Accelerating Carbon Capture Technology Development in Partnership with CCSI²

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RTI International

NAS CO_2 Capture Technology Development History

U.S. DEPARTMENT OF ENERGY | NATIONAL ENERGY TECHNOLOGY LABORATORY

arpa-e IMPACCT

RTI Lab-Scale Development & Evaluation (2010-2013)

Solvent screening and lab-scale evaluation

~$2.7MM

TRL 1-2

RTI Large Bench-Scale System (2014-2016)

Demonstration of key process features (≤ 2,000 kJ/kg CO_2) at bench scale

~$3 MM
6kW

~0.1 t-CO_2/day

TRL 2-3

SINTEF Pilot Testing at Tiller Plant (2015-2018)

Demonstration of all process components at pilot scale with real flue gas

~$3MM
60 kW

~1.0 t-CO_2/day

TRL 3-5

NCCC Pilot Testing at SSTU (2018)

Degradation, emission, and corrosion characterizations with real flue gas

~$0.75MM
50 kW

~1.0 t-CO_2/day

TRL 3-5

RTI Emissions control (2018-2021)

Effective emissions mitigation strategy for WLS at engineering-scale

~$3.5MM

~0.1 t-CO_2/day

TRL 2-3

TCM Engineering-Scale Validation (2018-2023)

Pre-commercial Demonstration at Technology Centre Mongstad, Norway

~$17.4 MM
12 MW

~200 t-CO_2/day

TRL 5-6

From lab to large scale demonstration through series of projects

Focus on DOE Performance Goal

New coal-fired power plants with CO_2 capture at a cost of electricity 30% lower than the baseline cost of electricity from a supercritical PC plant with CO_2 capture, or approximately $30 per tonne of CO_2 captured by 2030.

Breakdown of the Thermal Regeneration Energy Load

$$q_R = \left[\frac{C_P(T_R - T_F)}{\Delta\alpha} \cdot \frac{M_{sol}}{M_{CO_2}} \cdot \frac{1}{x_{sol}}\right] + \left[\Delta H_{V,H_2O} \cdot \frac{p_{H_2O}}{p_{CO_2}} \cdot \frac{1}{M_{CO_2}}\right] + \left[\frac{\Delta H_{abs,CO_2}}{M_{CO_2}}\right]$$

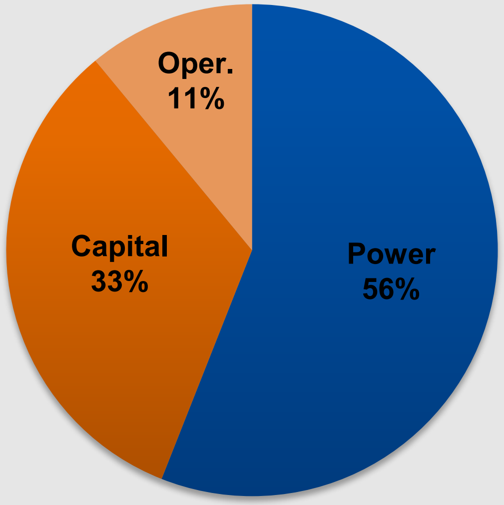
Reboiler Heat Duty — Sensible Heat — Heat of Vaporization — Heat of Absorption

Solvent	C_p [J/g K]	ΔH_{abs} [kJ/mol]	ΔH_{vap} [kJ/mol]	x_{solv} [mol solvent/mol solution]	$\Delta\alpha$ [mol CO_2/ mol solvent]	Reboiler Heat Duty [GJ/t-CO_2]
30 wt% MEA-H_2O	3.8	85	40	0.11	0.34	3.75
RTI's NASs	2.0	85	negl.	0.47	0.45	2.40

Heat of vaporization of water becomes a negligible term to the heat duty

Path to Reducing lCOE and Cost of CO_2 Avoided

- Primarily focused on reducing energy consumption – reboiler duty
- Reduce capital expenditure
  - Simplify process arrangement
  - Materials of construction
- Limit operating cost increase



[1] Rochelle, G. T. Amine Scrubbing for CO_2 Capture. *Science* **2009,** 325, 1652-1654.

Project Summary : DE-FE0031590

Description: Testing and evaluation of transformational non-aqueous solvent (NAS)-based CO_2 capture technology at engineering scale at TCM

Key Metrics

- Solvent performance including capture rate, energy requirements, solvent losses
- Solvent degradation, corrosion, emissions
- Technoeconomic and EHS evaluation

Specific Challenges

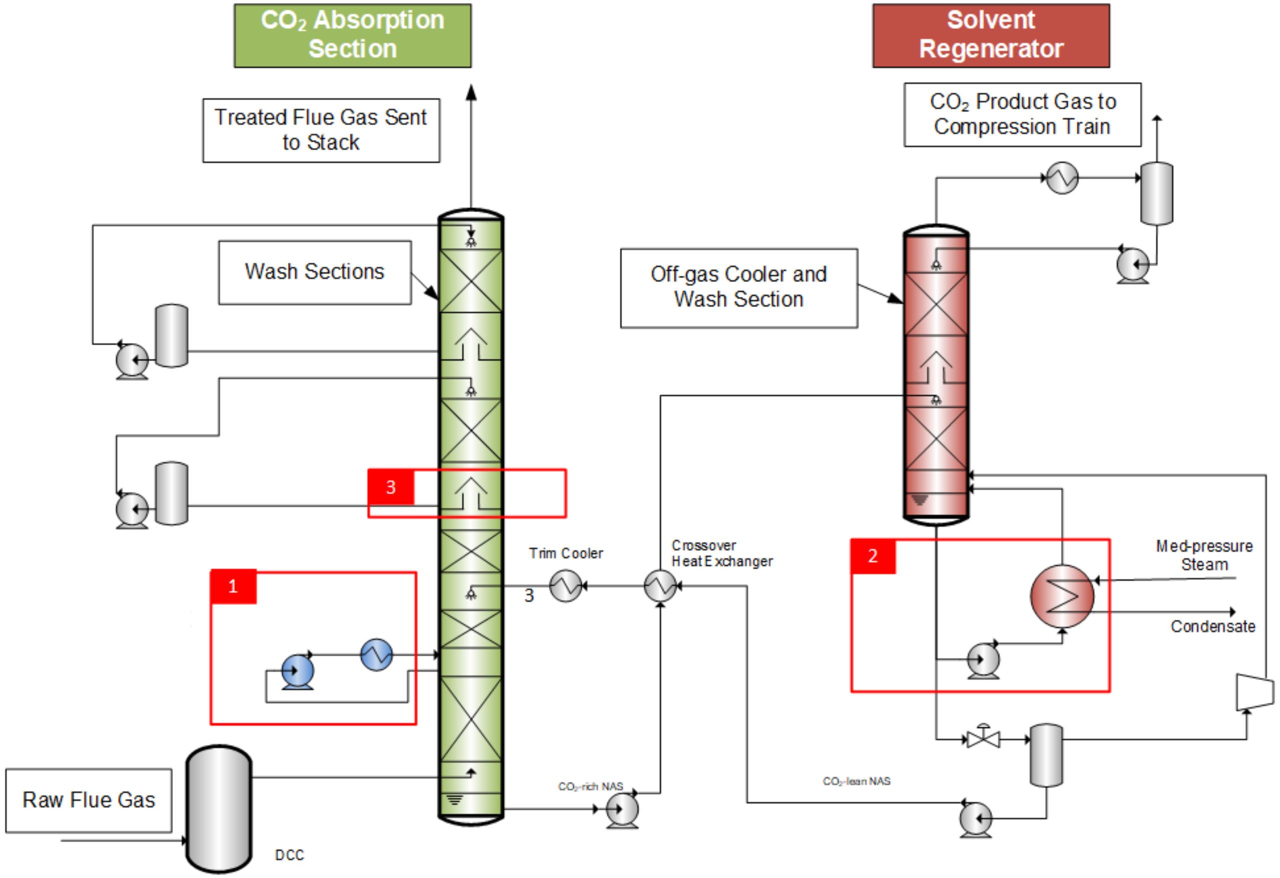
- Resolve remaining technical and process risks
- Operate TCM plant within emission requirements
- Minimize rise in absorber temperature
- Maximize NAS performance with existing hardware limitations

Timeframe: 8/8/18 to 06/30/23

Total Funding: $17,384,512

Partners: SINTEF, EPRI Electric Power Research Institute, CCSI² Carbon Capture Simulation for Industry Impact, CO2 Technology Centre Mongstad, Texas The University of Texas at Austin

TCM Amine Plant and NAS Modifications



TCM

- Amine plant modifications
- Leadership in detailed engineering, fabrication, and construction
- Process modeling expertise
- Excellence in operations

Absorber Modifications

- One interstage cooler
- Equipment within budget
- Control temperature bulge at top to decrease emissions

Regenerator Mods

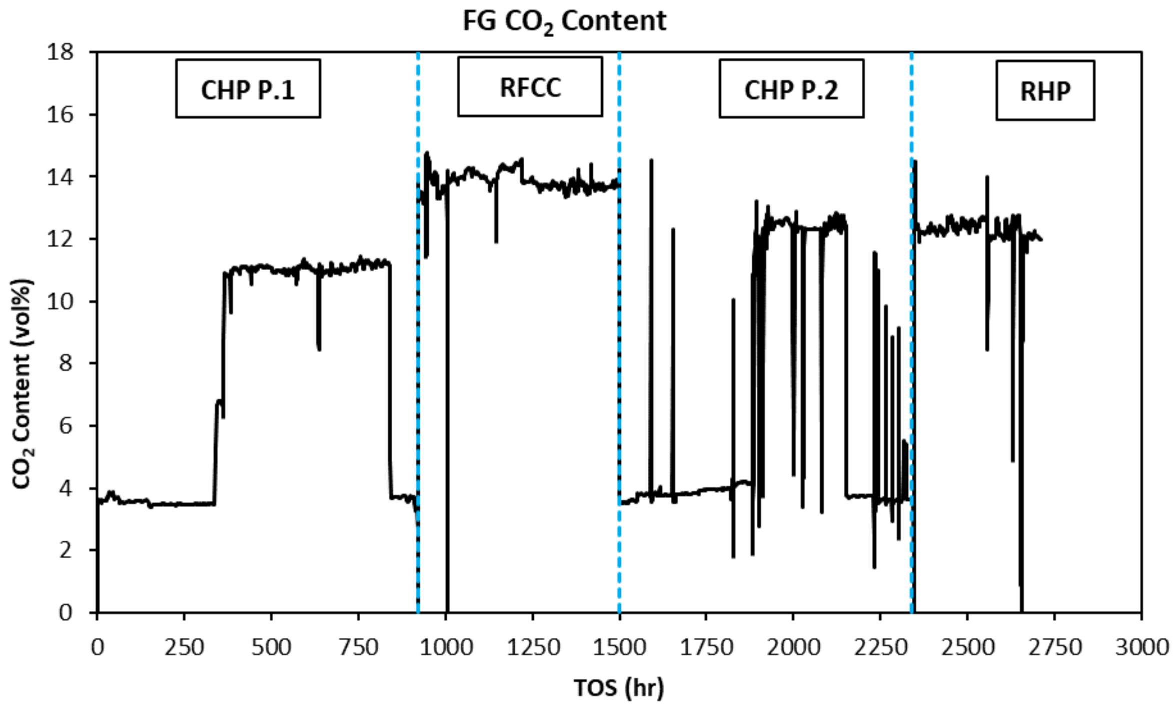
- Higher capacity pump for reboiler
- Force recirculation due to high boiling points of solvent components
- Equipment within budget

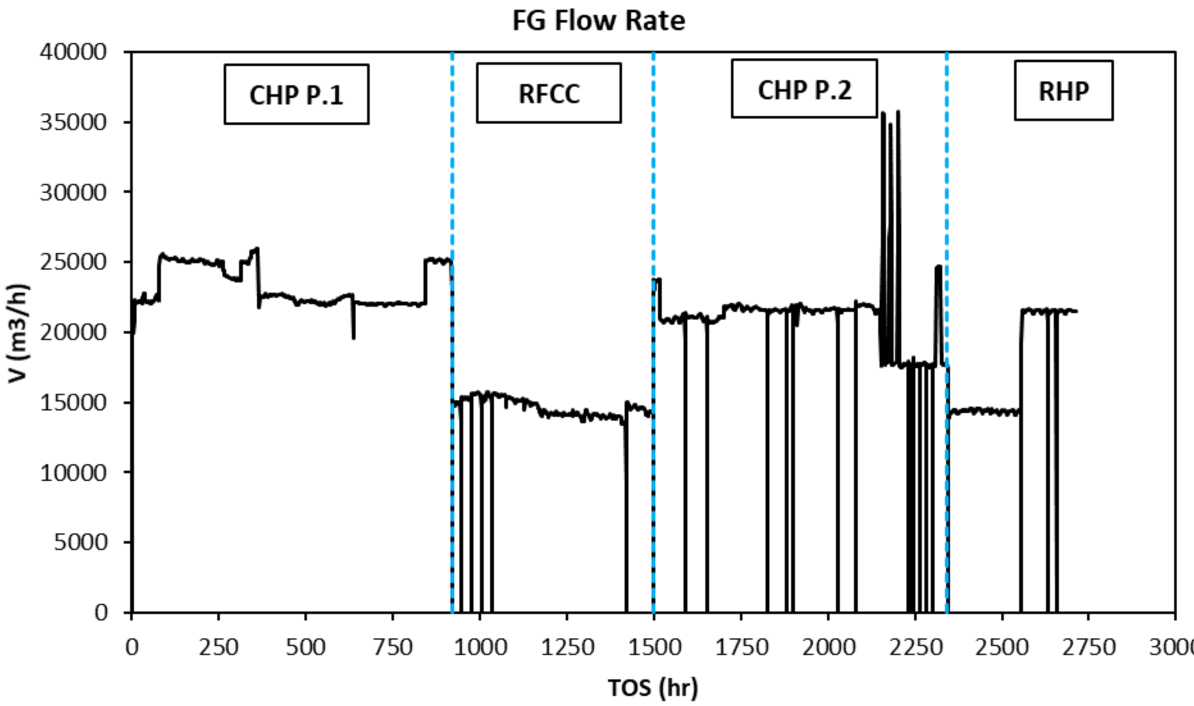
CCSI²

Carbon Capture Simulation for Industry Impact

- GEN1NAS modeling
- Thermodynamic data review
- TCM MEA model comparison
- Synergistic with TCM Advisory Services
- SDoE matrices for testing

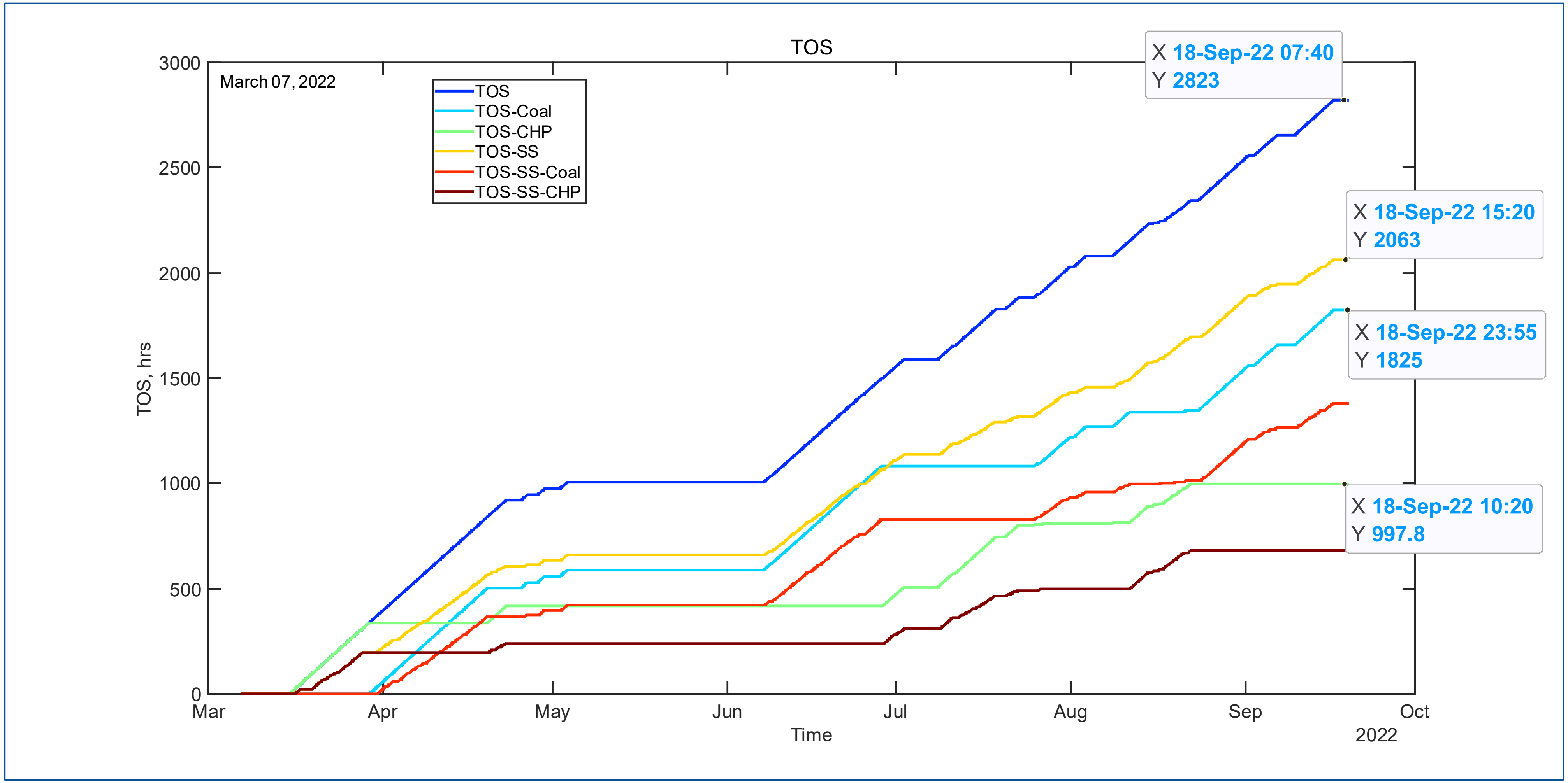
Test Campaign Segments and Flue Gas Characteristics





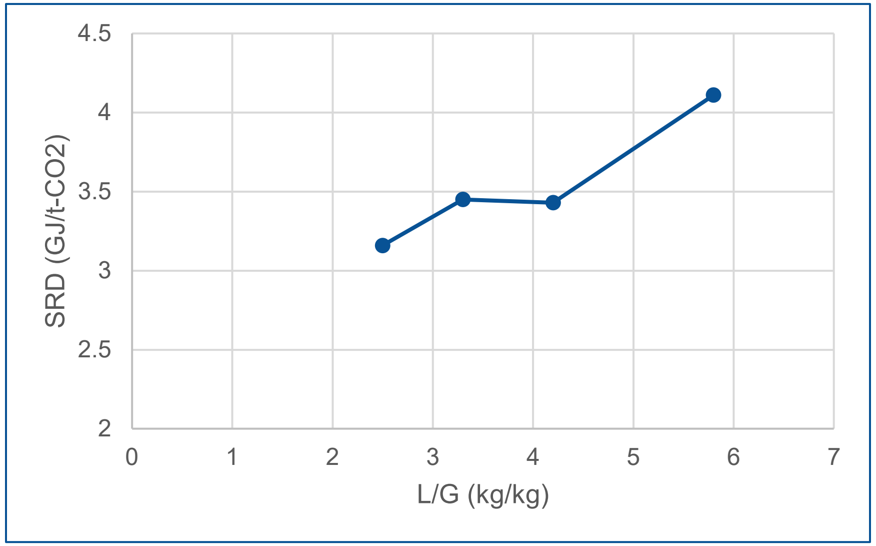
Flue Gas	CO_2 (vol %)	O_2 (vol%)	NO_2 (ppm)	NO (ppm)	SO_2 (ppm)
CHP	3.9	12.9	3.2	23.9	1.0
RFCC	14.7	2.4	1.2	66.5	0.0
CHP w/ Recycle (RFCC Mimic)	12.6	6.1	3.0	45.4	0.8
RHP (aka MHP)	13.7	4.6	4.6	50.9	0.4
RHP w/ Recycle (Cement Mimic)	18.0	4.6	5.0	3.4	0.0

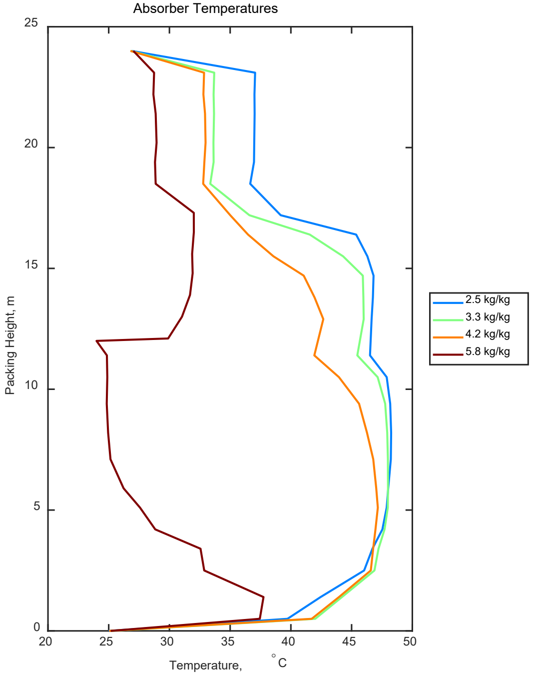
Time on Stream Highlights



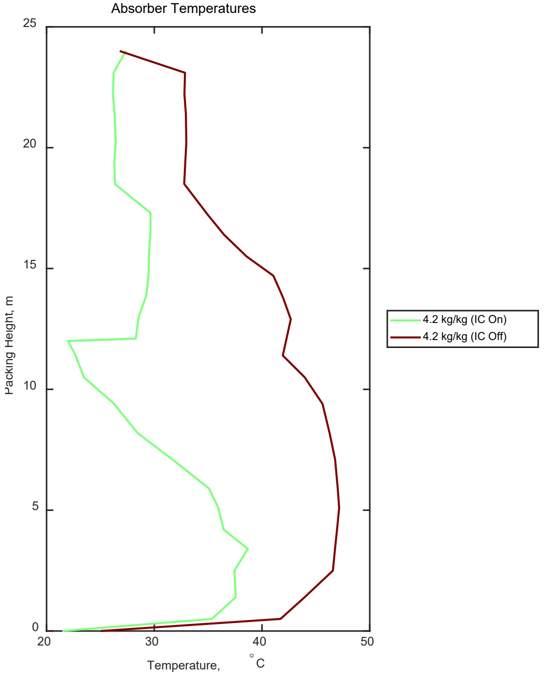
Time on stream:
2823 hours
Coal (RFCC):
1825 hours
NGCC (CHP):
998 hours
Steady state:
2063 hours

NGCC Performance: L/G Optimization

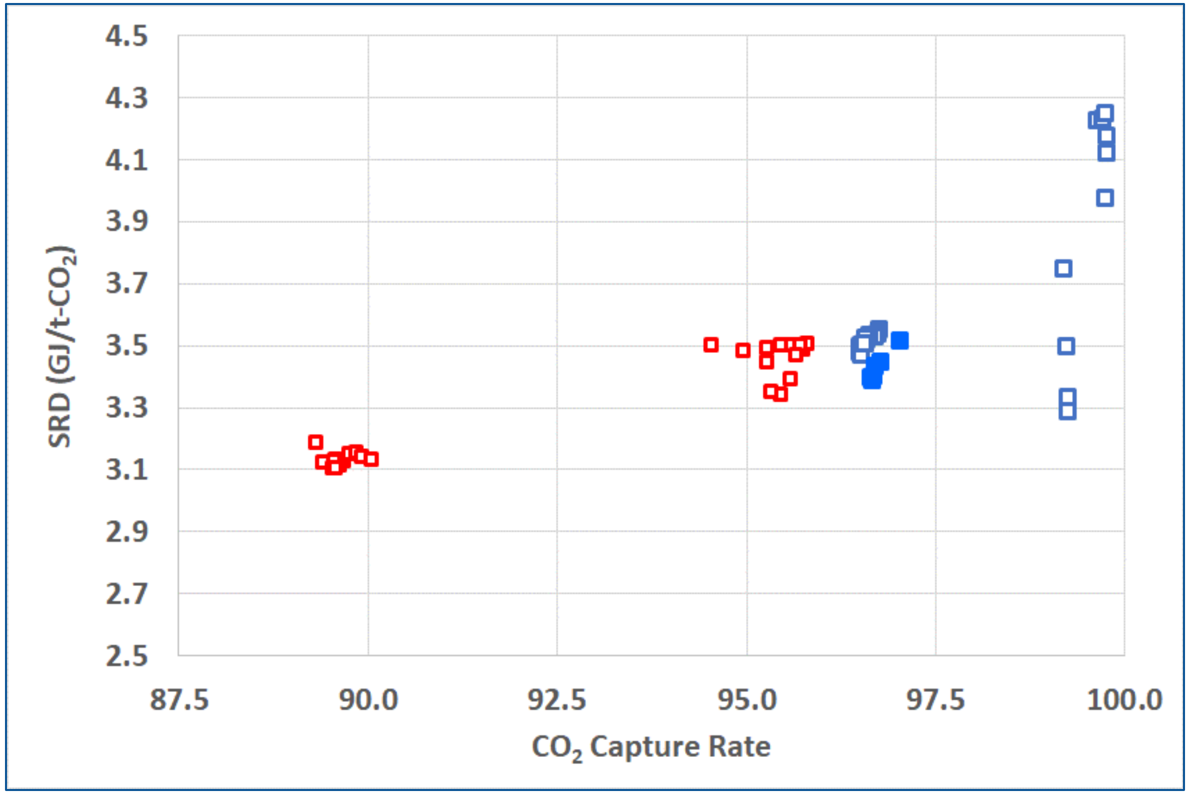




L/G Impact on bulge



Intercooler impact on bulge



NGCC SDoE Parametric Testing Results

Test Conditions

Run	L/G Ratio (kg/kg)	CO_2 Capture Rate (%)	Regen Pressure (barg)
1	4.5	95	1.0
2	4.0	95	1.0
3	3.0	85	1.0
4	3.5	90	1.0
5	3.5	85	2.1
6	4.0	90	2.1
7	3.0	95	2.1
8	2.5	90	2.1
9	3.5	95	3.2
10	3.0	90	3.2
11	2.5	85	3.2
12	4.5	85	3.2

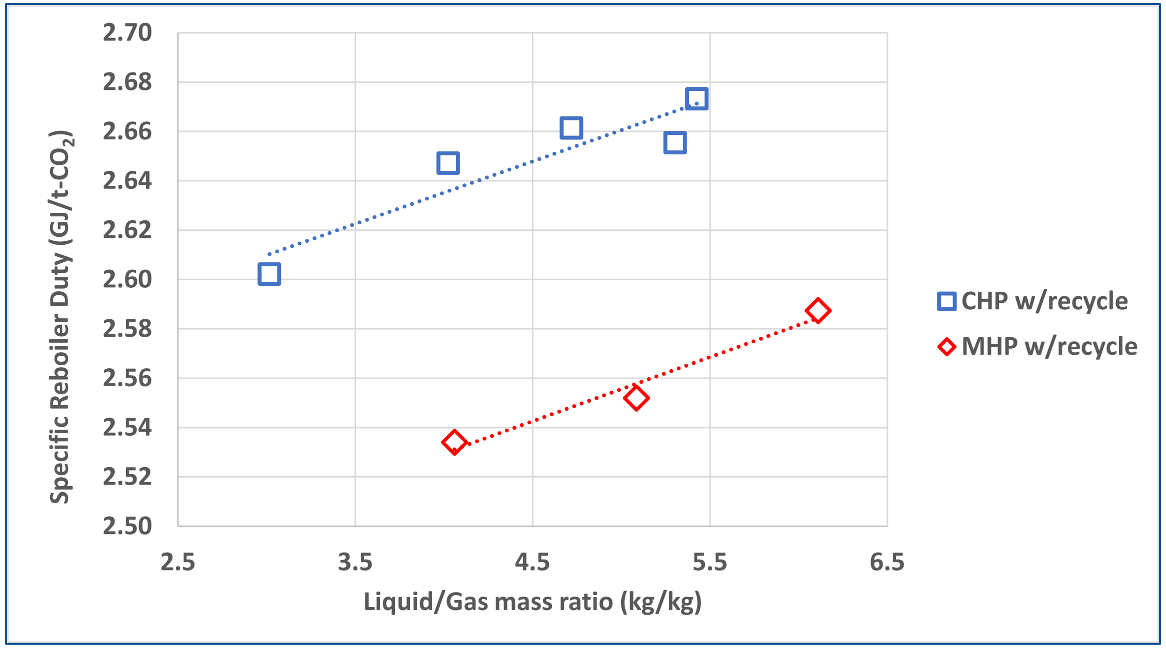
Results

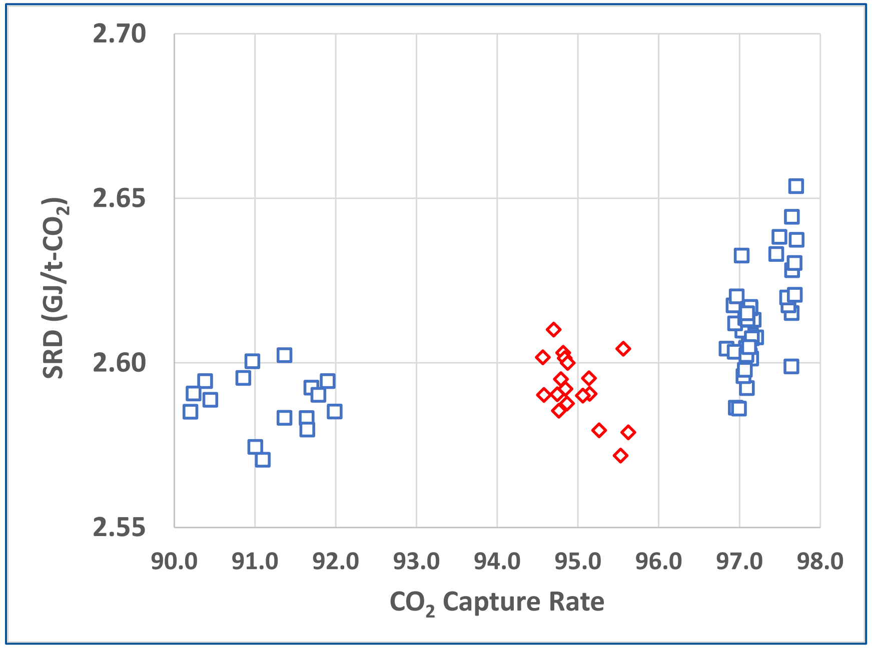
Run	Regenerator Pressure (barg)	Capture Rate	L/G (kg/kg)	Reboiler Temp (Celsius)	Flue gas flow (Sm^3/hr)	Observed T_approach (Celsius)	Observed SRD (GJ/t-CO_2)	SRD (w/ 5C T approach) (GJ/t-CO_2)
NGCC sDOE01	1.0	95.1	4.8	97.3	26861	15.4	5.85	3.60
NGCC sDOE02	1.0	95.4	4.2	95.7	26907	14.8	5.33	3.43
NGCC sDOE03	1.0	85.0	3.1	89.2	26932	14.4	4.63	3.13
NGCC sDOE04	1.0	90.3	3.7	90.5	26935	14.3	4.95	3.30
NGCC sDOE05	2.1	84.9	3.7	95.0	26927	16.1	5.32	3.32
NGCC sDOE06	2.1	90.3	4.2	96.9	26929	16.7	5.67	3.47
NGCC sDOE07	2.1	95.1	3.2	102.4	26928	15.6	4.65	3.14
NGCC sDOE08	2.1	89.8	2.6	100.7	26930	15.7	4.43	3.10
NGCC sDOE09	3.2	95.5	3.7	107.5	26976	16.9	4.85	3.11
NGCC sDOE10	3.2	90.5	3.1	104.5	26974	16.8	4.67	3.08
NGCC sDOE11	3.2	85.3	2.6	104.7	26977	16.7	4.38	3.01
NGCC sDOE12	3.2	85.3	4.7	99.6	26968	18.0	6.22	3.69

Impact

Variable	Weight
L/G	0.287
Capture rate	-0.034
Pressure	-0.025

Coal Performance: L/G Optimization





Gas	L/G (kg/kg)	L/G (kg/Sm³)	Flue Gas flowrate (Sm³/hr.)	CO_2 capture rate (%)	Regen Pressure (bar,g)	Reboiler Temp (Celsius)	SRD GJ/t-CO_2
CHP	5.4	7.0	28,420	89.7	0.96	94.3	2.67
CHP	5.3	6.8	28,994	90.0	0.96	94.8	2.66
CHP	4.7	6.1	28,443	89.9	0.96	97.2	2.66
CHP	4.0	5.2	28,205	90.5	0.95	100.5	2.65
CHP	3.0	3.9	28,103	90.0	0.95	105.4	2.60
MHP	6.1	7.7	27,847	91.0	3.17	106.3	2.59
MHP	5.1	6.5	27,863	90.4	3.17	110.0	2.55
MHP	4.1	5.1	27,854	89.6	3.16	115.1	2.53

Run	Stripper Pressure (barg)	Capture Rate	L/G (kg/kg)	Reboiler Temp (Celsius)	Flue gas flow (Sm³/hr)	SRD (w/ 5C Tapproach) GJ/t-CO2
RHP-1	3.2	91.0	6.11	106.3	21,982	2.59
Coal sDOE12a	3.2	95.0	6.52	107.0	21,982	2.59
CHC-2	3.2	97.1	6.11	112.2	21,982	2.61
CHC-3	3.2	97.6	6.11	113.9	21,982	2.63

Coal SDoE Parametric Testing Results

CCSI[2]
Carbon Capture Simulation for Industry Impact

Test Conditions

Run	L/G Ratio (kg/kg)	CO_2 Capture Rate (%)	Regen Pressure (bar,g)
1	4.5	95	1.0
2	4.0	95	1.0
3	3.0	85	1.0
4	3.5	90	1.0
5	3.5	85	2.1
6	4.0	90	2.1
7	3.0	95	2.1
8	2.5	90	2.1
9	3.5	95	3.2
10	3.0	90	3.2
11	2.5	85	3.2
12	4.5	85	3.2

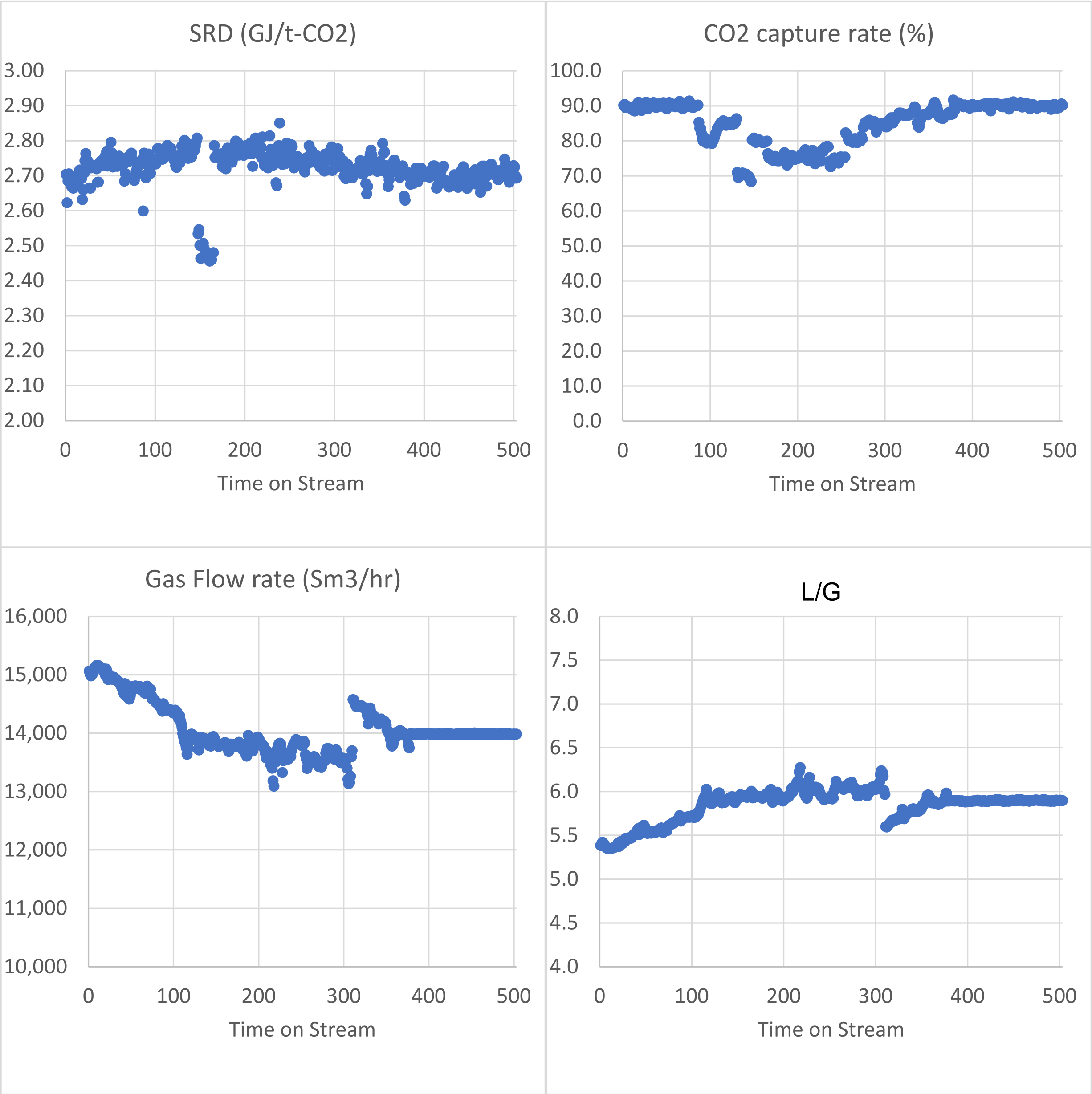
Results

Run	Stripper Pressure (barg)	Capture Rate	L/G (kg/kg)	Reboiler Temp (Celsius)	Flue gas flow (Sm^3/hr.)	SRD (w/ 5C Tapproach) GJ/t-CO_2
sDOE01	2.6	90.7	4.0	113.6	21,982	2.57
sDOE02	2.6	92.0	3.5	119.8	21,983	2.55
sDOE03	2.6	90.1	4.5	110.3	21,978	2.59
sDOE04	2.6	95.0	5.5	108.3	21,982	2.59
sDOE05	2.1	94.6	4.0	113.4	21,982	2.59
sDOE06	2.1	90.4	6.5	98.9	21,982	2.58
sDOE07	2.1	90.5	3.5	114.6	21,981	2.53
sDOE08	2.1	95.2	4.5	110.3	21,982	2.60
sDOE09	3.2	95.3	4.0	120.4	21,981	2.58
sDOE10	3.2	90.7	5.5	107.9	21,982	2.57
sDOE11	3.2	90.9	3.5	121.0	21,981	2.55
sDOE12	3.2	95.0	6.5	107.0	21,982	2.59

Impact

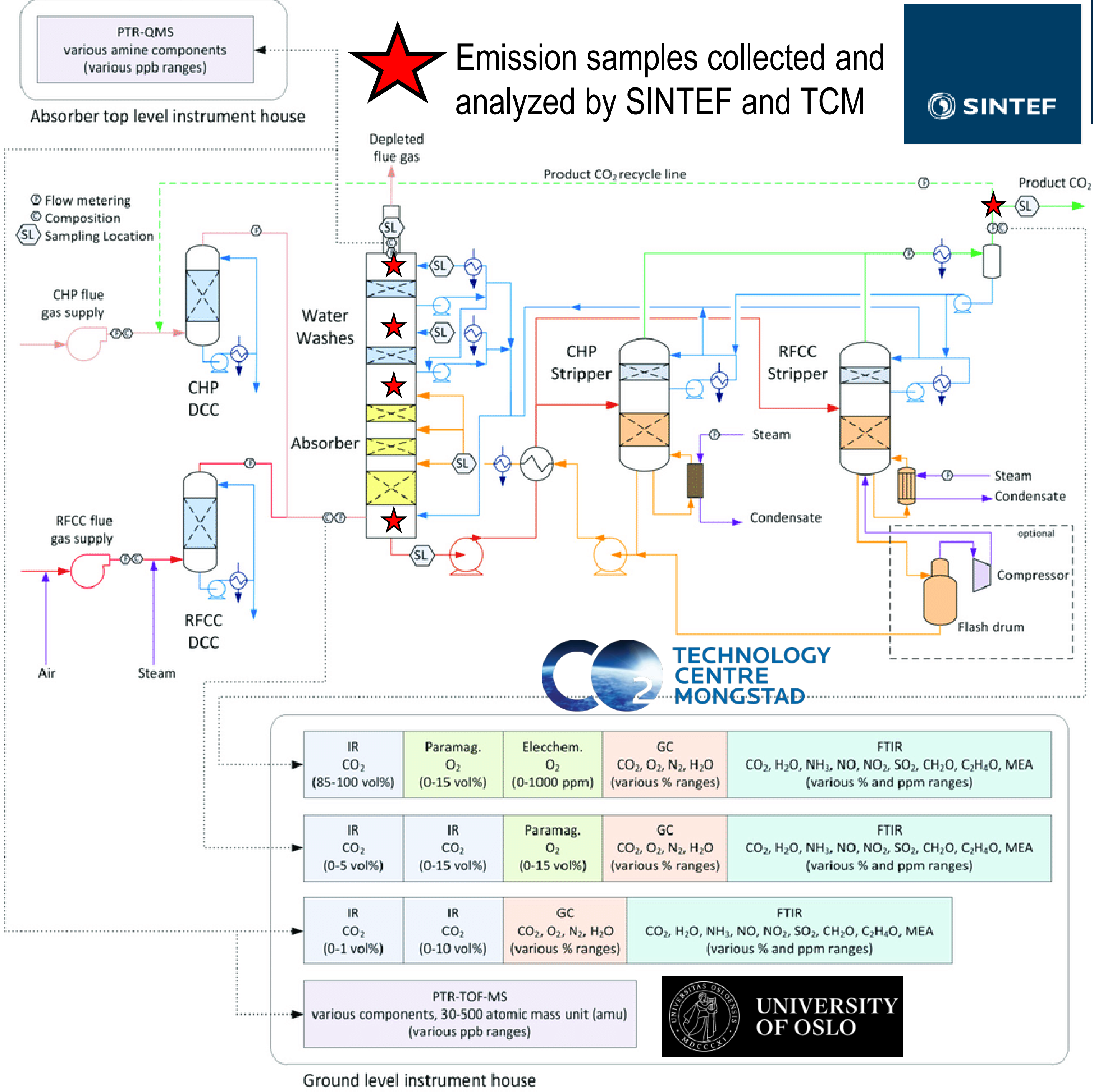
Variable	Weight
L/G	0.011
Capture rate	0.013
Pressure	-0.002

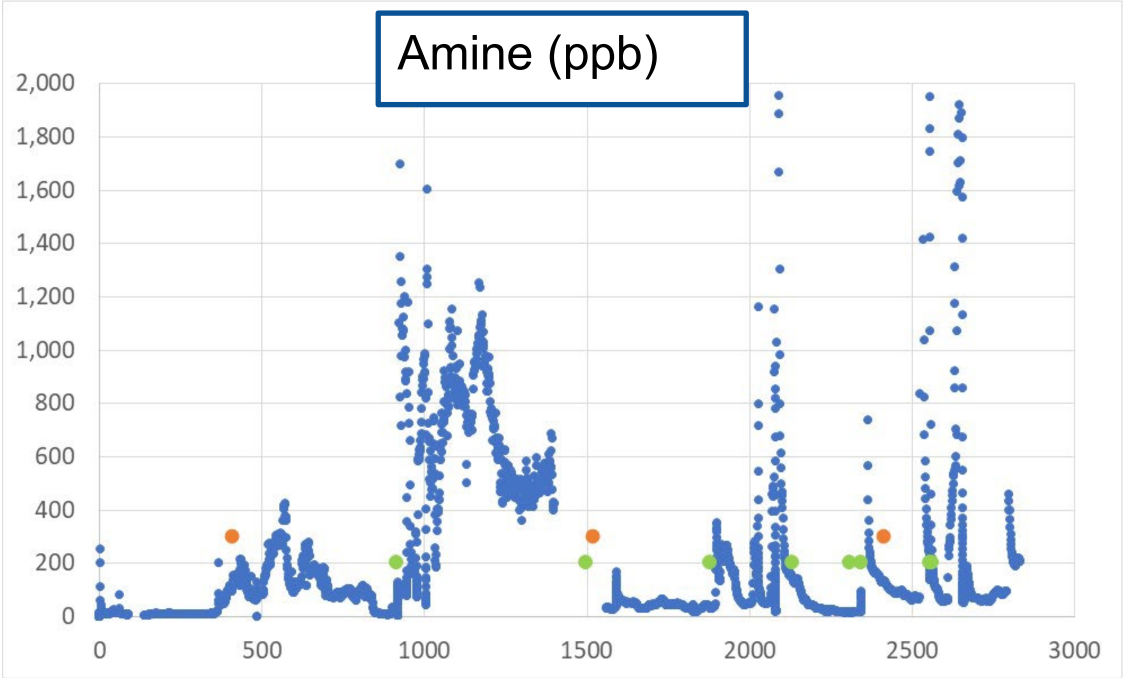
Coal Long Term Testing



Emissions including PTR-TOF MS

Emission samples collected and analyzed by SINTEF and TCM

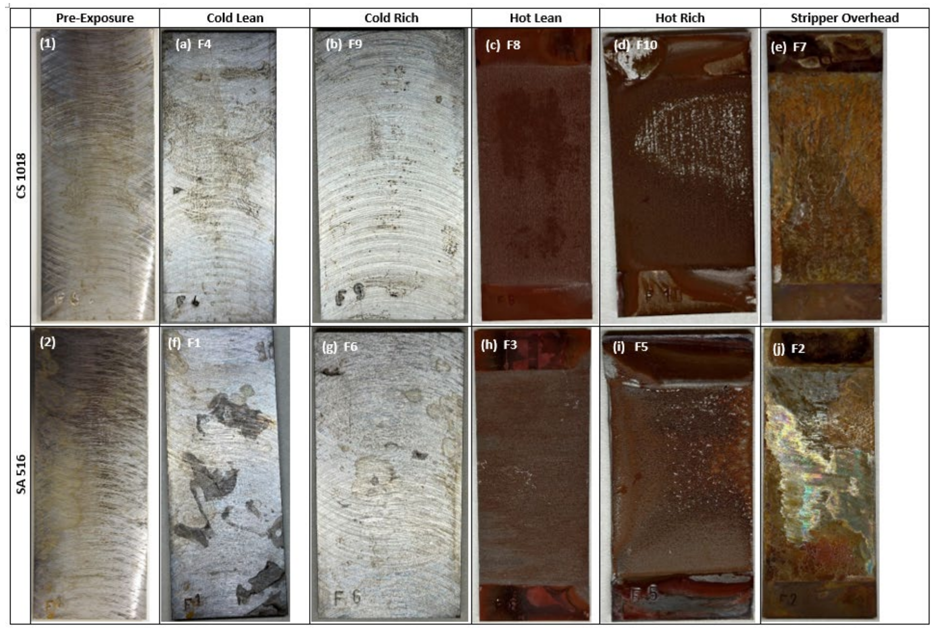


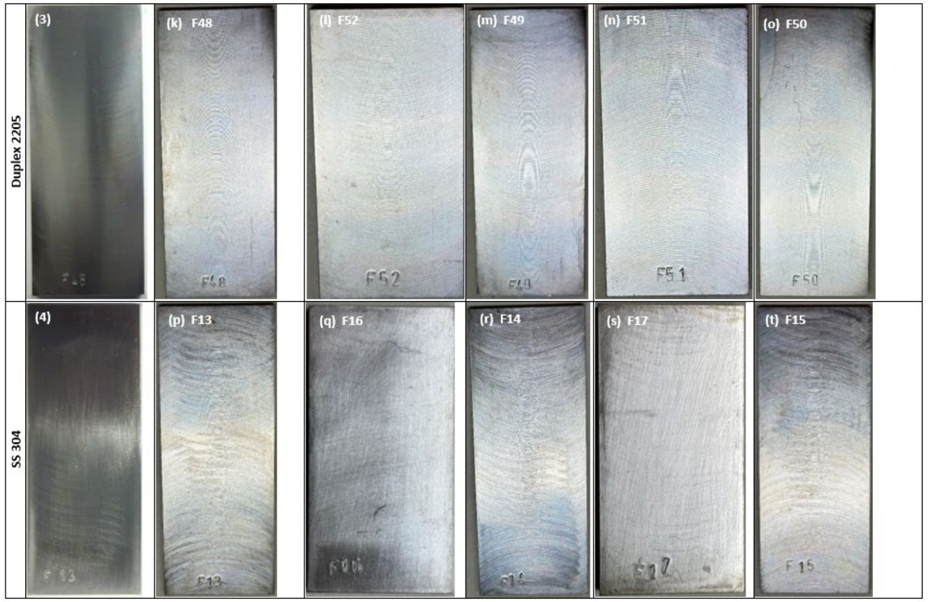


TOS (h)	Event (Green dots)
916	CHP ended, RFCC began
1499	RFCC ended, NGCC sDOE on CHP began
1881	NGCC sDOE ended, Coal sDOE began
2131	Coal sDOE ended, dynamic testing began
2331	Dynamic testing ended, deep capture NGCC began
2343	Deep capture NGCC ended, EF test began
2555	EF test ended, RHP test began

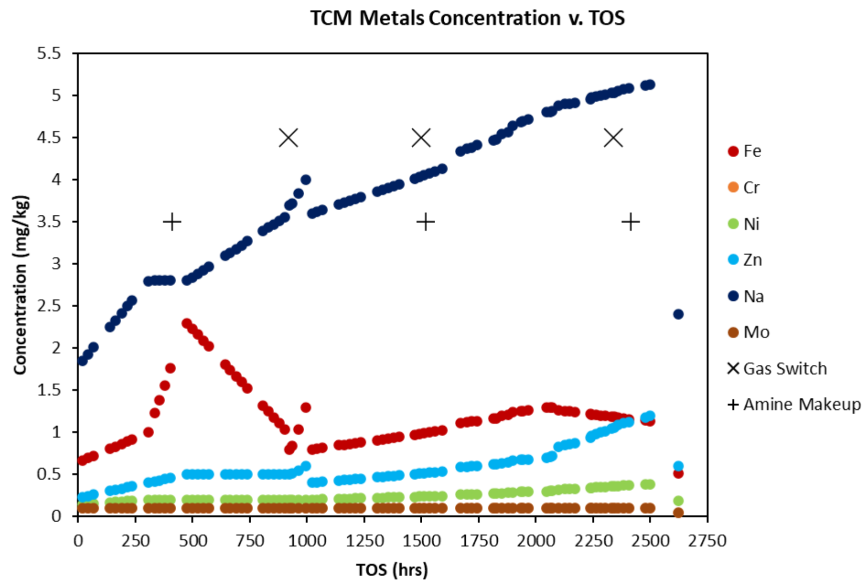
Aerosol modelling through TXCMP built confidence ahead of testing

Corrosion Coupon Testing Results





Rating	Corrosion Rate (µm/yr)
Outstanding	<25
Excellent	25—100
Good	100—500
Fair	500—1000
Poor	1000—5000
Unacceptable	>5000



		Cold Lean (8" Line)	Cold Rich (6" Line)	Hot Lean (8" Line)	Hot Rich (6" Line)	Stripper Overhead (12" Line)
Carbon Steels	CS 1010	-0.03 ± 0.06	-0.07 ± 0.08	383.02 ± 46.83	Lost	-0.51 ± 0.07
	CS 1018	-0.01 ± 0.14	0.01 ± 0.21	376.00 ± 10.84	956.22 ± 33.07	-0.27 ± 0.14
	SA 516	0.18 ± 0.14	0.06 ± 0.21	343.21 ± 9.90	1167.12 ± 40.36	-0.37 ± 0.14
	SA 516 Bent	0.12 ± 0.07	-0.08 ± 0.08	414.97 ± 64.57	Lost	-0.09 ± 0.04
Stainless Steels	Duplex 2205	-0.18 ± 0.14	-0.21 ± 0.21	-0.12 ± 0.14	-0.10 ± 0.21	-0.08 ± 0.14
	Duplex 2205 Bent	-0.07 ± 0.06	-0.07 ± 0.08	-0.03 ± 0.06	-0.06 ± 0.08	0.00 ± 0.04
	SS 304	-0.02 ± 0.14	-0.01 ± 0.20	0.00 ± 0.14	0.03 ± 0.20	0.00 ± 0.14
	SS 304 Bent	-0.04 ± 0.06	-0.03 ± 0.08	-0.02 ± 0.06	-0.01 ± 0.08	-0.02 ± 0.04
	SS 316	-0.03 ± 0.14	-0.01 ± 0.20	0.00 ± 0.14	0.02 ± 0.20	0.00 ± 0.14
Resin	Ultem Resin	-33.24 ± 5.73	20.85 ± 4.30	Lost	Lost	22.37 ± 3.89

Technoeconomic Analyses, 2023

EPRI ELECTRIC POWER RESEARCH INSTITUTE | NexantECA | RTI INTERNATIONAL

SC PC 97% Capture

Plant	B12B.97-RTI NAS
Gross Size	763 MWe
Net Size	653 MWe
Capacity Factor (CF)	85%
Total As-Spent Cost/Total Overnight Cost Ratio	1.154
Fixed Charge Rate (FCR)	0.0707
Total Overnight Cost (TOC), $MM	$2,579
Total As-Spent Cost (TASC), $MM	$2,977
Fixed Operating Cost, $MM	$67.8
Variable Operating Cost @ 100% CF, $MM	$73.2
Fuel Cost @ 100% CF, $MM	$138.8
Annual MWh (100% CF)	5,720,222
LCOE Breakdown, $/MWh	
Capital Charges	$43.3
Fixed O&M	$13.9
Variable O&M	$12.8
Fuel	$24.3
LCOE (excl. CO_2 T&S), $/MWh	$94.3
CO_2 T&S	$10.0
LCOE (incl. CO_2 T&S), $/MWh	$104.3
Breakeven CO_2 Sales Price, $/t-CO2	$29.8

NGCC F-class 95% Capture

Plant	B31B.95-RTI NAS
Gross Size	689 MWe
Net Size	641 MWe
Capacity Factor (CF)	85%
Total As-Spent Cost/Total Overnight Cost Ratio	1.093
Fixed Charge Rate (FCR)	0.0707
Total Overnight Cost (TOC), $MM	$1,246
Total As-Spent Cost (TASC), $MM	$1,362
Fixed Operating Cost, $MM	$31.5
Variable Operating Cost @ 100% CF, $MM	$21.4
Fuel Cost @ 100% CF, $MM	$179.0
Annual MWh (100% CF)	5,613,735
LCOE Breakdown, $/MWh	
Capital Charges	$20.2
Fixed O&M	$6.6
Variable O&M	$3.8
Fuel	$31.9
LCOE (excl. CO_2 T&S), $/MWh	$62.5
CO_2 T&S	$3.7
LCOE (incl. CO_2 T&S), $/MWh	$66.2
Breakeven CO_2 Sales Price, $/t-CO2	$52.0

NGCC H-class 99% Capture

Plant	B32B.99-RTI NAS
Gross Size	939 MWe
Net Size	866 MWe
Capacity Factor (CF)	85%
Total As-Spent Cost/Total Overnight Cost Ratio	1.093
Fixed Charge Rate (FCR)	0.0707
Total Overnight Cost (TOC), $MM	$1,837
Total As-Spent Cost (TASC), $MM	$2,008
Fixed Operating Cost, $MM	$44.9
Variable Operating Cost @ 100% CF, $MM	$31.4
Fuel Cost @ 100% CF, $MM	$238.0
Annual MWh (100% CF)	7,582,958
LCOE Breakdown, $/MWh	
Capital Charges	$22.0
Fixed O&M	$7.0
Variable O&M	$4.1
Fuel	$31.4
LCOE (excl. CO_2 T&S), $/MWh	$64.5
CO_2 T&S	$3.8
LCOE (incl. CO_2 T&S), $/MWh	$68.3
Breakeven CO_2 Sales Price, $/t-CO2	$57.5

Continuation of the Technology Development Path with DOE and CCSI[2]

FLECCS – Dynamic Capture from NGCC

(2021-2024)

Process intensification to enable flexible capture, reduce capital expense

100 t-CO_2/day

TRL 3-5

arpa·e

Large Pilot Testing for Cement Flue Gas

(2021-2024)

Process intensified absorbers to reduce capital expense from cement flue gas capture

1.0 t-CO_2/day

TRL 4-5

Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

GEN2NAS

(2023-2024)

Improved solvent chemistry with process intensification for higher capture rates at lower cost.

0.0015 t-CO_2/day

TRL 2-3

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FEED

(2023-2024)

Carbon capture plant FEED study for cement manufacturing

4000 t-CO_2/day

TRL 6

U.S. DEPARTMENT OF ENERGY | NATIONAL ENERGY TECHNOLOGY LABORATORY

Projects currently underway or recently awarded

Project Summary : DE-FE0032218

Office of
FOSSIL ENERGY AND CARBON MANAGEMENT

Description: GEN2NAS Solvents for CO_2 Capture from NGCC Plants

Key Metrics

- >97% capture rate
- SRD: 2.1-2.5 GJ/ton-CO_2
- Low vapor pressure, < 0.05 kPa (MEA's)
- Technoeconomic and Environmental Health, and Safety (EHS) evaluation

Specific Challenges

- Solvent scale-up
- Formulation optimization
- Process configuration

Timeframe: 04/01/23 - 09/30/24

Total Funding: $1,250,000

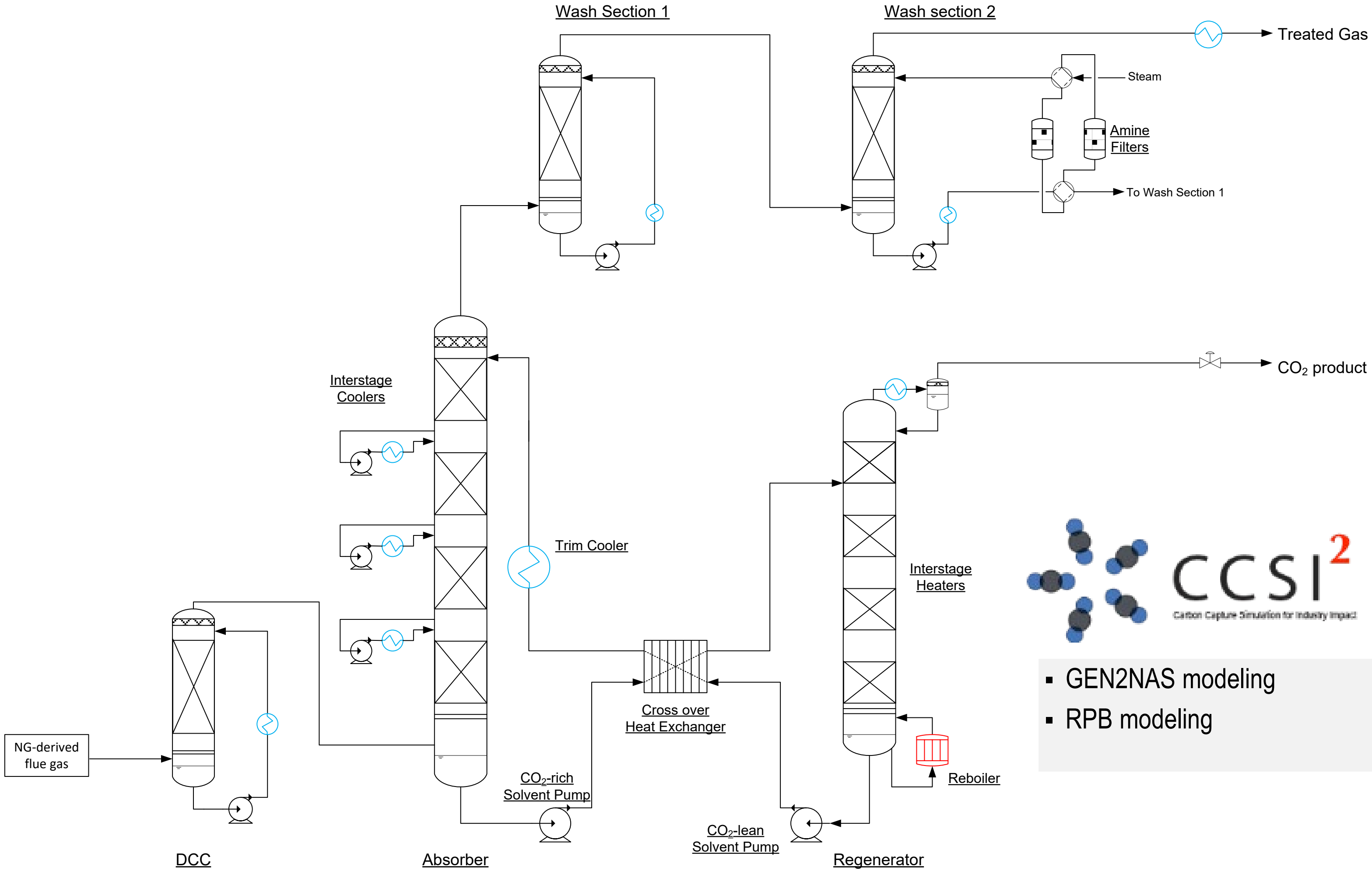
Partners:

slb

CCSI[2]
Carbon Capture Simulation for Industry Impact

Pacific Northwest
NATIONAL LABORATORY

Project Technical Merit

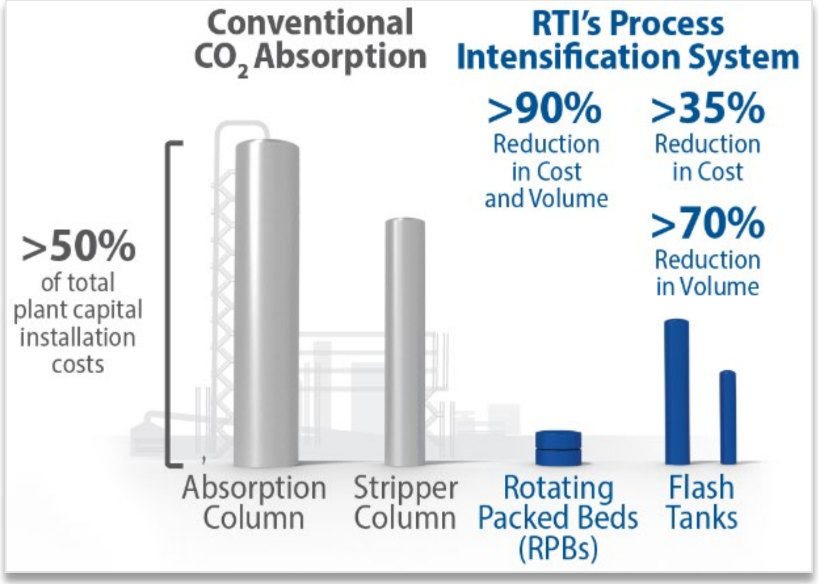


Current Process Configuration

Lower the cost of CO_2 capture by:

- Solvent formulation – low water content, increase X_{solv}
- Simplified gas polishing section - removing second wash and amine recovery unit
- Replace absorber with Rotating Packed-Bed (RPB)
- Replace Stripper with flash tanks

- GEN2NAS modeling
- RPB modeling



Schedule

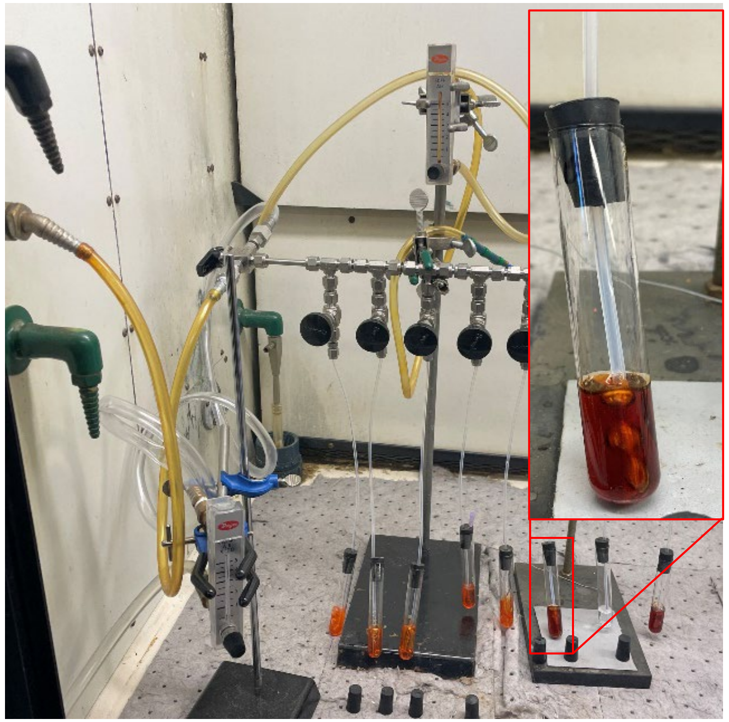
Task	Task title	Start date	End date	Budget Period 1 (BP1)																	
				2023									2024								
				Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
1.0	Project Management and Planning	04/01/23	09/30/24																		
1.1	Project Management Plan	04/01/23	09/30/24																		
1.2	Technology Maturation Plan	04/01/23	09/30/24																		
2.0	Lab Testing of GEN2NAS	04/01/23	03/31/24																		
2.1	Optimization of solvent blend	04/01/23	12/31/23																		
2.2	Lab-scale gas absorption testing of selected solvent blends	10/01/23	03/31/24																		
2.3	Characterization of pure solvent blend components	04/01/23	03/31/24																		
3.0	Kinetic Measurements of GEN2NAS	04/01/23	03/31/24																		
4.0	RPB Testing	01/01/24	09/30/24																		
4.1	Capture efficiency and Specific Reboiler Duty (SRD) measurements	01/01/24	06/30/24																		
4.2	Oxidative degradation measurements	04/01/24	09/30/24																		
5.0	Technoeconomic Assessment and Technology Maturation Plan Update	01/01/24	09/30/24																		
Milestone Log		*(proposal*	*table)*	A		B							C		D,E			F			G,H
Deliverables		*(As noted)*	*(As noted)*	D1		D2			D10				D3		D4,D5			D6-D9			D11
Reporting		*(See footnote.)*	*(See footnote.)*				Q			Q			Q			Q			Q		
Project Meeting		*(See footnote.)*	*(See footnote.)*	K				B												B	

Q = Quarterly report due one month after quarter's end; FR = Final report due three months after project end.

K = Project kick-off meeting; B = Project briefing (annual);

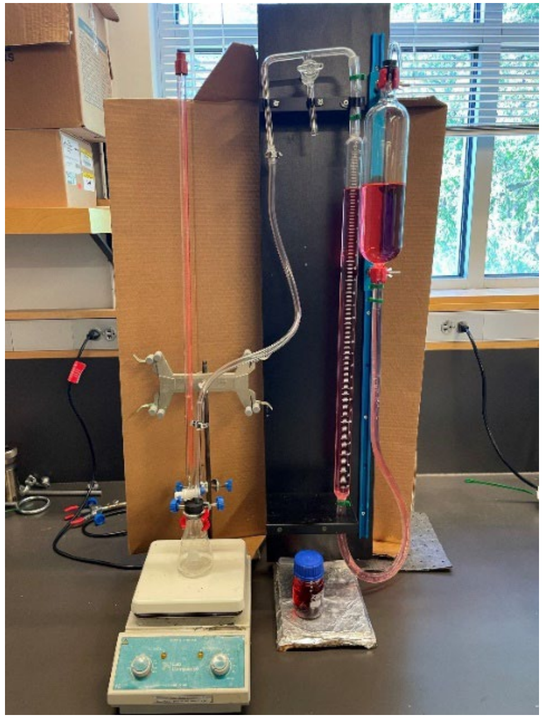
Characterization and Property Measurement

CO_2 saturation station



- 8 separate saturation stations
- 10-20 ml sample size
- Adjustable CO_2 content and flow rates

Chittick apparatus



- Determine sample CO_2 loading
- 3-5 ml per test
- Titration method
- CO2 quantified by gas volume displacement

Thermal conductivity measurement

- 20 ml sample size
- Temperature-controlled: 10-90 C
- Gas/liquid samples
- Ambient pressure cell

Viscometer

- cup-spindle design
- Jacketed cup for temperature control
- Ambient pressure

Characterization and Physical Property Measurement

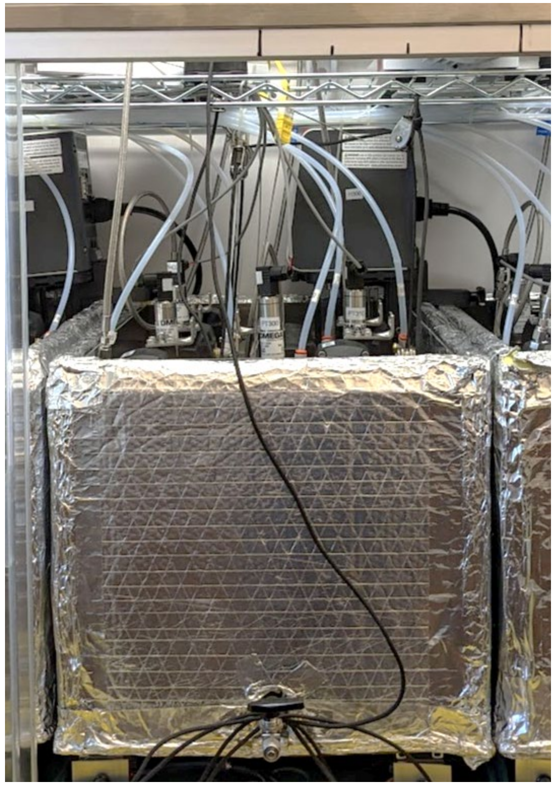
Setaram Calorimeter

- Determine heat capacity, heat of absorption
- Solid/liquid samples
- 10 ml per test

ATR-FTIR

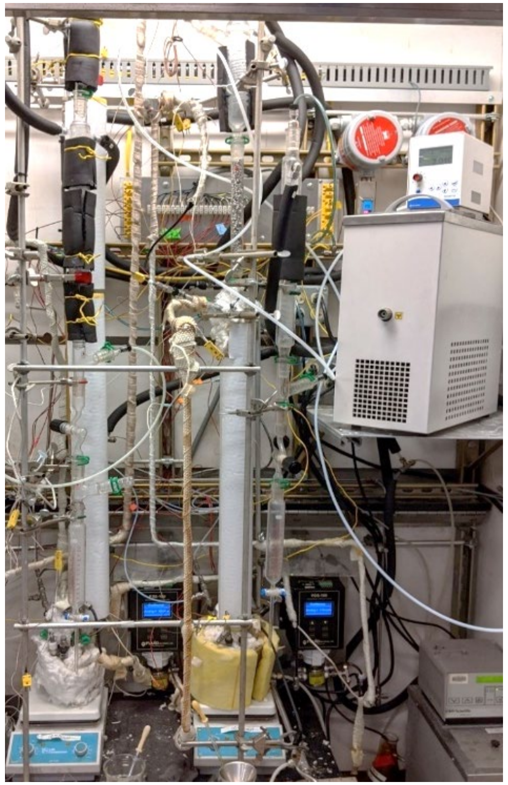
- 1 ml sample size
- Open cell measurement
- CO_2/H_2O suppression built-in
- Identify functional groups
- Measure at ambient condition

Automated HP-VLE cell



- Generate VLE at different CO_2 partial pressures and temperatures
- Fully automated system
- 50 cc sample size
- 6 stations with multiple fee gases (CH_4, C_2H_6, H_2S, CO_2, N_2)
- Up to 120 C and 1,000 psig

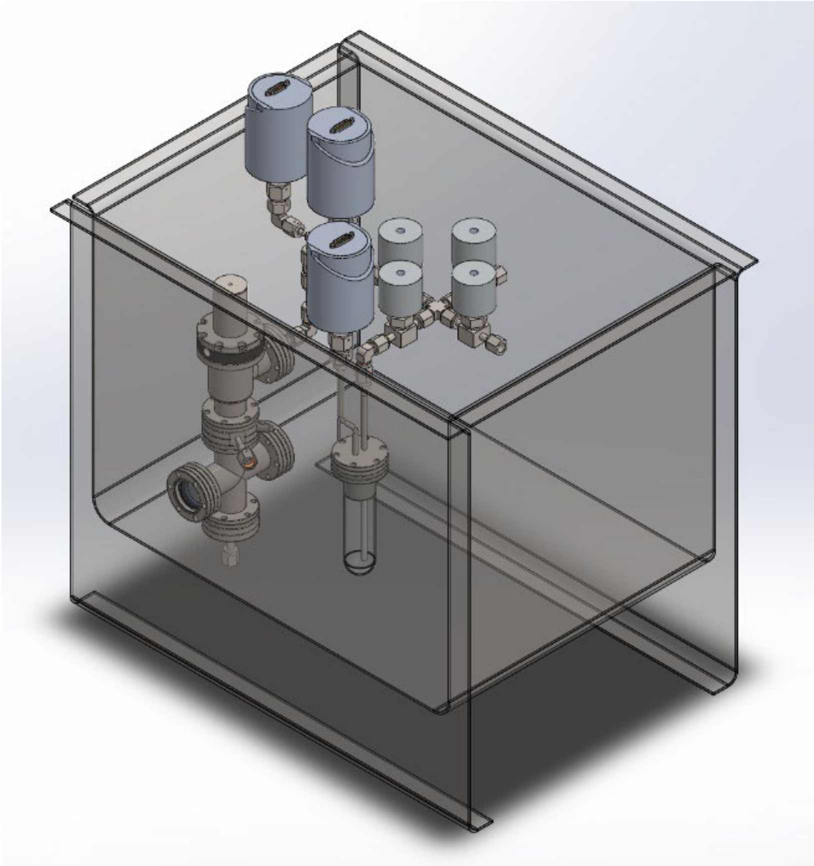
Lab-scale Gas Absorption Sys



- Continuous capture operation under relevant condition
- Fully automated system
- Qualitative energy input evaluation
- Emission monitoring and quantification
- 400 ml sample
- Ambient pressure operation

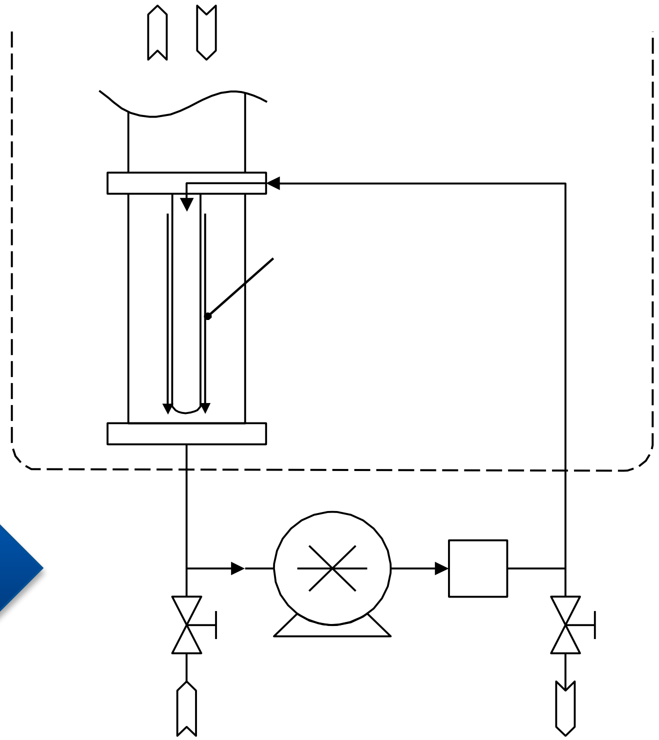
Kinetic Measurements

Pressure/Volume/Temperature (PVT) Cell



- Comprehensive measurements of vapor-liquid equilibria (PTx), mass transfer, and rheology on a single 50 mL sample

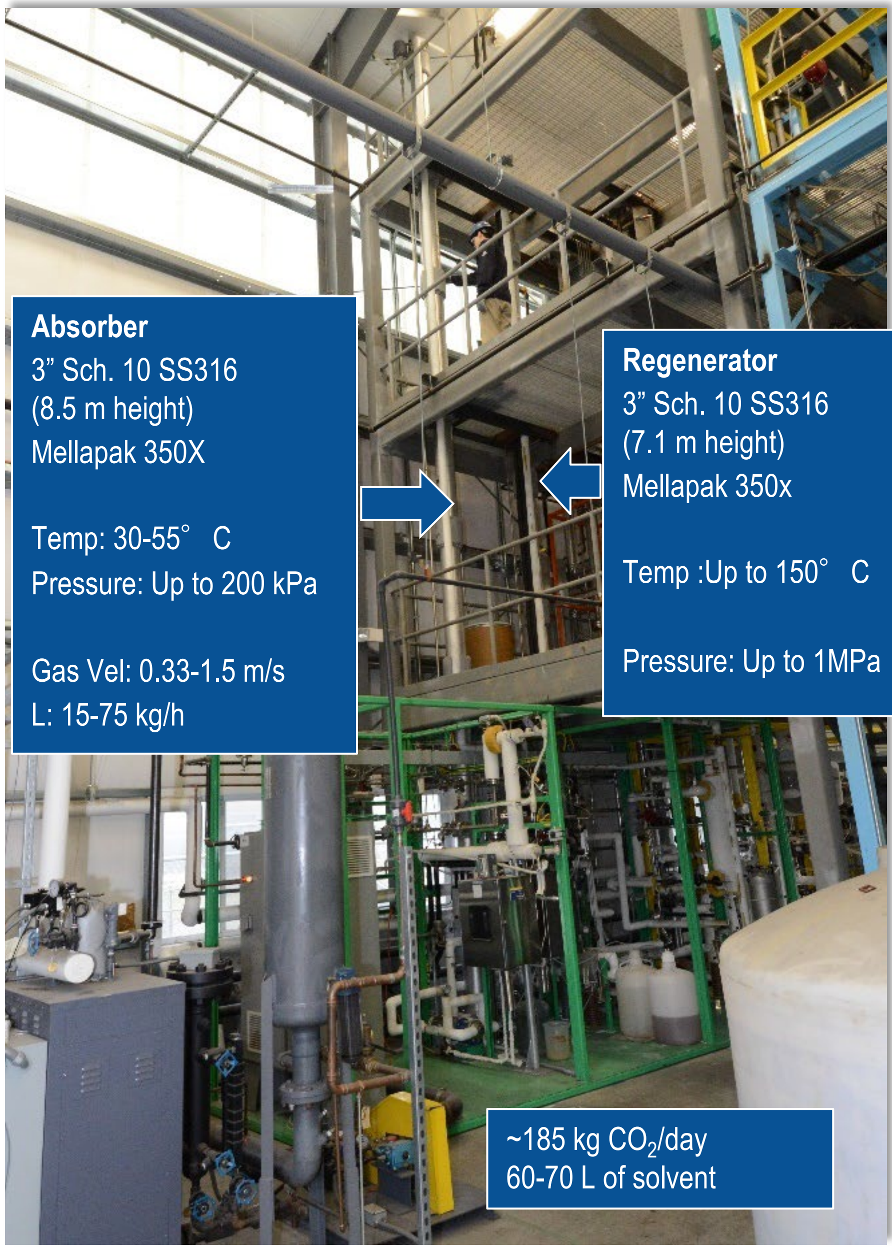
Wetted-Wall Column (WWC)



- Part of the PVT cell
- Kinetic data is collected with an internal mini wetted-wall contactor, where controlled adjustments of the cell volume allow for measurements of CO_2 flux

Performance Testing

- Continuous operation, fully-automated
- Wide range of feed gas composition – both simulated and real flue gases
- Capture rate, SRD, emissions, degradations



Absorber
3” Sch. 10 SS316
(8.5 m height)
Mellapak 350X

Temp: 30-55° C
Pressure: Up to 200 kPa

Gas Vel: 0.33-1.5 m/s
L: 15-75 kg/h

Regenerator
3” Sch. 10 SS316
(7.1 m height)
Mellapak 350x

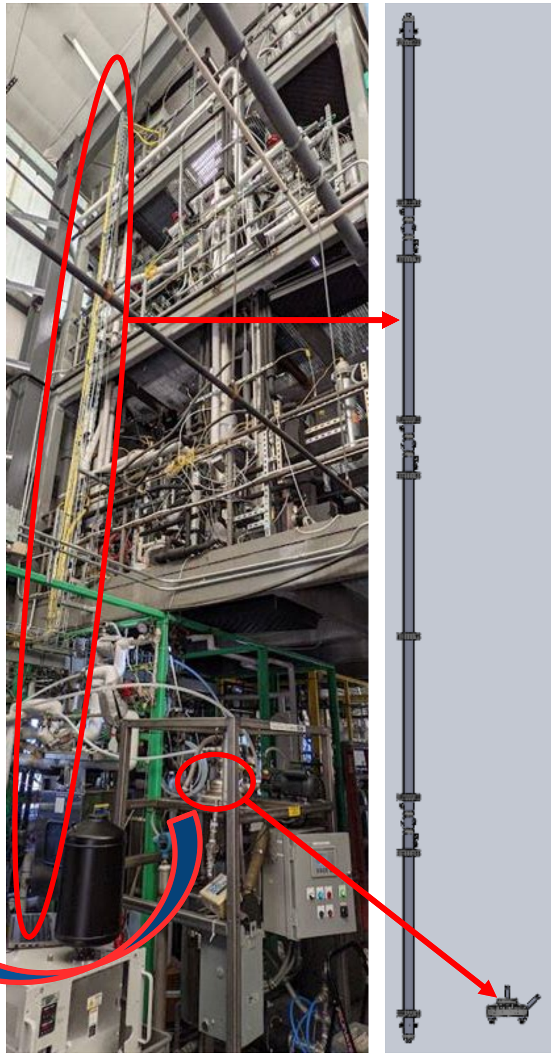
Temp :Up to 150° C

Pressure: Up to 1MPa

~185 kg CO_2/day
60-70 L of solvent

Conditions for Experimental Data

- **Absorber: 37-40° C**
- **Regenerator: 87-115° C**
- **Pressure: 1.5-7.5 barg**
- **Kettle reboiler/Flash regeneration**



- SDoE
- Testing Task 4 starting January 2024

Commercialization with SLB

News Release

Schlumberger and RTI International Partner to Accelerate the Industrialization of Innovative Carbon Capture Technology

Published: 10/17/2022

A unique, versatile nonaqueous solvent

SLB and RTI International have partnered to industrialize and scale up an absorption-based carbon capture technology. The proprietary nonaqueous solvent (NAS) can be applied across a broad range of industrial sectors—from cement and steel manufacturing, coal and gas power generation, chemicals, and hydrogen.

With low energy consumption, simple process configuration, low corrosion chemistry, and fast reaction rates, NAS technology reduces energy consumption by up to 40% during CO_2 capture and minimizes both capex and opex compared with traditional solvents.

Read press release →

Thanks for your attention!

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