Development of a Novel Biphasic CO_2 Absorption Process with Multiple Stages of Liquid–Liquid Phase Separation for Post-Combustion Carbon Capture (DE-FE0026434)

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2018 NETL CO_2 Capture Technology Project Review Meeting

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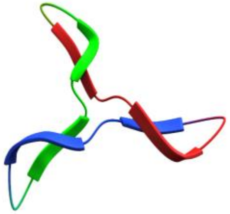


Project Overview

- Project objectives
  - Develop new biphasic solvents
  - Demonstrate process concept via laboratory column testing
  - Generate engineering and scale-up data
  - High-level process and techno-economic analysis

- Project duration
  - BP1: 10/1/15 to 06/30/17 (21 months)
  - BP2: 07/1/17 to 12/31/18 (18 months)

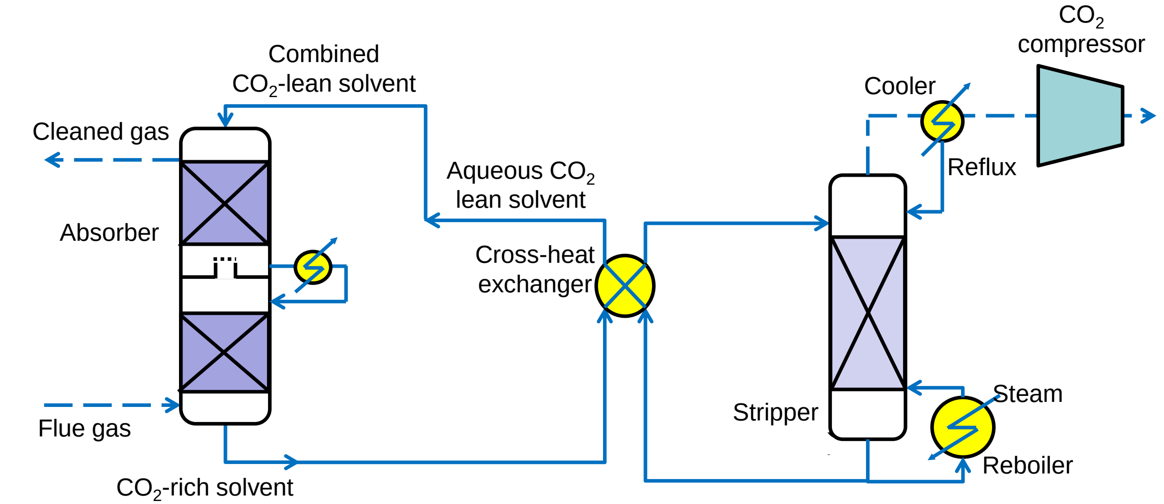
- Funding profile

DOE funding	**1,999,996**
BP1	1,079,663
BP2	920,333
Recipient cost share	**501,052**
BP1	269,920
BP2	231,132
Total	**2,501,048**

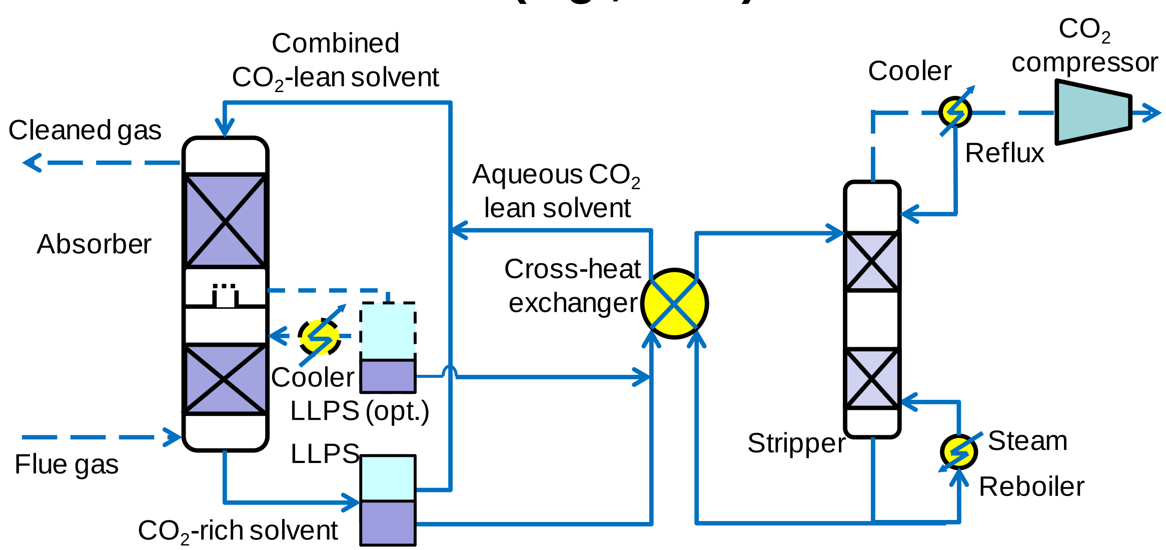
Project Participants

- **University of Illinois**
  - **Illinois State Geological Survey**
    - Solvent development
    - Process development
  - **Illinois Sustainable Technology Center**
    - Assessment of solvent stability and corrosion impacts
  - **Applied Research Institute**
    - Molecular dynamics simulation study for solvent screening
- **Trimeric Corporation**
    - Process feasibility and high-level TEA

Biphasic vs. Conventional Absorption Process



Conventional (Monophasic) Absorption Process (e.g., MEA)



Biphasic Absorption Process

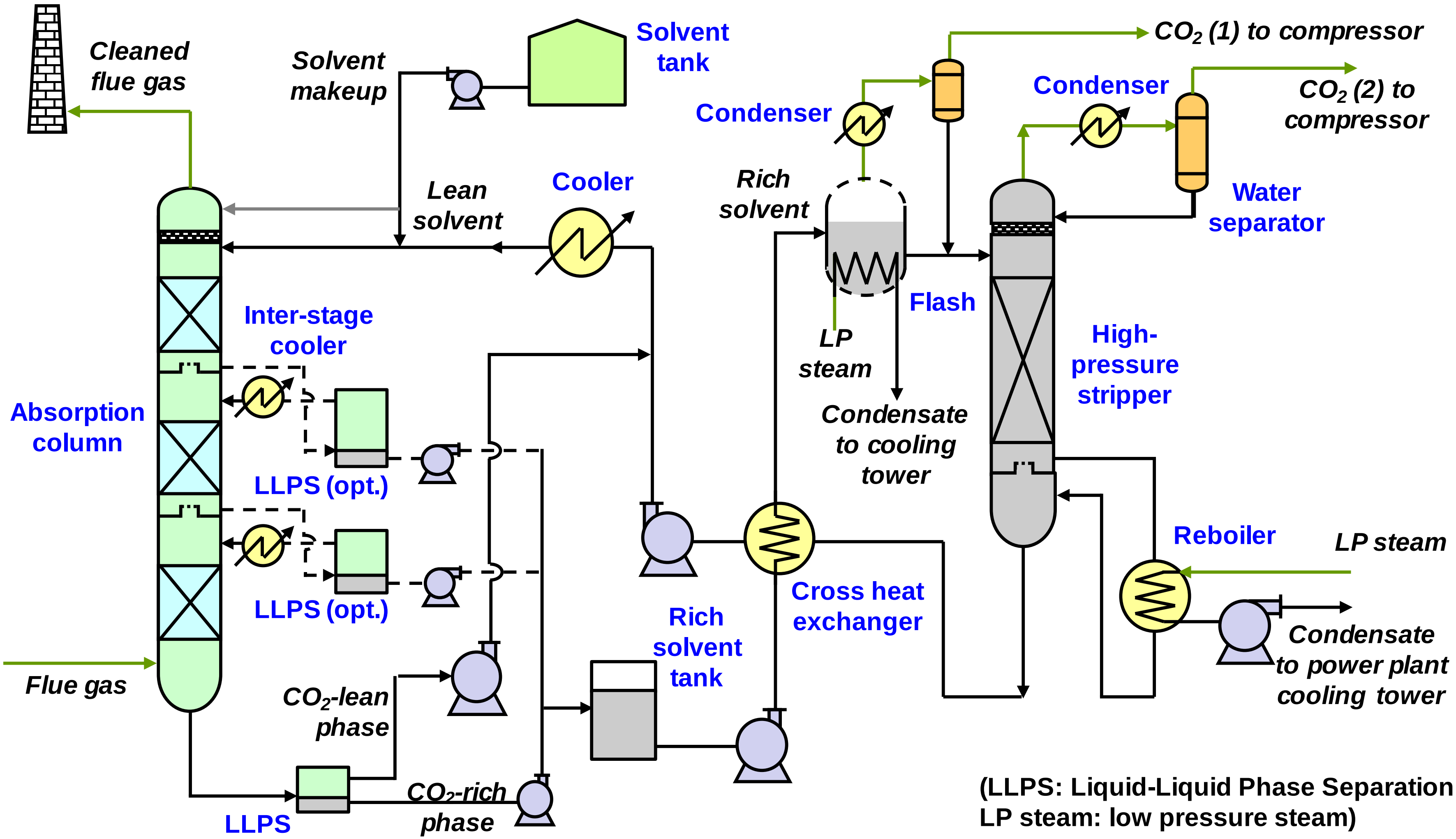
Benefits of biphasic process in stripper:

- Reduced equipment size due to reduced mass of solvent to be regenerated
- Reduced energy use and compression work due to reduced mass of solvent, high CO_2 loading, and elevated stripping pressure

Benefits in absorber via phase separation:

- Reduced viscosity with separation of rich, viscous phase improves mass transfer rate and allows use of viscous solvents

Biphasic CO_2 Absorption Process with Multi-Stages of Liquid-Liquid Phase Separation



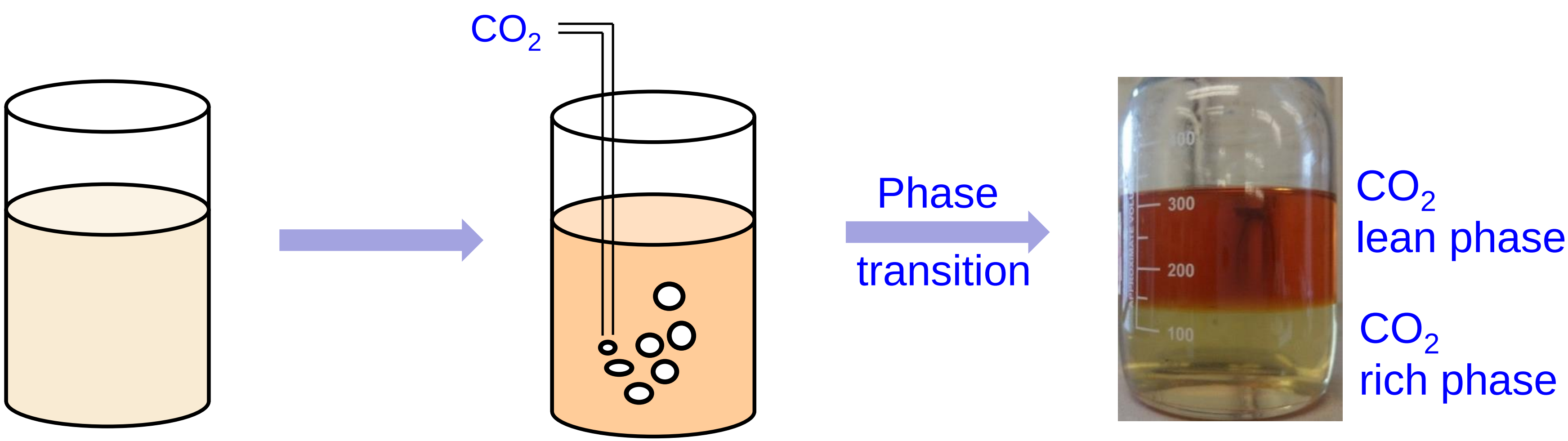
(LLPS: Liquid-Liquid Phase Separation; LP steam: low pressure steam)

Proposed Biphasic CO_2 Absorption Process (BiCAP)

Novel Biphasic Solvents

Amine-based solvent blends:

- Phase transition behavior tunable with a proprietary solvent formulation approach, allowing for a wide selection of solvent components
- Consider multi-criteria (capacity, rate, CO_2 enrichment, viscosity, desorption pressure, stability, corrosion, and availability/cost)
- Water lean but aqueous form suitable for humid flue gas application

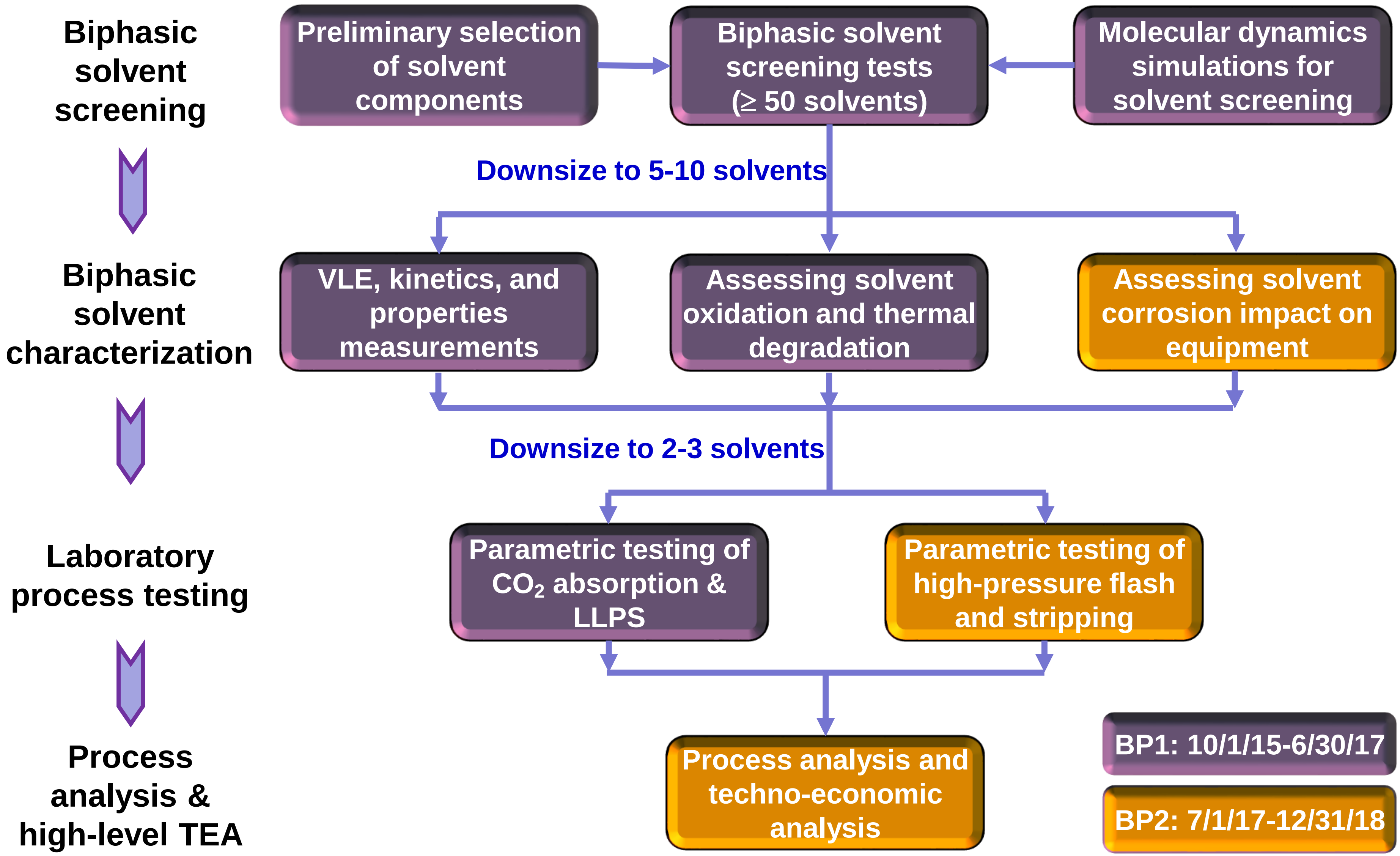


Lean solvent in a single phase

Phase transition induced by CO_2 loading

Two-phase system (w/ tunable phase vol.%)

Project Scope of Work



Project Schedule

SOPO BREAKOUT SCHEDULE"		START/END		BUDGET PERIOD 1							BUDGET PEIROD 2					
WBS	**Description**	**Start**	**End**	**Q1**	**Q2**	**Q3**	**Q4**	**Q5**	**Q6**	**Q7**	**Q8**	**Q9**	**Q10**	**Q11**	**Q12**	**Q13**
1.0	**Project management and planning**	**10/01/15**	**09/30/18**													
1.1	Project management and planning	10/01/15	09/30/18													
1.2	Briefings and reports	10/01/15	09/30/18													
2.0	**Screening and characterization of biphasic solvents**	**10/01/15**	**06/30/16**													
2.1	Solvent screening tests on CO_2 absorption and phase transition	10/01/15	06/30/16													
2.2	Solvent screening tests on CO_2 desorption performance	10/01/15	06/30/16			a										
2.3	Molecular simulation study for solvent screening	10/01/15	06/30/16			b										
3.0	**Measuring phase equilibria, absorption kinetics & solvent properties**	**01/01/16**	**09/30/16**				**A**									
3.1	Measurement of VLE data under absorption/desorption conditions	01/01/16	09/30/16													
3.2	Measurement of CO_2 absorption kinetics	04/01/16	09/30/16				c									
3.3	Measurement of solvent properties	07/01/16	09/30/16													
4.0	**Determining thermal and oxidation stabilities of selected solvents**	**04/01/16**	**12/31/16**													
4.1	Oxidation stability of biphasic solvents	04/01/16	12/31/16													
4.2	Thermal stability of biphasic solvents	04/01/16	12/31/16					e								
5.0	**Testing CO_2 absorption and phase separation in a packed-bed column**	**04/01/16**	**06/30/17**							**B**						
5.1	Modification of an exisiting absorption column	04/01/16	09/30/16				d									
5.2	Parametric testing of CO_2 absorption and phase separation	07/01/16	06/30/17							f						
5.3	Rate-based modeling of CO_2 absorption	10/01/17	06/30/17													
6.0	**Development of a process sheet and preliminary process analysis**	**04/01/16**	**06/30/17**													
6.1	Development of a conceptual process flow sheet	04/01/16	12/31/16													
6.2	Preliminary process analysis	07/01/16	06/30/17							g						
7.0	**Testing CO_2 desorption in a high-pressure flash and stripping column**	**07/01/17**	**06/30/18**											**C**		
7.1	Modification of an existing packed-bed column	07/01/17	12/31/17									h				
7.2	Parametric testing of high-pressure flash and stripping	10/01/17	06/30/18											j		
7.3	Rate-based modeling of CO_2 desorption	01/01/18	06/30/18													
8.0	**Assessing the impact of solvent corrosion on the equipment**	**07/01/17**	**03/31/18**													
8.1	Assessing the impact of solvent corrosion on the equipment	07/01/17	03/31/18										i			
9.0	**Technical and economic feasibility study**	**01/01/18**	**12/31/18**													**D**
9.1	Process simulation and mass & energy balance calculations	01/01/18	09/30/18													
9.2	Technical and economic feasibility study	04/01/18	12/31/18													k

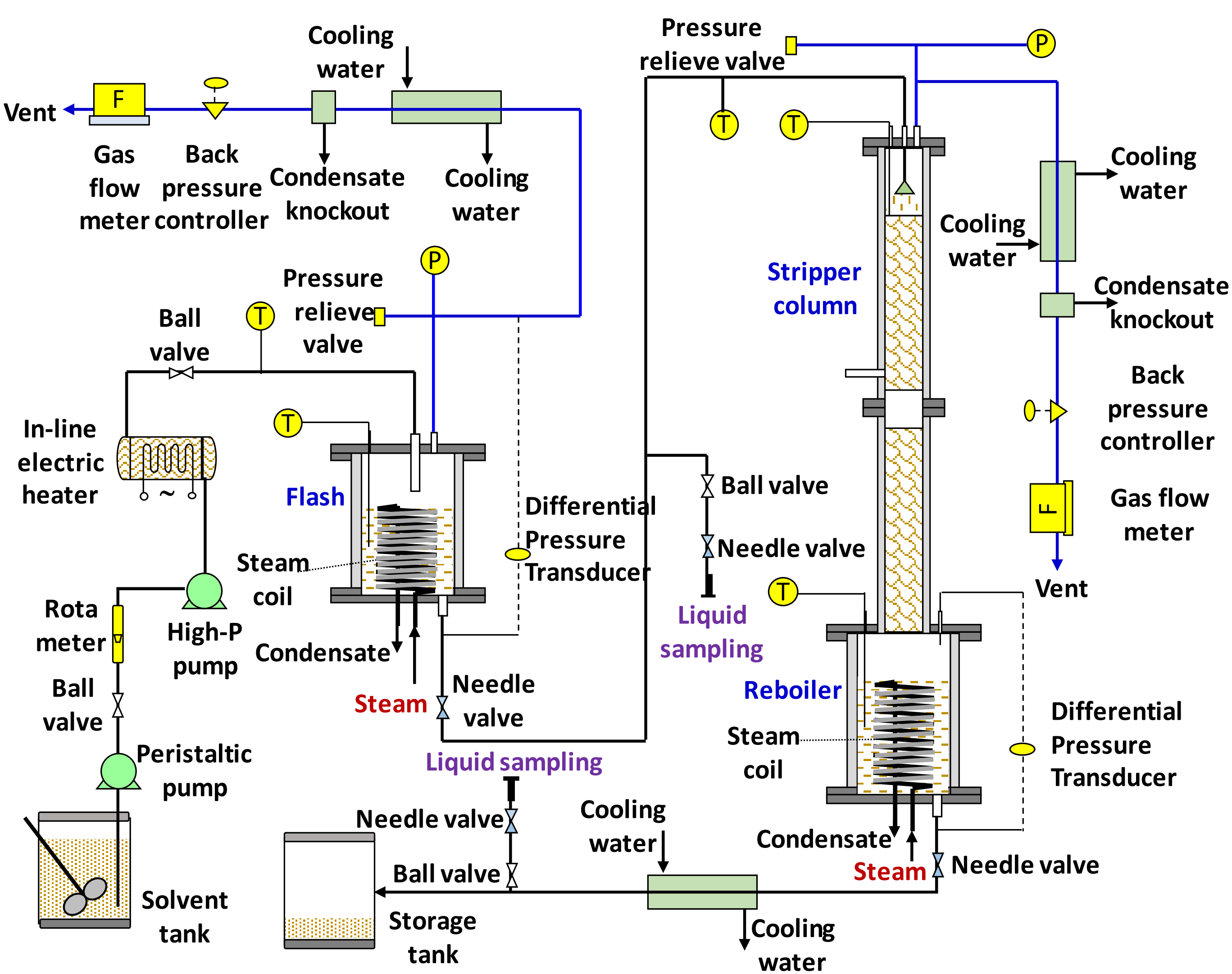
Current

- All milestones up to date (a – j) are completed

Overview of Project Progress and Status

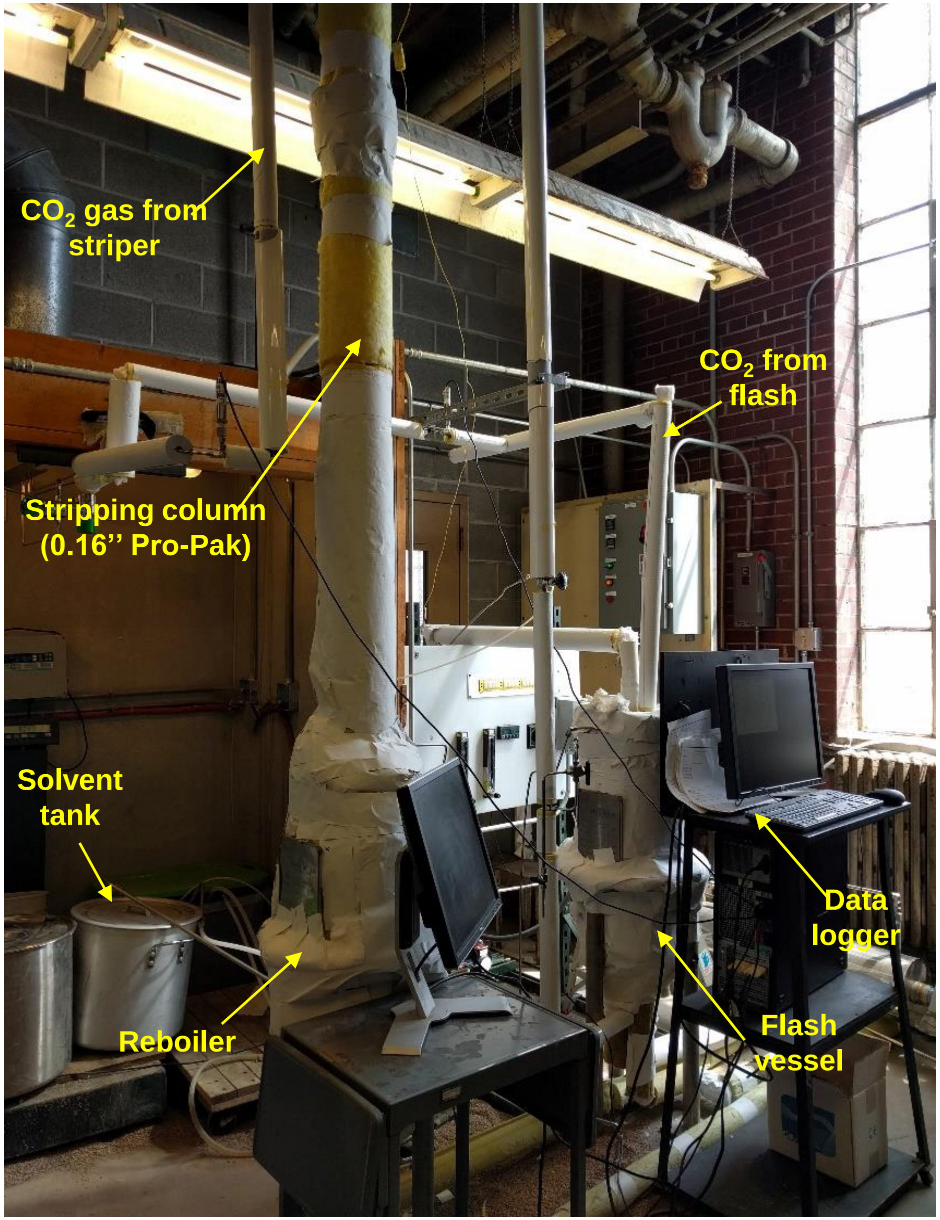
	Results	Status
~80 solvents screened	2 solvents selected	Completed in BP1
Vapor-liquid equilibria	VLE measured at both absorption & desorption conditions	Completed in BP1
Absorption kinetics	Measured under full ranges of CO_2 loadings	Completed in BP1
Oxidation and thermal stabilities	Thermal stability at 150°C = MEA at 120°C; Oxidation degradation ~8 times < MEA	Completed in BP1
Viscosity	CO_2-saturated rich phase < 50 cP at 40°C	Completed in BP1
CO_2 enrichment /phase transition	≥98% of total CO_2 uptake enriched in <50% of original solution	Completed in BP1
CO_2 absorption coupled with multiple stages of phase separation	Process concept demonstrated on a lab 10 kWe absorption system; Faster rates of 2 biphasic solvents than MEA	Completed in BP1
Corrosion effect	Updated in this presentation	Completed in BP2
CO_2 flash and stripping desorption process	Updated in this presentation	Completed in BP2

Task 7. Testing CO_2 Desorption in a High-Pressure Flash and Stripping Column

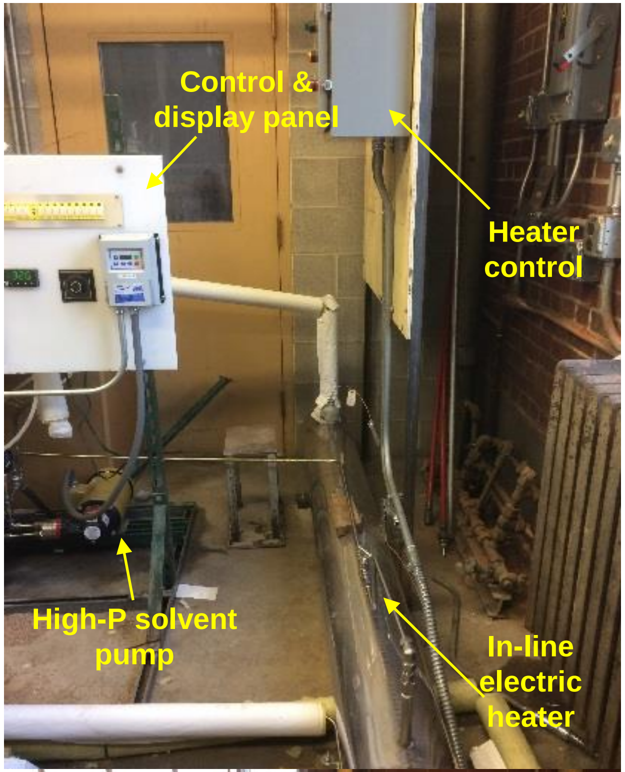


- 10 kWe equilavent
- Rated at 200 °C and 300 psig
- 5-in ID, 2-ft high flash
- 2-in ID, 10-ft high stripping column
- Heat supplied by an electric steam generator

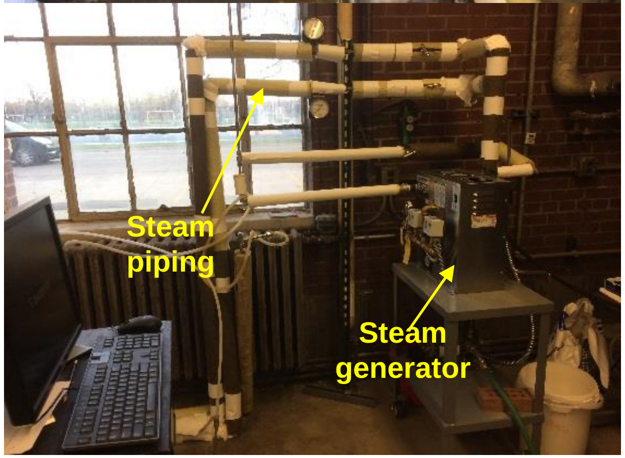
Contn’d



CO_2 gas from striper
Stripping column (0.16’’ Pro-Pak)
CO_2 from flash
Solvent tank
Reboiler
Data logger
Flash vessel

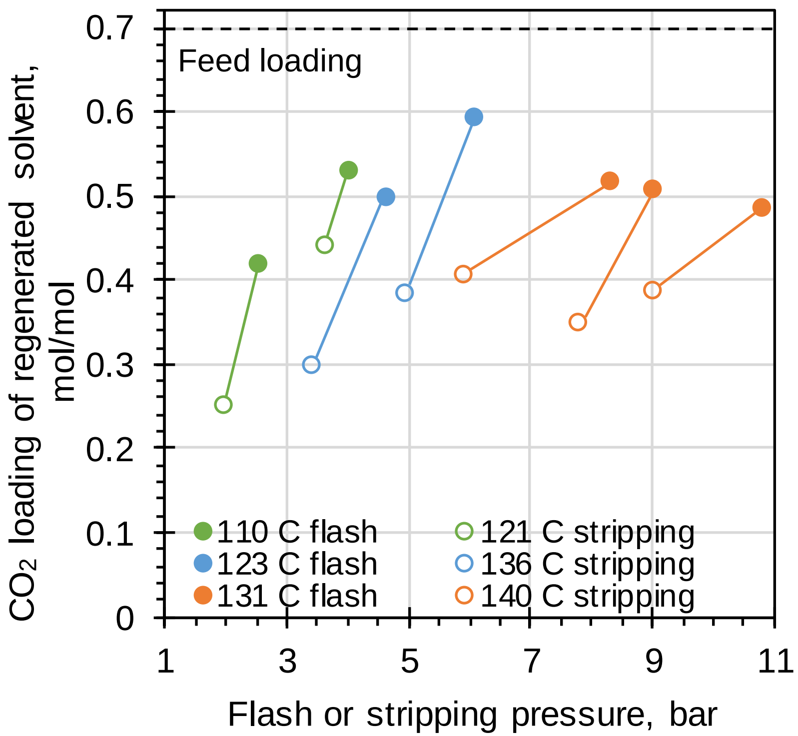


Control & display panel
Heater control
High-P solvent pump
In-line electric heater

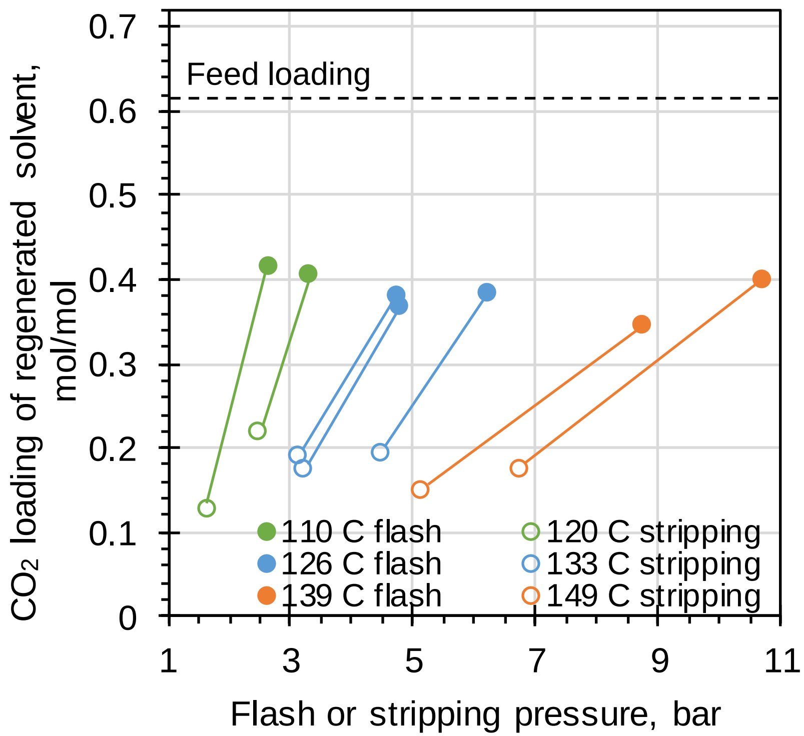


Steam piping
Steam generator

Combined Flash and Stripping Tests



BiS4 solvent

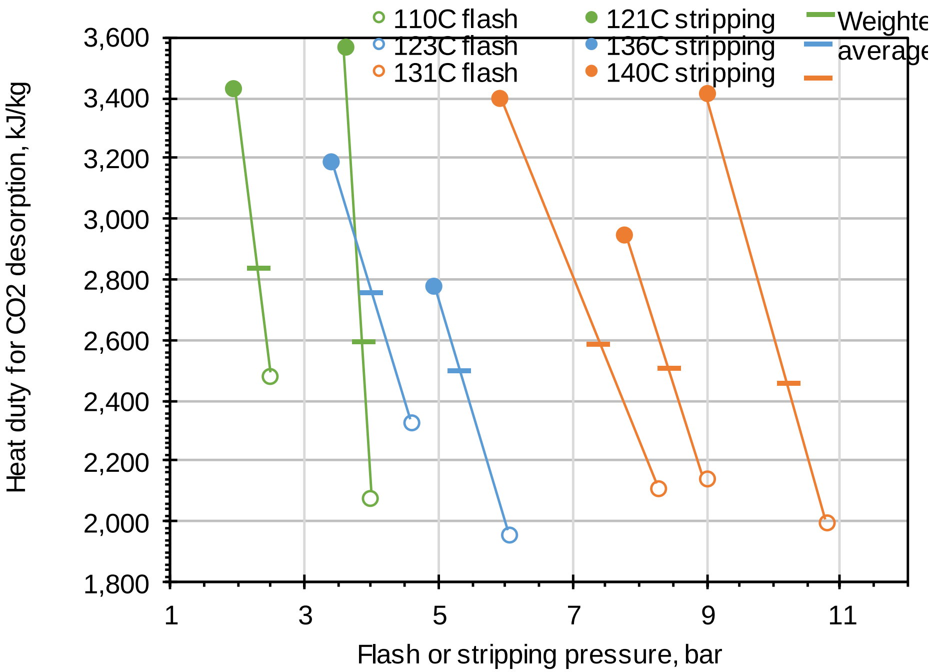


BiS6 solvent

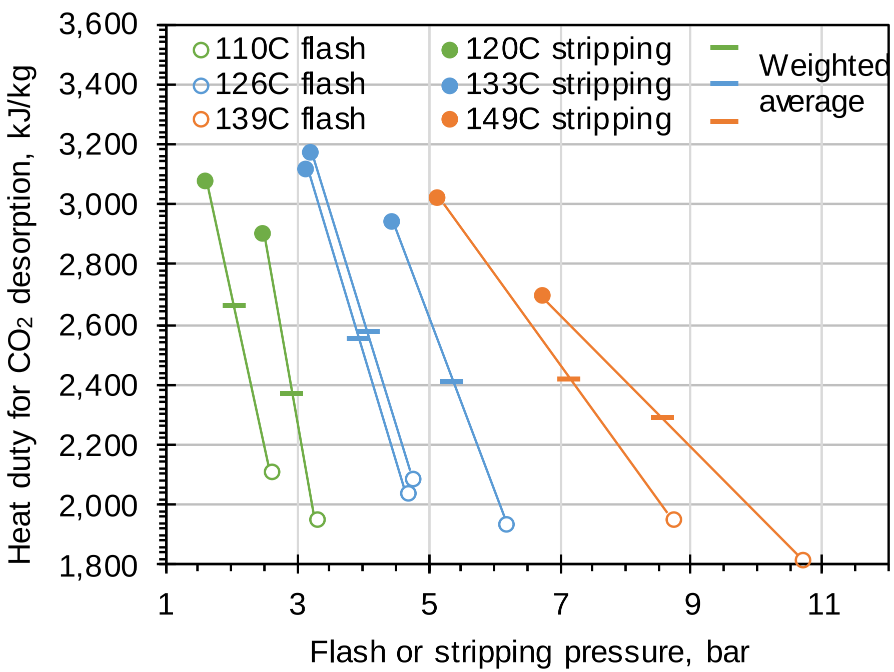
(Flash temperatures were ~10°C lower than stripper reboiler)

- 1/3 to 2/3 of total CO_2 desorption occurred in flash or stripper
- High pressures attained in flash (up to 11 bar) and stripper (up to 9 bar)

Heat Duty in Combined System



BiS4 solvent

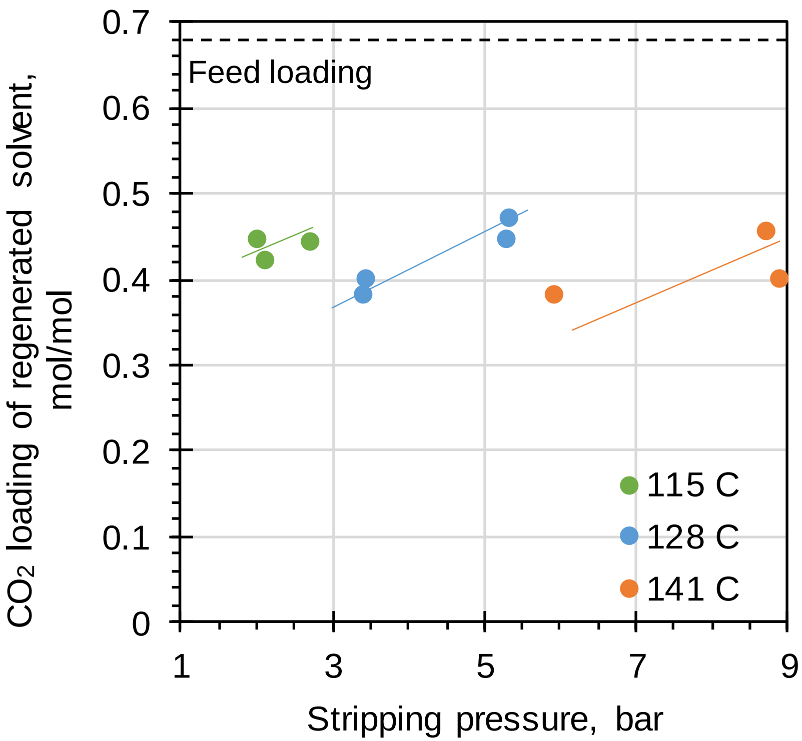


BiS6 solvent

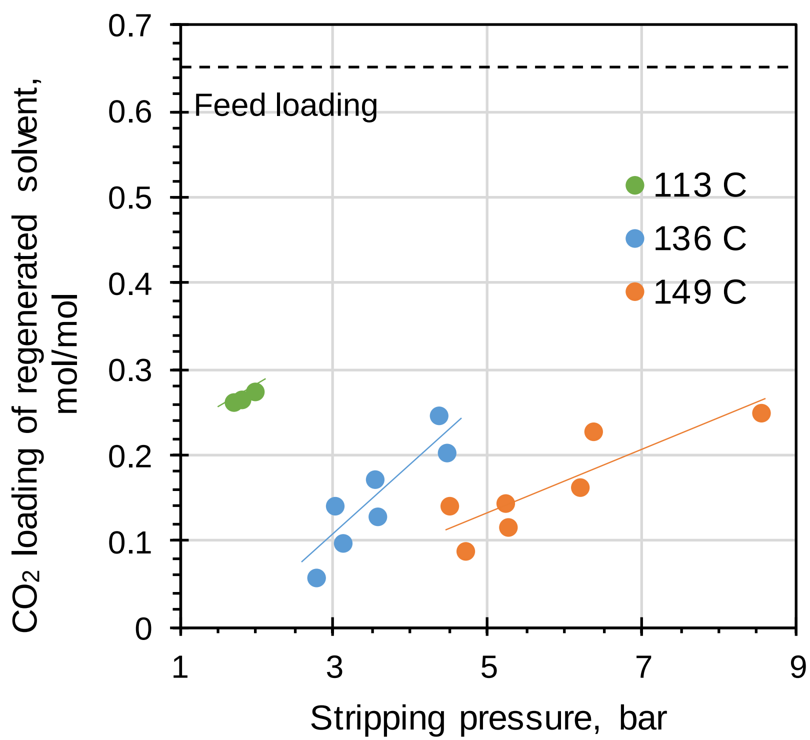
(Flash temperatures were ~10°C lower than stripper reboiler)

- Heat duty in flash or stripper decreased with increasing P at same T
- Heat duty in flash (higher P and lower T) < stripper
- Heat duty of BiS6 < BiS4

Single Stripper Tests



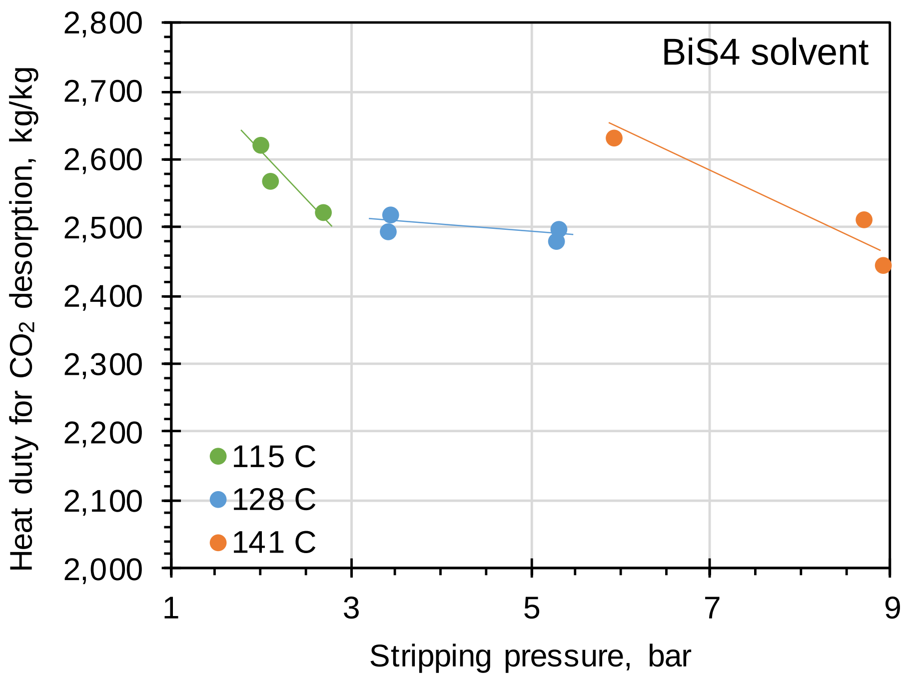
BiS4 solvent

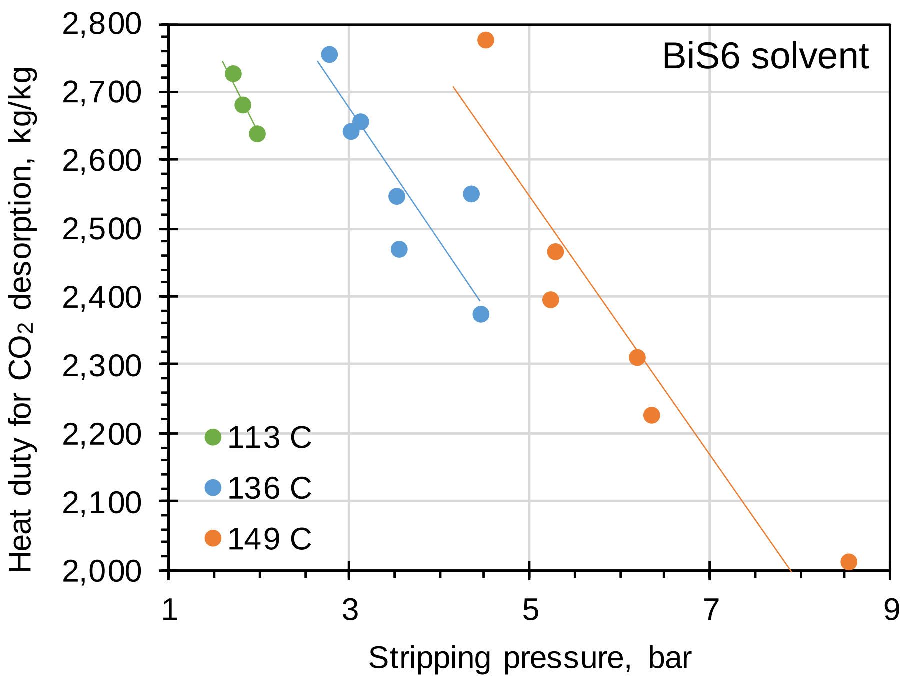


BiS6 solvent

- High stripping P at high T and high CO_2 lean loading
  - BiS4: ~9 bar at 140 °C and lean loading of 0.45 mol/mol
  - BiS6: ~7 bar at 149 °C and lean loading of 0.2 mol/mol
- 30-80% of CO_2 desorption obtained in stripper

Heat Duty in Single Stripper System





- Heat duty decreased with increasing stripping P at the same T
- Heat duty of BiS6 (2,000-2,800 kJ/kg) < BiS4 (2,400-2,600 kJ/kg)
- Heat duty in single stripper < combined flash/stripper system (2,300-2,800 kJ/kg)
  - Flash attained higher pressure, requiring less compression work

Task 8. Assessing the Impact of Solvent Corrosion on the Equipment

Two steel coupons to simulate equipment materials:

- Carbon steel C1010
- Stainless steel 316L

Weight-loss assessment method:

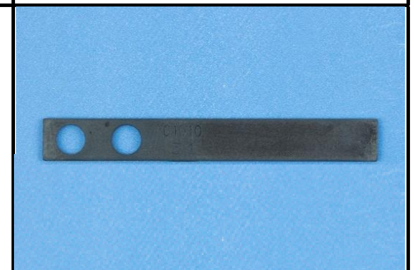
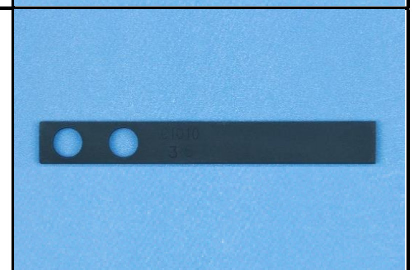
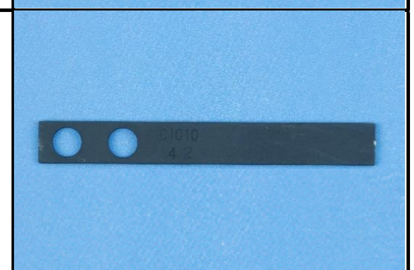
- Coupons saturated with solvents sealed in ½'' OD, 4.0" long stainless steel tubes
- Tubes kept in incubators at required temperatures and time periods (2 or 4 weeks)
- Coupons weighed to calculate weight losses after clean up including low-pressure glass bead blasting according to ASTM standard G1

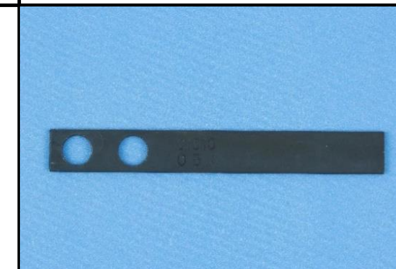
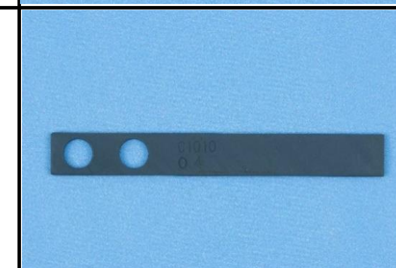
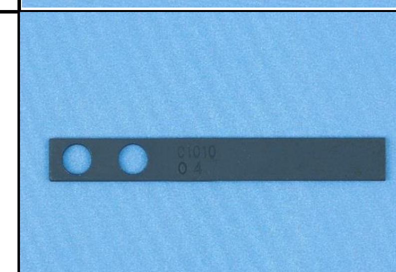
$$Corrosion\ rate\left(\frac{\mu m}{yr}\right) = \frac{Weight\ loss\ (g) \cdot K}{Alloy\ density\ (g/cm^3) \cdot Exposed\ area\ (cm^2) \cdot Exposed\ time\ (hr)}$$

Photographs of CS Coupons after Corrosion Tests

New coupon

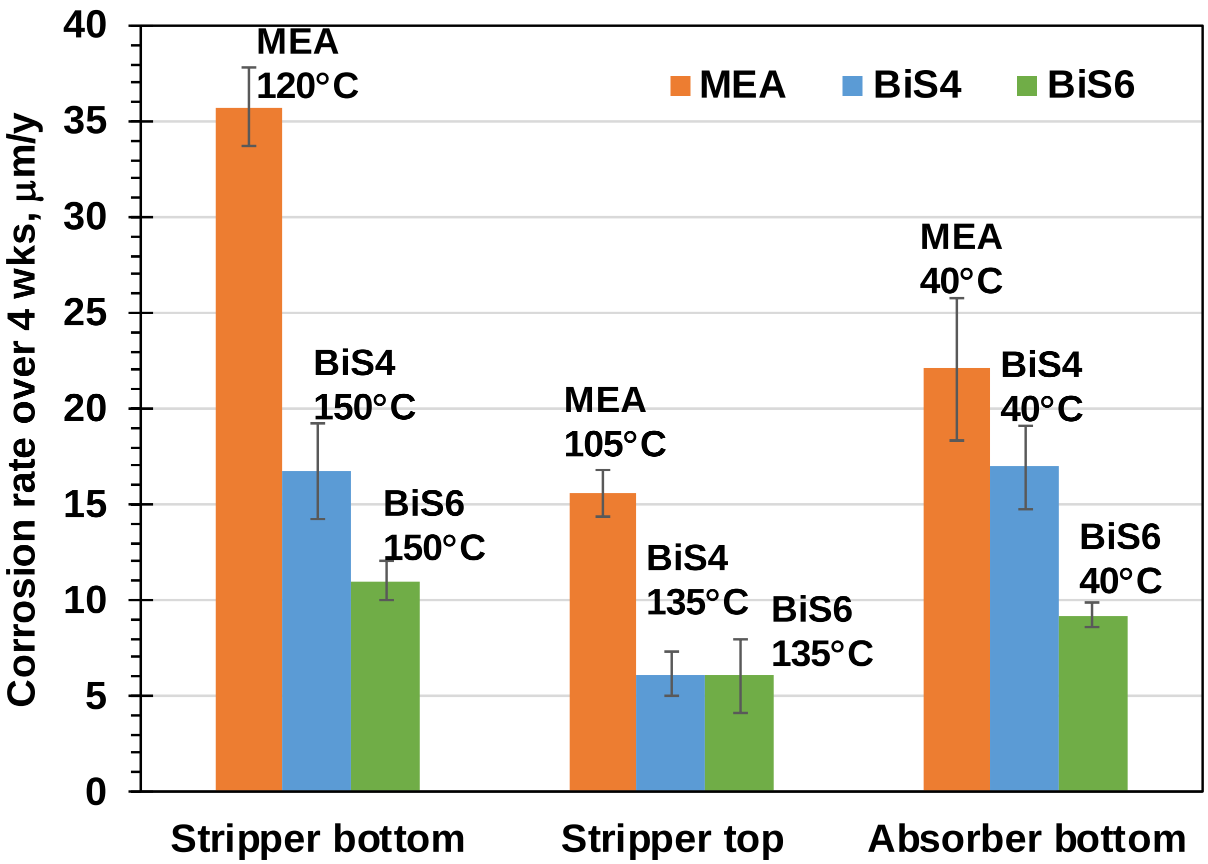
CS-C1010, 40°C	In CO_2 rich solvent for 4 wks
MEA (#8 & 12)	
BiS4 (#14 & 18)	
BiS6 (#20 & 22)	

CS-C1010, 120/150°C	In CO_2 lean solvent for 4 wks
MEA @120°C (#27 & 31)	
BiS4 @150°C (#33 & 36)	
BiS6 @150°C (#38 & 42)	

CS-C1010, 105/135°C	In CO_2 rich solvent for 4 wks
MEA @105°C (#50 & 53)	
BiS4 @135°C (#37 & 40)	
BiS6 @150°C (#43 & 47)	

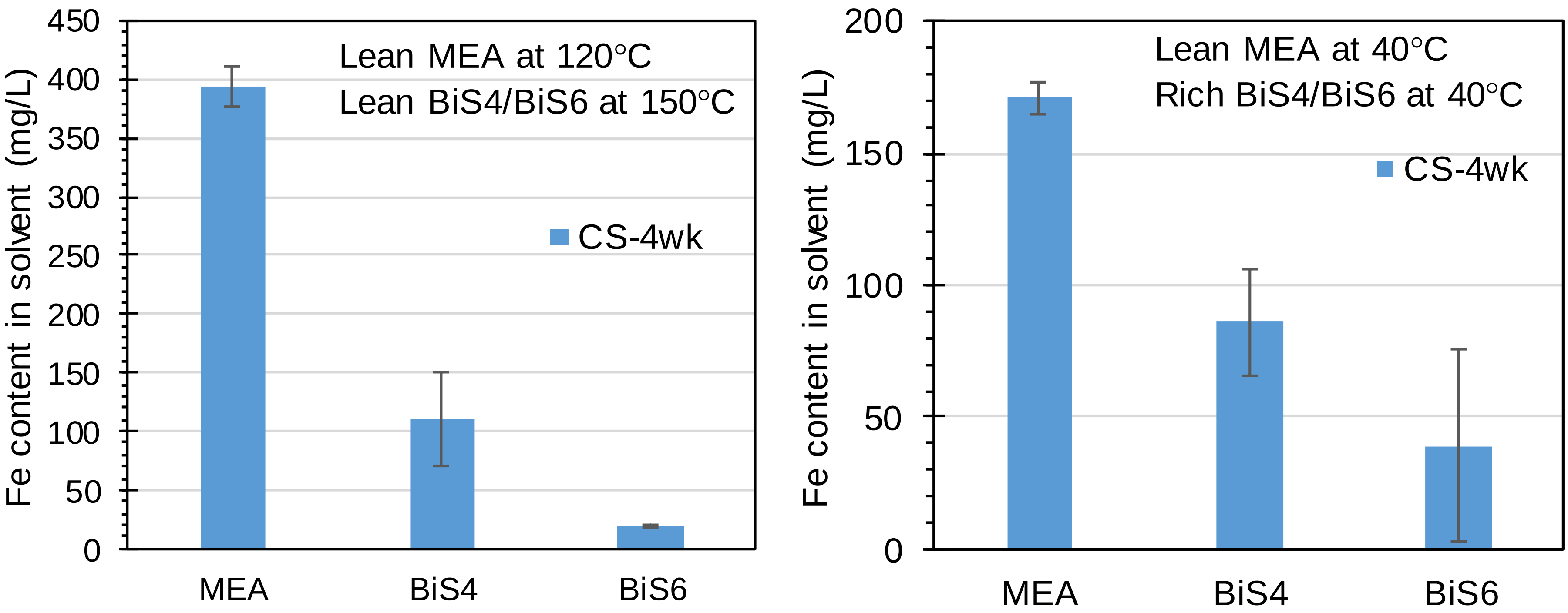
- Slightly darker color showed for CS-C1010 coupons in MEA compared with BiS4 and BiS6 (before glass bead blasting cleaning)
- No visible etching and pitting observed in all tests

Corrosion Rates of Carbon Steel (C1010) in 4 Weeks



- Corrosion rates of CS-C1010: BiS6 < BiS4 < MEA:
  - BiS6 and BiS4 were 2-3 times less corrosive than MEA
- Corrosion rates of SS-316L (1.5-4 µm/y, data not shown) << CS-C1010
  - Little difference observed in SS corrosion rate among 3 solvents

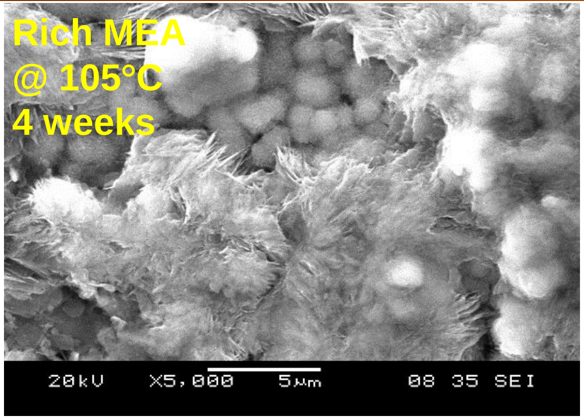
Dissolved Metals in Solvents in 4 Weeks

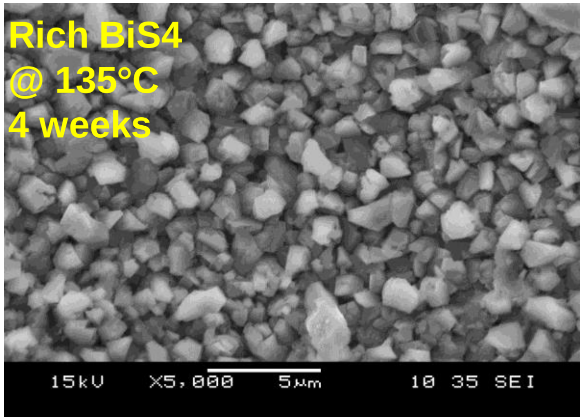


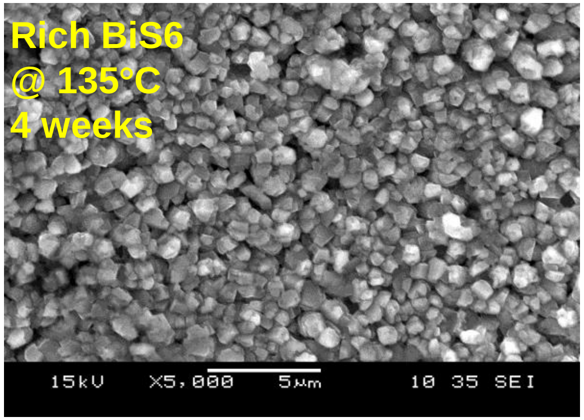
Analysis of dissolved Fe, Cr, Mn, Mo, and Ni with ICP-OES confirmed corrosion rate results:

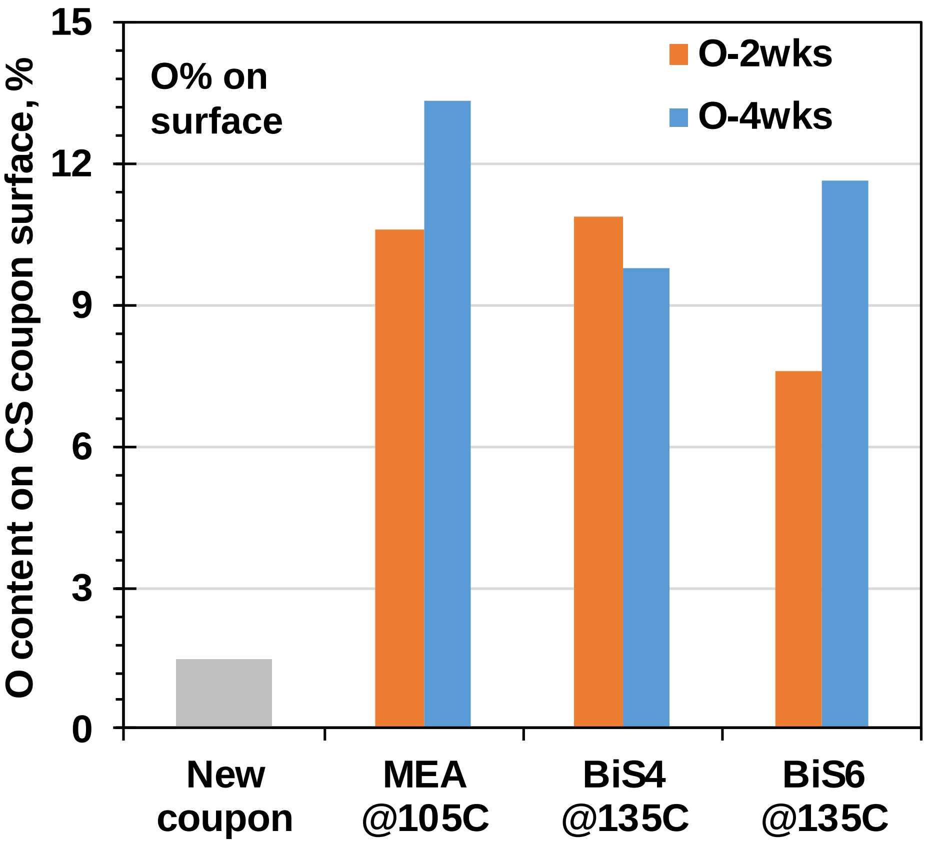
- BiS4 and BiS6 at 150°C less corrosive to CS and SS than MEA at 120°C.
- BiS4 and BiS6 less corrosive to CS than MEA at 40°C

SEM/EDX Analysis of Coupon Surface









- Increase in O% on coupon surface indicates formation of Fe_2O_3 (brown), Fe_3O_4 (black), and/or $FeCO_3$ (brown)

Task 9. TEA Feasibility Study: Summary of Key Results from Previous (BP1) Process Analysis

	BiCAP	DOE Case 12 Rev 2a	Difference vs. Case 12
CO_2 Capture & Compression Total Plant Costs 2007$	**$378 MM**	**$469 MM**	**-19%**
Total Parasitic Demands (MWe)	**176**	**252**	**-30%**
Capture Plant Steam Derate	103	139	-26%
Capture Plant Direct Electrical Derate	39	75	-48%
Power Plant Auxiliary Load	34	38	-10%
Other			
Solvent Make-Up Costs Due to Degradation	$2MM	$1MM	+100%

Energy Performance Analysis for an Updated Process Configuration in BP2

	BiCAP	DOE Case 12 (MEA)
Net Generating Capacity, MWe	**550**	**550**
Gross Generating Capacity, MWe	**700**	**802**
Amount of CO_2 captured, tonne/hr	**478**	**548**
Total Steam Derate, MWe	**71**	**139**
Reboiler/Flash Heat Duty, MWth	278	542
Thermal to Electric Energy, %	25.6	25.6
Direct Electrical Derate, MWe	**44.8**	**75.2**
Compression Duty, MWe	31.5	44.9
Other (Pumps, Fans, etc.), MWe	13.3	30.3
Total Derate for CO_2 Capture, MWe	**116**	**214**
Total parasitic use for entire plant, MWe	**150**	**252**

- Parasitic power use: 16.6% for BiCAP vs. 25.4% for MEA
- Total derate for BiCAP is 43% < MEA

Plan for Future Work in This Project

Project will be completed by 12/31/2018:

- Tests of CO_2 desorption under additional flash/stripping conditions with the laboratory 10 kWe desorption system (by 9/30/18)

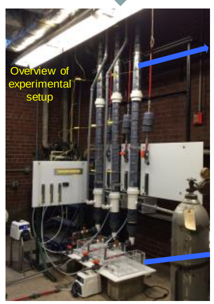
- Task 9. Final techno-economic analysis (by 12/31/18)
  - Update process simulation results and heat & material balance information
  - High-level cost analysis
  - Sensitivity analysis

BiCAP Technology Development Vision

This project to conclude by 12/31/18

Solvent study, Laboratory

Proof-of-Concept
Funding: *UI (Part of Dissertation Research, 2013-2015)*



10 kWe Test, Laboratory

Separate Absorber / Stripper
Funding: *DOE / UI (2015-2018)*

Bench-scale project started 4/6/18)

40 kWe Test, Laboratory & Power Plant Slipstream

Bench Scale Close-Loop Unit
Funding: *DOE / UI (2018-2021)*

0.2-1 MWe, Power Plant /Test Center

Small Pilot
Funding: *DOE / UI / Corporate partners/ State*

10 MWe, Power Plant

Large Pilot
Funding: *DOE / Corporate Partners /State / UI*

Acknowledgements

- **Project Members**

University of Illinois:

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- Kevin O'Brien; Wei Zheng; BK Sharma (ISTC)
- Santanu Chaudhuri (ARI)

Trimeric Corporation:

Ray McKaskle; Katherine Dombrowski, Kevin Fisher; Andrew Sexton; Darshan Sachde

- **DOE/NETL Project Manager:** Andrew Jones