Pilot Testing of a Highly Efficient Pre-combustion Sorbent-based Carbon Capture System
(Contract No. DE-FE-0013105)

Gökhan Alptekin, PhD
Ambal Jayaraman, PhD
Matt Cates
Mike Bonnema
David Gribble
Jim Dippo
Freya Kugler

2020 DOE/NELT Carbon Capture Technology Review Meeting

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TDA Research Inc. • Wheat Ridge, CO 80033 • www.tda.com
Project Summary

• The objective is to develop a new sorbent-based pre-combustion capture technology for Integrated Gasification Combined Cycle (IGCC) power plants

• Demonstrate techno-economic viability of the new technology by:
  1) Evaluating technical feasibility in 0.1 MWₑ slipstream tests
  2) Carrying out high fidelity process design and engineering analysis

• Major Project Tasks
  ✓ Sorbent Manufacturing
    ✓ Performance validation via long-term cycling tests
  ✓ Reactor Design
    ✓ CFD Analysis and PSA cycle optimization/adsorption modeling
  ✓ Fabricate a Pilot-scale Prototype for Demonstration
  ✓ Evaluations at various sites using coal-derived synthesis gas
  ✓ Techno-economic analysis
    ✓ High fidelity engineering analysis and process simulation
Project Partners

Project Duration
- Start Date = January 1, 2014
- End Date = March 31, 2021

Budget
- Project Cost = $9,929,228
- DOE Share = $7,943,382
- TDA and its partners = $1,985,846
TDA’s Sorbent

- TDA’s uses a mesoporous carbon with surface functional groups that remove \( \text{CO}_2 \) via strong physical adsorption
  - \( \text{CO}_2 \)-surface interaction is strong enough to allow operation at elevated temperatures
  - Because \( \text{CO}_2 \) is not bonded via a covalent bond, energy input for regeneration is low
- **Heat of \( \text{CO}_2 \) adsorption is 4.9 kcal/mol** for TDA sorbent
  - Net energy loss in sorbent regeneration is similar to Selexol; much higher IGCC efficiency can be achieved due to high temperature \( \text{CO}_2 \) capture
- **Favorable material properties**
  - Pore size is tuned to 10 to 100 A
  - Mesopores eliminates diffusion limitations

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US Pat. Appl. 61790193, Alptekin, Jayaraman, Copeland “Pre-combustion \( \text{CO}_2 \) Capture System Using a Regenerable Sorbent”
Advantages

- Higher mass throughput to gas turbine – higher efficiency
- Lower GT temperature – Reduced need for HP N₂ dilution hence lower NOₓ formation
- Elimination of heat exchangers needed for cooling and re-heating the gas
- Elimination of gray water treatment problem
- Potential for further efficiency improvements via integration with WGS
**Operating Conditions**

- CO$_2$ is recovered via combined pressure and concentration swing
  - CO$_2$ recovery at ~150 psia reduces energy need for CO$_2$ compression
  - Small steam purge ensures high product purity
- Isothermal operation eliminates heat/cool transitions
  - Rapid cycles reduces cycle time and increases sorbent utilization
- Similar PSA systems are used in commercial H$_2$ plants and air separation plants

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**Syngas Inlet**
- 240°C, 500 psia
- 40% CO$_2$
- $P_{CO_2} = 200$ psia

**Regen. Exit**
- 240°C, 150 psia
- 50% CO$_2$/Steam
- $P_{CO_2} = 75$ psia

**Syngas Exit**
- 250°C, 492 psia
- < 1% CO$_2$
- $P_{CO_2} < 5$ psia

**Regen. Inlet**
- 250°C, 158 psia
- 100% H$_2$O
- $P_{CO_2} = 0$ psia

*Source: Honeywell/UOP*
Technology Maturation Timeline


Bench-scale tests 0.5-1 kW tests at Wabash River IGCC Sorbent Scale-up IP secured 0.1 MW tests at NCCC Integrated with WGS Tests with Praxair

0.1 MW Tests at Sinopec/Yangtze Chemicals Nanhua Plant
Primary Focus

- 0.1 MW<sub>e</sub> evaluation in a world class IGCC plant to demonstrate full benefits of the technology
  - Testing with high pressure gas
- Demonstrate full operation scheme
  - 8 reactors and all accumulators
  - Utilize product/inert gas purges
  - H<sub>2</sub> recovery/CO<sub>2</sub> purity
- Evaluations at various sites using coal-derived syngas
  - Field Test #1 at NCCC – Air blown gasification
  - Field Test #2 at Sinopec Nanhua Petro-chemical Plant, Nanjing, Jiangsu Province, China – Oxygen blown gasification

<table>
<thead>
<tr>
<th>Nanhua Plant Syngas Supply</th>
<th>Composition</th>
<th>mol%</th>
</tr>
</thead>
<tbody>
<tr>
<td>H2</td>
<td>32.493</td>
<td></td>
</tr>
<tr>
<td>CO</td>
<td>0.546</td>
<td></td>
</tr>
<tr>
<td>CO2</td>
<td>24.715</td>
<td></td>
</tr>
<tr>
<td>H2S</td>
<td>0.083</td>
<td></td>
</tr>
<tr>
<td>COS</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>C1</td>
<td>0.021</td>
<td></td>
</tr>
<tr>
<td>N2</td>
<td>0.128</td>
<td></td>
</tr>
<tr>
<td>AR</td>
<td>0.05</td>
<td></td>
</tr>
<tr>
<td>NH3</td>
<td>0.069</td>
<td></td>
</tr>
<tr>
<td>HCN</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>HCL</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>H2O</td>
<td>41.895</td>
<td></td>
</tr>
</tbody>
</table>

温度 Temperature, C  265.6
压力 Pressure, MPaG  4
Slipstream Test Skid - Top View

- CO₂ Sorbent Vessels
- Recirculation buffer tanks
- CO₂ Sorbent Vessels
- LTWGS Reactor
- Inlet/Outlet Accumulators
- CO₂ Sorbent Vessels
- Trace Contaminant Removal
- 2-Stage HTWGS Reactors
- 2-Stage (Lead/Lag) Bulk Desulfurizers
Field Test Unit Installed at NCCC

- Fabrication is completed in 2016
- Installation with all the hook-ups were completed in March 2017
- Testing initiated in April 2017
A successful 30 day (707 hrs) evaluation was completed at NCCC

- Design flow at NCCC operating conditions was 1,420 SLPM (50 SCFM)
- 97.3% capture @ 1,500 SLPM
- 93% @ 1,800 SLPM
- 90% @ 2,100 SLPM

Pressure drop through the gas conditioning skid prevented flowing more than 2,100 SLPM of syngas through the PSA skids
Sorbent Evaluations – Multiple Cycles

- Long-term cycling of the scaled-up sorbent has been completed with stable performance over 60,000 cycles.
• Working with GTI, we developed a CFD model to support reactor design
• The model was tuned using the data from 1 kW and 0.1 MW systems evaluated at Wabash River IGCC Plant and NCCC field tests
• CFD simulations reached steady state in 6 cycles and the working capacity matched the data sets
• CFD model was also tuned using the data from Sinopec test
Cycle Optimization

D. 6-step PSA cycle with CoBLO, purge, PREQ & LPP

E. 8-step PSA cycle with CnBLO, purge, two PREQ & LPP

F. 10-step PSA cycle with CnBLO, purge, three PREQ & LPP

- Cycle Schemes D, E and F that use pressure equalizations and co-current blowdown met DOE targets of 90% capture and 95% CO₂ purity

Applied Energy, Volume 254, 15 November 2019, 113624
Minimization of Energy Penalty

- **Configuration F**: 10-step PSA cycle with three pressure equalizations: 95.7 kWh/tonne of CO$_2$ captured at productivity of 3.3 mol CO$_2$/m$^3$/s
- **Configuration D**: 6-step PSA cycle with one pressure equalization and a co-current blowdown: 140 kWh/tonne of CO$_2$ captured at productivity of 5.2 mol CO$_2$/m$^3$/s
- OPEX/CAPEX trade-off is being evaluated for a fully optimized PSA cycle
Reactor Design

- Different reactor concepts have been evaluated
- Multiple train vertical reactors with internal flow distribution are selected for final design

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**GE Gasifier**

<table>
<thead>
<tr>
<th></th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Syngas flow, kmol/h</td>
<td>34,747</td>
</tr>
<tr>
<td>Sorbent needed, kg</td>
<td>1,115,903</td>
</tr>
<tr>
<td>L</td>
<td>1,185,838</td>
</tr>
<tr>
<td>Cycle time, min</td>
<td>8</td>
</tr>
<tr>
<td>Ads. GHSV, h⁻¹</td>
<td>1,117</td>
</tr>
<tr>
<td>Total Beds</td>
<td>16</td>
</tr>
<tr>
<td>Bed. Volume, L</td>
<td>116,240</td>
</tr>
<tr>
<td>Bed. Volume, L</td>
<td>116,240</td>
</tr>
<tr>
<td>Diameter, ft</td>
<td>14</td>
</tr>
<tr>
<td>Length, ft</td>
<td>30.1</td>
</tr>
<tr>
<td>Vessel wall thickness, in</td>
<td>5.0</td>
</tr>
<tr>
<td>L/D</td>
<td>2.30</td>
</tr>
<tr>
<td>Particle size, in</td>
<td>1/8</td>
</tr>
<tr>
<td>Bed Pressure drop, psid</td>
<td>3.6</td>
</tr>
</tbody>
</table>

**Source:** Honeywell/UOP

- World-class PSA systems used in H₂ purification produces up to 400,000 m³/hr H₂ (compared to ~780,000 m³/hr flow rate used in TEA base case)
Full-scale System Design

Major Units
- 8 beds x 2 = 16
- 2 accumulator X 2 = 4
- Cycling Valves
  - 6 x 8 x 2 = 96
- 2 recycle compressors
- 2 isolation valves x 2 per train = 4
### Techno-economic Analysis

<table>
<thead>
<tr>
<th>Gasifier</th>
<th>Case</th>
<th>E-Gas</th>
<th>GE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>CO₂ Capture Technology</td>
<td>Cold Gas Cleanup</td>
<td>Warm Gas Cleanup</td>
<td>Cold Gas Cleanup</td>
</tr>
<tr>
<td>CO₂ Capture, %</td>
<td>Selexol™ TDA’s CO₂ Sorbent</td>
<td>Selexol™ TDA’s CO₂ Sorbent</td>
<td></td>
</tr>
<tr>
<td>Gross Power Generated, kW</td>
<td>710,789</td>
<td>670,056</td>
<td>727,633</td>
</tr>
<tr>
<td>Gas Turbine Power</td>
<td>464,000</td>
<td>425,605</td>
<td>464,000</td>
</tr>
<tr>
<td>Steam Turbine Power</td>
<td>246,789</td>
<td>244,450</td>
<td>257,657</td>
</tr>
<tr>
<td>Syngas Expander Power</td>
<td>-</td>
<td>-</td>
<td>5,977</td>
</tr>
<tr>
<td>Auxiliary Load, kW</td>
<td>194,473</td>
<td>124,138</td>
<td>192,546</td>
</tr>
<tr>
<td>Net Power, kW</td>
<td>516,316</td>
<td>545,917</td>
<td>535,087</td>
</tr>
<tr>
<td>Net Plant Efficiency, % HHV</td>
<td>31.0</td>
<td>34.1</td>
<td>32.0</td>
</tr>
<tr>
<td>Coal Feed Rate, kg/h</td>
<td>220,549</td>
<td>212,265</td>
<td>221,917</td>
</tr>
<tr>
<td>Raw Water Usage, GPM/MW</td>
<td>10.9</td>
<td>10.3</td>
<td>10.7</td>
</tr>
<tr>
<td>Total Plant Cost, $/kW</td>
<td>3,464</td>
<td>3,102</td>
<td>3,359</td>
</tr>
<tr>
<td>COE without CO₂ TS&amp;M, $/MWh</td>
<td>136.8</td>
<td>122.3</td>
<td>133.0</td>
</tr>
<tr>
<td>COE with CO₂ TS&amp;M, $/MWh</td>
<td>145.7</td>
<td>130.4</td>
<td>141.6</td>
</tr>
<tr>
<td>Cost of CO₂ Capture, $/tonne</td>
<td>43</td>
<td>30</td>
<td>37</td>
</tr>
</tbody>
</table>

- IGCC plant with TDA’s CO₂ capture system achieves higher efficiencies (34.5% and 34.1%) than IGCC with Selexol™ (32.0% and 31.0%) for the E-Gas™ and GE gasifiers.
- Cost of CO₂ capture is calculated as $31 and $30 per tonne for GE and E-Gas™ gasifiers, respectively (16-30% reduction against Selexol™).
- Cost of CO₂ capture is calculated as $40 and $28 per tonne for Shell and TRIG gasifiers, respectively (15-28% reduction against Selexol™).
Sinopec Field Test Update

- Both skids and one of the containers were late to the site
- One skid held up due to the hazardous nature of the WGS catalyst and regulations on some of the power equipment
- Catalyst, transformer, fiber optic cable etc. were procured locally
Installation Work at Sinopec

• Because of the delays getting all equipment to site, the test setup had to be moved to a different location in the plant

• An existing super-structure at the new site added complexity to installation
  • Skids were pipe rolled over berm and into place
  • Vessels were loaded manually via socks and buckets
Carbon Bed Filling

- Stainless mesh screens and Denstone deltaP media are added to the beds (not available in NCCC tests)
  - The inert ceramic beads eliminated some of the dead volume in the reactor top and bottom
  - Heavy Denstone beads also limits material movement in the bed during cycling
Pilot Plant Installed at Sinopec
Early Results

- Testing started on 8/27/2019 at 21:50 MST
- High syngas flow, high T, low P during start-up to avoid water/tar condensation in the system
- 2500 SLPM Syngas Flow
- ~85% CO\textsubscript{2} removal efficiency
- ~110 kg/hr CO\textsubscript{2} removal rate
Bed Temperatures

• Bed temperature gradients were as expected
• Larger gradients in the syngas inlet ends, while smaller gradients at the CO$_2$ free syngas end
• DeltaT of ~20-30°C was as predicted in the CFD simulations at GTI
Parametric Tests

- ~150 hours of testing with over 1,000 adsorption/desorption cycles were carried out using the same T cycle used at NCCC
  - ~86% CO$_2$ removal efficiency
  - ~110 kg/hr CO$_2$ removal rate (35 kg/hr CO$_2$ at NCCC)
- While a higher CO$_2$ adsorption capacity was observed than the evaluations at the NCCC, the removal efficiency were slightly lower than 90% due to the much higher amount of CO$_2$ that needed to be removed
  - A new cycle sequence was generated with shorter cycle time to switch the bed positions prior to CO$_2$ breakthrough, but not implemented
## Summary of Test Results

<table>
<thead>
<tr>
<th>flow rates (SLPM)</th>
<th>pressures (psia)</th>
<th>Syngas CO₂ concentration.</th>
</tr>
</thead>
<tbody>
<tr>
<td>feed</td>
<td>steam</td>
<td>syngas product</td>
</tr>
<tr>
<td>2,648</td>
<td>1,199</td>
<td>1,593</td>
</tr>
<tr>
<td>2,752</td>
<td>253</td>
<td>2,060</td>
</tr>
<tr>
<td>1,942</td>
<td>600</td>
<td>1,014</td>
</tr>
<tr>
<td>1,983</td>
<td>1,200</td>
<td>1,486</td>
</tr>
<tr>
<td>1,953</td>
<td>580</td>
<td>1,029</td>
</tr>
<tr>
<td>2,174</td>
<td>892</td>
<td>1,185</td>
</tr>
<tr>
<td>2,659</td>
<td>600</td>
<td>1,062</td>
</tr>
<tr>
<td>859</td>
<td>129</td>
<td>556</td>
</tr>
</tbody>
</table>

### Parameters Varied:
- **Syngas Flow** = 1500 to 2800 SLPM
- **Steam Flow** = 200 to 1200 SLPM
- **Bed Temperature** = 190 to 290°C
- **Adsorption Pressure** = 130 to 300 psia
- **Desorption Pressure** = 35 to 80 psia

### System Performance:
- 65-86% CO₂ removal efficiency
- Up to 122 kg/hr CO₂ removal rate
- 3X the CO₂ removal rate compared to our tests at NCCC
Sorbent Performance Summary

- Sorbent/PSA system maintained slightly higher CO$_2$ capacity than the earlier field tests at NCCC at ~60X scale
- At Sinopec we achieved a much higher capacity than in the previous oxy-fired gasification tests at Wabash River IGCC power plant
- Total Pressure – 340 vs 500 psia
Acknowledgements

- DOE/NELT funding under the DE-FE-0013105 project
- Project Manager, Andy O’Palko
- Chuck Shistla, GTI
- Ashok Rao, UCI
- Arvind Rajandran, UOA
- Frank Morton, NCCC