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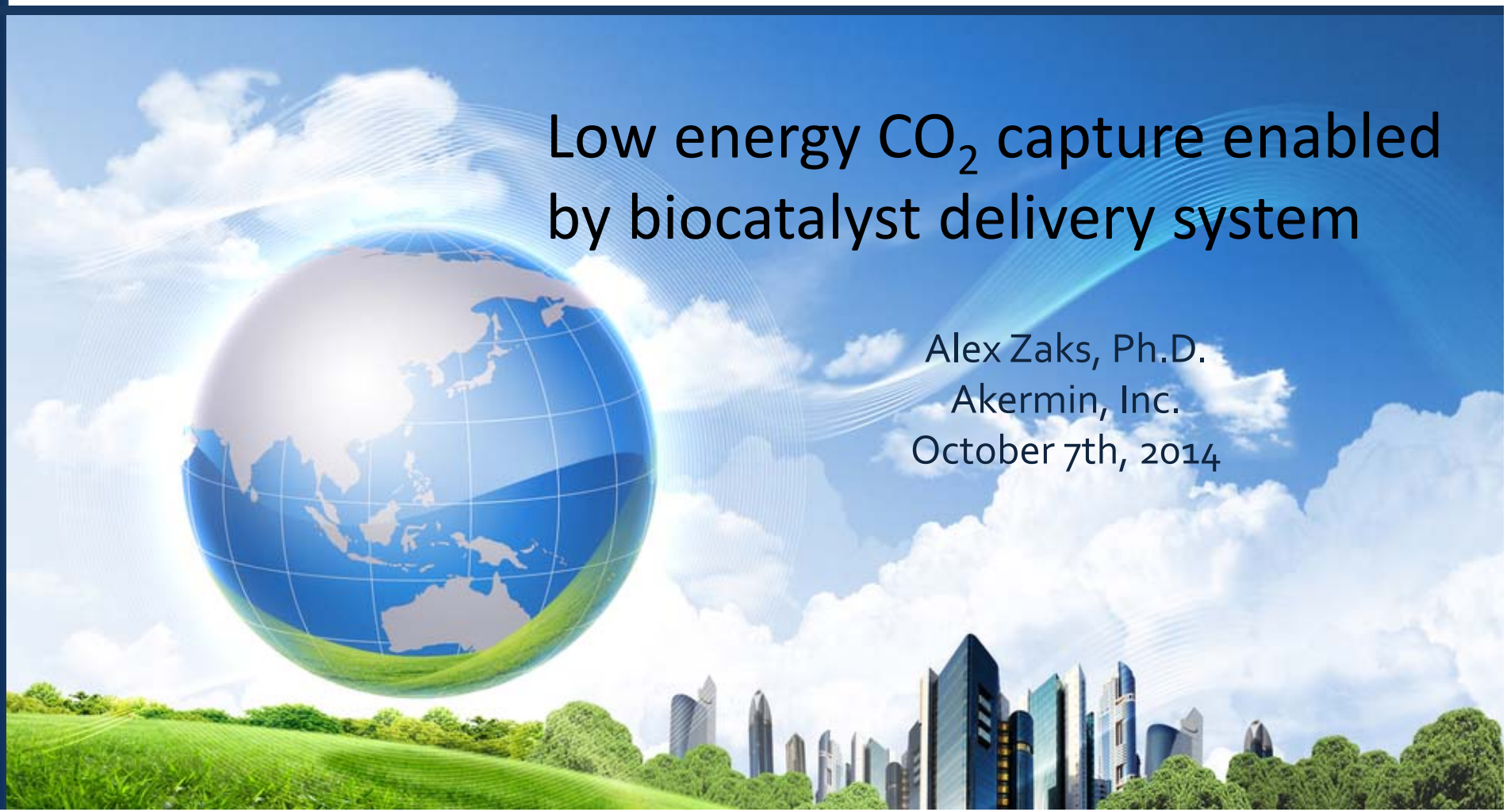
Putting enzymes to work™

INTERNATIONAL CONFERENCE ON GREENHOUSE GAS TECHNOLOGIES



Low energy CO_2 capture enabled by biocatalyst delivery system

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Akermin, Inc.
October 7th, 2014

DOMINANT APPROACH FOR CO_2 CAPTURE TODAY: CHEMICAL ABSORPTION WITH AMINES

Where does it fall short?

- High operating costs & poor environmental profile
  - Increases energy requirements
  - Relies on volatile solvents
  - Generates hazardous by-products
  - Accompanied by solvent degradation

- Inadequate for large-scale CO_2 capture from flue gas streams

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ALTERNATIVE SOLVENTS

$$K_2CO_3 + CO_2 + H_2O \rightleftharpoons 2KHCO_3$$

Solvent Characteristics	Baseline (Amines)	K_2CO_3
No amine aerosol emissions		X
Non-volatile (No VOC or HAPs)		X
Non toxic		X
High Capture Rate	X	
Oxidative stability		X
Low viscosity		X
Low corrosion		X
Limited flue gas polishing needed		X

K2CO3 is kinetically slow but otherwise highly attractive solvent

The use of K2CO3 requires a catalyst

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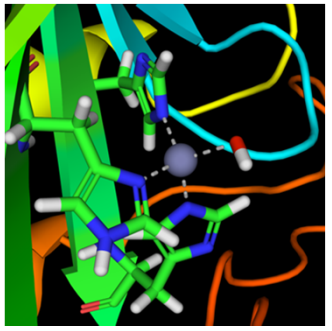
CARBONIC ANHYDRASE: NATURE'S PERFECT CATALYST

- Interconverts CO_2 and HCO_3^- to maintain acid-base balance and transport CO_2 out of tissues.
- A family of ubiquitous enzymes
  - Mammals, aquatic organisms, insects, plants, fungi, bacteria and archaea
- Active site contains metal (Zn^{2+})
- MW ~ 30,000
- Desirable characteristics:
  - Thermostable
  - Resistant to high pH (9.5-10.5)
  - Expressed at high levels with few impurities



$k_{cat}/K_M = 10^8\ M^{-1}s^{-1}$
$k_{cat} = 10^6\ s^{-1}$

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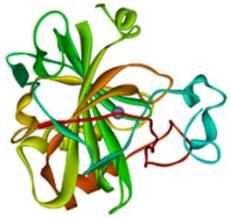
CHALLENGE



- How to make a biocatalyst evolved in nature work under industrial conditions with following stressors:

- Temperature (40- 105 °C)
- Extreme pH (9.8-10.2)
- Impurities (SOx, NOx, etc.)
- Shear Forces
- Multiphasic systems

Enzyme optimization and advanced delivery is critical

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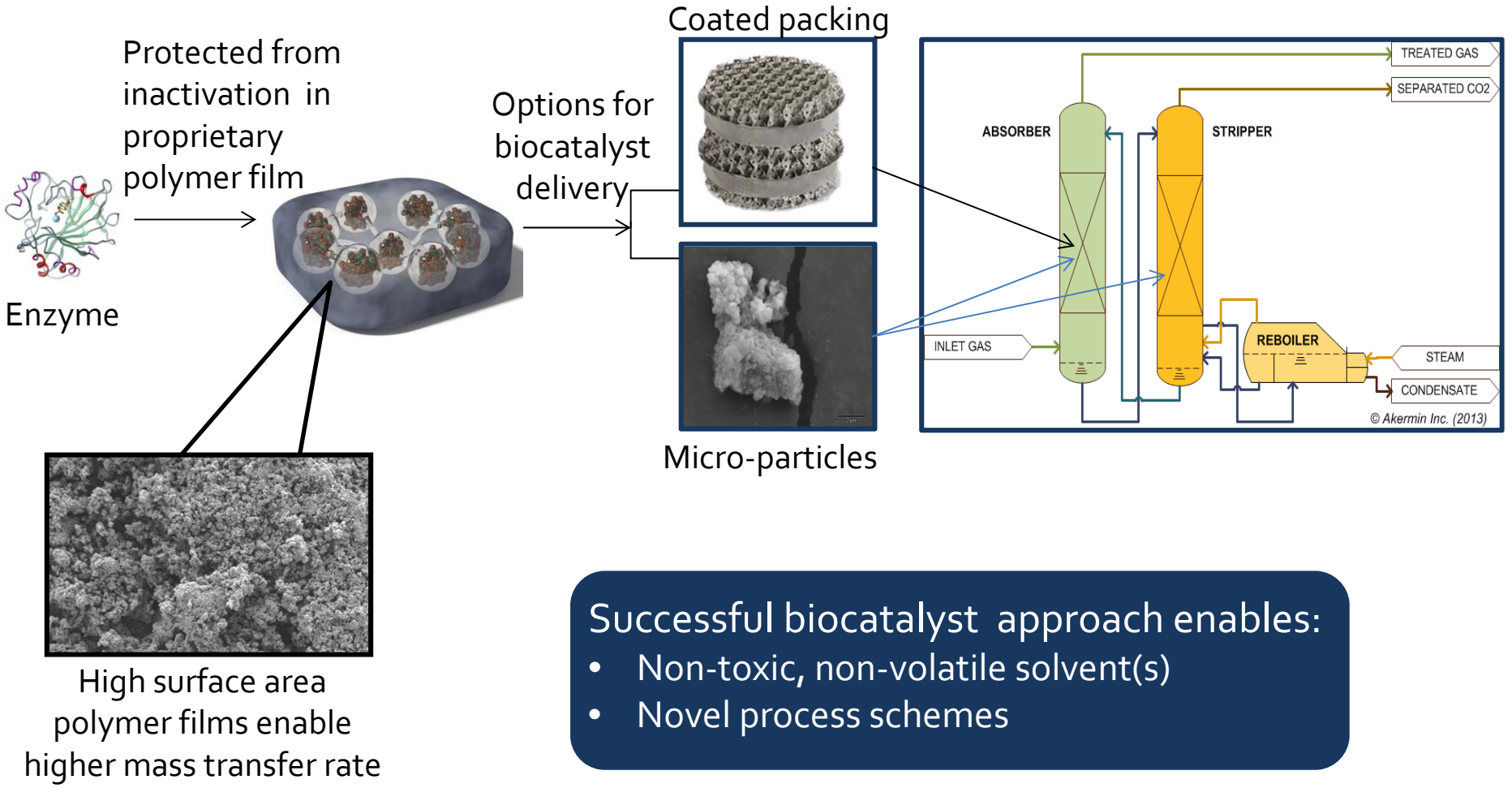
AKERMIN'S BIOCATALYST DELIVERY SYSTEM



Successful biocatalyst approach enables:

- Non-toxic, non-volatile solvent(s)
- Novel process schemes

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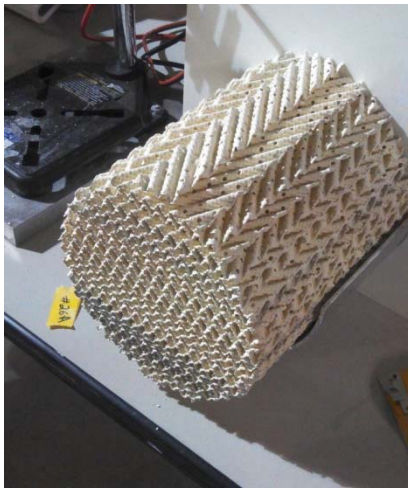
FIELD PILOT UNIT DEMONSTRATION

Installed at NCCC December 2012

- 8.33" ID x 26 ft packing
- Gas: 30 Nm^3/hr
- Liquid: 275 LPH



- Sulzer M500X

- **Unit with immobilized enzyme operated May – Oct 2013**

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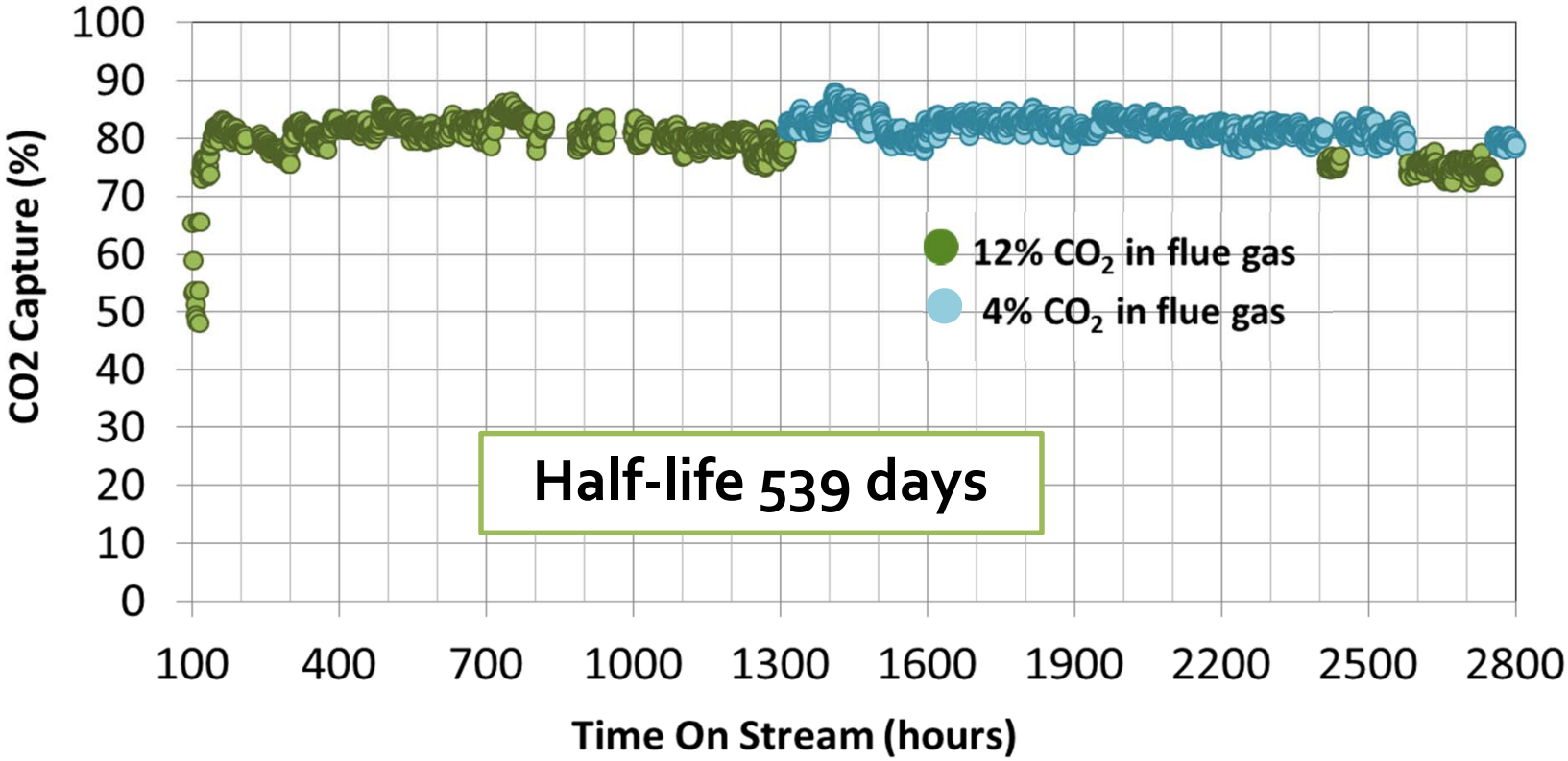
FIELD TRIAL: LONG-TERM PERFORMANCE



2,800 hours on CO2 steam with 99% availability

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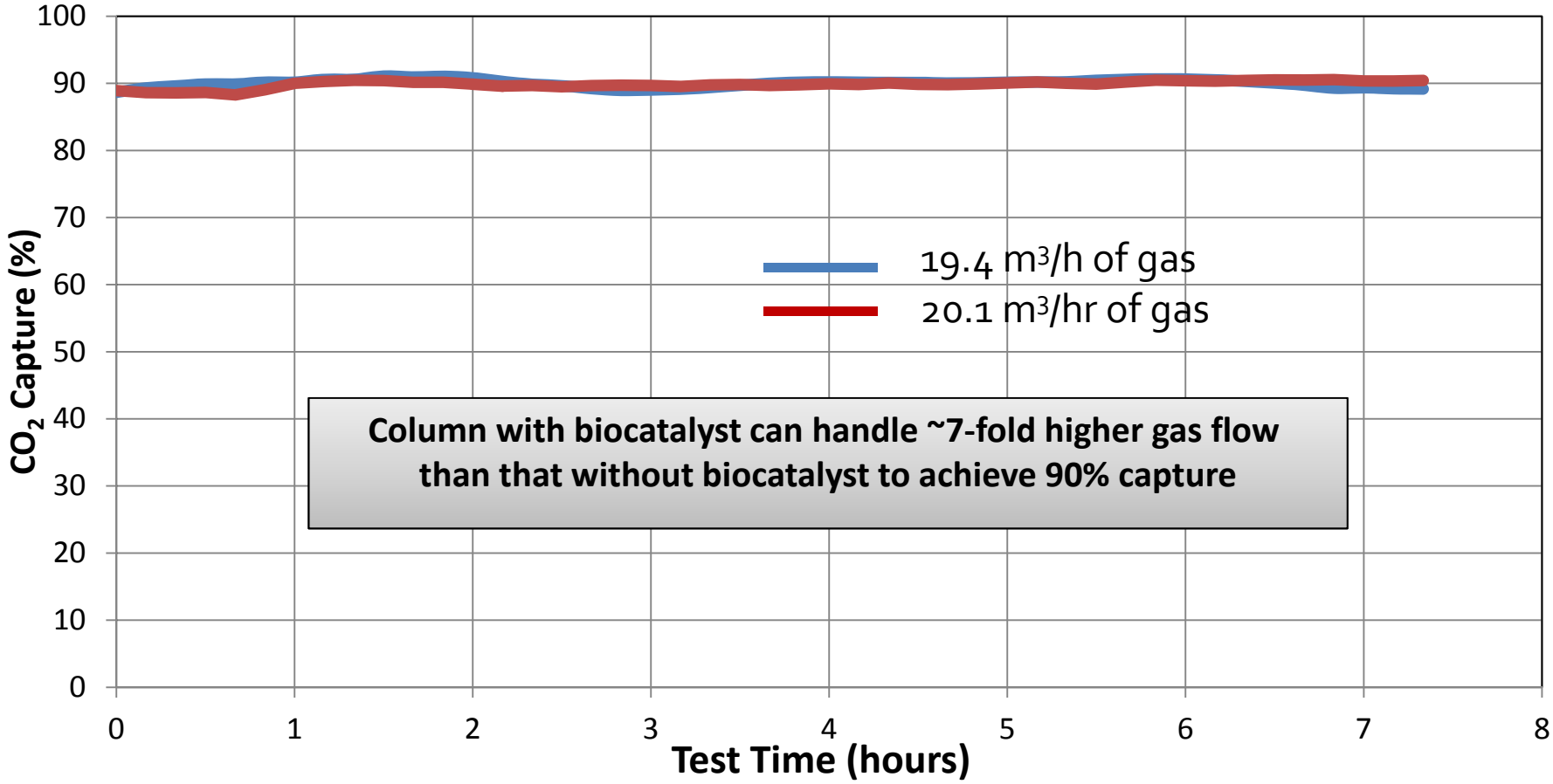
FIELD TRIAL: DEMONSTRATION OF 90% CAPTURE



90% capture with immobilized enzyme is achievable

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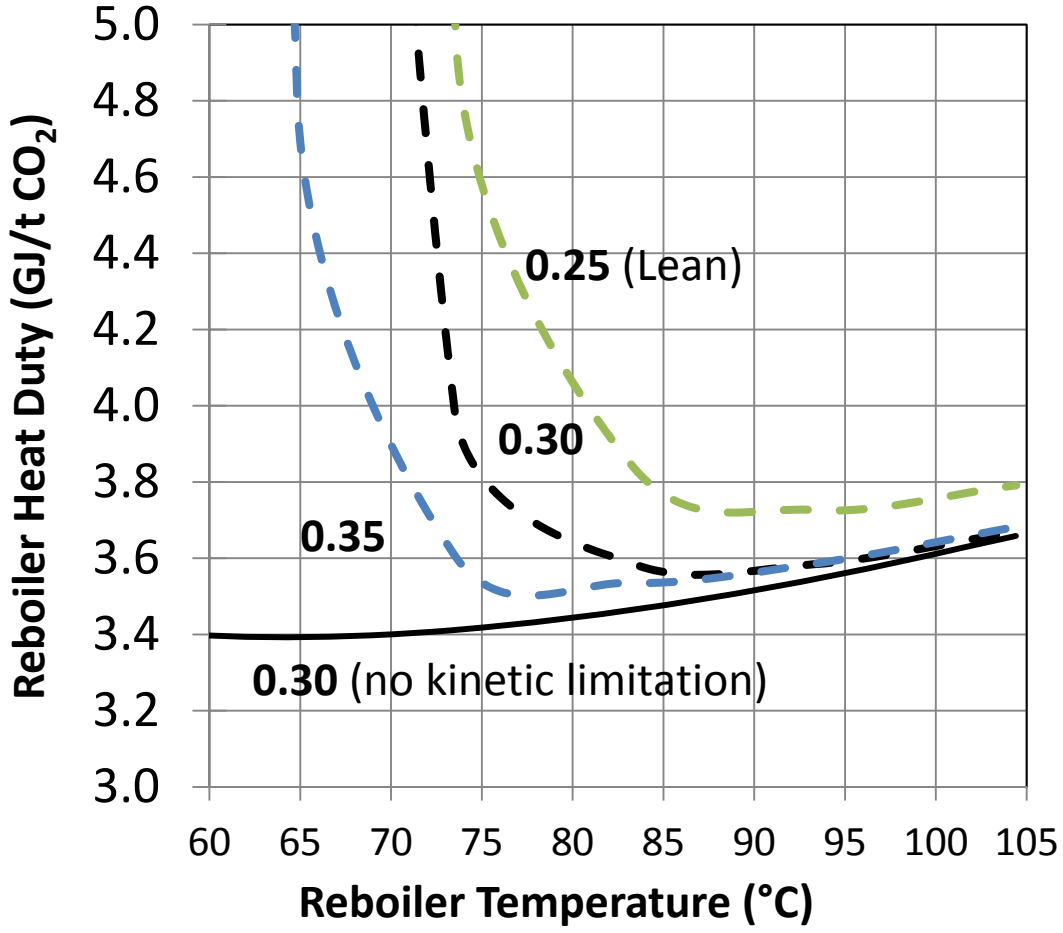
IMPACT OF KINETIC LIMITATIONS ON REBOILER DUTY OPERATED WITH $KHCO_3$



~3.4 GJ/t_{CO_2} with K_2CO_3, basic flow sheet

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CHALLENGE: HOW TO FURTHER MINIMIZE ENERGY

Second generation solvent, AKM24

- ✓ **High CO_2 loading**
- ✓ **Low regeneration energy**
- ✓ Non-volatile
- ✓ Low EH&S risks
- ✓ Low molecular weight
- ✓ Thermally stable
- ✓ Highly water-soluble
- ✓ Manufacturing route established
- ✓ Used in the past for gas treating

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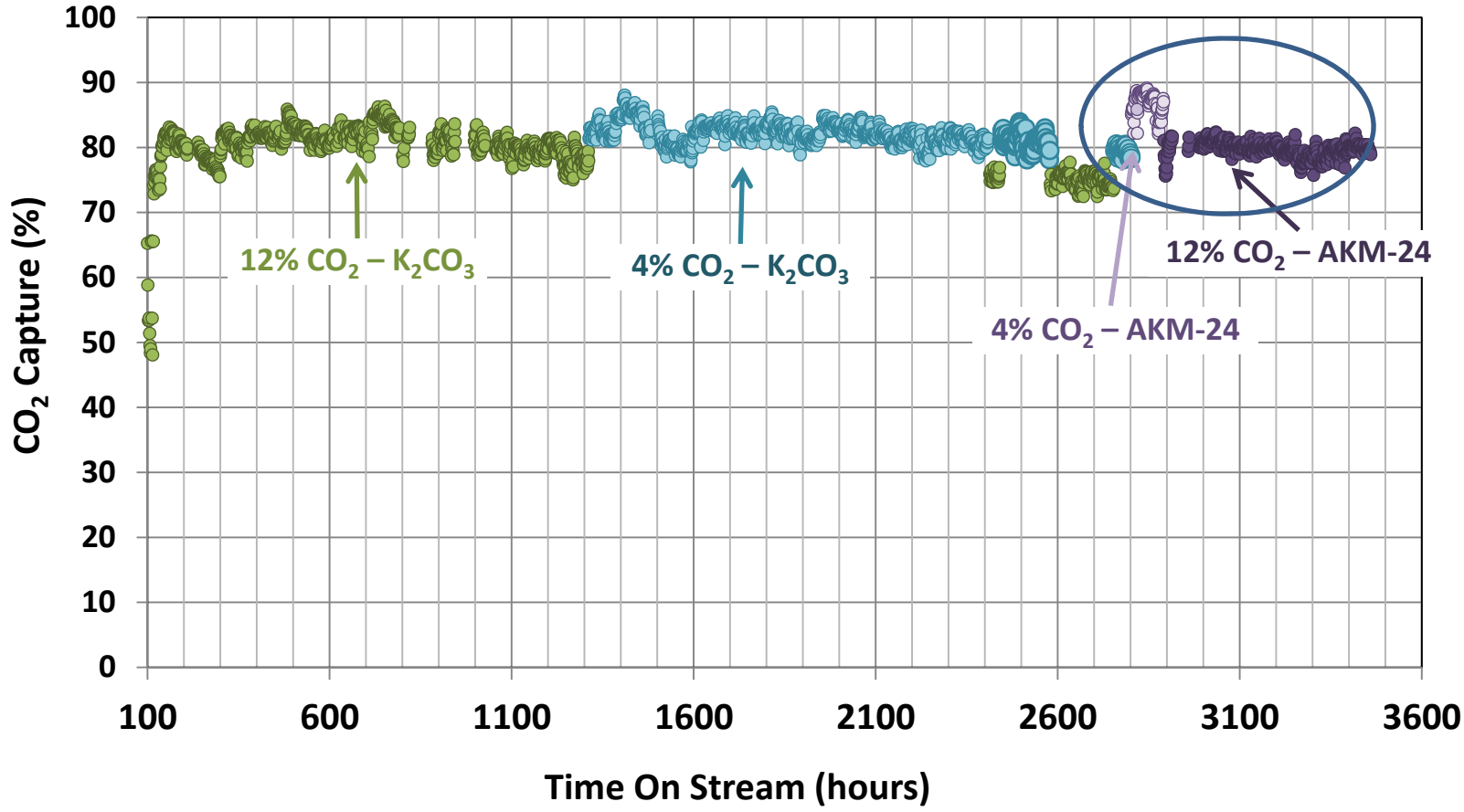
LONG-TERM PERFORMANCE OF THE PILOT WITH K_2CO_3 AND AKM24



Long-term stability with both solvents demonstrated

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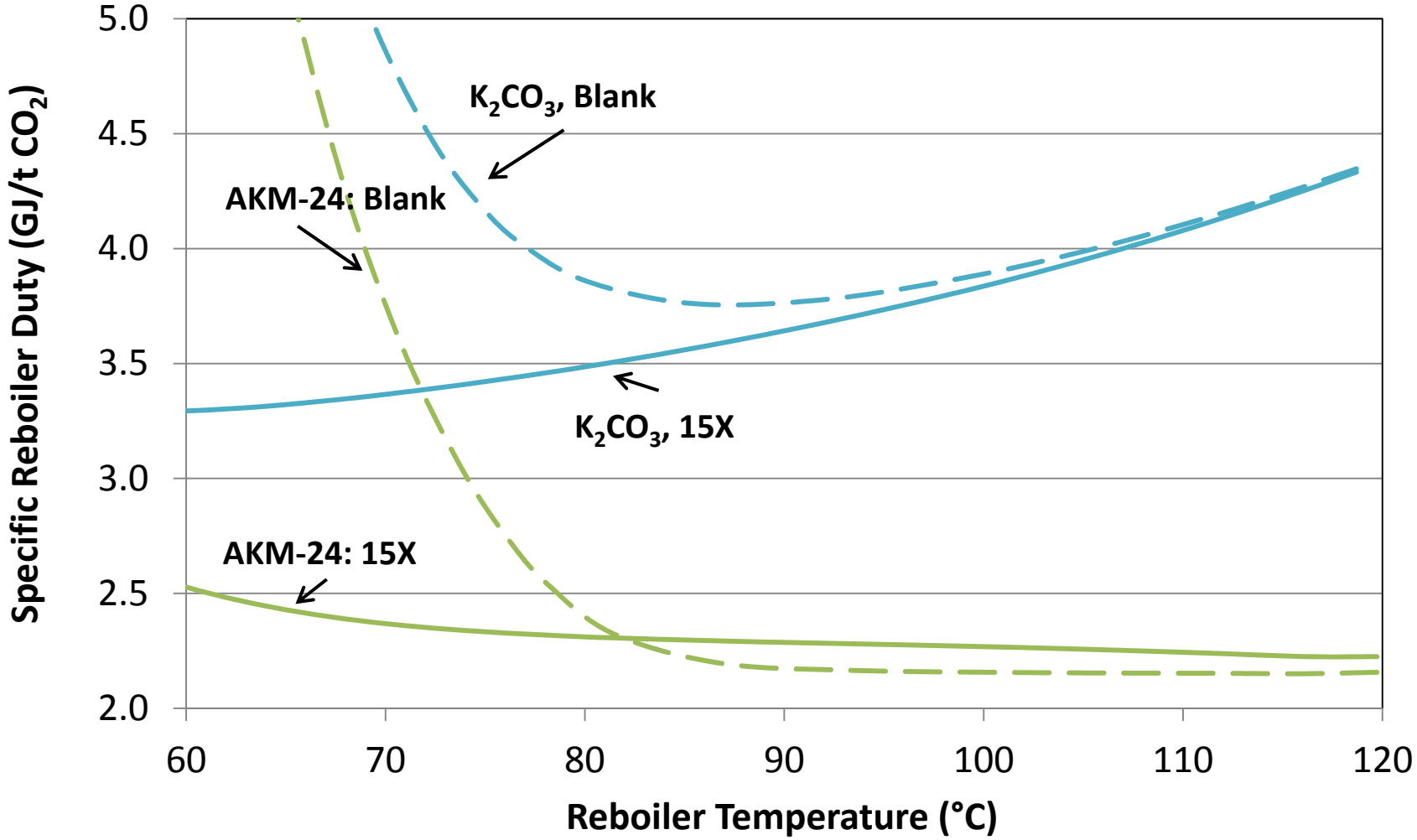
SPECIFIC REBOILER DUTY FOR K_2CO_3 AND AKM-24



AKM-24 is estimated to achieve **30%** reduction in reboiler heat duty

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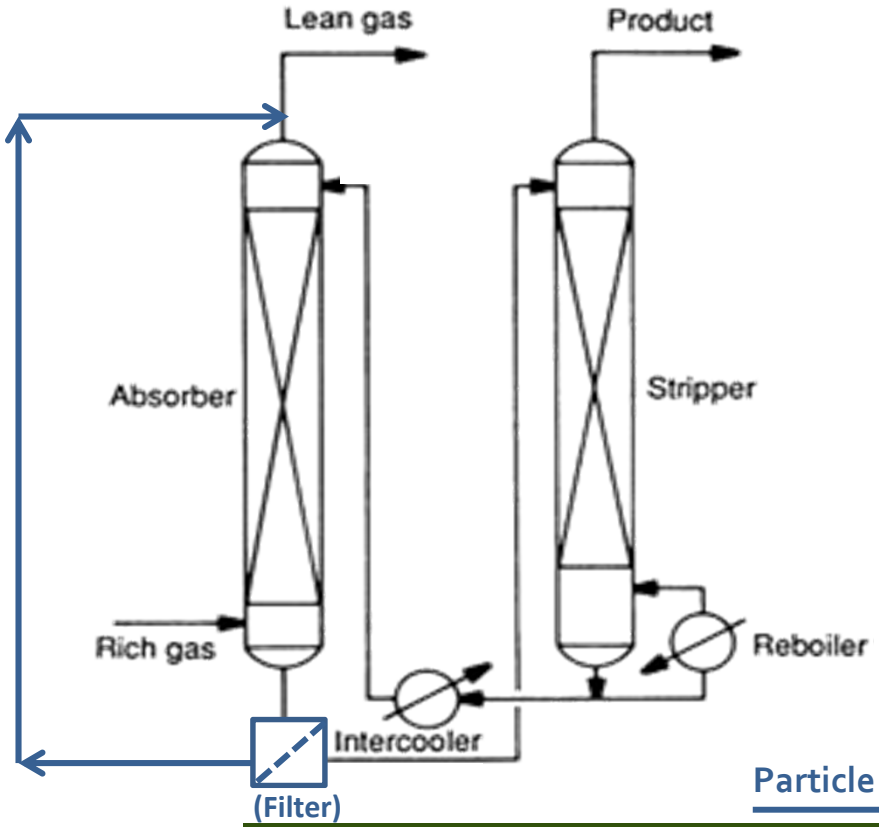
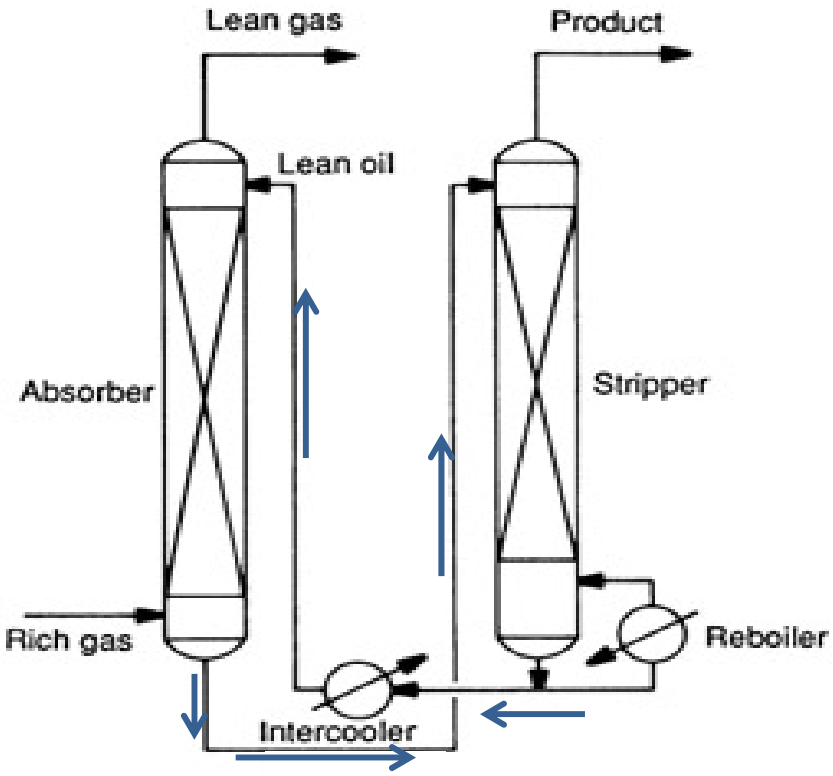
CHALLENGE: HOW TO REPLENISH BIOCATALYST AT COMMERCIAL SCALE?

Two concepts employing enzyme delivery as micro-particle:

Recirculation within absorber only (requires particle separation)



Continuous recirculation in absorber and stripper (req. lower temp. stripping)



Particle flow

NEW PROJECT SUPPORTED BY U.S. DEPARTMENT OF ENERGY

$3 million award; work initiated in Oct'13

- FOCUS ON MICRO-PARTICLE
- RECIRCULATION THROUGH ENTIRE SYSTEM
- AKM24

- Goals
  - Demonstrate delivery of enzyme on micro-particle
  - Complete characterization of AKM24
  - Test advanced system design
  - Further reduction of energy and capital costs

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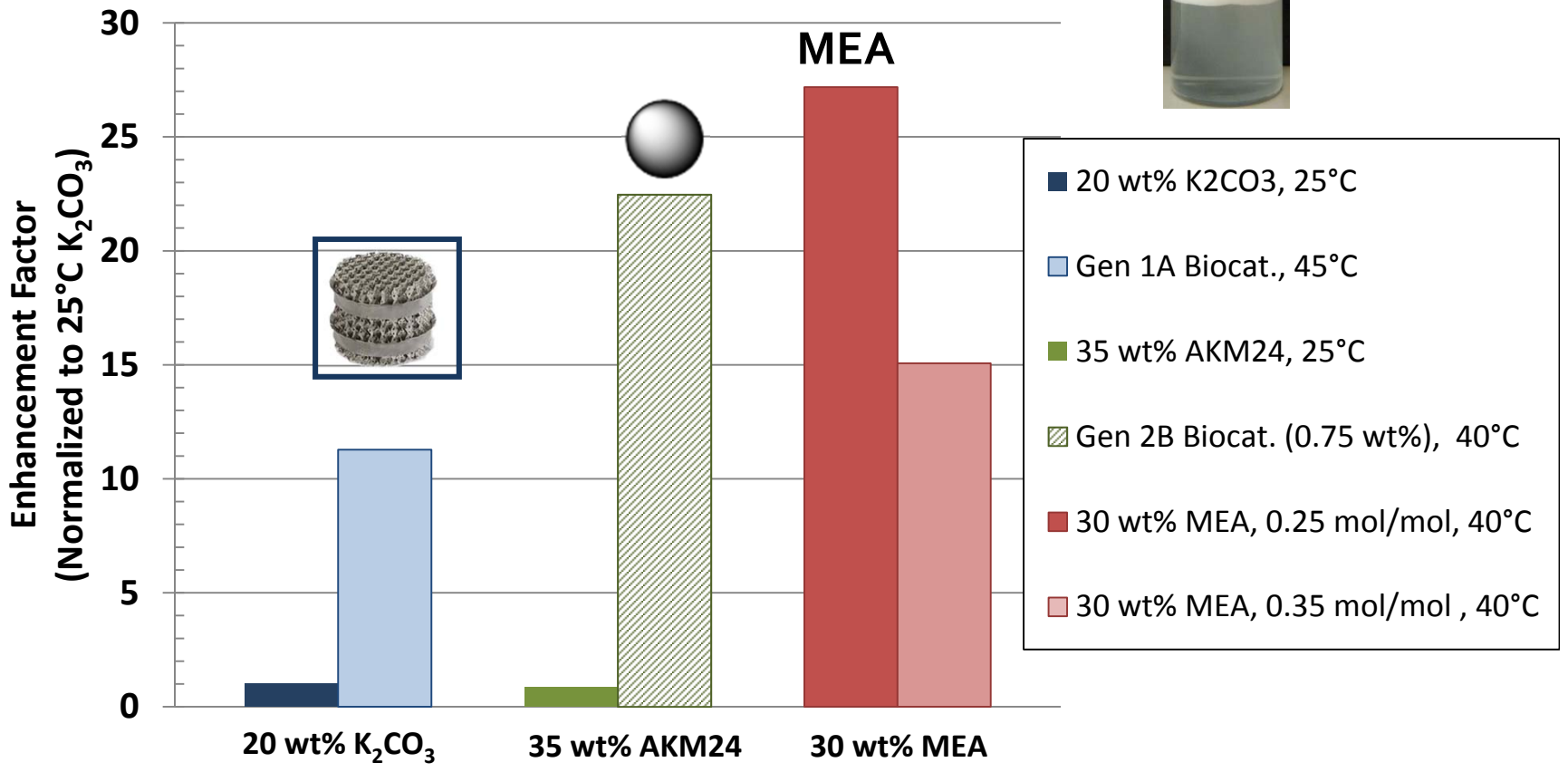
ENHANCEMENT FACTOR FOR GEN-1 (PACKING) AND GEN-2 (MICRO-PARTICLES)

- ***Micro-particles specifically designed to partition to gas-liquid interphase***



Micro-particles demonstrate a significantly higher acceleration potential than coatings

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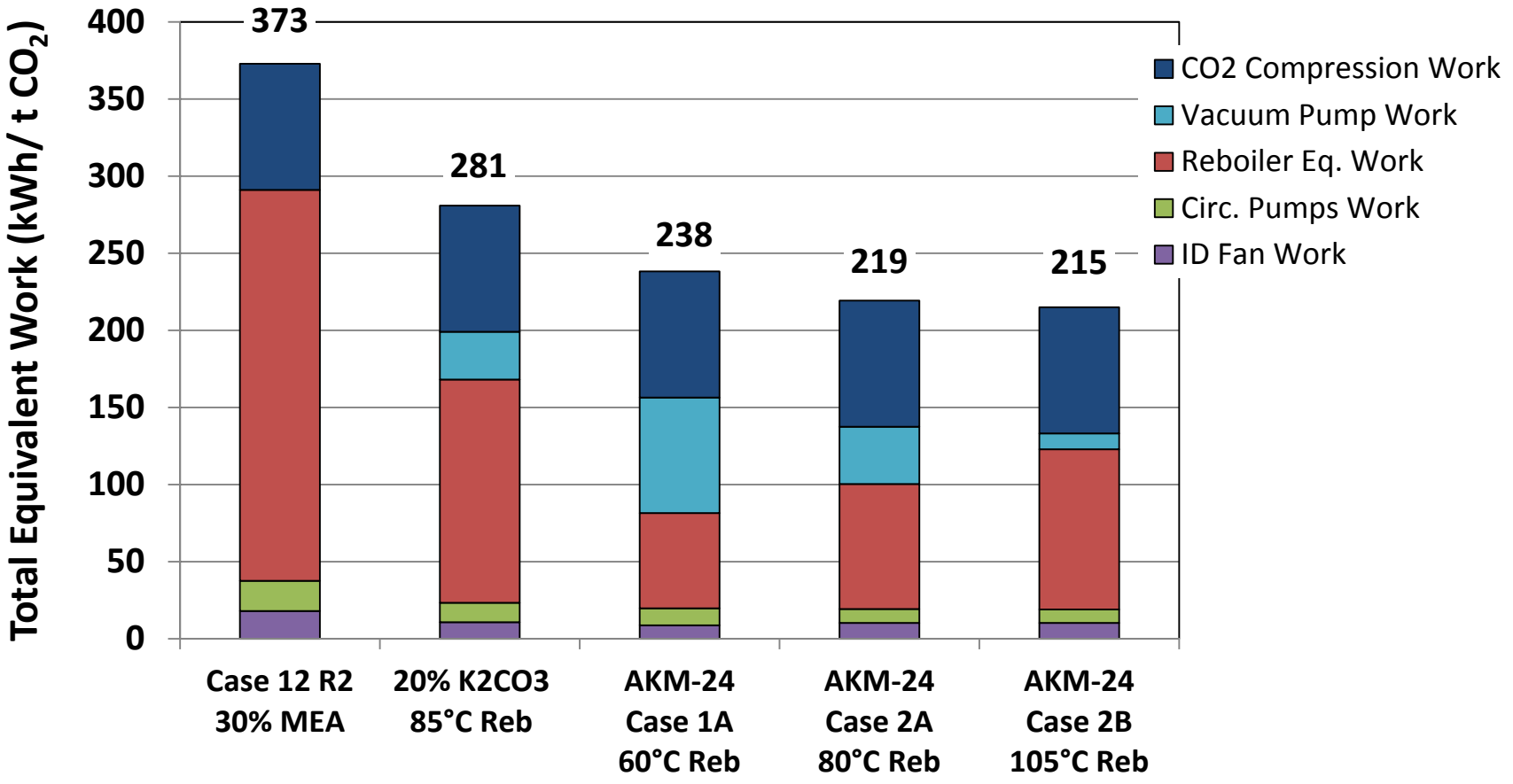
COMPARISON OF TOTAL EQUIVALENT WORK FOR VARIOUS CAPTURE SYSTEMS



Potential of reducing total equivalent work by 42% compared to Case 12

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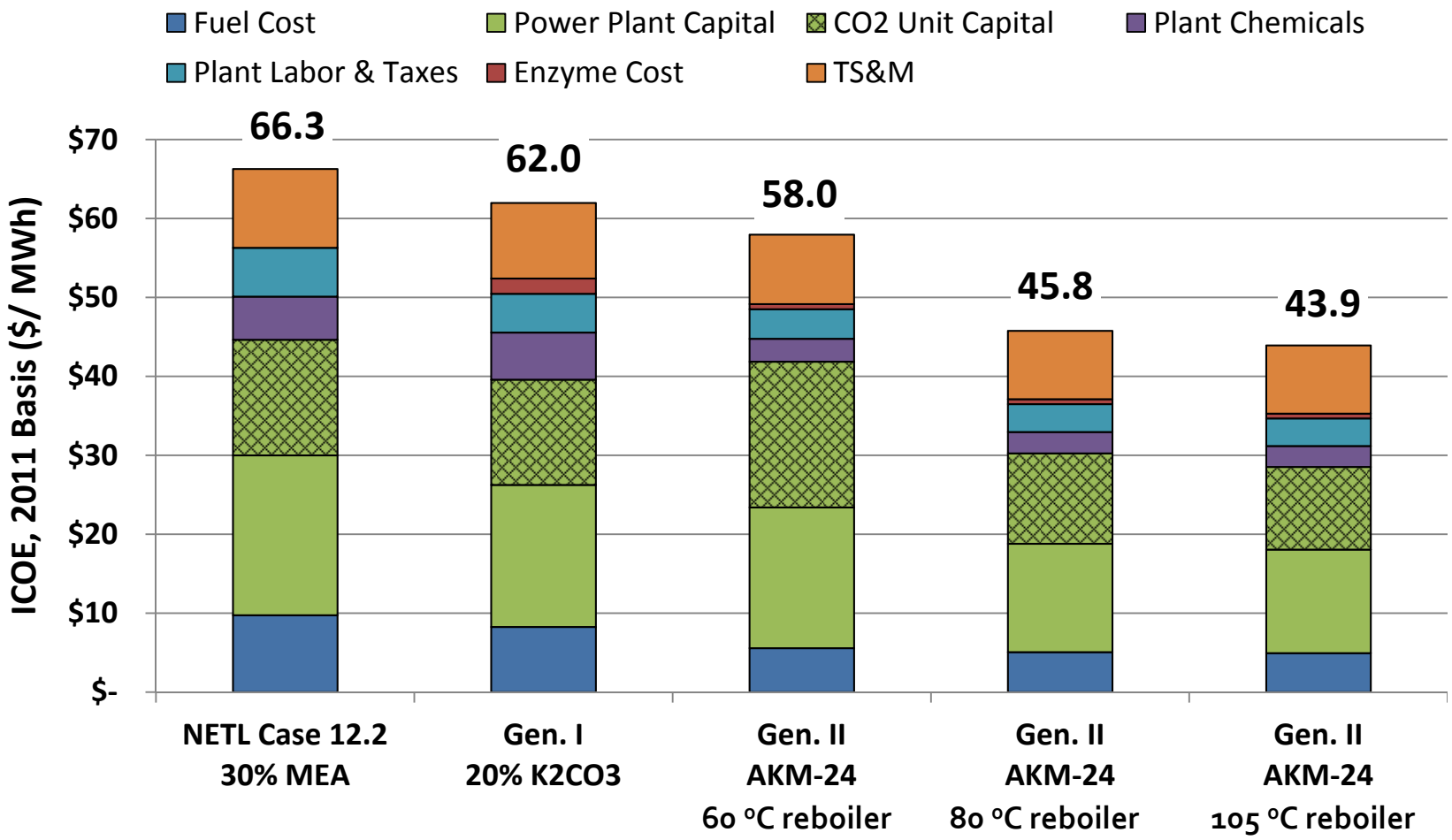
INCREMENTAL COST OF ELECTRICITY (ICOE) FOR VARIOUS CAPTURE SYSTEMS RELATIVE TO NETL CASE-11



~ 33% reduction in ICOE appears to be achievable

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FUTURE WORK AND NEXT SCALE ACTIVITIES

Commercial scale Biogas treating unit

- Size: 500 Nm^3/hr. biogas
  - (50% of avg. commercial unit)
- $7 MM, three year project
- 50% funding through EUDP (Danish Energy Agency)
- Schedule:
  - Project Kickoff – Jan 2014
  - Commissioning – May 2015
  - Operations – July 2015
- 24 months operation and testing

Upgrading biogas to pipeline specification at industrial scale using biocatalyst

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