Development of a Novel Gas Pressurized Stripping (GPS)-Based Technology for CO_2 Capture from Post-Combustion Flue Gases

DE-FE0007567

Carbon Capture Scientific, LLC.
CONSOL Energy Inc.
Nexant Inc.
Western Kentucky University
HiGee USA Inc.

Presented by Shiaoguo (Scott) Chen

Project Closeout Meeting at DOE/NETL
Pittsburgh, PA , December 18, 2015

CARBON CAPTURE SCIENTIFIC, LLC.

Acknowledgements and Disclaimer

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NETL : Andrew Jones, Timothy Fout and Lynn Brickett

NCCC: Supporting team

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Presentation Outline

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- Results and Findings
  - **Simulation Study and Optimization of the GPS process**
  - **Measurement of Solvent VLE, Thermal and Oxidative Stability, and Corrosion at High Temperature and high CO_2 loading**
  - **Lab-Scale Experimental testing of GPS process performance**
  - **continuous skid Testing of a Bench-scale GPS based process**
  - **Techno-economic study of GPS-based PCC process**
  - **Conclusions**
- **Major Success Criteria**
- **Achievements and Future Work**

Project Participants

Partner/ Organization	Lead Contact(s)	Key Role(s)
DOE-NETL	Andrew P. Jones, Project Manager	Funding & Sponsorship
Carbon Capture Scientific, LLC	Shiaoguo (Scott) Chen, PI Zijiang (John) Pan, Co-PI	Process optimization Bench-scale experiments
CONSOL Energy Inc.	Daniel P. Connell, Co-PI Richard Winschel, Technical advisor	Phase equilibrium experiments and related process design
Nexant Inc.	Gerald Choi, PI Robert Chu, Sr. Chemical Engineer	Techno-economic analysis
Western Kentucky University	Prof. Wei-Ping Pan	Consultant on corrosion testing
HiGee USA	Prof. Jiangfeng (Jeffery) Chen	Specialty equipment (RPB) provider

Project Duration and Budget

- **Project duration: 10/1/2011 – 9/30/2015**
- **BP1: 10/1/2011 - 9/30/2012**
- **BP2: 10/1/2012 - 6/30/2014 (9-month extension)**
- **BP3: 10/1/2014 - 9/31/2015 (3-month extension)**

	Budget, $
Total DOE/NETL Fund	3,528,494
CCS and Other Cost share (in kind)	896,119
Total	4,424,613

Project Tasks and Schedule: Oct.1, 2011 –Sept. 30, 2015

Tasks	Task Duration																Task Focus	Performer				
	1-12 BP1				13-33 BP2							34-48 BP3						CCS	HiGee	CONSOL	Nexant	WKU
Task 1. Project planning & management																	N/A	X				
Task 2. GPS column study and its optimization																	Process	X				
Task 3. Optimization of GPS process for existing plant																	Process	X				
Task 4. Simulations of Alternative Separations method for GPS stripping gas																	Process	X				
Task 5. Phase equilibrium data measurement																	Solvent	X		X		
Task 6. First absorption column testing																	Process	X		X		
Task 7. GPS column design/fabrication/testing																	Process	X		X		
Task 8. Second absorption column testing																	Process	X		X		
Task 9. Stability of solvent at high loading & T																	Solvent	X				X
Task 10. Corrosion test at high loading & T																	Solvent	X				X
Task 11. RPB unit evaluation at CCS Lab																	Equipment	X	X			
Task 12. Survey of EH&S of GPS process																	Solvent	X				
Task 13. Preliminary techno-economic analysis																	Economics				X	
Task 14. Revision of techno-economic analysis																	Economics				X	
Task 15. Updated techno-economic analysis																	Economics				X	
Task 16. Design/fabrication of a bench scale GPS unit with Conventional Columns																	Process	X				
Task 17. Bench-Scale Testing of the Skid Mounted Column Based GPS System																	Equipment	X				

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Project Objectives

Overall Objective

- Develop a breakthrough Gas Pressurized Stripping (GPS) process-based technology for CO_2 capture from post-combustion flue gases

Specific Objectives

- Perform bench-scale tests of individual process units to obtain necessary process design data for the pilot scale
- Conduct computer simulations to maximize the benefit of the GPS technology for existing power plants
- Carry out experimental investigation of selected solvents to minimize the economic risk of the GPS technology.
- Perform bench-scale tests of a rotating packed bed (RPB) to evaluate performance.
- Design, build, and test a GPS skid capable of processing 500 SLPM actual coal-derived flue gas in a column-based GPS system operating at the National Carbon Capture Center (NCCC).

Technology Background

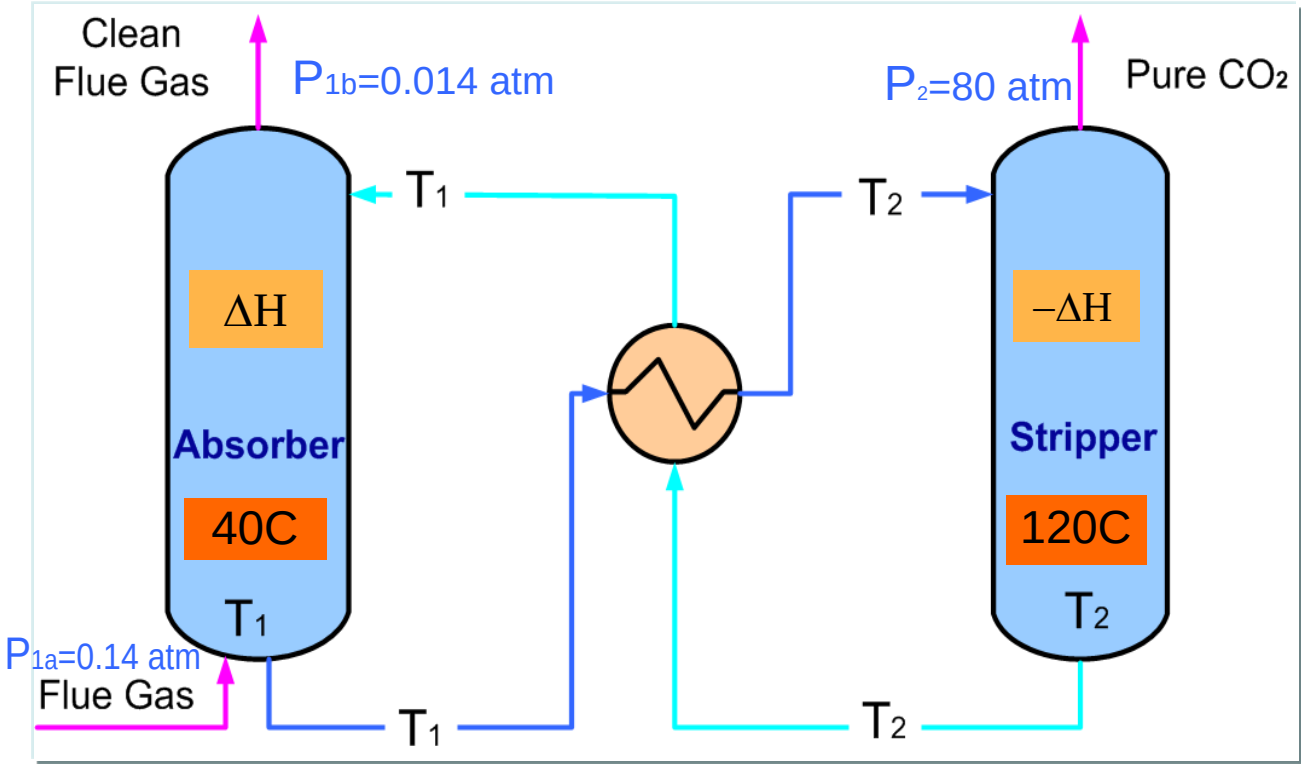
- Thermodynamics behind the GPS process
- Issues with conventional absorption/stripping processes
- History of the GPS process configurations
  - Initial GPS process
  - Alternative GPS process
  - Final GPS process
- Advantages of GPS process

Thermodynamics Behind the GPS Process

CO_2 Capture/ Regeneration:

$$M + CO_2 \Leftrightarrow N - \Delta H$$

$$K = \left(\frac{\gamma_N x_N}{\gamma_M x_M}\right)\frac{1}{P_{CO2}}$$

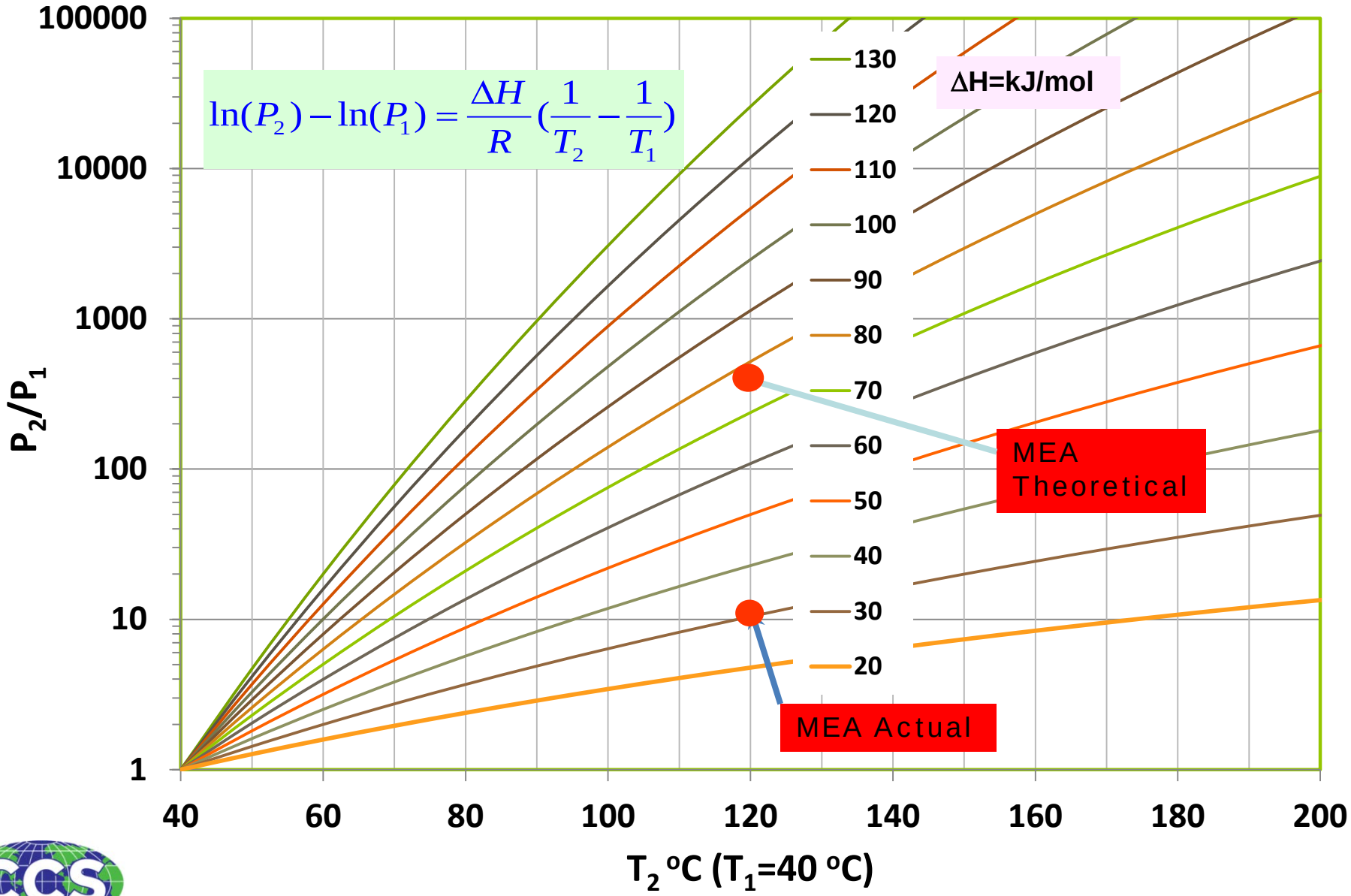


Ignore all the driving force for heat and mass transfer

***van't Hoff Equation*:**

$$\frac{dlnK}{dT} \approx \frac{-dlnP_{CO2}}{dT} = \frac{-\Delta H}{RT^2}$$

Thermodynamics Behind the GPS Process



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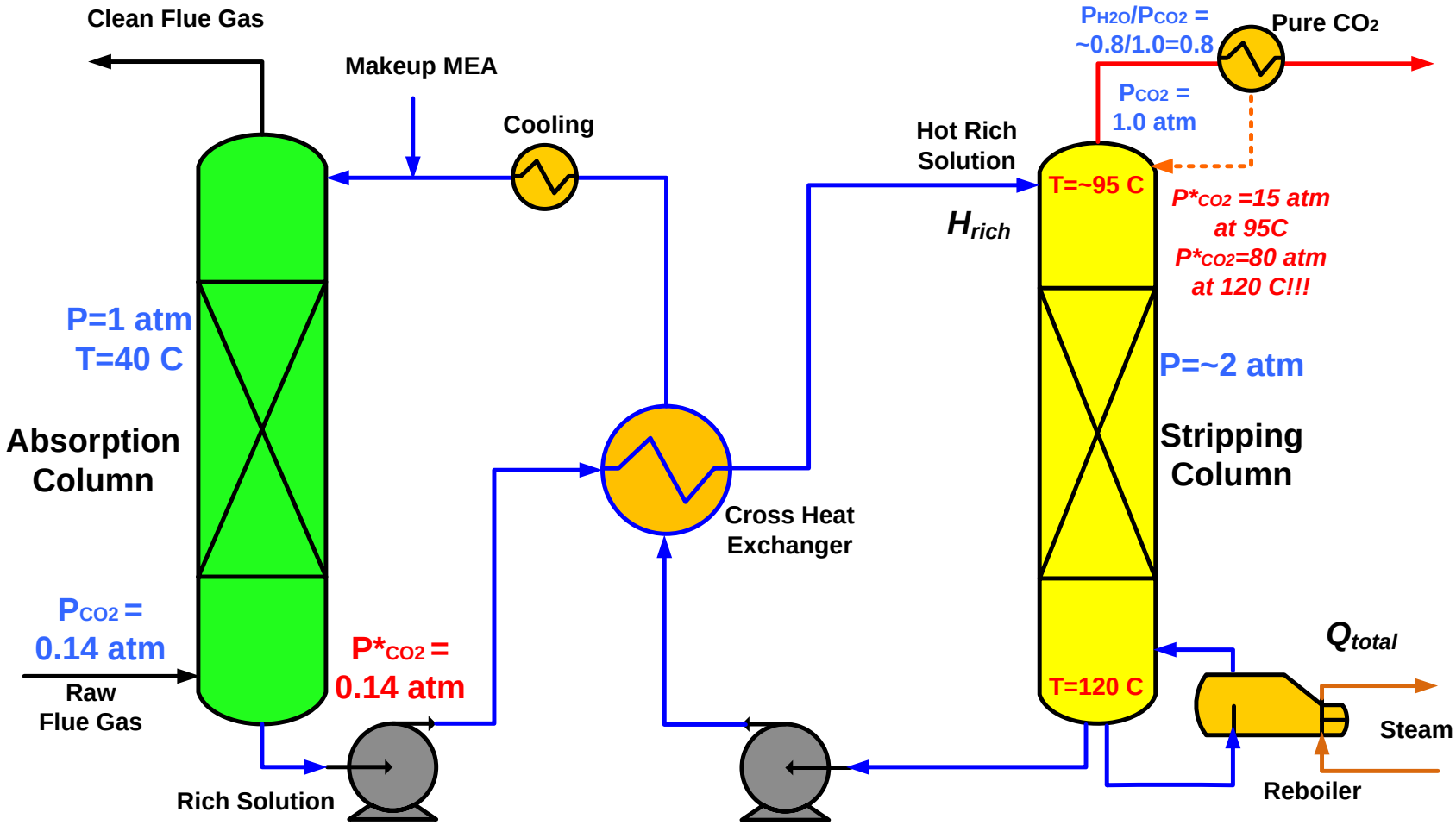
Issues with Conventional Absorption/Stripping Process



$$\ln(P_2) - \ln(P_1) = \frac{\Delta H}{R}\left(\frac{1}{T_2} - \frac{1}{T_1}\right)$$

$$P_2 / P_1 = 607 \text{ !!!}$$

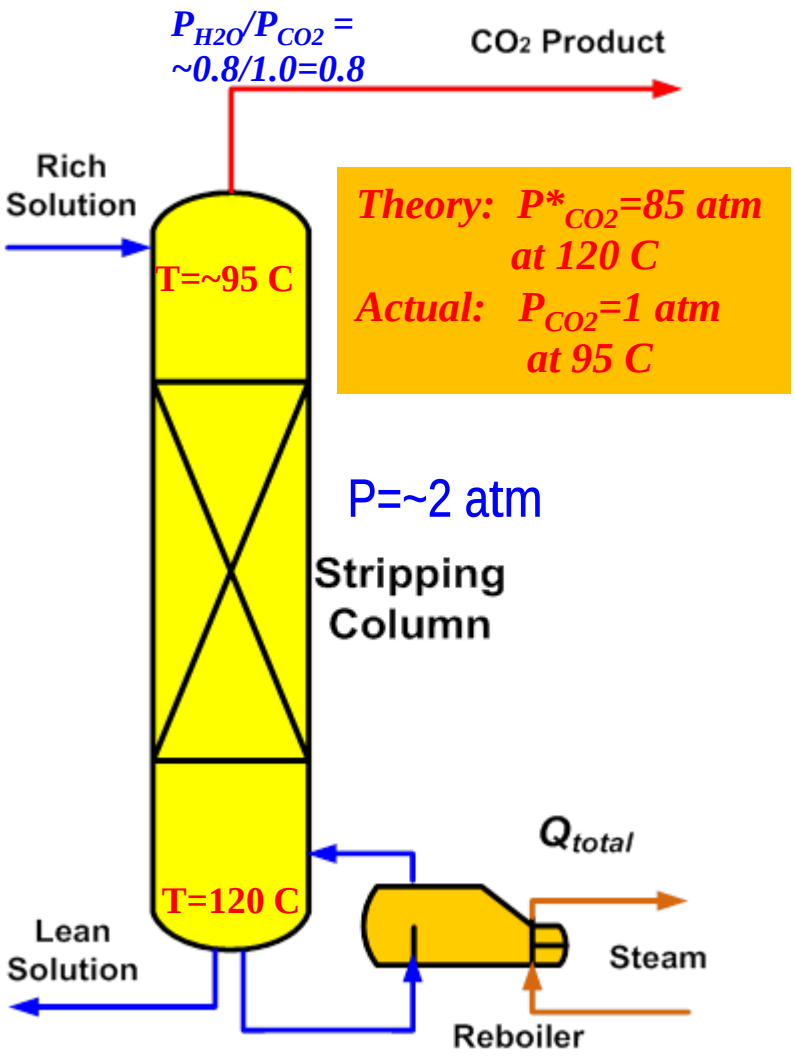
Issues with Conventional Strippers

- *Water vapor is used as stripping gas,* thus operating pressure is limited by the vapor pressure of the lean solution at the reboiler temperature
- *Water vapor is also used as a heat carrier* which leads to a temperature gradient along the column
- *Low operating pressure* results in a high ratio of P_{H2O}/P_{CO2} at the top of the stripper

Consequences:

–Low thermal efficiency

–High compression work

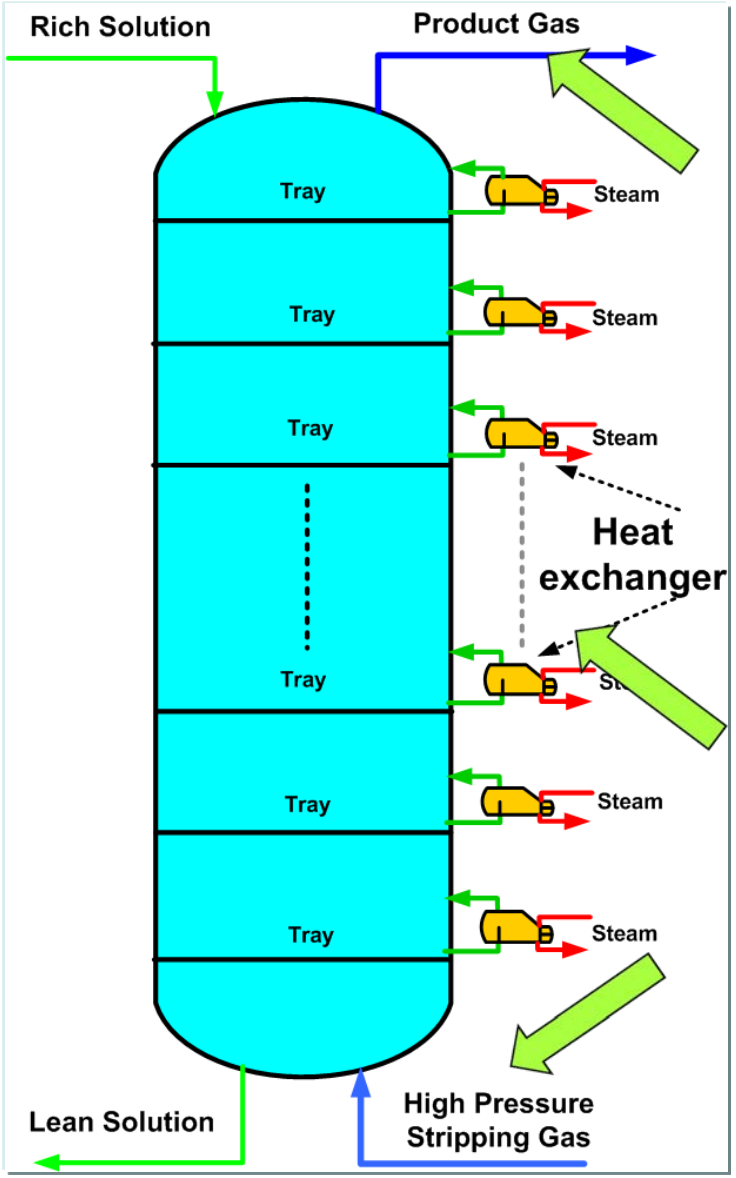


Energy Consumption of an MEA Process

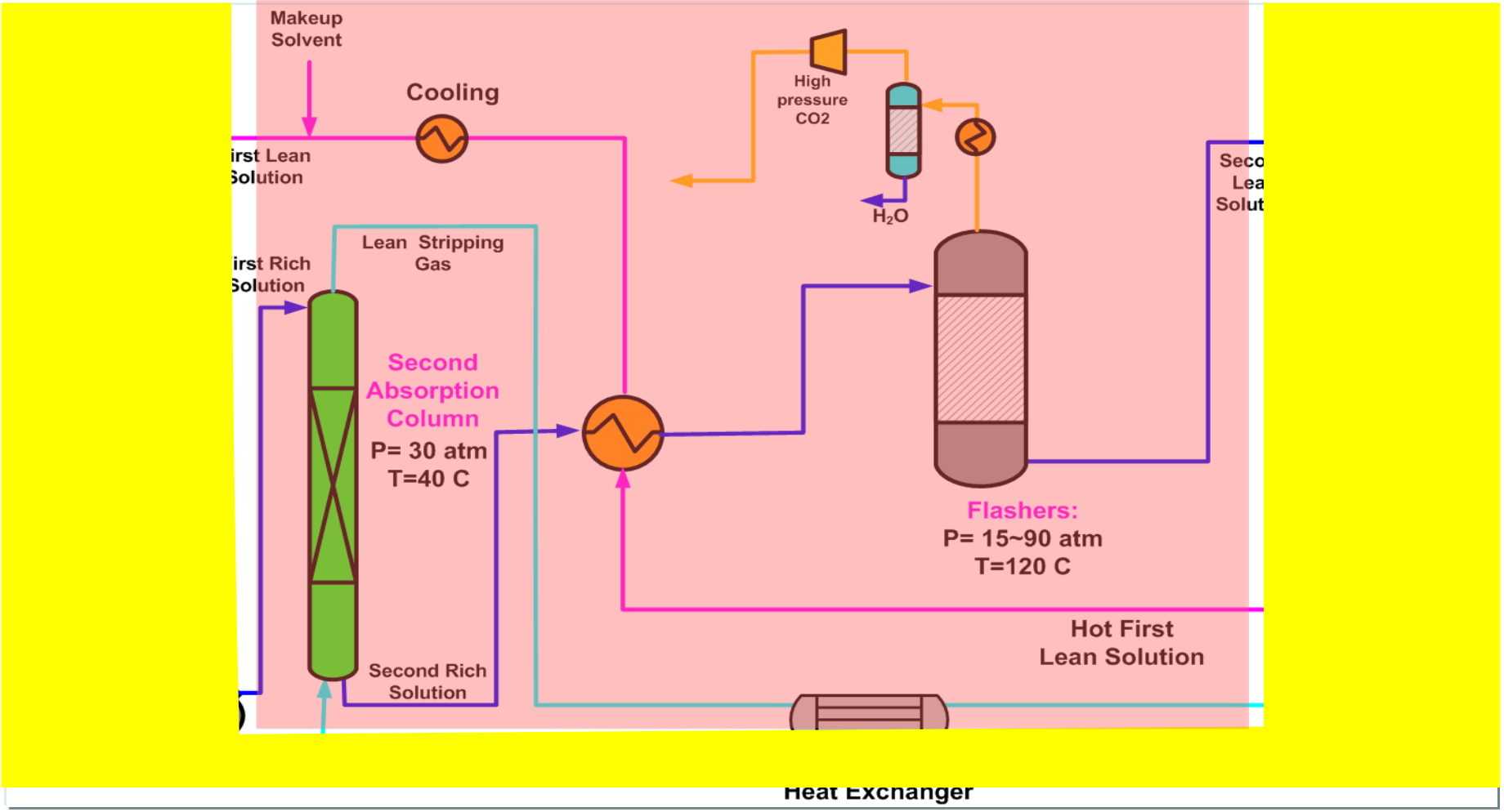
Heat Item	Quantity KJ/kgCO_2	Electricity equivalent kWh/kgCO_2
$Q_{sensible} = \frac{C_p (T_{lean\ hot} - T_{rich\ hot})}{\Delta Loading}$	**1,150**	**0.06**
$Q_{reaction} = \Delta H_{reaction}$	**1,875**	**0.10**
$Q_{stripping} = \left(\frac{P_{H_2O}}{P_{CO_2}}\right)_{\left(\begin{array}{l}Top\ of\\ the\\ stripper\end{array}\right)} \Delta H_{H_2O}$	**850**	**0.04**
$W_{compr.}$	**N/A**	**0.10**
Total	**3,875**	**0.30**

Novel Gas Pressurized Stripping (GPS) Column

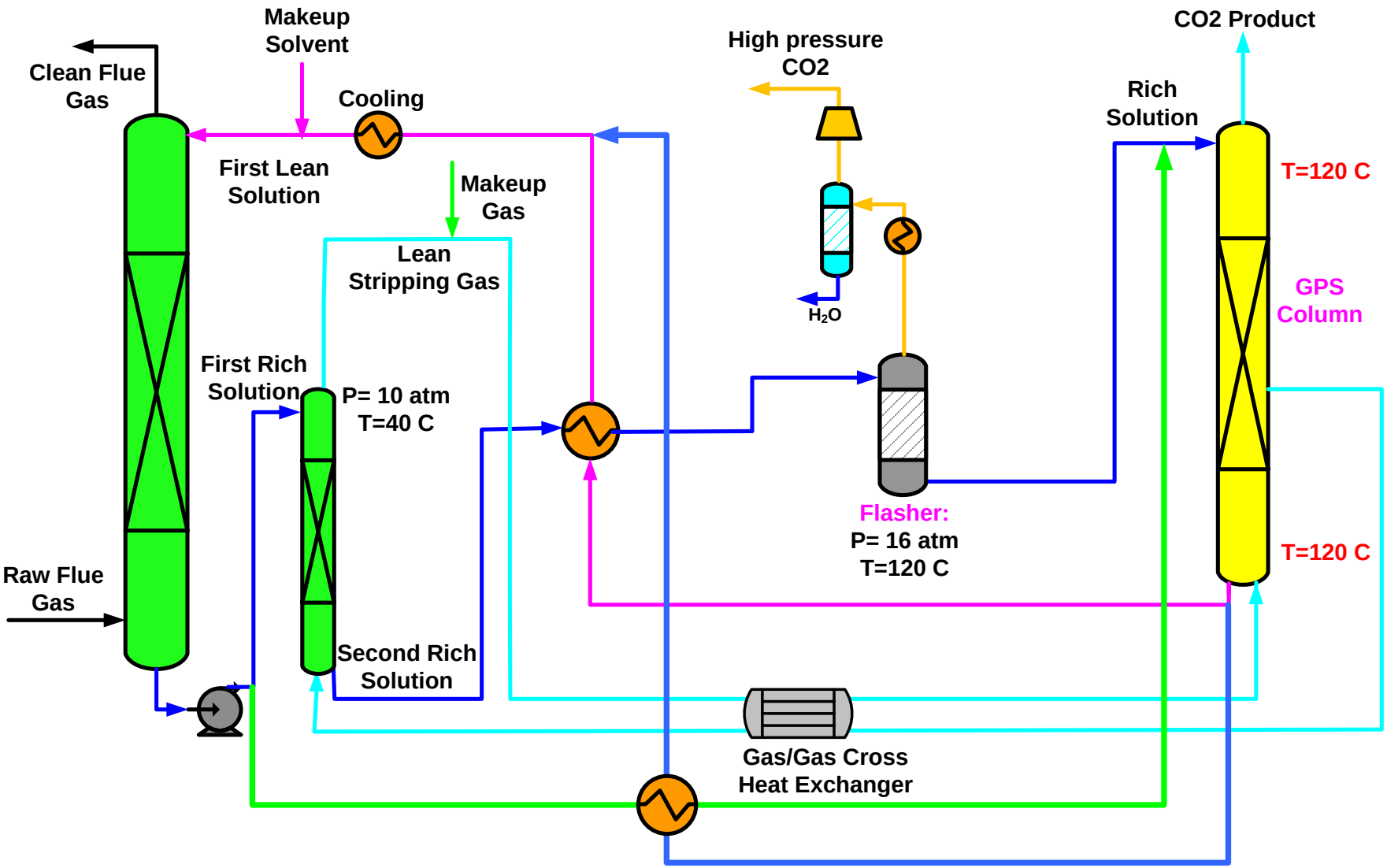
- Adding a high pressure stripping gas stream into the column
  - ✓ Eliminating water as stripping gas
  - ✓ Enables high operating pressure
- Adding side heaters to provide heat
  - ✓ Eliminates the necessity of using water vapor as heat carrier
  - ✓ Reduces temperature gradient in the stripper
- Product gas is a mixture of stripping gas and CO_2 along with water vapor
  - ✓ Increased CO_2 partial pressure
  - ✓ Requires a separation unit



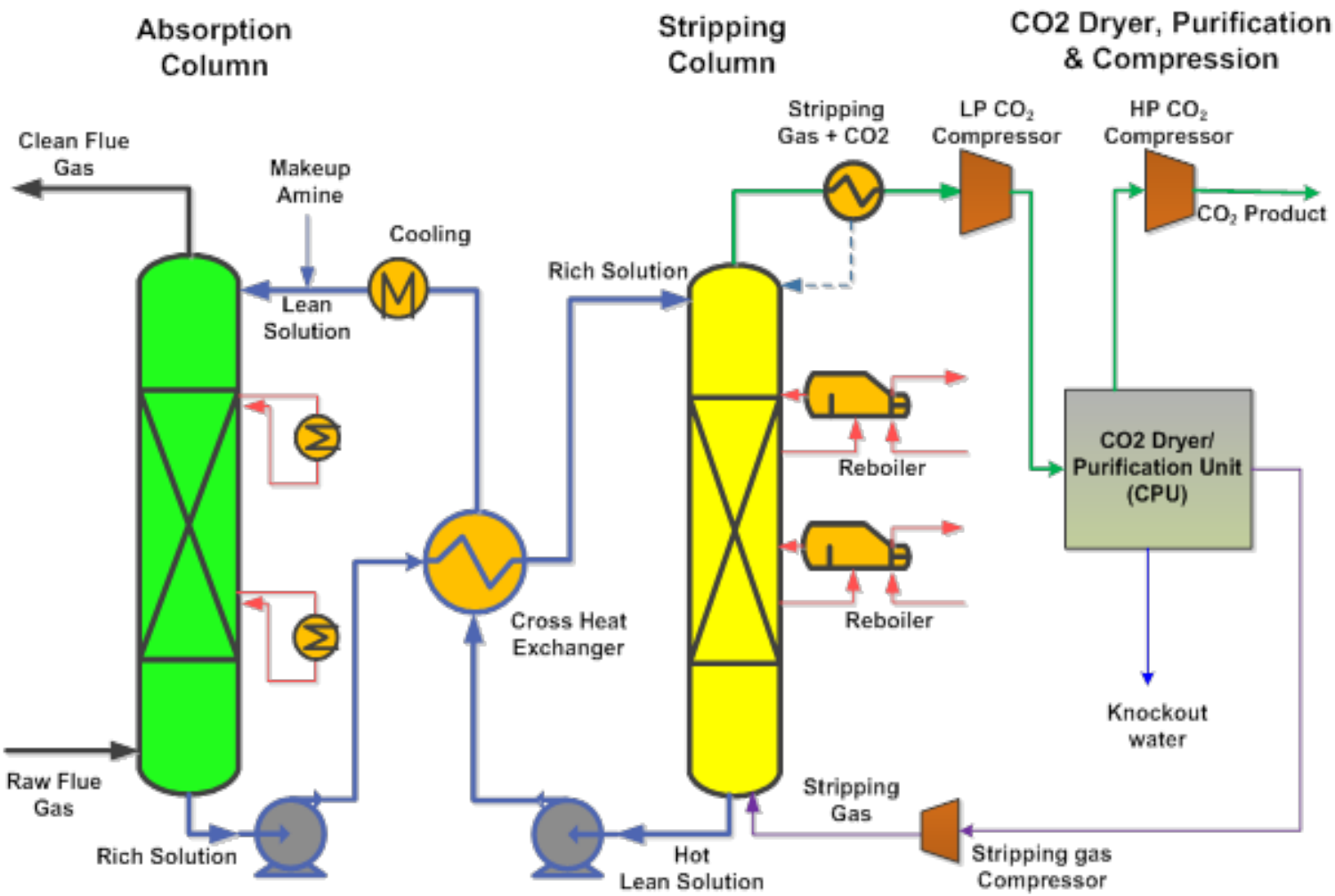
Initial GPS Process---One Solvent Process



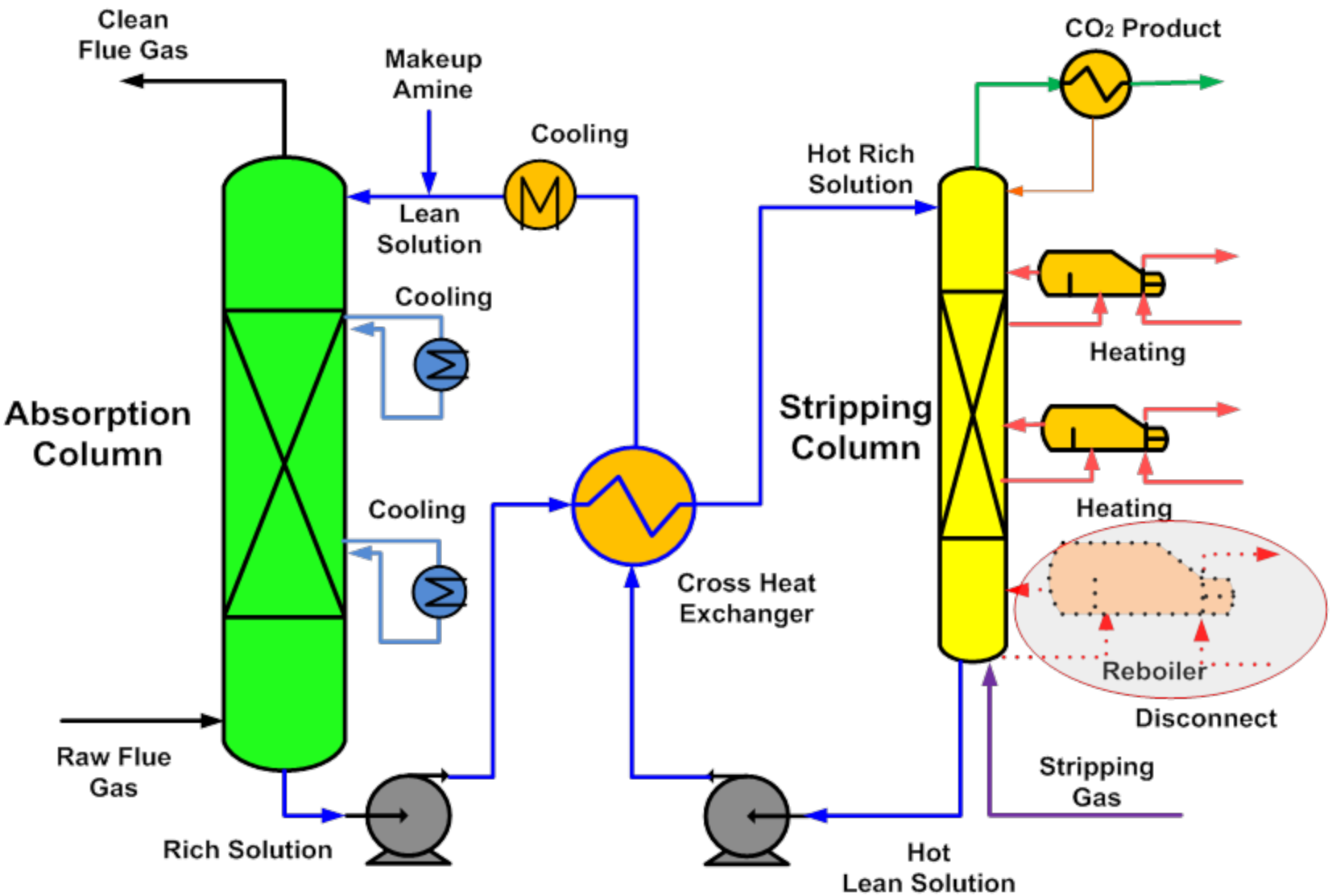
GPS Process With Split Flow



Alternative GPS Process



GPS Based Post-Combustion CO_2 Capture Technology



Optimized GPS Process

Advantages of GPS-Based Processes

- Uses commercial off-the-shelf technology
  - Proven unit operations
  - TRL should be as high as other conventional absorption/stripping processes
  - Suitable for large scale applications such as power plants
- High Thermal Efficiency
  - High stripping pressure thus reduced mechanical CO_2 compression work
  - Low stripping heat
- Flexible
  - Applicable to different solvents with different heat of reactions
  - Applicable to all absorption/stripping processes
  - Applicable to new or existing power plants
  - Applicable to existing amine based process with slight modifications

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Results and Findings

- **Simulation Study and Optimization of the GPS process (Tasks 2, 3, 4)**
- **Measurement of Solvent VLE, Thermal and Oxidative Stability, and Corrosion at High Temperature and high CO_2 loading (Tasks 5, 9, 10)**
- **Lab-Scale Experimental testing of GPS Process Performance (Tasks 6, 7, 8, 11)**
- **Continuous Skid Testing of a Bench-Scale GPS Based Process (Tasks 16, 17)**
- **Techno-Economic Study of GPS-Based PCC Process (Tasks 13, 14, 15)**
- **Conclusions and Recommendations**

Simulation Study and Optimization of the GPS process

- GPS column study and optimization
- Optimization of GPS process for existing PC power plant
  - Thermal compression may not be advantageous
  - High operating pressure not desired
- Simulation of alternative separation method for GPS product stream
- Final GPS process

Thermal Compression May Not Be Advantageous

Thermal Efficiency of Steam to Carnot Cycle Efficiency

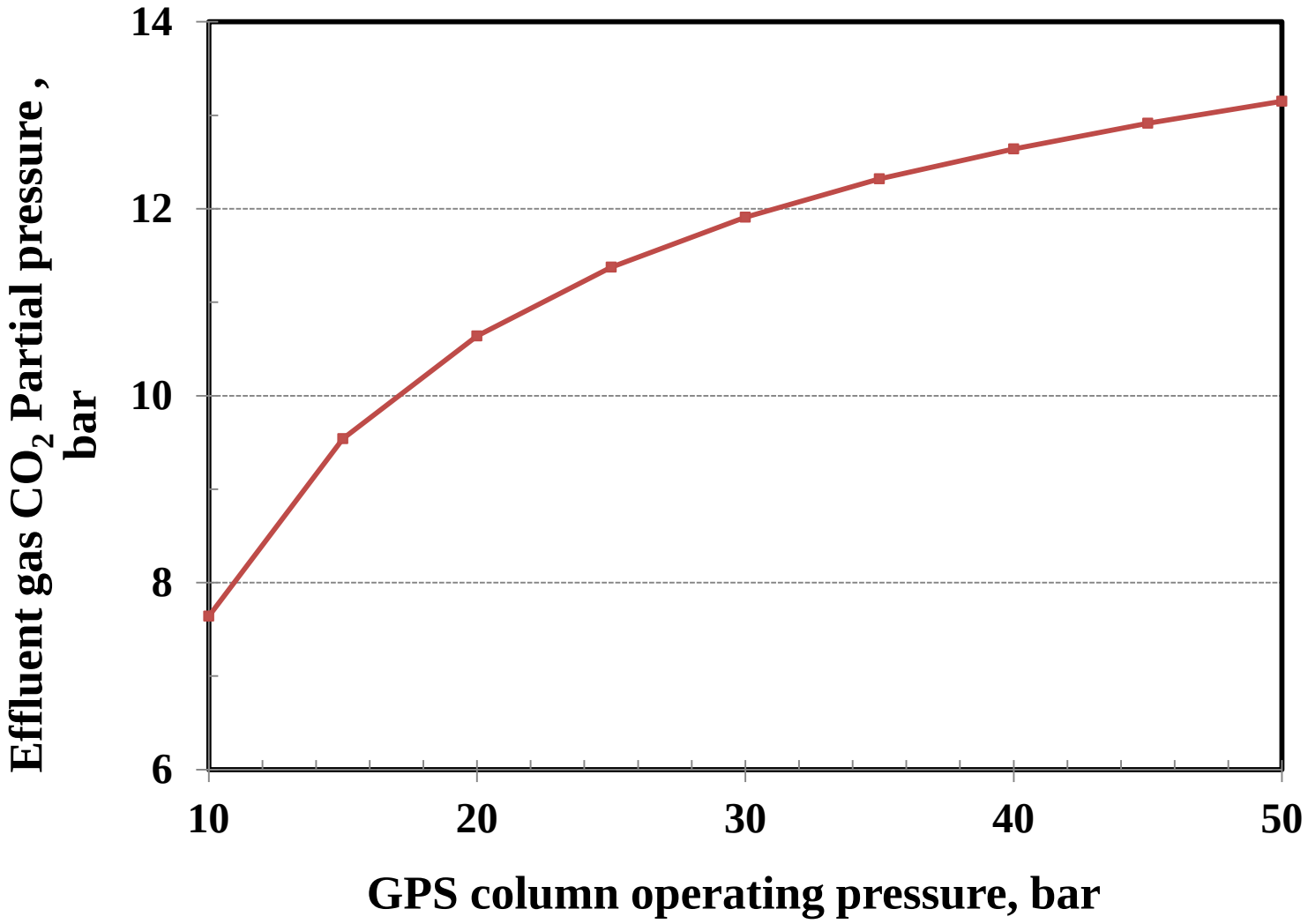
Process	Steam P (psia)	Saturation T (C)	Carnot Cycle Efficiency	Real Cycle Efficiency	Ratio
MEA	138	177.8	0.306	0.304	0.99
GPS	45	134.4	0.232	0.226	0.98

Using heat from steam and electricity from steam are virtually the same!

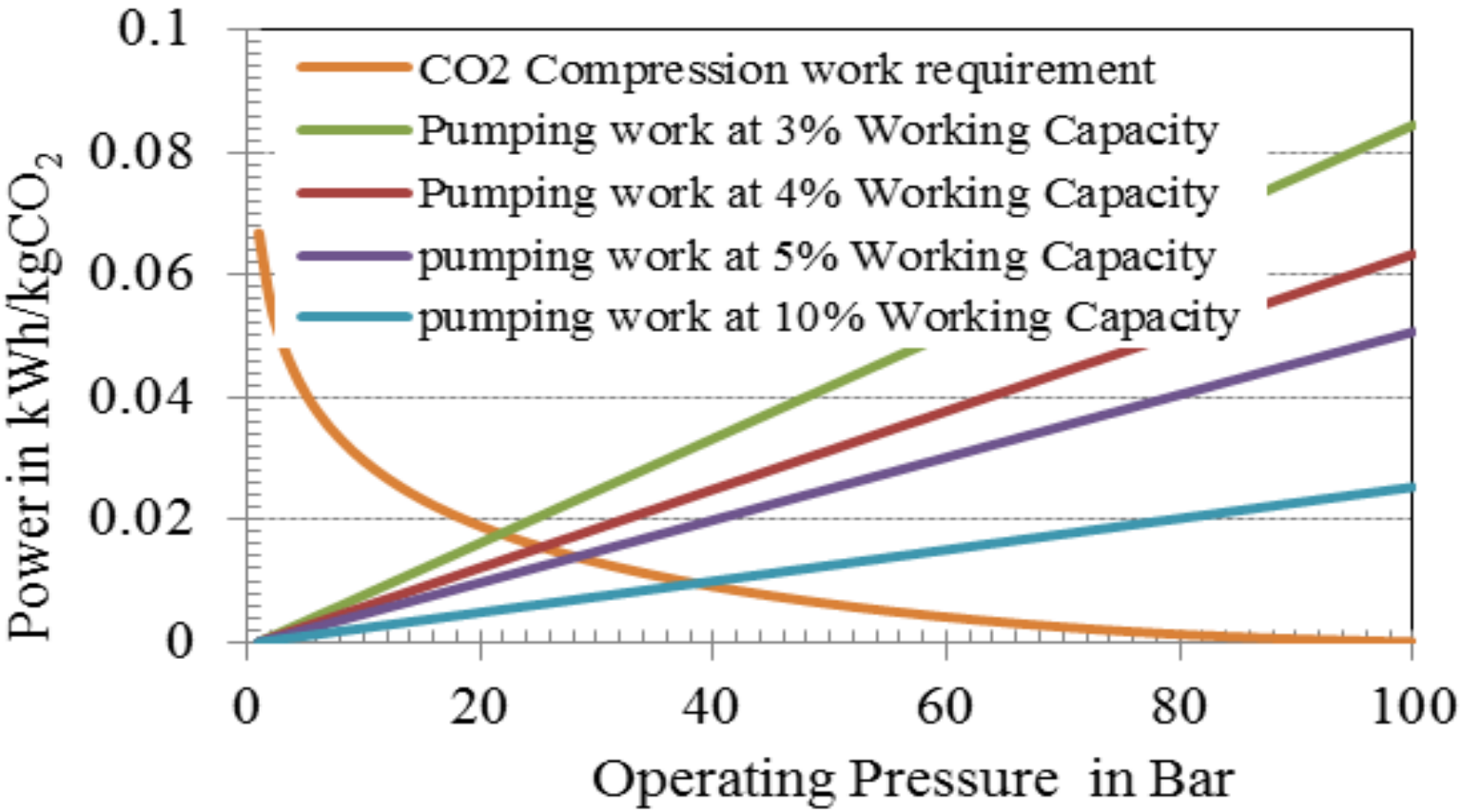
$$W_{reboiler} = 0.75 Q_{flash} \frac{T_{flash} + 5 - T_{sink}}{T_{flash} + 5} = 0.161$$

Significantly underestimate the electricity loss due to steam extraction!

Impact of GPS Operating Pressure on CO_2 Partial Pressure Recovery

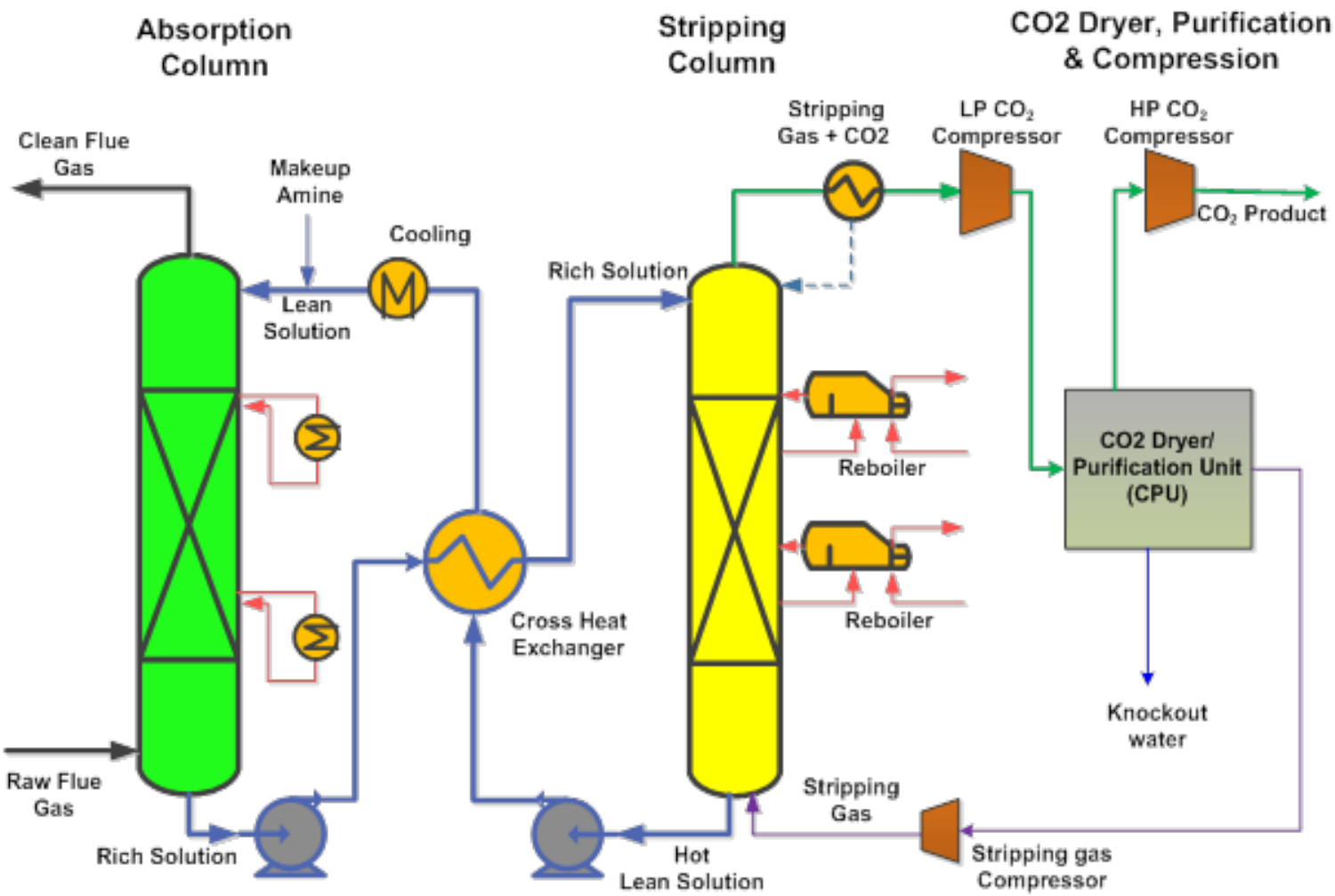


Comparison of Compression and Pumping Work



Compression Work $\propto$ ln (P_2/P_1) **Pumping Work $\propto \Delta(P_2-P_1)$**

Alternative Separation method for GPS stripping gas



Alternative separation method for GPS stripping gas

Accomplishment

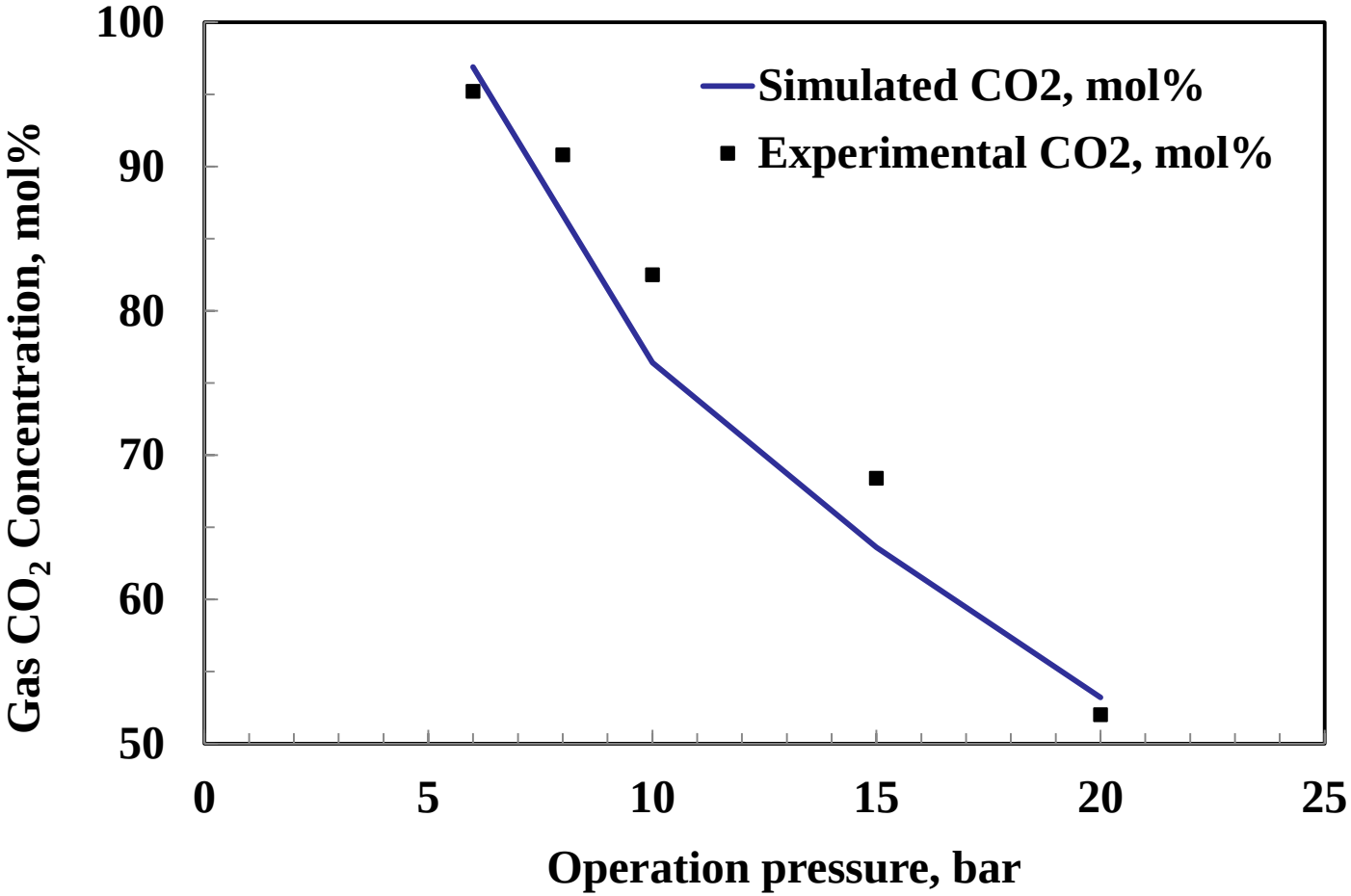
- Identified compression/refrigeration method as a better alternative to second absorption process, overall energy performance:

Capture percentage, %		90.20
CO_2 product purity mol.%	CO_2	97.63
	H_2O	0.24
	N_2	2.13
Heat requirement (electricity equivalent), kWh/kg CO_2		0.11
Electricity need, kWh/kg CO_2		0.10
Overall energy performance, kWh/kg CO_2		0.21

Disadvantages

- Added compression and refrigeration capital is still significant

Impact of GPS Column Operating Pressure On CO_2 Purity ---Simulation and Experimental Results



Overall Energy Performance of Column and Solvent

Overall energy performance of the GPS process:

Capture percentage, %	90.20
Product flow rate, kmol/hr	13,112
Product pressure, bar	153
Heat requirement (electricity equivalent), kWh/kg CO_2	0.131
Electricity need, kWh/kg CO_2	0.065
Overall energy performance, kWh/kg CO_2	0.196

CO_2 Specifications for GPS based CO_2 capture process:

Product compositions:	%mol
CO_2	97.63
H_2O	0.24
N_2	2.13

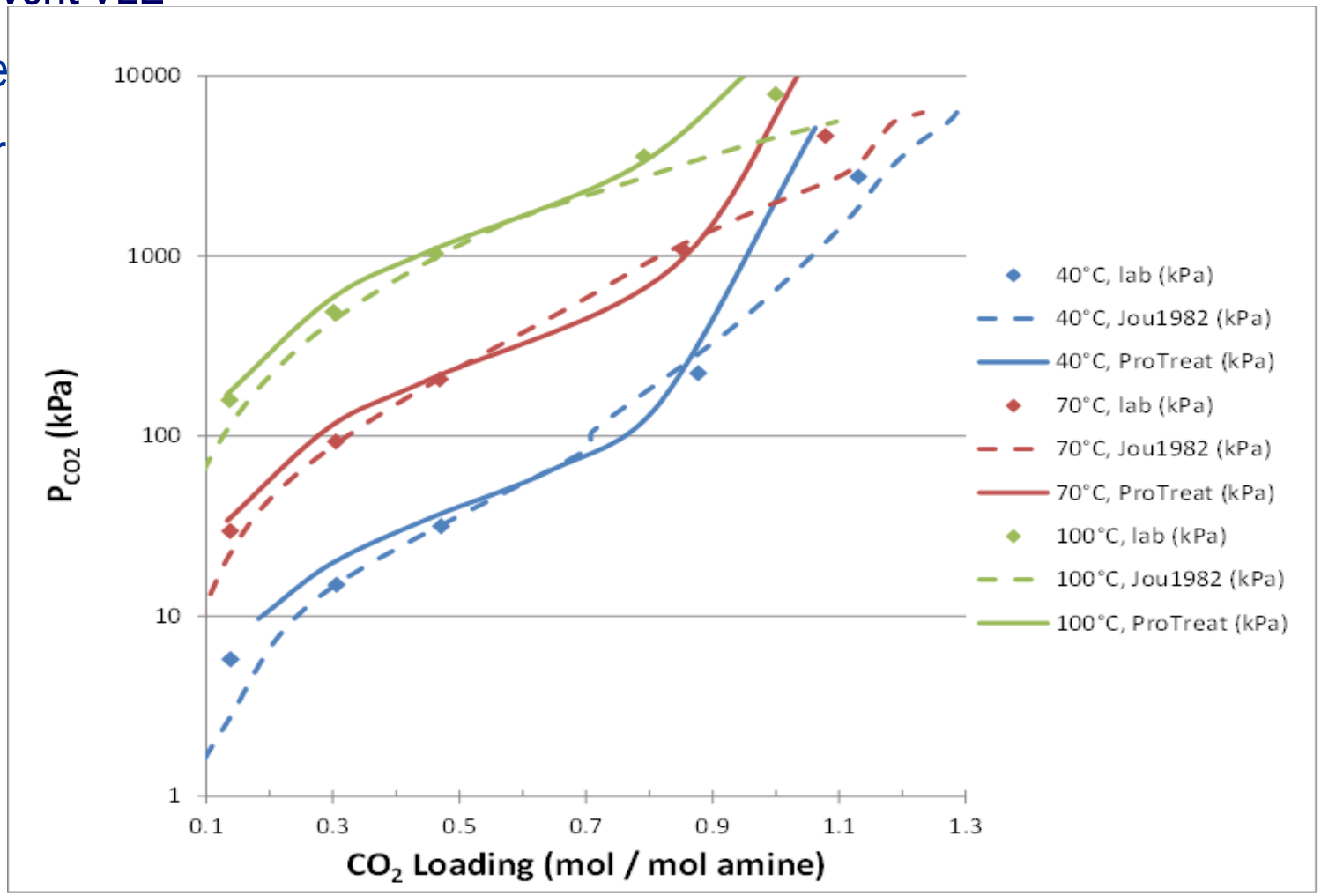
Achieved milestone of energy performance column and solvent ≤ 0.22 kwh/kgCO_2

Measurement of Solvent VLE, Thermal and Oxidative Stability, and Corrosion at High Temperature and CO2 loading

- Solvent VLE
- Thermal and Oxidative Stability
- Corrosion

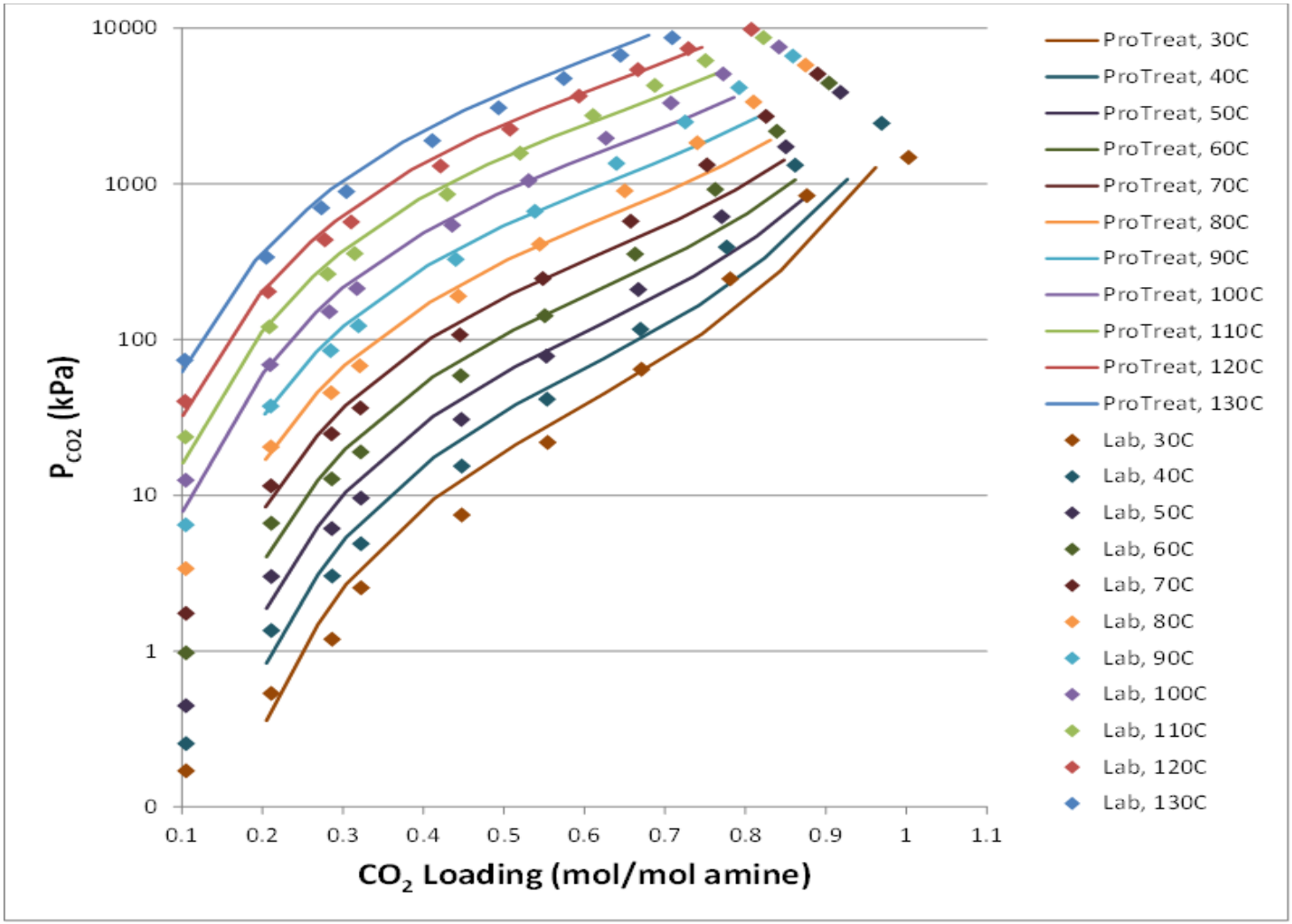
Typical VLE Data

- Solvent VLE
- The
- Cor



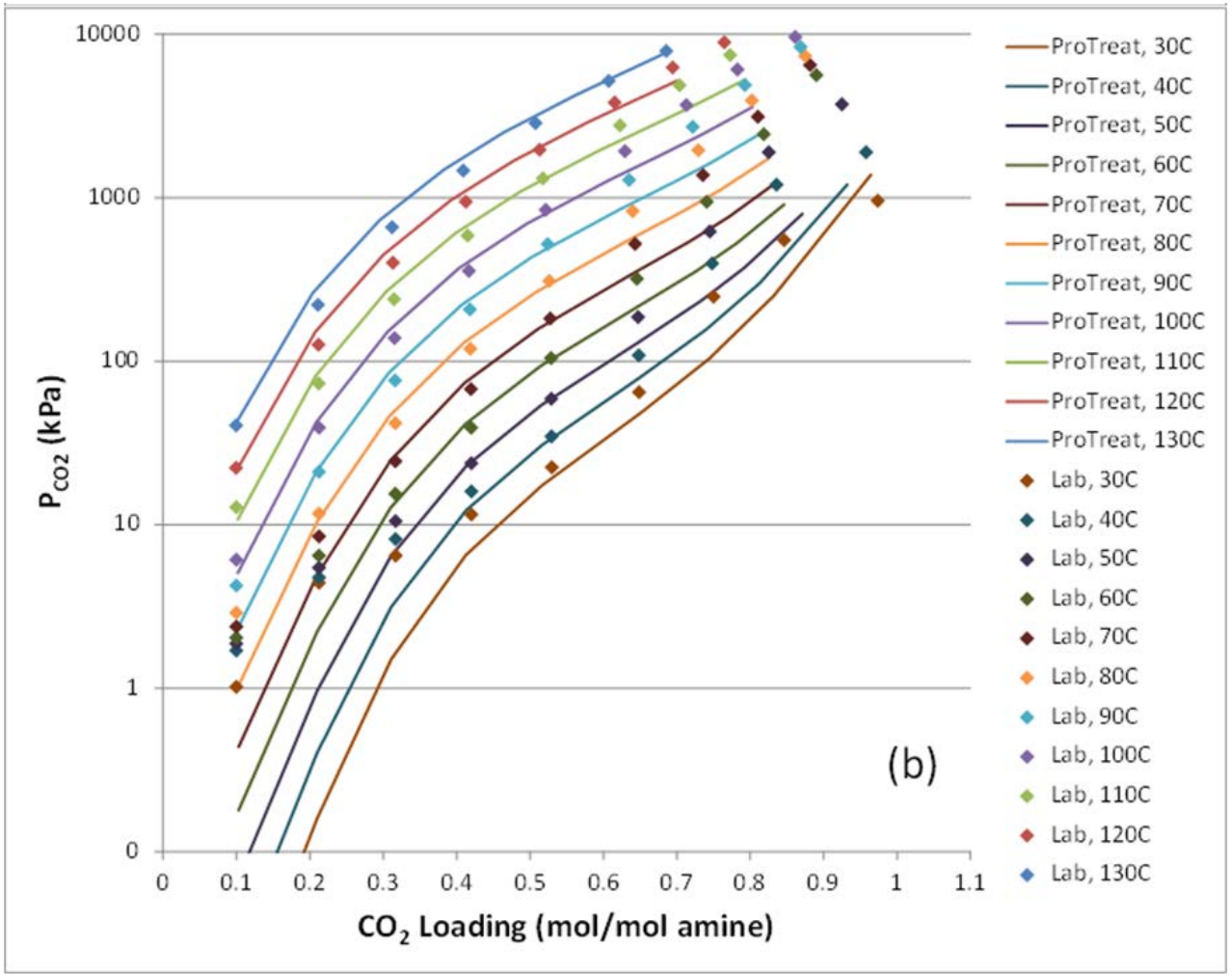
Phase Equilibrium Data Measurement

15% PZ / 35% MDEA / 50% H_2O (w/w) Solvent



Phase Equilibrium Data Measurement

20% PZ / 30% MDEA / 50% H_2O (w/w) Solvent



Solvent Oxidative Stability Measurement

Summary of oxidative stability testing

Solvent composition*	T	PZ Degradation (fraction/day)	MDEA Degradation (fraction/day)	PZ Degradation (kg/ton CO_2)	MDEA Degradation (kg/ton CO_2)	Total Degradation (kg/ton CO_2)
10/40/50	40°C	0	0	0	0	0
	50°C	0.00167	0.00071	0.00068	0.00117	0.00185
	60°C	0.00289	0.00099	0.00118	0.00163	0.00281
15/35/50	40°C	0	0.00033	0	0.00048	0.00047
	50°C	0.00280	0.00303	0.00172	0.00434	0.00606
	60°C	0.00052	0.00073	0.00032	0.00104	0.00136
20/30/50	40°C	0.00152	0.00162	0.00124	0.00199	0.00323
	50°C	0.00194	0.00261	0.00159	0.00321	0.00480
	60°C	0.00406	0.00230	0.00332	0.00283	0.00615

***PZ/MDEA/H_2O (wt%)**

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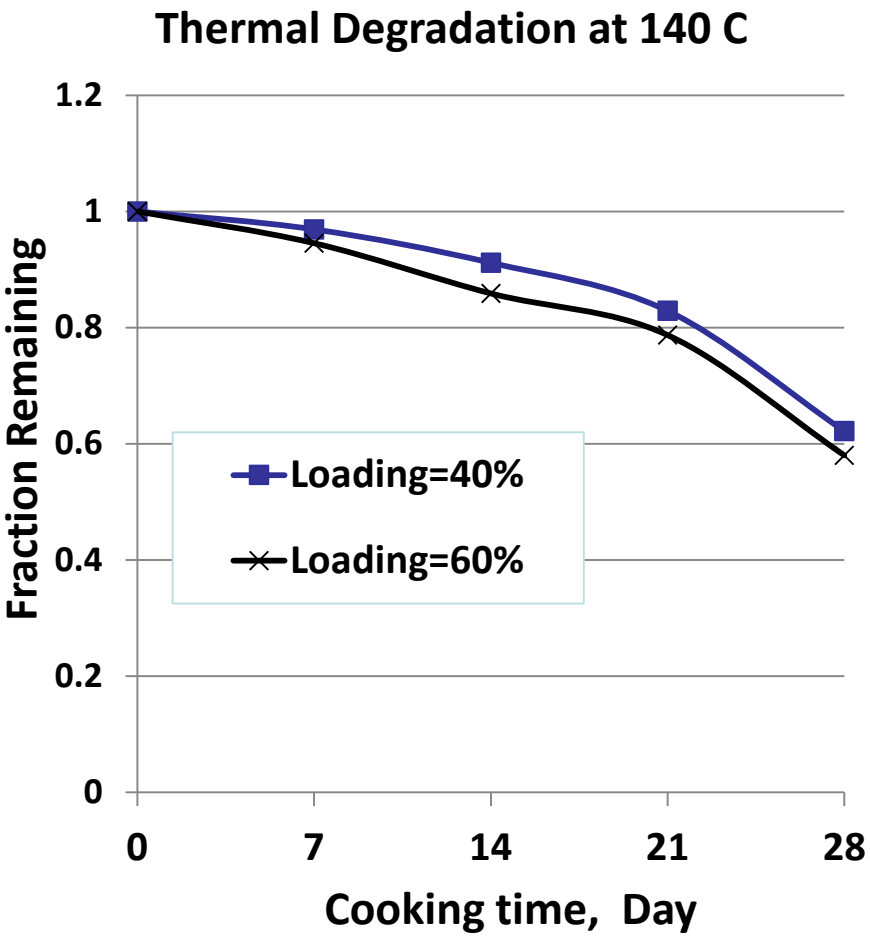
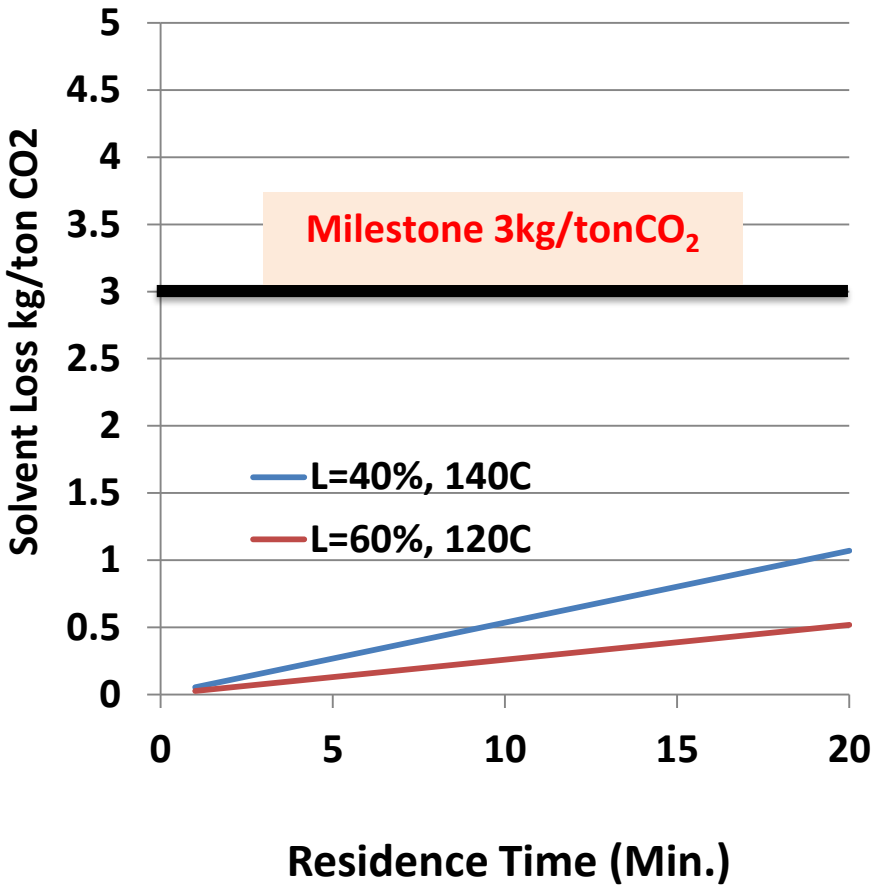
Stability of solvent at high loading and high T





Corrosion Testing

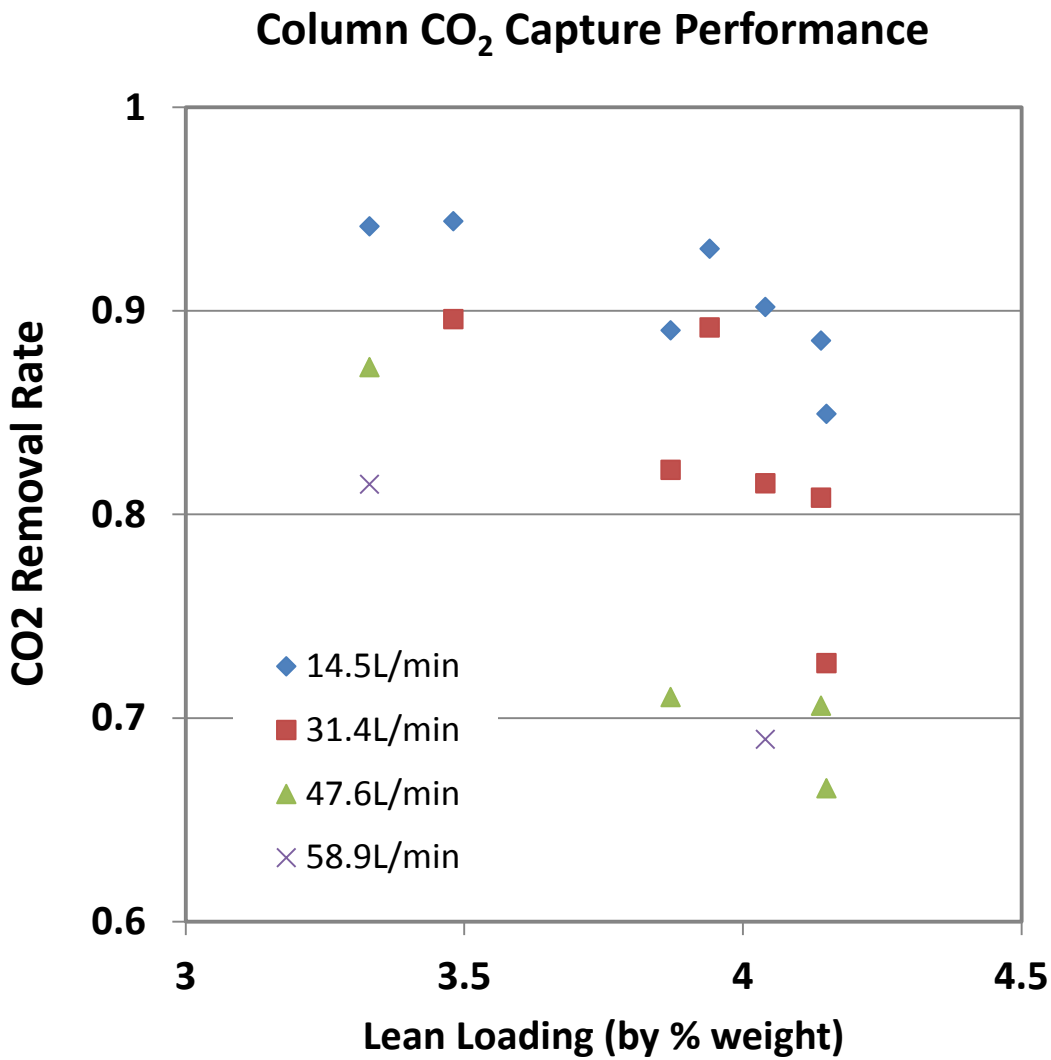
Summary of corrosion data rates in mils/year

	Rich solvent			Lean solvent					Lean Solvent with O2	
Temperature	20 C	50 C	80 C	20 C	50 C	80 C	100 C	110 C	20 C	50 C
Stainless 304L	0.032	0.044	0.08	0.031	0.097	0.058	0.306	0.961	0.011	0.048
Stainless 316 L	0.109	0.025	0.254	0.013	0.046	0.072	0.279	0.84	0.053	0.057
Carbon Steel (1010 grade)	0.024	0.035	0.114	0.033	0.035	0.27	0.363	1.23	0.035	0.197

Lab-Scale Experimental testing of GPS process performance

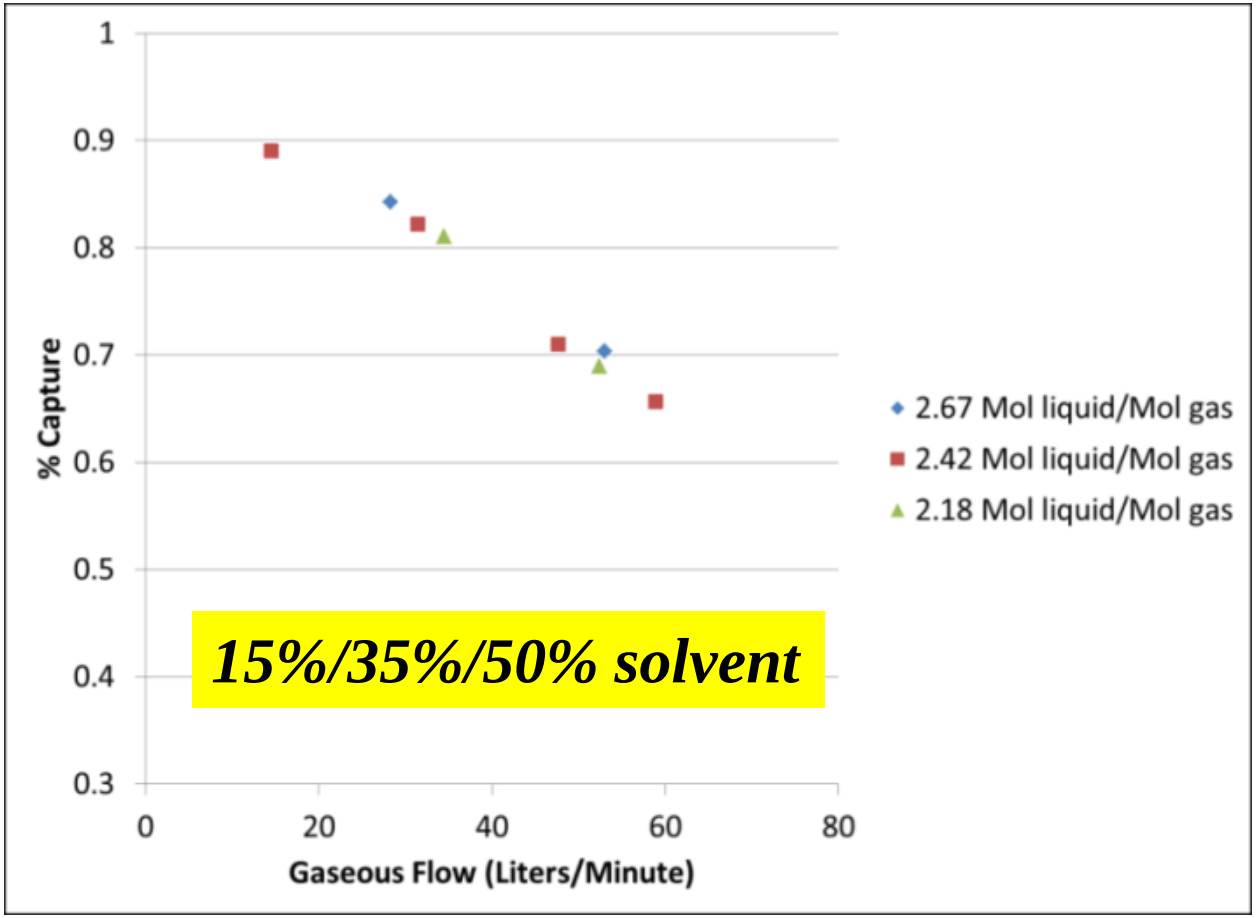
- First Absorption Column
- Second Absorption Column
- Flasher
- GPS Column

First Absorption Column Testing



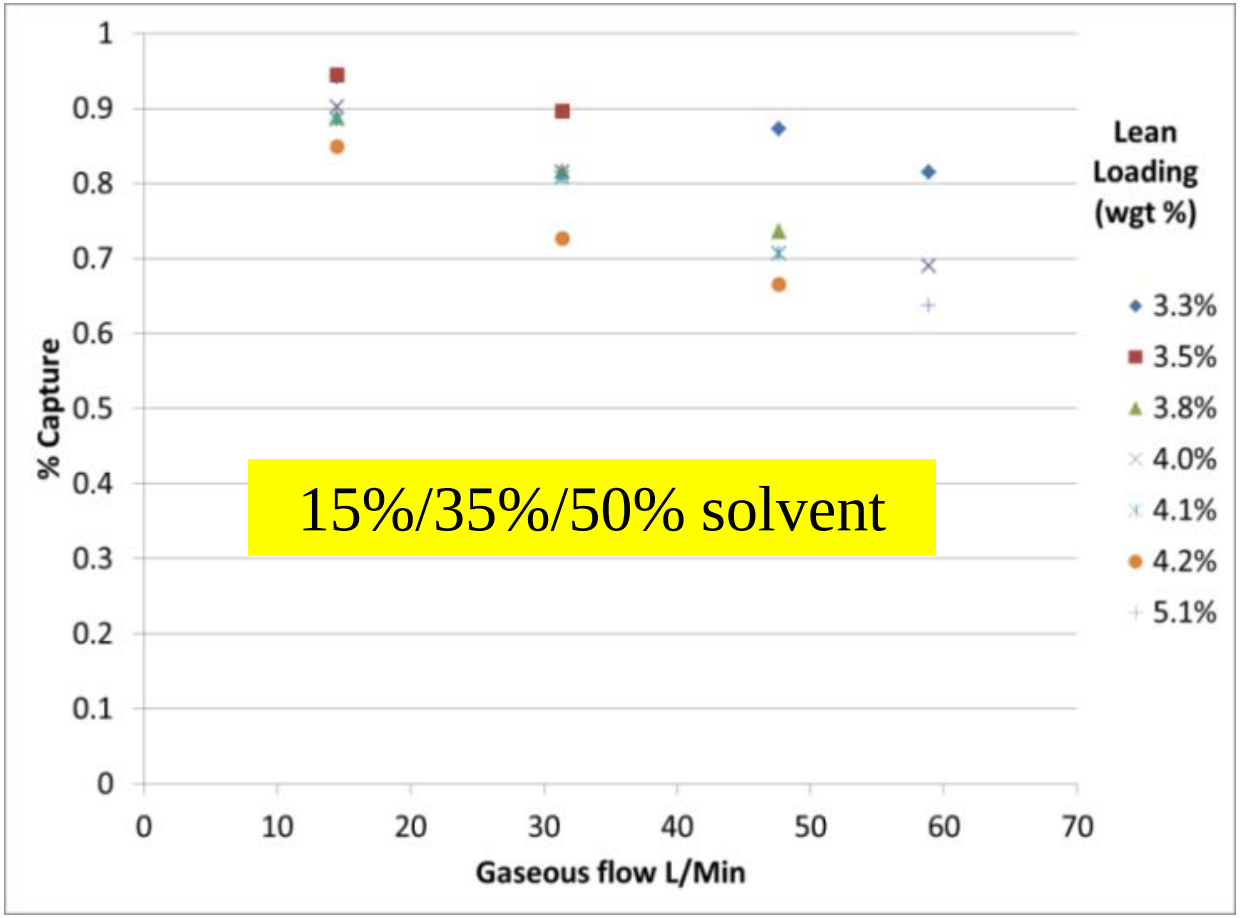
First Absorption Column Test

Impact of L/G Ratio and Gas Flow rate on performance



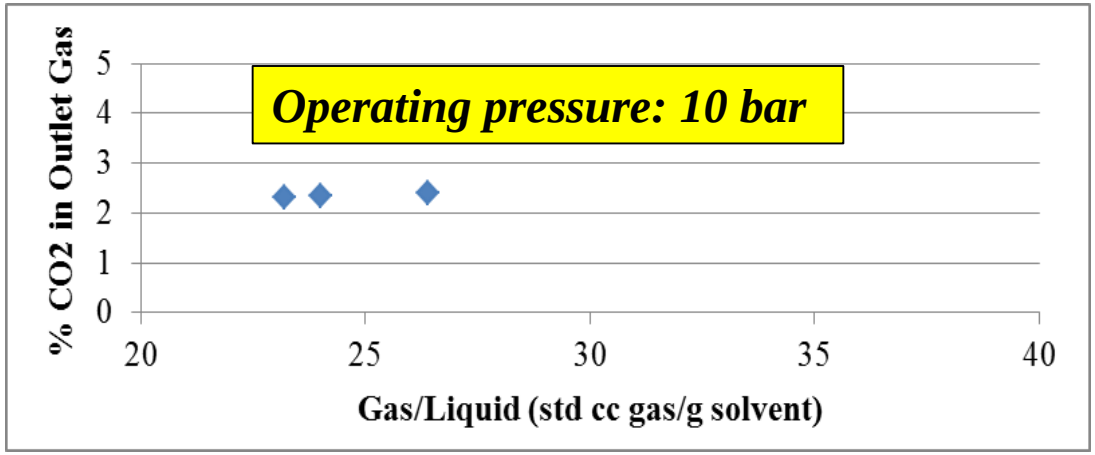
First Absorption Column Test

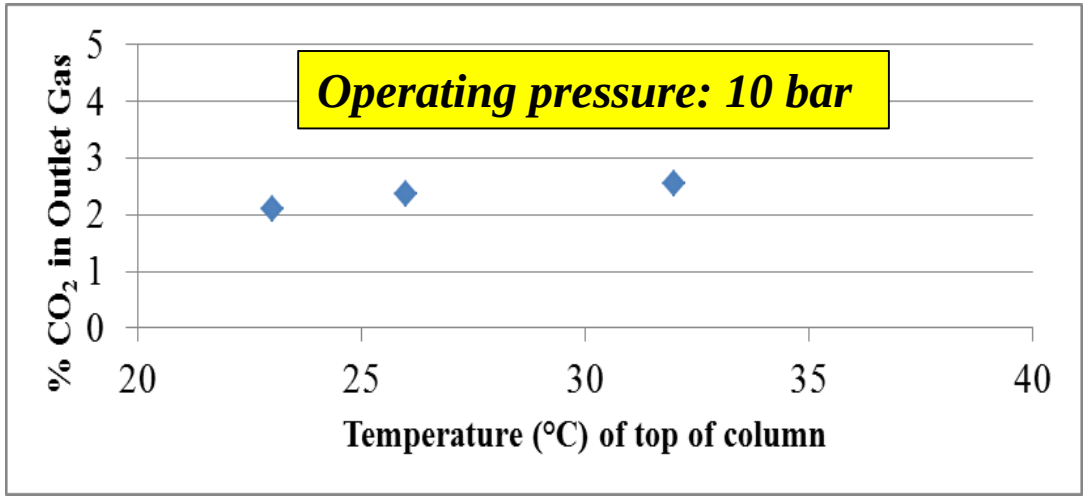
Impact of gas flow rate and lean loading on performance



Second Absorption Column Test

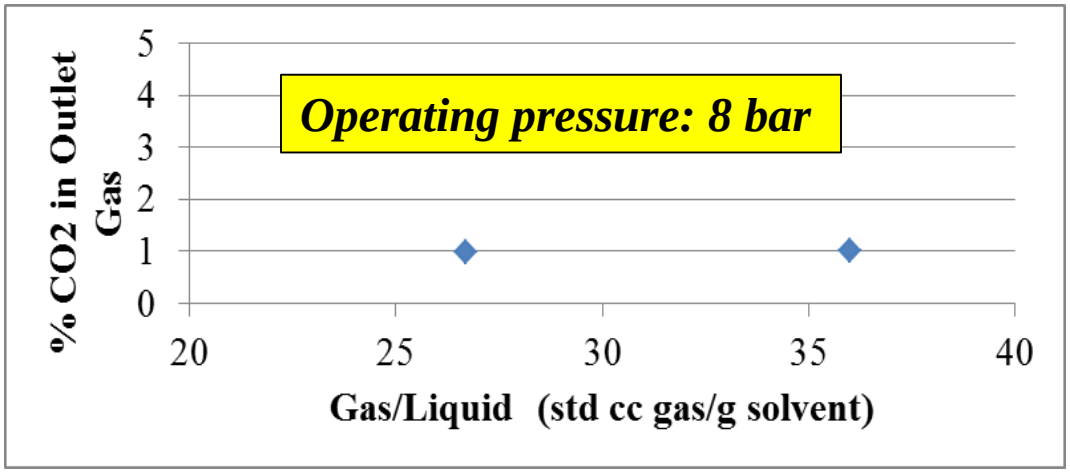
Effect of temperature on CO_2 level in outlet gas



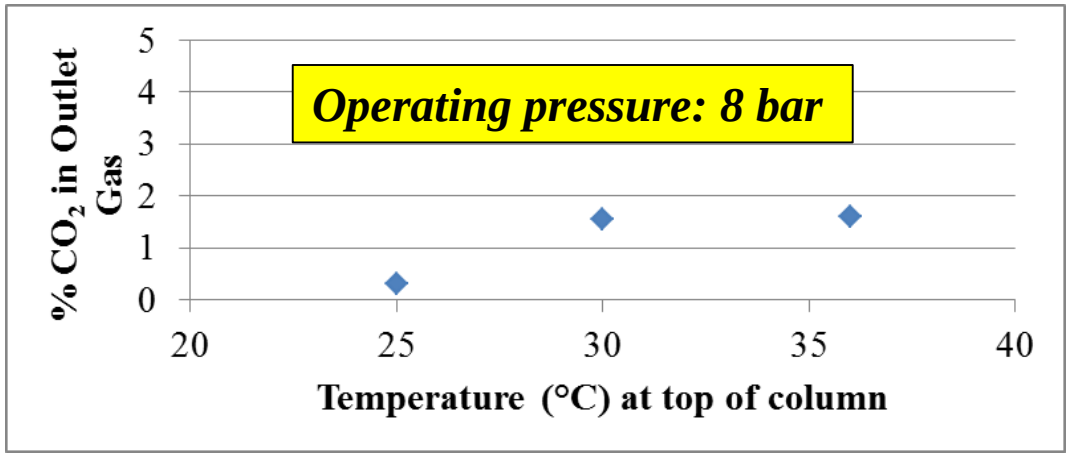


Second Absorption Column Test

Effect of gas/liquid on CO_2 level in outlet gas

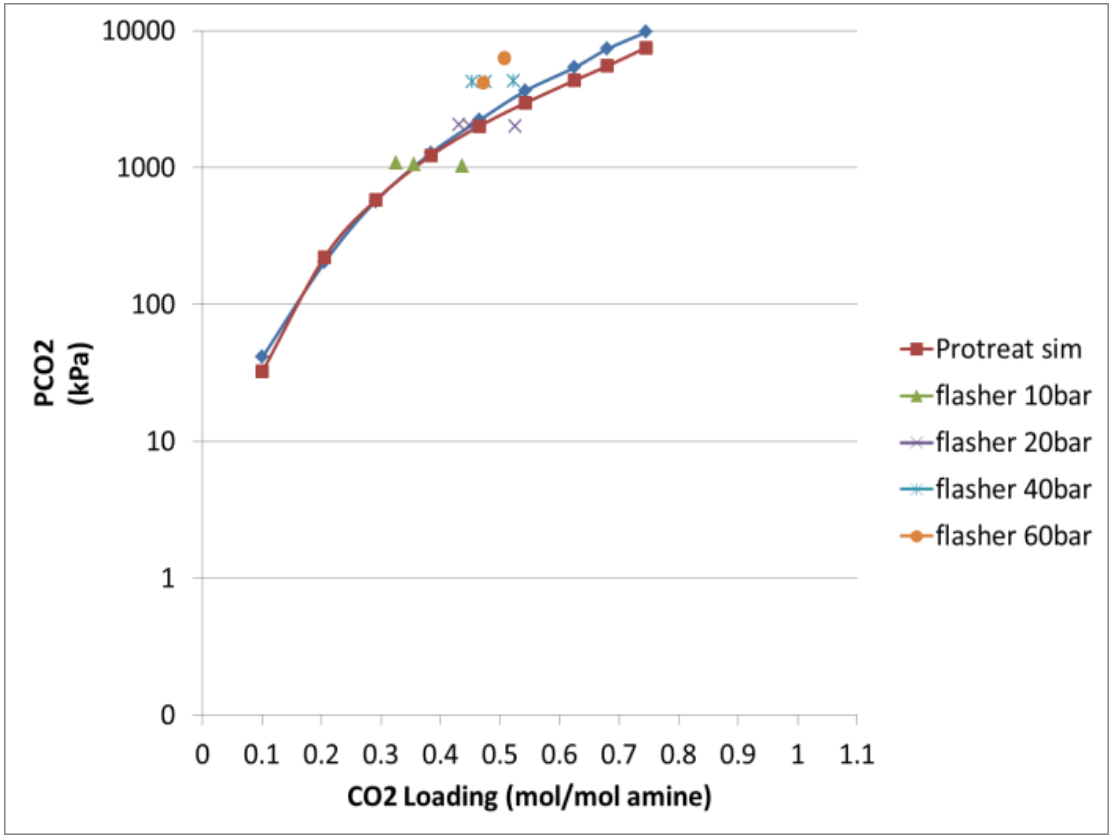


Effect of temperature on CO_2 level in outlet gas



Flasher Testing

Flasher measurements for CO_2 in 15PZ/35MDEA/50H_2O (w/w) solvent



GPS Column Design / Fabrication & Testing

- Process simulation
  - **Two Lab-Scale Experimental testing of GPS process performance**
  - **continuous skid Testing of a Bench-scale GPS based process**
  - **Techno-economic study of GPS-based PCC process**
  - **Conclusions and Recommendations**
- patents were granted for CO_2 capture technologies

GPS Column Thermal Performance

Run	1	2	3	4	5	6
liquid flow rate (g/min)	74.4	65.5	115	115	110	110
Heat GPS (W)	93.9	83	154.9	192.7	137	146
Sensible Heat (W)	29.0	25.5	64.1	96.1	48.9	73.5
Reaction + Stripping (W)	64.9	57.5	90.8	96.6	88.0	72.5
Equivalent Reaction + Stripping (KJ/Kg CO2)	1377	1386	1248	1327	1266	1042
Theoretical Minimum	818					

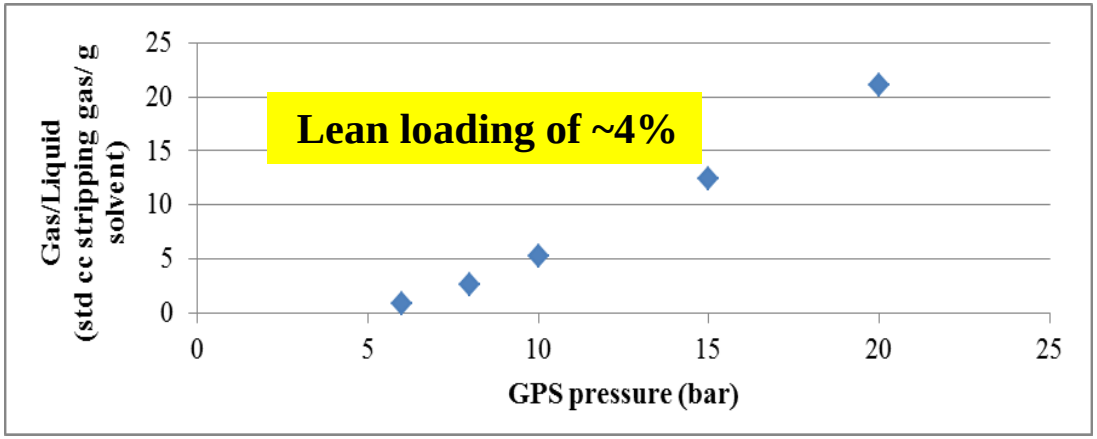
$$\Delta H_{min} = R\frac{T_2 T_1}{T_2 - T_1}\ln\left({}^{P_2}/_{P_1}\right)$$

$$\frac{\Delta H_{min}}{\Delta H_{exp}} = \frac{818\ {}^{\mathrm{kJ}}/_{\mathrm{kg}}\,\mathrm{CO_2}}{1274\ {}^{\mathrm{kJ}}/_{\mathrm{kg}}\,\mathrm{CO_2}} = 64\%$$

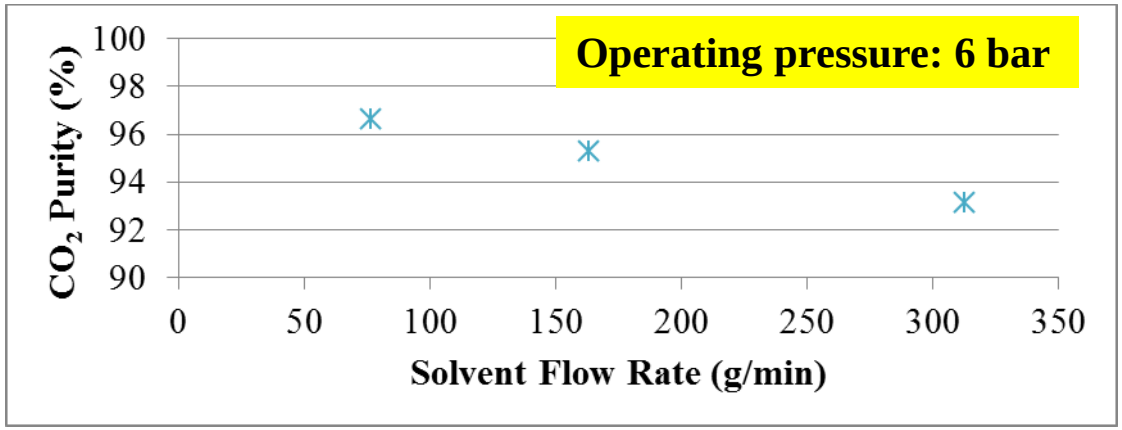
Experimentally observed GPS operations achieving a thermal efficiency of 64% (milestone of 50%)

GPS Column Testing

Impact of operating pressure on gas/liquid ratio

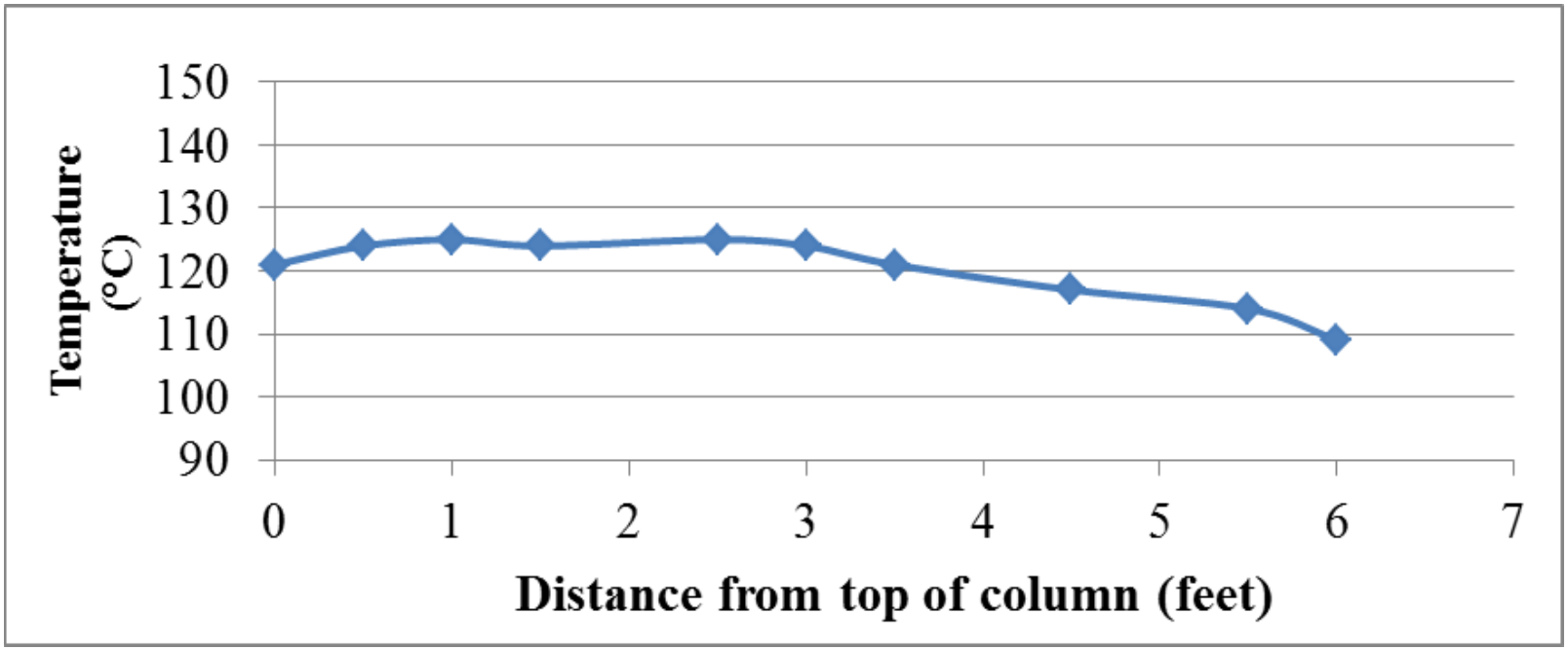


Impact of solvent flow rate on CO_2 purity



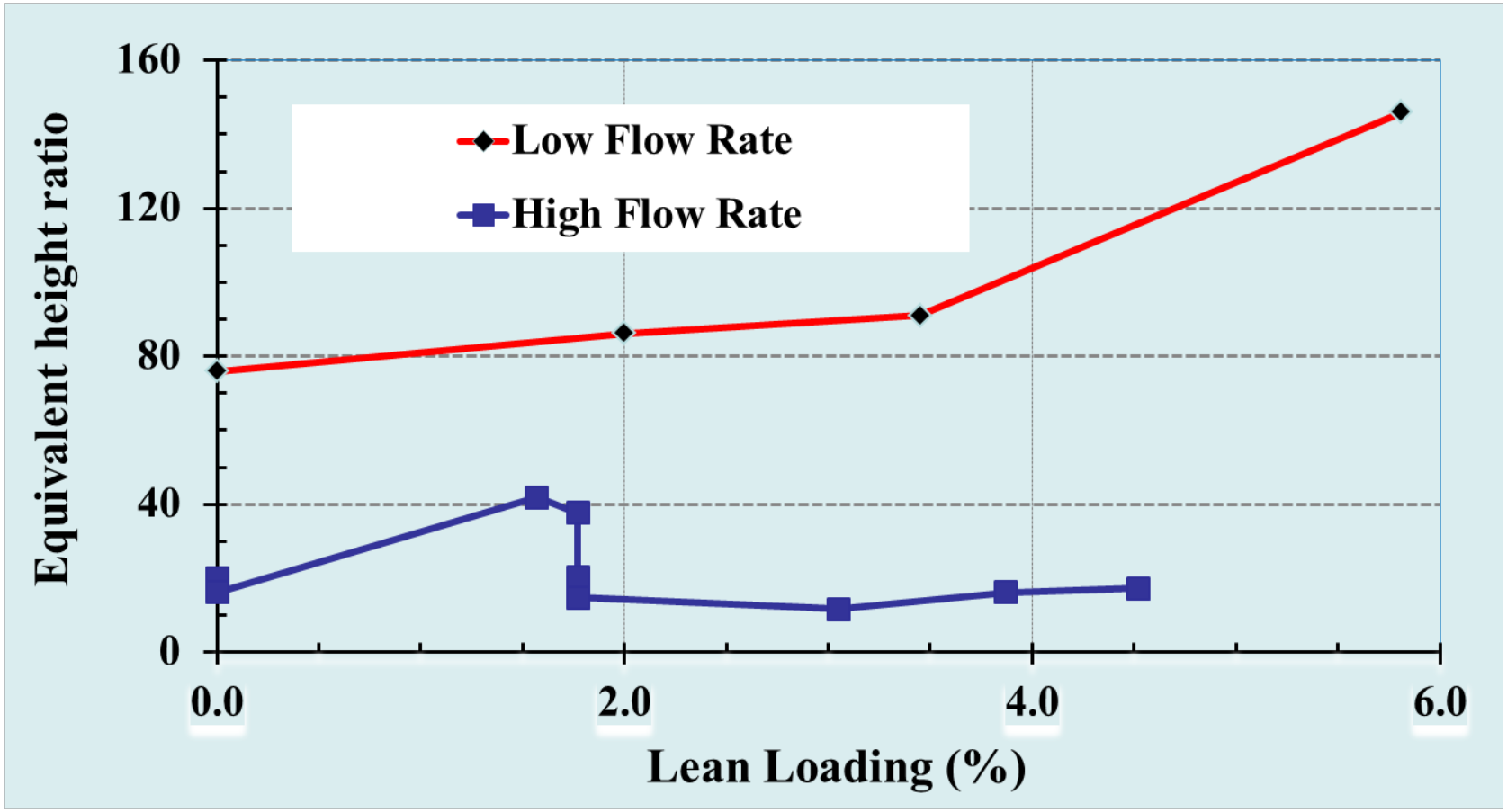
GPS Column Testing

Temperature profile along the length of GPS column



RPB Unit Evaluation at CCS Laboratories

Equivalent Height Ratio=
Equivalent Column packing height/RPB packing height



Continuous Skid Testing of a Bench-Scale GPS process

- Skid mounted GPS system
- Heat loss calibrations
- Parametric tests
- Continuous long term tests

Continuous Skid Testing of a Bench-Scale GPS process

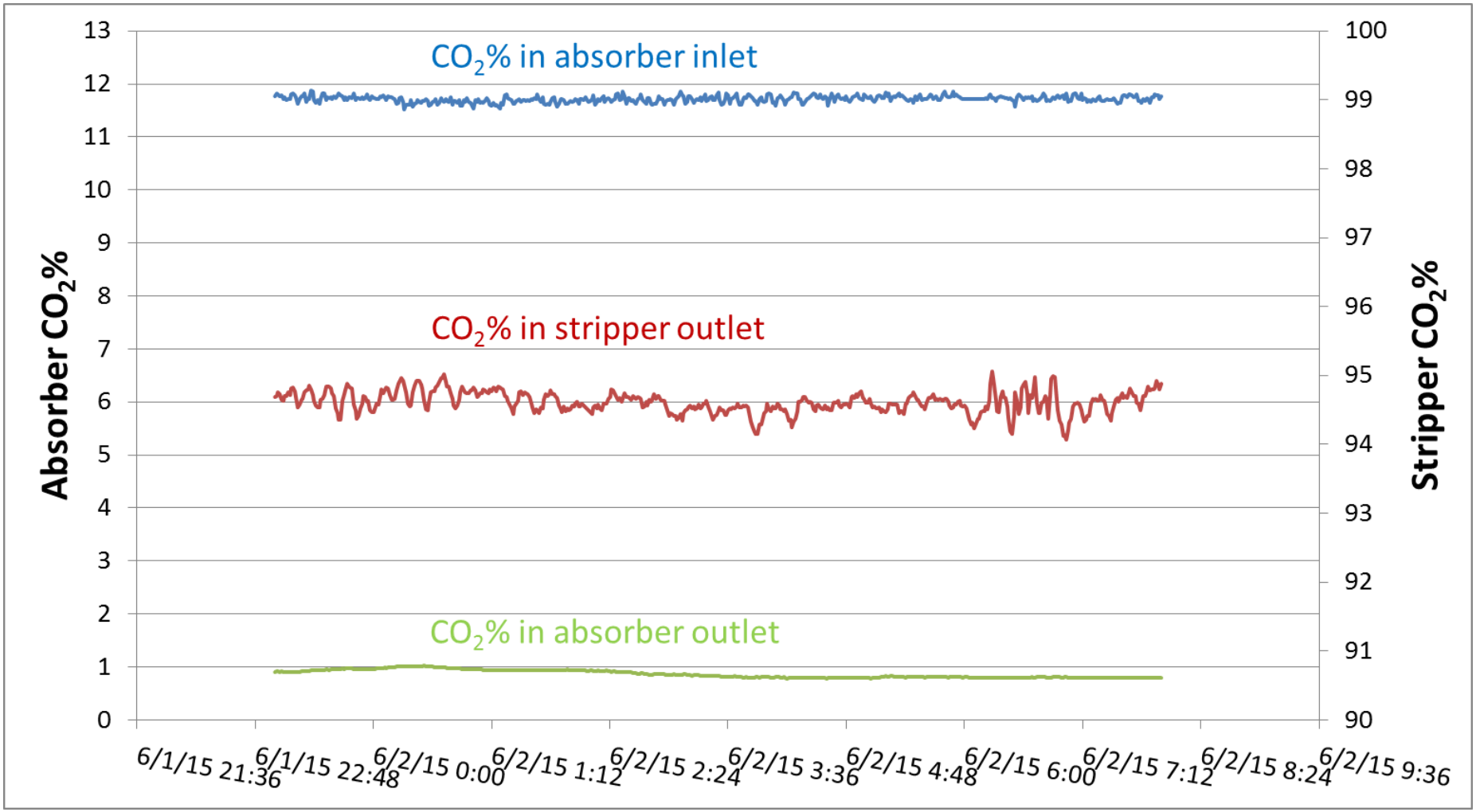
Two Columns:

- Absorber: ID=8”, H=32’
- Stripper: ID=6”, H=30’

Other Major Units:

- Cross heat exchanger
- Two inter-stage cooling
- Two inter-stage heating

Capture Performance of GPS Bench Unit at NCCC

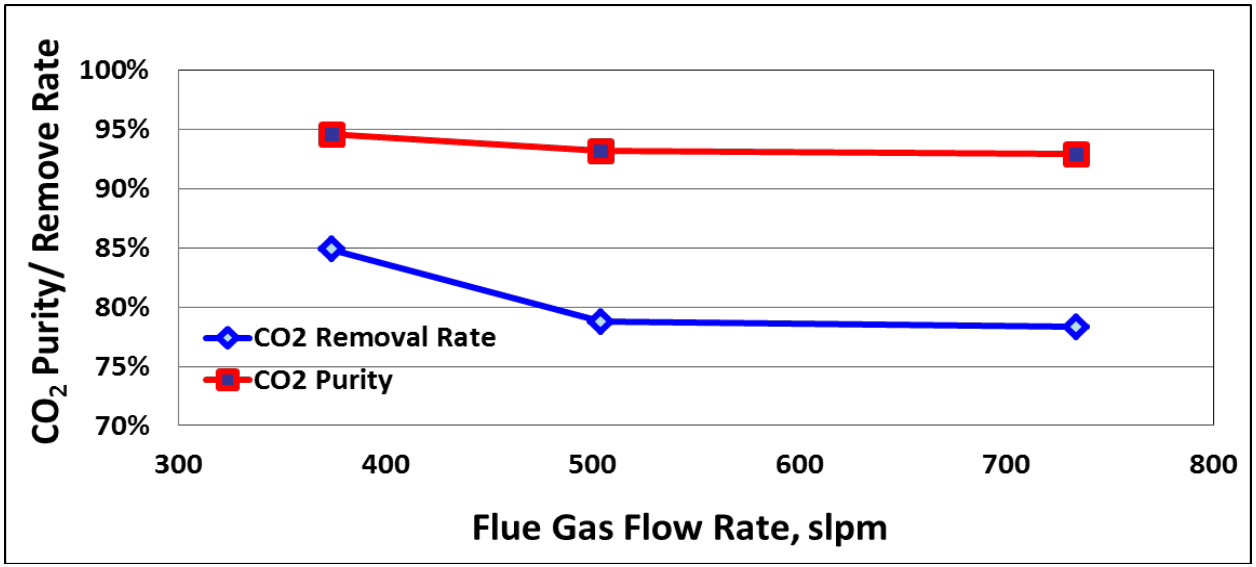


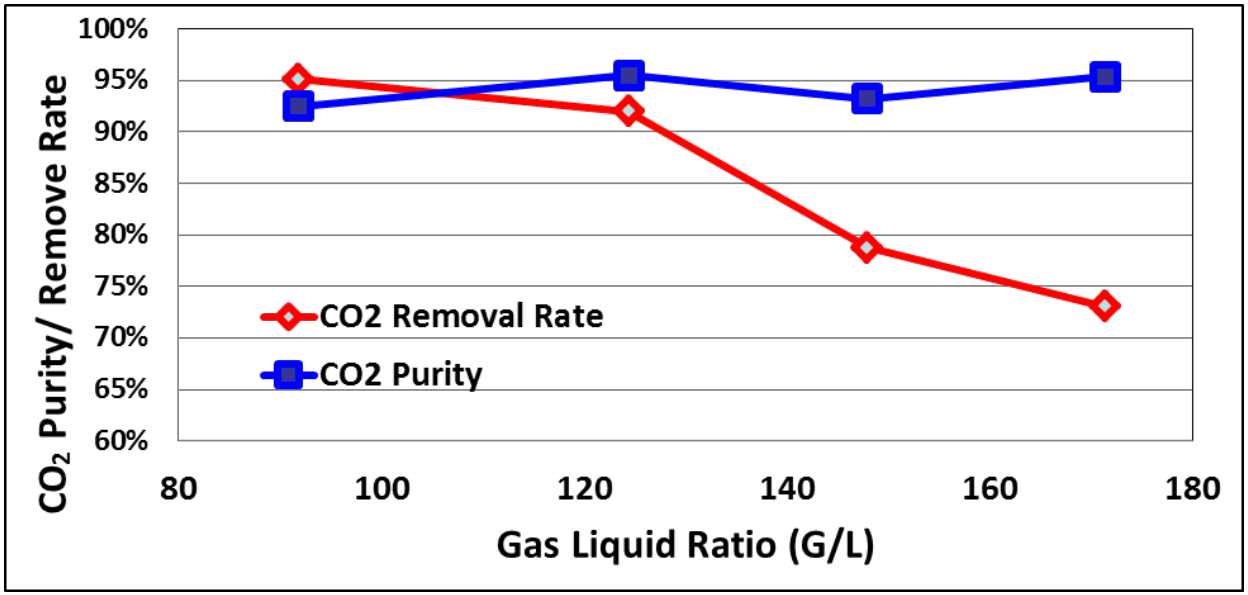
Bench Scale Test Results

Reaction heat and Stripping Heat of the GPS Bench-Scale Unit

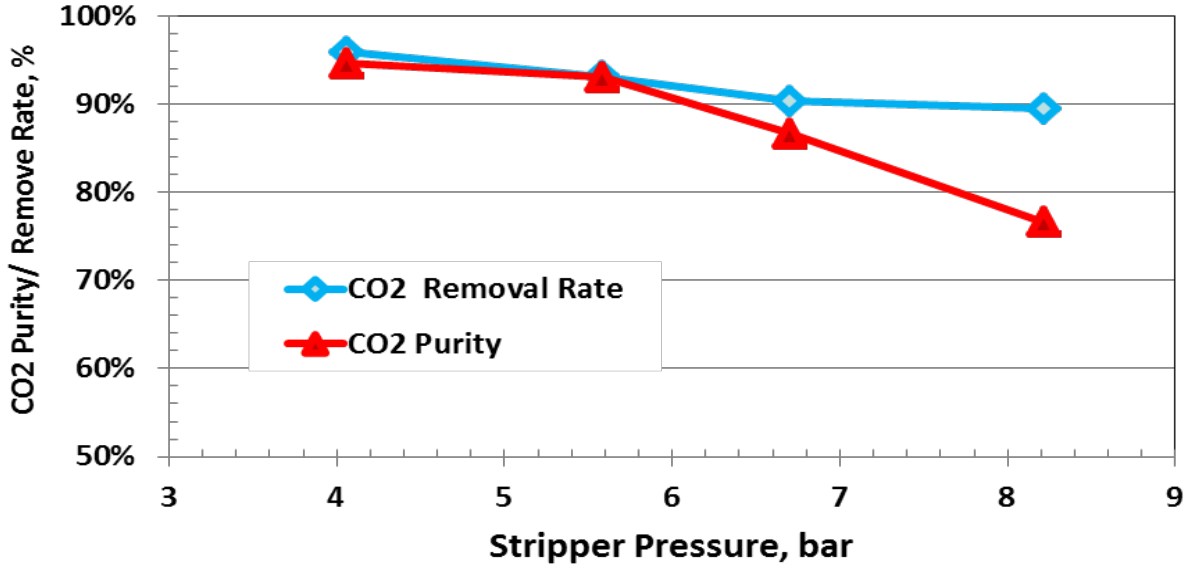
Run	CO_2 amount (kg/hr)	Total Steam Usage (lb/hr)	Steam Use Due to Sensible Heat and Heat loss (lb/hr)	Net Steam Usage (lb/hr)	(ΔH_R) + $Q_{stripping}$ (kJ/ kg CO_2)
1.	4.9	15.16	7.36	7.8	1562
2.	7.07	25.52	14.53	10.99	1600
3.	3.7	32.80	26.90	5.90	1597

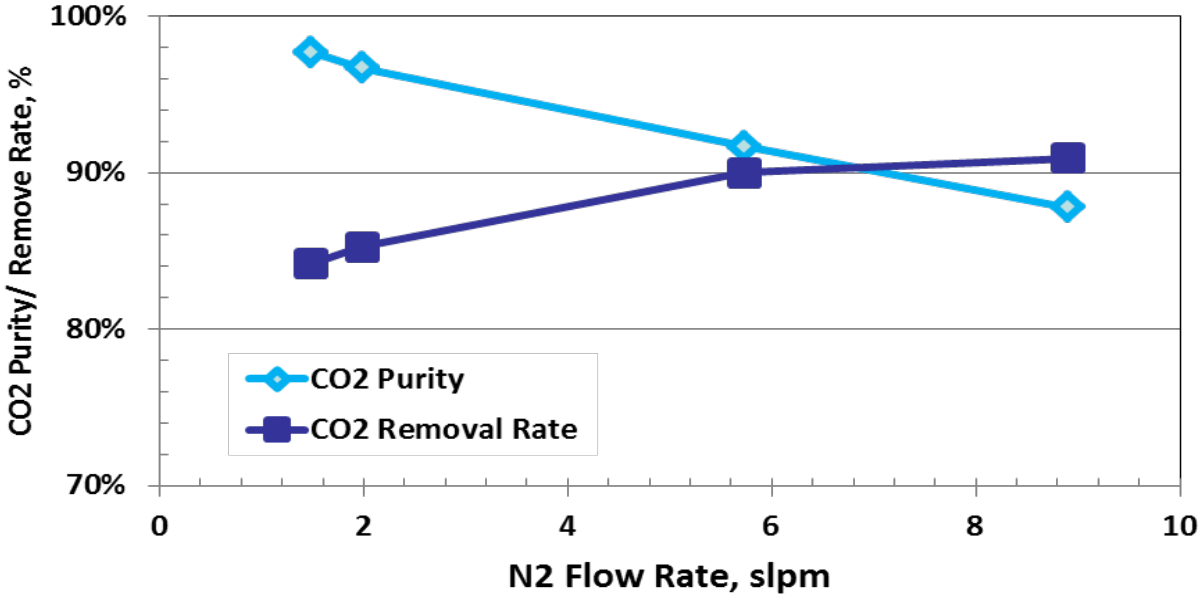
Bench Scale Test Results





Bench Scale Test Results





Energy Performance of the Optimized GPS Process

Process	Baseline MEA	GPS Process
Operating Pressure (atm)	1.8	~6
Reaction Heat (kJ/kgCO_2)	1870	1355
Sensible Heat (kJ/kgCO_2)	990	295**
Stripping Heat (kJ/kgCO_2)	690	231
Total Heat (kJ/kgCO_2)	3550	1881
Electricity Equivalent (kWh/kgCO_2)	0.29	0.12
Other load (kWh/kgCO_2)	0.04	0.04
Compression Work (kWh/kgCO_2)	0.09	0.07
Electricity Equivalent (kWh/kgCO_2)	0.42	0.23
Energy Penalty to SPC Plant (%)	30	18

***LMTD=5.12 ^{O}C*

Techno-economic study of GPS-based PCC process

- Power plant energy performance
  - Thermal efficiency of the power plant
  - Net plant heat rate
- Levelized cost of electricity
  - Increase compared to baseline
  - Levelized cost of electricity

Techno-economic Analysis

Type of CO_2 Capture Technology	Case 11	Case 12 MEA	Nexant Inc. MEA	GPS Process
Power Production, MW				
Gross Power	580	663	704	762
Net Power	550	546	575	647
Capital Cost, $MM				
Power Plant	866.4	1109.9	1114.9	1125.5
PCC Plant	0.0	410.8	390.6	430.8
CO_2 Compression and Drying	0.0	46.4	122.4	60.5
Start Up Costs (2% TPC before Contingency)	15.5	26.4	27.4	27.2
Total Capital Cost, $MM	881.9	1,593.5	1,655.4	1,644.0
Operating Cost excl Fuel, $MM/yr				
Fixed Operating Cost	13.8	20.5	21.0	22.6
Variable Operating Cost				
Non PCC related Opt Cost	20.0	33.6	35.5	34.6
NaOH		0.9	0.9	0.9
H_2SO_4		0.3	0.3	0.3
Amine M/U		1.0	1.1	2.0
Active Carbon		0.6	0.5	0.5
Corrosion Inhibitor/Solvent MU		0.0	0.0	0.0
Total Operating Cost excl Fuel, $MM/yr	33.8	56.9	59.3	61.1
Fuel Cost, $MM/yr	64.5	92.0	92.0	92.0
LCOE (excl CO_2 TS&M), mills/kWh	63.9	112.0	109.6	97.4
% of Case 11 LCOE - Compare to 2007	100%	175%	171%	152%

CARBON CAPTURE SCIENTIFIC, LLC.

Techno-economic Analysis

	Baseline Case	Nexant Inc. MEA	GPS Process
Total Output at Generator Terminals, kW	663,445	704,032	761,909
Auxiliary Load Summary, kW:			
Coal Handling and Conveying	490	490	490
Limestone Handling & Reagent Preparation	1,270	1,270	1,270
Pulverizers	3,990	3,990	3,990
Ash Handling	760	760	760
Primary Air Fans	1,870	1,870	1,870
Forced Draft Fans	2,380	2,380	2,380
Induced Draft Fans	10,120	10,120	10,120
SCR	70	70	70
Baghouse	100	100	100
FGD Pumps and Agitators	4,250	4,250	4,250
Misc Balance of Plant	2,000	2,000	2,000
Steam Turbine Auxiliaries	400	400	400
Condensate Pumps	630	630	630
Cooling Water Circulation Pumps **	12,260	15,817	15,356
Cooling Tower Fans	6,340	4,547	4,424
Transformer Losses	2,300	2,441	2,641
Amine CO_2 Capture Plant Auxiliaries	21,320	18,986	22,420
CO_2 Compression	46,900	59,187	42,223
Total Auxiliaries, kW	117,450	129,308	115,394
Net Power Export, kW	545,995	574,724	646,514
Net Plant Efficiency, % HHV	27.2	28.7	32.2
Net Plant Heat Rate, Btu/kW	12,536	11,910	10,587

CCS CARBON CAPTURE SCIENTIFIC, LLC.

Conclusions

- GPS process can achieve 90% CO_2 removal from PC flue gas
- CO_2 product from GPS column can achieve required purity (>95%)
- Overall electricity equivalent parasitic power load of the GPS process is *<0.23kWh/kgCO_2, or* energy penalty of 18% or thermal efficiency 32.2% for a supercritical PC power plant
- Capital cost of optimized GPS process is <5% increase over the Baseline MEA case
- LCOE of GPS process 97.4 mills/kWh (2007$) or CO_2 capture cost of *$37.7/tonne (without TS&M)*
- *Our technical approach proves that GPS technology has TRL level of conventional absorption/stripping processes*

Major Success Criteria

Description of Criteria	Actual
Solvent loss due to degradation of solvent is less than 3kg/ tonne CO_2	**<<3 kg/tonne CO_2**
At operating temperature around 120°C, the GPS column operating pressure >4 bar and CO_2 purity >95%	**6bar and >95%**
Overall electricity equivalent energy requirement of the GPS process less than 0.23kWh/kgCO_2	**<0.23kWh/kgCO_2**
Increase in capital equipment costs of less than or equal to 10% over existing process	**<5% higher**
CO_2 capture cost of <$45/tonne for NETL Baseline Case 12	***<$37.7/tonne (without TS&M)***

Achievement and Future Work

Project Achievements

- Completed all major individual process unit tests at lab
- Design, fabrication and installation of a bench scale (500SLPM) continuous skid-mounted GPS system and tested at NCCC
- Computer simulation tasks identified favorable GPS process configuration, leading to capital cost <5% increase over the Baseline MEA case
- Overall electricity equivalent energy requirement of the GPS process *<0.23kWh/kgCO_2 or energy penalty of 18%*
- CO_2 capture cost of *<$37.7/tonne (without TS&M)*

Future Work

- Pilot-scale test of GPS technology
- Further process integrations to reduce cost
- Test other promising solvents

Questions/ Comments?

Capture Cost Calculations

LCOE for GPS: 97.4 mills/kwh

LCOE for Case 11(2007): 63.9 mills/kwh

CO_2 removed: 13050 kmol/h=632.9 tons (US short)

Net power of GPS based: 647MW

CO_2 capture cost = (COE_{ccs} - COE_{nonccs})/(CO_2 captured/kWh)

=(97.4-63.9)/(632.9/647)

=$34.24/ton

=$37.7/tonne

GPS Process for MEA and AMP

Parameter	MEA	AMP
Solvent concentration, %wt	30	30
Pressure at GPS column, bar	3.1	5
Working capacity, %wt	3.8	4.2
Heat consumption, kJ/kg CO_2	2791	2229
Absorber height, m Mellapak M250Y	16	35
Absorber diameter, m	20.6	20.7
GPS column height, m Mellapak M170Y	10	8
GPS column diameter, m	10.8	9.8