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Putting enzymes to work™

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

Project Continuation Application
Project: DE-FE0012862
DOE-NETL; Pittsburgh, PA.

July 15, 2015

PROJECT OVERVIEW

Participants, Duration, Funding

- **Project awardee and subcontract TEA:**

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WorleyParsons
resources & energy

- **Enzyme Supply:**

novozymes®
Rethink Tomorrow

- **Fabrication:**

EPIC
MOVING AMERICAN MANUFACTURING FORWARD

Installation/Host Site:

National Carbon Capture Center

- **Funding:**

DOE Funding:	$ 4,053,160
Akermin Cost share:	$ 1,013,289 (20%)
Total Project:	$ 5,066,449

REDUCING COST OF CAPTURE IN SOLVENT SYSTEM

DOE Goal: 90% capture, less than 35% increase in COE (20.6 $/MWh ICOE)

- **Direct capital savings (lower cost capture unit)**
  - Smaller or no DCC (flue gas cooler)
  - Smaller absorber with smaller or no overhead wash
  - Smaller, more efficient stripper, cross-exchanger
- **Indirect capital savings (smaller power plant)**
  - Reduce parasitic power (smaller power plant per net power output)
  - Reduce reboiler heat duty - GJ/t CO_2
  - Reduce temperature of required steam extraction
  - Exploit thermal integration opportunities
- **Reduce operating cost (benefits of efficiency)**
  - Reduce fuel consumption (lower parasitic load)
  - Reduce chemicals consumption (solvent selection and increase plant efficiency)

Improving energy efficiency is key, impacts many areas;
reducing extraction steam temperature improves efficiency/cost

PROJECT MAIN GOALS

- Develop an enzyme-based approach to CO2 capture with significantly improved performance compared to NETL Case 12 meeting following targets:
  - parasitic power: <220 kWh/t CO_2
  - capital costs reduced by >20%
  - cost of capture reduced by >30%
- Complete demonstration at the NC3
  - Assess performance of a new non-volatile, environmentally benign solvent
  - Demonstrate *on-stream* biocatalyst maintenance

90% CO2 capture is assumed for all DOE goals

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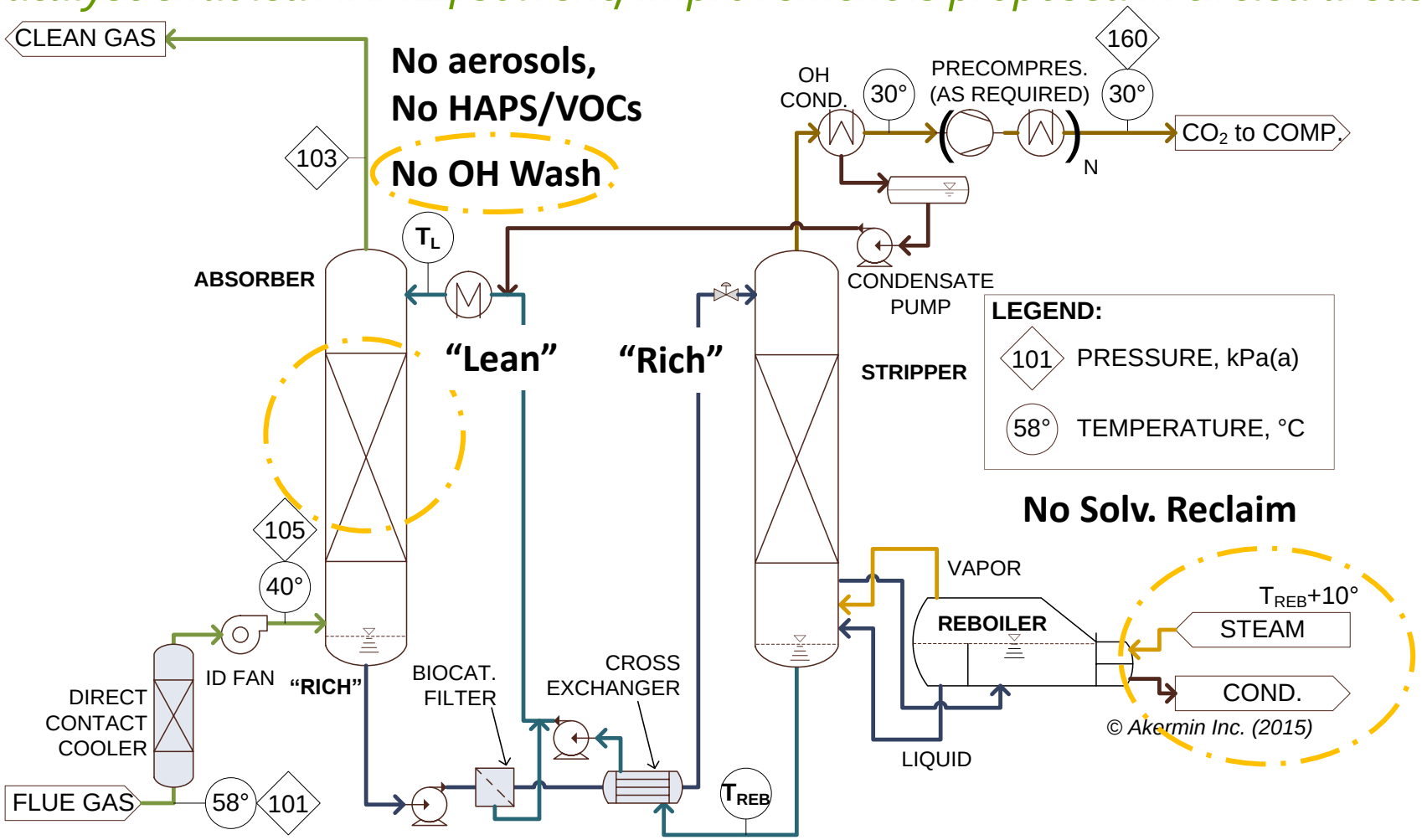
APPROACH: BIOCATALYST ENABLED SOLVENTS

Biocatalyst enabled AKM24 solvent; improvement is proposed in circled areas



Low energy, low volatility solvent AKM24 enabled by biocatalyst system

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BIOCATALYST ENABLED SOLVENT

Solvent, AKM-24

- ✓ **High CO_2 loading**
- ✓ **Low regeneration energy**
- ✓ Non-volatile
- ✓ Thermally stable
- ✓ Highly water-soluble
- ✓ Manufacturing route established
- ✓ Low EH&S risks

Biocatalyst, Carbonic Anhydrase (CA)

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

$k_{cat} = 10^6/sec$

- Thermostable
- Resistant to high pH (9.5-10.5)
- Expressed at high levels with few impurities

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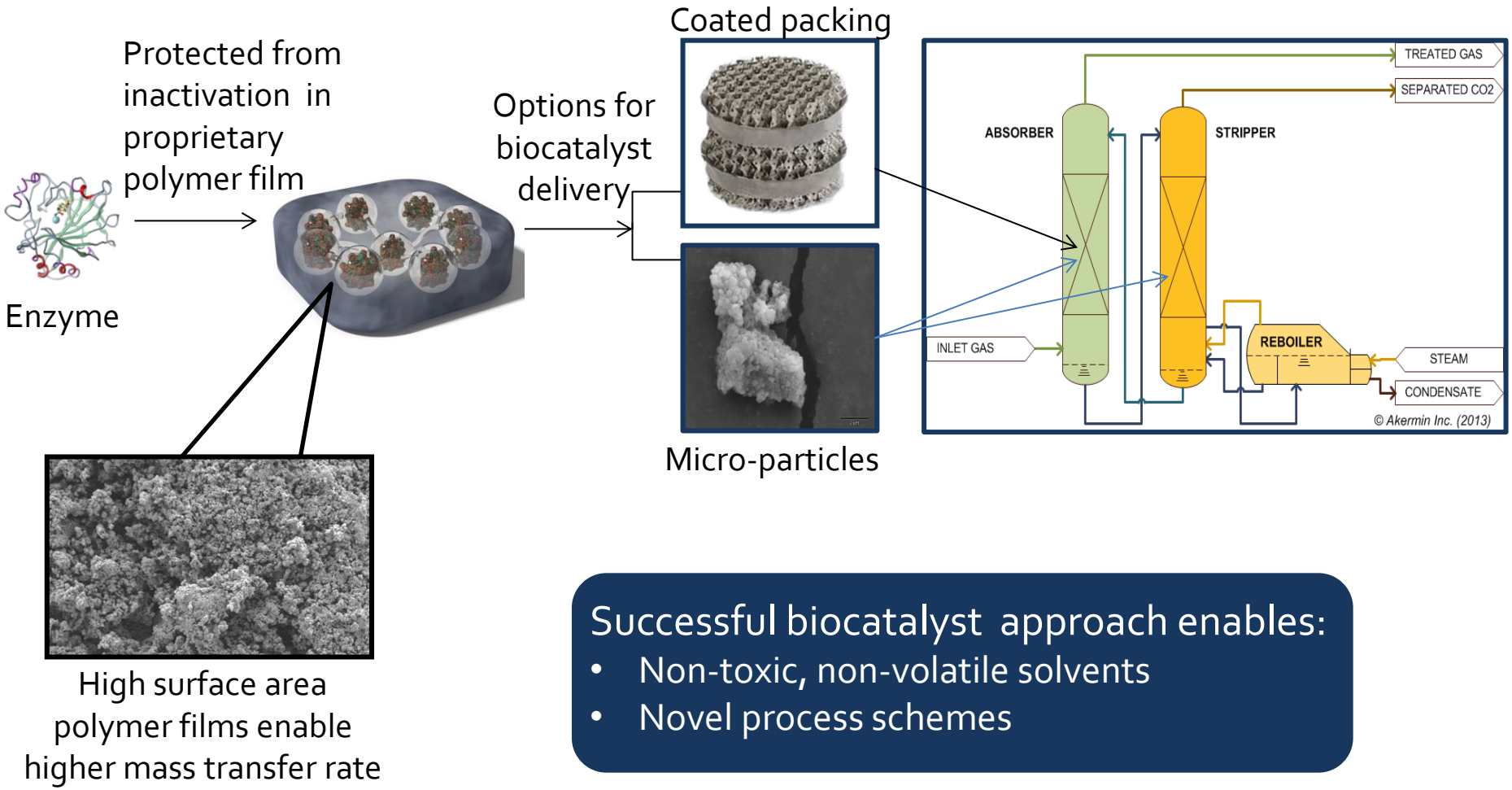
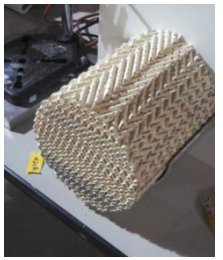
AKERMIN'S BIOCATALYST DELIVERY SYSTEM



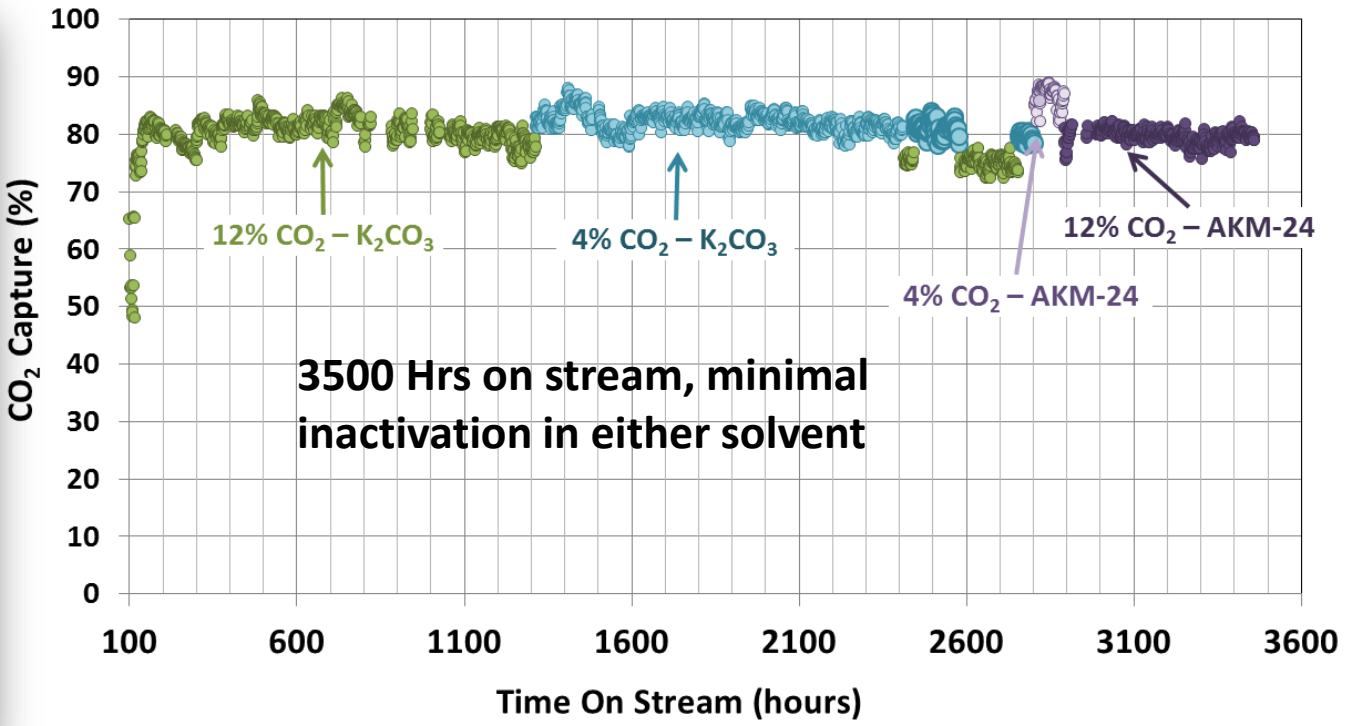
Successful biocatalyst approach enables:

- Non-toxic, non-volatile solvents
- Novel process schemes

PROOF OF CONCEPT: CATALYST ON PACKING



Two solvents tested: K2CO3 and AKM24 (May – Oct 2013)



Remaining challenges: further reduction of energy and in situ biocatalyst replacement

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BP1 REVIEW

BP1 SCOPE

- Task 1: Project management, reporting
- Task 2: Develop/Optimize Biocatalyst Delivery System.
- Task 3: Optimize the process, minimize equivalent work
- Task4: Develop preliminary TEA with WorleyParsons
- Task 5: Define bench unit mods, develop fixed cost estimate

SUBTASK 2.2 COMPETE – MODIFY LAB-SCALE CLR TO SUPPORT BDS TESTING

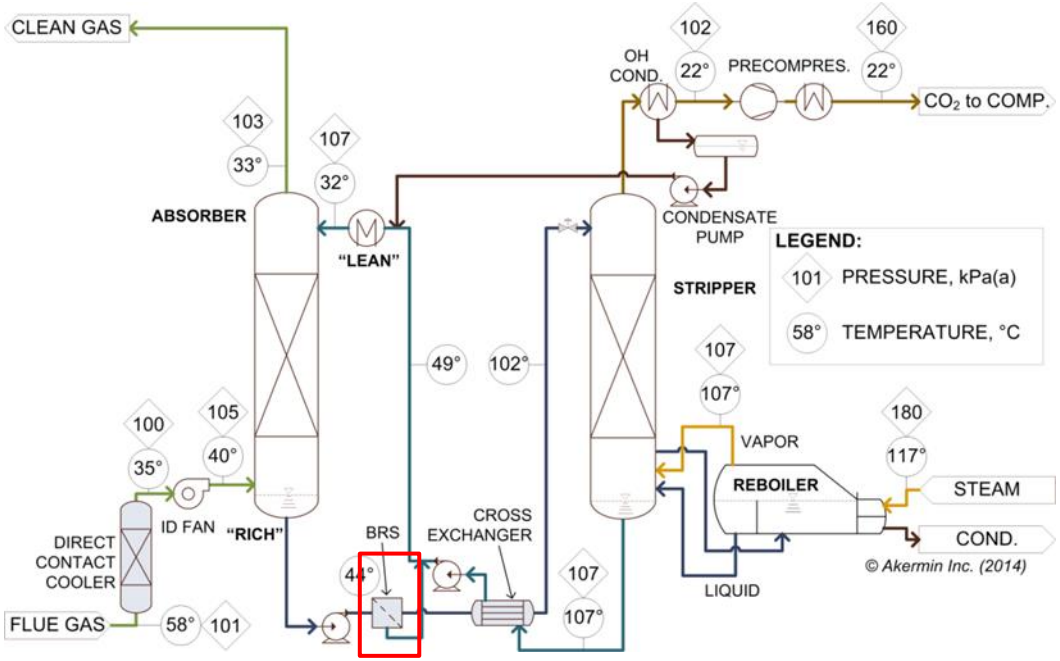
- Left image: the reboiler is in white near the wall
- Right image: the stripper column near the wall, the saturator column in the middle, and absorber column and gas analysis equipment on the far right.

BIOCATALYST TESTING IN MODIFIED CLR

Original proposal: recirculate particles throughout absorber and stripper; perform TEA and select optimal conditions to test at NC3

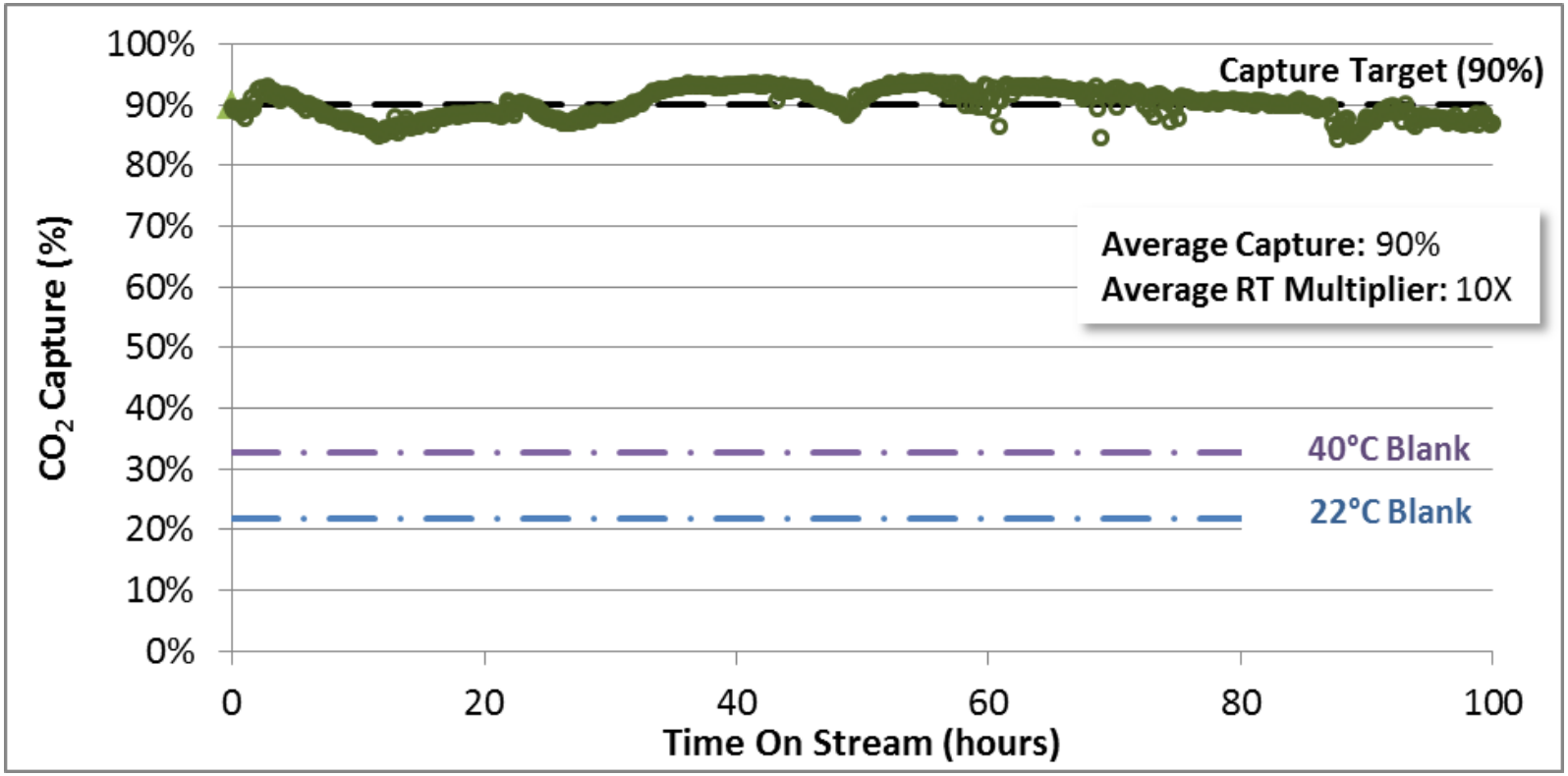
- TEA revealed that the most compelling option is case 2B with 105 °C reboiler (to be discussed later)
- Decision was made to proceed with 105 °C reboiler and particle separation unit

NEW SUBTASK 2.5 – DEVELOP BIOCATALYST RECOVERY SYSTEM (BRS) FOR EXISTING CLR, BENCH UNIT DESIGN (COMPLETE)



Process Flow Diagram for CO_2 Capture Unit with AKM24 Enabled by Biocatalyst

SUBTASK 2.3, MILESTONE "G" - DEMONSTRATE 100-HRS OF 10X BIOCATALYST RATE ENHANCEMENT IN THE INTEGRATED CLR SYSTEM (COMPLETE)



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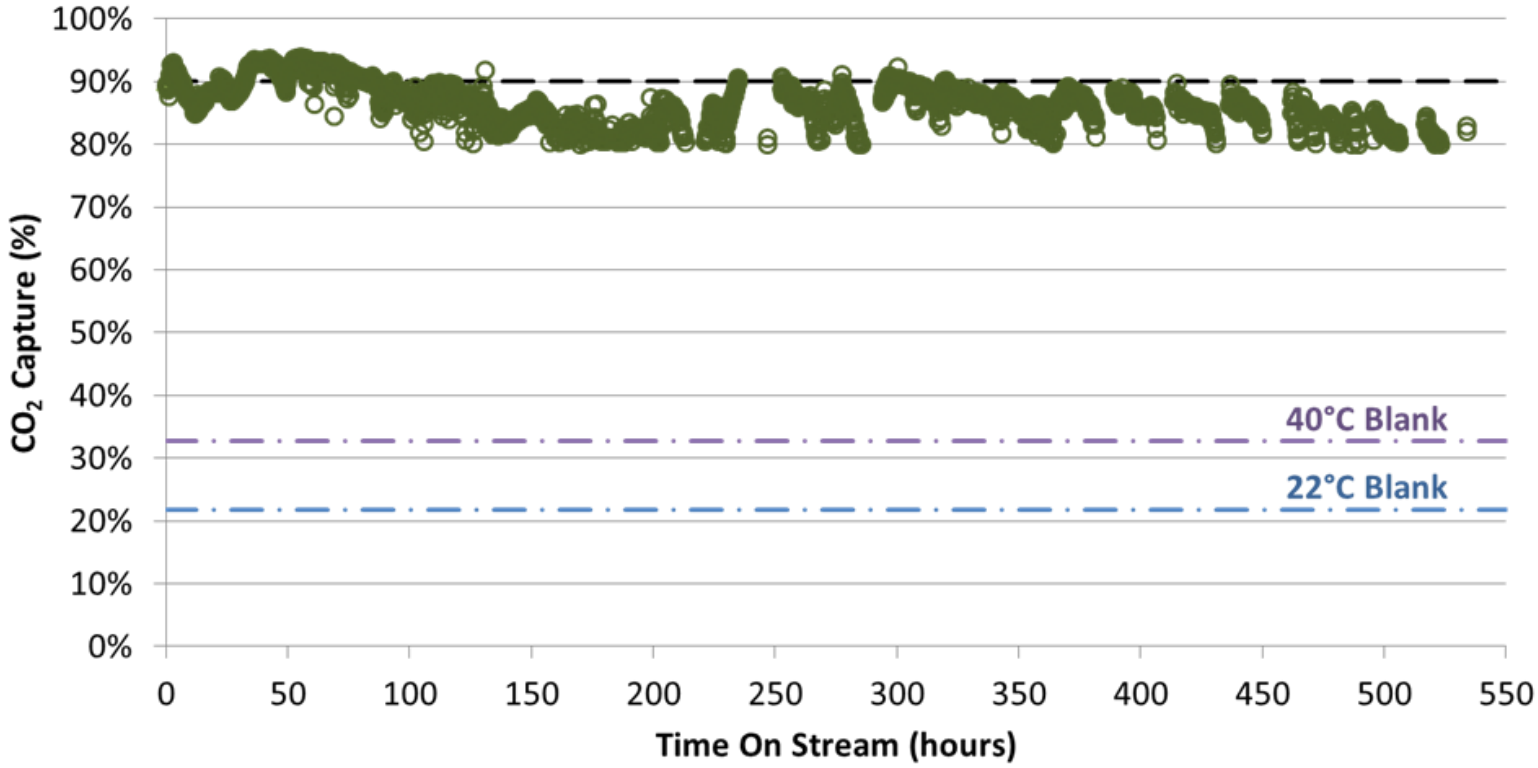
MILESTONE "H"- DEMONSTRATE 500-HRS, 90% CAPTURE, 10X ENHANCEMENT WITH INTEGRATED CLR SYSTEM



Subset of CO2 capture data

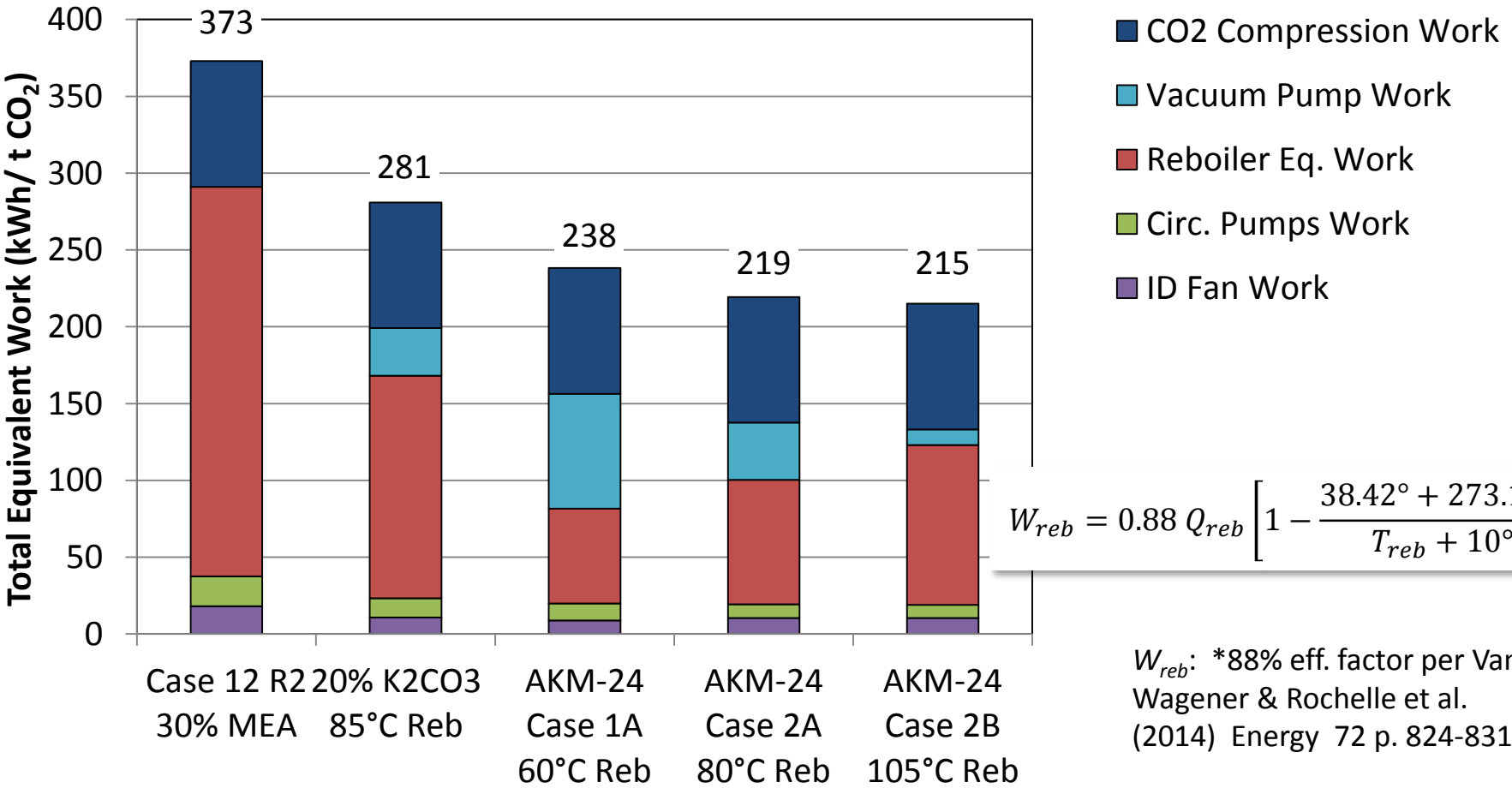
SUBTASK 3.2, OPTIMIZE FLOW SHEET

Three cases selected for study after initial trend screening

- **Case-1A:** Isothermal system (deeper vacuum stripping), no cross-exchanger, no flue gas cooler.
  - 40% AKM24, 50°C lean feed, 60°C reboiler
  - Biocatalyst particles circulate through the entire system
- **Case-2A:** Conventional , light vacuum assisted regeneration.
  - 35% AKM24, 40°C lean feed, 80°C reboiler
  - Biocatalyst particles circulate through the entire system
- **Case-2B:** Conventional absorption-desorption system with atmospheric pressure regeneration.
  - 35% AKM24, 40°C lean feed, 105°C reboiler
  - BRS separates biocatalyst, circulates only in absorber to avoid exposure to >100°C.

MILESTONE "f", EQUIVALENT WORK <220 kWh/tCO$_2$

Main compressor (1.6 bar to 152 bara) equiv. to NETL-12 (86% eff); VBL (80% eff.)



$$W_{reb} = 0.88\, Q_{reb}\left[1 - \frac{38.42° + 273.15K}{T_{reb} + 10°}\right]$$

W_{reb}: *88% eff. factor per Van Wagener & Rochelle et al. (2014) Energy 72 p. 824-831.

Milestone "f: Case-2A and Case-2B achieved < 220 kWh/tCO2,

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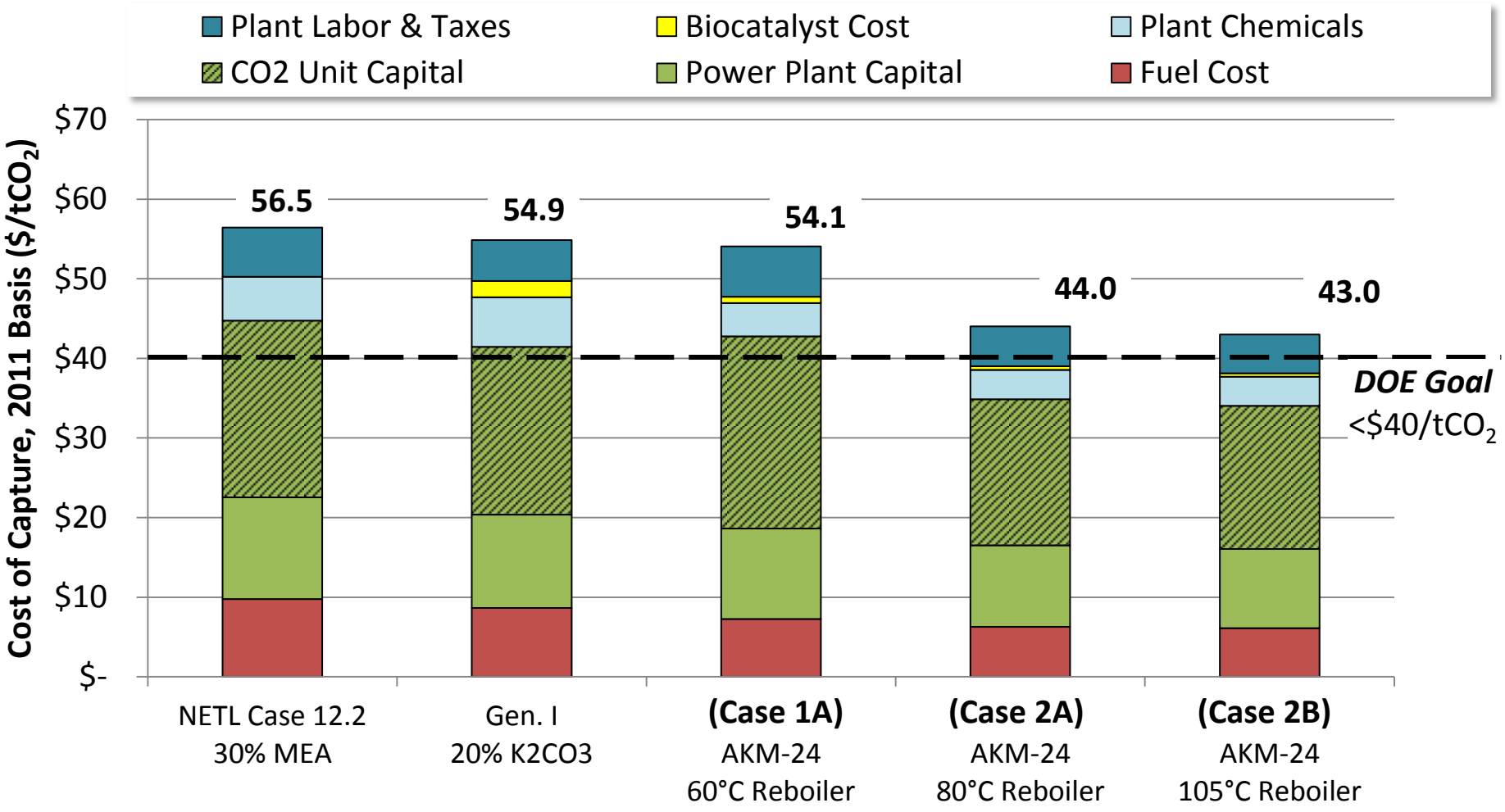
PRELIMINARY TEA RESULTS, PROGRESS TO $40/tCO$_2$ GOAL



Modeling results with WP, Separate contingencies applied to power plant and CO_2 unit capital

Preliminary TEA report submitted Feb. 6, 2015, successfully completing Milestone "i"

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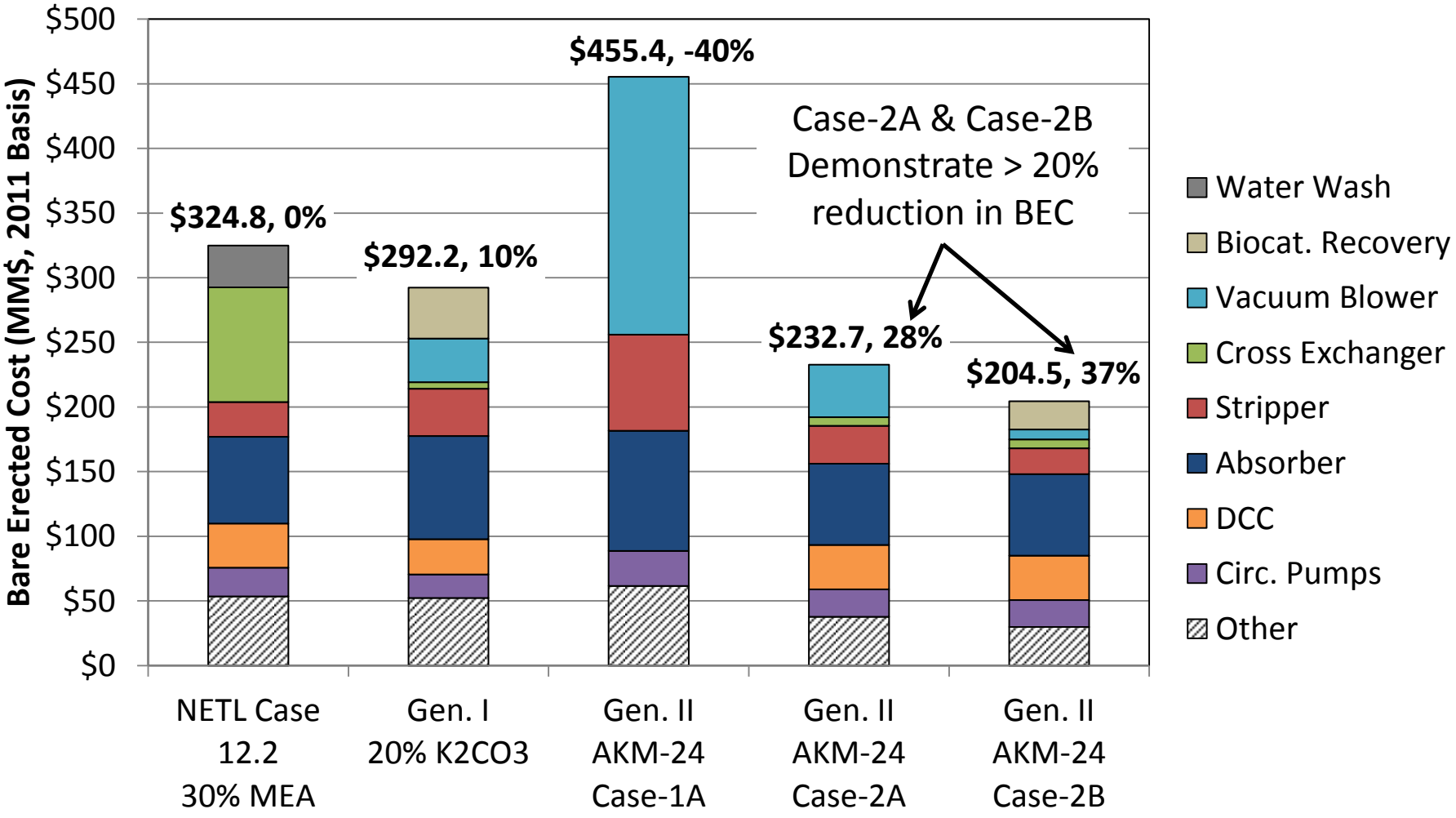
ACHIEVED >20% REDUCTION IN BEC (CAPITAL COST)



37% reduction in capital cost for Case-2B compared to Case 12, significantly better than goal of 20% reduction in BEC

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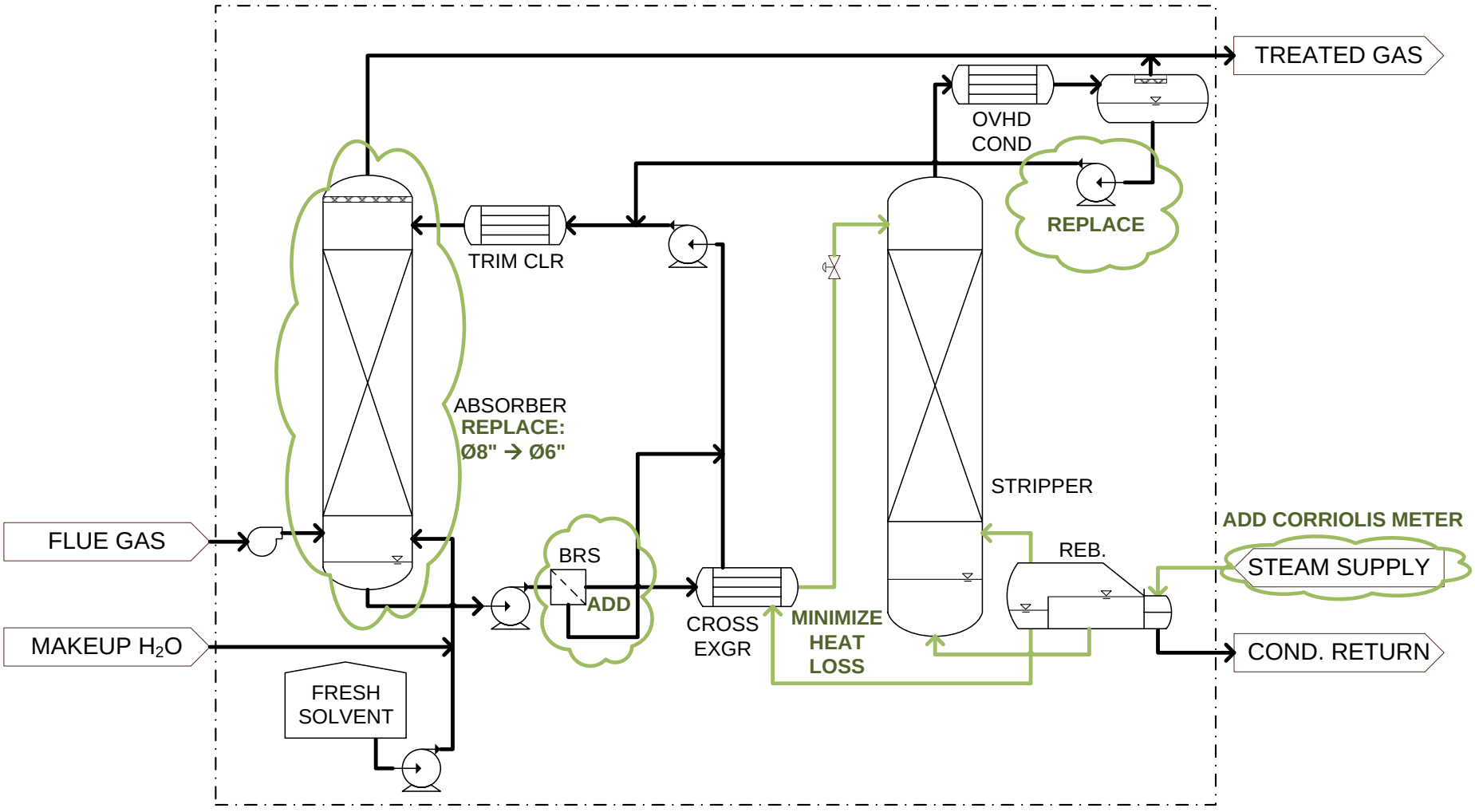
TASK 5: PLANNING BENCH UNIT MODS/COST EST. BASIS



EPIC Systems Inc. provided a fixed price bid to complete the bench unit mod. on July 6th, 2015, fulfilling Milestone "k"

BENCH UNIT MOD. PROCESS HAZARD ANALYSIS

- PHA conducted at Akermin on June 4th, 2015
  - *Facilitated by:* ABS Consulting
  - *Participants:* Akermin, EPIC systems, Southern Company (NCCC), and Proc. Eng. Consultants.
- Draft report received from ABS and submitted to DOE (June '15)

Milestone "i" fulfilled on June 4, 2015

REVIEW OF BP1 SUCCESS CRITERIA

- Completed BP-1 proposed scope of work
- Preliminary modeling demonstrated <220 kWh/t CO2,
- Target 500-hrs with 90% of initial activity (with < one full catalyst add)
- Deployed non-volatile, environmentally benign solution with (approx.) double CO_2 absorption capacity relative to previous work (20% K2CO3)
- Completed Preliminary TEA with WorleyParsons
- Transmitted fixed cost proposal for bench unit modifications
- Submitted continuation application for BP-2 (in review)

BP2 PLAN

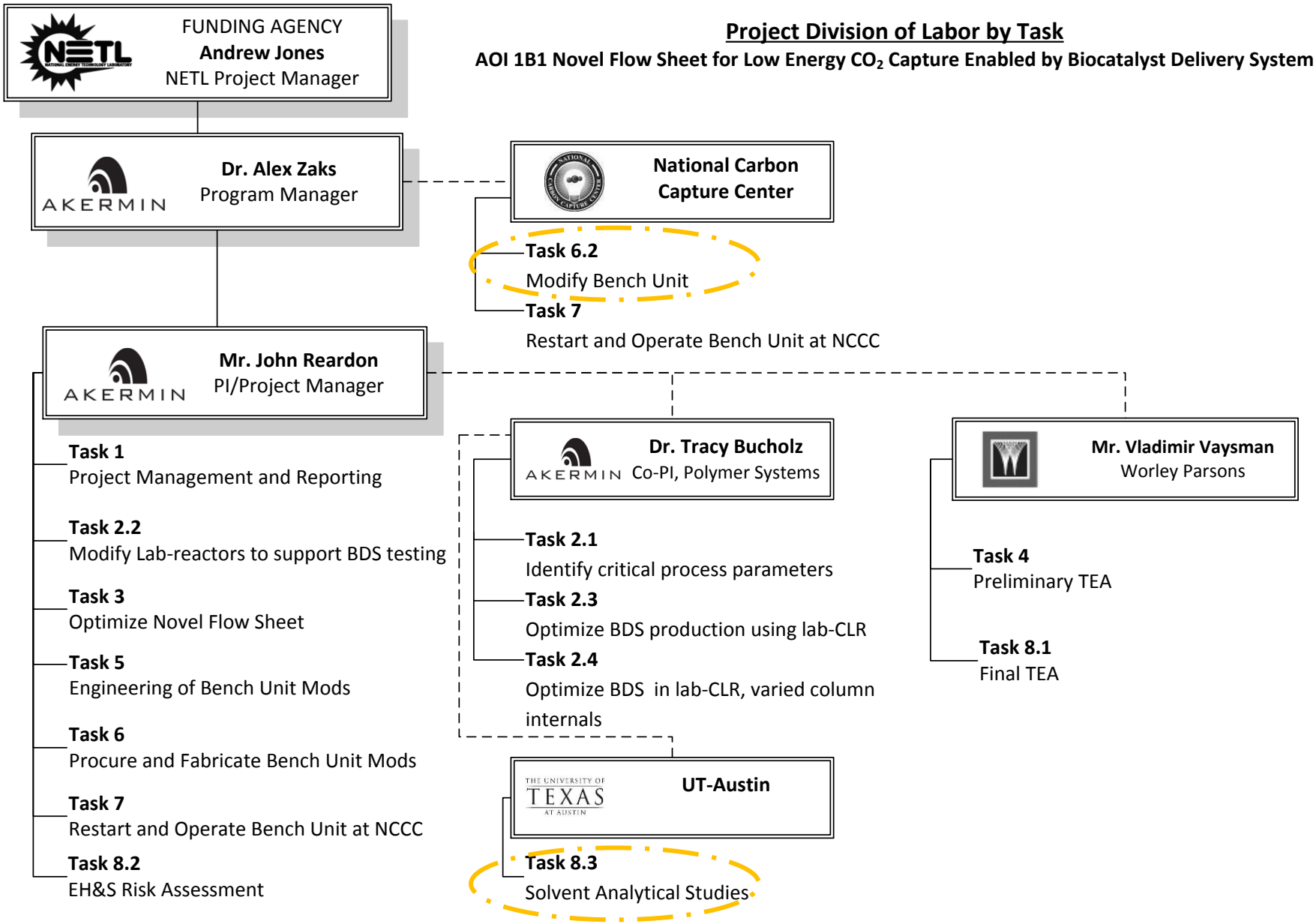
BP2 SCOPE, REVISED

- Task 1: Project management, reporting
  - Quarterly reports (RPPR), review meetings, and final report
- Task 6: Procurement and Installation of Bench Unit Mods.
  - 6.1 Eng. Proc. & Fab. key components (BRS, Absorber, instruments, tube)
    - EPIC Systems
  - 6.2 Field modification (R&R absorber column, +BRS, + tubing, +electrical)
    - Southern Company/NCCC
- Task 7: Restart and Operate Bench Unit (at NCCC)
  - 7.1 Commissioning and baseline testing
    - Akermin/NCCC support
  - 7.2 Endurance test with biocatalyst
    - Akermin/NCCC support (sampling and analysis)
- Task 8: Final Technology Assessment
  - 8.1 Final TEA
  - 8.2 EH&S Assessment
  - 8.3 Solvent analytical studies

NCCC: (6.2) installation; (7.2) operations , sampling, analytical support

UT Austin: 8.3 solvent analytical studies (degradation analysis)

NETL2, UPDATED PROJECT DIVISION OF LABOR



KEY PROJECT MILESTONES

New ID	Milestone Description	Planned Date
1a	Submit Updated Project Management Plan one month after notice to proceed.	08/31/2015
6a	Notice to proceed; Issue PO for 500 SLPM bench unit modifications to vendor	07/22/2015
6f	Complete installation and electrical checkout; ready to operate modified 500 SLPM bench unit	10/14/2015
7a	Complete modified bench unit start-up and establish baseline performance	10/30/2015
7b	Submit final test plan for the modified 500 SLPM operation with biocatalyst	10/30/2015
7c	Biocatalyst installed, demonstrate 90% CO_2 capture with modified 500 SLPM bench unit and report process and operating conditions	11/06/2015
7d	Complete at least 1,000 hours of testing with the modified 500 SLPM bench unit with biocat.	12/23/2015
8a	Complete Final TEA	3/31/2016
8b	Complete EH&S Risk Assessment, including results from isokinetic sampling and solvent degradation studies.	3/31/2016
FR	Draft final report	3/31/2016

BP2 SUCCESS CRITERIA

i	Successful completion of all work proposed in BP2.
ii	Modified bench unit demonstrates consistent perf. with >1000 hrs on-stream.
iii	Final TEA demonstrates >30% reduction in cost of CO_2 capture, cp. NETL-12.
iv	Final TEA demonstrates potential to achieve the DOE target of 90% CO_2 capture with less than $40/tonne CO_2 captured
v	Submission of a Topical Report - Final Techno-Economic Analysis
vi	Submission of a Topical Report – EH&S Risk Assessment
vii	Submission of a Final Report

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