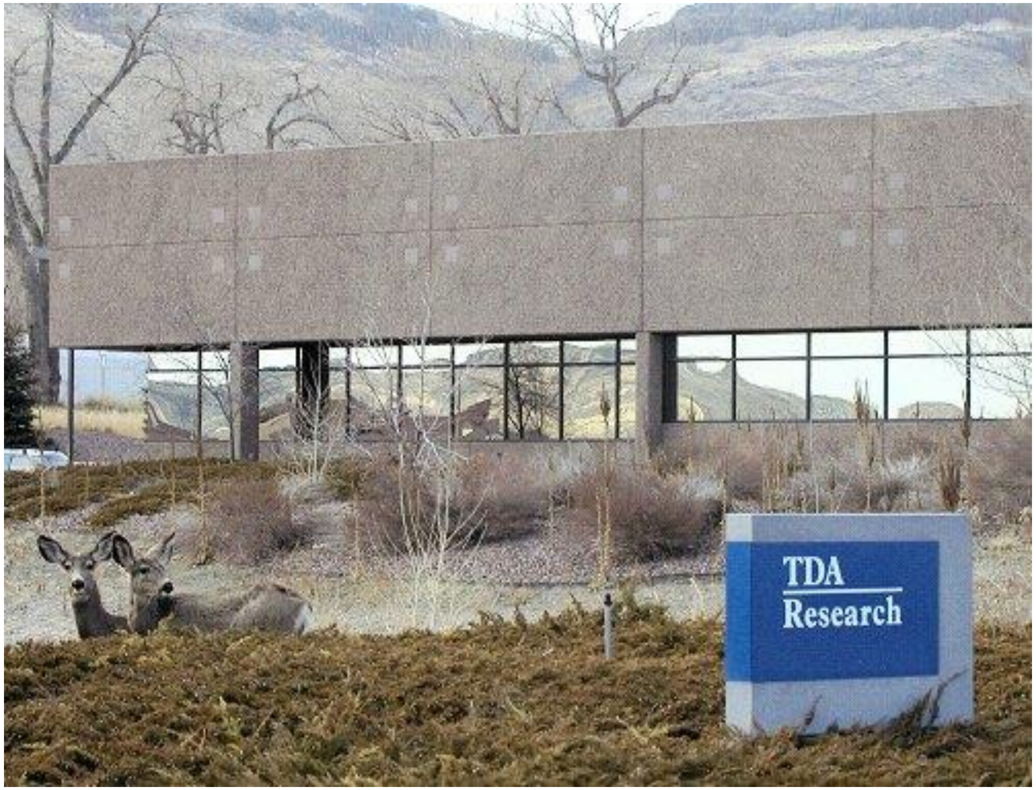
Membrane-Sorbent Hybrid System for Post-Combustion CO_2 Capture (Contract No. DE-FE-0031603)



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2018 DOE/NETL Carbon Capture Technology Meeting

Pittsburgh, PA

August 28, 2018

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 (Final Review in 09/19)
	✓ Completed Preliminary Techno-economic analysis
BY2	**- Fabrication of the test unit**
	- Site Preparation, Installation and Shakedown Tests
BY3	**- Field Tests (6-12 months duration)**
	- High Fidelity Techno-economic analysis

Project Team

Project Duration

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

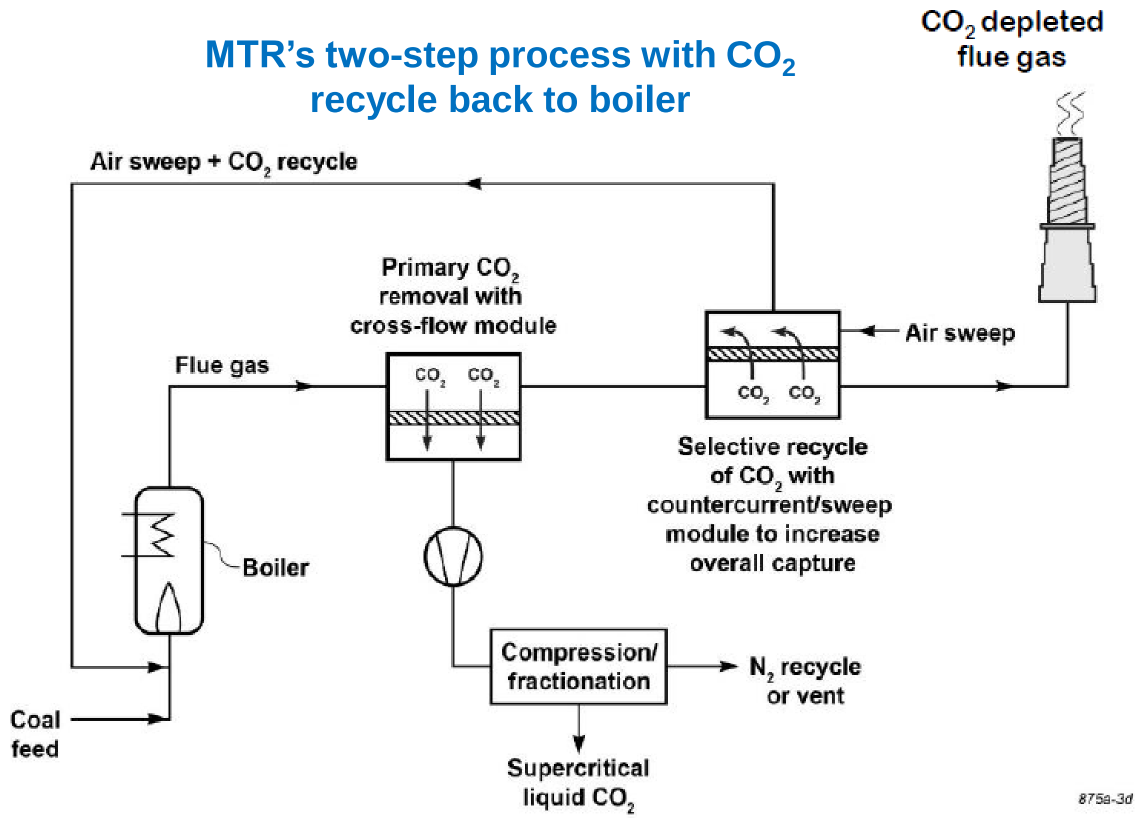
Budget

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

Two-Stage Membrane Approach

- **Two membranes in series**
  - Primary membrane to remove ~50% of the CO_2 in the flue gas
  - Secondary membrane uses air sweep to reduce the CO_2 released
- **Advantages**
  - Avoids high vacuum needed to achieve high CO_2 removal efficiency
  - Allows boiler to generate a high CO_2 flue gas

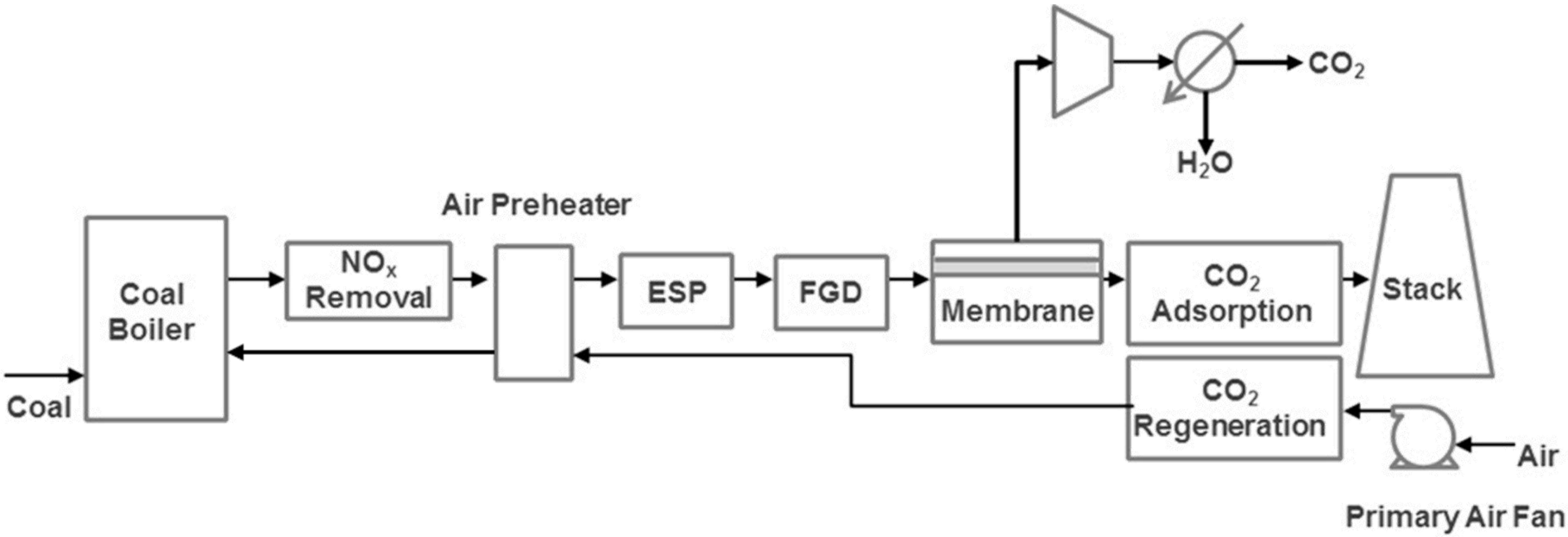
MTR's two-step process with CO_2 recycle back to boiler



U.S. Patents 7,964,020 and 8,025,715

- **Challenges**
  - The need to pressurize the flue gas to ~2-3 atm for reasonable performance in secondary membrane
  - High pressure drop in secondary membrane
  - Oxygen transfer from boiler air intake into the flue gas

Hybrid Membrane Sorbent Process



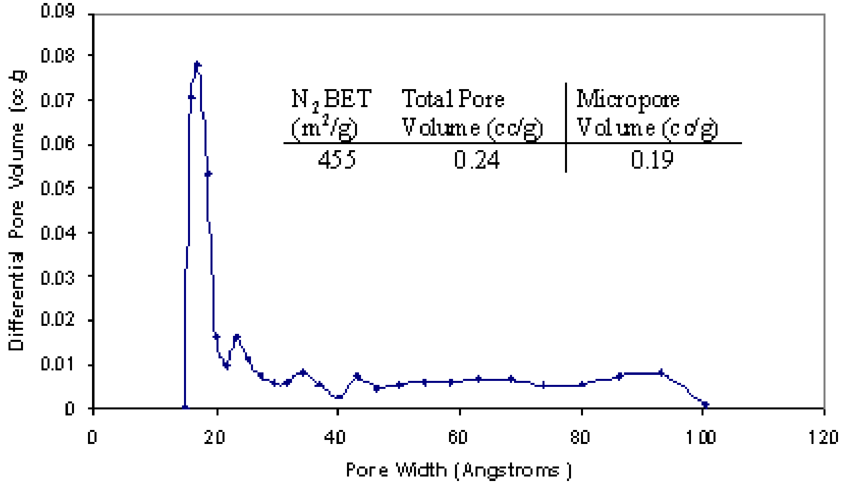
- **Membrane operates at ~50°C under mild vacuum, (~0.3 atm) removes ~50% of CO_2 and almost all water**
  - TDA's sorbent removes remaining CO_2 in the membrane effluent (retentate) ensuring 90% carbon capture
  - The boiler feed air is used as a sweep gas to facilitate sorbent regeneration
- **Advantages**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

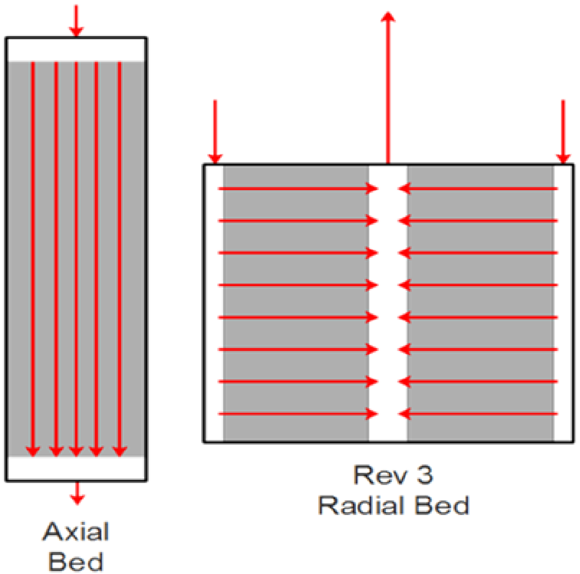
US Patent 9,120,079, Dietz, Alptekin, Jayaraman "High Capacity Carbon Dioxide Sorbent", US 6,297,293; 6,737,445; 7,167,354

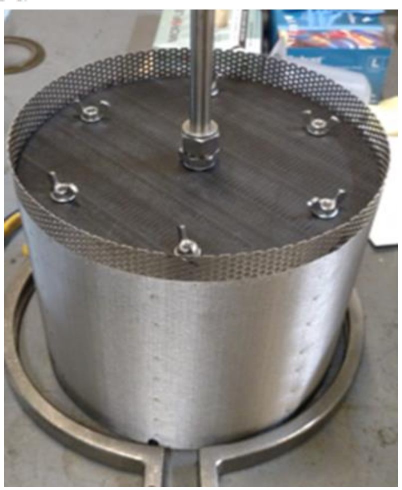
Sorbent optimization and production scale-up was completed in a separate DOE project (DE-0013105)



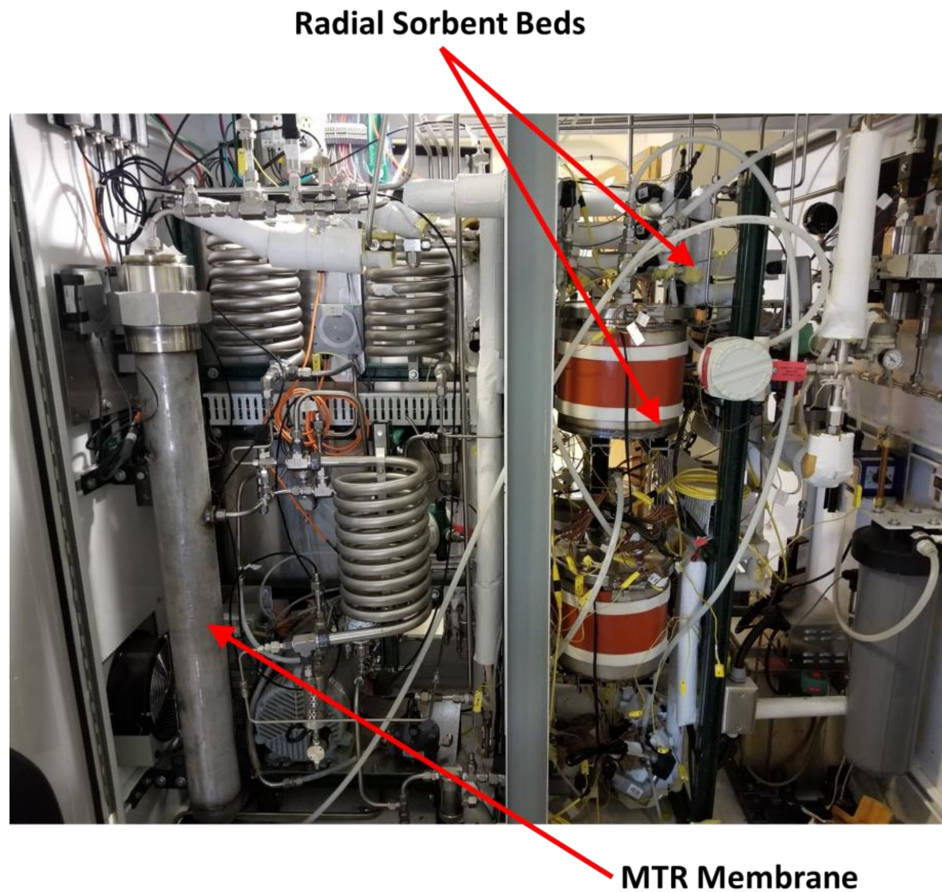
Sorbent operation in a VSA system was successfully demonstrated with actual flue gas (DE-0013105)

Early Work for Hybrid Systems





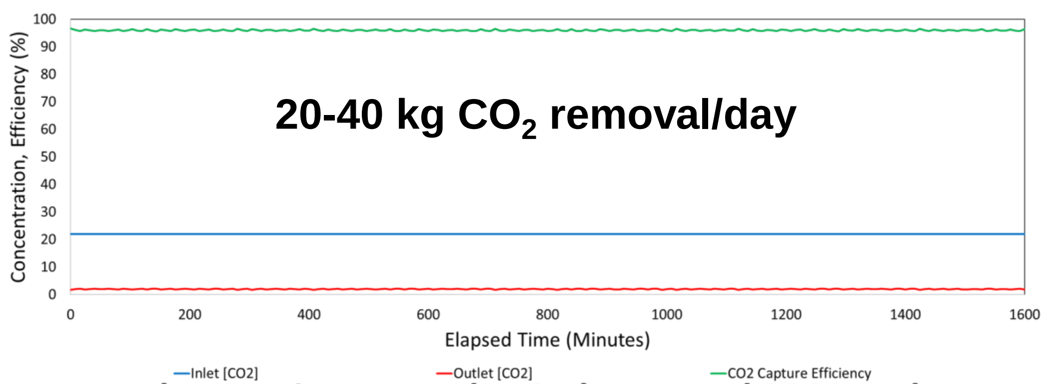
TDA's Radial Flow Sorbent Reactors



- **Lab/field tests were successful at 2-4 scfm (20-40 kg/day CO_2) scale hybrid-membrane sorbent system using simulated and actual coal-derived flue gas**

Testing at Western Research Institute

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



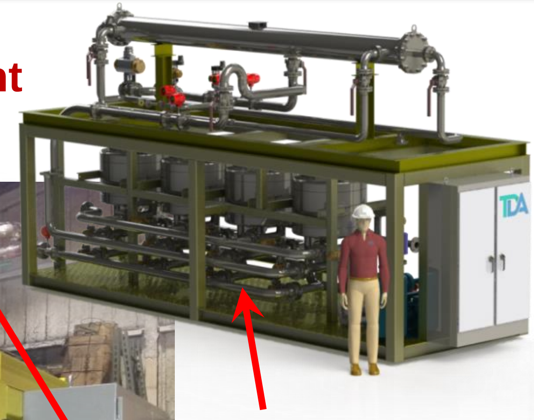
Total operation exceeds 525 hours and 3200 cycles

TDA RESEARCH

Development Under SBIR Phase IIB

Wyoming Integrated Test Center (WITC) near Basin Electric's Dry Fork Station in Gillette, WY

100 SCFM Membrane-Sorbent Hybrid Test System



4-Bed Sorbent Sub-System

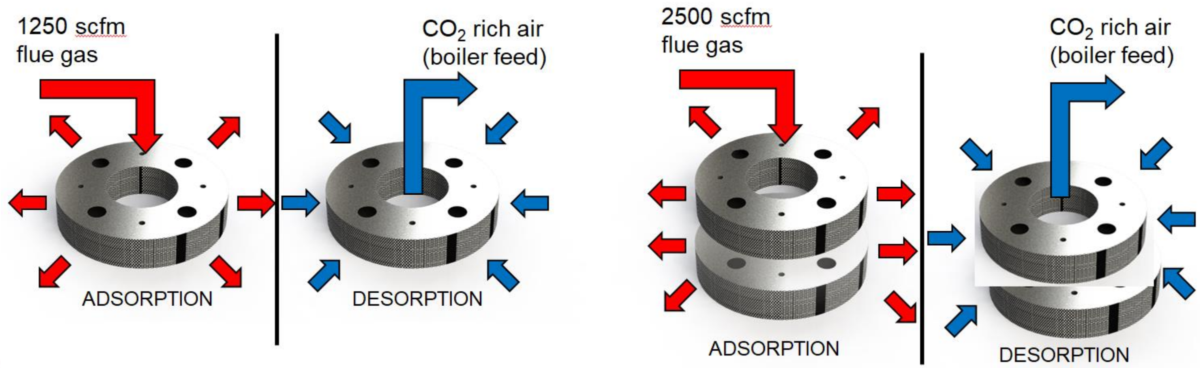
6-Element Membrane Housing (MTR)

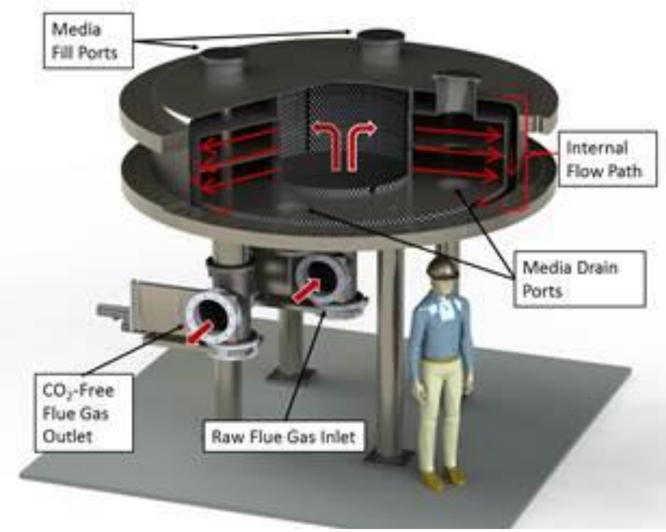
- **Completed fabrication of the 100 cfm membrane sorbent hybrid system capable of removing 1 ton per day CO_2**
- **Field tests scheduled at WITC in Fall 2019**

TDA RESEARCH

Current Project Focus

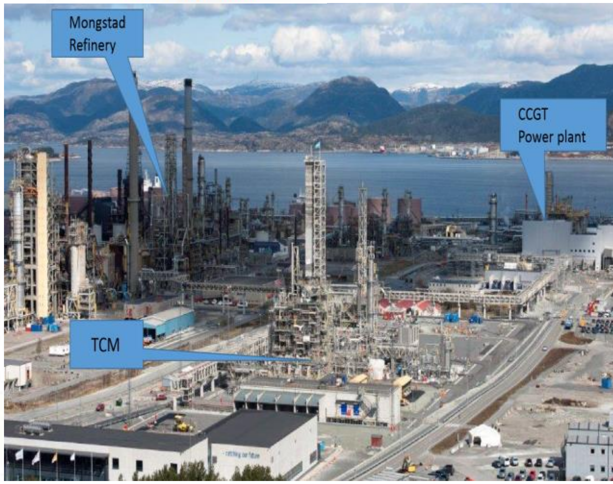
- **TDA will develop its modular sorbent bed concept**
- **MTR will modify an existing unit (20 tpd) previously evaluated at the NCCC**
- **TCM will host the evaluation of the integrated test unit**





TDA's Sorbent System

Existing MTR Membrane Module (20 TPD evaluated at NCCC)



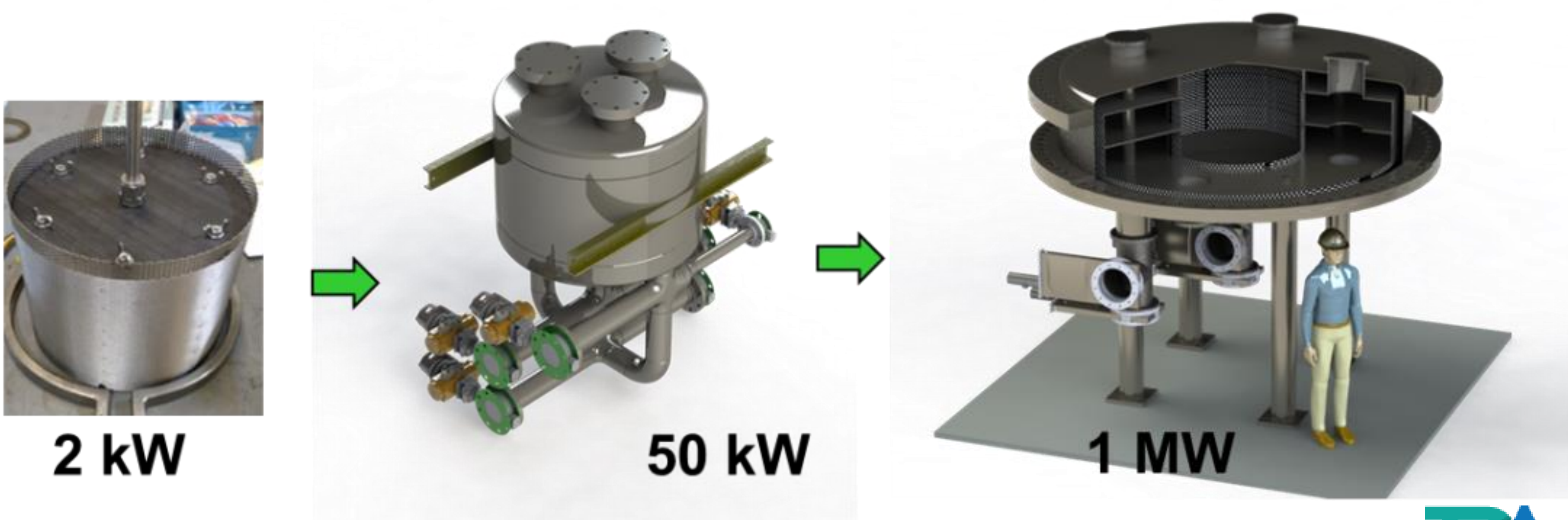
TCM Mongstad, Norway

Budget Year 1 Activities

- **System Design**
  - Design of the TDA Sorbent Vessels
  - Integration of the Sorbent System with MTR System
  - Installation of the Hybrid System to the Host Site
- **Preliminary Techno-economic analysis**

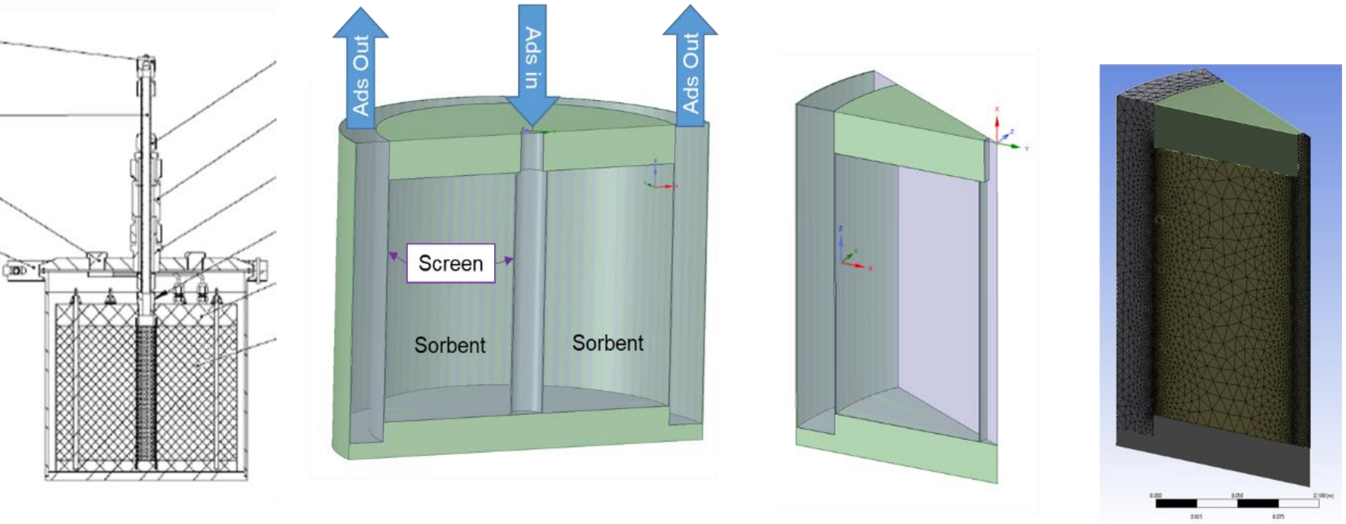
Design of the Sorbent Vessels

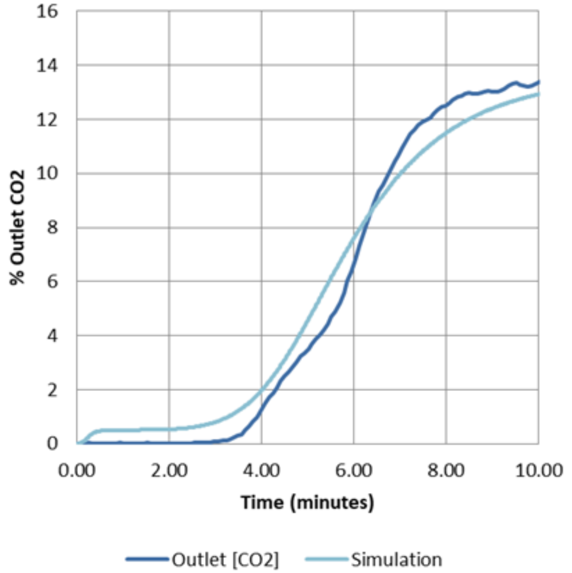
- **Design work is supported with CFD simulations to determine the intra-modular flow, concentration and temperature distributions**
  - The key design objective is to enhance sorbent utilization
  - Understanding flow distribution is critical to design an effective gas-solid contactor
- **Data validation from the smallest test module is now complete**
- **Further validation from 50 kW module will be available in late 2019**



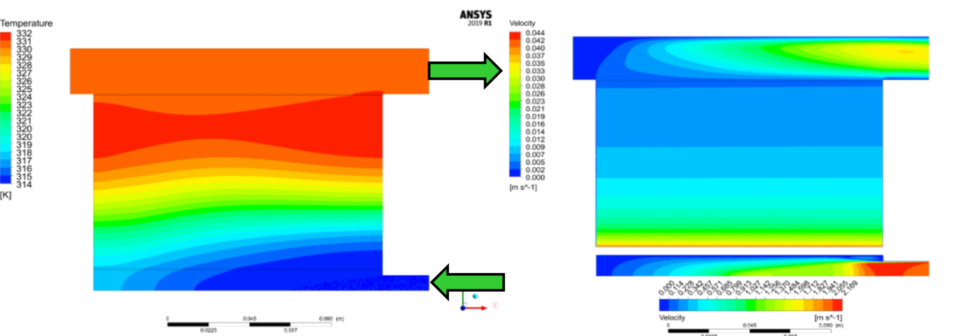
CFD Modeling

CFD Simulation of the 2 kW Module



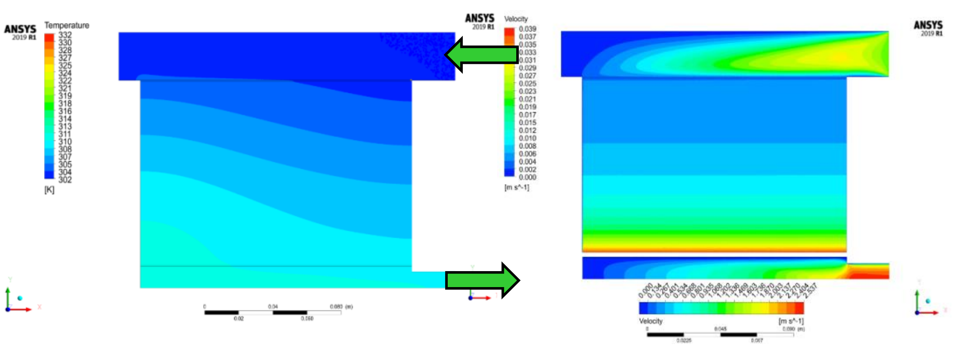


end of adsorption



Temperature Velocity

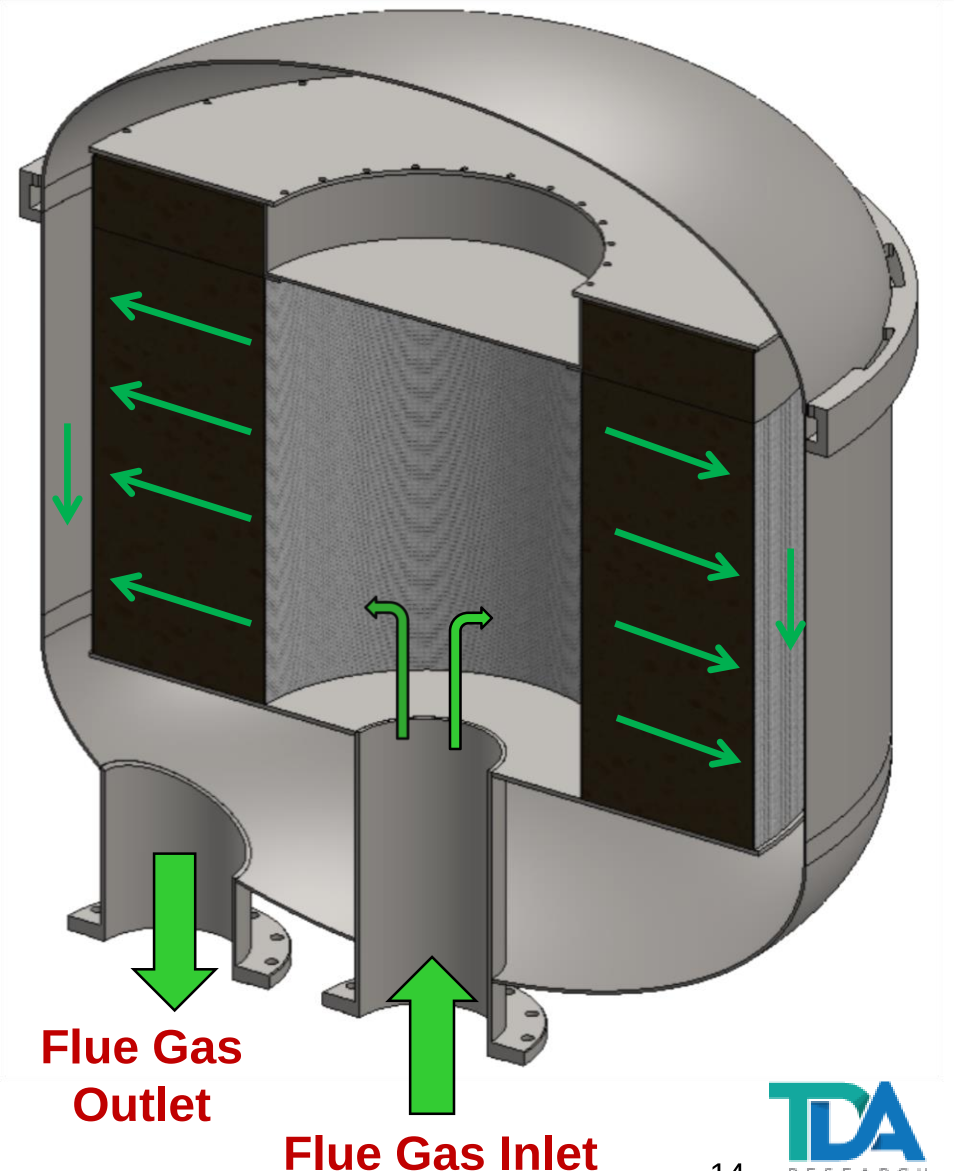
end of desorption



Temperature Velocity

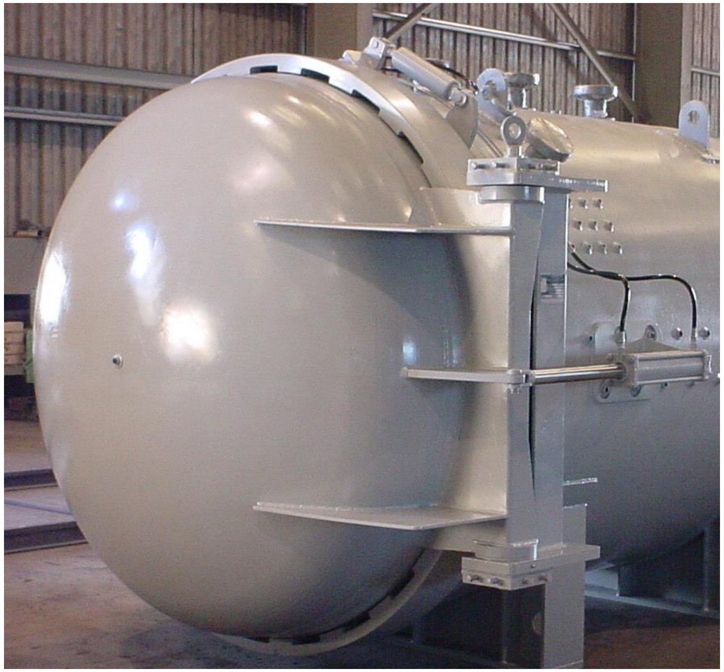
Design of the 1 MW Reactor

- 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
- Est. dP = 44 mbar (8x16 mesh sorbent)
- Est. dP = 106 mbar (12x40 mesh sorbent)

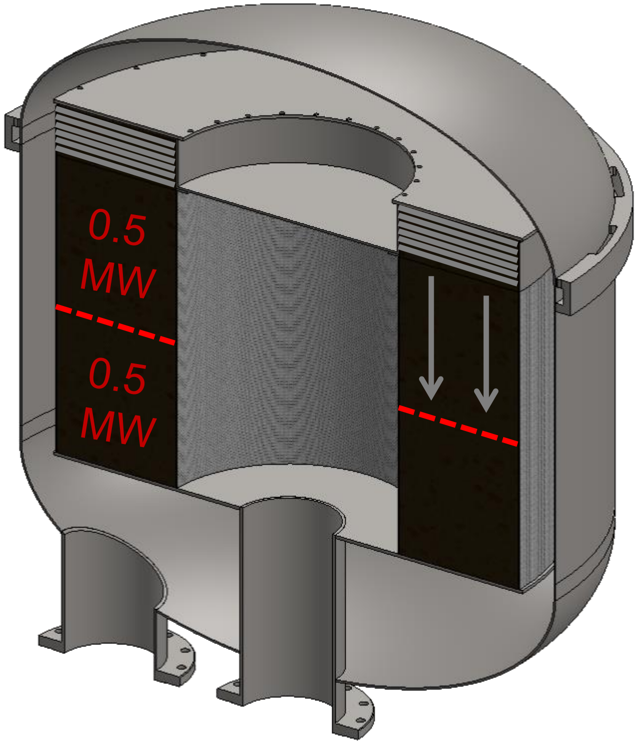


Access to the Module

Reactor head design with pneumatics to lift it open



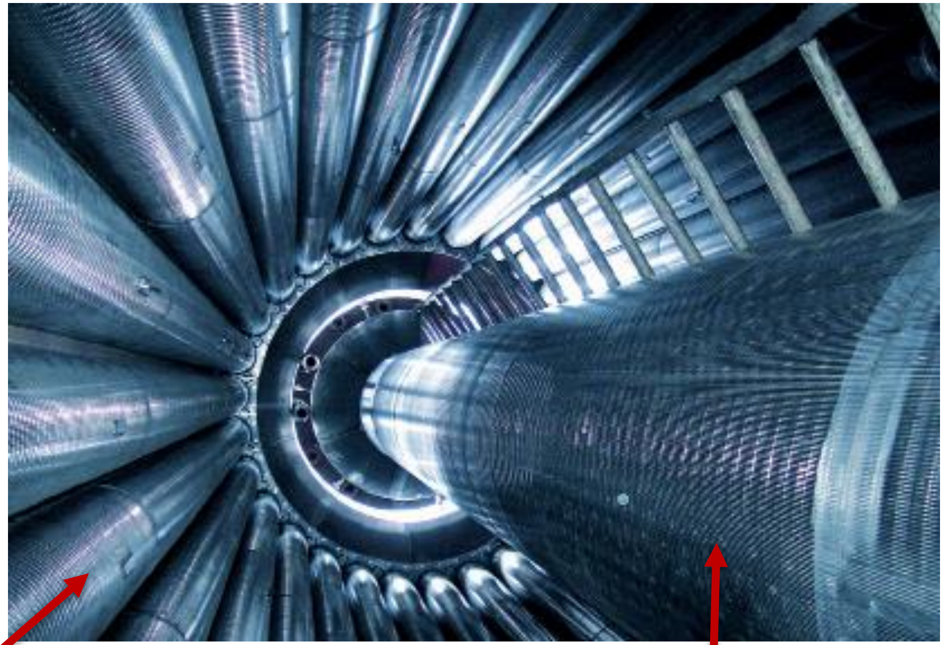
1 MW Module



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

Sorbent Bed Screens

"Box-Shaped" Wedge-Wire | Scalloped Plate | Wedge Wire



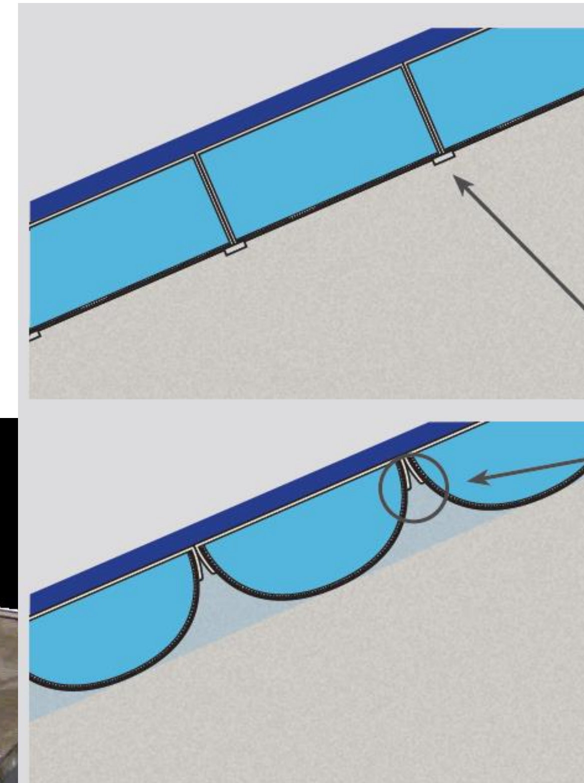
Scalloped plate design

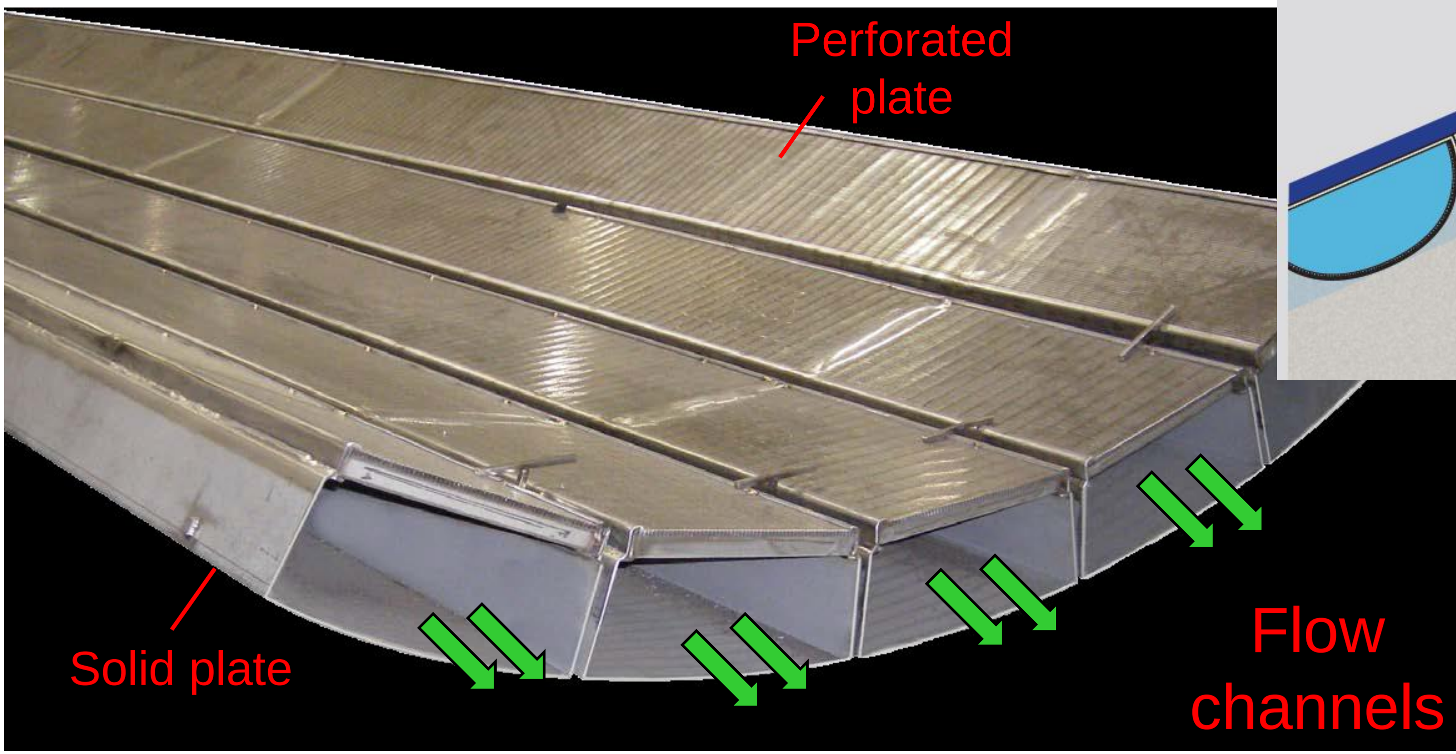
Center Screen

- **Johnson Screens wedge-wire design will be used to hold the sorbent bed in place (i.e., the donut-shaped basket)**
- **The sorbent will be loaded/emptied from the top**
- **Mesh size/design is optimized to provide the desired structural properties and gas distribution with minimum pressure drop**

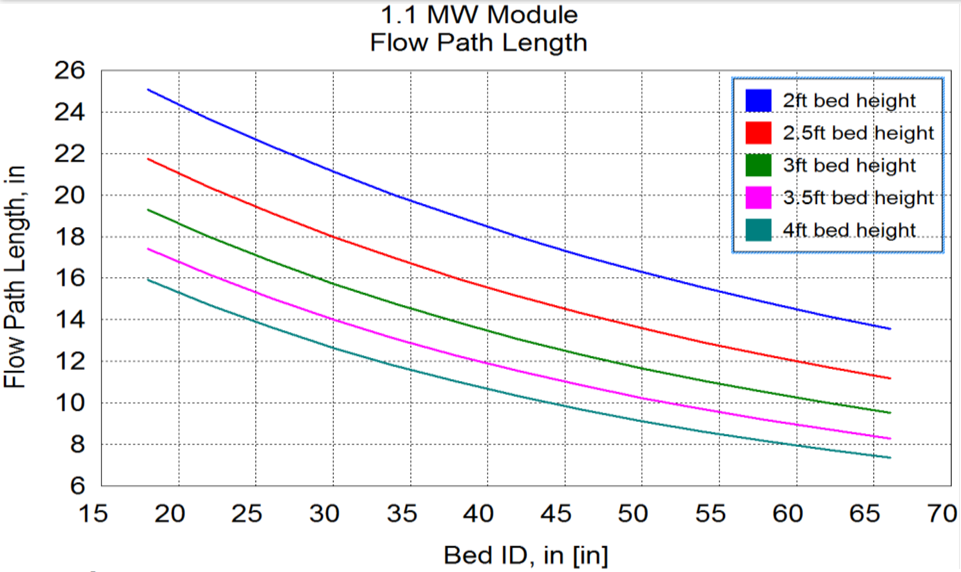
Box-Shaped Screens

- **Box-shaped wedge-wire configuration was selected for the final design**
- **The design will prevent sorbent being wedged in between two screen modules**
- **The box-size is optimized to shape the structure to fit well into the selected vessel**

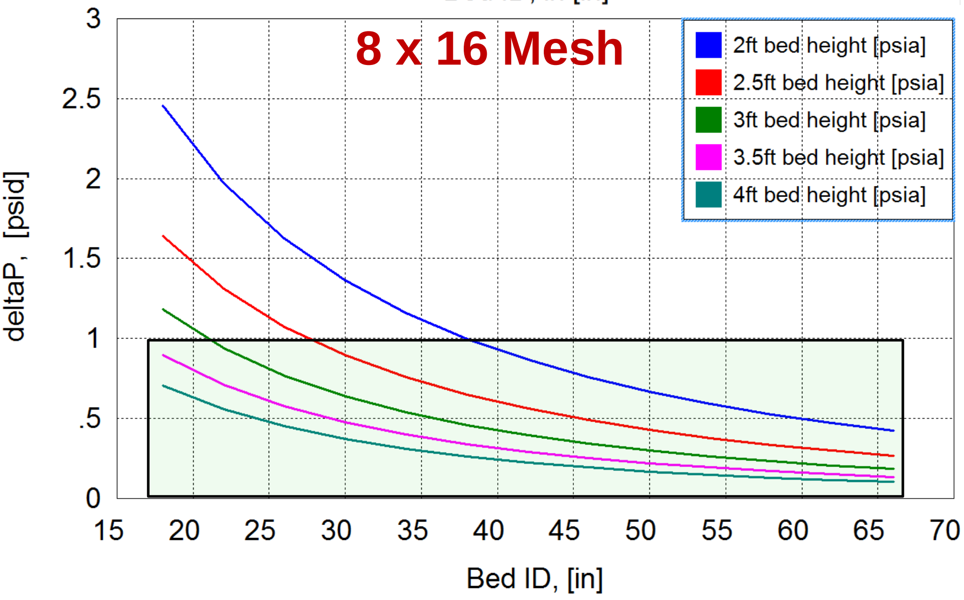


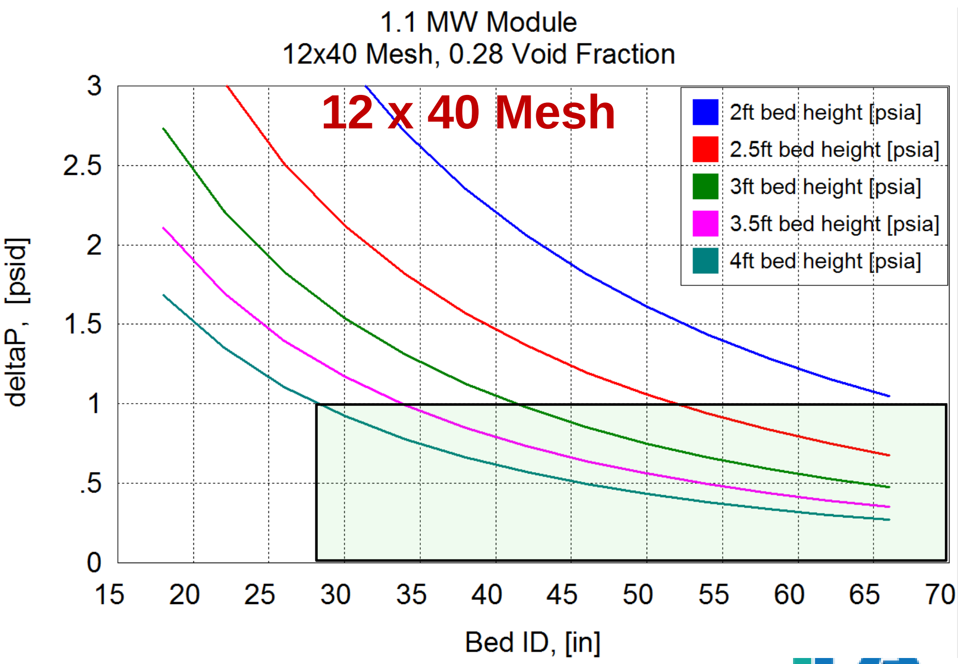


Particle Size vs Pressure Drop



- Trade-off between particle size and the minimum Bed ID was examined
- Design basis is a pressure drop of less than 1 psid (~ 70 mbar)
  - Minimum Bed ID for 12 x 40 mesh particles is about 16”
  - Minimum Bed ID for 8 x 16 mesh particles is about 28”

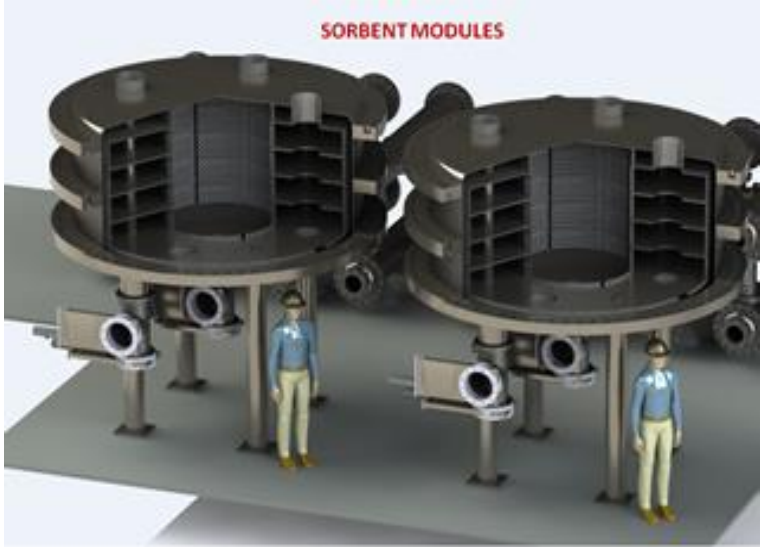




Integration of MTR and TDA Systems

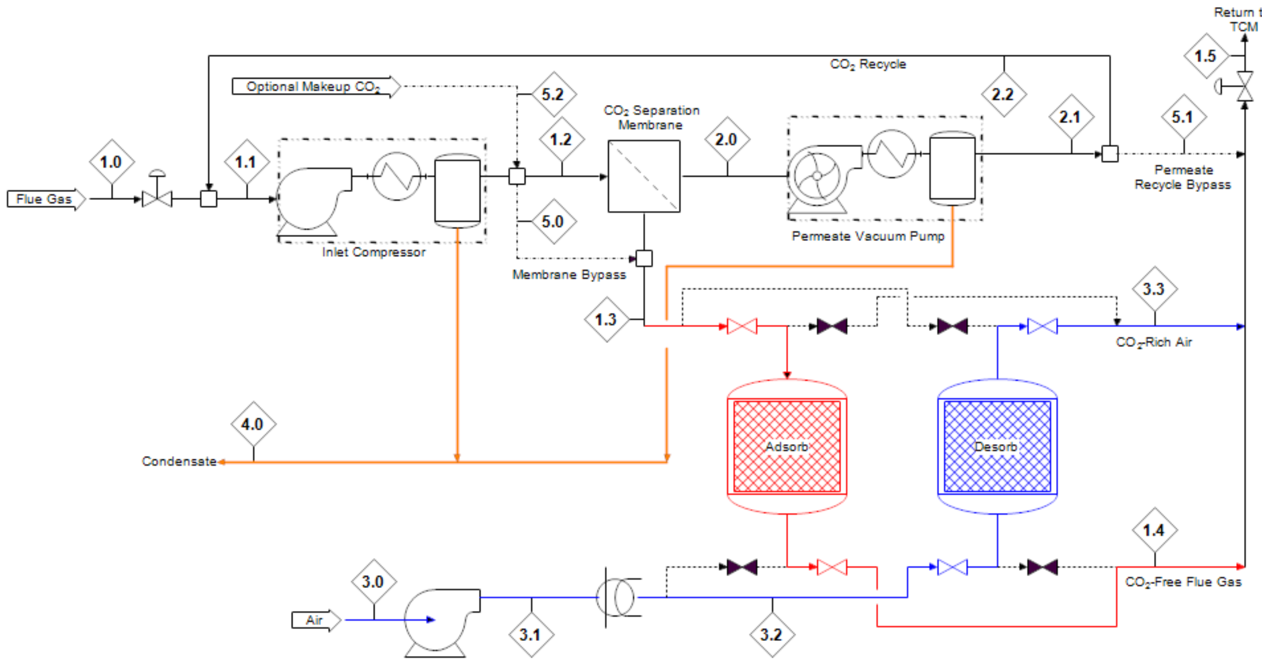
- **MTR has identified the modifications needed to their existing 20 TPD CO_2 removal membrane skid**
- **All major process equipment has been designed and selected**
  - Engineering drawings and 3-dimensional layouts for all critical equipment is complete
  - Process flow diagram and process instrumentation diagrams are complete
- **HAZOP review between TDA, MTR and TCM is scheduled on September 3-4, 2019**

Existing MTR Membrane Module
(20 TPD evaluated at NCCC)



TDA's Sorbent Module
(20 TPD to be built)

PFD and Stream Data - TCM 1MW

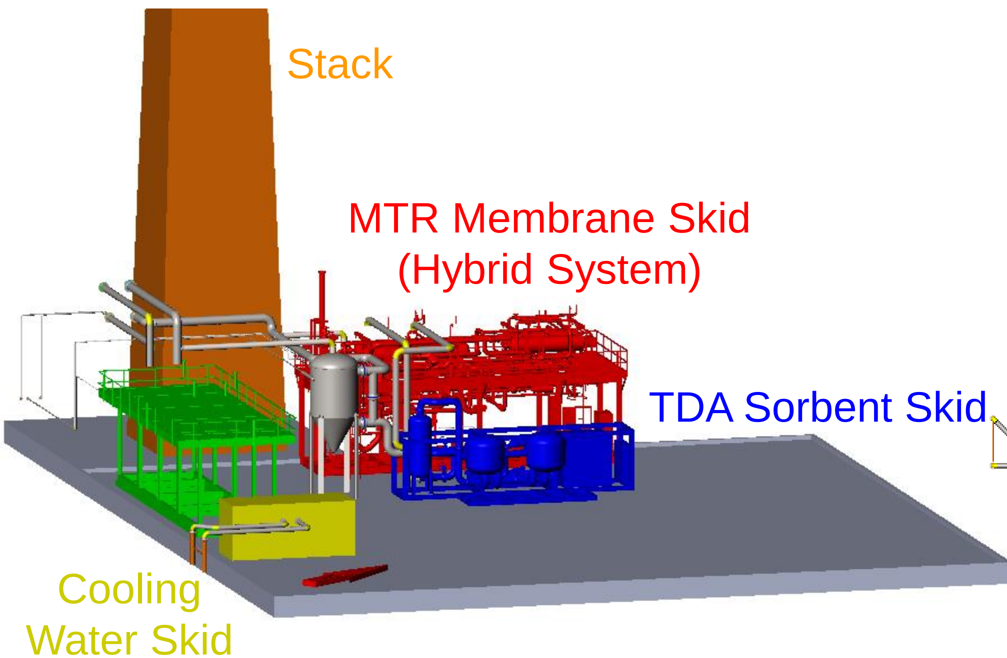


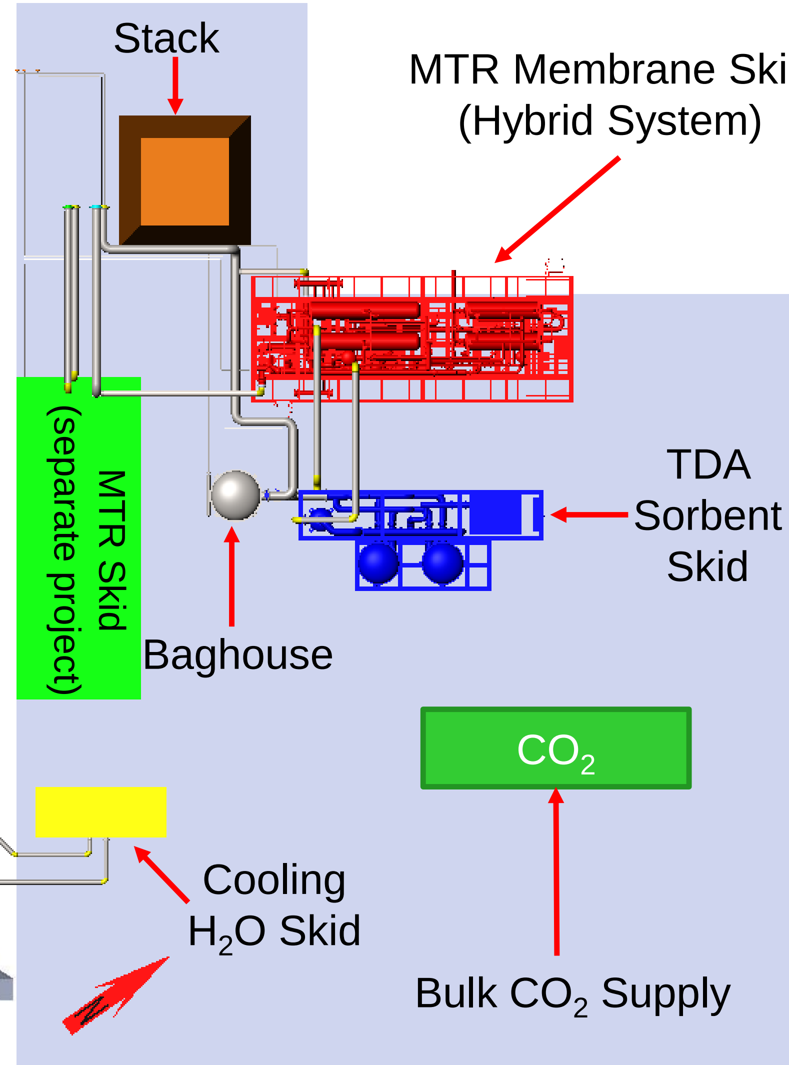
Case

Stream Number	1.0	1.1	1.2	1.3	1.4	1.5	2.0	2.1	2.2	3.0	3.1	3.2	3.3	4.0
Temperature, C	35.0	37.3	38.7	38.7	33.9	34.5	38.7	56.4	56.4	20.0	40.8	35.0	35.0	38.4
Pressure, bara	1.03	1.01	1.31	1.21	1.03	1.03	0.20	1.05	1.05	1.01	1.30	1.30	1.03	1.05
Mass Flow, kg/hr	4602	5159	5156	4599	3612	9001	557	557	557	4402	4402	4402	5389	3
Molar Flow, kmol/h	152.5	168.8	168.7	152.3	129.9	304.8	16.3	16.3	16.3	152.5	152.5	152.5	174.9	0.2
Volumetric Flow , acfm	2233	2531	1965	1921	1914	4989	1247	251	251	2161	1952	1916	2867	-
Volumetric Flow , scfm	2012	2227	2225	2010	1714	4021	216	216	216	2012	2012	2012	2308	-
Density, kg/m3	1.2	1.2	1.5	1.4	1.1	1.1	0.3	1.3	1.3	1.2	1.3	1.4	1.1	1050.1
Molecular Weight, kg/kmol	30.2	30.6	30.6	30.2	27.8	29.5	34.1	34.1	34.1	28.9	28.9	28.9	30.8	18.0
Mixture Specific Enthalpy, kJ/kg	10.1	12.4	13.8	13.8	9.4	9.6	13.5	31.2	31.2	-5.1	16.0	10.1	9.8	-2385.1
Dynamic Viscosity, cP	0.018	0.018	0.018	0.018	0.018	0.019	0.016	0.017	0.017	0.018	0.019	0.019	0.019	-
Heat Capacity, kJ/kg K	1.01	1.01	1.01	1.01	1.05	1.01	0.99	1.00	1.00	1.01	1.01	1.01	0.98	1.01
Vapor Fraction	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.0
Mole Percent														
H_2O	4.2%	5.4%	5.3%	4.1%	4.8%	2.0%	16.1%	16.1%	16.1%	0.0%	0.0%	0.0%	0.0%	100.0%
CO_2	14.7%	17.8%	17.8%	14.7%	0.0%	7.4%	47.0%	47.0%	47.0%	0.0%	0.0%	0.0%	12.8%	0.0%
O_2	3.2%	3.1%	3.1%	3.2%	3.8%	12.3%	2.2%	2.2%	2.2%	21.4%	21.4%	21.4%	18.7%	0.0%
Ar	0.9%	0.9%	0.9%	0.9%	1.1%	0.5%	0.5%	0.5%	0.5%	0.0%	0.0%	0.0%	0.0%	0.0%
N_2	77.0%	72.9%	72.9%	77.1%	90.4%	77.8%	34.1%	34.2%	34.2%	78.6%	78.6%	78.6%	68.5%	0.0%

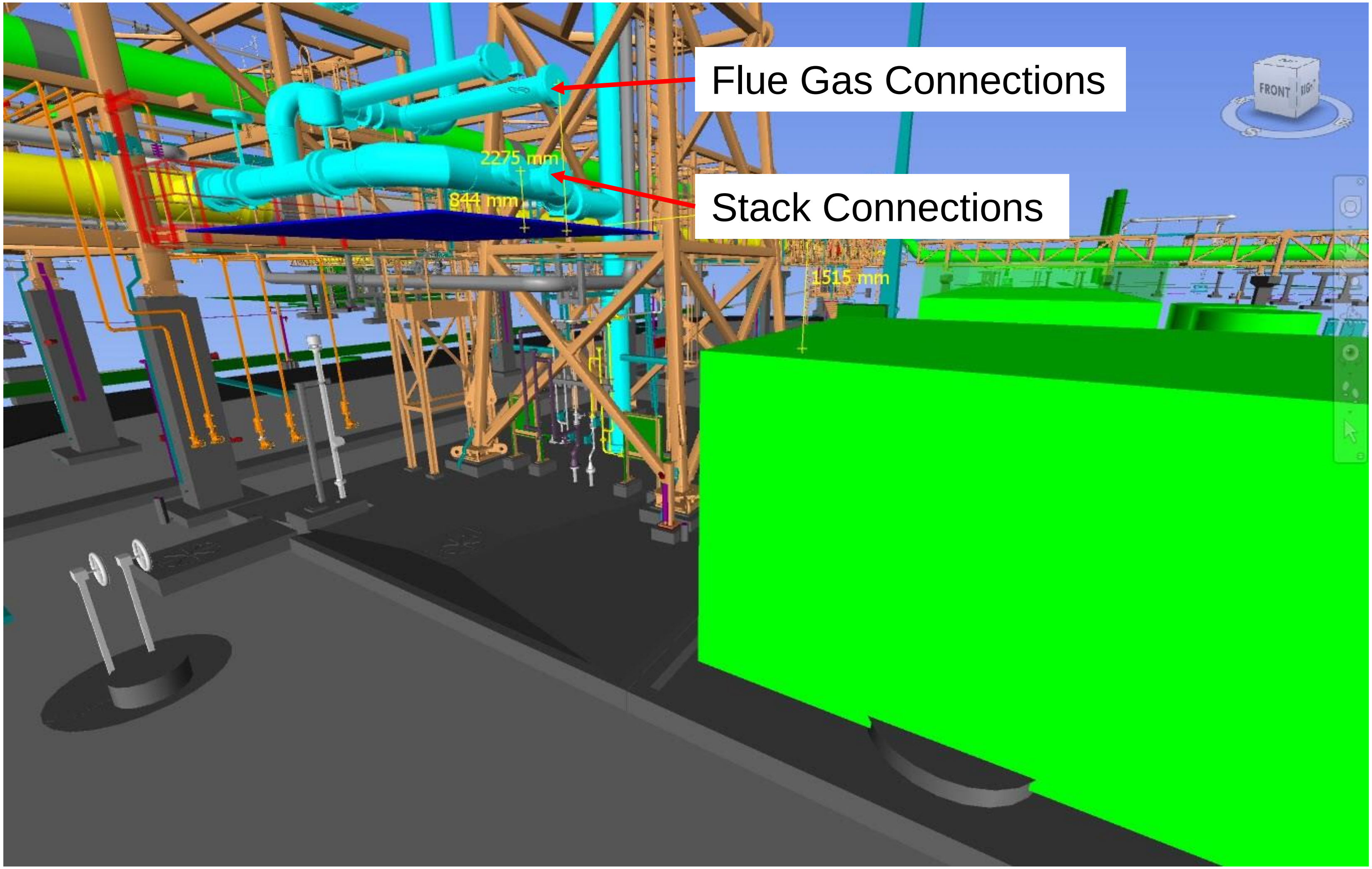
Site Connections

- **General arrangement drawings for the skids are completed**
- **The utility and site requirements for the field test unit has been finalized**
- **Site modifications are expected to be completed in Spring 2020**

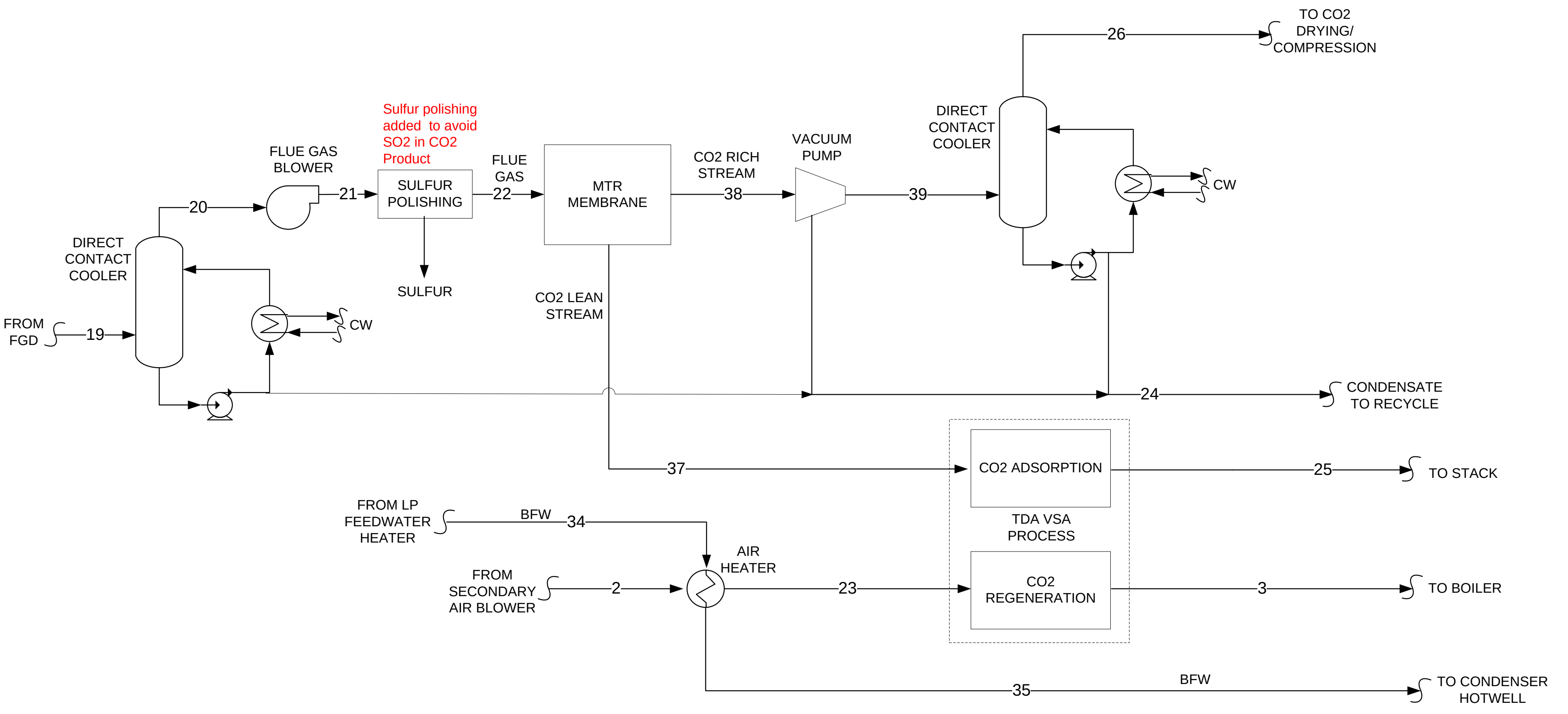




Interconnections to TCM



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

TDA RESEARCH

Preliminary TEA

- **TEA for supercritical power plants suggest substantial improvement in cycle efficiency and cost of CO_2 capture for the hybrid technology**

Power plant Type	Supercritical PC Plant		
CO_2 Capture Technology	No Capture	Amines	Hybrid
Case ID	Case 11 DOE	Case 12 DOE	TDA Case 1
Gross Power Generated, kWe	580,400	662,800	698,793
Auxiliary Load, kWe	112,830	112,830	148,793
Net Power, kWe	549,970	549,970	550,000
Net Plant Efficiency, % HHV	39.30	28.40	31.48
Coal Feed Rate, kg/h	185,759	256,652	231,832
Total Plant Cost, $/kWe	1,981	3,563	2,882
COE without CO_2 TS&M, $/MWh	82.27	137.45	116.55
COE with CO_2 TS&M, $/MWh	-	147.44	125.43
Cost of CO_2 Captured, $/tonne	-	55.24	38.59

- **1st year levelized CO_2 capture cost (excluding TS&M) for hybrid system at $38.59/tonne is lower than that for Case 12 by $16.65/tonne (30.14% lower)**
- **Additional efficiency penalties may be introduced due to purification needs on the CO_2 product stream and deviations in vacuum pump efficiency**

TDA RESEARCH

Next Steps for Budget Period 2

<u>Budget Period 2 (BP2: 8/15/2019– 8/14/2020)</u>

- **TDA and MTR complete the fabrication/integration of the 1 MW membrane-sorbent hybrid test unit**
- **TCM to carry out all the site modifications needed to host field tests**
- **Prepare and submit a test plan to DOE**
- **UCI will update the Aspen® process simulation model**
- **Ship and install the 1 MW pilot unit at TCM facilities in Mongstad, Norway**

Acknowledgements

- DOE/NETL funding provided the DE-FE-0031603 project is greatly acknowledged
- Project Manager, Andrew B. O'Palko

TDA RESEARCH