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Fog+Froth-Based Post-Combustion CO_2 Capture in Fossil Fuel Power Plants DE-FE0031733

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University of Kentucky
Lexington, KY

http://uknow.uky.edu/research/unique-public-private-research-consortium-established-caer-co2-capture-pioneers

2023 Carbon Management Research Project Review Meeting
August 28-September 1, 2023

Project Objective

Reduce CO_2 capture capital and operating costs by reducing the absorber size

Performance Dates: 5/1/2019-12/31/2023

BP1

5/1/2019-1/31/2021

- Test Plan, TMP
- Absorber Fabrication and Testing
- Absorber Integration into Existing UK Bench CO_2 Capture Unit
- Parametric Testing

BP2

2/1/2021-12/31/2023

- Long-term testing
- SPDT, TEA, EH&S, TGA
- Low Absorber Bottom T Performance Evaluation

Project Team and Funding

Project Participant	Scope of Work
University of Kentucky (UK)	• Project Lead • Nozzle selection, compact absorber design, fabrication and integration with existing facilities • Parametric and long-term study, data analysis, reporting and project management
Industrial Climate Solutions, Inc. (ICSI)	• Frothing generation design and section fabrication
NexantECA	• Techno-economic analysis (TEA)
ALL4	• Environmental, Health and Safety (EH&S) assessment

	DOE-NETL	Cost Share	Total
Total	**$2,947,404**	**$738,023**	**$3,685,427**
Percent Share	**80%**	**20%**	**100%**

Executive Summary

On Track to Meet Deliverables and Success Criteria

- Achieved over 2300 total hours of operation
- Absorber bottom T of 27 °C demonstrated
- TEA on low absorber bottom T case complete:
  - Net Power Output of 686 MWe, 5% increase from 2019 B12B
  - LCOE of 95.6 $/MWh (ex. T&S), 9% reduction from B12B
  - BESP of $36.7/tonne CO_2, 20% reduction from B12B

Previous Findings:

- 2.3 mol C/kg rich loading demonstrated, on par with traditional absorber performance with >2X absorption height
- Statistical analysis of long-term campaign data show residence time is limiting factor for CO_2 absorption and no performance change with increasing solvent degradation
- Solvent emissions after absorber consistent with small pilot data, supporting <1 ppm after water wash

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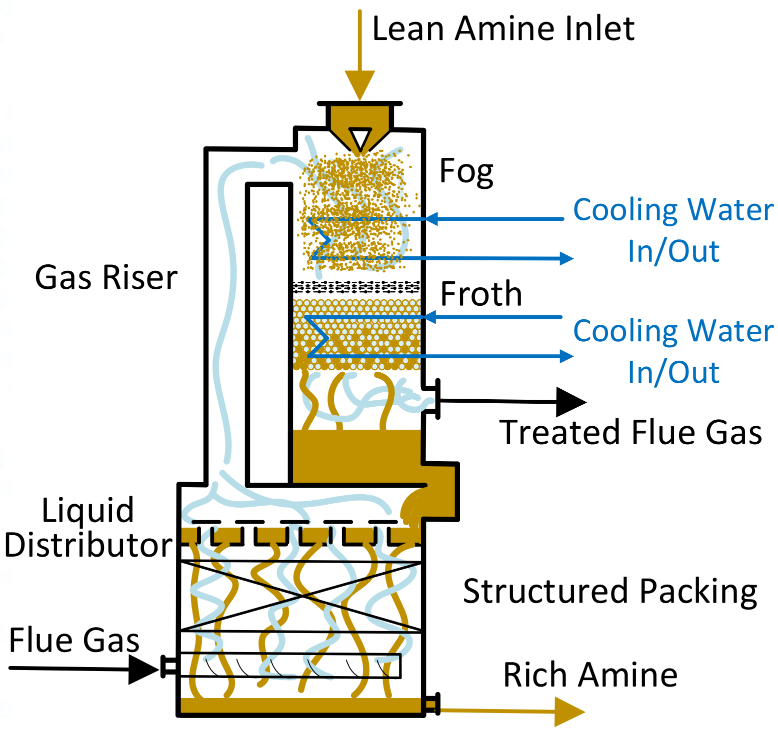
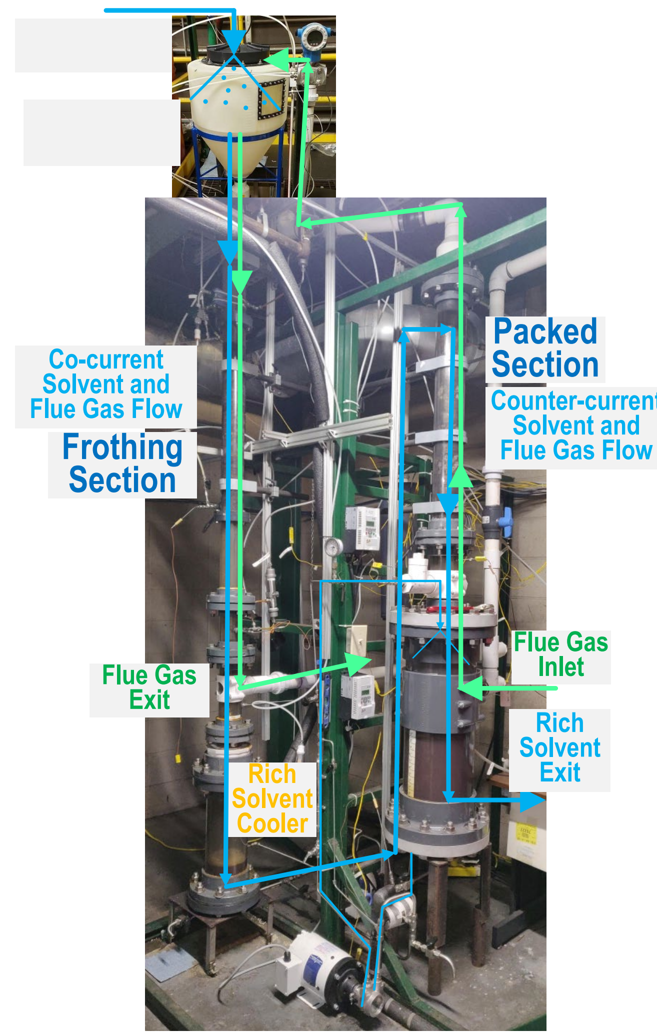
Technology Background

High Liquid-Gas Contact Surface Area
Low CO_2 Diffusion Resistance
→ Reduced Absorption Height Requirement
Lower CAPX and OPEX

Low Absorber Bottom T
→ Advantageous VLE For Higher Rich Loading
Lower Regeneration Energy Requirement





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CO_2 Capture Direct Costs

Equipment	**45%**
Columns	50%
Heat Exchangers	25%
Pumps	10%
Instrumentation and Control	5%
Balance of Plant	10%
Civil	20%
Installation	20%
Engineering Fee	10%
Insurance and Others	5%
	100%

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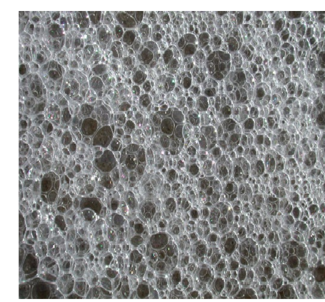
Increased A – Replace Packing with Fog and/or Froth

With a fog, the surface area is increased by 5 to 7 times that of 250Y structured packing.

Liquid-Gas Contact Surface Area at L/G=3.5 mass/mass					
Uniform Droplet Size (µm)	30	40	50	75	100
Liquid-Gas Contact Surface Area (m^2/m^3)	3119	2339	1871	1247	936
Improvement over 250Y Structured Packing	12.5X	9.4X	7.5X	5.0X	3.7X

With a froth, the surface area is increased by >4 times that of 250Y structured packing.

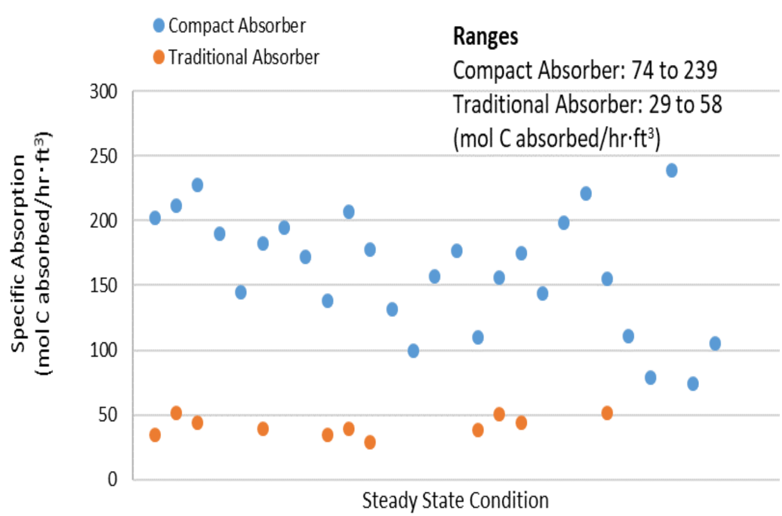
Liquid-Gas Contact Surface Area at L/G=3.5 mass/mass				
Uniform Bubble Size (mm)	3	4	5	8
Liquid-Gas Contact Surface Area (m^2/m^3)	2000	1500	1200	750
Improvement over 250Y Structured Packing	8X	6X	3X	3X



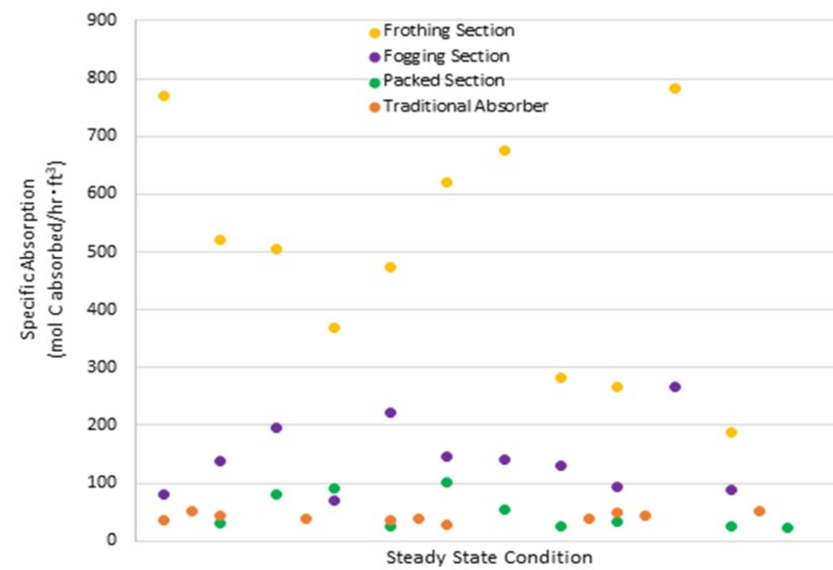
Increased k_g' – Replace Packing with Fog and/or Froth

Specific absorption 2.6 to 4.1X higher than in the traditional absorber, depending on the operating parameters.

Specific Absorption in the Compact Absorber Parametric Campaign Compared with that in a Traditional Absorber



Specific Absorption in Each Section of the Compact Absorber Compared with that in a Traditional Absorber



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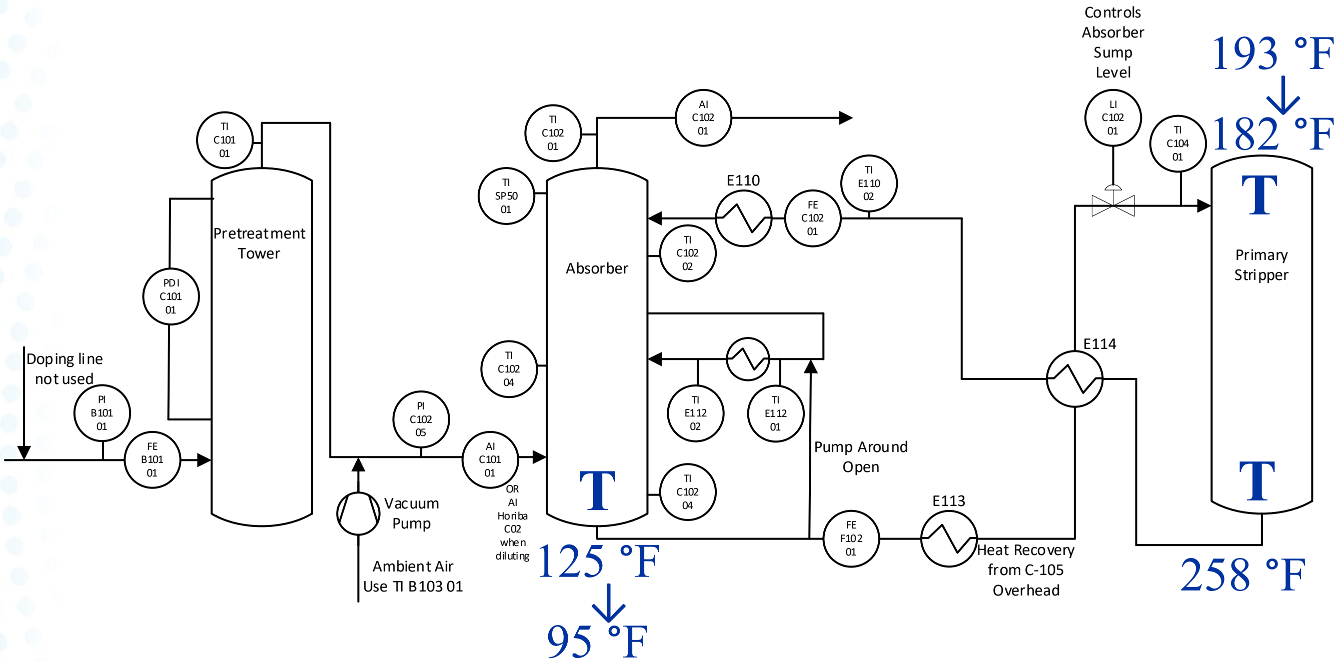
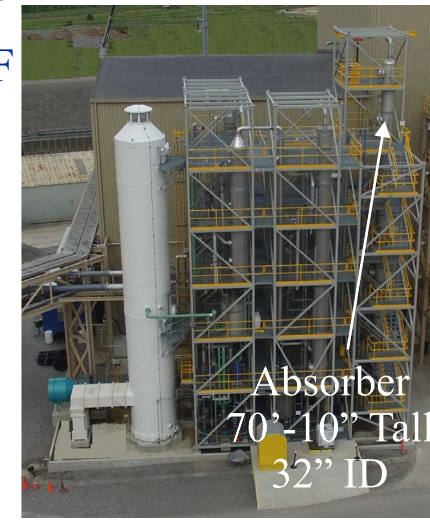
Lower Absorber Bottom Temperature

Lower Absorber Bottom T → Lower Stripper Top T → Increased Stripper Bottom to Top ΔT → Decreased Regeneration Energy





UK Small Pilot Evaluations with 14 & 4 vol% CO_2 Flue Gas by Dilution with Air

2022 Advanced Solvent Campaign Inlet CO_2 Concentration	Flue Gas Flow (acfm)	Lean Flow (lb/h)	Lean Absorber Inlet Temp. (°F)	Absorber Bottom Temp. (°F)	Stripper Bottom Temp. (°F)	Stripper Top Temp. (°F)	Stripper Bottom to Top Δ Temp. (°F)	% Capture	Heat Duty (KJ/kg CO_2)
14 vol%	**1300**	**10999**	**104**	**123**	**258**	**193**	**65**	**98**	**2631**
4 vol%	**550**	**4013**	**92**	**96**	**258**	**182**	**76**	**98**	**1767**

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Solvent Regeneration Process Requirements

Carrier gas flow and CO_2 desorption

$$Q_{stripper} = Q_{desorption} + Q_{sensible} + Q_{latent}$$

For 1 mole/s CO_2 at one condition of a selected solvent

$$Q_{sensible} = \frac{1}{\Delta\alpha} \cdot C_p \cdot \Delta T$$

$$Q_{latent} = \Delta U_{vapor} + P \cdot \Delta V$$

Where ΔU_{vapor} is the change in internal energy of the vapor, $E_{bottom\ T} - E_{rich\ inlet\ T}$

$$E_T = E_{CO_2}(T, P_{CO_2}) + E_{H_2O}$$

Rich Inlet T
Rich Loading

Bottom T
Lean Loading

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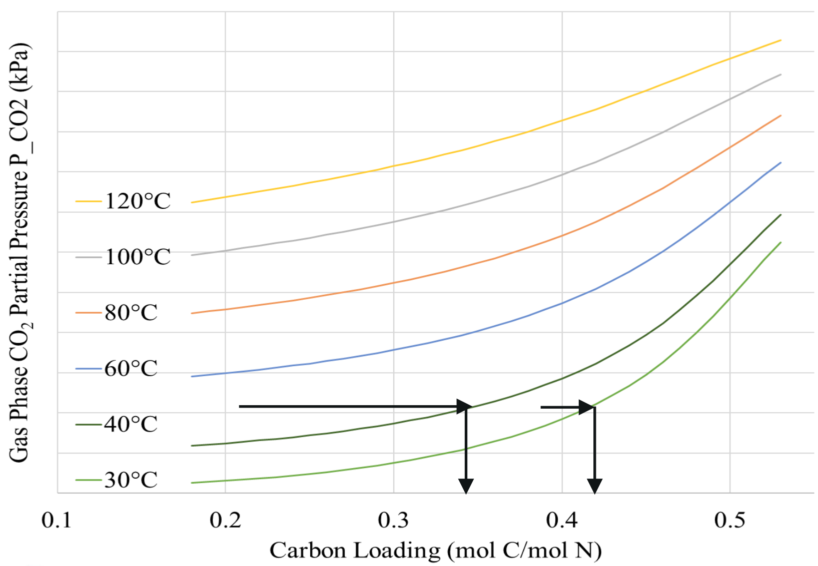
Lower Absorber Bottom Temperature

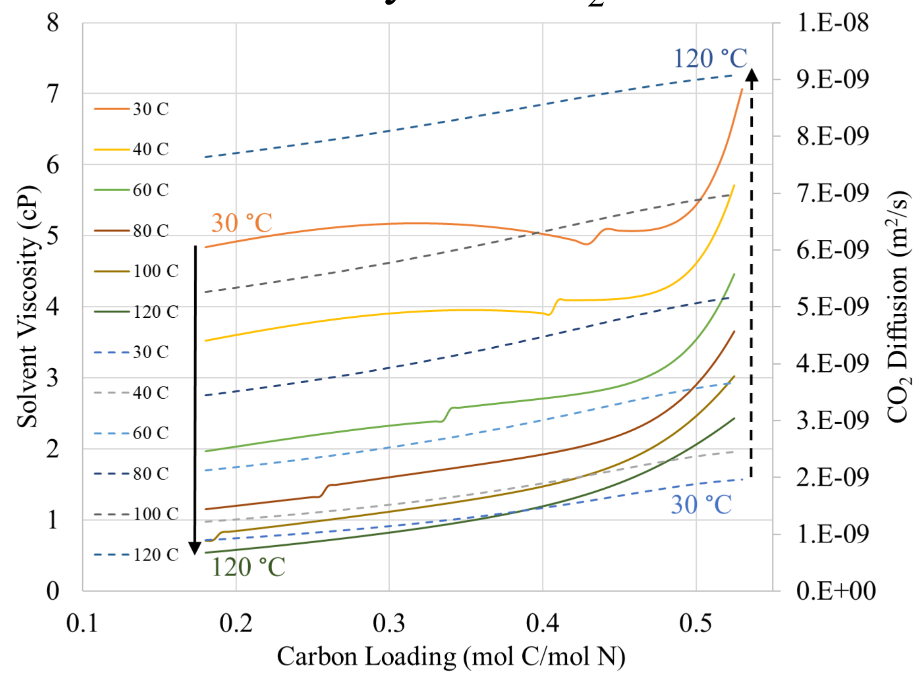
Lower Absorber Bottom T → Higher Achievable Rich Loading

Lower Absorber Bottom T → Increased Viscosity → Increased CO_2 Diffusion Resistance → Decreased CO_2 Diffusion

UK Solvent
Vapor-Liquid Equilibrium



UK Solvent
Viscosity and CO_2 Diffusion



Technical Approach

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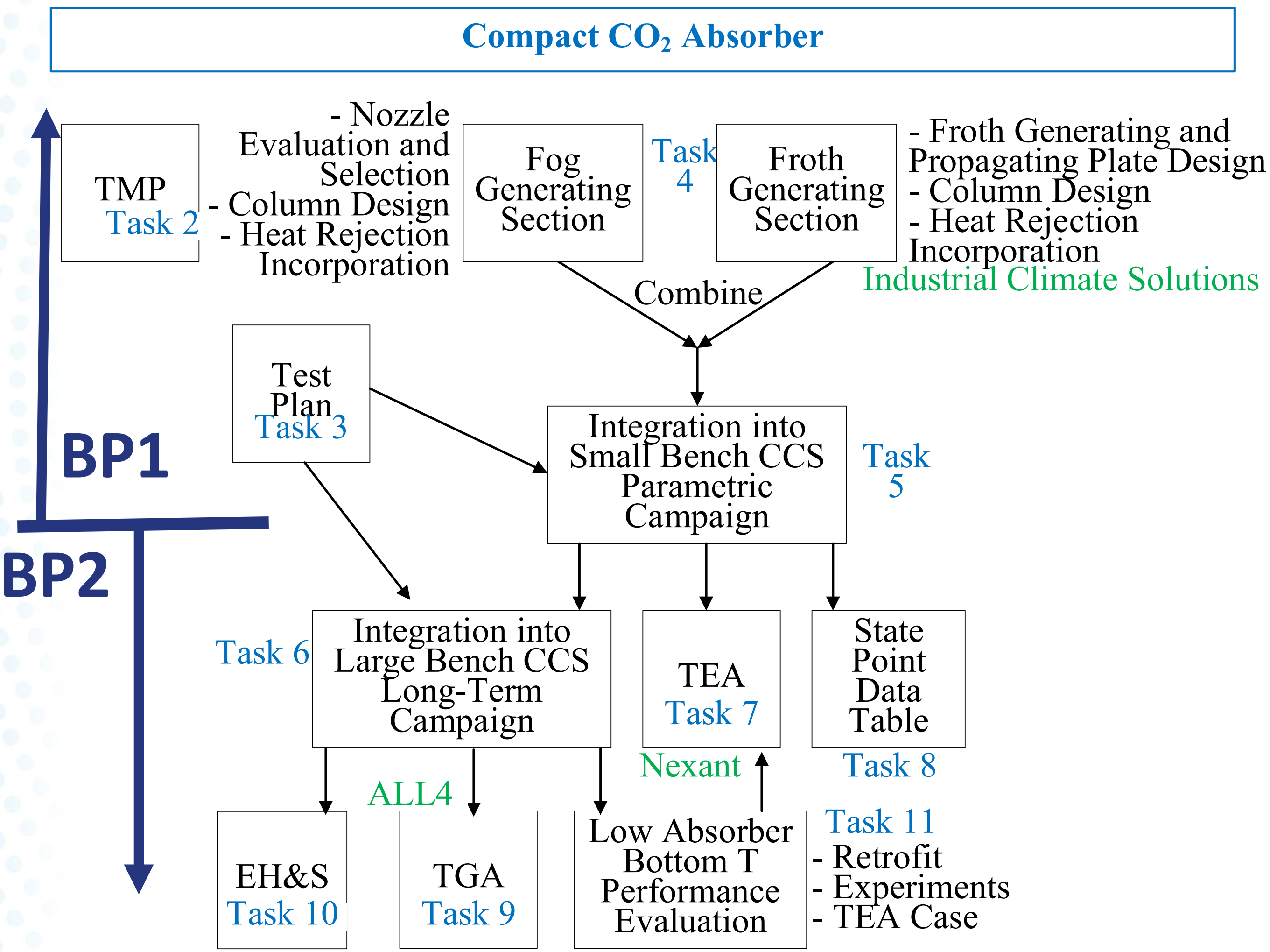

Design, Fabricate and Research a Compact Absorber

Atomizing Nozzle Selection

Froth Screen Design

In-Situ Heat Rejection

UK's Bench Post-combustion CO_2 Capture Facilities

Evaluation

Parametric Campaign

Long Term Campaign

TEA

EH&S

State Point Data Table

TMP

TGA

Cold Absorber Bottom T Evaluation

Additional TEA Case

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Project Milestones

	Milestone Title/Description	Planned Completion Date	Actual Completion Date
1	PMP Updated	5/31/2019	5/31/2019
2	Project Kickoff Meeting	7/31/2019	5/14/2019
3	Technology Management Plan (TMP) Updated	7/31/2019	7/25/2019
4	Test Plans Completed	8/31/2019	9/15/2019
5	Fog Section of Unit Constructed and Tested	9/30/2019	8/2/2019
6	Froth Section of Unit Constructed and Tested	9/30/2019	1/31/2020
7	Compact Absorber Constructed and Integrated into Small Bench Process	4/30/2020	6/30/2020
8	Parametric Test Campign Complete	1/31/2021	1/31/2021
9	Long-term Test Campaign Complete	6/30/2022	3/9/2022
10	Techno-economic Analysis (TEA) Complete	8/31/2022	9/7/2022
11	State Point Data Table Updated	4/30/2021	3/31/2021
12	Technology Gap Analysis (TGA) Complete	5/30/2023	7/31/2023
13	Environmental, Health and Safety (EH&S) Assessment Complete	10/31/2022	9/30/2022
14	Existing bench unit modified and achieves an absorber bottom temperature of ≤95°F at 2-20% CO_2 inlet concentration.)	3/31/2023	2/28/2023
15	Test plan approved by NETL that covers 80-95 °F absorber bottom temperatures and 2-20 vol% inlet CO_2 concentrations	4/30/2023	2/28/2023
16	Complete ~200 hours experiments between 2 to 8 vol% inlet CO_2 concentrations at 80-95 °F absorber bottom temperatures	6/30/2023	6/28/2023
17	Complete ~200 hours experiments between 8 to 14 vol% inlet CO_2 concentrations at 80-95 °F absorber bottom temperatures	8/31/2023	5/18/2023
18	Complete ~200 hours of experiments between 14 to 20 vol% inlet CO_2 concentrations at 80-95 °F absorber bottom temperatures	10/31/2023	
19	Additional TEA Case Complete and TEA Revised	12/31/2023	

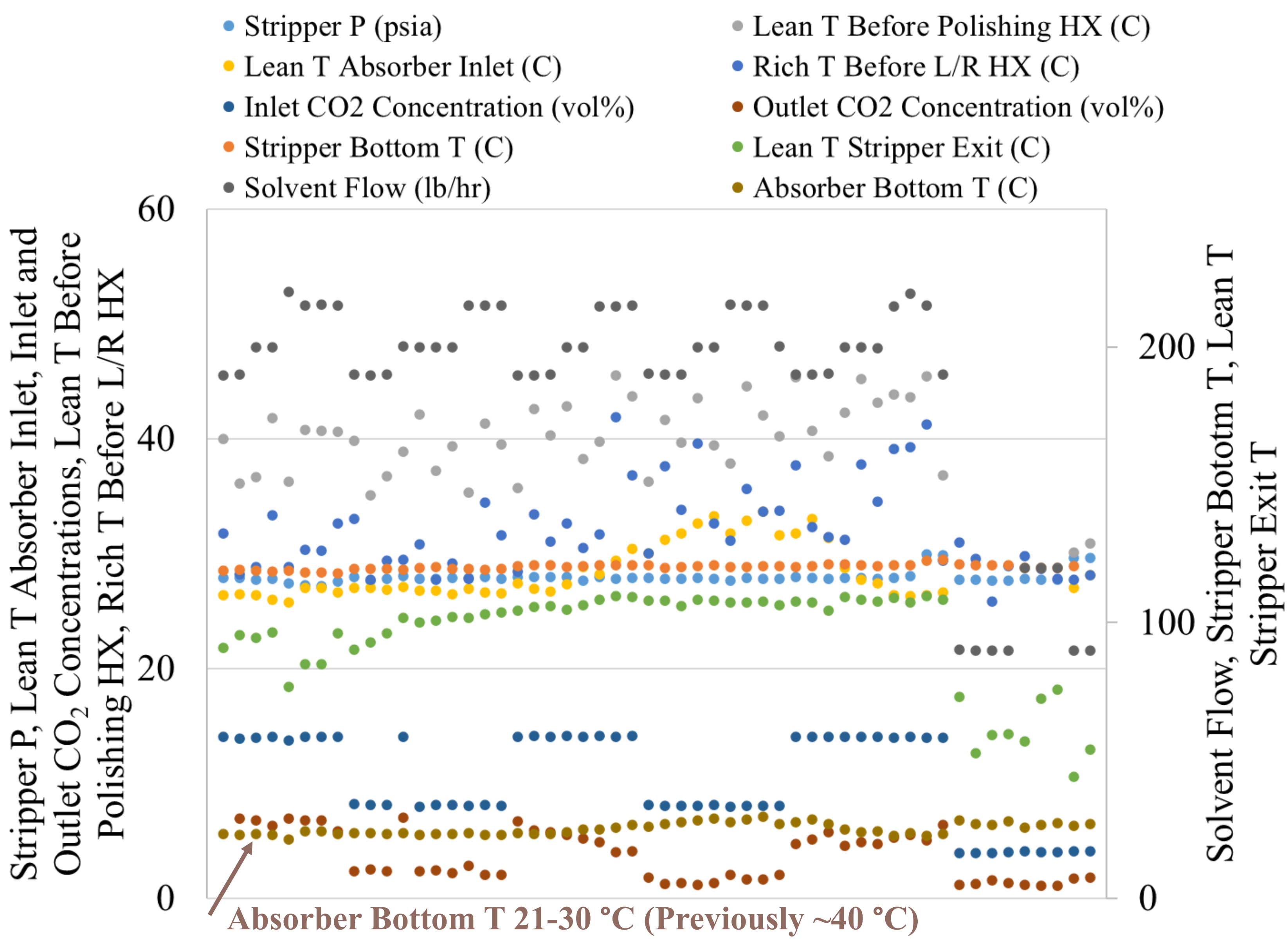
Project Success Criteria

BP1
1. Atomizing nozzles compared, selected and tested 2. Froth plates compared, selected and tested 3. Functioning fogging+frothing-based compact absorber with liquid/gas contact area increased by at least 5 times over structured packing 4. Mass transfer enhancement by at least 4 times 5. Fog droplet size of 10-50 µm 6. Froth bubble size of 3-5 mm with liquid film thickness of <10 µm 7. Open section of hybrid absorber captures 60-70% of the CO_2 and packed section captures 20-30% of the CO_2
BP2
8. Long term verification of fogging+frothing-based compact absorber functionality with solvent degradation, based on ~1000 run hours on the UK CAER bench CCS with at least the same baseline capture efficiency and regeneration energy 9. TEA shows the following: A) capital cost savings of ≥10% and cost of CO_2 capture reduction of ≥15% compared to DOE RC B12B, B) an absorber column that is ~70% shorter for the same CO_2 removal duty with ~50% electricity savings for the flue gas booster fan due to the shorter column and packing height, C) when the UK CAER advanced solvent is used (with a heat of desorption ~20% less than 30 wt% MEA), a specific reboiler duty (energy consumption) of 900 Btu/lb (2.1 GJ/tonne) CO_2 captured can be reached by reducing the primary stripper exhaust H_2O/CO_2 ratio to 0.25, and D) ~50% reduction in the CCS capital cost 10. EH&S assessment shows no impediment to technology development 11. When evaluated with varied absorber bottom temperatures, the compact absorber performance at least matches the baseline capture efficiency and rich solvent loading with reduced regeneration energy.

Project Risks and Mitigation Strategies

Environmental Impact	• An alternative solvent will be used or a system modification will be made, depending on the environmental problem identified.
Low Mass Transfer in Fogging and Froth Section	• Alternate nozzle/plate configuration may be used • Fixture installation to enhance gas/liquid interface will be considered • Solvent properties may be modified for fine mist •
Froth Stability and Bubble Size	• Froth generating plate will be modified • Alternate liquid distributor will be considered • Solvent physical properties will be adjusted and tuned
Impact of In-situ Heat Exchanger on Fog and Froth	• Heat exchanger design will be modified • Heat exchanger location will be adjusted
Impact of Solvent Degradation on Fog and Froth	• Alternate nozzle configuration will be used • Froth generation plate will be modified • Degradation inhibitors may be added to the solvent

Low Absorber Bottom T Achieved



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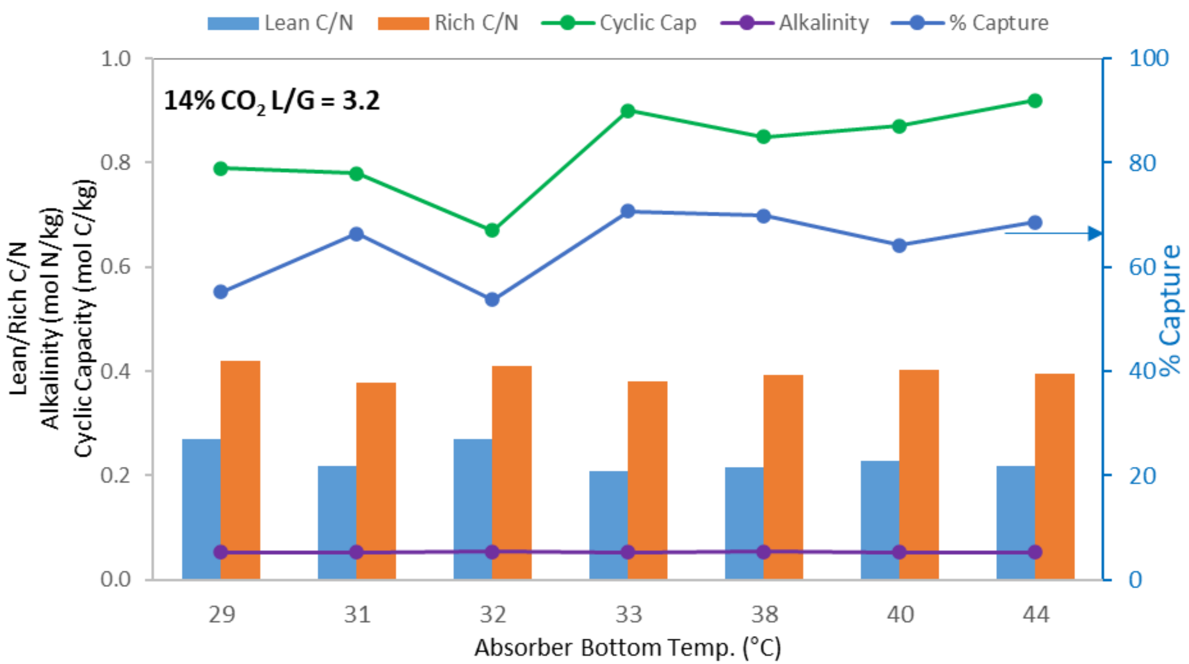
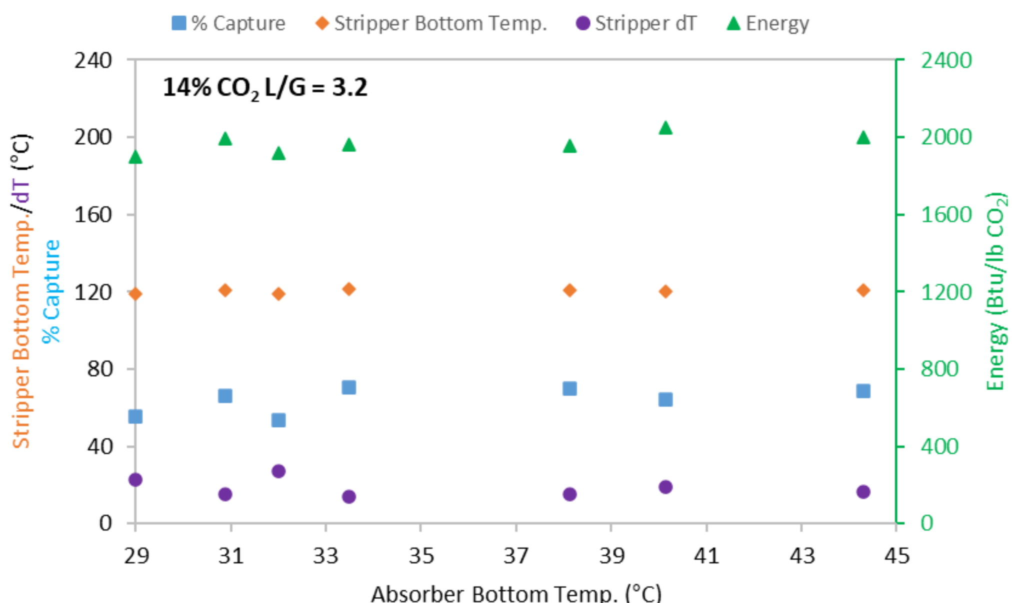
Bench Scale Performance Maintained

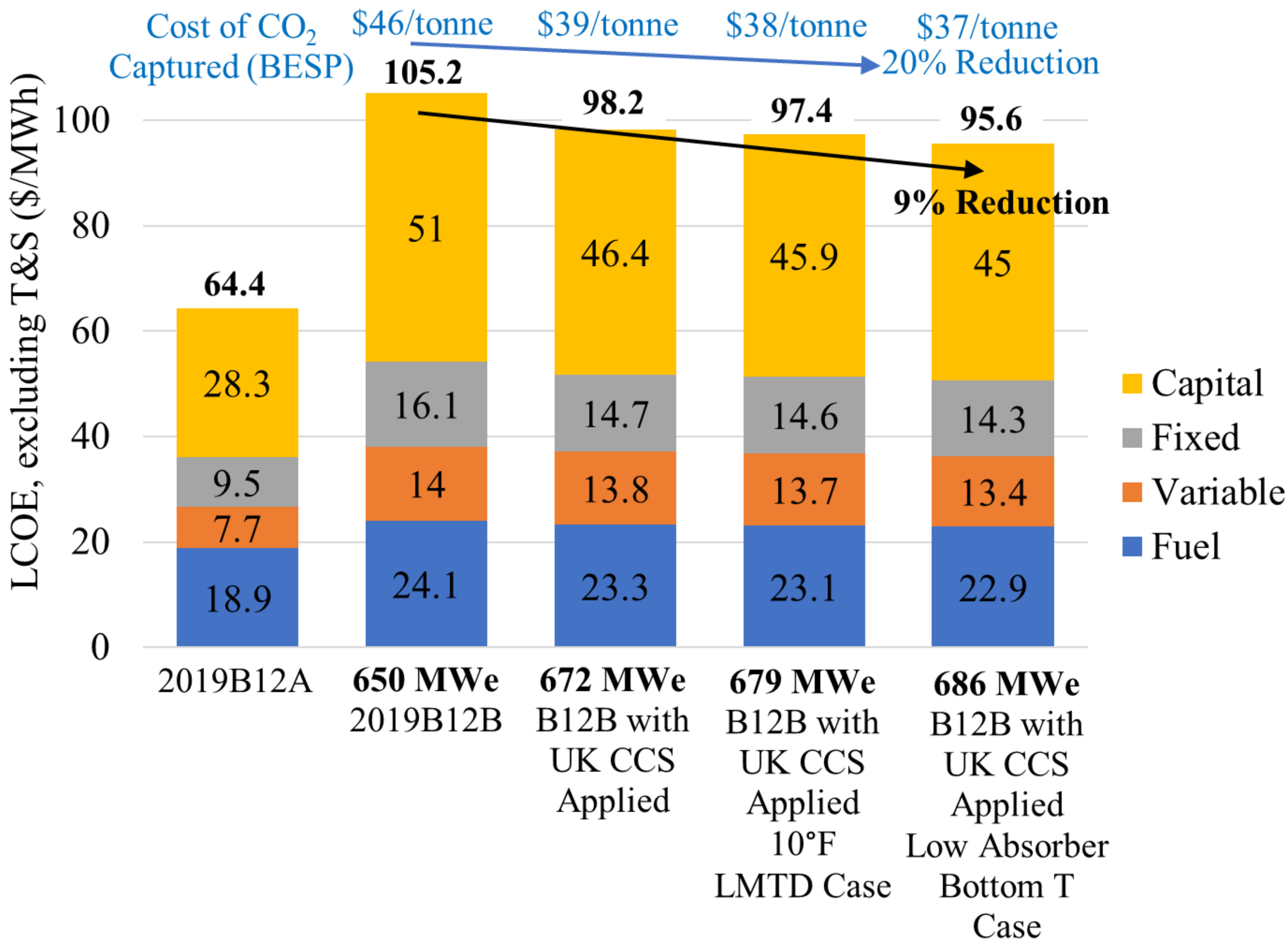


11 °C Lower Absorber Bottom T → Same Rich Loading and Cyclic Capacity **Because 4" ID Absorber is More Sensitive to Viscosity Increase**



11 °C Lower Absorber Bottom T → Same Stripper Top T and Bottom to Top ΔT **Because L/R Exchanger is Oversized at Bench Scale**

TEA Case with Low Absorber Bottom T



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Next Step:

Maintain

Inlet Free Amine Flux:Inlet CO_2 Flux

to Demonstrate Higher Rich Loading and Reduced Regeneration Energy

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Synergy Opportunities

Solvent spray to be applied at large pilot, engineering scale demonstrations, NGCC FEED and CO_2 removal.

Low absorber bottom temperature to be applied at low CO_2 concentration point sources.

Collaborating with PPL Corporation, Nucor Steel, Vitro Glass, WY ITC.

Lesson Learned

1. Advancing through the TRLs in small steps is necessary. Results differ at the lab, bench and pilot scales and the fundamental reasons must be understood.

2. 4” ID column is very sensitive to wall effects and solvent physical properties.

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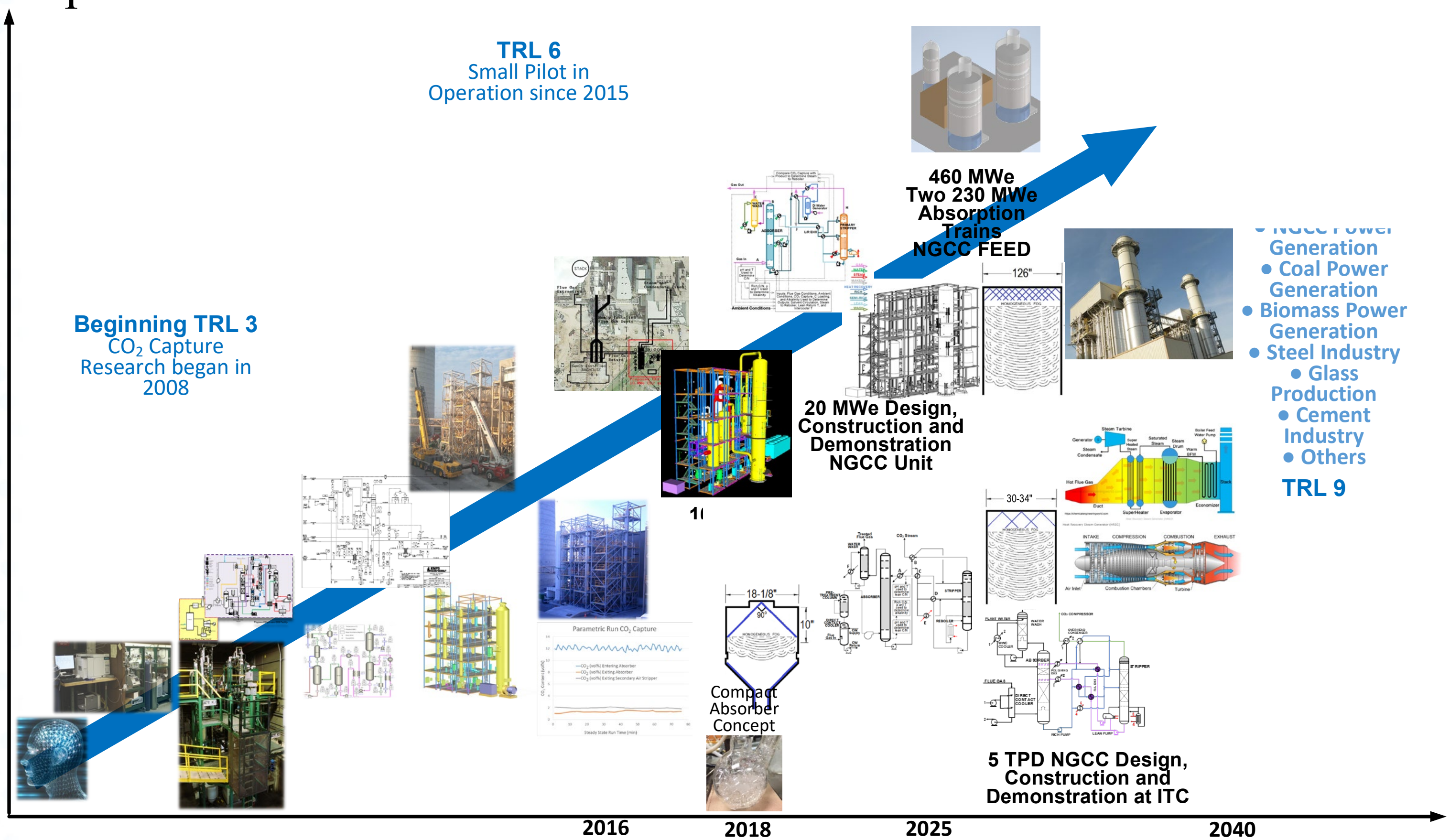
Development & Commercialization

Develop: Counter-current Solvent Spray and Nozzle Array Design for Large Scale Application

Demonstrate: Engineering Scale and Large Pilot, NGCC and Industrial Applications

Incorporate: Solvent Spray and Cold Absorber Bottom T into Suite of UK CO_2 Capture Processes for Reduced CAPX and OPEX



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Acknowledgements

U.S.DOE NETL: Carl Laird, Greg O’Neil, José Figueroa, Dan Hancu and Lynn Brickett

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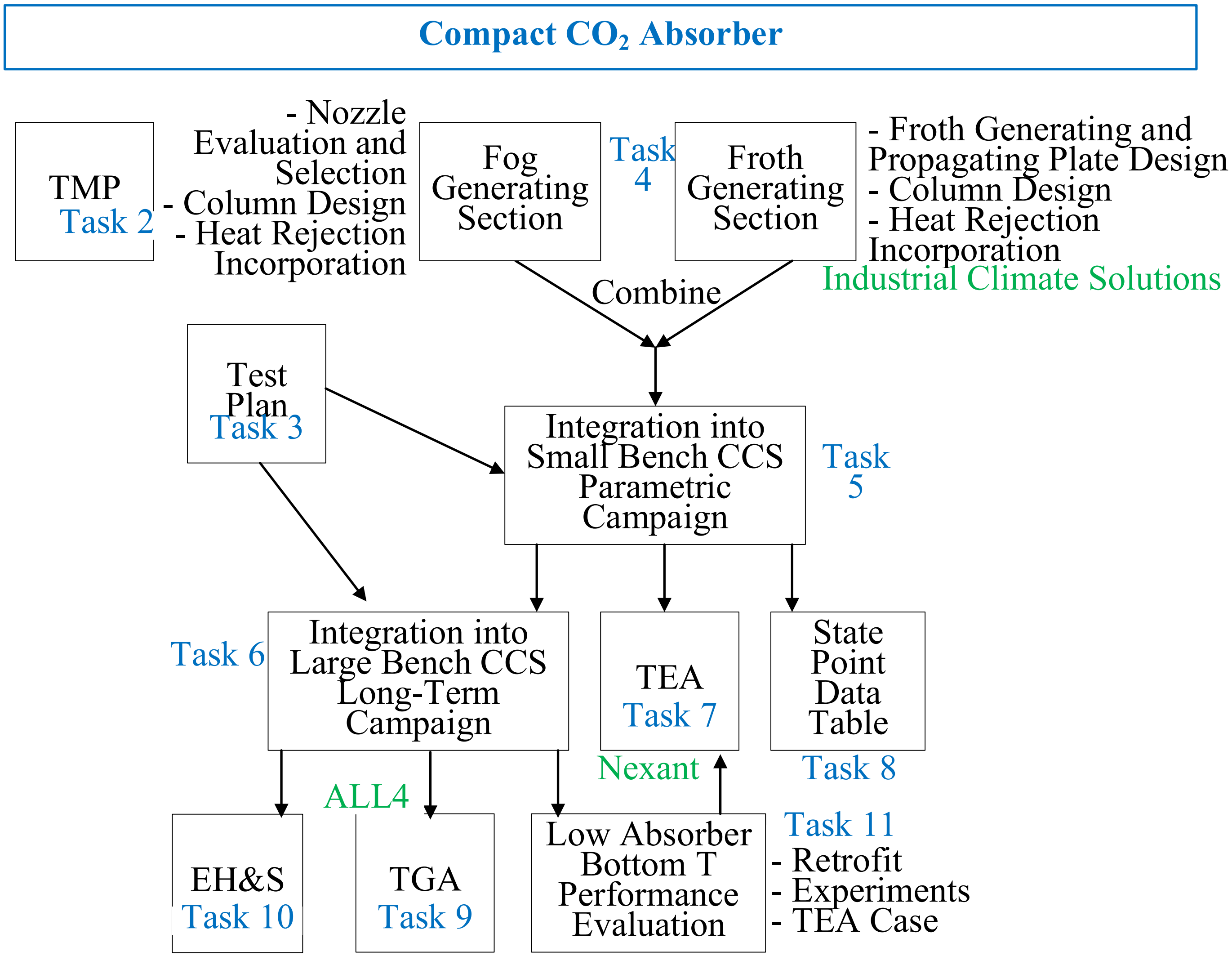
ALL4: Karen Thompson

UK: Reynolds Frimpong, Aaron Smith, Marshall Marcum, Len Goodpaster, Lisa Richburg, and Kunlei Liu

Appendix: Organizational Chart



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Appendix: Gantt Chart

Task Name	Start	Finish
Task 1 - Project Management and Planning	**Wed 5/1/19**	**Sun 12/31/23**
PMP Updated	*Fri 5/31/19*	*Fri 5/31/19*
Project Kickoff Meeting	*Wed 5/15/19*	*Wed 5/15/19*
Budget Period 1	**Wed 5/1/19**	**Sun 1/31/21**
Task 2 - Technology Maturation Plan	**Wed 5/1/19**	**Wed 7/31/19**
Technology Maturation Plan (TMP) Updated	*Wed 7/31/19*	*Wed 7/31/19*
Task 3 - Test Plan	**Thu 8/1/19**	**Sat 8/31/19**
Test Plan Completed	*Sat 8/31/19*	*Sat 8/31/19*
Task 4 - Fog and Froth Generation, Unit Fabrication and Testing	**Wed 5/1/19**	**Sat 11/30/19**
Subtask 4.1 - Atomozing Nozzle Selection or Design and Evaluation	**Wed 5/1/19**	**Mon 9/30/19**
Fog Section of Unit Constructed and Tested	*Mon 9/30/19*	*Mon 9/30/19*
Subtask 4.2 - Froth Generating Plate Design and Evaluation	**Wed 5/1/19**	**Mon 9/30/19**
Froth Section of Unit Constructed and Tested	*Mon 9/30/19*	*Mon 9/30/19*
Subtask 4.3 Optical Window Design	**Wed 5/1/19**	**Wed 7/31/19**
Subtask 4.4 Testing and Design Adjustment	**Tue 10/1/19**	**Thu 10/31/19**
Subtask 4.5 Heat Rejection Determination	**Fri 11/1/19**	**Sat 11/30/19**
Task 5 - Integration into the UKy-CAER Bench CCS	**Sun 12/1/19**	**Sun 1/31/21**
Subtask 5.1 - Absorber Design and Fabrication	**Sun 12/1/19**	**Mon 2/17/20**
Subtask 5.2 - In-situ Heat Exchanger Design	**Sun 12/1/19**	**Mon 2/17/20**
Subtask 5.3 - Retrofit and Commissioning	**Tue 2/18/20**	**Thu 4/30/20**
Compact Absorber Constructed and Integrated into Small Bench Process	*Thu 4/30/20*	*Thu 4/30/20*
Subtask 5.4 - Parametric Campaign	**Fri 5/1/20**	**Sun 1/31/21**
Parametric Test Campaign Complete	*Sun 1/31/21*	*Sun 1/31/21*
Subtask 5.5 - Data Analysis	**Fri 5/1/20**	**Sun 1/31/21**
Budget Period 2	**Mon 2/1/21**	**Sun 12/31/23**
Task 6 - Integration of Compact Absorber into the Large Bench	**Mon 2/1/21**	**Sun 7/31/22**
Subtask 6.1 - Retrofit and Commissioning	**Mon 2/1/21**	**Wed 3/31/21**
Subtask 6.2 Long-term Campaign	**Thu 4/1/21**	**Thu 6/30/22**
Long-term Test Campaign Complete	*Thu 6/30/22*	*Thu 6/30/22*
Subtask 6.3 - Data Analysis	**Thu 4/1/21**	**Sun 7/31/22**
Task 7 - Techno Economic Analysis	**Mon 2/1/21**	**Wed 8/31/22**
Subtask 7.1 - Modeling	**Mon 2/1/21**	**Fri 12/31/21**
Subtask 7.2 - TEA	**Sun 8/1/21**	**Sun 7/31/22**
Techno-economic Analysis (TEA) Complete	*Mon 1/31/22*	*Sun 7/31/22*
Task 8 - State Point Data Table	**Mon 2/1/21**	**Fri 4/30/21**
State Point Data Table Updated	*Fri 4/30/21*	*Fri 4/30/21*
Task 9 - Technology Gap Analysis	**Fri 10/1/21**	**Tue 5/30/23**
Technology Gap Analysis Complete	*Tue 5/30/23*	*Tue 5/30/23*
Task 10 - Environmental, Health and Safety Assessment	**Fri 10/1/21**	**Mon 10/31/22**
EH&S Assessment Complete	*Mon 10/31/22*	*Mon 10/31/22*
Task 11 - Low Absorber Bottom Temperature Performance Evaluation	**Sun 1/1/23**	**Sun 12/31/23**
Subtask 11.1 - Retrofit	**Sun 1/1/23**	**Fri 3/31/23**
Subtask 11.2 - Experimental Evaluation	**Sat 4/1/23**	**Tue 10/31/23**
Low Absorber Bottom Temperature Evaluation Complete	*Tue 10/31/23*	*Tue 10/31/23*
Subtask 11.3 - TEA Case	**Sat 4/1/23**	**Sun 12/31/23**
Additional TEA Case Copmplete and TEA Revised	Sun 12/31/23	Sun 12/31/23