Status of RTI/Eastman
Warm Gas Clean-up Technology and
Commercialization Plans

Raghubir Gupta, Brian Turk, and Markus Lesemann
RTI International

Jerry Schlather and David Denton
Eastman Chemical Company

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Syngas Cleaning Technology Platform

Sulfur
- Regenerable ZnO sorbents
- Transport reactor
- Direct Sulfur Recovery Process
- Regenerable NH₃/HCN adsorbents

Hg adsorbents (disposable)
- As adsorbents (disposable)
- Se adsorbents (disposable)
- HCl adsorbents (disposable)
- Regenerable CO₂ sorbents

Operating Temperatures > 250 °C (482°F)
Process Integration – Modular Approach

Gasifier

Quench

Water

Sour Shift

Desulfurization

CO₂ Removal

Multi-contaminant Control

Sulfur Recovery

CO₂ Recovery

Sulfur

CO₂ for use/sequestration

Power

- SO₂ < 1.4 lb SO₂/MWh gross
- NOₓ < 1.0 lb NOₓ/MWh gross
- PM < 0.0071 lb/MMBtu
- Hg > 90% removal

Chemicals/Fuels

- Sulfur < 50 ppb
- HCl < 10 ppb
- NH₃ < 10 ppm
- CO₂ > 90% removal
- As < 5 ppb
- Se < 0.2 ppm
- Cd < 30 ppb
- Hg < 5 ppbw

[NETL 2007]
Transport Desulfurization Reactor System

RTI – Eastman High Temperature Desulfurization Process

ZnO + H₂S → ZnS + H₂O  (600-1000ºF)  (300-600 psig)

ZnO + COS → ZnS + CO₂  (1200-1400ºF)  (300-600 psig)

ZnS + 3/2O₂ → ZnO + SO₂  (1200-1400ºF)  (300-600 psig)

RAW SYNGAS

CLEAN SYNGAS

SO₂ / N₂ TO DSRP

REGENERATED SORBENT TO ABSORBER MIXING ZONE

COMMERCIAL FCC REACTOR

Source: KBR
Desulfurization Sorbent Characteristics

- ZnO supported on zinc aluminate
  - High attrition resistance (mechanical stability)
  - Inert support (chemical stability)
- Unique highly dispersed ZnO nanostructures with grain size <50 nm
  - High reactivity (short residence time in the reactor)
- Produced on commercial scale by major catalyst manufacturer
- Covered by US/International patents
- Won 2004 R&D 100 Award
Installed Pilot Plant Systems
Eastman’s Kingsport, TN, Coal Gasification Facility

- Direct Sulfur Recovery Process (DSRP)
- Multi-contaminant Control Test System (MCC)
- High Temperature Desulfurization Process (HTDP)
Eastman Gasification Plant

RTI Field Test Systems
Typical Sulfur Concentrations in Effluent Syngas

Dirty syngas composition: 7,771 ppmv H₂S
440 ppmv COS

H₂S Removal > 99.97%

COS Removal > 99.96%

SO₂ removal data not shown in this image.
Desulfurization Pilot Plant
Summary of Parametric Testing

More than 3,000 hours of syngas operation

<table>
<thead>
<tr>
<th></th>
<th>Pressure, psig</th>
<th>300</th>
<th>450</th>
<th>600</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inlet Concentration, S ppmv</td>
<td></td>
<td>8,661</td>
<td>7,023</td>
<td>8,436</td>
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<tr>
<td>Effluent Conc. S ppmv</td>
<td></td>
<td>5.9</td>
<td>10.7</td>
<td>5.7</td>
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<tr>
<td>Range</td>
<td></td>
<td>0.4 – 9.3</td>
<td>2.4-20.6</td>
<td>3.3-18.1</td>
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<tr>
<td>S Absorbed, lbs/hr</td>
<td></td>
<td>4.1</td>
<td>4.4</td>
<td>5.0</td>
</tr>
<tr>
<td>S Removal, %</td>
<td></td>
<td>99.93</td>
<td>99.82</td>
<td>99.90</td>
</tr>
</tbody>
</table>

- Average attrition rate: 31 lbs/MM lbs of sorbent circulated

Typical attrition rate for FCC catalysts is 50-100 lbs/MM lbs of catalyst circulated.

All data are averages over multiple hours of operation
Desulfurization Process Reliability

**H₂S/ COS removal > 99.95%**

- **Regeneration rate**
- **Desulfurization rate**

**On-Stream Factor**
- Pre-improvements: ~60%
- Post-improvements: >80%
Direct Sulfur Recovery Process

Reaction chemistry:
\[
\begin{align*}
SO_2 + 2H_2 & \rightarrow \frac{1}{n} S_n + 2H_2O \\
SO_2 + 2CO & \rightarrow \frac{1}{n} S_n + 2CO_2
\end{align*}
\]

Temperature: 500-600ºC
Pressure: 300-600 psig
Reactor design: Fixed bed
DSRP Operations

- Integrated operation
  - Effluent from regenerator of transport desulfurization system
  - Real coal-derived syngas
- 99.8% SO₂ conversion
- Produced liquid sulfur product
Multicontaminant Control Removal

- Removal of contaminants other than sulfur from syngas under high-pressure, high-temperature conditions
  - Target contaminants: Hg, As, Cd, Se, HCl, Ammonia, HCN
  - Test program
    - Extensive sorbent screening at RTI
    - Capacity tests on selected sorbents
    - Evaluation of potential process integration issues
      - Effect of S on sorbent effectiveness for other contaminants
      - Multicontaminant effects
    - Field demonstration of most promising sorbents with coal-derived syngas at Eastman

Ammonia and trace metal skid for testing at Eastman
Multi-contaminant Control Test System (MCC)

Test Conditions with Coal-derived Syngas
- Temperature: 200ºC
- Pressure: 850 psig
- Flow: 500 scfh
- Time: 525 hours
Arsenic Removal during Field Test

- As loading at bed inlet was 1 wt%
  - 3 wt% capacity demonstrated with simulated syngas
- No As breakthrough observed

Demonstrated effective As removal from coal-derived syngas at high temperatures and pressures
Mercury Removal during Field Test

- High Hg concentrations detected at syngas inlet to As sorbent bed
- No Hg breakthrough observed
- Hg concentrations in Hg sorbent bed were below detection limits

Demonstrated effective multi-contaminant removal of Hg and As from coal-derived syngas at high temperatures and pressures
Ammonia/HCN Removal

• Acidic Adsorbent
  – Regenerated by temperature swing
• Multiple fixed-beds for continuous NH$_3$/HCN removal
• Results with coal-derived syngas
  – NH$_3$
    • Inlet NH$_3$: 440 - 500 ppmv
    • Outlet NH$_3$: 6-20 ppmv
  – HCN
    • Inlet HCN: ~50 ppmv
    • Outlet HCN: ~1 ppmv

Demonstrated effective NH$_3$ and HCN removal from coal-derived syngas at high temperatures and pressures.
Field Testing Summary

Field test demonstrated clean-up performance with real coal-derived syngas at high temperatures and pressures

• Phase I: Desulfurization technologies demonstrated
  – Transport desulfurization system
    • Desulfurization performance, process control, stability and reliability
  – Desulfurization sorbent
    • Mechanical strength, chemical activity, long-term stability
  – Direct Sulfur Recovery Process
    • Fully integrated operation of HTDP and DSRP

• Phase II: Modular fixed-bed cleanup for As, Hg, NH₃/HCN
  – Regenerable NH₃/HCN adsorbent
  – As and Hg sorbents
High-Temperature CO$_2$ Removal

- $\text{Li}_4\text{SiO}_4 + \text{CO}_2 \rightarrow \text{Li}_2\text{CO}_3 + \text{Li}_2\text{SiO}_3$
- $\text{CO} + \text{H}_2\text{O} \rightarrow \text{CO}_2 + \text{H}_2$
- Temperature: 250 to 500 °C, Pressure: 300-600 psig

CO$_2$ removal from syngas at high temperatures and pressures with lithium silicate sorbent in pre-pilot phase
Techno-economic Evaluation – Comparison Basis

Project technical analysis performed by Nexant

Common Elements
- Illinois No. 6 Coal (2006 DOE, preliminary)
- U.S. Midwest site
- Nominal 600 MW capacity
- GE Gasification – Radiant Cooling
- Conventional cryogenic ASU without integration to GT
- GE 7FB based power train

Different Elements

Base Case
- Gas Quench & Scrubbing
- Low Temp. Gas Cooling
- Selexol™ AGR
- Claus sulfur recovery with SCOT tail gas treating
- Ambient Temperature mercury removal

Warm Gas Clean-up
- Convective Cooler
- Warm Gas Desulfurization Process (WGDS)
- High Temperature Mercury Removal Process
- SCR (no LT cooling to remove NH₃)

Results from Nexant’s analysis have been confirmed by independent study by Noblis
## Performance Comparisons

<table>
<thead>
<tr>
<th>Imports or Feeds</th>
<th>IGCC Base Case</th>
<th>IGCC with WGCU</th>
<th>Improvement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal Feed, STPD (AR)</td>
<td>5,467</td>
<td>5,467</td>
<td>-0.0%</td>
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<tr>
<td>95% Oxygen, STPD</td>
<td>4,665</td>
<td>4,895</td>
<td>-4.9%</td>
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<tr>
<td>99% N2, STPD</td>
<td>7,024</td>
<td>3,959</td>
<td>43.6%</td>
</tr>
<tr>
<td>Make Up Water, GPM</td>
<td>5,646</td>
<td>4,288</td>
<td>24.1%</td>
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</table>

<table>
<thead>
<tr>
<th>Exports or Products</th>
<th>IGCC Base Case</th>
<th>IGCC with WGCU</th>
<th>Improvement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electric Power, MW</td>
<td>585</td>
<td>641</td>
<td>9.6%</td>
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<tr>
<td>Sulfur, STPD</td>
<td>137</td>
<td>137</td>
<td>0.0%</td>
</tr>
<tr>
<td>Slag &amp; Ash, STPD (dry)</td>
<td>562</td>
<td>562</td>
<td>0.0%</td>
</tr>
<tr>
<td>Waste Water, GPM</td>
<td>2,798</td>
<td>1,085</td>
<td>61.2%</td>
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</table>

<table>
<thead>
<tr>
<th>Thermal Efficiency</th>
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<tbody>
<tr>
<td>HHV %</td>
<td>37.6</td>
<td>41.2</td>
<td>9.6%</td>
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<tr>
<td>LHV %</td>
<td>39.3</td>
<td>43.1</td>
<td>9.7%</td>
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</table>

*Efficiency Improved 3.6 points HHV*
## Capital Cost Summary

<table>
<thead>
<tr>
<th>Capital Cost, $MM</th>
<th>IGCC Base Case</th>
<th>IGCC with WGCU</th>
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</thead>
<tbody>
<tr>
<td>Coal Handling</td>
<td>17.8</td>
<td>17.8</td>
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<tr>
<td>Gasification Block</td>
<td>227.3</td>
<td>227.3</td>
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<tr>
<td>Air Separation</td>
<td>80.5</td>
<td>83.2</td>
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<tr>
<td>COS Hydrolysis and LT Cooling</td>
<td>37.2</td>
<td>0.0</td>
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<tr>
<td>ARG and Sulfur Recovery</td>
<td>185.1</td>
<td>168.4</td>
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<tr>
<td>Plant Air &amp; N(_2) Compression</td>
<td>23.8</td>
<td>15.0</td>
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<tr>
<td>Gas Turbine Generators</td>
<td>146.4</td>
<td>145.0</td>
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<tr>
<td>HRSG &amp; BFW Systems</td>
<td>49.0</td>
<td>55.6</td>
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<tr>
<td>Steam Turbine Generator</td>
<td>49.2</td>
<td>56.1</td>
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<tr>
<td>Balance of Plant</td>
<td>196.4</td>
<td>187.2</td>
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<tr>
<td>Home Office Cost</td>
<td>101.3</td>
<td>95.5</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>1,114.0</strong></td>
<td><strong>1,051.1</strong></td>
</tr>
<tr>
<td>Net Power Export, MWe</td>
<td>585.0</td>
<td>641.0</td>
</tr>
<tr>
<td>Cost per Unit Output $/KWe</td>
<td>1,904.0</td>
<td>1,640.0</td>
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$264/KW CAPEX IMPROVEMENT
Summary of Techno-Economic Evaluation for Power Applications

• Comparison of Eastman/RTI Warm Gas Clean-Up technologies with conventional syngas clean-up technologies performed by Nexant
  – 600 MW case study
  – Increase efficiency by 3.6 points HHV
  – Dispatch 56 MWe more power
  – Reduce CAPEX by $264/KW
  – Reduce COE by 0.69 ¢/kwh

• Independent analysis performed by Noblis under NETL funding produced similar results
Conclusions

- Eastman/RTI Pilot Plant Testing:
  - Demonstrated technology readiness
  - Achieved desulfurization performance targets with real syngas
  - Additional fixed bed syngas cleaning options slipstream tested with real coal-derived syngas (HCl, NH₃, As, Hg, and Se)
- Technology package ready for power applications
- R&D efforts underway for chemicals/fuels application
- High-temperature CO₂ removal is being integrated
Commercialization

- Scale-up to 20-50 MW demonstration plant envisioned
- Discussions underway with potential test sites
- Engineering design package assembled
- Comprehensive technology package ready for power applications
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