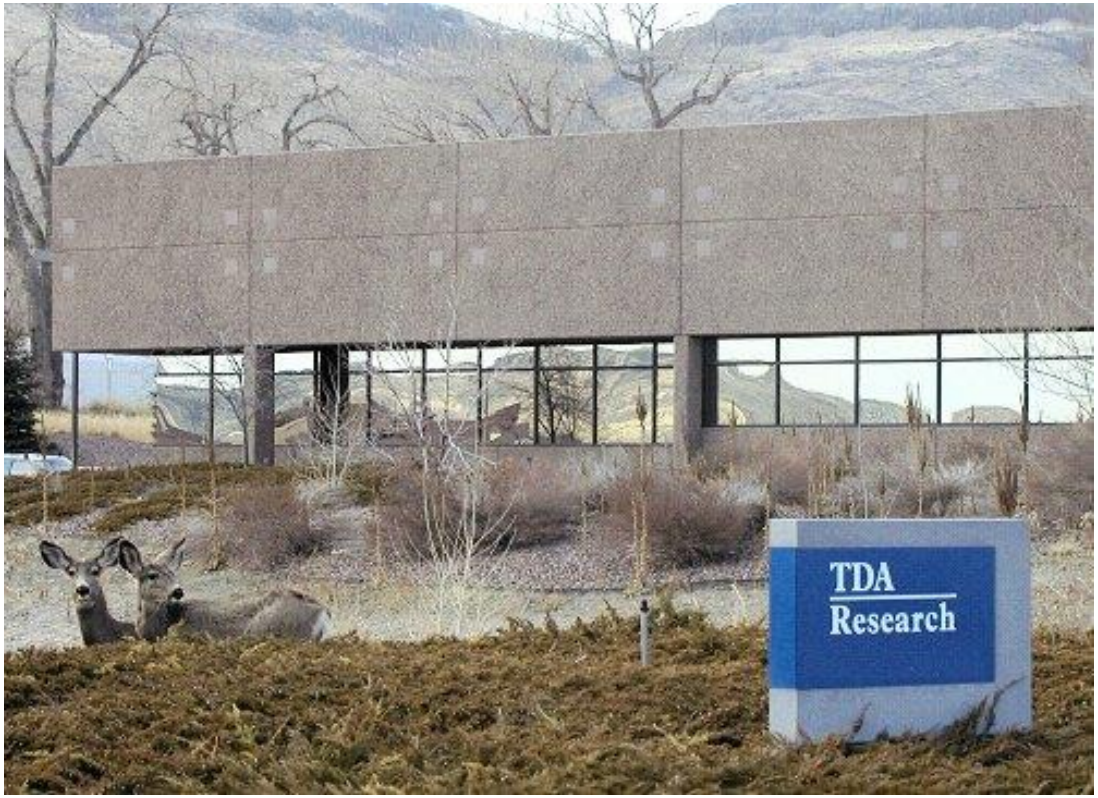
Membrane-Sorbent Hybrid System for Post-Combustion Carbon Capture (DE-FE00031603)



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August 28, 2023

Project Objectives and Project Team

- **Design and construct a ≈ 1 MW_e scale membrane-sorbent hybrid system for post-combustion carbon capture**
- **Hybrid process combines a polymer membrane and a low-temperature physical adsorbent to remove the CO_2 from flue gas**
  - Membrane has been developed by MTR
  - Adsorbent has been developed by TDA for post-combustion capture

Main Project Tasks

BY1	✓ Design of the Test Unit
	✓ Initial Design Review
	✓ Preliminary Techno-economic analysis
BY2	✓ Fabrication of the Test Unit
	✓ Site Preparation, Installation and Shakedown Tests
BY3	✓ Field Tests (ongoing; 6–12 months duration)
	✓ High Fidelity Techno-economic Analysis

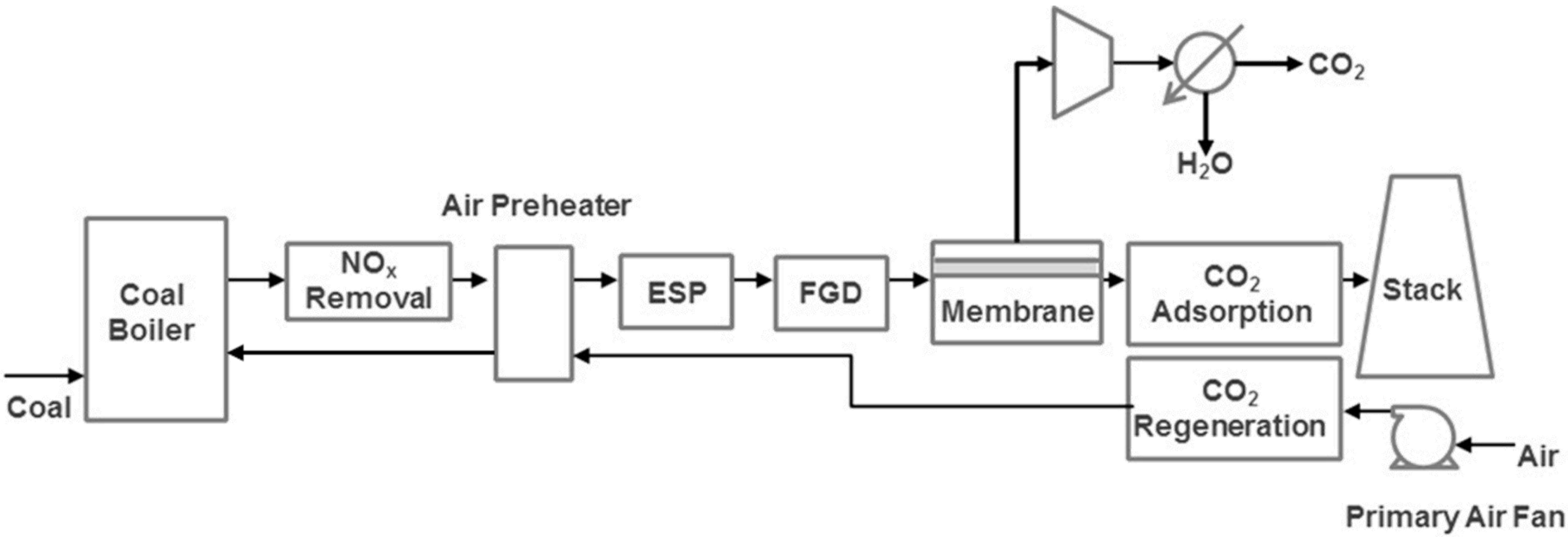
Project Duration

- **Start Date = August 18, 2018**
- **End Date = August 14, 2023**

Budget

- **Project Cost = $11,498,524**
- **DOE Share = $9,198,799**
- **TDA & its partners = $2,299,725**

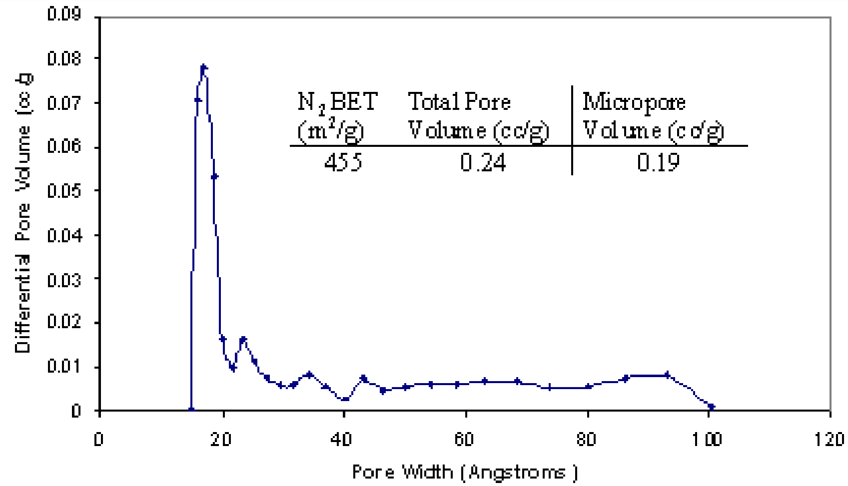
Hybrid Membrane Sorbent Process



- **Membrane operates at ≈50°C under mild vacuum (≈0.2 atm), removes ≈55–60% of CO_2 and almost all water**
  - TDA's sorbent removes remaining CO_2 in the membrane effluent (retentate) ensuring 90+% carbon capture
  - The boiler feed air is used as a sweep gas to facilitate sorbent regeneration
  - CO_2 circulation to the boiler air intake increases the CO_2 concentration in the flue gas, providing a higher driving force for the membrane

TDA Sorbent

- **TDA developed a mesoporous carbon sorbent modified with surface functional groups that remove CO_2 via strong physical adsorption**
  - CO_2-surface interaction is strong enough to allow operation at low partial pressures
  - Because CO_2 is not bonded, the energy input for regeneration is low
- **Heat of CO_2 adsorption is 4–5 kcal/mol**



Sorbent operation in a VSA system was successfully demonstrated with actual flue gas (DE-0013105)

US Patent 9,120,079, Dietz, Alptekin, Jayaraman "High Capacity Carbon Dioxide Sorbent", US 6,297,293; 6,737,445; 7,167,354

Sorbent optimization and production scale-up was completed in a separate DOE project (DE-0013105)

Technology Maturation

0.5–1 kW Sorbent Only Tests

Gas Technology Institute (GTI) Tests with pilot coal combustor

0.5–1 kW Hybrid Tests

Western Research Institute/ Thermosolv

50 kW Hybrid Tests

Wyoming Integrated Test Center (WITC) Basin Electric's Dry Fork Station Gillette, WY

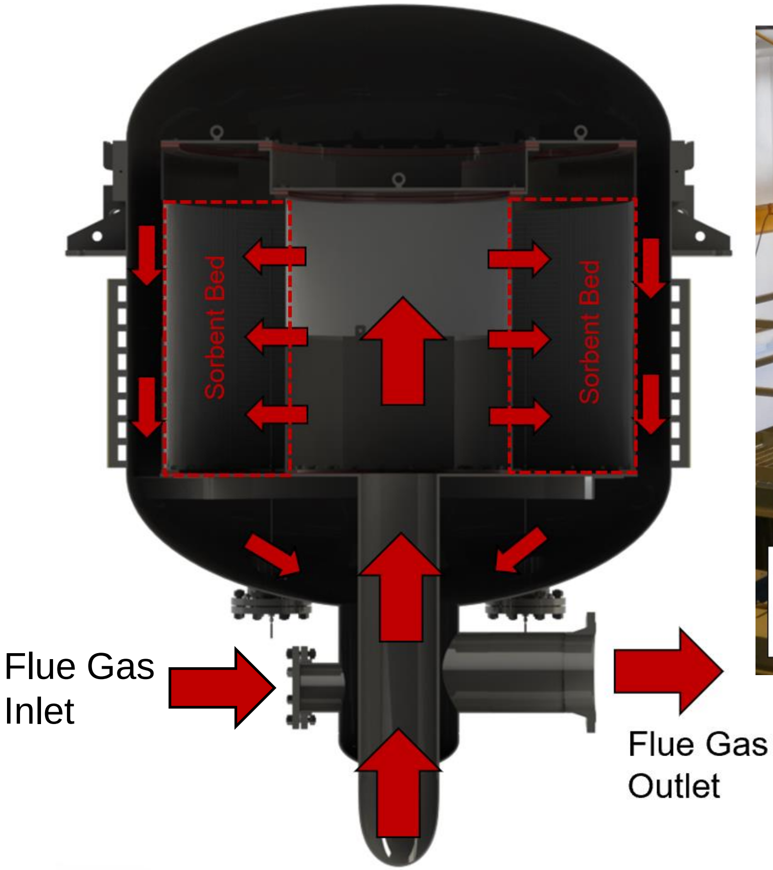
0.5–1 MW Hybrid Tests

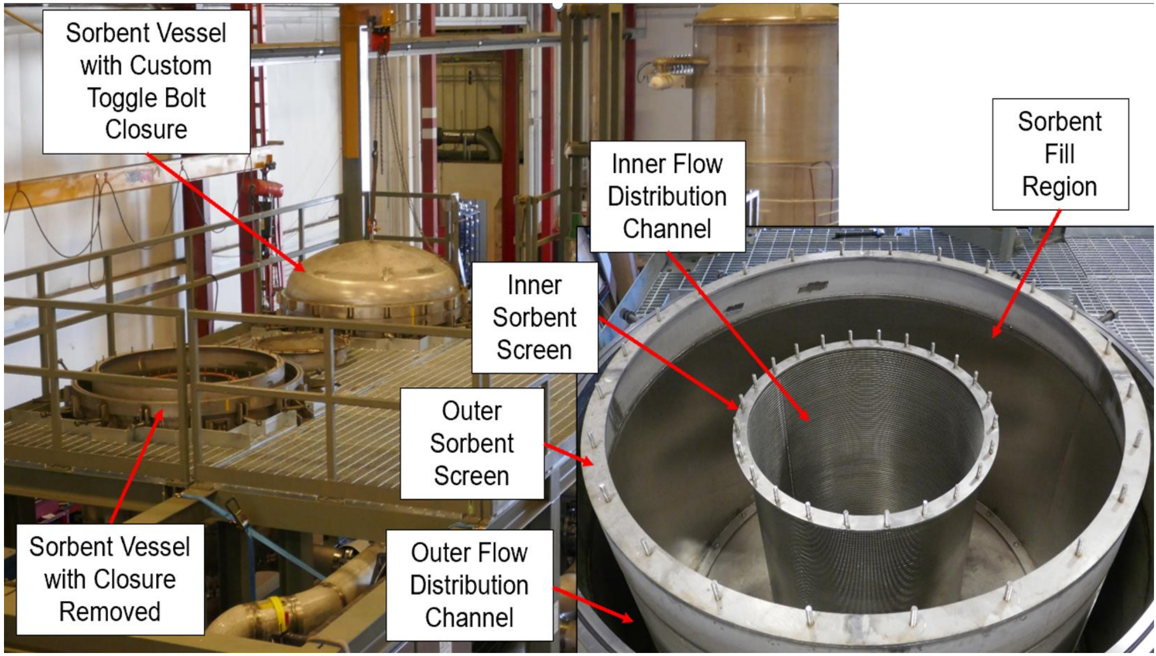
Technology Centre Mongstad (TCM) Norway

- **2011** – Bench-Scale tests
- **2014** – 0.5–1 kW Sorbent Only tests at TDA
- **2015** – 0.5–1 kW Sorbent Only tests at GTI Coal flue gas
- **2016** – Sorbent Scale-up IP secured
- **2017** – 0.5–1 kW hybrid tests at WRI with Coal flue gas
- **2019–20** – 50 kW hybrid tests at WTIC with Coal flue gas
- **2021–22** – 0.5–1 MW hybrid tests at TCM with Coal flue gas

TDA RESEARCH

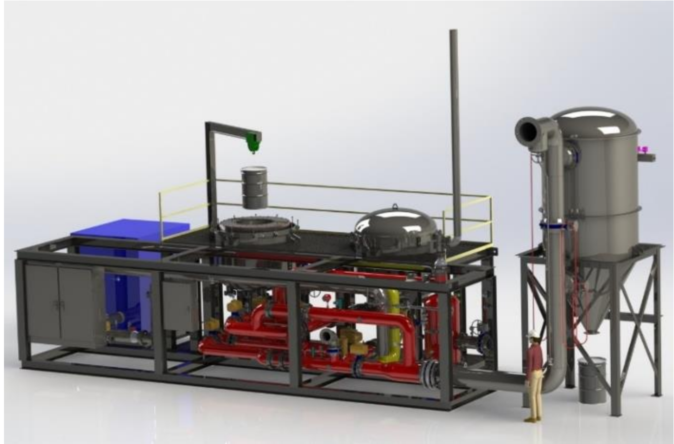
TDA Radial Flow Reactor Concept





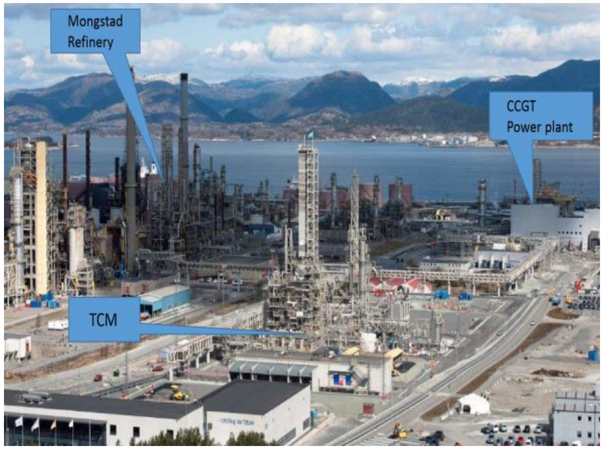
- Sorbent is loaded in annular section of the vessel
- The flow is in radial direction
- Higher cross-sectional area and lower bed depth minimize the dP through the bed

Project Focus



TDA's Sorbent System

Existing MTR Membrane Module

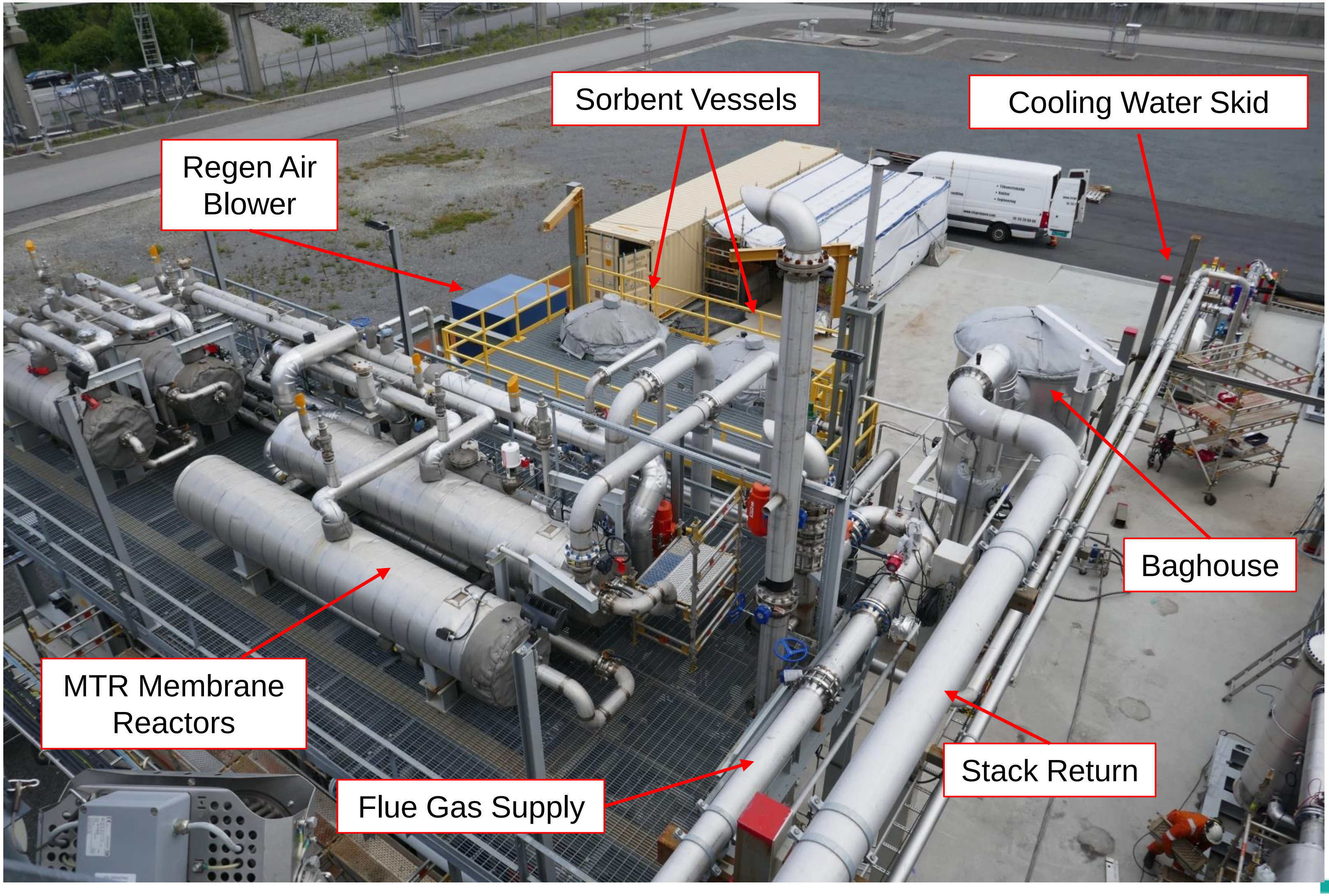


TCM Mongstad, Norway

- ✓ **Demonstrate sorbent performance**
  - ✓ CO_2 removal efficiency
  - ✓ CO_2 uptake capacity
- ✓ **Demonstrate the mechanical stability of the sorbent**
- ✓ **Demonstrate sorbent life**
- ✓ **Demonstrate effective operation of the radial flow reactors**
  - ✓ Low pressure drop and modular operation
  - ➢ Uniform flow distribution
- ✓ **Development/Validation of Design Models (CFD and Adsorption Models)**
- ✓ **Cycle optimization**
- ✓ **Optimization of the Hybrid System Operation**

TDA RESEARCH

Hybrid Membrane System Overview



Sorbent Vessels

Sorbent Loading into the Vessels


Drum Handler Operation

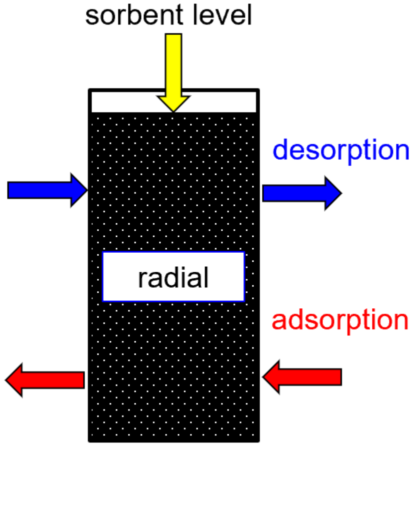

Final Sorbent Distribution


Gravimetric filling


Installation of Vessel Closure

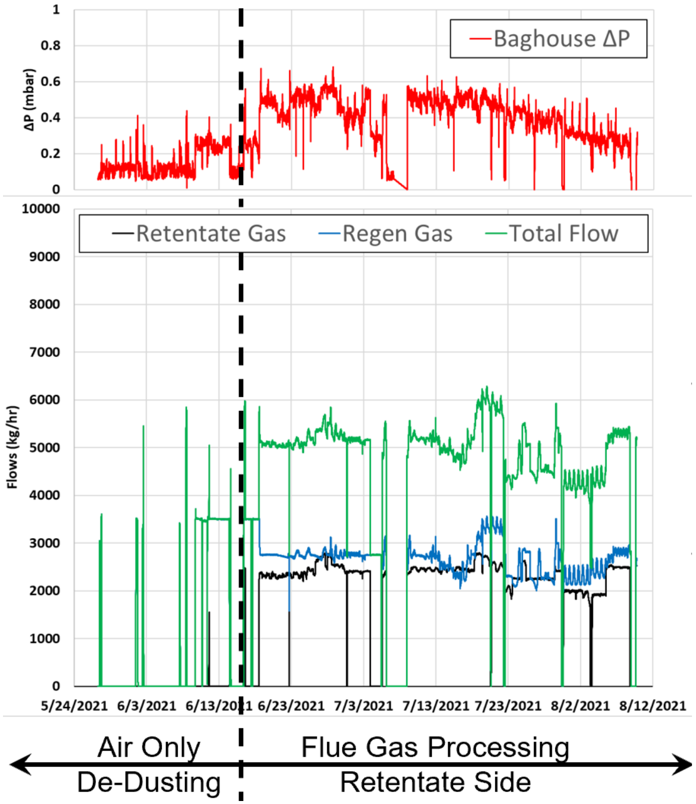
Sorbent Settling and Retainment

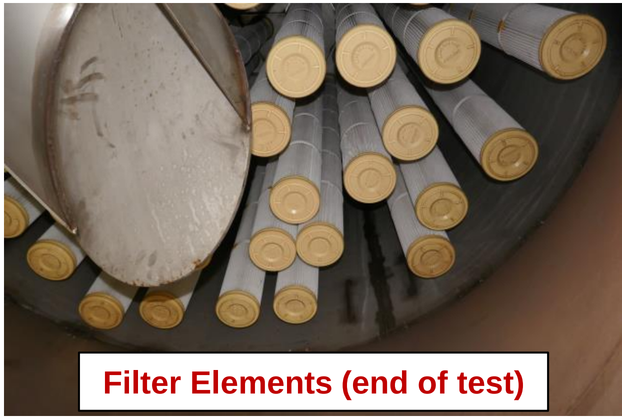
- Sorbent settling is not desirable as it generates a void at the top of the bed and cause flow by-pass
- System internals and loading procedures ensured effective pre-settlement
- Top of the sorbent bed is sealed with custom gaskets
- After a short run, the beds were topped off (<2% of total sorbent mass)

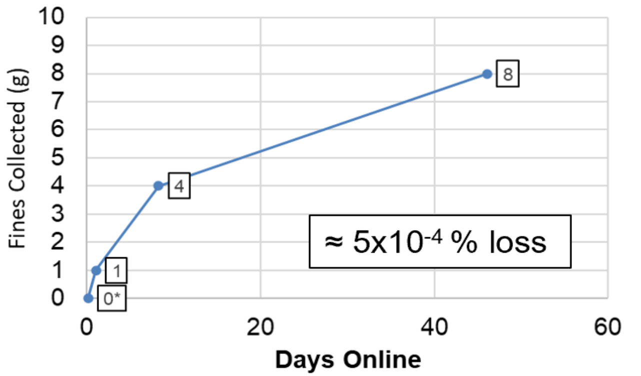


- Amount of dust generated was surprisingly low (much lower than we observed in axial beds)
- Sorbent retention was excellent; total fines collected in the baghouse over the first month of operation was ≤ 0.0006% wt. of the initial load

Measurement of Sorbent Dusting







- **Baghouse pressure drop was low and stable over time; consistent with a low rate of fines collection**
- **Total volume of dust collected in baghouse to date is ≈8 g; very low in comparison to the sorbent inventory of ≈1.7 tonne**

The collected particulate also included fabrication debris

Field Test Summary

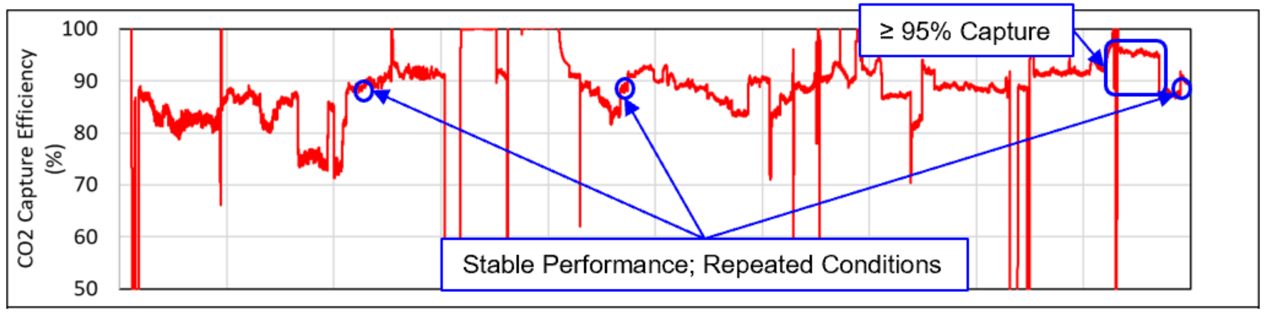
Time online (taking flue gas):

- 4,001 hours† (≈ 167 days)
- Availability 80.5%

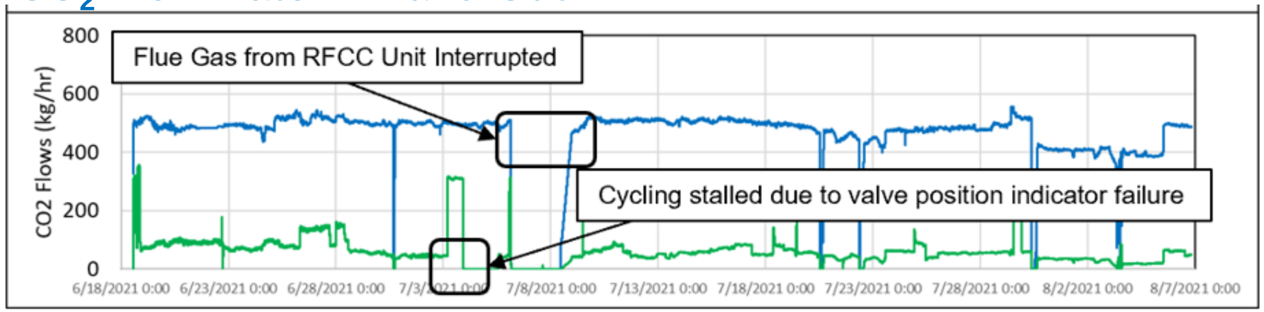
RFCC flue gas CO_2:

- 1,889 tonne received†
- 1,645 tonne captured
- 87.1% net capture efficiency (w/ upsets)
- 161,182 sorbent cycles

CO_2 Capture Efficiency



CO_2 Flow Rate – In and Out

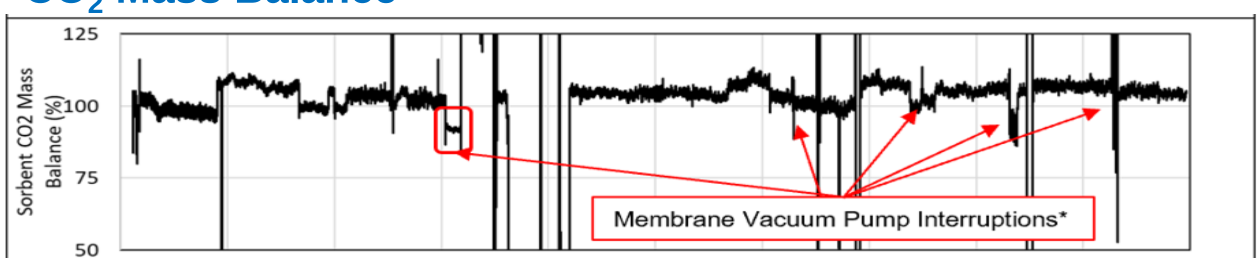


* - Membrane vacuum pump interruptions increase CO_2 load to the sorbent sub-system by 50–100%

CO_2 Capture Breakdown

	< 90%	> 90%	> 95%
hours	2,212	1,789	307
days	92	75	13
Percent of run time	55.3%	44.7%	7.7%

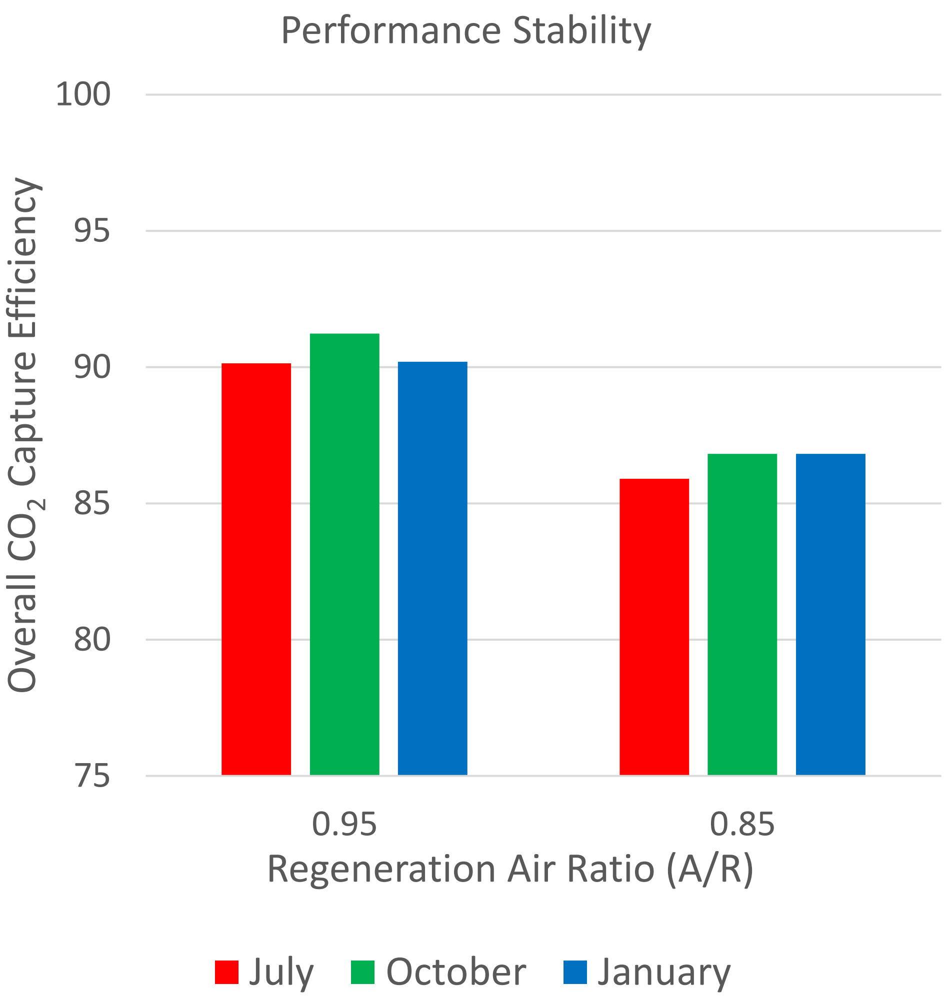
CO_2 Mass Balance



† - includes 70 hours (≈3 days) and 7.2 tonne of CO_2 from CHP flue gas testing at the end of the campaign

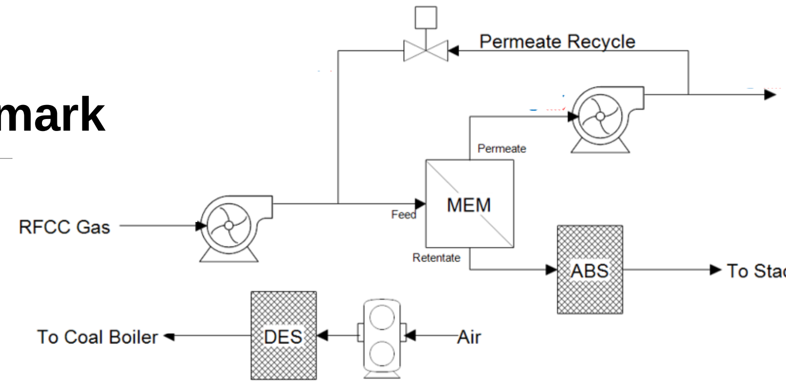
Performance Stability

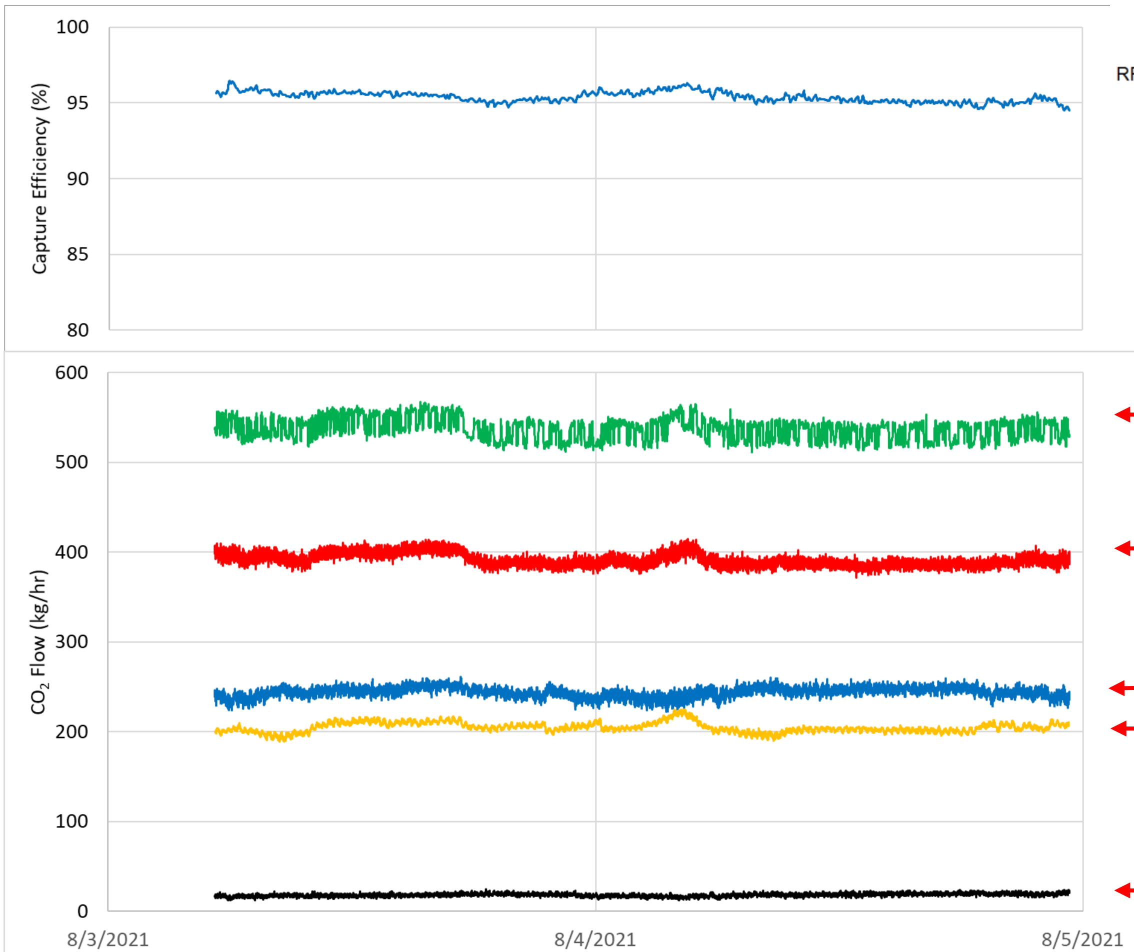
- **Performance stability is checked periodically under several baseline conditions**
  - Overall CO_2 capture efficiency of the system was measured over a range of regeneration air/retentate flow (A/R) ratios
  - The chart compares two A/R ratios in three different months (summer/fall/winter) during the test program
- **No measurable change in system performance was observed through eight months of testing**



High CO_2 Capture Efficiency (≥95%)

- **95% CO_2 removal efficiency was demonstrated in several 48-hour tests**
- **Data below are from 38 days total run time mark**





Membrane Feed (includes recycled permeate)

Flue Gas Inlet (Hybrid System Inlet)

Retentate (Sorbent Inlet)

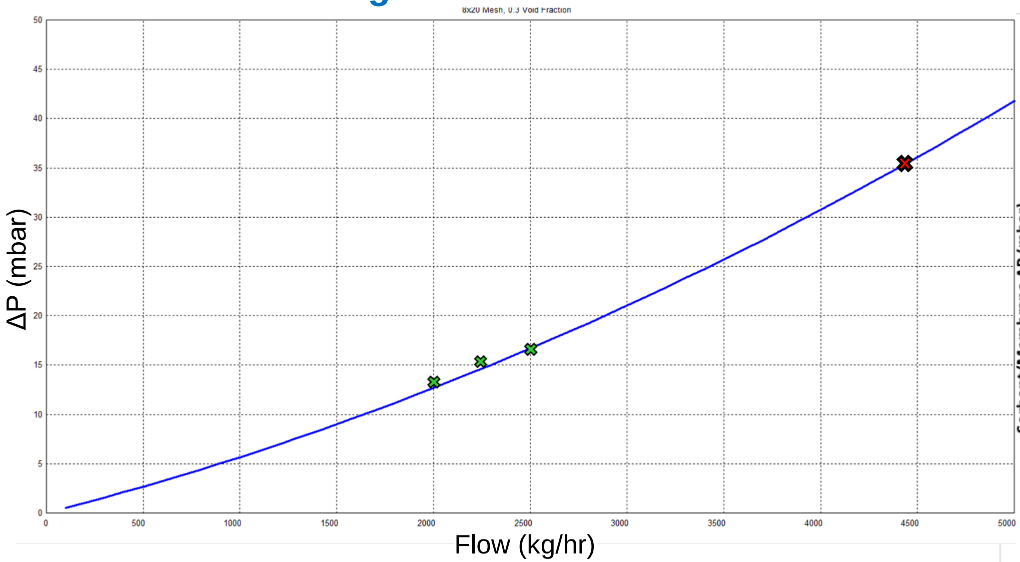
Permeate Product (excludes recycled CO_2)

CO_2 Slip (stack)

TDA RESEARCH

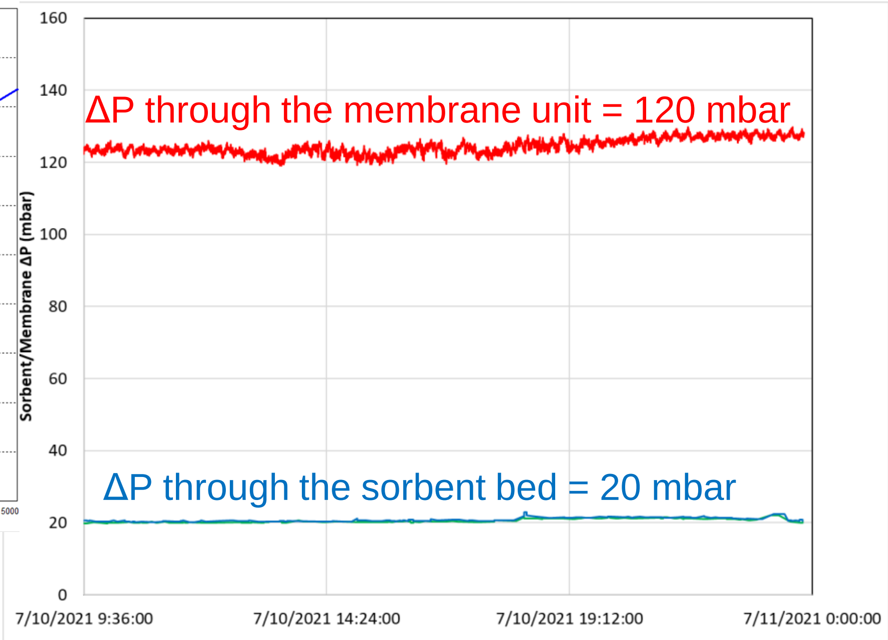
Pressure Drop Measurements

ΔP through the Bed vs. Flow Rate



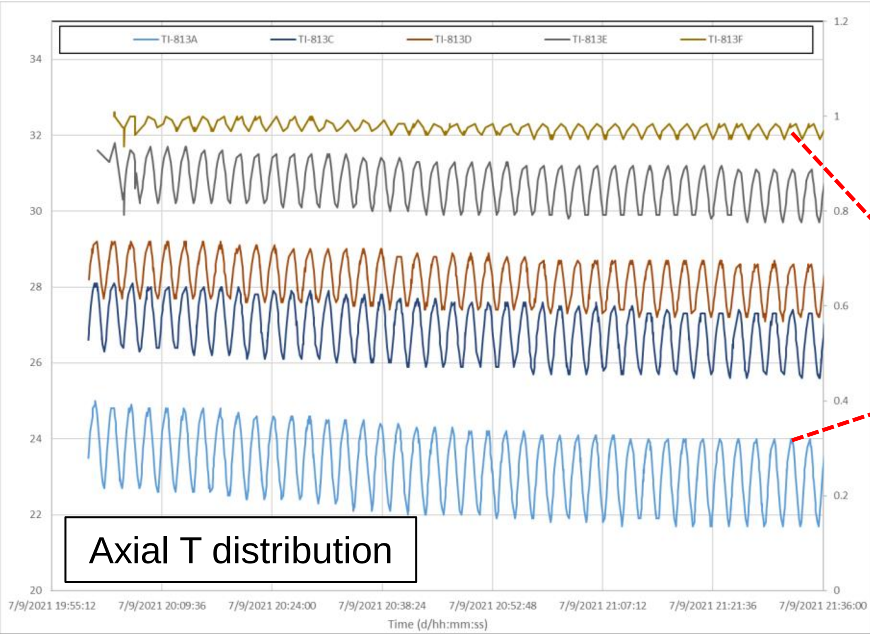
✖ Experimental pressure drop vs. flow data from TCM
✖ Highest possible flow through the system

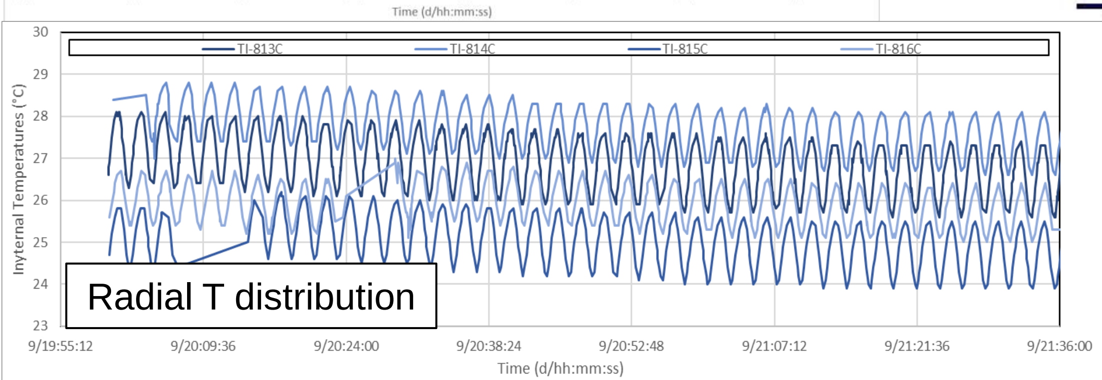
ΔP through the membrane and sorbent

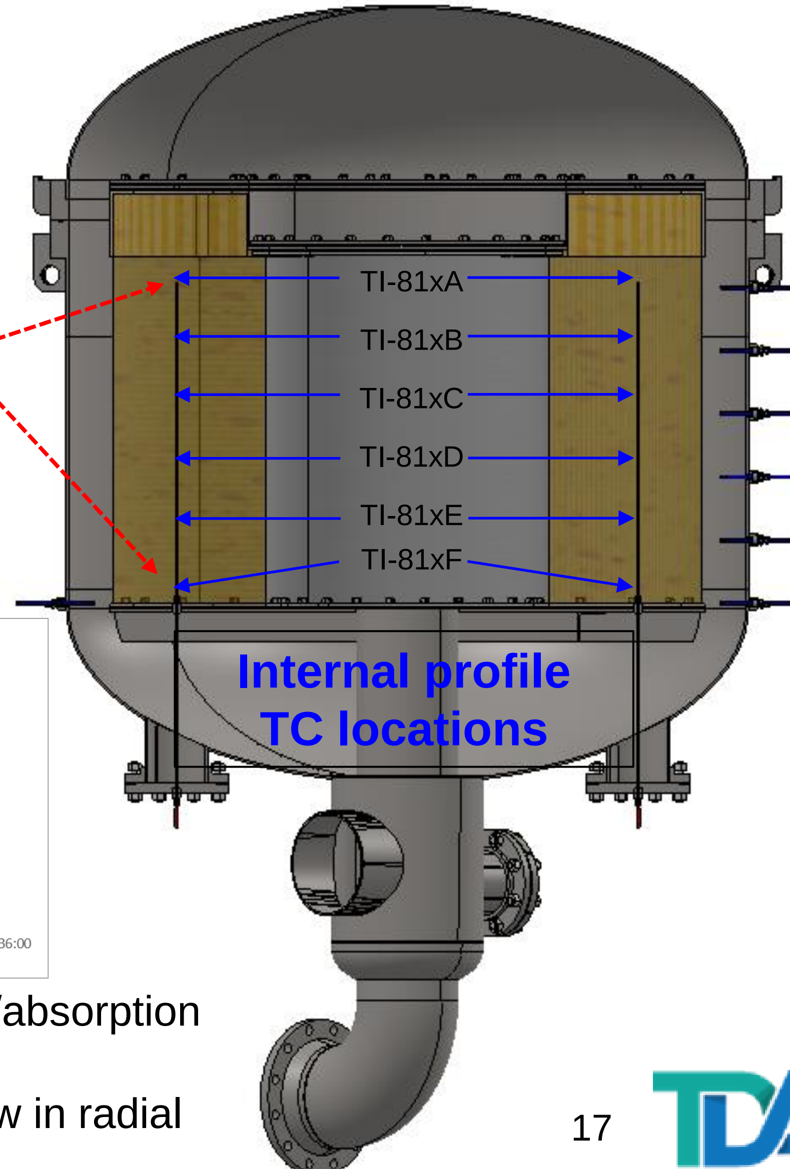


- **TDA's radial sorbent bed design achieved a very low pressure drop**
- **At the 2000–2500 kg/hr flue gas flow, the total ΔP was measured as <20 mbar**
- **Actual measured ΔPs agree well with the model results**
- **The membrane unit treating the same flue gas flow and rejecting the same amount CO_2 generated ≈120 mbar pressure drop (Stage 1 membrane)**

Temperature Distribution in the Bed



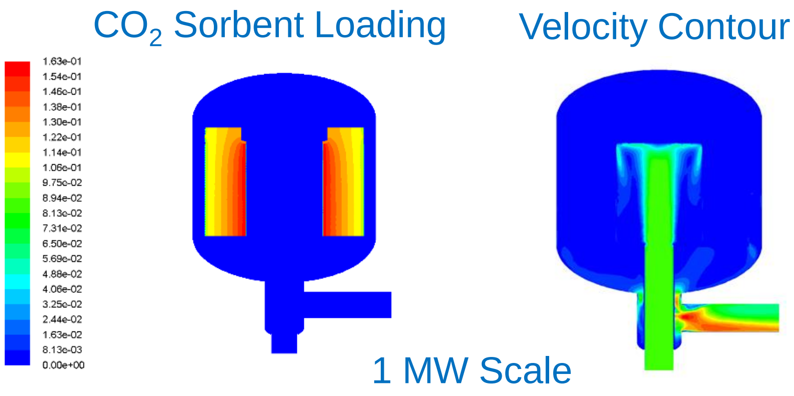


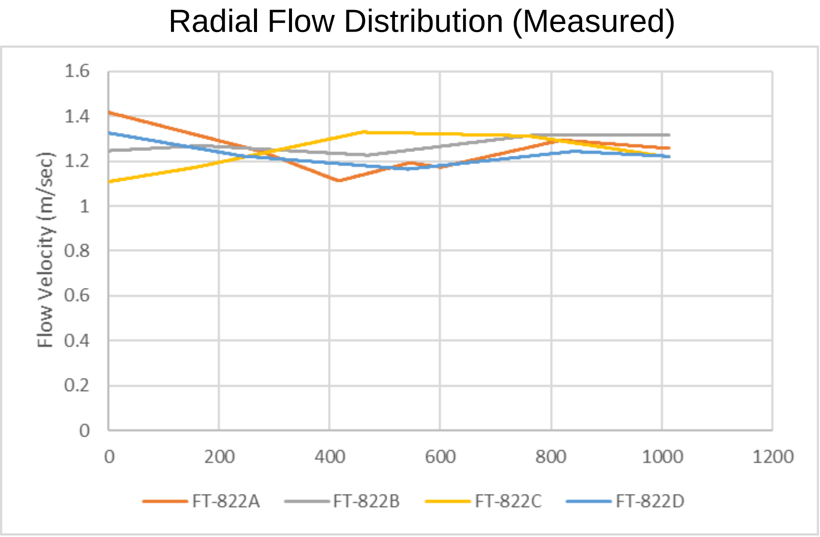


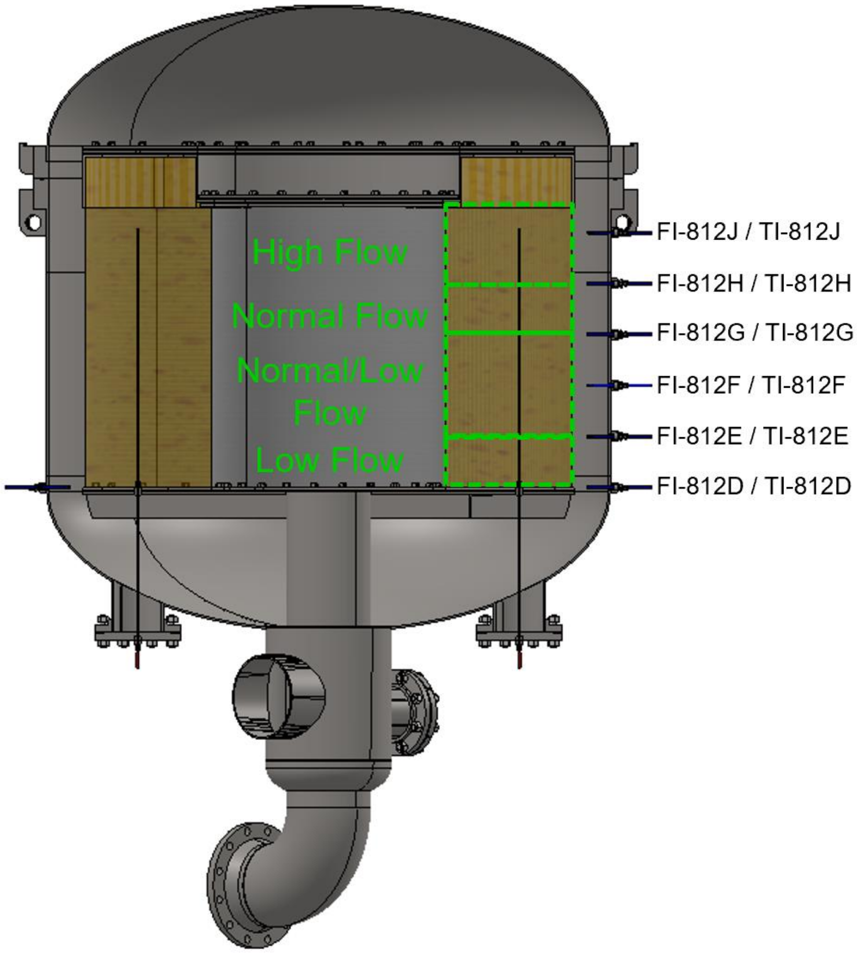
- Axial T distribution/cyclic ΔT indicates higher flows/absorption near the top
- Radial T distribution/cyclic ΔT indicates uniform flow in radial direction

TDA RESEARCH

Flow Distribution in the Bed





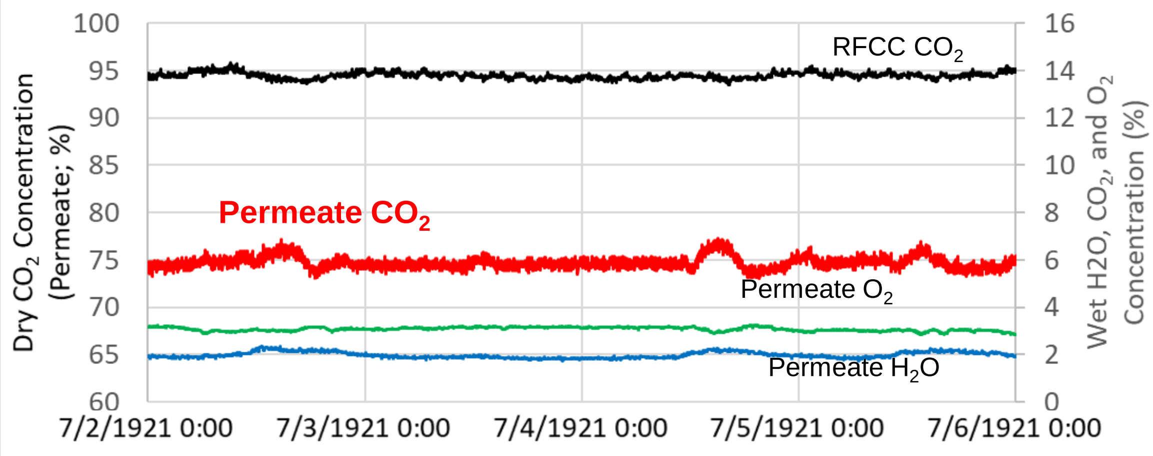


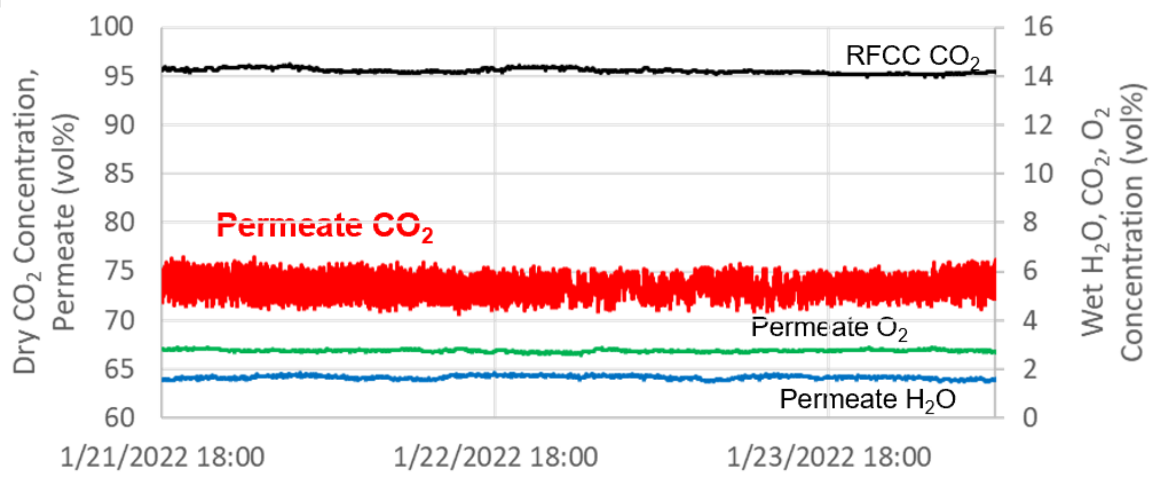
- Radial flow velocity measurements show uniformity within ± 2%
- Axial flow velocity measurements indicate a flow imbalance towards top of the bed

TDA RESEARCH

Membrane Performance

- **Hybrid system was fitted with MTR's Gen-1 Polaris membranes**
- **Stable performance with ≈78–80% vol. CO_2 purity (dry basis)**





Membrane modules being loaded with new membranes prior to shipment

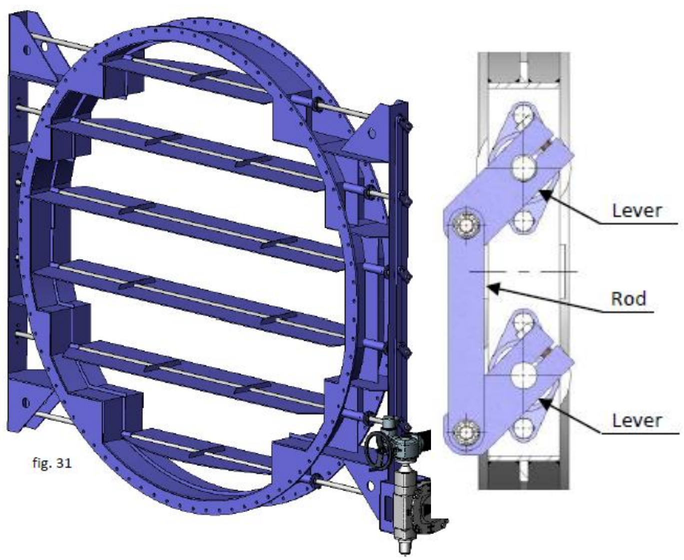
Reactor Vessel Design

Sorbent System - Hybrid

	Stage I	Stage II
Bed 1	Adsorption	Desorption
Bed 2	Desorption	Adsorption
60s	30s	30s

Adsorption - Flue gas flow

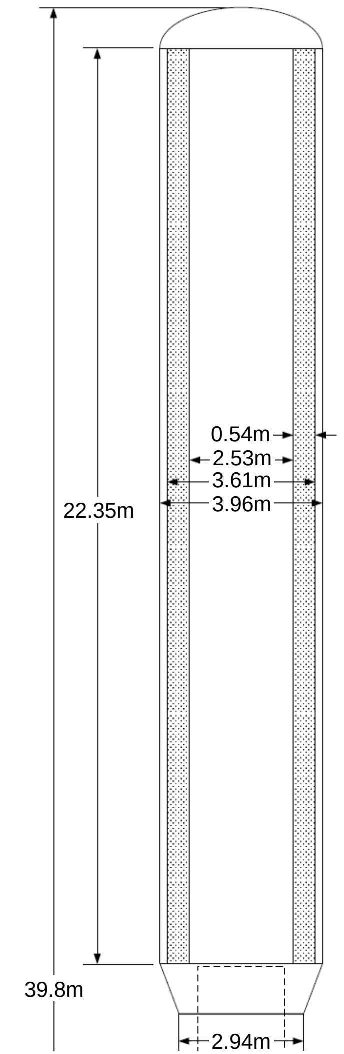
Desorption - Air Purge flow



ΔP=50 mbar

Module Size:	68.75	MW
No. of Trains:	8	
Beds/Train:	2	
Total Beds:	16	
Flue Gas Flow:	74.5	m^3/s
CO_2 Flow:	1.22	tonne/min
Capacity:	1.8%	Wt.
Cycle Time:	1	min
Sorbent Inventory:	67.8	tonne/m^3
Sorbent Density:	0.59	tonne/m^3
Bed Volume:	116.4	m^3
Bed Area:	12.3	m^2

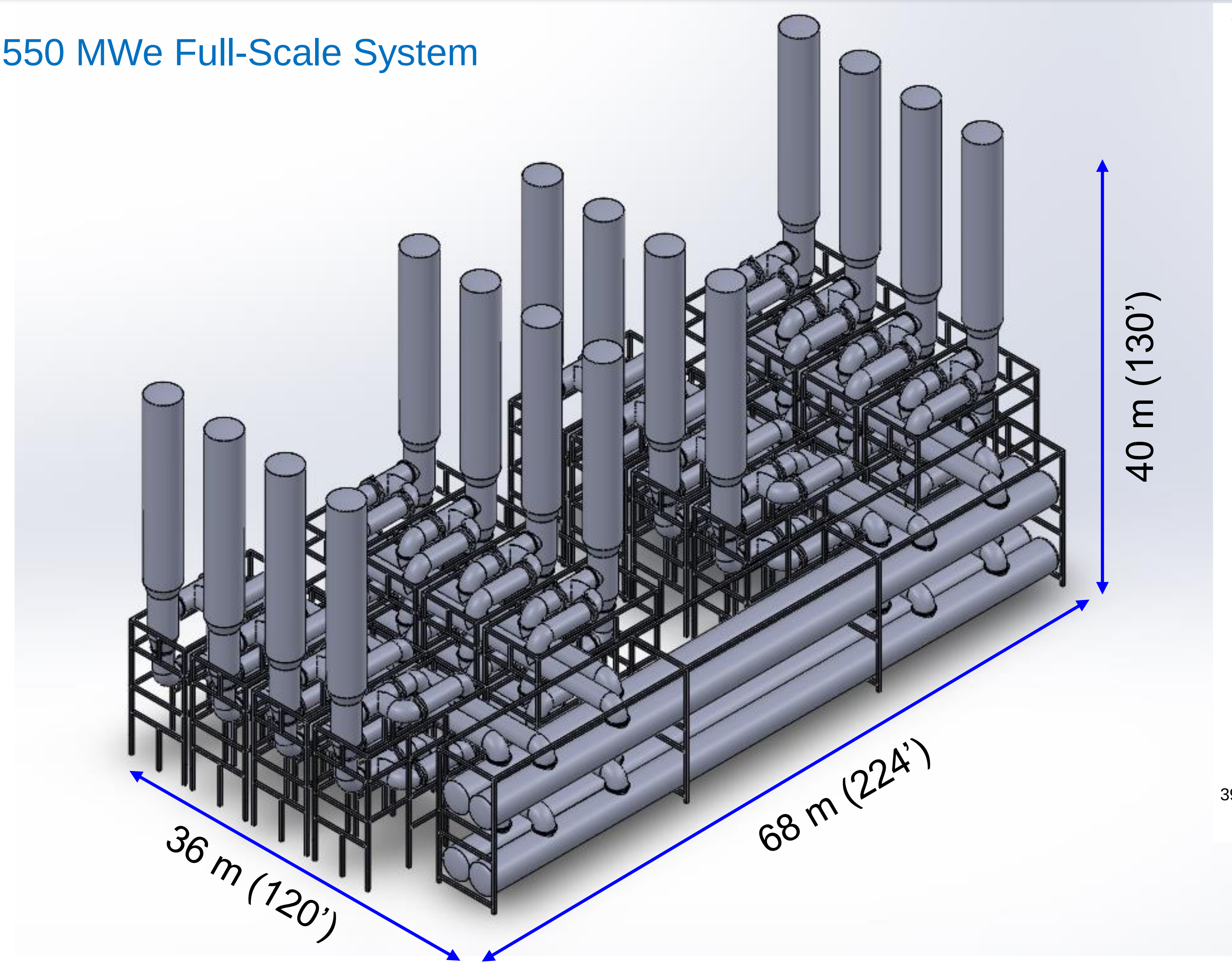
- Sixteen (16) radial beds
- SA516-70 carbon steel; 0.5” thickness
- 13 ft OD x $73^{1}/_{3}$ ft T/T

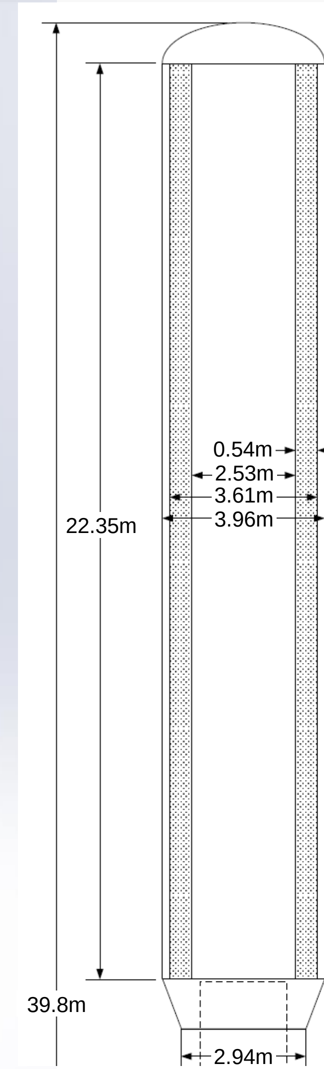


TDA RESEARCH

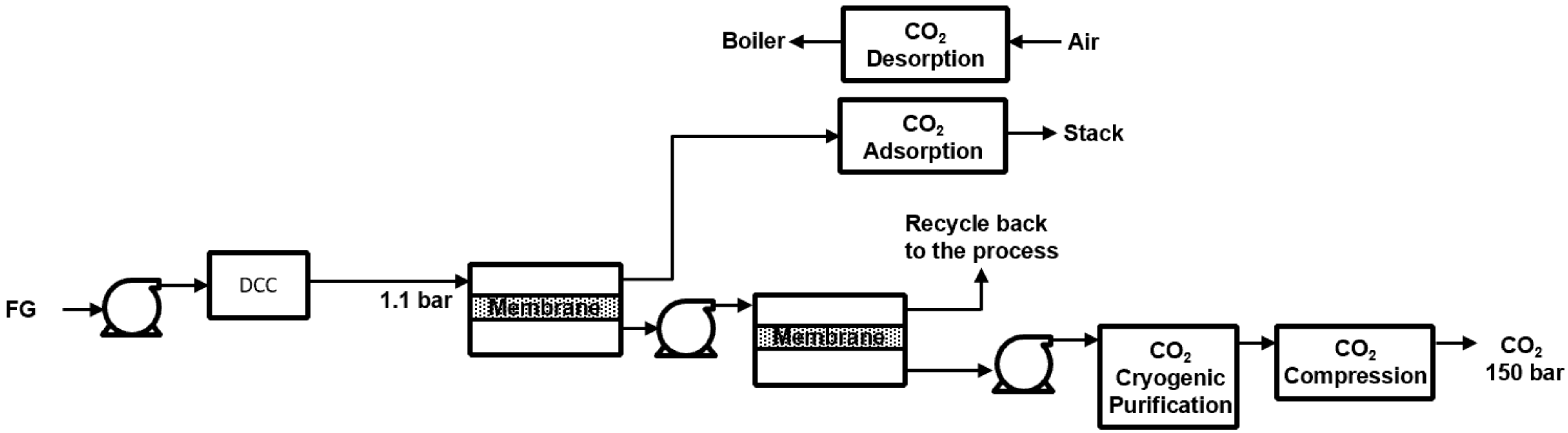
3-D Layout of the Hybrid Sorbent System

550 MWe Full-Scale System





Baseline Hybrid Process PFD



- A two-stage membrane process is utilized to recover the CO_2 at the desired purity
- A cryogenic purification system is used to ensure that the O_2 (<10 ppm) and other impurity levels in the CO_2 meets pipeline specifications
- In addition to the baseline study, other cases were also studies including one which does not require re-circulation of the CO_2 into the boiler

Final TEA - Rev. 4 $2018 Basis

Capture Technology	No Capture	Amine	Membrane-Sorbent Hybrid BP3	Membrane-Sorbent Hybrid Retrofit
Case Studies	**B12A**	**B12B**	**Baseline Case**	**No re-circ to boiler**
Gross Power, MWe	**685**	**770**	**905**	**902**
CO_2 Capture/Removal, MWe	-	30	129	126
CO_2 Purification, MWe	-	-	23	23
CO_2 Compression, MWe	-	44	56	55
Balance of Plant, MWe	35	46	47	48
Total Auxiliaries, MWe	**35**	**120**	**255**	**252**
Net Power, MWe	**650**	**650**	**650**	**650**
Net Plant Efficiency, % HHV	**40.3**	**31.5**	**30.0**	**30.6**
Carbon Capture, %	0	90	90	90
Coal Feed Rate, kg/h	214,112	273,628	287,191	281,990
Carbon Capture System (CCS) CAPEX $1,000s	-	738,606	351,305	346,060
FG Cleanup + CCS CAPEX inc. Compression	120,427	970,432	506,415	537,729
LCOE, $/MWh	**64.4**	**105.2**	**101.2**	3,450
LCOE inc. T&S, $/MWh		**114.2**	**110.6**	**99.4**
Breakeven CO2 Sales Price, $/tonne		**45.7**	**39.1**	**108.7**
Breakeven CO2 Emissions Penalty, $/tonne		73.5	68.5	**38.0**

- TDA's membrane sorbent hybrid system has a net plant efficiency of 30.0% compared to and a cost of capture of $39.1/tonne CO_2
    - 14.4% lower capture cost than the reference amine system on Rev. 4 Basis
- A stand-alone hybrid without any recirculation to the boiler was also simulated
    - $38/tonne CO_2 capture cost; 16.8% lower than reference amine cost

Acknowledgments

- DOE/NETL Project Manager, Andy O'Palko
- MTR Team, Thomas Hofmann, Jay Kniep, Tim Merkel, Erik Westling
- GTI Team, Chuck Shistla
- UCI, Ashok Rao
- TCM Team, Sundus Akhter, Magnus Aronsson, Kjetil Hantveit, Karstein Mangersnes, Blair McMaster, Stein Olav Nesse, Monica Iren Eidsheim Solend, Roger Solheim, Magne Andreas Tresvik