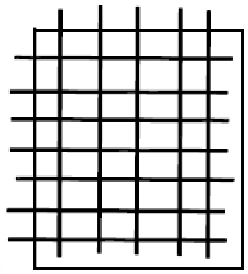
Single Zone - Common



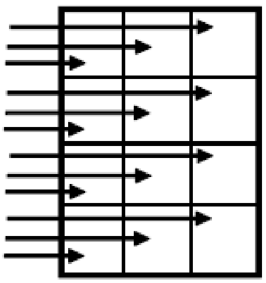
Double - Zone



Multiple Zone



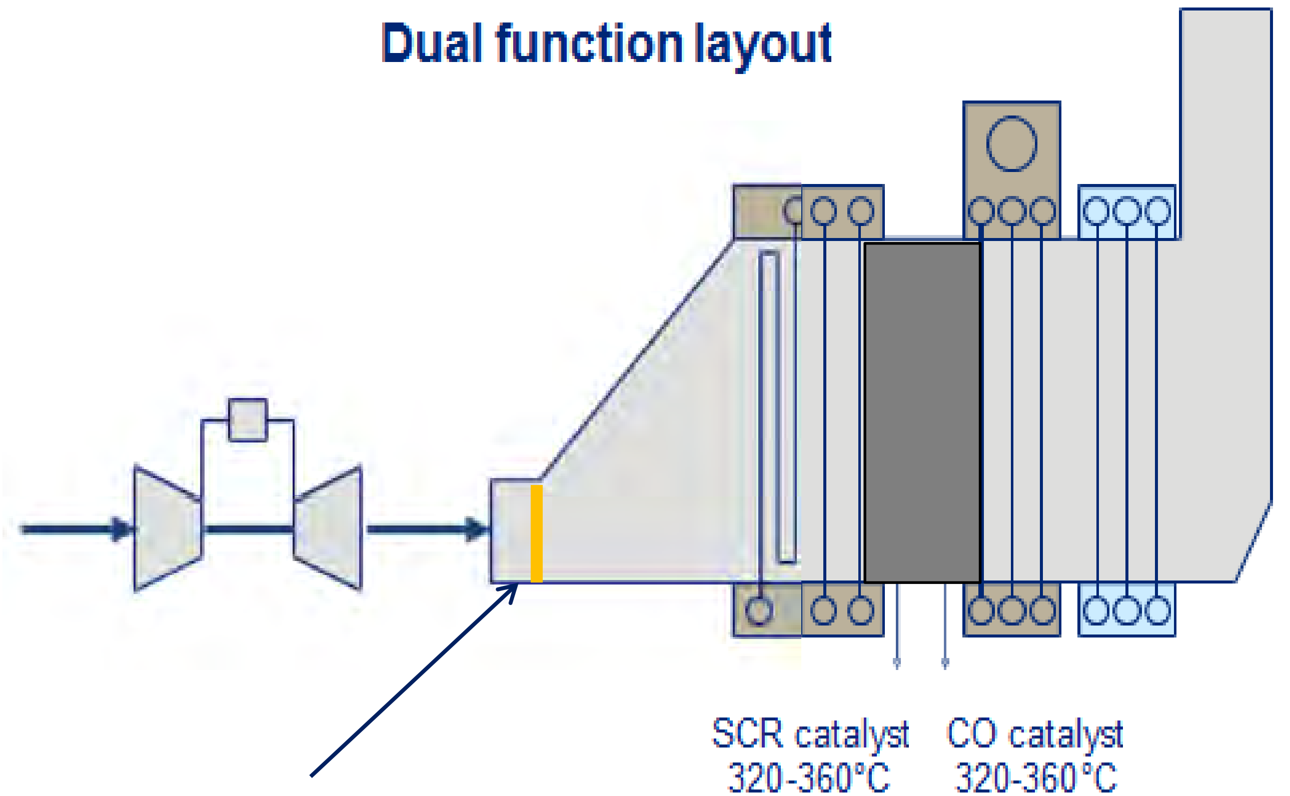
3 Zone – Vert. Adjustment



Permanent Sample/Test Grid

Sample lines run to ground level and labelled

Liquid Reagent Injection - HRSG



Direct Injection of Aqueous Ammonia or a Urea Solution

My Vision of the CCGT of the Future

- Lowest possible system pressure drop using dual function catalyst, additional reduction with use of frameless module design
- Elimination of AIG, dilution air fans, ammonia skid, interconnecting piping by using liquid ammonia/urea injection
- Reduce length of HRSG by 10 – 12 feet
- Lowest SO_2 oxidation rate, reduced backend deposition and corrosion
- Elimination of NO_2 concerns with dual function catalyst
- Elimination of traditional support frame for CO catalyst
- No CO catalyst acid cleaning as a result of sulphur fouling
- Improved ammonia to NOx distribution, required to meet >92% DeNOx and very low ammonia slip
- Installation of permanent sample grid after catalyst
- Substantial reduction in both Capex and future O&M costs