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

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DOOSAN

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NATIONAL LABORATORY
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UK
UNIVERSITY OF KENTUCKY
Center for Applied Energy Research

DE-FE0007741
NETL CO_2 Capture Technology Meeting
July 10, 2012

2012-13073-03

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

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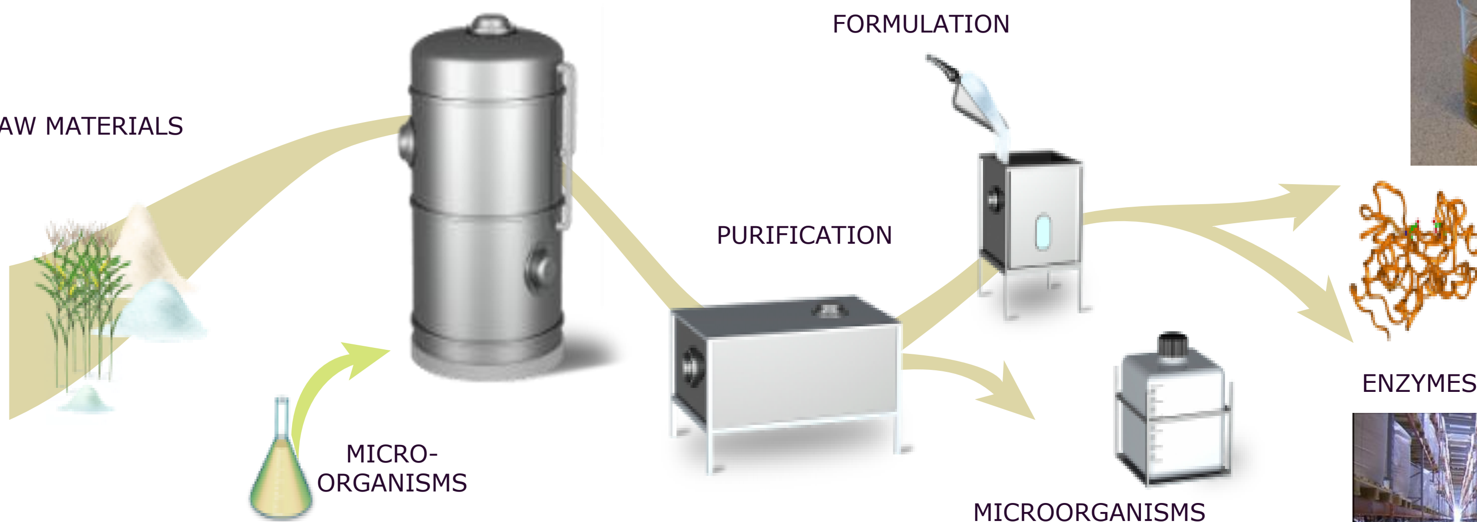
1. Improving the production host
Improving the microorganisms' ability to produce more enzymes per m^3 fermentation tank through genetic engineering

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

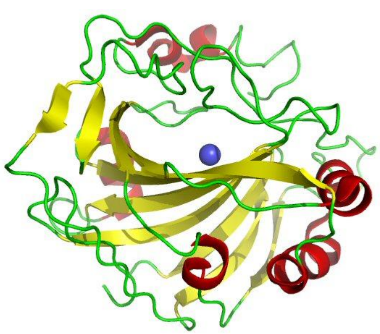
Enzyme-catalyzed CO_2 Reaction Mechanism

Carbonic anhydrase catalyzes (increases kinetic rates) the hydration of CO_2 and dehydration of bicarbonate resulting in enhanced absorption and desorption of CO_2 into and out of a CO_2 absorber solvent.

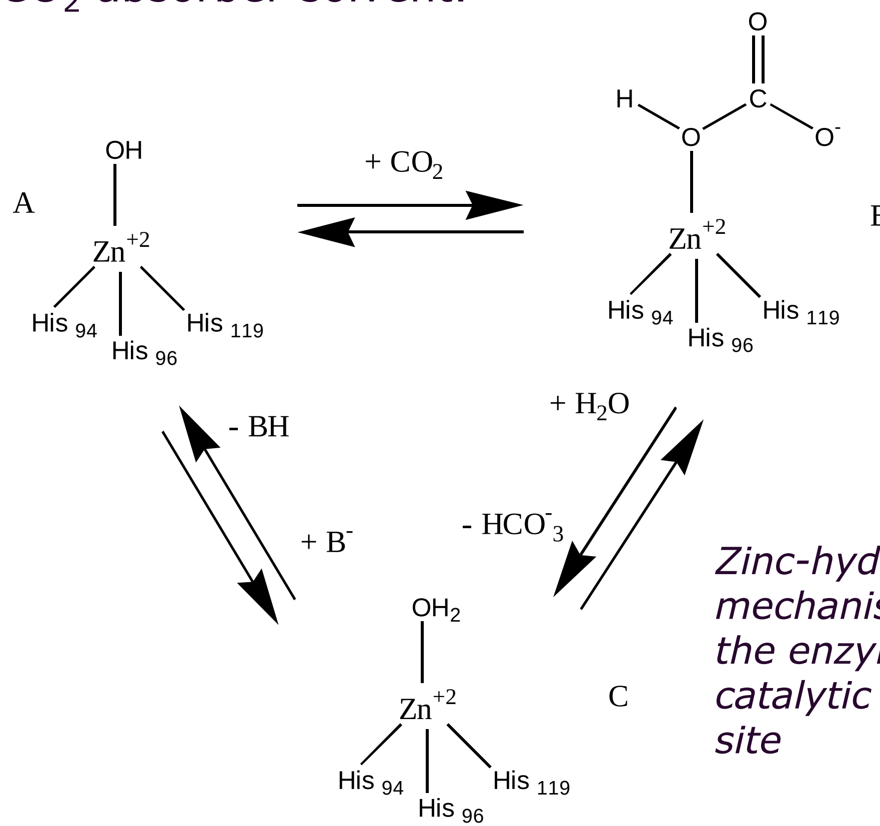
Hydration / Absorption

$$H_2O + CO_2 \underset{}{\overset{CA}{\rightleftharpoons}} HCO_3^- + H^+$$

Dehydration/ Desorption



3D structure of Human CAII



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

Project Overview

- DOE Project Manager: Andrew Jones
- Project Participants

Pacific Northwest National Laboratory	Doosan	Novozymes	University of Kentucky Center for Applied Energy Research
Ultrasonics & Aspen®	Full Process Analysis	Enzymes & Solvents	Kinetics & Bench-scale Tests

- Project Duration: Oct. 1,2011 – Dec. 31, 2014

- 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

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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

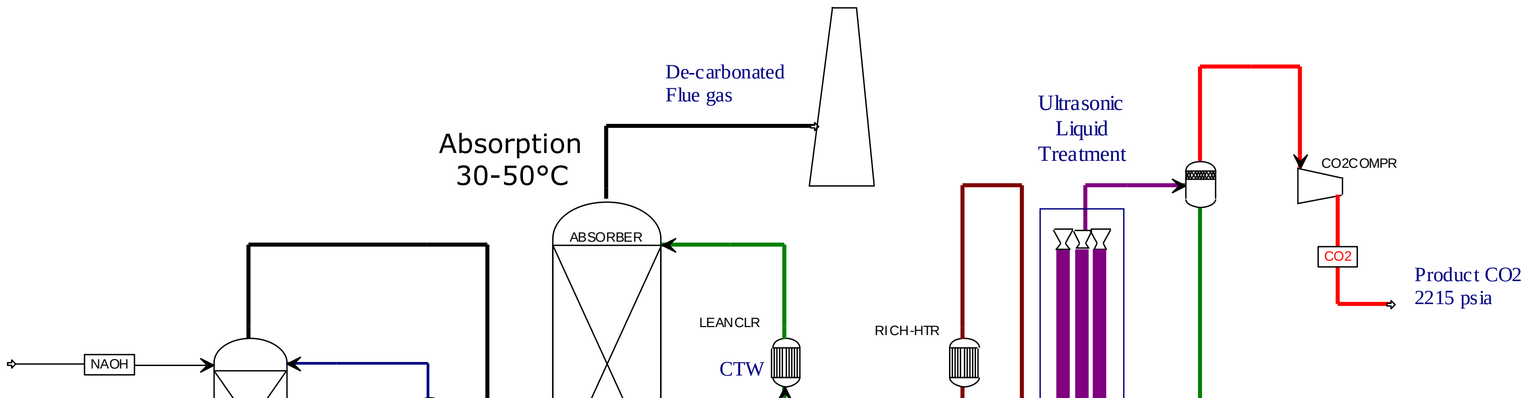
- a low-enthalpy, aqueous potassium carbonate-based solvent
- with an absorption-enhancing carbonic anhydrase enzyme catalyst
- and an ultrasonic-enhanced regenerator
- in a re-circulating absorption-desorption process configuration

DOE Program Objectives

Develop solvent-based, post-combustion technology that

- Can achieve ≥90% CO_2 removal from coal-fired power plants
- Demonstrates progress toward the DOE target of <35% increase in LCOE

Conceptual Process Design



- *Advantages*
  - Low enthalpy, benign solvent (catalyzed aq. 20% K_2CO_3)
  - Potential for ~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

BP1 09/2012

- Task 4 – Bench Unit Procurement & Fabrication
- Task 5 – Unit Operations Shakedown Testing & Integration
- Task 6 – Bench-scale Testing
- Task 7 – Full Technology Assessment

BP2 09/2013

BP3 12/2014

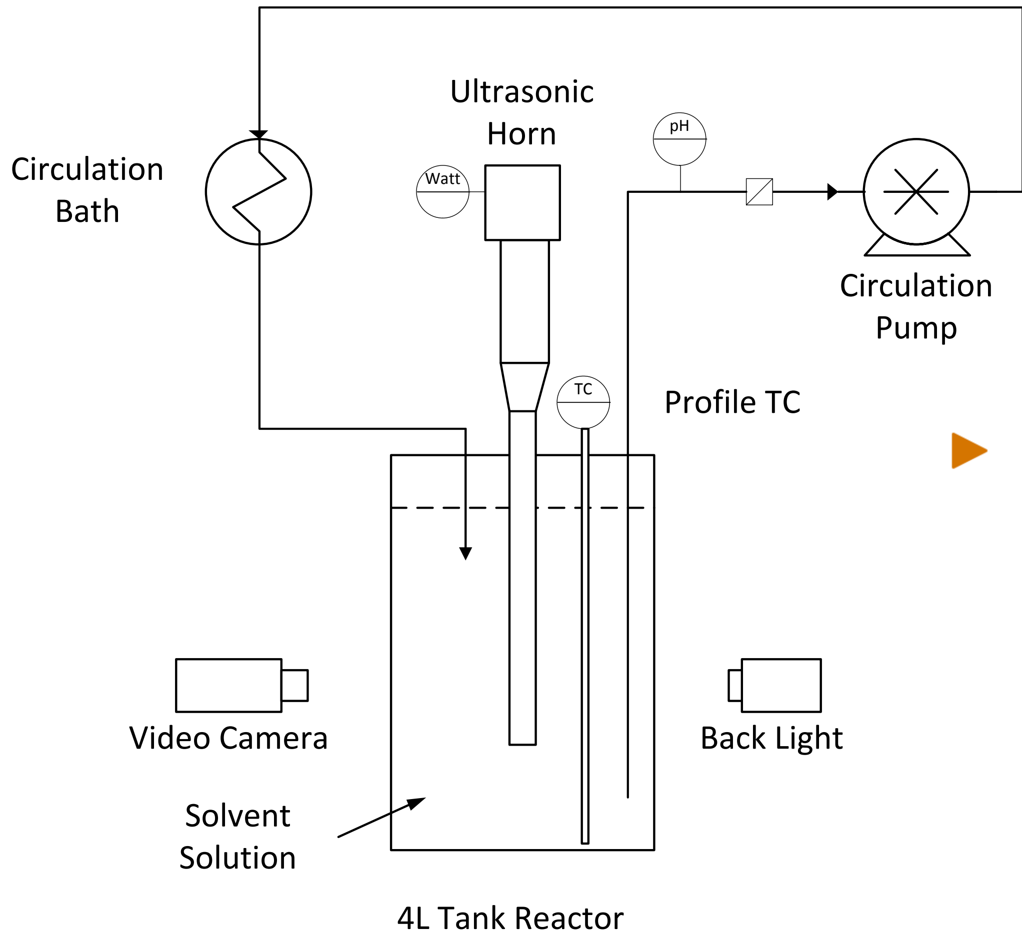
Project Progress Summary – Budget Period 1

Key Milestone	Success Criteria	Risk	Performance achieved so far
Optimize **Ultrasonic Regeneration** conditions	Ultrasonics achieves lean loading equivalent to vacuum stripping at 70°C	Rectified diffusion does not sufficiently enhance CO_2 gas release	Achieved 30% of CO_2 desorption working range target
WWC measurements demonstrate **Catalyzed Solvent Kinetics**	Enzyme-solvent kinetics are ≥ 50% versus 30 wt% MEA under same process conditions	Absorption kinetics do not meet the target	Milestone mass transfer achieved
Complete **Preliminary** technical and economic **Feasibility Study**	Study supports the technology could be a lower cost option	Estimated power requirements exceed target threshold	In progress
Additional Milestone – **Enzyme Compatibility** with ultrasonics	Enzyme activity Pass/Fail	Enzyme not compatible with required ultrasonic field	Enzyme passed initial ultrasonics stress test
Additional Milestone – **Enzyme Assay** Automation	Implement assay	Continue using resource - intensive manual method	Microtiter format assay developed and implemented

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^{o}C.

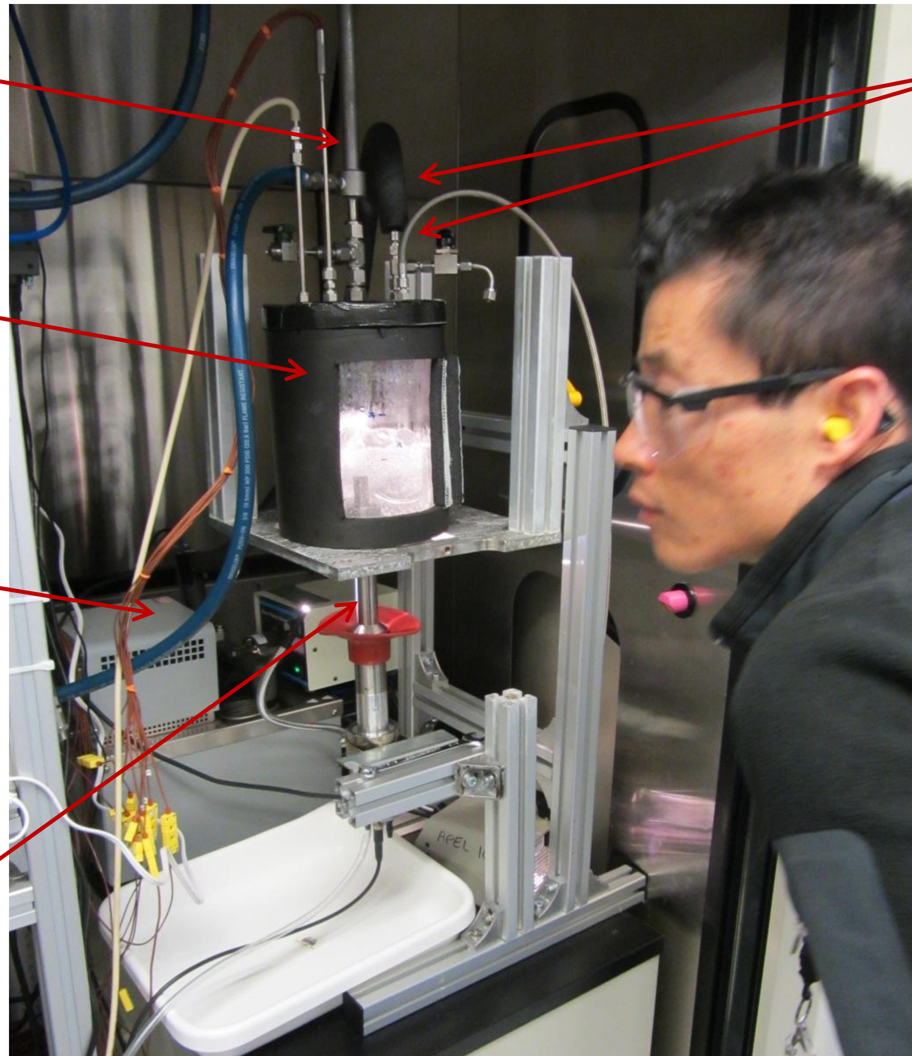
PNNL's Lab Ultrasonic Desorption System

Gas Exit w/ Condenser

Vessel

Temperature Controlled Bath

Ultrasonic Horn
(inverted horn configuration)



Solvent Recirculation Lines

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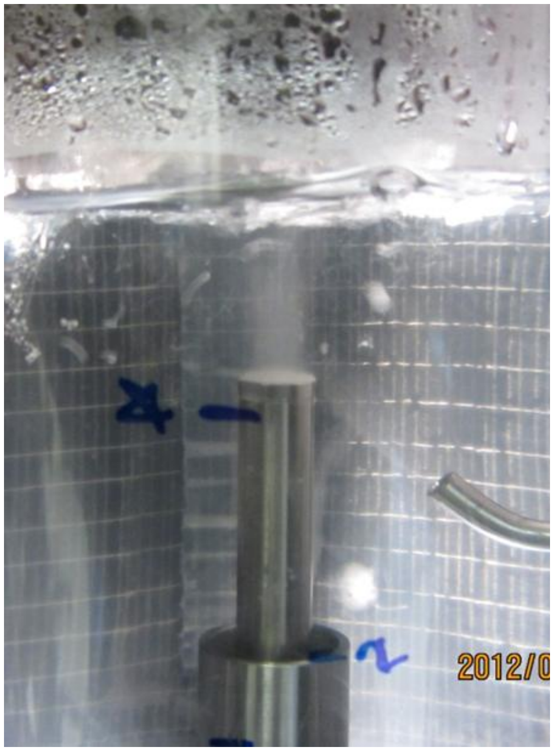
Photographs of Ultrasonic Desorption



Pure Water at 70°C – With Sonication

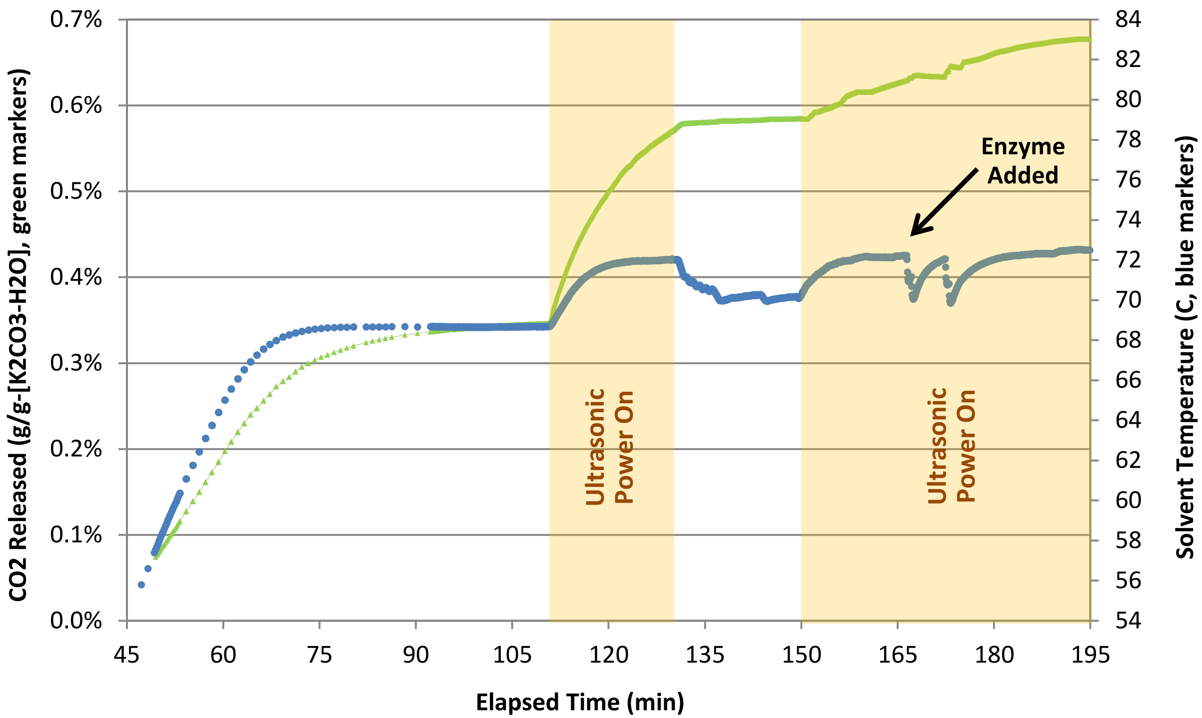
Loaded Solvent at 70°C – No Sonication

Loaded Solvent at 70°C – With Sonication

Significant agitation/ bubbling observed when ultrasonic power added to CO_2 loaded 20% K_2CO_3 solution at 70°C

Video of Ultrasonic Desorption

Ultrasonic Regeneration – Lab Test Results



- **Achieved approximately one third of the 2.1 wt% CO_2 desorption working range target**
- 40% of the released CO_2 from ultrasonic effect, the rest from heat
- Slow CO_2 release rates observed
  - Significant CO_2 re-dissolution suspected
  - Kinetic improvements expected with optimization

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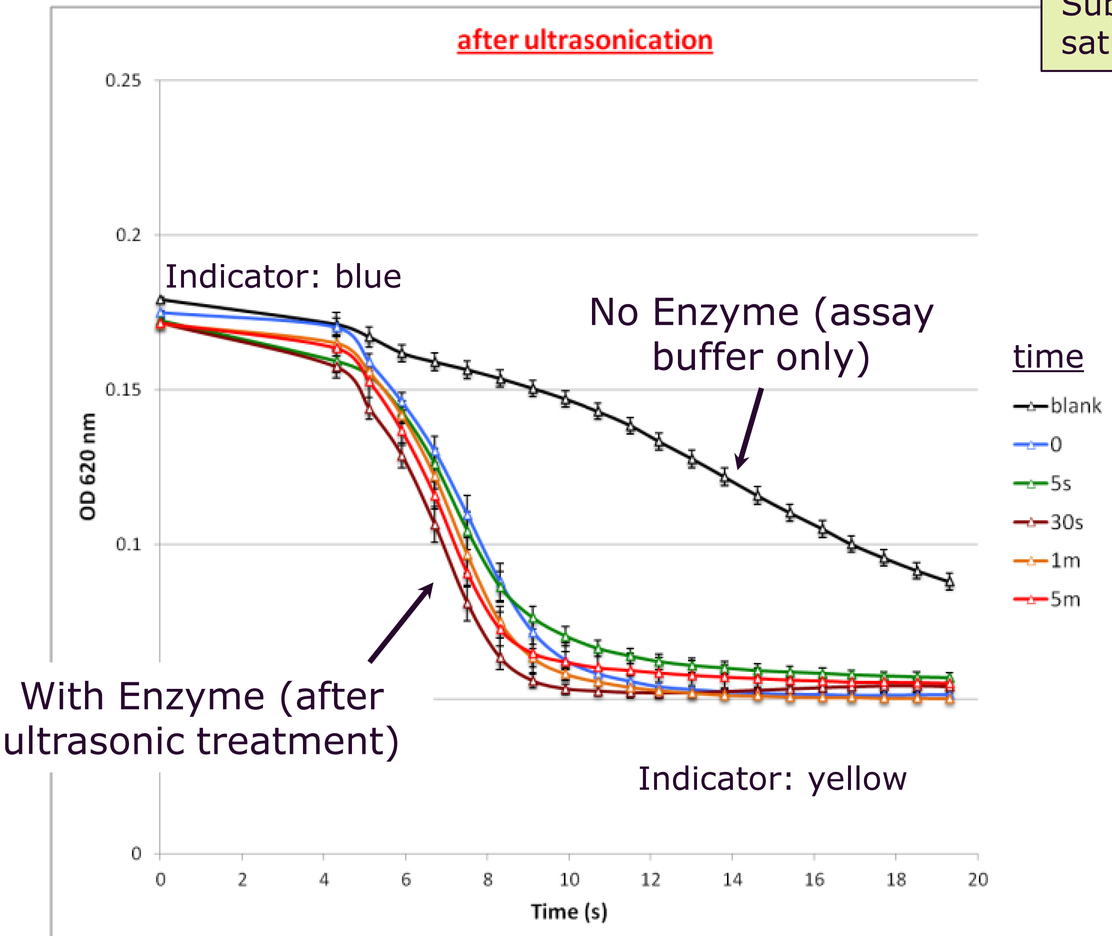
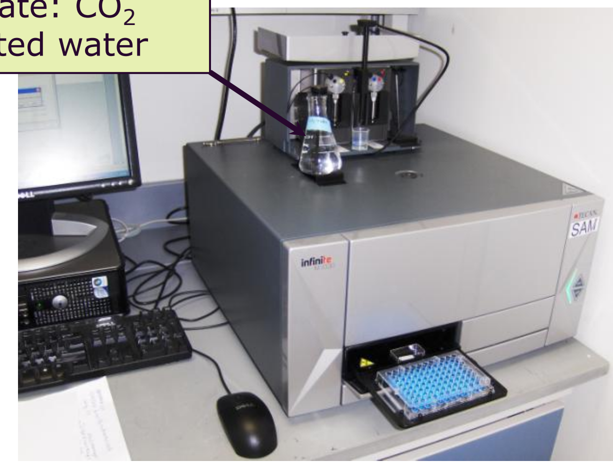
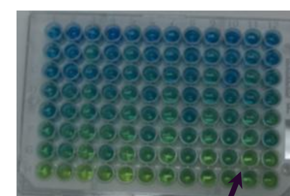
Enzyme Compatibility with Ultrasonic Treatment



Substrate: CO_2 saturated water



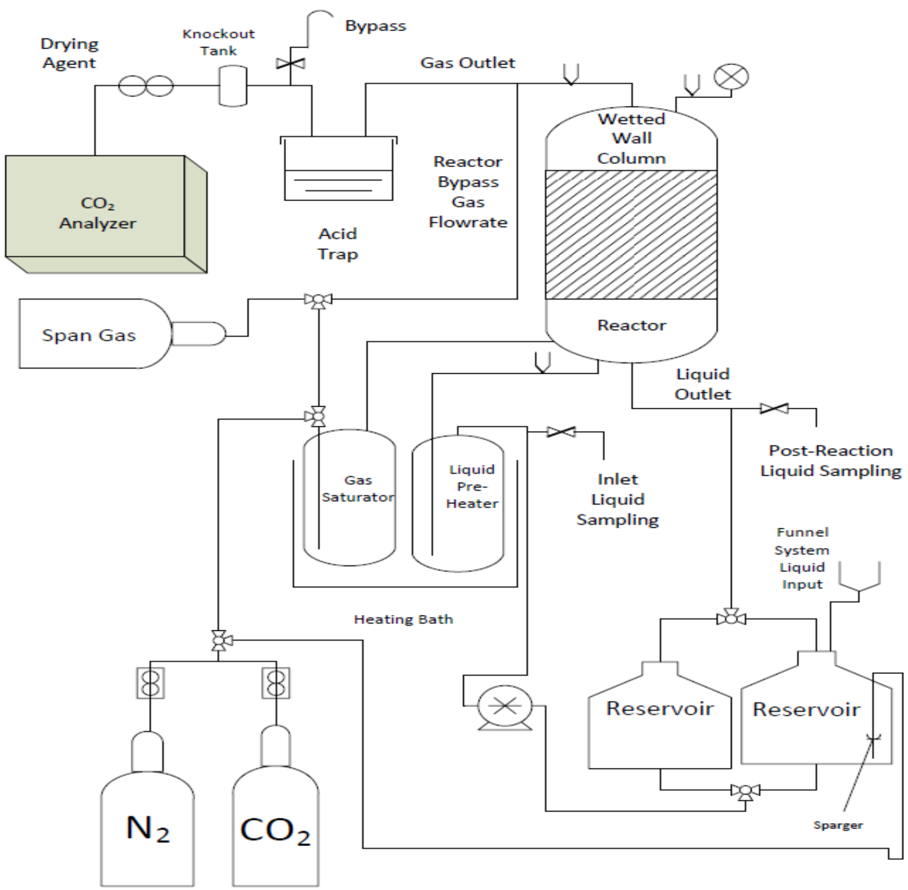
Indicator color changes due to pH decrease when CO_2 is hydrated to bicarbonate



$$CO_2 + H_2O \overset{CA}{\leftrightarrow} H^+ + HCO_3^-$$

- **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

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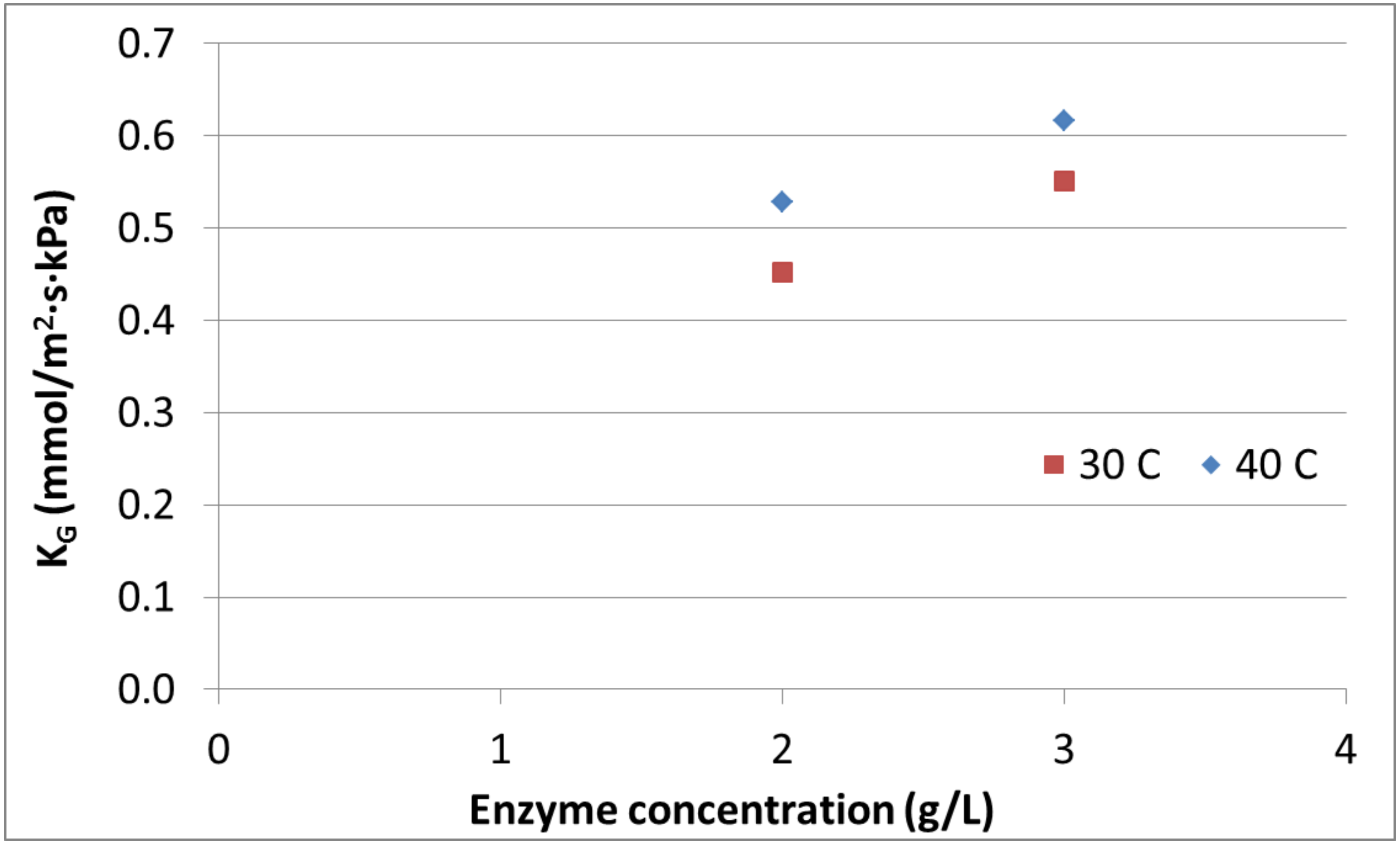
UK-CAER Mass Transfer Results



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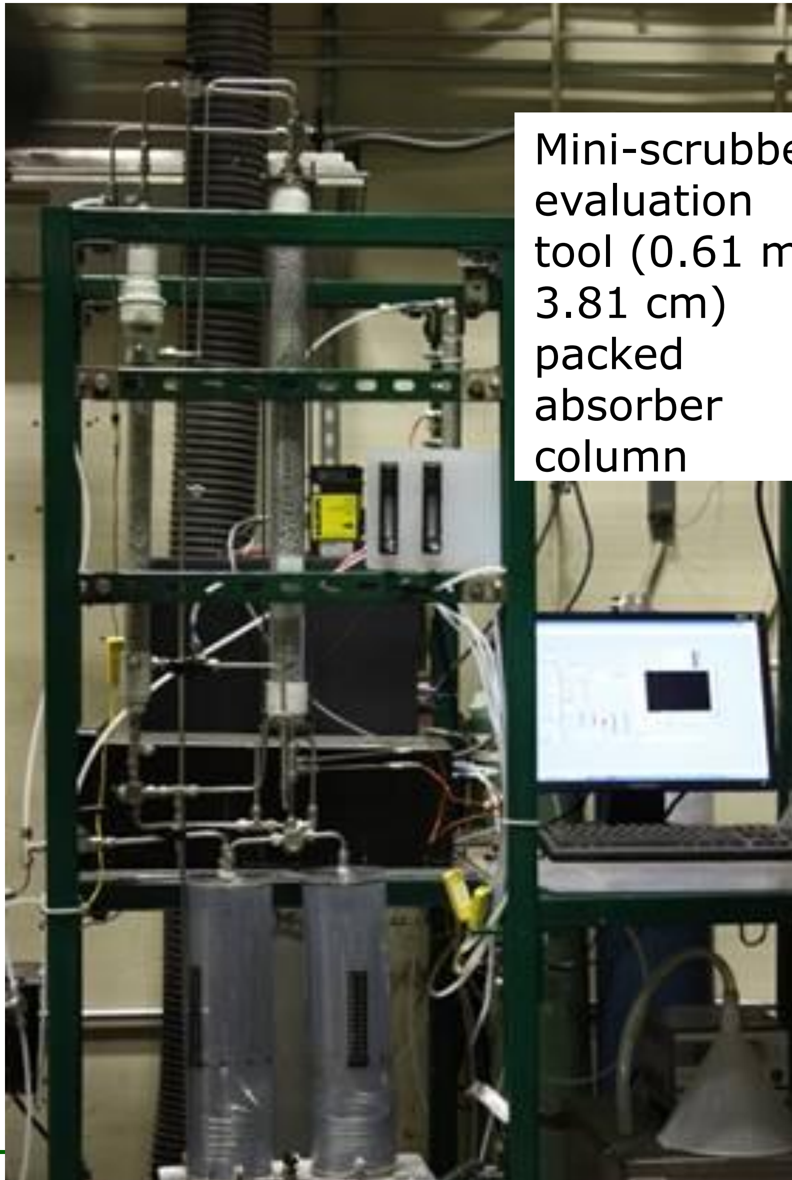
- Solvent: aq. 20% K_2CO_3 + carbonic anhydrase
- **Achieved Initial Milestone Enzyme-catalyzed Solvent Kinetics (Mass Transfer)**

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

Post-Combustion CO_2 Capture

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

Approach to Model Development

1. Develop the Boiler Turbine Generator Model with Flue Gas treatment (ThermoFlow™) based on NETL Case 9
2. Modeling of the PCC process (including compression) using Aspen Plus®.
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 K_2CO_3 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 K_2CO_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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