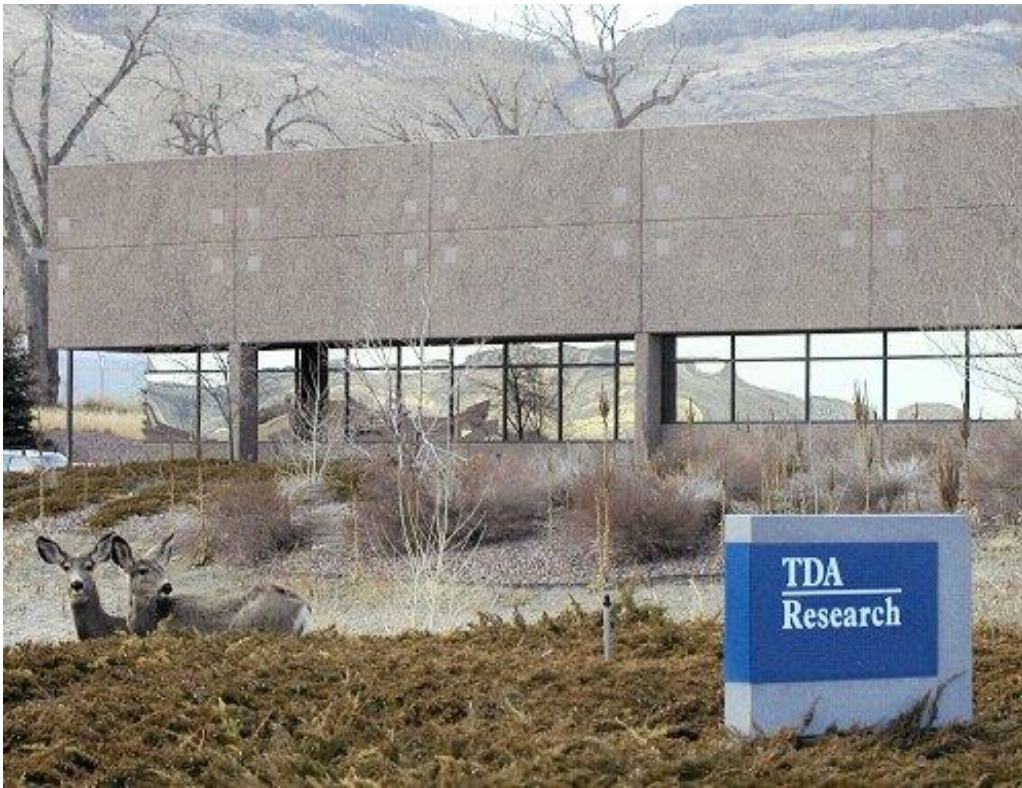


Membrane-Sorbent Hybrid System for Post-Combustion CO₂ Capture (Contract No. DE-FE-0031603)



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**DOE/NETL Carbon Capture
Project Review Meeting**

October 7, 2020

TDA Research Inc. • Wheat Ridge, CO 80033 • www.tda.com

Project Objective

- **Project objective is to design and construct a ~1 MW scale membrane-sorbent hybrid post-combustion carbon capture system and evaluate its operation in a long duration field test using flue gas**
- **Hybrid process consists of a polymeric membrane and a low temperature physical adsorbent to remove CO₂ from the flue gas**
 - Membrane is being developed by MTR
 - Adsorbent has been developed by TDA for post-combustion capture
 - Early proof-of-concept demonstrations in an SBIR Phase II/IIB project (DE-SC0011885) proved the feasibility of the hybrid system

Main Project Tasks

- | | |
|------------|---|
| BY1 | <ul style="list-style-type: none">✓ Completed the design of the 1 MW scale test unit✓ Completed the Initial Design Review✓ Completed Preliminary Techno-economic analysis |
| BY2 | <ul style="list-style-type: none">✓ Fabrication of the test unit- Site Preparation, Installation and Shakedown Tests (9/2020) |
| BY3 | <ul style="list-style-type: none">- Field Tests (6-9 months duration)- High Fidelity Techno-economic analysis |

Project Team



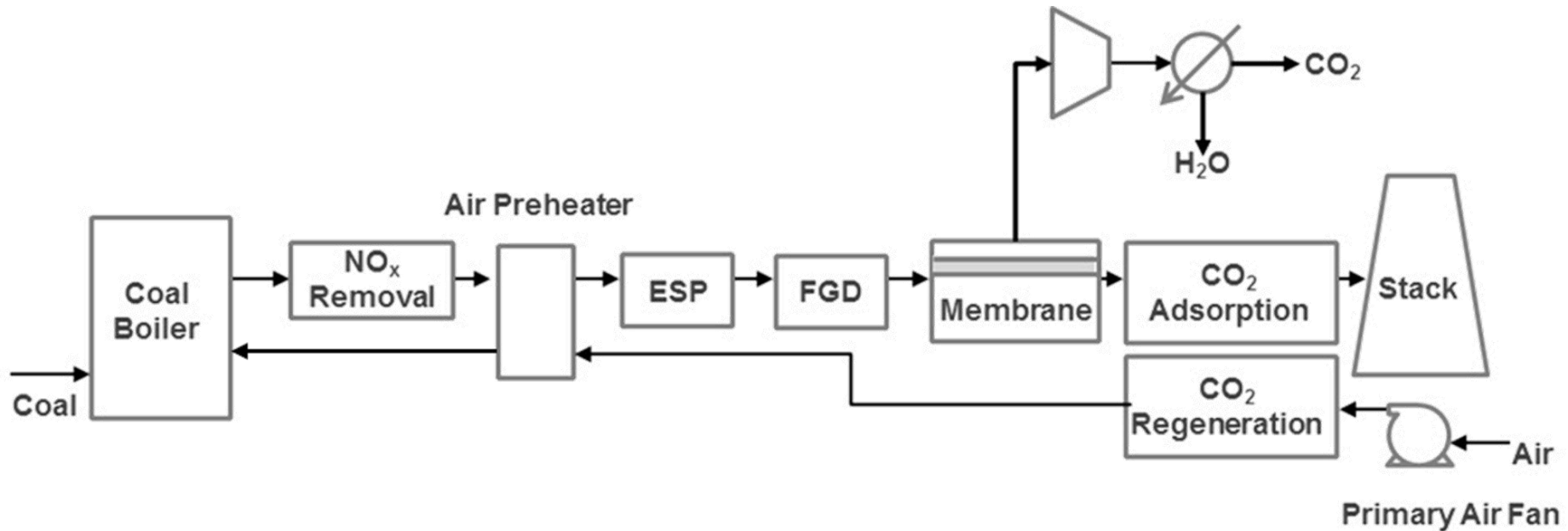
Project Duration

- Start Date = August 17, 2018
- End Date = August 16, 2021

Budget

- Project Cost = \$10,000,025
- DOE Share = \$8,000,000
- TDA and its partners = \$2,000,025

Hybrid Membrane Sorbent Process



- **Membrane operates at ~50°C under mild vacuum, (~0.3 atm) removes ~50% of CO₂ and almost all water**
 - TDA's sorbent removes remaining CO₂ 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} in the second stage
 - Greatly reduced oxygen transfer (from the air side to flue gas side)

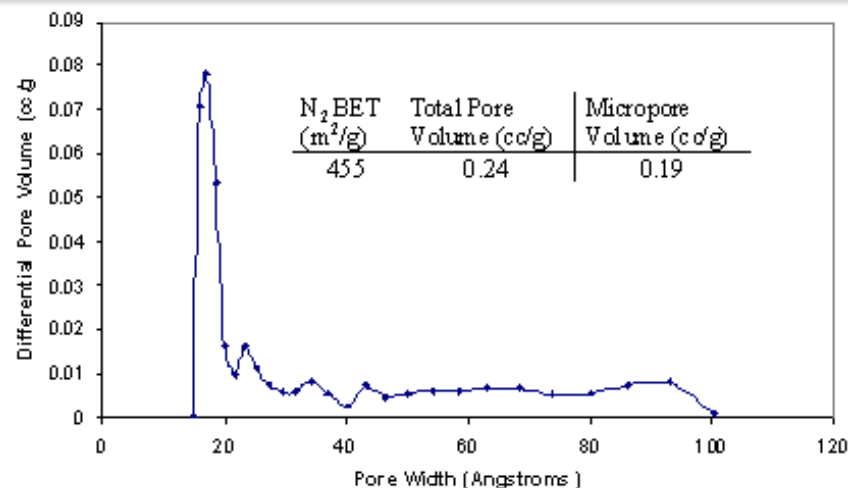
TDA Sorbent

- TDA developed a mesoporous carbon sorbent modified with surface functional groups that remove CO₂ via strong physical adsorption
 - CO₂-surface interaction is strong enough to allow operation at low partial pressures
 - Because CO₂ is not bonded, the energy input for regeneration is low
- Heat of CO₂ 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

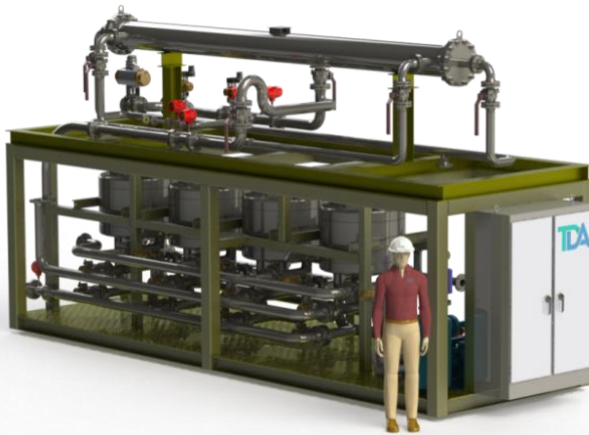
Sorbent optimization and production scale-up was completed in a separate DOE project (DE-0013105)



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



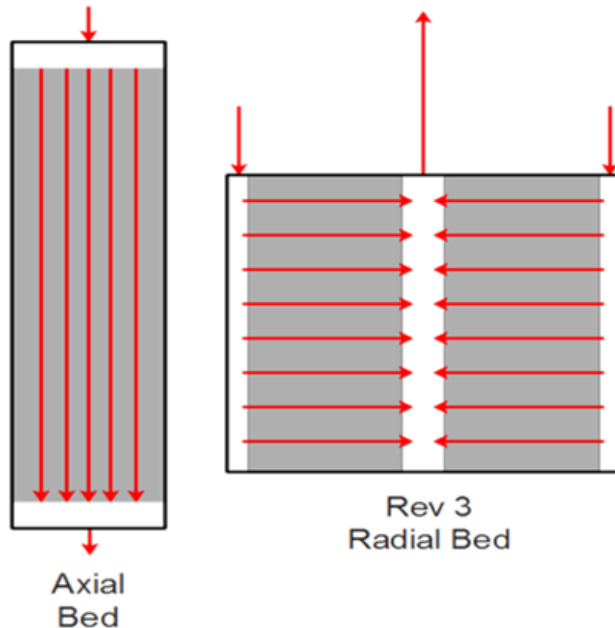
SBIR Phase IIB – Evaluation of the Hybrid System



100 SCFM Membrane-Sorbent Hybrid Test System



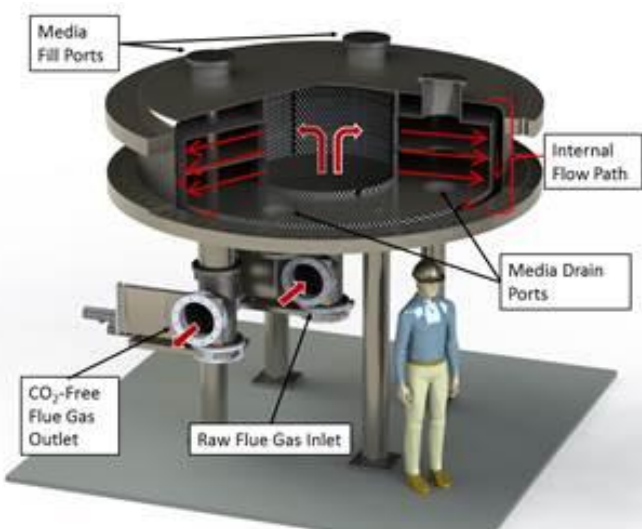
WITC near Basin Electric's Dry Fork Station in Gillette, WY



- 100 CFM evaluation removing 1 ton/day CO₂
- Field tests January-July 2020
- Successfully demonstrated the integrated operation with 95+% capture efficiency at the desired flow rate
- Both “hybrid operation” and “sorbent only” evaluations were carried out
 - 50-60% CO₂ purity with the membrane
 - 95+% CO₂ purity with the sorbent (due to low N₂ affinity over the sorbent)

Current Project Focus

- TDA will further develop/demonstrate its radial outflow sorbent reactor concept
- MTR will modify an existing unit (20 TPD) previously developed under the DOE funding
 - The unit will be equipped with MTR's legacy membranes
- The integrated test unit will be evaluated at the Technology Center Mongstad (TCM)



TDA's Sorbent System



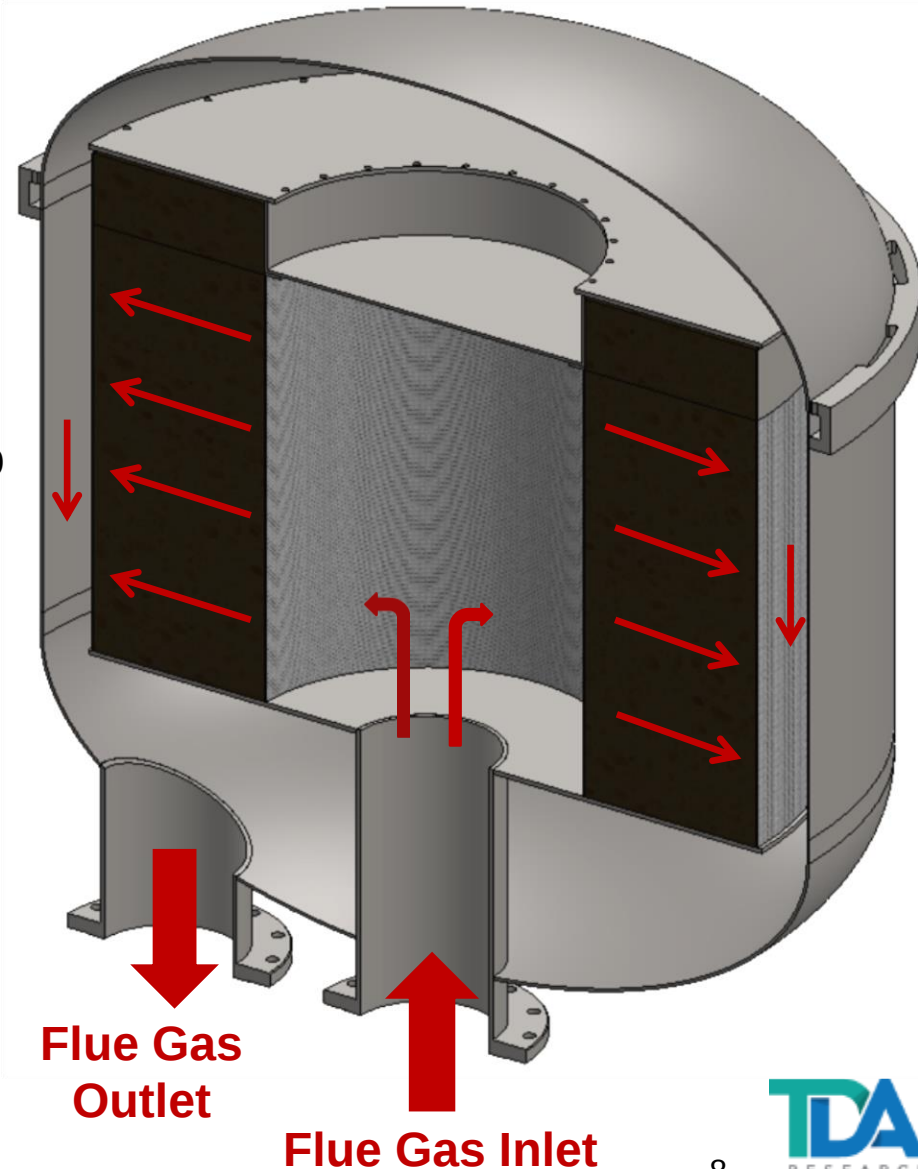
**Existing MTR Membrane Module
(20 TPD evaluated at NCCC)**



TCM Mongstad, Norway

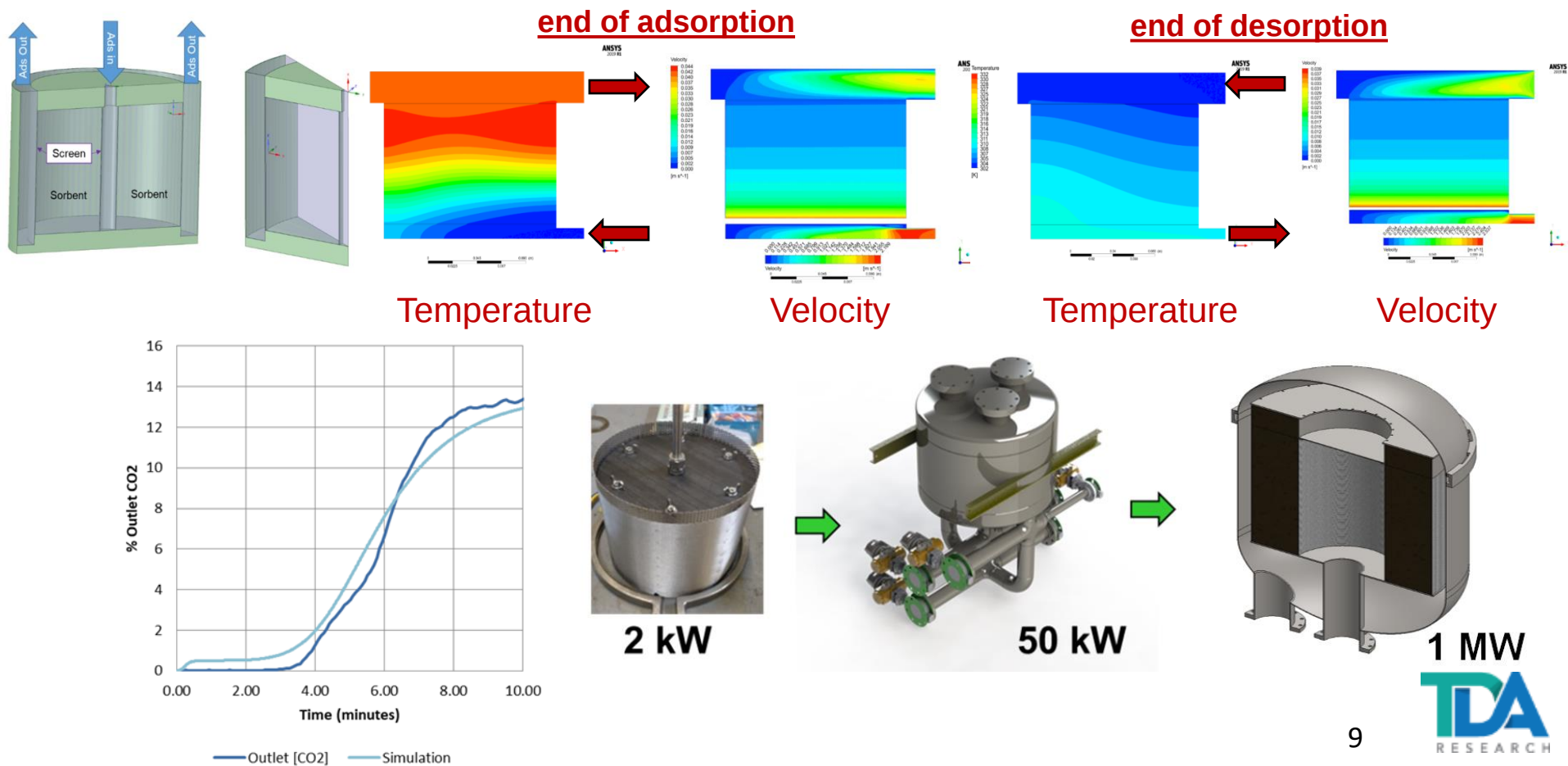
Design of the 1 MW Reactor

- Bed volume = 1.33 m³ (with additional room for contingencies)
- Inner screen dia. = 30"
- Outer screen dia. = 62"
- Vessel OD = 72"
- Piping = 12" SCH40S
- Locking ring flange for access
- Vessel weight (w/o sorbent) = 3,000 lb
- dP = 44 mbar (8x16 mesh sorbent)
- dP = 106 mbar (12x40 mesh sorbent)
- Removable reactor end cap/head to allow sorbent fill
- Sorbent bed is a donut shaped basket loaded from the top
- Blanked off section will prevent channeling due to bed shrinkage
- Minimal media handling is required to test modular reactor concept

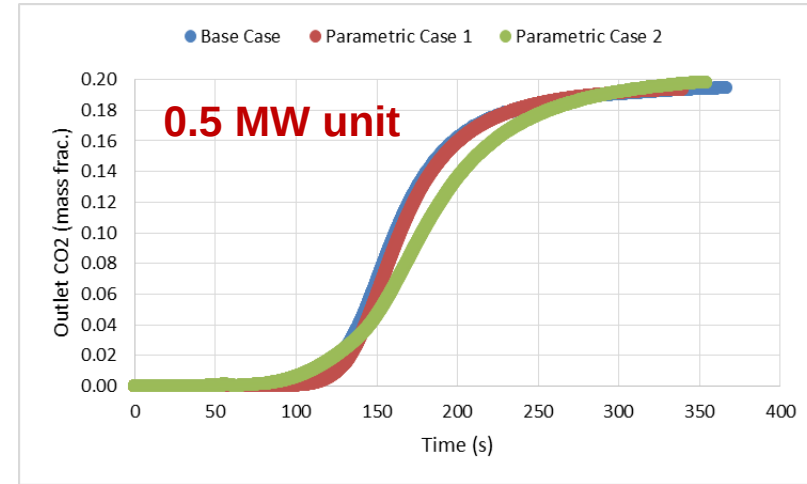
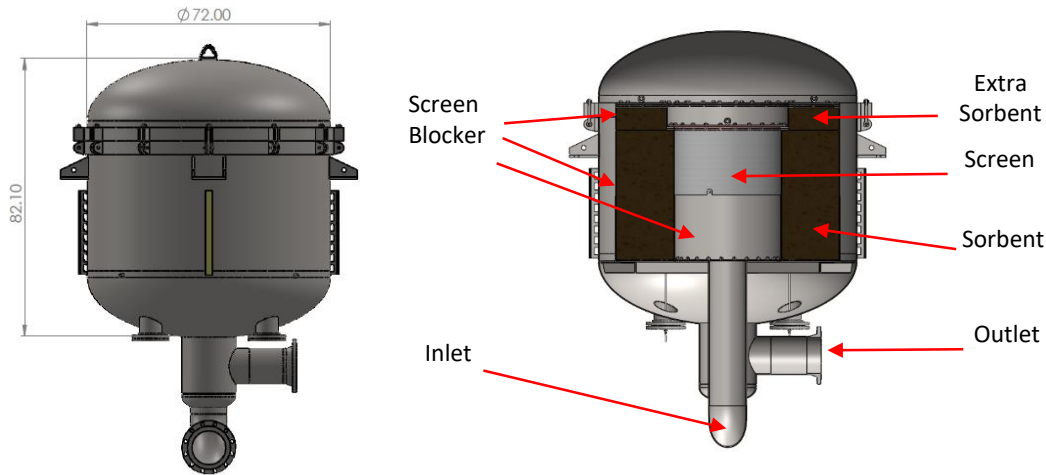


Design of the Sorbent Vessels

- Design work is supported with CFD simulations to determine the intra-modular flow, concentration and temperature distributions
 - Understanding flow distribution is critical to design an effective gas-solid contactor
- Data validation from the smallest test module is now complete

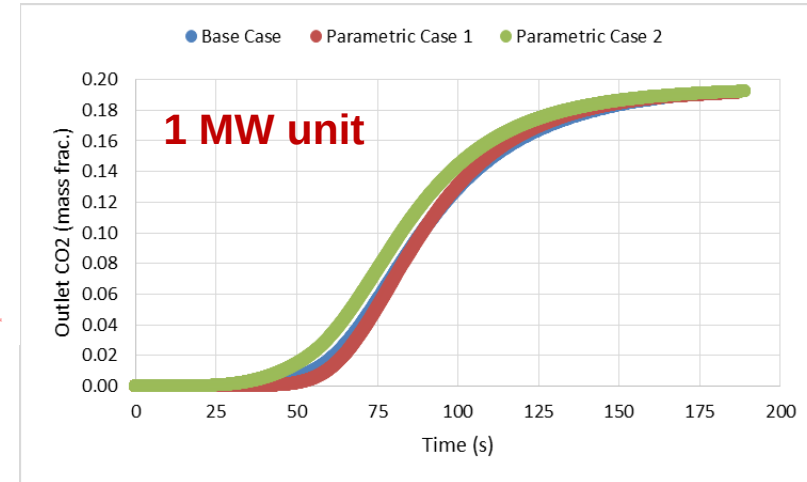
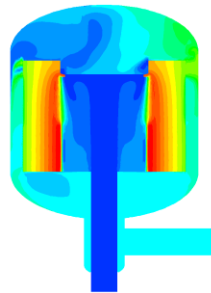
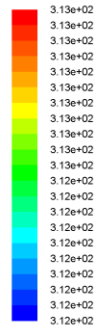
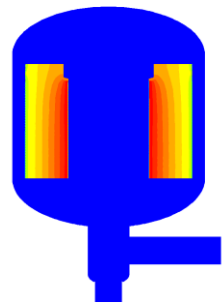
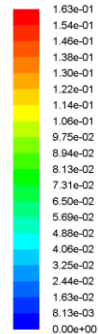


CFD Modeling of Sorbent Reactor



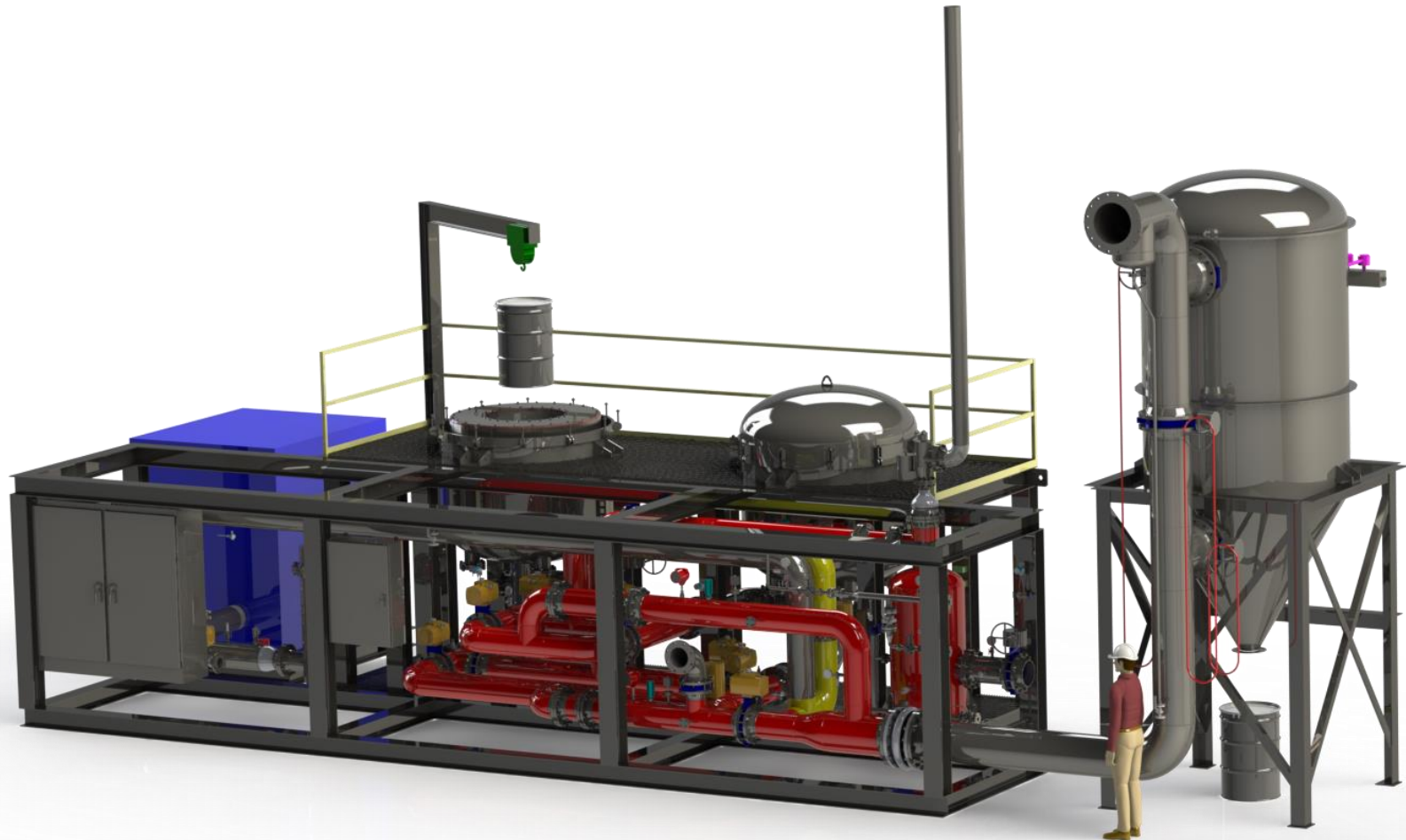
CO₂ Sorbent Loading

Temperature Contour



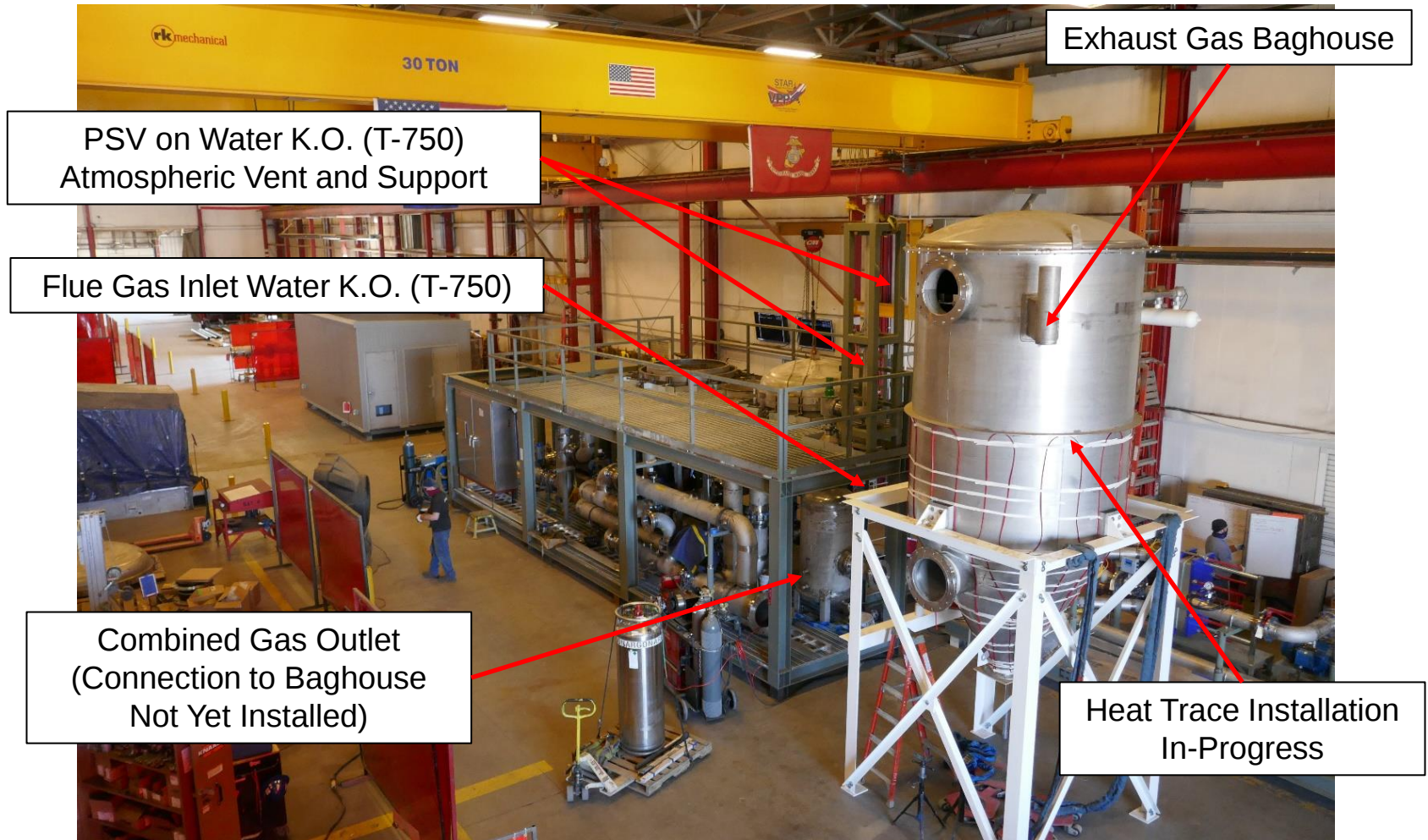
- GTI completed the model development for the radial sorbent beds that will be used in the field
- Clean breakthrough curves

Design of the Sorbent System

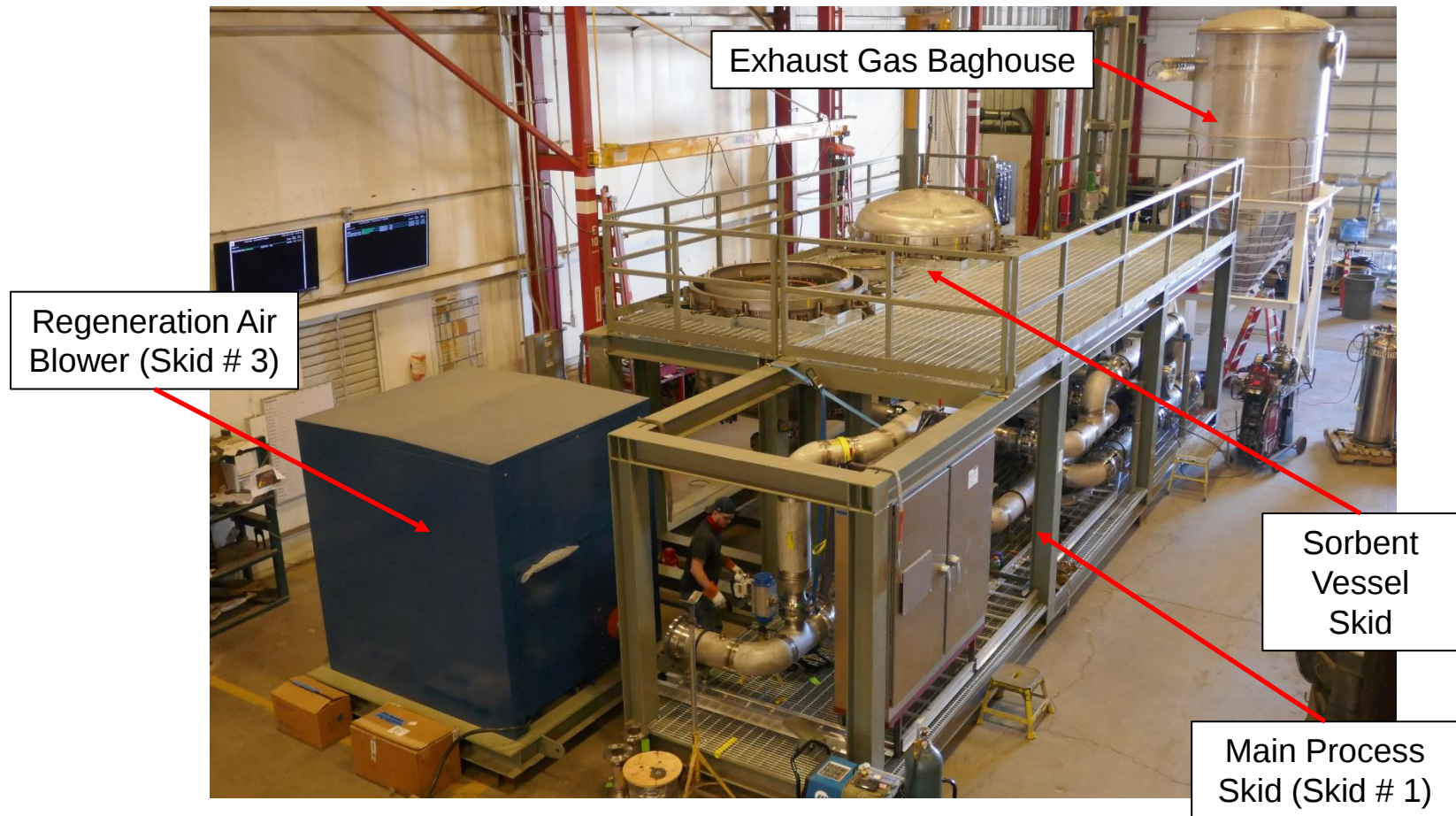


Assembled Onsite from Multiple Skids
(All Skids Pack Into Hi-Cube Conex for Low-Cost Shipping)

Sorbent Subsystem

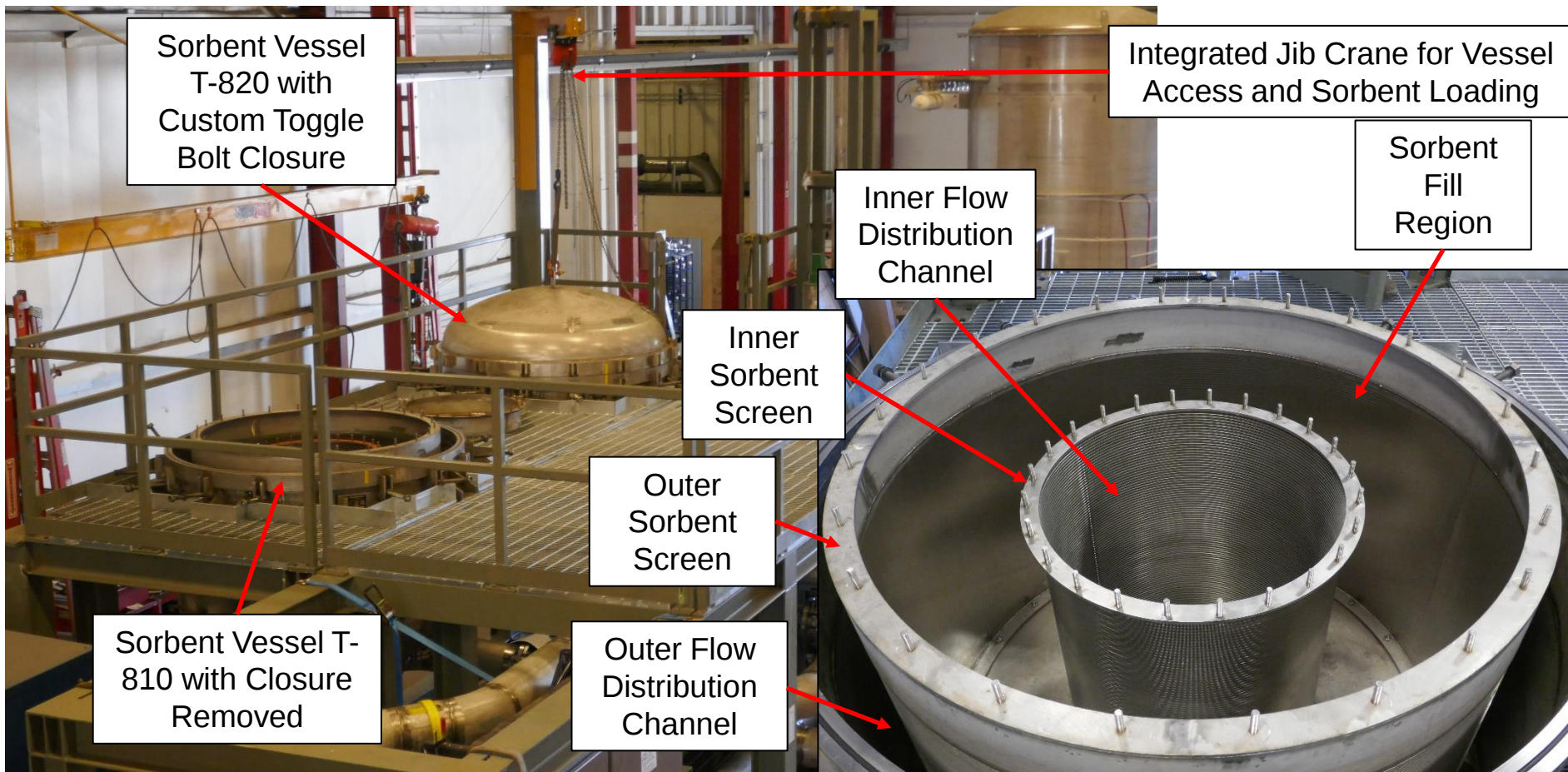


TDA's Dual-Bed Sorbent Subsystem



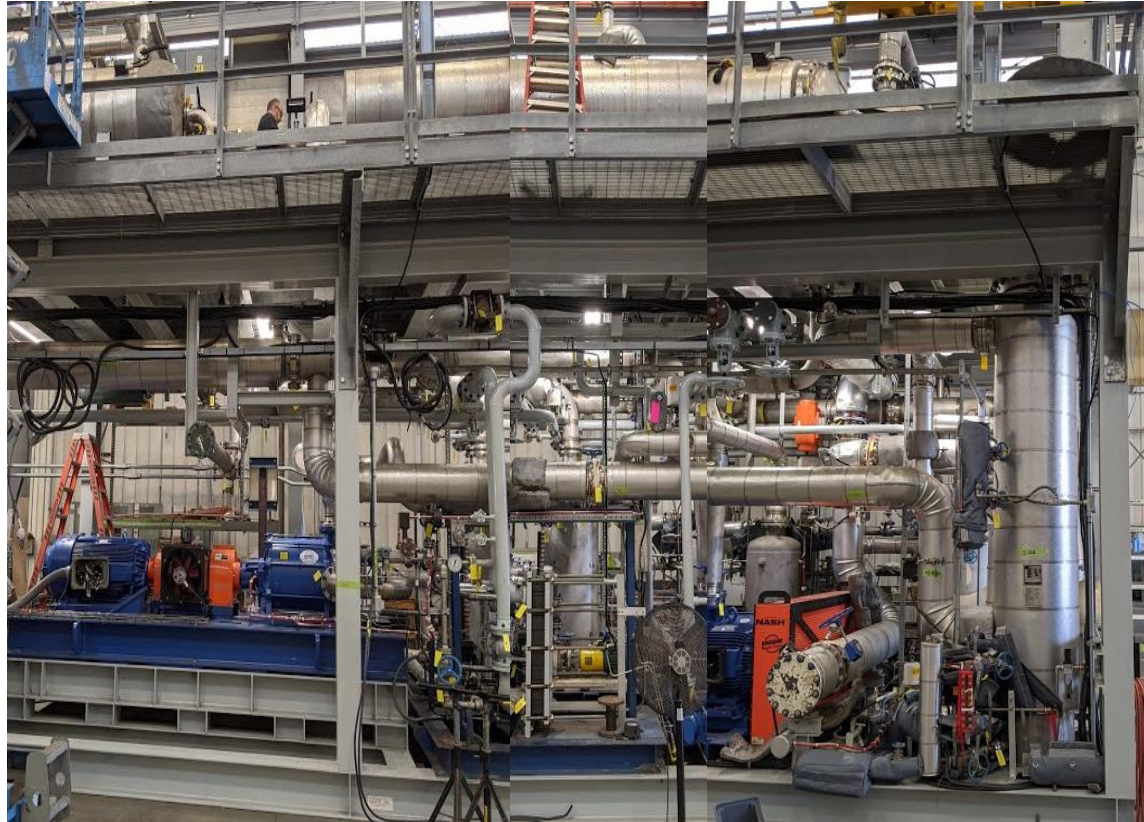
- TDA dual-bed sorbent system is fully assembled
- 3 skids + baghouse can be transported by low-boy trailer (domestic) or flat-rack (oceanic) for economical deployment

Progress on Skid #2 (Sorbent Vessels)



- Integrated Jib Crane (1/vessel) for self-sufficient sorbent loading/unloading & maintenance
- Custom wedge wire screens for sorbent retention (radial flow, Π -configuration)
- Upper decking and work platform with ladder, swing gate, and railing for safety

MTR Membrane Equipment

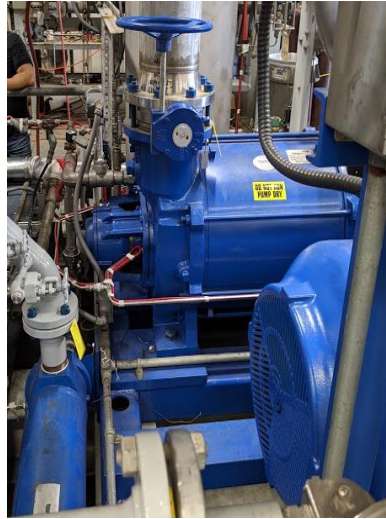


- **MTR membrane equipment is housed on two skids stacked vertically**
 - Lower skid houses the flue gas handling equipment
 - Membrane modules are located on the upper skid
- **The skids are assembled for testing at fabrication shop in Dupro, IL**

MTR Skid Modifications



Flue gas compressor



Vacuum pump

8" Vacuum
Regeneration

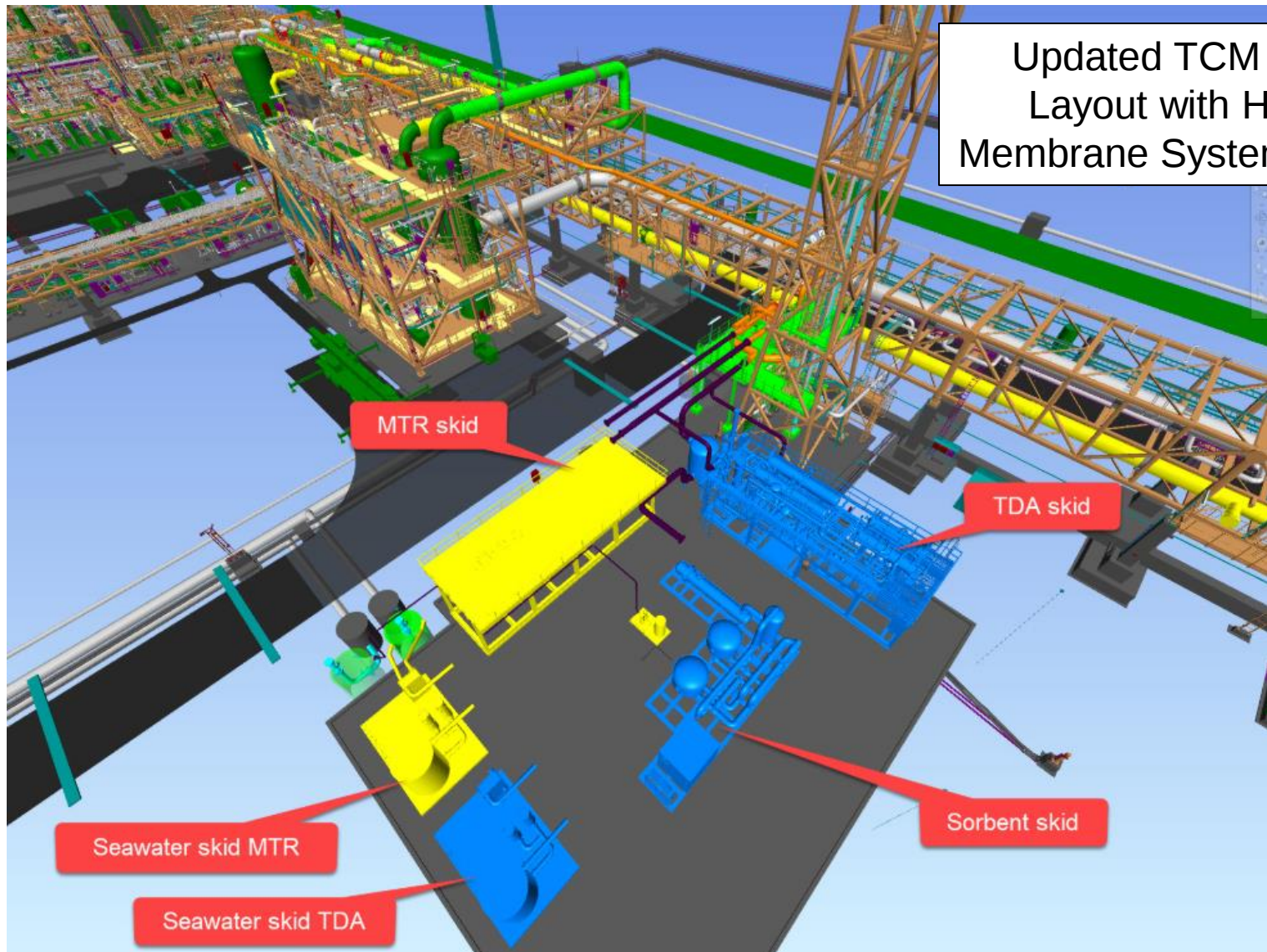
10" Membrane
Retentate

4" Supplemental
CO₂

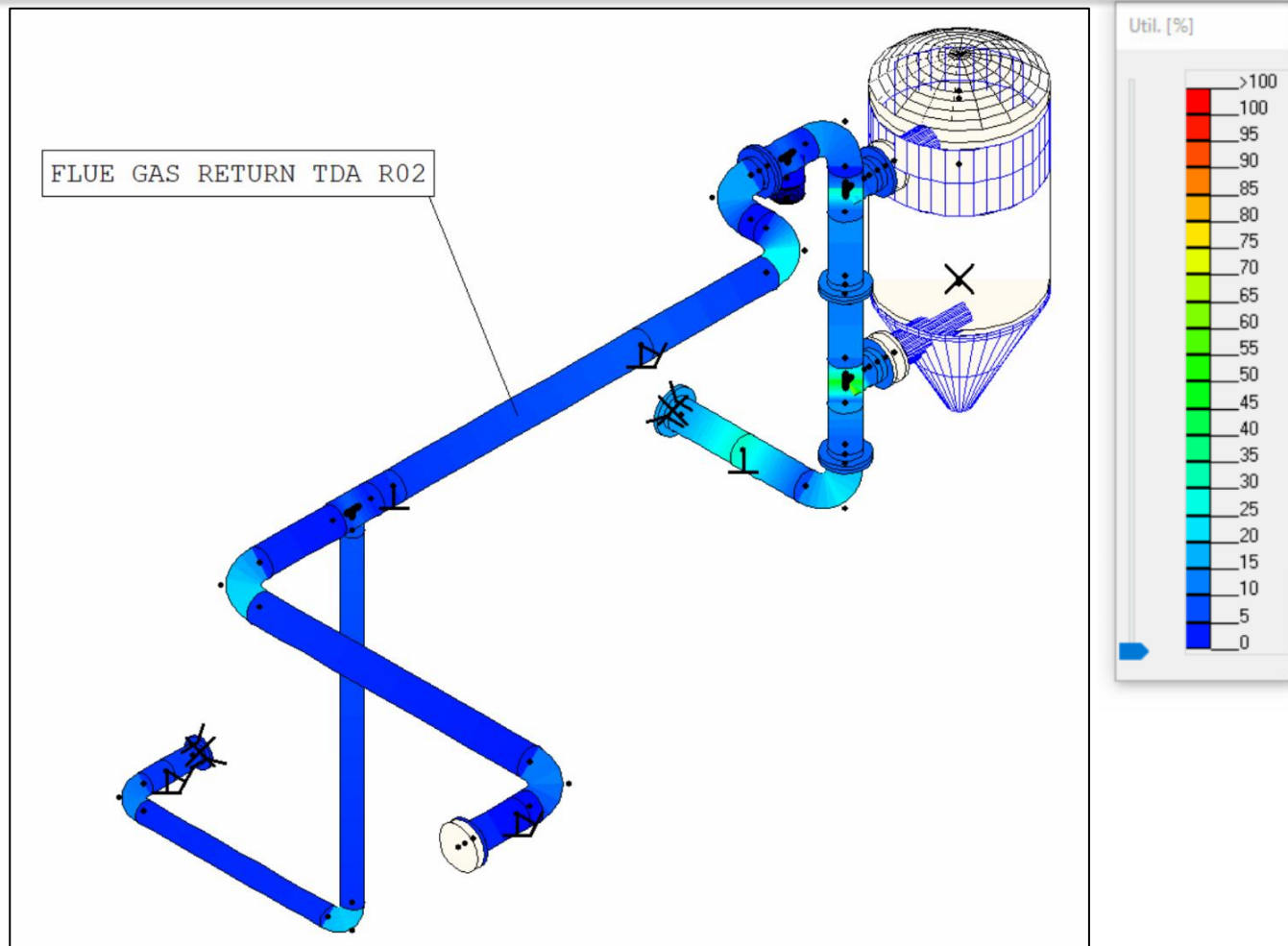
- Liquid ring compressor and vacuum pump were refurbished and retrofitted for use in Europe
- Addition of tie-points to the sorbent system have been completed
- Control system
 - Checked all five operating sequences for the membrane system
 - Checked all interlocks functionality



TCM Site Layout

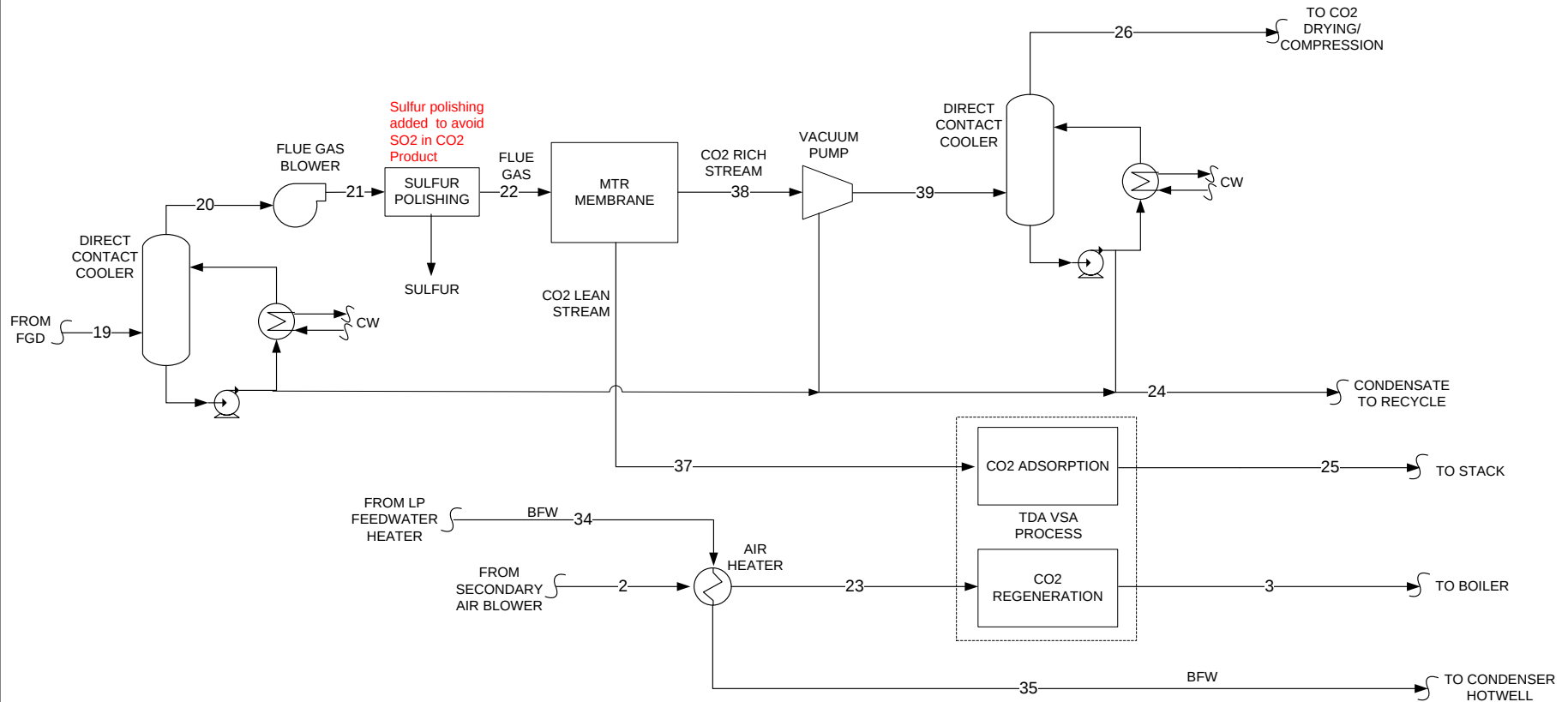


TCM Site Connections



- Pipe stress analysis has been complete with planned supports to API 660
- The 16" exhaust pipe is the largest/heaviest pipe and presents the greatest concern; TCM, TDA, and RKE collaborated to minimize stress on the baghouse flanges

Aspen Process Modeling (UCI)



Hybrid CO₂ Capture System (PFD)

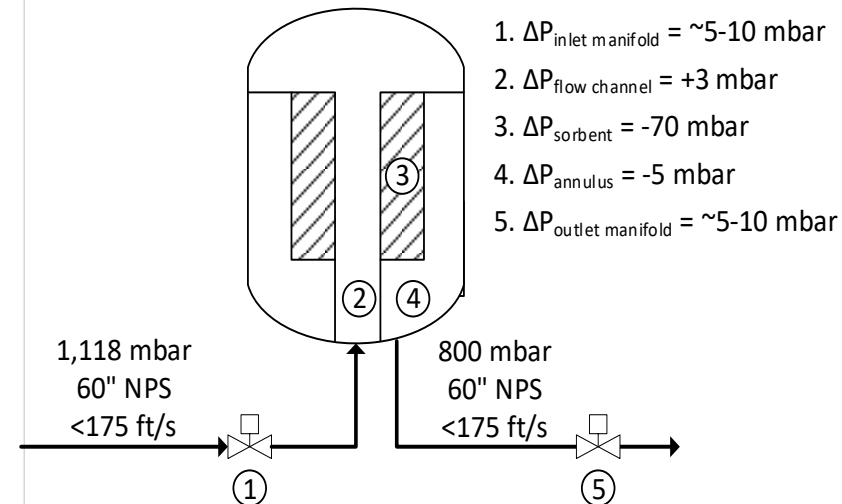
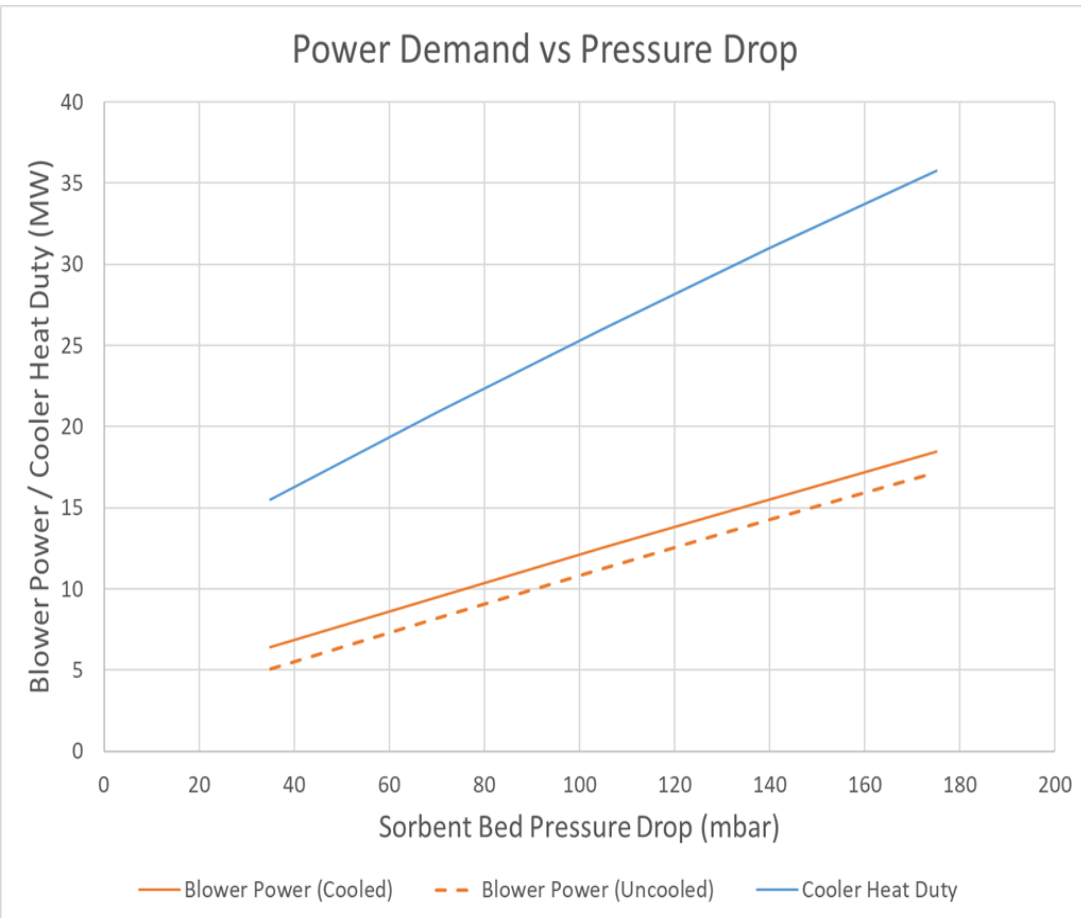
Advanced Power and Energy Program (APEP)	SBIR Phase 2 Study - Case 2
 UNIVERSITY OF CALIFORNIA, IRVINE	MTR-TDA PROCESS BLOCK FLOW DIAGRAM SUPERCritical PC POWER PLANT MEMBRANE + VSA CO ₂ CAPTURE

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

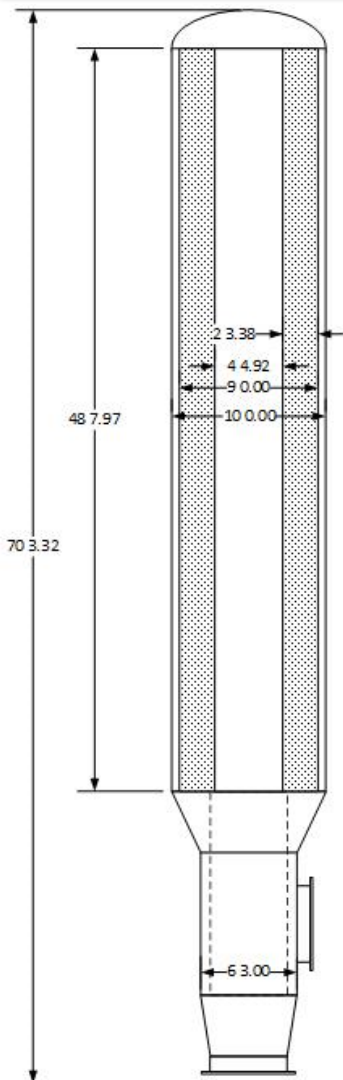
- TDA's membrane sorbent hybrid system has a net plant efficiency of 29.6% compared to 28.7% in MTR-Worley Parson Study which used compressed flue gas
 - Energy savings mainly from low pressure operation of membrane
 - More membrane area needed to achieve similar flux, impact on selectivity is minimal
- 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 System - Hybrid

	Stage I	Stage II
Bed 1		
Bed 2		
20s	60s	60s



Adsorption - Flue gas flow



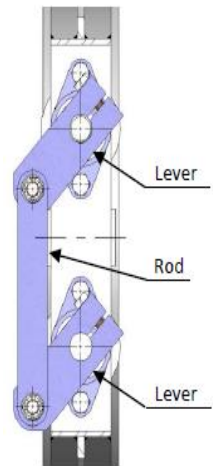
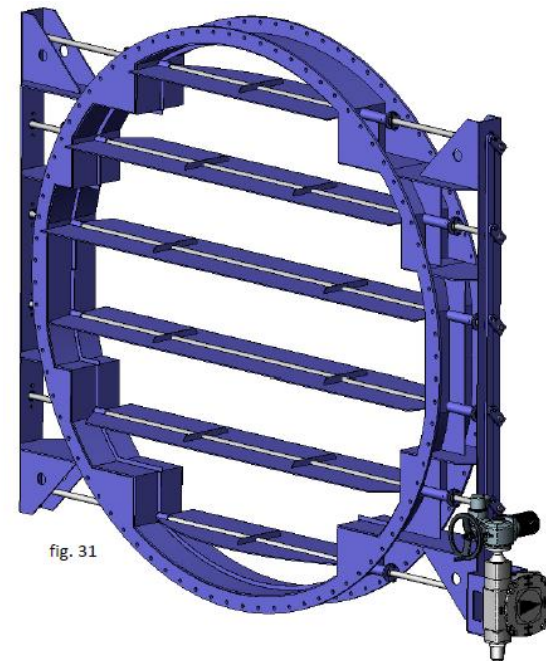
Desorption - Air Purge flow

$\Delta P = 105$ mbar

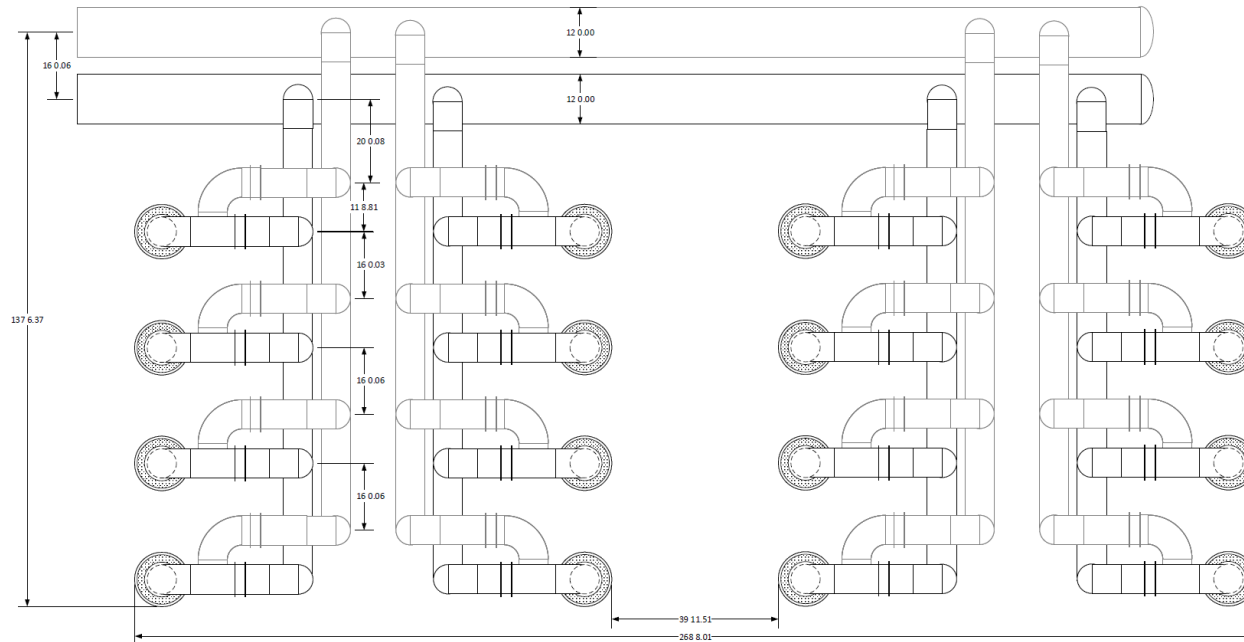
Module size	68.75 MW
No. of trains	8
No. beds per train	2
Total no. of beds	16
Flue gas flow	63.0 m ³ /s
CO ₂ flow	0.63 tonne/min
Capacity	1.7% wt. CO ₂
Bed online	1 min
Sorbent needed	37.2 tonne
density	0.56 tonne/m ³
Bed vol.	66.4 m ³
Bed CSA	6.6 m ²

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

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

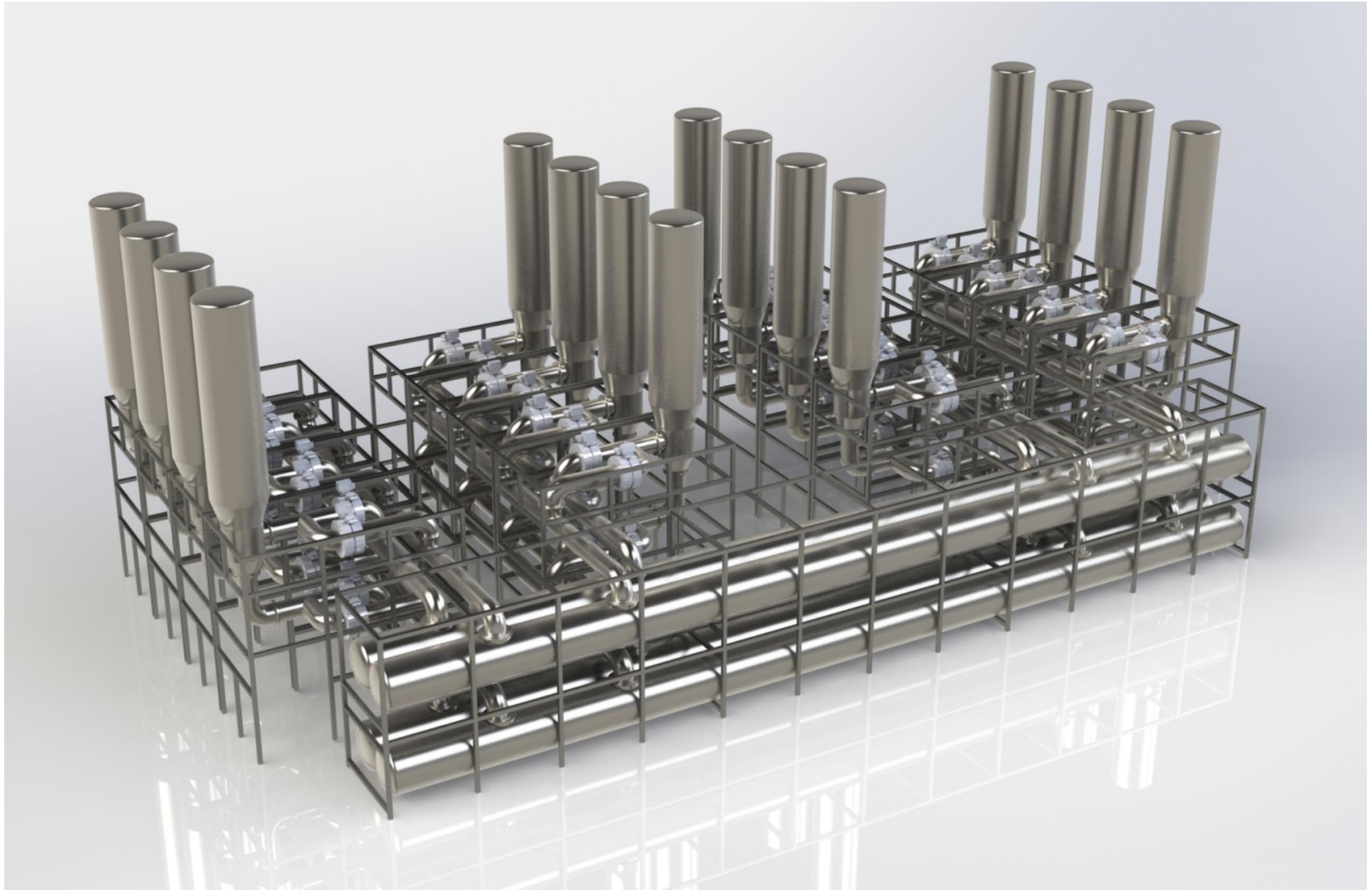


Piping Layout and Costing



- 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



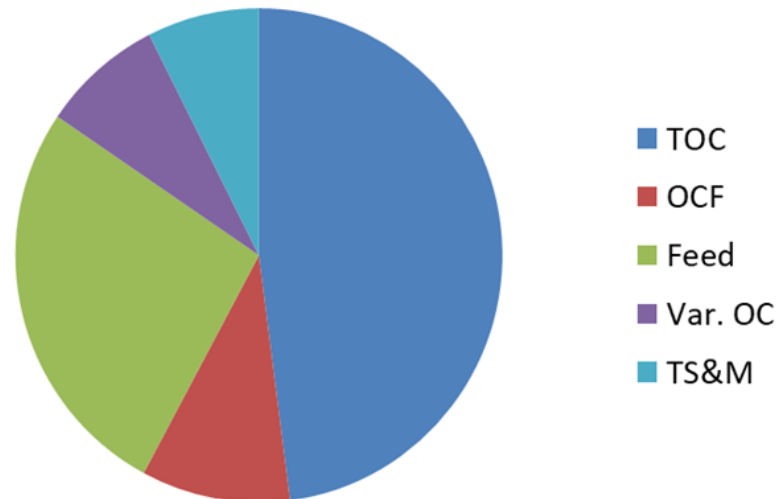
Hybrid CO₂ Capture System Cost

Acct		Equipment	Material	Labor		Bare Erected	Eng'g CM	Contingencies		TOTAL PLANT COST	
No.	Item/Description	Cost	Cost	Direct	Indirect	Cost \$	H.O. & Fee	Process	Project	\$	\$/kW
5A	FLUE GAS TREATMENT	7,668	2,089	4,175	-	13,932	1,343	-	3,054	18,329	33
5A.1	Flue Gas Blower	3,513	703	1,405	-	5,621	542	-	1,232	7,395	13
5A.2	Direct Contact Cooler	2,558	1,066	2,132	-	5,756	554	-	1,262	7,573	14
5A.3	Booster Air Fan	1,597	320	638	-	2,555	247	-	560	3,361	6
5B	CO2 REMOVAL	80,115	-	33,214	-	113,330	11,333	8,869	26,706	160,238	291
5B.1	Membrane Modules	13,907	-	13,907	-	27,815	2,781	5,563	7,232	43,391	79
5B.2	Sorbent Beds & Valves	11,020	-	5,510	-	16,530	1,653	3,306	4,298	25,787	47
5B.3	CO2 Purification Systems	16,472	-	4,118	-	20,590	2,059	-	4,530	27,178	49
5B.4	Vacuum Pump	38,716	-	9,679	-	48,395	4,840	-	10,647	63,882	116
5B.5	Compression System	48,646	-	18,072	-	66,718	6,672	-	14,678	88,068	160

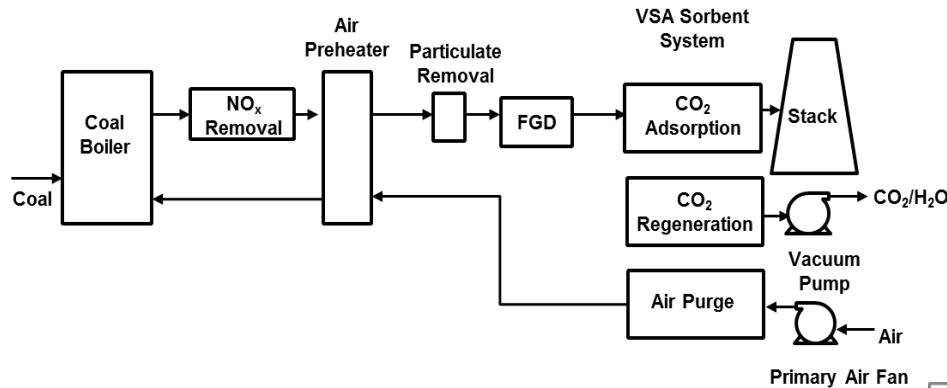
- CO₂ Capture System Cost for hybrid membrane sorbent process - \$160.2 MM
- With flue gas treatment subassembly (blowers , DCC etc.) - \$178.6 MM
- TDA's carbon Sorbent needed for initial load of 600 tonne at \$4/kg is \$2.4 MM

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
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Sorbent Only Recirculation - CAPEX

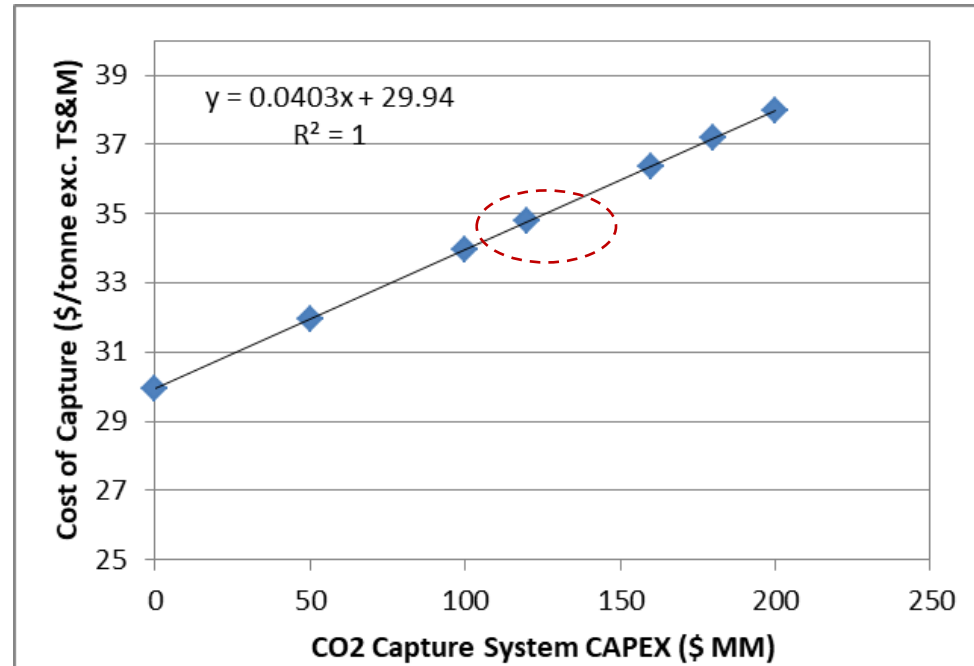


Sorbent Only System

	Stage I		Stage II		Stage III		Stage IV	
Bed 1	Adsorption - Flue gas flow		Cocurrent Blowdown		Desorption - CO2 Product Out		Desorption - Air Purge flow	
Bed 2								
Bed 3	Desorption - CO2 Product Out		Desorption - Air Purge flow		Desorption - Air Purge flow		Desorption - Air Purge flow	
Bed 4								
336s	21s	21s	21s	21s	21s	21s	21s	21s

Adsorption - Flue gas flow
 Desorption - CO2 Product Out
 Cocurrent Blowdown
 Desorption - Air Purge flow

- Membrane system can be replaced with a sorbent-only system
- Enables recovering CO₂ with high purity and reduce downstream purification systems and improve efficiency
- At a CAPEX of \$160 MM, the cost of carbon capture can be reduced to ~\$35/tonne



Acknowledgements

- DOE/NETL funding under the DE-FE-0013105 project
- Project Manager, Andy O'Palko
- Chuck Shistla, GTI
- Ashok Rao, UCI
- Arvind Rajandran, UOA
- Frank Morton, NCCC
- Chen Chaomei and Ruan Tian, Sinopec
- Yang Xujie, Yangtze Petrochemicals Nanhua Plant