Development and Demonstration of Waste Heat Integration with Solvent Process for More Efficient CO$_2$ Removal from Coal-Fired Flue Gas

DE-FE0007525

2017 NETL CO$_2$ Capture Technology Project Review Meeting

August 22$^{nd}$, 2017
1. Project Overview
2. Background Technologies
   - MHI CO₂ Capture Technology “KM-CDR Process®”
   - MHPS High Efficiency System “HES”
3. 25-MW Pilot Demonstration at Plant Barry
4. Test Results
5. Techno-Economic Analysis Results
6. Summary
1. Project Overview
Team-Members

Nick Irvin (P.I.)
Joe Kowalczyk
Jerrad Thomas

Katherine Dombrowski
Max Bernau
Jack Cline

Tim Thomas
Shintaro Honjo

Bruce Lani
Total Project Budget ($MM)

- DOE Share: 12.9
- Cost Share: 3.7

Total: $16.6 M
Overall Project Objectives

• The heat integration was chosen for its ability to provide:
  ✓ Increased plant efficiency,
  ✓ Mitigation of parasitic losses from a CO₂ capture system (CCS),
  ✓ Reduced water consumption and cooling water use, and
  ✓ Improvement in air quality system performance

• The heat integration included heat recovery for use in the coal EGU Rankine cycle. The heat was sourced from:
  ✓ A pilot CO₂ capture facility and
  ✓ The coal EGU flue gas.
Objectives – to quantify the benefit of heat integration

Quantify energy efficiency improvements
- Unit heat rate improvement
- Flue gas pressure drop

Identify and/or resolve integration problems
- Effect on water quality
- Corrosion, erosion, or plugging
- Issues with high-sulfur flue gas

Quantify ancillary benefits
- Better ESP performance
- Increased SO$_3$, Hg, Se capture
- Reduced water consumption and use
Overall Project Schedule

Nov 2011 – Mar 2013

BP1
• FEED and Target Cost Estimate
• Permitting

Apr 2013 – Apr 2015

BP2
• Engineering, Procurement, Construction

May 2015 – May 2017

BP3
• Operations
• Field Testing Analysis
2. Background Technologies
Post-Combustion Carbon Capture System

Coal-fired Power Station

Coal-fired Boiler → SCR → EP → FGD → CO$_2$ Capture → CO$_2$ Capture Plant

- SCR: Selective Catalytic NOx Removal
- EP: Electrostatic Precipitator
- FGD: Flue Gas Desulfurization

CO$_2$ Compression → CO$_2$-EOR / Storage

Clean Flue Gas

CO$_2$ Capture Plant

CO$_2$ Compressor
The flue gas is cooled to required temperature.

CO₂ is recovered from the flue gas by contacting with KS-1™ solvent.

The "CO₂-rich solvent" is pumped into the upper section of the stripper.

CO₂ is stripped from KS-1™ solvent in the Regenerator.

The flue gas is fed into the bottom section of the absorber and passed upward through the packing material inside the tower.
Petra Nova Project Overview

• “NRG Energy, JX Nippon complete world’s largest post-combustion carbon capture facility on-budget and on-schedule”

Conventional High Efficiency System

Hirono P/S Japan - 600MW

Reheater | FGD | Low Temp ESP | Flue Gas Cooler

Water Loop | Flue Gas

Plume Abatement
High Efficiency System (HES)

- Commercially proven technology
  - Installed & operated at ten coal-fired units in Japan since 1997
  - MHPS’s proprietary heat exchanger

Benefits of HES
- Removal improvement of hazardous air toxics (PM, SO$_3$, Hg, Se, etc.) across the ESP
- Reduction of makeup & cooling water
- AQCS (ESP, FGD & CCS) cost reduction
- Reduction of total energy penalty of CCS plant
- Potential to simplify boiler/steam turbine cycles

Tomato P/S Japan - 700MW
High Efficiency System (HES) (cont’d)

Heat Integration System with HES
- HES recovers waste heat from the flue gas by incorporating a heat extractor downstream of the air heater
- Recovered heat can be applied to the boiler feed water, thereby reducing the energy penalty of CCS plant

Application to boiler/steam turbine cycles
SO$_3$ Removal

Operates downstream of the APH

Mechanism for removal of SO$_3$ from flue gas

- $SO_3 (g) + H_2O (g) \rightarrow H_2SO_4 (g)$
- $H_2SO_4 (g) \rightarrow H_2SO_4 (l)$
- $H_2SO_4 (l)$ condenses on fly ash in flue gas and a protective layer of ash on tube bundles

Flue Gas Cooler tube skin temperature $< SO_3$ dewpoint

- Alkaline species in fly ash (Ca, Na) neutralize $H_2SO_4$
- Silicates, etc. physically adsorb $H_2SO_4$
Corrosion Mitigation Mechanism

Carbon steel tubes in good condition after 2 years of operation in Japan.

Example:
- Dust: 9000-14000mg/Nm³
- \(\text{H}_2\text{SO}_4 = \frac{30 \times 98}{22.4/0.8} = 164\text{mg/Nm}^3\)
- D/S ratio = 55 – 85

Higher fly ash or dust loading in the flue gas can mitigate corrosion rate.
3. 25-MW Pilot Demonstration at Plant Barry
Plant Barry 25-MW CCS Demonstration Plant

- Funded by industry consortium
- Fully integrated CO$_2$ capture/compression
- Storage in Citronelle Dome
- Capacity: 500 metric tons CO$_2$/day
Process Flow of 25-MW Pilot Demonstration Plant

- SCR → Air heater (700°)
- Air heater → Dry ESP (350°)
- Dry ESP → FGD
- FGD → Flue Gas Cooler (203°)
- Flue Gas Cooler → Steam Cycle (269°)
- Flue Gas Cooler → CO₂ Cooler in CCS Plant (167°)
- CO₂ Cooler in CCS Plant → Pilot ESP
- Pilot ESP → CCS Plant (25 MW)
- CCS Plant → SCR (To SCR Outlet)

- Flue Gas
- Boiler Condensate
- CO₂
- Boiler Condensate (101°)
Aerial View of Plant Barry Demonstration Plant

- Flue Gas Cooler
- Unit 5
- SCR
- CCS
- CO$_2$ Cooler
Flue Gas Cooler and CO$_2$ Cooler

CO$_2$ Cooler

Flue Gas Cooler
Flue Gas Blower and Pilot ESP

**Flue Gas Blower**

**Pilot ESP (0.25 MW)**
4. Test Results
## Baseline Performance

**Confirmed heat integration performance**
- 240-300 MMBTU/hr heat recovery for 550 MW base plant (Case 9)

<table>
<thead>
<tr>
<th>Source</th>
<th>Data collected</th>
<th>Units</th>
<th>w/o HES heat integration</th>
<th>w/ HES heat integration</th>
<th>w/ HES heat integration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flue gas flow rate</td>
<td>scfm</td>
<td></td>
<td>49,998</td>
<td>60,640</td>
<td>60,631</td>
</tr>
<tr>
<td>Flue gas temp FGC inlet</td>
<td>degF</td>
<td></td>
<td>288</td>
<td>323</td>
<td>314</td>
</tr>
<tr>
<td>Flue gas temp FGC outlet</td>
<td>degF</td>
<td></td>
<td>NA</td>
<td>200</td>
<td>186</td>
</tr>
<tr>
<td>Recovered heat</td>
<td>MMBtu/h</td>
<td></td>
<td>NA**</td>
<td>8.66</td>
<td>9.09</td>
</tr>
<tr>
<td><strong>CO₂</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flue gas flow rate*</td>
<td>scfm</td>
<td></td>
<td>73,800</td>
<td>73,800</td>
<td>73,800</td>
</tr>
<tr>
<td>CO₂ removal performance*</td>
<td>%</td>
<td></td>
<td>&gt; 90</td>
<td>&gt; 90</td>
<td>&gt; 90</td>
</tr>
<tr>
<td>BC flow rate</td>
<td>stph</td>
<td></td>
<td>0</td>
<td>38</td>
<td>50</td>
</tr>
<tr>
<td>BC temp CO₂ cooler inlet</td>
<td>degF</td>
<td></td>
<td>NA</td>
<td>128</td>
<td>123</td>
</tr>
<tr>
<td>BC temp CO₂ cooler outlet</td>
<td>degF</td>
<td></td>
<td>NA</td>
<td>167</td>
<td>167</td>
</tr>
<tr>
<td>Recovered heat</td>
<td>MMBtu/h</td>
<td></td>
<td>NA</td>
<td>2.9</td>
<td>4.4</td>
</tr>
<tr>
<td><strong>Plant</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Boiler Load net</td>
<td>MW</td>
<td></td>
<td>721</td>
<td>783</td>
<td>680</td>
</tr>
<tr>
<td>BC flow rate</td>
<td>stph</td>
<td></td>
<td>0</td>
<td>38</td>
<td>50</td>
</tr>
<tr>
<td>BC feed temp</td>
<td>degF</td>
<td></td>
<td>NA</td>
<td>128</td>
<td>123</td>
</tr>
<tr>
<td>BC return temp</td>
<td>degF</td>
<td></td>
<td>NA</td>
<td>280</td>
<td>264</td>
</tr>
<tr>
<td>Recovered heat</td>
<td>MMBtu/h</td>
<td></td>
<td>NA</td>
<td>11.1</td>
<td>13.6</td>
</tr>
<tr>
<td>Recovered heat for 550 MW base plant</td>
<td>MMBtu/h</td>
<td></td>
<td>NA</td>
<td>244</td>
<td>300</td>
</tr>
</tbody>
</table>
**Evaluation Results of Heat Integration**

Calculated heat integration benefit by Aspen model
- 18.3 MW was gained from the DOE Case 10 plant (subcritical PC EGU with CCS)
- 0.9% of plant efficiency was increased

<table>
<thead>
<tr>
<th>Description</th>
<th>Original Case 10 Value</th>
<th>Gain or Loss (-) Due to HES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total LP feedwater heater and deaerator steam extraction</td>
<td>421,000 lb/hr</td>
<td>-366,000 lb/hr</td>
</tr>
<tr>
<td>Turbine generation</td>
<td>673 MW</td>
<td>18.7 MW</td>
</tr>
<tr>
<td>Cooling fan and water pumps power consumption increase</td>
<td>-</td>
<td>1.6 MW</td>
</tr>
<tr>
<td>Induced draft fan power consumption</td>
<td>12.1 MW</td>
<td>-1.3 MW</td>
</tr>
<tr>
<td>Total Power Gain</td>
<td>-</td>
<td>18.3 MW</td>
</tr>
<tr>
<td>Plant Thermal Efficiency</td>
<td>26.2%</td>
<td>0.9% points</td>
</tr>
</tbody>
</table>
Water Consumption Reduction

- By cooling the flue gas, FGD makeup water can be reduced
- Percentage of water saved was calculated, not measured
- Up to 65% of the FGD makeup water can be saved
  - 502 gpm for a 550-MW plant
- 50-60% reduction of cooling water use in the CCS system
  - 45,000 gpm for a 550 MW plant
Impurities Removal Test

Test Conditions
- No FGC 300F: No water flowed through the FGC, the flue gas was not cooled
- FGC 203F + SO$_3$: The flue gas was cooled to 203F and SO$_3$ was injected
- FGC 203F: The flue gas at the FGC outlet was cooled to 203F
- FGC 185F: The flue gas was further cooled down to 185F

Test Methods and Locations

<table>
<thead>
<tr>
<th>Location</th>
<th>Analyte(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FGC Inlet</td>
<td>Particulate Matter, Metals (total and gas-phase), SO$_2$, SO$_3$</td>
</tr>
<tr>
<td>FGC Outlet</td>
<td>Flowrate only</td>
</tr>
<tr>
<td>ESP Inlet</td>
<td>Particulate Matter only</td>
</tr>
<tr>
<td>ESP Outlet</td>
<td>Particulate Matter, Metals (total and gas-phase), SO$_2$, SO$_3$</td>
</tr>
</tbody>
</table>
Impurities removal is enhanced by the Flue Gas Cooler operation due to operation of the FGC:
- Native mercury removal by fly ash increased significantly from 28 to >86% due to the Flue Gas Cooler.
- Selenium removal increased from 96 to 98%.
- No discernable effect due to temperature decrease from 203 to 185°F on either metal or particulate matter.
- SO$_3$ removal not calculated due to low concentrations.
SO\textsubscript{3} injection inhibits Mercury capture, no effect on Selenium or Particulate Matter due to SO\textsubscript{3} injection:

- Mercury removal decreased from >92 to 40%
- Mercury removal still higher during SO\textsubscript{3} injection than without FGC operation
- Selenium removal unchanged
- Particulate matter removal unchanged
- SO\textsubscript{3} removal not calculated due to low concentrations
Impurities Removal Test Results – Summary

Confirmed Impurities Removal performance
- PM removal: > 99.5%
- SO\(_3\) removal: less than 0.05 ppm at ESP outlet
- Hg removal: > 86% w/o SO\(_3\) injection, ~40% w/ SO\(_3\) injection
- Se removal: > 98%

<table>
<thead>
<tr>
<th>Condition, Day</th>
<th>Run Number, Day</th>
<th>SO(_3) con. at ESP outlet</th>
<th>Percent Removal Across FGC/ESP</th>
</tr>
</thead>
<tbody>
<tr>
<td>NO FGC 300F</td>
<td>R3-0 (12/15-16, 2015)</td>
<td>0.03</td>
<td>99.3% 28% 96%</td>
</tr>
<tr>
<td>FGC 203F+ SO(_3)</td>
<td>R3-2 (12/18-19, 2015)</td>
<td>0.04</td>
<td>99.7%* 40% 98%</td>
</tr>
<tr>
<td>FGC 203F</td>
<td>R3-1-1 (09/23-24, 2015)</td>
<td>0.04</td>
<td>99.7%* &gt;92% 98%</td>
</tr>
<tr>
<td>FGC 185F</td>
<td>R3-1-2 (09/25-26, 2015)</td>
<td>0.02</td>
<td>99.6% 86% 98%</td>
</tr>
</tbody>
</table>

* Calculated from the estimated inlet concentrations
Long-Term Durability Test Results (913 hours)

- Flue Gas Cooler internal surfaces were visually inspected before, during and after operation
- No mechanical damage to tubes found via visual inspection (see pictures below)
- No damage to soot blowers found via visual inspection
- No ash deposition or accumulation on tube walls

(a) Before operation  (b) October, 2015  (c) January, 2016*

*The remaining fly ash can be easily removed by soot-blowers.
Material Evaluation Test Results

- The sample with the most uniform corrosion provided a rate of 40 mils/year which has never been seen in commercial plants.
- Flue gas was not purged from the duct after operation like would be done in a full-scale plant.

Tested Tube Samples
5. Techno-Economic Analysis Results
TEA Cases

• Case 9
  - DOE/NETL case for a 550-MW subcritical coal EGU without CCS, burning bituminous coal;

• Case 10
  - DOE/NETL case for a 550-MW subcritical bituminous coal EGU using the monoethanolamine (MEA) solvent, Econamine, CCS system

• Case 10b
  - 550-MW subcritical bituminous coal EGU using the KM CDR Process for the CCS system, also has SO$_3$ control

• Case 10c
  - 550-MW subcritical bituminous coal EGU using the KM CDR Process for the CCS system, also has SO$_3$ control and High Efficiency System
## Summary of TEA Results

<table>
<thead>
<tr>
<th>Case</th>
<th>9</th>
<th>10</th>
<th>10b</th>
<th>10c</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plant Configuration</td>
<td>Subcritical PC w/out CCS</td>
<td>Subcritical PC w MEA CCS</td>
<td>Subcritical PC w KM CDR® CCS</td>
<td>Subcritical PC w KM CDR® CCS w heat integration</td>
</tr>
<tr>
<td>Avoided Cost /$/ton</td>
<td>$70.6</td>
<td>$58.5</td>
<td>$51.4</td>
<td></td>
</tr>
<tr>
<td>Total Overnight Cost /MM$</td>
<td>$1,098</td>
<td>$1,985</td>
<td>$1,800</td>
<td>$1,741</td>
</tr>
<tr>
<td>Cost of Electricity /mils/kWh</td>
<td>59.4</td>
<td>109.6</td>
<td>101.5</td>
<td>96.5</td>
</tr>
<tr>
<td>Percent Increase in COE from Case 9</td>
<td>-</td>
<td>98%</td>
<td>71%</td>
<td>62%</td>
</tr>
<tr>
<td>Percent Decrease in COE from Case 10</td>
<td>-</td>
<td>-</td>
<td>13.7%</td>
<td>18.0%</td>
</tr>
</tbody>
</table>
6. Summary
Summary – Energy Improvements

- Use of the HES can increase the generation of a 550-MW plant with CCS by 18.3 MW.

- Thermal efficiency can be increased by 0.9 percentage points (i.e. from 26.2 to 27.1%), alternately heat rate could decrease from 13,050 to 12,630 Btu/kWh.

- Pressure drop across the Flue Gas Cooler was measured to be 2-4 inWc.
• Boiler condensate water quality was found to be unaffected by the HES.

• Corrosion was found on the Flue Gas Cooler tubes. Corrosion may have been increased due to the lack of a flue gas purge.

• No plugging was found in the Flue Gas Cooler.

• Little to no \( \text{SO}_3 \) was measured in the flue gas, even during injection of \( \text{SO}_3 \).
Via the reduced flue gas temperature:

- ESP outlet flue gas particulate matter concentration decreased by 36%,
- ESP outlet flue gas mercury concentration decreased by 80%,
- ESP outlet flue gas selenium concentration decreased by 33-56%,
- Up to 65% of FGD makeup water can be saved, and
- 50-60% of CCS cooling water can be saved.
MOVE THE WORLD FORWARD