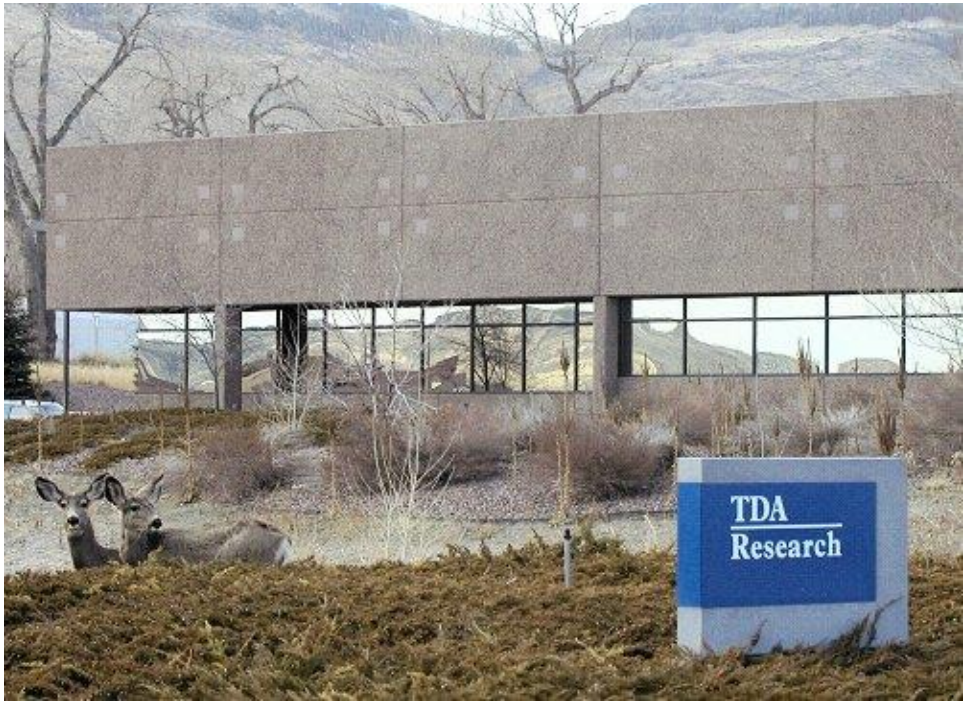
Membrane-Sorbent Hybrid System for Post-Combustion Carbon Capture (DE-FOA-0001791)



Gökhan Alptekin, PhD
Ambal Jayaraman, PhD
Mike Bonnema
Douwe Bruinsma, PhD
Matt Cates
Mike Cesario
Dave Gribble
Brandon Gushlaw
Jerrod Hohman
Freya Kugler

TDA Research, Inc.

Carbon Management and Oil and Gas Research Project Review Meeting

August 12, 2021

Project Team and Objectives

- **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 CO_2 from the flue gas**
  - Membrane is being developed by MTR
  - Adsorbent has been developed by TDA for post-combustion capture

Main Project Tasks

BY1	✓ Completed the Design of the Test Unit
	✓ Completed the Initial Design Review
	✓ Completed 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

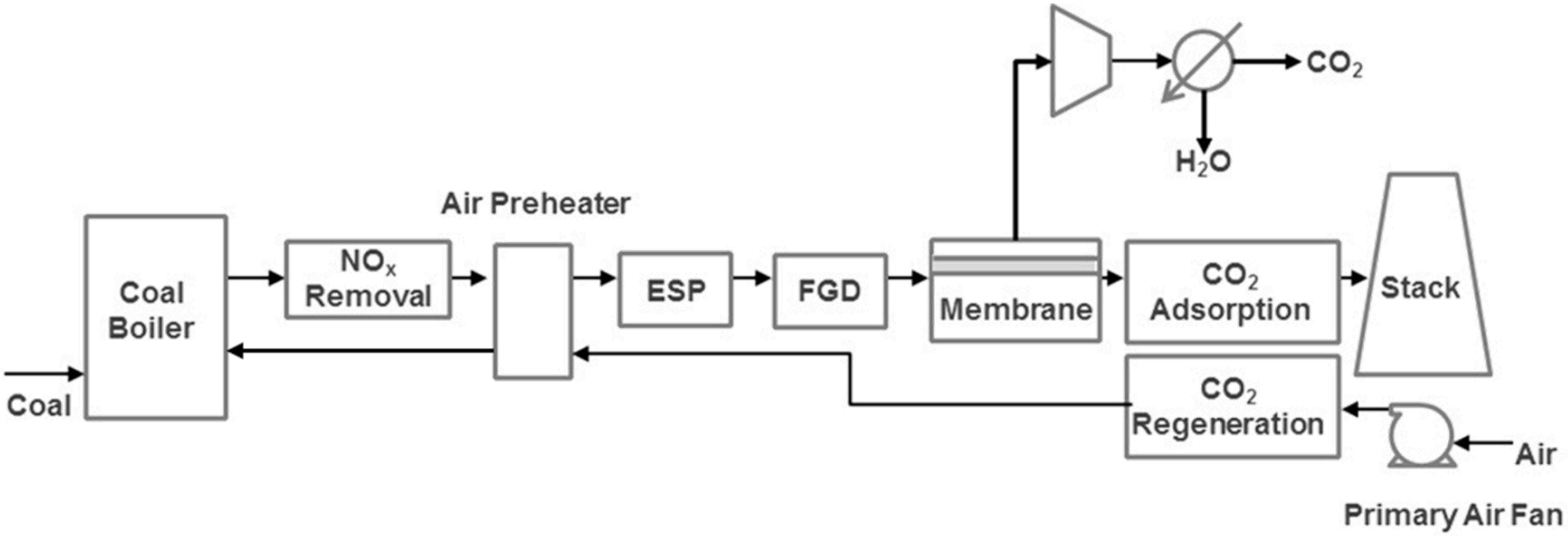
Project Duration

- **Start Date = August 18, 2018**
- **End Date = February 14, 2022**

Budget

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

Hybrid Membrane Sorbent Process



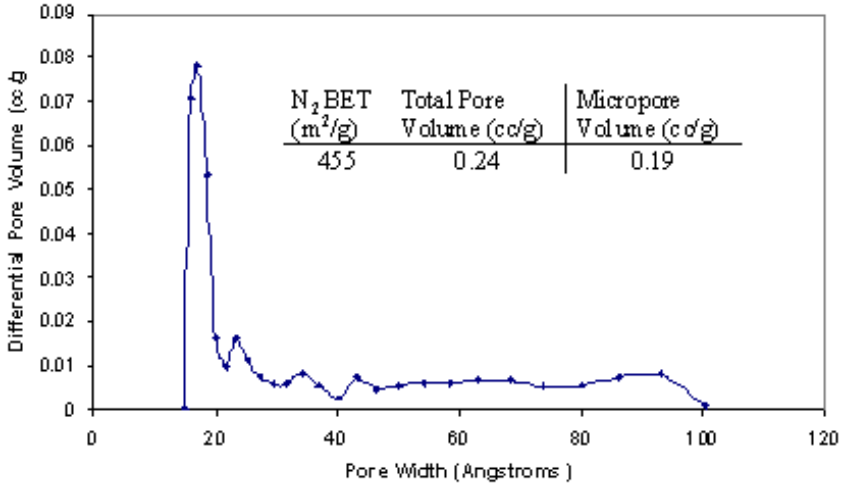
- **Membrane operates at T up to 50°C under mild vacuum, (~0.2 atm) removes ~50% of CO_2 and almost all water**
  - TDA's sorbent removes remaining CO_2 in the membrane effluent (retentate) ensuring 90+% carbon capture
  - The boiler feed air is used as a sweep gas to facilitate sorbent regeneration
  - 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**

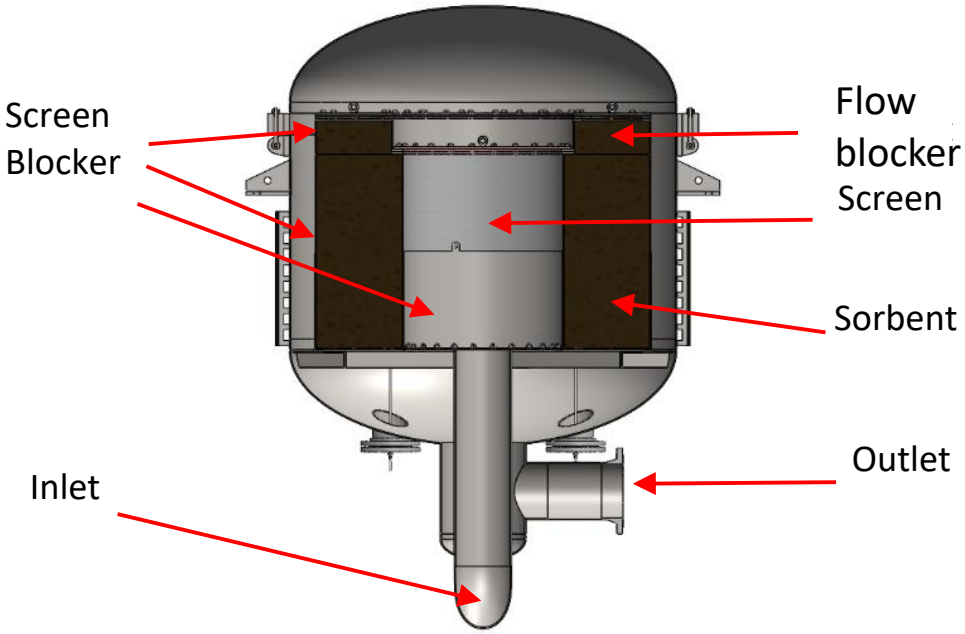
US Patent 9,120,079, Dietz, Alptekin, Jayaraman "High Capacity Carbon Dioxide Sorbent", US 6,297,293; 6,737,445; 7,167,354

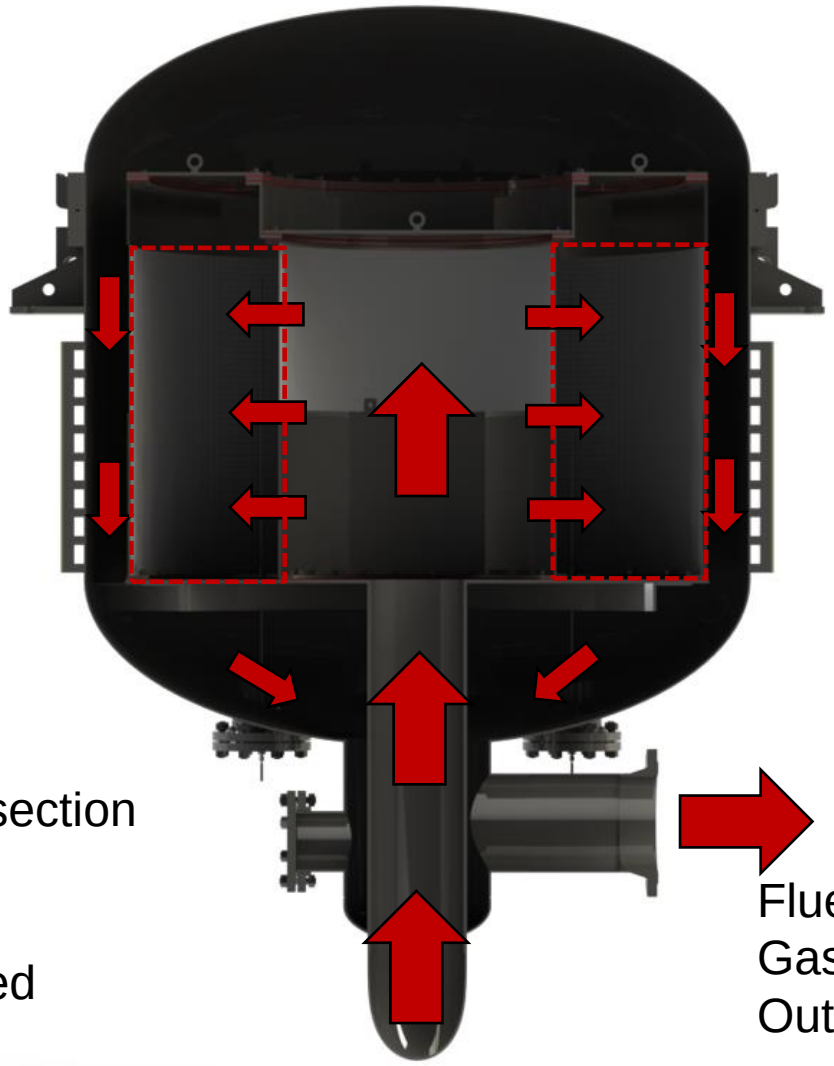
Sorbent optimization and production scale-up was completed in a separate DOE project (DE-0013105)



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

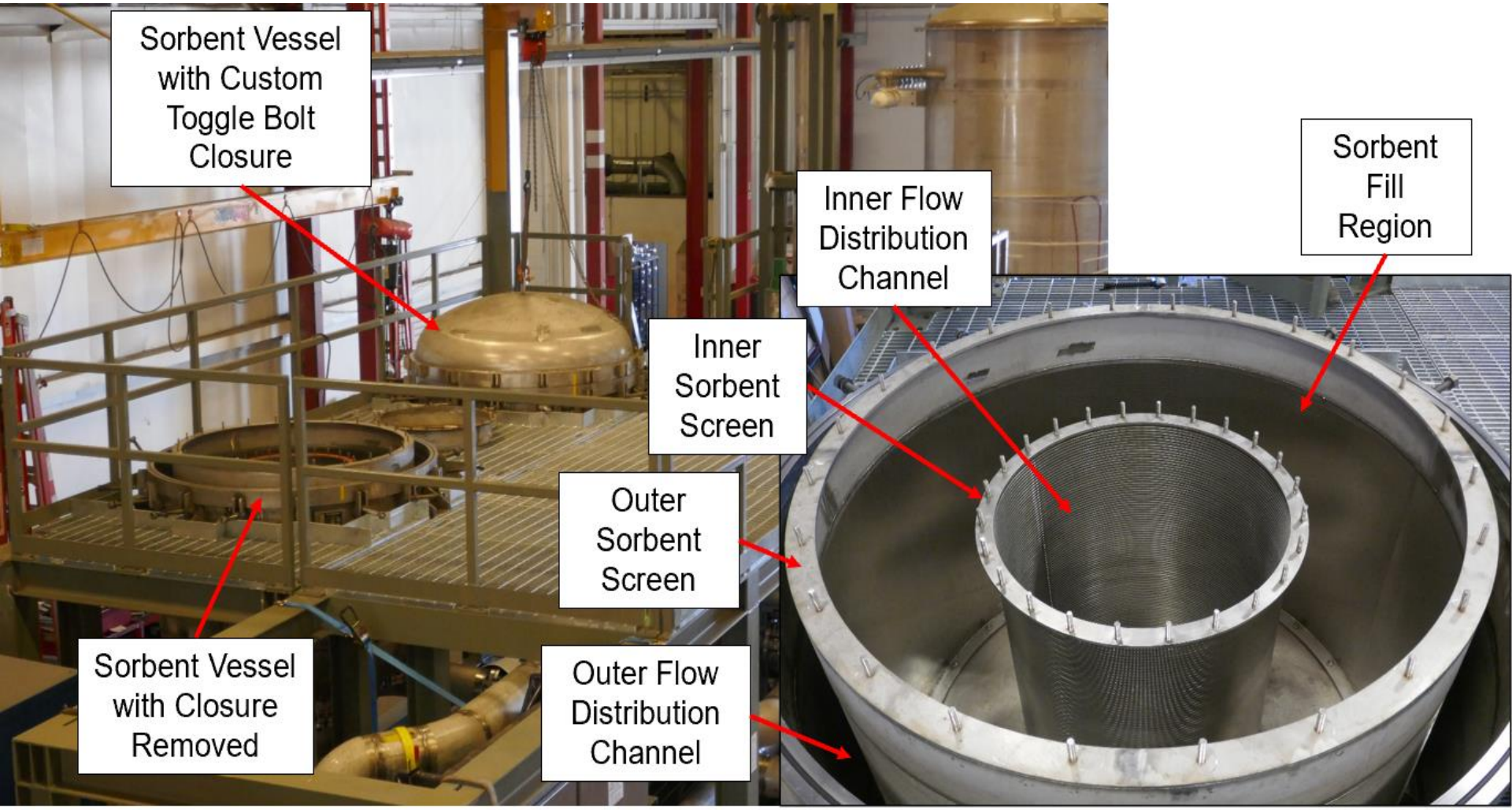
TDA Radial Flow Reactor Concept





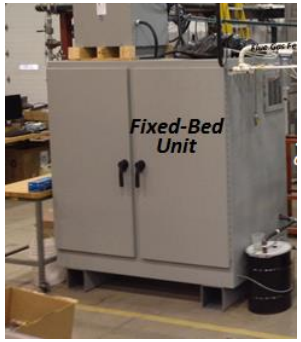
- Sorbent is loaded in an inner annular section in the vessel
- The flow is in radial direction
- Higher cross-sectional area and lower bed depth minimize the dP through the bed

TDA Radial Flow Reactor Concept



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

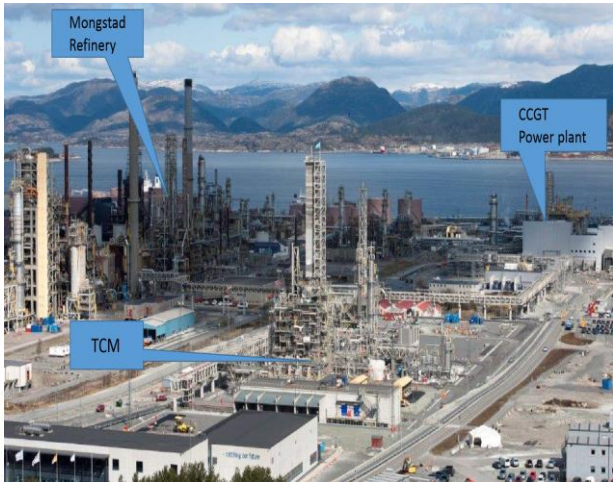
2011	2014	2015	2016	2017	2019-20	2021
Bench-scale tests	0.5-1 kW Sorbent Only tests at TDA	0.5-1 kW Sorbent Only tests at GTI Coal flue gas	Sorbent Scale-up IP secured	0.5-1 kW hybrid tests at WRI with Coal flue gas	50 kW hybrid tests at WTIC with Coal flue gas	0.5-1 MW hybrid tests at TCM with Coal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

Project Focus

- **TDA - Design and development of its modular sorbent reactor concept**
- **MTR - Modify an existing 20 TPD CO_2 capture system previously developed with DOE funding**
  - Utilizing one of MTR's early generation membranes with significant test history
- **TCM - Host the evaluation of the integrated test unit**

TDA's Sorbent System

Existing MTR Membrane Module (20 TPD evaluated at NCCC)

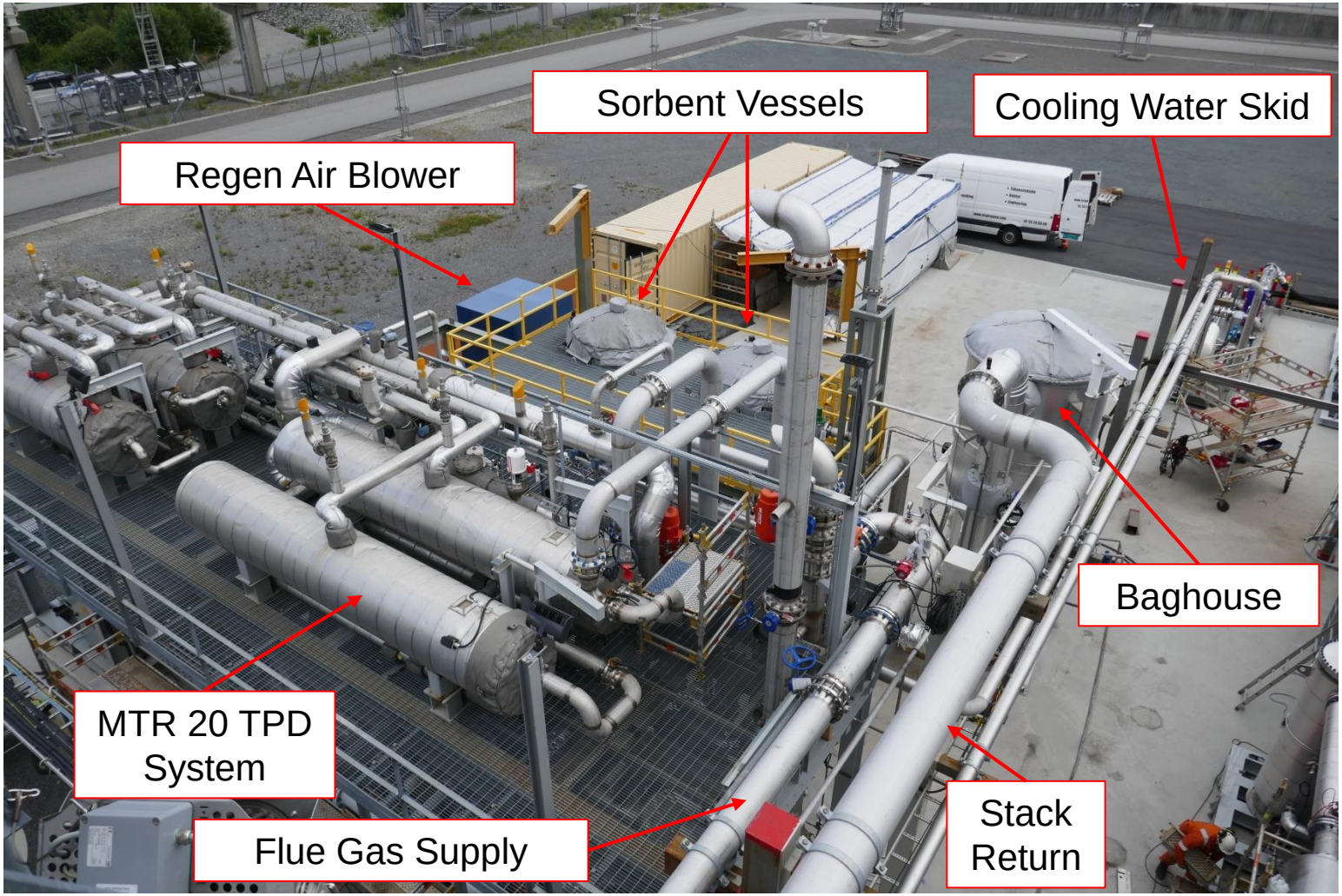


TCM Mongstad, Norway

Major Field-Test Objectives

- **Demonstrate sorbent performance**
  - ✓ CO_2 removal efficiency
  - ✓ CO_2 uptake capacity
- **Demonstrate the mechanical stability of the sorbent**
  - ✓ Quantify the dust generation from shipping, loading and operations
- **Demonstrate sorbent life**
- **Demonstrate effective operation of the radial flow reactors**
  - ✓ Low pressure drop
  - ✓ Uniform flow distribution
  - Modular operation
- **Validation of Design Models**
  - CFD and Adsorption Models
  - CCSI Model
- **Cycle optimization**
- **Optimization of the Operation of the Hybrid System**

Hybrid Membrane System Overview



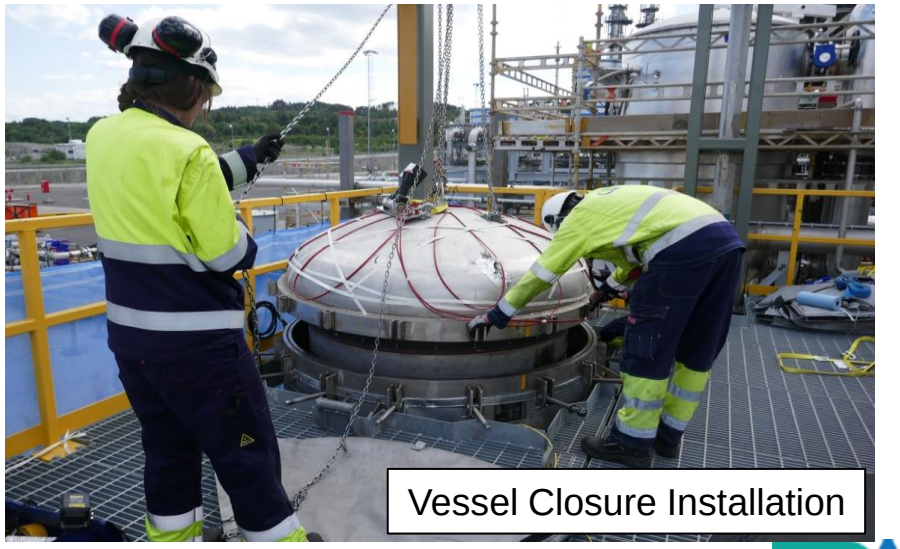
Sorbent Vessels

Sorbent Loading into the Vessels

Drum Handler Operation

Final Sorbent Distribution and Cleanup

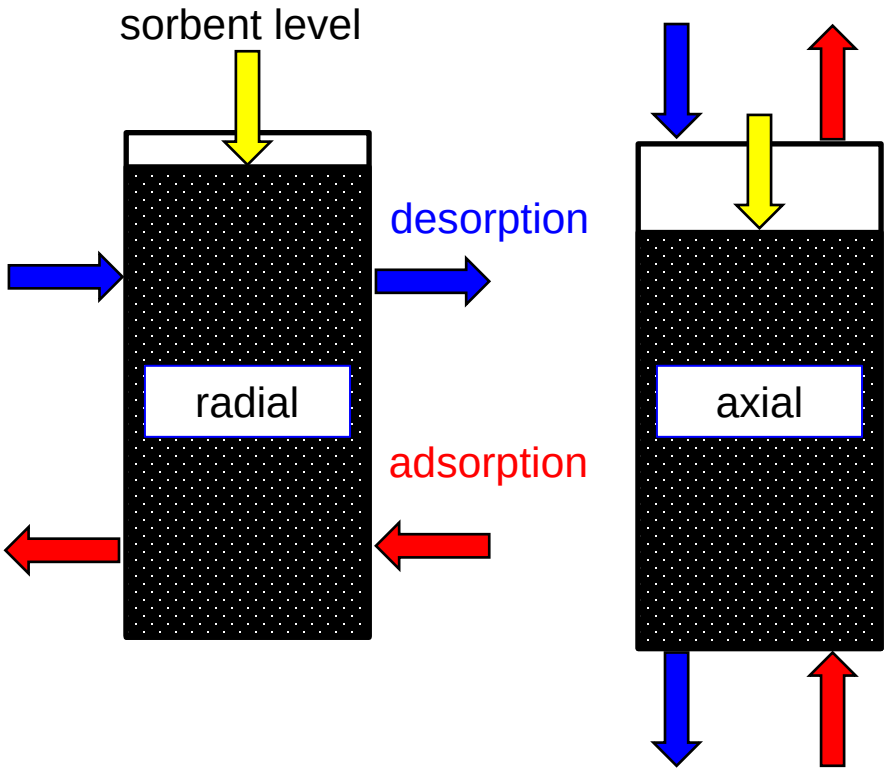
Gravimetric filling



Vessel Closure Installation

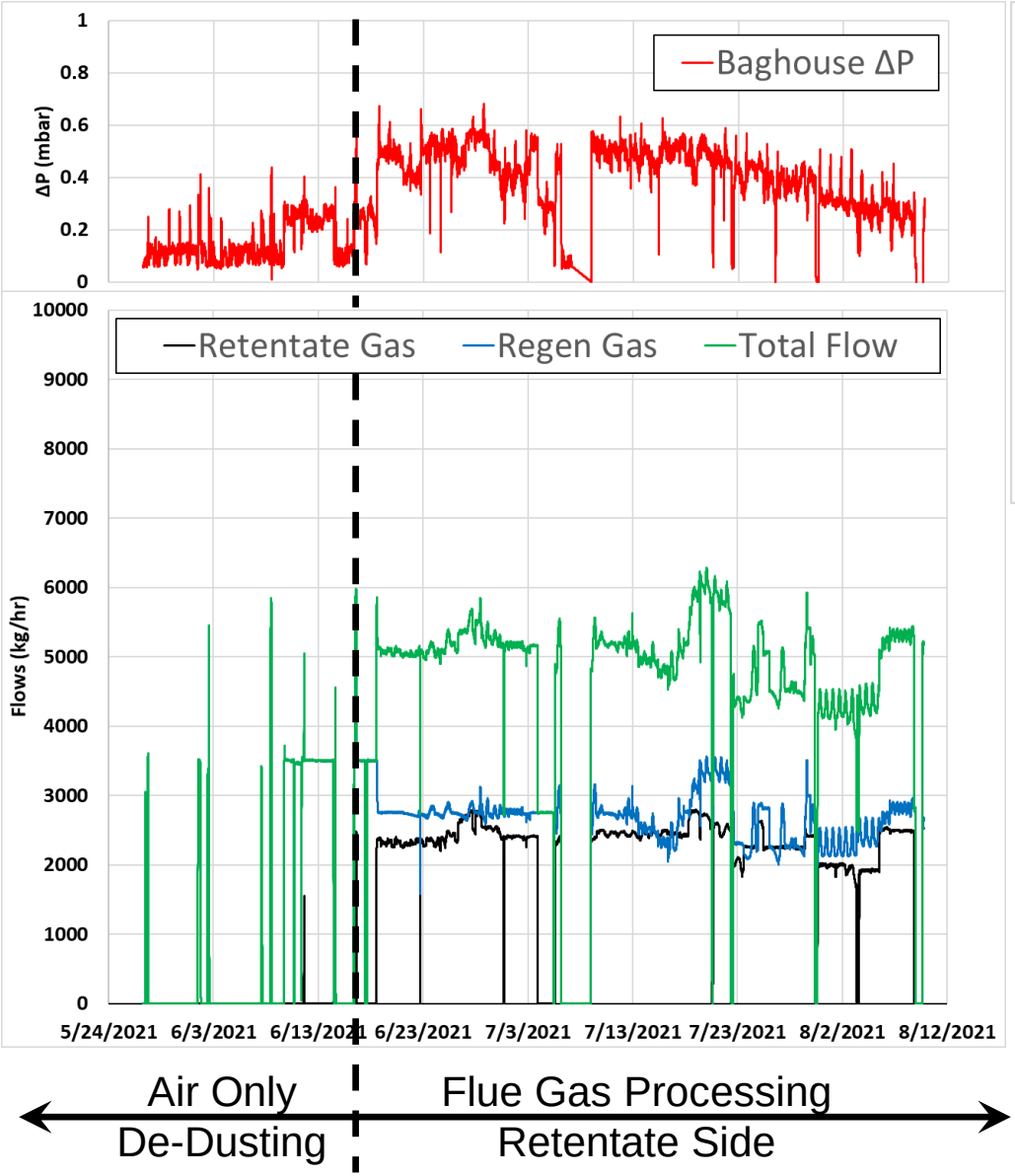
Sorbent Settling and Dusting

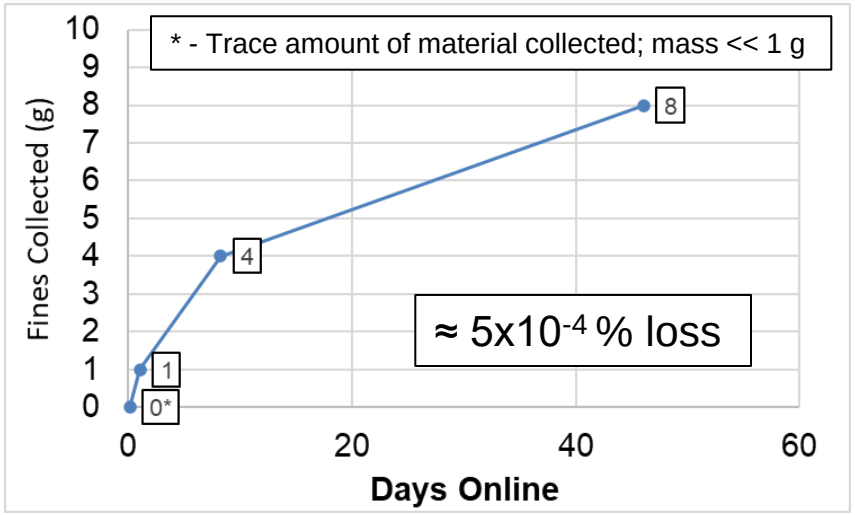
- Sorbent settling is not desirable as it generates a void at the top of the bed
  - Potential for bed by-pass
- System design and loading procedures effectively pre-settled the sorbent
- Top of sorbent bed is sealed with custom gaskets and a stainless steel plate
- Total sorbent used to top-off beds after settling was ≤ 2% of final sorbent mass



- Amount of dust generated was considerably lower than that observed in axial beds
- Sorbent retention has been excellent; total fines collected in the baghouse was ≤ 0.0006% wt. of the sorbent load over the first month of operation

Measurement of Sorbent Dusting





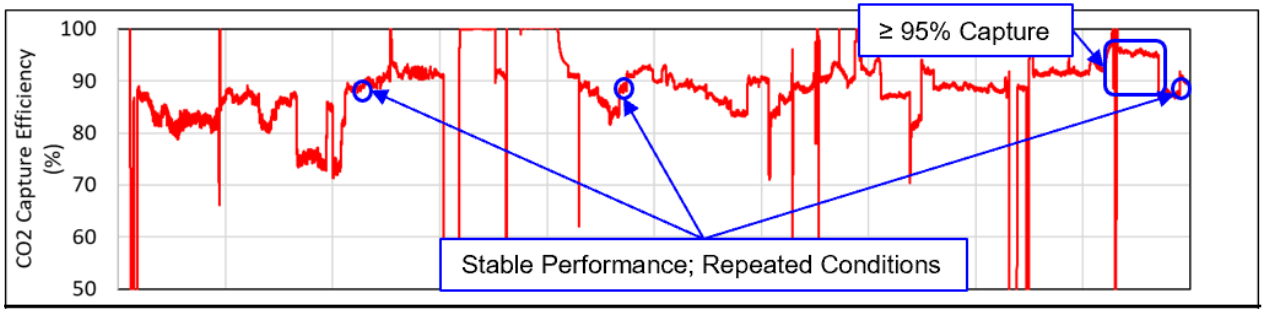
- **Baghouse pressure drop is low and stable over time; consistent with a low rate of fines collection**
- **Total volume of dust collected in baghouse to date is ≈ 8g (very low compared to total sorbent inventory of ~1.7 tonne)**
- **Collected particulate also contains traces of fabrication debris**

Test Summary Since Startup

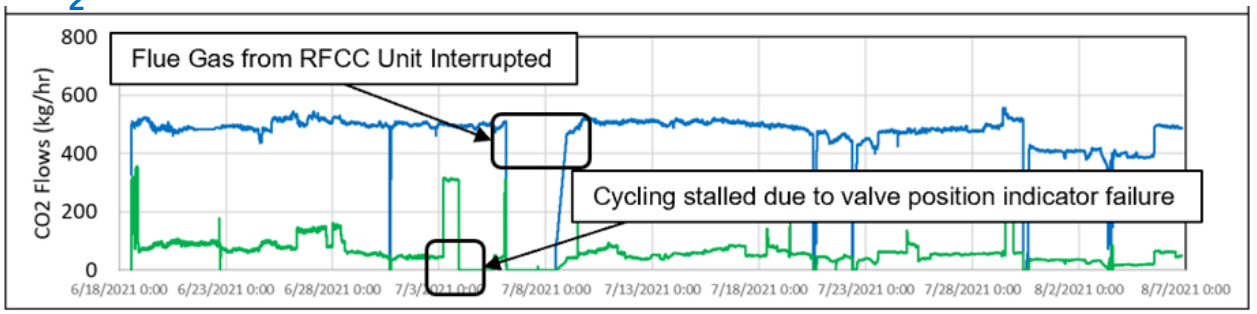
- **Total sorbent time online > 1,072 hours (45 days)**
  - Includes vacuum pump interruptions
- **Total CO_2 processed (from RFCC unit) > 513.7 tonne**
- **Total CO_2 capture (w/ upsets) = 86.4%**
- **Total # cycles > 33,000**

CO_2 Capture	< 90%	> 90%	> 95%
hours	575.1	496.5	63.9
days	24.0	20.7	2.7
Percent of run time	53.7%	46.3%	6.0%

CO_2 Capture Efficiency

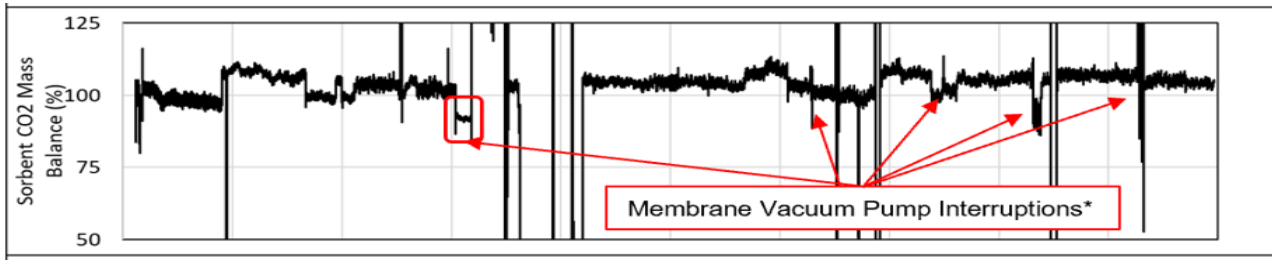


CO_2 Flow Rate – In and Out



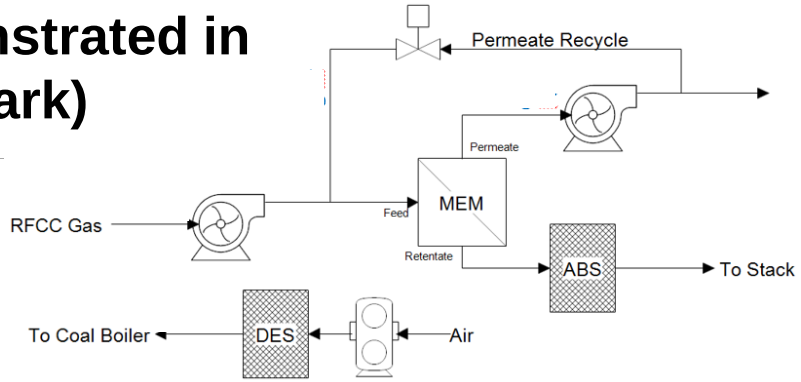
* - Membrane vacuum pump interruptions increase CO_2 load to the sorbent sub-system by 50–100%

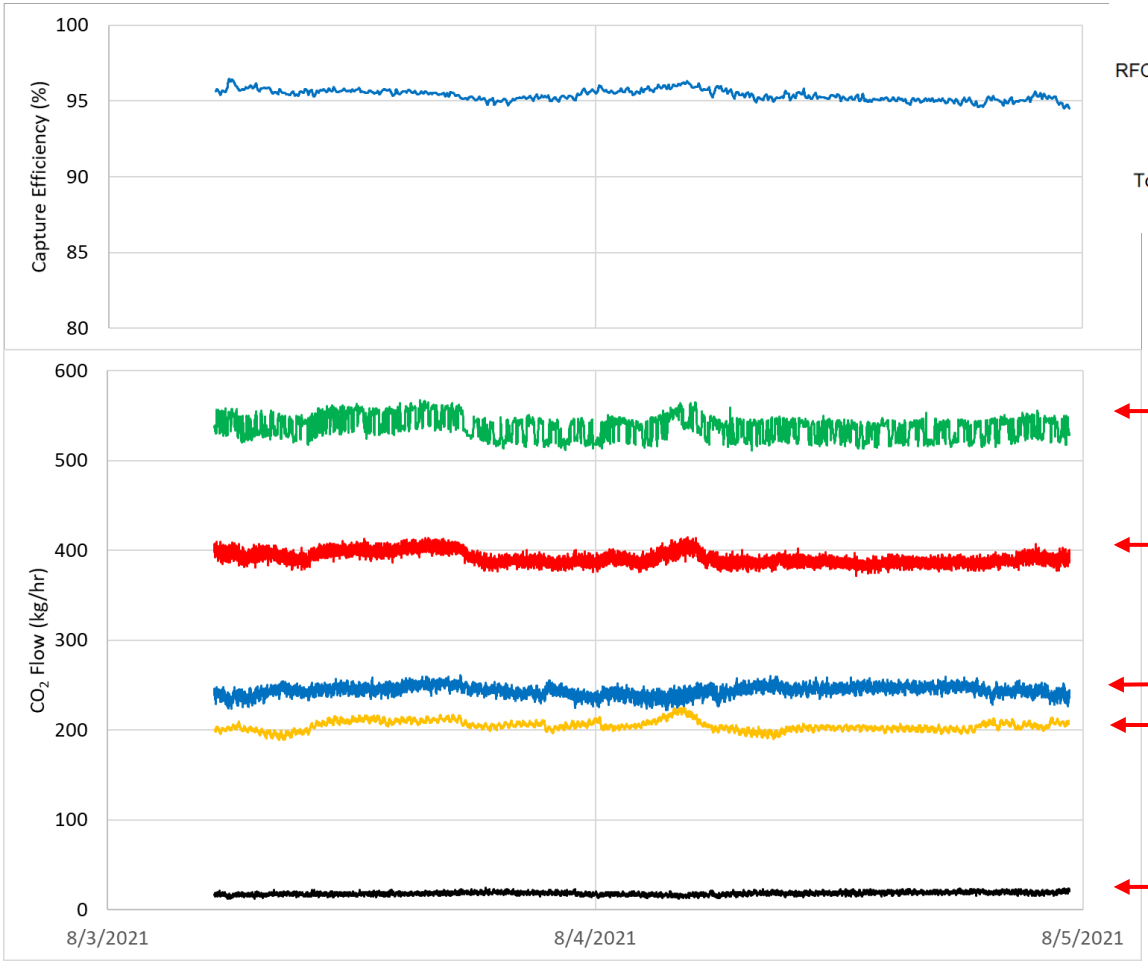
CO_2 Mass Balance



High CO_2 Capture Efficiency (≥95%)

- **95% CO_2 removal efficiency was demonstrated in a 48 hr test (at 38 days total run time mark)**





Membrane Feed
(includes recycled permeate)

Flue Gas Inlet (Hybrid System Inlet)

Retentate (Sorbent Inlet)

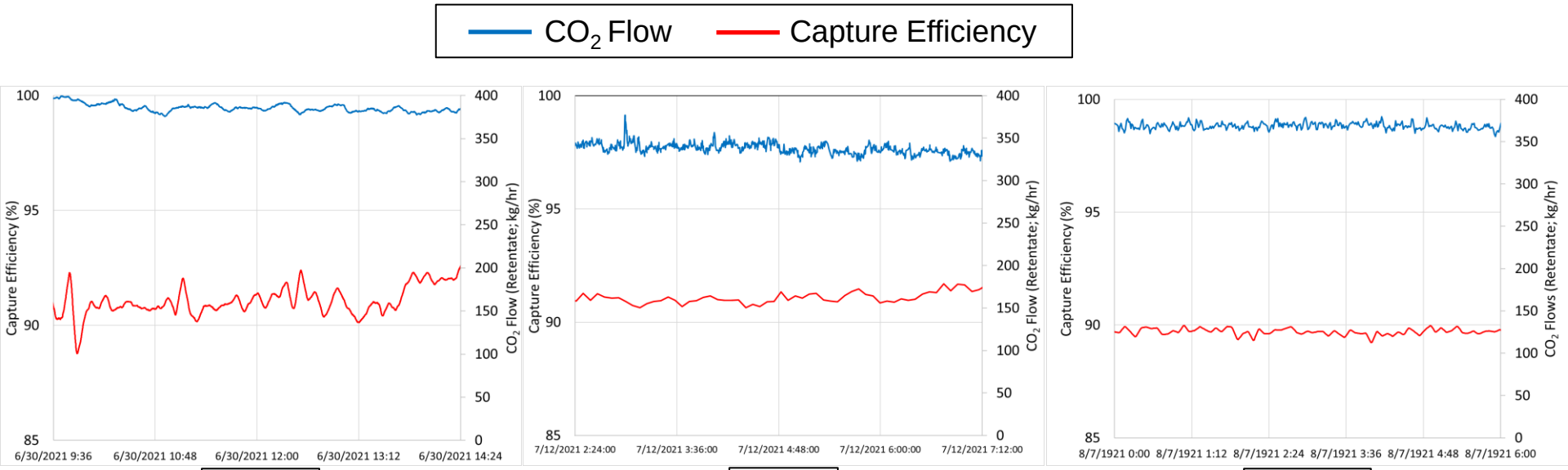
Permeate Product
(excludes recycled CO_2)

CO_2 Slip (stack)

TDA RESEARCH

Stable Performance

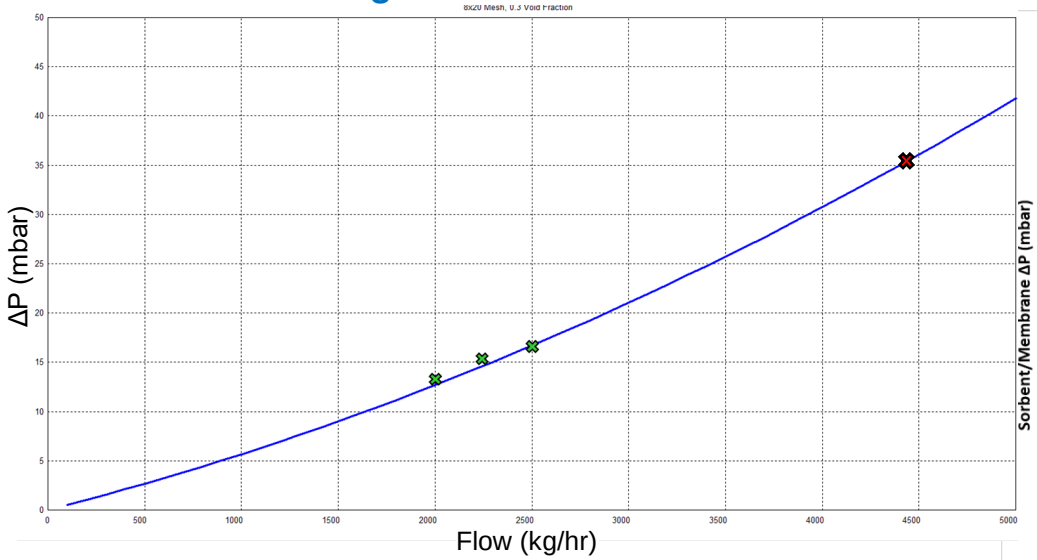
- **Identical test conditions were maintained on June 30, July 12 and August 7 during parametric tests**
- **Stable and repeatable sorbent performance over 5-week testing interval**
- **Slight changes in the CO_2 capture rate is attributed to the increased CO_2 load in the retentate flow**
  - The integration of sorbent operation with the membrane system makes it difficult to set an exact flow rate to the sorbent bed



June 30 | July 12 | August 7

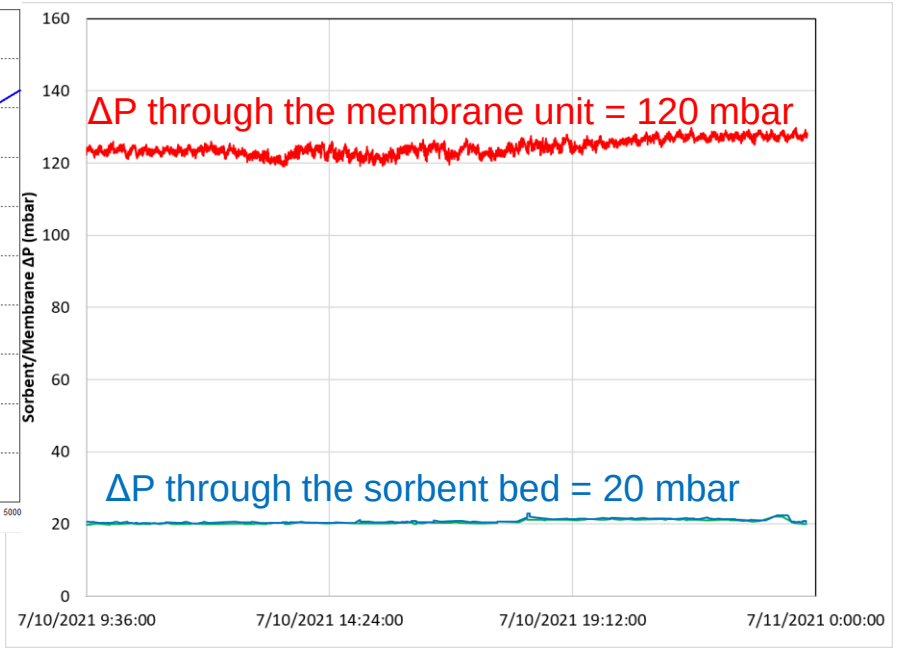
Pressure Drop Measurements

ΔP through the Bed vs. Flow Rate



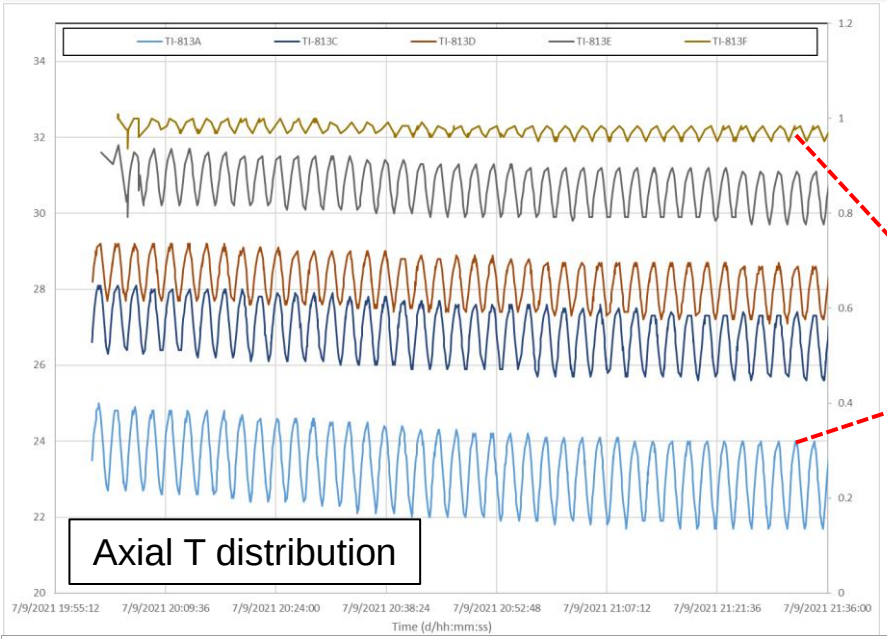
- Experimental pressure drop vs. flow data from TCM
- Highest possible flow through the system

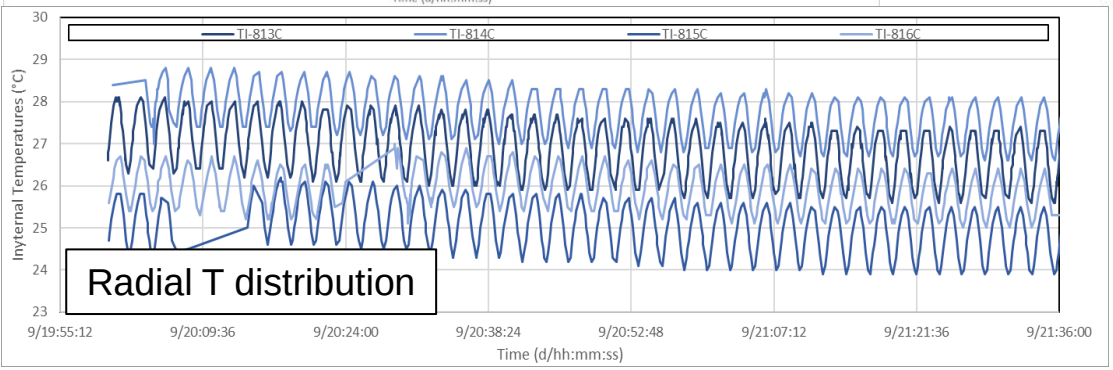
ΔP Comparison for the membrane and sorbent

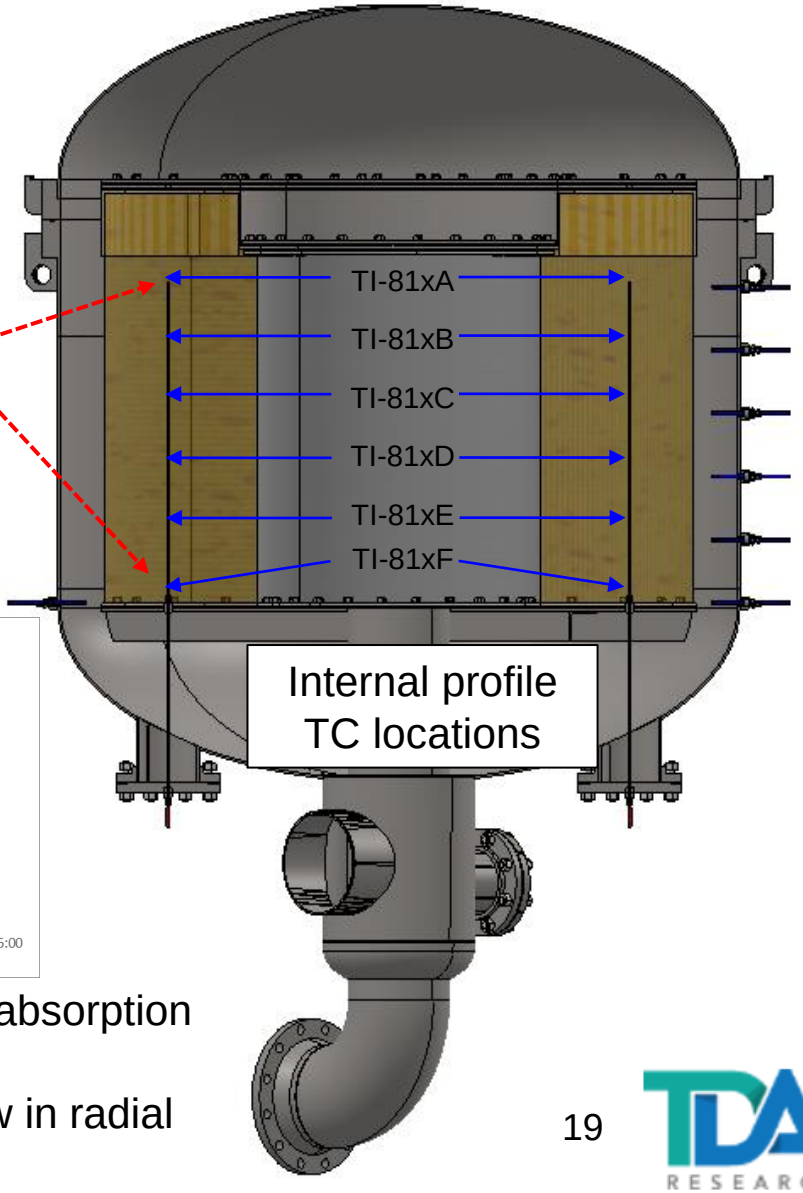


- **TDA's radial sorbent bed design achieved a very low pressure drop**
- **At the 2000-2500 kg/hr flue gas flow, the total ΔP was measured as <20 mbar**
- **Actual measured ΔPs agree well with the design model**
- **The membrane unit treating the same flue gas flow and rejecting the same amount CO_2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

Temperature Distribution in the Bed

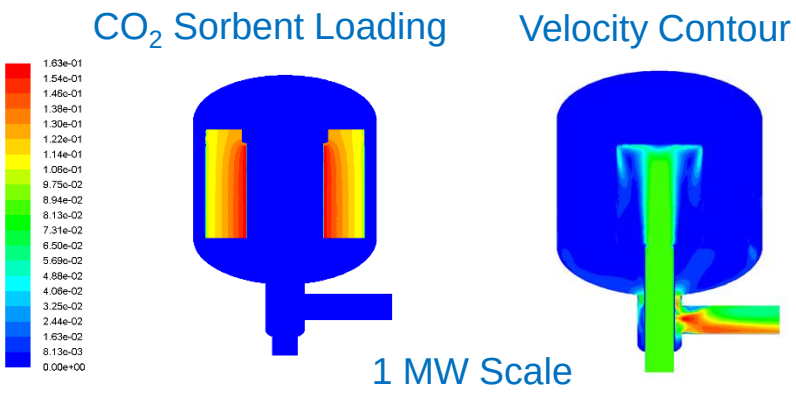


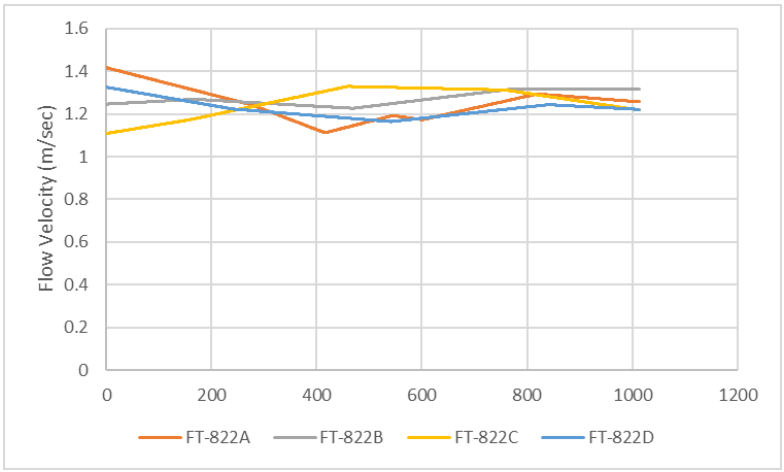


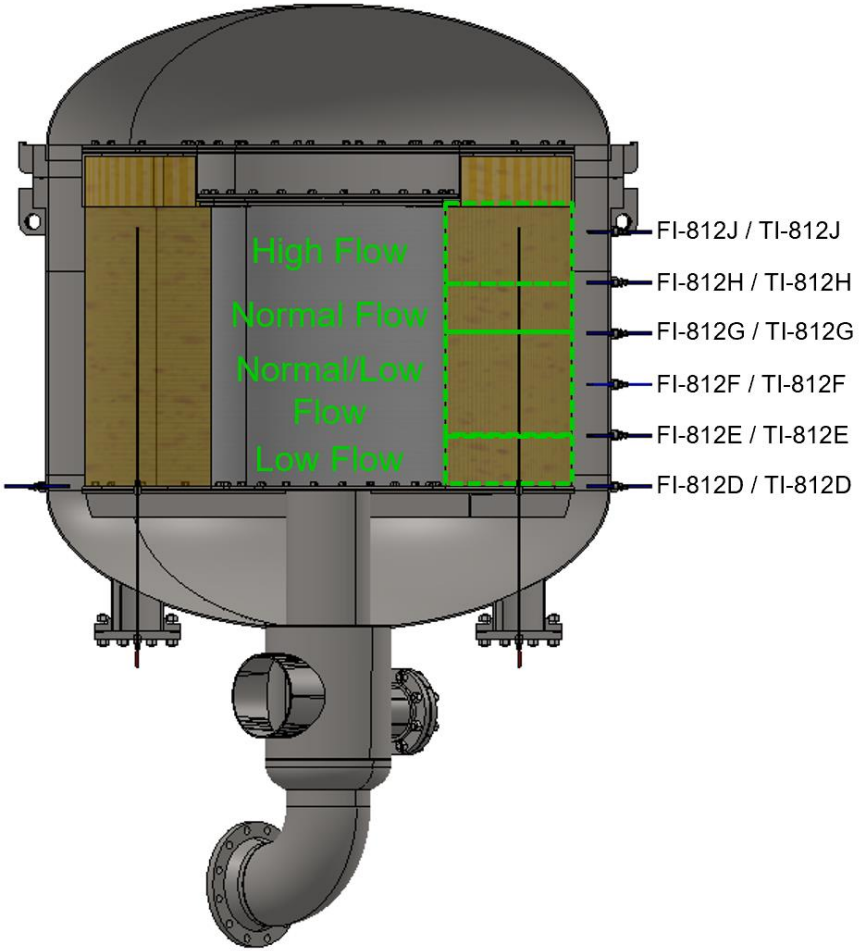


- Axial T distribution/cyclic ΔT indicates higher flows/absorption near the top
- Radial T distribution/cyclic ΔT indicates uniform flow in radial direction

Flow Distribution in the Bed



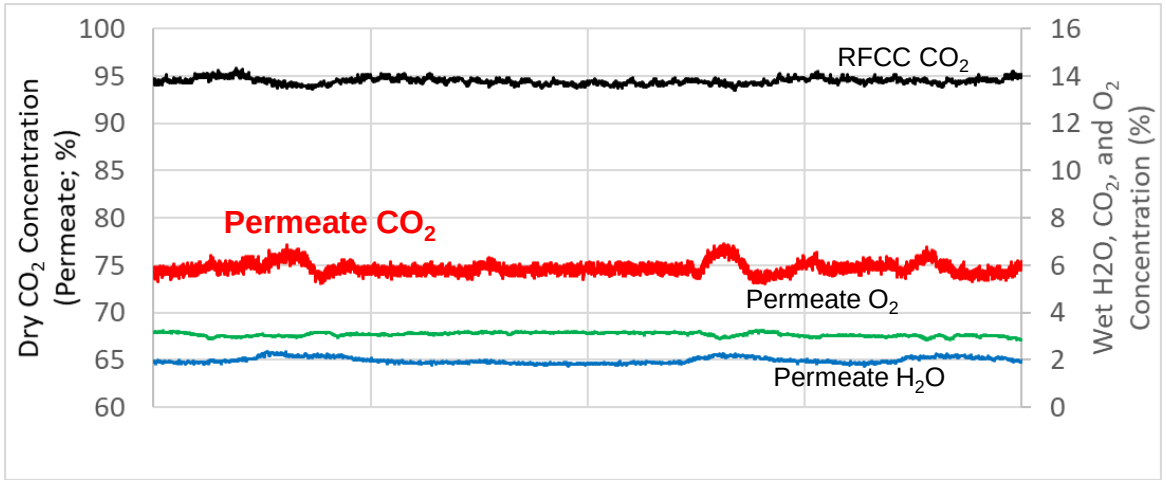


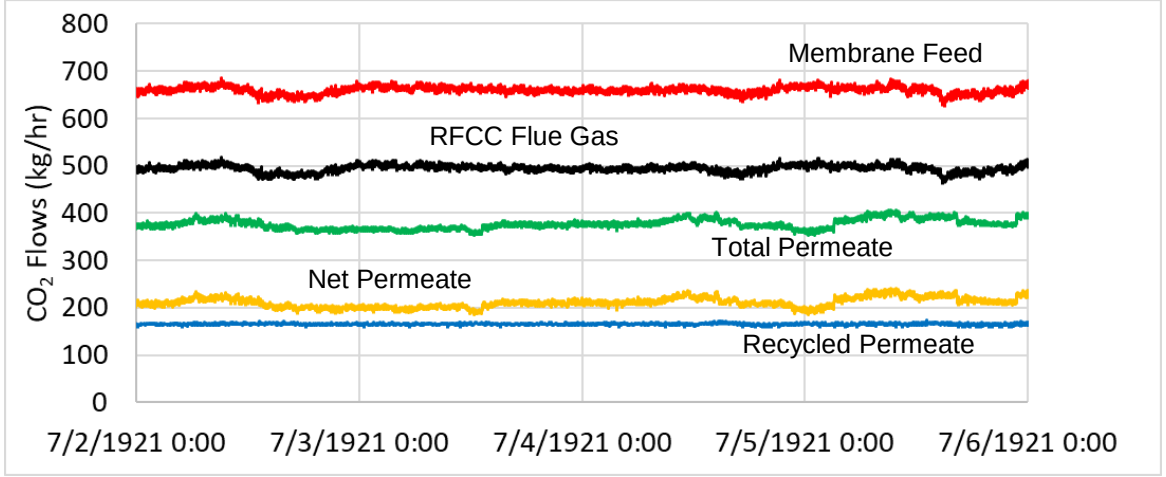


- Radial flow velocity measurements show uniformity within ± 2%
- Axial flow velocity measurements indicate a flow imbalance towards top of the bed
- Flow velocity probes are evenly spaced within the outer flow channel

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 and Costing

Sorbent System - Hybrid

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

Adsorption - Flue gas flow

Desorption - Air Purge flow

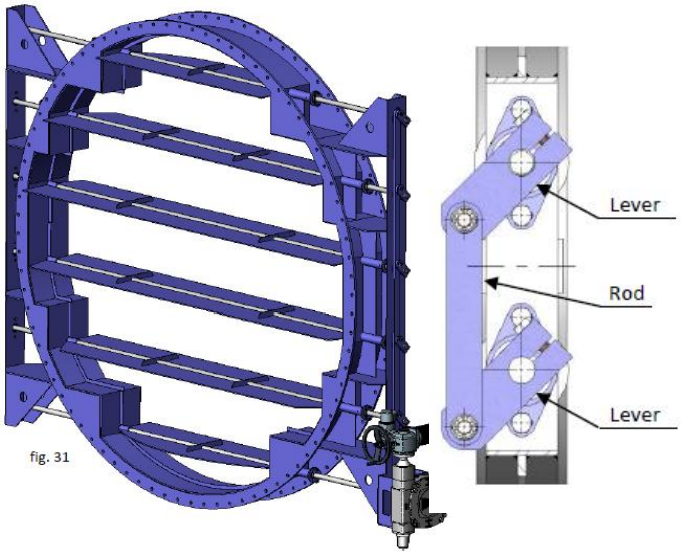
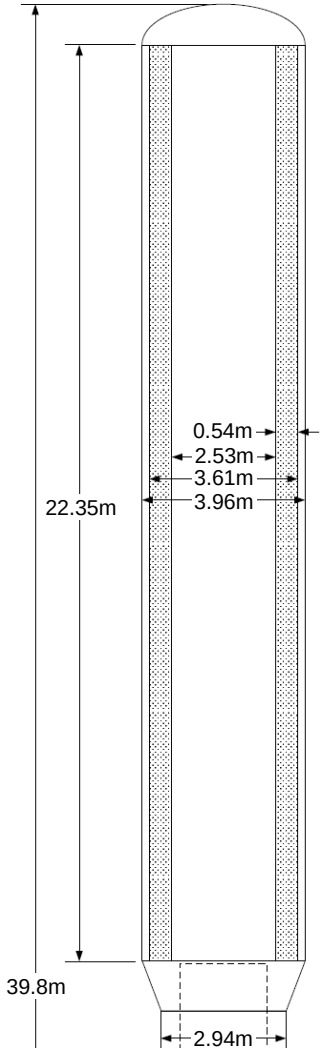


fig. 31

ΔP=105 mbar

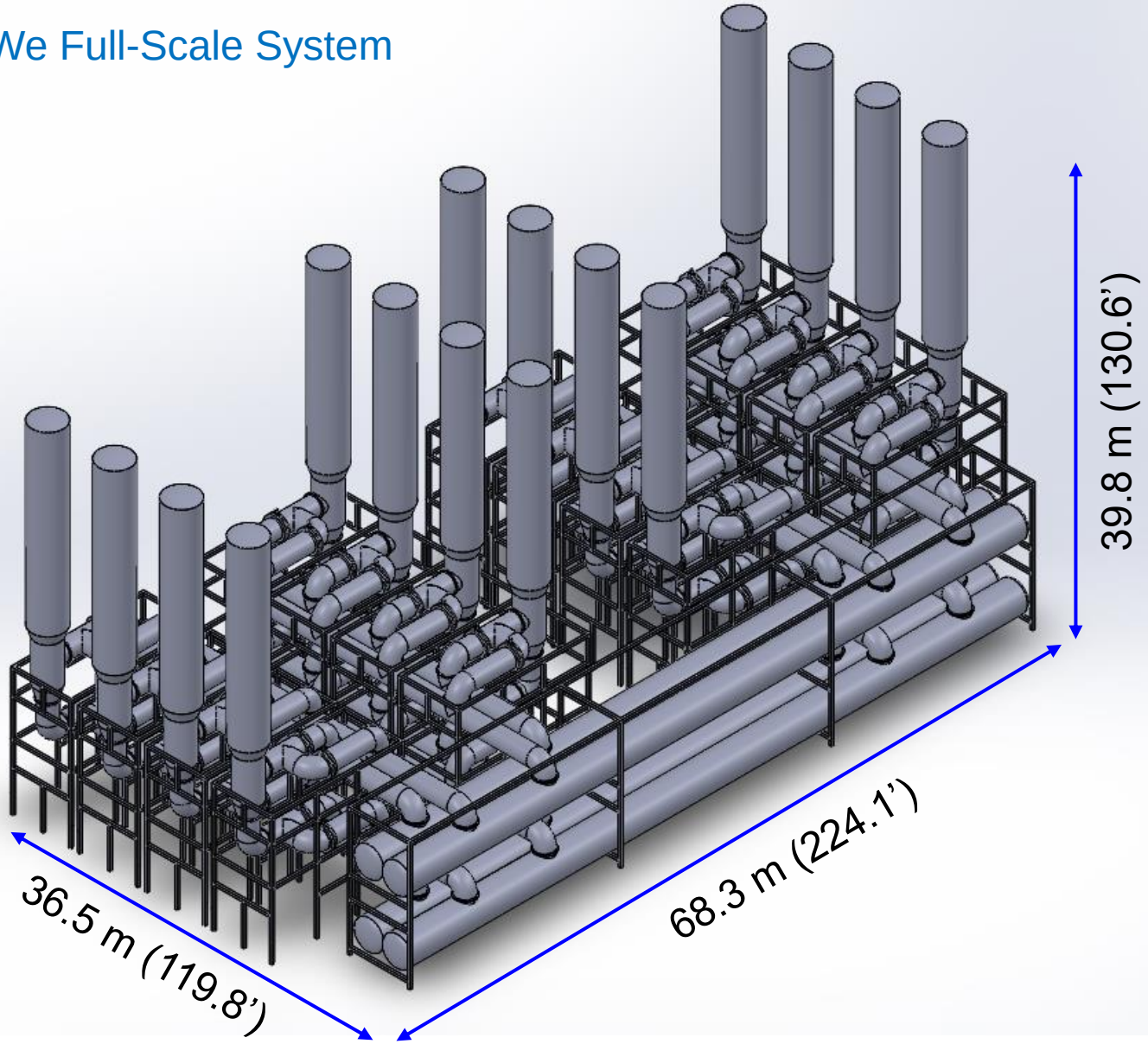
Module Size:	68.75	MW
No. of Trains:	8	
Beds/Train:	2	
Total Beds:	16	
Flue Gas Flow:	74.5	m^3/s
CO_2 Flow:	1.22	tonne/min
Capacity:	1.8%	Wt%
Cycle Time:	1	min
Sorbent Inventory:	67.8	tonne/m^3
Sorbent Density:	0.59	tonne/m^3
Bed Volume:	116.4	m^3
Bed Area:	12.3	m^2

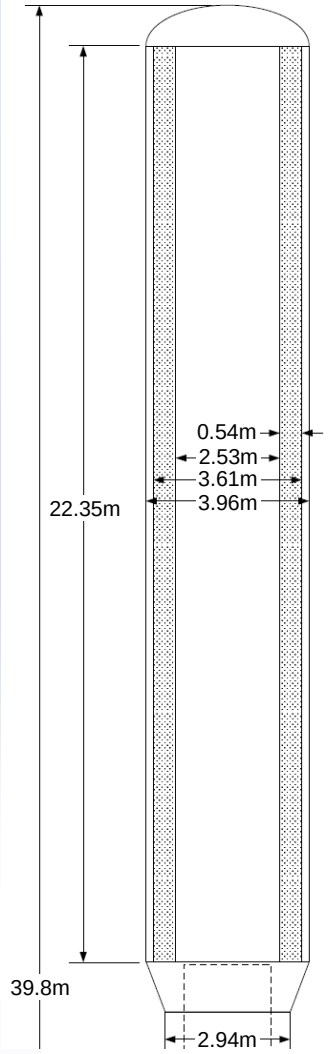
- Sixteen (16) radial beds
- SA516-70 carbon steel, 0.5” thickness
- 13 ft OD x 73 1/3 ft T/T



3-D Layout of the Hybrid Sorbent System

550 MWe Full-Scale System





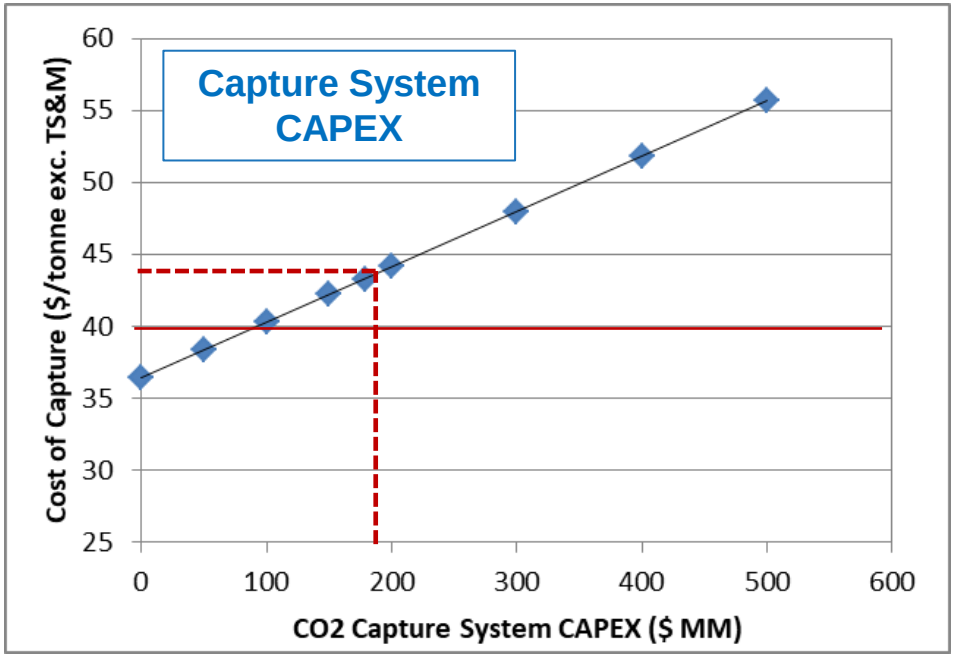
Techno-economic Analysis

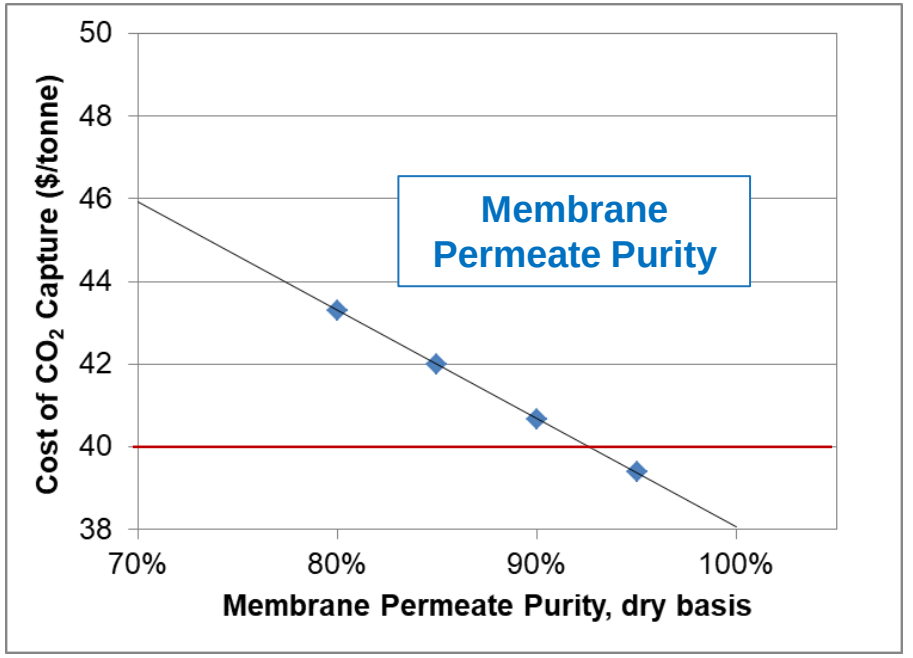
CASE NO.	UNITs	DoE 11	DoE 12	MTR WP Study	TDA + MTR 3
CO_2 capture technology		Reference No Capture	Reference Amine	Membrane Only	Membrane-Sorbent Hybrid
CO_2 purity from separation Module			**95%**	**80%**	**80%**
Steam turbine power	kWe	580,400	662,800	780,795	750,371
Total auxiliary consumption	**kWe**	**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**

- TDA's 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 the flue gas treatment subassembly, including 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 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, Tim Merkel, Jay Kneip, Thomas Hofmann, Erik Westling**
- **GTI Team, Chuck Shistla**
- **UCI, Ashok Rao**
- **TCM Team, Kjetil Hantveit, Sundus Akhter, Stein Olav Nesse, Magne Andreas Tresvik, Magnus Aronsson**