“Integrating HRSG & Catalyst Design For High Performance & Low Cost”

Mr. Joshua D. Gillespie
July 15, 2014
2013 ABMA Annual Meeting
Environmental Session
Range of Applications

EmeraChem is an OEM developer and manufacturer of catalytic products to control air pollution from

- large gas turbines
- large reciprocating engines
- Industrial boilers

...in the power generation and natural gas markets
>240 Combustion Turbines
Oxidation Catalyst & Support Structure
>240 Catalyst Systems for GTs

<p>| | |</p>
<table>
<thead>
<tr>
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</thead>
<tbody>
<tr>
<td>GE 7H</td>
<td>2</td>
</tr>
<tr>
<td>GE 7FA</td>
<td>33</td>
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<tr>
<td>GE 7EA</td>
<td>3</td>
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<tr>
<td>GE FRAME 6 F</td>
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<tr>
<td>GE FRAME 6 B</td>
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<td>GE LM6000</td>
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<td>Mitsubishi 501G</td>
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<td>Siemens SGT 5000</td>
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<td>Siemens SGT 400</td>
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<td>Pratt &amp; Whitney FT-8</td>
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<td>Alstom GTX 100</td>
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<td>Solar TITAN 130</td>
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<tr>
<td>Solar TAURUS 70</td>
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<td>Solar TAURUS 60</td>
<td>8</td>
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<td>Solar CENTAUR 40</td>
<td>2</td>
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<td>Solar SATURN 20</td>
<td>3</td>
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<td>Rolls Royce TRENT 60</td>
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<td>Westinghouse W251B</td>
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<td>AVON MK 1533</td>
<td>1</td>
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<td>VS-7</td>
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<tr>
<td>Unspecified GTs</td>
<td>33</td>
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</table>

Individual projects ranging from 24 to 2400 catalyst elements

>40,000 MW controlled by EmeraChem catalyst

THE POWER OF CATALYSIS
Starting Point: Application Design
(system variables that affect emissions)

- **Information input**
  - engine name and model
  - fuel type(s) and sulfur content
  - water injected or evap cooling? (water quality)
  - HRSG or simple cycle (no. starts/stops/yr.)
  - Duct firing? Fuel type.
  - exhaust mass flow rate, catalyst operating temp,
  - % flow and temperature variation
  - Inlet emissions, (CO, VOC, NO/NO$_2$, SO$_2$)
  - performance requirements
    - (% reduction CO, VOC, NO-NO$_2$, SO$_2$-SO$_3$)
    - Start-up & shutdown performance included?
  - desired warranty period and service life
  - installation information;
    - NEW or REPLACEMENT
    - Gas Path Size
    - allowable pressure drop

It’s possible to “over specify”:
- low temperature
- very high performance
- very low pressure drop
- small gas path
- lot’s of starts & stops
- long warranty period
- “cheap”
Catalyst Design
(catalyst variables that affect emissions)

- substrate cell geometry and geometric surface area
- wash coat formulation & loading
- precious metal formulation
- precious metal loading
- method of applying precious metals
- gas hourly space velocity
Substrate Design Variables

- Cell structure geometry and surface area
- Cell density
- Pressure drop
- Diffusion bonded (10-yr mechanical warranty)

“discrete cell”
Geometric Surface Area as a Function of Cell Density

- **Metal**
  - Geometric Surface Area: 116
  - Cell Density: 400

- **Ceramic**
  - Geometric Surface Area: 76
  - Cell Density: 200

Graph showing the relationship between geometric surface area and cell density for both metal and ceramic materials.
Performance as a Function of Cell Density

The graph shows the catalyst performance efficiency (%) as a function of cell density (CPSI). The efficiency increases with increasing cell density. The efficiency is measured at a given temperature, GHSV, and formulation. The graph indicates that the catalyst performance efficiency increases significantly with cell density, suggesting improved catalytic activity at higher densities.
Pressure Drop as a Function of Cell Density

![Graph showing pressure drop as a function of cell density.](image)

- **300 cps**: Red line
- **260 cps**: Black line
- **230 cps**: Green line

**Pressure Drop (in. W.C.)**

- **Linear Velocity (fpm, actual T)**

**THE POWER OF CATALYSIS**
Variations in Cell Structure & Geometry

- “discrete cell”
  - diffusion bonded; 10-yr warranty
- “tortuous path”
  - loosely layered “herringbone”
Oxidation Catalyst Performance
Discrete Cell vs. Tortuous Path

Identical wash coats and precious metals were applied to both substrates.

Performance of discrete cell substrate geometry equal to or better than tortuous path.
What is a VOC?
U.S. EPA Definition of VOC

40 CFR Ch. 1, Subpart F - Procedural Requirements, Section 51.100 – Definitions, Paragraph (S) - VOCs, Subparagraph (1)

(s) Volatile organic compounds (VOC) means any compound of carbon, excluding carbon monoxide, carbon dioxide, carbonic acid, metallic carbides or carbonates, and ammonium carbonate, which participates in atmospheric photochemical reactions.

(1) This includes any such organic compound other than the following, which have been determined to have negligible photochemical reactivity: methane; ethane; methylene chloride (dichloromethane); 1,1,1-trichloroethane (methyl chloroform); etc.

origin of “NMNEHC”
## Similarity Between Fuel Gas and Exhaust Gas THC Composition

<table>
<thead>
<tr>
<th>THC Constituent</th>
<th>Fuel Composition</th>
<th>Exhaust Composition</th>
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<tbody>
<tr>
<td>Methane</td>
<td>82.0%</td>
<td>79%</td>
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<tr>
<td>Ethane</td>
<td>12.4%</td>
<td>11%</td>
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<tr>
<td>Ethylene</td>
<td></td>
<td>3.0%</td>
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<tr>
<td>Propane</td>
<td>4.42%</td>
<td>3.9%</td>
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<tr>
<td>Propylene</td>
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<td>0.5%</td>
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<tr>
<td>Butane</td>
<td>0.98%</td>
<td>0.9%</td>
</tr>
<tr>
<td>Formaldehyde</td>
<td></td>
<td>2.0%</td>
</tr>
<tr>
<td>Acetaldehyde</td>
<td></td>
<td>0.0%</td>
</tr>
</tbody>
</table>
Estimating Catalytic Performance on VOCs

<table>
<thead>
<tr>
<th>THC Constituent</th>
<th>Exhaust Composition</th>
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<tr>
<td>Methane</td>
<td>79%</td>
</tr>
<tr>
<td>Ethane</td>
<td>11%</td>
</tr>
<tr>
<td>Ethylene</td>
<td>3.0%</td>
</tr>
<tr>
<td>Propane</td>
<td>3.9%</td>
</tr>
<tr>
<td>Propylene</td>
<td>0.5%</td>
</tr>
<tr>
<td>Butane</td>
<td>0.9%</td>
</tr>
<tr>
<td>Formaldehyde</td>
<td>2.0%</td>
</tr>
<tr>
<td>Acetaldehyde</td>
<td>0.0%</td>
</tr>
</tbody>
</table>

Not included in measurement of VOCs: Formaldehyde and Acetaldehyde.

Catalytic performance is different for every compound.

Overall performance is a weighted-average.
Oxidation Performance for CO & VOC Families

At 700°F and a given cell density and formulation

Catalyst Performance Efficiency (%)

Gas Hourly Space Velocity

LOW FLOW

HIGH FLOW

CO, formaldehyde, toluene, propane
Hydrocarbon Conversion over Pt Oxidation Catalyst

At a given GHSV, cell density and formulation.
Estimating Catalytic Performance on VOCs

<table>
<thead>
<tr>
<th>THC Constituent</th>
<th>Exhaust Composition</th>
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</thead>
<tbody>
<tr>
<td>Ethylene</td>
<td>3.0%</td>
</tr>
<tr>
<td>Propylene</td>
<td>0.5%</td>
</tr>
<tr>
<td>Formaldehyde</td>
<td>2.0%</td>
</tr>
<tr>
<td>Butane</td>
<td>0.9%</td>
</tr>
<tr>
<td>Propane</td>
<td>3.9%</td>
</tr>
</tbody>
</table>

- High oxidation efficiency
- More difficult to oxidize
- Most stable and most difficult to oxidize

Overall performance is a weighted-average
Field Experience >240 GTs
Low Catalyst Temps Impose Other Risks to Owner

- **BEWARE**: Below 600°F a number of contaminants are prone to accumulation
  - Even common masking agents (sulfur) could be problematic
  - If mixed with high temp cases, desorption is possible
- Of >240 installations the few that experienced high levels of contamination
  - All below 600°F
  - All accumulated enormous amounts of sulfur and phosphorous
High Surface Area Coatings

55 football fields of surface area in every cubic foot of catalyst!
Examples of Chemical Contamination

- ash & carbon nanoparticles
- sulfur masking
- Pt alloy formed with contaminant
- wash coat
- oxidized foil
- platinum

THE POWER OF CATALYSIS
Case Study #1: Sulfur Accumulation at Low Temperature

<table>
<thead>
<tr>
<th>Turbine Make &amp; Model</th>
<th>GE 7EA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Catalyst Operating Temperature</td>
<td>505 (unfired) - 615F (fired)</td>
</tr>
<tr>
<td>Catalyst GHSV</td>
<td>106,000 - 163,000</td>
</tr>
</tbody>
</table>

- Sulfur Accumulation: 14,613 mg S/ft³ after 250 hours (10 days) (exacerbated by carbon buildup)

- Operation typically <600F
- Pipeline quality natural gas
- H2S in evap water
14,613 mg sulfur accumulated on every ft³ of catalyst in 250 hours (10 days)!!

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Effects of Sulfur on Catalyst

- **Effect on precious metal:** \(<570^\circ F\) \(SO_2\) chemisorbs on Pt sites & reduces sites for CO
  
  “steric hindrance” – large sulfate group adsorbed on the surface physically interferes with CO molecules reaching a platinum crystal

- **Effect on substrate:** \(SO_2\) converted to \(SO_3\) and reacts with \(Al_2O_3\) in the wash coat forming \(Al_2(SO_4)_3\) which damages structure
Effects of Sulfur on Precious Metals

- Physically blocks access
- Reduces catalytic activity
- Platinum (Pt) has durability and poison resistance
  - regenerable with chemical washing
- Palladium (Pd) vulnerable to permanent deactivation
  - weak & unpredictable response to chemical washing
Case Study #2: Sulfur Accumulation at Low Temperature

<table>
<thead>
<tr>
<th>Turbine Make &amp; Model</th>
<th>Alstom GT-26</th>
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</thead>
<tbody>
<tr>
<td>Catalyst Operating Temperature</td>
<td>500 - 640F (mostly &lt;600F)</td>
</tr>
<tr>
<td>Catalyst GHSV</td>
<td>65,000 design (130,000 max)</td>
</tr>
</tbody>
</table>

- Operation typically <600F
- Sulfur higher than pipeline quality natural gas

Sulfur Accumulation

- 13,624 mg S/ft³ after 238 hours (10 days)
Case Study #3: Sulfur Accumulation At Low Temperature

<table>
<thead>
<tr>
<th>Turbine Make &amp; Model</th>
<th>GE 7FA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Catalyst Operating Temperature</td>
<td>504 (unfired) - 647F (fired)</td>
</tr>
<tr>
<td>Catalyst GHSV</td>
<td>118,000 - 197,000</td>
</tr>
</tbody>
</table>

| Sulfur Accumulation | 19,036 - 20,943 mg S/ft³ after 22 days |

- Operation typically <600F
- pipeline quality natural gas
20,000 mg sulfur accumulated on every cubic foot of catalyst in 22 days!!
Platinum Catalyst Responds to Chemical Washing

Catalyst Type: Platinum Oxidation
Condition: Temp = 525 F

<table>
<thead>
<tr>
<th>GHSV</th>
<th>Pre-Wash CO Performance</th>
<th>Post-Wash CO Performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>(HI-flow)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>357,000</td>
<td>6.4%</td>
<td>62.5%</td>
</tr>
<tr>
<td>200,000</td>
<td>12.7%</td>
<td>85.8%</td>
</tr>
<tr>
<td>(LO-flow)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>150,000</td>
<td>15.7%</td>
<td>93.8%</td>
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Catalyst Manufacturer: EmeraChem, LLC
Date of Manufacture: June 2000
## Selecting Precious Metals for Oxidation Catalyst

<table>
<thead>
<tr>
<th></th>
<th>Platinum</th>
<th>Palladium</th>
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<tbody>
<tr>
<td>CO</td>
<td>Best</td>
<td>Good when new</td>
</tr>
<tr>
<td>VOCs</td>
<td>Best</td>
<td>Good when new</td>
</tr>
<tr>
<td>Light-off temp</td>
<td>250-400°F</td>
<td>400-650°F</td>
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<tr>
<td>Catalytic activity</td>
<td>High</td>
<td>Moderate</td>
</tr>
<tr>
<td>Thermal stability</td>
<td>Good to 1200°F</td>
<td>Good to 1200°F</td>
</tr>
<tr>
<td>Poison resistance</td>
<td>High</td>
<td>Low</td>
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<tr>
<td>Response to chemical washing</td>
<td>Good</td>
<td>Poor</td>
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<tr>
<td>Durability</td>
<td>High</td>
<td>Low to moderate</td>
</tr>
<tr>
<td>Price per troy oz.</td>
<td>$1560</td>
<td>$690</td>
</tr>
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</table>
Oxidation Performance
Platinum vs. Palladium

Performance for a given 
GHSV, cell density and 
total PGM loading 

Start-up emissions 

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Performance as a Function of Precious Metal Loading

At a given temp, GHSV and cell density

more economical

more durable
What effect has platinum escalation had on catalyst design and price?
Escalation of Platinum

$477/T.O.  
$2212/TO  
$1563/TO
Example: GE7FA gas turbine

- **Exhaust**
  - 3,603,880 lb/hr exhaust
  - 20 ppmv CO at GT exhaust
  - 2.0 ppmv CO at stack
  - 90% CO removal efficiency

- **Catalyst**
  - GHSV ~200,000
  - 247 cuft catalyst
Effect of Pt Price on Catalyst Design and Price

- August 2001
  - Platinum was similar in cost to the foil substrate
  - Catalyst companies used more platinum rather than more substrate volume
  - Platinum loading of 28 to 42 g/ft³ was common
  - Extremely durable
    - High-performance
    - Low-temperature light-off
    - Sulfur tolerant & regenerable
    - Tolerant of many start/stop cycles
    - 10-year life
  - Pt cost for the GE 7FA was $136,000 for 36 g/ft³
Effect of Pt Price on Catalyst Design and Price

- **August 2001**
  - Pt loading 36g/ft³ costs **$136,000**
- **May 2008**
  - Same Pt loading would have cost ~**$633,000**
  - Outcry from end users! **“No way!”**
  - Holding cost to $136,000 would buy <8 g/ft³
    - Too risky; vulnerable to low-T and sulfur; low durability
  - Some catalyst companies switched to **palladium**
    - $459/TO vs. $2,212 for platinum
    - Light-off temp higher than Pt (poor for startup emissions)
    - Poisoned by sulfur; not responsive to washing
    - Low durability
Effect of Pt Price on Catalyst Design and Price

- **August 2001**
  - 36 g/ft³ loading for $136,000

- **May 2008**
  - 36 g/ft³ for $633,000; <8 g/ft³ for $136,000

- **Today, January 2013**
  - Pt loading of 36 g/ft³ would cost ~$447,000 *(too costly)*
  - Spending $136,000 would buy 11 g/ft³ *(too low)*
  - Improved substrate & wash coat
  - Improved Pt application techniques (Pt size, distribution)
  - Restrictions on low-temp, sulfur, no. starts/stops
  - 10-yr expected life reduced to 3+ years
Simultaneous Collateral Reactions

- **NO-NO$_2$ Oxidation**
  - Favors NO$_2$ at low temps; NO at high temps
  - Effects SCR reactions, NH$_3$ consumption
  - Destroys sulfur bound carbon nanoparticles

- **SO$_2$-SO$_3$ Oxidation**
  - Increases with temperature
  - Precursor to particulate matter
  - Ammonia slip reacts to form bi-sulfate particulate after SCR

- Catalyst formulations can suppress these
Overall Effect of Operating Temp on Catalyst Reactions

For a given GHSV, cell density & formulation

CO DRE
VOC DRE
SO2-SO3
NO-NO2

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Putting it all together…

How does HRSG temperature effect catalyst design and price?
Effect of HRSG Temperature Zone on Oxidation Catalyst Performance

- ~1000°F
- Hi CO performance
- Hi VOC performance
- Lowest catalyst volume
- Lo NO to NO₂ conversion
- Hi SO₂ to SO₃ conversion
- Lower Pt
- Lowest cost catalyst
Effect of HRSG Temperature Zone on Oxidation Catalyst Performance

- ~750°F
- Hi CO performance
- Good VOC performance
- Moderate catalyst volume
- Moderate NO to NO₂ conversion
- Moderate SO₂ to SO₃ conversion
- Economical Pt-loading
Effect of HRSG Temperature Zone on Oxidation Catalyst Performance

500-550°F

• Risk of sulfur accumulation with decreased life
• Increase Pt for low-T lightoff and protection from masking & poisoning
• Good CO performance
• Lo VOC performance
• Larger catalyst volume
• High NO to NO₂ conversion
• Low SO₂ to SO₃ conversion
• Highest catalyst $$

500-550°F

• Risk of sulfur accumulation with decreased life
• Increase Pt for low-T lightoff and protection from masking & poisoning
• Good CO performance
• Lo VOC performance
• Larger catalyst volume
• High NO to NO₂ conversion
• Low SO₂ to SO₃ conversion
• Highest catalyst $$
Effect of HRSG Temperature Zone on Catalyst System Price

• Examine EmeraChem catalyst in >70 large GTs
  – GE 7H, 501G
  – 7FA, 501F
  – 7EA, 501D5A

• Three temperature ranges
  – 500-650°F
  – 700-825°F
  – 850-1000°F

• Example of a GE7FA.05 at 3 temperatures
Effect of HRSG Temperature Zone on Catalyst System Price

- Flow rate: 4,024,000 lb/hr
- 90% CO reduction (10 to 1 ppm)
- 67% VOC reduction (3 to 1 ppm)
- Gas path: 72’x27’
- Consider three temperature options:
  - 550°F
  - 790°F
  - 1000°F
## Effect of HRSG Temperature Zone on Catalyst System Price

<table>
<thead>
<tr>
<th></th>
<th>550 F</th>
<th>790 F</th>
<th>1000 F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Catalyst GHSV*</td>
<td>175,000</td>
<td>200,000</td>
<td>215,000</td>
</tr>
<tr>
<td>Catalyst Volume</td>
<td>310 ft³</td>
<td>270 ft³</td>
<td>250 ft³</td>
</tr>
<tr>
<td></td>
<td>most catalyst due to lower activity</td>
<td>least catalyst due to high activity</td>
<td></td>
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<tr>
<td>Platinum Loading</td>
<td>~1.5X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td></td>
<td>more Pt due to likely accumulation of contaminants</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Frame Material</td>
<td>carbon steel</td>
<td>carbon steel</td>
<td>stainless steel</td>
</tr>
</tbody>
</table>

* Catalyst GHSV is approximate for illustration only, based upon a given cell density and formulation.
Effect of HRSG Temperature Zone on Catalyst System Price

Catalyst and frame prices are approximate for illustration only, based upon a given exhaust characteristic, catalyst design, gas path and Pt price.
Evaluate all operating cases
(temp, flow, performance)

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>Units</th>
<th>DESIGN BASIS</th>
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<th>102</th>
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<td><strong>GENERAL INFORMATION</strong></td>
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<td>GT Load</td>
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<td>50%</td>
<td>100%</td>
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<td>Temp at Catalyst</td>
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<td>824</td>
<td>955</td>
<td>845</td>
<td>958</td>
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<tr>
<td><strong>EXHAUST CHARACTERISTICS FROM GT</strong></td>
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<td>GT Flow with Tempering Air</td>
<td>lb/hr</td>
<td>647,792</td>
<td>666,129</td>
<td>629,703</td>
<td>522,225</td>
<td>874,486</td>
<td>517,015</td>
<td>492,086</td>
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<td>Gas Composition % vol</td>
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<td>N2</td>
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<td>100.00</td>
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<td>99.99</td>
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<td>99.99</td>
<td></td>
</tr>
<tr>
<td>Flow Rate (wet)</td>
<td>scfh</td>
<td>8,593,971</td>
<td>11,610,925</td>
<td>8,384,926</td>
<td>7,030,717</td>
<td>11,607,285</td>
<td>6,922,442</td>
<td>6,008,366</td>
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<tr>
<td>Flow Rate (dry)</td>
<td>scfh</td>
<td>8,083,203</td>
<td>10,594,153</td>
<td>7,821,332</td>
<td>6,337,931</td>
<td>10,880,855</td>
<td>6,339,469</td>
<td>6,001,203</td>
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<tr>
<td>O2 Concentration Dry</td>
<td>%</td>
<td>15.47</td>
<td>15.07</td>
<td>15.85</td>
<td>14.95</td>
<td>15.00</td>
<td>15.08</td>
<td>15.04</td>
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</tbody>
</table>

**CO AT CATALYST INLET**

| CO as ppmvd at 15% O2 | 70.10 | 25.02 | 70.20 | 69.99 | 24.99 | 69.99 | 69.99 |
| CO Flow | 38.6 | 19.4 | 34.7 | 33.1 | 20.1 | 32.3 | 30.8 |

**CO AT CATALYST OUTLET**

| CO as ppmvd at 15% O2 | 5.5 | 5.5 | 5.5 | 5.5 | 5.5 | 5.5 | 5.5 |
| CO Destruction Required | % | 92.2 | 92.0 | 92.2 | 92.1 | 78.0 | 92.1 | 92.1 |

**VOC AT CATALYST INLET**

| VOC as ppmvd at 15% O2 | 8.41 | 3.00 | 8.42 | 8.40 | 3.00 | 8.40 | 8.40 |
| VOC Flow | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 |
| VOC Destruction Required | % | 76.2 | 33.4 | 76.3 | 76.2 | 33.3 | 76.2 | 76.2 |

**ADDITIONAL DATA**

| Required Pressure Drop | °H2O | 2.0 | 2.0 | 2.0 | 2.0 | 2.0 | 2.0 |
| Expected Pressure Drop | °H2O | 0.7 | 1.0 | 0.7 | 0.7 | 1.0 | 0.7 |

Determine “GHSV” for each flow rate and temperature to achieve required CO & VOC performance.
Determine “GHSV” for each flow rate & temp to achieve CO & VOC performance

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>1%GS</th>
<th>2%GS</th>
<th>3%GS</th>
<th>4%GS</th>
<th>5%GS</th>
<th>6%GS</th>
<th>7%GS</th>
<th>8%GS</th>
<th>9%GS</th>
<th>10%GS</th>
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</thead>
<tbody>
<tr>
<td>Catalyst Temp (°F)</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td>Ethylene</td>
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<td>Total</td>
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</table>

<table>
<thead>
<tr>
<th>Catalyst Performance (%)</th>
<th>50%</th>
<th>60%</th>
<th>70%</th>
<th>80%</th>
<th>90%</th>
<th>100%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas Hourly Space Velocity</td>
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<td></td>
<td></td>
</tr>
</tbody>
</table>

Catalyst Temp F

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Convert GHSV into catalyst volume

- GHSV varies by
  - performance level
  - compound
  - temperature
  - formulation and loading of precious metals
  - formulation of wash coating

- Catalyst volume (cubic feet) calculated by dividing volumetric gas flow rate (s-ft³/hr) by GHSV (1/hr)

\[
\frac{8,593,971 \text{ scfh}}{165,000 \text{ hr}^{-1}} = 52.1 \text{ ft}^3
\]
Calculate the required catalyst volume for each case.

\[
\text{Flow Rate} = \frac{8,593,971 \text{ scfh}}{165,000 \text{ hr}^{-1}} = 52.1 \text{ ft}^3
\]

**Identify Case Requiring Highest Catalyst Volume**

“Design Case”
Calculate catalyst depth
Remember…

- Catalyst performance dictates catalyst volume
  - (for a given cell density, Pt loading, wash coat, etc)
- Once catalyst volume is determined
  - Changing duct size results in thicker or thinner catalyst (to maintain volume)
  - Large frontal area and thin vs. small area and thick
- However, 100 ft$^3$ of catalyst in 100 modules costs less than 100 ft$^3$ in 120 modules
- There is a practical *minimum* thickness
Performance Over Time

![Graph showing performance over time with a safety factor at 3 years. The graph compares performance with the warranty line.](image)
Origin of “Safety Factor”

• Emission performance over time is a function of system variables
  – type of combustion turbine
  – start-up profiles (no. starts/stops/yr.)
  – water injection & evap cooling
  – exhaust gas temperature
  – engine fuel composition – particularly Sulfur
  – seals, leakage and bypass
  – contaminants present in engine exhaust
  – effect of engine lube oil on catalyst

• Owners don’t report data over time for every combination
Thank you from EmeraChem

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