Gas Turbine & Industrial SCR Systems

Lessons Learned Firing NG and ULSD in Large Frame Simple Cycle Gas Turbine Hot SCR Systems

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MITSUBISHI HITACHI POWER SYSTEMS

PRESENTATION OVERVIEW
Gas Turbine & Industrial SCRs

Corporate Qualifications
Drivers Impacting GT Emission Control Market
SCR Systems, Controls & Catalyst
CFD & Isothermal Reactor Modeling
Tempering Air Systems
SCR Systems Constructability

MHPSA Key Facilities

MHPS Canada

MD&A

Houston Repair Center

MHPS de Mexico

Savannah Machinery Works

MH Power Systems de Venezuela

Mechanical Dynamics & Analysis

MHPS Americas
Energy and Environment

MHPS Americas

Orlando Service Center

MHPS Puerto Rico

CBC

● Office

● Office with manufacturing

Headquarters

Lake Mary, FL - U.S.A.

Gas Turbines, Steam Turbines, and Emerging Products

Products

- Gas turbines (30MW to 327MW)
- Steam turbines (30MW to 1,600MW)
- Gas engines (300kW to 15MW)
- Combined cycle systems
- Combined heat and power (CHP)
- Organic Rankine Cycle (ORC) systems (200kW to 15MW)
- Balance of plant equipment (chiller systems, boilers, electrical aux.)
- Portable power MegaNinja system

Engineering

- Project evaluation & planning
- Testing & project implementation

Environmental Services & Solutions

Basking Ridge, NJ - U.S.A.

Solid Fossil Fuel Services & AQCS

Sales Service & Engineering

- ***SCR for simple cycle gas turbines***
- *SCR for Industrial fired applications*
- *SCR for coal-fired applications*
- Flue Gas Desulfurization (FGD)
- Fabric Filters
- Lox NOx Burner (LNB)
- Catalysts
- Enhanced All-Dry Scrubber (EAD)
- Waste Spray Dryer (WSD)

Repair Services

- Engineering studies for emission reduction
- Fuel conversions
- Catalyst testing, optimization & replacement
- ESP to fabric filter conversions

Upgrades

- Catalyst
- Low NOx burners
- Scrubbers
- AQCS upgrades on dry and wet systems

MHPSA – Global Solutions for SCR Systems

Installations Worldwide – An Original Pioneer Of SCR Technology

Over 400 SCRs Installed on Gas Turbines

86 SCRs Installed for Simple Cycle applications

MHPSA		Japan, Asia, North & South America
Boiler	Coal	173
	Oil	103
	Gas	52
Gas Turbine		423
Diesel Engine		224
FCC & Refinery Heater		48
Total Units Installed		**1023**

Over 40 years of first hand experience

High Temp SCR Reference Units

Project	K-Point	SMUD McClellan	TEPCO Yokosuka	Carson IceGen	NRG Marsh Landing	Calpine Mickleton	Calpine Carll's Corner	PNM La Luz
CT	M701F	GE 7EA	M701DA	LM 6000	SGT6 5000F	W501AC	P&W FT 4 TwinPac	LM6000
Gas Temp Deg. F	1112	1020	986	875	1146	900	900	<900
DeNOx Eff.	86%	90%	60%	90%	87%	75%	76%	>94%
Start of Operation	Jul. 1992	Apr. 2004	Aug. 1992	June 1995	Apr. 2013	May 2015	May 2015	Nov. 2015
Operating Hours	3,000	>1000	4,081	25,000	>2500	>300	>250	>200
Tempering Air Fan	YES	NO	NO	NO	YES	NO	NO	Yes

Environmental Market Drivers For Simple and Combined Cycle Gas Turbines

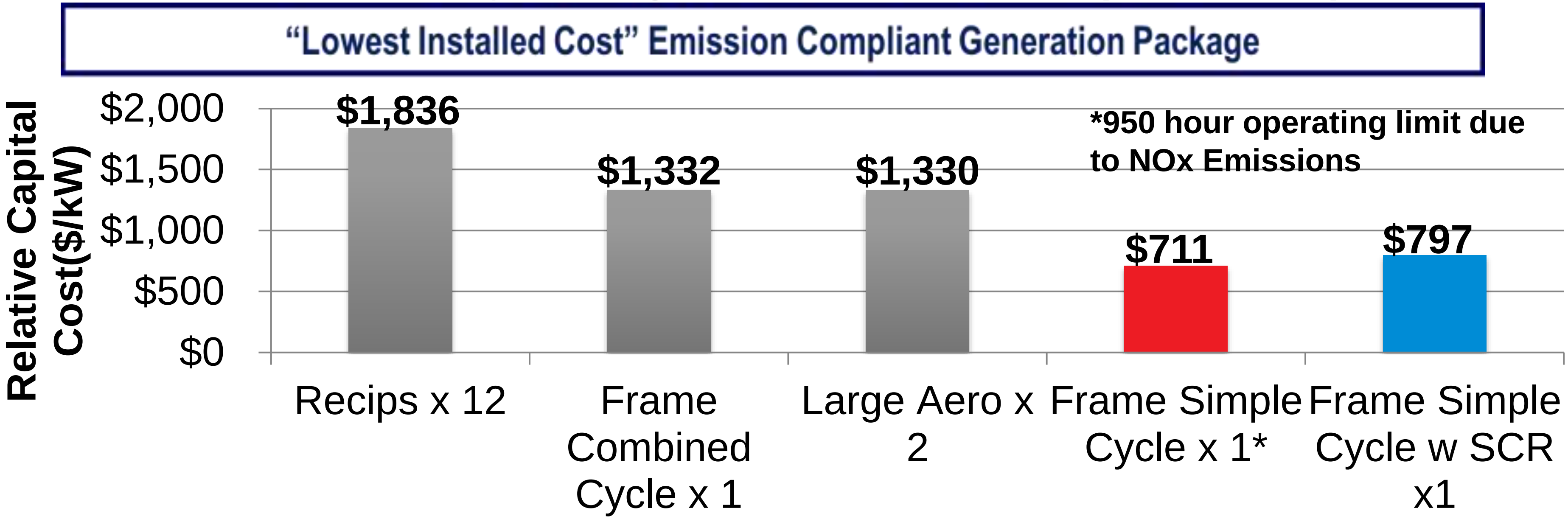
Regulation	Status	Pollutant Targeted	Compliance Options	Expected Date of Compliance	Market Impact
Nonattainment New Source Review	Affect All New Gas Turbines	CO, NO_2, O_3, PM, SO_2	SCR, Low NOx Combustors	All new permits and ongoing SIP Review of existing sources	Gas turbine and gas fired boiler – All new plants or expansions
National Ambient Air Quality Standards Ozone limit - 70ppb October 2015	Final 8 hr Ozone Rule issued Oct. 2015	CO, Pb, NO_2, O_3, PM, SO_2 and VOCs	SCRs and ULNBs for Gas Turbines, Industrial Boilers & Process Heaters	Compliance begins 2018 through the next 20 years	Gas turbine and industrial gas fired boilers, heaters May affect existing sources
FERC Ruling Increased Generation Reliability in PJM June 2015	Requires dual fuel or face significant penalty for fail to provide generation during NG curtailment	NOX, CO	ULSD Fuel Addition will require SCR Systems for gas turbine plants in PJM	2018/2019 Affects all existing and new sources after Aug 2015	Power Generation Gas turbines all sizes SC and CC
FERC Ruling Docket No.: ER14-500-000 January 2014	**Enacted = Favored Economic Consideration to Frame Simple Cycle Gas Turbine**	NOX, CO, VOC and PM	SCR Systems or reduced capacity factor preferential evaluation to Frame GT w/SCR	All new permits for peaking plant applications after January 2014	Utilities - economic analysis for Recips, SC, CC Frame and Aero GTs

The NAAQS Ozone Rule will require more SCR's on Gas Turbines in 515 Counties

The FERC Secure Fuel rule will affect all gas turbines in Delaware, Illinois, Indiana, Kentucky, Maryland, Michigan, New Jersey, North Carolina, Ohio, Pennsylvania, Tennessee, Virginia, West Virginia and District of Columbus

NYISO Comparison of Capital Costs for Peakers[1]

Cost Effectively Meeting NOx Emissions Limits (BACT/LAER)



Utilizing Frame Simple Cycle with SCR (No Operating Limitations) results in the most cost effective peaking application

No operating limitation of frame with SCR outweighs the $86/kW increase in CAPEX

FERC January 2014 Ruling[2]

"We find that NYISO's proposal to use the F class frame unit with SCR technology peaking unit for developing the capital cost estimate for NYC, LI, and the G-J Locality is reasonable."

[1]Initial NYISO Report before FERC ruling; Zone C from Table 3 and Appendix B: *Proposed NYISO Installed Capacity Demand Curves For Capability Years 2014/2015, 2015/2016 and 2016/2017*

[2]*FERC ORDER ACCEPTING TARIFF FILING SUBJECT TO CONDITION AND DENYING WAIVER 146 FERC ¶ 61,043. 28 January 2014*

MHPSA Solution for Simple Cycle Gas Turbine SCR

Ongoing work to educate FERC, EPA, EPRI, ISOs of technology and performance

Project Features

- Four (4) F Class CTG's
- GT Peaking plant nominal 750 MW
- Max operating temp: 1,146F

Emission Limits (15% O_2 Dry Basis)

- NOx & CO 2.0 ppm
- VOC 1.0 ppm

COD May 1, 2013 on schedule

- As of 12/2015, AOH : 633, 562, 555, 533 = 2283
- As of 12/2015, Starts : 119, 95, 102, 85 = 401

Many 1st in class technologies

- Patented tempering air injection
- Hybrid hot gas/electric heated vaporization skids
- Self mixing high density ammonia injection
- Triple Loop NOx control over ramp conditions
- Process ammonia trim back TDL

NRG Marsh Landing
SCR for Large Frame Simple Cycle

Additional Frame Experience List

Project	GT Frame
K-Point	M701F
SMUD McClellan	EA Class
TEPCO Yokosuka	M701DA
Calpine Mickleton	W501A

Frame Simple Cycle SCR Firing Natural Gas and ULSD

Gas Turbines for Peaking/Load Following Applications

Project Features

- Two (2) F7 MS-7001-B CTG's
- GT Peaking plant nominal 100 MW
- Max operating temp: ~975F

MID McClure
SCR-Frame Simple Cycle

Emission Limits (15% O_2 Dry Basis)

- NOx NG 2.5 ppm / ULSD 4.2 ppm
- CO 5.0 ppm
- VOC 50% removal

2005/2006 Retrofit SCR COD

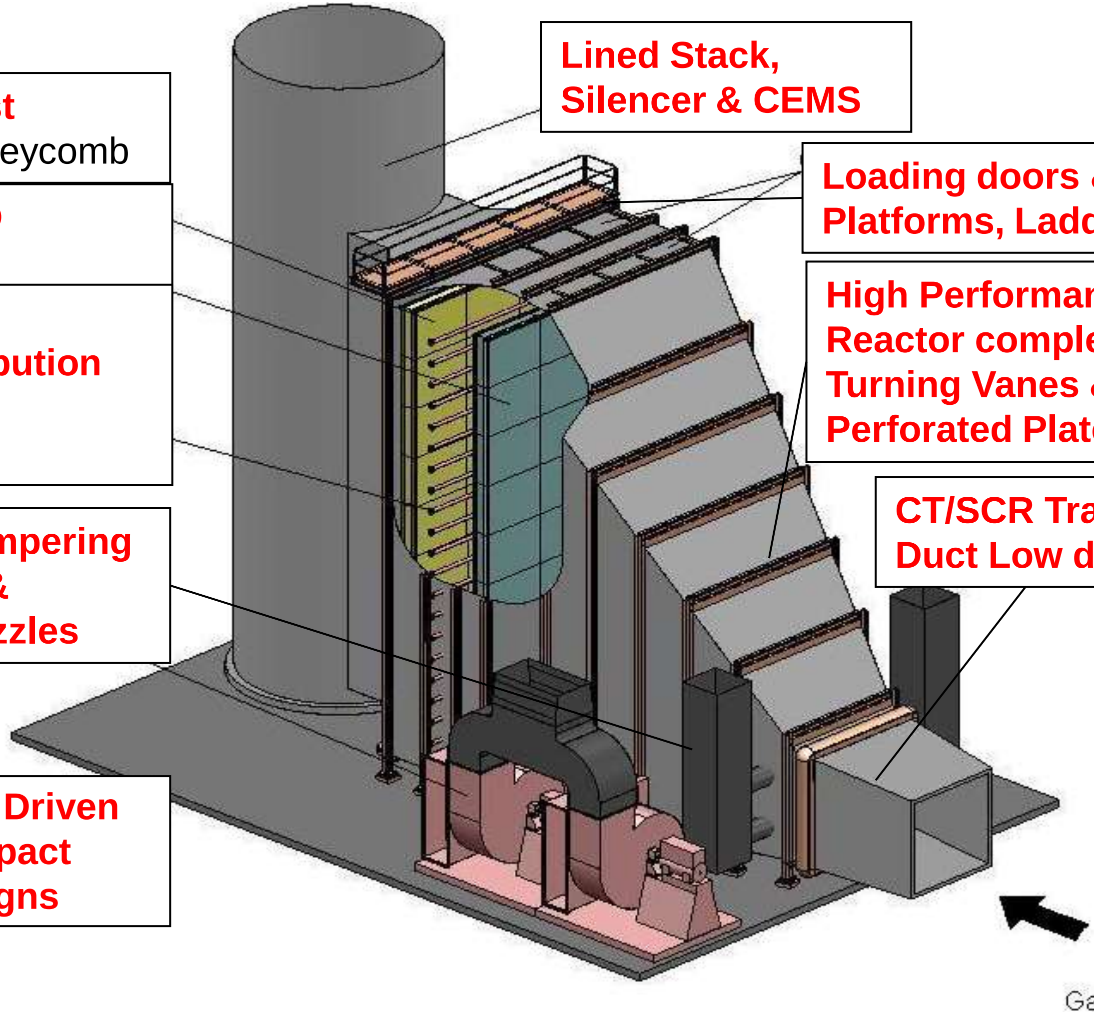
- Unit1 - 1,512 fired hours predominantly on ULSD
- Unit 2 -1,943 fired hours predominantly on NG

Advanced Technology Designs

- High flow tempering air systems multi ported - reduced pressure drop design
- Fully cold flow modeled from turbine diffuser through turbine exhaust stack
- Fully integrated SCR controls into Turbine Control System
- Designed for duel fuel firing both independently and commingled fuel during transition

MHPSA SCR Hot Simple Cycle Frame Class Turbine

State of the Art – Advanced Class Technology

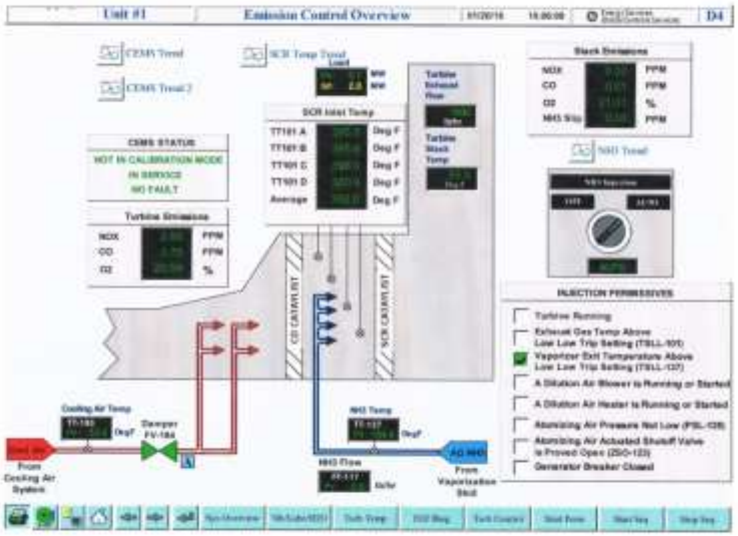


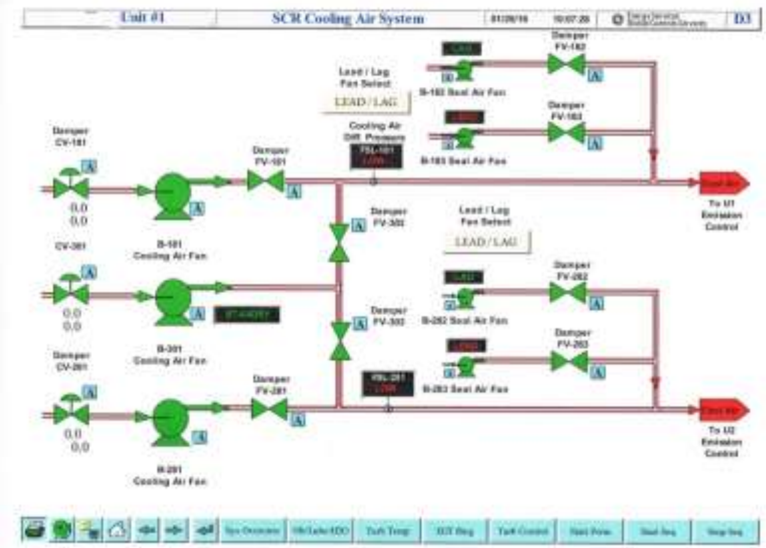
Add'l Scope
- AFCU
- PLC
- Tech Advisor
- Training

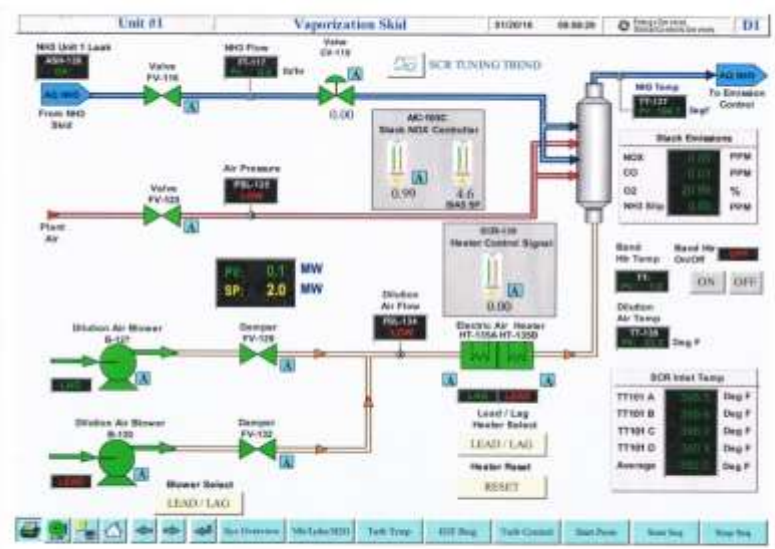
Options
- Ammonia Tank
- Pump Skid

Guarantees
- NOx; CO; VOC
- Ammonia Slip
- Parasitic Power
- Pressure drop
- Noise
- Catalyst Life

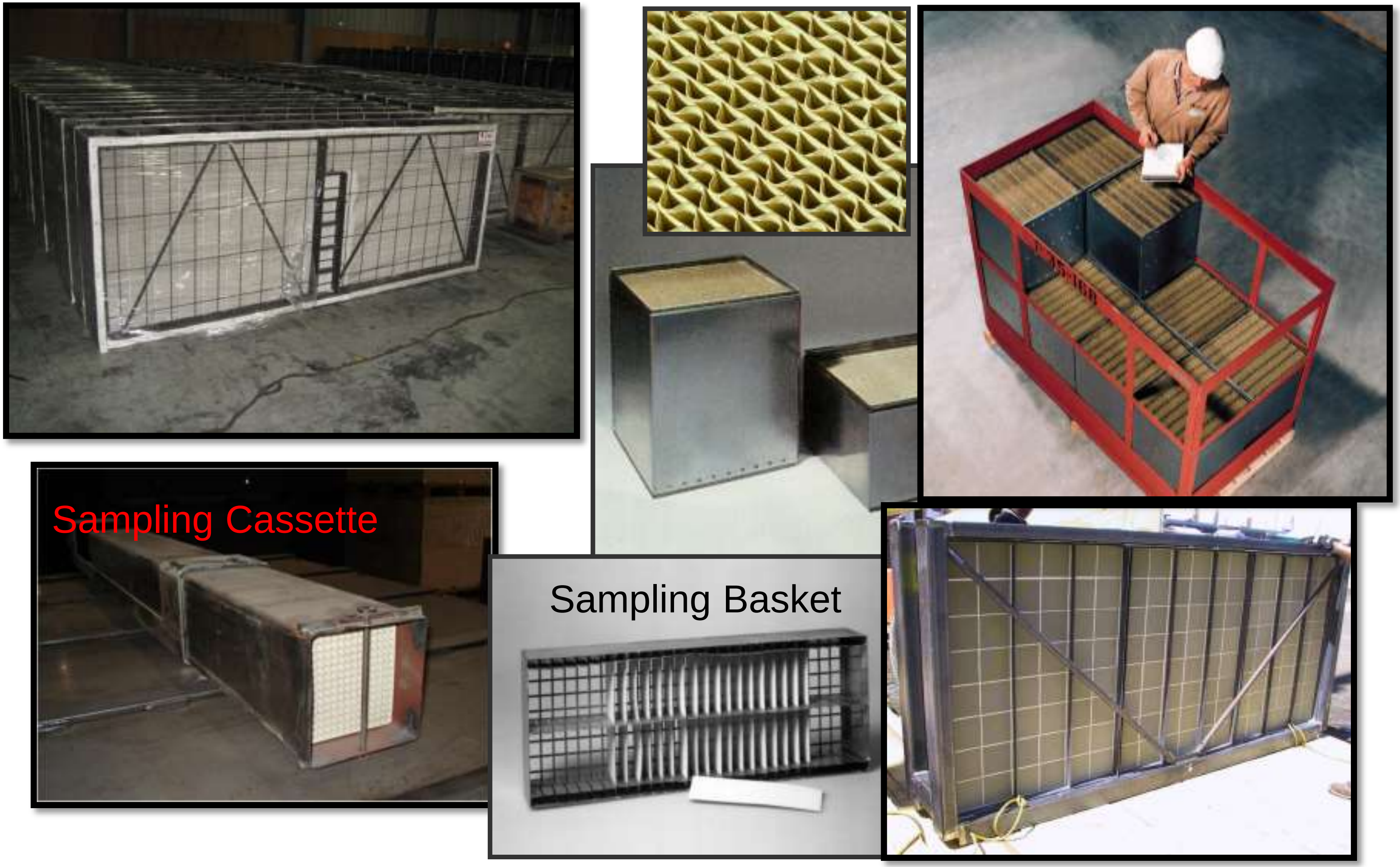
Typical SCR System Overview Screens





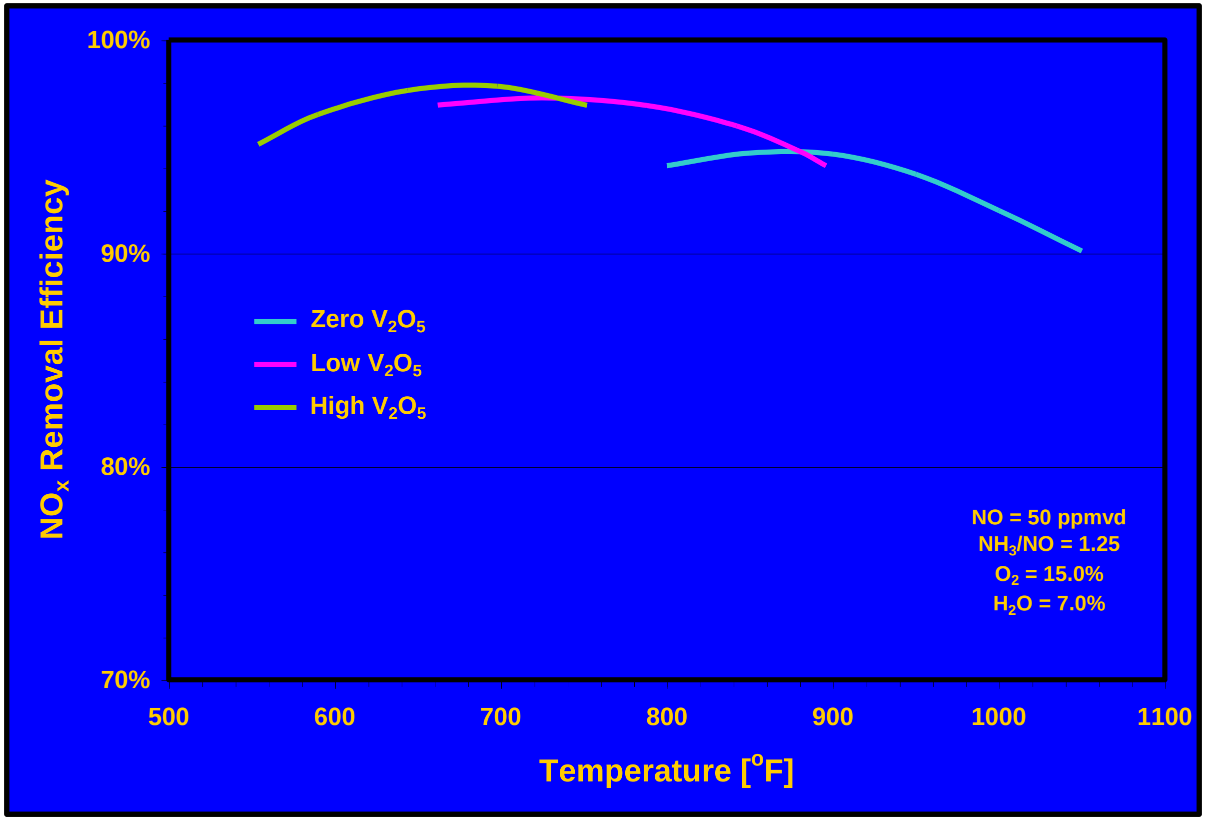


Catalyst Modules & test coupons/blocks

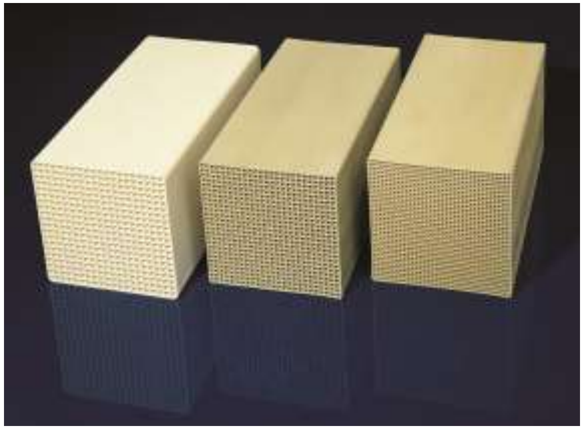


CATALYST SELECTION: TEMP. VS. ACTIVITY
Today's Technology

Large operating temperature range (350 - 1100°F)



- High temp catalyst: 900F ~ 1,100F
- Medium-high temp catalyst: 800F ~ 900F
- Medium (Standard) catalyst: 450F ~ 800F



Extruded catalyst consistently demonstrates uniform cell sizing and pressure drop prediction

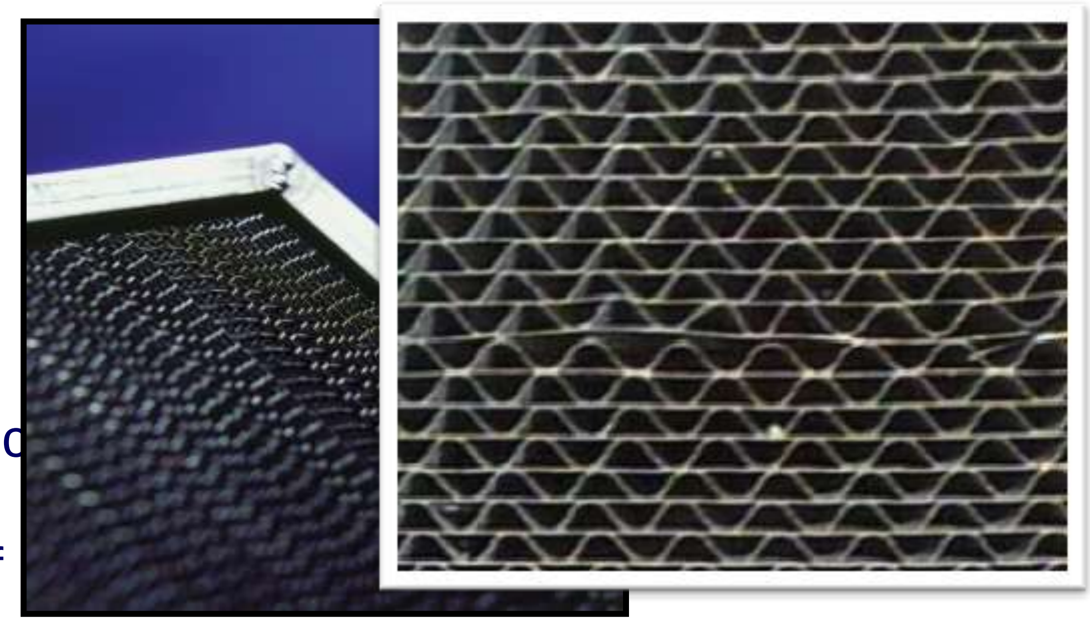
At higher temps, reduce V:W ratio
- Stronger NH3 adsorption
- Lower NH3 decomp rate
- Higher DeNOx rate
- Lower sintering rate

Catalyst Poisoning & Degradation Mechanism

Degradation Source	Mechanism
High Temperature > 930F	Decreases available surface area by thermal sintering of ceramic material
Fine particulate	Reduces available surface area by masking surface and preventing diffusion into pre structure
Ammonia-sulfur compounds	Plugs pores and prevents diffusion
Alkaline metals, Na, K	Ion exchange with active sites
Alkaline earth metals, Ca, Mg	Typically in form of sulfates, bond with acid sites reducing the ability of catalyst to absorb NH_3 I.e. formation of $CaSO_4$
Halogen	May react with and volatilize active metal sites
Arsenic	Gaseous arsenic diffuses into catalyst and covers active sites, preventing further reaction
V, Pt, Cr and Family	Deposit onto catalyst, increasing NH_3 to NO and/or SO_2 to SO_3

CO & VOC catalyst

- Platinum or other PGM promotes CO to CO_2 oxidation.
- Brazed joint corrugated metallic foils, stacked corrugated foil or ceramic cells to provide high surface area per cu.ft. of catalyst
- Oxidation occurs on “surface” of catalyst.
- Pressure drop is directly dependent on catalyst depth and compactness



CO Catalyst Failures at Turbine Sites

- Insufficient foil retaining devices
- High velocity flue gas flow
- Incorrectly installed catalyst
- Mechanical failure of catalyst substrate

Perforated plate eliminated turbulent zones

Key Considerations for Gas Turbines SCR

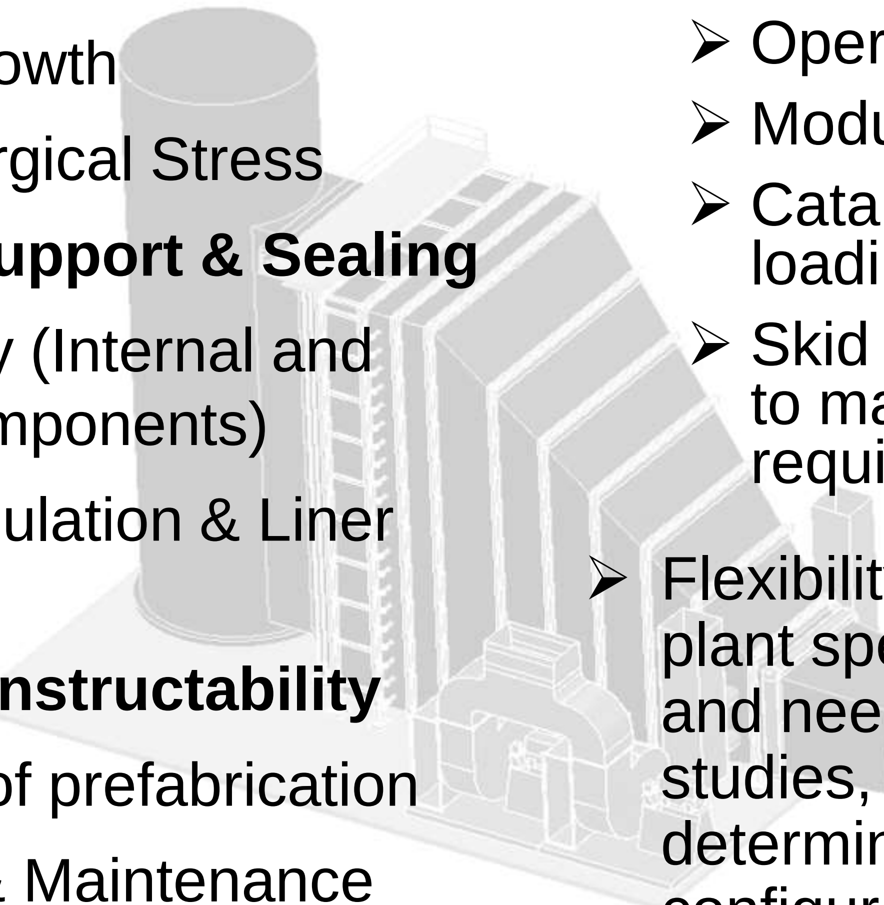
Service life year/hours (customer requirement)	Ammonia slip end of life
Exhaust gas temperature	Catalyst temperature
Turbine exhaust NO_X levels	Reactor duct configuration
Required NO_X removal	Flue gas flow/temperature distribution
Pressure loss allowance	SO2 to SO3 Conversion Potential PM formation
Volumetric flow rate variable	NH_3/NO_X distribution

Key Maintenance Considerations
Gas Turbine SCR Systems

Service life year/hours (customer requirement)	Periodic sampling to validate activity, ammonia quality/concentrate
Exhaust gas temperature	Fine tune injection start cycle for NH3 optimization
Turbine exhaust NO_X levels	Verify GT operations for consistent performance
Required NO_X removal	NH3 skid maintenance and sealing systems
Pressure loss allowance	Periodic catalyst cleaning
NH_3/NO_X distribution	AIG Inspection, rebalance Reactor internal inspection

Follow Recommended Maintenance Evolutions

SCR System Design Considerations



- **Seismic and Wind Loads**
- Thermal Growth
  - Metallurgical Stress
- **Catalyst Support & Sealing**
- Accessibility (Internal and external components)
- Thermal Insulation & Liner Systems
- **Design Constructability**
  - Extent of prefabrication
- Operation & Maintenance

- Standardized design
  - Operational philosophy
  - Modular design
  - Catalyst modules and loading system
  - Skid design (optimized to match site requirements)
- Flexibility to design around plant specific restrictions and needs. Carry out flow studies, as necessary, to determine best layout and configuration

Why Flow Modeling Is Necessary

1) Develop flow distribution devices and injection ports to;
   a) Achieve acceptable velocity distributions through CO and SCR catalyst: (RMS) 15% to 20%
   b) Achieve acceptable ammonia distribution at the inlet to the SCR catalyst: (RMS) 5% to 10%
   c) Achieve acceptable temperature distributions at the catalyst inlets: (Mean Deviation) +/- 25 to +/- 50 deg F
2) To determine from model measurements the system pressure loss for the final configuration

- ❖ Typical Boundaries: Gas Turbine Diffuser Outlet through Stack Outlet.
- ❖ CFD and CFM results, validates ammonia injection design, ammonia mixing devices, tempering air distribution through injection ports, turning vanes, perforated plates and flow straightening devices.

Various SCR Failures at Turbine Sites

- Insufficient tempering air
- Poor tempering air mix into flue gas path
- Catalyst failure from higher temperature
- Poor AIG design - maldistribution
- Catalyst seal failures from sintering
- Insufficient ammonia injection capability
- Seal material issues from hot spots

Cold Flow Modeling (Isothermal)

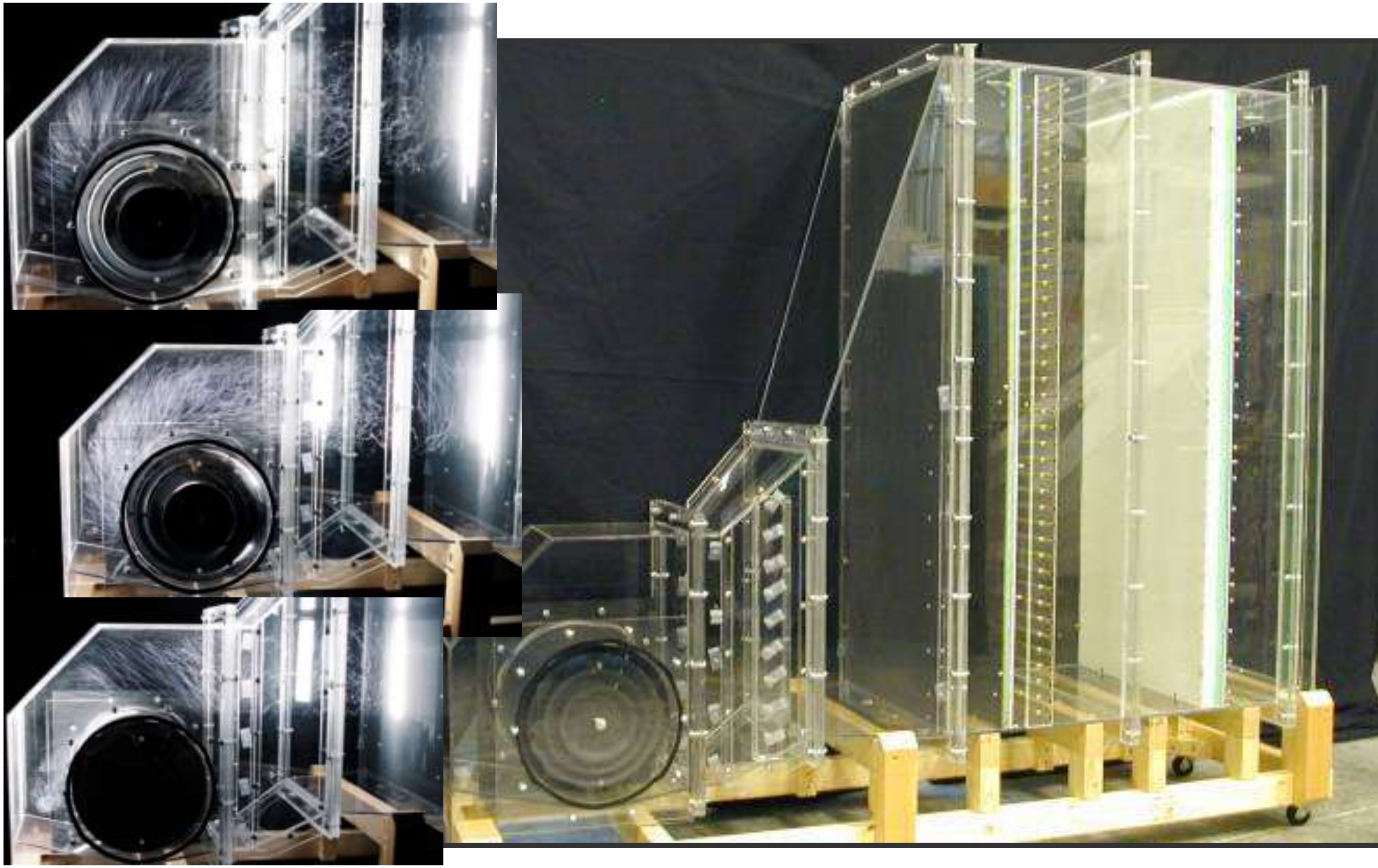
- Cold flow modeling is the core method of determining complex flow fields.
- 1/12th three dimensional scale model use .
- Geometrically similar to full size unit
- Construction uses ¼” clear Plexiglas
- Model extends from gas turbine outlet through cooling air duct, CO catalyst, AIG, SCR through silencer and stack
- All significant internal structures simulated
- Drawings and onsite inspection validates design

Flue Gas Path Management
(NH_3 Mixing - Cold Flow Model)

Near Side

Center

Far Side



Simple Cycle Physical 1/12th Scale Model

Sidewall Baffles & Horizontal Turbine Vanes

Tempering Air & Ammonia Mixing Challenges

- Major Design Concern;

a) Short Distance Available to Mix the Air

b) Conflicting requirement at the inlet duct

Mix the air into flue gas (Turbulence)

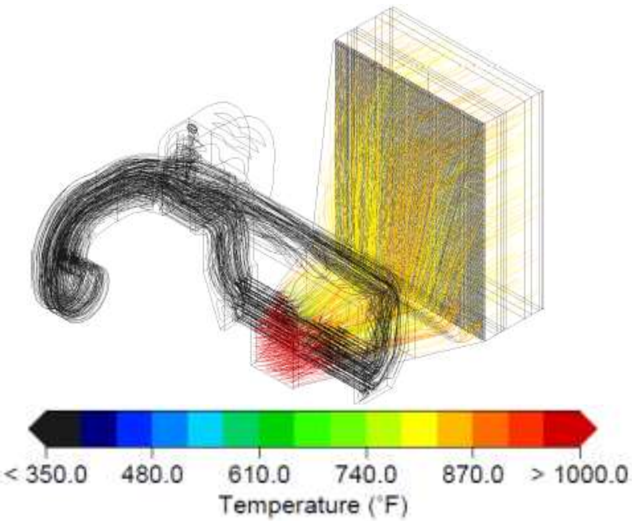
versus

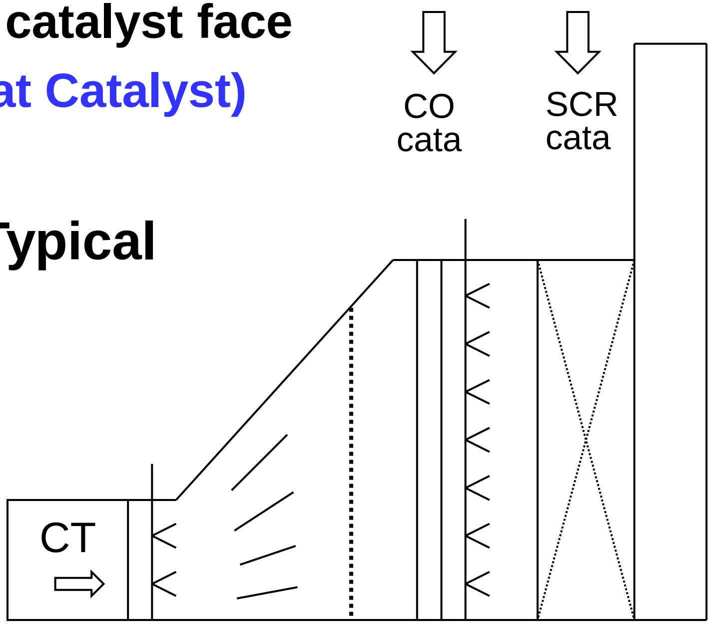
Uniform gas flow necessary at CO catalyst face.

versus

Homogeneous ammonia mix in flue gas at SCR catalyst face

(Flow Straightening & Velocity Normalizing at Catalyst)





Challenging Turbine Exhaust Conditions – Typical

Flue gas exiting turbine diffuser up to ~140 FPS

Tempering air ~ 30% total flue gas volume

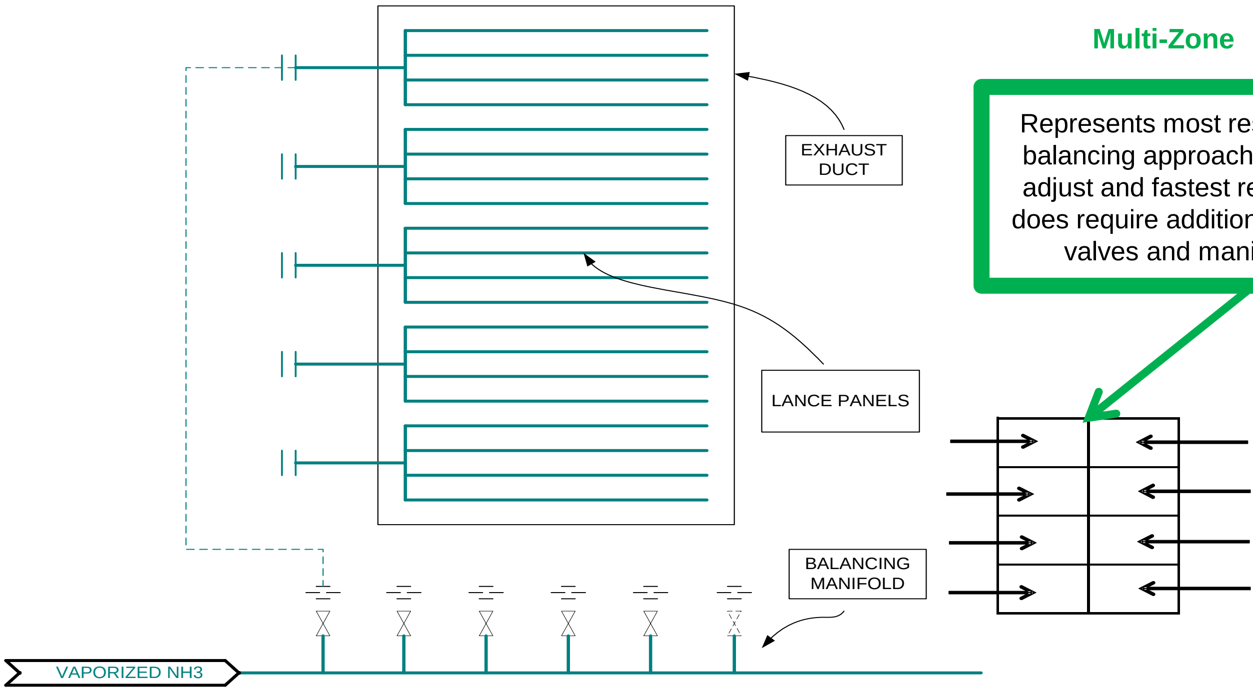
High exhaust gas temperature ~ 1200 def.

Contrasting optimum catalyst temperature profiles

PERFORATED PLATE & TURNING VANES

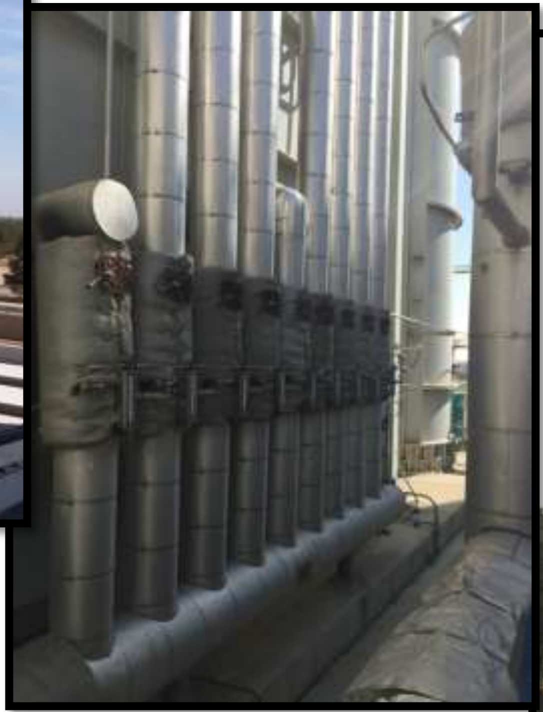
High Density Ammonia Injection Grid

Multi-Zone



- Double entry balancing valves manifold to bias AIG
- Lance panels allows expedient optimization
- High density drilling, dense ammonia injection pattern
- Orifice flow measurements validate ammonia panel flow field balance
- Allows for future optimizing as catalyst ages or turbine performance degrades

AIG Header & Valve Locations



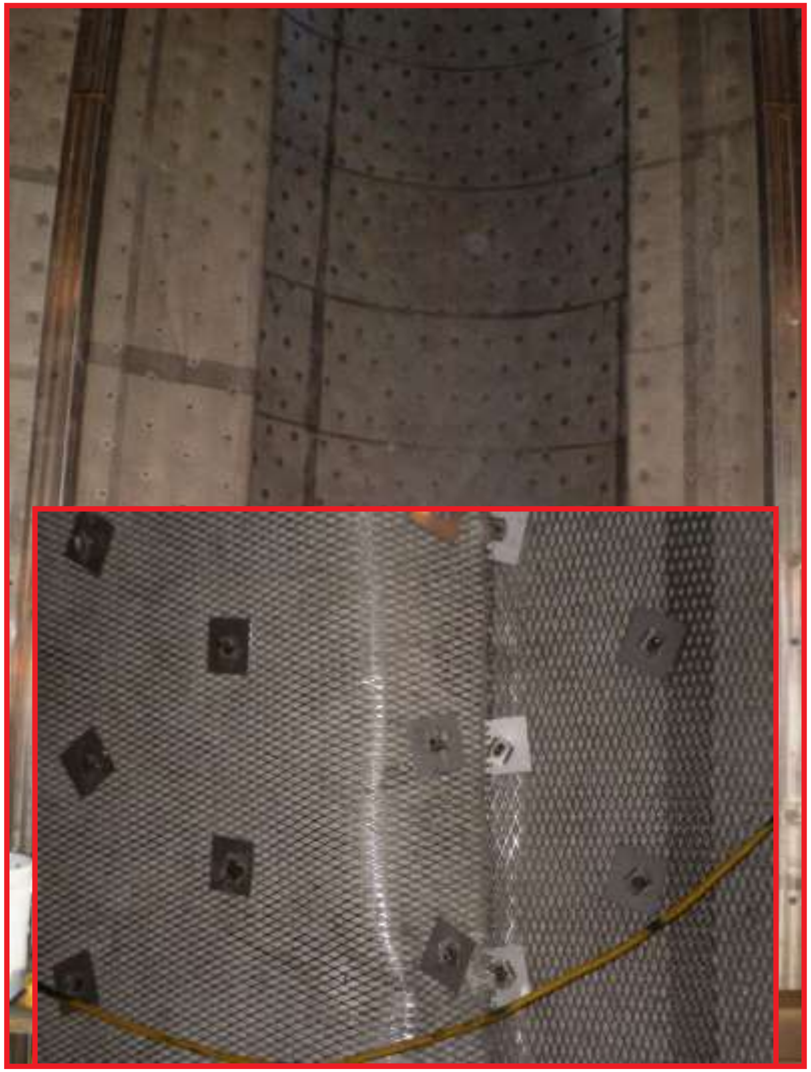
Location & access of AIG balance valve array is generally lowest cost supply unless customer defined. Variations may affect price, real estate consumed and equipment sizing for transfer piping and fan size.

Plant A (Modular Construction)

Plant B (Panel Construction)

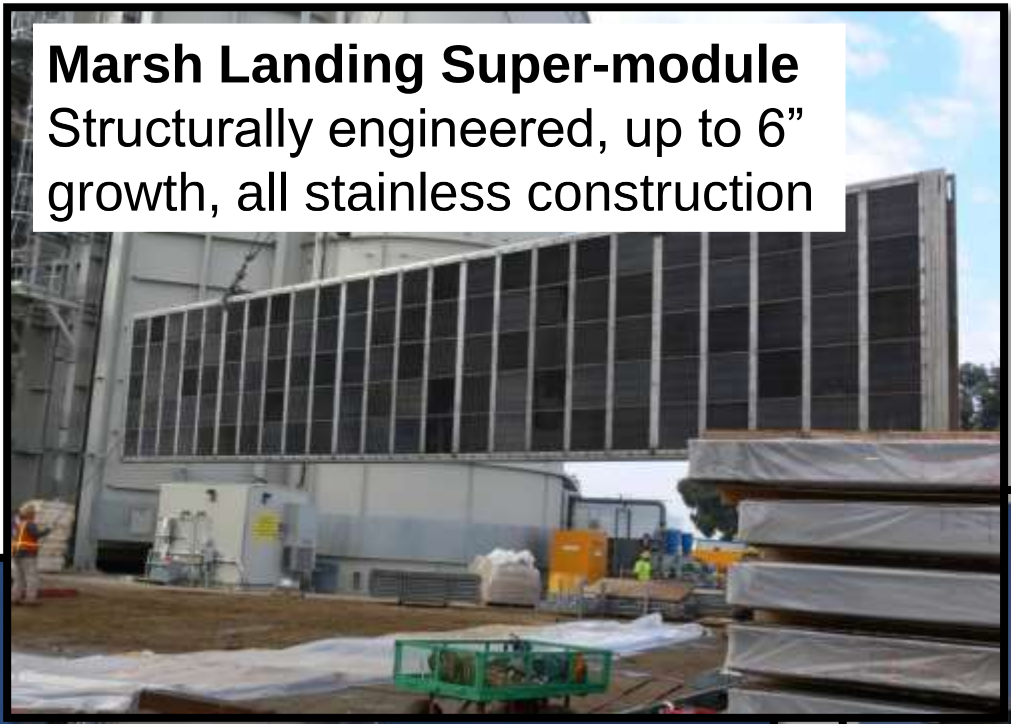
Plant C (Semi-Modular Construction)

RIGHT - Solid Liner Plate System & Welded Stud Anchoring
WRONG - Expanded Metal Liner & Wire Welded Retainers



Catalyst Sealing Mechanism – Good & Bad

GT SCR & CO Catalyst Loading



Marsh Landing Super-module
Structurally engineered, up to 6" growth, all stainless construction

MHPSA - Experienced Technology Provider

- 'Knowledge' and 'Expertise' built over 40 years - Over 1000 SCR systems worldwide
  - (Original pioneer of SCR technology)
- Successfully completed the most difficult and challenging projects for Frame & Aero GT's
  - Ultra Low NOx & Slip (< NOx 2ppm/NH3 2ppm)
  - Zero-Slip ammonia systems for gas turbines
  - High temperature SCR systems SCGT's
  - Tempered air systems for SC Frame Turbines
  - **More than 400 SCR** systems for gas turbines
- Proven track record. (translates to *Low Risk*)
  - Have always met or exceeded performance guarantees
  - Only OEM supplier of SCR catalyst and SCR systems
  - We do not walk away
- Competitive offerings, high reliability systems
- Experienced US Design Build team , Japan R&D Centers
- Financial stability

High Temp SCR System EA SCGT
>10 years Operation

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