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

Technology Background

Scope of Work/Technical Approaches

Progress and Current Status

Plan for Future R&D and Scale-Up

Objectives

- Advance the development of biphasic solvents and absorption process from lab- to bench-scale
- Design, fabricate and test an integrated 40 kWe bench-scale capture unit with simulated and real coal flue gases
- Demonstrate the technology progressing toward achieving DOE's Transformational Capture goals

Participants and Major Roles:

- Illinois State Geological Survey:
  Solvent & process development; Oversight of equipment fabrication & assembly; Bench tests
- Illinois Sustainable Technology Center:
  Chemical analysis for tests; EH&S study
- Trimeric Corporation:
  Equipment specs and design; TEA study

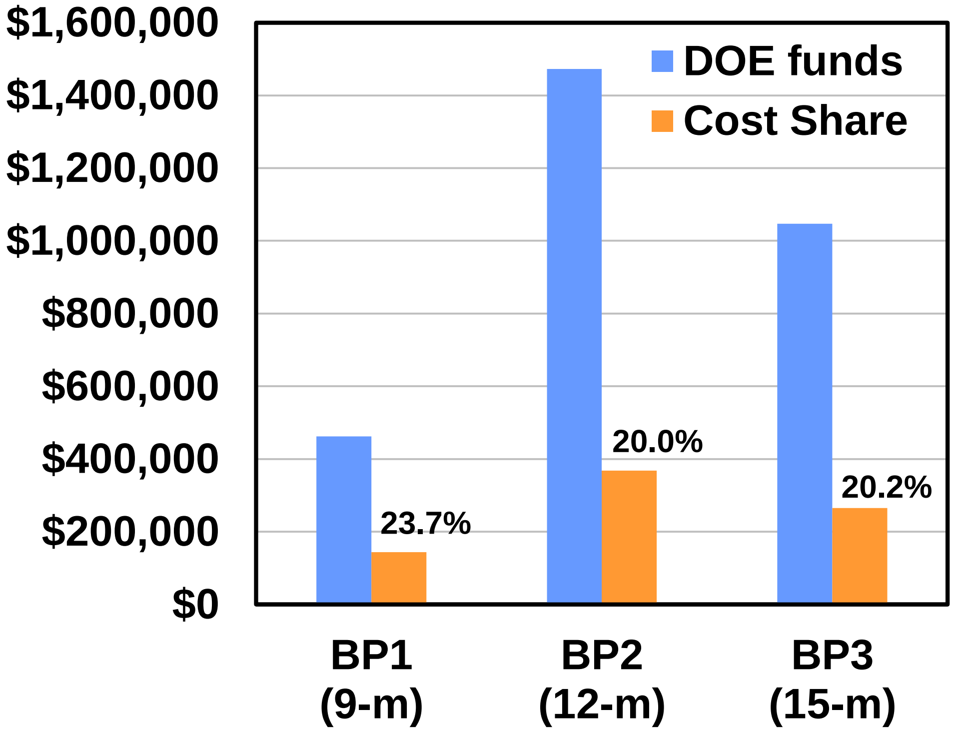
Project Duration and Budget

Project duration: 36 mon (4/6/18–4/5/21)

- BP1: 9 mon (4/6/18-1/5/19)
- **BP2: 12 mon (1/6/19-1/5/20)**
- BP3: 15 mon (1/6/20-4/5/21)

Funding Profile:

- DOE funding of $2,981,778
- Cost share (in-kind & cash) of $776,896 (20.7%)



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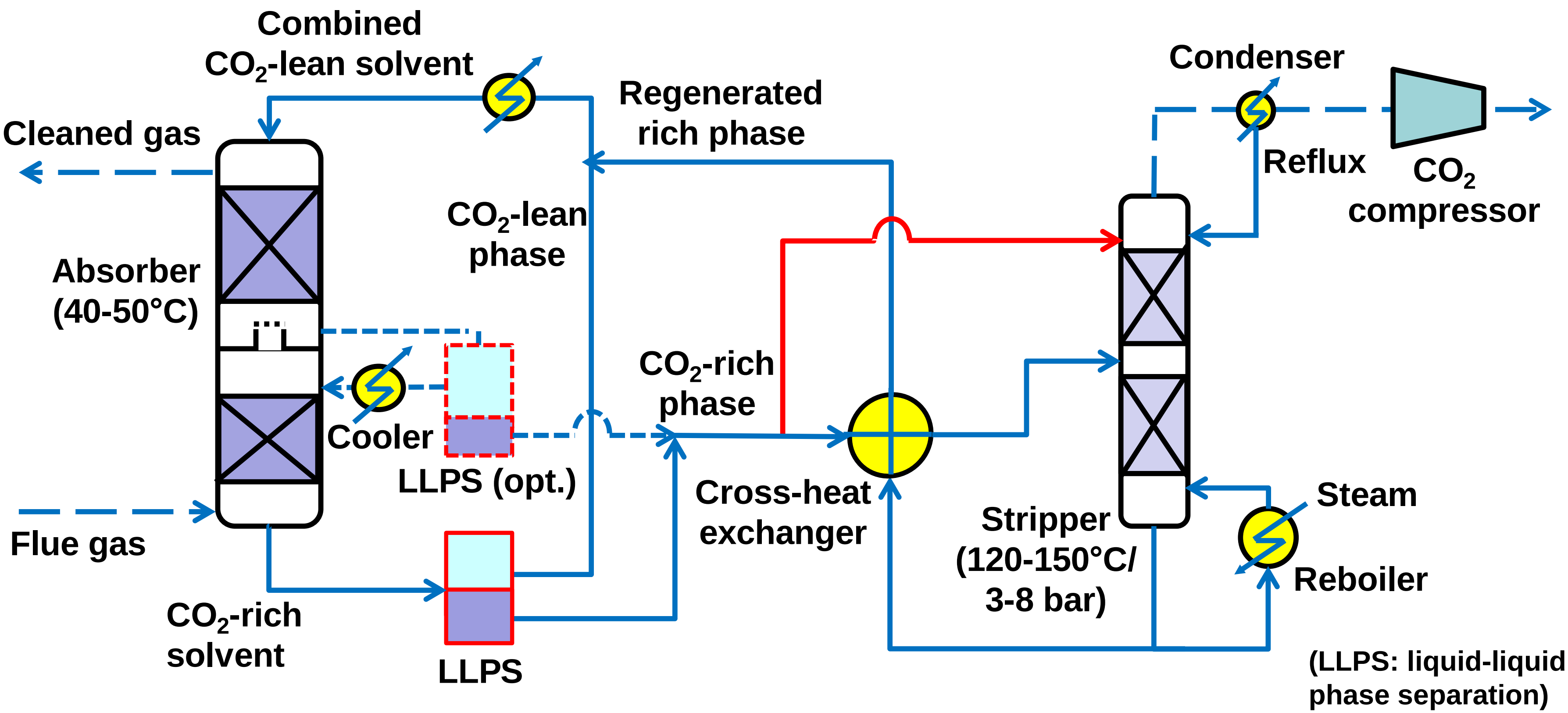
Biphasic CO_2 Absorption Process (BiCAP)



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)

Impact on absorber:

- Applicable for high-viscosity solvents via multi-stage LLPS to enhance rate

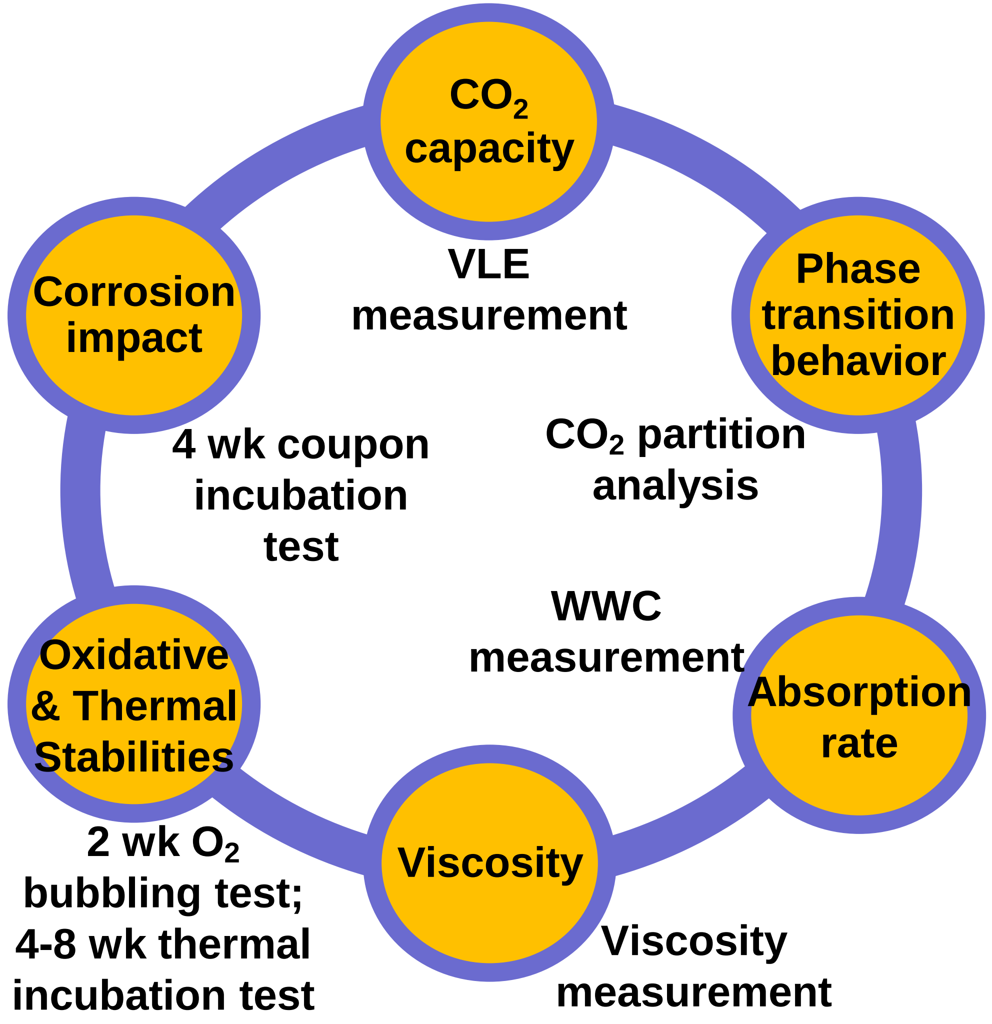
Novel BiCAP Solvents

Water-lean aqueous/organic amine blends:

- Tunable phase transition behavior (e.g., vol.% and loading partitions)
- In aqueous form suitable for humid flue gas application

Lab screening tests of ~80 solvents based on multiple criteria:

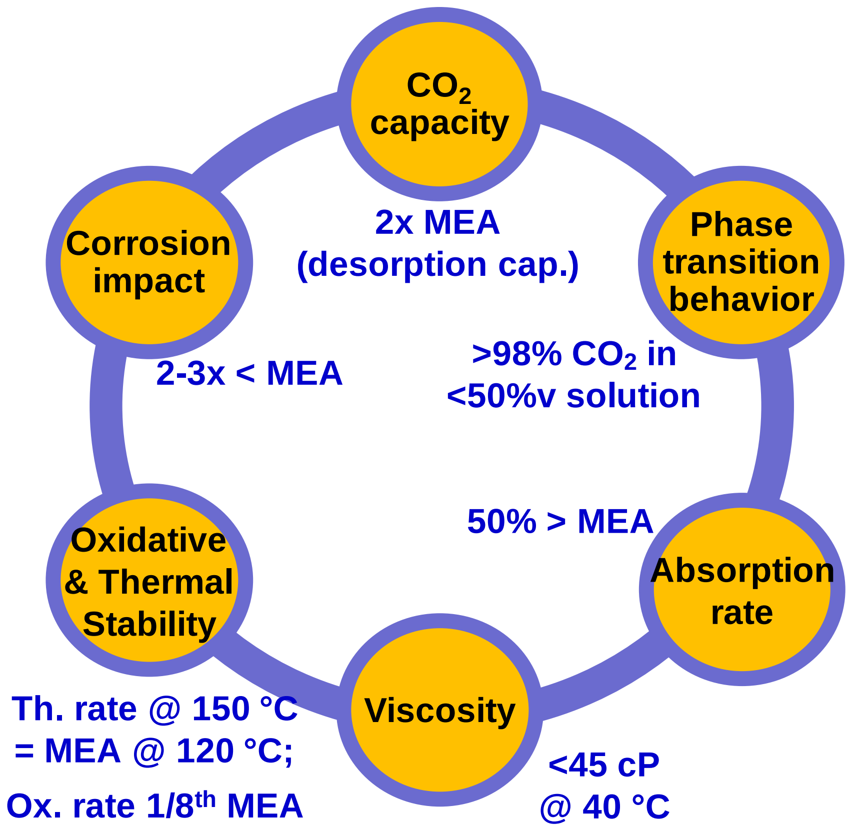
- 2 identified meeting all criteria (BiCAP-1 and BiCAP-2)



Lab experiments for biphasic solvent screening conducted in previous project

Features of BiCAP Solvents and Process

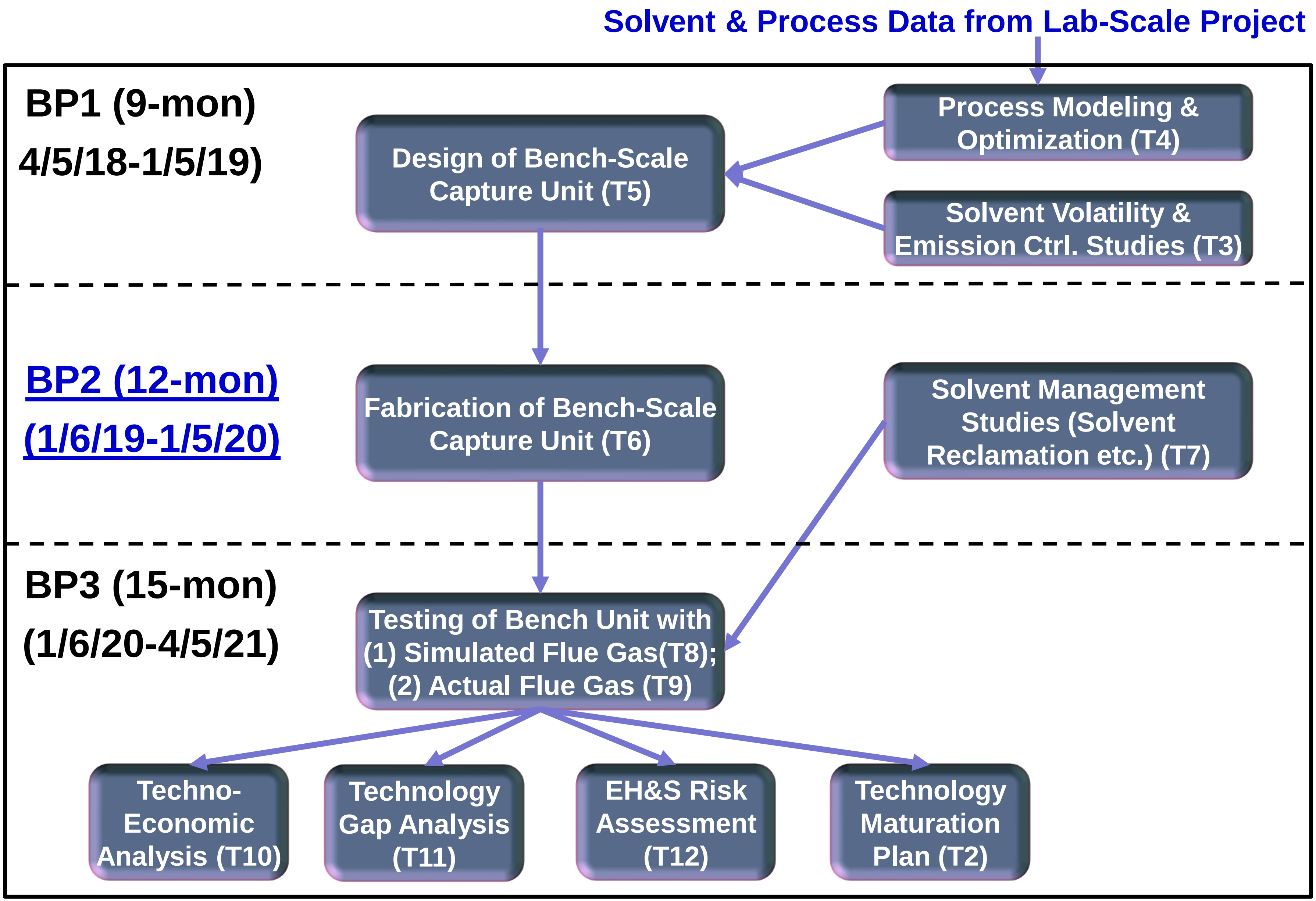
Two top-performing BiCAP solvents developed in previous project:



Lab-scale 10 kWe absorption and stripping column tests conducted in previous project:

- *Absorption rate:*
  50% > MEA under respective operating conditions
- *Reboiler heat duty:*
  35-45% < MEA under respective stripping conditions
- *Stripping pressure*:
  ~6 bar (max. ~8.5 bar)

Project Scope of Work



Main Success Criteria and Milestones

	Basis for Decision/Success Criteria
BP1	Solvent vapor and aerosol emissions assessed
	Power plant Host Site Agreement issued
	Completion of 40 kWe bench unit design (Design heat duty ≤ ~2,100 GJ/tonne of CO_2 and stripping P ≥ ~4 bar)
BP2	Identify suitable options for reclamation of biphasic solvents
	Fabrication of 40 kWe bench-scale unit
BP3	Bench unit install, commissioning & testing including 6-month parametric testing with a simulated flue gas and 2-week continuous testing with a slipstream of power plant flue gas; Demonstrate continuous operation & total energy use of ≤0.22 kWh//kg

BP1: All 7 milestones reached on schedule and all 3 criteria fulfilled;

BP2: 2 milestones in progress as scheduled

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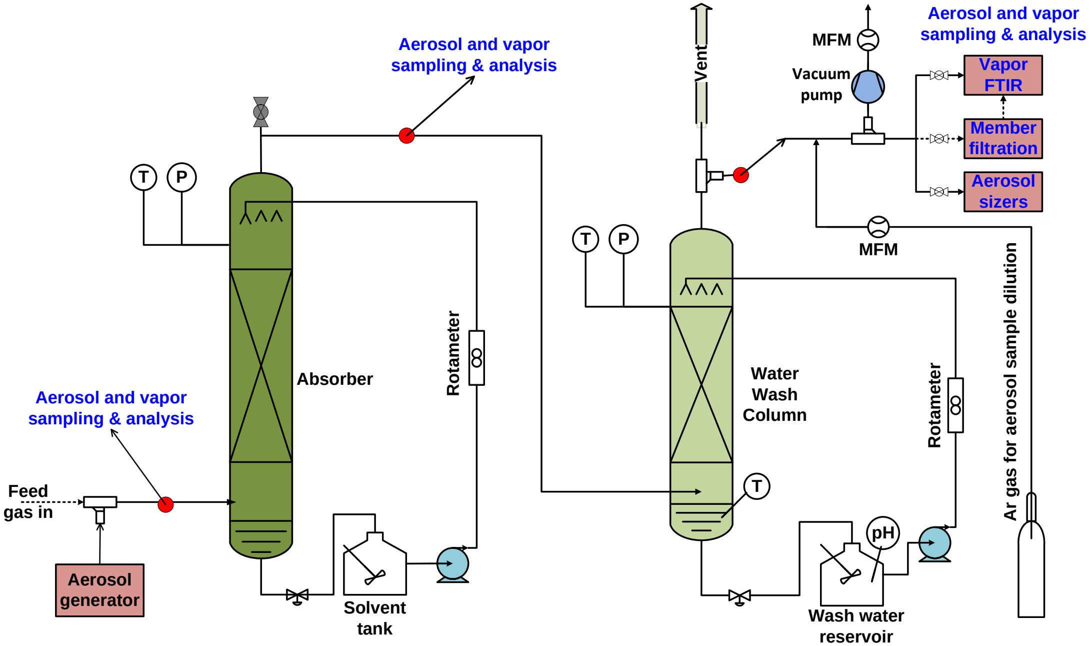
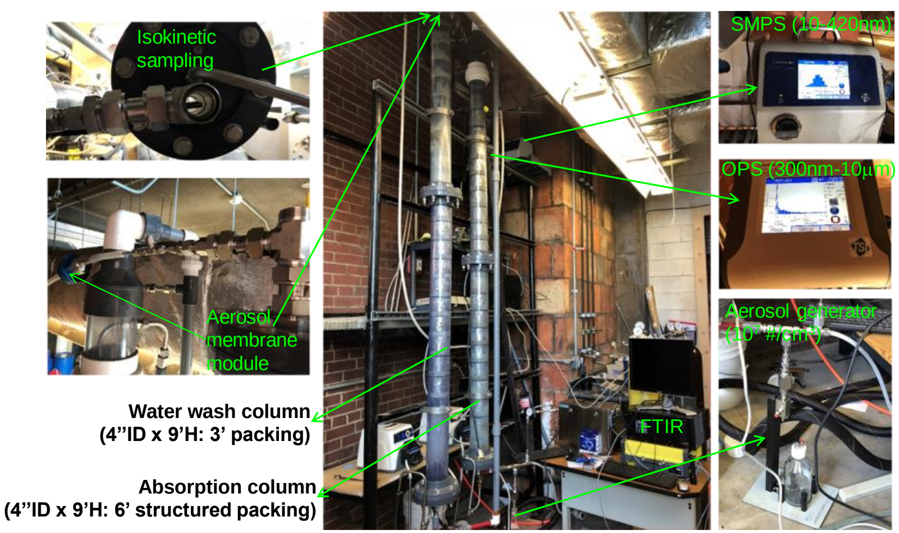
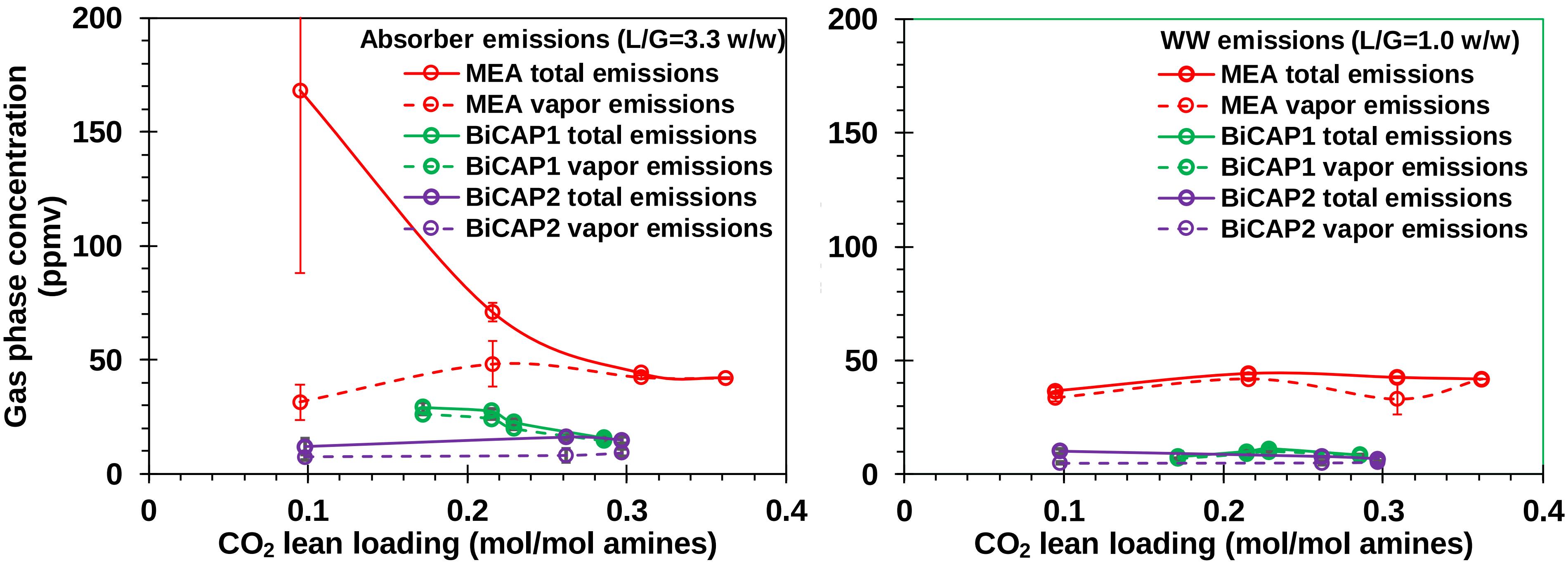
(1) Solvent Volitivity, Emissions and Mitigation (T3)





- **Aerosols generated** (10^6-10^7 #/cm^3) to simulate flue gas
- **Both vapor & aerosols monitored:**
  - FTIR for measuring vapor
  - Scanning Mobility Particle Sizer (SMPS) and Optical Particle Sizer (OPS) combined for measuring 10-nm to 10-μm aerosols
  - Membrane filters for collecting aerosols for GC-MS analysis

Gas-Phase Amine Emissions during Absorption & Water Wash

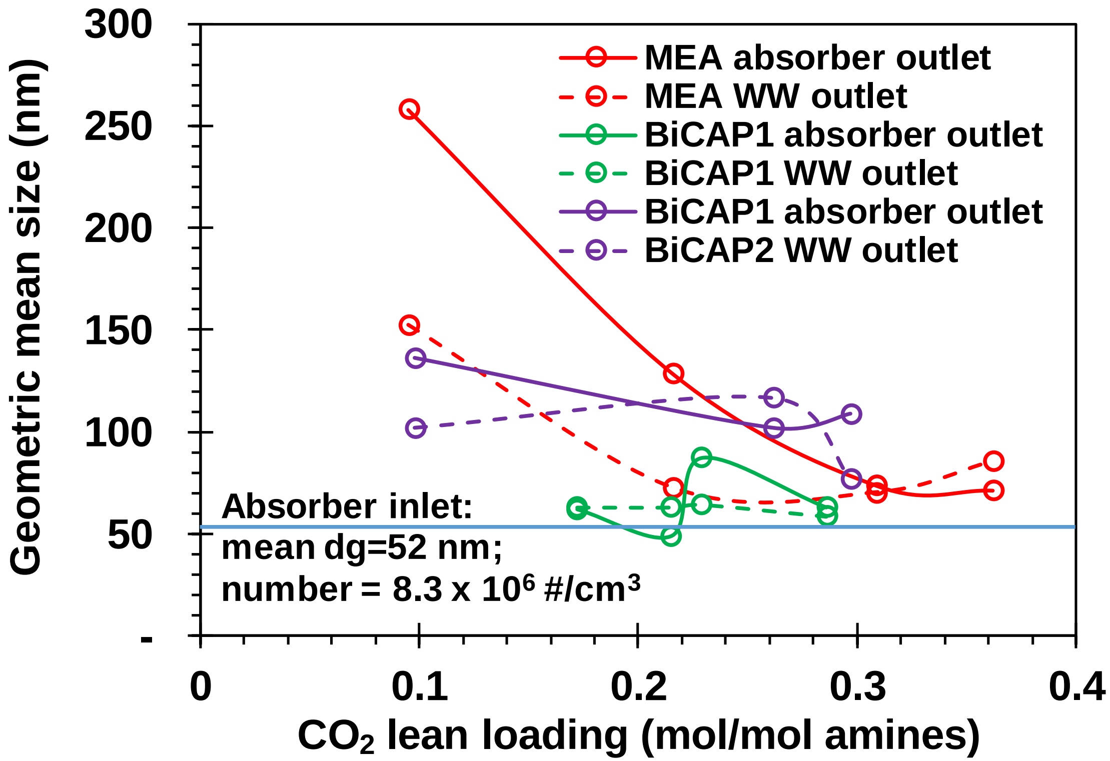


Emissions from absorber **Emissions after WW column**

(Total emissions: amine vapor + vaporized aerosols (w/o filtration) measured by FTIR; Vapor emissions: amine vapor only (with filtration) by FTIR)

- MEA mist/droplets visually present at sampling port of absorber exit
- BiCAP solvents 2-4 times less emissions from absorber than MEA
- ~50-95% of BiCAP amine emissions were vapor in these tests
- Water wash removed ~20-70% of total amine emissions

Aerosol Emissions during Absorption & Water Wash



- Absorber:
  - Aerosol size grew (agglomeration, condensation, reaction-diffusion, etc.)
  - Aerosol number concentration reduced significantly (by 60-90%)
- WW column
  - Aerosol size tended to decrease
  - Particles might be generated/removed depending conditions

(2) Biphasic Solvent Degradation and Reclamation

Methods under lab testing to replace / reduce thermal reclamation needs:

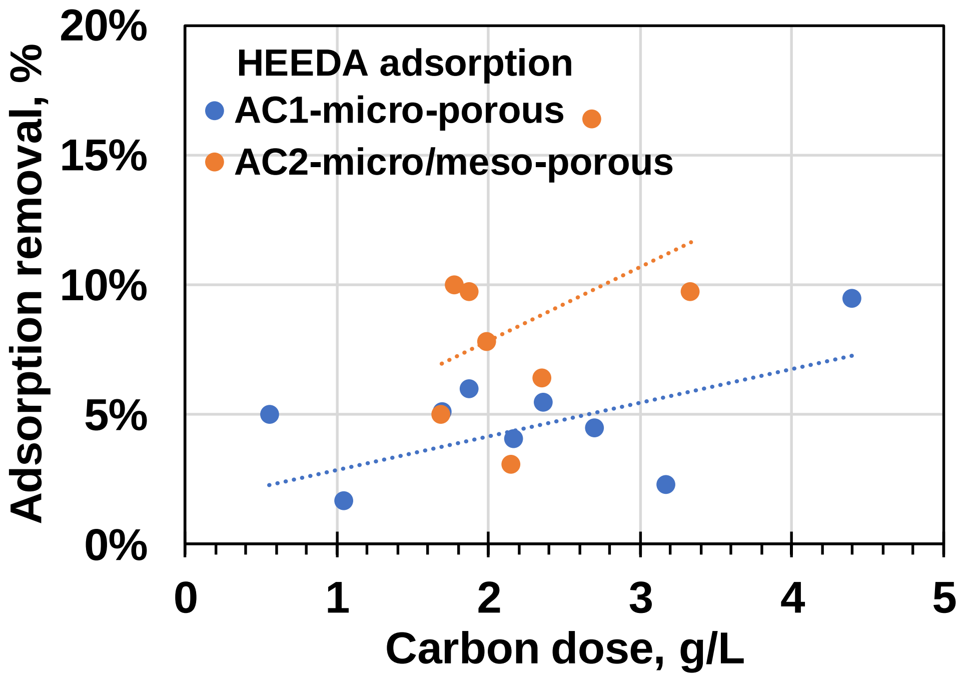
- Ion exchange adsorption
- Activated carbon adsorption
- Membrane nanofiltration
- Thermal reclamation (baseline)

Selected degradation products as model compounds used in experiments

	Model Compound	Abbreviation	MW	Analytical technique
Thermal degradation products	N,N'-di(2-hydroxyethyl)urea	MEA Urea	60	GC-MS, LC-MS
	1-(2-hydroxyethyl)-2-imidazolidinone	HEIA	130	GC-MS, LC-MS
	N-(2-hydroxyethyl)ethylenediamine	HEEDA	179	GC-MS, LC-MS
Oxidative degradation products	Acetic acid	AcOH	60	LC-MS
	Oxalic acid	OA	90	LC-MS
	Formic acid	FA	46	LC-MS

Adsorption of Thermal Degradation Products with Carbons

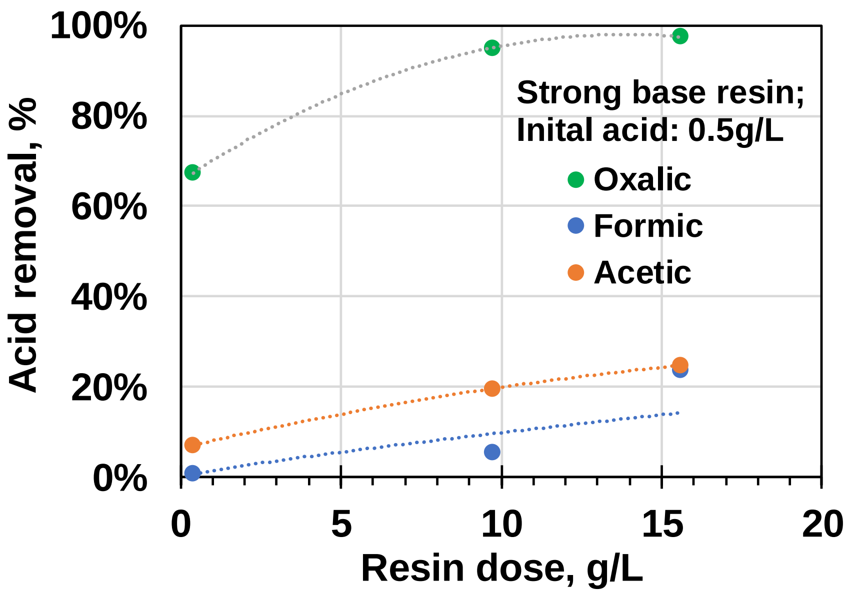
- Two commercial carbons (microporous and micro/mesoporous) tested
- Adsorption of selected thermal HSS products not significant
- Work in progress to modify carbon surface polarity and functionalities to improve HSS adsorption

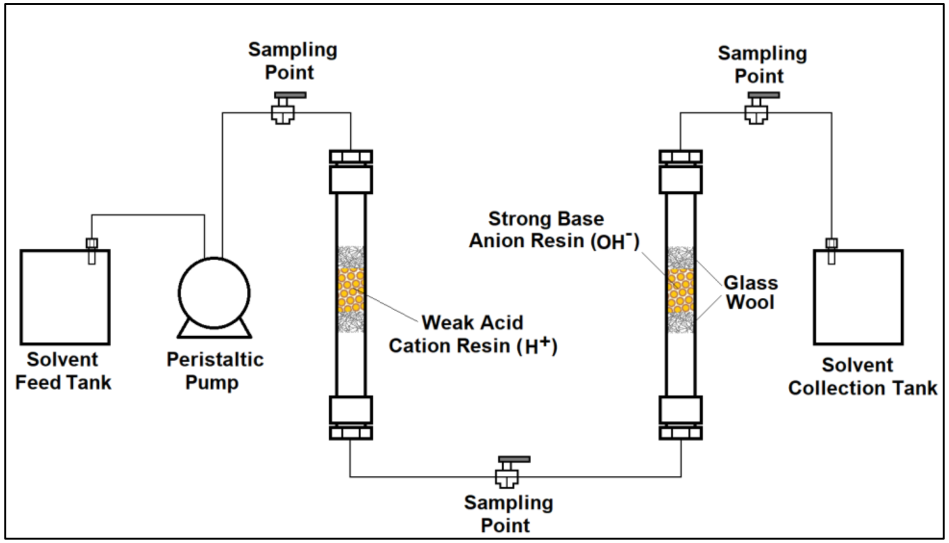


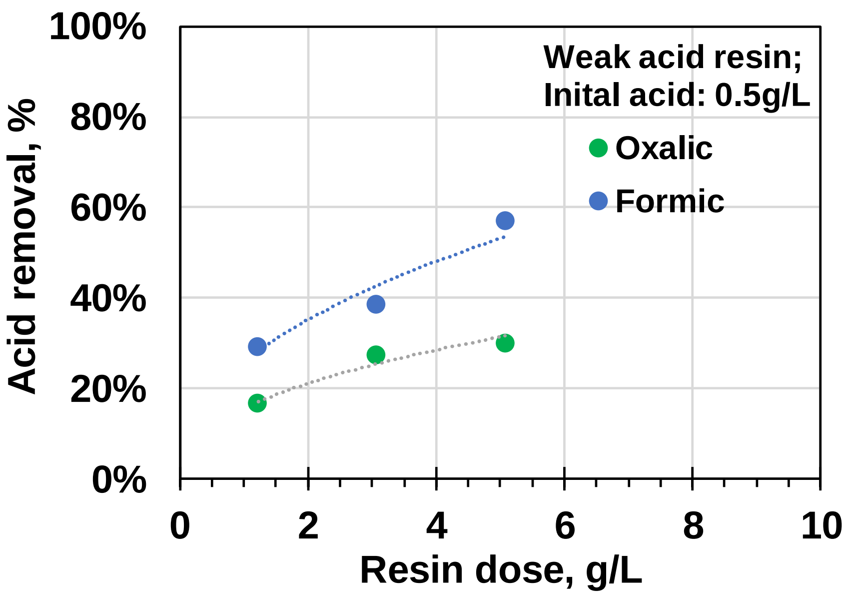
Rotating tumbler used for adsorption isotherm measurements at 23±1 °C

Removal of Oxidative Degradation Products with Ion Exchange Resins

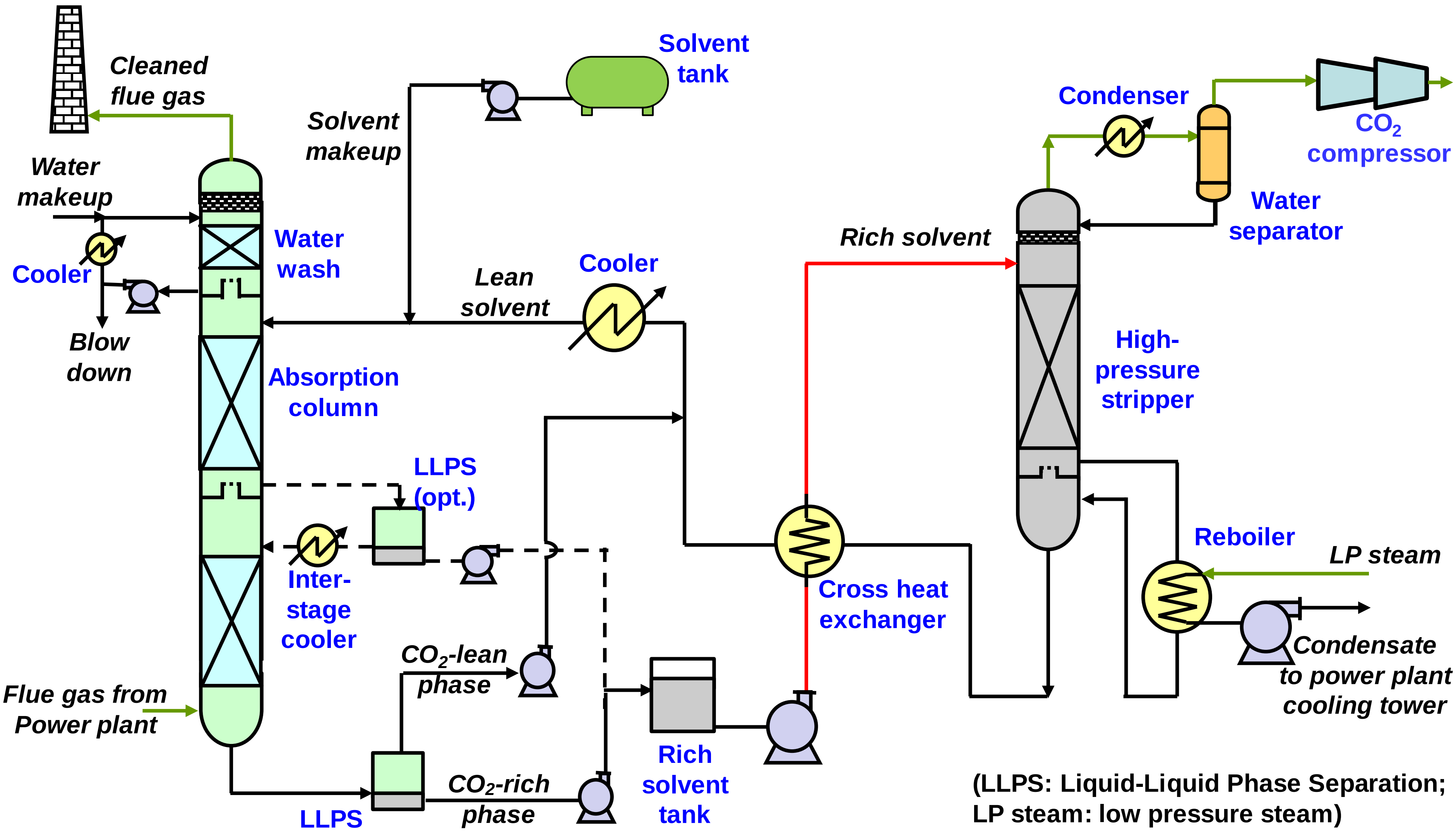
- Isotherms of two resins measured:
  - Strong base resin showed high affinity to oxalic acid
  - Weak acid resin showed some affinity to formic acid
- Ion exchange column breakthrough tests in progress







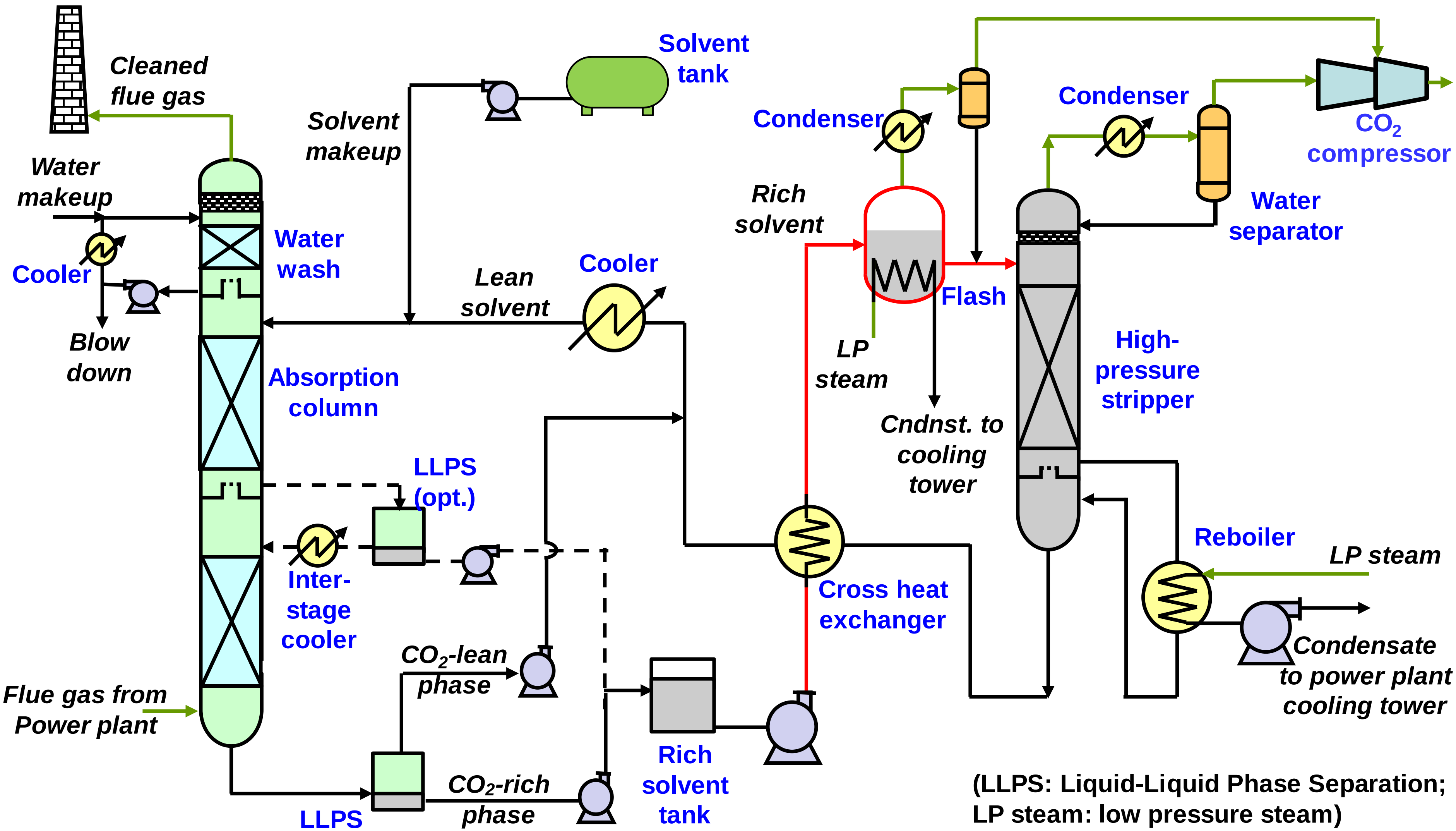
(3) Design & Fabrication of Bench-Scale BiCAP Unit: Process Configuration Optimization (T4)



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

Simple Stripper

Contn'd



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

Flash + Stripper

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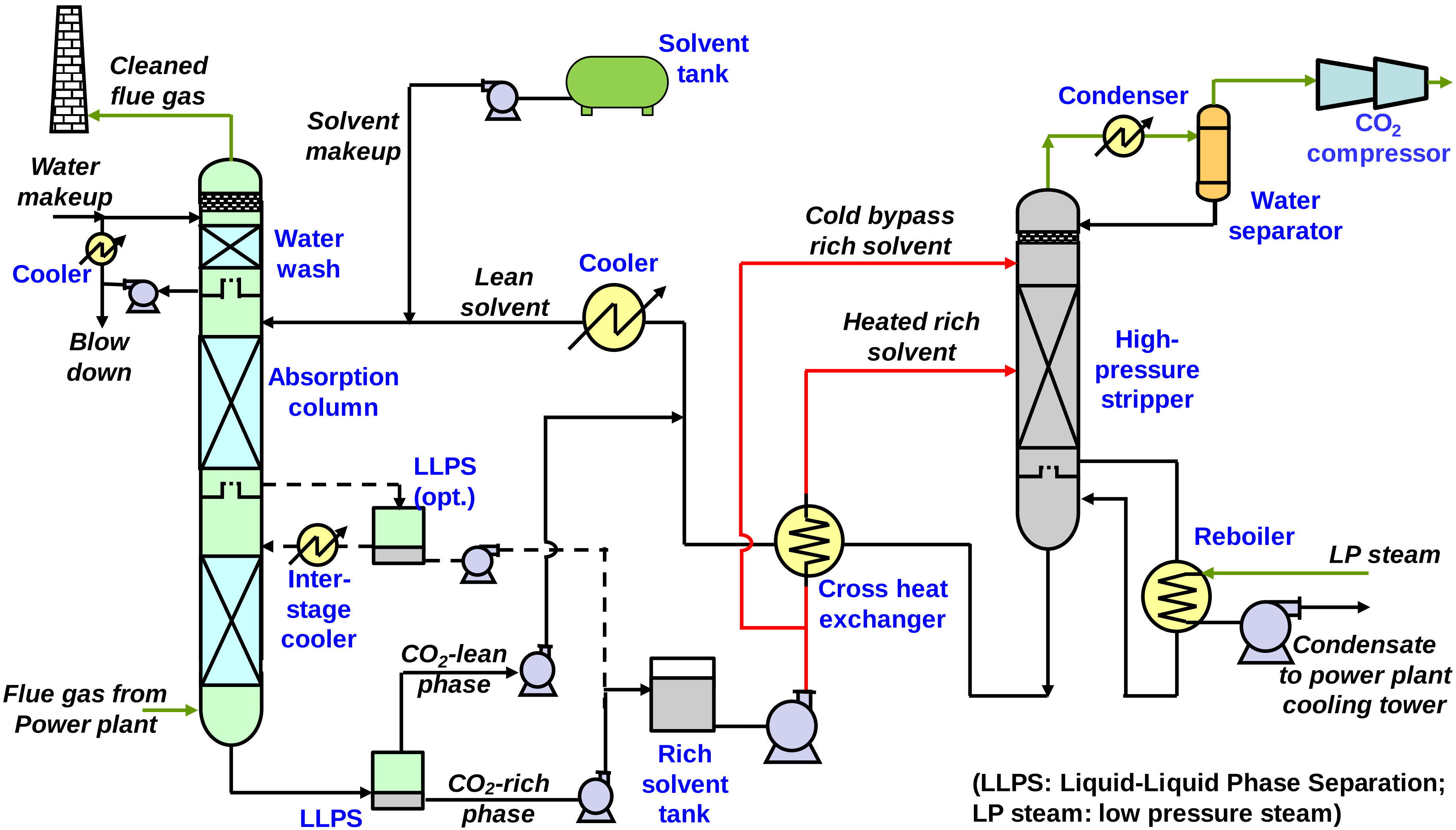

Cold Bypass

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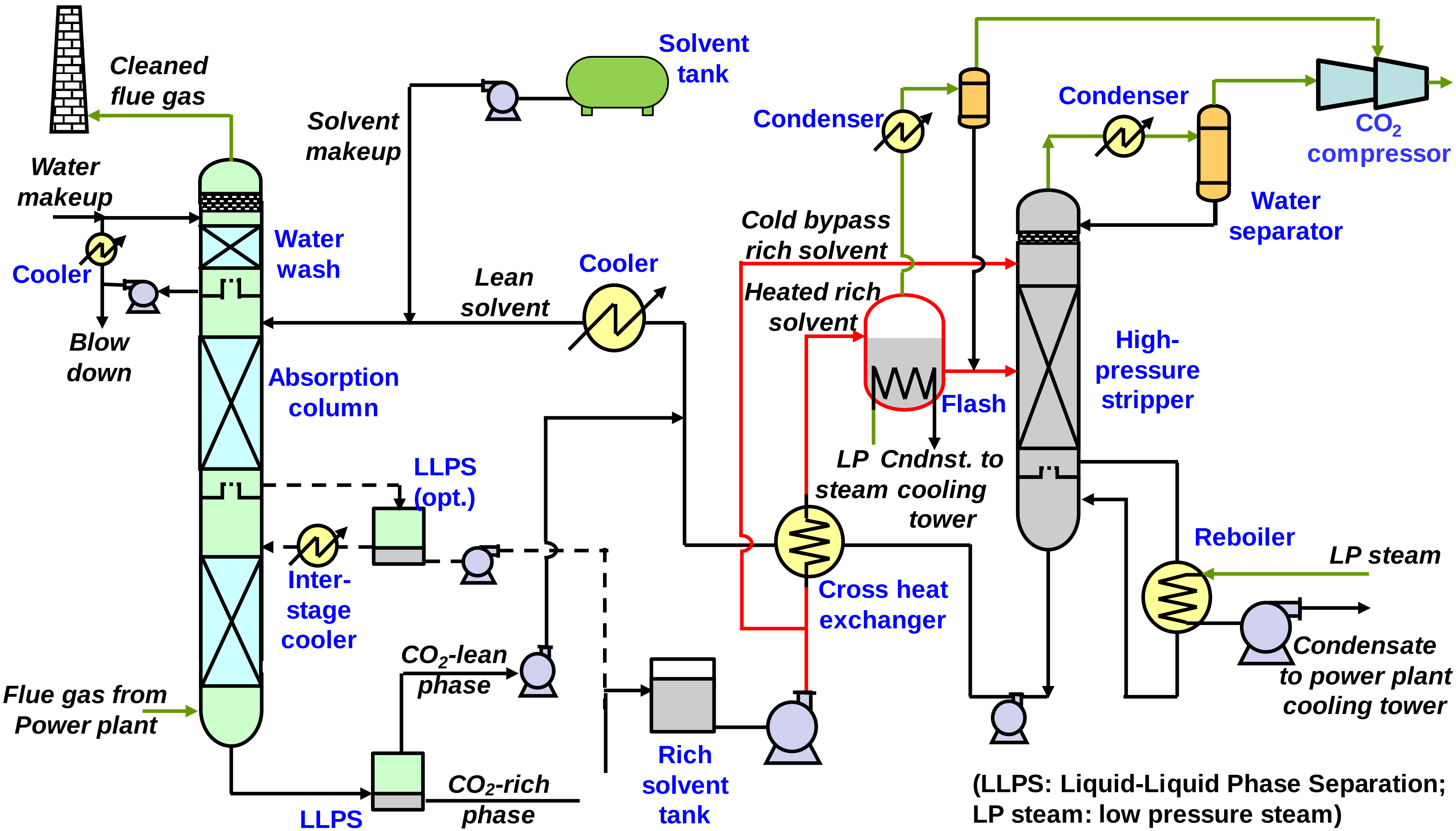


(LLPS: Liquid-Liquid Phase Separation;
LP steam: low pressure steam)

Cold Bypass and Flash + Stripper

Energy-Efficient BiCAP Configuration Identified

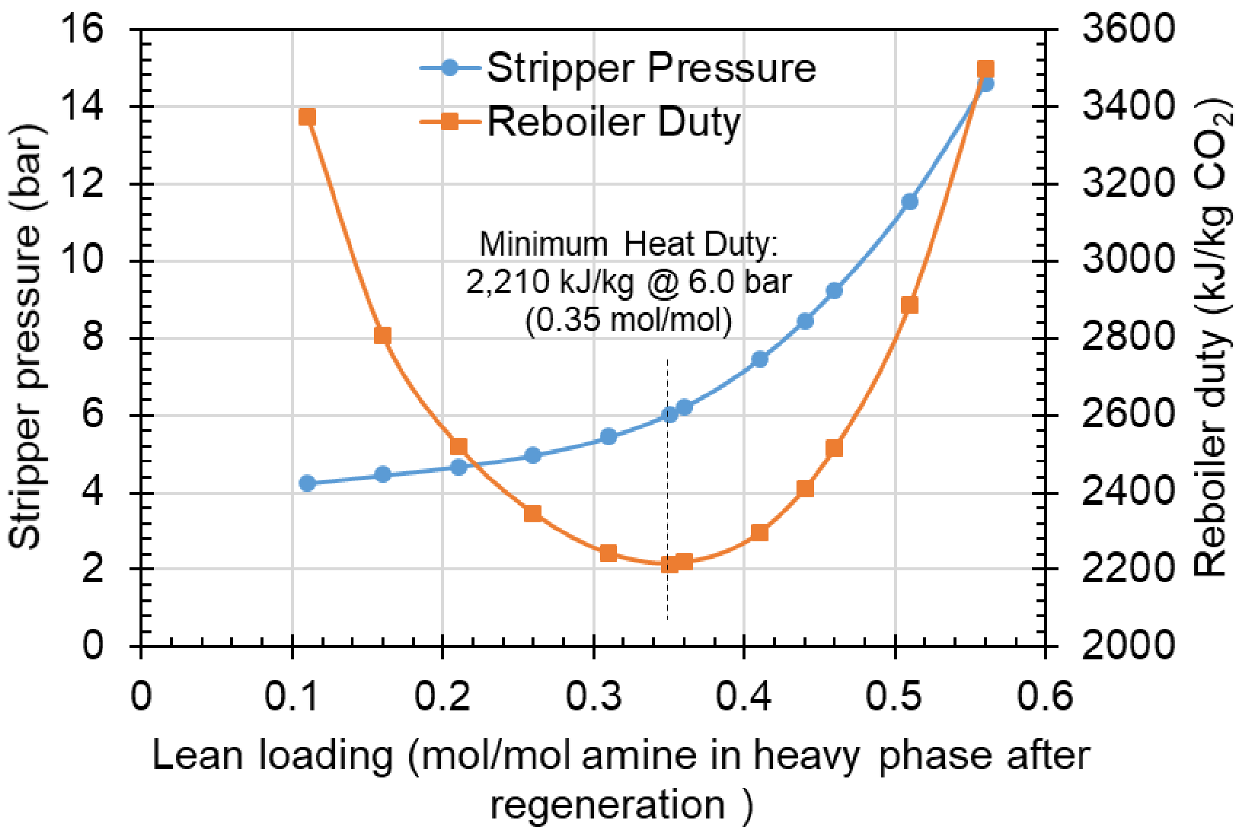
	Simple Stripper	Flash+ Stripper	Cold Bypass	Cold Bypass+ Flash/Stripper
Flash pressure, bar	n/a	9.7	n/a	9.7
Flash temperature, °C	n/a	140	n/a	144.5
Stripper pressure, bar	5.1	5.0	5.1	5.1
Reboiler temperature, °C	150	150	~150	~150
CO_2 release from flash, %	0%	34.50%	0%	28.75%
CO_2 release from stripper, %	100%	65.50%	100%	71.25%
IP/LP steam use				
Overall heat duty, kJ/kg CO_2	2,613	2,649	2,132	2,441
Parasitic power loss, kWh/kg CO_2	0.186	0.188	0.152	0.174
Compression work, kWh/kg CO_2	0.058	0.053	0.058	0.054
Total energy use, kWh/kg CO_2	**0.244**	**0.242**	**0.209**	**0.227**

*** BiCAP-1 solvent (vs. best-performing BiCAP-2) used for modeling**

- Cold Bypass: high energy efficiency and low equipment complexity

Design Optimization of 40 KWe Bench-Scale Unit

- Rigorous rate-based Aspen Plus model developed
- BiCAP-1 solvent (vs. best-performing BiCAP-2) used for design modeling



(Stripper (4" ID) with 15' height of Mellapak 250Y packing at fixed rich loading of 0.73 mol/mol amines in heavy phase and 150°C reboiler)

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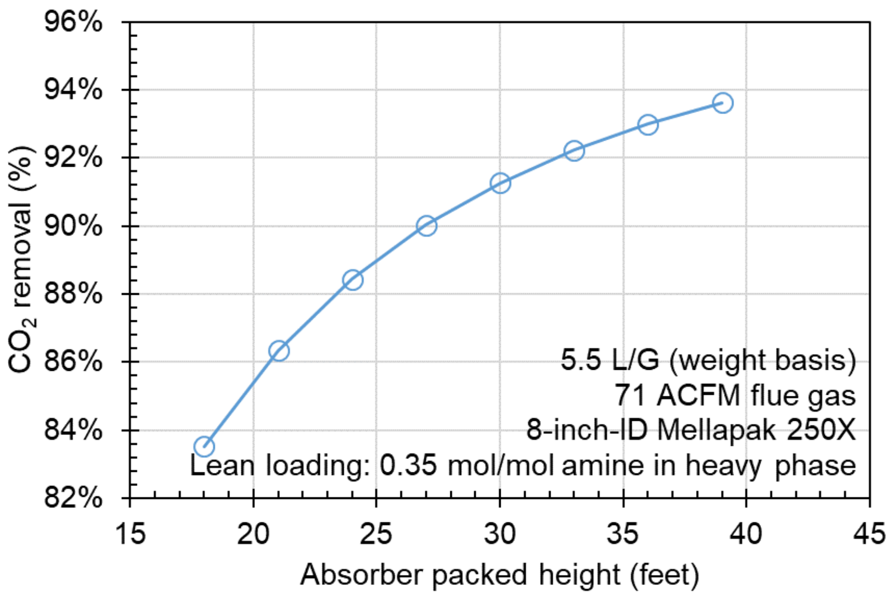
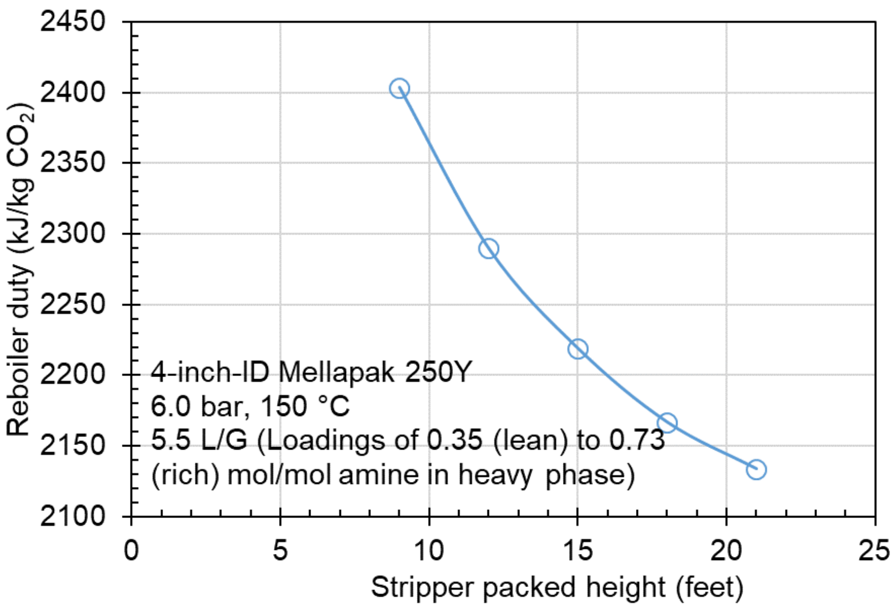


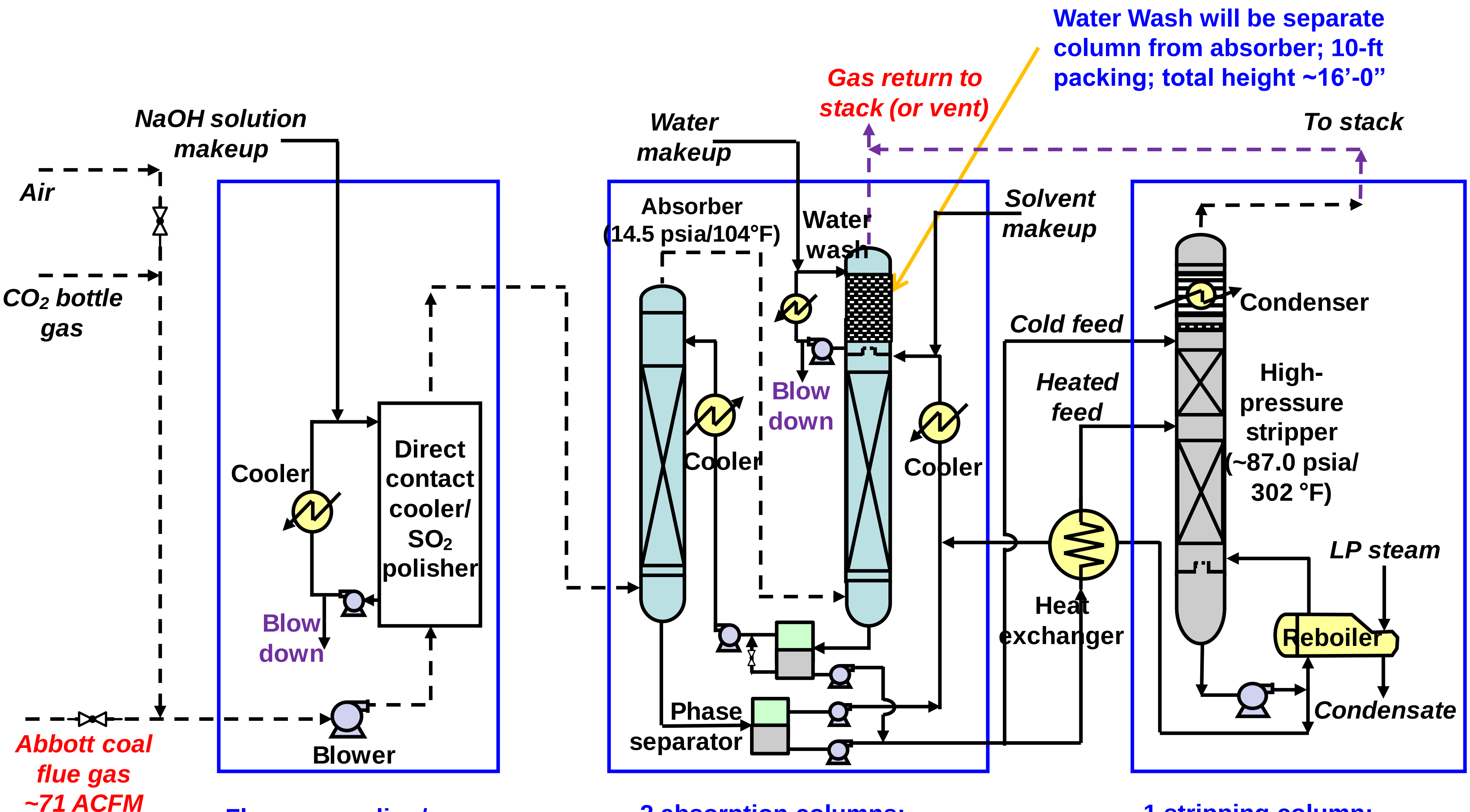
CO_2 removal from 40 kWe flue gas in absorber at fixed L/G of 5.5 (w/w)



Reboiler duty as a function of stripper packed height (90% CO_2 removal)

- 27' packing achieves 90% capture
- Higher L/G leads to shorter packing requirement, but may increase stripper heat duty
- Stripper packing height directly affects heat duty: a taller column achieving better energy performance

Schematic of 40 kWe Bench-Scale Capture Unit

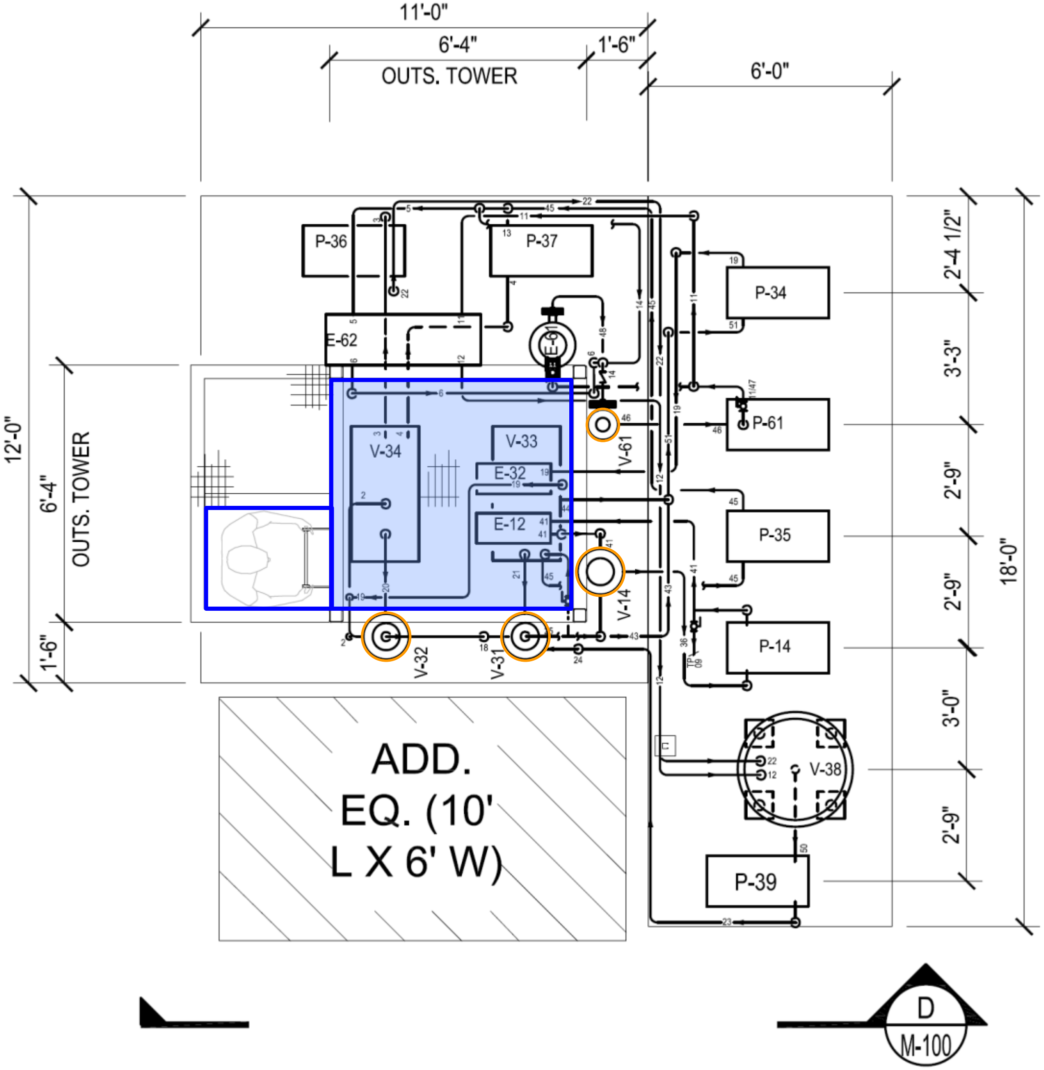


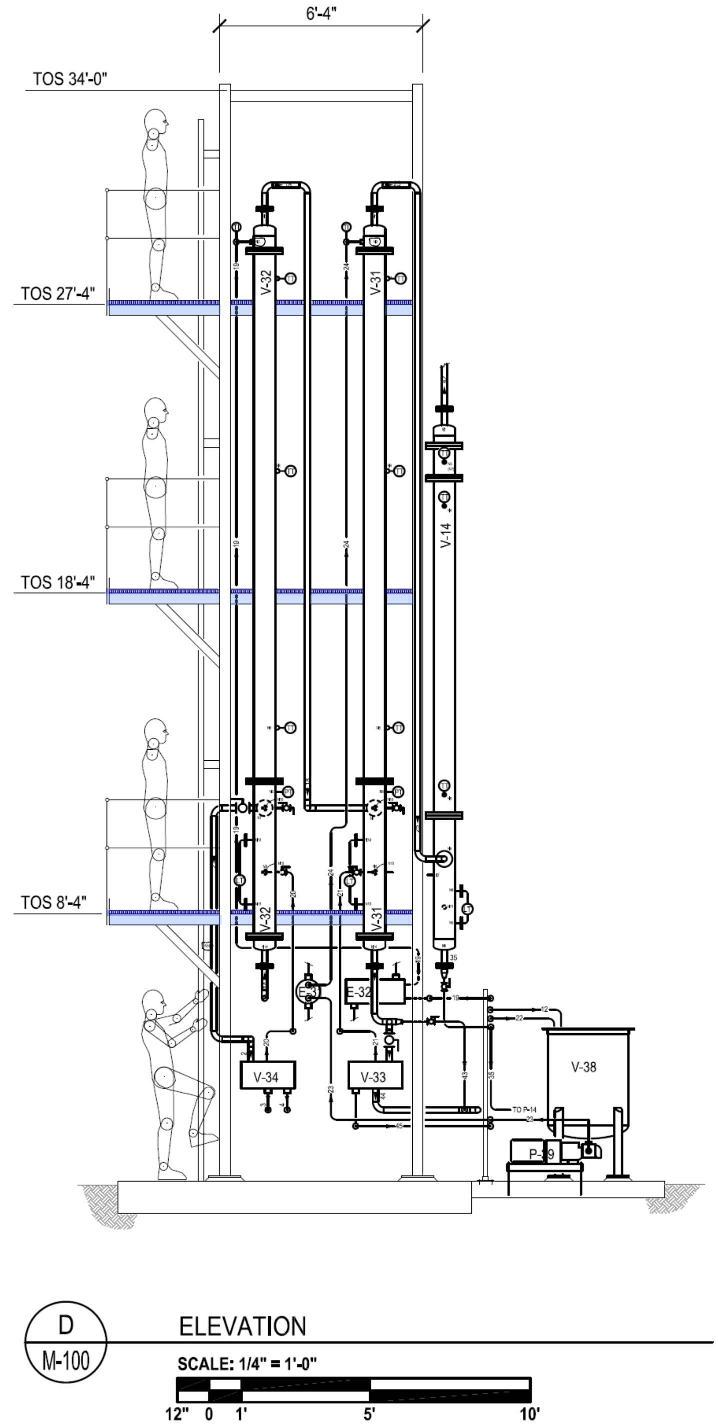
Flue gas cooling/ polishing treatment

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

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

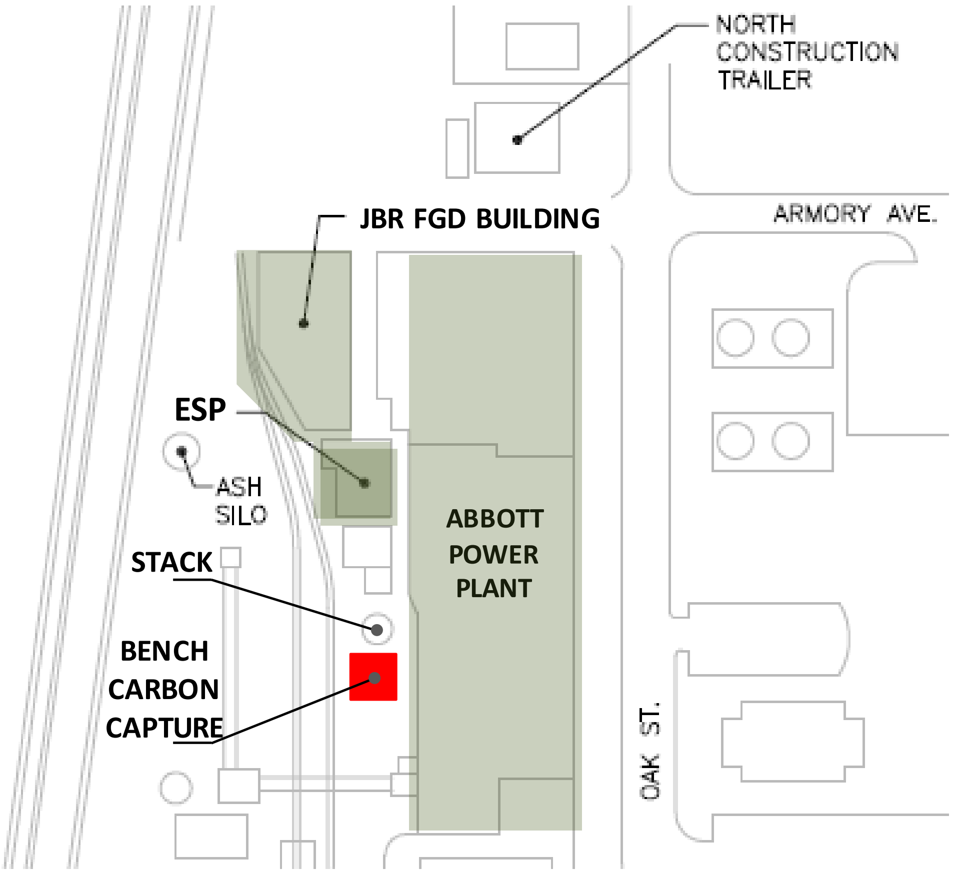
Preliminary Skid Footprint

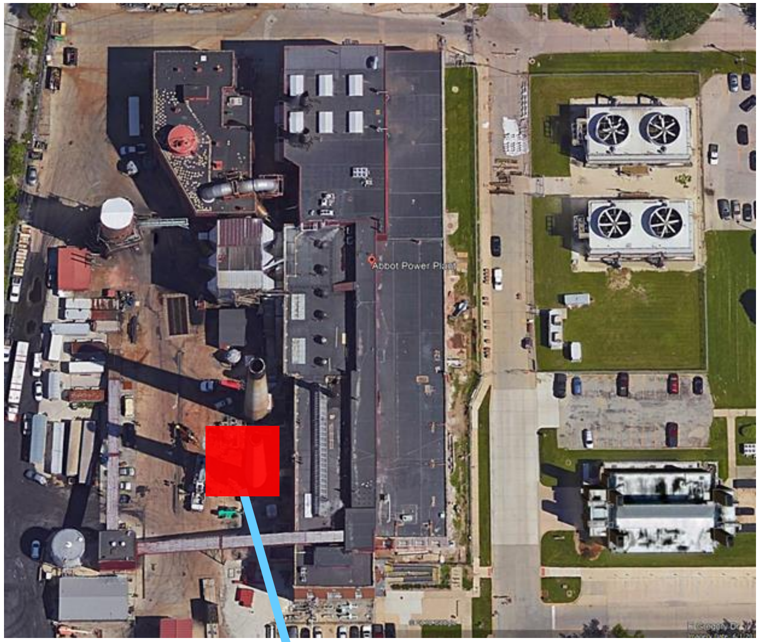




- Skid and control panel design by ITG-Henneman
- Skid fab/assembly by UIUC Facilities & Services

Location of Bench-Scale Unit at Abbott power plant





Site used for (1) parametric testing with simulated flue gas for 6 months and (2) continuous testing with actual flue gas for 2 weeks

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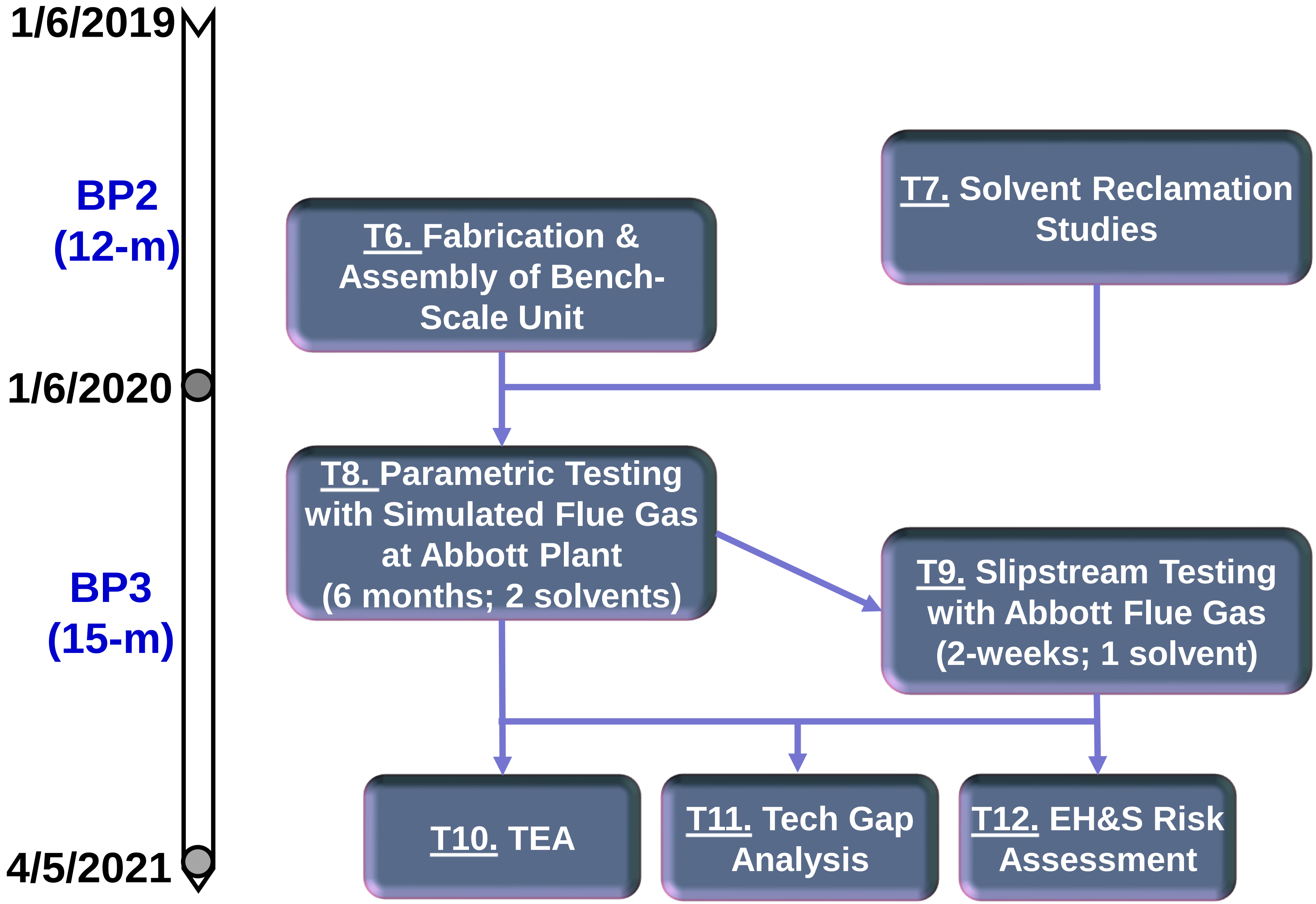
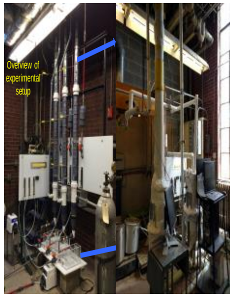
BP2 and BP3 Work Plan



Progression of BiCAP Technology Development

Solvent study,
Laboratory

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



10 kWe Tests,
Laboratory

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

Currently

40 kWe Tests,
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*

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Project Contributors:

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