Low-Energy Solvents for Carbon Dioxide Capture Enabled by a Combination of Enzymes and Ultrasonics
Outline

- Novozymes Company Brief
- Project Overview
- Project Progress Summary
- Technology Descriptions and Test Results
- Plans for Future Testing and Development
Novozymes in Brief – World Leader in Bioinnovation
Producing large volume enzymes for industrial applications

1. Improving the production host
   Improving the microorganisms’ ability to produce more enzymes per m³ fermentation tank through genetic engineering

2. Optimizing the industrial production
   Traditional production optimization
   • Process optimization
   • Equipment optimization
   • Input optimization

3. Improving the enzyme produced
   Improving the efficacy of the enzymes through protein engineering to meet application conditions and process economy requirements

www.novozymes.com
Enzyme-catalyzed CO₂ Reaction Mechanism

Carbonic anhydrase catalyzes (increases kinetic rates) the hydration of CO₂ and dehydration of bicarbonate resulting in enhanced absorption and desorption of CO₂ into and out of a CO₂ absorber solvent.

Hydration / Absorption

H₂O + CO₂ ⇌ HCO₃⁻ + H⁺

Dehydration / Desorption

Zinc-hydroxide mechanism at the enzyme’s catalytic active site

3D structure of Human CAII
Project Overview

- DOE Project Manager: Andrew Jones
- Project Participants

- Total Project Budget: $2,088,643
  - FFRDC Share: $489,949
- Total Project Award: $1,598,694
  - DOE Share: $1,168,670
  - Total in-kind Cost Share: $430,024
Overall Project Objective

Complete a *bench-scale study* and corresponding full technology assessment to validate the potential in meeting the DOE Program Objectives of a *solvent-based post-combustion carbon dioxide capture* system that integrates

- a low-enthalpy, aqueous potassium carbonate-based solvent
- with an absorption-enhancing carbonic anhydrase enzyme catalyst
- and an ultrasonic-enhanced regenerator
- in a re-circulating absorption-desorption process configuration

**DOE Program Objectives**

Develop solvent-based, post-combustion technology that

- Can achieve ≥90% CO₂ removal from coal-fired power plants
- Demonstrates progress toward the DOE target of <35% increase in LCOE

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*Problem:* How can we design a solvent-based, post-combustion carbon dioxide capture system that meets the DOE Program Objectives?  

*Solution:* Complete a bench-scale study and corresponding full technology assessment to validate the potential in meeting the DOE Program Objectives of a solvent-based post-combustion carbon dioxide capture system that integrates a low-enthalpy, aqueous potassium carbonate-based solvent, with an absorption-enhancing carbonic anhydrase enzyme catalyst, and an ultrasonic-enhanced regenerator in a re-circulating absorption-desorption process configuration.

*DOE Program Objectives:* Develop solvent-based, post-combustion technology that can achieve ≥90% CO₂ removal from coal-fired power plants and demonstrates progress toward the DOE target of <35% increase in LCOE.
Conceptual Process Design

- **Advantages**
  - Low enthalpy, benign solvent (catalyzed aq. 20% $\text{K}_2\text{CO}_3$)
  - Potential for $\sim$50% regeneration energy vs. MEA

- **Challenges**
  - Demonstrate atmospheric regeneration at 70°C
  - Demonstrate overall techno-economic feasibility (energy demand and enzyme requirement)
Project Schedule

- Task 1 – Project Management and Planning
- Task 2 – Process optimization
  - Ultrasonic Unit Optimization
  - Solvent & Enzyme-Solvent Compatibility Optimization
  - Solvent Physical Properties & Kinetic Measurements
  - Design Integrated Bench-Scale System
- Task 3 – Initial Technical & Economic Feasibility
- Task 4 – Bench Unit Procurement & Fabrication
- Task 5 – Unit Operations Shakedown Testing & Integration
- Task 6 – Bench-scale Testing
- Task 7 – Full Technology Assessment
# Project Progress Summary – Budget Period 1

<table>
<thead>
<tr>
<th>Key Milestone</th>
<th>Success Criteria</th>
<th>Risk</th>
<th>Performance achieved so far</th>
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<tbody>
<tr>
<td>Optimize Ultrasonic Regeneration conditions</td>
<td>Ultrasonics achieves lean loading equivalent to vacuum stripping at 70°C</td>
<td>Rectified diffusion does not sufficiently enhance CO₂ gas release</td>
<td>Achieved 30% of CO₂ desorption working range target</td>
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<tr>
<td>WWC measurements demonstrate Catalyzed Solvent Kinetics</td>
<td>Enzyme-solvent kinetics are ≥ 50% versus 30 wt% MEA under same process conditions</td>
<td>Absorption kinetics do not meet the target</td>
<td>Milestone mass transfer achieved</td>
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<tr>
<td>Complete Preliminary technical and economic Feasibility Study</td>
<td>Study supports the technology could be a lower cost option</td>
<td>Estimated power requirements exceed target threshold</td>
<td>In progress</td>
</tr>
<tr>
<td>Additional Milestone – Enzyme Compatibility with ultrasonics</td>
<td>Enzyme activity Pass/Fail</td>
<td>Enzyme not compatible with required ultrasonic field</td>
<td>Enzyme passed initial ultrasonics stress test</td>
</tr>
<tr>
<td>Additional Milestone – Enzyme Assay Automation</td>
<td>Implement assay</td>
<td>Continue using resource - intensive manual method</td>
<td>Microtiter format assay developed and implemented</td>
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Ultrasonics Regeneration Mechanism

- Create a population of seed bubbles above a critical radius via a ultrasonic cavitation in the liquid
- Bubbles expand and shrink in an ultrasonic field
  - Expanding bubbles = lower pressure/ higher surface area
  - Shrinking bubbles = higher pressure/ lower surface area
- Rectified diffusion results when expanding bubbles allow for a biased transfer of dissolved gas into the bubble from solution
  - Frequency optimization likely required due to its impact on the threshold pressure, and bubble growth
- Remove bubbles grown via rectified diffusion before they can dissolve back into the liquid
PNNL’s Lab Ultrasonic Desorption System Schematic

- System allows for introducing ultrasonic power while maintaining temperature to within 2°C.
PNNL’s Lab Ultrasonic Desorption System

- Gas Exit w/ Condenser
- Vessel
- Temperature Controlled Bath
- Ultrasonic Horn (inverted horn configuration)
- Solvent Recirculation Lines
Photographs of Ultrasonic Desorption

- Pure Water at 70°C – With Sonication
- Loaded Solvent at 70°C – No Sonication
- Loaded Solvent at 70°C – With Sonication

Significant agitation/bubbling observed when ultrasonic power added to CO₂ loaded 20% K₂CO₃ solution at 70°C
Video of Ultrasonic Desorption
Ultrasonic Regeneration – Lab Test Results

- Achieved approximately one third of the 2.1 wt% CO₂ desorption working range target
- 40% of the released CO₂ from ultrasonic effect, the rest from heat
- Slow CO₂ release rates observed
  - Significant CO₂ re-dissolution suspected
  - Kinetic improvements expected with optimization
Enzyme Compatibility with Ultrasonic Treatment

- **Enzyme tolerates initial ultrasonic tests** with no apparent loss of activity
- **Automated enzyme assay was developed** for use throughout the project
UK-CAER Wetted Wall Column Schematic

Measures gas to liquid flux
UK-CAER Mass Transfer Results

- Solvent: aq. 20% K₂CO₃ + carbonic anhydrase
- Achieved Initial Milestone Enzyme-catalyzed Solvent Kinetics (Mass Transfer)
Foundation for Bench-scale CO$_2$ Capture Process

Mini-scrubber evaluation tool (0.61 m x 3.81 cm) packed absorber column

0.1 MW$_{th}$ coal flue gas CO$_2$ capture pilot plant
Doosan Power Systems offers:

- Advanced amine scrubbing technology
- Partnership with the University of Regina for solvents (specialists in CO$_2$ capture since 1987)
- Full EPC carbon capture plant capability
- Optimisation with the full plant
- Development centre based in Renfrew with 100 engineers and scientists

Boundary Dam
Operated since 2000

Emissions Reduction Test Facility, Renfrew

Ferrybridge/CC Pilot 100+
Start of operations: November 2011

Nov 2011 | Corporate Presentation
Approach to Model Development

1. Develop the Boiler Turbine Generator Model with Flue Gas treatment (ThermoFlow™) based on NETL Case 9


3. Cost estimation of the PCC process to be performed using AspenTech Process Economic Analyser (PEA)

4. Initial feasibility and sensitivity studies to be performed based on the fixed coal feed rate as per Case 10 (MEA) for the enzyme enhanced K₂CO₃ solvent.

5. Perform the final Techno-economic assessment by integrating the PCC process for a net 550 MWe power plant island.
Preliminary Feasibility Study – Key Progress

- Estimation of the costing model for NETL Case 9 analysed to identify key assumptions.
- The PCC process has been modelled based on Case 10 (MEA).
  - Analysis underway to identify key process parameters such as L/G ratio, column sizes, rich and lean loadings etc.
- Current solvent
  - A preliminary Aspen simulation has been set up for the $\text{K}_2\text{CO}_3$ case.
  - The initial feasibility study will be performed using a vacuum stripping process to mimic the ultrasonic desorption.
- Initial cost-estimation calculations provide a promising outlook for the process, including technical challenges to overcome.
Plans for Future Testing and Development

- **Current Budget Period**
  - Continue ultrasonic desorption optimization in lab scale
    - Run vacuum stripping test to better quantify the comparison case
  - Continue absorption mass transfer kinetics enhancement tests
  - Stress-test enzyme at expected bench-scale design limits
  - Design integrated bench-scale system
  - Finalize preliminary feasibility study

- **Next Budget Periods**
  - Proceed to bench-scale build, testing & Technology Assessment

- **Next Project**
  - Scale-up beyond bench-scale depends on
    - Bench-scale Full Technology Assessment
    - Possible need for further component development
Thank You

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