Bench-Scale Development & Testing of a Novel Adsorption Process for Post-Combustion CO₂ Capture

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About InnoSepra

- Started in 2007 by founders with 70+ years of industrial gas experience
- > 50 commercialized technologies in > 150 plants (20-2,000 tons per day) at BOC (> $10 B in sales in 2006)
  - PSA and TSA Air purification, UHP N₂ production for electronics, Nitrogen PSA, Oxygen PSA and VSA, CO₂ production and purification, and NOₓ control
- >> $100 million in value creation at BOC
- 110 U.S. and over 500 international patents at BOC, and two major technology awards
  - 2001 Kirkpatrick Award for an ozone-based NOₓ control process
  - 1997 Kirkpatrick Award for olefin / paraffin separation
- InnoSepra’s current focus is on CO₂ capture, removal of pollutants from power plant flue gas, biogas purification and reduction in water usage for power production
Executive Summary

- Physical sorption based process
  - Treats flue gas after the FGD
  - Produces dry CO$_2$ at high purity (>98%) and high recovery (~90%)
- Significant CO$_2$ capture improvement over MEA
  - >50% reduction in capital
  - >40% reduction in parasitic power
- Current DOE Project Goals
  - Demonstrate process at one ton per day scale
  - Document performance on real flue gas
  - Address the process risks
  - Effect of contaminants
  - Confirm process economics
The Project Overview
# Project Budget

<table>
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<th>Source</th>
<th>BP1 10/1/11-12/31/12</th>
<th>BP2 1/1/13-8/31/13</th>
<th>BP3 9/1/13-3/31/14</th>
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<tr>
<td>Dept of Energy</td>
<td>$850,187</td>
<td>$946,848</td>
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<td>Cost Share</td>
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<td>$155,000</td>
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<td>$1,101,848</td>
<td>$1,020,658</td>
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</table>
Project Participants

DOE/NETL
- Elaine Everitt (Project Manager), Lynn Brickett, Shailesh Vora, James Black, Angela Harshman and David Lang

InnoSepra
- Technology development at lab and pilot scale leading to commercial adoption (more than 25 technologies in more than 100 plants)

EPRI
- Process modeling, plant testing, economic assessment and cost share

NRG
- Field testing, commercial feedback and cost share

New Mexico State University
- Fundamental adsorption data

PNNL
- Environmental, Health & Safety (EH&S) assessment

Adsorptech
- Mechanical design, equipment costing and commissioning
Project Overview: Schedule

Tasks:

1. Project Management
2. Bench Scale Unit Oper Conditions
3. Heat & Mass Transfer Data
4. Contaminants Removal
5. Adsorption Isotherms
6. Process Model
7. Heat Transfer Design
8. Prelim Techno-economic Analysis
9. Prelim Bench Unit Design/Costing
10. Detailed Bench Unit Design
11. Fabricate Bench Unit
12. Mechanical Testing of Bench Unit
13. Field Installation
14. Field Testing
15. Decommission
16. Commercial Process Configuration
17. Updated Process Economics
18. EH&S Assessment
Project Objectives

The Overall Project Objective
• Demonstrate the effectiveness of the InnoSepra process in achieving at least 90% CO₂ removal with a potential pathway for no more than a 35% increase in LCOE

Specific Project Objectives
• Confirm the design basis for bench-scale testing based on lab scale results and process modeling
• Design, build and test the bench scale unit on actual coal-based flue gas (NRG, Indian River) at the one ton per day scale
• Perform process scale up and costing for installation of the technology at a commercial 550 MW power plant to estimate LCOE (Levelized Cost of Electricity) and CO₂ capture cost
Background Information
Sorption-Based CO$_2$ Capture

- **Capture CO$_2$ by physical sorption**
  - 140-240 kcal/kg (26-44 kJ/mol) heats of adsorption
    - Significantly lower than the total energy (heat of reaction + sensible heat + latent heat) for amine systems

- **Capture CO$_2$ by chemical reaction** with amine or carbonate based sorbents
  - 740-940 kcal/kg (136-174 kJ/mol) heats of reaction
  - Similar to the aqueous amine-based absorption systems
  - Ex. $\text{Na}_2\text{CO}_3 + \text{CO}_2 + \text{H}_2\text{O} \rightleftharpoons 2 \text{NaHCO}_3$
    - $\Delta H_{\text{rxn}} = -740 \text{ Kcal/kg (136 kJ/mol)}$ of CO$_2$
  - Possible degradation due to SO$_x$, NO$_x$, and O$_2$
  - May not result in energy savings compared to MEA
Effect of Adsorption Capacity on Regeneration Energy

<table>
<thead>
<tr>
<th></th>
<th>Carbonaceous adsorbent</th>
<th>Sodium carbonate adsorbent</th>
<th>Hypothetical Physical adsorbent</th>
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<tbody>
<tr>
<td>Net CO₂ Capacity, wt%</td>
<td>1.5</td>
<td>2.5</td>
<td>7.0</td>
</tr>
<tr>
<td>Adsorbent Density, lbs/ft³</td>
<td>30</td>
<td>50</td>
<td>40</td>
</tr>
<tr>
<td>Heat of Adsorption, kcal/kg CO₂</td>
<td>160</td>
<td>740</td>
<td>200</td>
</tr>
<tr>
<td>Adsorbent Sensible Heat, kcal/kg CO₂</td>
<td>700</td>
<td>420</td>
<td>150</td>
</tr>
<tr>
<td>Total Heat Required Excluding Vessel Heating, kcal/kg CO₂</td>
<td>860</td>
<td>1160</td>
<td>350</td>
</tr>
</tbody>
</table>

• Both high net CO₂ capacity and low heat of adsorption are needed to minimize parasitic power
• Flue gas pretreatment to remove moisture and SO\textsubscript{x} to <1 ppm each, adsorption at 25-40\degree\text{C} and regeneration at about 100\degree\text{C}

• High purity CO\textsubscript{2} (>98% CO\textsubscript{2}, <30 ppm O\textsubscript{2}) at ~90% recovery

• Key innovation is the combination of process and materials (physical sorbents) that provides performance similar to or better than reactive systems and a total regeneration energy requirement of less than 450 Kcal/Kg of CO\textsubscript{2}

• The key scale up challenges are likely to be engineering based
Comparison with MEA for DOE Baseline Study

Current Project Status
Project Scope

Budget Period I – Lab Testing & Design
- Lab scale process data, adsorption/desorption isotherms and heat and mass transfer rate measurements
- Identification of the adsorbents for the removal of contaminants
- Development of a rigorous process model
- Preliminary technical and economic feasibility study
- Preliminary design & costing of the bench scale unit

Go/No-Go Decision point

Budget Period II – Procurement and Construction
- Bench unit process and mechanical design and construction (~one tpd CO₂)
- Mechanical testing of the bench scale unit

Go/No-Go Decision point

Budget Period III – Installation, Testing and Evaluation
- Installation and testing at the NRG, Indian River coal fired power plant
- Final techno-economic assessment
- Preliminary technology EH&S risk assessment
Project Overview: Key Milestones

1. Identify two adsorbent materials based on CO₂ recovery and capacity ✔
2. Obtain heat and mass transfer data ✔
3. Obtain estimate of adsorbents for moisture and contaminants ✔
4. Obtain adsorption and desorption isotherms for the preferred adsorbents ✔
5. Develop a rigorous process model ✔
6. Preliminary Technical and Economic Feasibility Study ✔
7. Detailed engineering and mechanical design of the bench scale process unit ✔
8. Fabricate the bench scale unit
9. Commission the bench-scale unit
10. Bench-scale testing with flue gas from NRG’s Indian River Plant
11. Final Technical and Economic Feasibility study
Laboratory Testing of Preferred Sorbents

- For a CO₂ purity of >99% and a CO₂ recovery of >90%, net CO₂ capacities of over 6 wt% have been obtained for flue gas temperatures of 25-30°C and a feed CO₂ concentration of 15%

- Same or higher CO₂ purity, recovery and net loading compared to reactive adsorbents using materials with much weaker affinity for CO₂. Cycle modifications allow production of CO₂ with 10-30 ppm O₂.
Heat and Mass Transfer Data, Contaminants Removal

- Heat and mass transfer data were obtained for various process configurations and during various process steps.
- The heat transfer rates during the adsorption and regeneration steps are adequate for our process conditions and cycle times.
- Moisture and SO\textsubscript{X} removed to a level of <1 ppm each.
- The equipment size for moisture and SO\textsubscript{2} removal is much smaller than the equipment for CO\textsubscript{2} adsorption.
- The impact of SO\textsubscript{2} and moisture removal on LCOE and the CO\textsubscript{2} capture cost is small.
Representative Adsorption Isotherms

**N₂ on Material 1**

**CO₂ on Material 1**

**O₂ on Material 1**

- High isotherm CO₂ capacities (>14 wt%) at the feed conditions ($P_{CO₂}$ ~ 15 kPa, 30°C)
- Fairly high separation factors between CO₂ & N₂, and CO₂ & O₂ at the flue gas conditions
- Low heat of adsorption, 190 kcal/kg
Process Simulation Models

- Rigorous solution of coupled heat and mass transfer partial differential equations with both the in-house simulator and ASPEN Adsorption. EPRI is involved in modeling as well as in integration with the power plant.
  - The models have been modified to include the heat transfer equipment
- Single component adsorption isotherms and diffusivities from New Mexico State Data
  - Langmuir mixing rules to obtain the multicomponent isotherms from single component isotherms
- Lumped parameter model for mass transfer
  - Micropore, macropore and film diffusion resistances are combined
  - Overall mass transfer coefficient obtained by fitting the experimental data to the simulation
- The simulation is continued until a cyclic steady state is obtained
  - The simulation is computationally intensive, typically requiring more than three days for attainment of cyclic steady state
- The model has been validated with laboratory data and will be updated with data from larger test units to improve the predictions
  - The model is expected to be very useful for modeling heat transfer in full scale plants and for providing estimates of the thermal and electrical energy needed
Techno-economic Analysis

The Parasitic Power

• Electric power for the blower, various pumps and the CO$_2$ compressor
• Heat energy required for the removal of moisture & impurities and for CO$_2$ desorption
• Heat energy required for adsorbent and vessel heating

The Capital Cost

• Heating and cooling system cost including direct contact cooler, pumps, blowers and heat exchangers
• Adsorption system cost including adsorption vessels, switching valves, pumps and heat exchangers, electrical, controls, adsorbents, piping skids, shipping, engineering and installation
• CO$_2$ compression system cost including CO$_2$ compressors and interstage coolers
### Techno-economic Analysis for a 550 MW Supercritical PC Power Plant

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Estimated Capital Cost</td>
<td>$246 MM</td>
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<tr>
<td>Power consumption including compression</td>
<td>94 MW</td>
</tr>
<tr>
<td>Steam cost per 1,000 lb for the base plant</td>
<td>$5.83</td>
</tr>
<tr>
<td>Increase in steam cost with capture*</td>
<td>45%</td>
</tr>
<tr>
<td>Electricity cost for the base plant</td>
<td>$0.064/kWh</td>
</tr>
<tr>
<td>Increase in electricity cost with capture*</td>
<td>45%</td>
</tr>
<tr>
<td>CO₂ production rate, million tons/yr</td>
<td>3.5</td>
</tr>
<tr>
<td>CO₂ Recovery Cost**</td>
<td>$40.7/ton</td>
</tr>
</tbody>
</table>

*85% plant utilization factor

**Includes capital charge, maintenance, CO₂ transportation cost, and parasitic power. No increase in LCOE if CO₂ can be sold for this price.
Bench Scale Unit Skid Layout

Adsorption Skid

Heating and Cooling Skid
**Future Plans**

**Current DOE Project**
- Fabricate the Bench Scale Unit
- Install and commission at NRG’s Indian River plant
- Test with actual flue gas for 8-12 weeks
  - Vary feed flow, feed temperature and cycle time
  - EPRI sampling and evaluation of used adsorbents
- Set commercial unit process configuration
- Independent techno-economic analysis (EPRI)
- Prepare EH&S risk assessment (PNNL)

**Next Scale Up Phase**
- Testing at 0.5-2.0 MW scale and also address engineering challenges related to scale up
- Can be used to design up to 500 tpd CO₂ capture systems
- Pursuing other applications that can provide technology validation in commercial applications
Overall Accomplishments

• The InnoSepra CO₂ capture process combines several innovative features to reduce the capital and power cost of CO₂ capture

• It is possible to obtain very high recovery (~90%), and high purity (>99%) CO₂ with physical sorbents while meeting the EOR/sequestration oxygen specification (10-30 ppm O₂)

• $\Delta H_{ads} < 200$ Kcal/Kg, parasitic power < 450 Kcal/kg

• The capital cost and parasitic power estimates based on a detailed component level analysis indicate that we are close to DOE’s LCOE target (<35% increase) and the CO₂ cost target (<$40/ton)

• Field testing at the one ton per day scale will further validate the technology
Summary

- Physical sorption to produce dry CO₂ at high purity and high recovery from the flue gas after the FGD
- Capital and the parasitic power estimates based on an externally funded technology study and internal estimates indicate the potential for more than 50% reduction in capital and more than 40% reduction in parasitic power
- Significant progress has been made since the start of the DOE project validating some of the process data and the bench scale unit construction is underway
- Potential approaches to further decrease the cost of CO₂ capture have been identified
- The InnoSepra process can provide CO₂ at a cost and quality suitable for enhanced oil recovery (EOR) which can make CO₂ capture profitable even in the absence of climate legislation
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