Fog+Froth-based Post-combustion CO_2 Capture In Fossil-fuel Power Plants

DE-FE0031733

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Center for Applied Energy Research

Lexington, KY

https://caer.uky.edu/power-generation/

U.S. Department of Energy

National Energy Technology Laboratory

Carbon Management and Natural Gas & Oil Research Project Review Meeting

Virtual Meetings August 2 through August 31, 2021

Project Overview

Title: Fog+Froth-based Post-combustion CO_2 Capture In Fossil-fuel Power Plants

Award Number: DE-FE0031733

	Performance Period	Federal Share	Cost Share	Total
BP1	5/1/2019-1/31/2021	$1,462,428	$371,077	$1,833,505
BP2	2/1/2021-4/30/2022	$1,484,976	$366,946	$1,851,922
Total	5/1/2019-4/30/2022	$2,947,404	$738,023	$3,685,427

Overall Goal: Reduce CO_2 capture capital cost by reducing the absorber size

Project Participants:

Center for Applied Energy Research

NexantECA

ICS Industrial Climate Solutions INC

ALL4

DOE-NETL Team: Carl Laird, Project Manager; Patrick Mayle, Contract Specialist; and Angela Harshman, Contract Officer

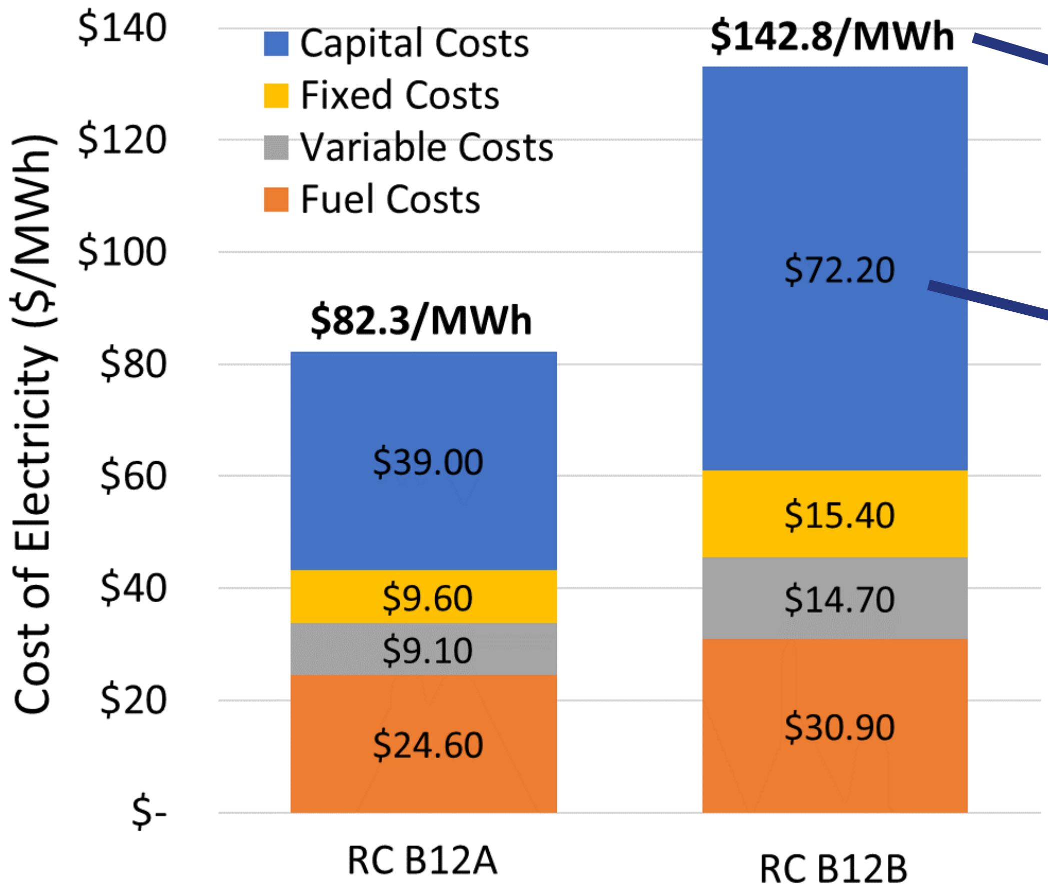
Outline

- Executive Summary
- Technology Background
- Project Scope
- Progress and Current Status
- Challenges and Solutions
- Future Work
- Summary
- Organization Chart
- Gantt Chart

Executive Summary

- **All BP 1 Deliverables Met and Success Criteria Achieved**
- **On Track to Meet BP 2 Deliverables and Success Criteria**
- Fog and froth sections fabricated and commissioned, 8/30/2019
- Fogging and frothing sections connected with existing 0.1 MWth facility, batch and continuous operations conducted by 1/31/2020
- Parametric Campaign complete on 2/19/2021 after 827 hours of testing with bottled gas
- 60+% CO_2 capture and 0.45 mol C/mol N rich loading demonstrated with 3 ft Fog-n-Froth and 2 ft structured packing, on par with traditional absorber performance with >2X of structured packing
- Long-term Campaign began on 3/3/2021 with ~350 hours of testing with fossil fuel-derived flue gas
- State Point Data Table completed on 4/26/2021 for the UK CAER hindered amine blend solvent

Technology Background
CAPEX and OPEX (DOE Baseline)



ICOE: **$50.9/MWh**
(= 142.8 - 9.6 - 82.3)

T&S Cost

ICAPx: **$33.2/MWh**
(= 72.2 - 39.0)

ICAPx/ICOE:
65.2%

Cost and Performance Baseline for Fossil Energy Plants Volume 1: Bituminous Coal and Natural Gas to Electricity Revision 3, (DOE/NETL-2015/1723), United States Department of Energy (DOE), National Energy Technology Laboratory (NETL), Pittsburgh, Pennsylvania, July 2015.

Technology Background
CCS 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%

Technology Background

Use the WFGD example to compare and contrast with CCS.

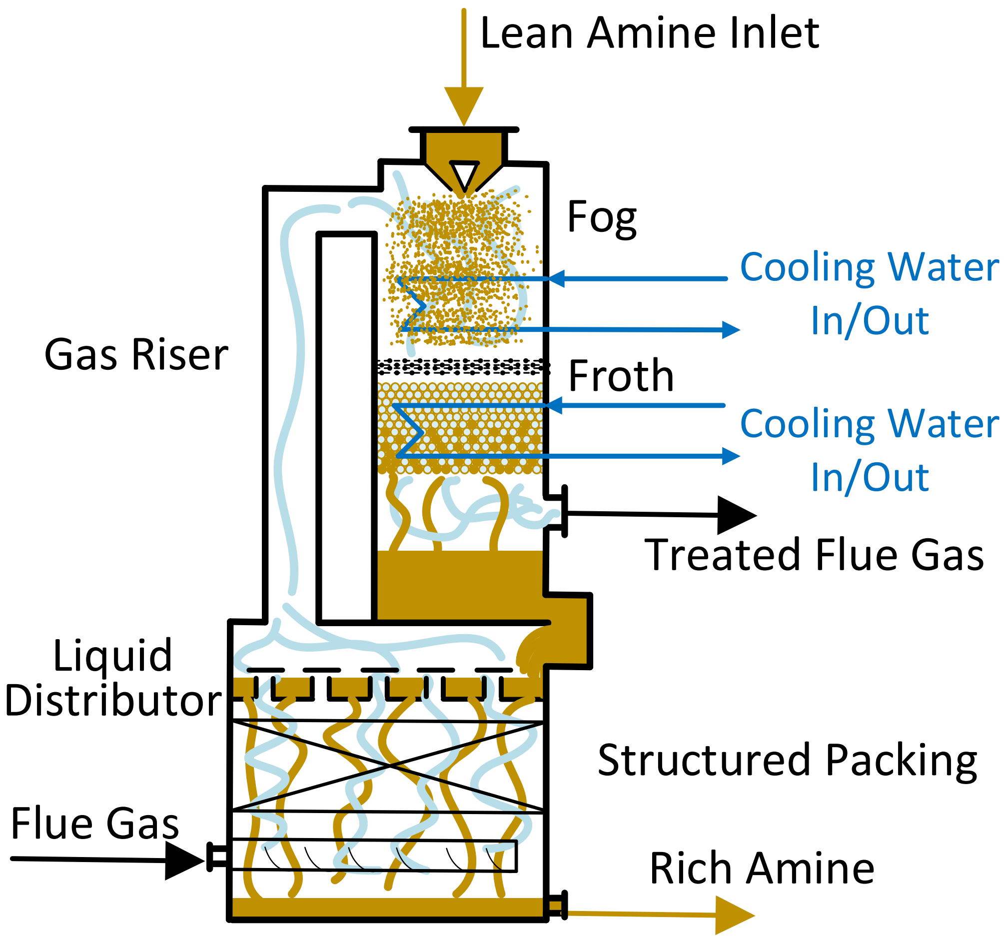
Aspects	Unit	WFGD	CCS
L/G	-	10	3.5
Effective Wet Surface per Unit of Volume	m^2/m^3	1523.8	200.0
Reactant Concentration	mol/m^3	0.03	1262.5
Diffusivity	m^2/s	1.2E-05	2.0E-09
Reaction Kinetics, K_2	M^{-2}	10000	3000
Inlet Concentration	vol %	0.3	12.5
Outlet Concentration	vol %	0.01	1.6
Log Mean Driving Force	kPa	0.07	4.33

$$k_g' = \frac{\sqrt{D_{CO2} K_2 [Am]}}{H_{CO2}}$$

$$flux = A \cdot k_G (P^g{}_{CO_2} - P^*{}_{CO_2})$$

Assuming Pseudo-first Order	WFGD	Traditional CCS	Compact Absorber
Henry's Law Constant	1	1	
Reaction Kinetics in Absorber	1	0.5	
k_g’	1	2.0	5.6
Effective Surface Area	1	0.13	0.39
Driving Force	1	62.34	
Overall Mass Transfer per Volume	**1**	**16.6**	**137**
Removal Loading @ 90% CO_2 and 99% SO_2 captured	1	37.88	
The Absorber Size Required	**1**	**2.28**	**0.28**

Compact Absorber Configuration



Technical Tasks and Project Scope

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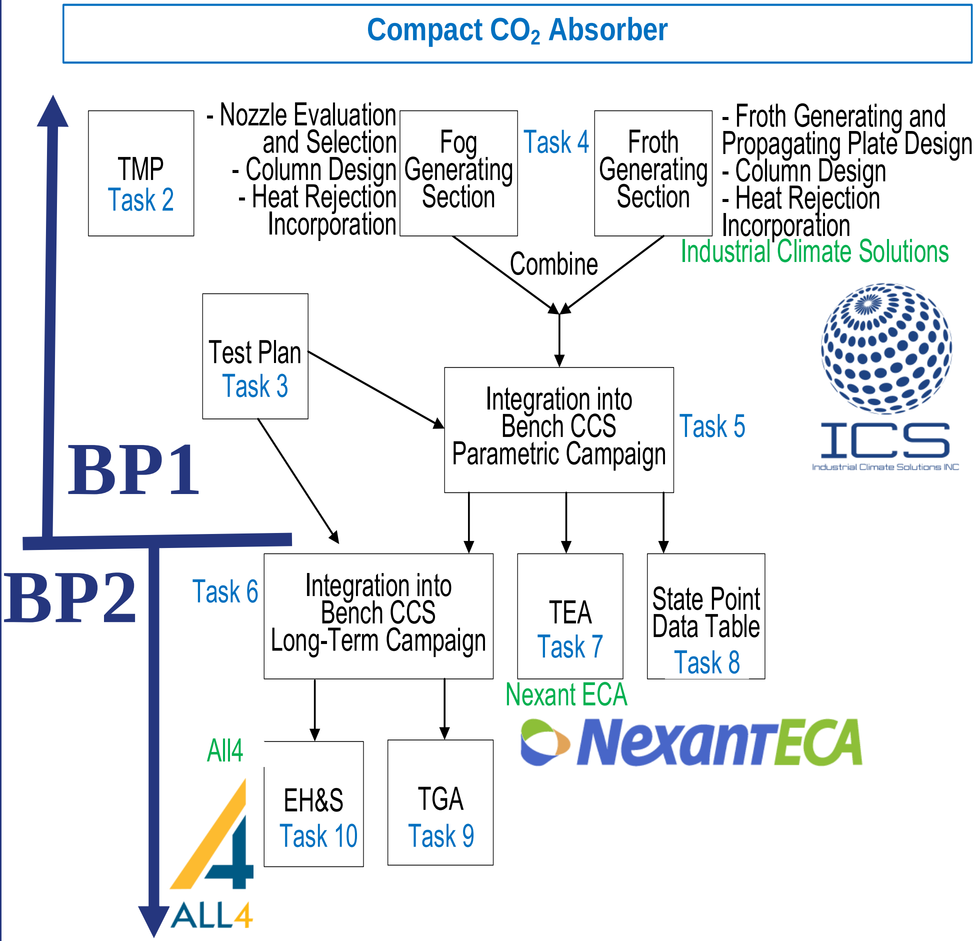


Reduce CO_2 Capture Capital and Operating Costs by Reducing the Absorber Size

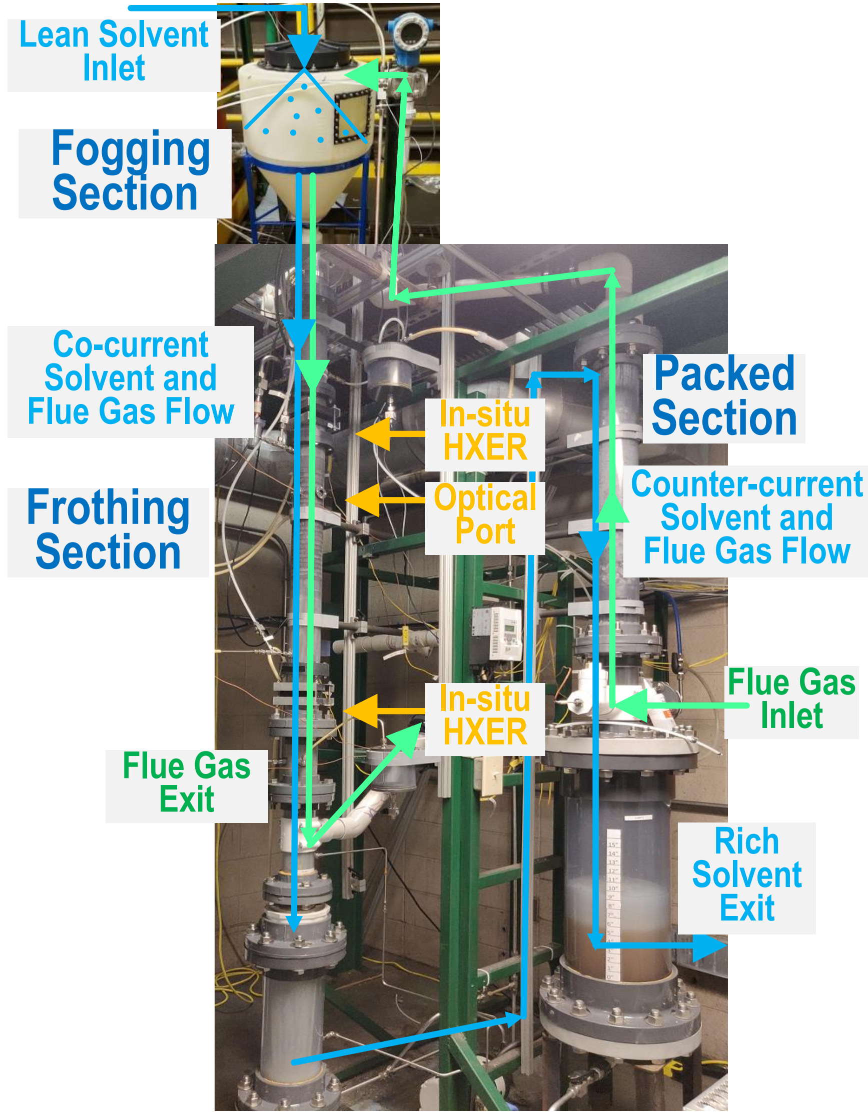
- **Design, Fabricate and Research a Compact Absorber**
  - Atomizing Nozzle Selection
  - Froth Plate Design
  - In-Situ Heat Rejection
  - UK CAER's bench post-combustion CO_2 capture facilities
- **Evaluation**
  - Parametric Campaign
  - Long Term Campaign
  - TEA
  - EH&S
  - State Point Data Table
- **Develop**
  - TMP

Milestones and Success Criteria

Milestones	Completion Date
1. PMP Updated	5/31/2019
2. Project Kickoff Meeting	5/14/2019
3. TMP Updated	7/25/2019
4. Test Plans Completed	9/15/2019
5. Fog Section of Unit Constructed and Tested	8/2/2019
6. Froth Section of Unit Constructed and Tested	1/31/2020
7. Compact Absorber Integrated into Bench Process	6/30/2020
8. Parametric Test Campaign Complete	1/31/2021
9. Long-term Test Campaign Complete	
10. TEA Complete	
11. State Point Data Table Updated	3/31/2021
12. TGA Complete	
13. EH&S Assessment Complete	

Success Criteria
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 ✓
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 UKy-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

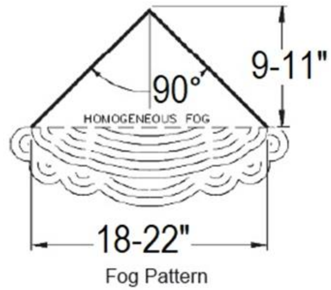
Bench-scale Unit

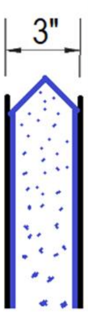


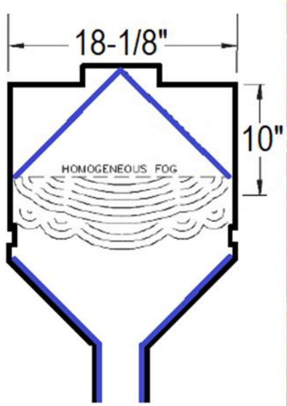
Progress: The Impact of Fog Formation

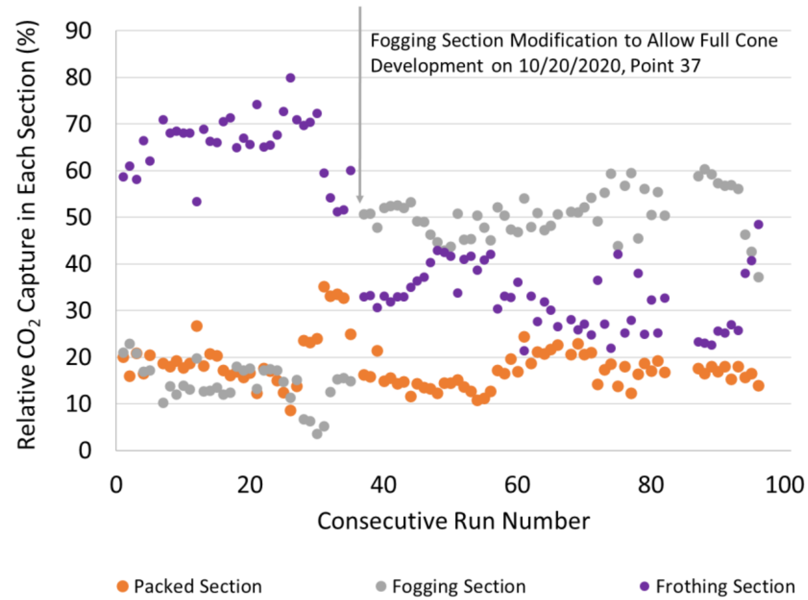
Demonstration of Fog in 3" ID Column

Full Cone Development Fogging Section









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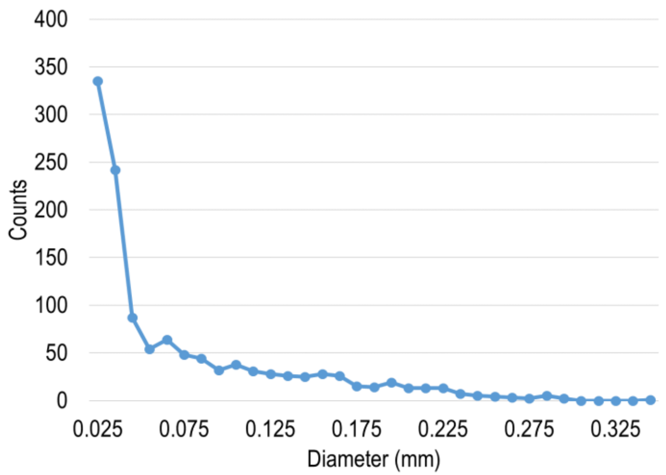
Progress: Fog Droplet Size

Targeting droplets of <100 µm to increase surface area by 3.7X

The BETE® PJ32 hydraulic misting nozzle initially selected and evaluated as the best commercially available option for evaluation.
Subsequently, the PJ24 and PJ20 nozzles have been incorporated.

Comparison of BETE® PJ32, PJ24 and PJ20 Nozzles with Water.			
	BETE® PJ32	**BETE® PJ24**	**BETE® PJ20**
Reference Back Pressure (psi)	200	200	200
Spray Angle (degrees)	90	90	90
Spray Pattern	Full Cone of Homogeneous Fog	Full Cone of Homogeneous Fog	Full Cone of Homogeneous Fog
Published Flow Rate per nozzle (gpm)	0.40	0.22	0.15
Published Orifice Diameter (in.)	0.032	0.024	0.020
Published Coverage (in.)	22	16	12
Published Height (in.)	11	8	6
Published Sauter Mean Diameter (µm)	61	46	41

Evaluation of Water Droplets Produced from BETE® PJ32 Nozzle



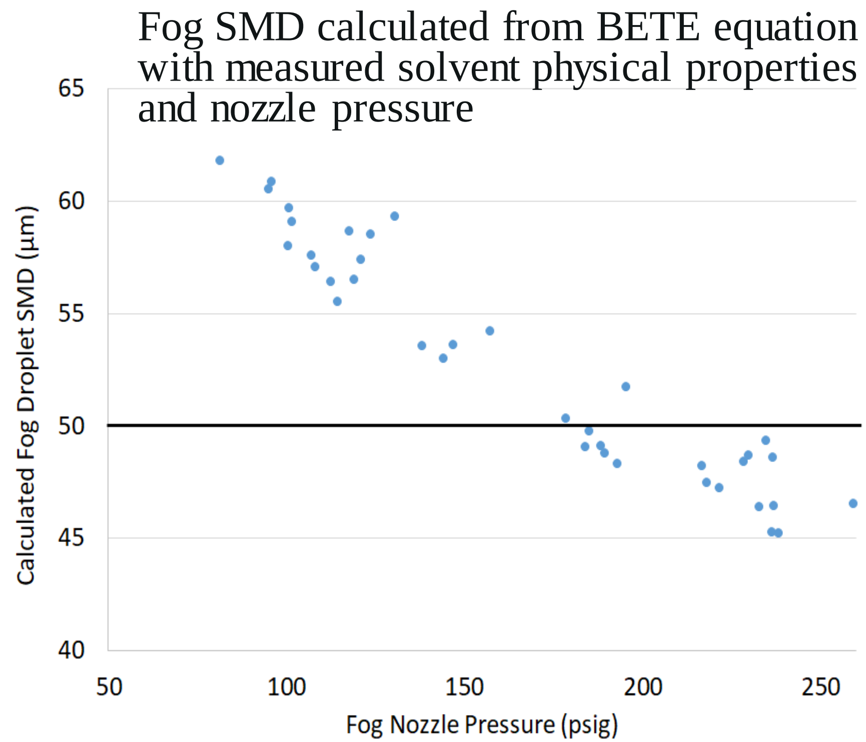
Progress: Fog Droplet Size

The fog droplet Sauter mean diameter (SMD) was estimated by using an equation published by the nozzle manufacturer, BETE. According to this equation, when the compact absorber nozzle pressure exceeds 175 psig, the fog droplet SMD is ≤50 µm.

$$D_2 = D_1 \left(\frac{P_2}{200}\right)^{-0.3} (V_2)^{0.2} \left(\frac{ST_2}{73}\right)^{0.5} (SG_2)^{0.3}$$

Where:

D_2 is the calculated droplet SMD
D_1 is the BETE measured SMD of water at 200 psi nozzle pressure
P_2 is the experimental nozzle pressure in psig
V_2 is the experimental solution viscosity in cP
ST_2 is the experimental solution surface tension in Dynes/cm at 20 °C
SG_2 is the experimental solution specific gravity



Progress: Froth Bubble Size

Target Froth bubble size of 3-5 mm with liquid film thickness of <10 μm

Based on fogging section mass transfer the bubble size is <3.7 mm.

$$Mass\ Transfer\ Rate = A \cdot k_G(P^g_{CO_2} - P^*_{CO_2})$$

$$k'_g = \frac{\sqrt{D_{CO_2} K_2 [Am]}}{H_{CO_2}}$$

Specific Absorption in Each Section of the Compact Absorber Parametric Campaign Compared with that in a Traditional Absorber and Corresponding Fog Droplet and Froth Bubble Size.a

	Specific Absorption (mol C/hr·ft^3)	**Improvement Over Traditional Packed Absorber**	**Droplet Size (μm) and Bubble Size (mm) Based on Measured Mass Transfer**
Compact Absorber Fogging Section	69-266	2.3-4.6 times	82-165 μm
Compact Absorber Frothing Section	189-782	6.5-13.5 times	<3.7 mm
Compact Absorber Packed Section	22-102		
Traditional Packed Absorber	29-58		

Progress: Increased Liquid-Gas Surface Area

Target increased by at least 5 times over structured packing.

The surface area is increased by 6.8 times that of 250Y structured packing.

Fogging Section

Expected Liquid-Gas Contact Surface Area at Target Operation of L/G=3.5 mass/mass									
Uniform Droplet Size (μm)	10	20	30	40	50	75	100	200	400
Liquid-Gas Contact Surface Area (m^2/m^3)	9356	4678	3119	2339	1871	1247	936	458	234
Improvement over 250Y Structured Packing	37.4 X	18.7X	12.5X	9.4X	7.5X	5.0X	3.7X	1.9X	0.9X

Frothing Section

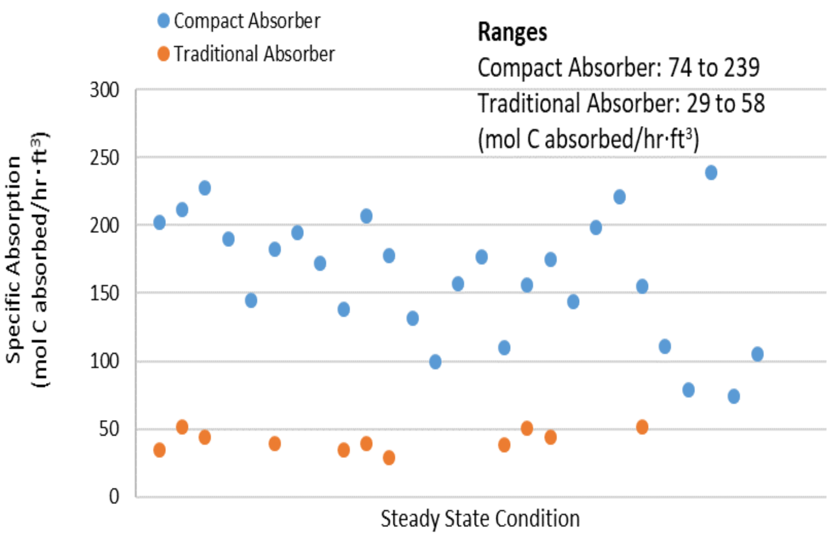
Expected Liquid-Gas Contact Surface Area at Target Operation of L/G=3.5 mass/mass				
Uniform Bubble Size (mm)	3	4	5	8
Liquid-Gas Contact Surface Area (m^2/m^3)	2000	1500	1200	750
Improvement over 250Y Structured Packing	8X	6X	3X	3X

Progress: Increased Mass Transfer

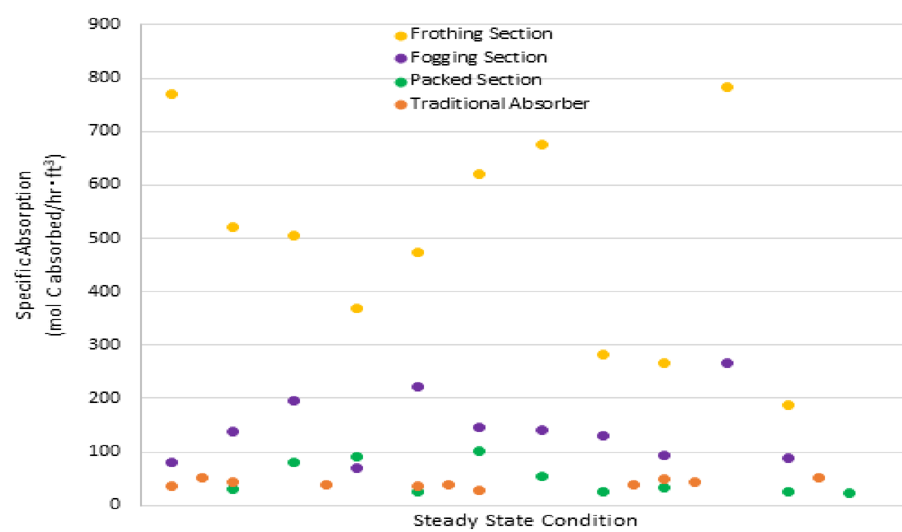
Target Mass Transfer Enhancement by 4X.

Comparing the UK CAER compact absorber performance with a previous campaign using a traditional absorber (structured packing) with the same solvent and varying operating conditions, the specific absorption in the compact absorber is notably higher than in the traditional absorber, 2.6 to 4.1X, depending on the operating parameters.

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

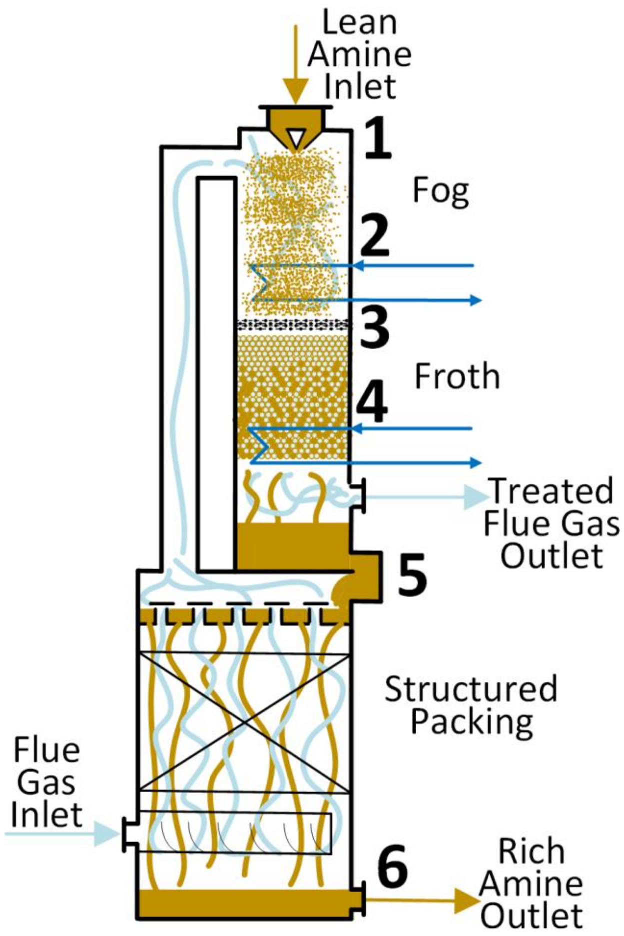


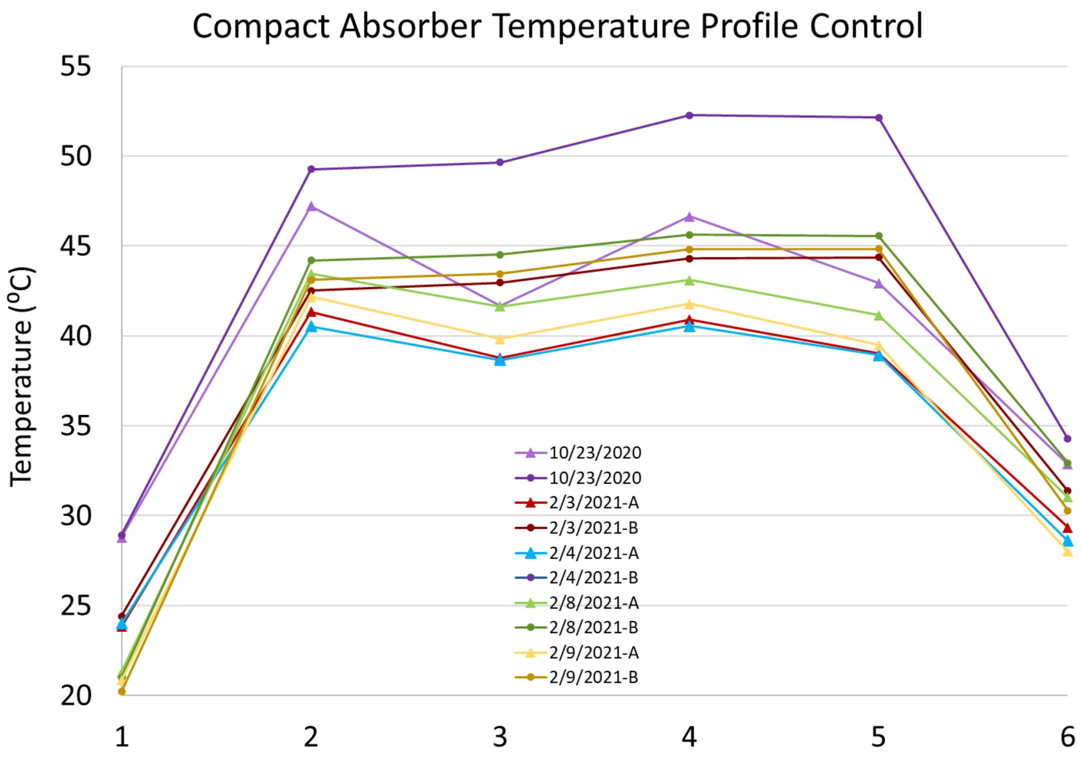
Specific Absorption in Each Section of the Compact Absorber Parametric Campaign Compared with that in a Traditional Absorber



Progress: Column Temperature Control

Target flatter absorber temperature profile obtained with in situ heat exchangers.





Progress: Frothing Section Configuration

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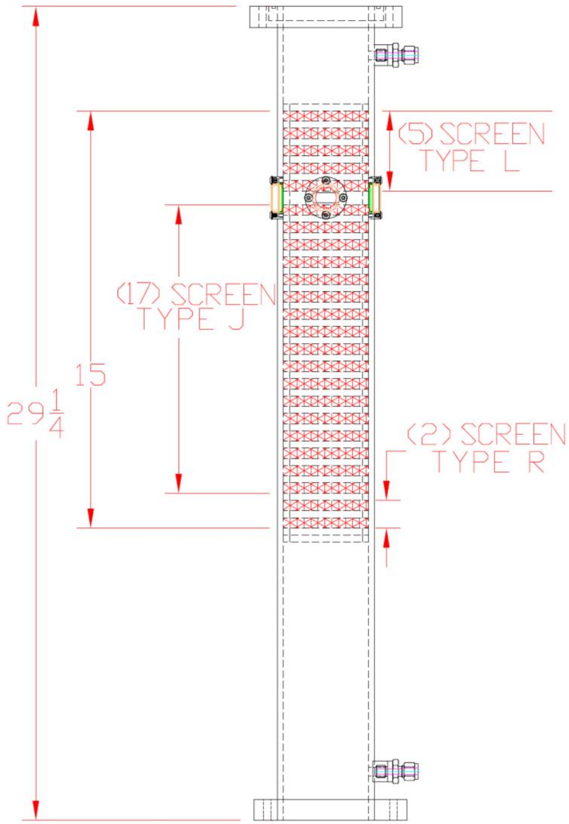
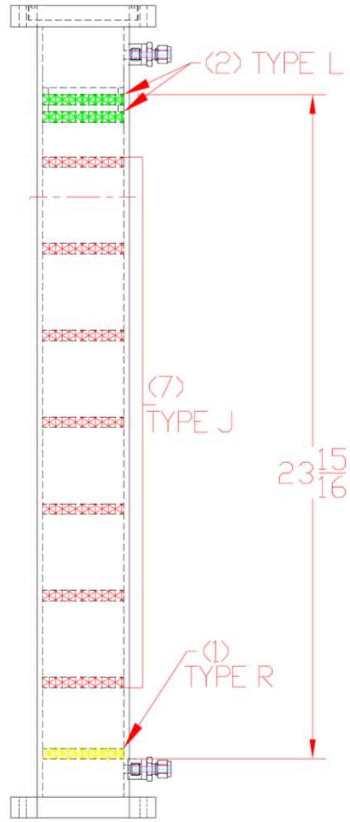
A



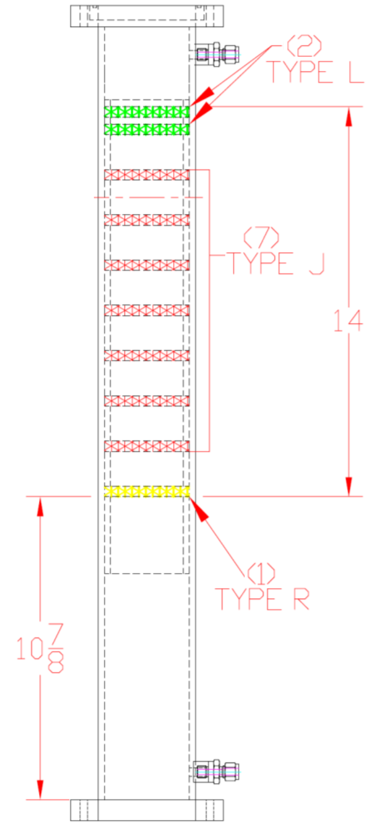
Can dP be reduced?

B



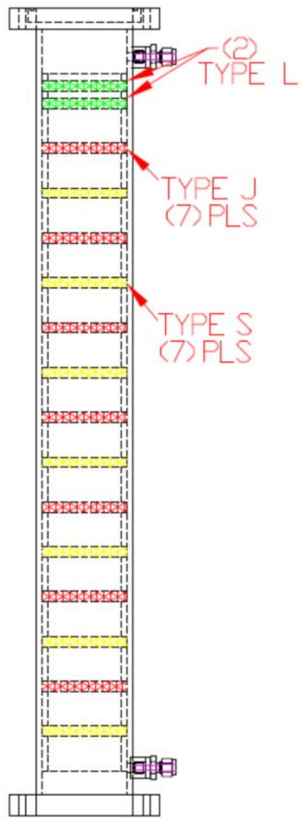
Can specific absorption be increased?

C



Can overall performance be increased?

D



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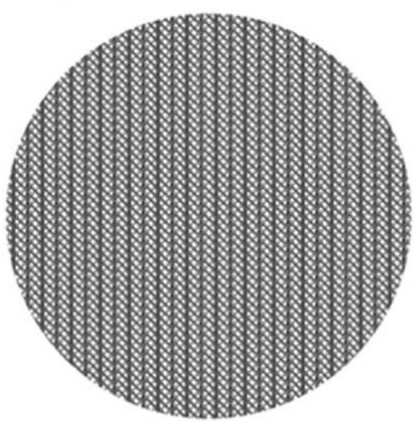
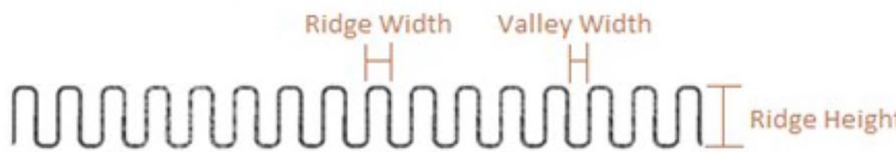
Progress: Frothing Section dP

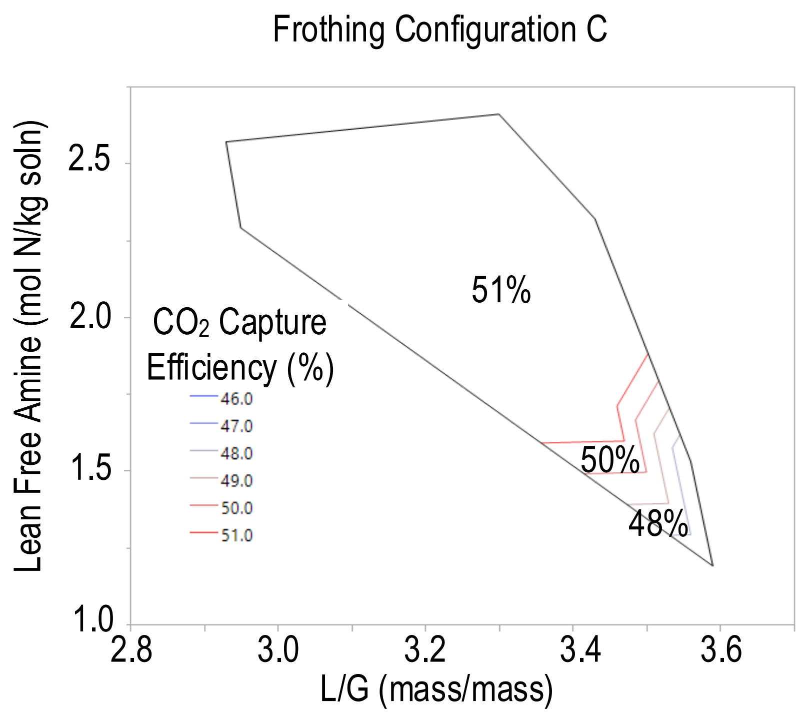
Target <5 in H_2O

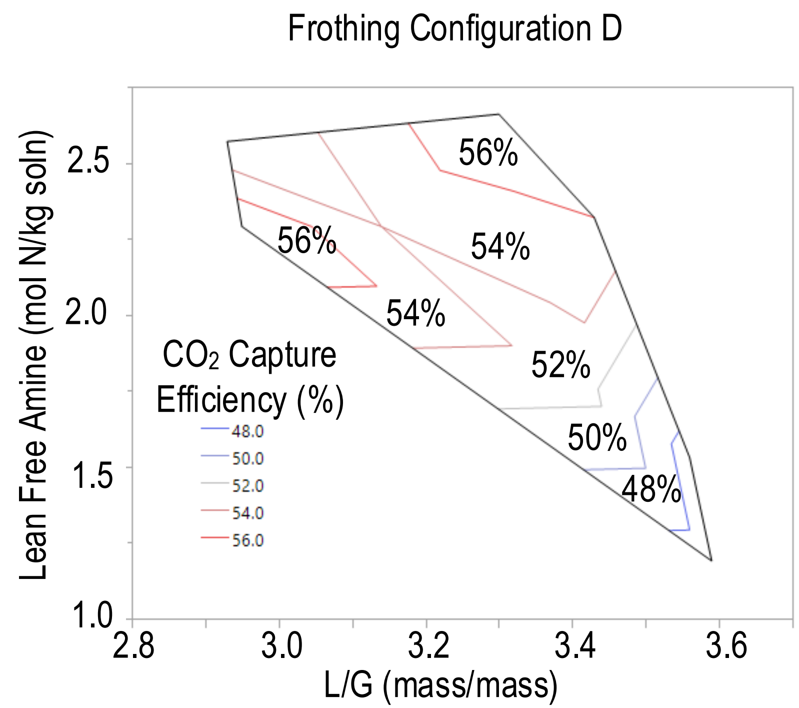
	L/G (mass/mass)	Gas Velocity (m/s)	Pressure Drop (in. H_2O)
Evaluation with Water and Gas	4.62	1.7	4.5
Operation with UK CAER Solvent			
A	2.9-3.6	1.5	6.2-7.8
B	2.8-3.5	1.5	2.4-2.7
C	2.9-3.6	1.4	2.2-2.9
D	2.9-3.6	1.4	1.9-3.4





Current Status





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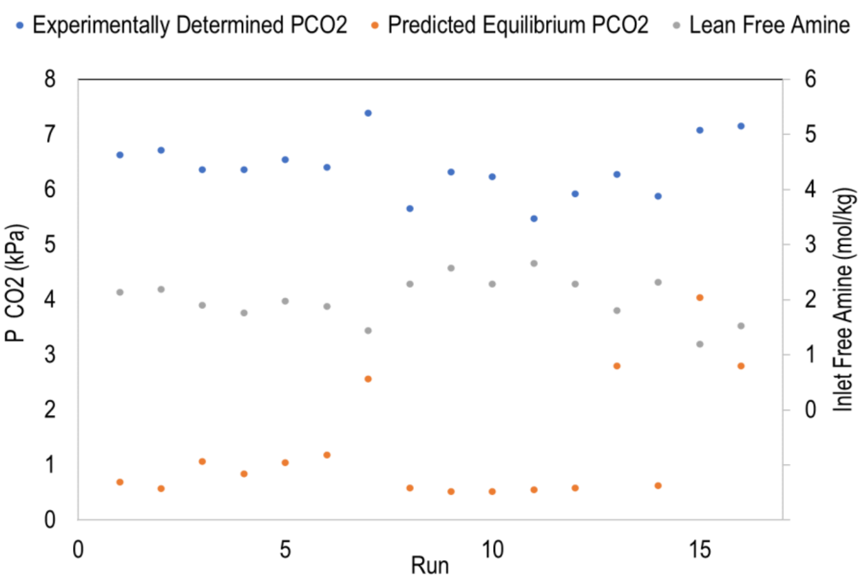
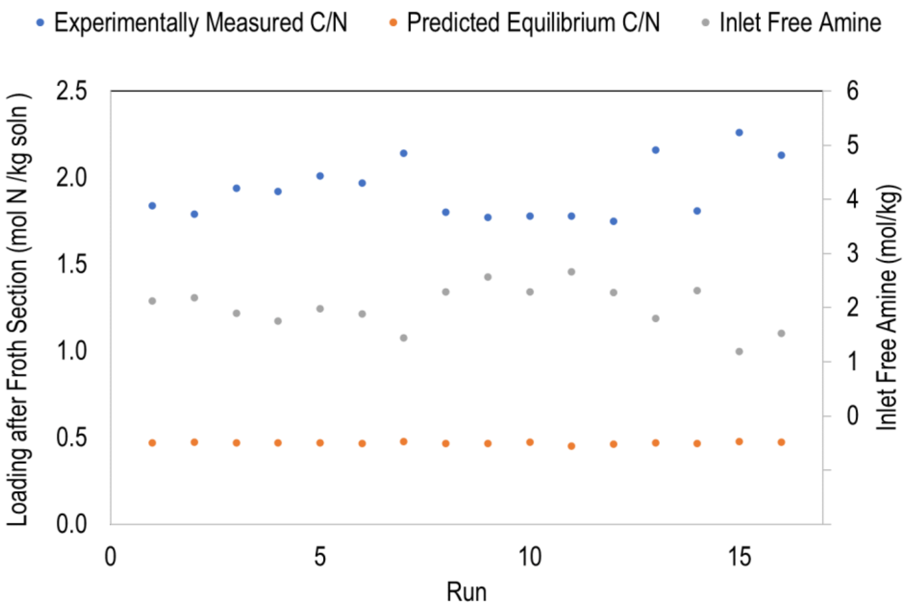
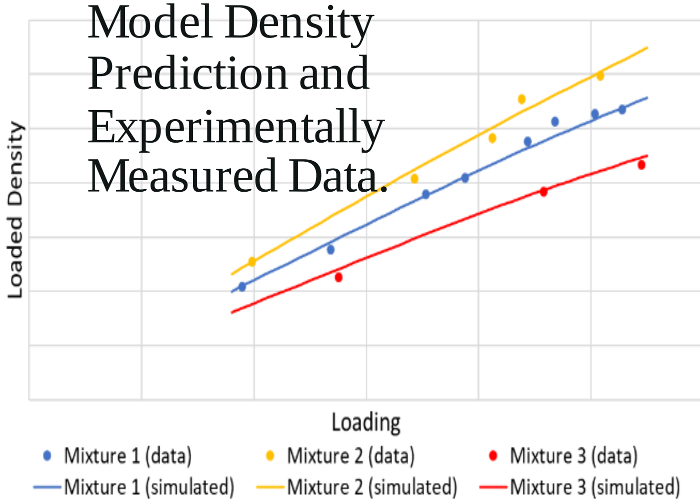




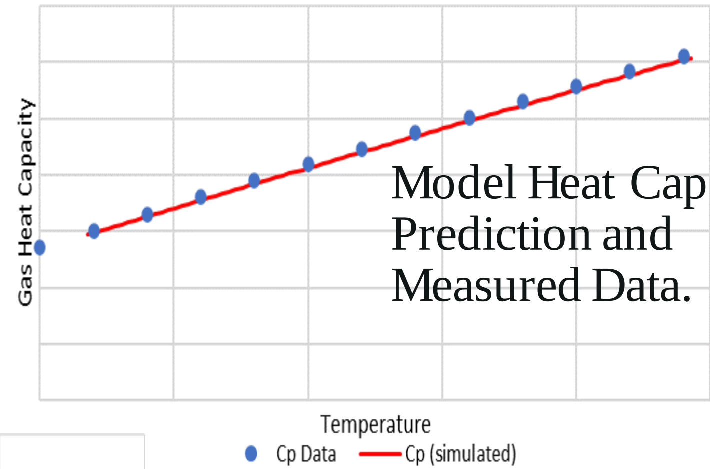
Current Status

Rate based solvent model complete with good physical property and absorber profile prediction ability.

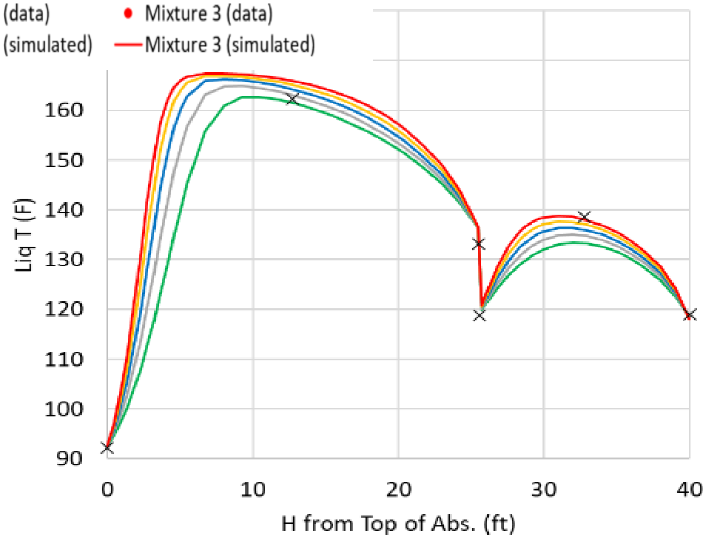
Process model underway for H&MB stream table generation.



Model Density Prediction and Experimentally Measured Data.

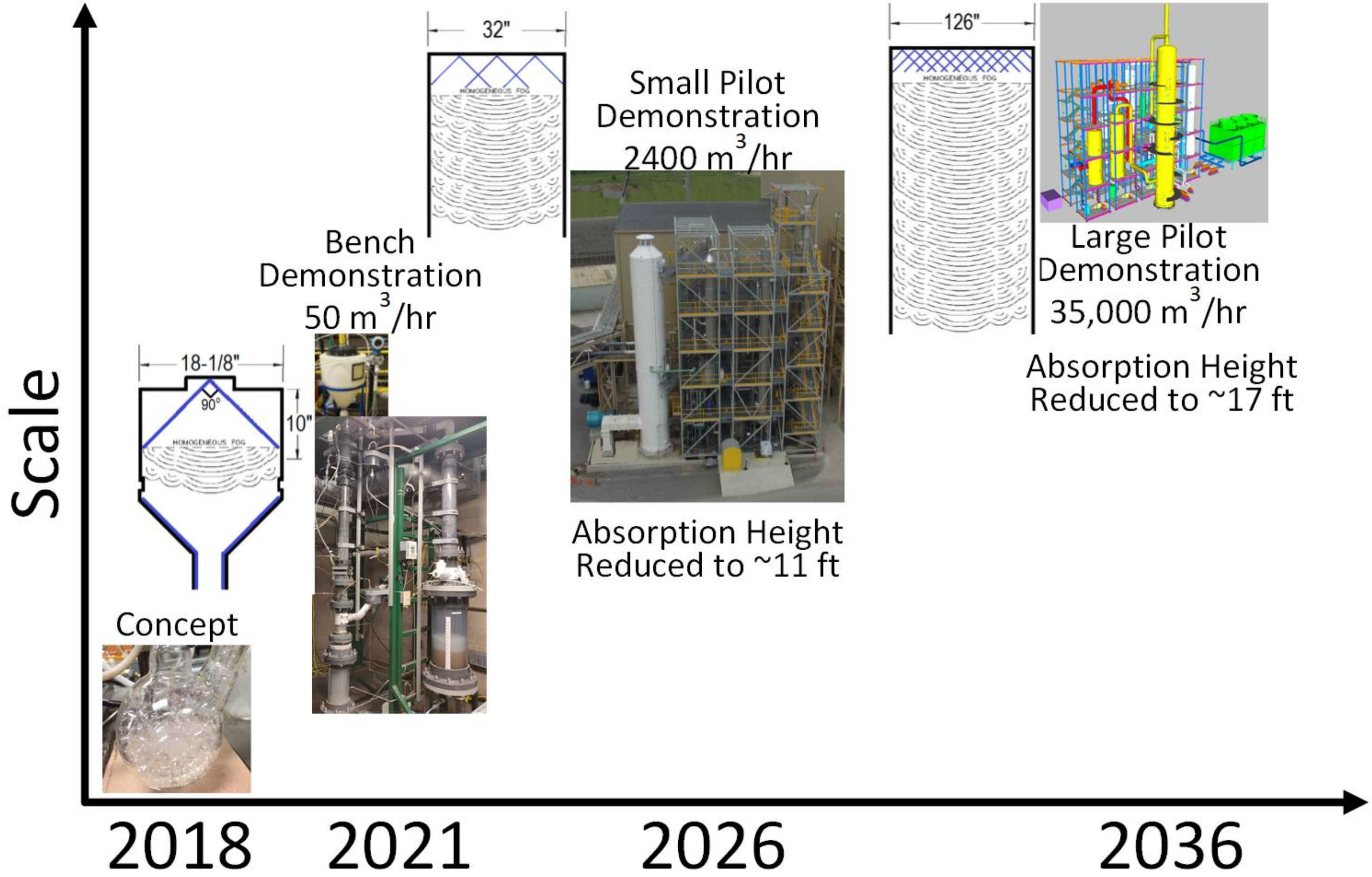


Model Heat Capacity Prediction and Measured Data.



Model Predicted Absorber Temperature Profile Interfacial Area Sensitivity Study (solid lines) and UK CAER 0.7 MWe Small Pilot Experimental Data (X).

Future Testing and Development



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Summary

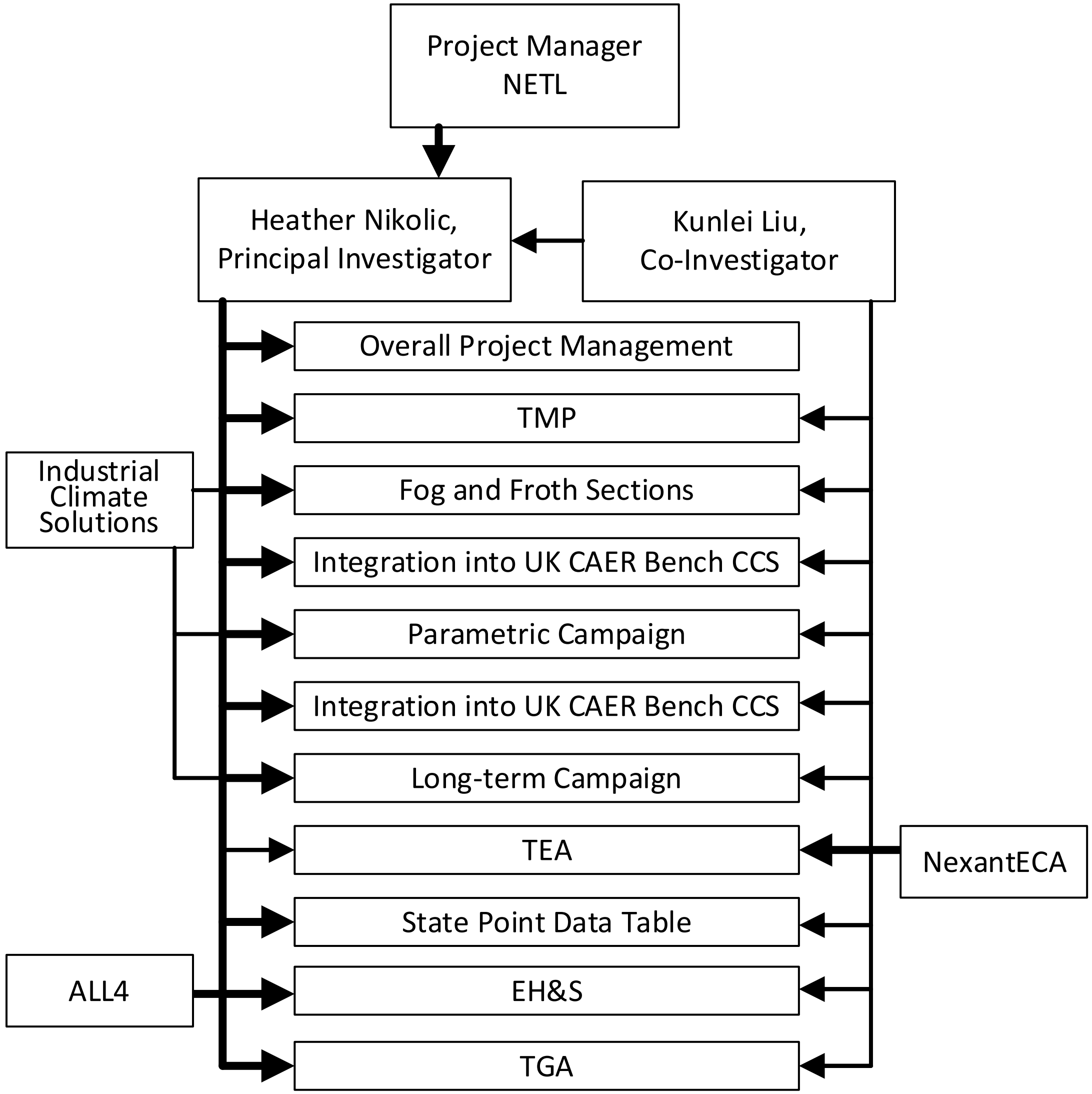
- All BP1 Deliverables and Milestones Met; All BP1 Success Criteria Achieved
- On Schedule to meet an achieve BP2 Deliverables, Milestones and Success Criteria
- 60+% CO_2 capture and 0.45 mol C/mol N rich loading demonstrated, on par with traditional absorber performance with >2X of structured packing
- Fog droplet SMD ≤50 μm in diameter
- Froth bubble size <3.7 mm in diameter
- Up to 4.1X increased absorption than traditional column
- 6.8X greater surface area in fogging and frothing sections than 250Y structured packing
- 65-90% absorption occurs in the fogging and frothing sections
- Multimedia i-poster presentation at 2020 Virtual AIChE Meeting, 11/16/2020-11/20/2020

Acknowledgements

Thank you to:

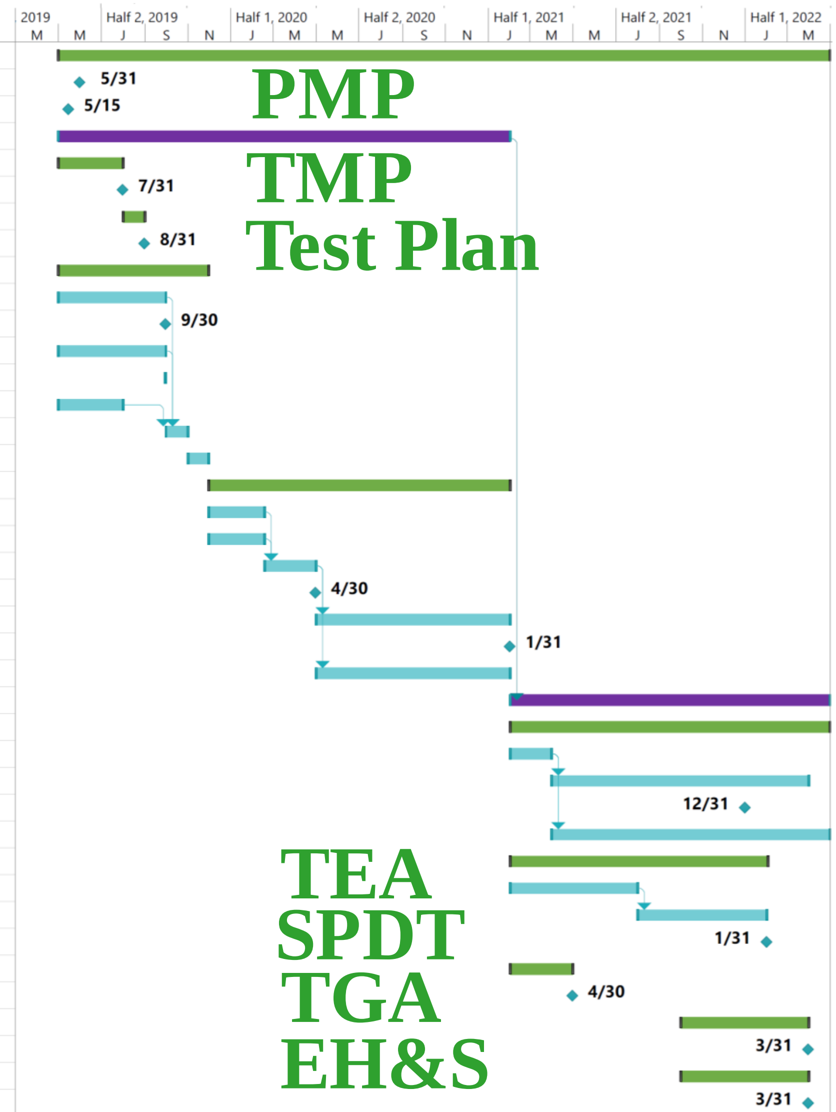
- **Carl Laird, Patrick Mayle and Angela Harshman**, DOE NETL
- **Bill Hargrove and Richard Adamson**, ICSI
- **Clay Whitney**, ALL4
- **Haoren Lu**, NexantECA
- **Shanice Edwards, Reynolds Frimpong, Len Goodpaster, Roger Perrone, Aaron Smith, Xiaoshuai Yuan and Kunlei Liu**, UK CAER

Organization Chart



Gantt Chart

Task Name	Start	Finish
Task 1 - Project Management and Planning	**Wed 5/1/19**	**Sat 4/30/22**
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**	**Sat 4/30/22**
Task 6 - Integration of Compact Absorber into the Large Bench	**Mon 2/1/21**	**Sat 4/30/22**
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 3/31/22**
Long-term Test Campaign Complete	*Fri 12/31/21*	*Fri 12/31/21*
Subtask 6.3 - Data Analysis	**Thu 4/1/21**	**Sat 4/30/22**
Task 7 - Techno Economic Analysis	**Mon 2/1/21**	**Tue 2/1/22**
Subtask 7.1 - Modeling	**Mon 2/1/21**	**Sat 7/31/21**
Subtask 7.2 - TEA	**Sun 8/1/21**	**Mon 1/31/22**
Techno-economic Analysis (TEA) Complete	*Mon 1/31/22*	*Mon 1/31/22*
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**	**Thu 3/31/22**
Technology Gap Analysis Complete	*Thu 3/31/22*	*Thu 3/31/22*
Task 10 - Environmental, Health and Safety Assessment	**Fri 10/1/21**	**Thu 3/31/22**
Environmental, Health and Safety (EH&S) Assessment Complete	*Thu 3/31/22*	*Thu 3/31/22*



State Point Data Table for CAER Hindered Primary Amine Blend Solvent.		
	Units	Measured/Estimated Performance During BP2
Pure Solvent		
Molecular Weight	g mol^{-1}	<90
Normal Boiling Point	°C	160
Normal Freezing Point	°C	2
Vapor Pressure @ 15 °C	bar	$0.0007^{\$}$
Working Solution		
Concentration	kg/kg	<45*
Specific Gravity (15 °C/15 °C)	g/mL	1.01*
Specific Heat Capacity @ 30 °C and 1 bar	kJ/kg·K	3.5*
Viscosity @ 40 °C	cP	2.8 (fresh condition, C/N=0)*
Surface Tension @ STP	dyn/cm	51*
Absorption		
Pressure	bar	1
Temperature	°C	35-55*
Equilibrium CO_2 Loading	gmol CO_2/kg	2.3*
Heat of Absorption	kJ/mol CO_2	$55\text{-}60^{\#}$
Solution Viscosity @ 40 °C	cP	4.3 (rich condition)*
Desorption		
Pressure	bar	1.6 – 2.2*
Temperature	°C	117-120*
Equilibrium CO_2 Loading	gmol CO_2/kg	1.1-1.4*
Heat of Desorption	kJ/mol CO_2	$55\text{-}60^{\#}$

*Experimental data, $^{\#}$ Estimated, $^{\$}$ Calculated based on VLE