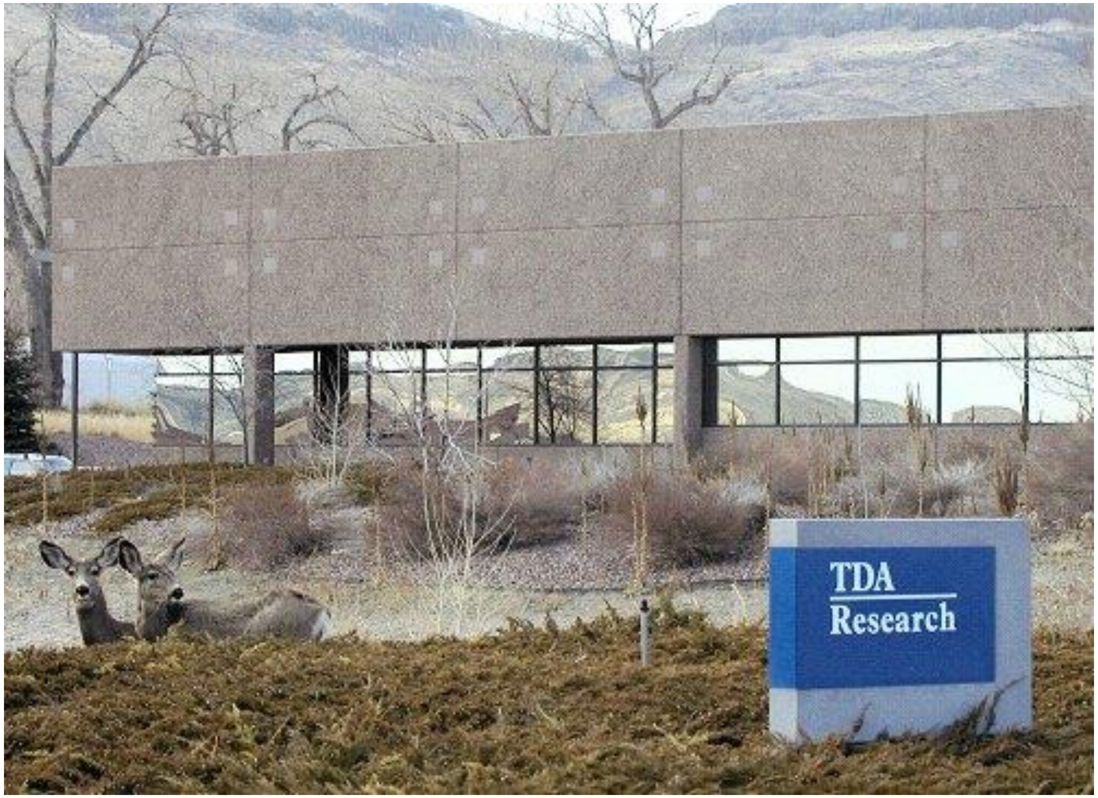
Membrane-Sorbent Hybrid System for Post-Combustion Carbon Capture (DE-FE-00031603)



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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 is being 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

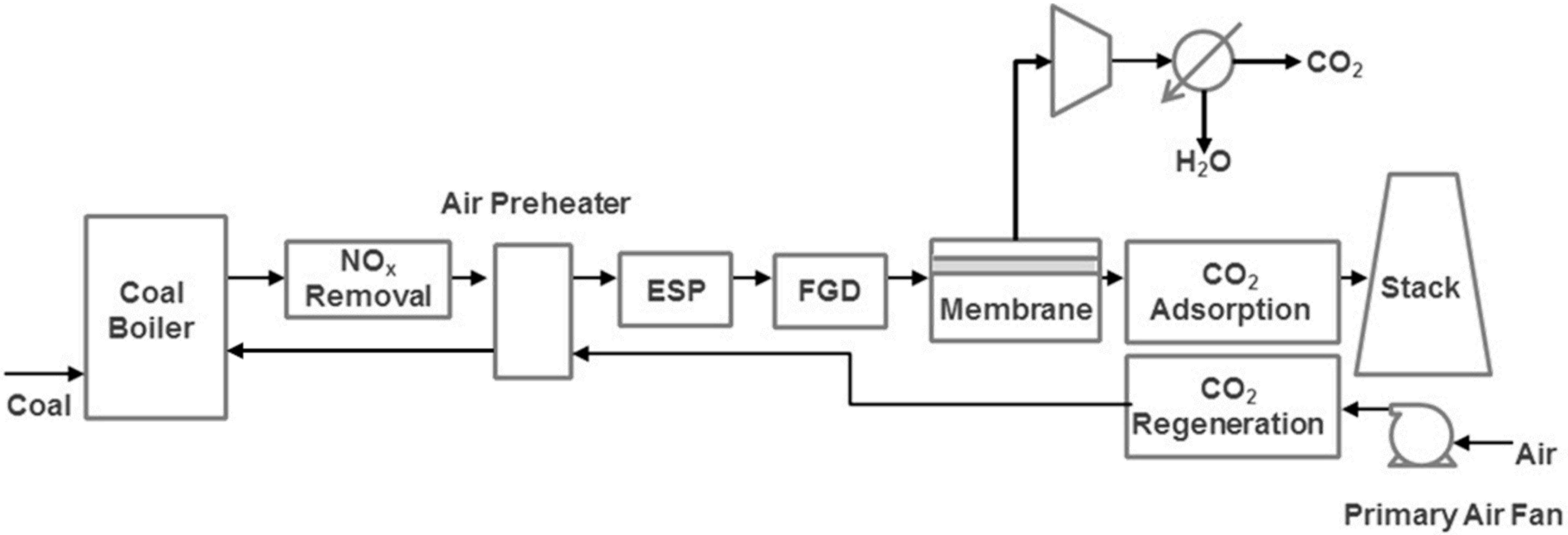
Project Duration

- **Start Date = August 18, 2018**
- **End Date = February 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 ~50ºC 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 RESEARCH

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

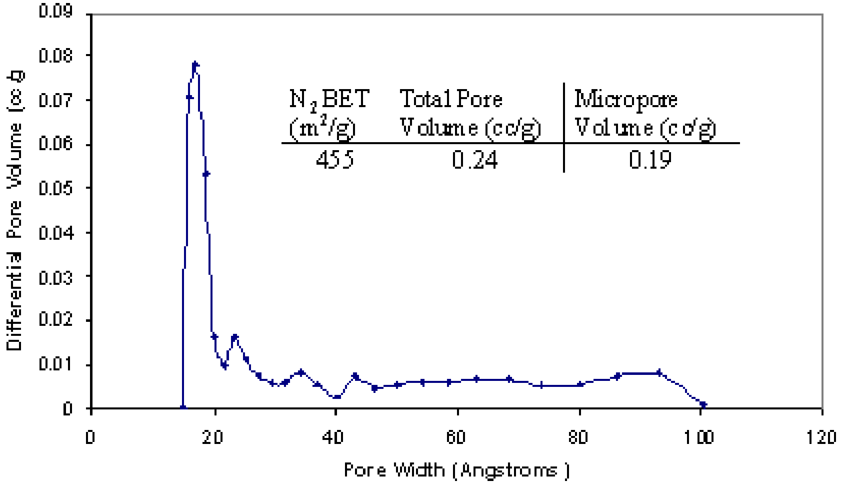
Technology Centre Mongstad (TCM) Norway

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

TDA RESEARCH

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**

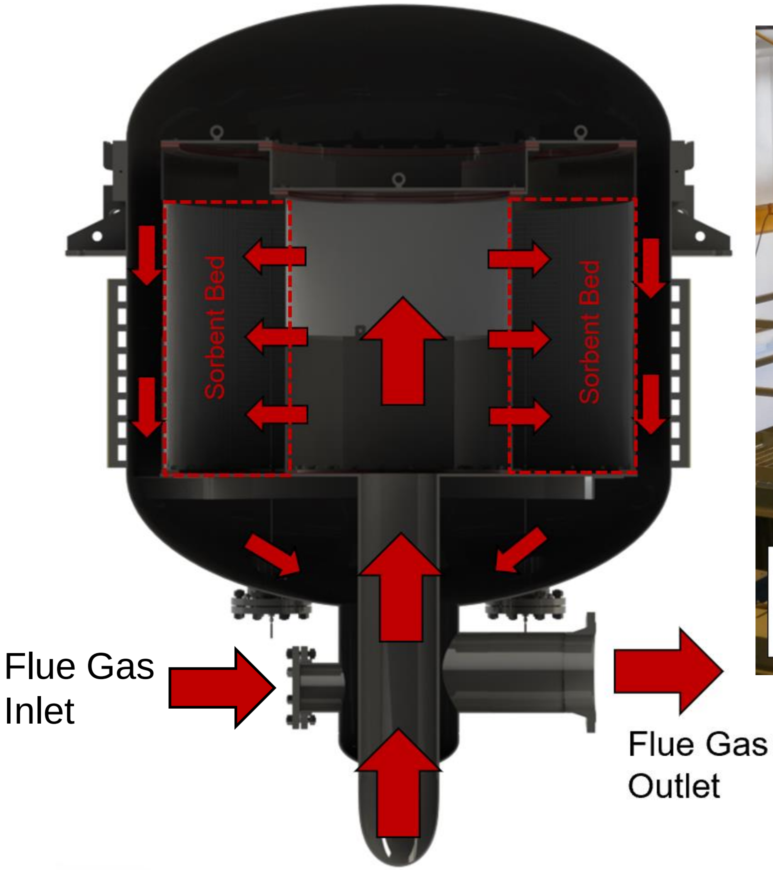


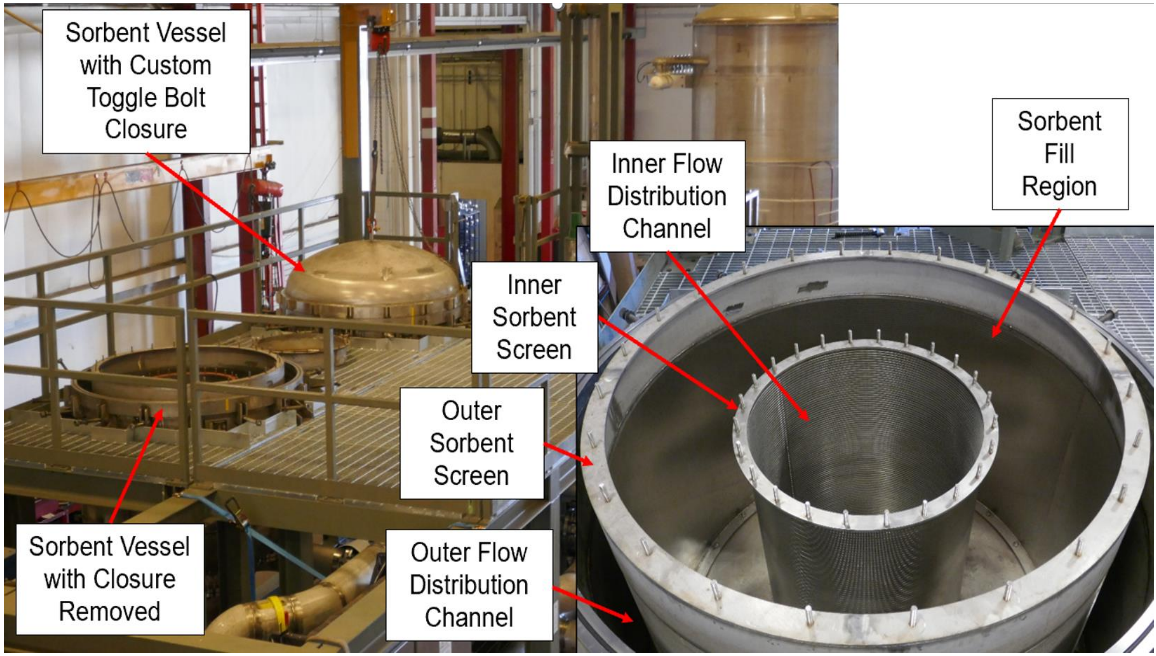
Sorbent operation in a VSA system was successfully demonstrated with actual flue gas (DE-0013105)

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)

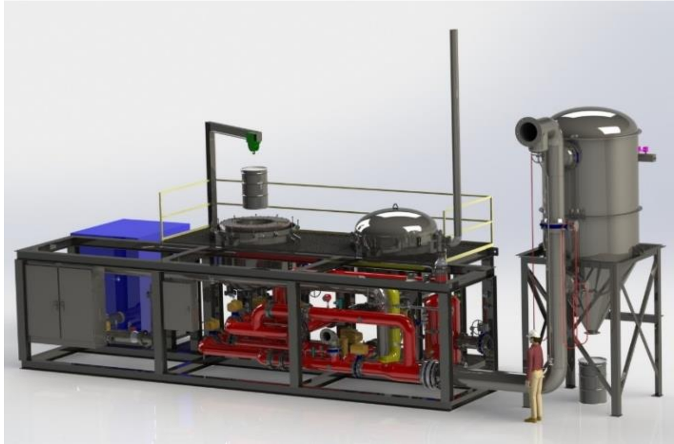
TDA Radial Flow Reactor Concept





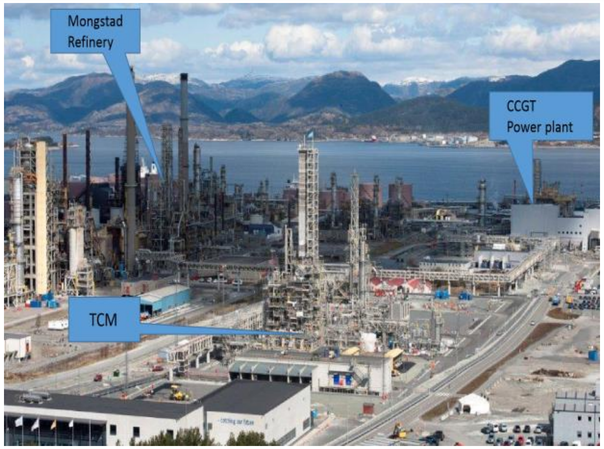
- Sorbent is loaded in annular section of the vessel
- The flow is in radial direction
- Higher cross-sectional area and lower bed depth minimize the dP through the bed

Project Focus



TDA's Sorbent System

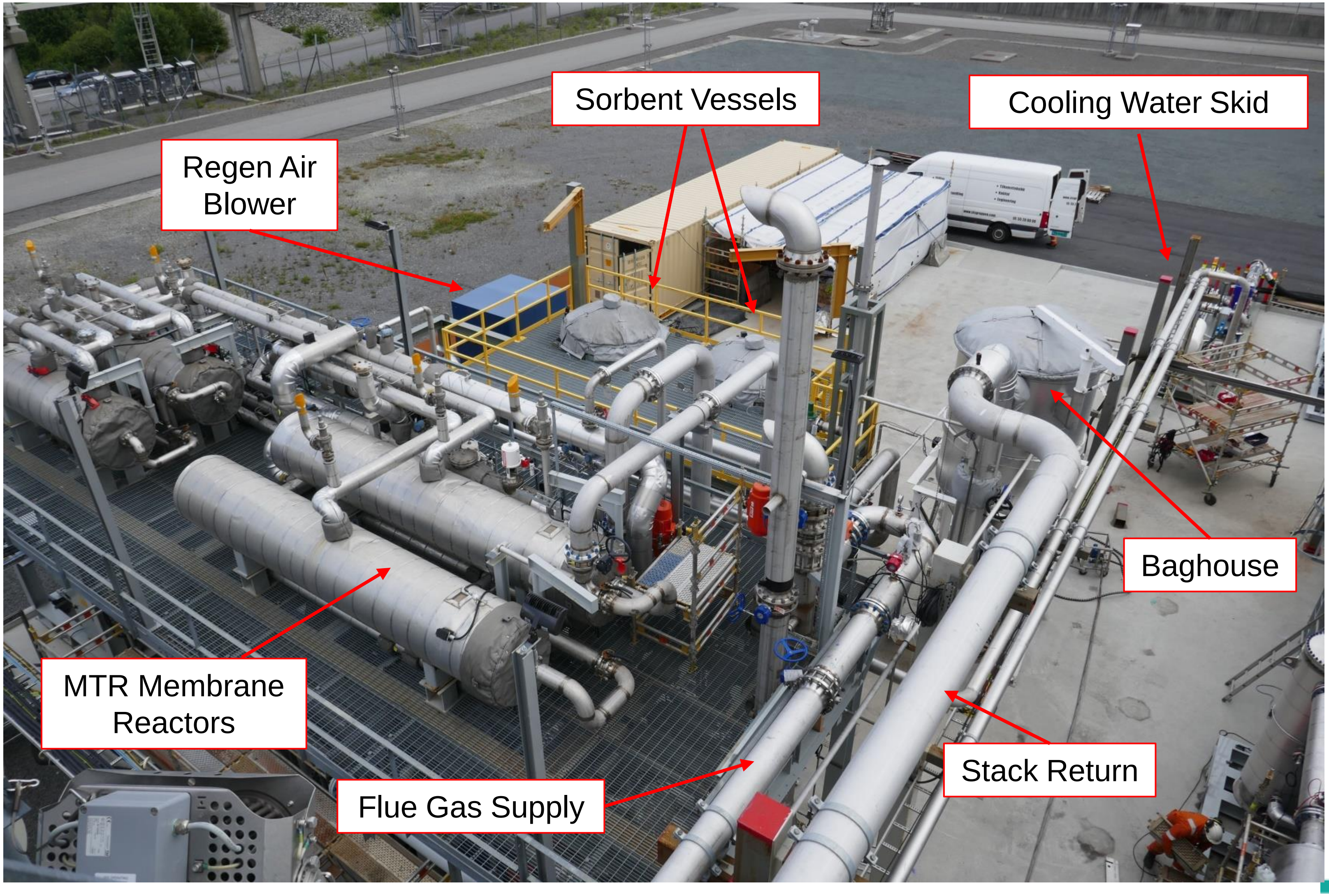
Existing MTR Membrane Module



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**

Hybrid Membrane System Overview

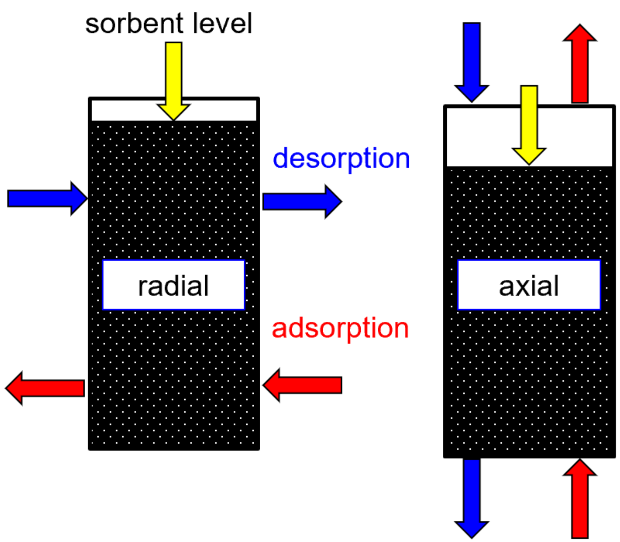


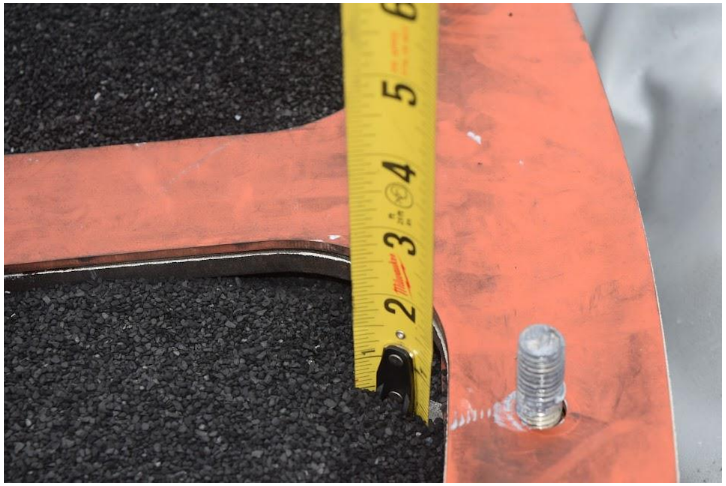
Sorbent Vessels

Sorbent Loading into the Vessels

Sorbent Settling and Retainment

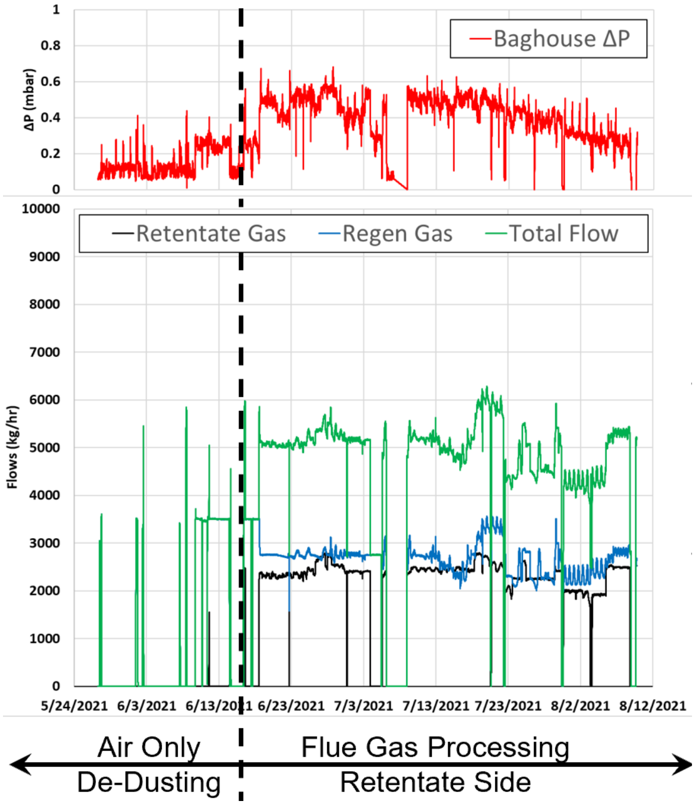
- Sorbent settling is not desirable as it generates a void at the top of the bed and cause flow by-pass
- System design and loading procedures ensured effective pre-settlement
- Top of the sorbent bed is sealed with custom gaskets
- After a short run, the beds are topped off (≤ 2% of total sorbent mass)

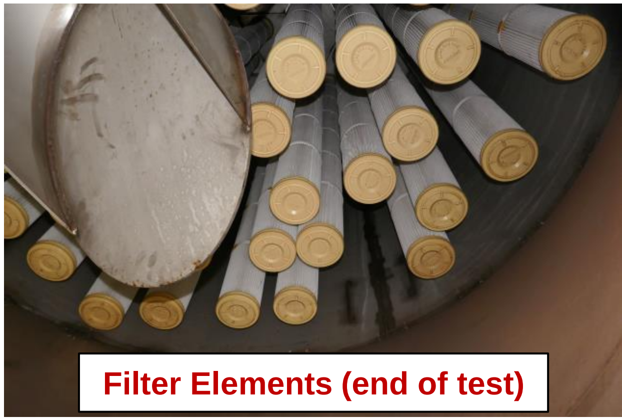


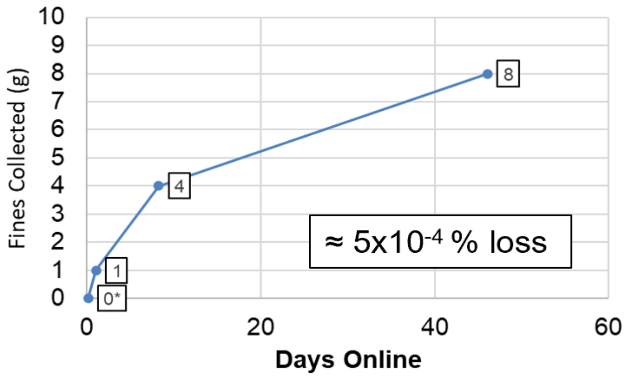


- Amount of dust generated was surprisingly low (much lower than we observed in axial beds)
- Sorbent retention was excellent; total fines collected in the baghouse over the first month of operation was ≤ 0.0006% wt. of the initial load

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 ≈ 8g (very low compared to total sorbent inventory of ~1.7 tonne)**
  - The collected particulates also included fabrication debris

Field Test Summary

Time online (taking flue gas):

- 4,001 hours† (≈ 167 days)
- Availability 80.5%
  - *Excludes 1-month planned TCM maintenance stoppage and holiday break*

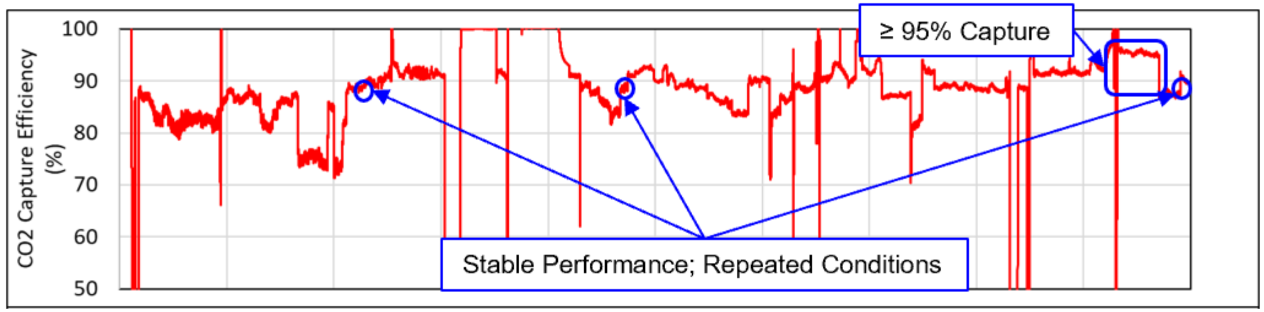
RFCC flue gas CO_2:

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

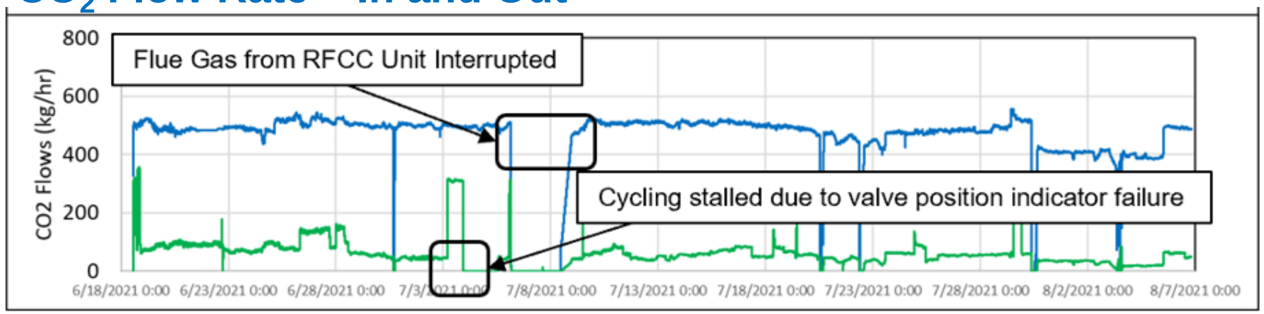
CO_2 Capture Breakdown

	< 90%	> 90%	> 95%
hours	1,789	1,482	307
days	92	75	13
Percent of run time	55.3%	44.7%	7.7%

CO_2 Capture Efficiency

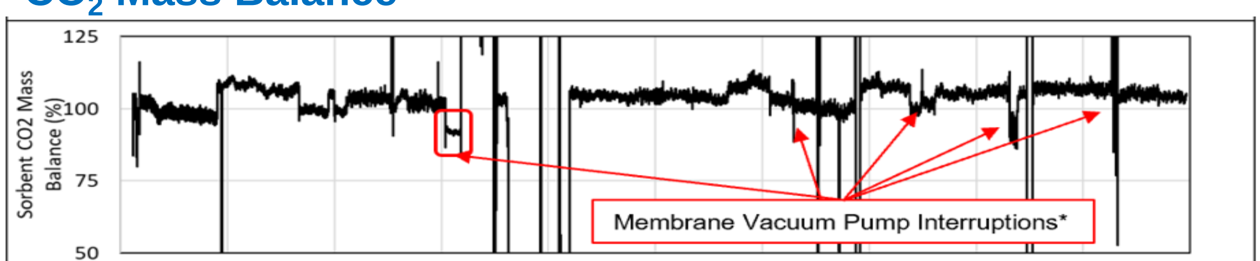


CO_2 Flow Rate – In and Out



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

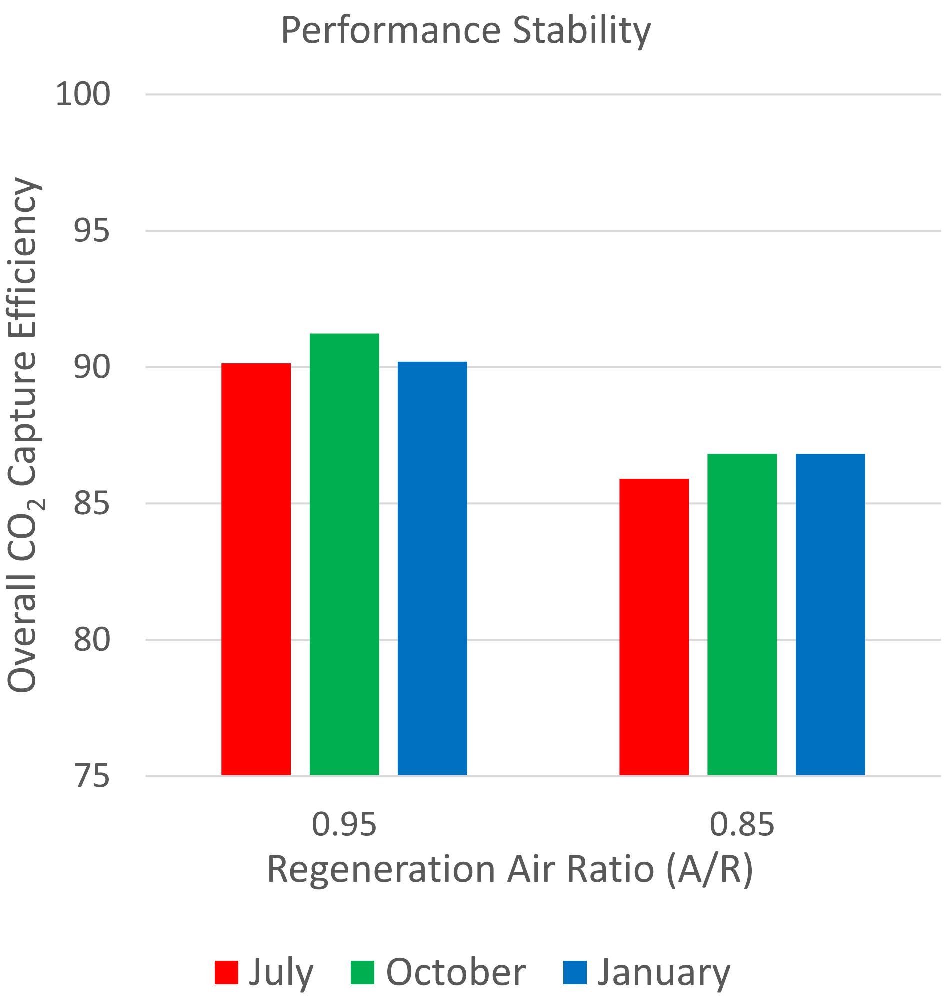
CO_2 Mass Balance



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

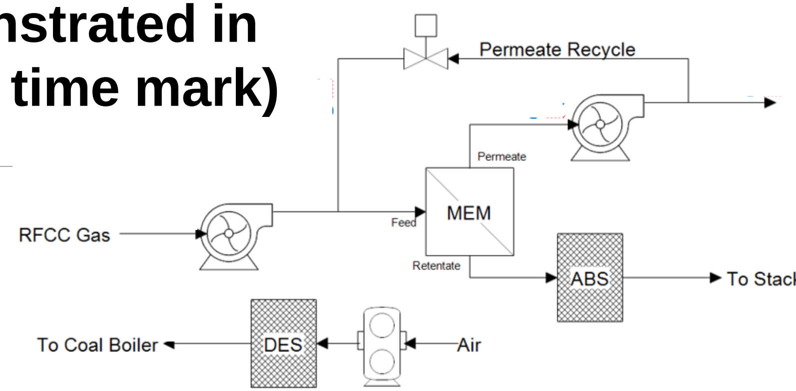
Performance Stability

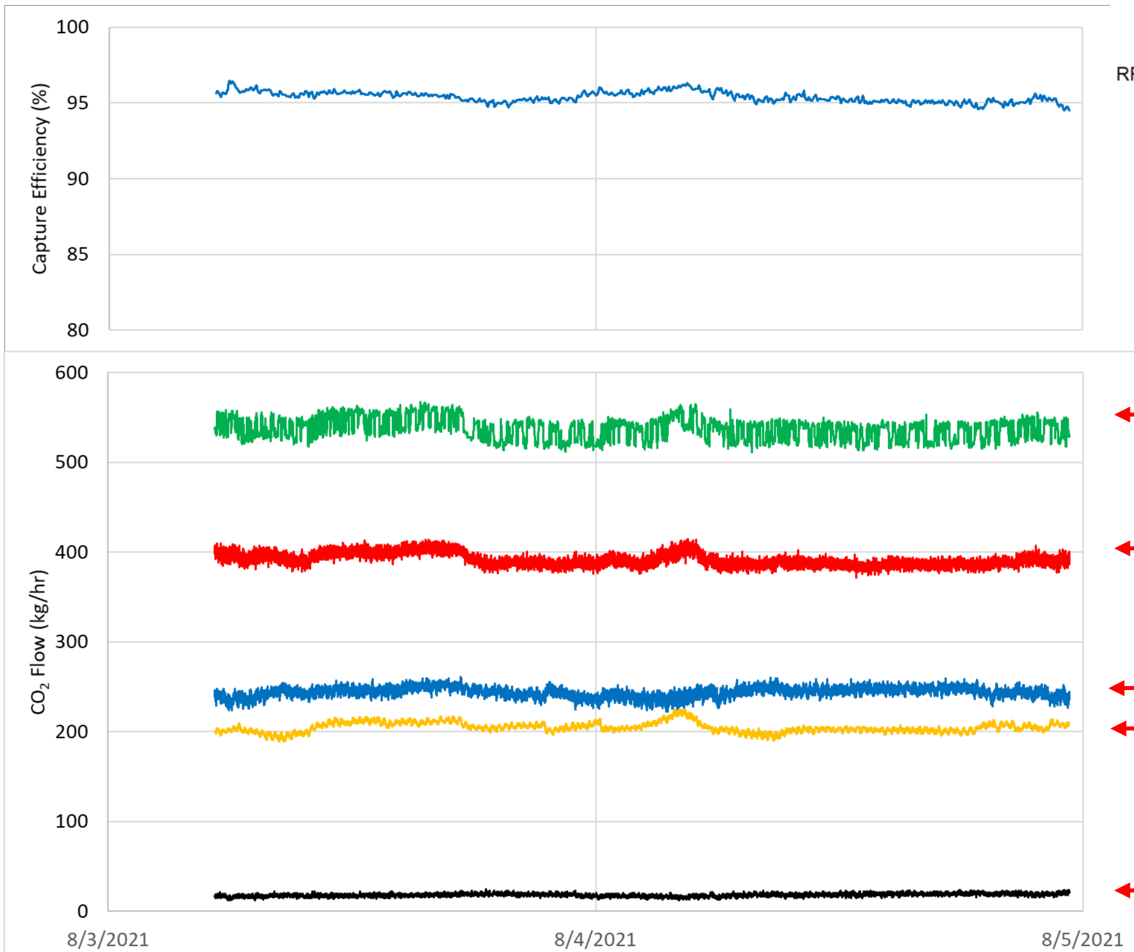
- **Performance stability is checked periodically under several baseline conditions**
  - Overall CO_2 capture efficiency of the system was measured over a range of regeneration air/retentate flow (A/R) ratios
  - The chart compares two A/R ratios in three different months (summer/fall/winter) during 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 hr tests (at 38 days total run time mark)**





Membrane Feed (includes recycled permeate)

Flue Gas Inlet (Hybrid System Inlet)

Retentate (Sorbent Inlet)

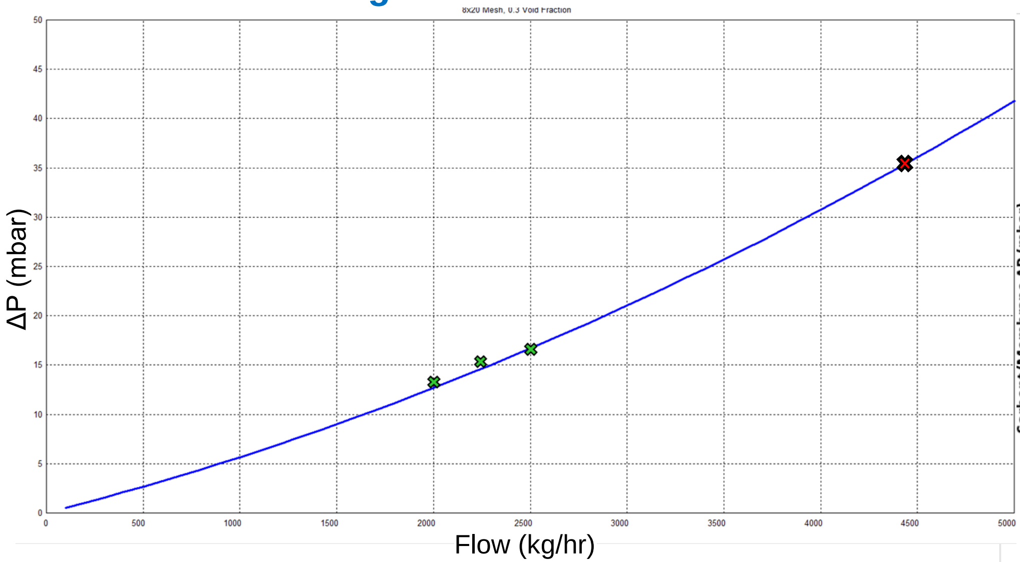
Permeate Product (excludes recycled CO_2)

CO_2 Slip (stack)

RESEARCH

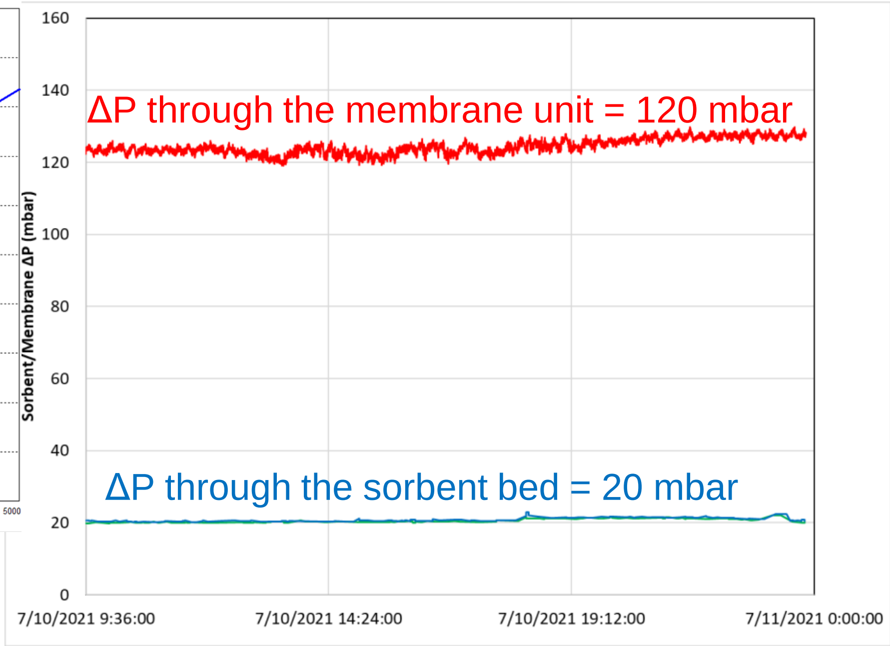
Pressure Drop Measurements

ΔP through the Bed vs. Flow Rate



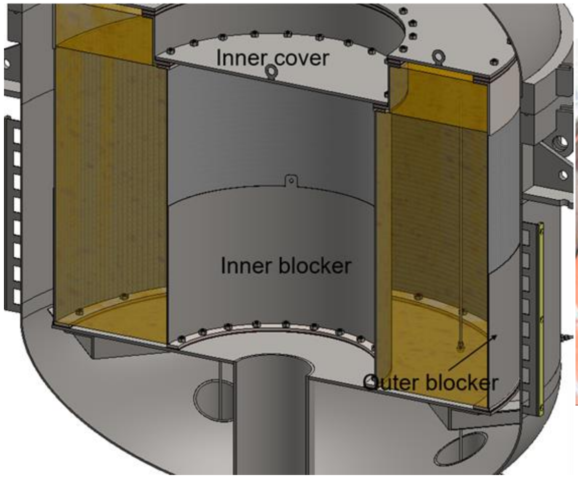
✖ Experimental pressure drop vs. flow data from TCM
✖ Highest possible flow through the system

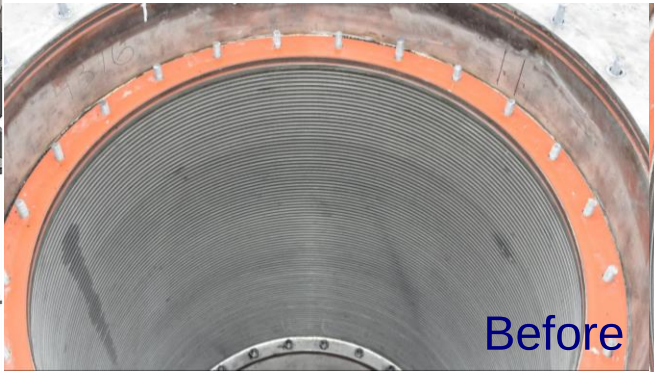
ΔP through the membrane and sorbent

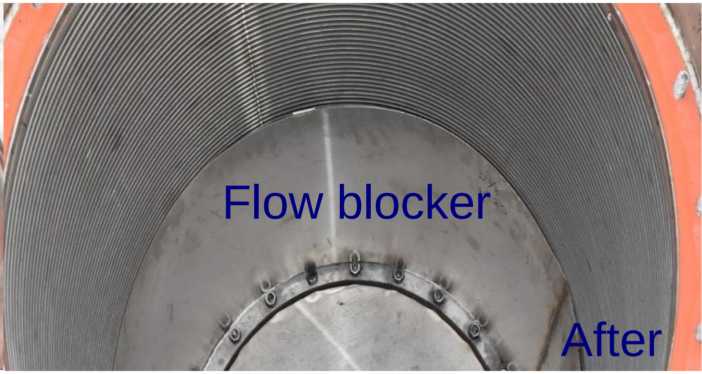


- **TDA's radial sorbent bed design achieved a very low pressure drop**
- **At the 2000-2500 kg/hr flue gas flow, the total ΔP was measured as <20 mbar**
- **Actual measured ΔPs agree well with the design model**
- **The membrane unit treating the same flue gas flow and rejecting the same amount CO_2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

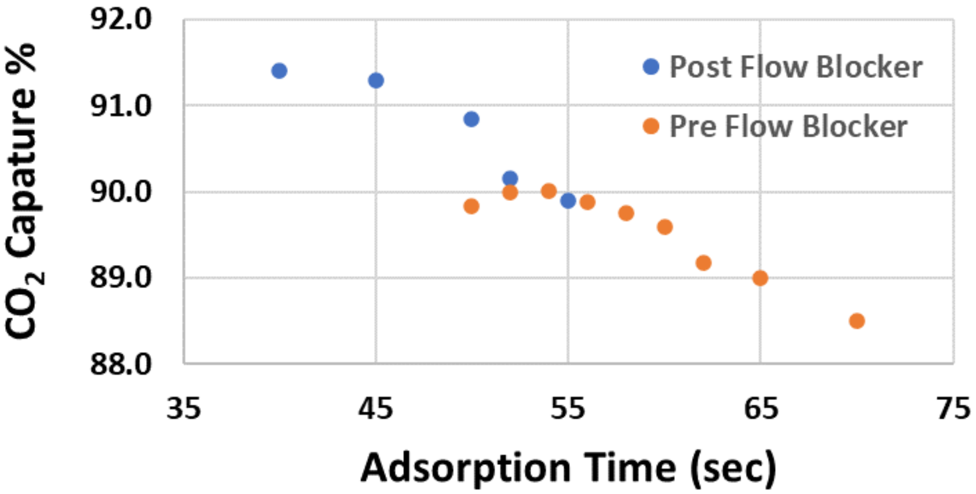
Installation of Flow Blockers



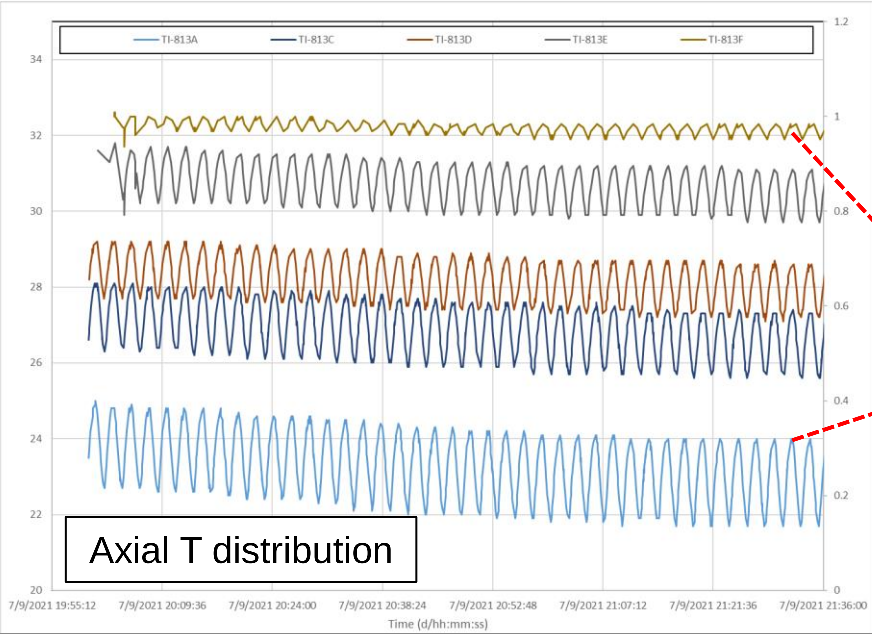


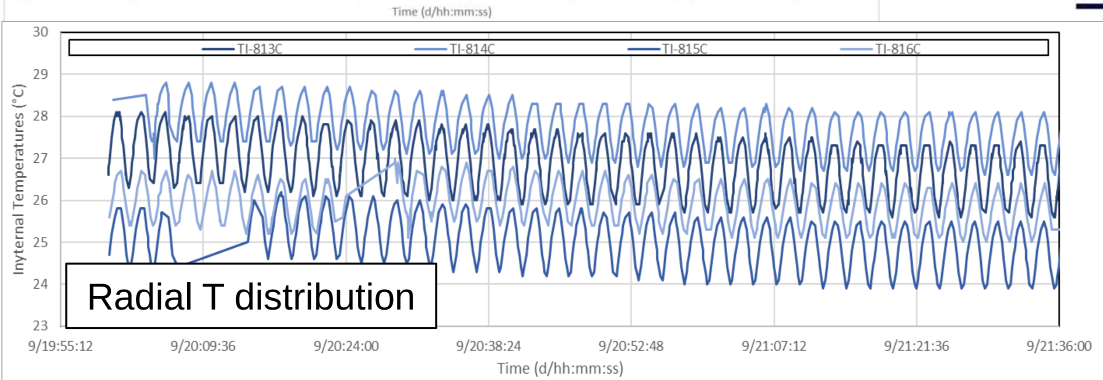


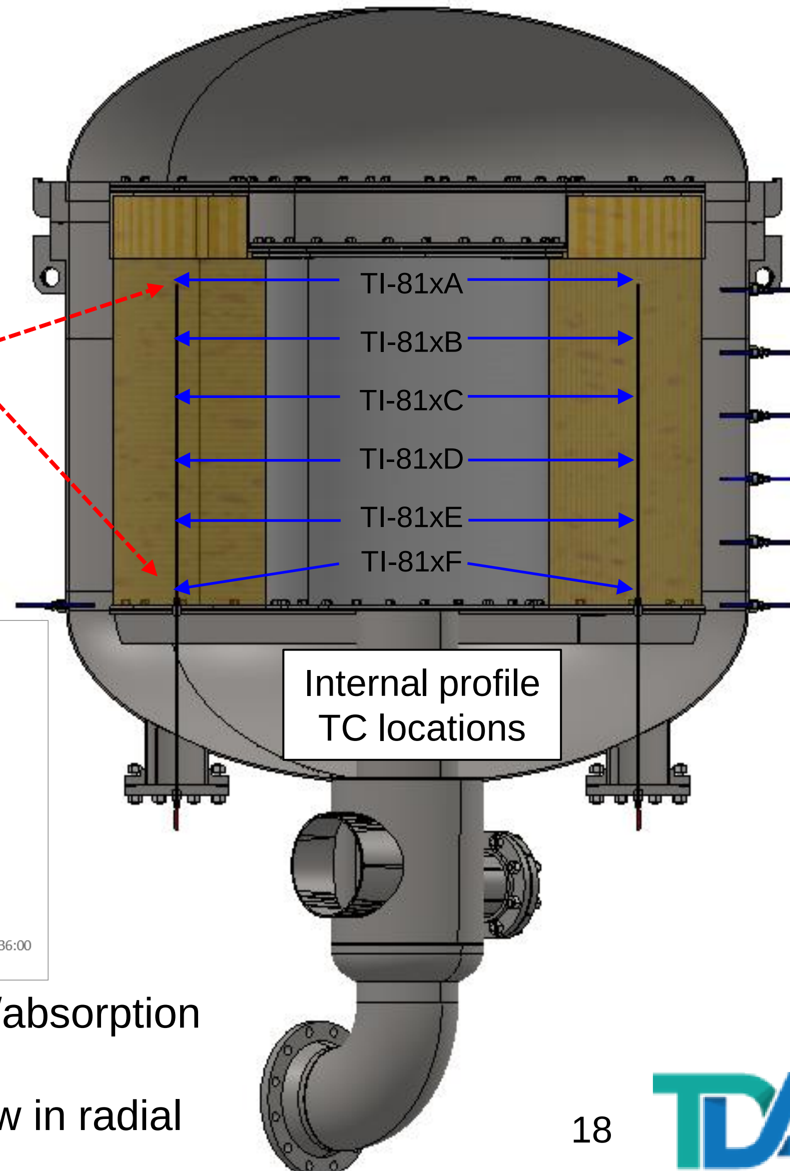
- Flow blockers are installed to block the flue gas flow into ~1/2 of the bed
- The optimum cycle time was determined at ~40 sec following the installation of flow blockers
- Blocking half of the bed resulted only in a short reduction in the cycle time



Temperature Distribution in the Bed



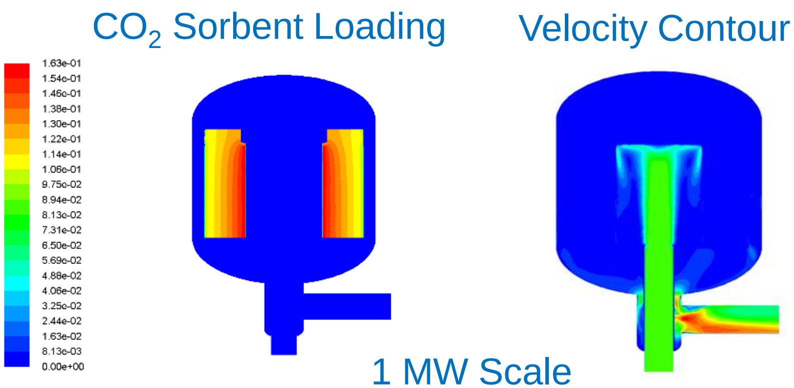


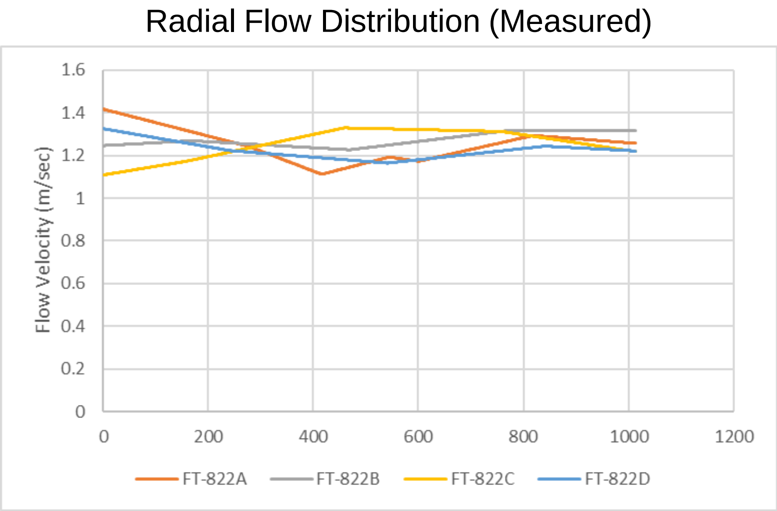


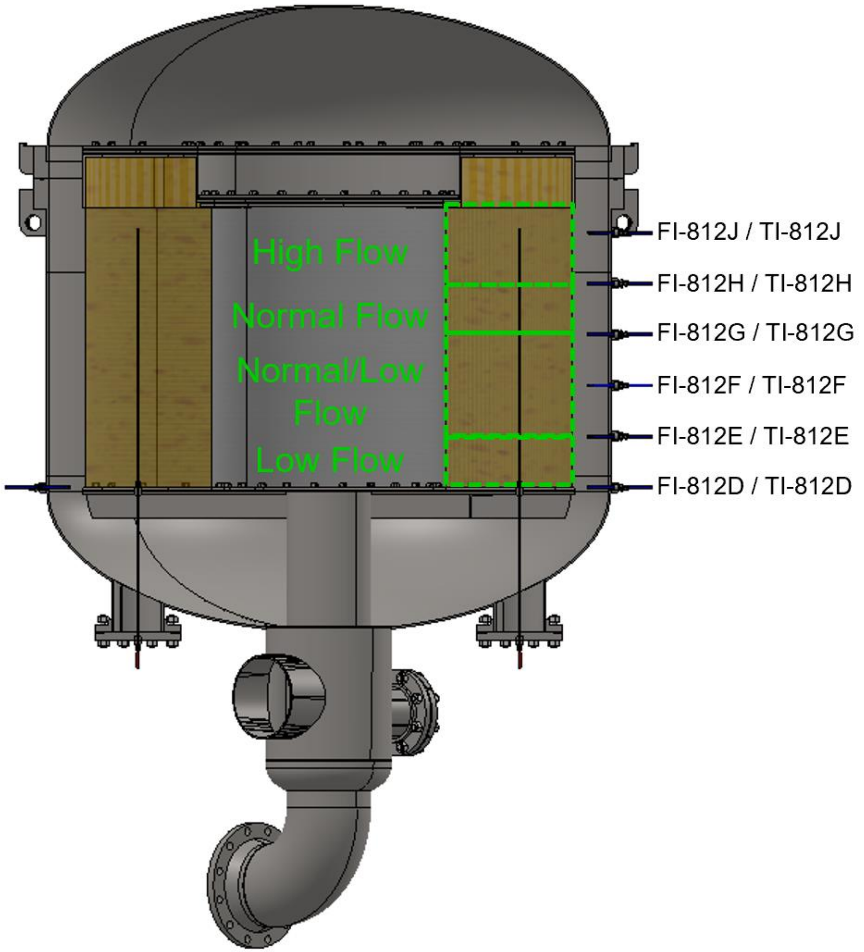
- Axial T distribution/cyclic ΔT indicates higher flows/absorption near the top
- Radial T distribution/cyclic ΔT indicates uniform flow in radial direction

TDA RESEARCH

Flow Distribution in the Bed





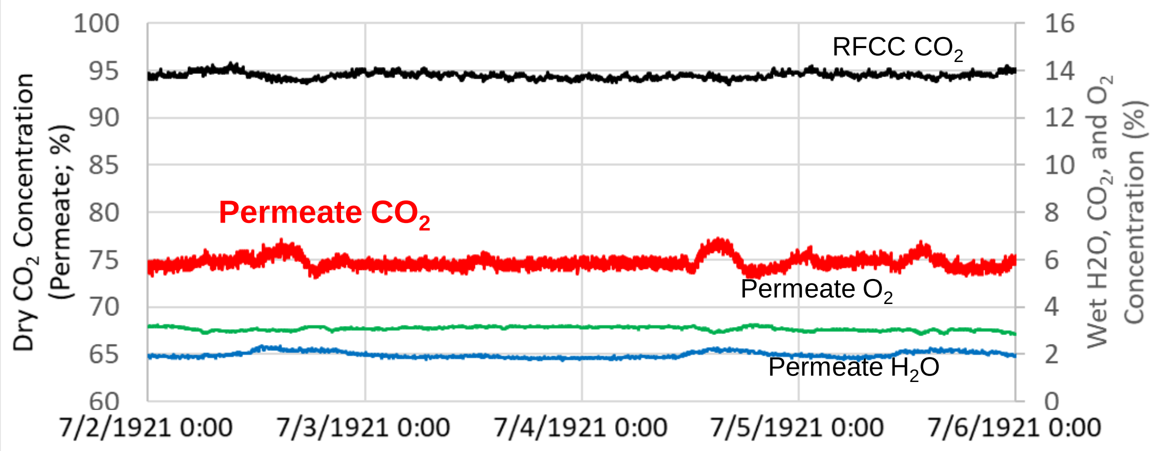


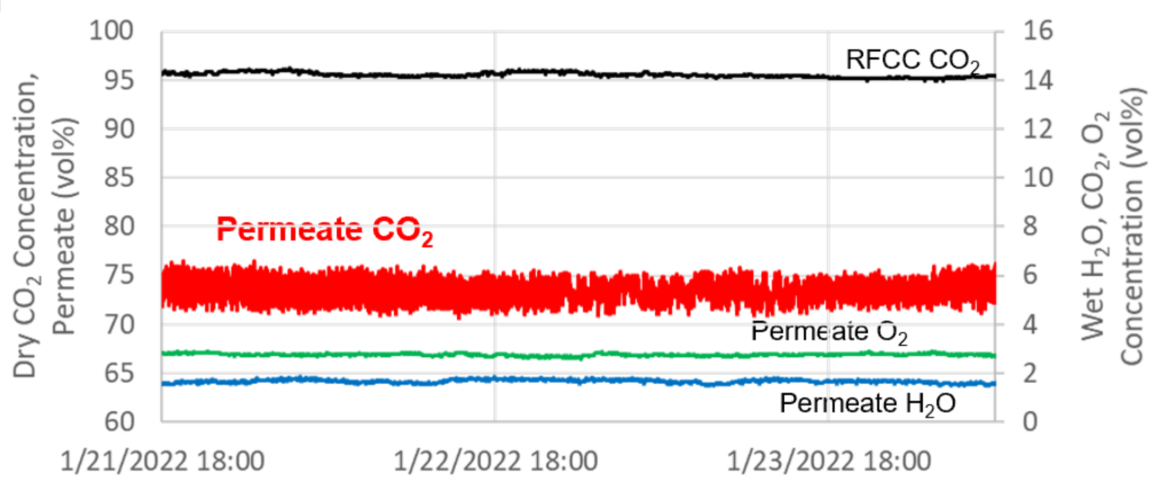
- Radial flow velocity measurements show uniformity within ± 2%
- Axial flow velocity measurements indicate a flow imbalance towards top of the bed

TDA RESEARCH

Membrane Performance

- **Modified unit 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

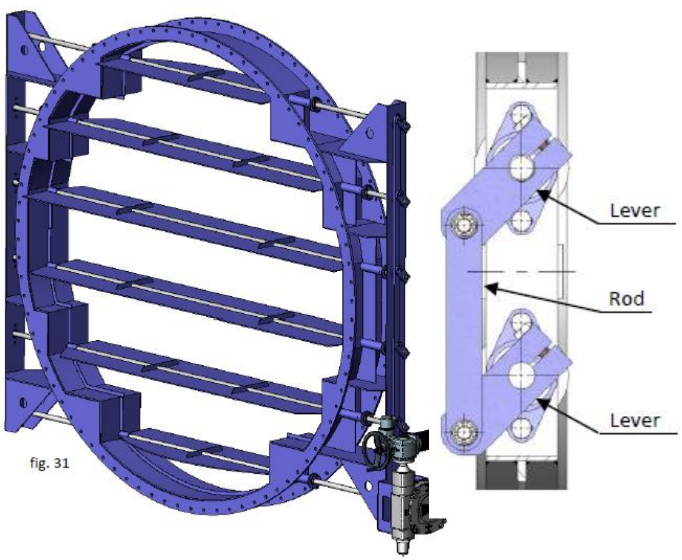
Reactor Vessel Design

Sorbent System - Hybrid

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

Adsorption - Flue gas flow

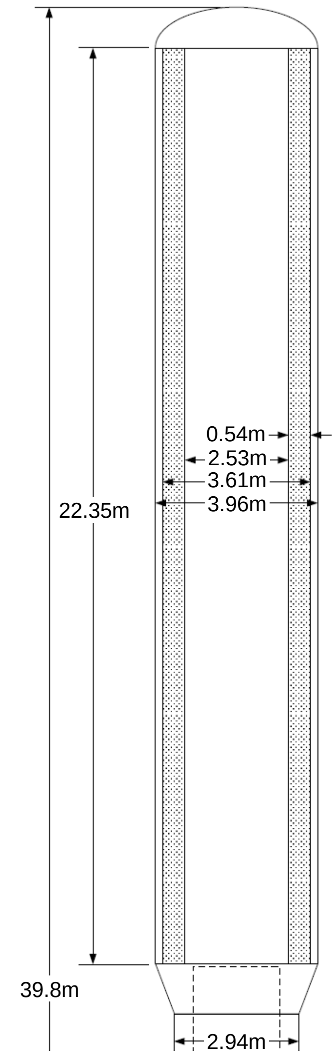
Desorption - Air Purge flow



ΔP=105 mbar

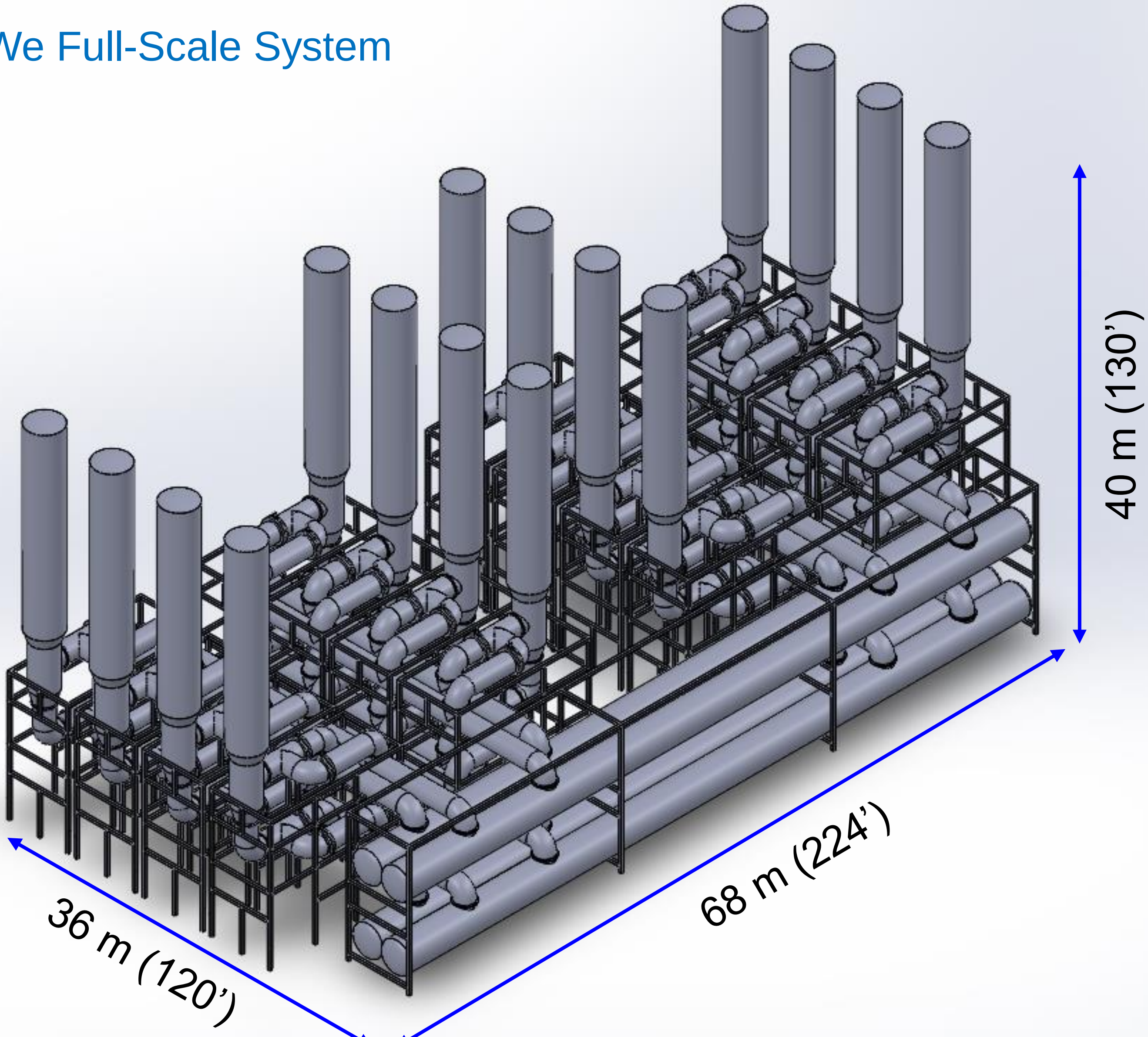
Module Size:	68.75	MW
No. of Trains:	8	
Beds/Train:	2	
Total Beds:	16	
Flue Gas Flow:	74.5	m^3/s
CO_2 Flow:	1.22	tonne/min
Capacity:	1.8%	Wt.
Cycle Time:	1	min
Sorbent Inventory:	67.8	tonne/m^3
Sorbent Density:	0.59	tonne/m^3
Bed Volume:	116.4	m^3
Bed Area:	12.3	m^2

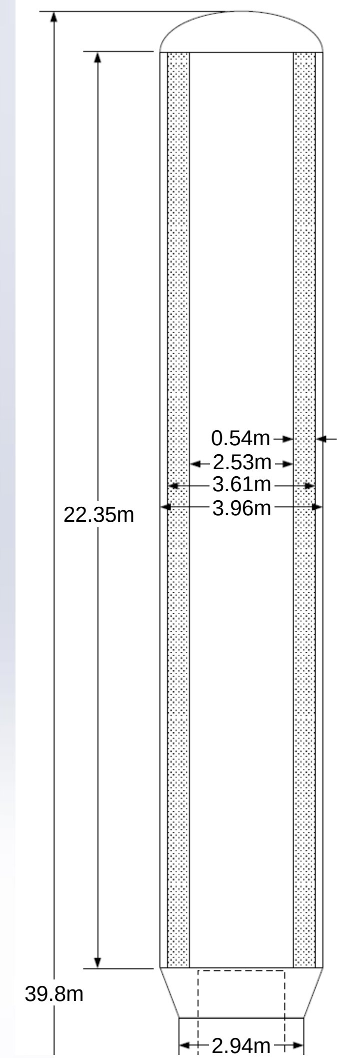
- Sixteen (16) radial beds
- SA516-70 carbon steel, 0.5” thickness
- 13 ft OD x 73 $^{1}/_{3}$ ft T/T



3-D Layout of the Hybrid Sorbent System

550 MWe Full-Scale System





TDA RESEARCH

Techno-economic Analysis

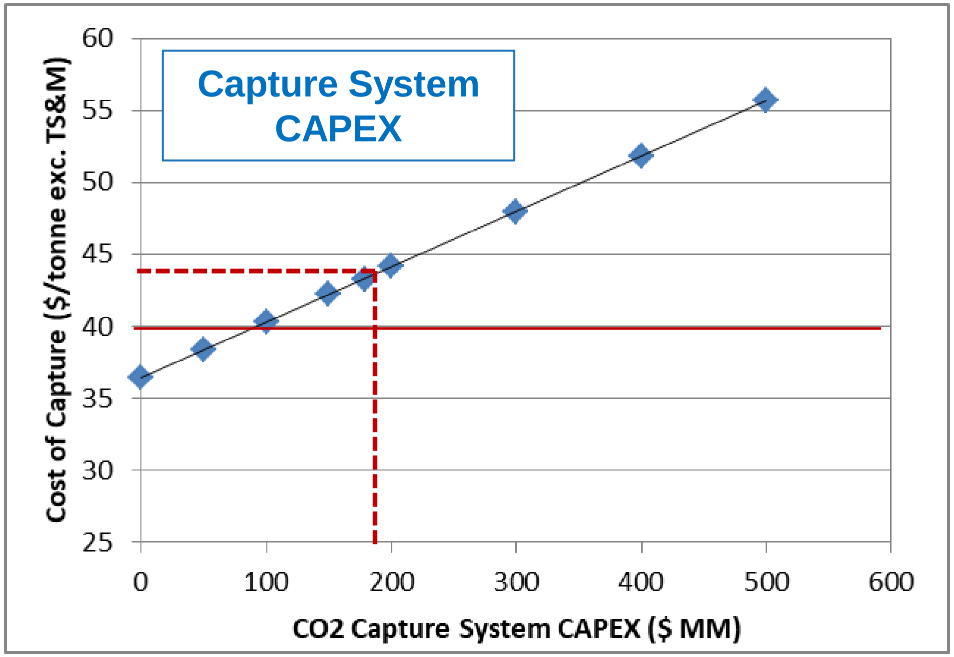
CASE NO.	UNITs	DoE 11	DoE 12	MTR WP Study	TDA + MTR 3
CO_2 capture technology		**Reference No Capture**	**Reference Amine**	**Membrane Only**	**Membrane-Sorbent Hybrid**
CO_2 purity from separation Module			**95%**	**80%**	**80%**
Steam turbine power	kWe	580,400	662,800	780,795	750,371
Total auxiliary consumption	**kWe**	**30,410**	**112,830**	**224,605**	**200,371**
Net power output	**kWe**	**549,990**	**549,970**	**556,190**	**550,001**
Auxiliary load summary					
Flue gas booster + CO_2 removal	kWe	0	20,600	50,170	17,074
VSA Vacuum pump	kWe	0	0	37,475	33,578
CO_2 compression	kWe	0	44,890	75,768	74,456
CO_2 cryogenic purification	kWe	0	0	20,397	23,214
Common Auxiliaries	kWe	30,410	47,340	40,795	52,049
% Net plant efficiency	**% HHV**	**39.3**	**28.4**	**28.7**	**29.45**
As-received coal feed	kg/h	185,759	256,652	256,715	247,755
Carbon captured	**%**	**0**	**90**	**90**	**90**
Total Plant Cost	**$/kWe**	**1,981**	**3,563**	**3,461**	**3,006**
Cost of Electricity (COE)	**$/MWh**	**$ 80.95**	**$ 137.30**	**$ 132.30**	**$ 121.85**
Cost of CO_2 Captured	**$/tonne**	**-**	**$ 56.49**	**$ 52.00**	**$ 43.30**

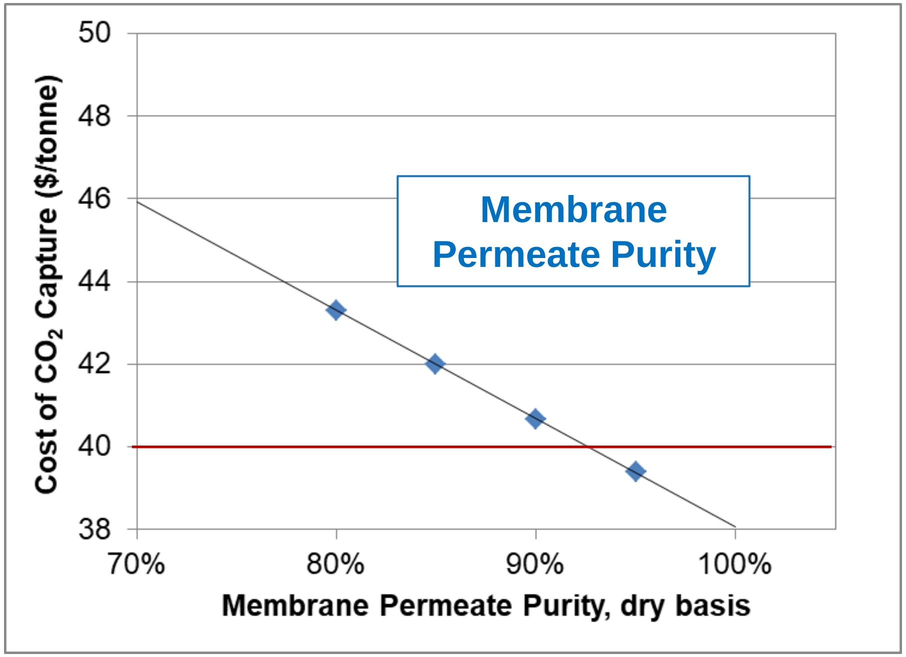
Final TEA Updates Underway Update to Rev. 4 basis

- Membrane sorbent hybrid system has a net plant efficiency of 29.45% compared to 28.7% in MTR-Worley Parson Study for membrane only system
- TDA's membrane sorbent hybrid system has 23% lower cost of capture compared to reference amine system

TDA RESEARCH

Sensitivity Analysis





- Cost of CO_2 Capture is estimated as $43.3/tonne for the hybrid process at capture system cost of $178.6 MM
  - Includes flue gas treatment subassembly, blowers, DCC etc.
- DOE 2030 Target of $40/tonne can be met if CAPEX is reduced to $110 MM
  - Trade off between dP/parasitic power loss and vessel dead volume/cost will be analyzed
- The DOE 2030 Target will also be met if the CO_2 purity gets above 92% by vol.

Acknowledgments

- DOE/NETL Project Manager, Andy O'Palko
- MTR Team, Thomas Hofmann, Jay Kniep, Tim Merkel, Erik Westling
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