2017 NOx-Combustion-CCR Round Table Presentation

February 27 & 28, 2017, in Cleveland, OH / Hosted by FirstEnergy
Advances in Catalyst Solutions
For Gas Fired Applications

NOx-Combustion-CCR Round Table

February 28, 2017
Overview

• Key needs for gas-turbine air pollution control
• Advanced tools to meet needs
• Case studies
• Other applications
• Wrap-up
Key Needs for Gas-Turbines

• Meet emissions control requirements
  – DeNOx
  – CO and VOC reduction
  – NH₃ slip limit
  – Under a variety of conditions
    • Temperature - Combined Cycle & Simple Cycle
    • High NO₂
    • Start-up and load cycling

• While minimizing cost of compliance
  – Low capital cost
  – Low maintenance cost
  – Low parasitic power loss (Low pressure drop)
  – Minimize NH3 usage
  – Minimize or eliminate operation constraints
Advanced Tools to Meet Needs

Stand-alone or combinations

State-of-the-art emission control solution capability
Traditional Horizontal Flow Modules

- Pressure drop reductions require costly duct expansions.
- Difficult to add catalytic capacity without increasing pressure drop.
- In some cases, sealing requires maintenance.
Advanced Module

More frontal area in same space results in >40% Lower Pressure Loss!

No need to expand duct to achieve lower pressure loss.

Patented: US 8,329,126
Elite™ Platform

Combines three advanced tools

- **Pleated Module**
- **Advanced Catalyst Potential 60% Higher**
- **Integrated Seal**

Result:

- **Step-change** reduction in pressure drop: **60–75% Lower!**
- **Vastly improved** emission control solution capability
- **Innovative** seal to prevent need for maintenance

*Patent Pending*
Pleated Module w Integrated Seal

*Single 150 x 150 mm Element*

*Inlet face*

*Top View*

*One Pleat*

*Flow Direction*

Patent Pending
Reduced Pressure Loss

- Standard Module
- Advanced Module (patented)
- Elite™ (patent pending)
Financial Benefit of Reduced Pressure Drop

Actual 240 MW GT Example

- Reduced DP by 2” H₂O

**Full load:**
- Increased power sold.

**Intermediate load:**
- Lowered gas consumption.

**Total Benefit: $95K/yr**

*Lower DP achieves tangible financial benefits*

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### Saving due to new pressure loss @ Full Load

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>GT gross MW generated</td>
<td>240</td>
</tr>
<tr>
<td>Pressure drop reduction (inch H₂O)</td>
<td>2</td>
</tr>
<tr>
<td>Natural Gas price $/MMBtu</td>
<td>3</td>
</tr>
<tr>
<td>Catalyst guarantee (year)</td>
<td>5</td>
</tr>
<tr>
<td>Operating hours per year</td>
<td>4380</td>
</tr>
<tr>
<td>Annual gross power output MW</td>
<td>1051200</td>
</tr>
<tr>
<td>Price of electricity sold $/MWh</td>
<td>30</td>
</tr>
<tr>
<td>Power output correction with correction curves for pressure drop</td>
<td>1.002</td>
</tr>
<tr>
<td>Total revenue for electricity sold</td>
<td>157,680,000</td>
</tr>
<tr>
<td>Total revenue for electricity sold with new pressure drop</td>
<td>157,995,360</td>
</tr>
<tr>
<td>Increase revenue from power sold over 5 years</td>
<td>315,360</td>
</tr>
<tr>
<td>Annual revenue increase from power sold/unit/year</td>
<td>63,072</td>
</tr>
</tbody>
</table>

### Saving due to new pressure loss @ Intermediate Load

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>GT gross MW generated</td>
<td>200</td>
</tr>
<tr>
<td>GT Gross Heat Rate Btu/kWh (HHV)</td>
<td>11500</td>
</tr>
<tr>
<td>Pressure drop reduction (inch H₂O)</td>
<td>2</td>
</tr>
<tr>
<td>Natural Gas price $/MMBtu</td>
<td>3</td>
</tr>
<tr>
<td>Catalyst guarantee (year)</td>
<td>5</td>
</tr>
<tr>
<td>Operating hours per year</td>
<td>3066</td>
</tr>
<tr>
<td>Heat rate correction with correction curves for pressure drop</td>
<td>0.9985</td>
</tr>
<tr>
<td>Total gas consumption</td>
<td>105,777,000</td>
</tr>
<tr>
<td>Total gas consumption corrected with new pressure drop</td>
<td>105,618,335</td>
</tr>
<tr>
<td>Gas consumption saving from improved heat rate over 5 years</td>
<td>158,666</td>
</tr>
<tr>
<td>Annual gas consumption saving/ unit/ year</td>
<td>31,733</td>
</tr>
<tr>
<td>Total net benefit over 5 years</td>
<td>474,026</td>
</tr>
<tr>
<td>Annual net benefit/unit/year</td>
<td>94,805</td>
</tr>
</tbody>
</table>

Table as presented at POWER-GEN International 2016 by Cormetech, ENGIE, Ennis

Lower DP achieves tangible financial benefits
Supercharged SCR

Elite™ with Advanced Catalyst Potential enables with much less pressure loss penalty

Potential emissions control solutions:

- Reduced NH₃ slip / Reduced ammonia usage
  - Reduces ammonia cost
  - Less tube fouling
- Higher NOx reduction
- Longer life
- Added features, e.g. CO reduction
Traditional HRSG Layout

→ CO Oxidation Catalyst → AIG → SCR Catalyst
Multi-functional METEOR™

All in one catalyst layer

Oxidizing Function:
CO oxidation to CO₂
VOC oxidation to CO₂ and H₂O

Reduction Function:
4NO + 4NH₃ + O₂ → 4N₂ + 6H₂O
2NO + 2NO₂ + 4NH₃ → 4N₂ + 6H₂O
6NO₂ + 8NH₃ → 7N₂ + 12H₂O

- SCR functionality → V₂O₅-WO₃/TiO₂
- Oxidation functionality → PGM (Pd and/or Pt)
- Initially developed and patented by Siemens Energy (US 7,390,471)
- Optimized and fully developed into commercial production by Cormetech
DeNOx and CO oxidation → high conversion rates over wide temperature range.
- Active for VOC oxidation → rate depends on hydrocarbon speciation.
- PGM loading can be adjusted to optimize performance at low/high temperature.
- Applications: CCGT, SCGT, diesel/gas RE, refinery process units

**DeNOx and CO Oxidation**

<table>
<thead>
<tr>
<th>Test Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>NOx = 25 ppm</td>
</tr>
<tr>
<td>CO = 25 ppm</td>
</tr>
<tr>
<td>O₂ = 15%</td>
</tr>
<tr>
<td>H₂O = 7%</td>
</tr>
<tr>
<td>NH₃ slip 3 - 7 ppm</td>
</tr>
<tr>
<td>Constant SV</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Propane or Propylene Oxidation Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test Conditions</td>
</tr>
<tr>
<td>NOx = 25 ppm</td>
</tr>
<tr>
<td>O₂ = 15%</td>
</tr>
<tr>
<td>H₂O = 7%</td>
</tr>
<tr>
<td>[C₃H₈ = 20 ppm, or C₃H₆ = 20 ppm]</td>
</tr>
<tr>
<td>NH₃ slip 3 - 7 ppm</td>
</tr>
<tr>
<td>Constant SV</td>
</tr>
</tbody>
</table>
METEOR™ - Sulfur Tolerant

- **Similar** SO₂ oxidation rate as traditional SCR catalyst.
- Short-term exposure to **50 ppm SO₂** has **no significant impact** on CO oxidation.

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**SO₂ Oxidation**

<table>
<thead>
<tr>
<th>Test Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>T = 350°C</td>
</tr>
<tr>
<td>NOx = 35 ppm</td>
</tr>
<tr>
<td>Inlet MR = 1.1</td>
</tr>
<tr>
<td>O₂ = 15%</td>
</tr>
<tr>
<td>H₂O = 8%</td>
</tr>
<tr>
<td>CO = 100 ppm</td>
</tr>
<tr>
<td>SO₂ = 500 ppm</td>
</tr>
<tr>
<td>Constant SV</td>
</tr>
</tbody>
</table>

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**Sulfur Durability**

<table>
<thead>
<tr>
<th>Test Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>NOx = 25 ppm</td>
</tr>
<tr>
<td>Inlet MR = 1.1</td>
</tr>
<tr>
<td>O₂ = 15%</td>
</tr>
<tr>
<td>H₂O = 5%</td>
</tr>
<tr>
<td>CO = 100 ppm</td>
</tr>
<tr>
<td>Constant SV</td>
</tr>
</tbody>
</table>

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NOx-Combustion-CCR Round Table February 2017
**METEOR™ - Benefits**

- **Simplicity:** *one catalyst layer vs. two.*
  - Smaller footprint in HRSG.
  - Lower pressure drop.
  - Lower capital and O&M costs.

- **Flexibility:** applicable to new units, retrofits, and replacements.

- **Lower SO₂ oxidation rate,** relative to the traditional two catalyst layout.
  - Potential for reduced backend fouling.

- **Highly resistant to sulfur** compounds in the flue gas.
  - Broader load flexibility from reduced sensitivity to sulfur fouling agents when operating at low temperature.
Plant Ennis Case Study

As presented at POWER-GEN International 2016

- Combination of advanced tools deployed:
  - METEOR™ for combined NOx, CO, and VOC reduction
  - Elite™
    - Pleated modules with Integrated Seal
    - Advanced Catalyst Potential

Ennis Power Company, LLC
FULL-SCALE INSTALLATION
Ennis Power Company, LLC

- Ennis Power Company, LLC (Ennis, Texas).
- Siemens 501G unit combustion turbine (340MW combined cycle mode).
- METEOR™ MPC / ELITE™ replaced existing SCR catalyst in November 2015.
- Guaranteed emission reductions of NOx, NH₃ slip, CO and VOC.
- Successfully operating. Currently at >5,000 hours run time.
FULL-SCALE INSTALLATION
Ennis Power Company, LLC
Motivation

Replacement of existing SCR layer with a METEOR™ MPC catalyst layer enabled:
(1) Capability to operate at lower loads while maintaining CO emission compliance.
(2) Faster compliance of CO emissions during unit startup.

Data slide courtesy of Siemens.

As presented at POWER-GEN International 2016
### Field testing validation:
- Measured SCR inlet and outlet gas composition.
  - SCR inlet = GT exhaust gas.
  - **Fresh catalyst** achieved ~99% CO oxidation at 36% GT load point.
  - DeNOx achieving target value. NH₃ slip is very low due to the fresh catalyst state.

<table>
<thead>
<tr>
<th>GT Load</th>
<th>SCR Temperature (°C)</th>
<th>GT Exhaust Gas Composition</th>
<th>SCR Outlet Gas Composition</th>
<th>Meteor SCR Catalyst Performance</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>GT Exhaust CO (ppm)</td>
<td>SCR Outlet CO (ppm)</td>
<td>SCR Outlet NOx (ppm)</td>
</tr>
<tr>
<td>98%</td>
<td>342</td>
<td>0.5</td>
<td>0.0</td>
<td>7.8</td>
</tr>
<tr>
<td>76%</td>
<td>334</td>
<td>0.6</td>
<td>0.0</td>
<td>6.7</td>
</tr>
<tr>
<td>36%</td>
<td>322</td>
<td>172</td>
<td>2.2</td>
<td>6.7</td>
</tr>
</tbody>
</table>

*As presented at POWER-GEN International 2016*
FULL-SCALE INSTALLATION
Ennis Power Company, LLC
Plant Operating Data

- CO emissions reduced after METEOR™ MPC installed.

As presented at POWER-GEN International 2016
FULL-SCALE INSTALLATION
Ennis Power Company, LLC
Plant Operating Data

- CO emissions vs. GT load: impact of METEOR™ MPC installation.
FULL-SCALE INSTALLATION
Ennis Power Company, LLC
Plant Operating Data

- METEOR™ MPC installation increased the unit’s turndown capability.

As presented at POWER-GEN International 2016
FULL-SCALE INSTALLATION
Ennis Power Company, LLC
Plant Operating Data

- Same NOx emissions (per design).

As presented at POWER-GEN International 2016
FULL-SCALE INSTALLATION
Ennis Power Company, LLC
Plant Operating Data

- Lower NH$_3$ slip emissions (fresh catalyst).

As presented at POWER-GEN International 2016
FULL-SCALE INSTALLATION
Ennis Power Company, LLC
Plant Operating Data

- No change in NH$_3$ usage rate after METEOR™ MPC installation.
FULL-SCALE INSTALLATION
Ennis Power Company, LLC
Plant Operating Data

- ~2 inch H₂O reduction in system backpressure (compared at constant flow)

As presented at POWER-GEN International 2016
FULL-SCALE INSTALLATION
Ennis Power Company, LLC
Catalyst Audit

Inspected catalyst on October 25, 2016:
The catalyst was in excellent condition, and the cells were clean and open.
These observations are consistent with the measured back pressure trends.

Successful Operation Continues
High NO₂ SCR Catalyst

NO₂ can be >50% of NOx under certain conditions. When >50%, “Slow” SCR reaction effect:

6NO₂ + 8NH₃ → 7N₂ + 12H₂O

High NO₂ Catalyst accelerates rate of “Slow” SCR Reaction:

- Much higher activity than conventional catalyst under high NO₂ conditions.
- Faster transient responses at high NO₂.
- Improved load following and cold start-up performance.

Example: 332°C, NO₂/NOₓ = 95%

In Operation in Several Gas Turbine SCRs Worldwide
Tools for Various Temperature Ranges

Formulations to meet a range of operating windows:

![Graph showing DeNOx levels across different temperatures for various applications.]

- Blue: Formulation for Combined Cycle GT Applications
- Green, Yellow, Red: Formulations for Simple Cycle GT Applications
Case Study – Plant A

Customized Catalyst Formulation for 100MW Simple Cycle GT

• Needs:
  – Operate at 840 °F (450 °C)
  – DeNOx: 91%
  – Ammonia slip: 7 ppm
  – CO reduction: 95%

• Solution:

  - Extended Temperature Range Formulation
  - METEOR™ For High Temperature

Custom combination achieves high DeNOx and high CO reduction while maintaining good ammonia utilization
Other Applications of Advanced Tools

- **METEOR™** applied to ammonia slip reduction
  - Solving a transient emissions problem during cycling of load

- **METEOR™** for gas-firing on coal-fired boiler
  - Exploring potential in order to meet CO emissions requirements

- Reciprocating engines
  - Integrated seal
  - Advanced Catalytic Potential
  - **METEOR™**
  - Customized Formulations

![24 inch ULFA Canisters](image)

![13 inch LFA Canisters](image)
Meeting Needs with Advanced Tools

Elite™

Meeting emissions control requirements
- DeNOx
- CO and hydrocarbon reduction
- NH₃ slip limit
- Under a variety of conditions

While minimizing cost of compliance
- Low capital cost
- Low maintenance cost
- Low parasitic power loss
- Minimize NH₃ usage
- Minimize or eliminate operation constraints

State-of-the-art emission control solutions!