Development and Bench-Scale Testing of a Novel Biphasic Solvent-Enabled Absorption Process for Post-Combustion Carbon Capture (DE-FE0031600)

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Project Overview (1)

Objectives:

- Design, fabricate, and test an integrated 40 kWe bench-scale unit for post-combustion carbon capture, and
- Demonstrate the technology performance progressing toward achieving DOE's Transformational Capture Goals

Participants:

- University of Illinois:
  - Prairie Research Institute (ISGS & ISTC): Solvent & process development, testing, and evaluations
  - Facilities & Services: Bench-scale unit installation
  - Abbott Power Plant: Host site
- Trimeric Corporation: Process design/equipment specs; TEA support
- ITG Henneman Engineering: Detailed engineering design; startup support

Project Overview (2)

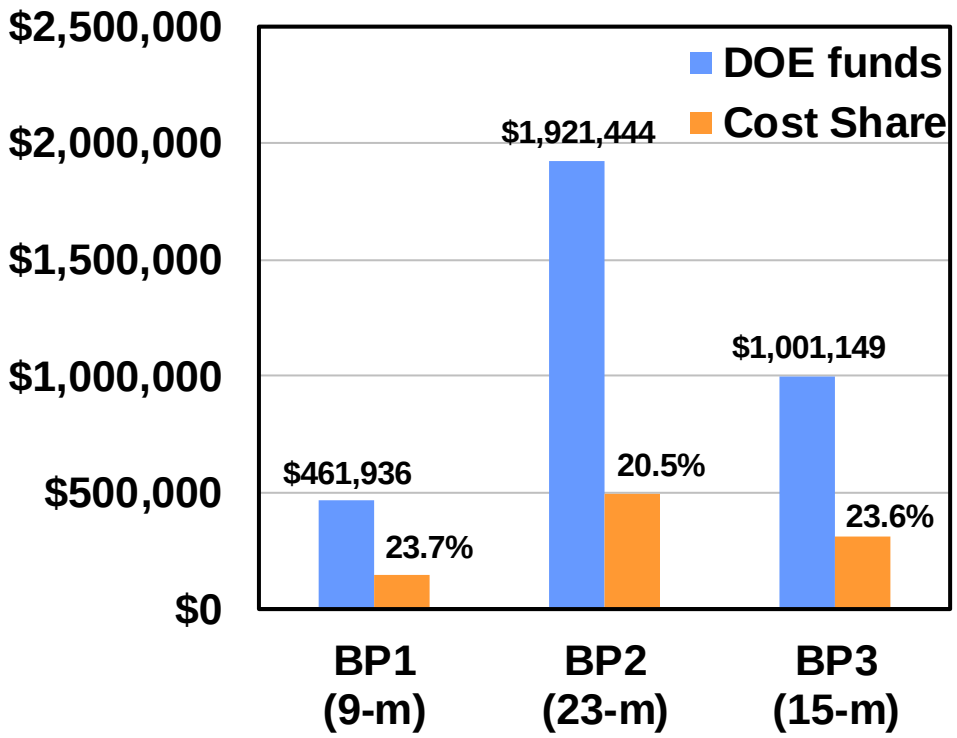
Project Duration: 4/6/18–8/31/22

- BP1: 9 mon (Apr 2018 – Dec 2019)
- BP2: 23 mon (Jan 2019 – Nov 2020)
- BP3: 15 mon (Dec 2020 – Aug 2022)*

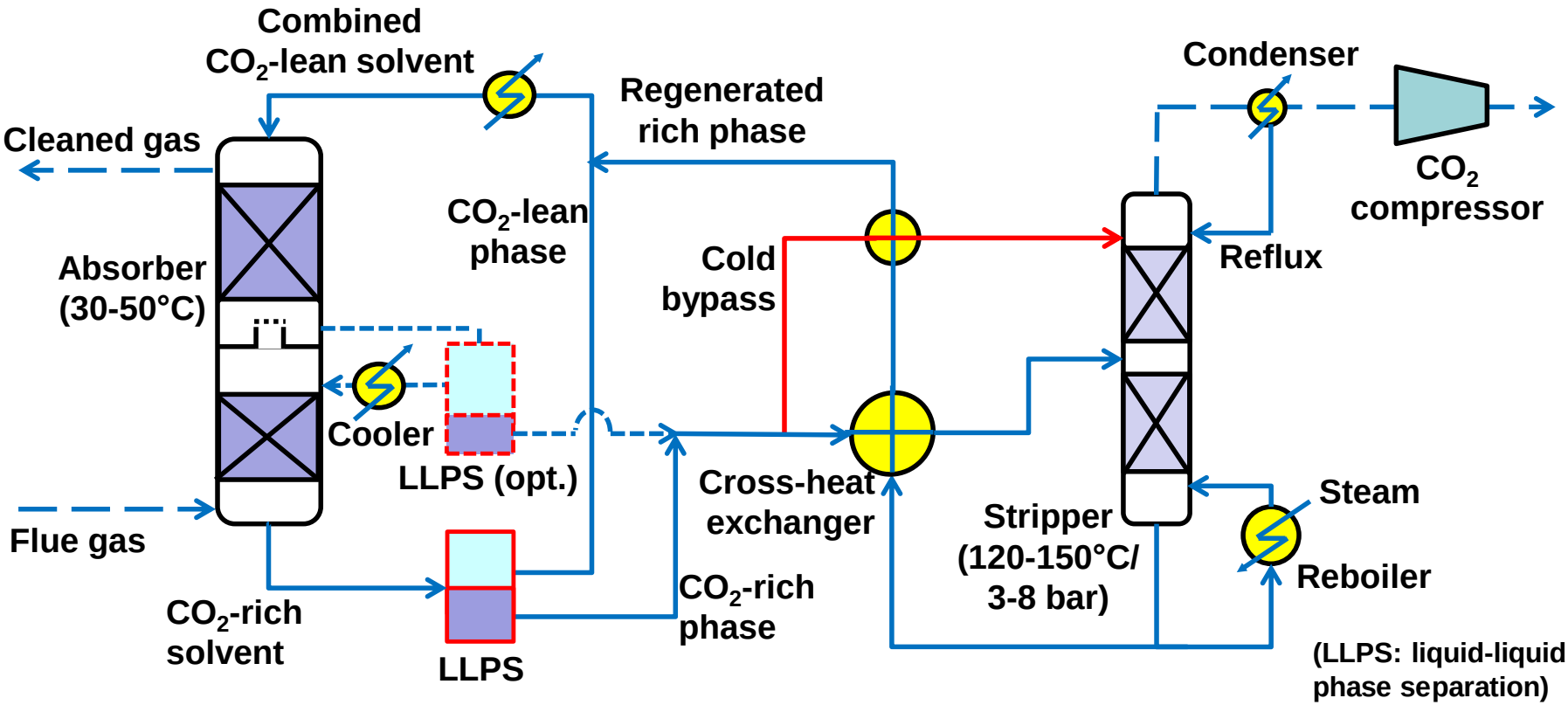
(* Currently in a request for a 6-mon extension to perform additional testing)

Funding Profile:

- DOE funding of $3,384,529
- Cost share (in-kind and cash) of $949,741 (~22%)



Technology Background: Biphasic CO_2 Absorption Process (BiCAP)



Impact on absorber:

- Higher absorption rate compared with MEA
- Applicable for high-viscosity solvents via multi-stage LLPS to enhance rate

Impact on stripper:

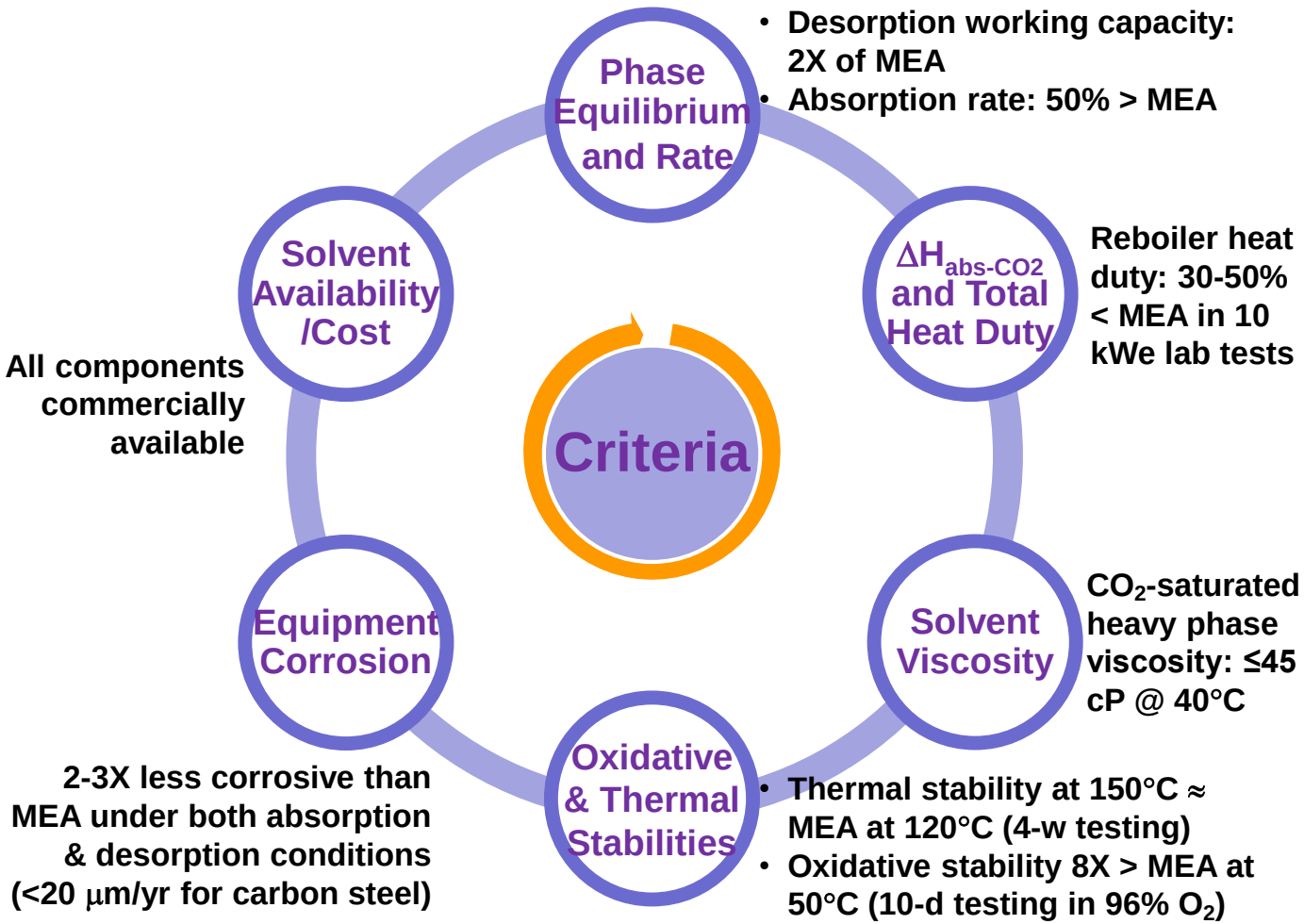
- Reduced solvent mass to stripper leads to low sensible heat use and small equipment size
- Enriched CO_2 loading leads to high stripping pressure (i.e., low stripping heat and CO_2 compression work)
- Cold bypass further reduces stripping heat

Novel Biphasic Solvents Developed from Previous Work

Biphasic solvents:

- Tunable partitions of volume and species in two liquid phases
- CO_2 loading highly concentrated (>98%) in rich phase
- Water-lean (<30% water)

Two top-performing solvents identified from a previous screening study of ~80 solvents



Progression of BiCAP Technology Development

- Lab proof-of-concept studies of biphasic solvents
- Funding: UI (Graduate dissertation research)

- Solvent screening & characterization (~80)
- 10 kWe lab scale: Separate absorber & stripper testing
- Funding: DOE / UI

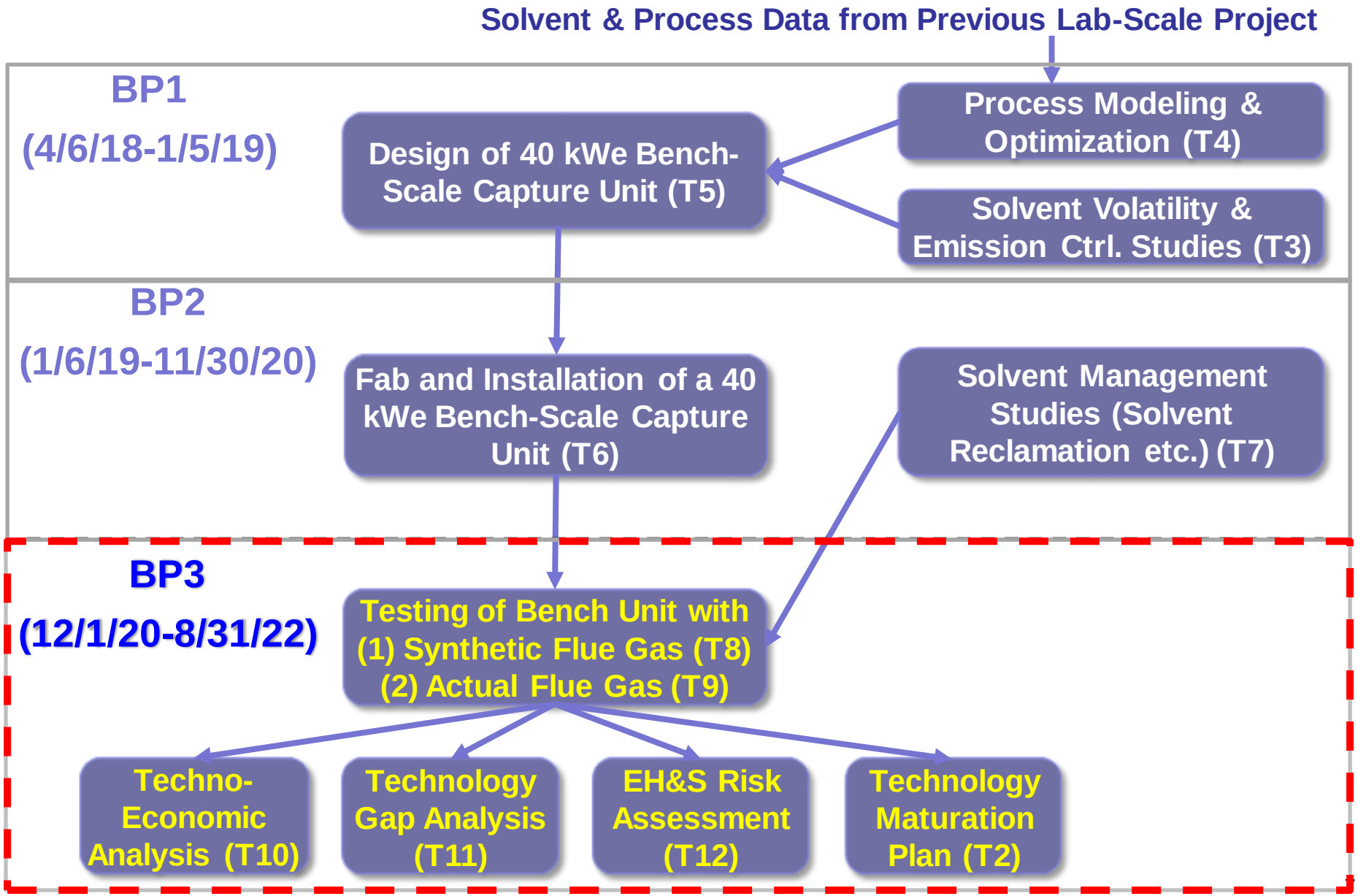
- 40 kWe bench scale: Closed-loop system at Abbott Power Plant
- Solvent handing studies (aerosol emissions, reclamation, etc.)
- Funding: DOE / UI

Jan 2013 — Jul 2015 — Apr 2018 — Aug 2022

Prior Work

Current Project

Technical Approach / Project Scope

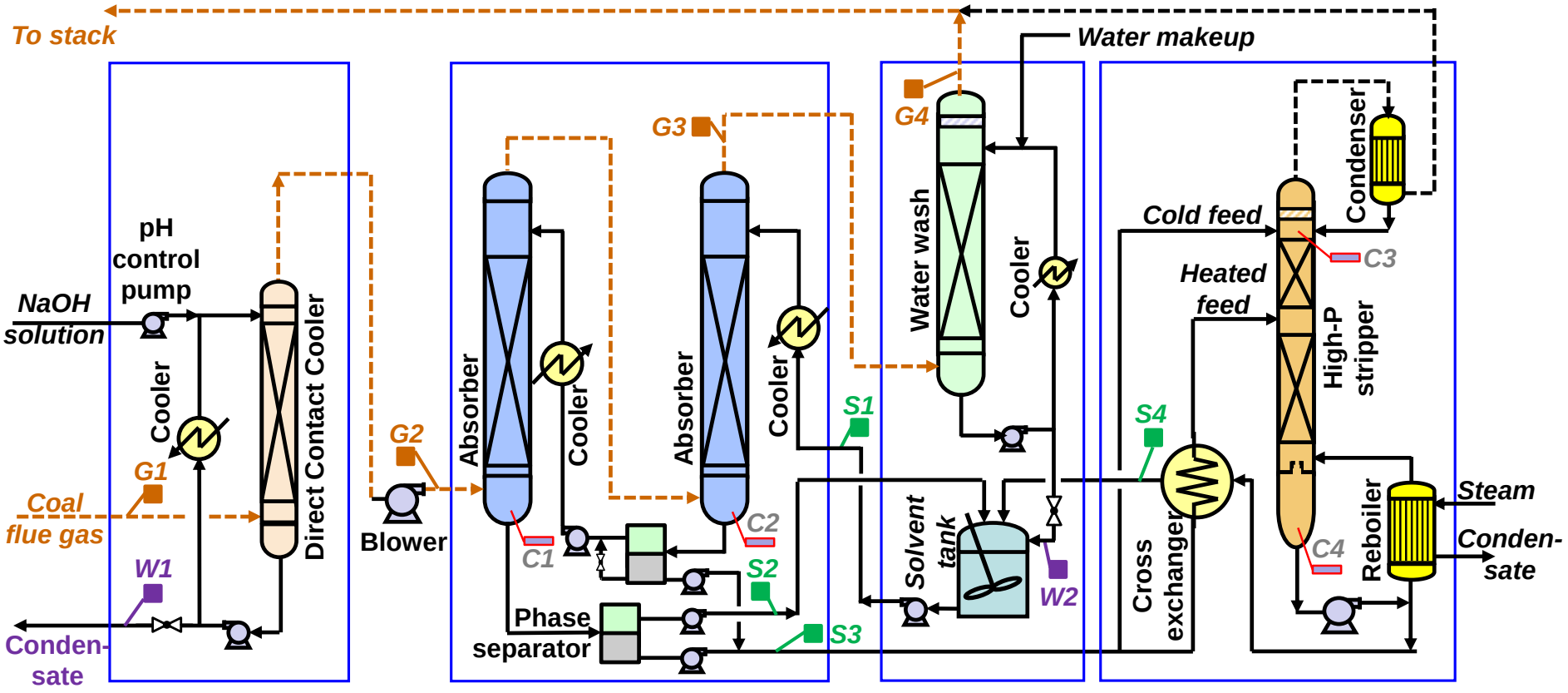


Main Milestones and Success Criteria

	Basis for Decision/Success Criteria
BP1 (4/6/18-1/5/19)	✓ Solvent emissions (vapor & aerosols) and mitigation assessed ✓ Power plant Host Site Agreement issued ✓ Completion of 40 kWe bench unit design
BP2 (1/6/19-11/30/20)	✓ Identify suitable options for reclamation of biphasic solvents ✓ Fabrication and installation of 40 kWe bench-scale unit
BP3 (12/1/20-8/31/22)	✓ **7-mon parametric testing with synthetic flue gas completed in May-Dec 2021** ✓ **2-week continuous testing with a slipstream of coal flue gas at Abbott Power Plant completed in Jan-Feb 2022** ✓ **TEA studies performed and a topical report submitted in June 2022** **(Demonstrated continuous operation with a heat duty of ≤2,200 kJ/kg of CO_2 and stripping pressure of ~65 psia)**

Additional 3-week slipstream testing (not part of the original project scope) is currently under planning

Specs of the 40 kWe Bench-Scale BiCAP Unit



Flue gas cooling/ polishing treatment

2 absorption columns: Each with 8-in ID × 15-ft packing & a total height ~22'-2"

1 water wash column: 8-in ID x 10-ft packing & a total height of ~16'-0"

1 stripping column: 4-in ID × 15-ft packing & a total height ~26'-6"


Abbott Stack
Vent
40 kWe Biphasic Skid at Abbott Power Plant
Water Wash
Stripper
Absorbers
Analytical/ Control Trailer
DCC
PLC/ MCC
Blower
Surge Tank

Translating Lab to Bench Scale Phase Separator

- Phase separation based on static settling with a density difference in two liquid phases
- Level of liquid-liquid interface automatically stabilizes based on a static pressure balance

Lab-Scale Phase Separator

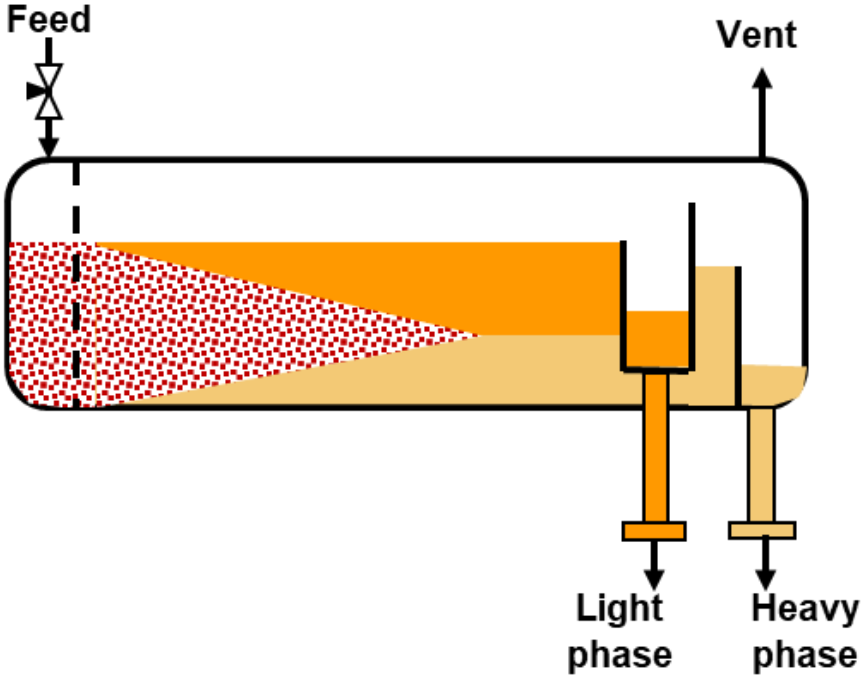
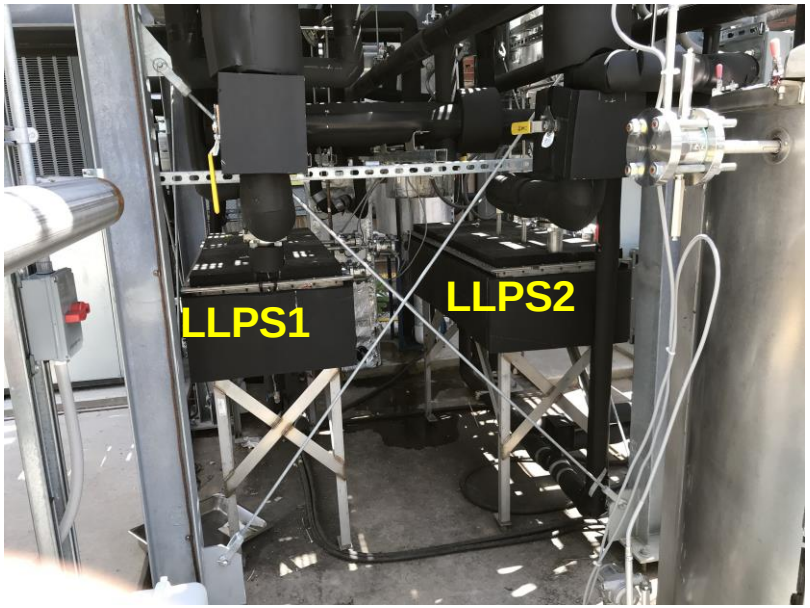


Illustration of Phase Separation Operation



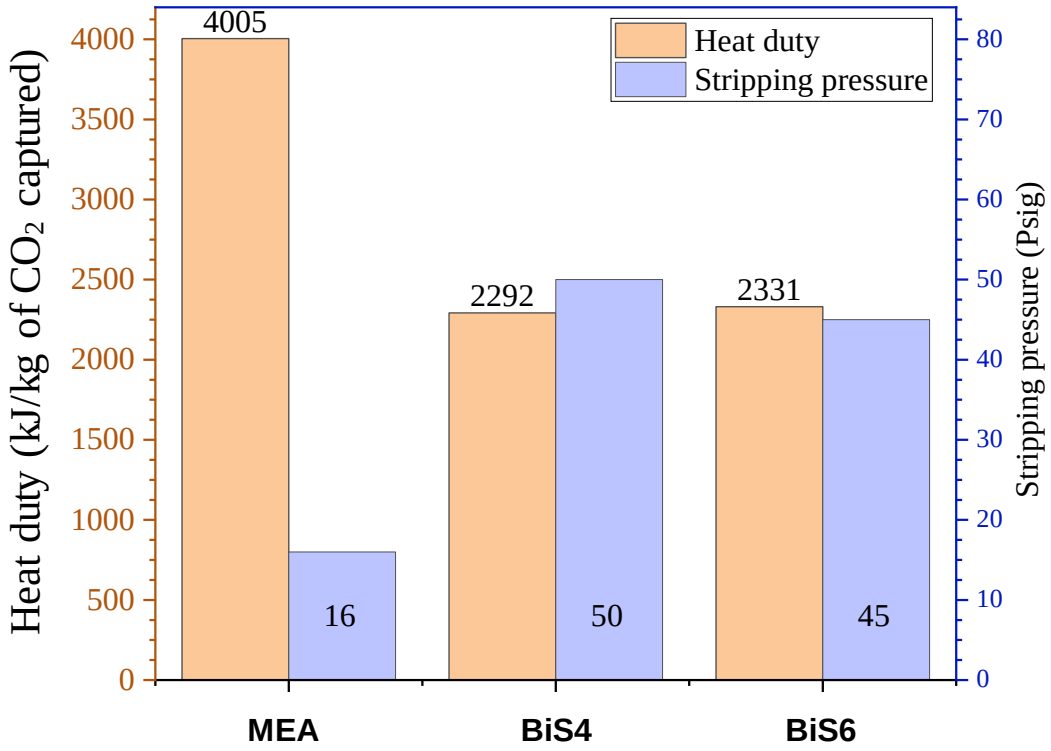
Bench-Scale Separator at Abbott Plant

7-Month Parametric Tests for MEA, BiS4 and BiS6 Solvents with Synthetic Flue Gas (CO_2 + Air), May to Dec 2021

Operating parameters examined included:

- Gas flow rate
- CO_2 vol% in flue gas
- Solvent flow rate
- L/G ratio
- CO_2 loadings
- % of cold solvent feed
- Stripping P
- Striping T

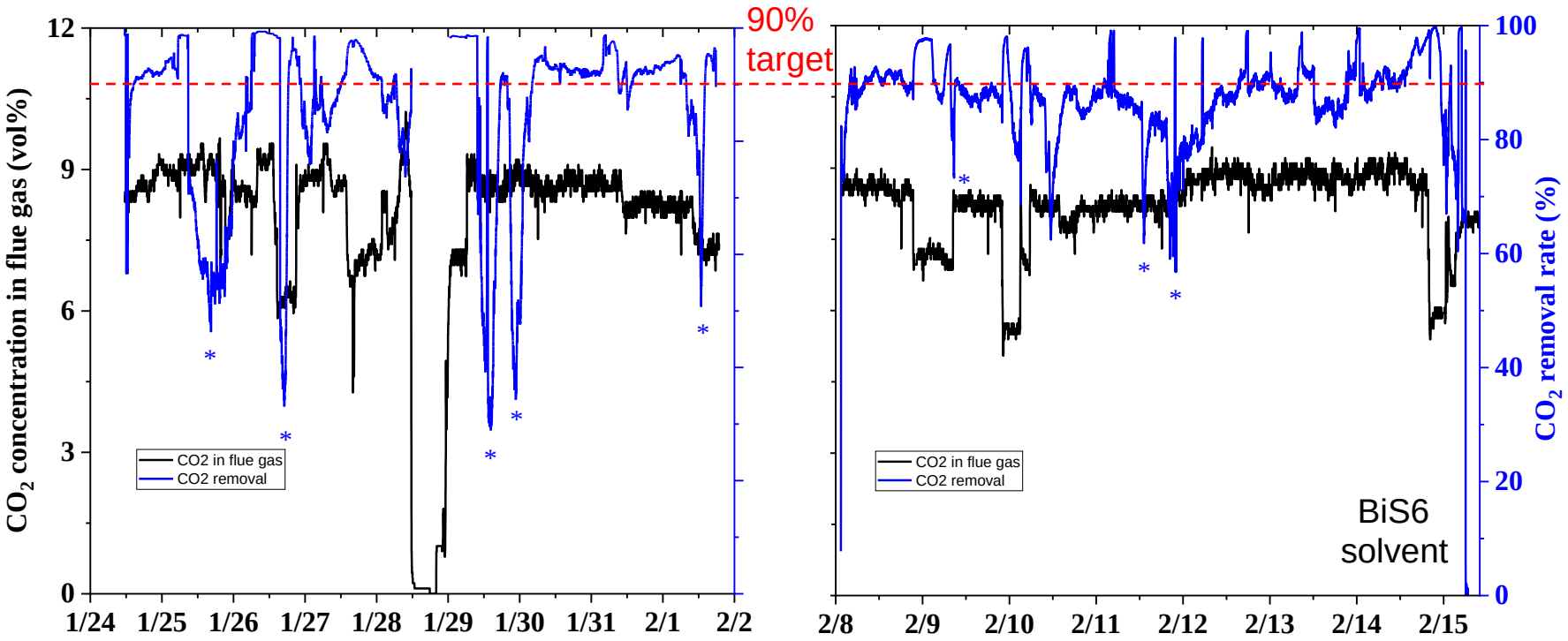
Comparison of BiS4, BiS6 and MEA at representative operating conditions



At representative conditions:

- Heat duty of either BiS4 or BiS6 was ~40% < MEA
- Higher stripping pressure for BiS4 or BiS6 led to a lower CO_2 compression work requirement

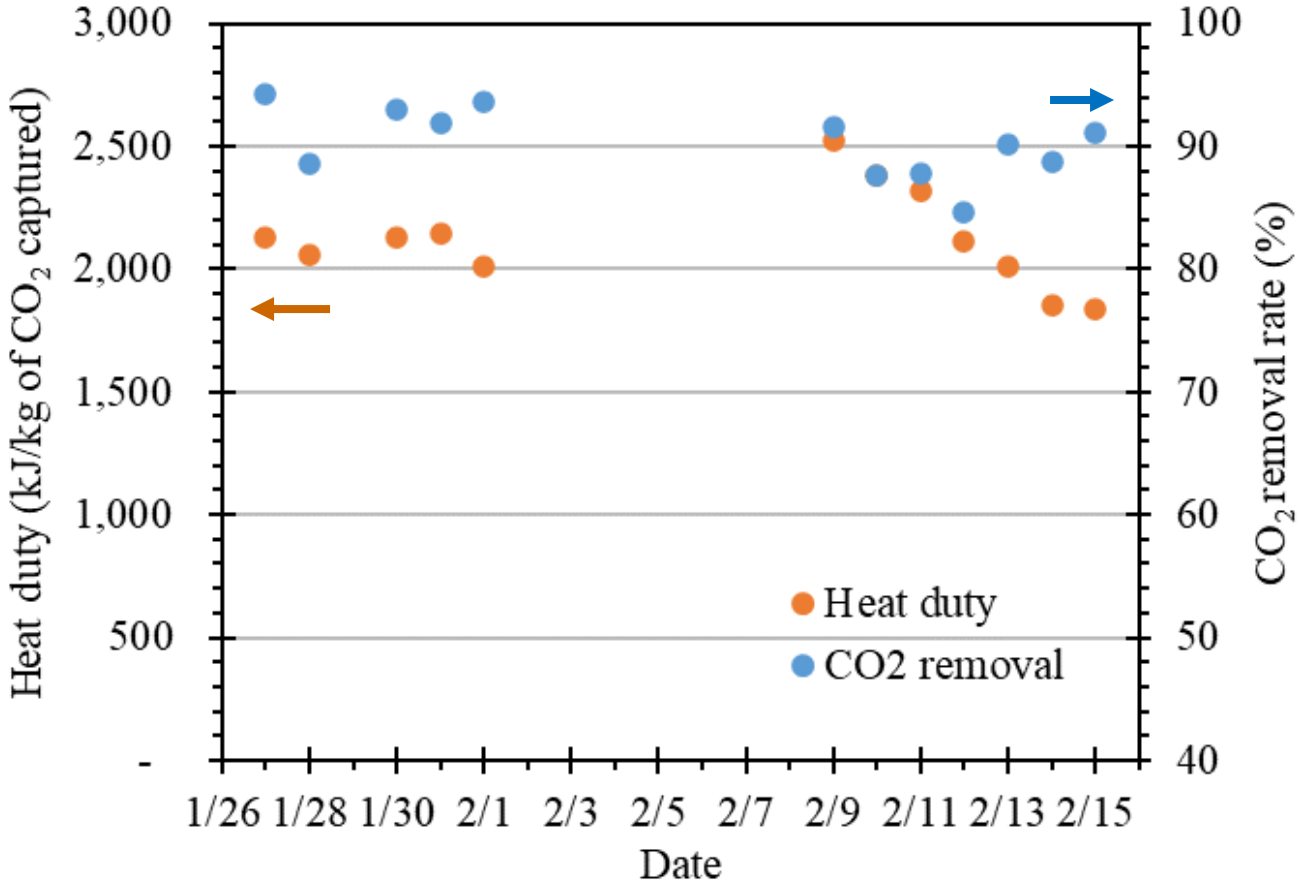
2-Week Continuous Testing with a Slipstream of Abbott Coal Flue Gas, Jan to Feb 2022



(* Drops in CO_2 removal rate caused by steam supply interruption during these periods)

- CO_2 concentration in Stoker boiler coal flue gas: 6.5-9.0 vol% (wet basis)
- CO_2 removal fluctuated within 85-95% (90% removal is project target)
- 95% CO_2 removal achievable via adjusting operating conditions

Daily Average CO_2 Removal Rate and Heat Duty During the 2-Week Slipstream Testing



- CO_2 removal rate within 85-95% during the two weeks
- Heat duty ranged from 1,838 to 2,527 kJ/kg of CO_2 captured (based on a cross exchanger temperature approach of 9 °F)
  - Two-week average heat duty of 2,183 kJ/kg of CO_2 captured

Energy Comparison of BiCAP vs. DOE Base Cases

	Units	DOE Case B12A (SCPC, No Capture)	DOE Case B12B (Cansolv)	BiCAP (with BiS6)
Energy requirements				
Net Electricity Produced	MWe	650	650	650
HHV Net Plant Efficiency, %	%	40.3%	31.5%	33.2%
CCS De-rate				
Compression & Dehydration	MWe	0	44.4	29.1
Pumps, Blower, etc.	MWe	0	27.3	21.9
Regeneration Steam De-rate	MWe	0	105.4	90.6
Total De-rate by CCS	MWe	0	177.1	141.6
Base Plant Auxiliary Load	MWe	35.1	48.3	40.3

- Capture de-rate for BiCAP: ~20% < Case B12B (Cansolv)

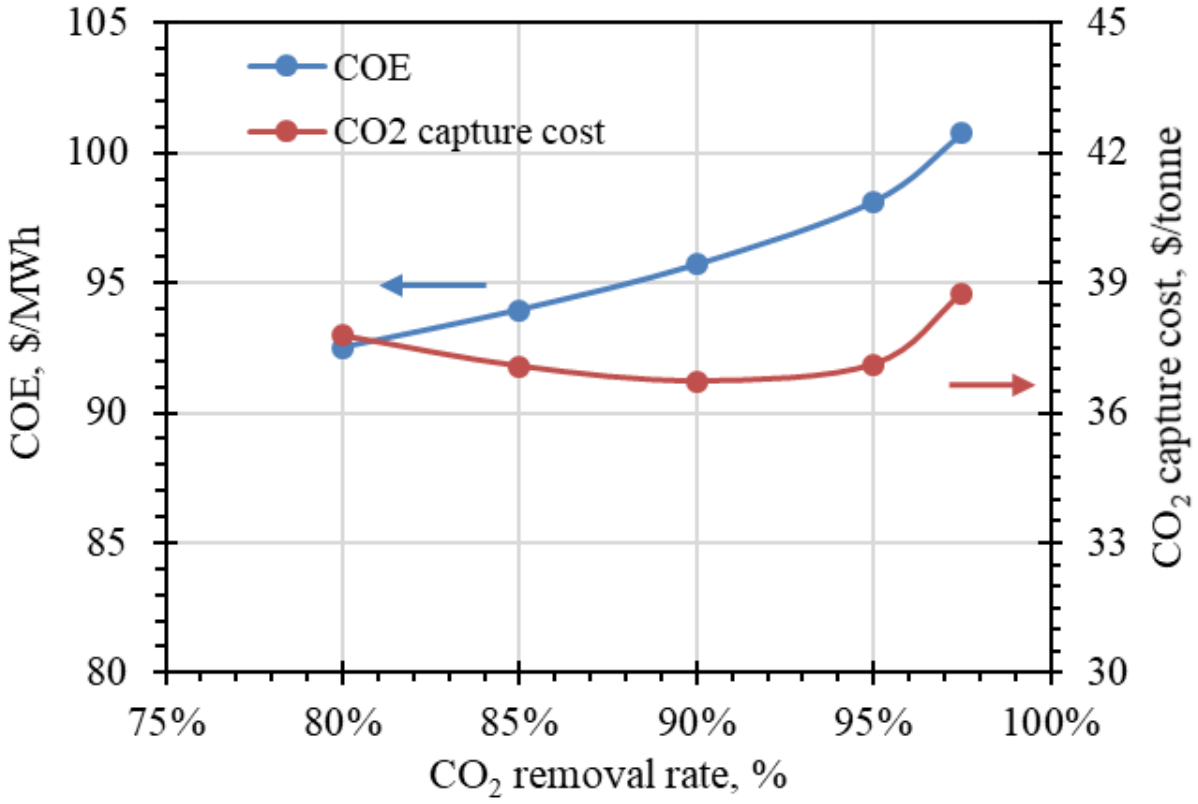
Cost Comparison of BiCAP vs. DOE Base Cases (2018$)

Item	Unit	DOE Case B12A (no capture)	DOE Case B12B (Cansolv)	BiCAP with BiS6 solv.
Net power output	MWe	650	650	650
Capital costs				
Total Plant Cost (TPC)	$/kW(net)	2,099	3,800	3,376
Total Overnight Costs (TOC)	$/kW(net)	2,582	4,654	4,180
Total As-Spent Costs (TASC)	$/kW(net)	2,981	5,372	4,824
O&M costs				
Total Fixed Operating Costs	MM$/year	45.9	78.1	70.4
Total Variable Operating Costs	MM$/year	37.4	67.8	59.9
Fuel	MM$/year	91.3	116.7	111.2
Cost of Electricity (COE)				
COE - No TS&M	mills/kWh	64.4	105.3	95.3
COE - Total (including TS&M)	mills/kWh	64.4	114.3	104.2
Increase in COE - No TS&M	%	n/a	63.5%	48.0%
Increase in COE - Total	%	n/a	77.5%	61.8%
Cost of CO_2 Capture - No TS&M	$/tonne	n/a	45.73	36.73
Cost of CO_2 avoidance – W/TS&M	$/tonne	n/a	73.64	58.92

BiCAP compared to Case B12B (Cansolv):

- COE reduced by 9.5%; CAPAX reduced by 10.2%
- CO_2 capture cost (i.e., breakeven sales price) reduced by 19.7%

Sensitivity Analysis for CO_2 Removal Rate



(CO_2 removal rate varied by varying L/G ratio)

- COE increased by 2.5% from 90% to 95% CO_2 removal
- Cost of CO_2 capture was minimum at ~90% removal; No substantial increase of cost of CO_2 capture from 90% to 95% CO_2 removal

Plans for Future Work in This Project

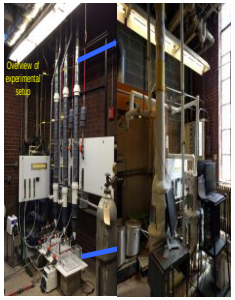
Remaining work in the following 3-6 months:

- Additional Slipstream Testing at Abbott Power Plant (for ~3 weeks)
- EH&S Risk Assessment
- Technology Gap Analysis
- Technology Maturation Plan

Plans for Next Stage Development after This Project

Current Project

40 kWe Testing, Coal-Fired Power Plant Slipstream



10 kWe Testing, Laboratory

Bench Scale Close-Loop Unit
Funding: *DOE / UI (2018-2022)*

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

Solvent study, Laboratory

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

Small pilot (40 kW-0.5 MW), NGCC Plant

Small pilot/pilot, industrial sources (e.g., waste-to-energy, cement, steel)

Pilot (0.5-1 MWe), Coal-Fired Power Plant /Test Center

Summary

- Biphasic solvents developed based on multiple practical criteria for post-combustion CO_2 capture
- Testing of a 40 kWe unit at Abbot Power Plant:
  - Continuous operation validated with coal slipstream testing in Mid-West wintertime
  - ~90% CO_2 removal (95% CO_2 removal achievable)
  - Average heat duty of 2,183 MJ/tonne of CO_2 captured
- BiCAP shows techno-economic advantages over DOE base case
  - Parasitic power loss reduced by ~20.0%
  - CO_2 capture cost reduced by ~19.7% ($36.7/tonne)
- Next step: Small pilot/pilot testing for NGCC, industrial sources, and coal boilers

Acknowledgements

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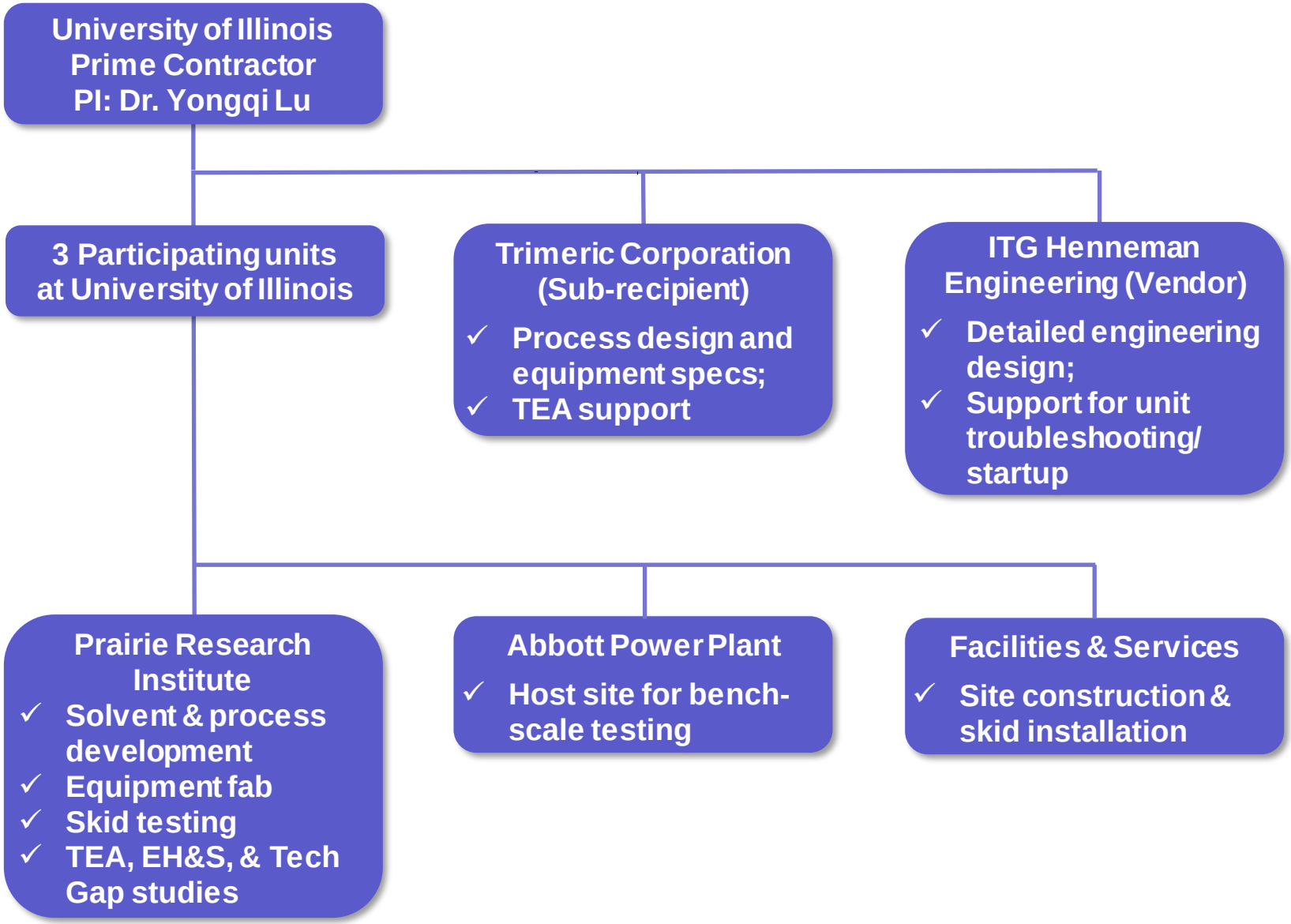
- **Project Team Members**
  - ✓ **University of Illinois:** Paul Nielsen; Hong Lu; Hafiz Salih; Justin Mock; Luke Schideman; Eric Roman; Drew Feldstein; Kevin O'Brien; Wei Zheng; Sarmila Katuwal; Scott Prause; Bajio Varghese Kaleeckal; Ryan Larimore; Jason Dietsch; Stephanie Brownstein; Vinod Patel; Mike Larson; Mike Brewer; Josh Rubin; Mohamed Attalla
  - ✓ **Trimeric Corporation:** Ray McKaskle; Katherine Dombrowski; Kevin Fisher
  - ✓ **ITG-Henneman:** David Kryszczynski; Darren Timlin

Appendix 1. Organization Chart



Appendix 2. Gantt Chart

ID	Task Name	Start	Finish	Resource Names
1	**Task 1.0 - Project Management and Planning**	**4/1/18**	**2/28/23**	**UIUC**
2	1.1 - Project Monitoring and Control	4/2/18	2/28/23	UIUC
3	1.2 - Briefings and Reports	4/2/18	2/28/23	UIUC
4	a - Updated Project Management and Planning	4/30/18	4/30/18	
5	b - Project kickoff meeting	6/30/18	6/30/18	
6	**Task 2.0 - Developing & Implementing a Technology Maturation Plan**	**4/1/18**	**2/28/23**	**UIUC**
7	c - Technology Maturation Plan prepared	6/30/18	6/30/18	
8	**Task 3.0 - Studies of Solvent Volatility and Losses**	**4/1/18**	**12/31/18**	**UIUC**
9	3.1 - Solvent Volatility Measurement	4/1/18	9/30/18	UIUC
10	3.2 - Testing of Solvent Losses in a Laboratory Absorption Column	7/1/18	12/31/18	UIUC
11	d - Volatility measurement and preliminary results of water wash performance obtained	9/30/18	9/30/18	
12	**Task 4.0 - Modeling & Optimization of Biphasic CO2 Absorption Process**	**4/1/18**	**9/30/18**	**UIUC**
13	4.1 - Process Modeling and Optimization	4/1/18	5/15/18	UIUC
14	4.2 - Bench-Scale Unit Process Simulations	5/16/18	6/30/18	UIUC
15	e - Optimal process configuration identified	9/30/18	9/30/18	
16	**Task 5.0 - Design of Bench-Scale Capture Unit**	**7/1/18**	**12/31/18**	**Trimeric**
17	5.1 - Design of Bench-Scale Capture Unit	7/1/18	11/30/18	Trimeric
18	5.2 - Design Review and Approval	12/1/18	12/31/18	Trimeric
19	f - Bench-scale equipment design completed	12/31/18	12/31/18	
20	g - Host Site Agreement obtained	12/31/18	12/31/18	
21	**Task 6.0 - Fabrication and Installation of Bench-Scale Capture Unit**	**1/1/19**	**11/30/20**	**UIUC**
22	6.1 - Solicitation and Selection of a Manufacturing Vendor	1/1/19	6/30/19	UIUC
23	6.2 - Fabrication and Installation of Bench-Scale Capture Unit	7/1/19	11/30/20	UIUC
24	6.3 - Host Site Air Emission EH&S Modeling Assessment	4/1/19	9/30/19	UIUC
25	h - Air emission modeling assessment completed	9/30/19	9/30/19	
26	i - Bench-scale unit fabricated and installed	11/30/20	11/30/20	
27	**Task 7.0 -Solvent Management Studies**	**1/1/19**	**12/31/19**	**UIUC**
28	7.1 - Solvent Degradation and Reclamation Study	1/1/19	9/30/19	UIUC
29	7.2 - CO2 Loading Correlation and In-Situ Measurement	7/1/19	12/31/19	UIUC
30	j- Solvent reclamation option identified	9/30/19	9/30/19	
31	**Task 8.0 - Parametric Testing of Bench-Scale Unit with a Simulated Flue Gas Stream**	**12/1/20**	**11/30/21**	**UIUC**
32	8.1 - Commissioning	12/1/20	2/28/21	UIUC
33	8.2 - Parametric Testing of the Bench-Scale Unit	3/1/21	11/30/21	UIUC
34	k- Bench-scale unit commissioned	2/28/21	2/28/21	
35	l - Parametric testing of bench-scale unit completed	11/30/21	11/30/21	
36	**Task 9.0 - Testing of Bench-Scale Capture Unit at a Power Plant**	**12/1/21**	**12/31/22**	**UIUC**
37	9.1 - Test Preparation	12/1/21	1/15/22	UIUC
38	9.2 - Bench-Scale Testing with Actual Flue Gas	1/16/22	2/15/22	UIUC
39	Additional Bench-Scale Testing with Actual Flue Gas	11/1/22	11/30/22	UIUC
40	m- Field test plan prepared	1/15/22	1/15/22	
41	n- Field testing with a slipstream of coal combustion flue gas completed	2/15/22	2/15/22	
42	**Task 10.0 - Techno-Economic Analysis**	**1/1/22**	**12/31/22**	**UIUC,Trimeric**
43	10.1 - Process Analysis and Updating Mass & Energy Balance Calculations	1/1/22	3/31/22	UIUC
44	10.2 - Techno-Economic Analysis	4/1/22	6/30/22	UIUC,Trimeric
45	o - Techno-Economic Analysis topical report completed	6/30/22	6/30/22	
46	p - State-Point Data Table updated	12/31/22	12/31/22	
47	**Task 11.0 - Technology Gap Analysis**	**7/1/22**	**12/31/22**	**UIUC**
48	q - Technology Gap Analysis topical report completed	12/31/22	12/31/22	
49	**Task 12.0 - Environmental Health and Safety Risk Assessment**	**7/1/22**	**12/31/22**	**UIUC**
50	r - Environmental Health & Safety Risk Assessment topical report completed	12/31/22	12/31/22