Bench Scale Development of a Hybrid Membrane-Absorption CO_2 Capture Process

DE-FE0013118

Brice Freeman, Jay Kniep, Richard Baker, Tim Merkel, Pingjiao Hao, Gary Rochelle, Eric Chen, Yue Zhang, Junyuan Ding, Brent Sherman

Project Review Meeting
June 13, 2017

Project Overview

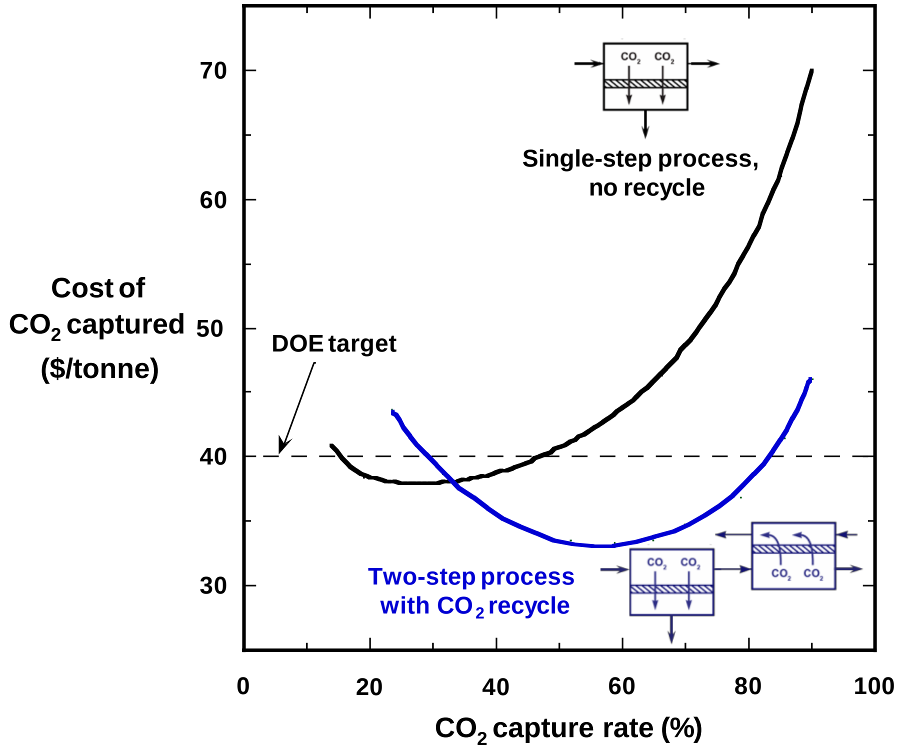
- **Award name:** Bench-Scale Development of a Hybrid Membrane-Absorption CO_2 Capture Process (DE-FE0013118)
- **Project period:** 10/1/13 to 5/31/18
- **Funding:** $3.2 million DOE + $0.75 million cost share
- **DOE-NETL Project Manager:** Andy Aurelio
- **Participants:** MTR, University of Texas at Austin
- **Overall goal:** Evaluate a hybrid post-combustion CO_2 capture process for coal-fired power plants that combines membrane and amine absorption/stripping technology.
- **Project plan:** The key project work organized by budget period is as follows:
  - **BP1**: Develop process simulations and initial cost assessments for the hybrid process, determine preferred hybrid configuration. Fabricate membrane modules.
  - **BP2**: Prepare the SRP pilot plant for hybrid testing. Test each capture system separately under hybrid conditions.
  - **BP3**: Conduct a parametric tests on the integrated hybrid capture system at UT-Austin's SPR Pilot Plant. Use test data to refine simulations and conduct TEA.

MTR

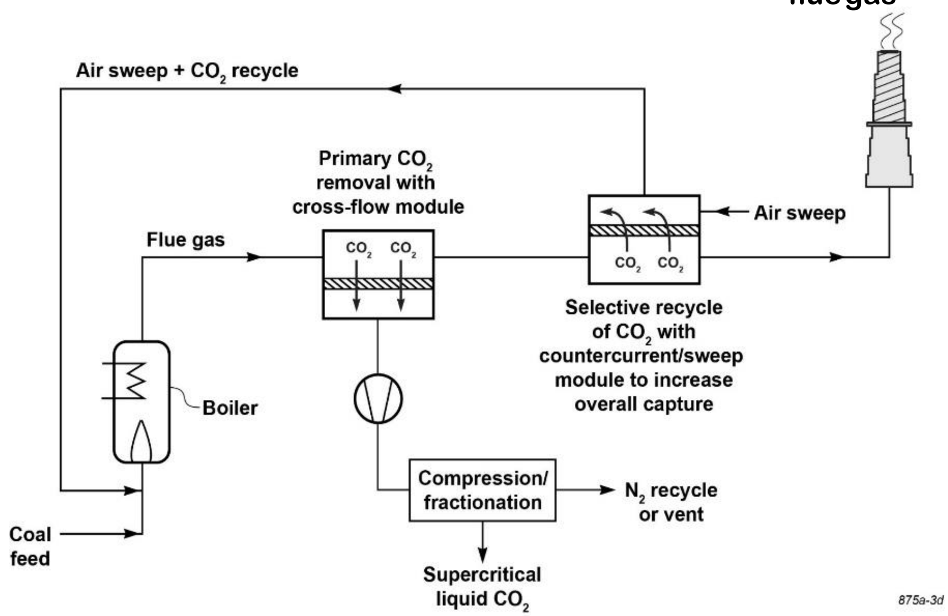
Outline

- Motivation, background, and objectives
- BP1 and BP2 results
- Review plan for BP3
- Questions and feedback

Motivation for the Hybrid Process



Two-step process with CO_2 recycle

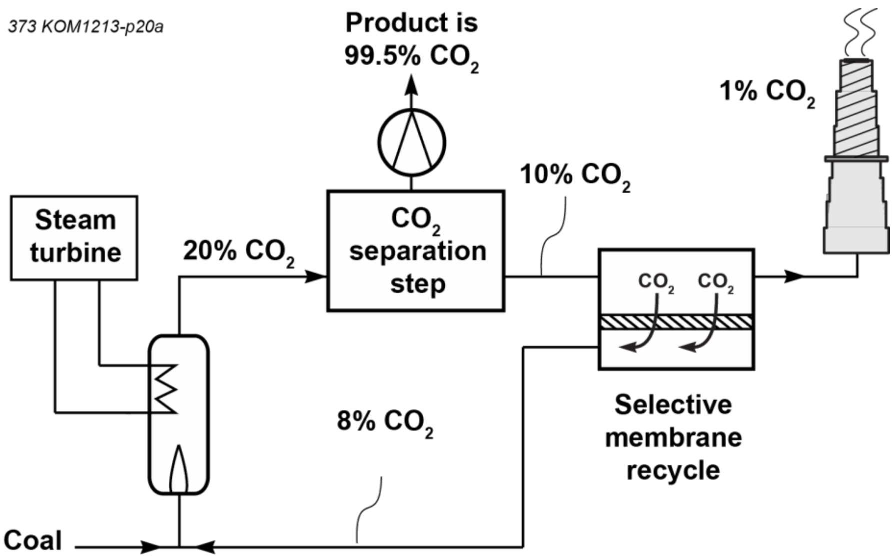


U.S. Patents 7,964,020 and 8,025,715

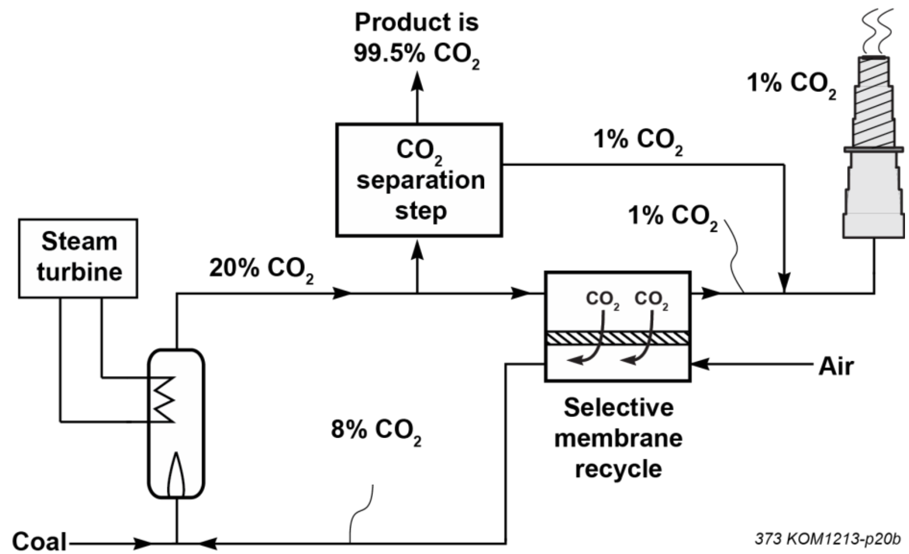
MTR

Two Hybrid Configurations

Hybrid-Series Arrangement



Hybrid-Parallel Arrangement

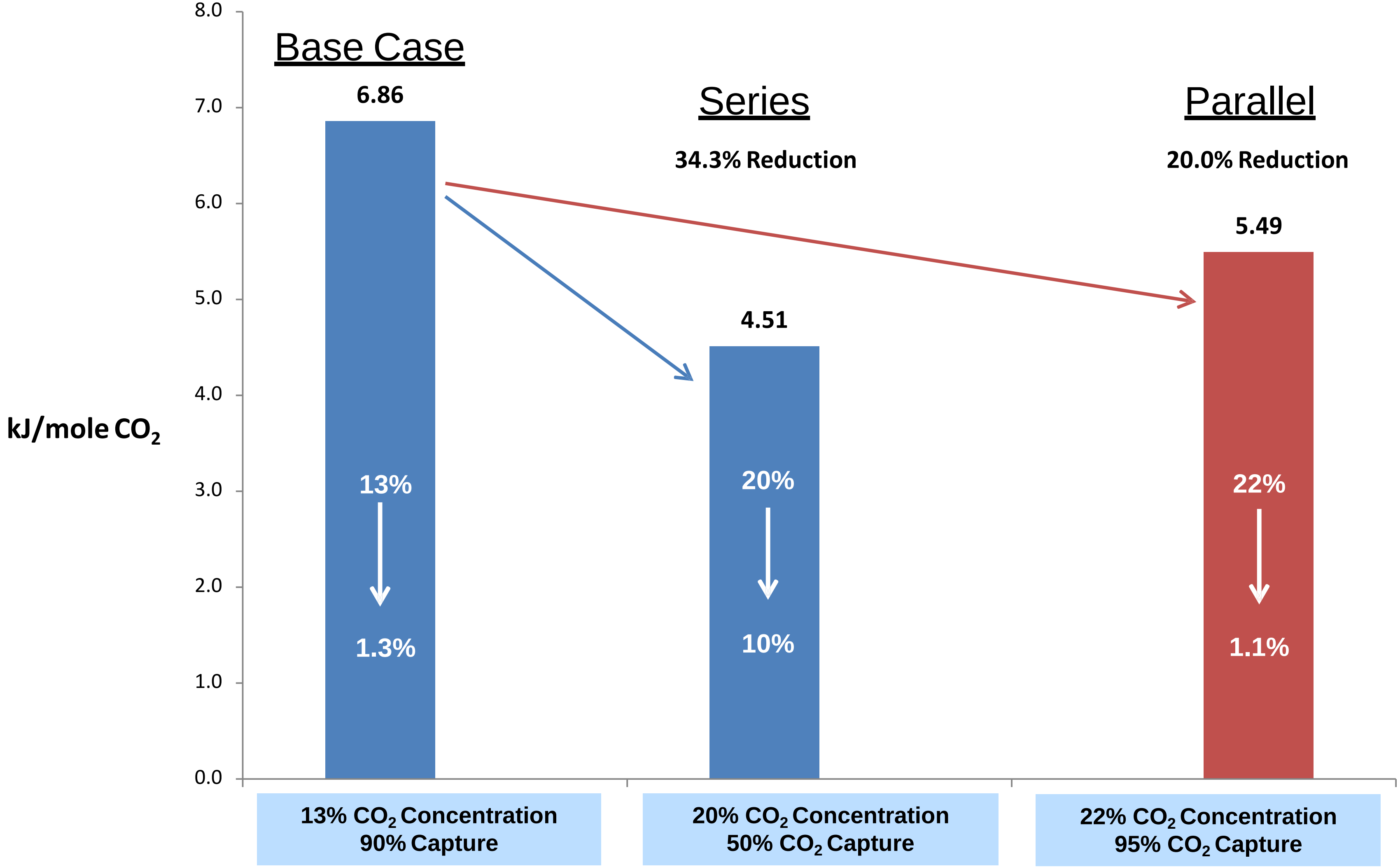


Depending on the arrangement, the selective recycle membrane can:

- Significantly increase the concentration of CO_2 in flue gas, and;
- Reduce the removal requirements for the capture unit (Series)
- Reduce the volume of gas sent to the capture unit (Parallel)

MTR

Minimum Energy of Separation for the Hybrid Partner



Assumes 98% CO_2 product purity. Does not include CO_2 compression.

MTR

Benefits and Challenges of the Hybrid Capture Process

Benefits:

- Increases the concentration (driving force) of CO_2 in flue gas.
- Air sweep is a very efficient use of membranes.
- MTR's membrane contactor is modular and compact.
- Hybrid concept can be used with different capture technologies.

Challenges:

- The sweep stream impacts boiler performance; ~0.75% efficiency derating from CO_2 recycle in a retrofit application.
- Hybrid partner must be able to capitalize on higher CO_2 concentrations, and operate efficiently in either the series or parallel condition.
- Overall, hybrid systems increase operational complexity.

List of Project Tasks – BP1

Task 2

- **Initial Cost Assessment.** A cost assessment will be developed with model assumptions; basis for selecting the preferred hybrid configuration
- **Develop 5 m PZ Process Model.** UT Austin will adapt their current "Independence" Aspen Plus process simulation model for the advanced absorber intercooling and advanced flash stripper design for 20-25% inlet CO_2 flue gas concentration.

Task 3

- **Manufacture Membrane.** MTR will fabricate several Polaris membrane rolls using commercial-scale membrane equipment.
- **Determine Membrane Batch Characteristics.** Membranes will be checked for integrity by measuring pure-gas carbon dioxide and nitrogen permeances.

List of Project Tasks – BP1

Task 4

- **Make Modules.** Plate-and-frame membrane contactor modules will be produced. These modules are designed to have a very low pressure drop of less than 1 psi to circulate gas on the feed and permeate side of the membrane.

- **Test Modules.** The integrity of each module will be determined in MTR's lab test station. By measuring the CO_2 removal from the feed, the permeance and selectivity of the modules can be tested.

MTR

List of Project Tasks – BP1

Task 5. Design and Construct Large Module System

- Produce a pilot test system containing five low-pressure plate-and-frame membrane contactors.

Task 6. Hybrid Process Model Development and Integration Optimization

- MTR's simulation models will be adapted for the hybrid membrane-series and parallel configurations, then used to develop the heat and material balances for the hybrid system.

- A range of operating conditions will be simulated including varying flue gas splits and CO_2 removal rates by the membrane and 5 m PZ AFS capture plant.

List of Project Tasks – BP2

Task 7. Operation of Membrane Test System

- MTR will test the membrane system over the full range of conditions to collect sufficient operating experience to reliably predict its operational performance and validate the simulation model.

Task 8.

- **Modify the SRP Pilot Plant** Modify the SRP Pilot Plant to operate in the preferred hybrid configuration; additional absorber section, water wash, solvent intercooler, upgraded heat exchanger.

- **Operation of the Absorber/Stripper Test Unit with 20-25% CO_2.** Tests will simulate the full range of operating conditions expected in the parallel operating mode. Important operating conditions that will be varied include: the simulated flue gas CO_2 concentration, solvent lean loadings and circulation rates, and pressure of the stripper system.

MTR

List of Project Tasks – BP2

Task 8, cont.

- Based on test results, the best mode of operation of an integrated membrane-absorption system will be identified, and a parametric test plan will be prepared for integrated testing in BP3.

Task 9, Initial Techno-economic Analysis and Prepare Parametric Test Plan

- Results from parametric studies performed in Tasks 7 and 8 will be used to develop a framework technoeconomic assessment which will be updated to produce the final TEA after integrated testing (Task 11, BP3)

MTR

List of Project Tasks – BP3

Task 10.

- **Install Membrane System at the UT Austin Pilot Plant.** The plate-and-frame membrane unit will be installed at the UT Austin's SRP pilot plant. The project team will complete shakedown tests.

- **Parametric Test of Integrated Membrane-Absorption Test Unit.** The integrated membrane-absorption system will be operated for a full campaign in the hybrid-parallel mode. The objective will be to demonstrate optimal performance and operation of the hybrid membrane-absorber/stripper process with 5 m PZ.

List of Project Tasks – BP3

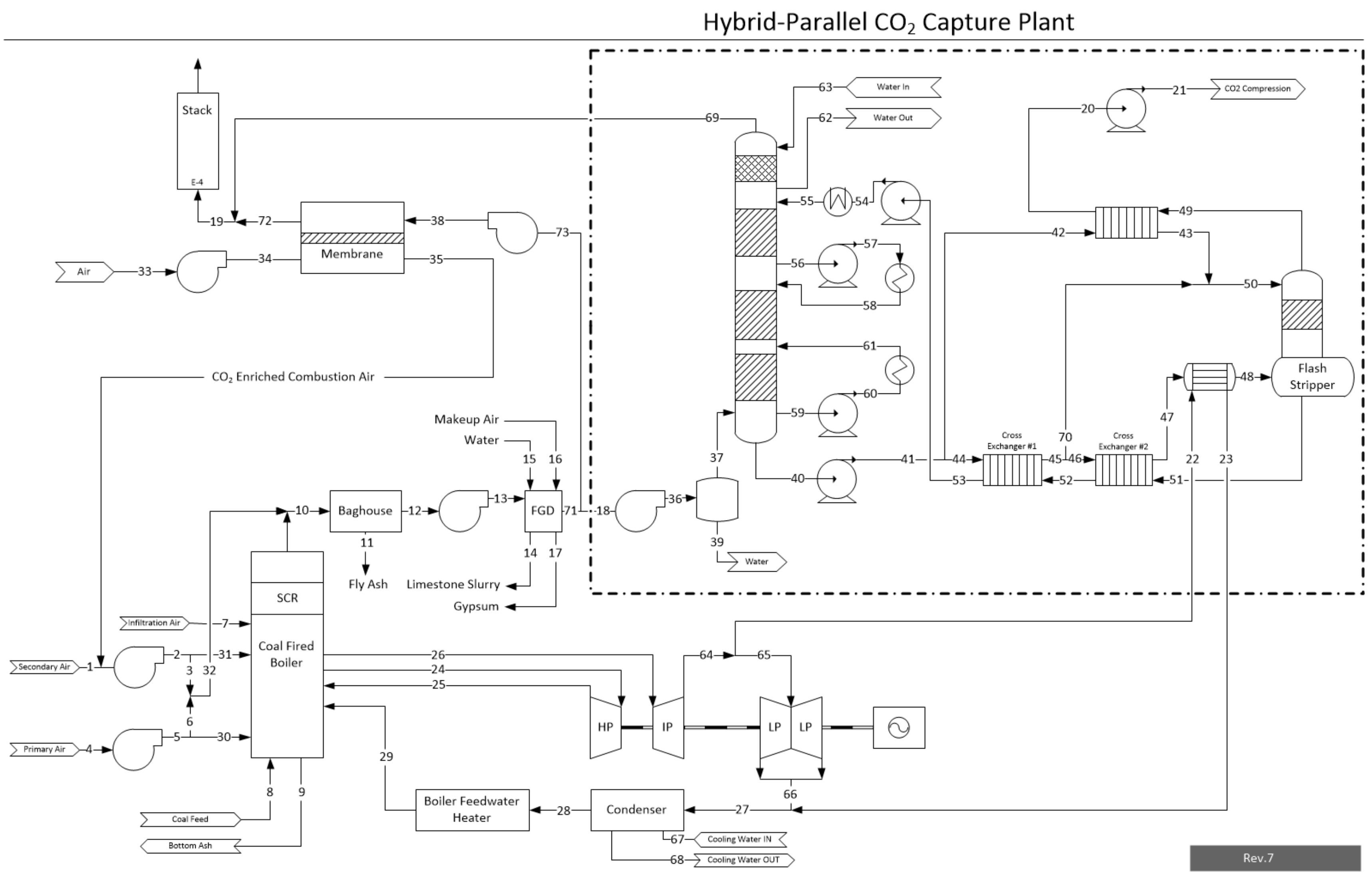
Task 11. TEA and Final Report

- Findings from integrated testing (Task 10) will be used to refine MTR's membrane model and UT Austin's Independence model as needed.
- The updated models will be exercised to develop heat and material balances for a hybrid-parallel capture process scaled to 550 MW_e in the most promising configuration.
- A TEA will be produced based on the techno-economic analysis prepared Task 9.
- The TEA will be included in the final project report which will document the project's work, key findings and lessons learned.

Outline

- Motivation, background, and objectives
- BP1 and BP2 results
- Review plan for BP3
- Questions and feedback

Process Diagram of Hybrid Capture System



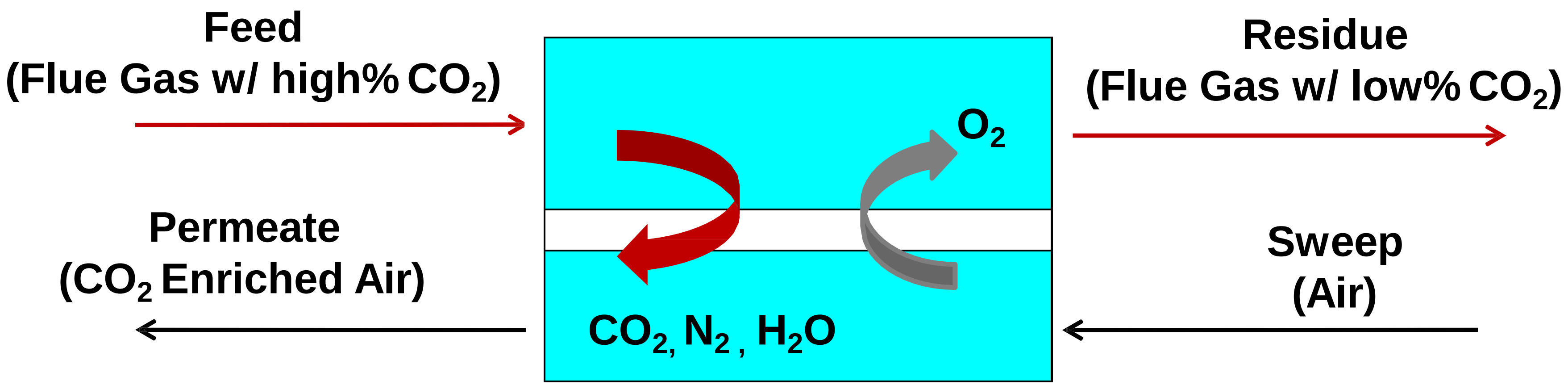
MTR

Membrane Process Model Assumptions

- Power plant performance based on NETL Case #11.
- System CO_2 capture rate is 90%
- Membrane: CO_2 2,000 GPU; CO_2/N_2 selectivity 50.
- Pressure drop in the feed and sweep side = 3 psi (0.2 bar)
- O_2 concentration in combustion air entering the boiler is 18% for retrofit.
- Membrane system is modeled in ChemCAD, PZ Capture Plant (Independence model) in Aspen Plus.

MTR

Factors Affecting O_2 Concentration in the Combustion Air



O_2 Concentration in the Combustion Air (Permeate) is a factor of:

- CO_2 dilution
- N_2 dilution
- Water dilution
- O_2 Loss

MTR

Hybrid Parallel Configuration is Superior (593 MWe, 5 m PZ)

	Series		Parallel	
Project Case ID	**#13**	**#14**	**#18**	**#19**
CO_2 removal in absorber (%)	60	60	99	95
Lean ldg (mol CO_2/eq PZ)	0.29	0.38	0.23	0.30
Weq (kJ/mol CO_2)	33.5	49.0	34.0	33.3
Exchanger PEC ($MM)	23	74	16	26
TOTAL PEC ($MM)	78	159	68	80

Other Solvents Are Not Significantly Better

MDEA/PZ a toss up, but comes with degradation
HMPD/PZ competitive but unavailable

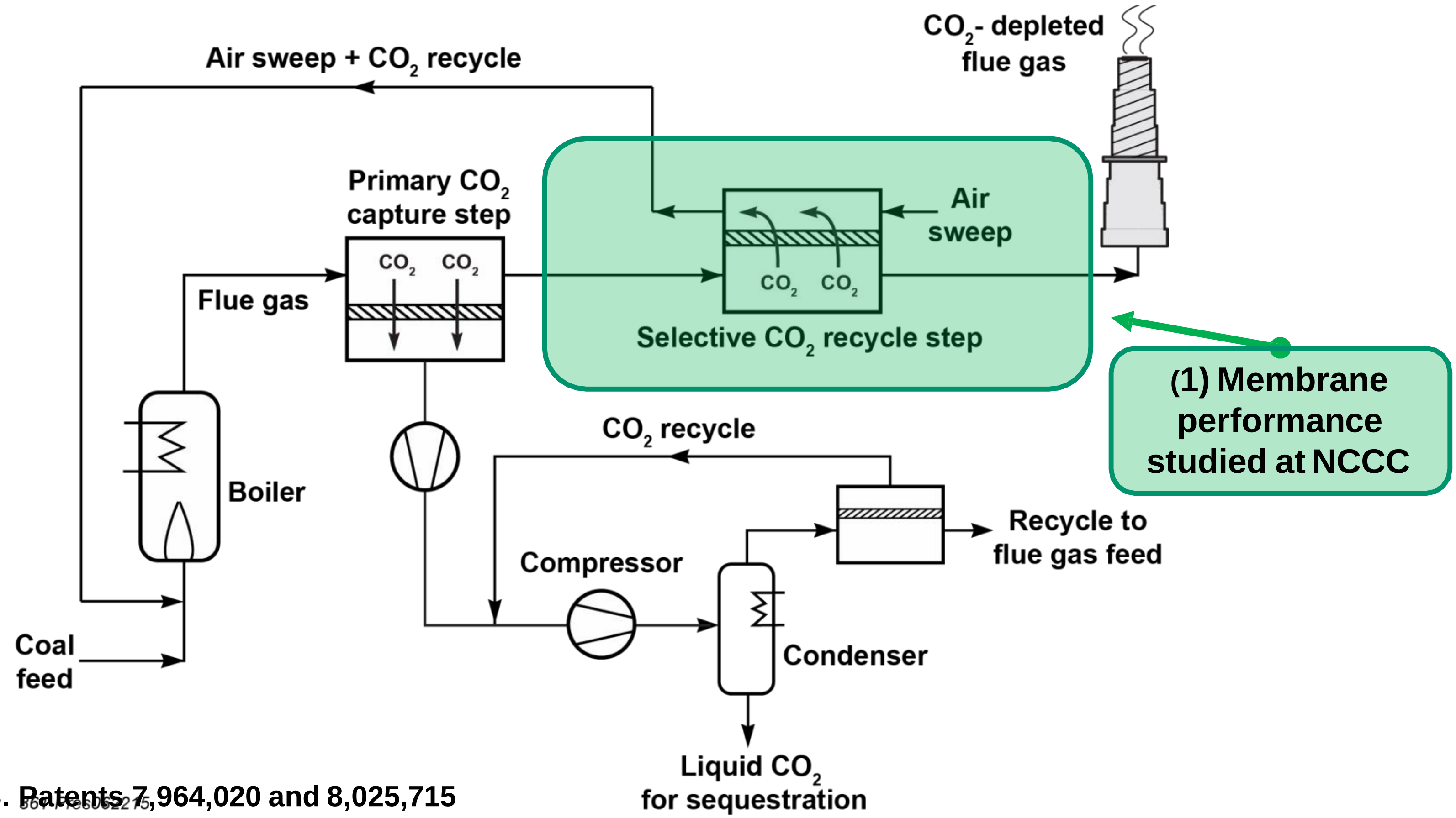
CO_2 removal in absor.	99% Case #18		95% Case #19		
Solvent (m)	**5 PZ**	5 MDEA /5 PZ	**5 PZ**	5 MDEA /5 PZ	3 HMPD /2PZ
Lean ldg (mol CO_2/eq PZ)	0.23	0.29	0.30	0.21	0.26
Rich ldg	0.40	0.40	0.41	0.40	0.47
Weq (kJ/mol CO_2)	34.0	32.3	33.3	32.5	32.1
TOTAL PEC ($MM)	68	71	80	74	66

Findings from Process Modeling

- Hybrid-parallel offers lower-cost of capture than hybrid-series.
- Recycling to 18% O_2 in combustion air, gave 21% CO_2 in flue gas; 17% O_2 gave 23%+ CO_2
- Membrane area = 280,000 m^2
- 5 m PZ offers the best performance with lean loading of 0.23 mol-CO_2/mol-alk. and a rich loading of ~0.40 mol-CO_2/mol-alk.

MTR

Incorporating Test Results from NCCC



U.S. Patents 7,964,020 and 8,025,715

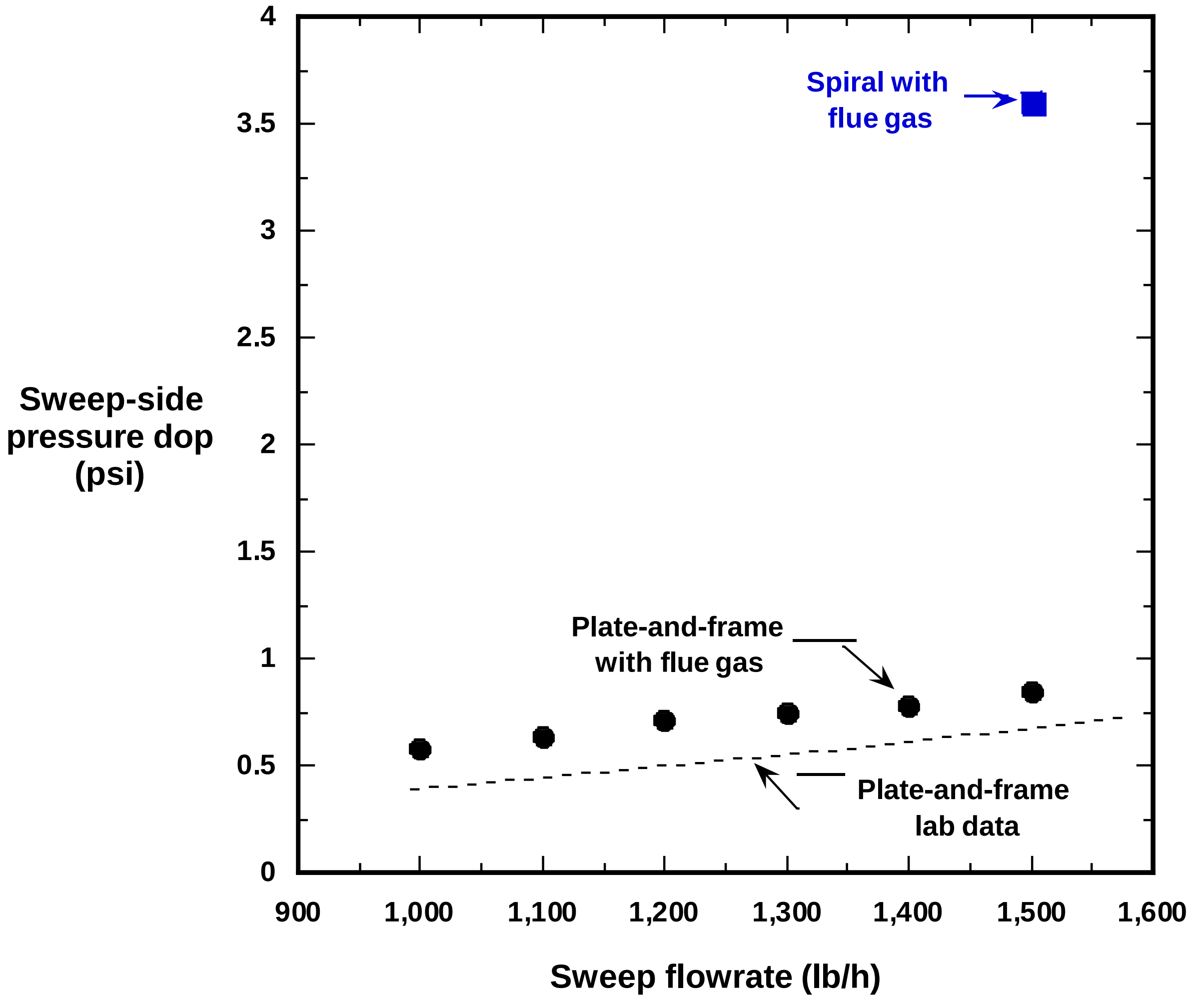
System Tests Scaled-Up Membrane Modules (FE0007553)

Spiral wound sweep modules — **Tested Against** → **Polaris plate-and-frame sweep modules (designed in DE-FE007553)**

Advanced plate-and-frame modules demonstrate lower cost and pressure drop

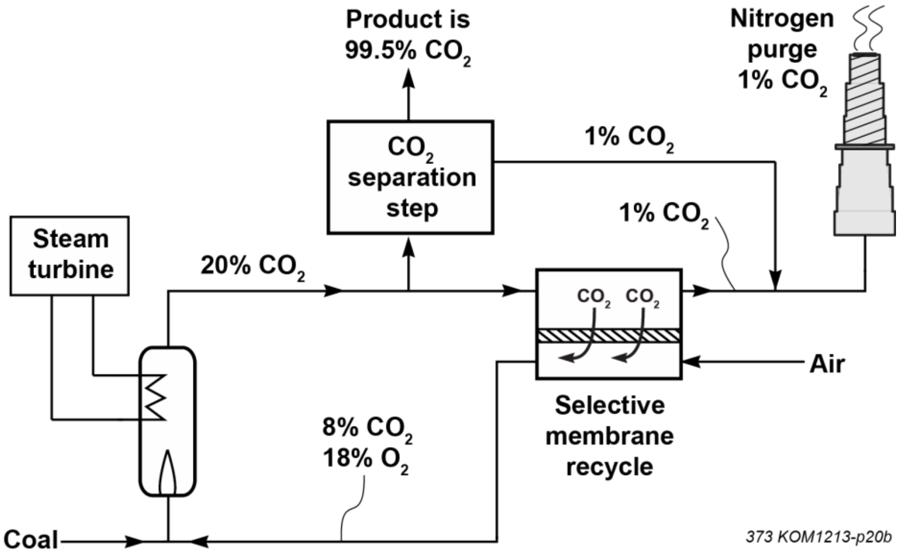
MTR

New Modules Demonstrate Improved Pressure Drop Performance (FE0007553)



- Field data is consistent with lab results, and confirms much lower air sweep pressure drop in new modules
- At full scale, the difference in pressure drop amounts to savings of about 10 MW_e

BP2 - Sweep Module Testing in Hybrid-Parallel Conditions



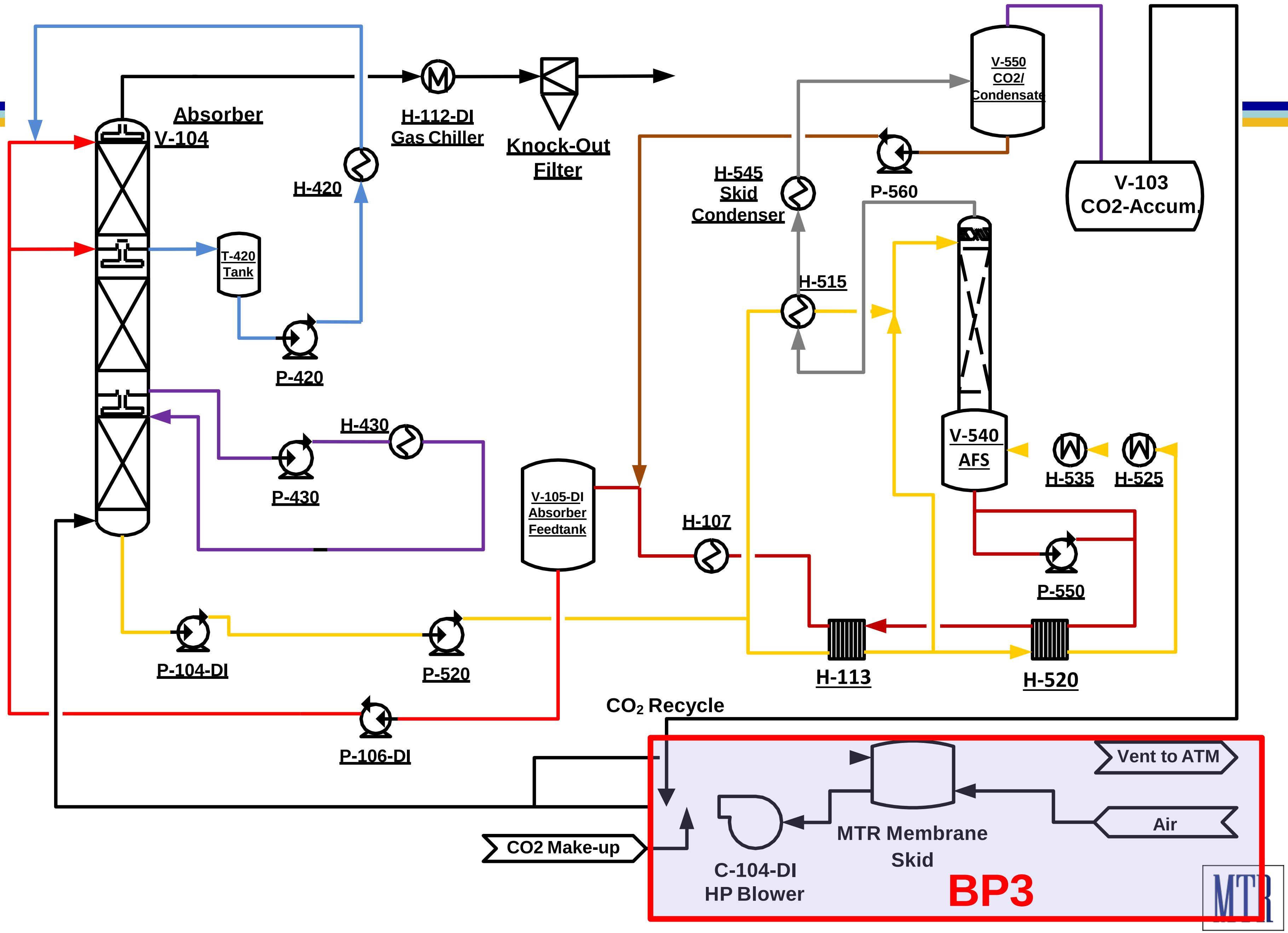
	Feed Flue Gas	Residue	Sweep Air In	Sweep Air Out
Gas flow rate (ft³/min)	6.9	4.7	12.2	14.6
Temp (°C)	19.4	20	20	19.7
Pressure (psia)	15.5	15.4	15.5	15.2
Pressure drop (psi)	--	0.1	--	0.3
Mol fraction CO_2 (%)	23.9	2.2	0.0	10.8
CO_2 Removal Rate	91%			

MTR

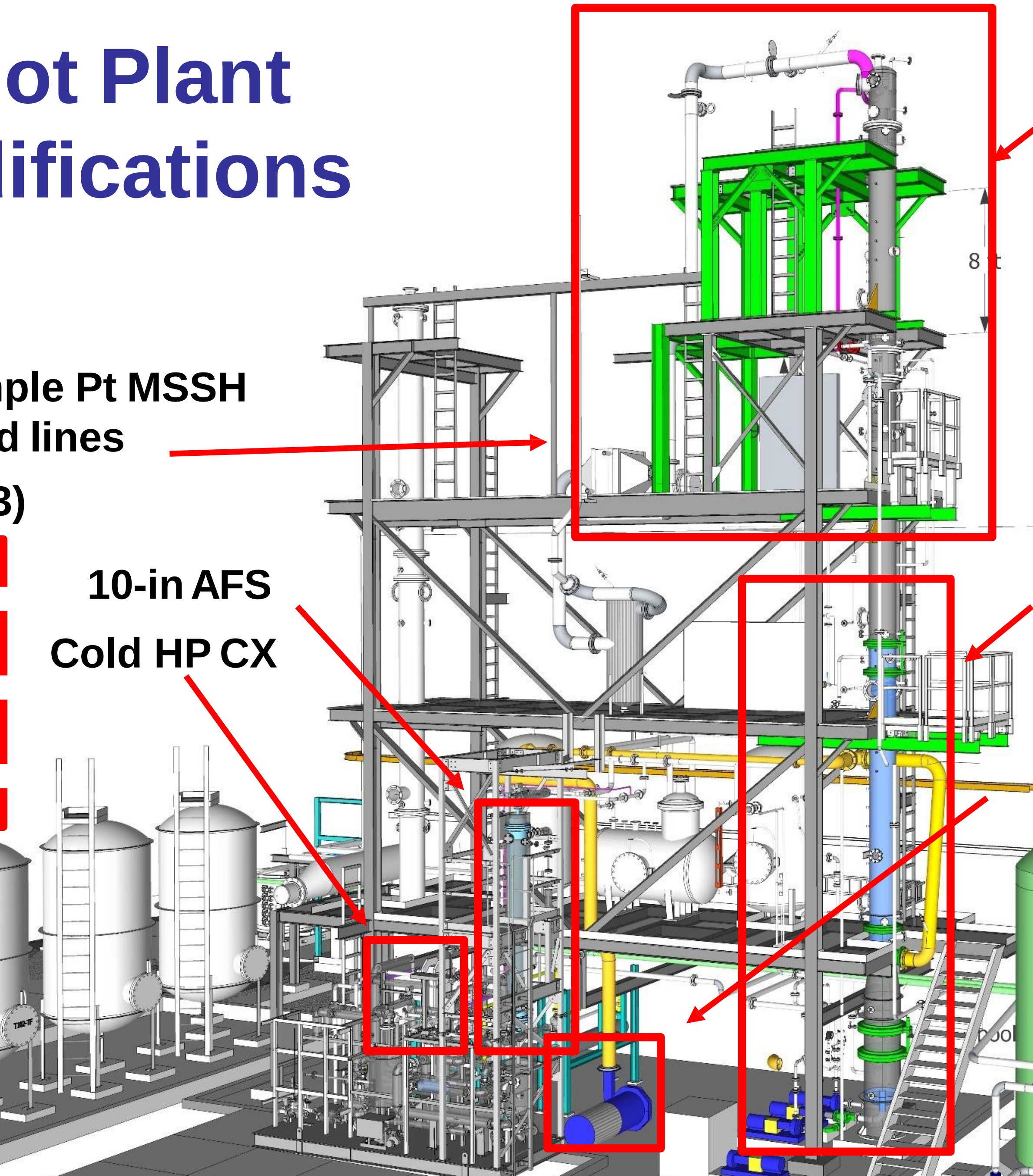
SRP Pilot Plant Modifications

- **Objectives: Upgrade pilot plant for 20% CO_2 and 99% removal**
  - Absorber – new 10 ft packing section, water wash intercooling, sump section, new level 5 platform
  - Stripper – 10" diameter advanced flash stripper column
  - Low temperature cross-exchanger – higher T&P rating
  - Intercooler skid and water wash cooling skid
  - FTIR analyzer and multi-point sampling system – 20% CO_2 gas analysis
  - New gas and liquid piping connections
  - DP, P, and T transmitters, conduit and wiring
  - DeltaV process control system

SRP PILOT PLANT FLOWSHEET



Pilot Plant Modifications



Structure modification

FTIR
5 Sample Pt MSSH
Heated lines

MTR Skid (BP3)

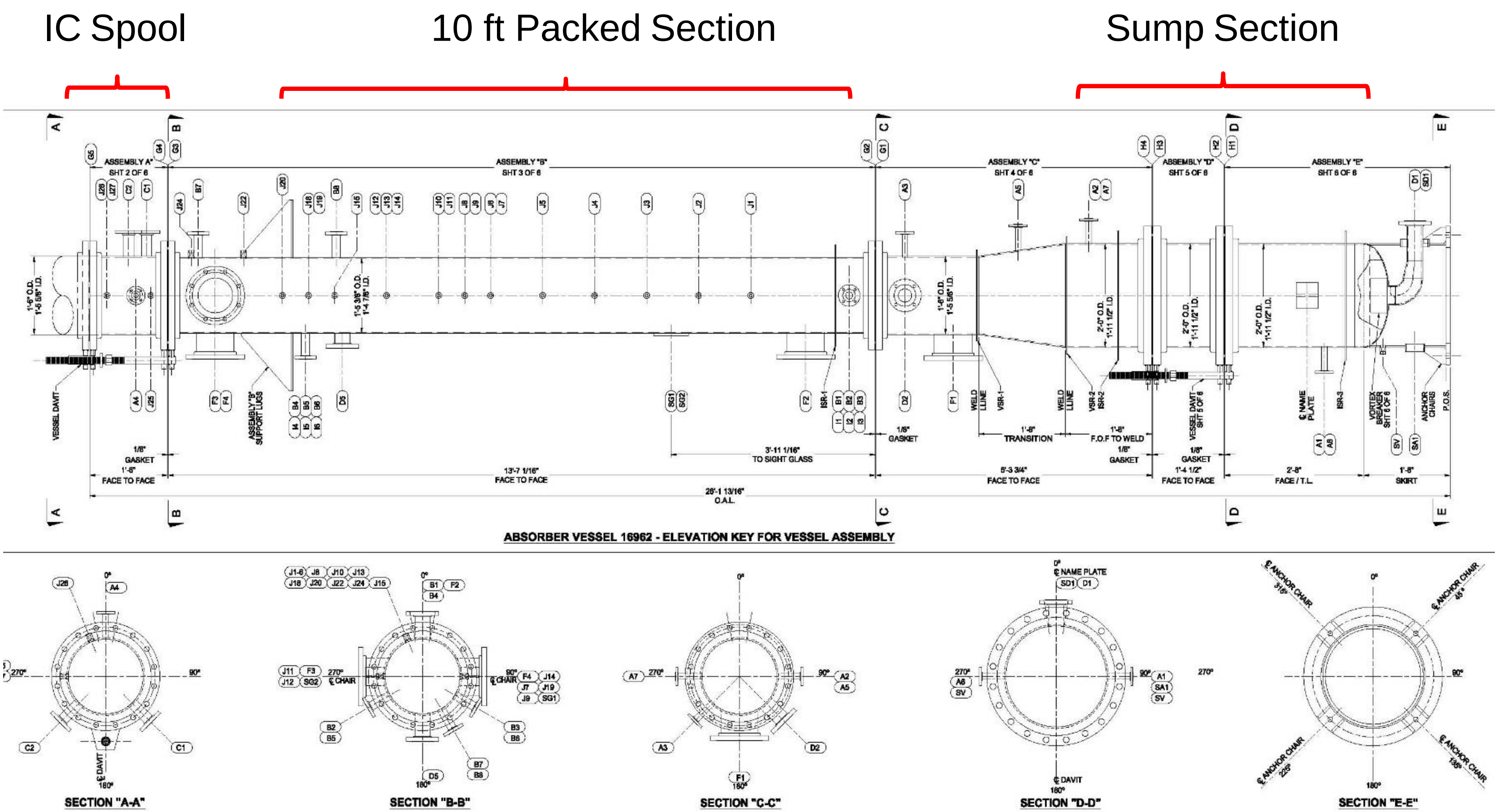
10-in AFS

Cold HP CX

Column Ext & Intercooling skids

HP Blower (BP3)

Absorber Column Extension



Absorber Columns Delivered

Absorber Pad and Column Installation

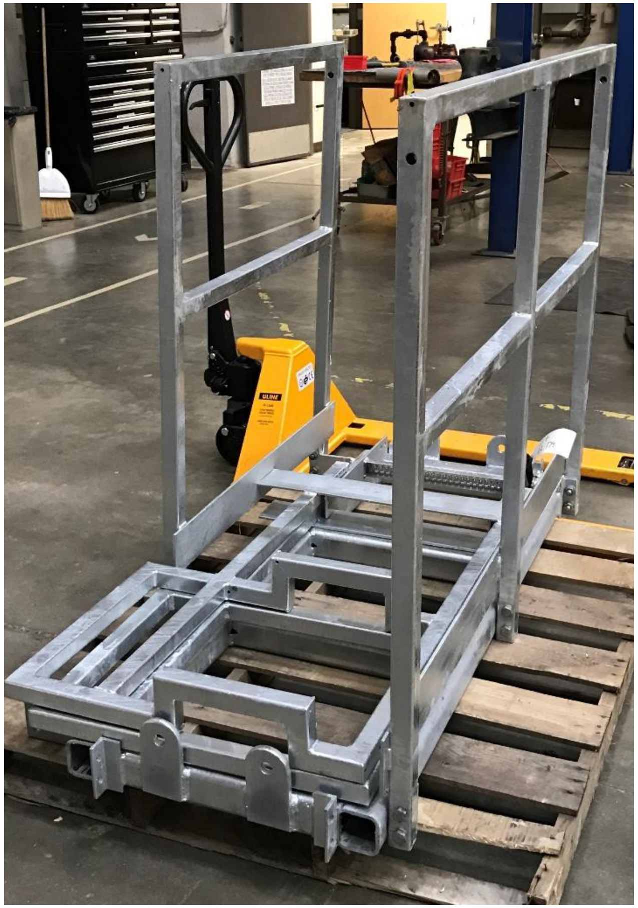
Existing Column Section Installed

Absorber and Stripper Internals Fabrication

New Level 5 Platform and L2 & L3 Extension Beams

6 month delay due UT PMCS Issues

Level 2 and 3 Extension Platforms



Intercooler & Water Wash Skids Fabrication

MTR

Intercooler and Water Wash Skids Installation

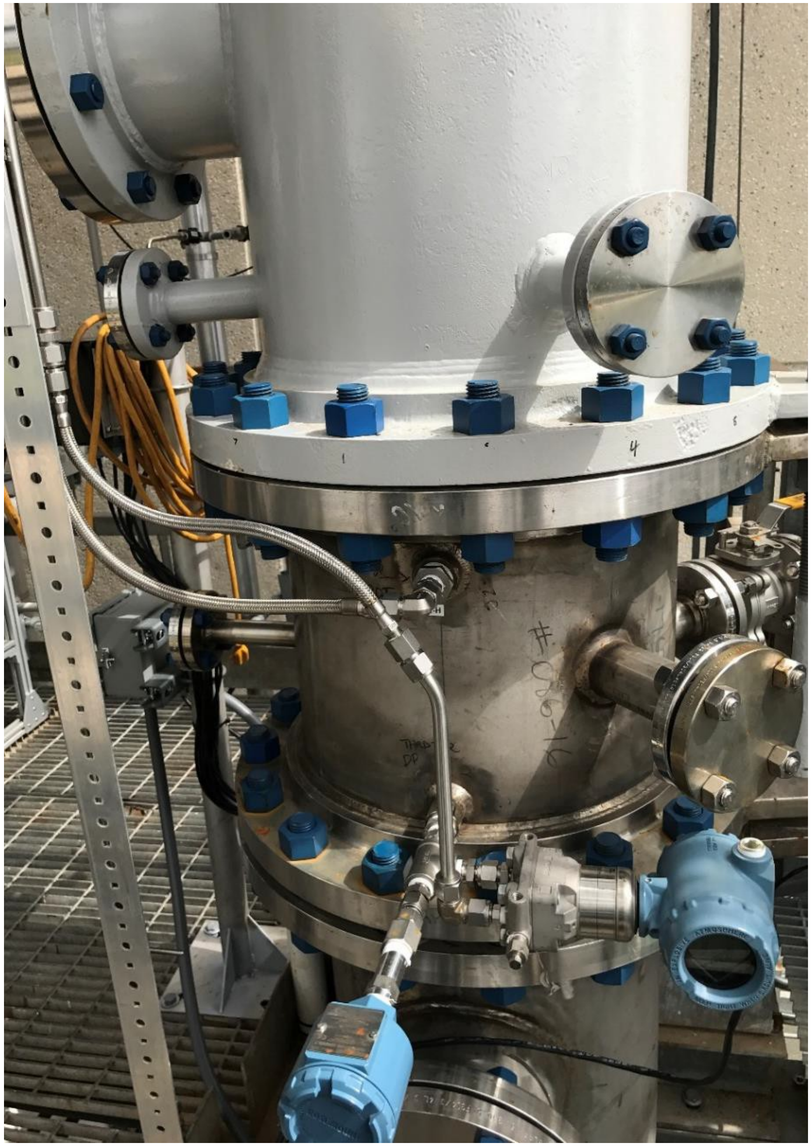
Absorber Gas and Liquid Outlet Piping

MTR

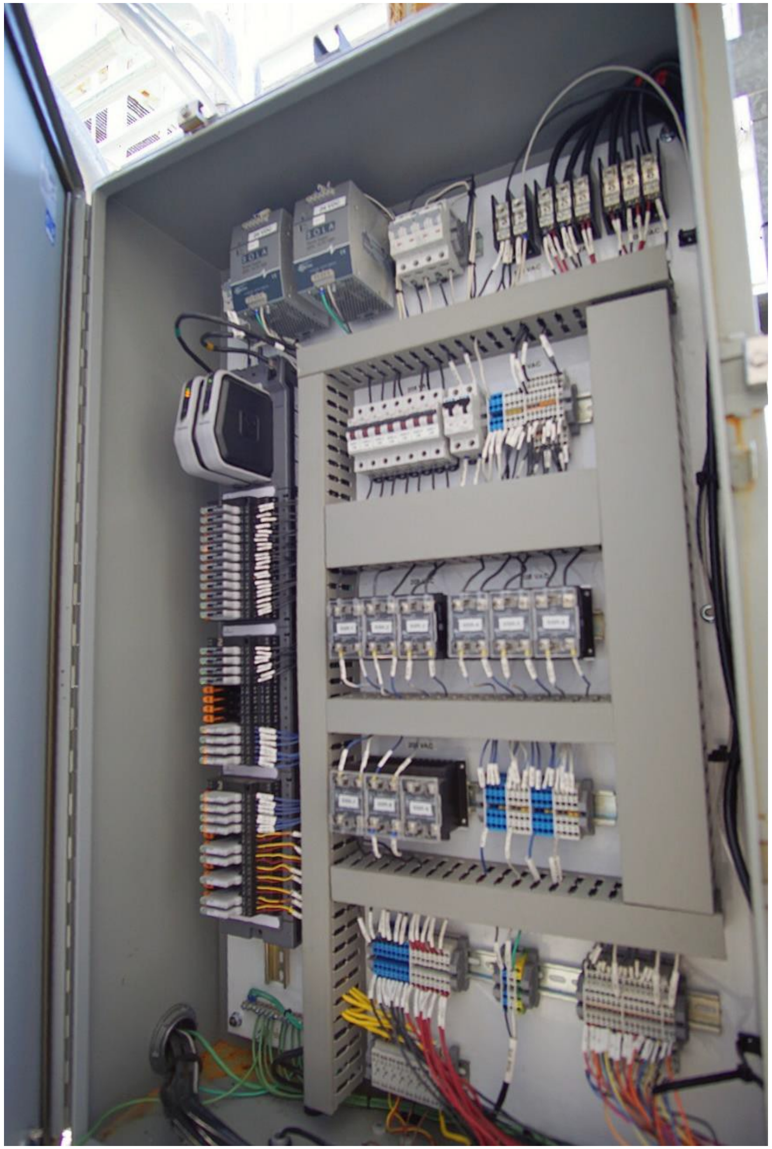
Absorber Feed and IC & WW Piping

MTR

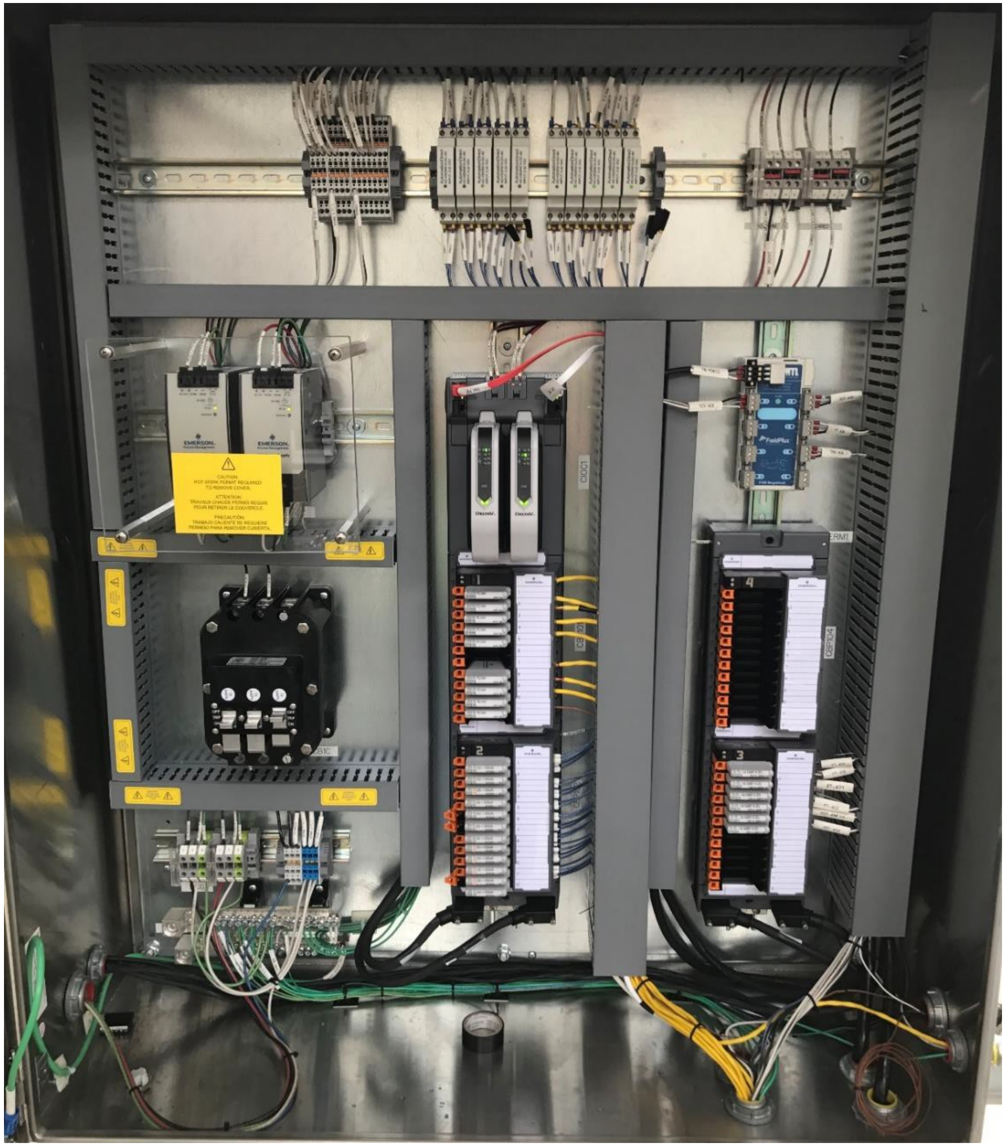
RTD and DP/P Instrumentation



FTIR MSSH Stream Switching Box

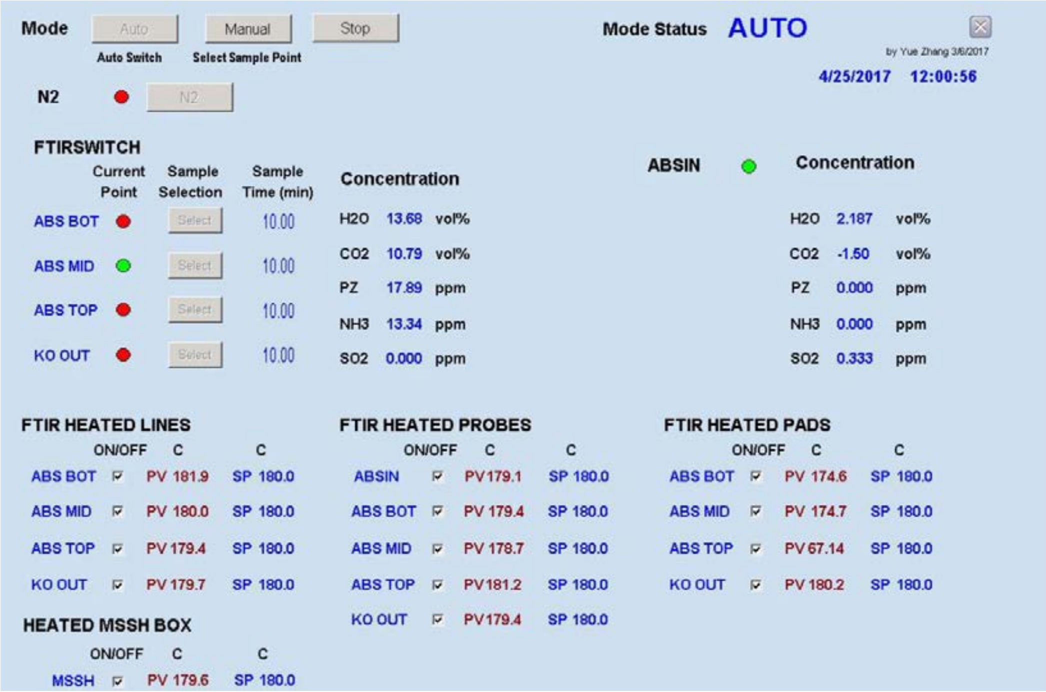


CHARMS Junction Box FTIR Heated Probes & Lines



MTR

FTIR Heated Probes and Lines
Five Locations and DeltaV



MTR

AFS 10” Column and Piping Mods

10” AFS Column Installed

MTR

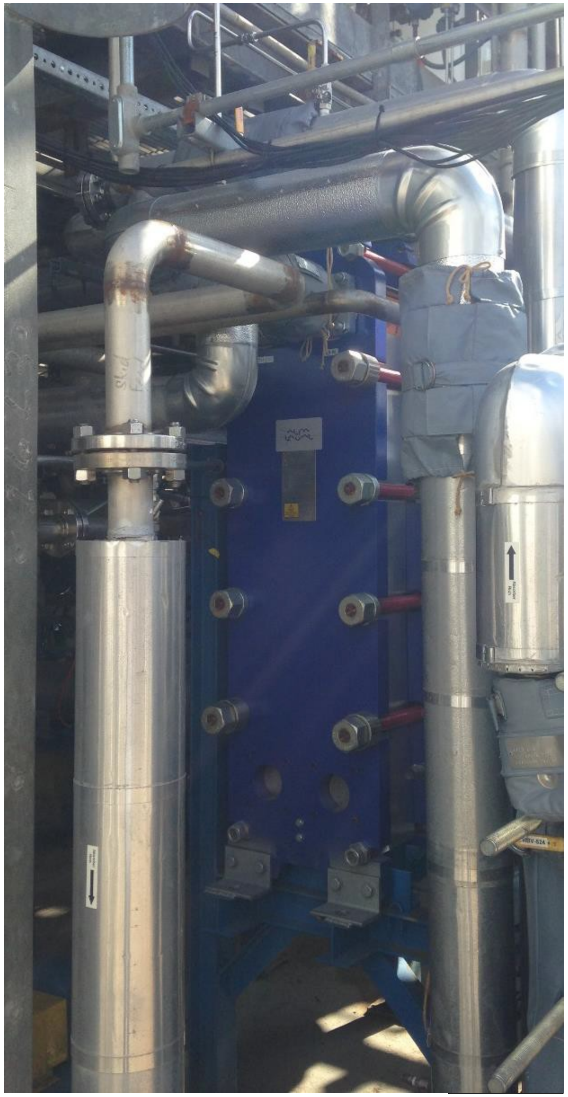
LP Cross-Exchanger Replacement

- New Alfa Laval TL10-BFS installed at the cold-rich bypass junction
- Operating pressure upgraded to 300 psi (vs. 150 psi for old HX)

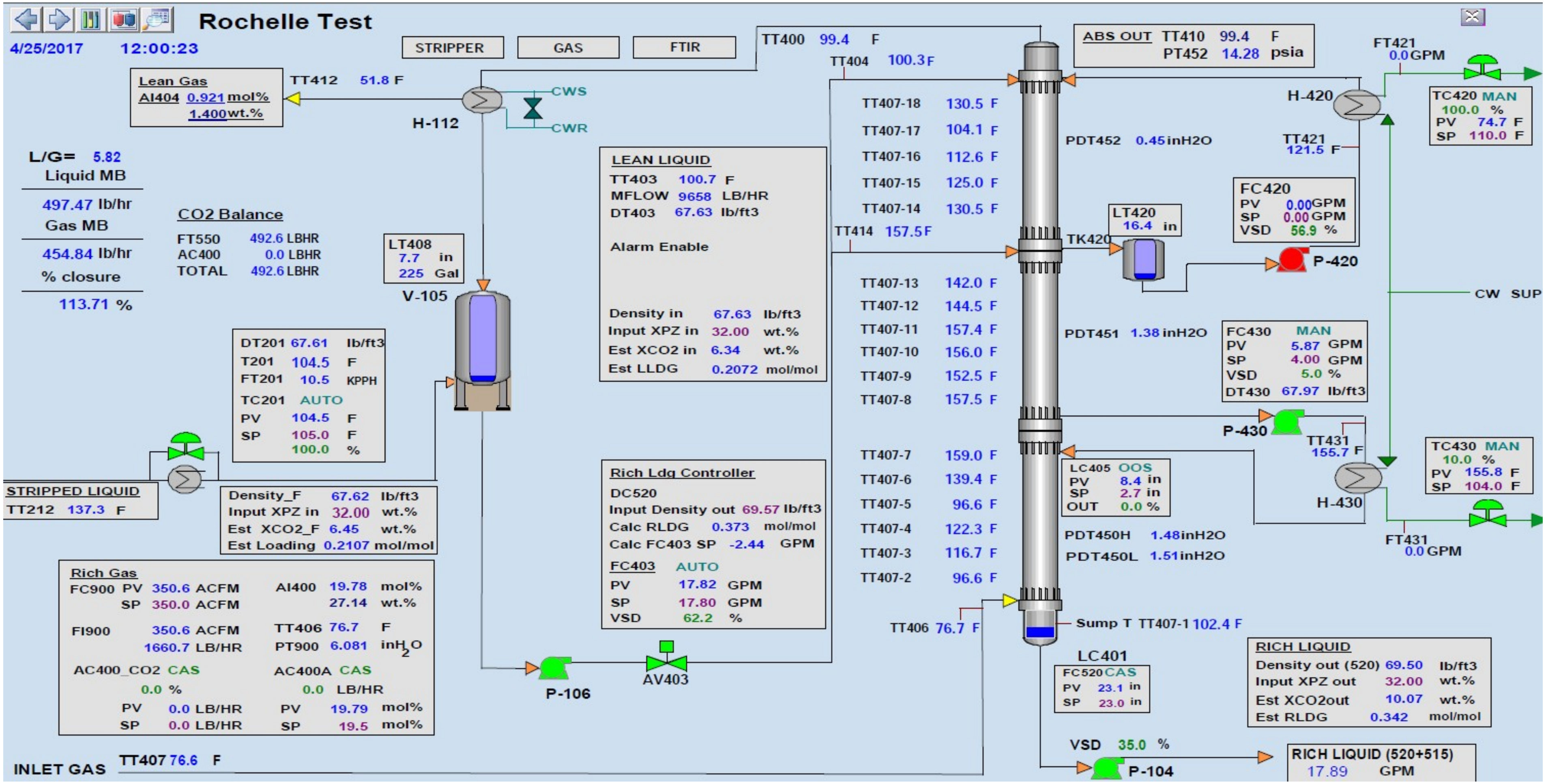
✓ System installed with connecting insulated piping

✓ Pressure tested

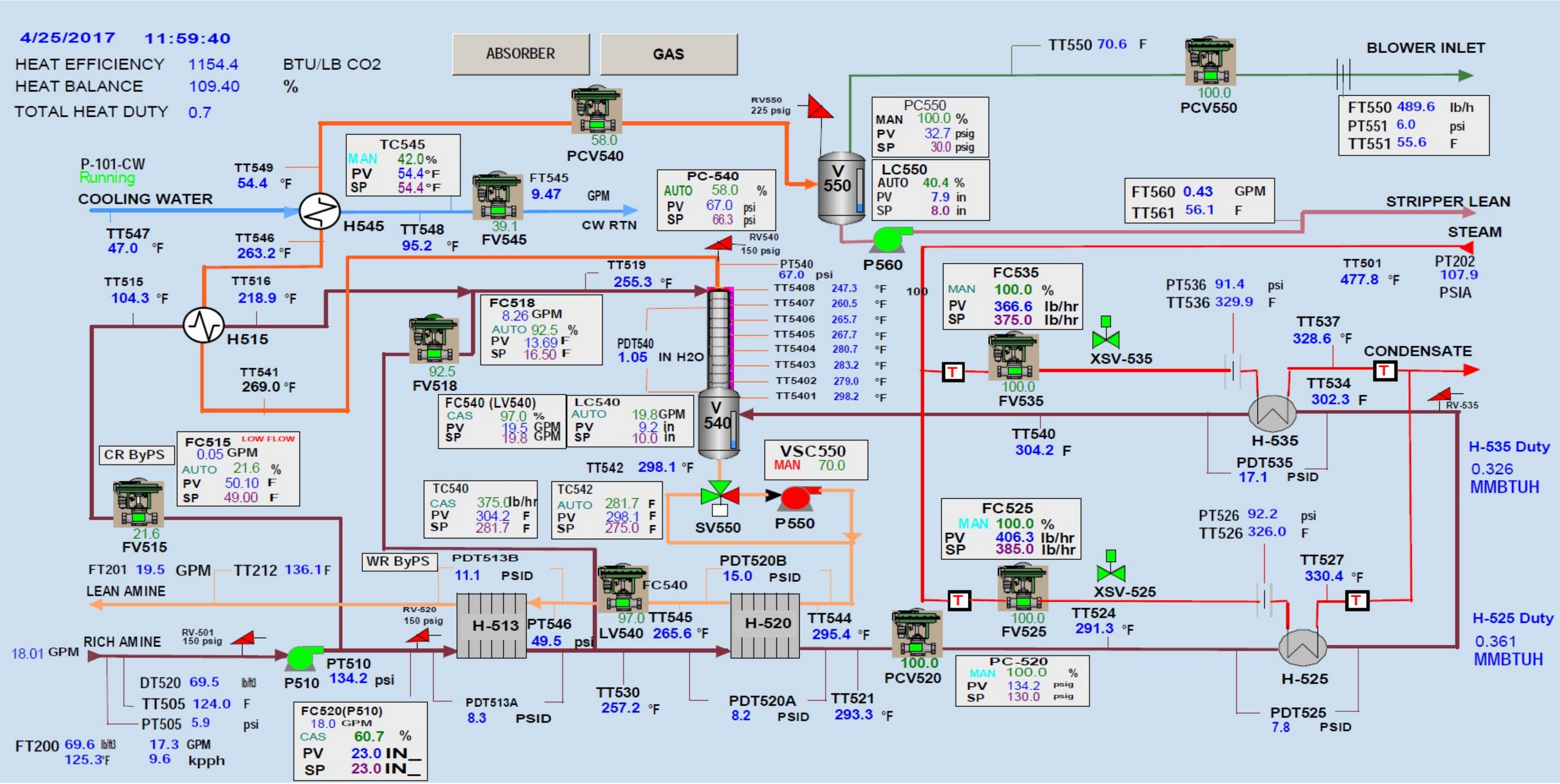
✓ Ready for operation



DeltaV Process Control System Absorber



DeltaV Process Control System Stripper

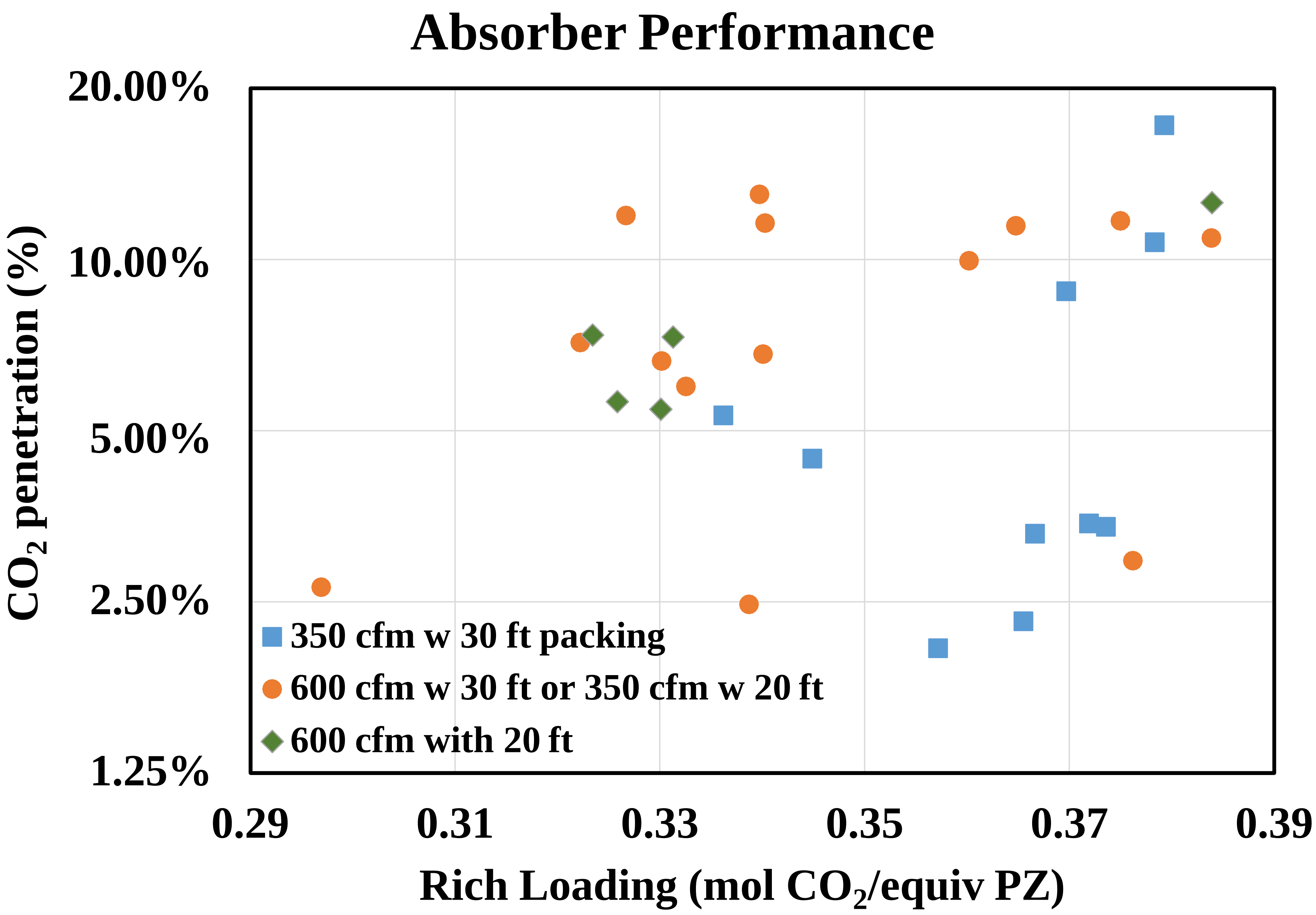


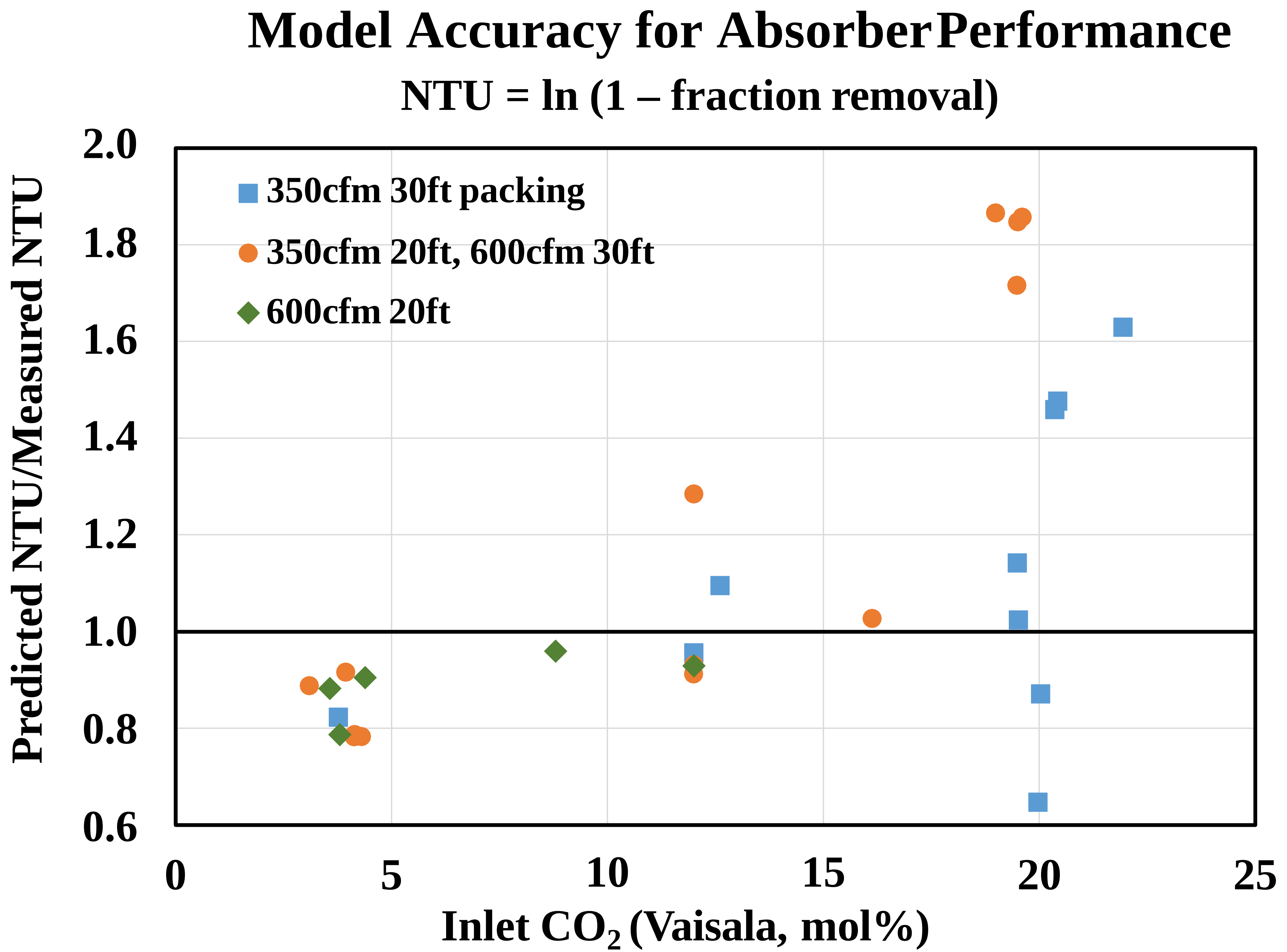
![MTR logo]

SRP Pilot Plant

Pilot Plant Data Set

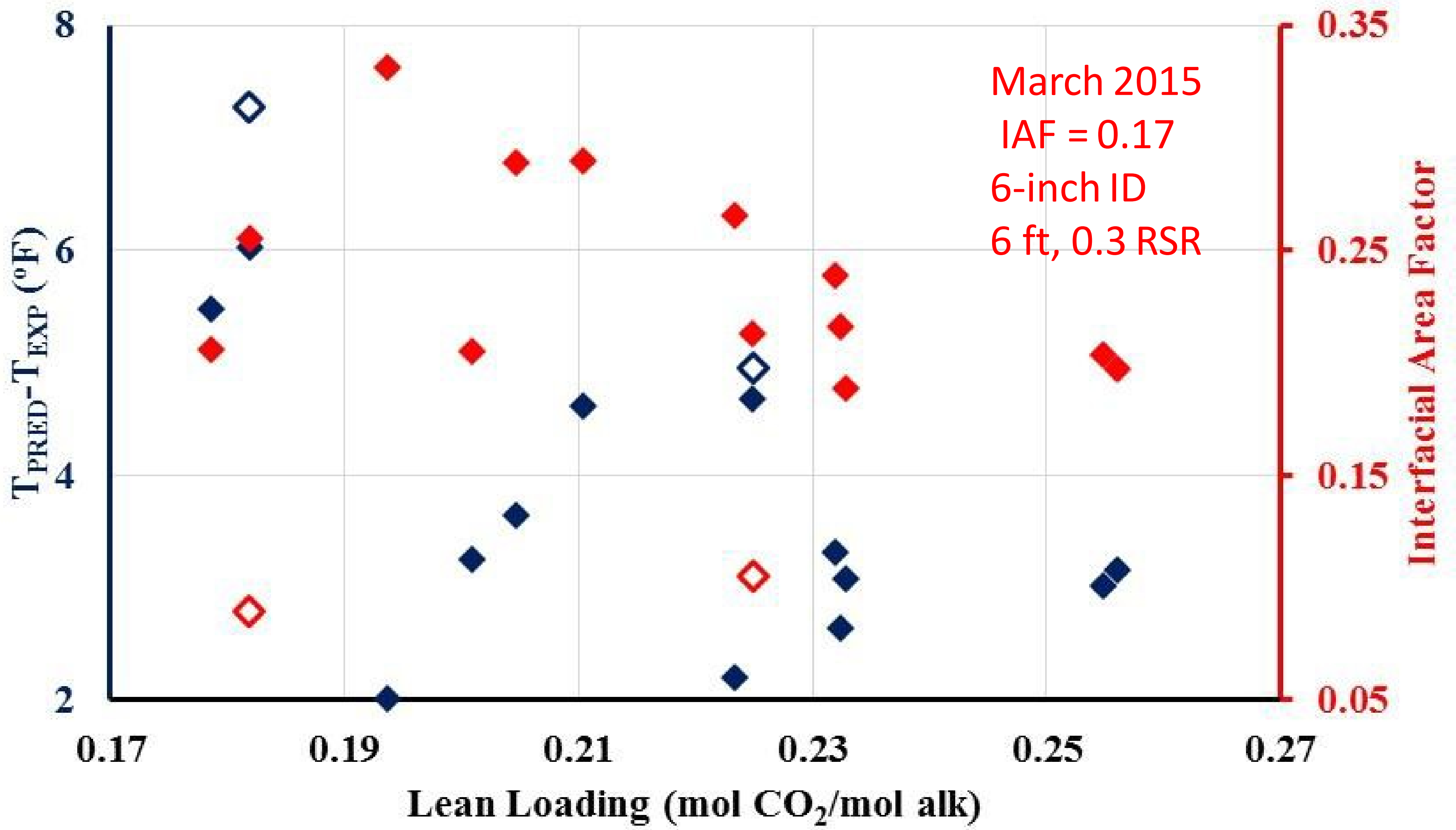
- 29 conditions with 5 m (30 wt%) Piperazine
- Inlet CO_2: 12 & 20% (DOE/MTR), 4% (CCP4)
- Solvent Rate: 3 – 24 gpm with 350 or 600 cfm air
- Lean loading: 0.18 – 0.27 mol CO_2/equivalent PZ
- Rich loading: 0.30 – 0.38
- 84 to 99 % CO_2 removal
- Two absorber configurations
  - 3x10 ft solvent
  - 2x10 ft solvent, 10 ft water wash
- Stripper T: 150^{o}C, 135^{o}C
- Analysis in progress, preliminary results will change


Absorber Performance
20.00%
10.00%
5.00%
2.50%
1.25%
CO_2 penetration (%)
0.29
0.31
0.33
0.35
0.37
0.39
Rich Loading (mol CO_2/equiv PZ)
350 cfm w 30 ft packing
600 cfm w 30 ft or 350 cfm w 20 ft
600 cfm with 20 ft

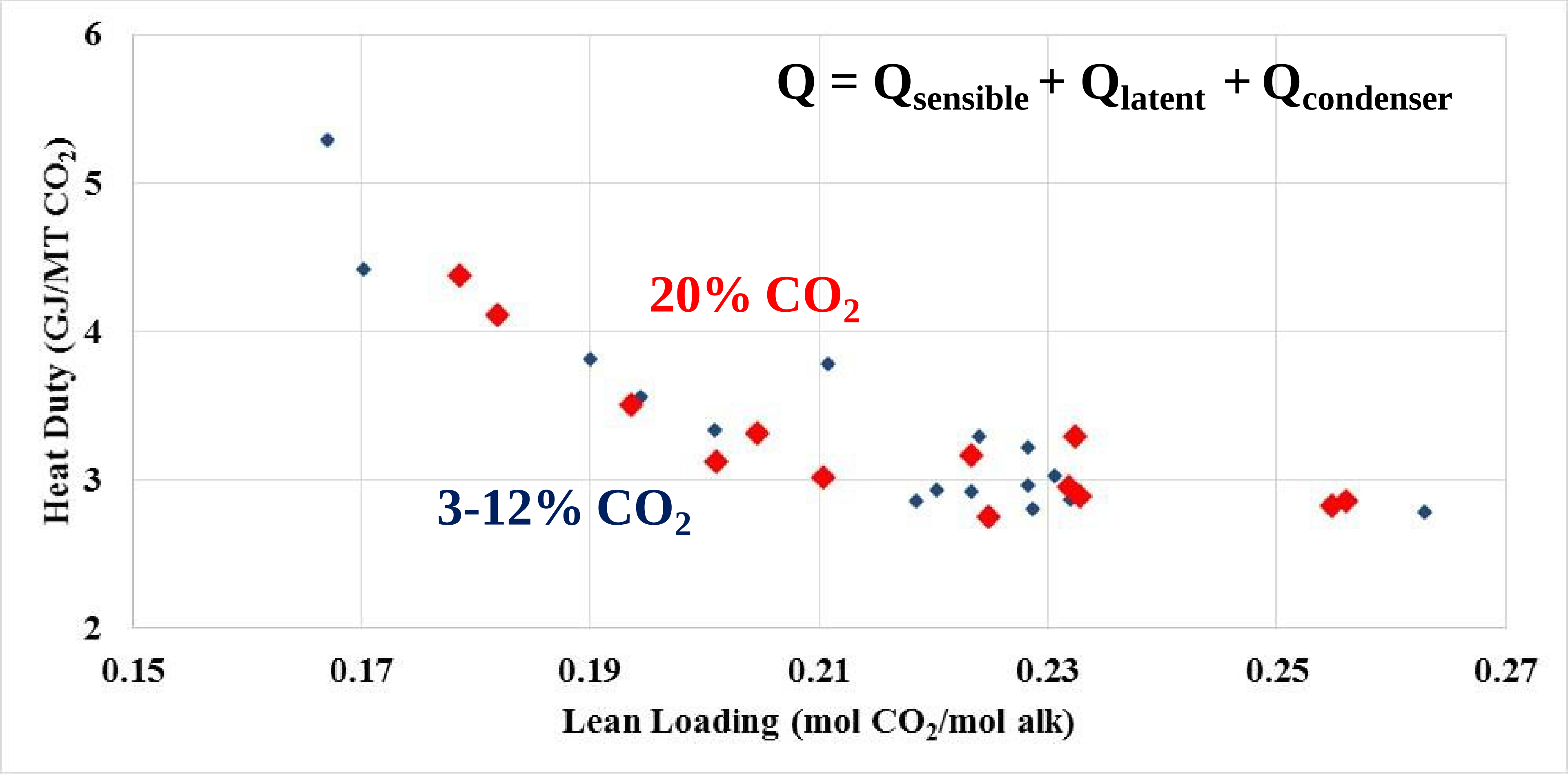

Model Accuracy for Absorber Performance
NTU = ln (1 – fraction removal)
350cfm 30ft packing
350cfm 20ft, 600cfm 30ft
600cfm 20ft
Predicted NTU/Measured NTU
Inlet CO_2 (Vaisala, mol%)
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0
5
10
15
20
25

Stripper Modeling of April 2017 data

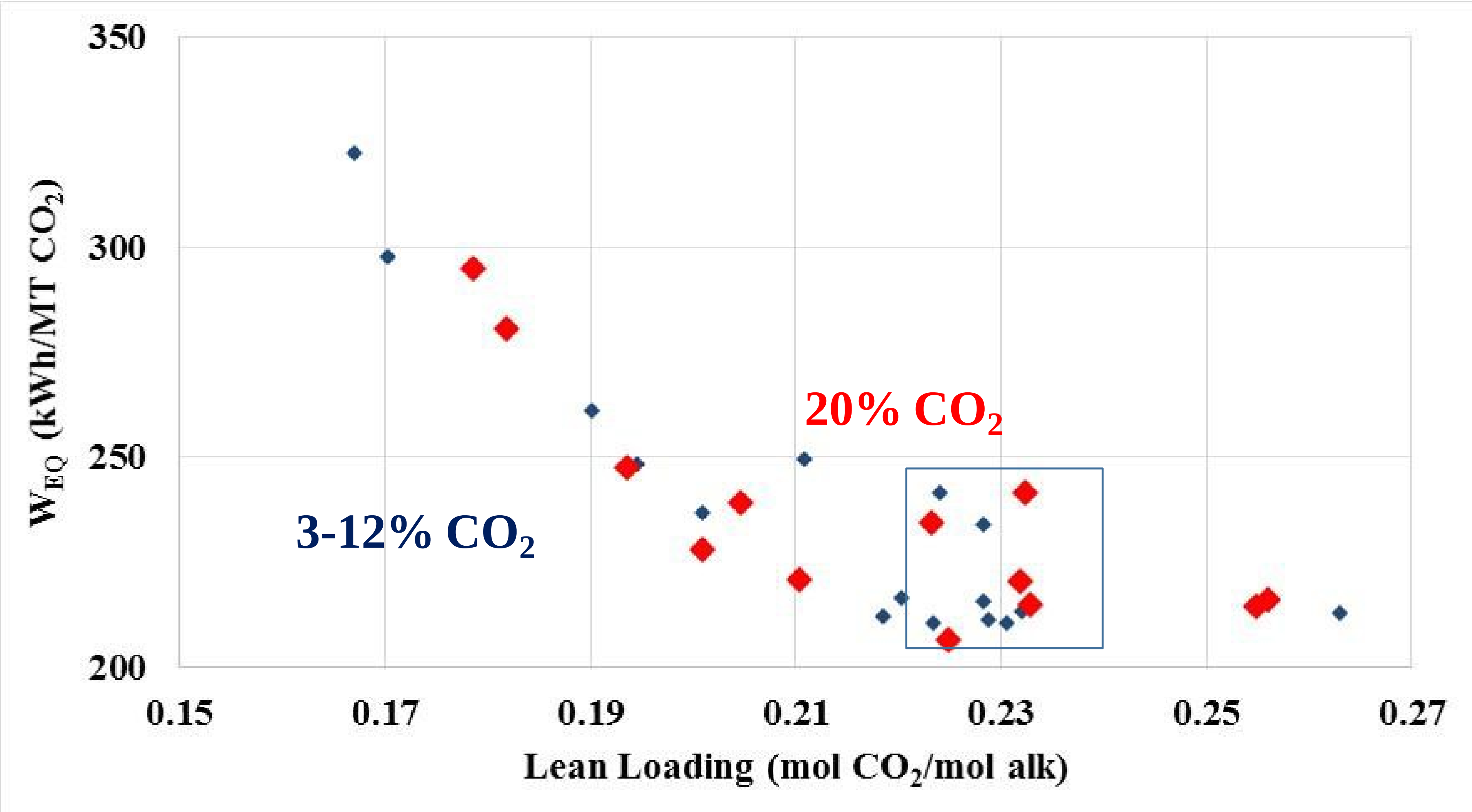
20% CO_2, 10-inch OD, 7 ft 0.5 RSR



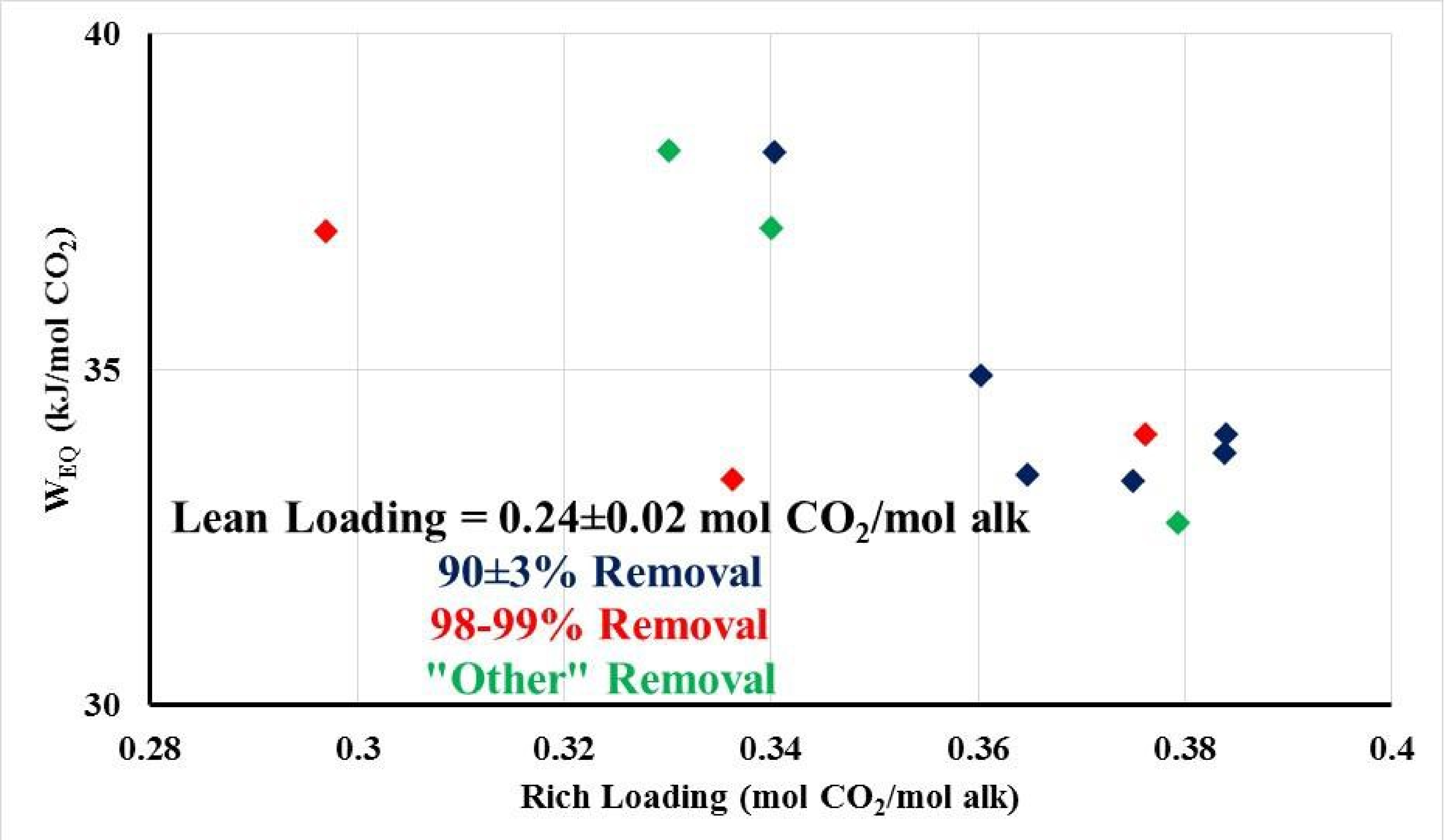
Heat Duty Including Some Heat Loss
Optimum Lean Loading > 0.21-0.27



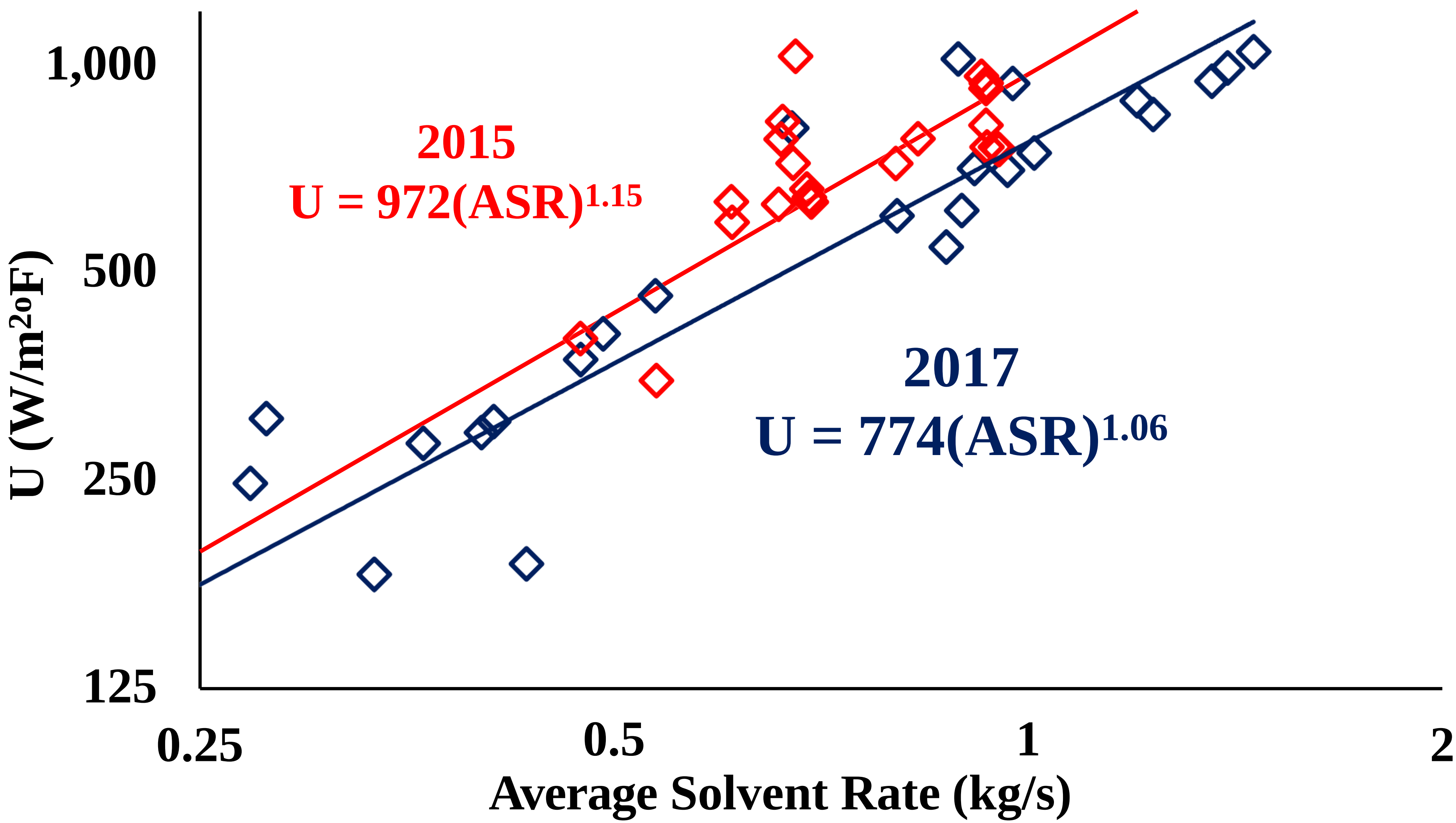
Total Equivalent Work (incl. some heat loss)
Est. compression to 150 bar
$W_{EQ} = W_{Steam} + W_{Compressor} + W_{Pump}$

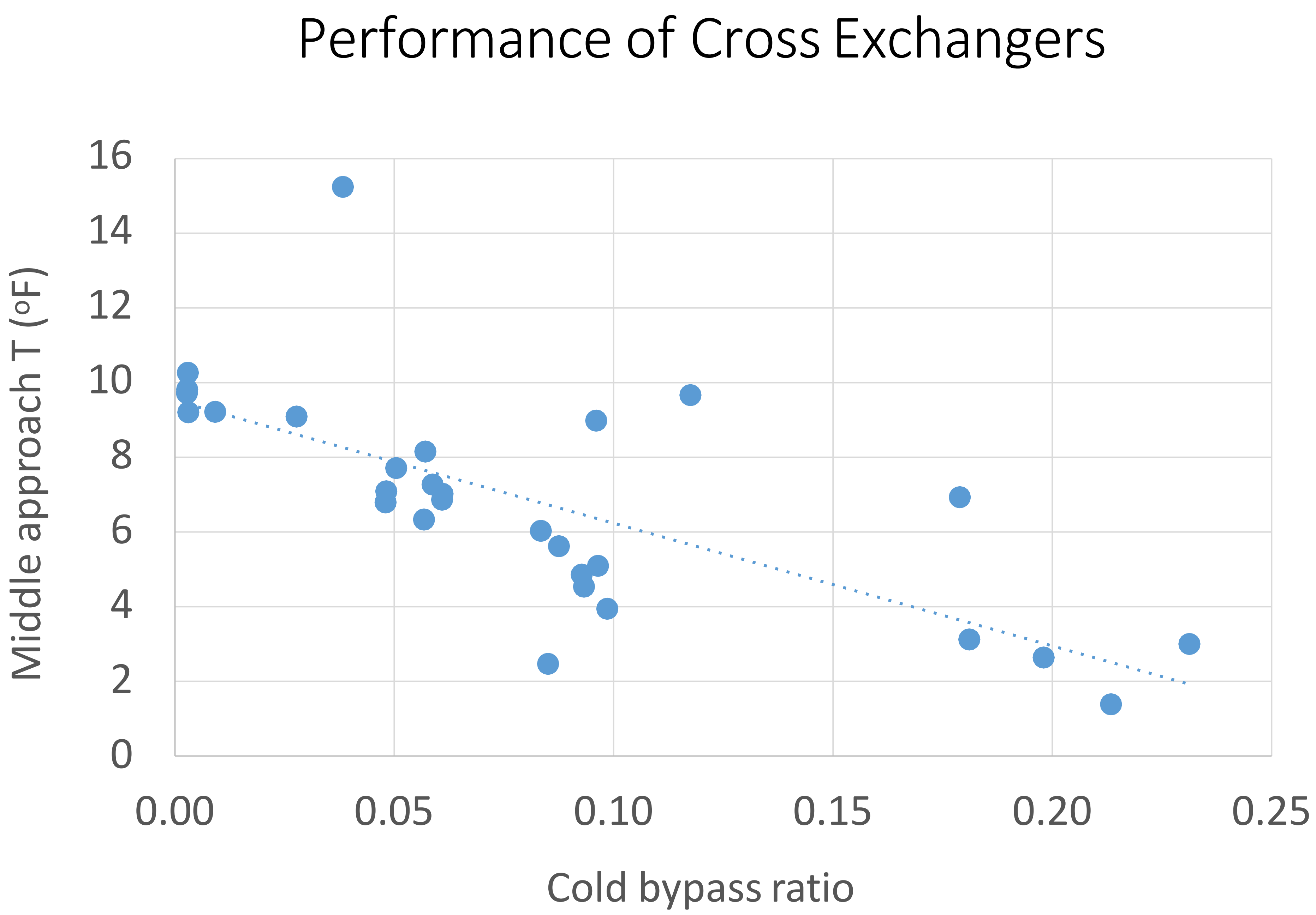


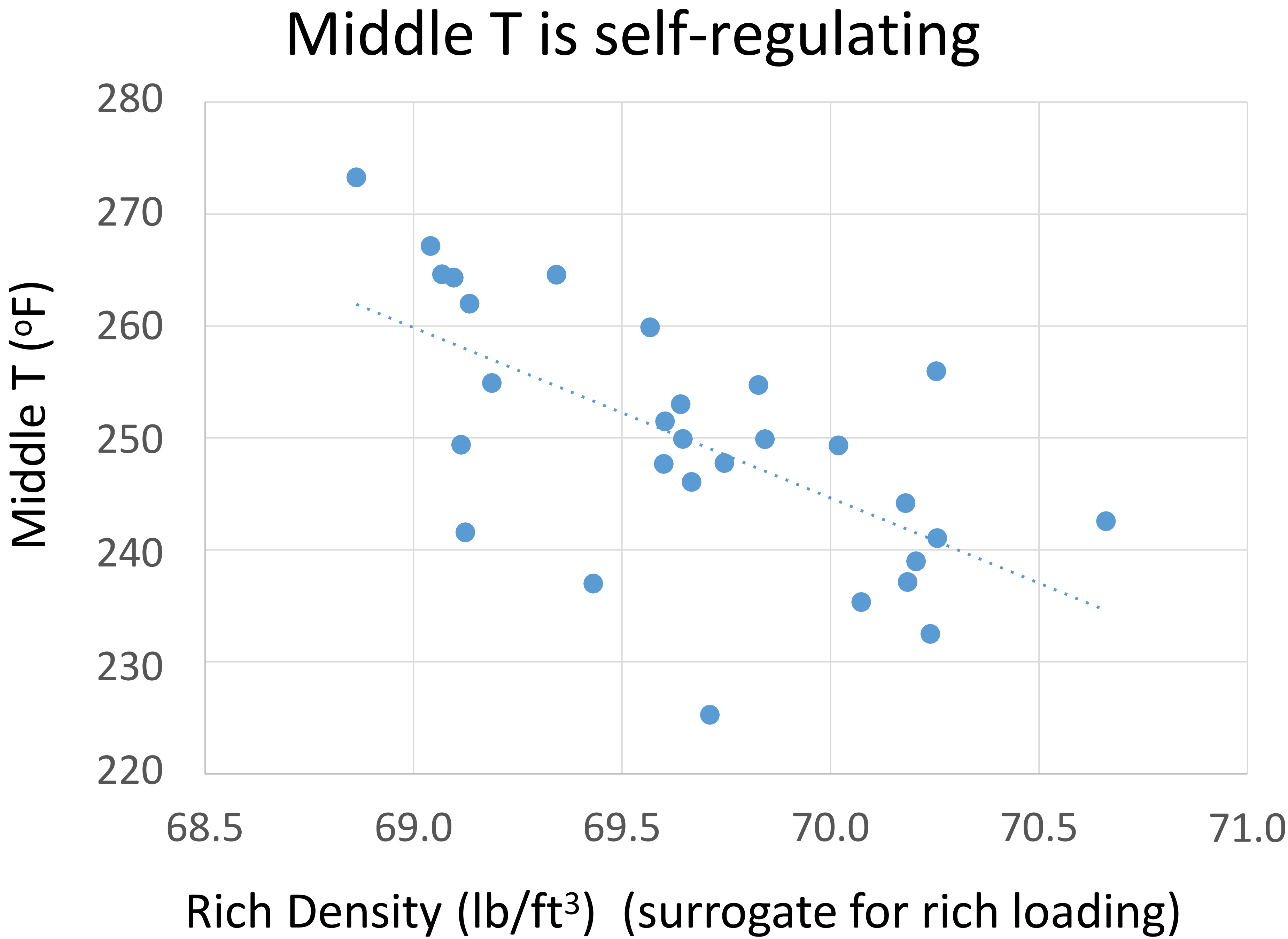
Expanded W_{eq} Near Optimum Loading



Performance of Cold Cross Exchanger

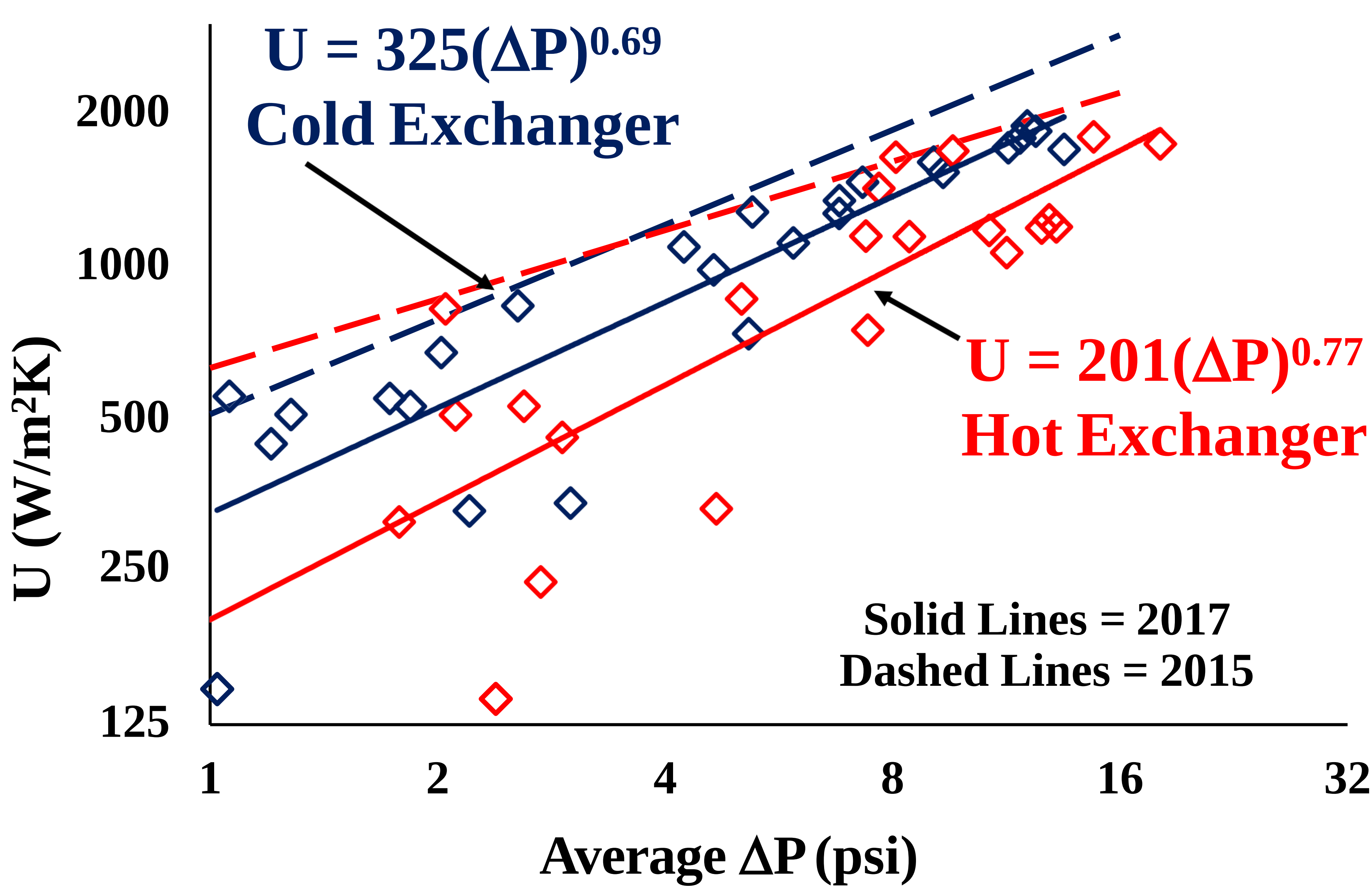



Performance of Cross Exchangers
Middle approach T (oF)
16
14
12
10
8
6
4
2
0
0.00
0.05
0.10
0.15
0.20
0.25
Cold bypass ratio



Middle T is self-regulating
280
270
260
250
240
230
220
68.5
69.0
69.5
70.0
70.5
71.0
Middle T (°F)
Rich Density (lb/ft³) (surrogate for rich loading)

Role of ΔP in Exchanger Performance



PZ Management Results

Precipitation minimized by 5 m PZ (only one incident)

Instr. air loss + chilled water to IC = precipitation

Melted at 80^{o}C with heat gun

Foaming Unexpected

Moderate unexpected absorber ΔP at high gas rate

Reduced to normal by antifoam

Oxidation is acceptable

NH_3 emissions of 3 to 10 ppm, could still be reduced

Aerosol requires high SO_3

PZ emissions doubled with addition of 5 -20 ppm SO_3

Corrosion of CS could be acceptable for stripper shell

175 (SS), 325 (CS) μm/yr in hot lean PZ

Tentative Conclusions from BP2 pilot campaign

Absorber predicted acceptably by “Independence”

- absorber model most accurate for 4% and 12% CO_2
- additional analysis needed for 20% CO_2

Energy requirement independent of Inlet CO_2

- heat loss needs more analysis
- nominal minimum W_{eq} = 215 kWh/t at 0.23 lean ldg

Exchangers provide 4-8^{o}F pinch with 5 to 10% cold bypass

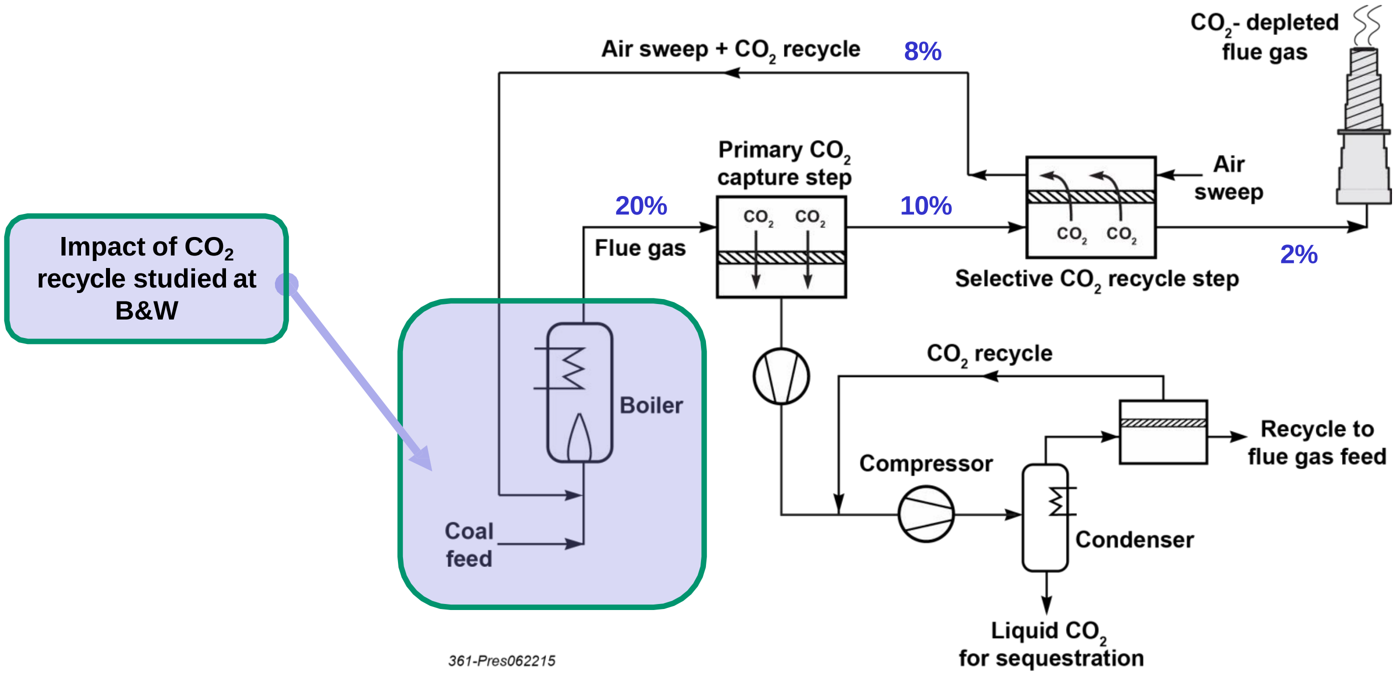
Hot flashing P&F exchanger provides reliable heat transfer

Objectives of BP3 Pilot Plant Campaign

1. Demo conditions for hybrid parallel configuration
2. Measure performance of membrane
   - Vary CO_2 - gas rate, membrane area
3. Measure absorber/stripper perf. at additional conditions
   - 20% CO_2 - 550 cfm (max stripper capacity)
   - 25% CO_2 - 350 cfm
   - 20% CO_2 - 10 ft packing (50% removal, series configuration?)

1. Address piperazine management
   - Volatile and aerosol emissions of PZ
     - Inject SO_3, characterize aerosols, test water wash, test cyclonic separator
   - Amine oxidation – test nitrogen sparging
   - Corrosion – monitor with ER, test carbon steel steam heater
   - Foaming – add carbon filter

Objectives of B&W Integrated Project (FE-0026414)



- Use MTR's 1 MW_e MTR small-pilot membrane system to test integrated operation (with CO_2 recycle to boiler) on an appropriately-sized boiler (B&W SBS-II)
- Validate prior B&W modeling and testing showing modest effect of recycled CO_2 on boiler performance

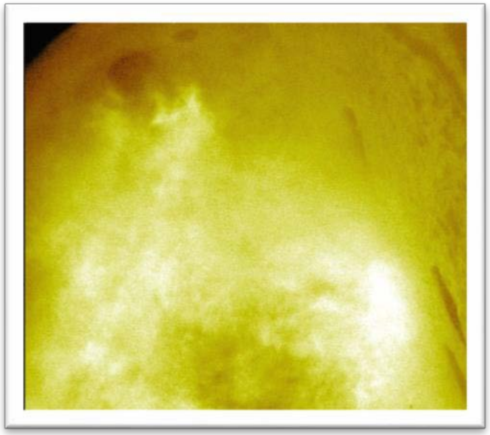
MTR Skids at B&W's SBS-II Research Facility (FE-0026414)

Main skid and smaller low-pressure drop sweep module anchored to foundation

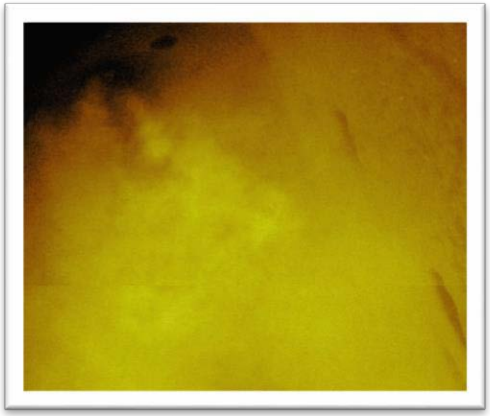
B&W Pilot Testing Highlights (FE-0005795)

- Stable and attached flames with air (21% O_2) and CO_2-enriched air (16-18% O_2)
- CO_2-enriched flame was less luminous than air-fired case
- Lower furnace heat absorption but higher convection pass/air heater heat transfer for CO_2-enriched operation relative to air
- No burner modifications necessary
- Net reduction in plant efficiency of ~0.75% with no boiler modifications (retrofit)

Flame image from combustion of PRB coal with air (21% O_2)

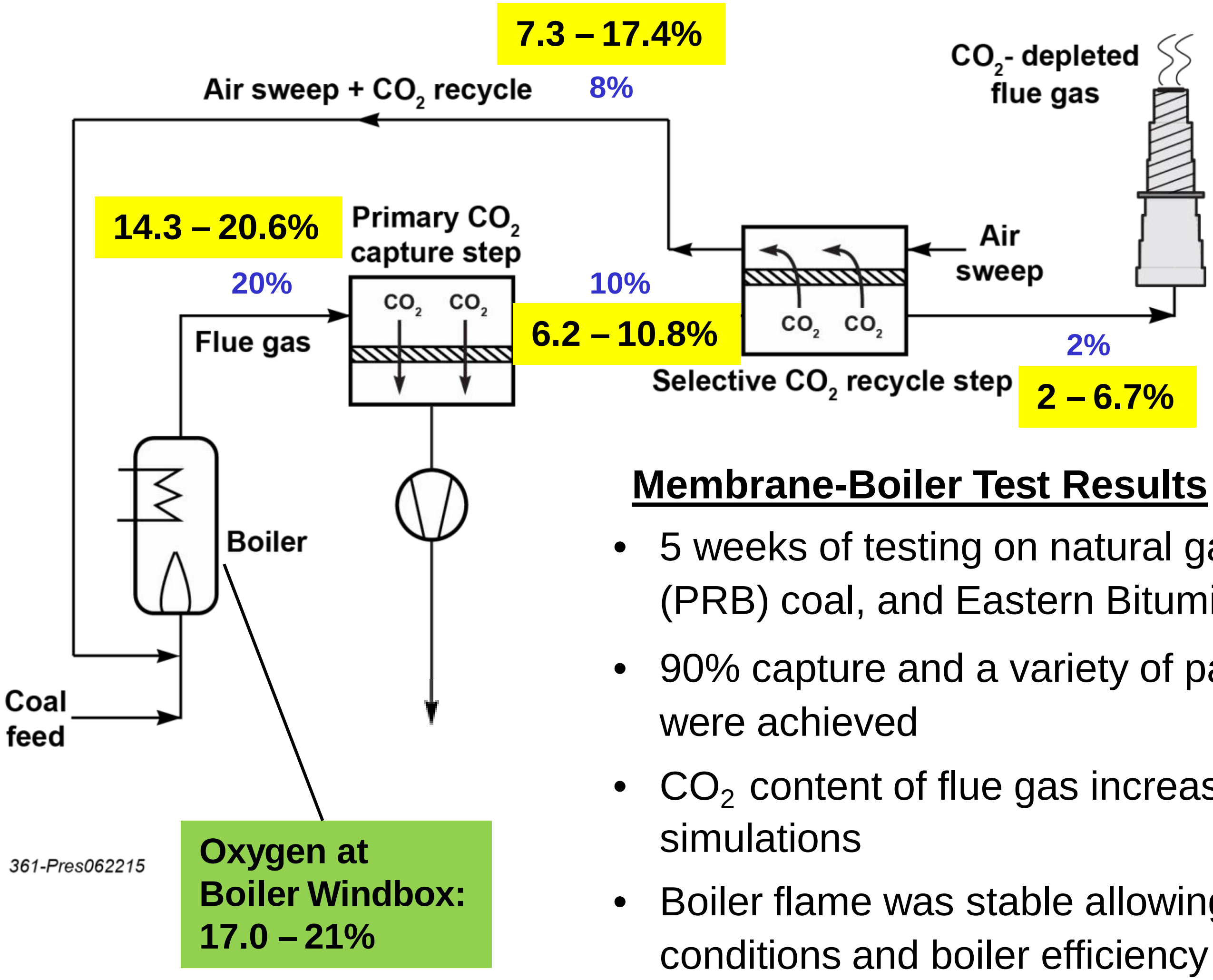


Flame image from combustion of PRB coal with CO_2–enriched (18% O_2)



MTR

Sample Results from B&W Integrated Tests (FE-0026414)



361-Pres062215

Membrane-Boiler Test Results

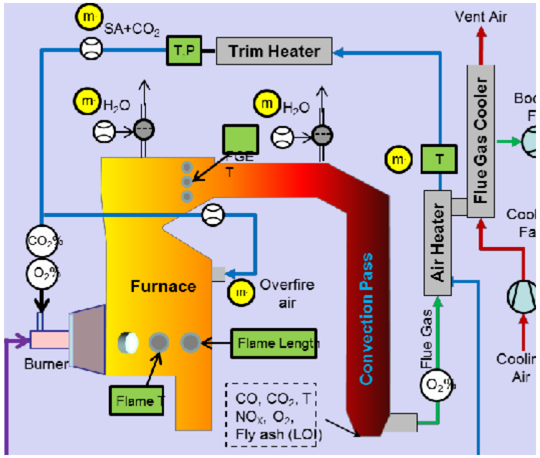
- 5 weeks of testing on natural gas, Powder River Basin (PRB) coal, and Eastern Bituminous coal completed
- 90% capture and a variety of partial capture conditions were achieved
- CO_2 content of flue gas increased as expected in simulations
- Boiler flame was stable allowing a full battery of stream conditions and boiler efficiency measurements to be conducted (analysis is ongoing)

MTR

Boiler Impacts from B&W (FE-0026414)

- Furnace heat absorption is lower resulting in higher furnace exit gas temperature (FEGT)
- Convection pass heat absorption is higher
- Convection pass outlet heat flux is higher
- Air heater heat absorption is higher
- Air heater flue gas outlet heat flux is higher
- Total heat absorption is reduced
- "Furnace" refers to the radiant heat transfer section of the boiler upstream of the tube banks in the convection pass.

Test Name		Coal 30P M1 & M2	Coal 27P M2 Only
Date		20-Oct-16	18-Oct-16
Test Duration	(h:mm)	7:00	7:15
Fuel		PRB	PRB
Load	(MW)	1.5	1.4
FEGT	(°C)	1,179	1,259
Convection Pass Exit Temperature	(°C)	397	380
Air Heater Exit Temperature (Flue Gas)	(°C)	217	210
Membrane Secondary Air Ratio		**53%**	**0%**
Furnace Absorption	(MW)	0.52	0.66
Convection Pass Absorption	(MW)	0.96	0.91
Convection Pass Outlet Heat Flux	(MW)	0.50	0.43
Total Heat Absorption	(MW)	1.62	1.68
Air Heater Absorption	(MW)	0.19	0.16
Air Heater Outlet Heat Flux (Flue Gas)	(MW)	0.31	0.27



Task 9 – Initial TEA

- Develop a cost framework using BBS Case #11
- Incorporates lessons learned from membrane testing and UT Austin's AFS capture process under simulated hybrid-parallel conditions
- Includes relevant lessons learned from NCCC and B&W membrane testing
- Based on prior TEAs conducted by Worley Parsons (MTR) and Trimeric (UT Austin)
- Will be updated in Task 11 (BP3) which will include:
  - Full fidelity
  - Scaling to 550 MWe (June, 2011 cost basis)
  - Sensitivities for cost-of-capture

MTR

Task 9 – Preview of Results

- Cost of capture calculated for the capture plant only. Includes place holders for some equipment performance and cost. Mixed base year dollars.
  - TOC $349,620,415
  - OCfix $7,820,527
  - OCvar $147,754,339
  - CF 85%, CCF 0.124, incl. 25% process cont.
  - Capturing 848.94 t/hr @ 100%CF; (90% capture rate)
  - Cost of capture $48.95

BP2 Milestones

Milestone Number	Task/ Subtask No.	Milestone Description	Planned Completion	Actual Completion	Verification Method
Budget Period 2 Milestones					
9a	7.1	Membrane module completely assembled and ready for parametric testing	9/30/2015	7/31/2015	Photos
10	8.1	Complete modifications of SRP Absorber	3/31/2017	4/10/2017	Quarterly report file and photos
9b	7.2	Complete parametric testing operation of membrane module in a test system	9/30/2016	9/30/2016	Quarterly report and test data (see Success Criteria below)
11	8.2	Complete operation of pilot plant at 20% CO_2 conditions	5/31/2017	5/23/17	Quarterly report and test data (see Success Criteria below)
12	9	Techno-economic model updated	5/31/2017	Est. 6/23/17	Updated Topical Report
13	9	Hybrid testing plan prepared	5/31/2017	6/06/17	Quarterly report file with detailed test plan

Decision Point	Date	Success Criteria
End of BP 2: Continue with integrated membrane testing at the Pilot Plant	5/31/2017	• Parametric test of membrane system and absorber/stripper successful. 90% CO_2 removal is achieved at conditions that simulate the hybrid process with membrane, • SRP Pilot Plant modifications are complete.

MTR

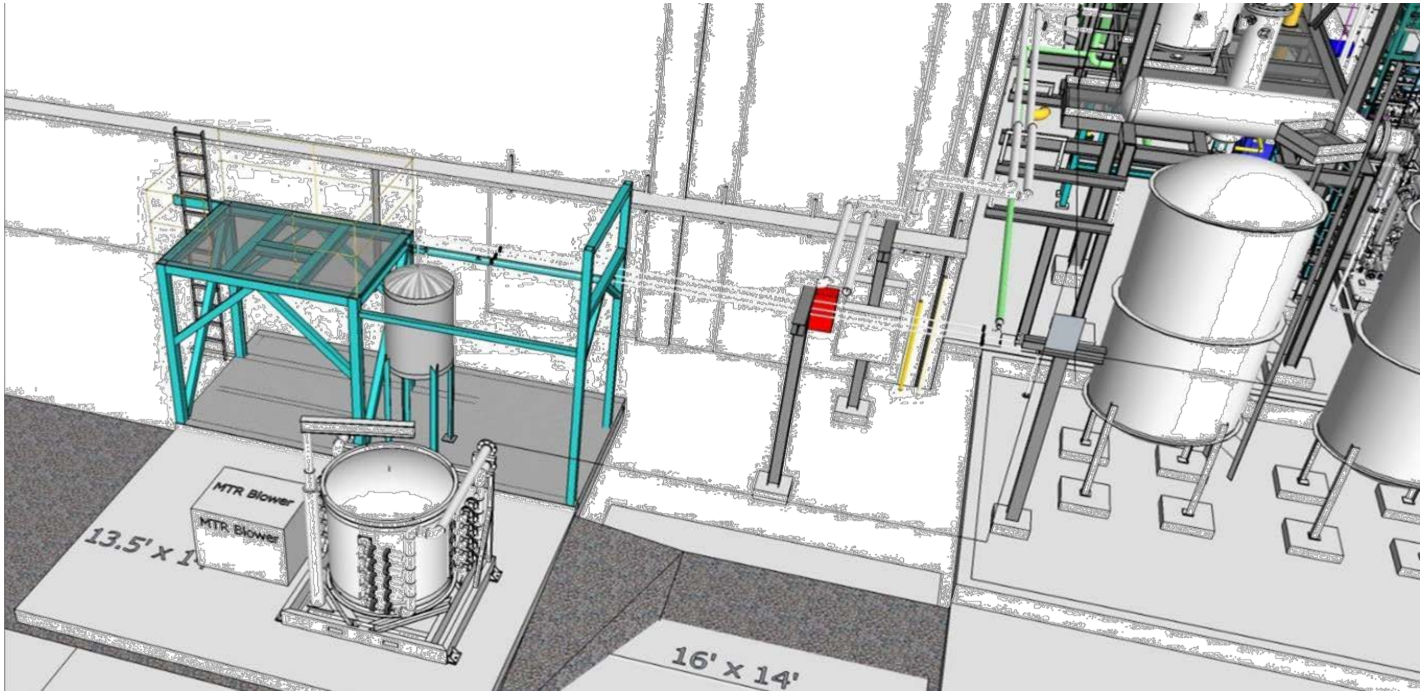
Outline

- Motivation, background, and objectives
- BP1 and BP2 results
- Review plan for BP3
- Questions and feedback

BP3 Next Steps

Budget Period 3

- Integrate MTR's plate-and-frame skid with UT Austin's SRP Pilot Plant
- Select and purchase blower for plate-and-frame skid
- Perform integrated testing campaign under hybrid-parallel conditions
- Final report and updated TEA based on test results

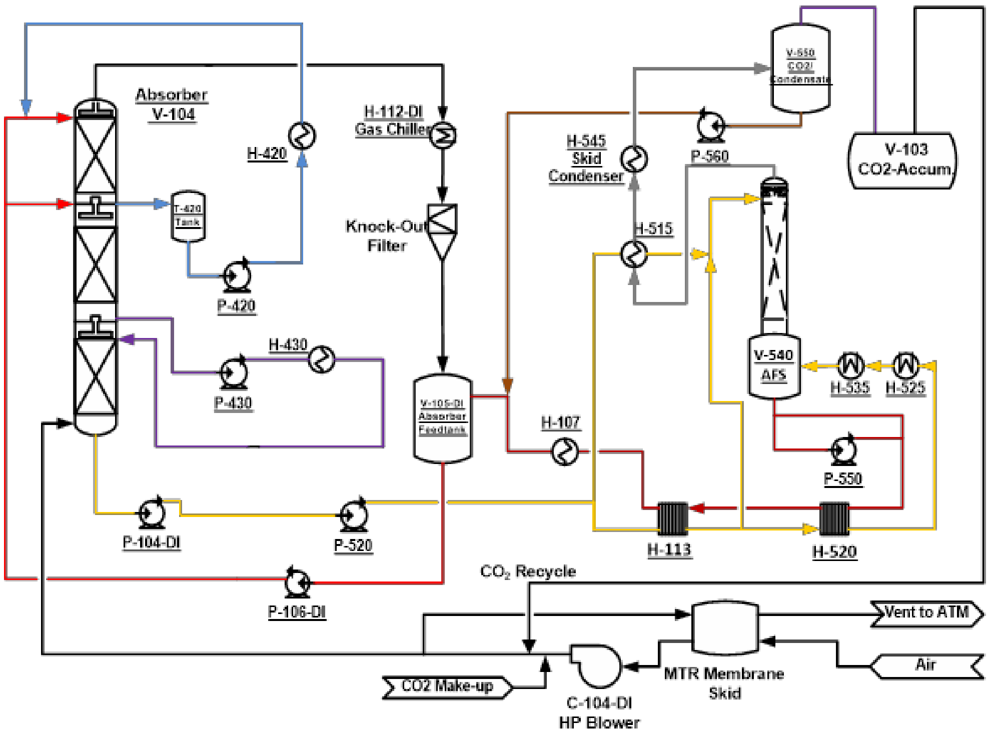


MTR

Plan for BP3 Integrated Testing (Task 10)

The SRP testing plan includes many parametric test cases to vary important process variables:

- Stripping pres.: 3.5 to 7.5 bara
- Inlet CO_2 concent.: 12 and 20%
- CRB split: 2 to 17%
- WRB split: 19 to 60%
- Lean loading: 0.18 to 0.27
- Rich loading: 0.38 to 0.40
- CO_2 removal: 81 to 99.7%



MTR

Task 11 – TEA and Final Report

- BBS Rev 2., with updated cost (June 2010)
- The most promising configuration will be scaled to 550 MW_e (Case #11 power plant reference)
- Develop heat and material balances, size and cost equipment
- Determine O&M costs reflecting predicted costs for consumables and membrane replacement.
- Include TEA sensitivities identified by NETL and project team in BP3.
- If the results are sufficiently encouraging, a roadmap to carry the technology forward will be prepared.

MTR

Topics for Further Study

- Investigate optimization methods used for coal to cement and/or steel applications.
- Perform a “cost of concentration study”
- Examine boiler derating effects in retrofit vs. new build applications.
- Option use the existing/resized secondary air fan to draw sweep air through the membrane.
- Hybrid costs as a function of system CO_2 removal?
- Hybrid as a phased approach to capture.
- Hybrid for natural gas boilers, gas turbines.
- Other topics?

BP3 Schedule

MTR-DOE Project Schedule - Hybrid Membrane with 5 m PZ	BP3											
	2017/8											
MTR-DOE SCOPE												
	J	**J**	**A**	**S**	**O**	**N**	**D**	**J**	**F**	**M**	**A**	**M**
Task 10: Install Membrane System at SRP & Run Parametric Testing												
10.1: Install membranes at SRP												
Process Design & PFD												
Equipment Specification & PID												
Update Test Plan												
Safety Review/HAZOP												
Procurement for SRP equipment modifications												
Installation of SRP equipment modifications												
Site preparation for MTR membrane skid												
Installation of membrane skid												
Process connections to membrane skid												
E&I connections to membrane skid												
10.2: Parametric testing of integrated system												
Commissioning												
Startup												
Plant Operation												
Shutdown												
Task 11: Final TEA and Process Model Updates												
Aspen - ChemCAD process model update												
Final TEA and report												

BP3 Spending Plan

Baseline Reporting Quarter	TOTAL	Budget Period 3: 6/1/17-5/31/2018					TOTAL	Project Totals
	BP2	Q15	Q16	Q17	Q18	Q19	BP3	
Baseline Cost Plan (from SF424A)	*10/1/15-5/31/17*	*6/1-6/30/17*	*7/17-9/17*	*10/17-12/17*	*1/18-3/18*	*4/18-5/18*	*6/1/17-5/31/18*	
Federal Share	$1,202,179	$77,101	$178,102	$166,730	$220,184	$154,202	$796,319	$3,159,652
Non-Federal Share	$300,544	$19,275	$44,526	$41,683	$55,046	$38,551	$199,080	$789,913
Total Planned (Federal and non-Federal)	$1,502,723	$96,376	$222,628	$208,413	$275,230	$192,753	$995,399	$3,949,565
Cumulative Baseline Cost (Project)	$2,954,166	$3,050,543	$3,273,170	$3,481,583	$3,756,813	$3,949,565	$3,949,565	$3,949,565
Actual Incurred Costs								
Federal Share	$1,164,134	$-						$2,363,334
Non-Federal Share	$417,149	$-						$734,299
Total Actual (Federal and non-Federal)	$1,581,283	$-						$3,097,632
Cumulative Baseline Cost (Project)	$3,097,632	$-						
Variance								
Federal Share	$38,045							$796,318
Non-Federal Share	$(116,605)							$55,615
Total (Federal and non-Federal)	$(78,560)							$851,933
Cumulative Baseline Cost (Project)	$(143,466)							$659,180

BP3 Milestone Log and Success Criteria

Milestone Number	Task/ Subtask No.	Milestone Description	Planned Completion*	Actual Completion	Verification Method
Budget Period 3 Milestones					
14	10.1	Membrane system installed at SRP Pilot Plant	12/31/2017		Presentation file and photos
15	10.2	Parametric testing of hybrid membrane-absorption system completed	4/30/18		Quarterly report with test data (see Success Criteria below)
16	11	Techno-Economic Assessment completed	5/31/2018		Topical report (see Success Criteria below)
17	11	Final Report including EH&S Assessment completed	5/31/2018		Final Report file

BP3 Success Criteria

Decision Point	Date	Success Criteria
End of BP 3: Hybrid testing completed	5/31/2018	• Hybrid system shakedown operations completed, • Steady-state testing of the hybrid capture system demonstrates stable 90% CO_2 capture, • Updated TEA shows process potential of $40/tonne CO_2 capture target.

MTR

Outline

- Motivation, background, and objectives
- BP1 and BP2 results
- Review plan for BP3
- Questions and feedback

Hybrid Project Team

- **DOE-NETL:**
  - Andy Aurelio (Federal Project Manager)
- **MTR:**
  - Brice Freeman (PI)
  - Richard Baker (Technical Advisor)
  - Pingjiao “Annie” Hao (Sr. Research Scientist)
  - Jay Kniep (Research Manager)
  - Tim Merkel (Dir. R&D)
- **U. Texas - Austin:**
  - Gary Rochelle (co-PI)
  - Eric Chen (Research Associate)
  - Frank Seibert (Sr. Research Engineer)
  - Darshan Sachde (Graduate Student)
  - Brent Sherman (Graduate Student)
  - Yue Zhang (Graduate Student)
  - Junyuan Ding (Graduate Student)