Membrane-Sorbent Hybrid System for Post-Combustion CO_2 Capture (Contract No. DE-FE-0031603)

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DOE/NETL Carbon Capture Project Review Meeting

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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 CO_2 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	✓ Completed the design of the 1 MW scale test unit
	✓ Completed the Initial Design Review
	✓ Completed Preliminary Techno-economic analysis
BY2	✓ Fabrication of the test unit
	- Site Preparation, Installation and Shakedown Tests (9/2020)
BY3	- Field Tests (6-9 months duration)
	- High Fidelity Techno-economic analysis

TDA RESEARCH

Project Team

Project Duration

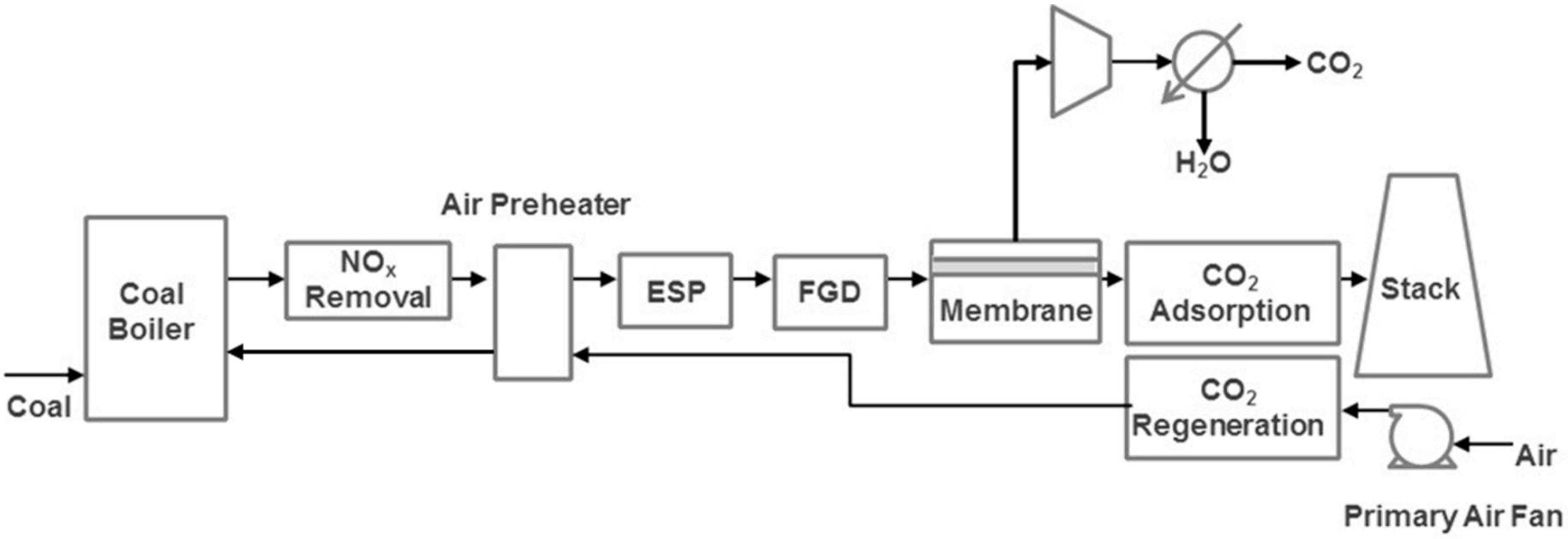
- **Start Date = August 17, 2018**
- **End Date = August 16, 2021**

Budget

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

TDA RESEARCH

Hybrid Membrane Sorbent Process



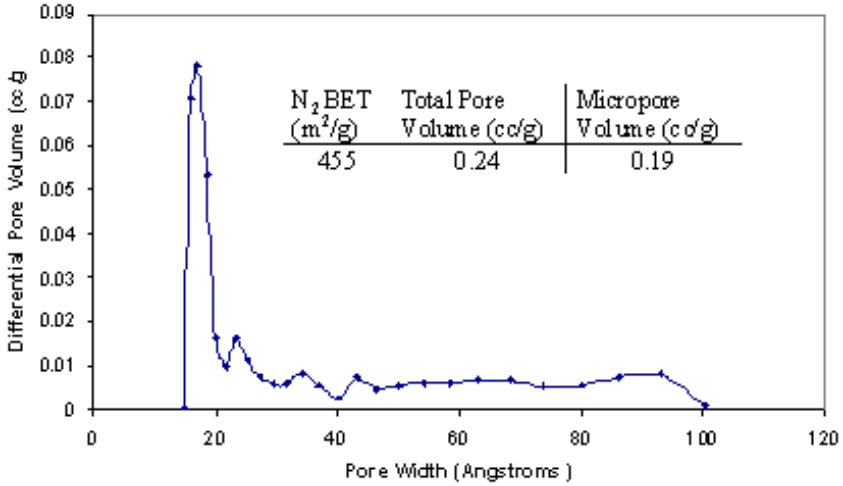
- **Membrane operates at ~50°C under mild vacuum, (~0.3 atm) removes ~50% of CO_2 and almost all water**
  - TDA's sorbent removes remaining CO_2 in the membrane effluent (retentate) ensuring 90% carbon capture
  - The boiler feed air is used as a sweep gas to facilitate sorbent regeneration
- **Advantages**
  - 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 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)

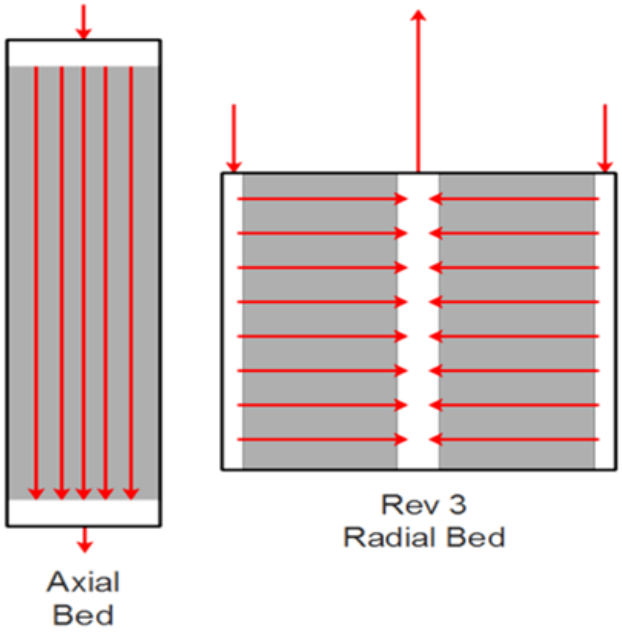


Sorbent operation in a VSA system was successfully demonstrated with actual flue gas (DE-0013105)

SBIR Phase IIB – Evaluation of the Hybrid System

100 SCFM Membrane-Sorbent Hybrid Test System

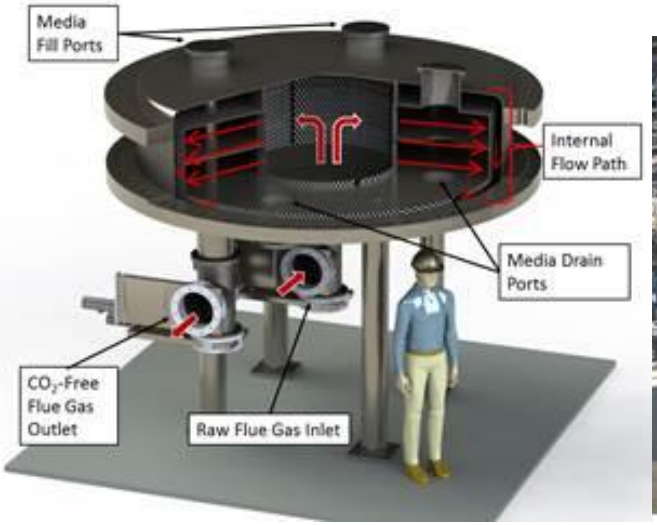
WITC near Basin Electric's Dry Fork Station in Gillette, WY



- **100 CFM evaluation removing 1 ton/day CO_2**
- **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% CO_2 purity with the membrane
  - 95+% CO_2 purity with the sorbent (due to low N_2 affinity over the sorbent)

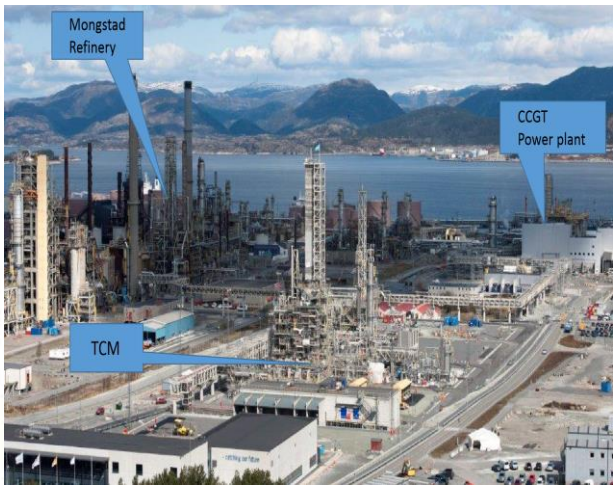
Current Project Focus

- **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)

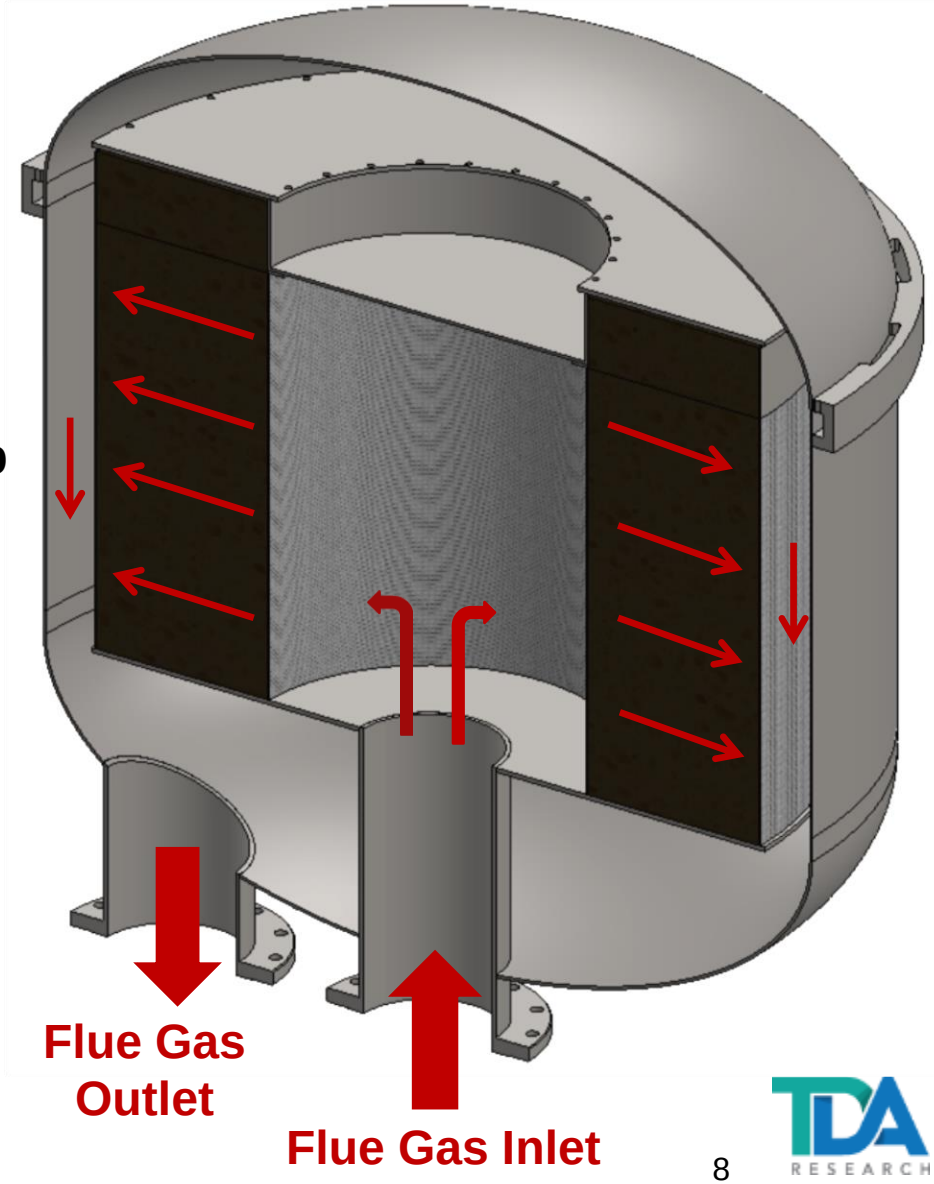


TCM Mongstad, Norway

Design of the 1 MW Reactor

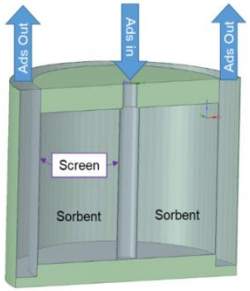
- Bed volume = 1.33 m^3 (with additional room for contingencies)
- Inner screen dia. = 30”
- Outer screen dia. = 62”
- Vessel OD = 72”
- Piping = 12” SCH40S
- Locking ring flange for access
- Vessel weight (w/o sorbent) = 3,000 lb
- dP = 44 mbar (8x16 mesh sorbent)
- dP = 106 mbar (12x40 mesh sorbent)

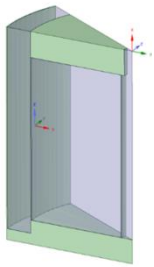
- Removable reactor end cap/head to allow sorbent fill
- Sorbent bed is a donut shaped basket loaded from the top
- Blanked off section will prevent channeling due to bed shrinkage
- Minimal media handling is required to test modular reactor concept



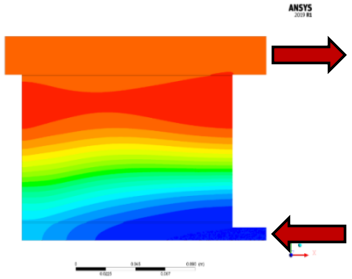
Design of the Sorbent Vessels

- **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**

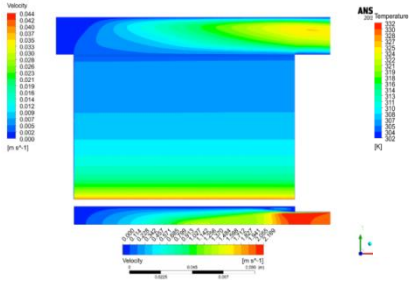




end of adsorption

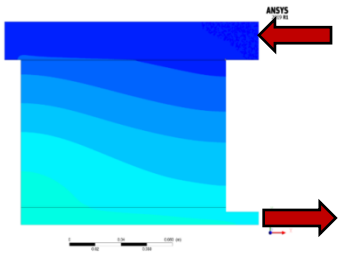


Temperature

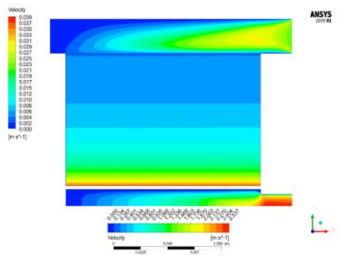


Velocity

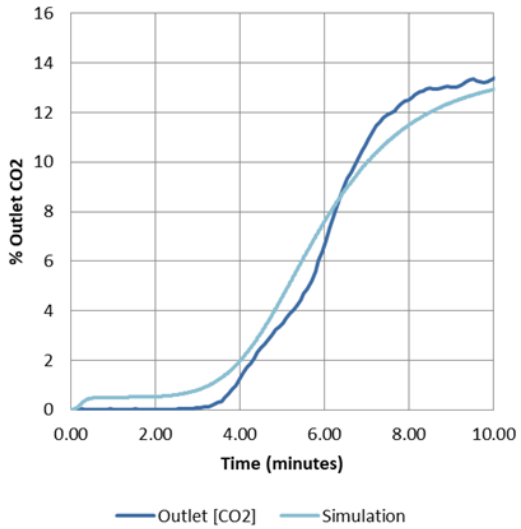
end of desorption

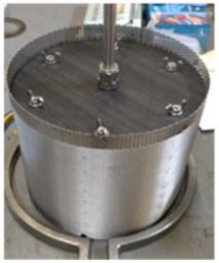


Temperature

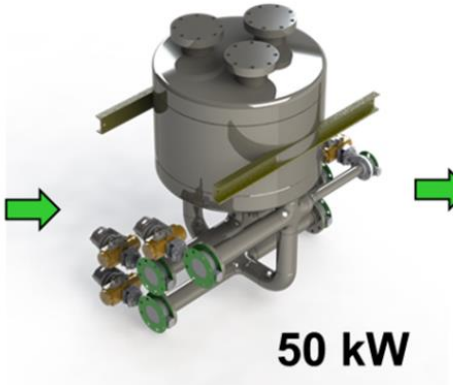


Velocity

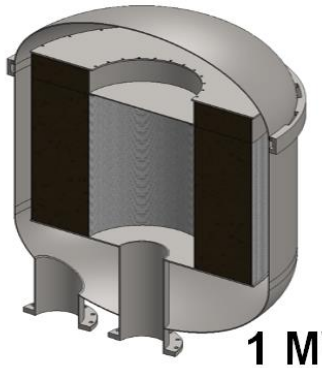




2 kW

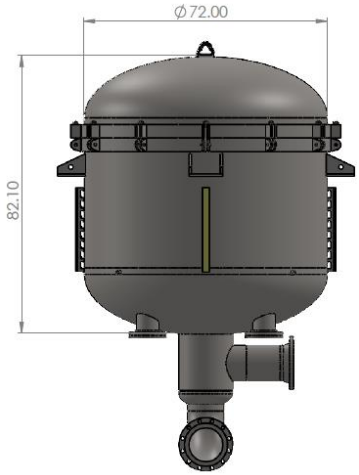


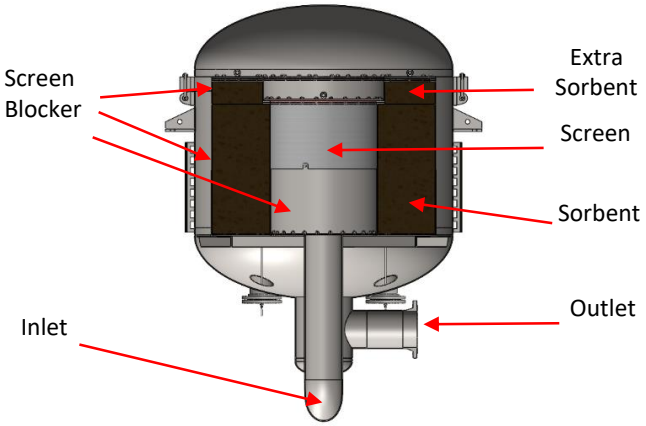
50 kW

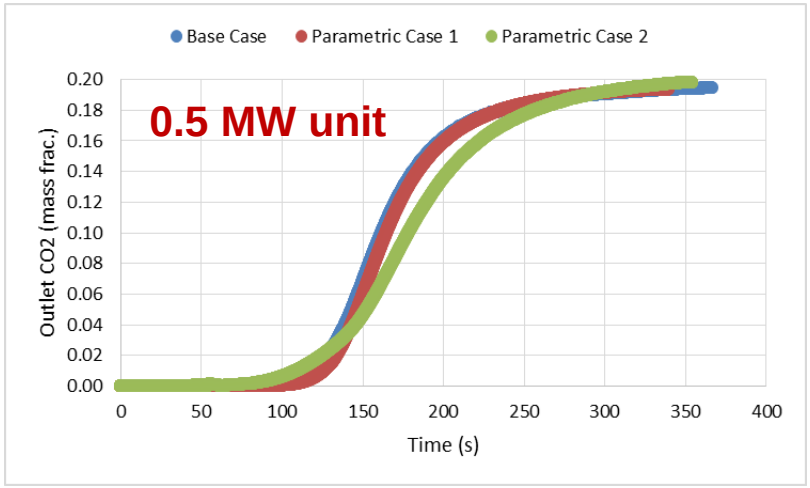


1 MW

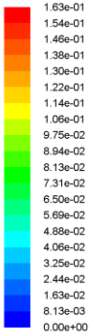
CFD Modeling of Sorbent Reactor

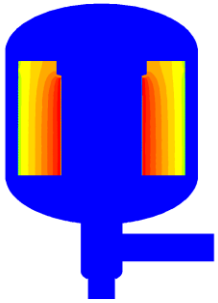




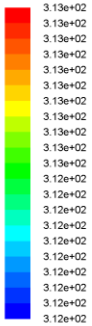


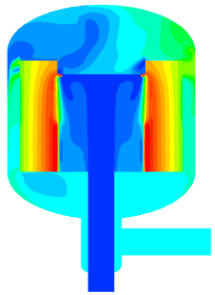
CO_2 Sorbent Loading

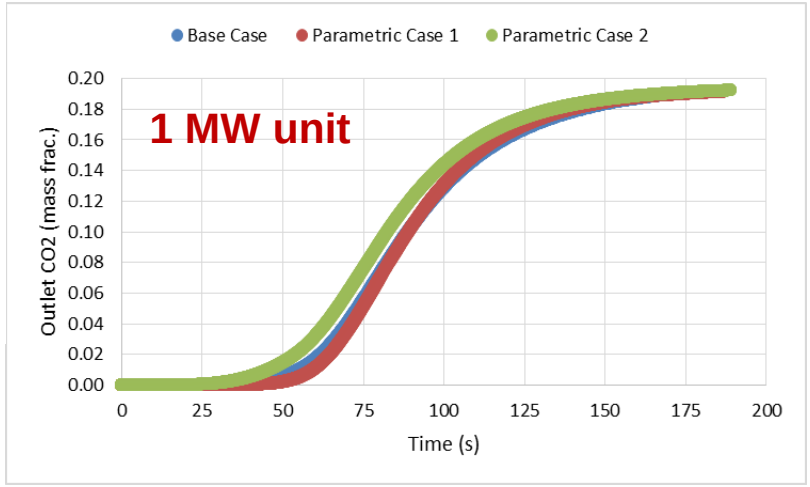




Temperature Contour

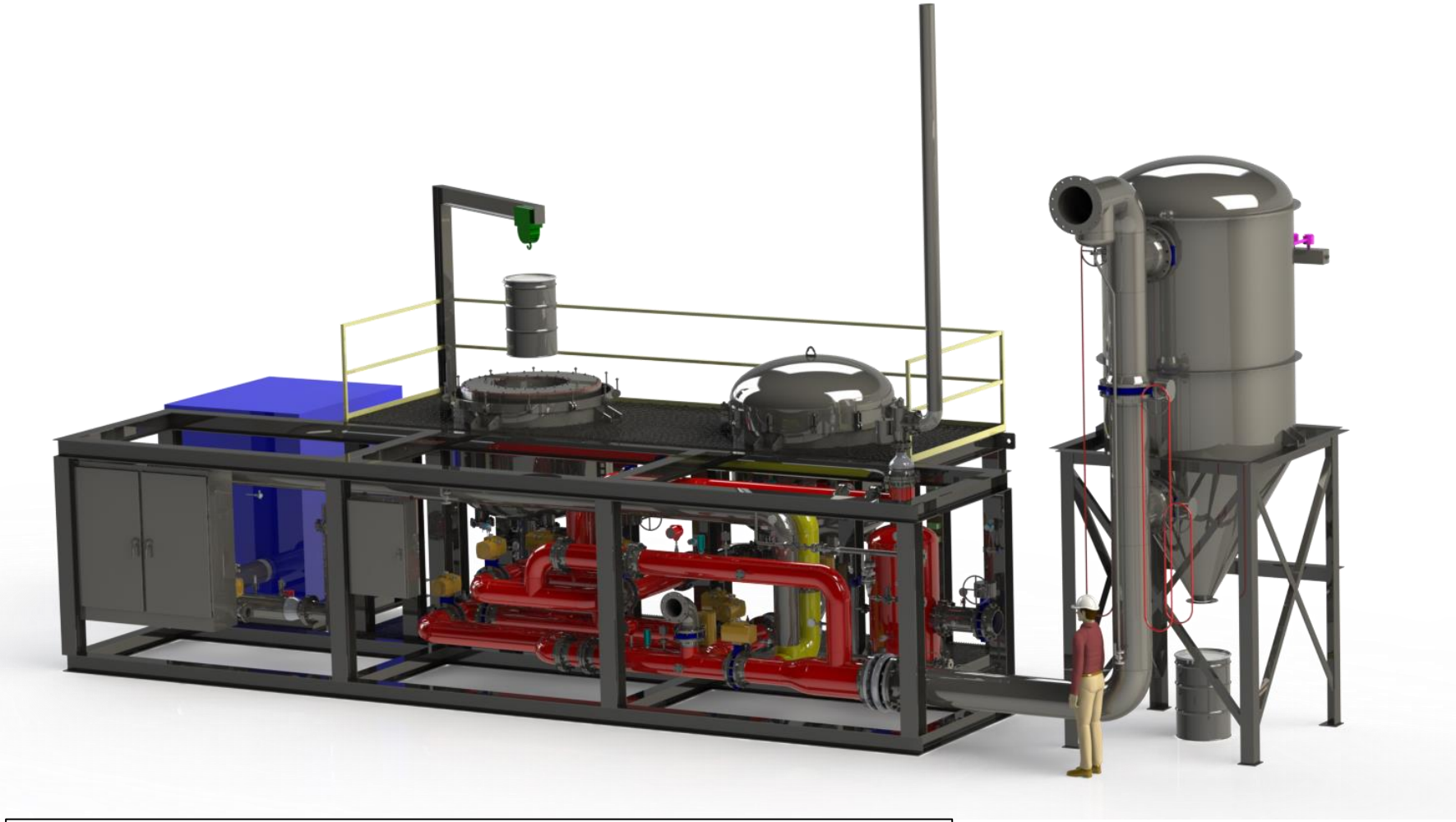






- GTI completed the model development for the radial sorbent beds that will be used in the field
- Clean breakthrough curves

Design of the Sorbent System

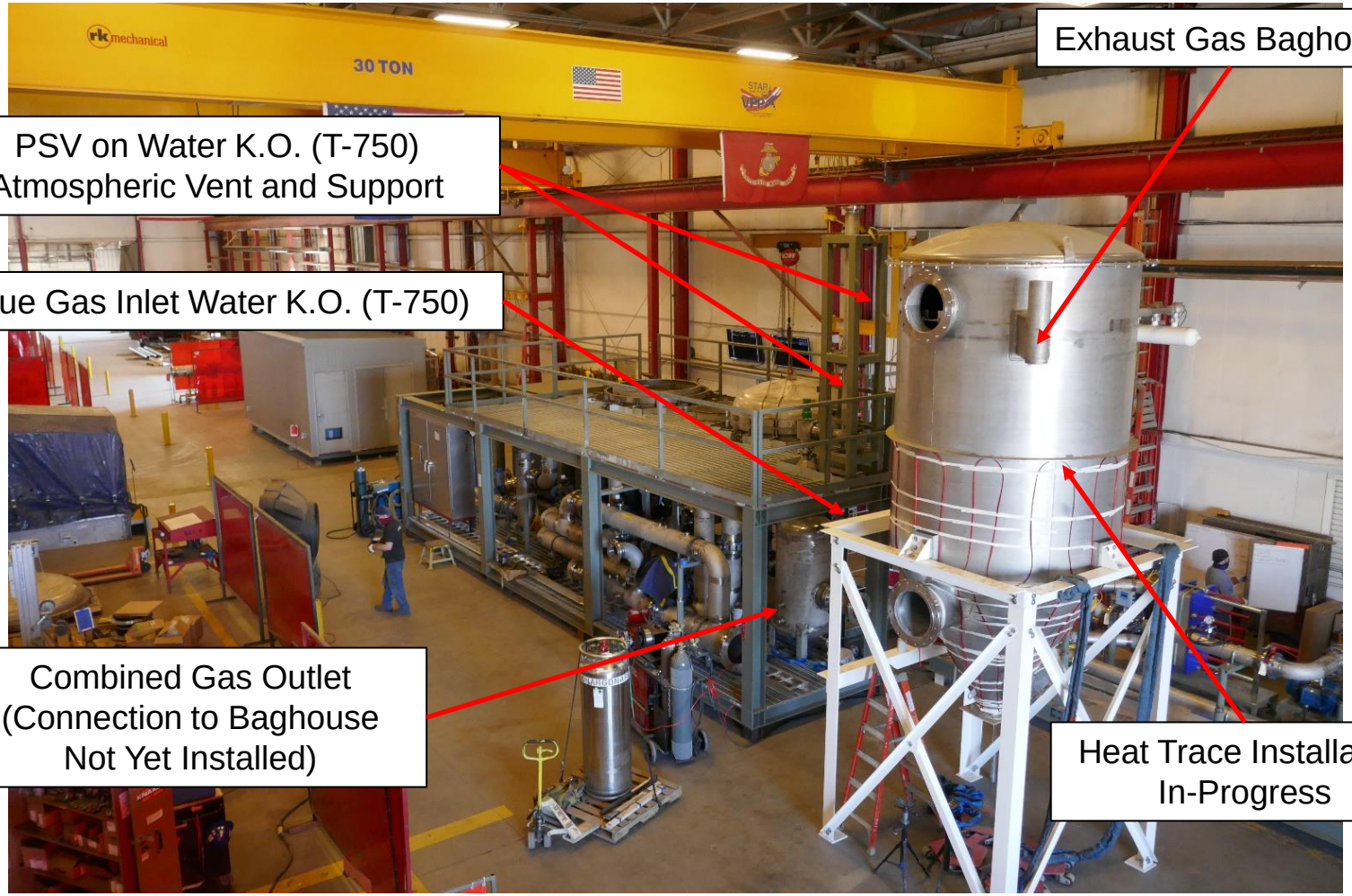


Assembled Onsite from Multiple Skids

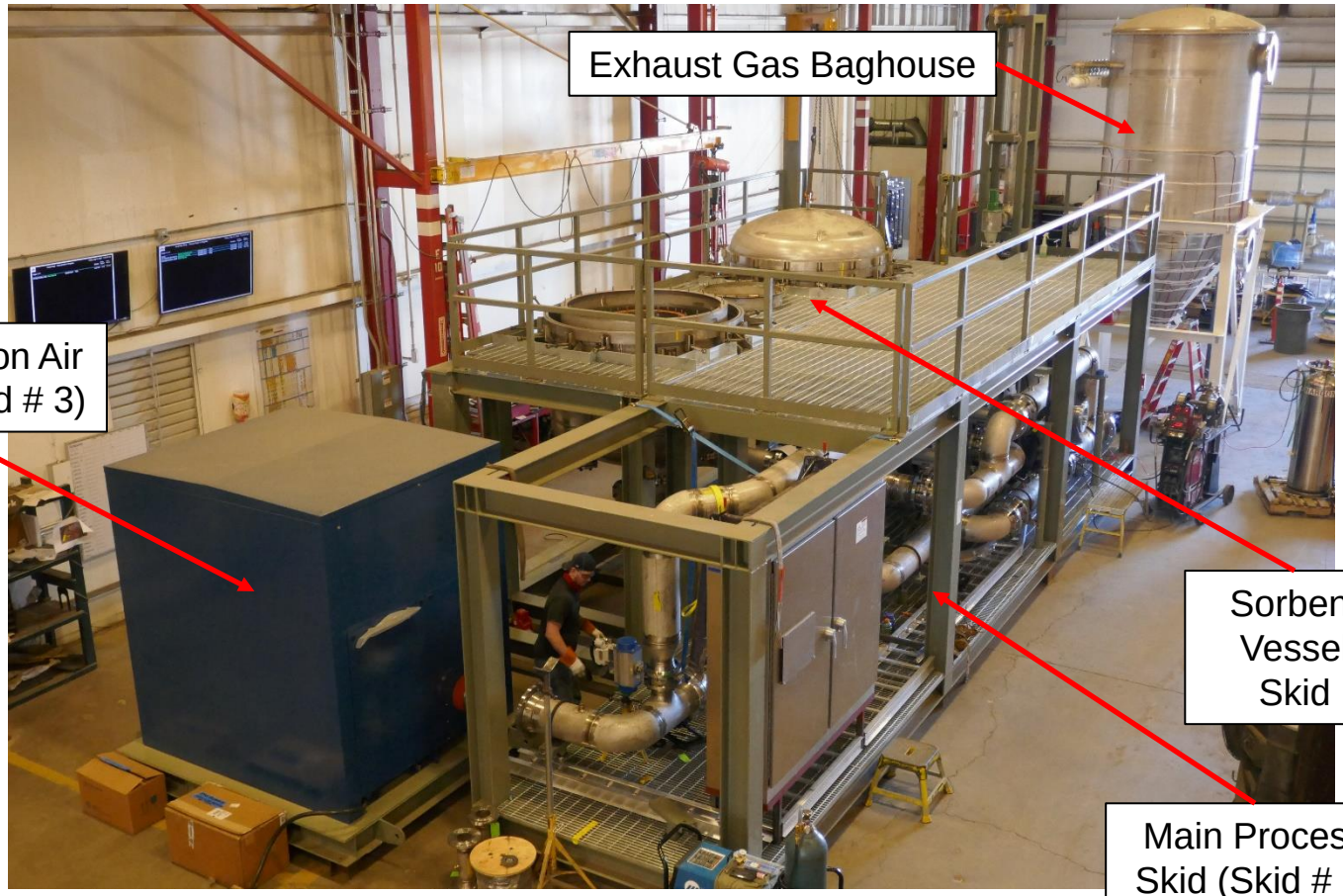
(All Skids Pack Into Hi-Cube Conex for Low-Cost Shipping)

TDA RESEARCH

Sorbent Subsystem

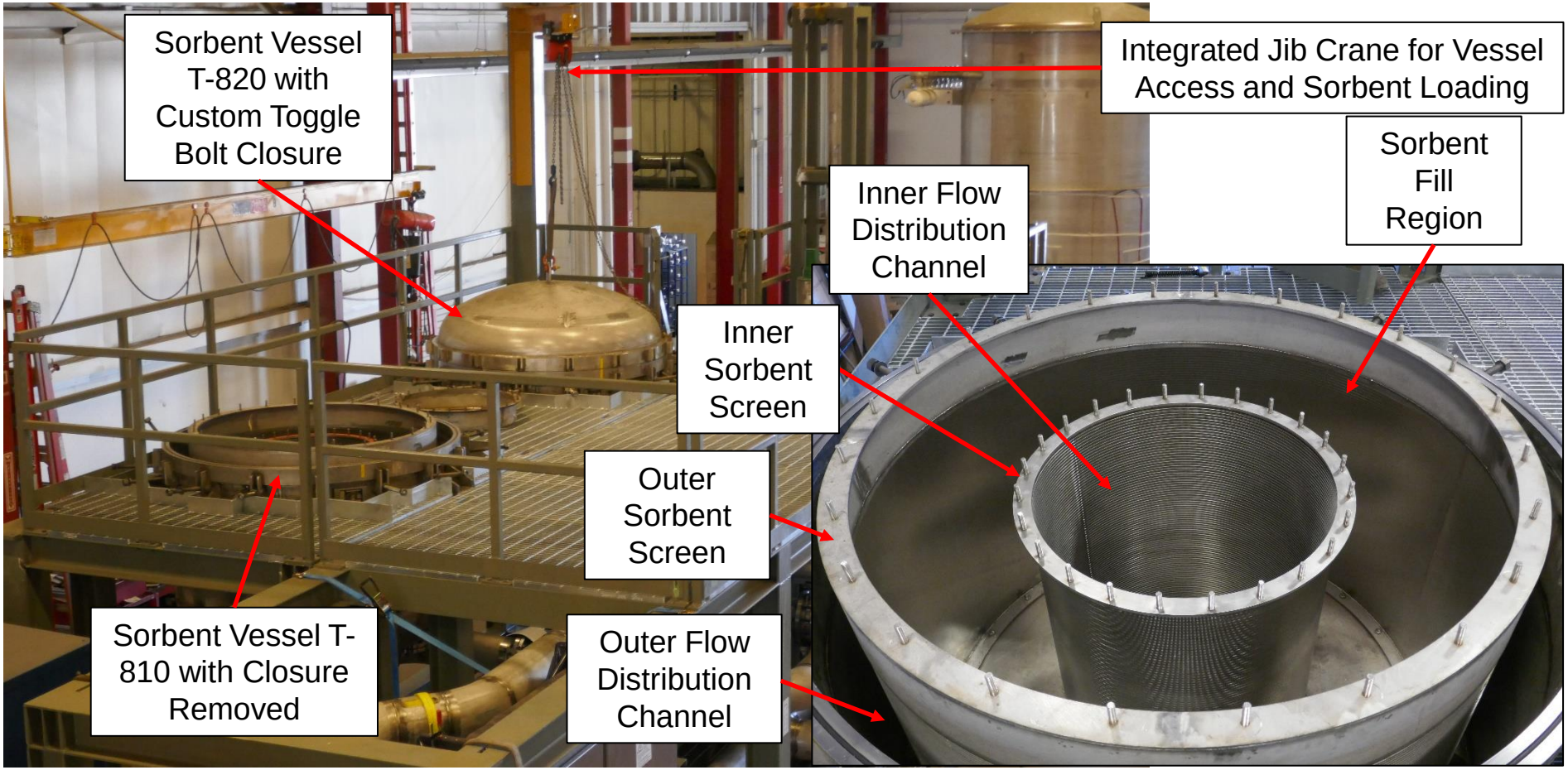


TDA's Dual-Bed Sorbent Subsystem



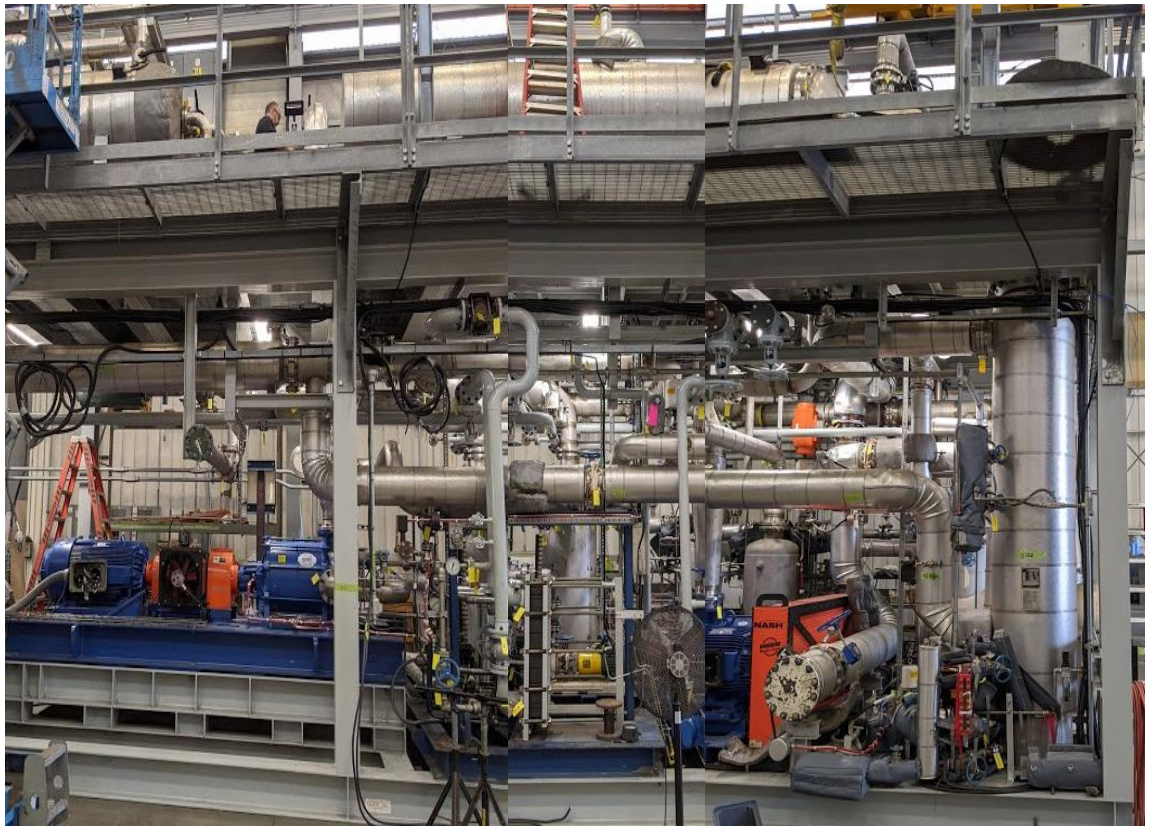
- TDA dual-bed sorbent system is fully assembled
- 3 skids + baghouse can be transported by low-boy trailer (domestic) or flat-rack (oceanic) for economical deployment

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

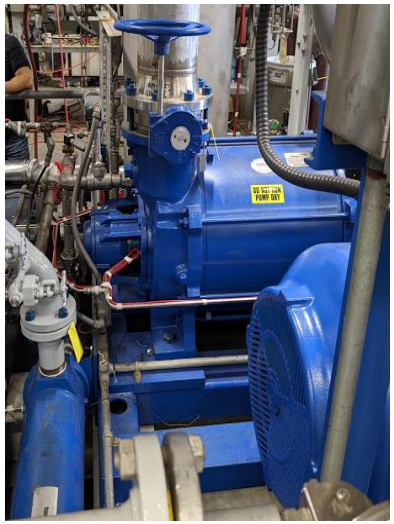


- **MTR membrane equipment is housed on two skids stacked vertically**
  - Lower skid houses the flue gas handling equipment
  - Membrane modules are located on the upper skid
- **The skids are assembled for testing at fabrication shop in Dupo, IL**

TDA RESEARCH

MTR Skid Modifications

Flue gas compressor



Vacuum pump

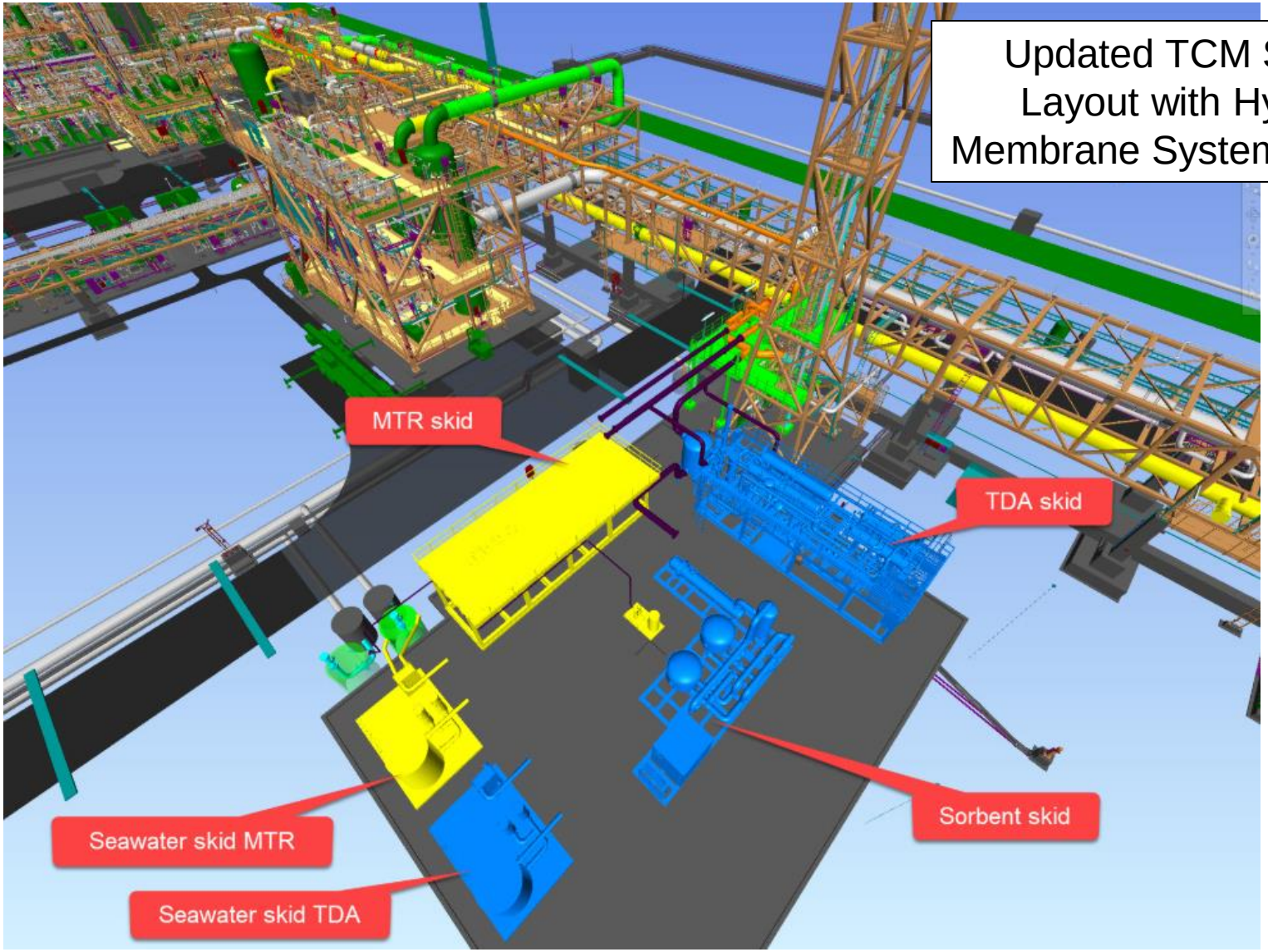
8” Vacuum Regeneration

10” Membrane Retentate

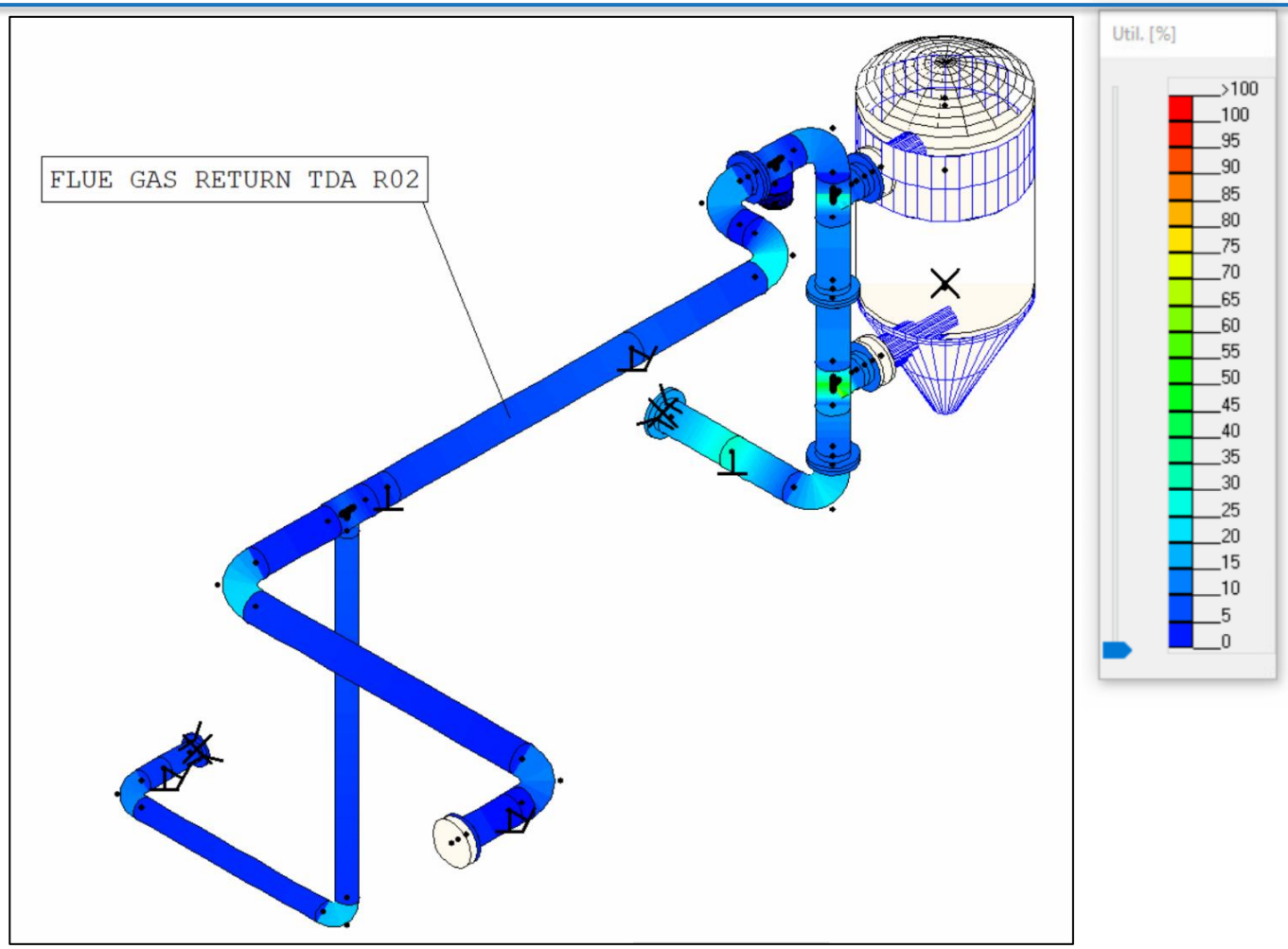
4” Supplemental CO_2

- **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

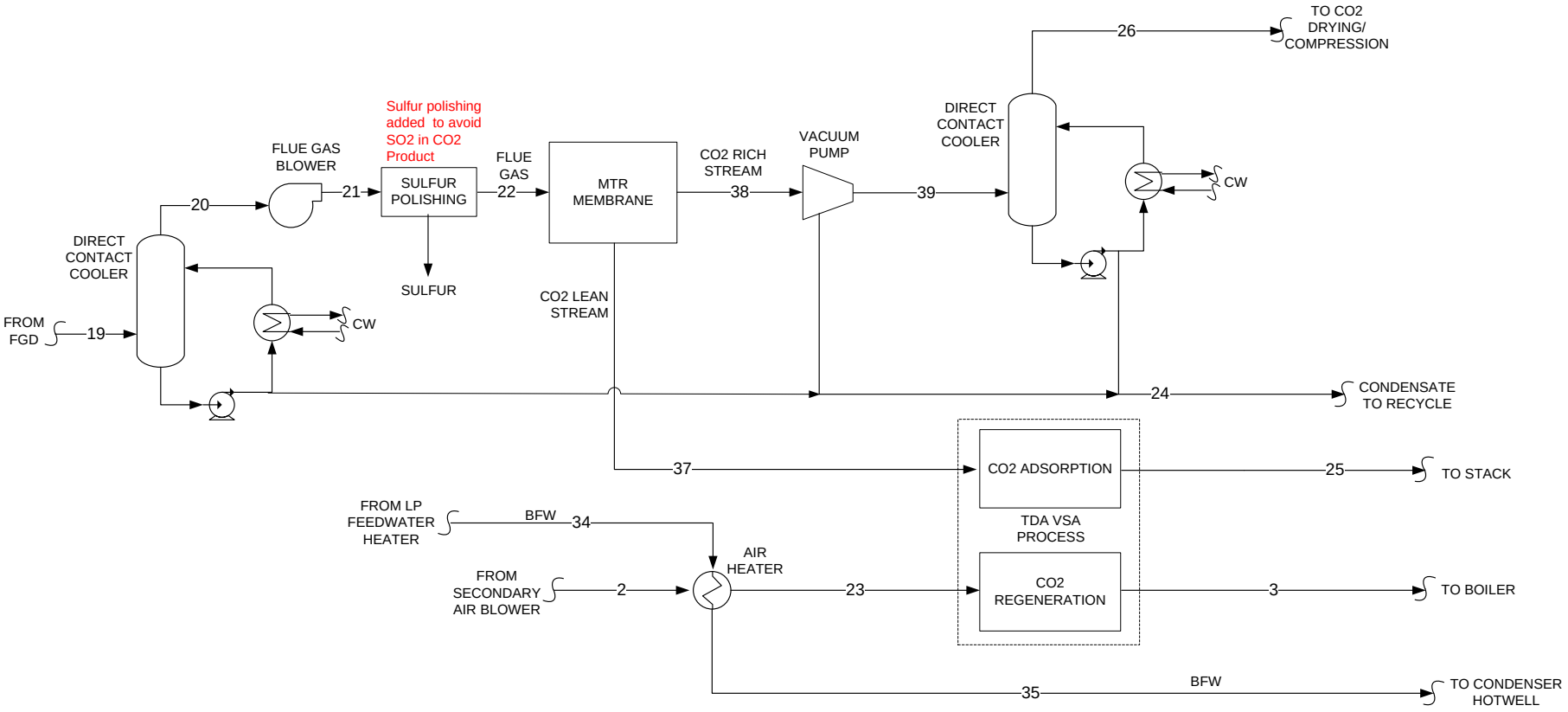


TCM Site Connections



- 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 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

IDA RESEARCH

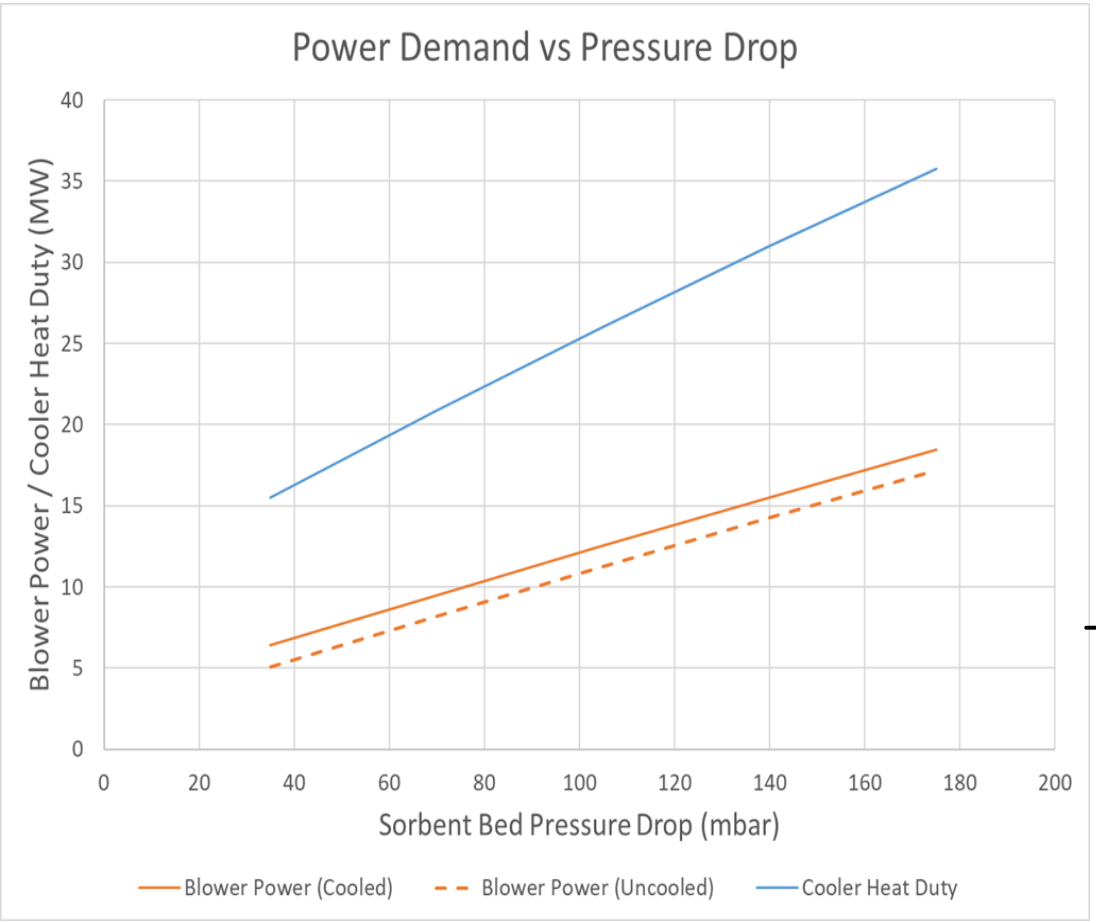
Plant Performance

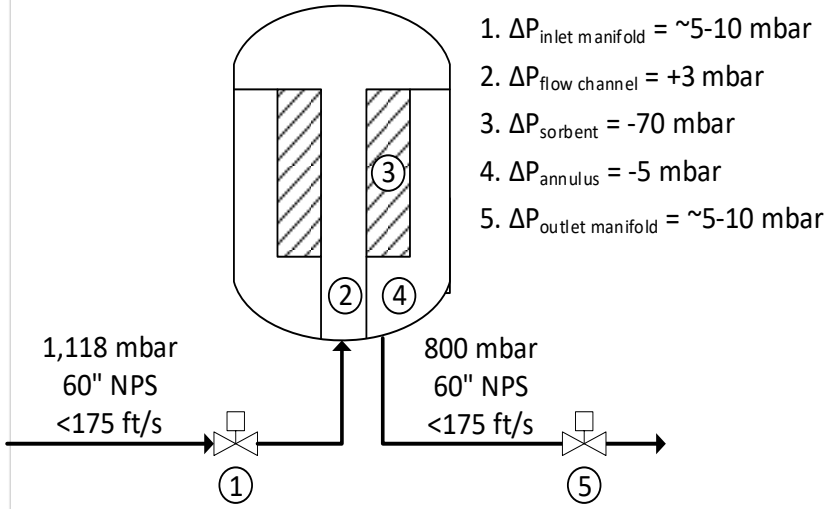
CASE NO.	UNITs	DoE 11	DoE 12	MTR WP Study	TDA + MTR 3	Sorbent Only	Sorbent Only
CO_2 capture technology		Reference No Capture	Reference Amine	Membrane Only	Membrane-Sorbent Hybrid	Sorbent Only - Recirculation	Sorbent Only - Steam Purge
CO_2 purity from separation Module			**95%**	**80%**	**80%**	**95%**	**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

TDA RESEARCH

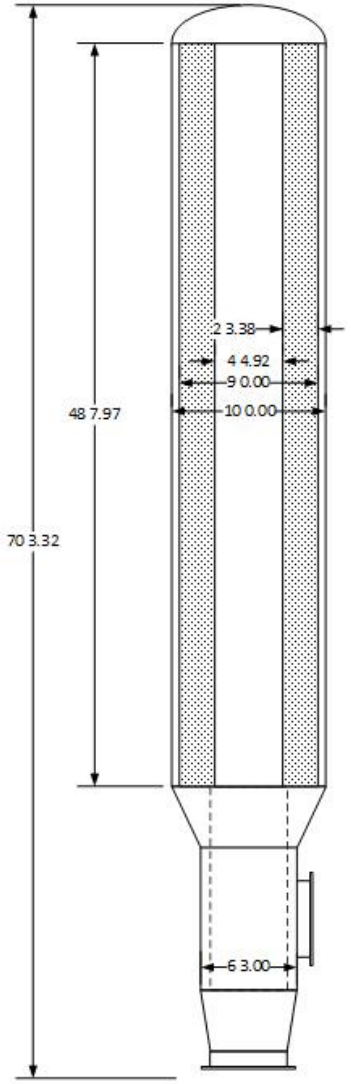
Pressure Drop Constraint





- **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

orbent System - Hybrid

	Stage I	Stage II
ed 1		
ed 2		
20s	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

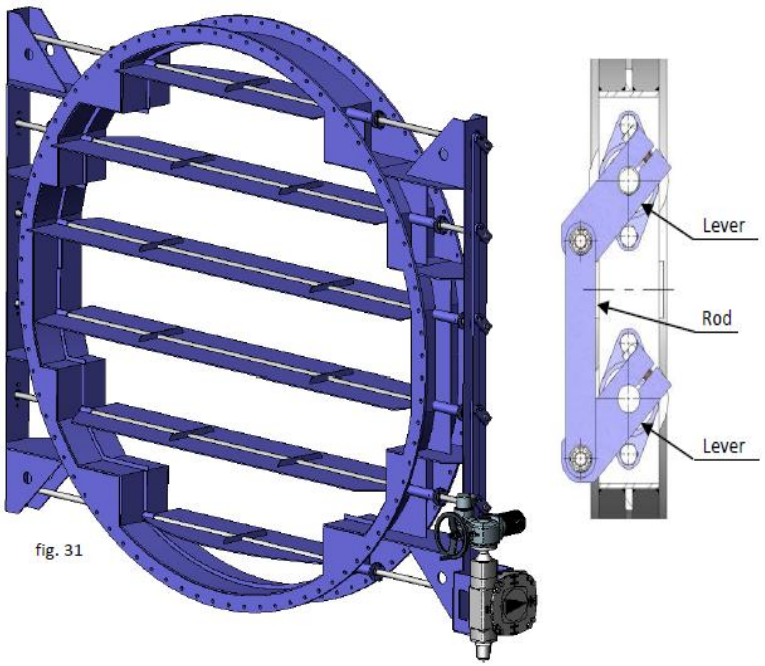
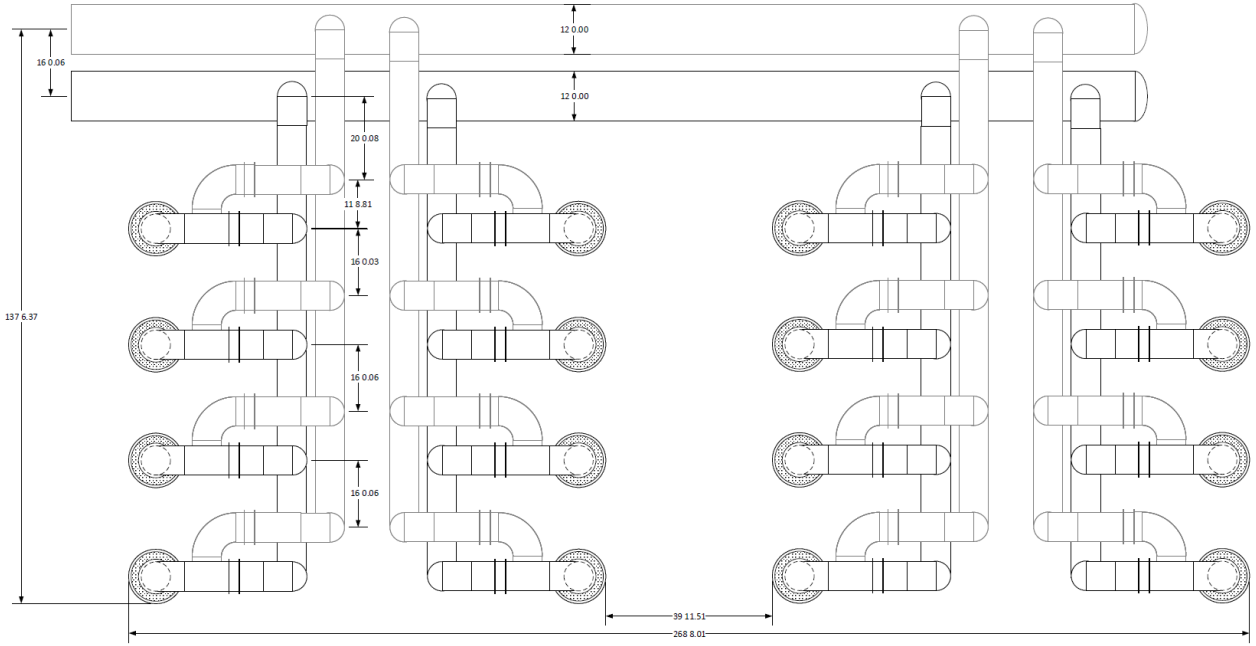


fig. 31

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

TDA RESEARCH

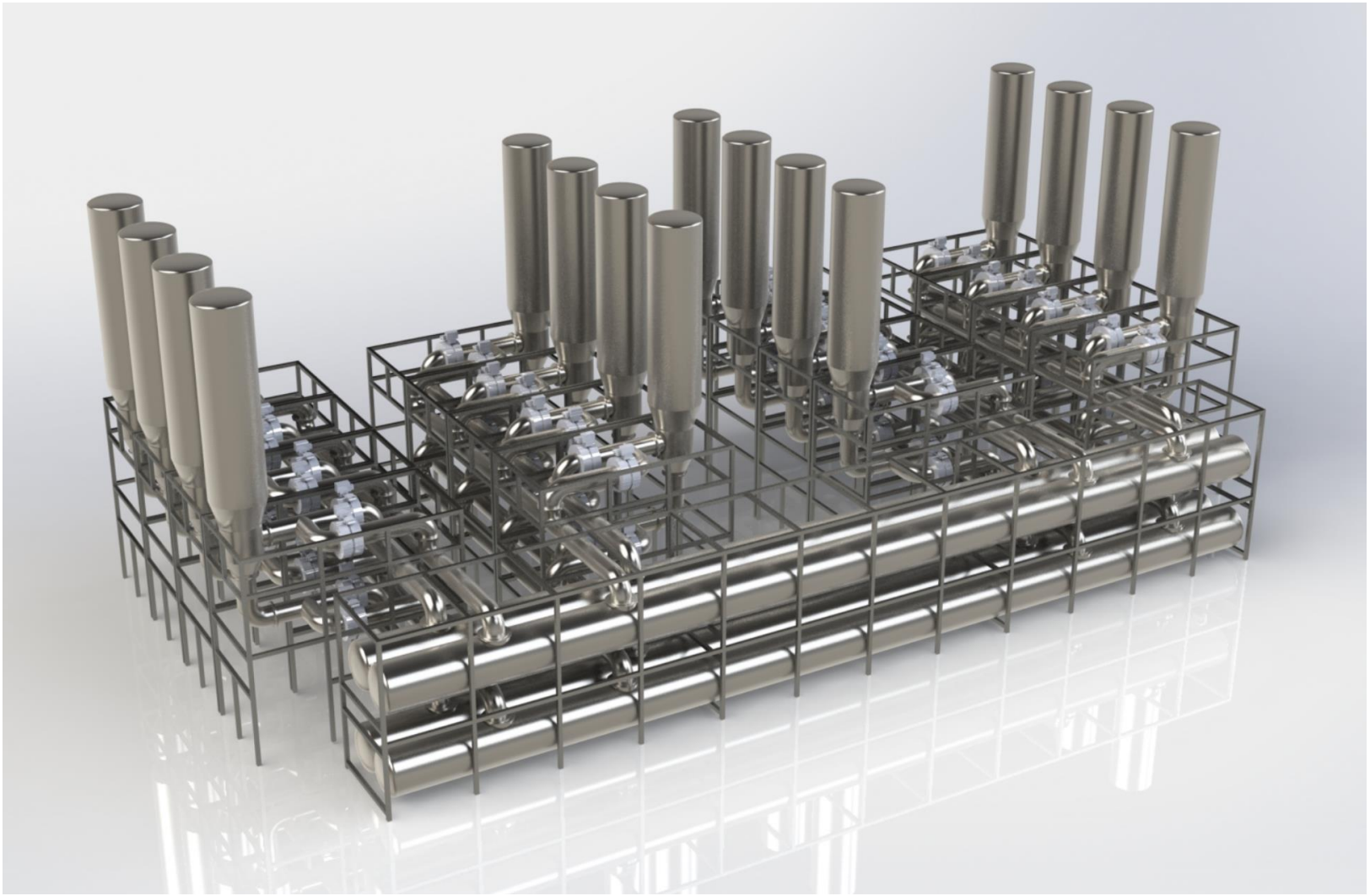
Piping Layout and Costing



- 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)

TDA RESEARCH

3-D Layout of the Hybrid Sorbent System



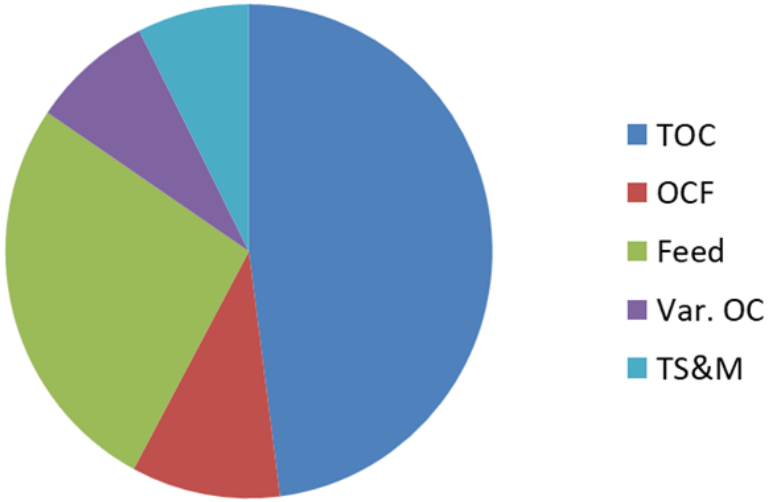
Hybrid CO_2 Capture System Cost

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

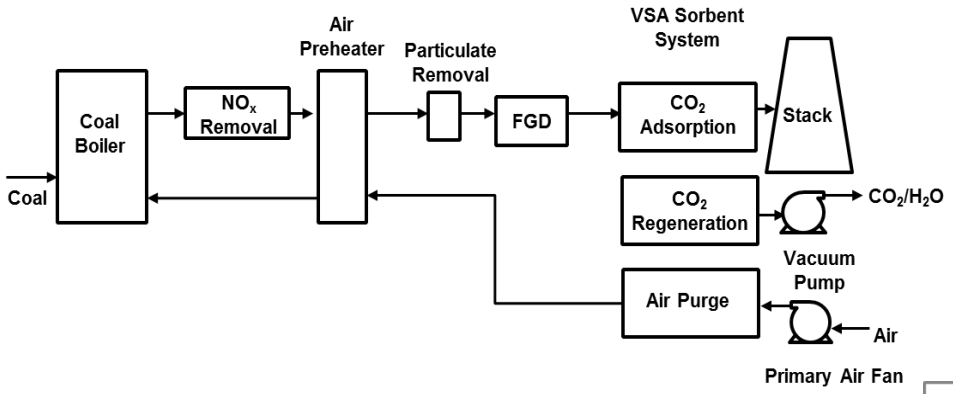
- CO_2 Capture System Cost for hybrid membrane sorbent process - $160.2 MM
- With flue gas treatment subassembly (blowers , DCC etc.) - $178.6 MM
- TDA's carbon Sorbent needed for initial load of 600 tonne at $4/kg is $2.4 MM

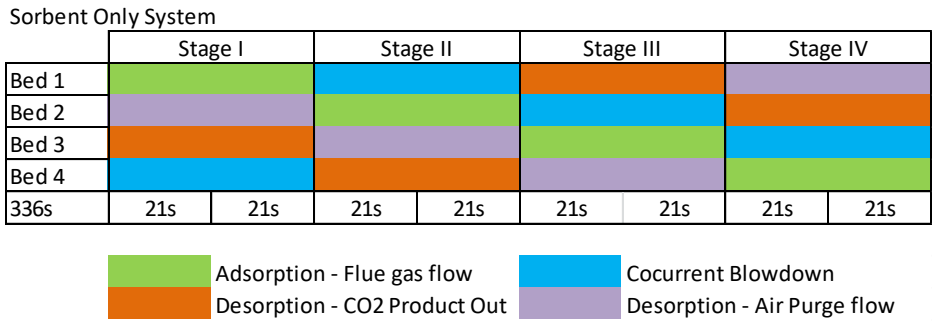
Cost of Electricity	$ 2011 basis
TOC	61.03
OCF	12.56
Feed	33.84
Var. OC	10.25
TS&M	9.44
COE $/MWh	117.68
COE w TS&M $/MWh	127.13

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

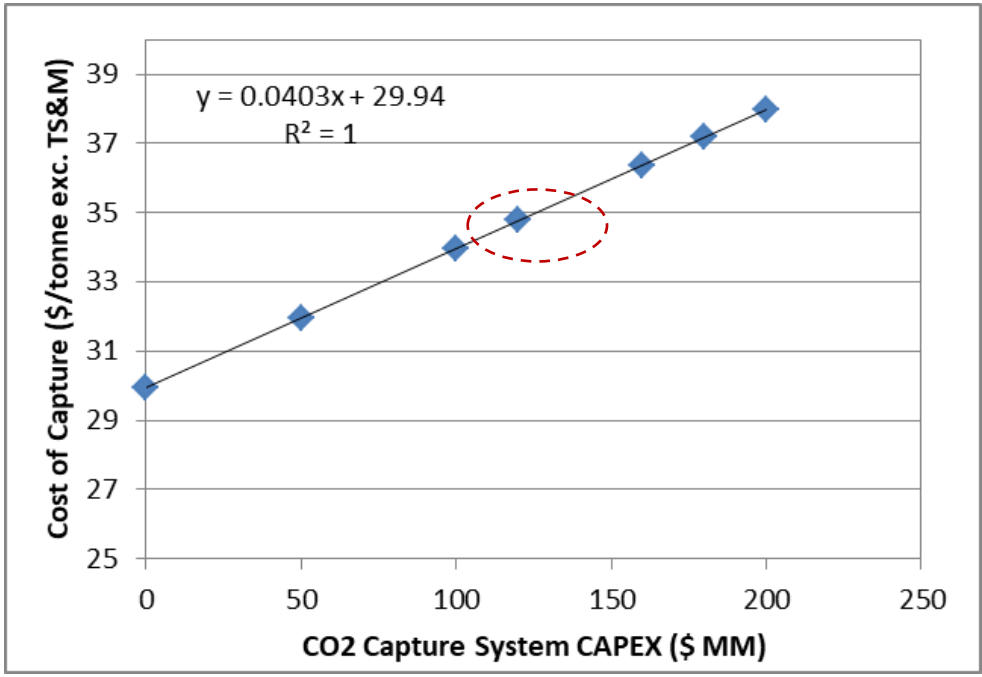


Sorbent Only Recirculation - CAPEX





- Membrane system can be replaced with a sorbent-only system
- Enables recovering CO_2 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



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