Status of the Carbon-dioxide Absorber Retrofit Equipment (CARE) Program

2013 CO₂ Capture Technology Meeting

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NeuStream® Pollution-to-Products™ Systems

Pollutants
- Sulfur Oxides (SO\textsubscript{x})
- Nitrogen Oxides (NO\textsubscript{x})
- Carbon Dioxide (CO\textsubscript{2})
- Particulates (PM)
- Heavy Metals, Organics

Industrial Products
- Sulfuric Acid $2.3M/yr*
- Gypsum $0/yr*
- Fertilizer $12M/yr*
- Enhanced Oil Recovery $867M/yr*
- Rare Earth Metals $59M/yr*
- Nitric Acid $3.8M/yr*
- Fertilizer $5M/yr*

Pollutants captured and transformed into vital industrial products

>$1 BILLION revenue from P-to-P from a single 550MW coal plant*
Benefits of High Surface Area Jets for Pollution Control

**Parameter** | **Benefit**
--- | ---
High specific surface area: $a_s > 1000 \text{ m}^2/\text{m}^3$; High volumetric mass transfer kinetics, $10 \times K_L a_s$ over conventional systems | High process efficiency; Greatly reduced column footprints
Low $\Delta P_{\text{Gas}} \sim 1\text{inWC/m}$; Low $\Delta P_{\text{Liq}} = <6 \text{ PSI}$ | Reduced hydrodynamic/auxiliary power
Aerodynamic shaped jets | Reduced liquid entrainment in the gas flow
Factory fabrication of modular/serviceable units | Standardization/lower cost fabrication; Rapid scaling per customer needs
Flat Jet Gas-Liquid Contactor

**Advantages:**
- Reduced absorber volume due higher contact area
- Horizontal (gas flow) orientation simplifies installation
- Ability for turndown of system
  - Vary gas flow through system 4-8 m/s
  - Turn off stages of absorption

**Challenges:**
- Maintaining a high contactor surface area AND a manageable parasitic power
CARE Project Overview

• Project Objectives
  – Design and Fabricate 0.5 MWe Carbon Capture System
    • Demonstrate NSG flat-jet gas-liquid contactor as CO₂ absorber
    • Minimize system parasitic power through efficient design
  – Demonstrate
    • 2 month steady-state operation with Multi-Stage Absorber and Stripper
    • 90% CO₂ capture efficiency
  – Show unit traceability/scalability to commercial scale

• Partners:
  – DOE/NETL
  – Colorado Springs Utilities (Host Site, Resource Provider)
  – EERC (TEA, EH&S, Consulting – System Integration)
  – Mr Robert Keeth of URS (Consulting – Construction/Installation)
  – Dr Gary Rochelle and Dr Eric Chen of UT (Consulting – Solvent Regeneration)
Project Overview:
Project Status as of May 31, 2013

• Project CARE: $7,164,392 Federal Funding, started May 2012
  – April 2013: Completed budget period 1 (BP1) – Design Phase
  – May 2013: Started BP2 – Construction Phase (9mo)
  – Feb 2014: Start date for BP3 – Testing Phase (12mo)

• $2,799,662 costed of project total value of $9,098,441 (30.8%); Cost share currently at value of $693,132 (24.8%)

• Earned Value Assessment of Project:
  – 30.6% complete
  – CPI of 1.040
  – SPI of 0.966
Capture Subsystem

DVT Stand

- 0.8 m (length) x 0.2 m (width)
  Horizontal Gas, Vertical Jet Absorber
- MEA solvent with flash stripper
- Adjustable gas flow: 4–16 m/s
- Adjustable reactor height: 28-79 cm (11-31 in)
- Adjustable jet pressure: 4-12 psi
- Interchangeable jet plate
  - ULFT or LF nozzles
  - Jet spacing of 3 or 4 mm
- CO₂ capture efficiency measured with Testo & FT-IR and CO₂ Mass flow controller
- Demonstrated specific surface area of greater than 400 m²/m³
CARE System Layout
Isometric Views
Absorber Unit
Absorber Design

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Units</th>
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<tbody>
<tr>
<td>Stage Width</td>
<td>58.4 (23)</td>
<td>cm (in)</td>
</tr>
<tr>
<td>Stage Height</td>
<td>30.5 (12)</td>
<td>cm (in)</td>
</tr>
<tr>
<td>Stage $a_s$</td>
<td>425</td>
<td>m²/m³</td>
</tr>
<tr>
<td>Unit Length</td>
<td>2.75 (108.3)</td>
<td>m (in)</td>
</tr>
<tr>
<td>Capture Efficiency</td>
<td>90%</td>
<td></td>
</tr>
<tr>
<td>Number of Pseudo-Stages</td>
<td>12</td>
<td></td>
</tr>
</tbody>
</table>

4x Absorbers at 2.75 m each = 11 m Total Length

L = 7.6 m total length
$a_s = 438$ m²/m³
Lean = .28
Rich = .38
Flue Gas = 1204 SCFM (0.6MWe)
Absorber Module
Design - 90% Capture of 0.6MW

- At CSU’s Drake: 2300 SCFM/MW, 12.5% CO₂ and 0.8 atm requires **11 meters** with 12 stages to get the necessary 2.2 sec residence time.
Absorber Module
Design - 90% Capture of 0.6MW

• At CSU’s Drake: 2300 SCFM/MW, 12.5% CO₂ and 0.8 atm requires **11 meters** with 12 stages to get the necessary 2.2 sec residence time.

• Using NETL Case 9 Plant: 2007 SCFM/MW, 13.5% CO₂ and 1 atm requires **7.6 meters** with 12 stages to get the necessary 2.2 sec residence time.

• This absorber moved to the Case 9 plant could scrub 0.9MW at 90%
Stripper Module
Aspen/Process Flow Diagram

- Hot rich solvent injected through NSG jets
  - 6 rows x 45 LF nozzles at 6 psi = 55 gpm
- Cold Rich Bypass crosses with CO₂ gas in HEX, becoming warm rich
- Warm rich solvent sprays onto packing where heat transfer occurs through direct contact of gas/liquid
- Reboiler heat supplied through Stab-in-Bundle HEX
Flue Gas Heat Extraction

- Flue Gas Reheat to 350°F to simulate NETL Case 9 Flue Gas out of the bag house
- 10% (5gpm) cold, rich solvent pulled to low pressure stripping
- Size flue gas HEX to offset vaporization cooling and maintain higher temperatures
- Simple flash stripper for gas/liquid separation – operated at 4 bar
- Modeled lean loading – 0.30 mol CO₂/mol alk; results in a steam offset of 8%
NOx Removal using O₃

- Gas phase oxidation using ozone:
  \[2(NO + O_3) \rightarrow 2NO_2 + O_3 \rightarrow N_2O_5\]
- Total NOₓ removal demonstrated at 81% on central Pennsylvania eastern bituminous coal (flue gas concentration of 182ppm)
- Need to increase ozone production to achieve higher capture rate
0.5MW CARE Program

- **CARE Innovations**
  - NSG nozzles incorporated in FGD, FGD Polish/DCC, CO₂ Absorber, Amine Wash, and Stripper (for heat transfer)
  - NOx reduction through O₃ injection into flue gas upstream of SOx scrubber
  - Flue gas heat extraction to reduce steam usage
  - Custom Stripper configuration to take advantage of the operating properties of the piperazine solvent (developed with Drs. Rochelle/Chen)
  - Designed for use with concentrated Piperazine, although system is solvent agnostic and at the very least will be run with MEA solvent
Capture Subsystem

Future Work: 5MW Design

- Defined unit cell as 5 MW
  - WxH: 0.85 m (33.3”) x 0.76 m (30”)
  - Once 5 MW unit cell performance has been verified; scaling to commercial will have minimal risk utilizing this unit cell.

- 5MW cell:
  - Need 14.5 m of length for 90% capture;
  - Gas velocity is 7.5 m/s
  - Image shows a 2-stage 5 MW unit with 2.9m length (5x units needed in series).
Capture Subsystem

Traceability to Commercial Design

- Commercial module can easily be tailored for specific needs:
  - Can support 2 or 3 levels/tiers
  - Each level/tier can support up to 9x 5 MW unit cells
  - A single stage is shown with the maximum number (27x) of 5 MW cells: 135 MW

- Switch in pump type
  - Axial flow pumps are cheaper than split-case, double-suction pumps
a) Single-stage, 135 MW unit that utilizes 27x 5-MW unit cells

b) 10-units stacked in series to achieve the necessary residence time at 7.5 m/s gas velocity for 90% capture of 135 MW flow

c) A 1-meter (depth) FGD/polishing scrubber and amine wash added to the CO₂ absorber to complete the module

d) 4-135 MW modules in parallel to achieve CO₂ capture of 540 MW
Comparison

Typical Packed Tower vs. NeuStream®-C

- Counter-current liquid/gas
- Tall height requires expensive support structure
- Contactor area is 100-200 m²/m³
- Gas velocities limited to 1-2 m/s
- High pressure drop across packing (1-2 inWC per meter)

- Counter-current liquid/gas
- Horizontal arrangement requires significantly less structural support
- Contactor specific surface area of >400 m²/m³ demonstrated
- Acceptable gas velocity up to 7.5 m/s
- Pressure drop of 1inWC per meter of jets at 4 m/s gas velocity
BD3 project information:
- BD3 is expected to gross approximately 165 MW after boiler upgrade
- Carbon Capture System expected to operate at 21% parasitic power
- Net power from BD3 will be approximately 110-115MW

NeuStream™-C system:
- Designed for 165 MW; utilizing 27x 5-MW cells
- Estimated 26.5% parasitic power using current performance metrics:
  - Stripper = 16.5%; Compression = 4.3%; Absorber (including FD fan, FGD polish scrubber, CO₂ absorber and Amine wash) = 5.5%
### Energy Audit

#### Design Performance

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Flow (GPM)</th>
<th>TDH (ft)</th>
<th>Efficiency</th>
<th>Power (hp)</th>
<th>Power (kW)</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Absorber Recirc 1</td>
<td>66728.3</td>
<td>30</td>
<td>0.78</td>
<td>648.100</td>
<td>483.288</td>
<td>0.36%</td>
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<td>Absorber Recirc 6</td>
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<tr>
<td>Absorber Recirc 7</td>
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<tr>
<td>Absorber Recirc 9</td>
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<td>30</td>
<td>0.78</td>
<td>648.100</td>
<td>483.288</td>
<td>0.36%</td>
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<tr>
<td>Absorber Recirc 10</td>
<td>66728.3</td>
<td>30</td>
<td>0.78</td>
<td>648.100</td>
<td>483.288</td>
<td>0.36%</td>
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<tr>
<td>Amine Wash Recirc Pump</td>
<td>35747.3</td>
<td>30</td>
<td>0.75</td>
<td>361.084</td>
<td>269.260</td>
<td>0.20%</td>
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<tr>
<td>FGD Polish/DCC</td>
<td>35747.3</td>
<td>30</td>
<td>0.75</td>
<td>361.084</td>
<td>269.260</td>
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<td>Solvent Cooling Pump</td>
<td>7500</td>
<td>15</td>
<td>0.75</td>
<td>37.879</td>
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<td>0.02%</td>
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<tr>
<td>Condenser Cooling Pump</td>
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<td>0.75</td>
<td>37.879</td>
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<td>Rich Pump</td>
<td>11150</td>
<td>380</td>
<td>0.75</td>
<td>1426.599</td>
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### Equipment AFCM

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Press Drop (in H2O)</th>
<th>Efficiency</th>
<th>Power (hp)</th>
<th>Power (kW)</th>
<th>%</th>
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<td>Blower Loss</td>
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<td>17</td>
<td>0.7</td>
<td>1120.58</td>
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### Heat Requirements

<table>
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<tr>
<th>Equipment</th>
<th>Heat (kW)</th>
<th>Stripper Temp (°C)</th>
<th>Equivalent Work</th>
<th>%</th>
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</thead>
<tbody>
<tr>
<td>Stripper 1</td>
<td>35100</td>
<td>150</td>
<td>8299.35</td>
<td>6.15%</td>
</tr>
<tr>
<td>Stripper 2</td>
<td>57857</td>
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<td>13680.24</td>
<td>10.13%</td>
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### Compression Requirements

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<tr>
<th>Equipment</th>
<th>Flow Rate (mol/min)</th>
<th>Pressure (bar)</th>
<th>Avg. Press. (bar)</th>
<th>Equivalent Work (kJ/mol)</th>
<th>Equivalent Work (kW)</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stripper 1</td>
<td>19093</td>
<td>8</td>
<td>9.3</td>
<td>8.33</td>
<td>6051.19</td>
<td>4.48%</td>
</tr>
<tr>
<td>Stripper 2</td>
<td>24493</td>
<td>11</td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tbody>
</table>

### Totals

<table>
<thead>
<tr>
<th>Equipment</th>
<th>CO2 Flow (mol/s)</th>
<th>Equivalent Work (kJ/mol)</th>
<th>Equivalent Work (kW)</th>
<th>%</th>
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<tbody>
<tr>
<td>Stripper</td>
<td>726.429</td>
<td>30.26</td>
<td>21979.59</td>
<td>16.28%</td>
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<tr>
<td>Compression</td>
<td>726.429</td>
<td>8.33</td>
<td>6051.19</td>
<td>4.48%</td>
</tr>
<tr>
<td>Auxiliary</td>
<td>726.429</td>
<td>3.43</td>
<td>2494.44</td>
<td>1.85%</td>
</tr>
<tr>
<td>Absorber</td>
<td>799.071</td>
<td>6.65</td>
<td>4832.88</td>
<td>3.58%</td>
</tr>
<tr>
<td>Total</td>
<td>48.67</td>
<td>35358.094</td>
<td>26.19%</td>
<td></td>
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</table>

- Scrubber sized for NETL Case 9 power plant (1 atm, 2007 SCFM/MW)
- ULFT nozzles separated at 3mm on a tube; tube-to-tube separation of 3.5cm operated at 6 psi
- Amine Wash and FGD polishing scrubbers are included in Auxiliary equipment
  - AW and FGD each have 1m of reactor depth
  - 4mm nozzle-nozzle separation
  - ULFT nozzles with same 0.76 m jet length
Levelized Cost of Electricity
CARE System - Preliminary

- All numbers are from EERC TEA Report for 550 MW plant
- NSG supplied absorber cost
- Did not include updated CARE energy audit
  - (used 30% from EERC)
- 40% increase in LCOE
- CO₂ Removal Cost = $28.50/ton
- Needs Absorber Module Cost Updated Before New TEA Can Be Generated.

<table>
<thead>
<tr>
<th>Category</th>
<th>LCOE</th>
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<tr>
<td>CapEx Total Plant Cost</td>
<td>$44.44</td>
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<tr>
<td>OpEx Fixed Operating Cost</td>
<td>$12.30</td>
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<tr>
<td>OpEx Fuel Cost</td>
<td>$21.00</td>
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<tr>
<td>OpEx Variable Operating Costs</td>
<td>$7.25</td>
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<tr>
<td>CapEx CO₂ Capture System</td>
<td>$4.95</td>
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<td>Total</td>
<td>$89.94</td>
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Schedule/Future Work

• Status/Plans
  – Critical design review (FEED) completed March ‘13
  – Procurement/Fabrication began May ‘13
  – Construction/Installation to begin in Sept ‘13
  – Testing begins Feb ’14

• Development Plan
  – **2014**: Demonstrate 0.5MW and gather data to support the 5MW system
  – **2016**: Demonstrate at 5MW, which represent base unit where scaling occurs by increasing the number of 5MW cells
  – **2020**: Demonstrate at commercial scale (>50MW)
Conclusions

- NeuStream™-C
  - High mass transfer G/L contactor
  - Up to 10x smaller volume than traditional CO₂ capture systems
  - Significantly reduced CapEx
    - < $30/ton CO₂ capture and compression costs

- Successfully proven at bench-scale (80kW)

- 0.5MW pilot demonstration in progress
  - NOx, SOx controls
  - Flue gas heat extraction
  - Innovative Stripper design

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