Low-Cost Enzyme-Based Technology for Carbon Capture

2012 NETL CO₂ Capture Technology Meeting
July 11, 2012
Pittsburgh, PA
Luan Nguyen
Outline

- Project Highlights
- Codexis Company Background
- Codexis Approach to Carbon Capture
- Introduction to CodeEvolver™ Directed Evolution Technology
- Project Status
  - Bench-scale enzyme activity and stability results
  - Field pilot testing at NCCC
  - Aspen+ process modeling
- Techno-Economic Analysis
- Summary and Next Steps
- Acknowledgements
DOE Disclaimer

- A portion of this program is funded in part by the Advanced Research Projects Agency – Energy (ARPA-E), an agency of the United States Department of Energy, under Award Number DE-AR0000071.

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Project Highlights

Developed an **enzyme-based technology** (Gen 1) for carbon capture that, when compared with MEA based capture, could

1. Reduce CAPEX >$100M for PCCC plant
2. Increase net power production by >75 MWe (vs. ~550 MWe)
3. Enable a novel biocatalytic process for carbon capture w/
   \[
   \text{LCOE} = 97.0 \text{ mills/kWh}
   \]
   (41% LCOE increase vs. 85% increase from State-of-Art MEA process)

Field demonstrated pilot-scale CO₂ capture process with industrial flue gas at the National Carbon Capture Center in May 2012
About Codexis

We develop enzymes and microorganisms that enable cost-advantaged production of biofuels, bio-based chemicals, and pharmaceuticals

- Founded 2002
- HQ in Redwood City, CA
- 340 Employees

Revenue, $M’s

<table>
<thead>
<tr>
<th>Year</th>
<th>Pharma Product Sales</th>
<th>R&amp;D Funding</th>
<th>Guidance</th>
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<tbody>
<tr>
<td>2009</td>
<td>$83</td>
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<tr>
<td>2010</td>
<td>$107</td>
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<td>2011</td>
<td>$124</td>
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<tr>
<td>2012E</td>
<td>≥$124</td>
<td></td>
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Guidance: ≥$124

Our Core Assets

**CodeXyme™**
Cellulase
Enzymes to Enable 2nd Gen Fuels and Chemicals

**CodeXol™**
Detergent Alcohol
Bio-Based Chemicals For Consumer Products

**Pharma**
Established, Growing Pharma Business
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</table>

Our Partners & Customers

- **CodeXyme™** Cellulase
- **CodeXol™** Detergent Alcohol
- **Pharma**
  - MERCK
  - PFIZER
  - VERTEX
  - RANBAXY LABORATORIES LIMITED
  - DSM
Current solvent capture is either too slow or energy intensive

- Increases cost of electricity >85%, reduces power output by >30%

Solvents are used in large amounts and must be heated to release CO₂

Biological catalysts are very fast, but not stable under industrial conditions

Black Arrows: Gas
Blue Arrows: Solvent

Large solvent amount required

Significant heat required
**Codexis Approach to Carbon Capture**

- Carbonic anhydrase (CA) accelerates an otherwise negligible reaction.
- CA turnover rate up to 1 million CO₂ molecules/s/s \(^1\).
- A ‘biomimetic’ approach based on millions of years of evolution.

\[ \text{CO}_2 + \text{H}_2\text{O} + \text{MDEA} \rightarrow \text{HCO}_3^- + \text{MDEAH}^+ \]

<table>
<thead>
<tr>
<th>Low-Energy Solvent (^2)</th>
<th>(\Delta H_{\text{Des}}) (kJ/gmol)</th>
<th>(k_2 \times e^3) (M(^{-1}) s(^{-1})) @25°C</th>
<th>Degradation</th>
<th>Corrosion</th>
<th>(P^*_{\text{Solvent}}) (atm x 10(^3)) @40°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>MEA</td>
<td>84</td>
<td>6</td>
<td>High</td>
<td>High</td>
<td>0.1</td>
</tr>
<tr>
<td>MDEA</td>
<td>60</td>
<td>0.005</td>
<td>Moderate</td>
<td>Moderate</td>
<td>0.003</td>
</tr>
<tr>
<td>AMP</td>
<td>60</td>
<td>0.6</td>
<td>Low</td>
<td>Low</td>
<td>≈0.03</td>
</tr>
<tr>
<td>(K_2\text{CO}_3)</td>
<td>20</td>
<td>0.05</td>
<td>None</td>
<td>High</td>
<td>0</td>
</tr>
</tbody>
</table>

Soluble enzyme in an energy efficient solvent could enable a low-cost process for carbon capture.


Directed Evolution Strategy to create an enzyme that is adapted to perform in harsh environments.
Selecting Best CA for MDEA

Selection Criteria:
1. High activity in MDEA.
2. High thermo- and solvent-stability.
3. Can be produced economically.

Thermophilic CA:
- Very thermostable.
- Low activity and stability in high MDEA concentrations.

Human CAII:
- Good activity, low stability.

CA-102:
- Accelerates CO₂ absorption rate at modest concentrations (<1 g/L SF powder).
- Good thermostability.
- Produced economically.

**CO₂ Absorption Acceleration in 1 M MDEA at 40°C using 250 mg/L Enzyme in Reactor**

- Thermophilic CA
- Human CAII
- CA-102

**Carbonic Anhydrase (CA)**
CA Evolution: Tiered Screening Approach

1 High Throughput Screen
- Challenge at high T and/or solvent
- $\text{H}_3\text{O}^+$ consumption via colorimetric dye
- Spectrophotometric assay

2 Medium Throughput Screen
- Increasingly harsh conditions (e.g., solvent, T, time)

3 Biocatalysis
- Process emulation
- Low throughput

Refine for process relevant criteria

Stirred Cell Reactor (SCR)
• Created enzymes that increased rate of CO₂ capture >25-fold under industrial conditions (NCCC)
• Created enzymes with 10⁶-10⁷ increased stability with rates of catalysis of 10⁶ fold
• Now screening at temperatures higher than boiling point of water (107°C!)

\[
\text{CO}_2 + \text{H}_2\text{O} \rightarrow \text{HCO}_3^- + \text{H}^+
\]
Top performers were tested for activity after being challenged at 4.2M MDEA for up to 14-weeks at 50°C.

All of the variants tested were still active after the 14-weeks at 50°C.

Some variants retained up to 70% of their initial activity.
Evolved CA has high tolerant for flue gas contaminants SOx/NOx in 4.2 M MDEA at 50°C.

No observable effects from typical leachable metals from equipment/piping, etc.
Field Testing at the National Carbon Capture Center

**Objectives:**

- Demonstrate CA-accelerated process concept.
- Demonstrate enzyme performance:
  - Long-term stability with real flue gas (e.g., Mercury, SOx, NOx, Heavy Metals...)
  - Quantify mass transfer enhancement
- Collect engineering data for model validation.

**Codexis Test Unit – 10 kWe:**
- Gas flow rate – 400 SLPM
- Liquid flow rate – 2 LPM
- CO₂ removal ~150 kg CO₂/day

**Absorber column:**
- Diameter = 100 mm (4" ID)
- Packing Height = 6.3 m
- Packing type: 16 mm (5/8") Pall Rings
- Surface area: 350 m²/m³; efficiency ~10-15%

**Desorber tank (No packing):**
- Volume = 15 L
- Residence time = 30-60 sec
Absorber Module

Enzyme-Assisted Desorber

4” Abs. column

HeatXger Bank

Desorber Tank
CA-assisted MDEA process allows thermodynamically favorable operating conditions.

‘Novel’ Process Configuration w Enzyme-Assisted Desorption
Long-Term Stability under Industrial Flue Gas Conditions

- Stable enzyme performance after 6 days under industrial flue gas conditions (ie., Mercury, heavy metals, SOx, NOx, etc.) with ~0.2 g/L of CA.
- Stable desorber operation at $T_{\text{desorption}}=87^\circ\text{C}$
- Achieved solvent capacity for CO$_2$ removal, $\Delta \alpha \approx 0.2$ (mol CO$_2$/mol MDEA)
- No solid precipitation after 6 days of operation.
- Robust system operation with multiple start-up/shut-down cycles.
Enzyme Acceleration in Low-Energy Solvent

- Increased Mass Transfer Coefficient by ~20-fold with 0.2 g/L of CA under industrial conditions.
- Collected engineering data over wide range of conditions for Aspen model validation:
  - e.g., MDEA concentration (25-50wt%), CA loading (0-1 g/L), $T_{\text{abs}}$ (30-50°C), $T_{\text{des}}$ (85-95°C), L & G flow rates (to achieve 30-95% CO$_2$ capture).
• Codexis enzyme-based technology could significantly reduce CAPEX:
  - ~95% reduction in CO₂ absorber column size with low-energy solvent MDEA.
  - ~80% reduction in desorber volume without use of structure packings.
• Enzyme-assisted desorption could
  ▪ Reduce parasitic load by 20 - 40% vs. MEA, i.e., lower steam extraction requirement.
  ▪ Increase enzyme life-time and decrease solvent degradation rate, i.e., lower OPEX.
Nexant PC/Codexis PCC Plant Integration

- **Codexis to develop enzyme-base CO$_2$ capture models in Aspen**
  - Established heat and material balance, equipment sizing, PCC operating conditions, etc.

- **Plant integration by Nexant**
  - Developed an integrated design combining a PC and PCC plant.
  - Set-up a GateCycle model for the combined PC and PCC plant
  - Run the model to estimate the performance of the combined system

- **Cost Estimate and Economic Assessment by Nexant**
  - Estimated CAPEX and OPEX
  - Set-up a Power System Financial Model (PSFM) using financial parameters established by DOE
  - Estimated incremental levelized cost of electricity (LCOE) using the PSFM.
CA Enabling Low-Cost Biocatalytic Process for Carbon Capture

Low-cost CA-accelerated MDEA process for CO₂ capture w/LCOE = 97.0 mills/kWh

LCOE Break Down¹

<table>
<thead>
<tr>
<th>Description</th>
<th>LCOE (mills/kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DOE Case 11 w/o CO₂ Capture</td>
<td>69.0</td>
</tr>
<tr>
<td>DOE Case 12 with Econoamine CO₂ Capture</td>
<td>121.9</td>
</tr>
<tr>
<td>Codexis CA-accelerated MDEA (High Temp Desorption)</td>
<td>117.4</td>
</tr>
<tr>
<td>Codexis CA-accelerated MDEA (Low Temp Desorption)</td>
<td>97.0</td>
</tr>
</tbody>
</table>

¹ Escalated to 2010 dollars.
Techno-Economic Analyses (Con’t)

Codexis enzyme-based technology (Gen 1) for carbon capture could
- Reduce CAPEX by **146M $US** for PCCC plant
- Increase net power production by **78 MWe** (vs. ~546 MWe)

1 Assume N\textsuperscript{th} kind of plants w/o added process contingency, interest, or debt-to-equity penalties.
Summary

• Created enzymes that increased rate of CO$_2$ capture >25-fold under industrial conditions (NCCC).

• Created enzymes with $10^6$-$10^7$ increased stability with rates of catalysis of $10^6$ fold.

• Demonstrated successfully at pilot-scale of enzyme-based technology for carbon capture.

  - Highly stable enzyme performance under real industrial flue gas conditions.
  - No observable impacts from flue gas contaminants on performance.
Enzyme-Based Technology Provides Cost Savings

- Reduce CAPEX by **$146M** for PCCC plant
  - 90% reduction in CO₂ absorber column size
  - 80% reduction in desorber volume, eliminate the use of expensive packings

- Reduce energy consumption by ~30%
  - Increase net power production by **78 MWe**
  - Potential to use LP steam

- Provide Low-cost biocatalytic process for carbon capture w/LCOE = **97.0 mills/kWh**
  - ~ 41% increase in LCOE.
Next Steps

- Design and scale-up process/equipment for 0.1-0.5 MWe slip-stream demonstration.

- Continue to evolve enzyme via CodeEvolver™ for Gen 2 Biocatalyst/Technology with higher activity/stability and lower production cost.

- Engage with strategic commercialization partners.
Joint Development Agreement

CO₂ Solution and Codexis working exclusively together to validate enzyme catalysis for economical capture of CO₂

CO₂ Solution holds a number of issued patents for use of carbonic anhydrase (CA) for carbon capture
  • Enzyme-solvent formulations
  • Processes
  • Sector applications

Complements Codexis IP portfolio in enzyme evolution and optimized carbonic anhydrases

Selected CO₂ Solution Patents

<table>
<thead>
<tr>
<th>Patent #</th>
<th>Area of Carbonic Anhydrase (CA) CO₂ Capture Application</th>
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<tbody>
<tr>
<td>US 7,740,689</td>
<td>Amine solvents</td>
</tr>
<tr>
<td>US 7,596,952</td>
<td>Power plants</td>
</tr>
<tr>
<td>US 7,176,017</td>
<td>Triphasic reactor</td>
</tr>
<tr>
<td>US 6,524,843</td>
<td>Packed column system</td>
</tr>
<tr>
<td>US 6,908,507</td>
<td>Cement production</td>
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<tr>
<td>US 7,521,217</td>
<td>Thermally stable CA variants</td>
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<tr>
<td>US 7,514,056</td>
<td>Air fractionation / oxygen production</td>
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<tr>
<td>US 61/231038</td>
<td>CA on micro-particles</td>
</tr>
<tr>
<td>US 61/231037</td>
<td>Carbonate solvents</td>
</tr>
<tr>
<td>US 61/231039</td>
<td>Amino acid solvents</td>
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Intellectual Property generated under Award Number DE-AR0000071
  • 8 Subject Invention disclosures
  • 2 US provisional patent applications
  • 2 US non-provisional applications
  • 2 International applications
Validation of ARPA-E Investments in Breakthrough Technology

![Graph showing estimated LCOE over project timeline (Yr) comparing Gen 1 and Gen 2. Gen 1 experiences a 35% LCOE increase.]
Acknowledgements

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Codexis Labs Redwood City, CA
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Other factors that could materially affect actual results, levels of activity, performance or achievements can be found in Codexis’ Quarterly Report on Form 10-Q filed with the SEC on May 10, 2012, including under the caption “Risk Factors.” If any of these risks or uncertainties materialize, or if our underlying assumptions prove to be incorrect, actual results, levels of activity, performance or achievement may vary significantly from what we projected.

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