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Putting enzymes to work™

NOVEL FLOW SHEET FOR LOW ENERGY CO_2 CAPTURE ENABLED BY BIOCATALYST DELIVERY SYSTEM

2014 NETL CO2 Capture Technology Meeting
Pittsburgh, PA.

Project: DE-FE0012862

July 30, 2014

PROJECT OVERVIEW

Participants, Duration, Funding

- **Project awardee and subcontract for TEA:**

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WorleyParsons
resources & energy

- **Enzyme Supply:**

novozymes®
Rethink Tomorrow

- **Duration: 36 months** (Oct 2013 to Sept 2016)

- **Funding:**

DOE Funding:	$ 2,999,560
Akermin Cost share:	$ 2,066,889 (40.8%)
Total Project:	$ 5,066,449

PROJECT OBJECTIVES

- Deploy a non-volatile, environmentally benign solvent with double the CO_2 absorption capacity compared to 20% K2CO3
  - AKM24
- Demonstrate *on-stream* biocatalyst replacement
- Achieve Techno-Economic Analysis Goals
  - parasitic power: <220-kWh/t CO_2
  - capital costs reduced by >20%
  - cost of capture reduced by >30%
- Complete six-month demonstration at the National Carbon Capture Center (NCCC) using coal combustion flue gas
- Demonstrate progress toward DOE long-term goals

90% CO2 capture is assumed for all DOE goals

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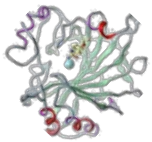
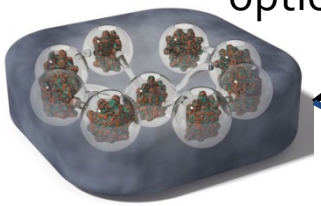
BIOCATALYST DELIVERY SYSTEM

Fundamentals driving the technology

Protected from inactivation in proprietary polymer

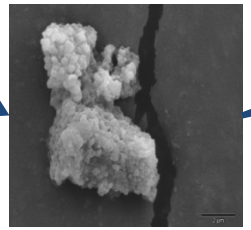


Enzyme

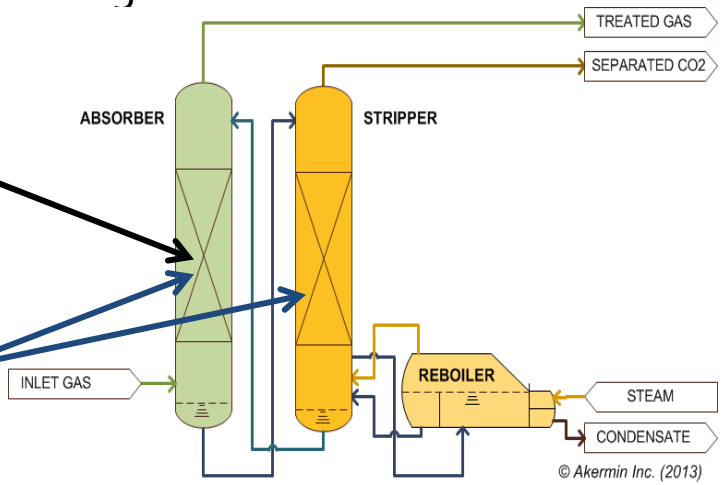


biocatalyst delivery options

1st Gen: Coated packing



2nd Gen: micro-particles



$$CO_2 + H_2O \overset{[E]}{\leftrightarrow} HCO_3^- + H^+$$

$$B^- + H^+ \leftrightarrow BH$$

The successful biocatalyst system will:

- Enable non-toxic, **non-volatile** solvents
- Enable novel **low-energy** process schemes

Leverages existing solvent and biocatalyst production technologies: readily scalable for retro-fit and greenfield opportunities

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BENCH UNIT AT NCCC

Installed at NCCC December 2012

- Sulzer M500X
- 8.33" ID x 26 ft packing
- Gas: 30 Nm^3/hr
- Liquid: 275 LPH

Module Design and Fabrication:

EPIC
MOVING AMERICAN MANUFACTURING FORWARD

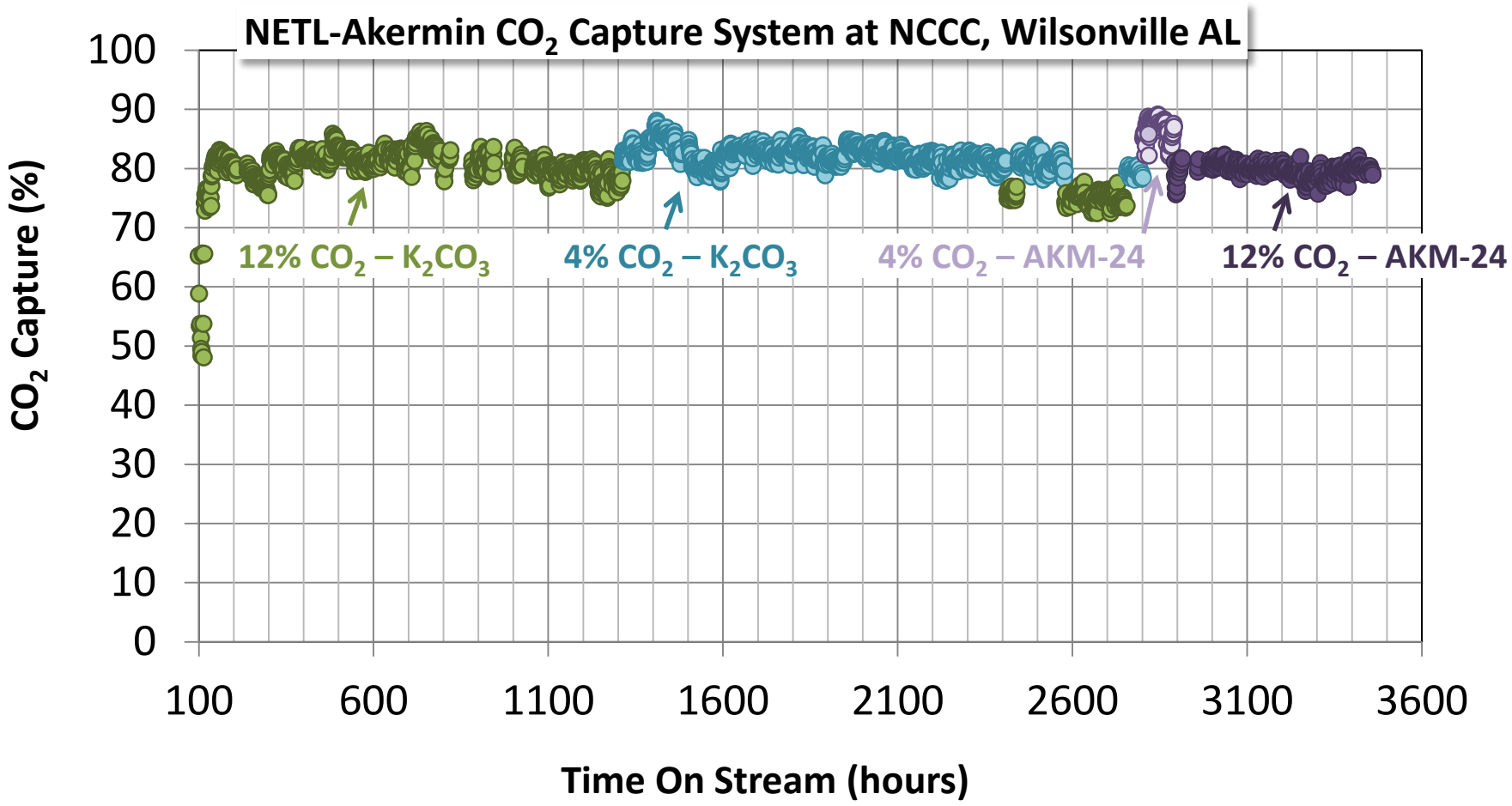
Instrumentation and controls:

EMERSON

- AKM24 solvent w/ Gen-1 Biocatalyst Delivery System (data follows)
- New project will modify existing system to accommodate Gen-2 biocatalyst delivery system, demonstrate on-line biocatalyst make-up

PREV. WORK: K_2CO_3, AKM-24 AT NCCC, GEN-1 BIOCATALYST

Time on-stream, data at design flow (31.5 Nm^3/hr, 275 LPH, $X_{C,Lean}$ ~ 25%)



Startup: 5/7/2013; 11 PM; **3460 Hrs On Stream**

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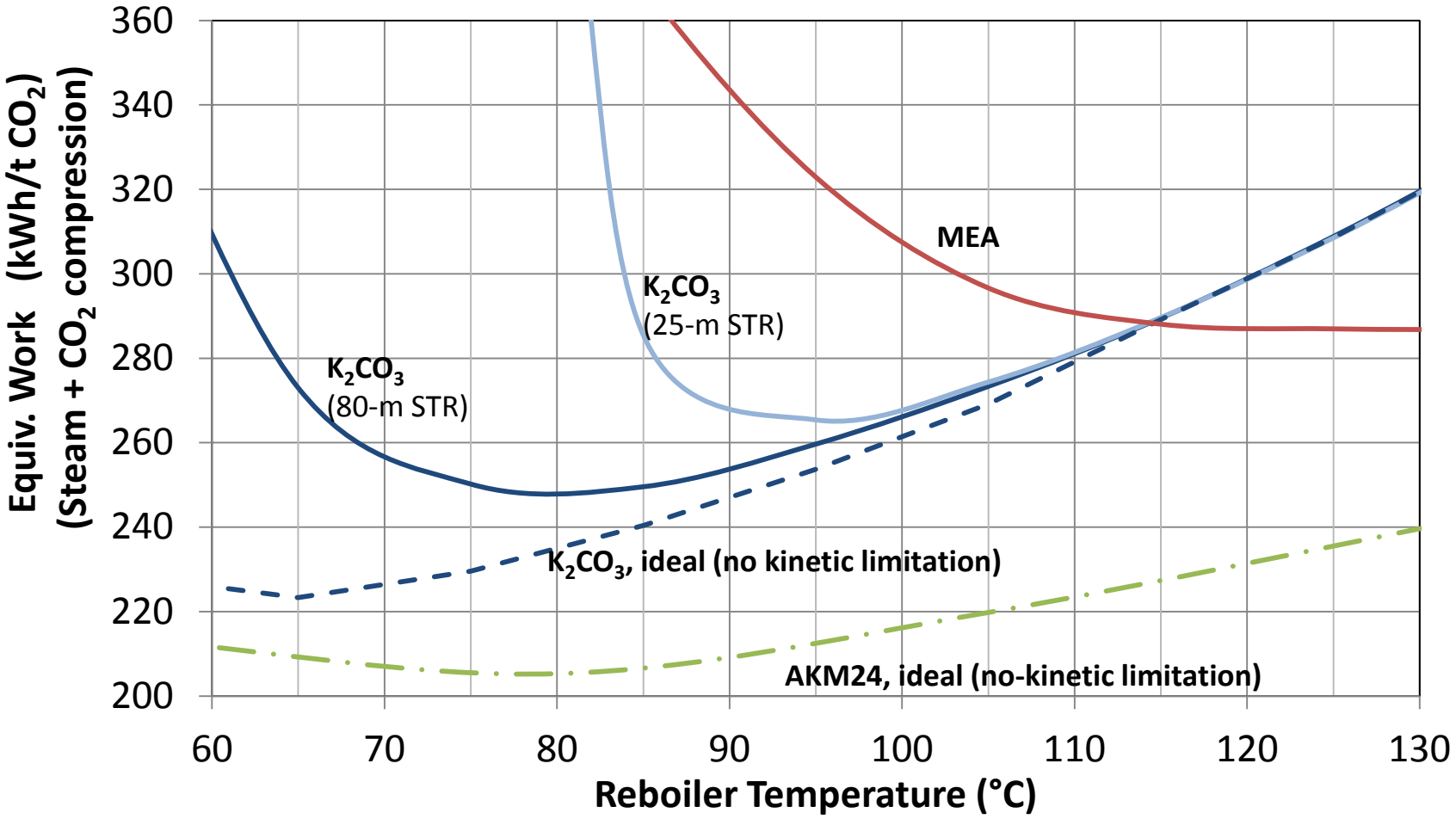
PREVIOUS STUDY: EQUIV. WORK (STEAM + COMPRESSION)

30% MEA (~83 kJ/mol), 20% K2CO3 (~28 kJ/mol) and AKM24 compared



Our challenge: lower equivalent work by addressing kinetic limitations and by using new solvent

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ADVANTAGES OF NEW SYSTEM

- AKM24 is non-toxic, non-volatile, and higher capacity
- Flow sheet improvements reduce capital equipment costs
- Potential to reduce total equiv. work by 40% cp. to Case-12.2
- Significant potential to reduce cost of capture (>30%)
- 2nd Gen biocatalyst :
  - enables on-stream catalyst management
  - has higher flux potentials, enriched at gas-liquid interface
  - production is lower cost and scalable

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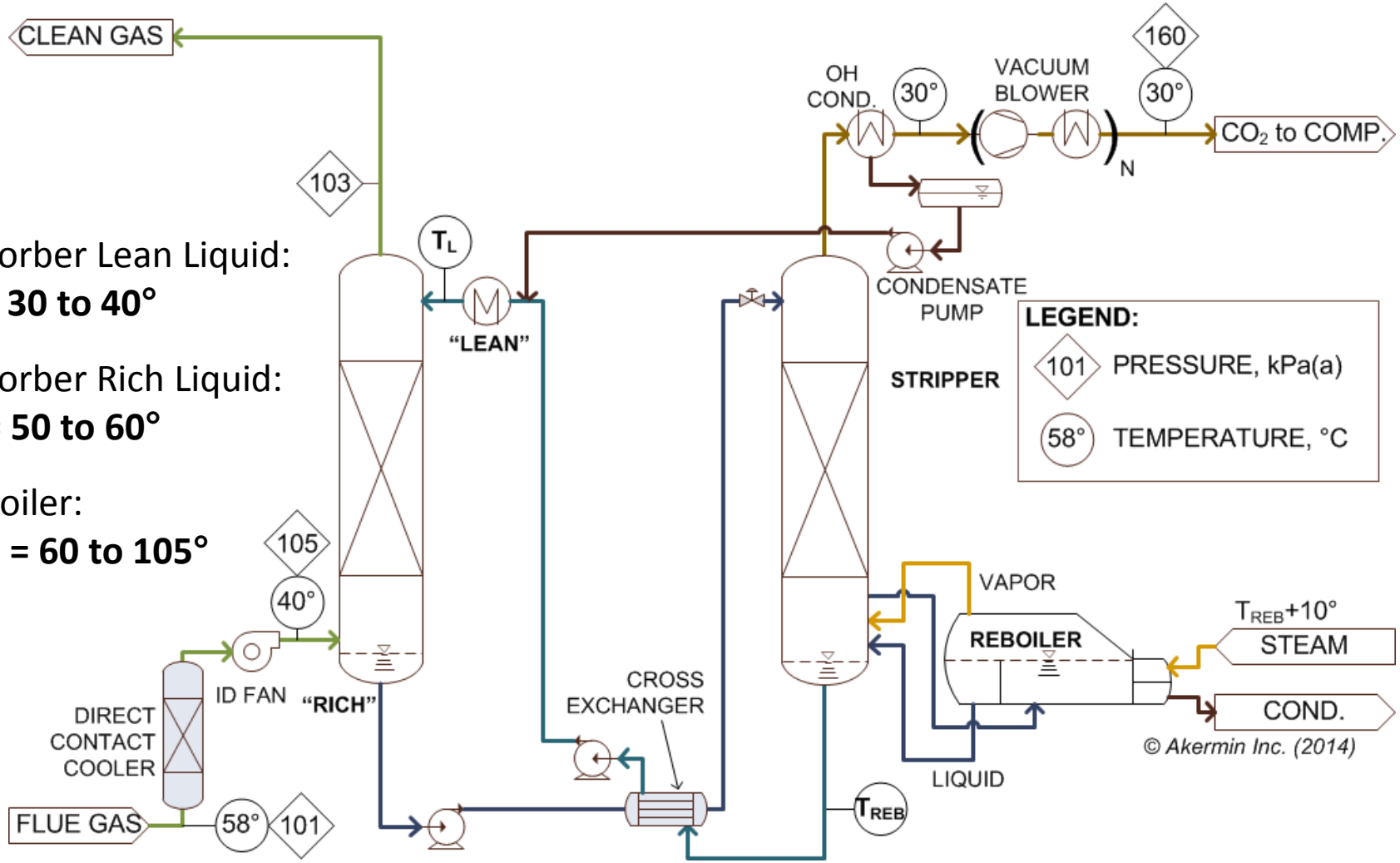
PROCESS FLOW DIAGRAM

Absorber Lean Liquid:
T_L = 30 to 40°

Absorber Rich Liquid:
T_R = 50 to 60°

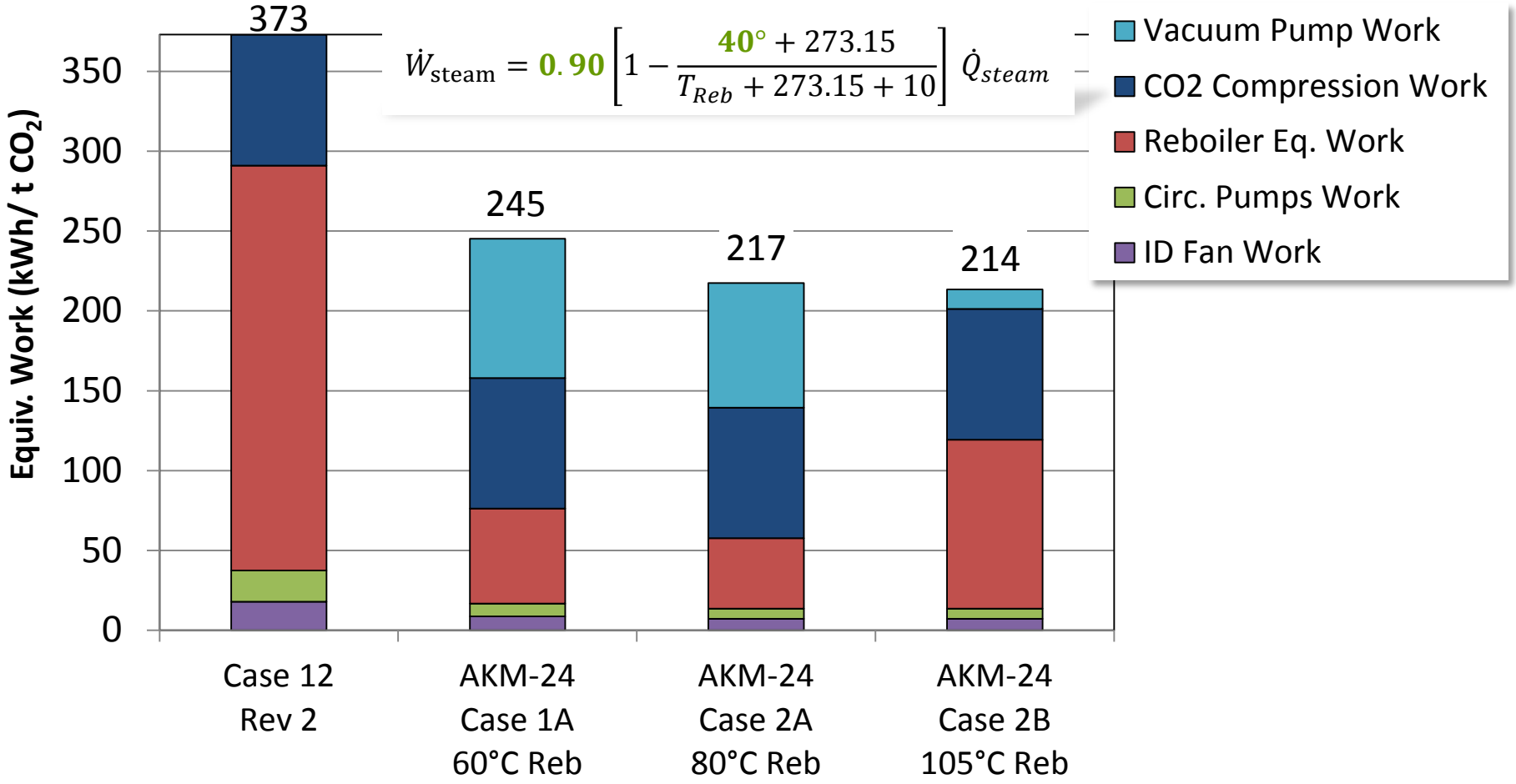
Reboiler:
T_{REB} = 60 to 105°



Optimization to identify conditions that meet total equivalent work goals.

TOTAL EQUIVALENT WORK ESTIMATES

Total equivalent work using Aspen after input of thermodynamic and kinetic data



Modeling identified cases w/ total equivalent work < 220 kWh/t CO_2
>40% reduction relative to baseline (Case 12 , Rev. 2)

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TECHNICAL APPROACH

- Task-1: Project management
- Task-2: Optimize biocatalyst
  - Identify critical process parameters, screening tests, analytics
  - Scale-up for laboratory closed loop reactor endurance tests
- Task-3: Optimize process flow sheet
  - Collect thermodynamic, physical property, and rate data as inputs to Aspen
  - Optimize for energy, equivalent work, and capital cost
- Task-4: Preliminary techno-economic analysis (TEA) with WorleyParsons
- Task-5: Engineering of bench unit modifications
- Task-6: Procure bench unit modifications
- Task-7: Operate bench unit at NCCC for up to six months
- Task-8: Complete final TEA with WorleyParsons.

Budget Period-1: Tasks 1-5; 18 Month plan
Budget period-2: Tasks 1, 6-8; planned completion by 9/2016

BP-1 SUCCESS CRITERIA MILESTONES

Budget Period 1 (Key milestone dates are indicated)

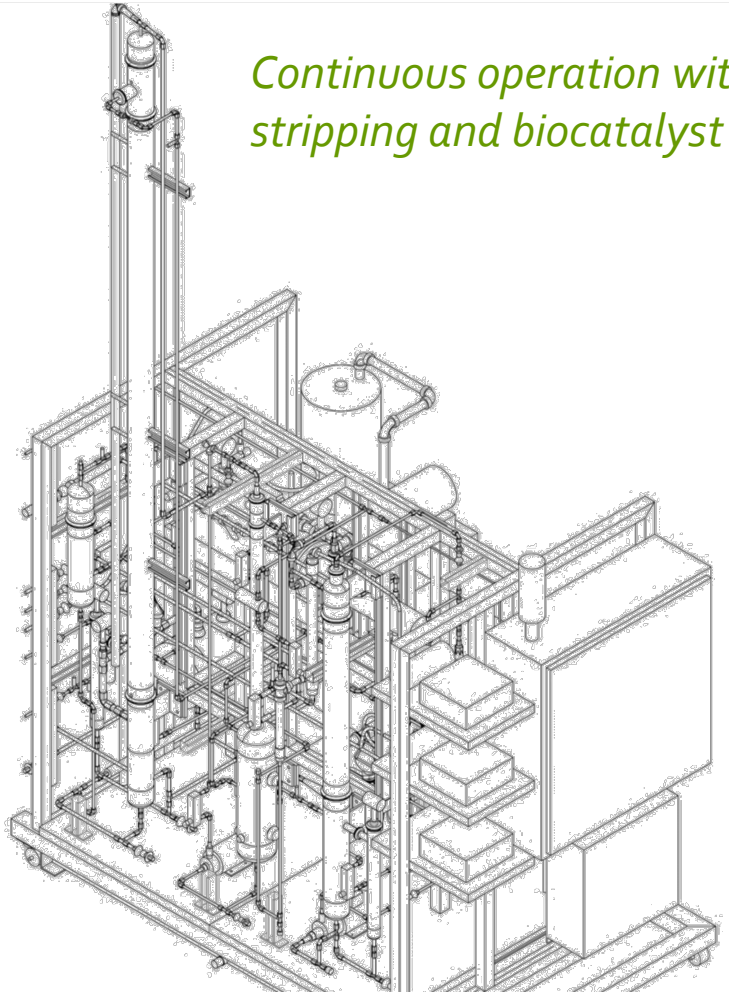
Demonstrate a non-volatile, environmentally benign solution that doubles CO_2 absorption capacity relative to 20% K2CO3	03/2013
(f) Preliminary modeling shows < 220 kWh/tCO2	05/2014
(g) 100-hrs on-stream, >10X rate enhancement (at 40°C)	10/2014
(h) 500-hrs on-stream, 90% capture, one catalyst makeup cycle	11/2014
(i) Submit preliminary Techno Economic Analysis	11/2014
20% CAPEX savings relative to NETL-12 demonstrated in TEA	11/2014
(k) Submit fixed cost proposal for bench unit modifications	02/2015
Submit and have approved a continuation application for BP-2	03/2015

BP-2 SUCCESS CRITERIA MILESTONES

Budget Period 2 (Key milestone referenced where applicable)

(r) Modified bench unit demonstrates > 2000 hrs on-stream	07/2016
(s) Submit final Techno Economic Analysis	09/2016
Final TEA demonstrates > 30% reduction in cost of capture relative to NETL-12, version 2.	09/2016
Final TEA demonstrates potential to achieve DOE target of 90% capture with <$40/t CO_2	09/2016
(t) Submit EH&S risk assessment	09/2016
Submit final report	09/2016

UPGRADED LAB-SCALE CLOSED LOOP REACTOR (CLR)



Continuous operation with vacuum stripping and biocatalyst particles

CLR: 3.3-Liter Absorber, 20-Liter Stripper; M500X Packing

CLR Upgrade Milestone completed 5/28/2014

SUMMARY OF PROGRESS TO DATE

- Produced and tested multiple biocatalyst production batches
- Lab-scale closed loop reactor upgrade is complete
- Lab closed loop reactor testing achieved >10X enhancement at 40°C
- Equilibrium and rate data collected for baseline AKM24 for a range of concentrations, temperatures, and CO2 loadings
- Aspen programmed with equilibrium constants, blank rate parameters, and kinetic model for CA enzyme, validated with enzyme kinetic model with data
- Identified cases with total equivalent work < 220 kWh/t CO2

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
  - Start Operations – July 2015
- 24 months operation and testing

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novozymes Rethink Tomorrow

AMMONGAS

BIOFOS

DGC

eUDP Energiteknologisk udvikling og demonstration

Upgrading biogas to pipeline specification at industrial scale using innovative biocatalyst solution

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