Proven Products. Real Results.

Low-Cost Enzyme-Based Technology for Carbon Capture

2012 NETL CO_2 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

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DOE Disclaimer

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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 **$US** for PCCC plant
2. Increase net power production by >**75 MWe** (vs. ~550 MWe)
3. Enable a novel biocatalytic process for carbon capture w/

   LCOE = **97.0 mills/kWh**

   (41% LCOE increase vs. 85% increase from State-of-Art MEA process)

Field demonstrated pilot-scale CO_2 capture process with industrial flue gas at the National Carbon Capture Center in May 2012

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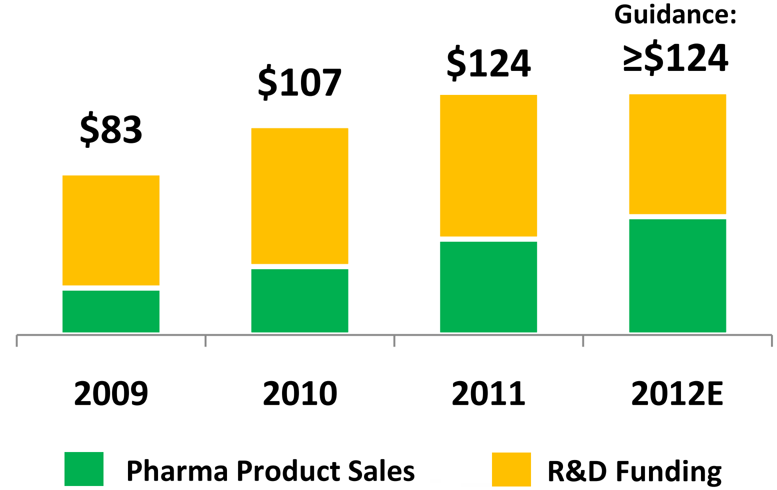
About Codexis

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



Our Core Assets

CodeXyme™ Cellulase	CodeXol™ Detergent Alcohol	Pharma
Enzymes to Enable 2nd Gen Fuels and Chemicals	Bio-Based Chemicals For Consumer Products	Established, Growing Pharma Business

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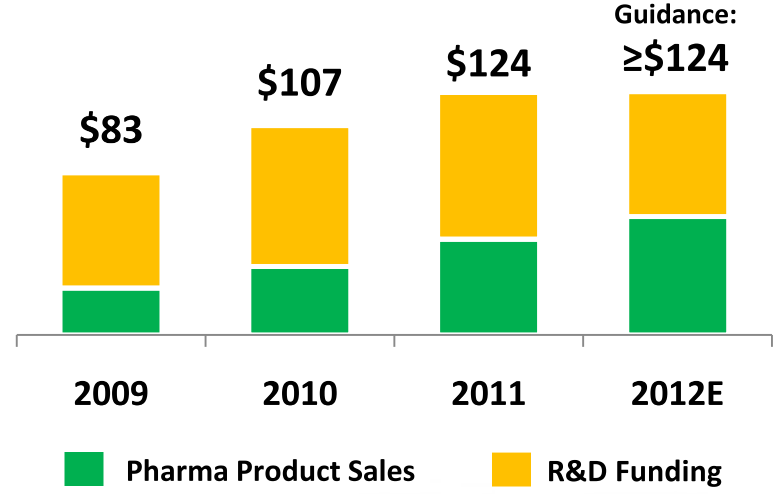

Our Partners & Customers

CodeXyme™
Cellulase
Shell
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CodeXol™
Detergent Alcohol
Chemtex
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Pharma
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Pfizer
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Arch
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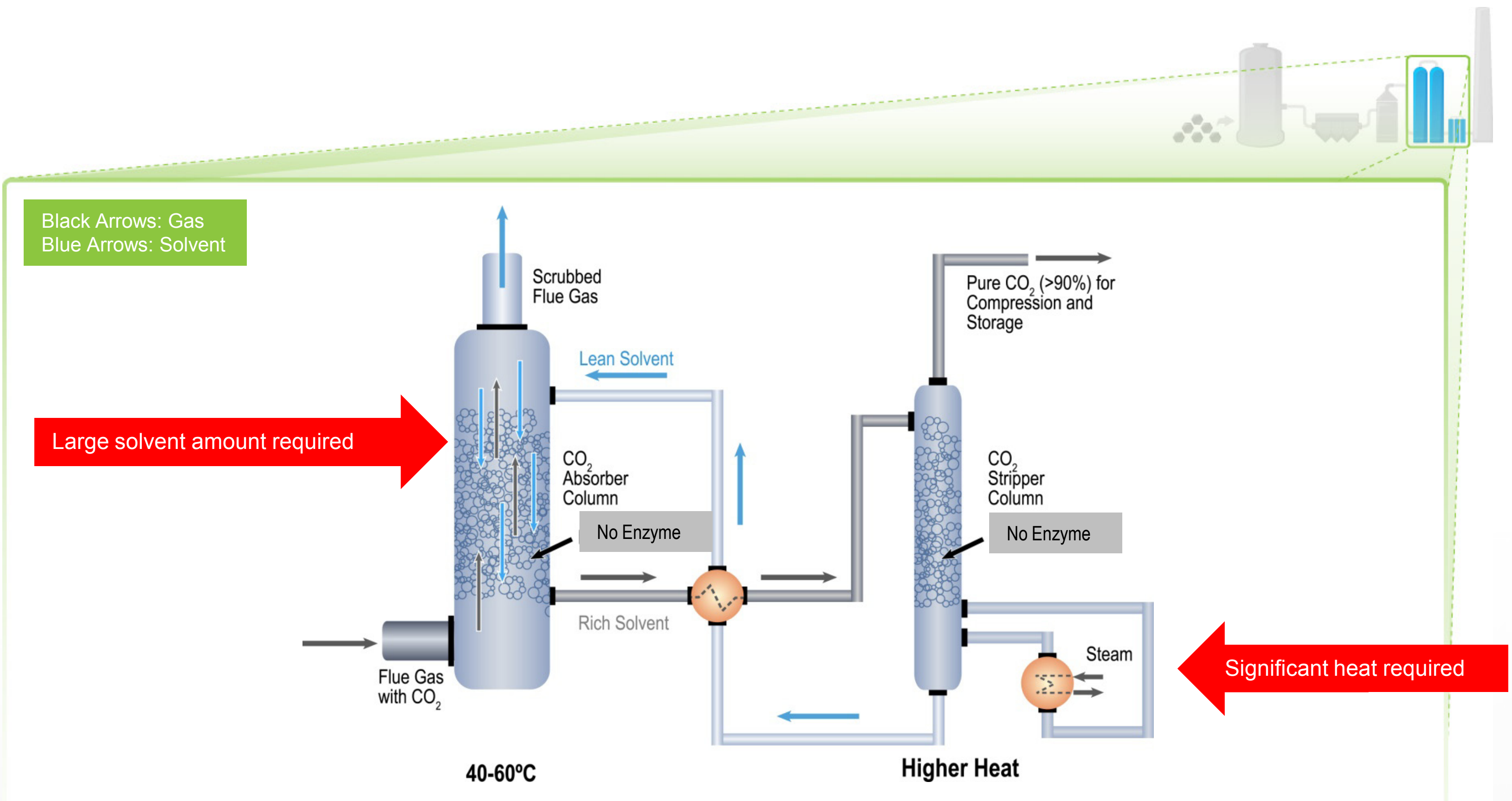
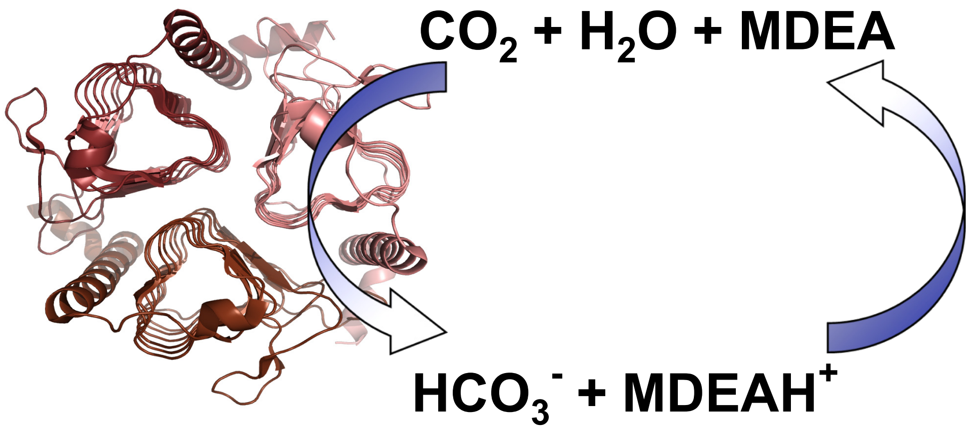
Current Capture Technology is Costly



- ❑ 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 CO_2
- ❑ Biological catalysts are very fast, but not stable under industrial conditions

Codexis Approach to Carbon Capture



- Carbonic anhydrase (CA) accelerates an otherwise negligible reaction.
- CA turnover rate up to 1 million CO_2 molecules/s/s [1].
- A 'biomimetic' approach based on millions of years of evolution.

Low-Energy Solvent[2]	ΔH_{Des} (kJ/gmol)	$k_2 \times e^3$ ($M^{-1} s^{-1}$) @25°C	Degradation	Corrosion	$P^*_{Solvent}$ (atm x 10^3) @40°C
MEA	84	6	High	High	0.1
MDEA	60	0.005	Moderate	Moderate	0.003
AMP	60	0.6	Low	Low	≈0.03
K_2CO_3	20	0.05	None	High	0

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

[1] Khalifah, R.; Silverman, D. N., Carbonic Anhydrase Kinetics and Molecular Function, The Carbonic Anhydrase In Plenum Press: New York, 1991; pp 49-64.

[2] Extracted from G. Rochelle, "CO_2 Capture by Aqueous Absorption/Stripping", Presentation to MIT Carbon Sequestration Forum VII, October 31,2006.

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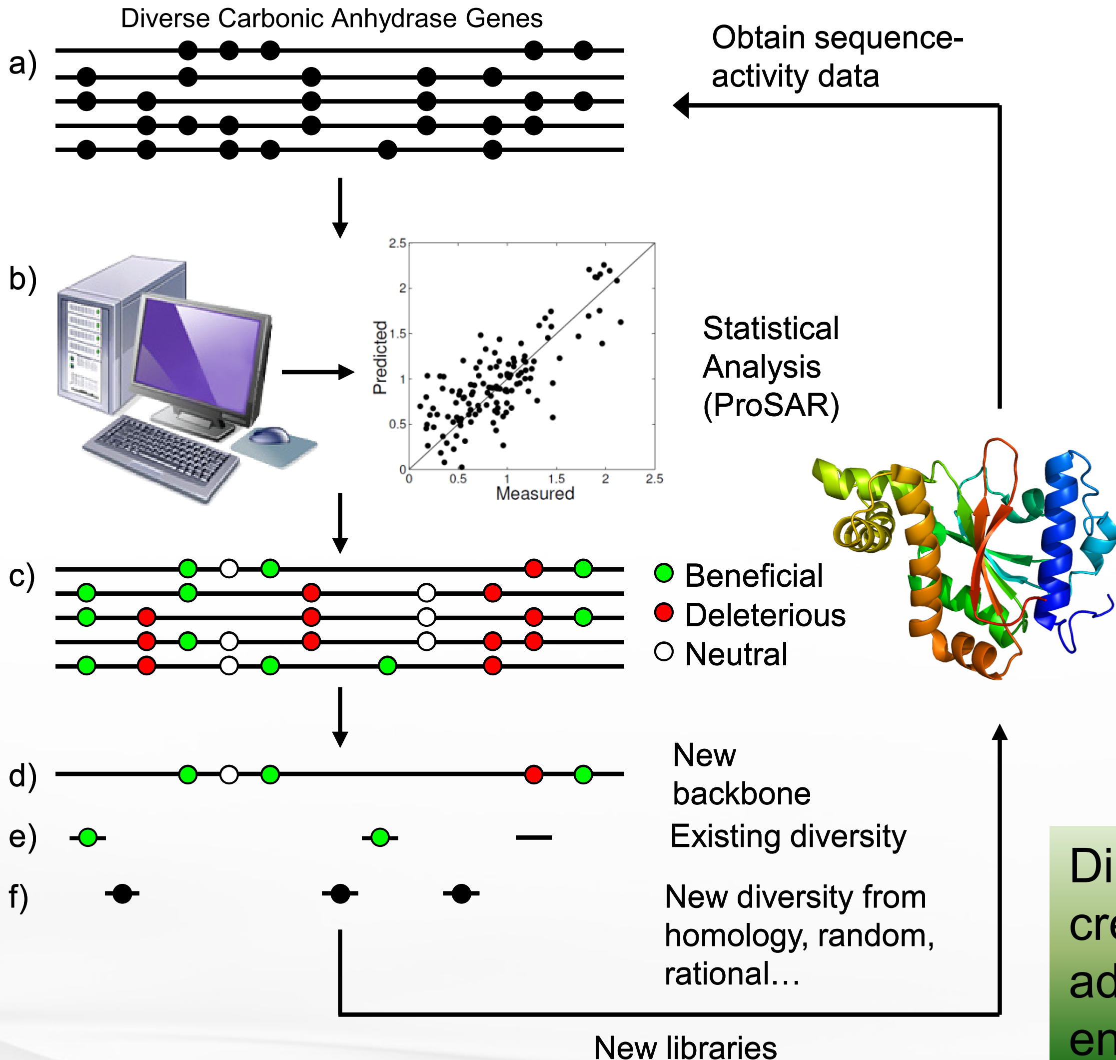
Codexis Directed Evolution Technology

CODEXIS CodeEvolver™



$CO_2 + H_2O$

$\rightleftarrows$

$HCO_3^- + H^+$

- Solvent
- pH
- Temperature
- Inhibitors

Screen under process-relevant conditions

Directed Evolution Strategy to create an enzyme that is adapted to perform in harsh environments

Fox & Huisman TibTech 2008

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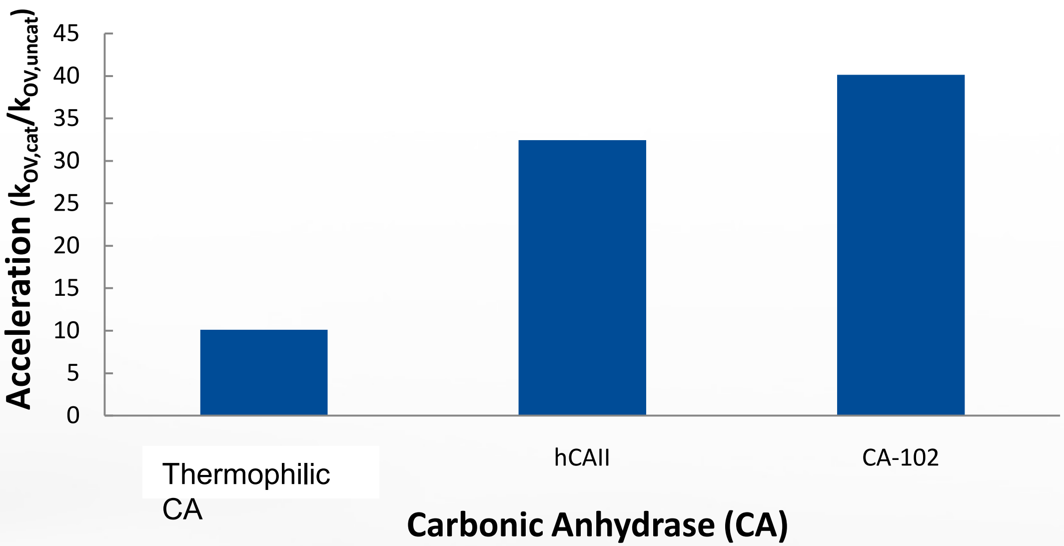
Selecting Best CA for MDEA

Selection Criteria:

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

CO_2 Absorption Acceleration in 1 M MDEA at 40°C using 250 mg/L Enzyme in Reactor



Thermophilic CA:

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

Human CAII:

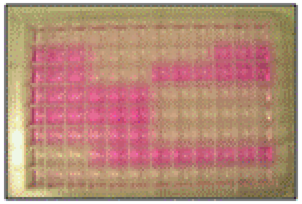
- Good activity, low stability.

CA-102:

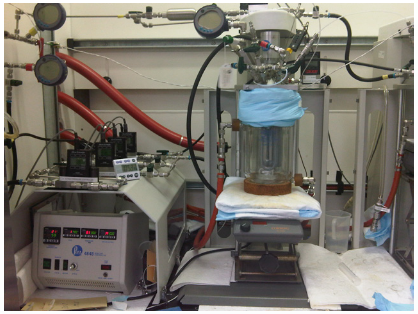
- Accelerates CO_2 absorption rate at modest concentrations (<1 g/L SF powder).
- Good thermostability.
- Produced economically.

CA Evolution: Tiered Screening Approach

1 **High Throughput Screen**
- Challenge at high T and/or solvent
- H_3O^+ consumption via colorimetric dye
- Spectrophotometric assay

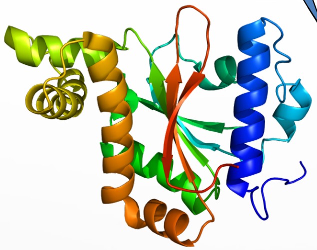


2 **Medium Throughput Screen**
- Increasingly harsh conditions (e.g., solvent, T, time)



Stirred Cell Reactor (SCR)

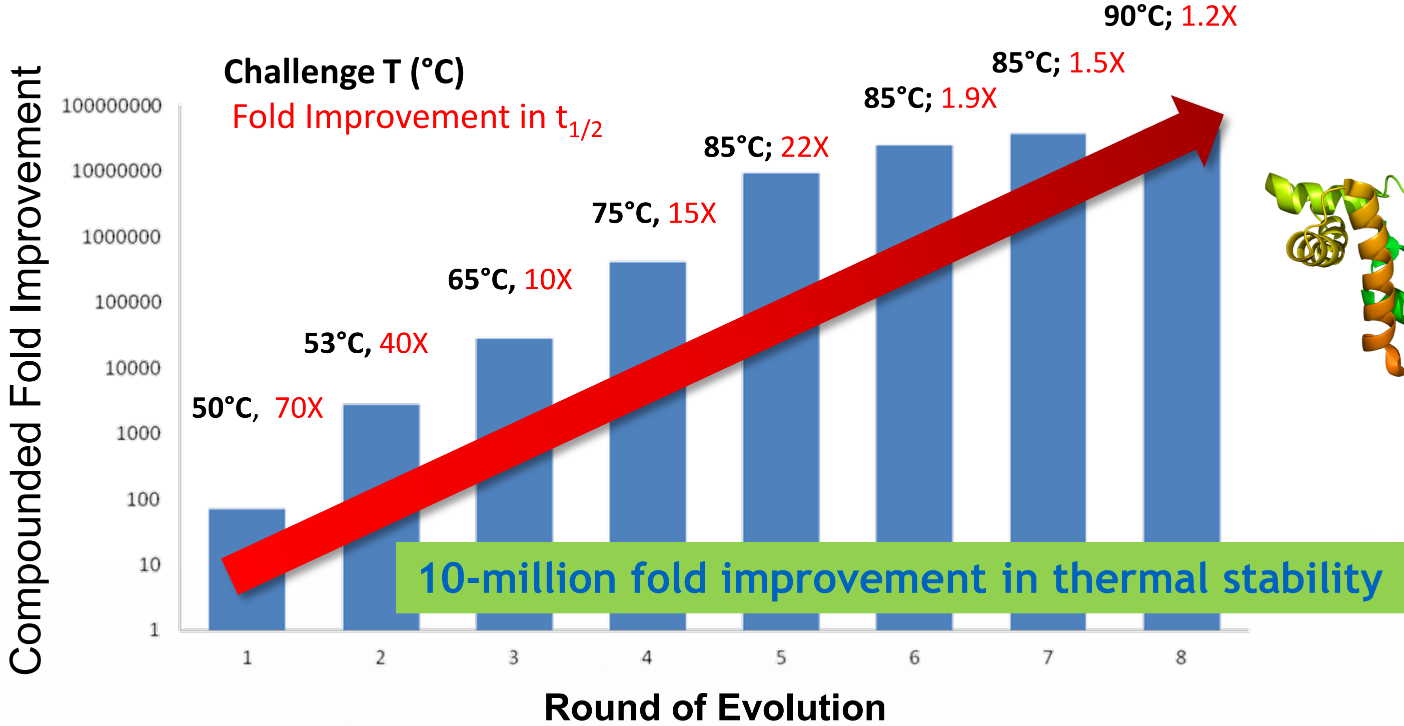
Refine for process relevant criteria

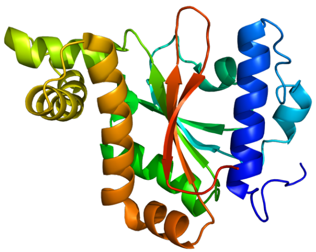


3 **Biocatalysis**
- Process emulation
- Low throughput

Pilot Plant

CodeEvolver™ Biocatalyst for Accelerated Carbon Capture



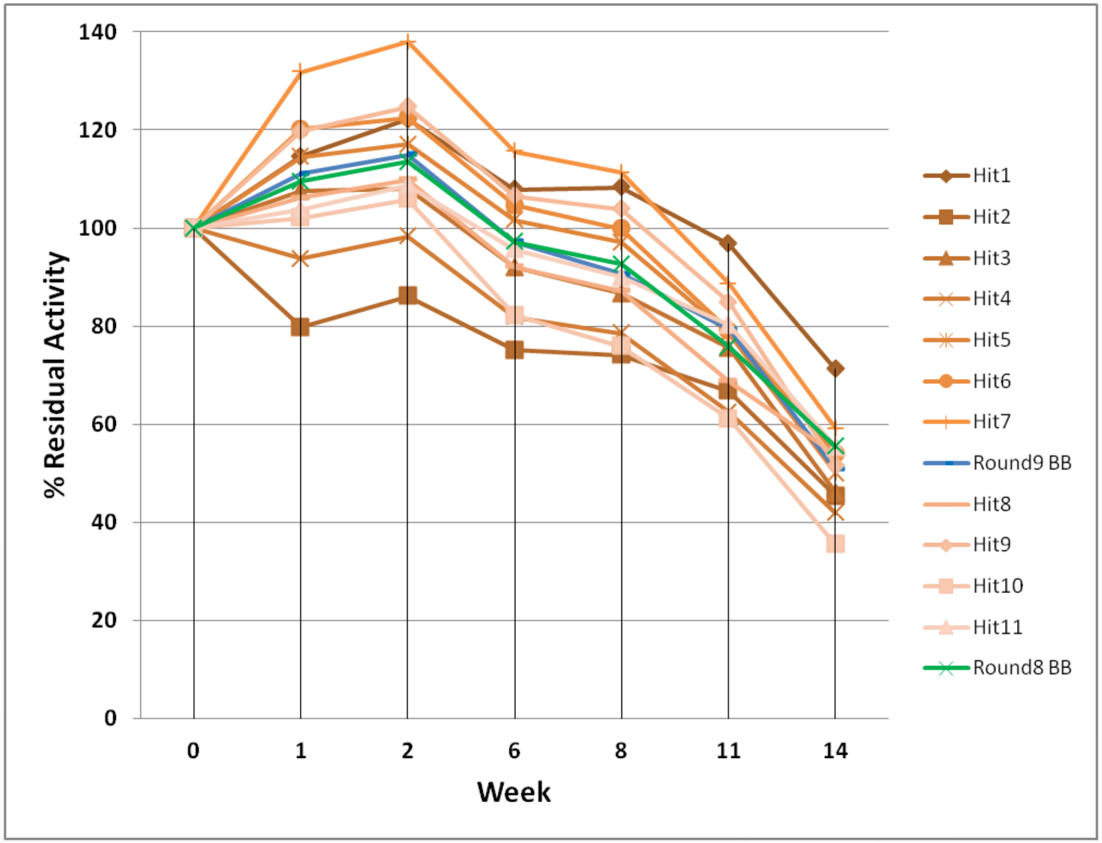


$$CO_2 + H_2O \rightleftharpoons HCO_3^- + H^+$$

- 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
- Now screening at temperatures higher than boiling point of water (107°C!)

Long-Term Stability Under Absorber Condition

4.2M MDEA, 50 C Challenge (n=6)

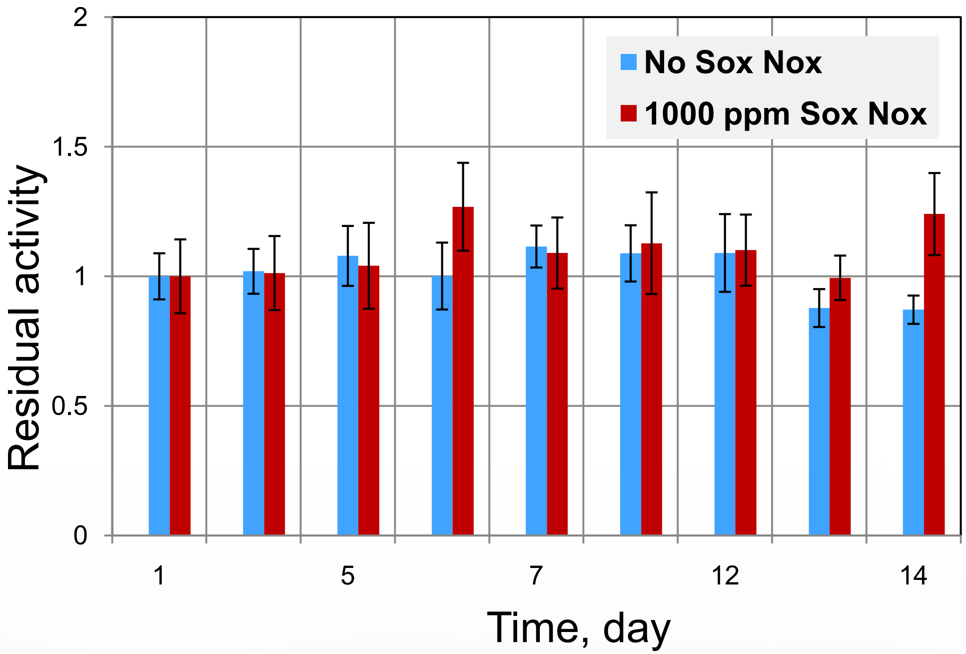


- Top performers were tested for activity after being challenged at 4.2M MDEA for up to 14-weeks at 50°C.
- All of the variants tested were still active after the 14-weeks at 50°C.
- Some variants retained up to 70% of their initial activity.

CA Tolerance to Flue Gas Contaminants

Stability of MDEA Variant in SOx/NOx

4.2M MDEA, incubated at 50°C, assayed at 50°C



Other Metals from Process/Equipment

Compound	MW	Conc. [mM]	Conc Metal [ppm]
$FeSO_4 * 7 H_2O$	278	0.4	22.3
$Fe(NO_3)_3 * 9 H_2O$	404	0.1	5.6
$Cr(NO_3)_3 * 9 H_2O$	400	0.1	5.2
$NiSO_4 * 7 H_2O$	281	0.1	5.9
$CuSO_4 * 5 H_2O$	250	0.5	31.8

- 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.

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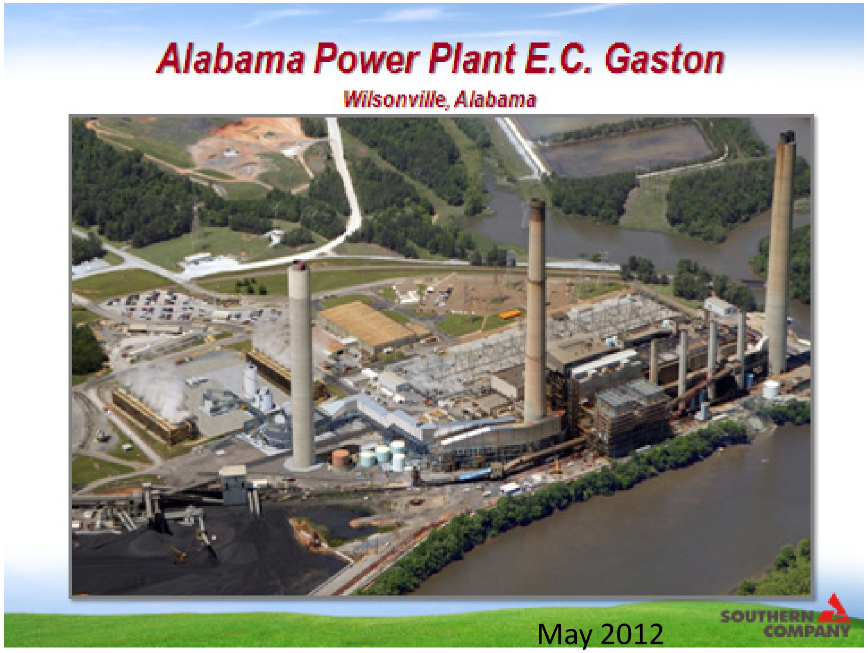
Field Testing at the National Carbon Capture Center



Objectives:

- Demonstrate CA-accelerated process concept.
- Demonstrate enzyme performance:
  - ❑ Long-term stability with real flue gas (eg., 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
CO_2 removal ~150 kg CO_2/day
Absorber column:
Diameter = 100 mm (4" ID)
Packing Height = 6.3 m
Packing type: 16 mm (5/8") Pall Rings
Surface area: 350 m^2/m^3; efficiency ~10-15%
Desorber tank (No packing):
Volume = 15 L
Residence time = 30-60 sec

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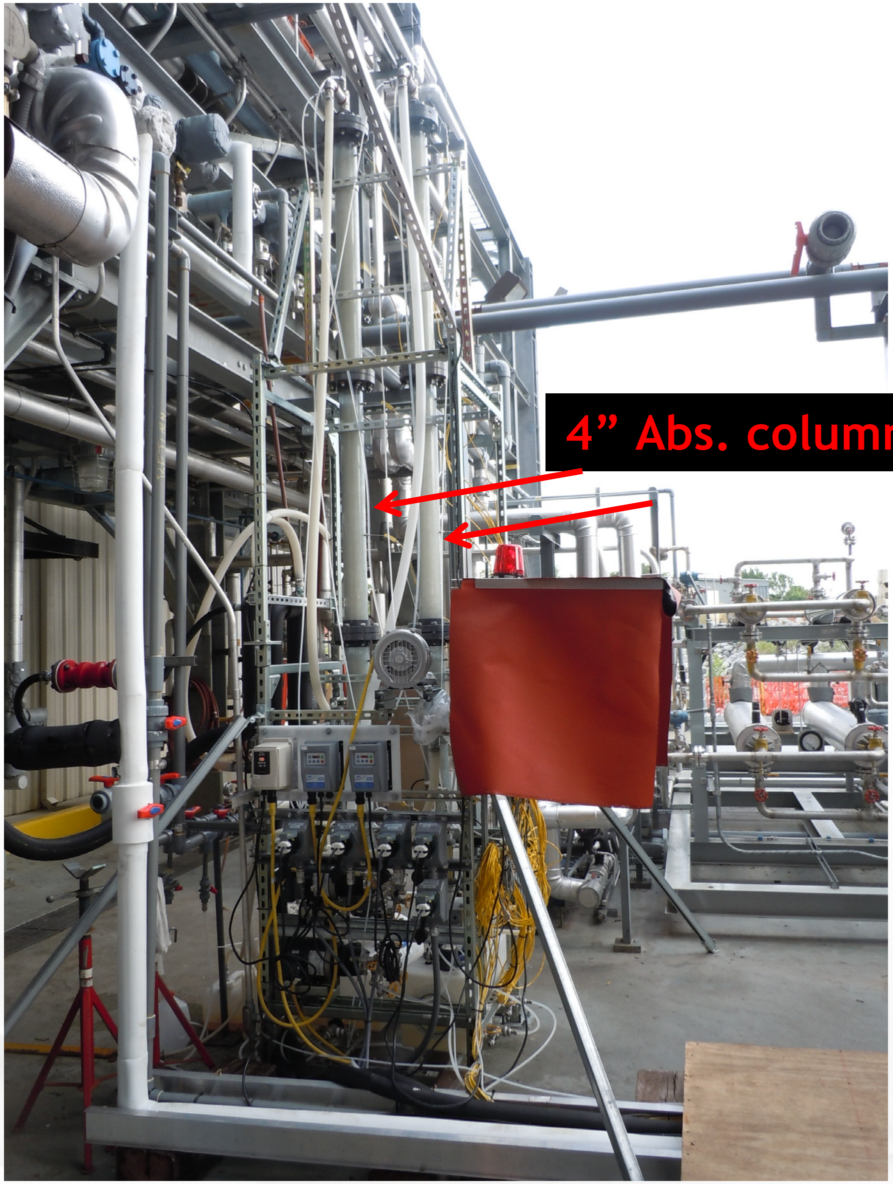
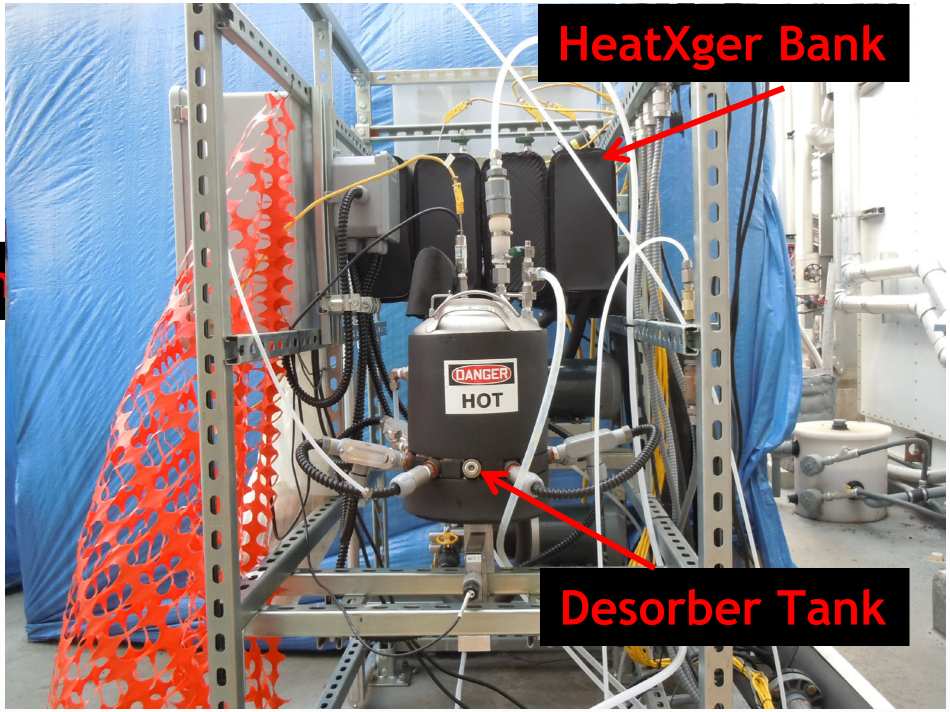
Absorber Module

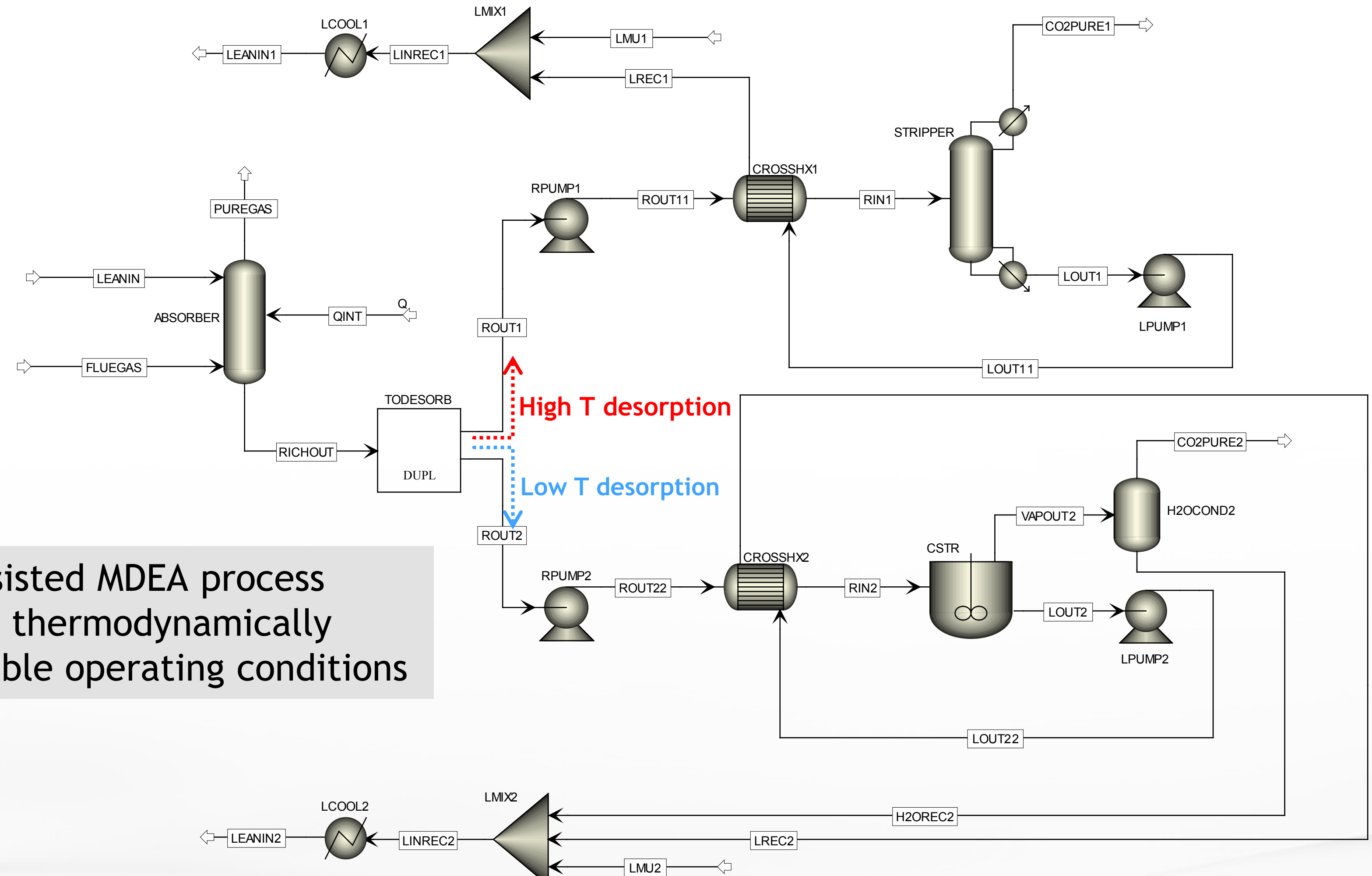
Enzyme-Assisted Desorber





Developed Aspen+ Model with Proprietary Enzyme Kinetics

Conventional Process Configuration w Thermal Desorption



CA-assisted MDEA process allows thermodynamically favorable operating conditions

'Novel' Process Configuration w Enzyme-Assisted Desorption

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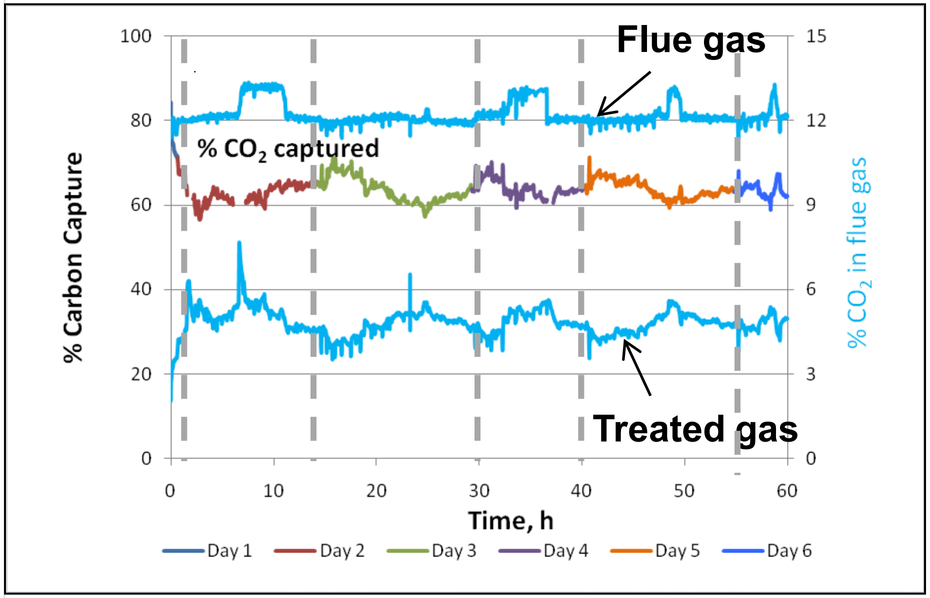
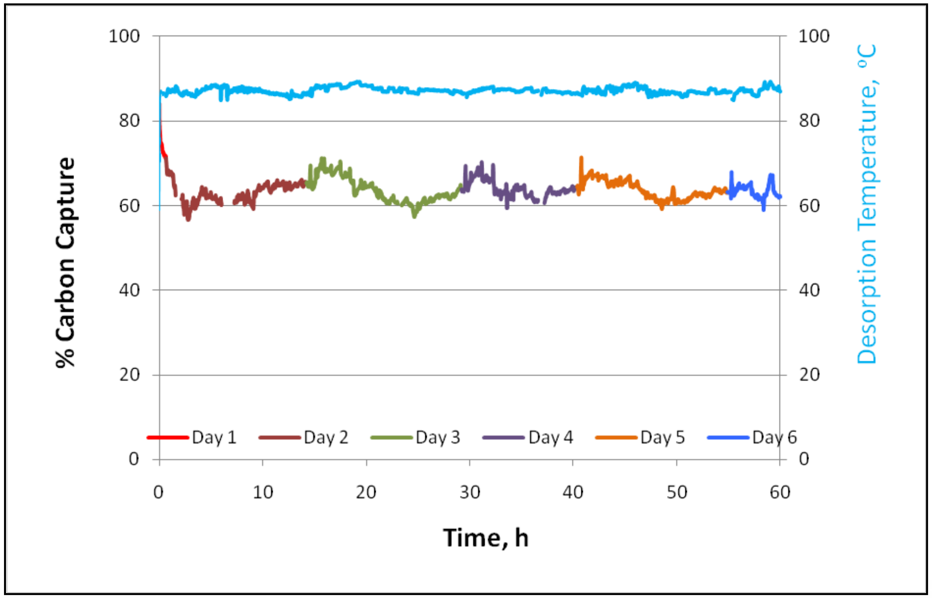
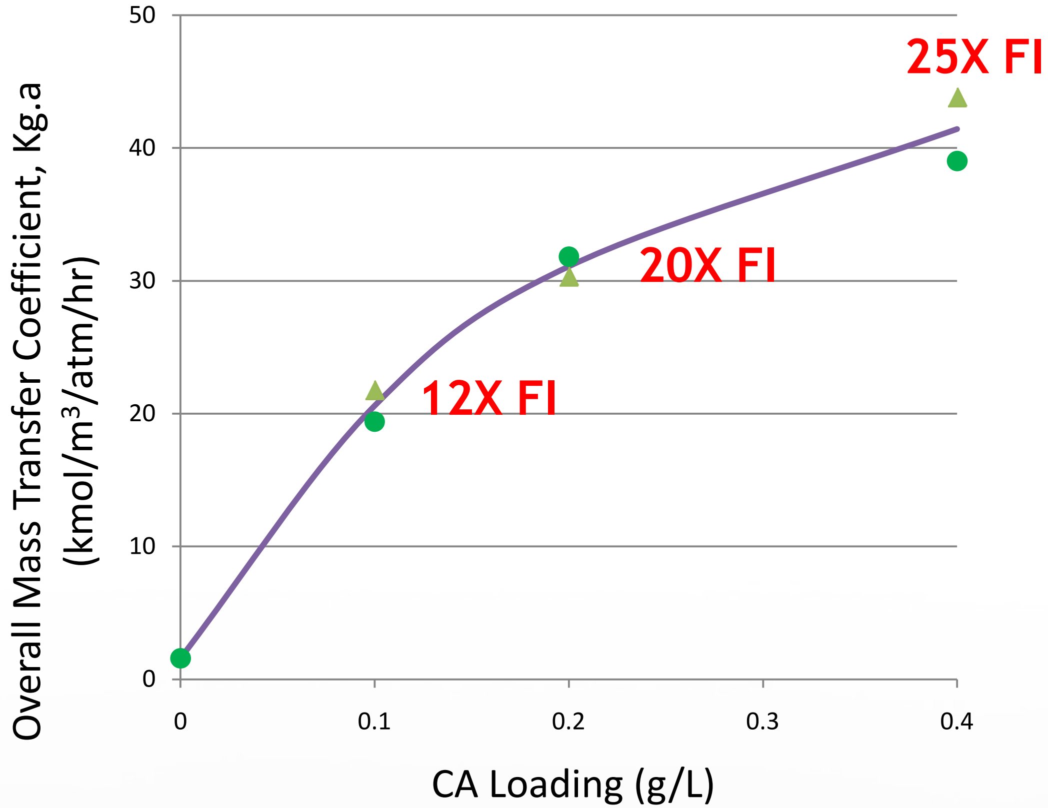
Long-Term Stability under Industrial Flue Gas Conditions





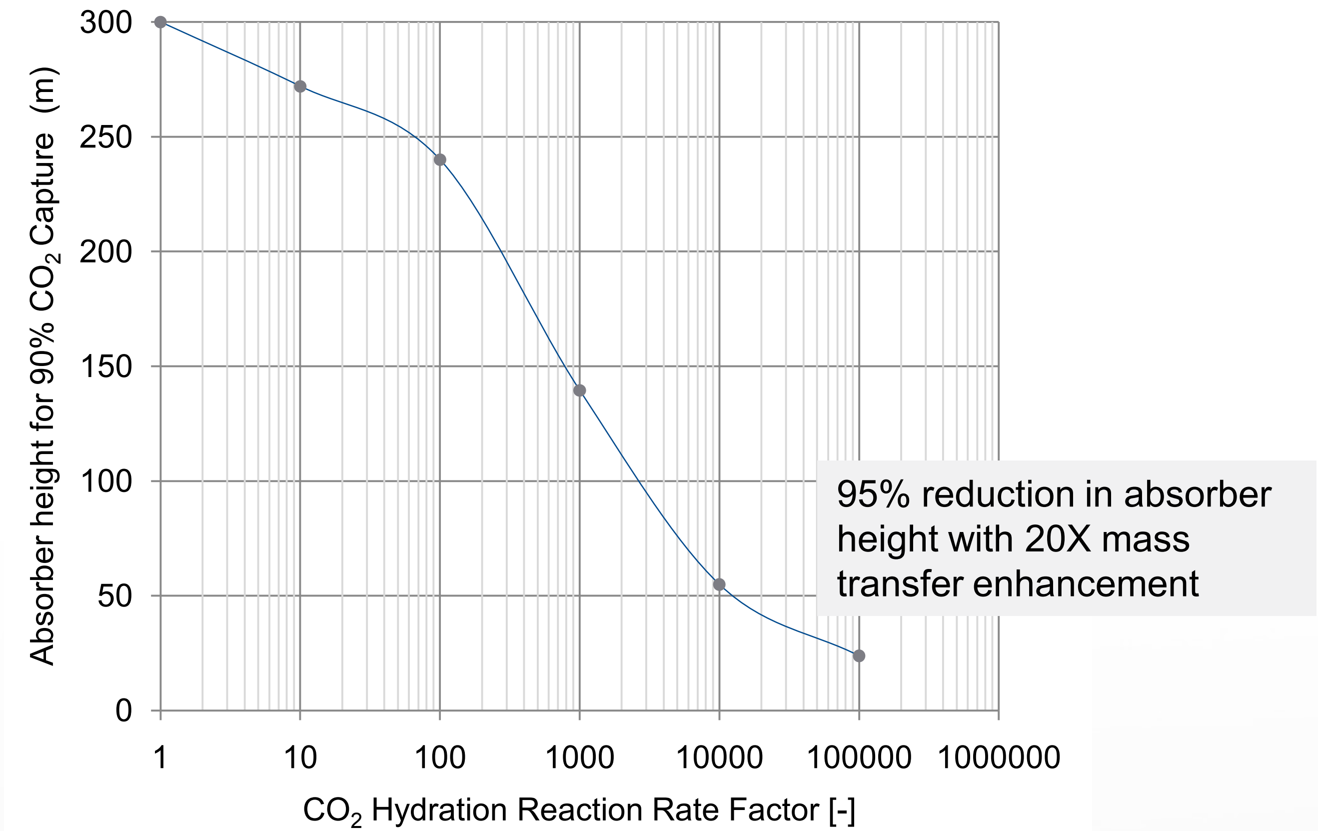
- Stable enzyme performance after **6 days** under industrial flue gas conditions (ie., Mercury, heavy metals, SOx, NOx, etc.) with ~**0.2 g/L of CA.**
- Stable desorber operation at $\mathbf{T_{desorption}=87°C}$
- Achieved solvent capacity for CO_2 removal, $\Delta\alpha \approx 0.2$ (mol CO_2/mol 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_{abs} (30-50 C), T_{des}(85–95 C), L & G flow rates (to achieve 30–95% CO_2 capture).

Predicted Impact of Enzyme on Absorber & Desorber Size



- Codexis enzyme-based technology could significant reduce CAPEX:
  - ~95% reduction in CO_2 absorber column size with low-energy solvent MDEA.
  - ~80% reduction in desorber volume without use of structure packings.

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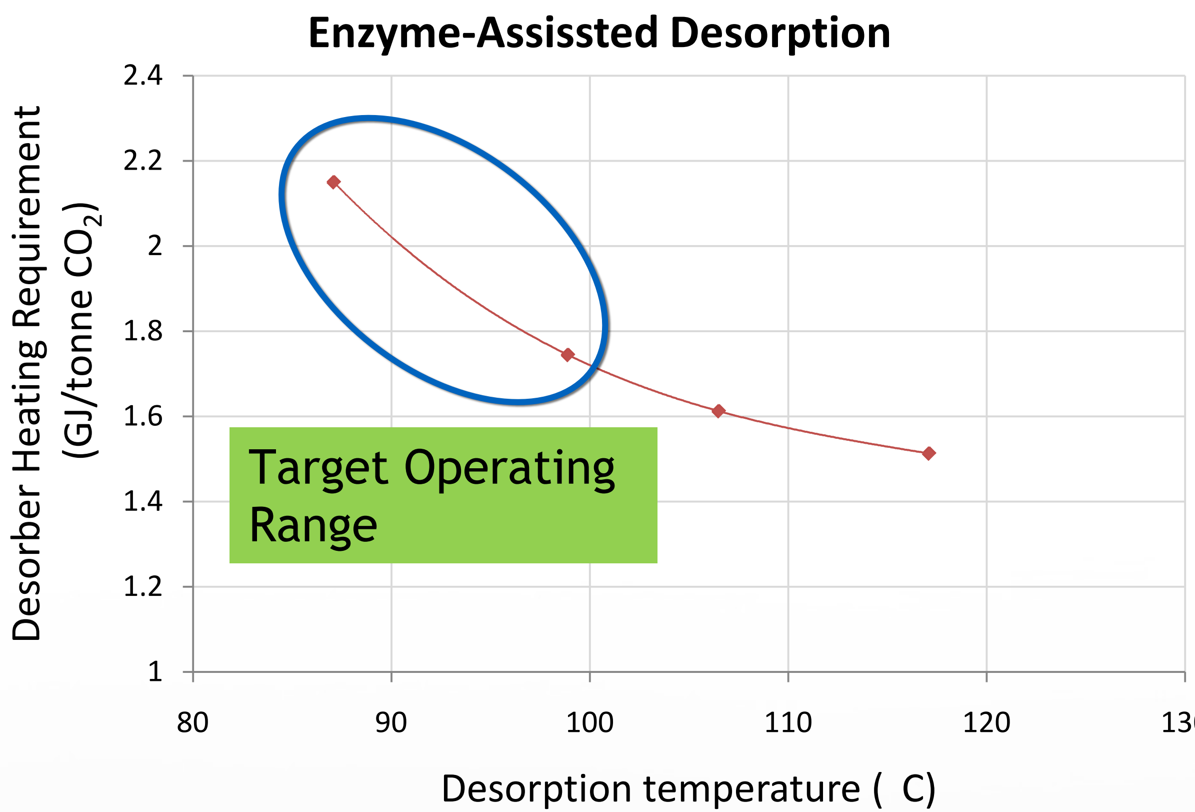
Predicted Enzyme-Assisted Desorption Energy Reduction



- Enzyme-assissted 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.

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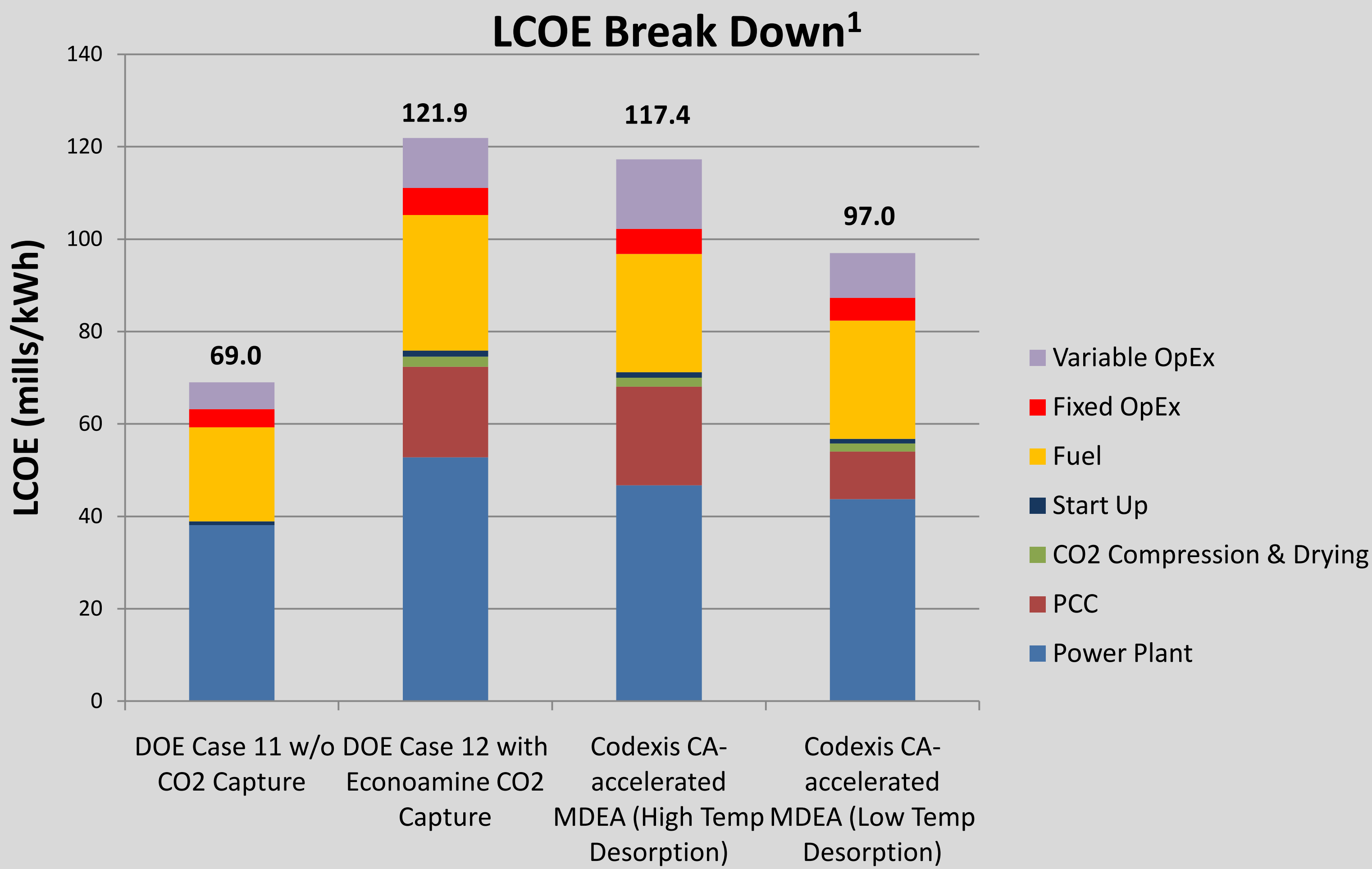
Nexant PC/Codexis PCC Plant Integration

- **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.

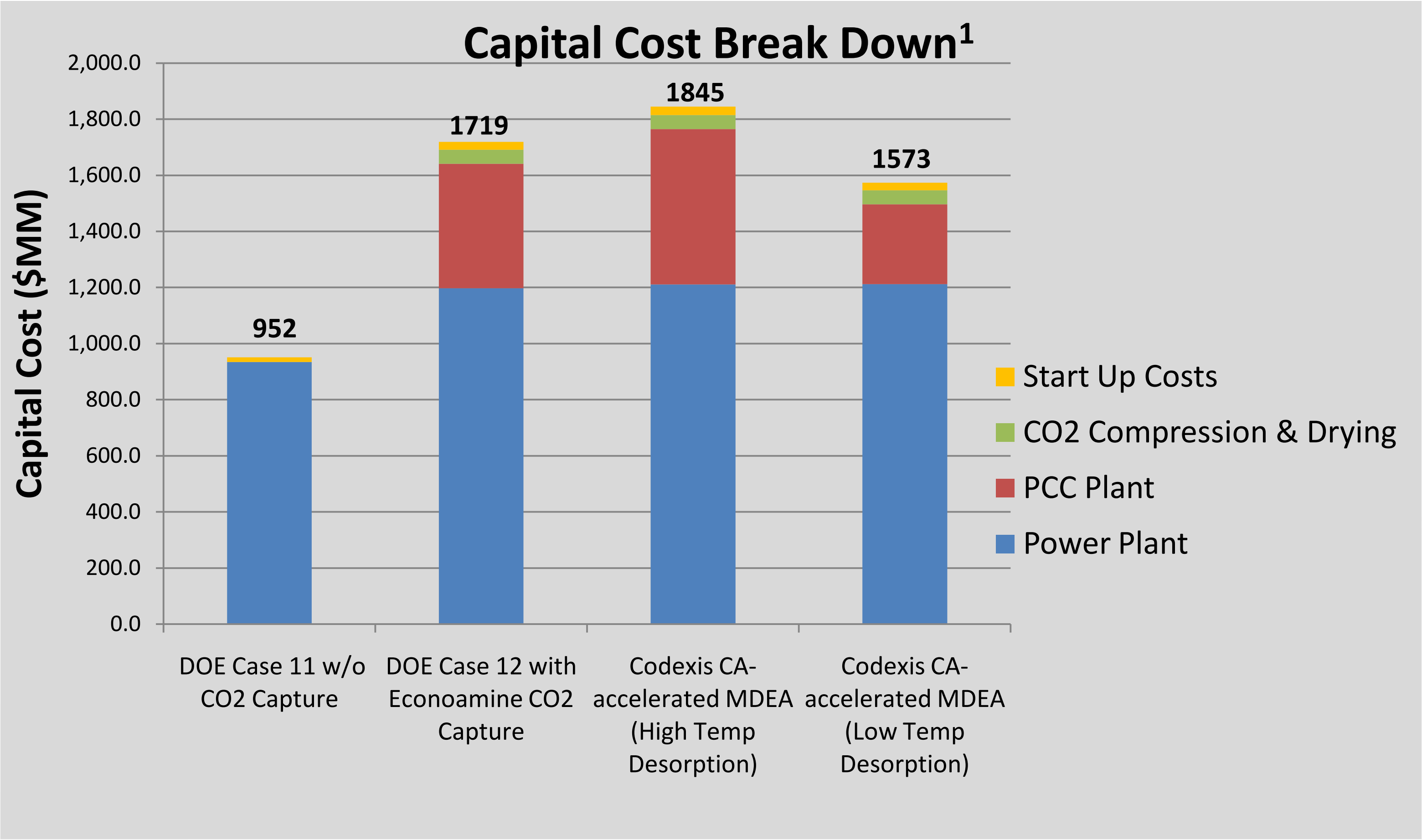
CA Enabling Low-Cost Biocatalytic Process for Carbon Capture



[1] Escalated to 2010 dollars.

Low-cost CA-accelerated MDEA process for CO_2 capture w/LCOE = 97.0 mills/kWh

Techno-Economic Analyses (Con't)



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

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)

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Summary

- Created enzymes that increased rate of CO_2 capture >25-fold under industrial conditions (NCCC).

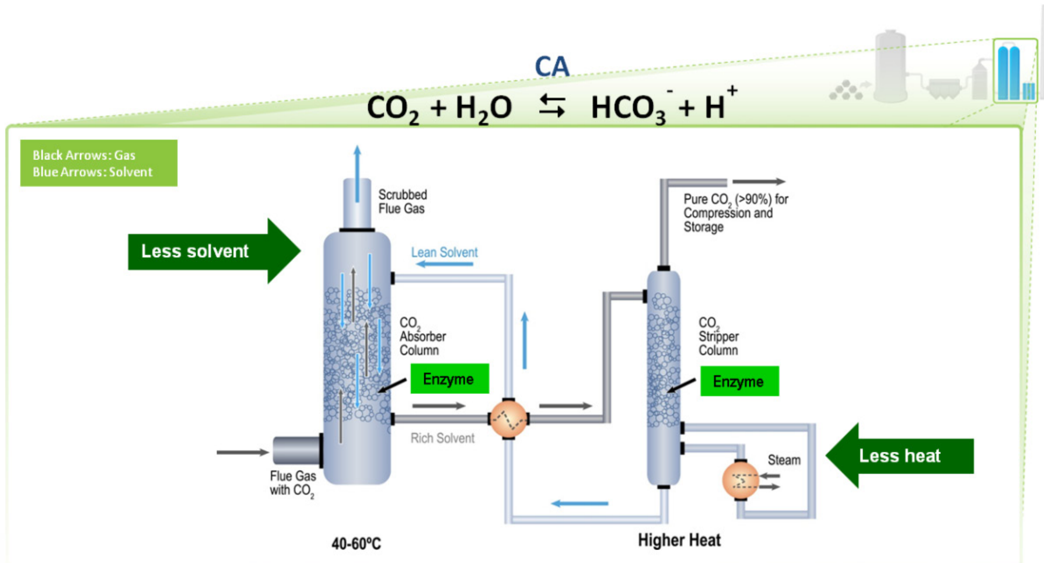
- Created enzymes with 10^6-10^7 increased stability with rates of catalysis of 10^6 fold.

- 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

CA Enables Energy Efficient Solvents



- Reduce CAPEX by 146M $US for PCCC plant
  - ❑ 90% reduction in CO_2 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.

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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.

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Codexis & CO_2 Solution IP

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

Joint Development Agreement

CO_2 Solution and **Codexis** working exclusively together to validate enzyme catalysis for economical capture of CO_2

CO_2 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 CO_2 Solution Patents

Patent #	Area of Carbonic Anhydrase (CA) CO_2 Capture Application
US 7,740,689	Amine solvents
US 7,596,952	Power plants
US 7,176,017	Triphasic reactor
US 6,524,843	Packed column system
US 6,908,507	Cement production
US 7,521,217	Thermally stable CA variants
US 7,514,056	Air fractionation / oxygen production
US 61/231038	CA on micro-particles
US 61/231037	Carbonate solvents
US 61/231039	Amino acid solvents

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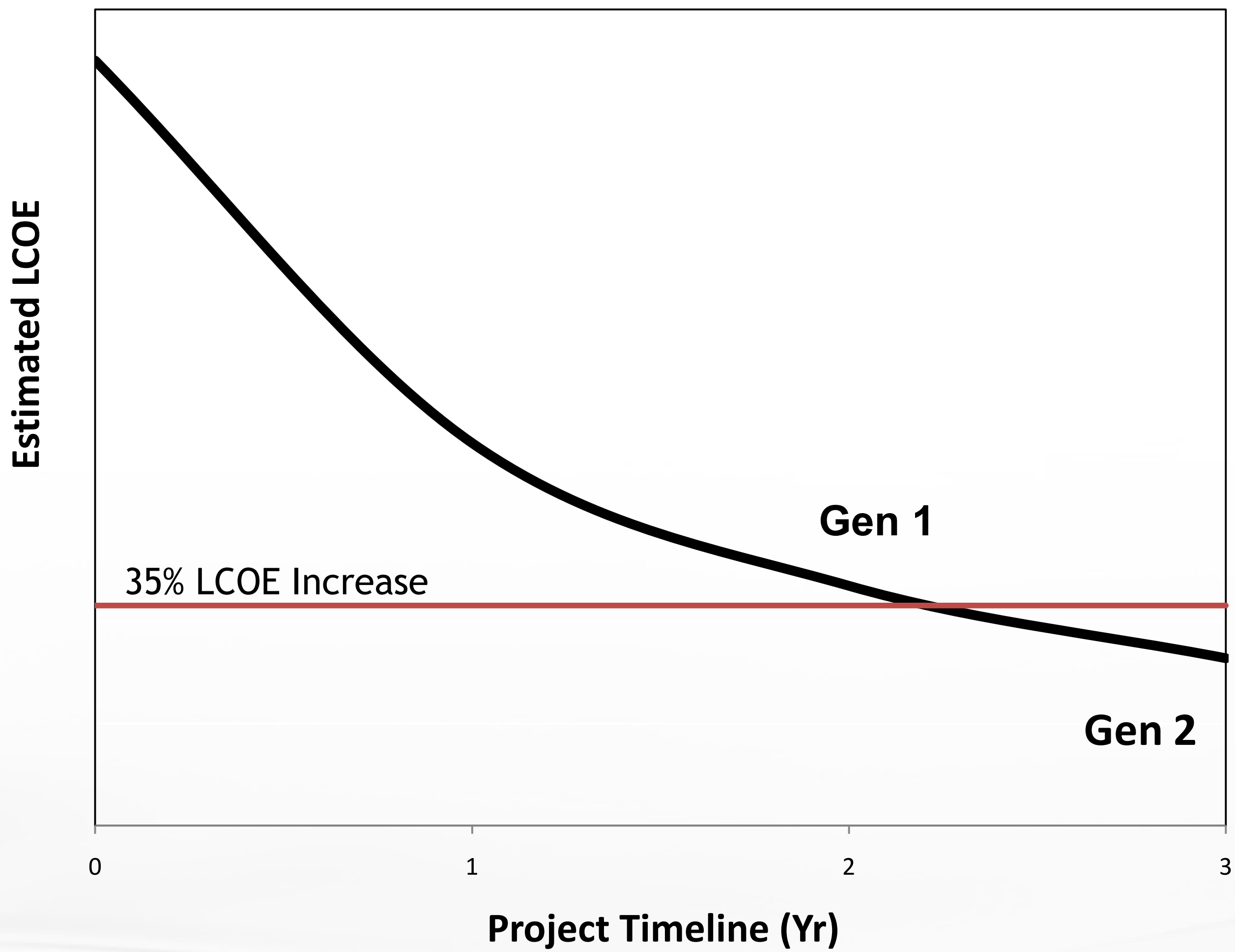
Validation of ARPA-E Investments in Breakthrough Technology



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Jamie Bresson
Jeff Pollack
Trish Choudhary
Svetlana Gitin
Janelle Muranaka
Svetlana Balatskaya
Ann Lao
Jim Lalonde (PI)

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Gerald Choi

NCCC/NETL

Thomas Carter
Frank Morton

ARPA-E

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Forward-Looking Statements

These slides and the accompanying oral presentation contain forward-looking statements that involve risks and uncertainties. These statements relate to future events or our future financial or operational performance and involve known and unknown risks, uncertainties and other factors that could cause our actual results, levels of activity, performance or achievement to differ materially from those expressed or implied by these forward-looking statements. Forward-looking statements include all statements that are not historical facts. In some cases, you can identify forward-looking statements by terms such as “may,” “will,” “should,” “could,” “would”, “expects,” “plans,” “anticipates,” “believes,” “estimates,” “projects,” “predicts,” “potential,” or the negative of these terms, and similar expressions and comparable terminology intended to identify forward-looking statements. These forward-looking statements represent our estimates and assumptions only as of the date hereof, and, except as required by law, we undertake no obligation to update or revise publicly any forward-looking statements, whether as a result of new information, future events or otherwise.

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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