Post-Combustion CO$_2$ Capture with Low Cost Solid Sorbent Slipstream Testing
Project # DE-FE0012870

2016 NETL CO$_2$ Capture Technology Meeting
August 9, 2016

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Dr. Bob Copeland

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Project Objectives

• The objective is to develop solid sorbent capture technology that captures CO₂ at less than $40 per tonne w/o TS&M

• Demonstrate TDA’s sorbent technology under realistic conditions at 0.5 MWₑ (~10 tpd) scale to collect data necessary for scale up to next level plant

• Major Project Tasks
  • Design, construction, and operation of slipstream test unit to capture CO₂ from flue gas at the National Carbon Capture Center (NCCC)

• Successful project completion will move the technology along the commercialization road map towards slipstream demonstrations and multi MW installations by 2020-2025

DoE Project DE-FE0012870
Funding - Total Project $6,480,377
TDA’s Approach

TDA Research has developed:
- A low-cost, solid alkalized alumina adsorbent, and
- A CO$_2$ capture process designed around this process

TDA CO$_2$ Capture on Supercritical 550 MW plant
TDA’s Post Combustion CO₂ Capture

- **Process advantages:**
  - Low cost sorbent material
  - Regenerates with low pressure (inexpensive) steam
  - Operates at near isothermal conditions, ambient pressure
  - Does not require heat recovery from the solid sorbent
  - Uses counter-current operation to:
    - Maximize capture efficiency
    - Maximize sorbent loading

- **Patents filed July 2014**
  - Pending U.S. and PCT applications
  - Two applications have received notices of allowance

Heat of adsorption ranges from 3 kcal/mole at higher CO₂ concentrations of 10-14%, to 10.3 kcal/mole at CO₂ concentrations of 1-5%.
Simulated Moving Bed Process

- Slipstream project builds on previous DoE funded research
  - Contract #DE-NT0005497
  - $1,714,846 Project
- Investigated capture process in single fixed bed reactor
- Demonstrated continuous CO$_2$ capture in 8 bed bench-scale unit

![Diagram of Simulated Moving Bed Process]

Demonstrated in field testing with coal derived flue gas at Western Research Institute (Laramie, WY)
Project Scope

• **Budget Period 1: Optimization & Design**
  - April 2014 to Feb 2016

• **Budget Period 2: Construction & Installation**
  - March 2016 to May 2017

• **Budget Period 3: Operation**
  - June 2017 to Aug 2018
Progress to Date

- Redesigned a bench-scale apparatus to test and optimize the design of the slip stream unit we plan to build and test.
- Preliminary TEA carried out by University of California Irvine UCI (Nov 2014). Further analysis of improved (and demonstrated) process (Jan 2016) gave a CO$_2$ capture cost of $38.7/tonne, which meets DoE’s goal of capturing CO$_2$ at <$40/tonne without TS&M.
- Formal Process Hazard Analysis (PHA) on September 29-30, 2015, facilitated by the Process Improvement Institute.
- Completed Design Package for 0.5 MW$_e$ Pilot Unit and submitted it to DoE on Feb 10, 2016.
- Budget Period 1 Review March 7, 2016.
- Sorbent continues to advance in sorbent scale up.
- Further evaluation of process design trade-offs with improved sorbent.
- Subcontract awarded for pilot unit construction to Springs Fabrication, Inc.
Budget Period 1 Tasks

- **Task 1: Project Management**
- **Task 2: Preliminary Techno-Economic Analysis**
  - based on integration with a nominal 550 MW$_e$ greenfield supercritical plant
- **Task 3. Pilot Plant Design Optimization**
  - Process experiments to finalize process design
  - Basic Process Specification and Design
- **Task 4. Pilot Plant Detailed Design and Engineering**
  - Design a 0.5 MW$_e$ pilot plant to capture 10 tons per day of CO$_2$,
  - Perform an initial Environmental, Health and Safety (EH&S) study
  - Hazard Review
- **Task 5. Determine Slipstream Unit Construction Cost**
  - Develop a firm cost estimate for the slipstream unit
Design Optimization

- Process optimization in bench-scale unit conducted to determine optimum flow/cycling logic for pilot unit
  - Previous 8 bed apparatus had limited ability to simulate recycle options

- Multiple design improvements, modifications, and experimental tests

- The bench-scale experimental data for the optimal process was used for the preliminary TEA and as design basis for pilot unit
Multiple Bed Process Design

- **Multiple Fixed Bed Contactor**
  - Provides counter-flow contact between the solids and gases

- **Beds cycle between adsorption and regeneration functions**

- **Gas flows in parallel through adsorption beds and in series across regeneration beds**

- System expanded to 12 bed to increase stages and evaluate transition steps

- Separate control for transition
Features & Benefits of Multi-Bed Design

- Previous TDA bench-scale apparatus had 8 beds and limited ability to simulate recycle step options
- Bench-scale unit was rebuilt with 12 bed apparatus to allow evaluation of improved flow patterns and better simulation of slip stream unit/commercial system

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<th>Feature</th>
<th>Advantage</th>
<th>Benefit</th>
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<td>12 beds (vs. 8 beds)</td>
<td>Additional regeneration stages</td>
<td>• Additional stripping for same steam usage</td>
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<td>• Beds needed for transition steps</td>
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<td>• Trade-off of adding more beds</td>
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<td>Steam saver recycle with controlled flow and timing</td>
<td>Steam recycled back to regeneration side to rehydrate bed can be optimized in controlled manner</td>
<td>• Steam usage decreased</td>
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<td>• Steam saver can now be tuned for maximize benefit</td>
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<td>Purge</td>
<td>Additional regeneration</td>
<td>• Higher capture rate</td>
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<td>• Less steam usage</td>
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<td>Adsorption Breakthrough recycle</td>
<td>Effluent flue in last adsorption bed recycle back to feed to keep capture up</td>
<td>• This recycle option was not available in previous bench-scale apparatus</td>
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- TDA collected data to evaluate optimized process conditions and performance of recycles/purge steps
Flow Pattern Comparison Testing

- Collected data to evaluate optimized process conditions and performance of recyclers/purge steps
  - Optimum number of beds in adsorption and regeneration
  - Flow pattern options: steam saver, air strip, and breakthrough recycle
  - Flow direction up and down for steam saver and air strip
  - Time/flow for steam saver step
- Experimental results used in TEA
Preliminary Techno-Economic Analysis

• Integration with greenfield supercritical 550 MW coal fired power plant
  • Cost and Performance Baseline for Fossil Energy Plants (Black 2010) Case 12
• Analysis followed DoE guidelines
• Work performed with University of California at Irvine (UCI)
  • Dr. Ashok Rao of Advanced Power and Energy Group developed ASPEN model around process and determine cost of CO₂ capture
• TEA performed at start of BP1 based on performance at end of previous project (Contract #DE-NT0005497) and after process improvement in BP1
TEA on Improved Process

• Based on experimental data (SV, steam usage) for expanded process

• Boiler Feed Water used to heat flue gas (coal derived heat)

• Included costs of 12 beds, air blower, condenser on air purge outlet, boost flue gas for breakthrough recycle

• Very recent data shows further optimization of sorbent and process which we are analyzing in additional TEA

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<th>No Capture Case 11</th>
<th>Amine Capture Case 12</th>
<th>TDA</th>
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<td>Carbon Captured,%</td>
<td>0</td>
<td>90</td>
<td>90</td>
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<td>Steam Turbine Power, KWe</td>
<td>580,400</td>
<td>662,800</td>
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<td>Total Auxiliary Consumption, KWe</td>
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<td>Net Power Output, KWe</td>
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<td>% Net Plan Efficiency, HHV</td>
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<td>As-received coal feed, kg/h</td>
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<td>Natural Gas Feed, kg/h</td>
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<td>Raw Water Withdrawal, min³/min</td>
<td>20.1</td>
<td>38.1</td>
<td>34</td>
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<td>1rst year cost of electricity (COE), $/MWh, 2007$</td>
<td>58.9</td>
<td>100.9</td>
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<td>1rst year CO₂ capture cost w/o TS&amp;M, $/tonne, 2007$</td>
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<td>42.1</td>
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<td>1rst year CO₂ capture cost w/o TS&amp;M, $/tonne, 2011$</td>
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<td>46.9</td>
<td>38.7</td>
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Cost of CO₂ Captured = \( \frac{(COE_{\text{With cc}} - COE_{\text{Without cc}})}{CO₂ \text{ Captured}} \)

CO₂ Capture cost = $38.7/ tonne (2011 $)

• Design system (demonstrated in bench-scale experiments) meets DoE goal of CO₂ capture < $40/tonne without TS&M
**Pilot Unit**

- 0.5 MW$_e$ slip stream test with 5000 lb/hr of flue gas
- Adsorber/Regeneration Contractor is a multiple fixed bed unit
- Sorbent is regenerated by steam
- Adsorber/Regenerator operates near isothermal (adiabatically) at 120 to 140°C with about 17 psia steam
- Operation pressure is near atmospheric pressure
- Coal flue gas: 12.14% CO$_2$, 13.3% H$_2$O and 5.2% O$_2$
- Designed based on bench-scale experimental data

**4 Skid Mounted Units:**
- Two sorbent bed trailers
- **Service unit** (heat exchangers, blowers, flow metering, exhaust coolers)
- **Instrument unit** (control system and gas analysis)
Pilot Unit Design

2 Sorbent Bed Trailers
- Sorbent trailer houses sorbent beds and manifold piping
- Each trailer is insulated and heated to provide an isothermal environment within

1 Service Unit Trailer
- Pressure, temperature and flow control for each process gas
- Each process gas routed to both sorbent bed trailers

1 Instrument Unit
- Houses the control system and all electrical components for power allocation
- A full suite of on-board analyzers to evaluate system performance

System was planned to be located at NCCC Post-Combustion Pilot Bay #3

- Computational fluid dynamics (CFD) calculations to analyze flow paths and pressure drops through the sorbent beds.
- Design package submitted to DoE
A preliminary EH&S study was completed (June 2015) on the pilot plant operation and sorbent production.

- The sorbent is comprised of low hazard materials, primarily inorganic compounds. All are solids at ambient temperatures, and have low NFPA ratings for health, fire, and reactivity risk.
- The sorbent production process does not utilize any toxic or hazardous materials.
- Sorbent loading and unloading will be conducted in accordance with all relevant regulations with appropriate PPE to manage dust exposure.
HAZOP Review

• Before finalizing the Pilot Unit’s PI&Ds, TDA conducted a preliminary Hazard Review with NCCC on May 12, 2015.

• A detailed Failure Modes and Effect Analysis (FMEA) was also carried out at TDA to identify safety vulnerabilities and correct them in the design.

• A formal Process Hazard Analysis (PHA) was conducted on September 29-30, 2015.
  • Facilitated by Process Improvement Institute, Inc. with the National Carbon Capture staff in attendance
  • Used HAZOP analysis along with the What-If? methodology
  • All recommendations incorporated into Pilot Unit design
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Budget Period 2 Tasks

- Task 6. Sorbent Production Scale-up and Quality Assurance
  - Scale-up production of the sorbent to 30,000 lbs
    - Two producers had competitive prices for sorbent production
  - Sorbent is alkalized alumina - not exotic material
  - Sorbent QA/QC testing at TDA in bench-scale unit
  - Sorbent will be tested under proposed test conditions
  - Evaluation of optimum steady state conditions

- Task 7. Procurement of Components and Fabrication of Units
  - Construction of four skid-mounted units
  - Fabricator constructing skid structure, manifolds and beds on two sorbent trailers. Instrument unit will be built at TDA
  - Beds fabrication will be inspected prior shipment, control system shakedown on cold system, 30 days FAT testing
Budget Period 2 Tasks

- **Task 8. Finalize Test Plan**
  - Operating conditions and key parameter parametric conditions selected
  - Operator training

- **Task 9. Pilot Plant Installation at NCCC**
  - Units transported to NCCC
  - Skid Units installed
  - Beds filled with sorbent
  - Tie-ins with NCCC
Sorbent Production

- Contacted five companies about toll production of the sorbent
- Sorbent production cost ranged from $6.5/lb to $20/lb
- Based on discussions with the manufacturers, this sorbent could be made for $2/lb when the technology is commercialized and installed across the power plant sector
- Intermediate scale-up to 100 lb batches planned for September 2016, and then full production scale-up
Continued Progress

- During sorbent production scale-up research, the sorbent performance has continued to advance.

- We evaluated the improved sorbent and compared the trade-off with steam usage and process complexity.
  - TDA analysis showed the breakthrough recycle process step does not benefit overall process economics.
  - Increase in SV with some increase in regeneration steam usage looks promising.

- Four additional cases with UCI to define sensitivity of capital, operating cost and regeneration steam usage.
Sorbent Trailers and Gas conditioning units are being fabricated by Spring Fabrication, Inc. in Colorado Springs.

Instrument control unit is being fabricated at TDA.

System now planned to be located at NCCC Pilot Bay #2 ~42’ x 35’
Pilot Unit Skids

- Pilot Unit operates at ambient pressure with near isothermal operation at 140°C
• Two Sorbent Trailers (8.5 ft x 33 ft) each contain five cylindrical packed sorbent beds
Service Unit

- Service Unit controls the flow, pressure and temperature of the flue gas and steam to the sorbent beds.

Service Unit Skid (23 ft x 8ft)
Instrument Unit

- The instrument unit contains the control system, operator interface, and equipment for gas analysis.
- To calculate capture rate and sorbent loading we will continuously sample the flue feed, flue effluent and product stream
  - Measure total flow and gas composition
- We can also monitor the concentration of individual sorbent beds with a mass spectrometer to tune performance and optimize system operation
## Budget Period 3 Schedule

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<td>Task 14. Final H&amp;S Study</td>
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<td>Task 15. Update Techno-Economic Analysis</td>
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<td>Milestone 15-1: Complete Updated TEA</td>
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<td>Milestone 15-2: Year 3 Annual Review</td>
<td>8/31/2018</td>
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Budget Period 3 Tasks

• Task 10. Shakedown of slipstream unit.

• Task 11. Operation of Slipstream Unit
  • Demonstrate this process in slipstream testing at the NCCC under both parametric and steady state conditions using coal derived flue gas.

• Task 12. Post-Testing Sorbent Analysis
  • Characterize physical and chemical properties of sorbent after testing
  • Determine Sorbent cost, useful life and replacement rate

• Task 13. Slipstream Testing Data Analysis
  • Data from the pilot plant test will be used to develop recommendations for the next level of scale up
Budget Period 3 Tasks

• **Task 14. Update EH&S Study**
  - Update based on results of slipstream test
  - Review CO₂ capture process and sorbent manufacturing

• **Task 15 Update Techno-Economic Analysis**
  - Incorporate performance data from slipstream test into TEA and update results
  - Determine cost of electricity for TDA’s sorbent based CO₂ capture process
  - Compare to current state of the art technology
  - Work performed with UCI
Summary

- TDA has improved the multiple fixed bed CO$_2$ Capture process
  - New flow process demonstrated experimentally in our bench-scale apparatus
- Preliminary TEA showed Capture Cost of $38.7/tonne
- Experimental results form design based for 0.5 MW Pilot Unit
- Detailed design, HAZOP Review and Preliminary EHS review completed.
- Strong technical and economic merit established for conducting pilot unit test at NCCC
- Project is in Budget Period 2, focused on sorbent scale-up and fabrication
Acknowledgements

- Project funding provided under DoE Contract # DE-FE0012870
- Andy O’Palko
- Lynn Brickett