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

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2022 Carbon Management Project Review Meeting
Capture from Power Generation
Pilot-Scale Research

August 16, 2022

TDA Research Inc. • Wheat Ridge, CO 80033 • www.tda.com
Objective is to carry out a pilot scale evaluation TDA’s sorbent-based pre-combustion capture technology
- Evaluate technical feasibility in 0.1 MW\(_e\) slipstream tests
- High fidelity process design and engineering analysis

**Main Project Tasks**
- Sorbent Manufacturing
  - Long-term cycling life tests
- Reactor Design
  - PSA cycle optimization
- Fabricate a Pilot-scale Unit for field tests
- Evaluations at various sites using coal-derived synthesis gas
  - Decommissioning
- Techno-economic analysis

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**Project Objectives and Team**

**Project Duration**
- Start Date = January 1, 2014
- End Date = September 30, 2022

**Budget**
- Project Cost = $9,929,228
- DOE Share = $7,943,382
- TDA and its partners = $1,985,846
Integration to the IGCC Power Plant

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

- CO₂ is recovered via a combined pressure and concentration swing process
  - CO₂ recovery at ~150 psia reduces the energy need for CO₂ 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 H₂ plants and air separation plants

Source: Honeywell/UOP
TDA’s Sorbent

- TDA’s uses a mesoporous carbon with surface functional groups that remove CO₂ via strong physical adsorption
  - CO₂-surface interaction is strong enough to allow operation at elevated temperatures
  - Because CO₂ is not bonded via a covalent bond, energy input for regeneration is low
- Heat of CO₂ 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 CO₂ capture
- Favorable material properties
  - Mesopores (10 to 100 Å) reduce diffusion limitations

US Pat. Appl. 61790193, Alptekin, Jayaraman, Copeland “Precombustion CO₂ Capture System Using a Regenerable Sorbent”
Technology Maturation Timeline

2008
Bench-scale tests
0.5-1 kW tests at NCCC

2011
0.5-1 kW tests at Wabash River IGCC

2013
Sorbent Scale-up
IP secured

2014

2017
0.1 MW tests at NCCC

2018
Integrated with WGS Tests with Praxair/Linde
Tests at Sinopec/Yangtze Chem. Nanhua Plant

2019
0.1 MW
Project 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 Composition</th>
<th>mol%</th>
</tr>
</thead>
<tbody>
<tr>
<td>H&lt;sub&gt;2&lt;/sub&gt;</td>
<td>32.493</td>
</tr>
<tr>
<td>CO</td>
<td>0.546</td>
</tr>
<tr>
<td>CO&lt;sub&gt;2&lt;/sub&gt;</td>
<td>24.715</td>
</tr>
<tr>
<td>H&lt;sub&gt;2&lt;/sub&gt;S</td>
<td>0.083</td>
</tr>
<tr>
<td>COS</td>
<td>0.000</td>
</tr>
<tr>
<td>C1</td>
<td>0.021</td>
</tr>
<tr>
<td>N&lt;sub&gt;2&lt;/sub&gt;</td>
<td>0.128</td>
</tr>
<tr>
<td>AR</td>
<td>0.05</td>
</tr>
<tr>
<td>NH&lt;sub&gt;3&lt;/sub&gt;</td>
<td>0.069</td>
</tr>
<tr>
<td>HCN</td>
<td>0.000</td>
</tr>
<tr>
<td>HCl</td>
<td>0.000</td>
</tr>
<tr>
<td>H&lt;sub&gt;2&lt;/sub&gt;O</td>
<td>41.895</td>
</tr>
</tbody>
</table>

Nanhu Plant Syngas Supply

Temperature, C: 265.6
Pressure, MPaG: 4
Field Test Unit Installed at NCCC

- Installation with all the hook-ups were completed in March 2017
- Testing started 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
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 using socks
Testing Results at Sinopec

- High syngas flow, high T, low P during start-up to avoid water/tar condensation in the system
- Up to 2500 SLPM Syngas Flow
- ~85% CO₂ removal efficiency
- ~110 kg/hr CO₂ removal rate
## Summary of Test Results

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

### System Performance
- DeltaT of ~20-30°C was measured as predicted in CFD simulations
- % CO₂ removal efficiency
- Up to 122 kg/hr CO₂ removal rate
- 3X the CO₂ removal rate compared to our tests at NCCC

### Table of Test Results

<table>
<thead>
<tr>
<th>feed (SLPM)</th>
<th>steam (SLPM)</th>
<th>syngas product (SLPM)</th>
<th>CO₂ and steam out (SLPM)</th>
<th>CO₂ concentration</th>
<th>bed T (°C)</th>
<th>Feed (%)</th>
<th>HP product (%)</th>
<th>CO₂ removed (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2,648</td>
<td>1,199</td>
<td>1,593</td>
<td>1,513</td>
<td>305</td>
<td>72</td>
<td>225</td>
<td>48</td>
<td>17</td>
</tr>
<tr>
<td>2,752</td>
<td>253</td>
<td>2,060</td>
<td>481</td>
<td>298</td>
<td>59</td>
<td>249</td>
<td>37</td>
<td>17</td>
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<tr>
<td>1,942</td>
<td>600</td>
<td>1,014</td>
<td>1,272</td>
<td>276</td>
<td>61</td>
<td>213</td>
<td>48</td>
<td>13</td>
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<tr>
<td>1,983</td>
<td>1,200</td>
<td>1,486</td>
<td>1,262</td>
<td>298</td>
<td>61</td>
<td>192</td>
<td>45</td>
<td>11</td>
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<tr>
<td>1,953</td>
<td>580</td>
<td>1,029</td>
<td>1,314</td>
<td>293</td>
<td>57</td>
<td>218</td>
<td>45</td>
<td>13</td>
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<td>2,174</td>
<td>892</td>
<td>1,185</td>
<td>1,273</td>
<td>304</td>
<td>36</td>
<td>214</td>
<td>47</td>
<td>14</td>
</tr>
<tr>
<td>2,659</td>
<td>600</td>
<td>1,062</td>
<td>1,761</td>
<td>246</td>
<td>51</td>
<td>183</td>
<td>45</td>
<td>15</td>
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<tr>
<td>859</td>
<td>129</td>
<td>556</td>
<td>128</td>
<td>134</td>
<td>79</td>
<td>288</td>
<td>46</td>
<td>15</td>
</tr>
</tbody>
</table>

System Performance
- DeltaT of ~20-30°C was measured as predicted in CFD simulations
- % CO₂ removal efficiency
- Up to 122 kg/hr CO₂ removal rate
- 3X the CO₂ removal rate compared to our tests at NCCC
• ~150 hours of testing with over 1,000 adsorption/desorption cycles were carried out using the same cycle sequence employed at the NCCC tests
  • ~86% CO\textsubscript{2} removal efficiency
  • ~110 kg/hr CO\textsubscript{2} removal rate

• While CO\textsubscript{2} capacity was higher compared to NCCC tests, CO\textsubscript{2} removal efficiency were lower than 90% due to the much higher CO\textsubscript{2} concentration in the gas
  • A sequence with shorter cycle time to switch the bed positions prior to CO\textsubscript{2} breakthrough was developed but not implemented
Sinopec completed all the decommissioning activities and got the units prepared for shipment from Nanjing, China.

TDA worked with the shipping company (DSV Nanjing) to get the units picked up and shipped to USA through Houston, TX.

Units are delivered to TDA in June 2022 and are now shrink wrapped and stored in Colorado.
Working with GTI, we developed a CFD model to support reactor design. The model was tuned using the data from 0.1 MW system evaluated at the NCCC and Sinopec field tests (as well as data from smaller scale evaluations). CFD simulations reached steady state with the working capacity matching those reported in the data sets.
Measurement of Sorbent Life

- Long-term cycling with the scaled-up sorbent showed stable performance for over 60,000 cycles

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Synthesis Gas</th>
<th>Simulated Gas</th>
<th>Steam Purge</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure</td>
<td>200°C</td>
<td>200°C</td>
<td>200°C</td>
</tr>
<tr>
<td>Composition</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(\text{H}_2)</td>
<td>42.8%</td>
<td>53.4%</td>
<td>50.0%</td>
</tr>
<tr>
<td>(\text{CO}_2)</td>
<td>30.0%*</td>
<td>30.0%</td>
<td>-</td>
</tr>
<tr>
<td>(\text{H}_2\text{O})</td>
<td>26.6%</td>
<td>26.6%</td>
<td>50.0%*</td>
</tr>
<tr>
<td>CO</td>
<td>0.6%</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

* adjusted for purge with 100% steam at 150 psia
PSA Cycle Optimization

- Cycle schemes that can meet DOE’s 90% capture and 95% CO₂ purity targets were identified

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

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

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

**Configuration D:** 6-step PSA cycle with one equalization and a co-current blowdown: 140 kWh/tonne of CO₂ captured at productivity of 5.2 mol CO₂/m³/s

**Configuration F:** 10-step PSA cycle with three pressure equalizations: 95.7 kWh/tonne of CO₂ captured at productivity of 3.3 mol CO₂/m³/s

OPEX/CAPEX trade-off was evaluated for a fully optimized PSA cycle.
Reactor Design

- Different reactor concepts have been evaluated
- Multi-train fixed bed reactors are selected for final design

### GE Gasifier

<table>
<thead>
<tr>
<th>Parameter</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></td>
<td>L 1,859,838</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 Dimensions</td>
<td></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>

- 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
IGCC plant with TDA’s CO₂ capture system achieves higher efficiencies (34.4% and 34.0%) than IGCC with Selexol™ (31.9% and 30.8%) for E-Gas™ and GE gasifiers.

- Cost of CO₂ capture is calculated as $29 and $28 per tonne for GE and E-Gas™ gasifiers, respectively (24-35% reduction against Selexol™).
- Cost of CO₂ capture is calculated as $40 and $28 per tonne for Shell and TRIG gasifiers, respectively (20-33% reduction against Selexol™).
Acknowledgements

- DOE/NETL funding under the DE-FE-0013105 project
- Project Manager, Andrew O’Palko
- Chuck Sishtla, GTI
- Ashok Rao, UCI (retired)
- Arvind Rajendran, UOA
- Frank Morton, NCCC
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