Membrane Integrated Sorbent Adsorption Process for Carbon Capture (Contract No. DE-SC0011885)

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Phase IIB Project Review Meeting

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Project Summary

- The project objective is to demonstrate scalability of a new hybrid post-combustion CO_2 capture process for coal-fired power plants
- The hybrid process uses a polymeric membrane and CO_2 adsorbent system for cost effectively removing CO_2 from flue gas
  - TDA's mesoporous carbon adsorbent
  - MTR's polymeric membrane

<u>**Phase I**</u>

- Process design and simulation
- Sorbent Optimization and Laboratory Evaluations

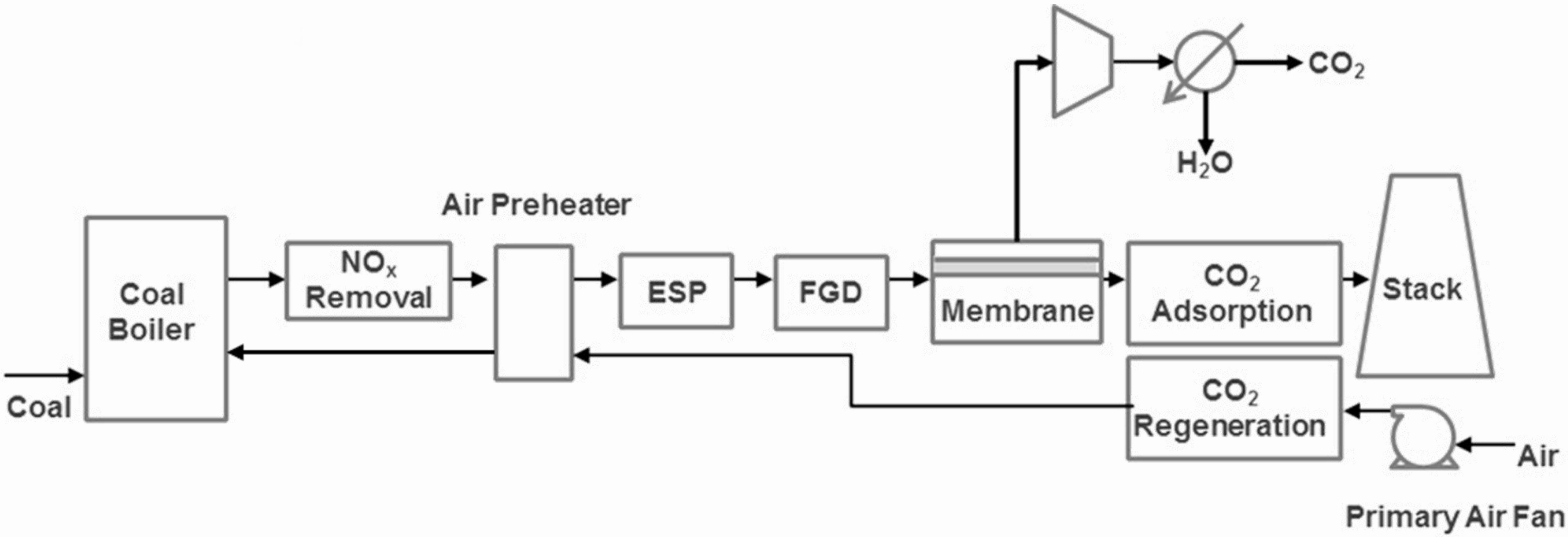
<u>**Phase II**</u>

- Sorbent optimization, multiple-cycle testing, and design/optimization of radial sorbent contactor and bed sequence
- High-fidelity field demonstration of integrated test unit (1.7 kW scale) with coal-derived flue gas

<u>**Phase IIB**</u>

- Demonstrate process performance and refine economics at 42 kW scale (≈ 25X of prior field of phase II field testing)

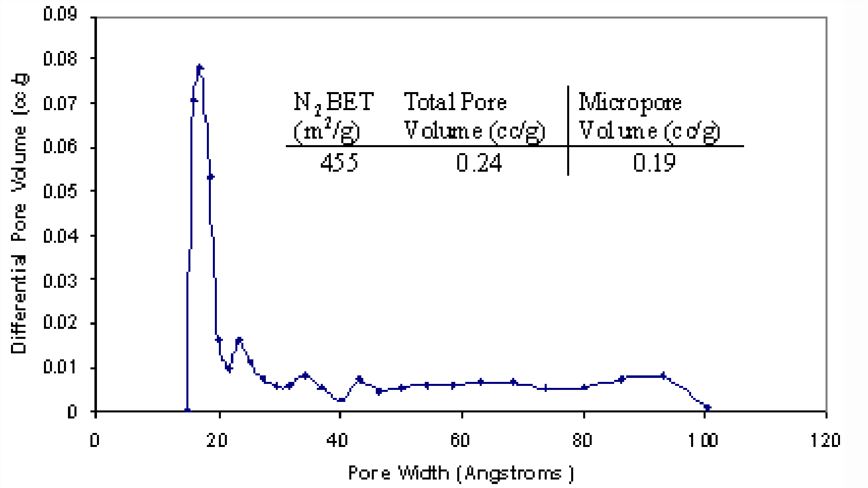
Sorbent-Membrane Hybrid Process



- **Membrane removes ~50% of CO_2 and almost all water at ~50°C under mild vacuum, (~0.3 atm)**
- **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
- **Advantages**
  - Low pressure drop and high performance at the low P_{CO2}
  - Greatly reduced oxygen transfer (from the air side to flue gas side)

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**



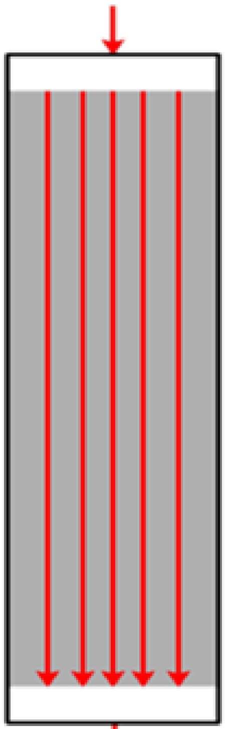
Sorbent operation in a VSA system was successfully demonstrated with actual flue gas (DE-0013105)

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

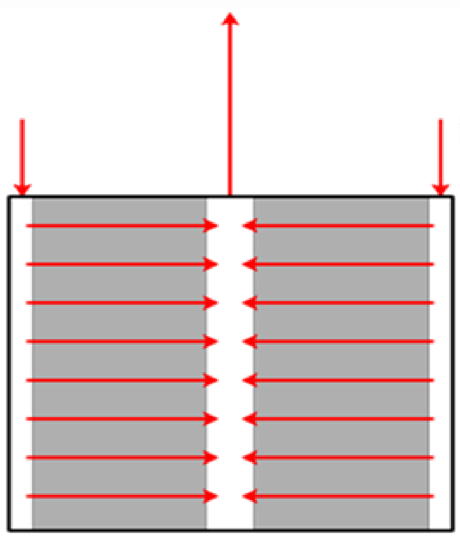
Sorbent optimization and production scale-up was completed in a separate DOE project (DE-0013105)

Phase II - Radial Flow Reactor Development

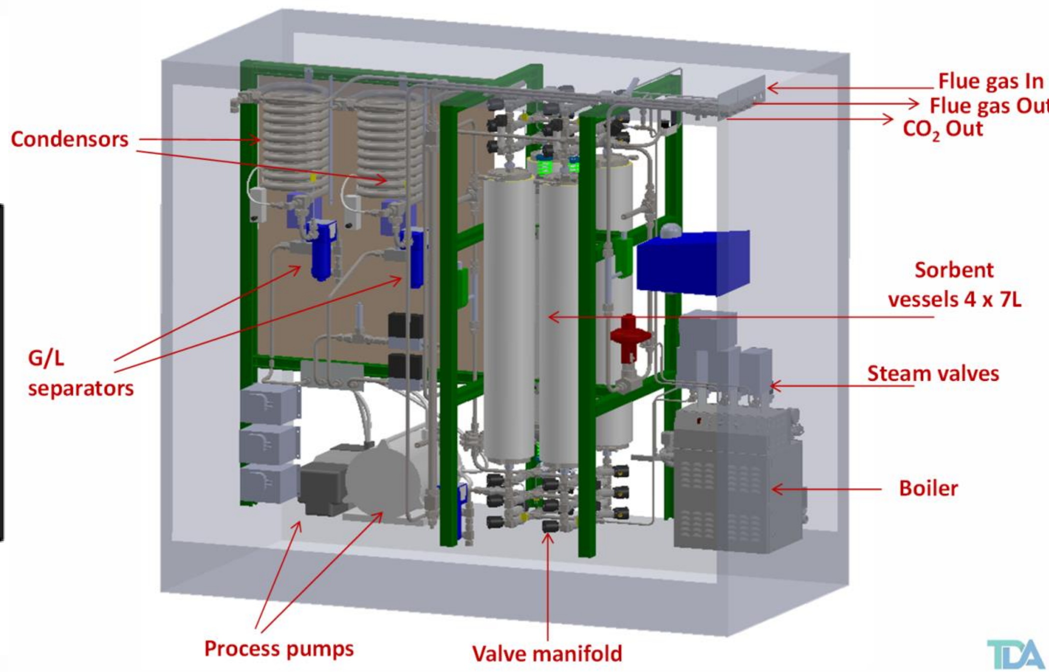
- In addition to demonstrate the hybrid operation, we have carried out the development of the radial flow reactors
- This design is to reduce the pressure drop experienced in the fixed-bed systems
- An existing 4-bed unit is modified with radial flow reactors



Axial Bed

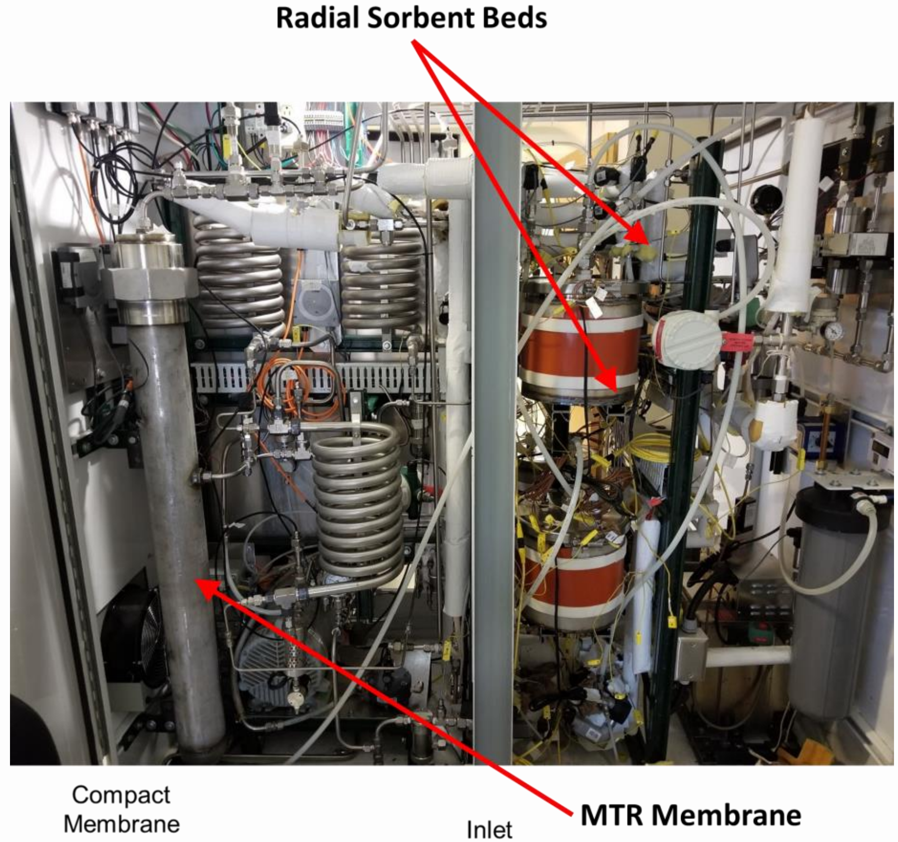


Rev 3 Radial Bed

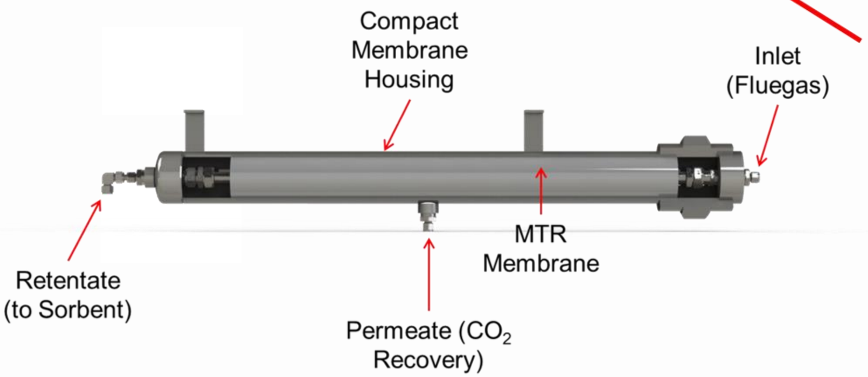


Membrane-Sorbent Tests at the Lab

- **In a SBIR Phase II project, lab and field tests were carried out at a 2-4 scfm (20-40 kg/day CO_2 captured) scale hybrid-membrane sorbent unit with coal-derived flue gas at Western Research Institute (Laramie, WY)**

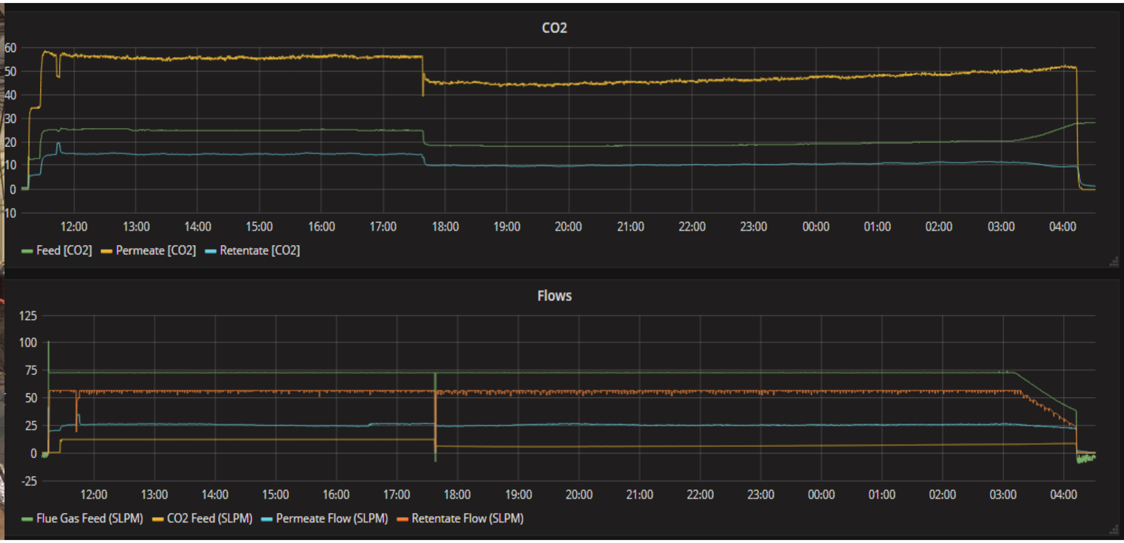


Gen3 Radial Sorbent Bed

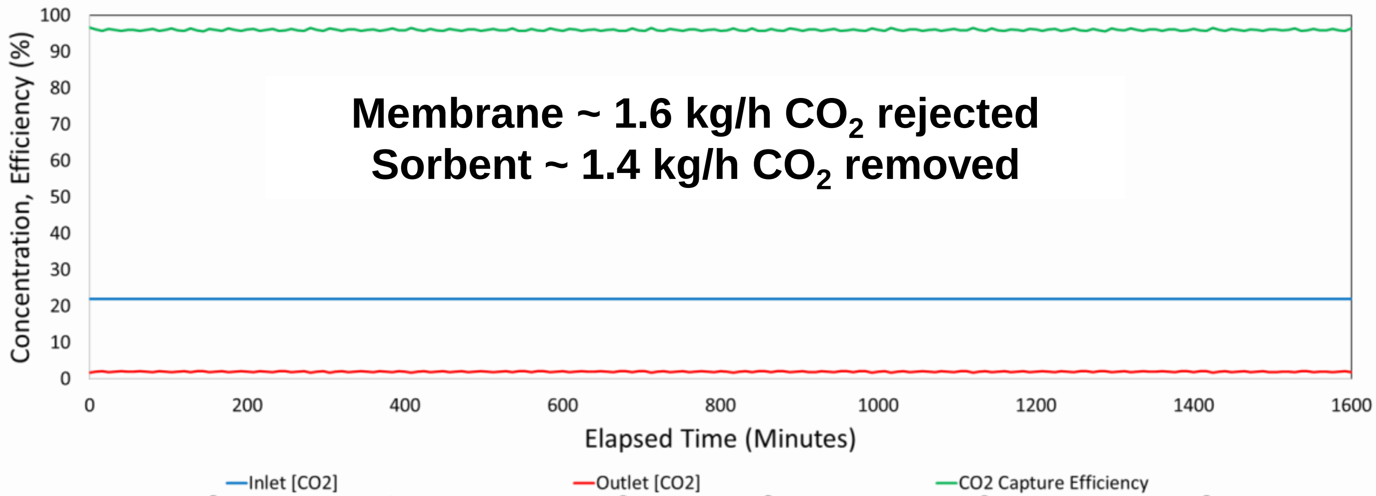


Membrane Module

Hybrid Performance (3 SCFM)

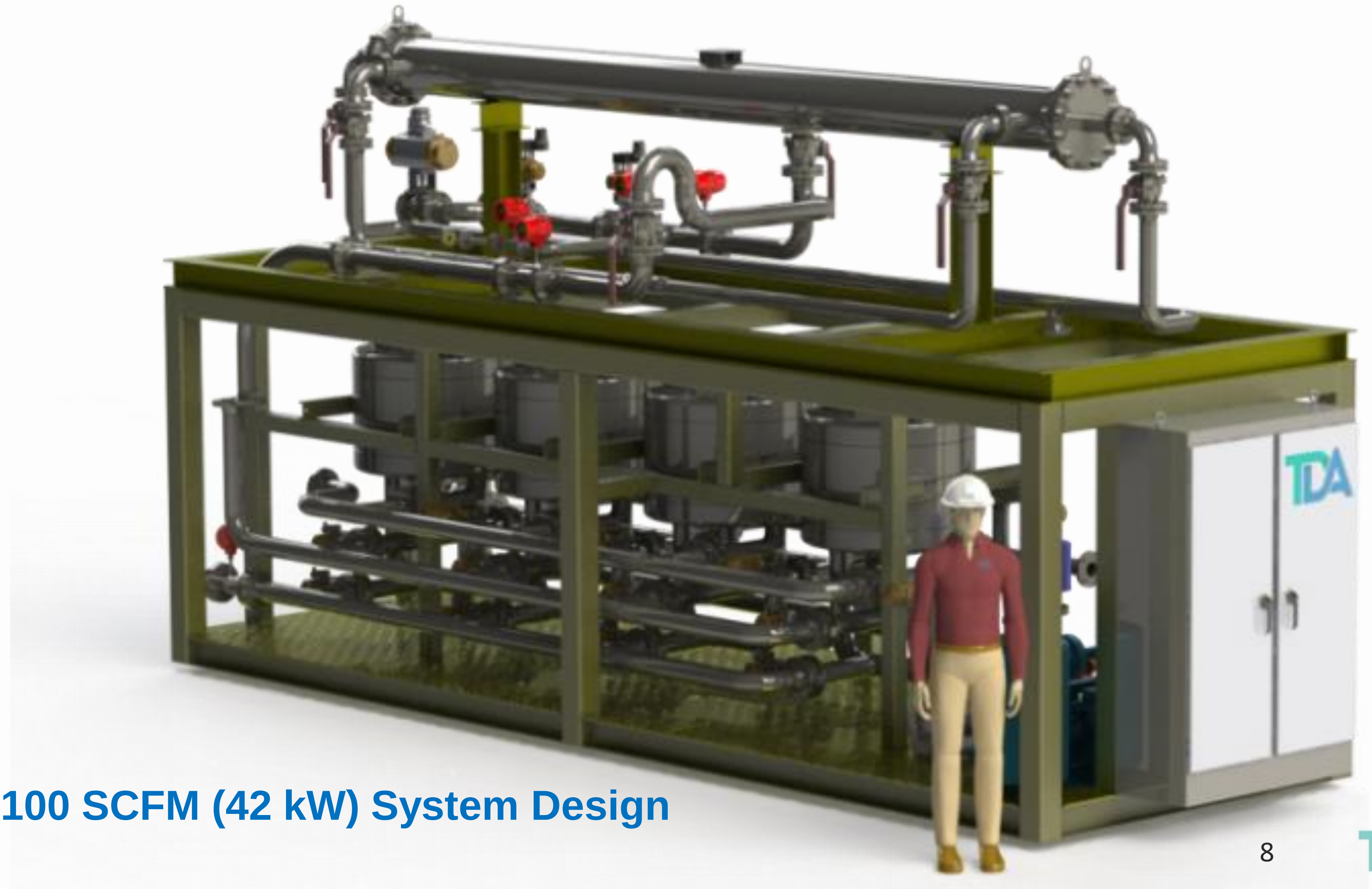


Continuous 4-Bed Cycling Performance (Cycle# 2,000 -2,160)



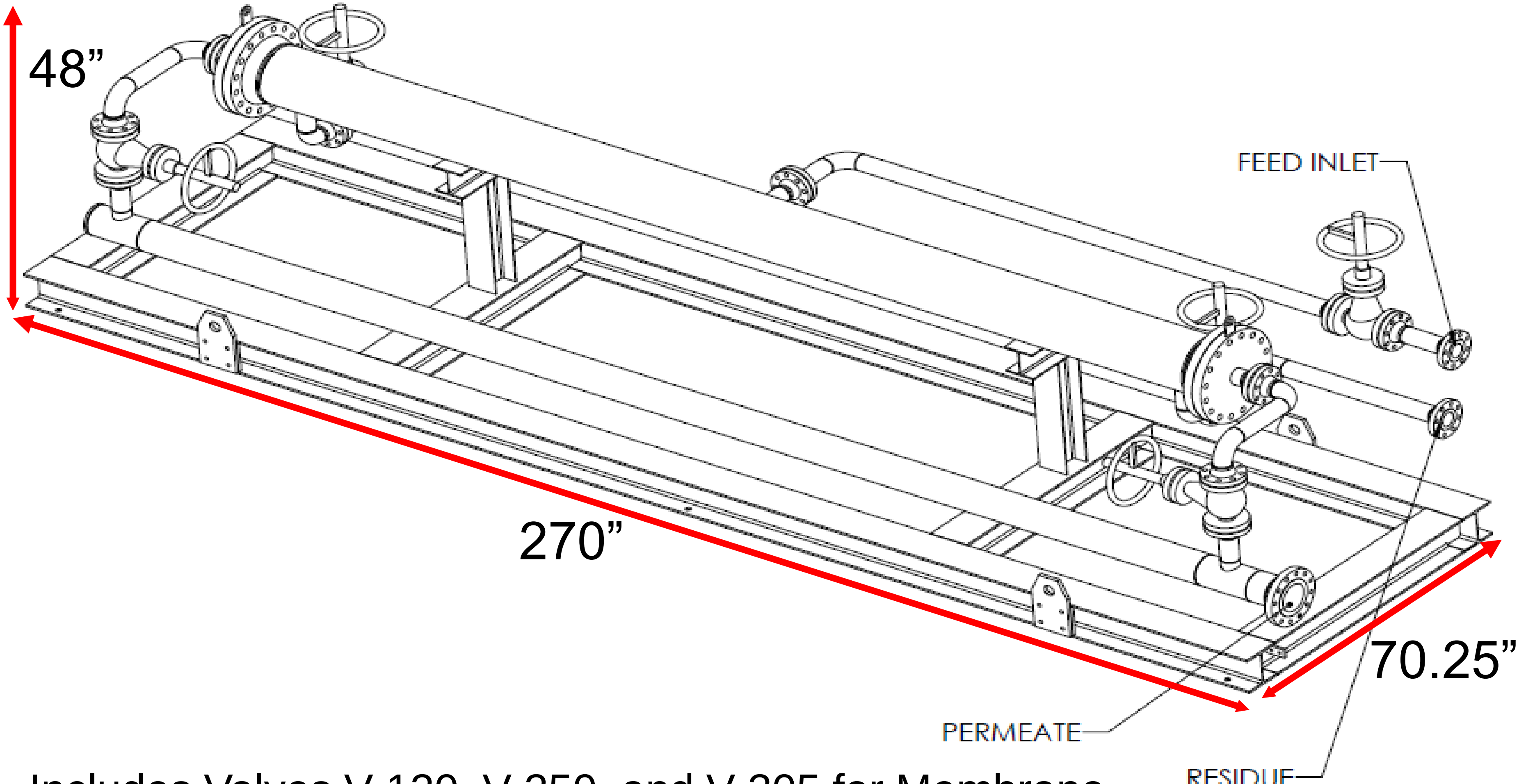
Total operation exceeds 525 hours and 3200 cycles

Phase IIB Project – Evaluation in a Larger Prototype Unit



100 SCFM (42 kW) System Design

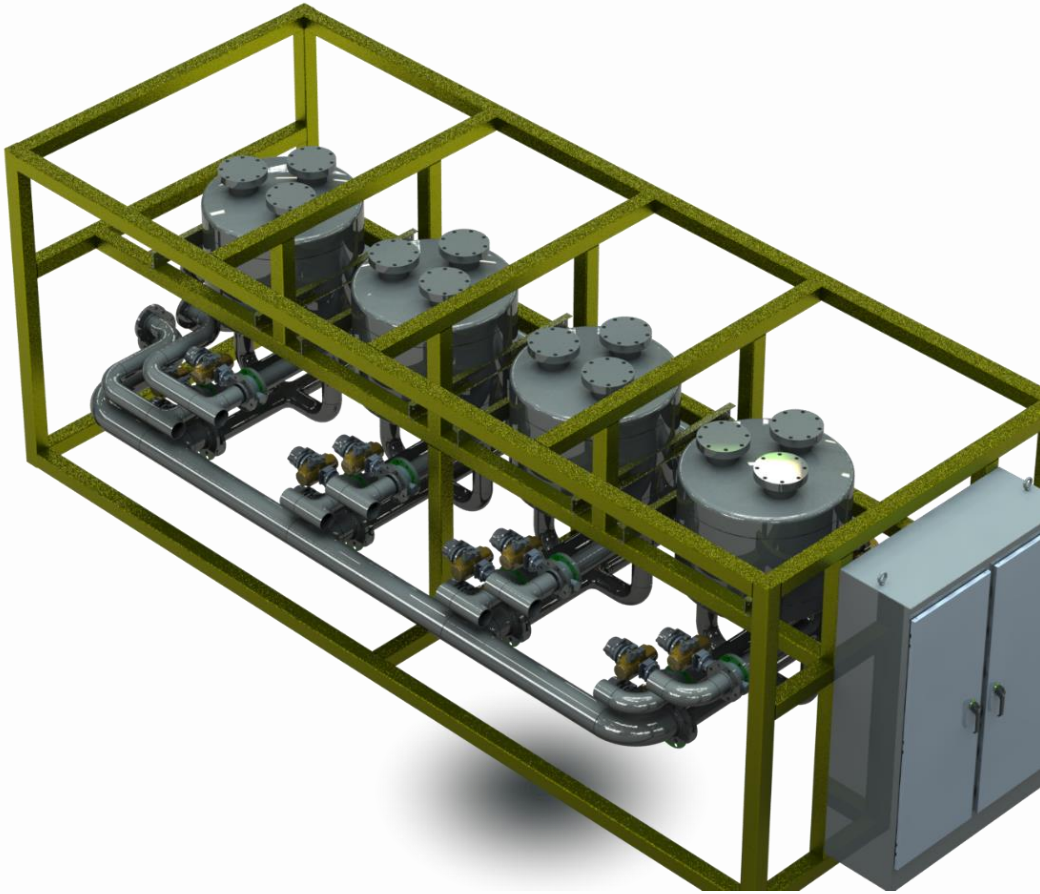
Skid-Mounted MTR Membrane



Includes Valves V-120, V-250, and V-305 for Membrane Isolation/Bypass

Design of the Sorbent Reactors

- Designed as stackable 2-skid system for over-road transport
- 4-Bed sorbent contactor skid houses sorbent beds, regen air blower, vacuum pump, and control cabinet
- Membrane skid houses membrane and associated instrumentation/valving
- All process valving is automated with electropneumatic control with manual controls for membrane bypassing and vacuum inlet stream selection
- All equipment is designed for continuous outdoor operation in C1DII hazardous locations to allow for deployment to various field test sites

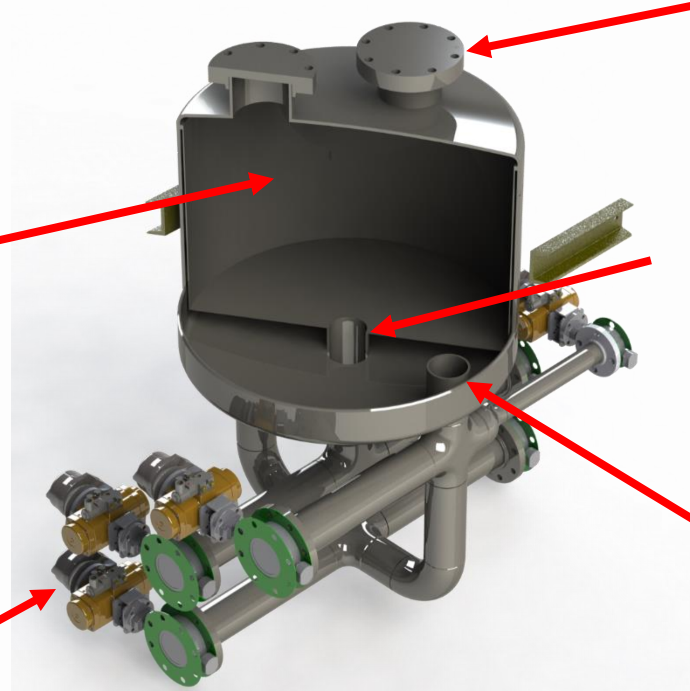


4-Bed Sorbent Contactor Skid

TDA's 4th Generation Radial-Flow Sorbent Contactor

Fill/Drain Access
6" 150-Lb Flanges

Inner Sorbent Basket
w/ Porous Walls



Replaceable
Central Gas
Distribution Chanel
(not shown)

Twin Outer Gas
Distribution Channels

Butterfly Valves and
Gas Distribution Manifolds

≈ 200 L Sorbent per Vessel
Adsorption Time ≈ 60–120 s/Vessel

Fabrication of the Radial Flow Bed Internals

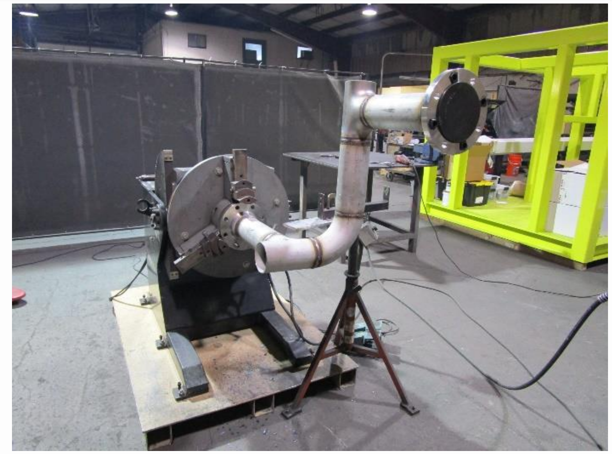
3 Complete Inner Radial Beds (Upside Down)
Awaiting Wire Cloth and Outer Pressure Vessel

Complete Inner Basket - 304 SS

Perforated SS Outer Wall
Covered in 100 Mesh Wire Cloth

Fabrication of Radial Bed Housing

Outer Pressure-Containing Shell and Heads
Tack Welded Around Inner Sorbent Basket



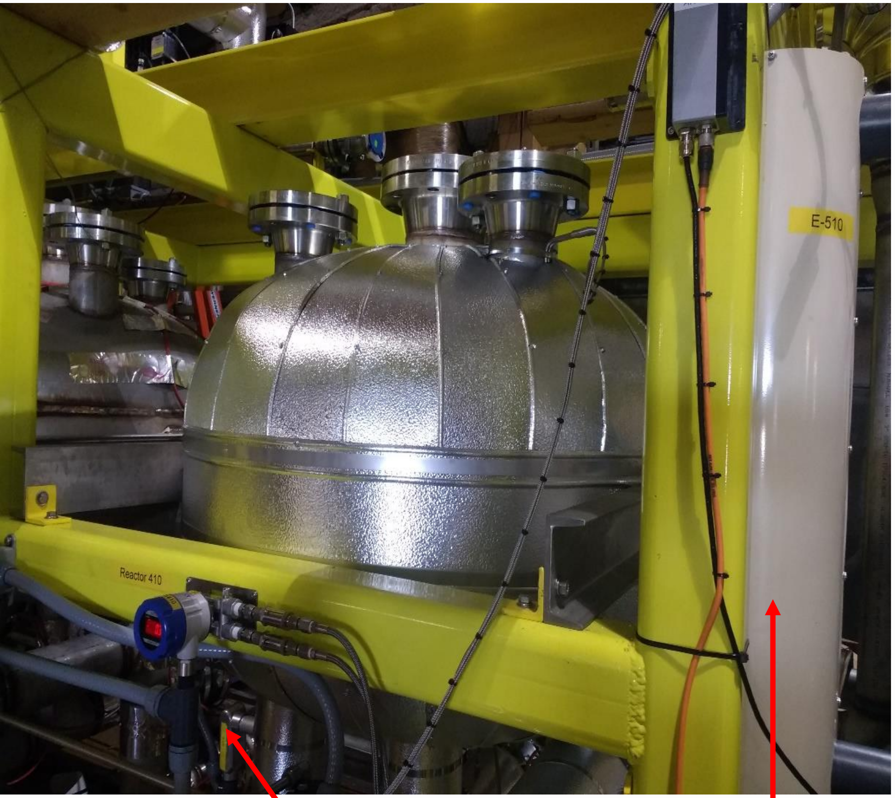
Complex Weldment Fabrication
on Welding Positioner

Sorbent Vessel with
5-Way Inlet/Outlet
Manifold

All 4 Radial Beds Complete with
Inlet/Outlet Piping

Assembly of the System

Radial Sorbent Bed (R-410) After
Heat Trace and Insulation Installation



Differential Pressure
Gauge for Radial Bed 410

Regen Air
Heater

Fully assembled unit

Delivery to the Site

TDA Shipment Arriving at WITC

Crane Lifting and Locating DTA Demo System

Skid Placement to Painted Alignment Marks

Main Skid and Auxiliary Skid Sited

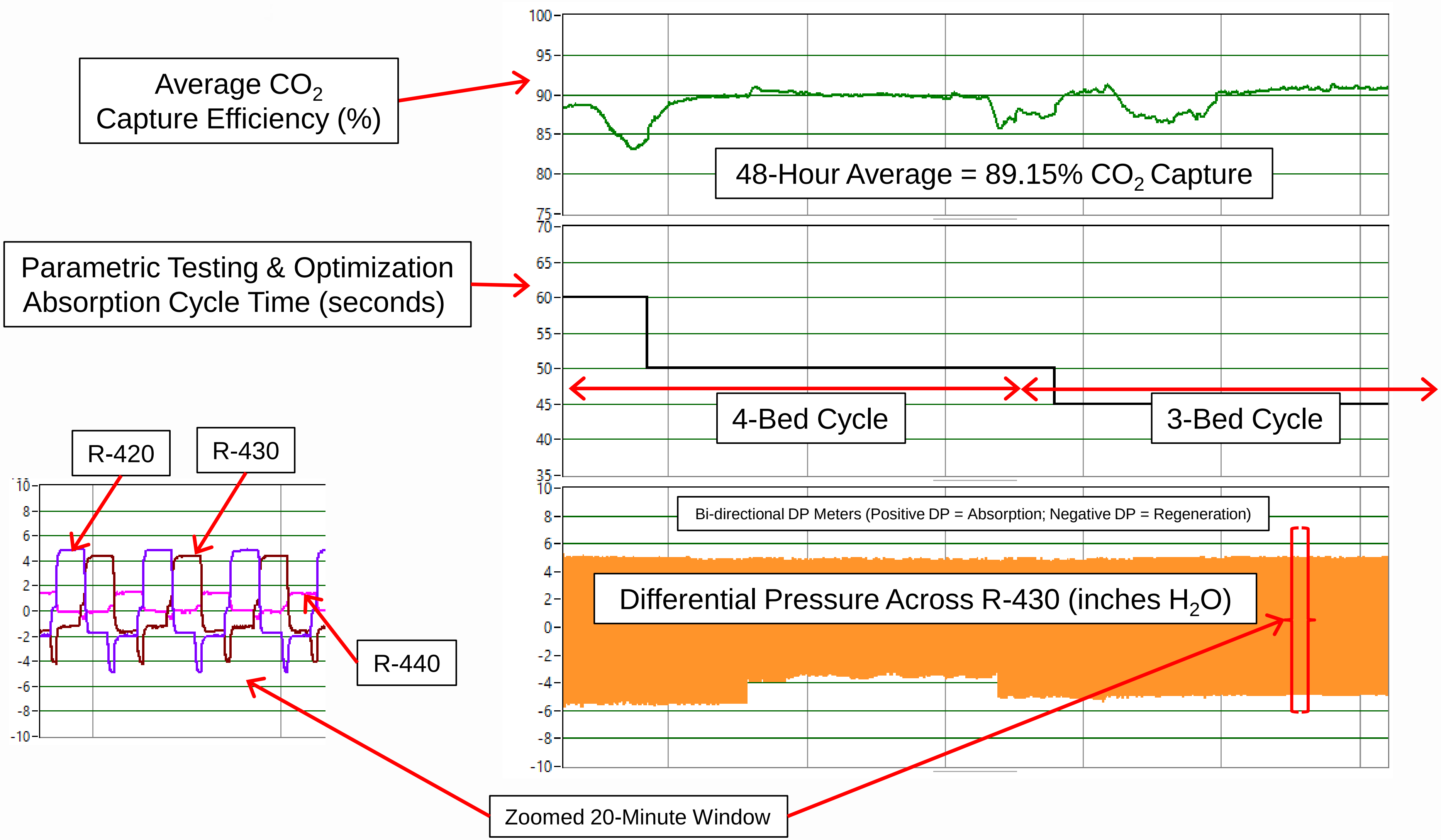
Dry Fork Station in Background

Results of Test Campaign I - III

- Campaign I only evaluated the sorbent system
- Campaign II resumed testing following a long hiatus stemming from Covid-19 restrictions at TDA and WITC
- All system fixes completed in June 2020
- Successful operation with 94-95% CO_2 capture efficiency was demonstrated in Test Campaigns IIIa and IIIb

Test Campaign	Time Online	CO2 Processed: Total System Inlet CO2	CO2 Processed: Slipped/ Released CO2	Capture Efficiency
	hours	kg	kg	%
I	129.9	6709	1234	81.6
II	87	4162	872.3	79
IIIa	166	6865	308.3	95.5
IIIb	135.4	5183	278.5	94.6
Total	518.3	22918	2692.7	89.1

48-Hour Data Subset



Low pressure drop through the radial bed reduces parasitic power loses in both directions.

8-Hour Data Subset

3-Bed Cycle with 2-Bed Simultaneous Regeneration

<u>Constant 3-Bed Cycle Time = 135 Seconds Throughout</u>

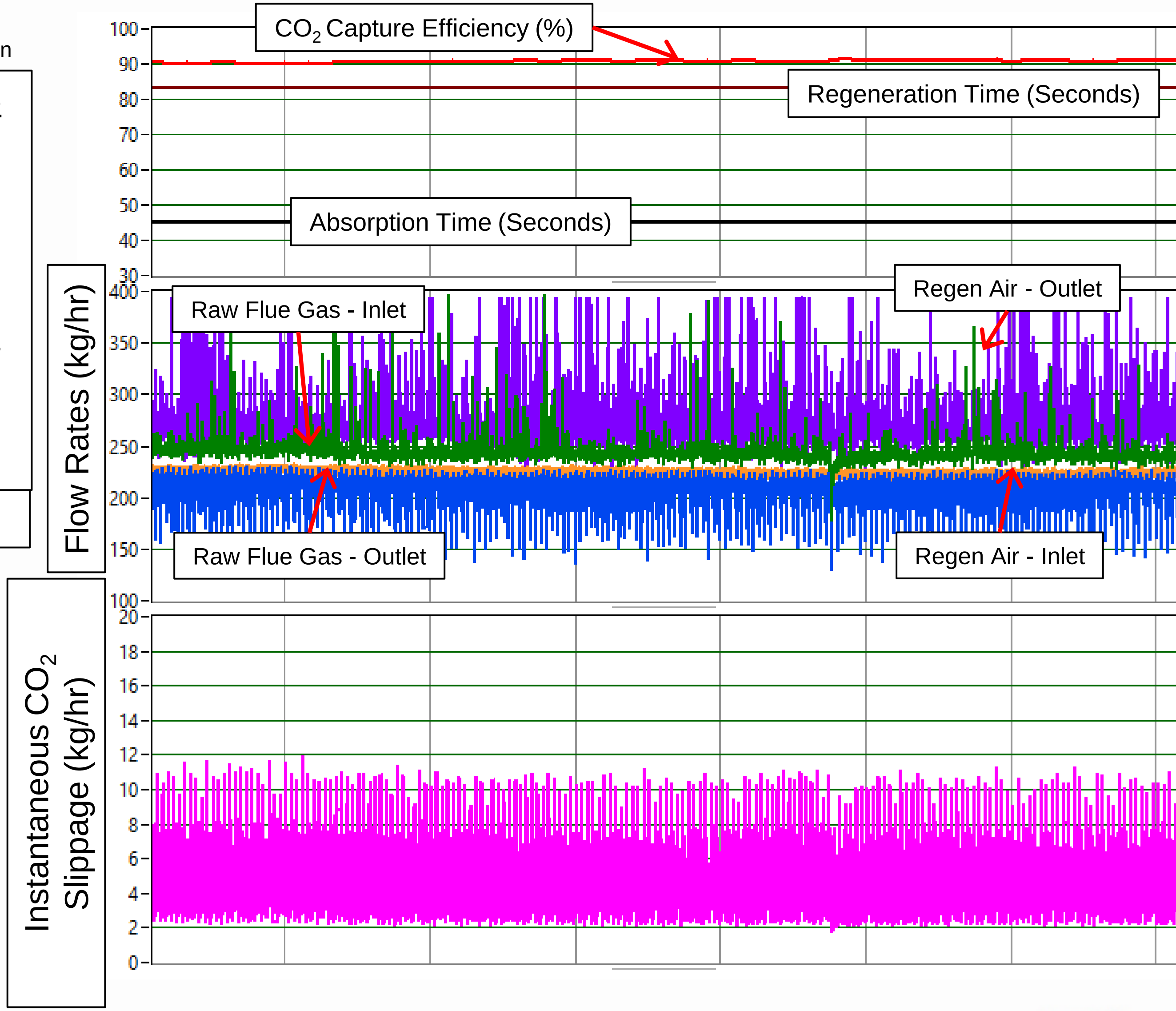
Bed Pressurization Time = 2 Seconds (Not Shown)

Bed Absorption Cycle Time (45 Seconds)

Bed Regeneration Cycle Time (82 Seconds)

Bed Hold Time = 5 Seconds (Not Shown)

CO_2 Capture ≥ 90%



20-Minute Data Snapshot

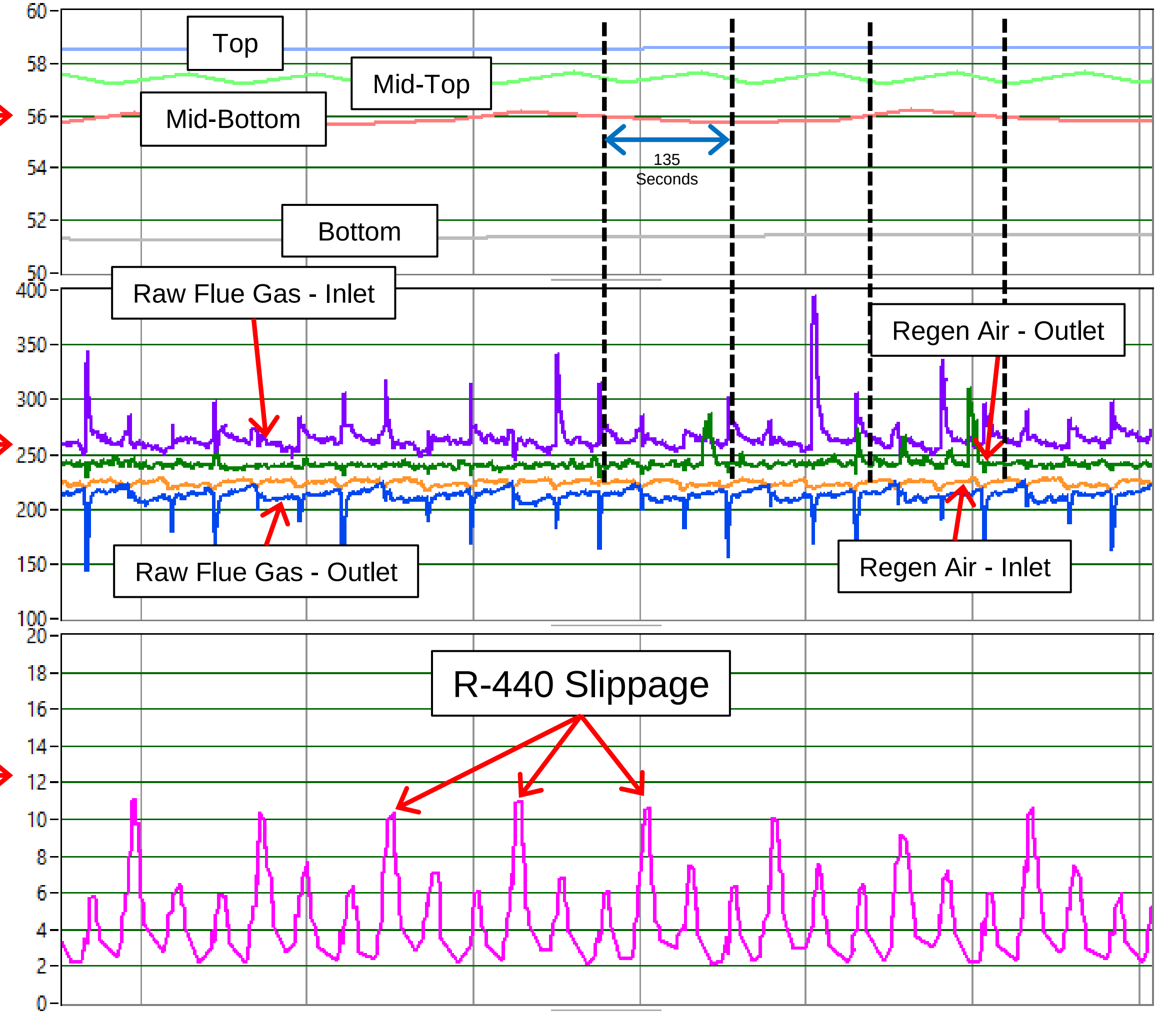
R-420 Internal Bed Temperatures (°C)

Preliminary internal temperature measurements indicate some flow non-uniformity within the bed

Flow Rates (kg/hr)

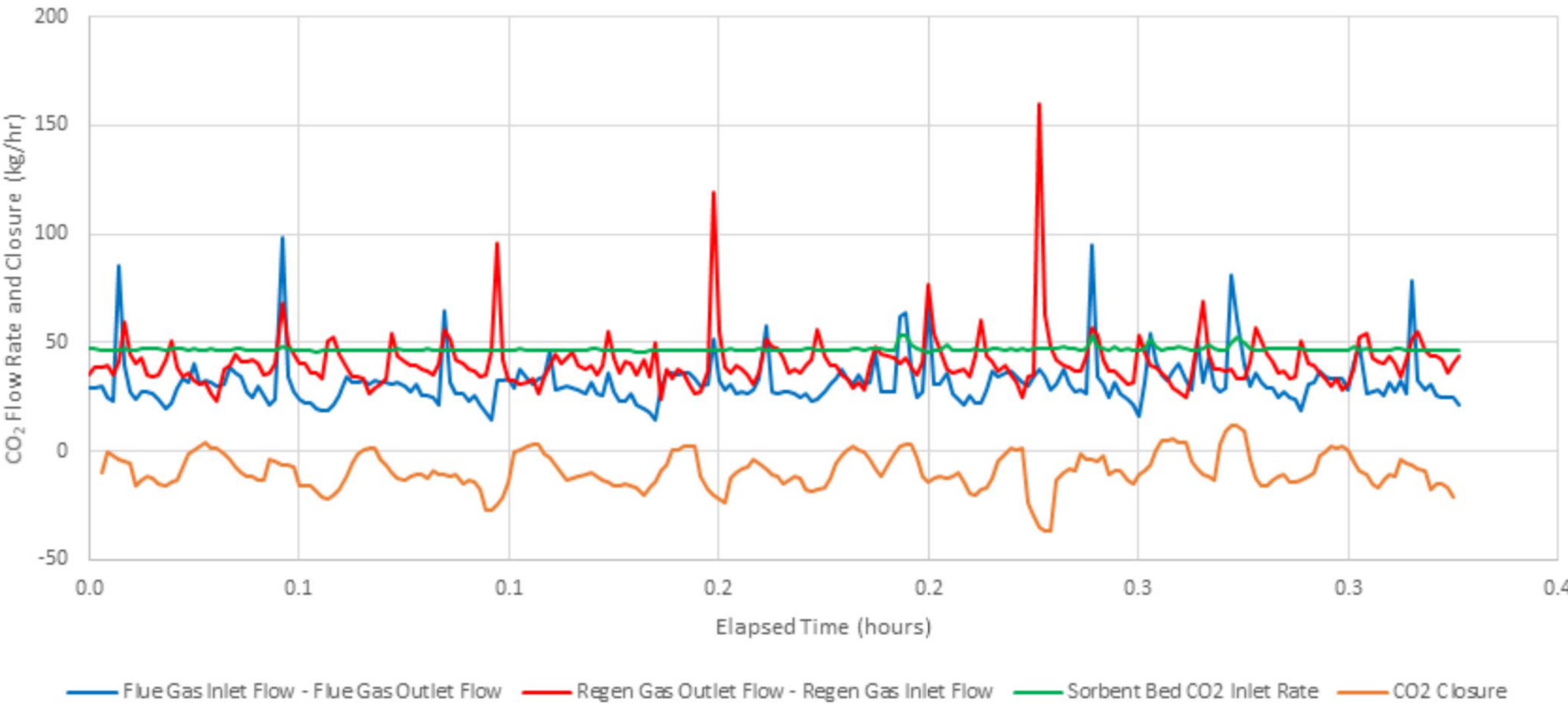
Flue gas flow pulsing due to bed pressurization and switching

Instantaneous CO_2 Slippage (kg/hr)



- Some variation in capacity and CO_2 slippage was observed for one of the beds, due to improper packing

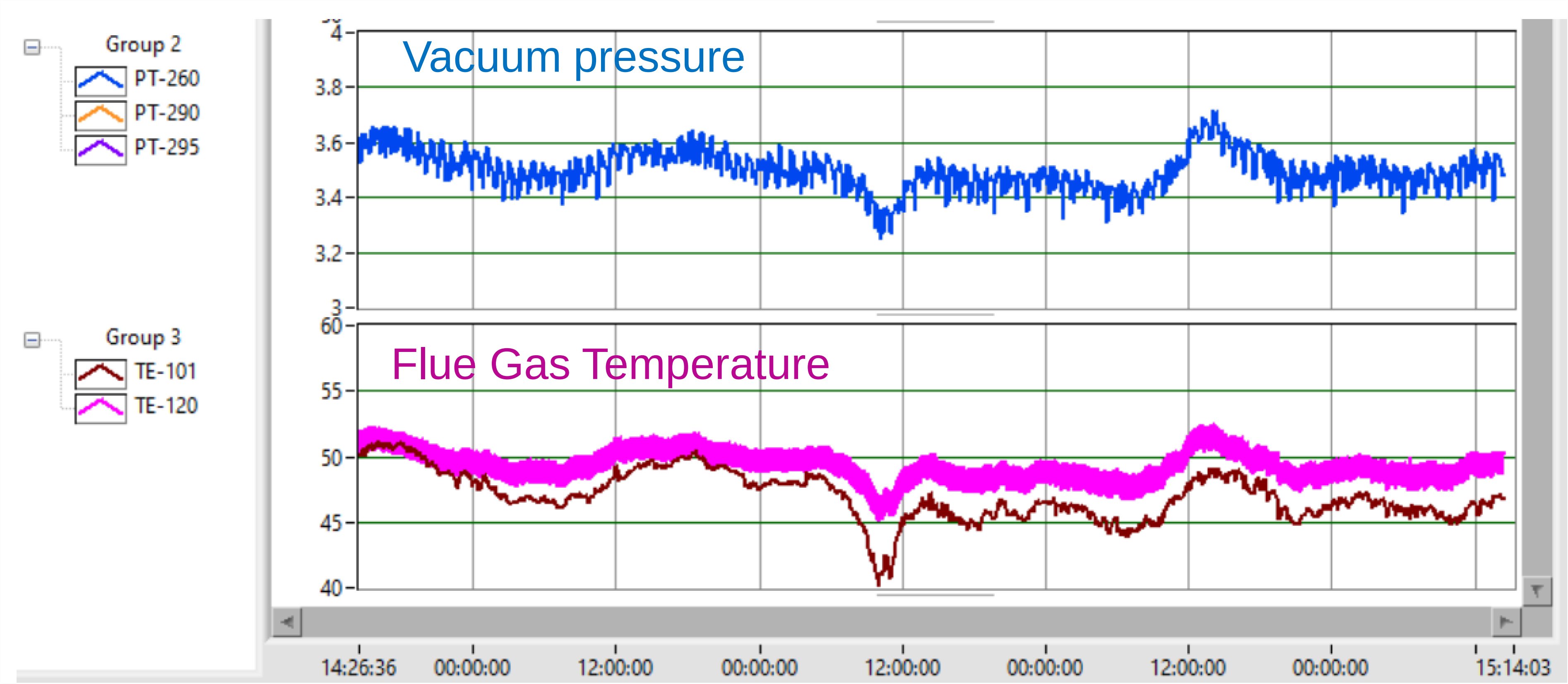
CO_2 Removal/Recovery Mass Balance



Data does not correct raw flow measurements for actual compositions

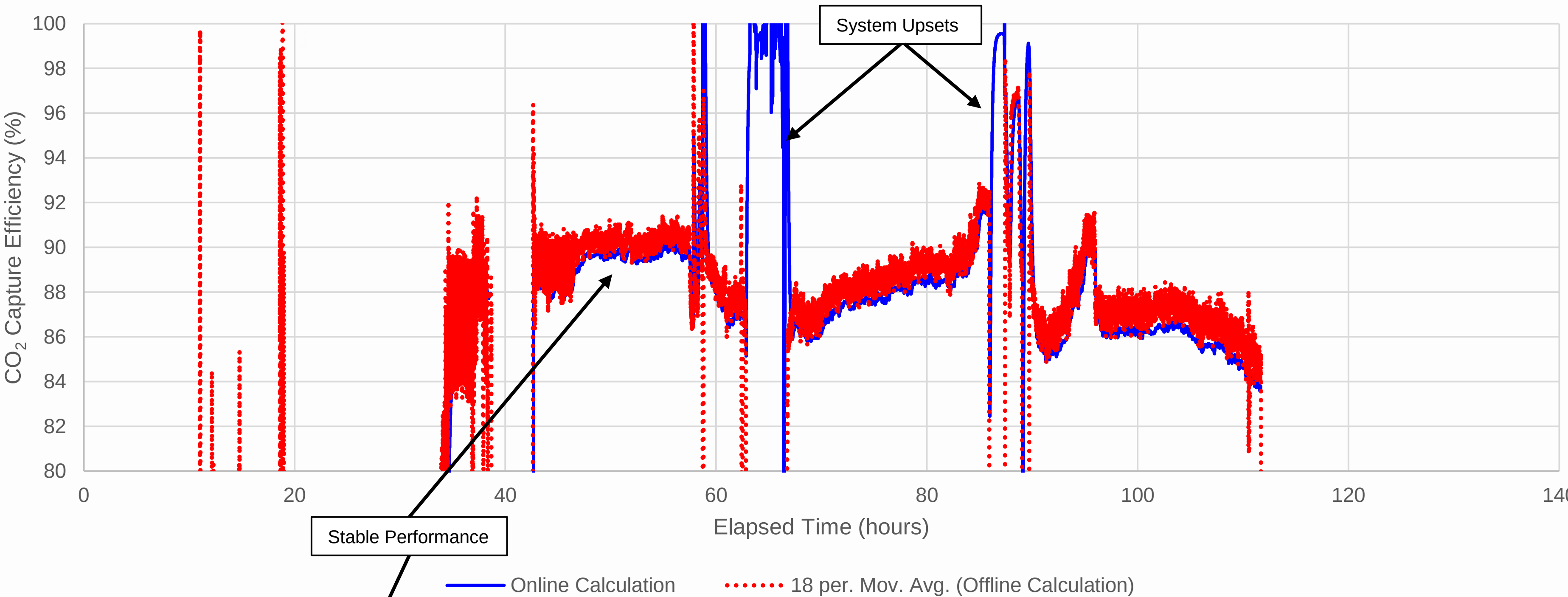
- Good closure of CO_2 mass balance measured on the inlet and outlet ends

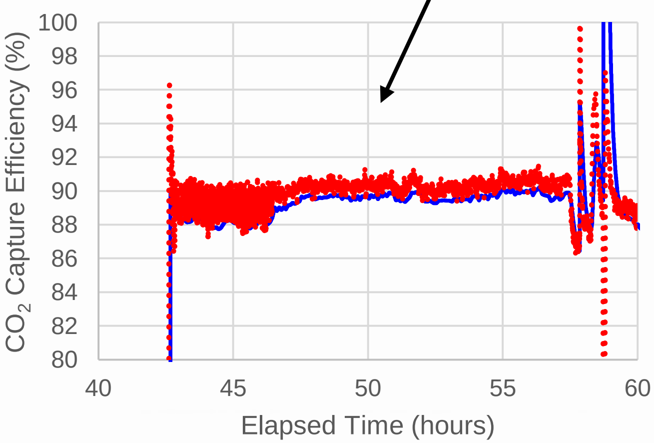
Campaign III - Operating Parameters



- A vacuum pressure of 3.5 psia (+/- 0.2 psia) was maintained to remove the CO_2 across the membrane
- The flue gas temperature entering the membrane (and to the most part to the sorbent bed) was varied at 45-50^oC range

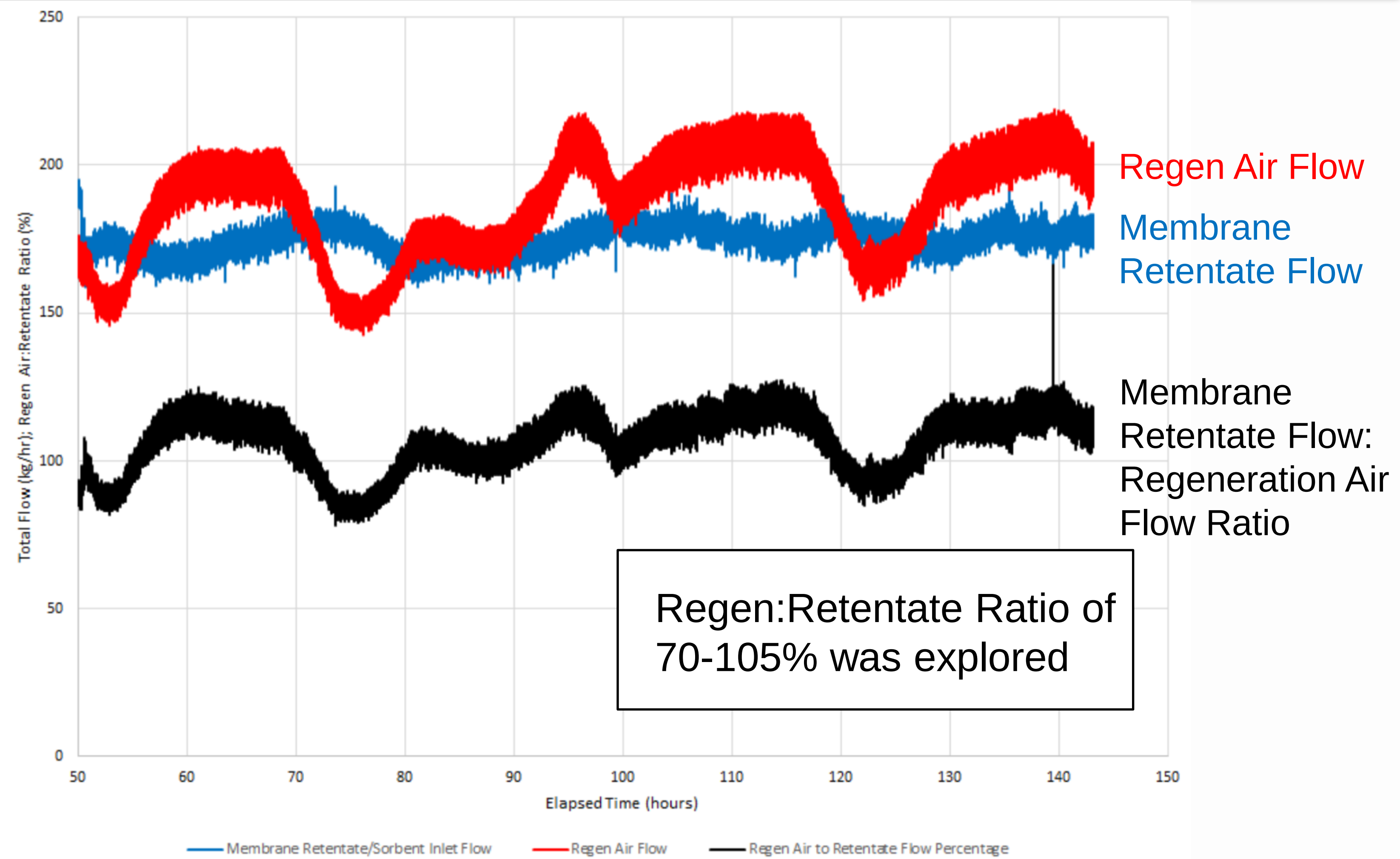
Campaign III - Performance Overview





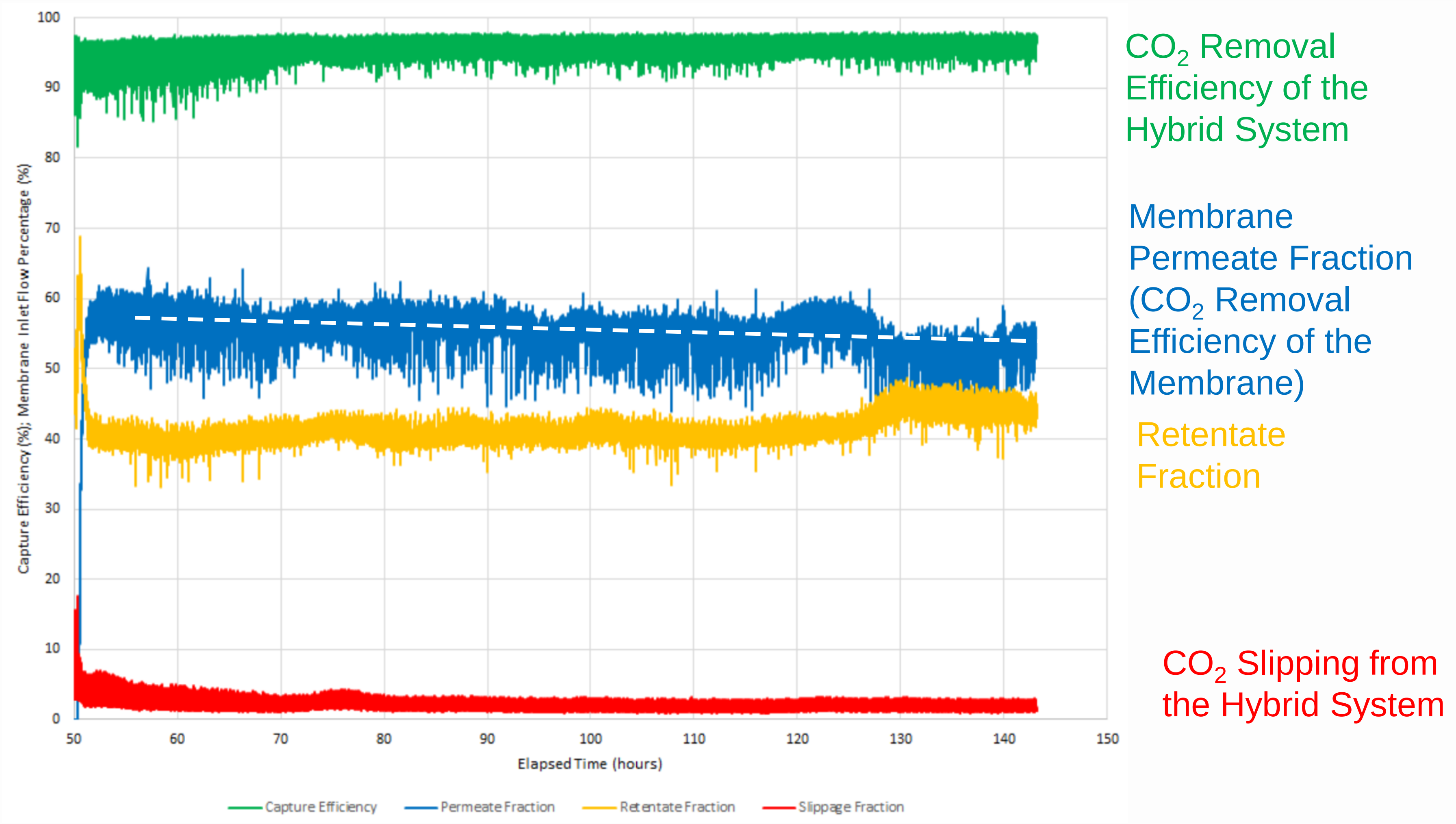
- Online calculation uses a fixed (average) inlet CO_2 concentration provided by Dry Fork Station to determine a running average for CO_2 capture efficiency
- Offline calculation corrects for water KO from the incoming flue gas (increases inlet CO_2 concentration) and adjusts for pressure effects on gas analyzers

Flows Around Sorbent System



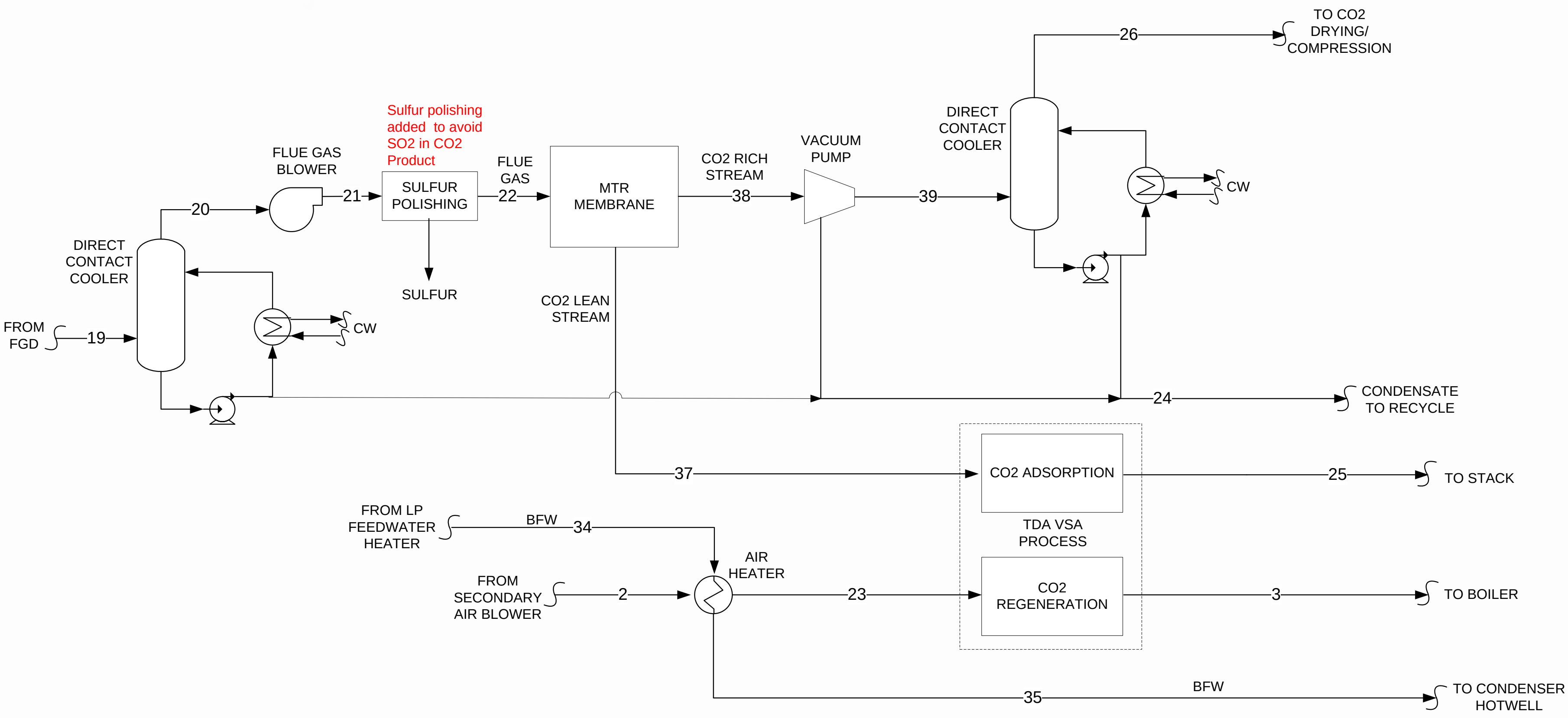
- CO_2 recovered from the membrane is recycled to the inlet of the process to increase the CO_2 concentration to the skid (to simulate the recycle to the coal boiler)

Campaign IIIb - CO_2 Capture Efficiency



- 95+% CO_2 capture efficiency is achieved with the hybrid system

Aspen Process Modeling (UCI)



Hybrid CO_2 Capture System (PFD)

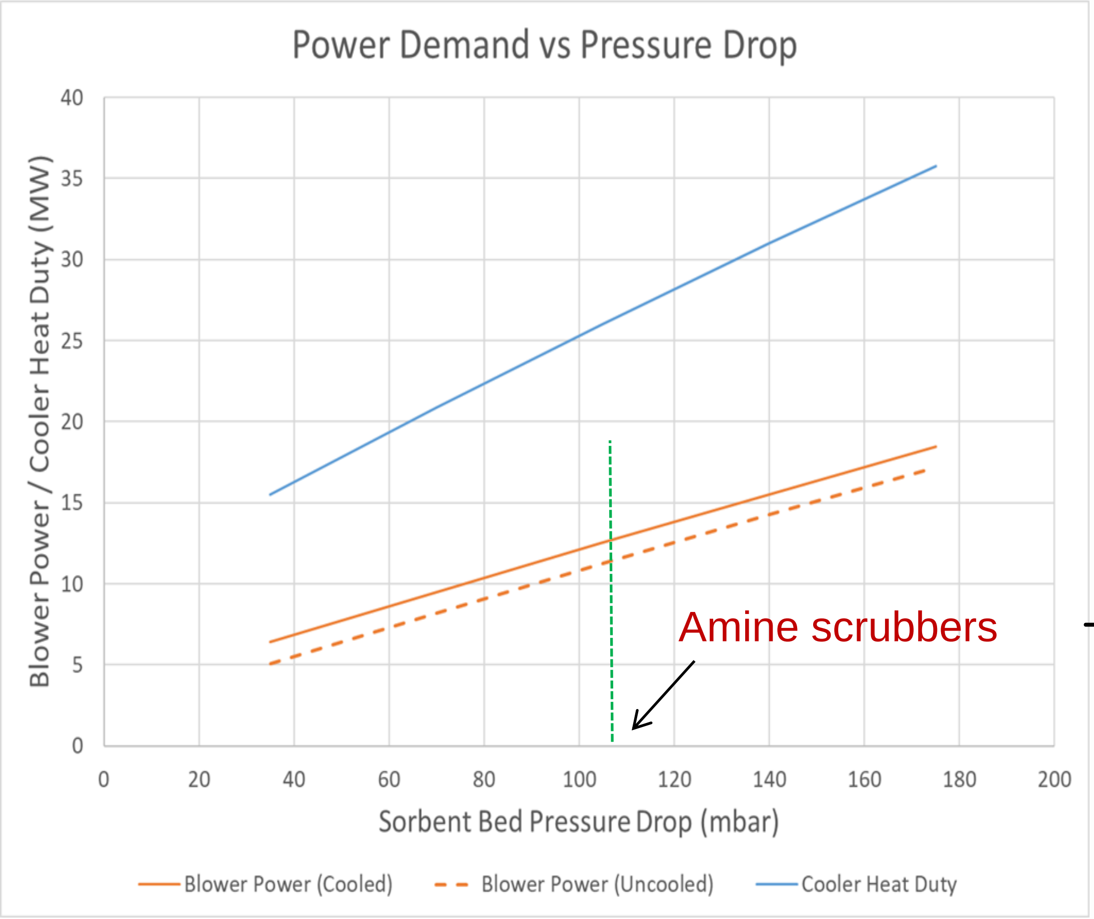
Advanced Power and Energy Program (APEP)	SBIR Phase 2 Study - Case 2
UCIrvine University of California, Irvine	MTR-TDA PROCESS BLOCK FLOW DIAGRAM SUPERRITICAL PC POWER PLANT MEMBRANE + VSA CO2 CAPTURE

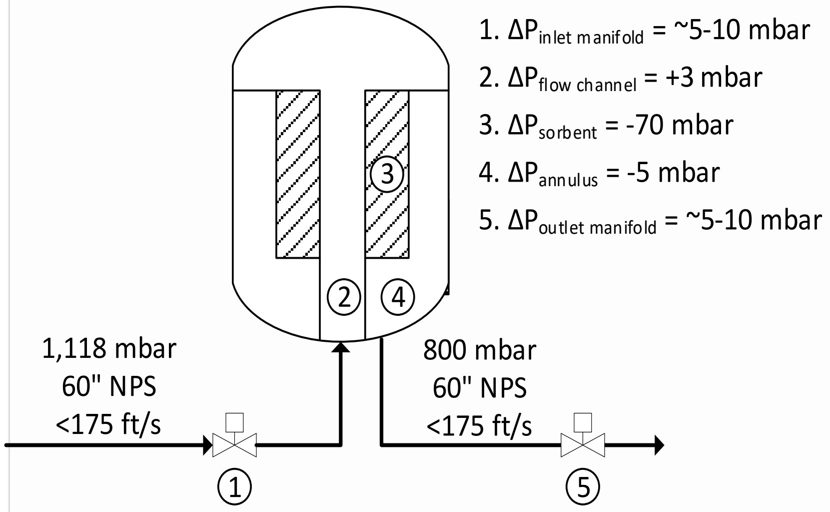
Plant Performance

CASE NO.	UNITs	DoE 11	DoE 12	MTR WP Study	TDA + MTR 3	Sorbent Only	Sorbent Only
CO_2 capture technology		**Reference No Capture**	**Reference Amine**	**Membrane Only**	**Membrane-Sorbent Hybrid**	**Sorbent Only - Recirculation**	**Sorbent Only - Steam Purge**
CO_2 purity from separation Module			**95%**	**80%**	**80%**	**95%**	**95%**
Steam turbine power	kWe	580,400	662,800	780,795	750,371	706,396	696,828
Total auxiliary consumption	kWe	30,410	112,830	224,605	197,832	156,393	146,829
Net power output	**kWe**	**549,990**	**549,970**	**556,190**	**552,539**	**550,003**	**549,999**
Auxiliary load summary							
Flue gas booster + CO_2 removal	kWe	0	20,600	50,170	20,630	11,839	7,513
VSA Vacuum pump	kWe	0	0	37,475	33,578	50,932	49,891
CO_2 compression	kWe	0	44,890	75,768	72,900	48,828	45,842
CO_2 cryogenic purification	kWe	0	0	20,397	18,675	0	0
Common Auxiliaries	kWe	30,410	47,340	40,795	52,049	44,794	43,583
% Net plant efficiency	**% HHV**	**39.3**	**28.4**	**28.7**	**29.6**	**30.8**	**32.5**
Net heat rate	kJ/kWh	9,165	12,663	12,585	12,223	11,677	12,462
Condenser cooling duty	10^6 kJ/h	2,298	1,737	3,077	2,966	2,794	3,035
Consumables							
As-received coal feed	kg/h	185,759	256,652	256,715	247,755	236,681	224,207
Carbon captured	**%**	**0**	**90**	**90**	**90**	**90**	**90**

- TDA's membrane sorbent hybrid system has a net plant efficiency of 29.6% compared to 28.7% in MTR-Worley Parson Study which used compressed flue gas
  - Energy savings mainly from low pressure operation of membrane
  - More membrane area needed to achieve similar flux, impact on selectivity is minimal
- Comparatively using a sorbent only system with recirculation like the hybrid system will allow us to achieve the 95% purity target in a single system resulting in a net plant efficiency of 30.8%
- Sorbent Only System with VLP Steam Purge could provide 32.5% efficiency

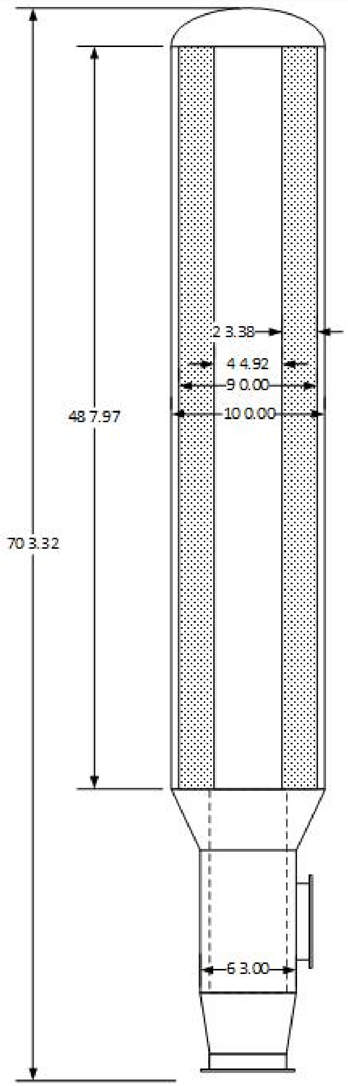
Pressure Drop Constraint





- **Parasitic power demand for gas compression is estimated to range from 1% to 3.5% of plant capacity**

Reactor Vessel Design / Valve Selection



SORBENT VESSEL DIMENSIONS

Sorbent System - Hybrid

	Stage I	Stage II
Bed 1	Adsorption - Flue gas flow	Desorption - Air Purge flow
Bed 2	Desorption - Air Purge flow	Adsorption - Flue gas flow
120s	60s	60s

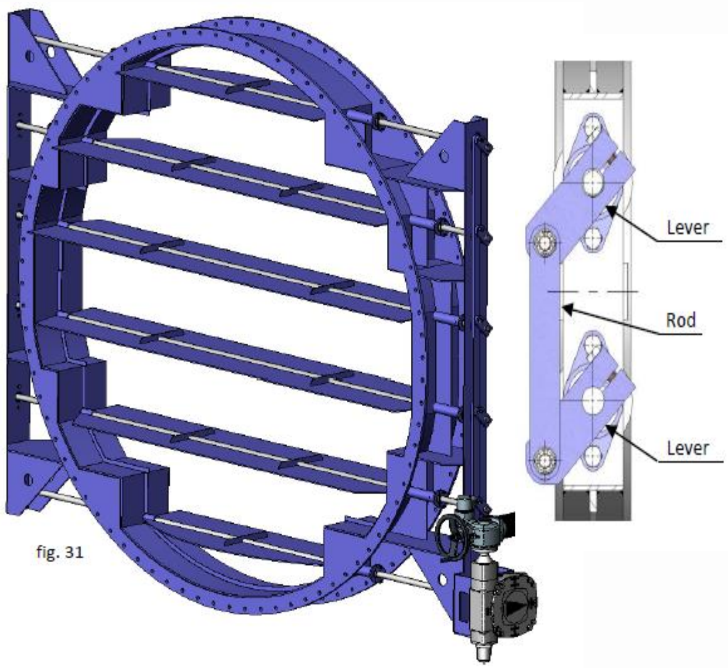
Adsorption - Flue gas flow

Desorption - Air Purge flow

ΔP=105 mbar

Module size	68.75 MW
No. of trains	8
No. beds per train	2
Total no. of beds	16
Flue gas flow	63.0 m3/s
CO2 flow	0.63 tonne/min
Capacity	1.7% wt. CO2
Bed online	1 min
Sorbent needed	37.2 tonne
density	0.56 tonne/m3
Bed vol.	66.4 m3
Bed CSA	6.6 m2

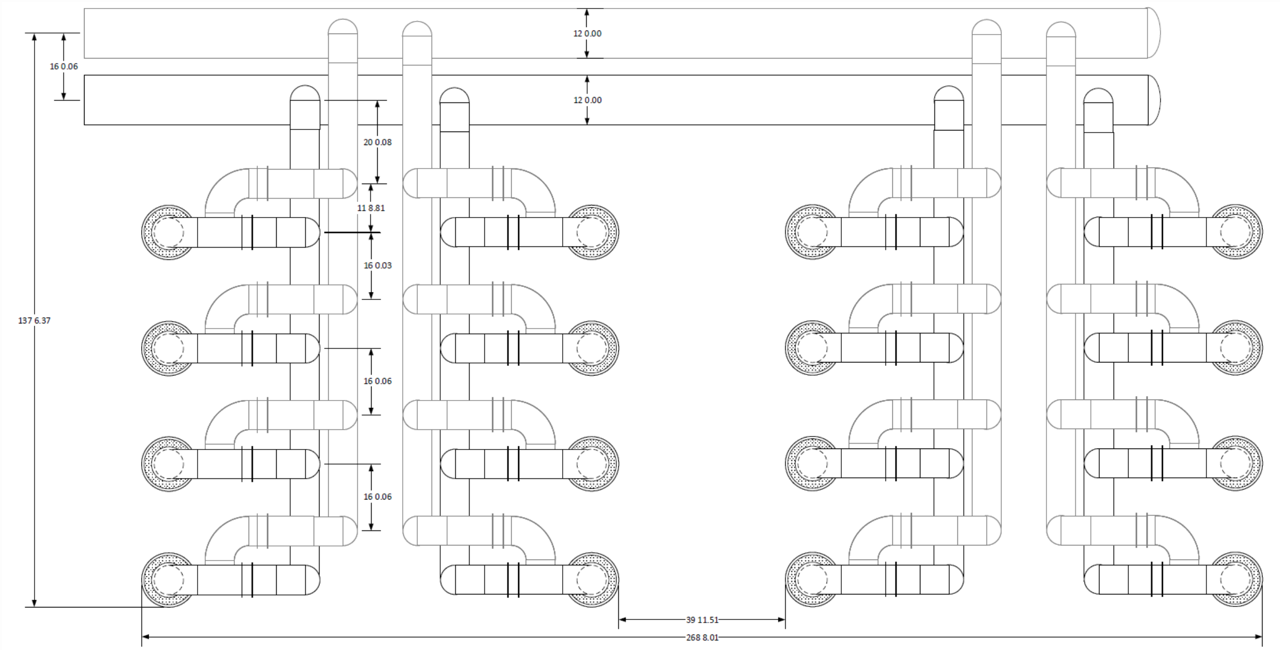
- Reactor design and valve selection is interdependent
- Double acting pneumatic actuator with travel time of 3-5 seconds were identified



- Sixteen (16) radial beds
- SA516-70 carbon steel, 0.5” thickness, 120 in OD x 565 in T/T

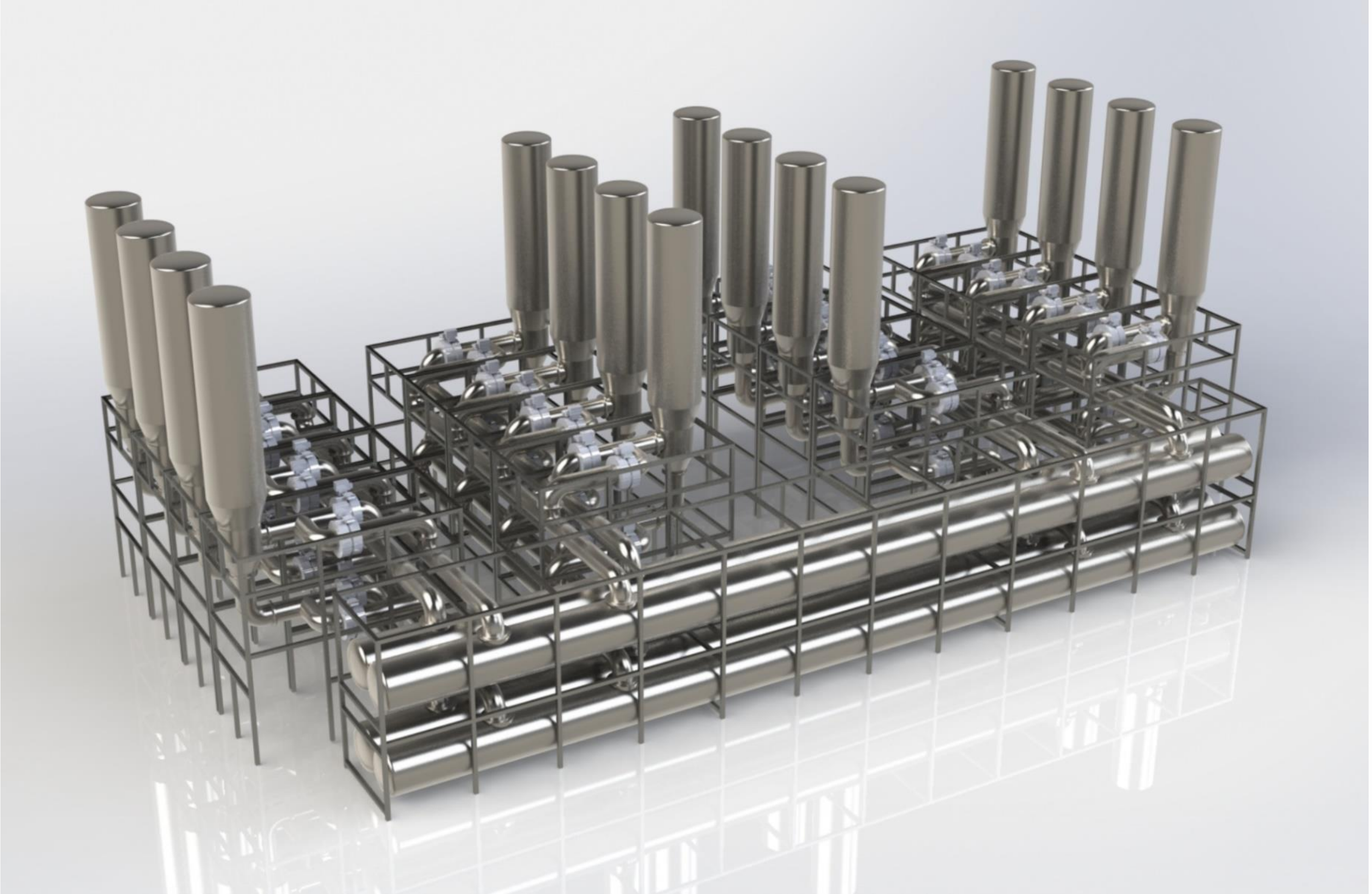
TDA RESEARCH

Piping Layout and Costing



- 60 in NPS, 0.375 in thickness (standard schedule) piping for flue gas and air regeneration lines
- Two (2) 12 ft OD flue gas distribution and return manifolds
- 2,000 linear feet, estimated from concept layout
- Weight of steel 240 lb/ft
- Assumed cost of steel $1.73 / lb (SA-106B)
- Total piping cost $1,094,679 (CEPCI 607.5 2019)

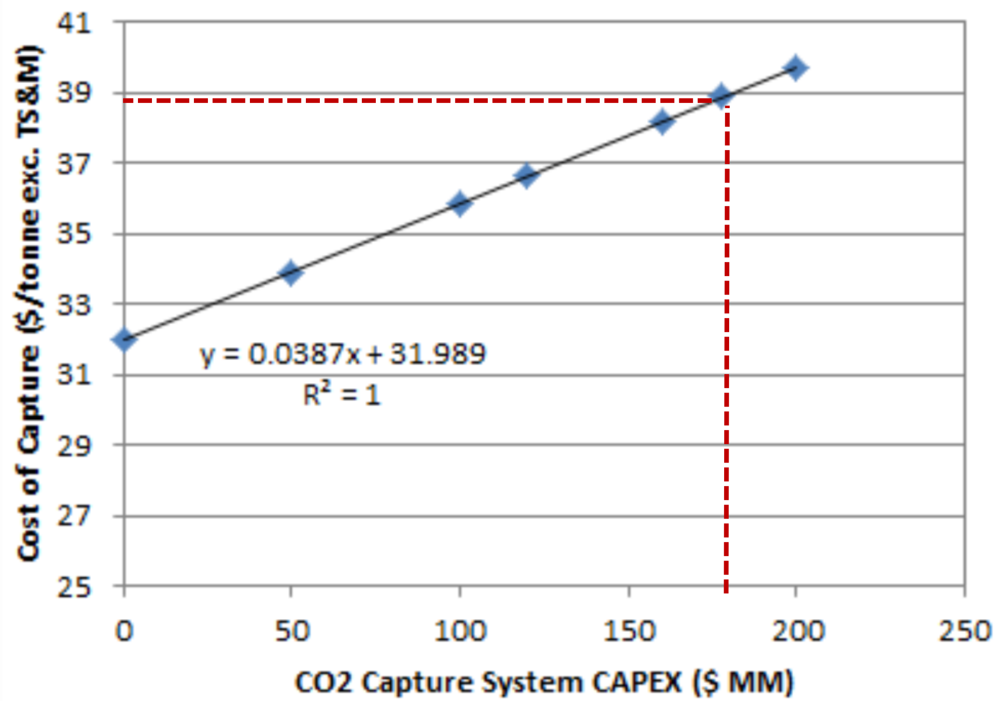
3-D Layout of the Hybrid Sorbent System



CO_2 Capture Cost

Cost of Electricity	$ 2011 basis
TOC	61.03
OCF	12.56
Feed	33.84
Var. OC	10.25
TS&M	9.44
COE $/MWh	117.68
COE w TS&M $/MWh	127.13

Cost of CO2 Captured exc. TS&M ($/tonne)	$ 38.89



- The cost of CO_2 Capture is estimated as $38.9/tonne System Cost for hybrid membrane sorbent process
- Based on total capture system cost of $178.6 MM (including the flue gas treatment subassembly, including blowers, DCC etc.)
- Meets the DOE 2030 Target using two mature technologies (TDA Mesoporous Carbon sorbent and Polaris I membrane)