Pilot Testing of a Highly Efficient Pre-combustion Sorbent-based Carbon Capture System (Contract No. DE-FE-0013105)

Gökhan Alptekin, PhD
Ambal Jayaraman, PhD
Matt Cates
Douwe Bruinsma
Freya Kugler
Jim Dippo

2021 Carbon Management and Oil and Gas Research Project Review Meeting

Point Source Capture — Lab, Bench, and Pilot-Scale Research

August 13, 2021

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

Project Summary

Project Duration

- Start Date = January 1, 2014
- End Date = March 31, 2022

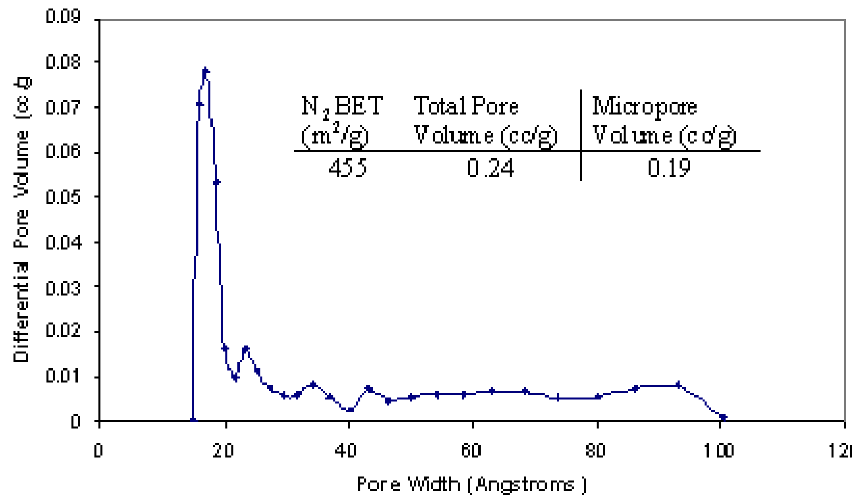
Budget

- Project Cost = $9,929,228
- DOE Share = $7,943,382
- TDA & its partners = $1,985,846

- To develop a new sorbent-based pre-combustion capture technology
- Demonstrate techno-economic viability of the new technology by:
    1) Evaluating technical feasibility in 0.1 MW_e slipstream tests
    2) Carrying out high fidelity process design and engineering analysis
- Major Project Tasks
    - ✓ Sorbent Manufacturing
        - ✓ Long-term cycling tests
    - ✓ Reactor Design
        - ✓ CFD Analysis/PSA cycle optimization
    - ✓ Fabricate a Prototype for Demonstration
    - ✓ Evaluations at various sites using coal-derived synthesis gas
    - ✓ Techno-economic analysis
    - Decommissioning and Shipping from China

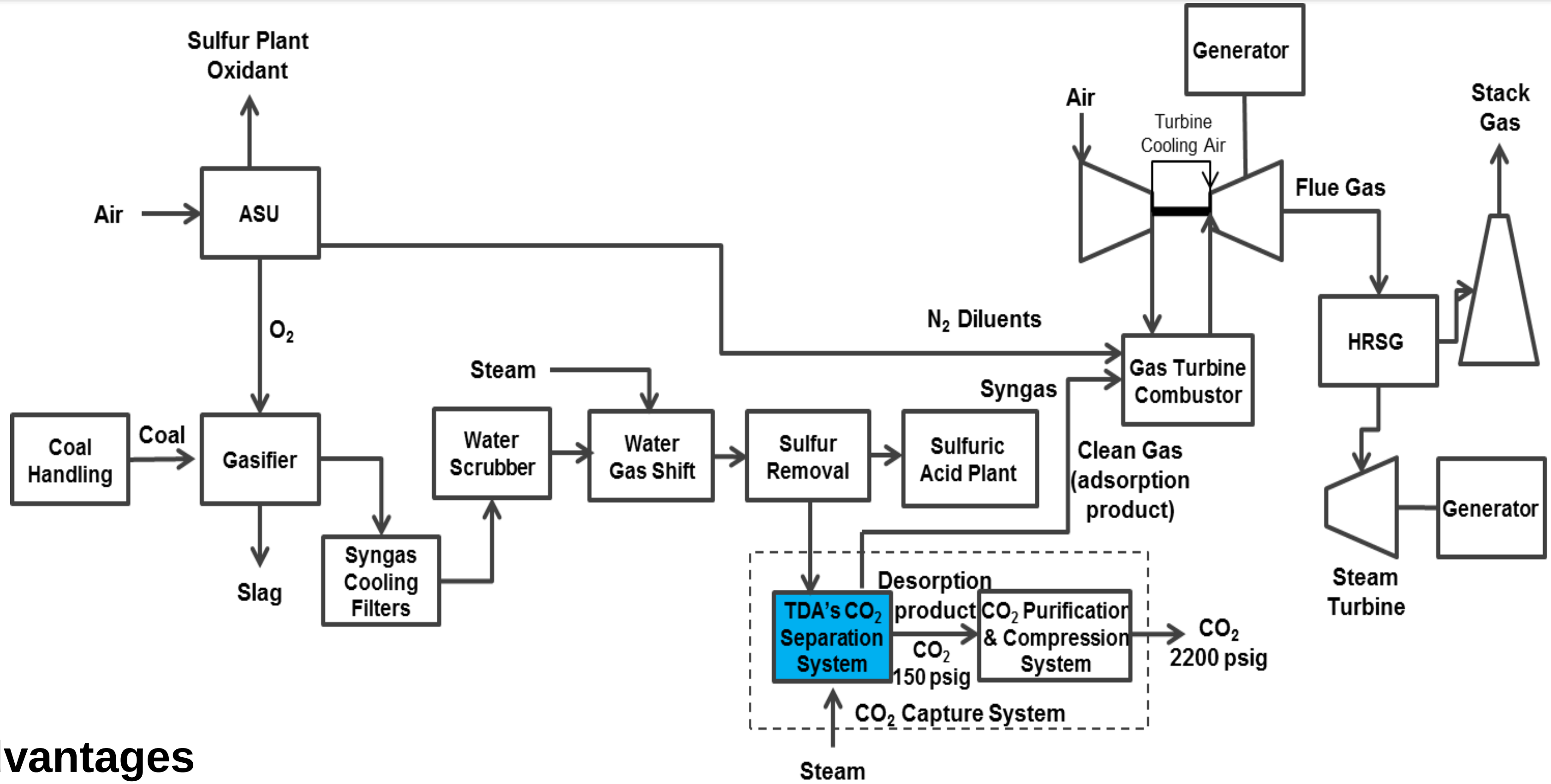
TDA's Sorbent

- **TDA's uses a mesoporous carbon with surface functional groups that remove CO_2 via strong physical adsorption**
  - CO_2-surface interaction is strong enough to allow operation at elevated temperatures
  - Because CO_2 is not bonded via a covalent bond, energy input for regeneration is low
- **Heat of CO_2 adsorption is 4.9 kcal/mol for TDA sorbent**
  - Net energy loss in sorbent regeneration is similar to Selexol; much higher IGCC efficiency can be achieved due to high temperature CO_2 capture
- **Favorable material properties**
  - Pore size is tuned to 10 to 100 A
  - Mesopores eliminates diffusion limitations



US Patent 9,120,079, Dietz, Alptekin, Jayaraman "High Capacity Carbon Dioxide Sorbent", US 6,297,293; 6,737,445; 7,167,354
US Pat. Appl. 61790193, Alptekin, Jayaraman, Copeland "Pre-combustion CO_2 Capture System Using a Regenerable Sorbent"

Integration to the IGCC Power Plant

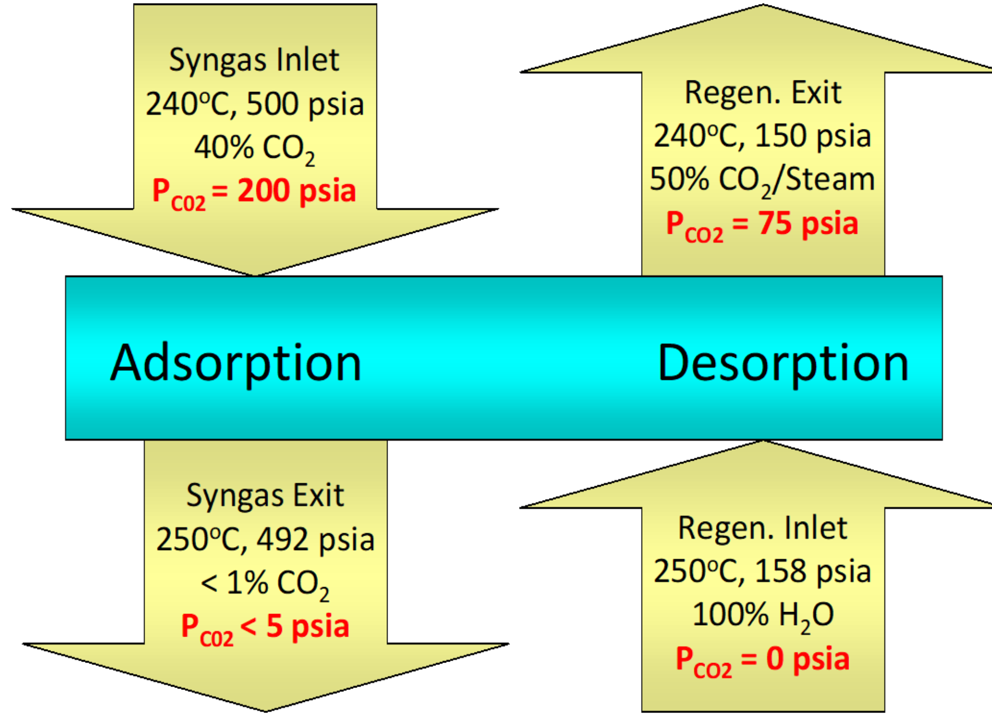


Advantages

- Higher mass throughput to gas turbine – higher efficiency
- Lower GT temperature – Reduced need for HP N_2 dilution hence lower NO_X formation
- Elimination of heat exchangers needed for cooling and re-heating the gas
- Elimination of gray water treatment problem
- Potential for further efficiency improvements via integration with WGS

Operating Conditions

- CO_2 is recovered via combined pressure and concentration swing
  - CO_2 recovery at ~150 psia reduces energy need for CO_2 compression
  - Small steam purge ensures high product purity
- Isothermal operation eliminates heat/cool transitions
  - Rapid cycles reduces cycle time and increases sorbent utilization
- Similar PSA systems are used in commercial H_2 plants and air separation plants



Source: Honeywell/UOP

TDA RESEARCH

Primary Focus

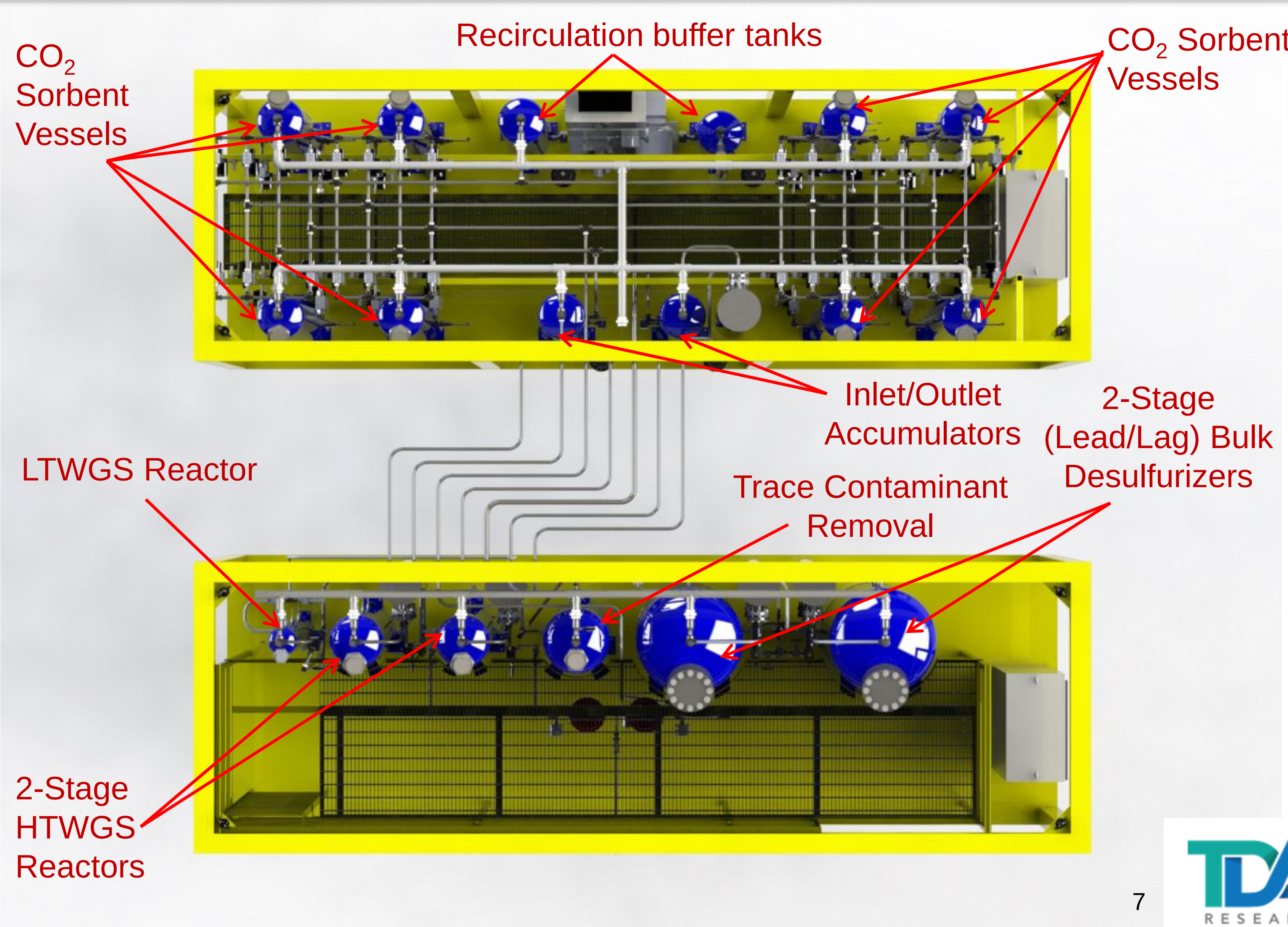
- **0.1 MW_e evaluation in a world class IGCC plant to demonstrate full benefits of the technology**
    - **Testing with high pressure gas**
- **Demonstrate full operation scheme**
    - 8 reactors and all accumulators
    - Utilize product/inert gas purges
    - H_2 recovery/CO_2 purity
- **Evaluations at various sites using coal-derived syngas**
    - Field Test #1 at NCCC – Air blown gasification
    - Field Test #2 at Sinopec Nanhua Petro-chemical Plant, Nanjing, Jiangsu Province, China – Oxygen blown gasification

Nanhua Plant Syngas Supply	
Composition	**mol%**
H2	32.493
CO	0.546
CO2	24.715
H2S	0.083
COS	0
C1	0.021
N2	0.128
AR	0.05
NH3	0.069
HCN	0
HCL	0
H2O	41.895
温度 Temperature, C	265.6
压力 Pressure, MPaG	4

National Carbon Capture Center

Sinopec/Yangtzi Chemicals Petro-chemical Compl

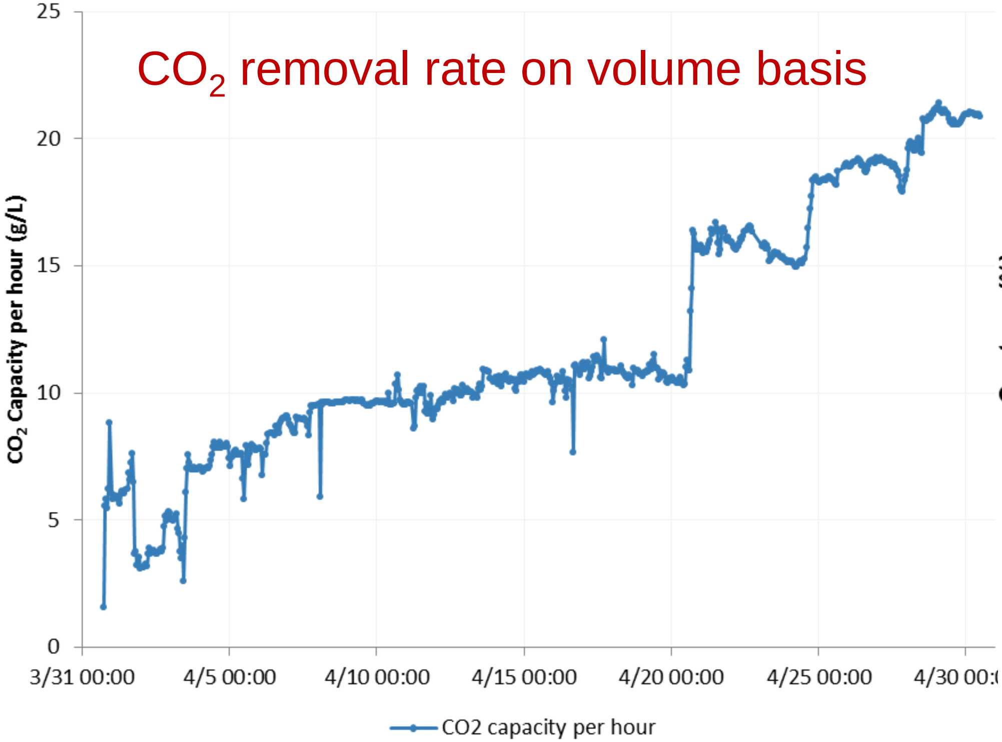
Slipstream Test Skid - Top View

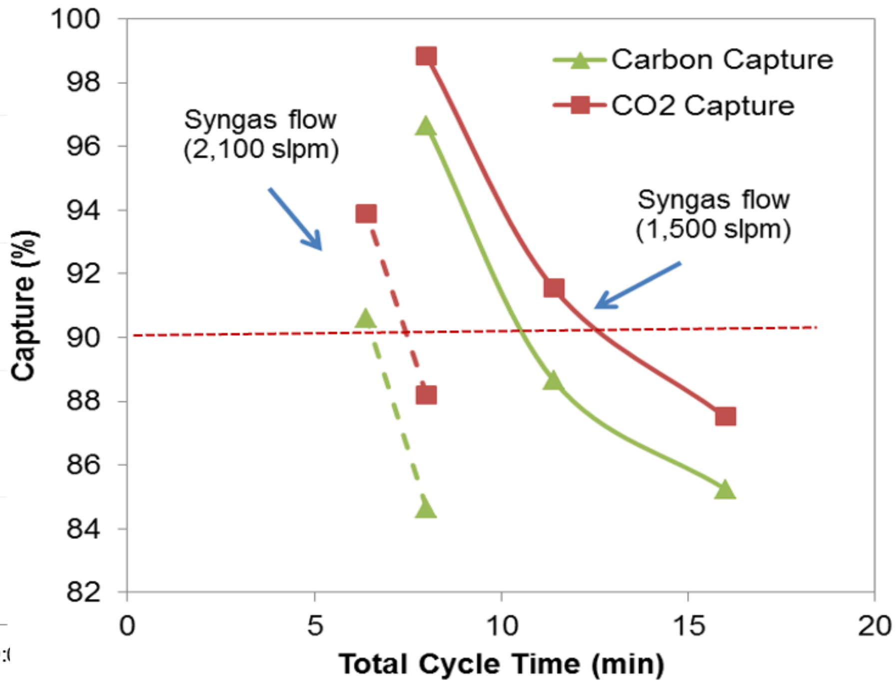


TDA RESEARCH

Field Test Unit Installed at NCCC

Working Capacity of the Sorbent





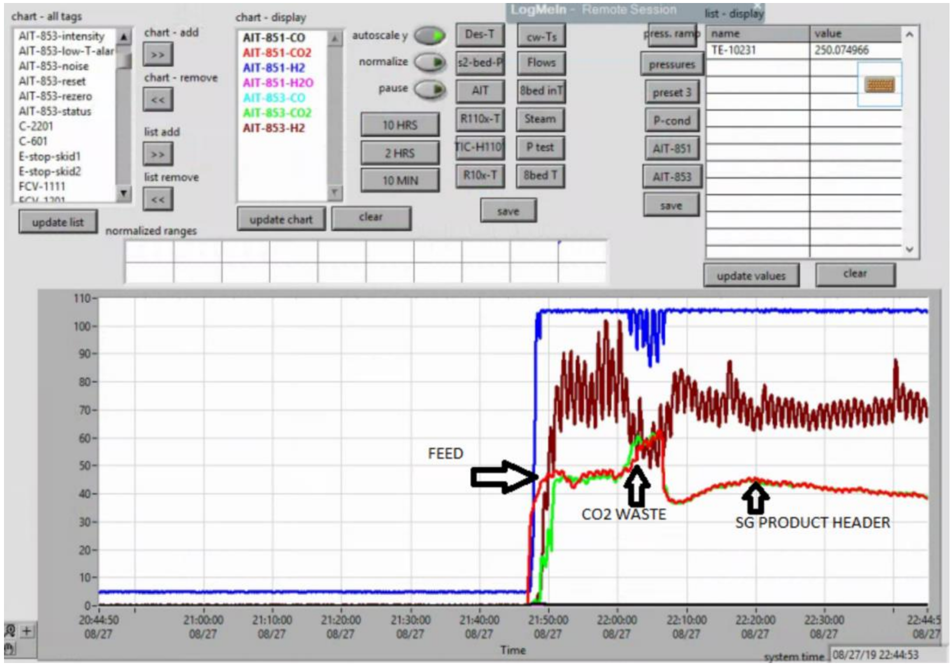
- **A successful 30 day (707 hrs) evaluation was completed at NCCC**
  - Design flow at NCCC operating conditions was 1,420 SLPM (50 SCFM)
  - 97.3% capture @ 1,500 SLPM
  - 93% @ 1,800 SLPM
  - 90% @ 2,100 SLPM
- **Pressure drop through the gas conditioning skid prevented flowing more than 2,100 SLPM of syngas through the PSA skids**

Installation Work at Sinopec

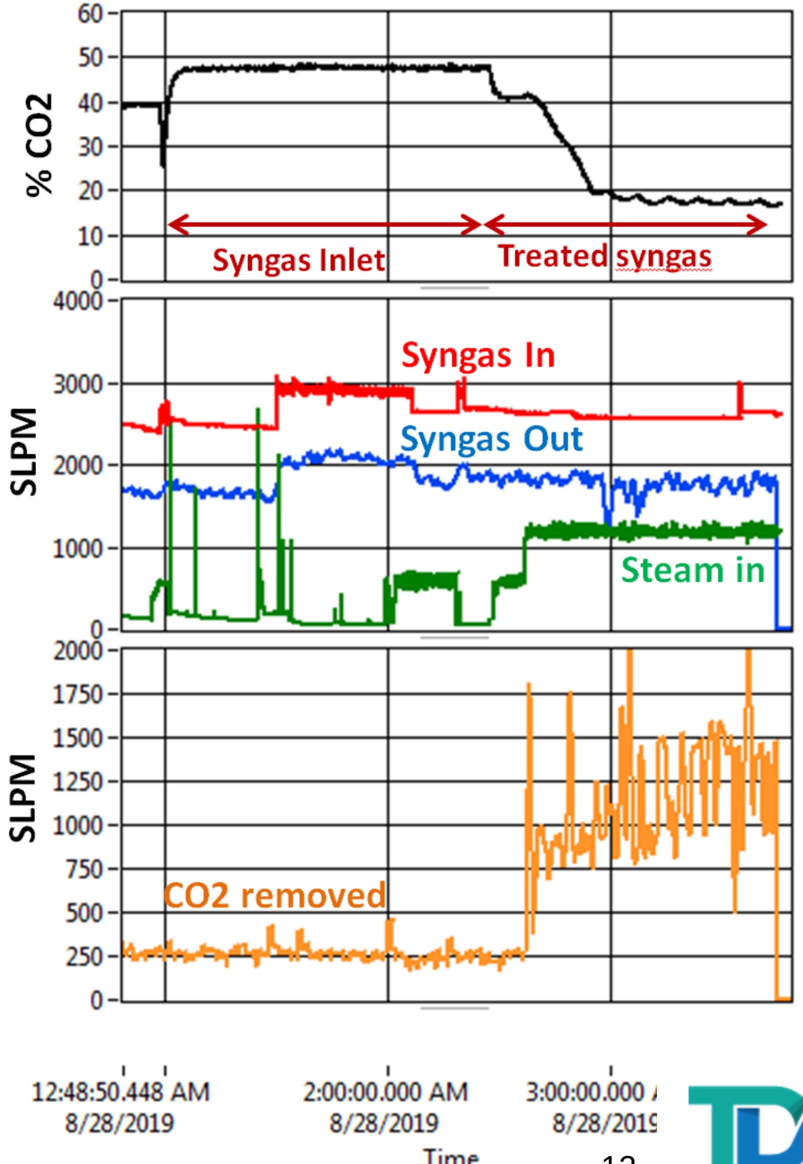
- **Because of the delays getting all equipment to site, the test setup had to be moved to a different location in the plant**
  - WGS catalyst, transformer, fiber optic cable etc. were procured locally
- **An existing super-structure at the new site added complexity to installation**
  - Skids were pipe rolled over berm
  - Vessels were loaded manually via socks and buckets

Pilot Plant Installed at Sinopec

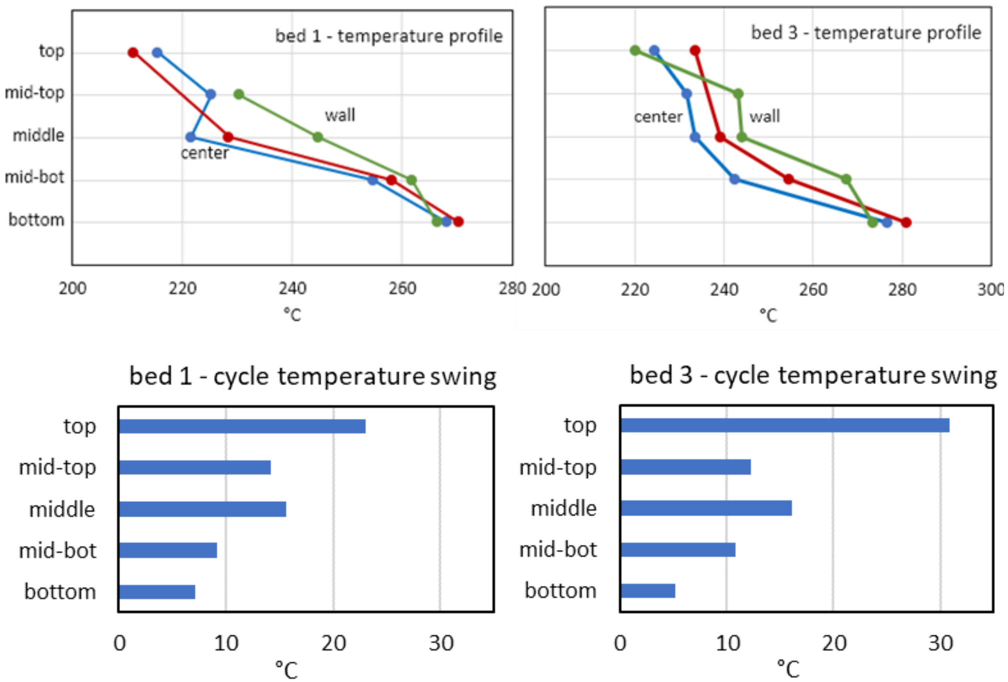
Test Results

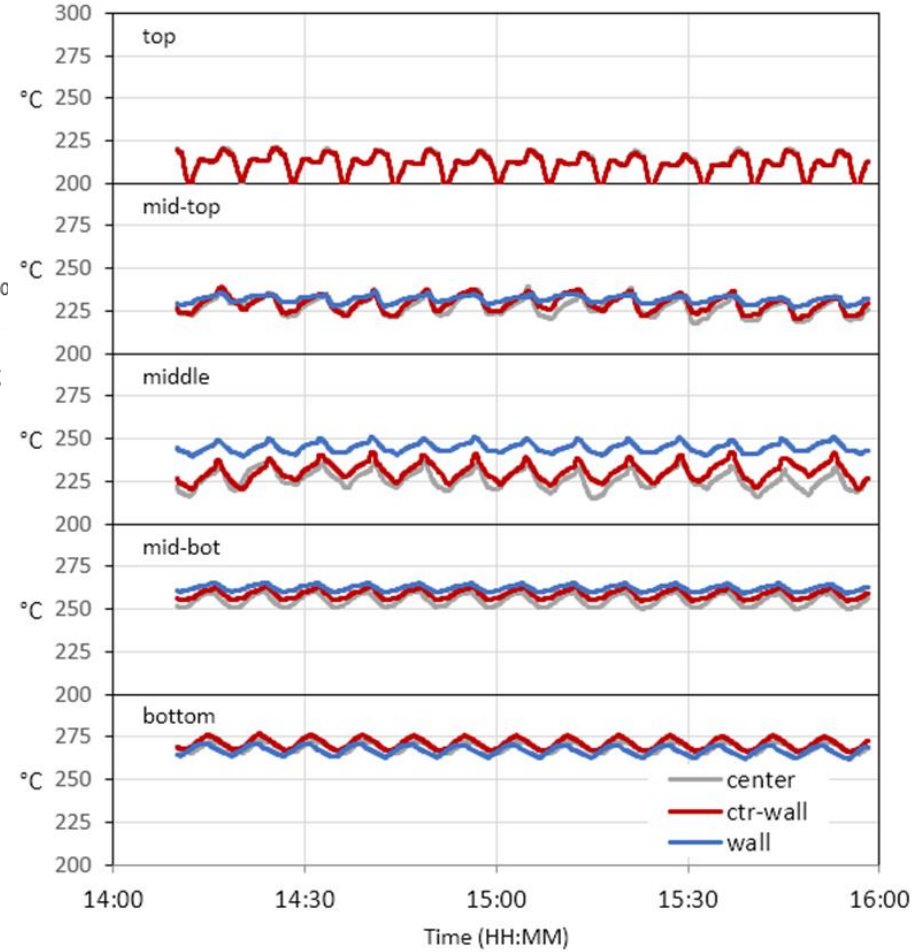


- **Testing started on 8/27/2019 at 21:50 MST**
- **High syngas flow, high T, low P during start-up to avoid water/tar condensation in the system**
- **2500 SLPM Syngas Flow**
- **~85% CO_2 removal efficiency**
- **~110 kg/hr CO_2 removal rate**



Bed Temperatures

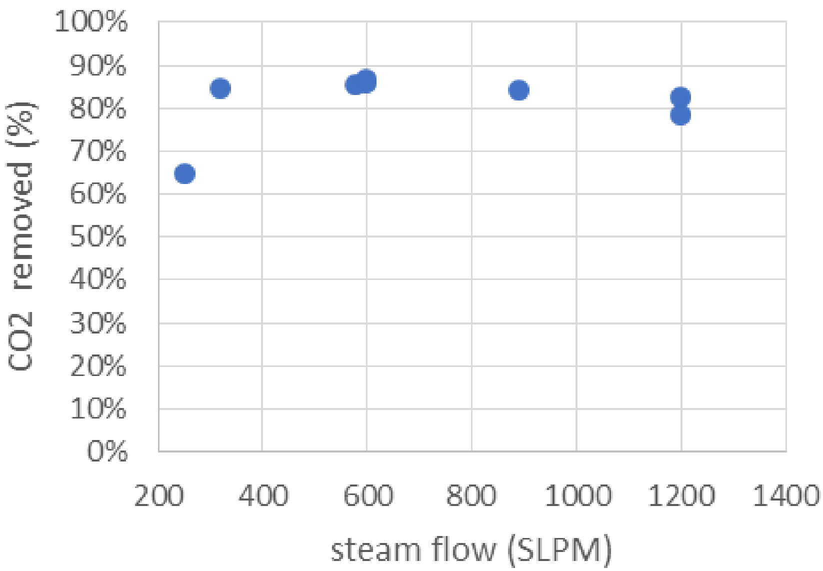


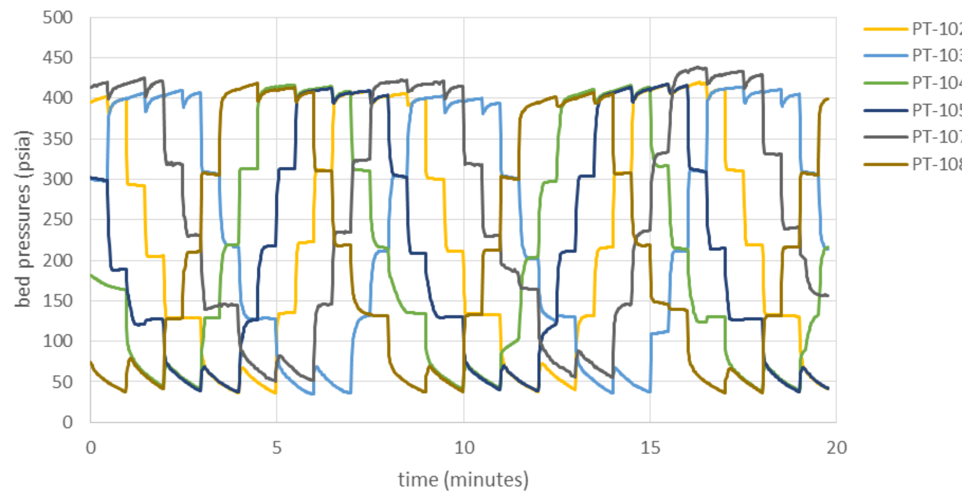


- **Bed temperature gradients matched our estimates and model predictions**
- **Larger gradients were evident in the syngas inlet side, while smaller gradients at the CO_2 free syngas end**
- **DeltaT of ~20-30°C was as predicted in the CFD simulations at GTI**

TDA RESEARCH

Parametric Tests





- **~150 hours of testing with over 1,000 adsorption/desorption cycles were carried out using the same T cycle used at NCCC**
  - ~86% CO_2 removal efficiency
  - ~110 kg/hr CO_2 removal rate
- **While a higher CO_2 adsorption capacity was observed than the evaluations at the NCCC, the removal efficiency were slightly lower than 90% due to the much higher amount of CO_2 that needed to be removed**
  - A new cycle sequence was generated with shorter cycle time to switch the bed positions prior to CO_2 breakthrough, but not implemented

Summary of Test Results

flow rates (SLPM)				pressures (psia)			Syngas CO_2 Concentration		
feed	steam	syngas product	CO_2 and steam out	ads	des	bed T (°C)	Feed (%)	HP product (%)	CO_2 removed
1,942	600	1,014	1,272	276	61	213	48	13	86%
1,983	1,200	1,486	1,262	298	61	192	45	11	83%
1,953	580	1,029	1,314	293	57	218	45	13	85%
2,174	892	1,185	1,273	304	36	214	47	14	84%
2,659	600	1,062	1,761	246	51	183	45	15	86%
2,648	1,199	1,593	1,513	305	72	225	48	17	78%
2,752	253	2,060	481	298	59	249	37	17	65%
859	129	556	128	134	79	288	46	15	78%

Parameters Varied:

- **Syngas Flow = 1500 to 2800 SLPM**
- **Steam Flow = 200 to 1200 SLPM**
- **Bed Temperature = 190 to 290°C**
- **Adsorption Pressure = 130 to 300 psia**
- **Desorption Pressure = 35 to 80 psia**

System Performance:

- **65-86% CO_2 removal efficiency**
- **Up to 122 kg/hr CO_2 removal rate**
- **3X the CO_2 removal rate compared to our tests at NCCC**

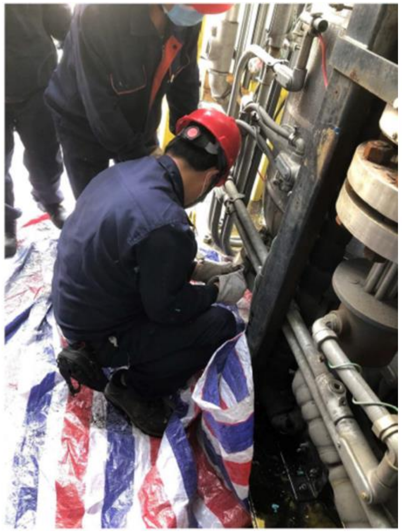
TDA RESEARCH

Decommissioning

All Inter-connects have been disassembled

All plant connections have been disconnected

Sorbent and Catalyst have been unloaded

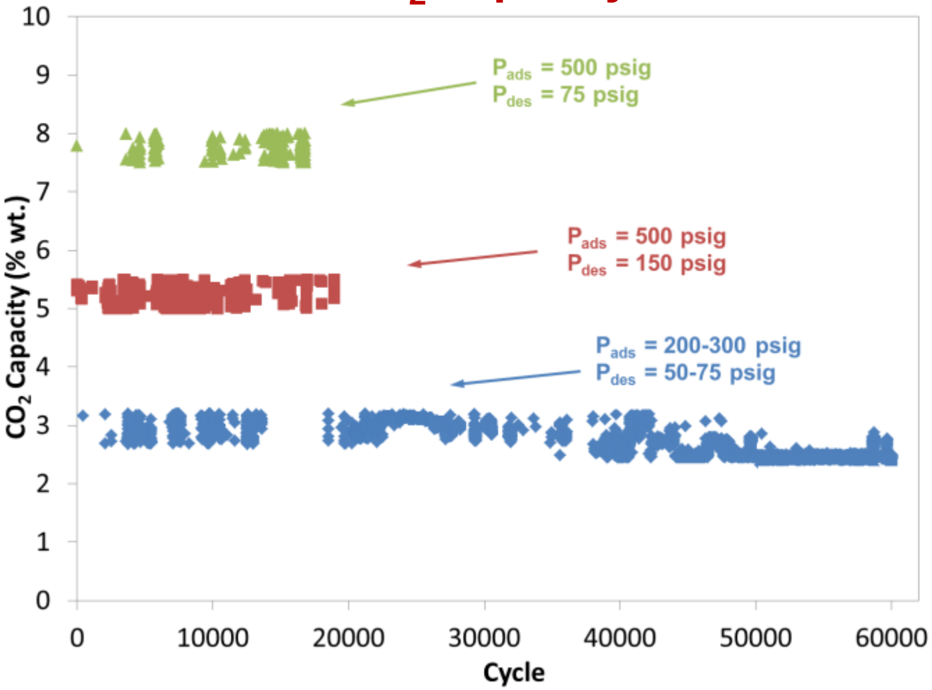


- Sinopec has completed the extract the rigs from the plant
- The pick-up is scheduled (scheduling of cranes and the crew)
- All used sorbents and catalysts have been removed from their tanks and will be disposed of by Sinopec
- Due to the international shipment bottleneck, our shipment is wait-listed, with the expectation of shipping the units in couple of months

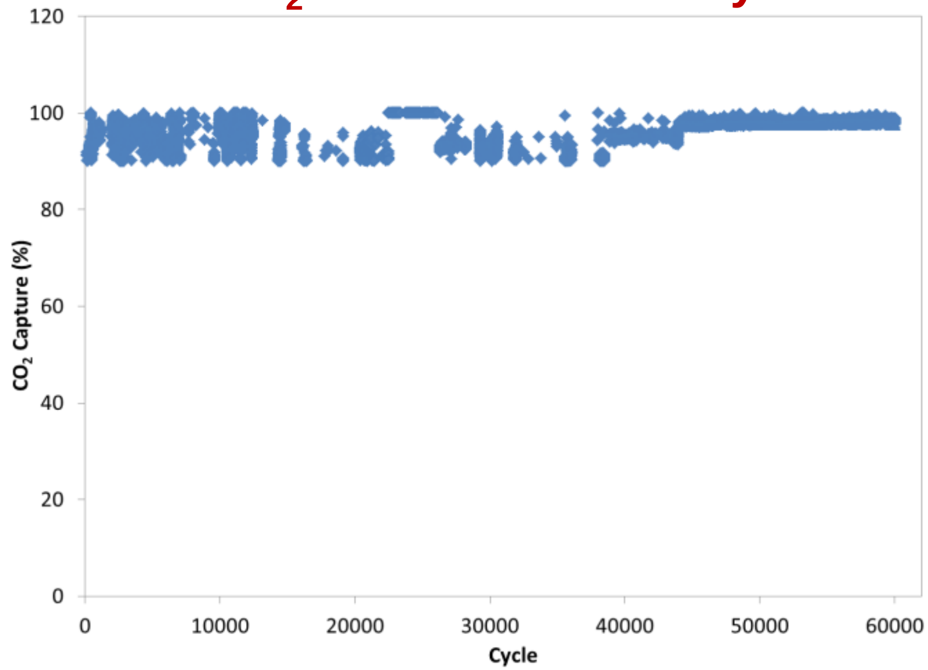
TDA RESEARCH

Sorbent Life Tests

CO_2 capacity



CO_2 Removal Efficiency

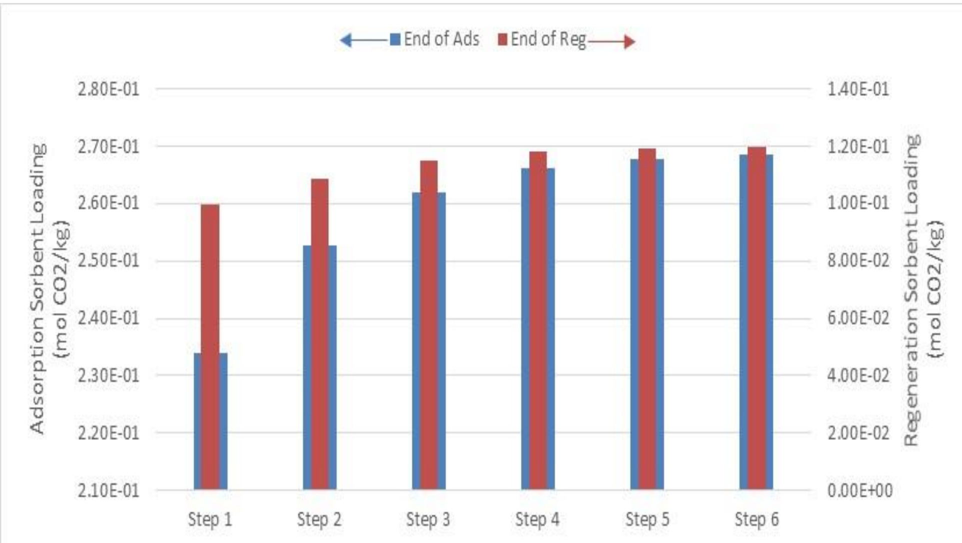


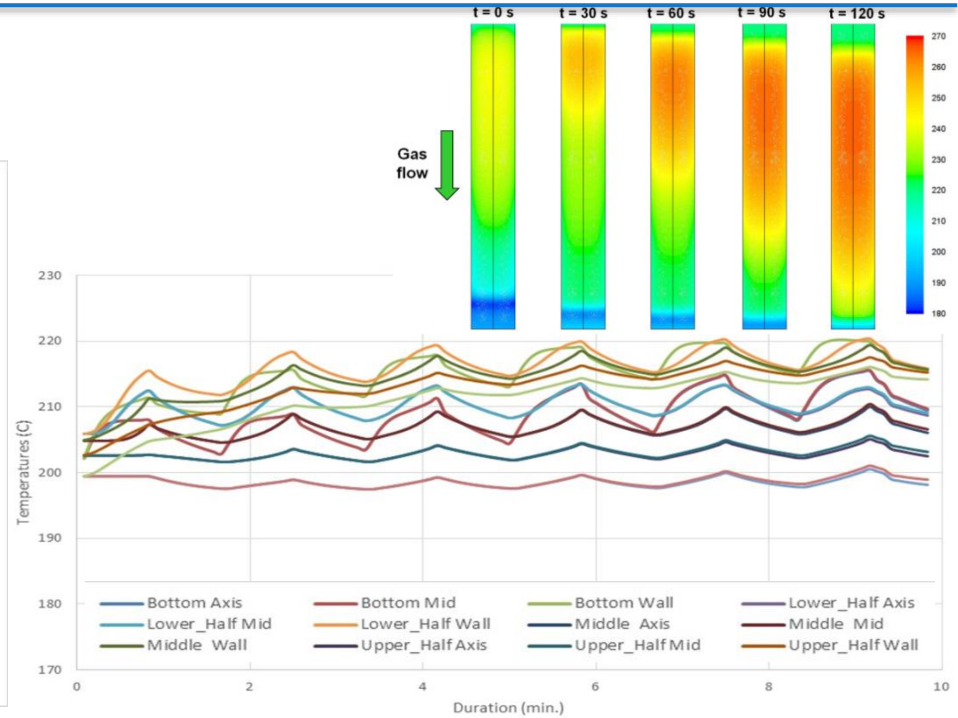
	Synthesis Gas	Simulated Gas	Steam Purge
Temperature	200°C	200°C	200°C
Pressure	500 psig	200-500 psig	50-300 psig
	Composition		
H_2	42.8%	53.4%	50.0%
CO_2	30.0%*	30.0%	-
H_2O	26.6%	26.6%	50.0%+
CO	0.6%	-	-

+ adjusted for purge with 100% steam at 150 psia

- **Long-term cycling of the scaled-up sorbent has been completed with stable performance over 60,000 cycles**

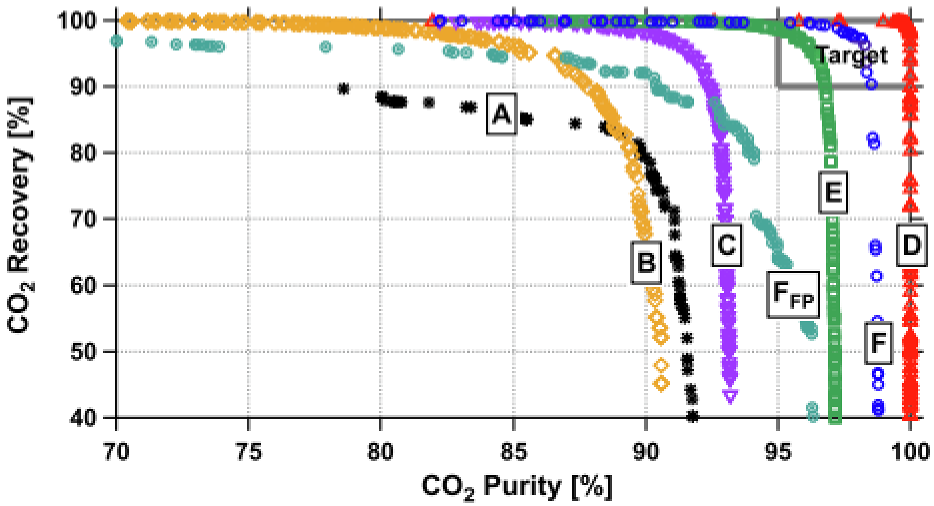
CFD Model Tuning

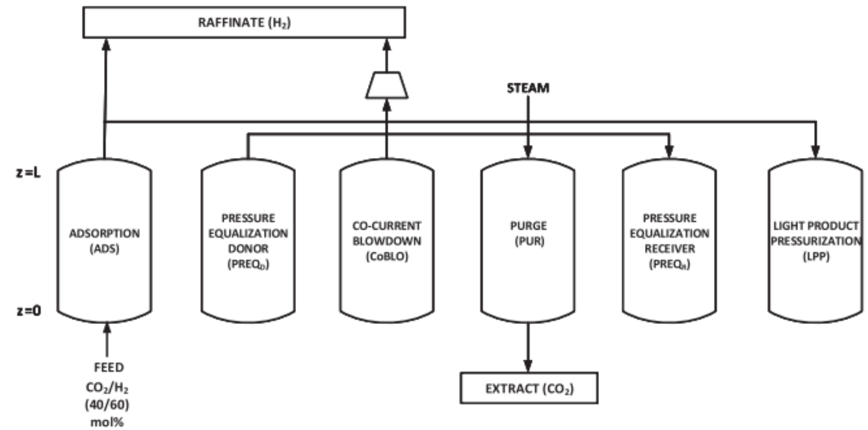




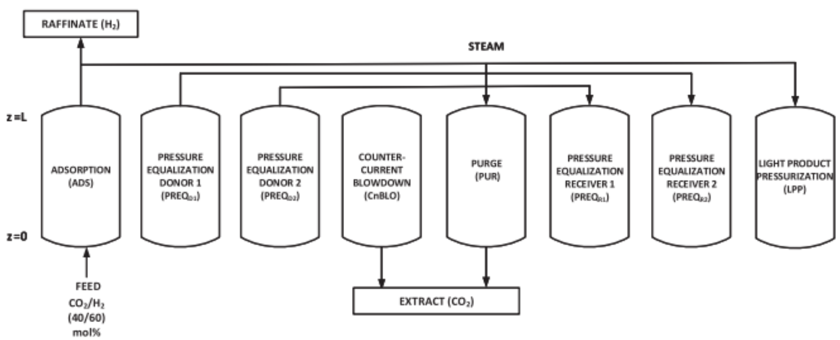
- **Working with GTI, we developed a CFD model to support reactor design**
- **The model was tuned using the data from 1 kW and 0.1 MW systems evaluated at Wabash River IGCC Plant and NCCC field tests**
- **CFD simulations reached steady state in 6 cycles and the working capacity matched the data sets**
- **CFD model will be further tuned using data from Sinopec field datasets**

PSA Cycle Optimization

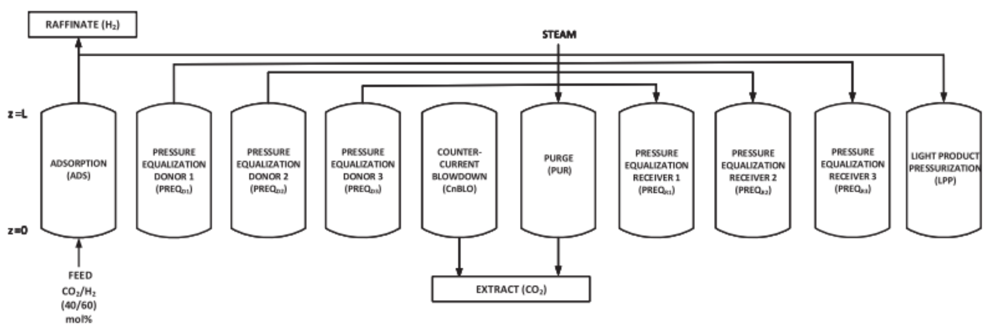




D. 6-step PSA cycle with CoBLO, purge, PREQ & LPP



E. 8-step PSA cycle with CnBLO, purge, two PREQ & LPP



F. 10-step PSA cycle with CnBLO, purge, three PREQ & LPP

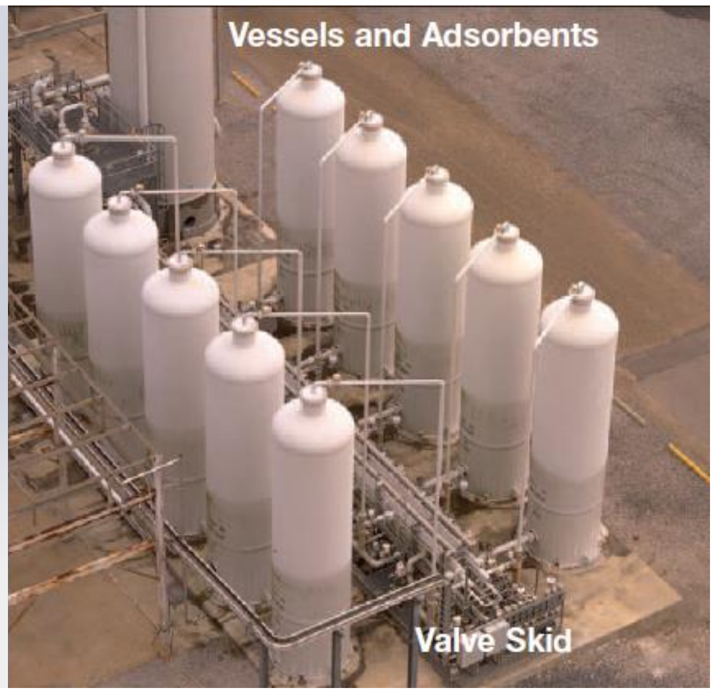
Applied Energy, Volume 254, 15 November 2019, 113624

- **Cycle Schemes D, E and F that use pressure equalizations and co-current blowdown met DOE targets of 90% capture and 95% CO_2 purity**

Reactor Design

- **Different reactor concepts have been evaluated**
- **Multiple train vertical reactors with internal flow distribution are selected for final design**

TDA Design

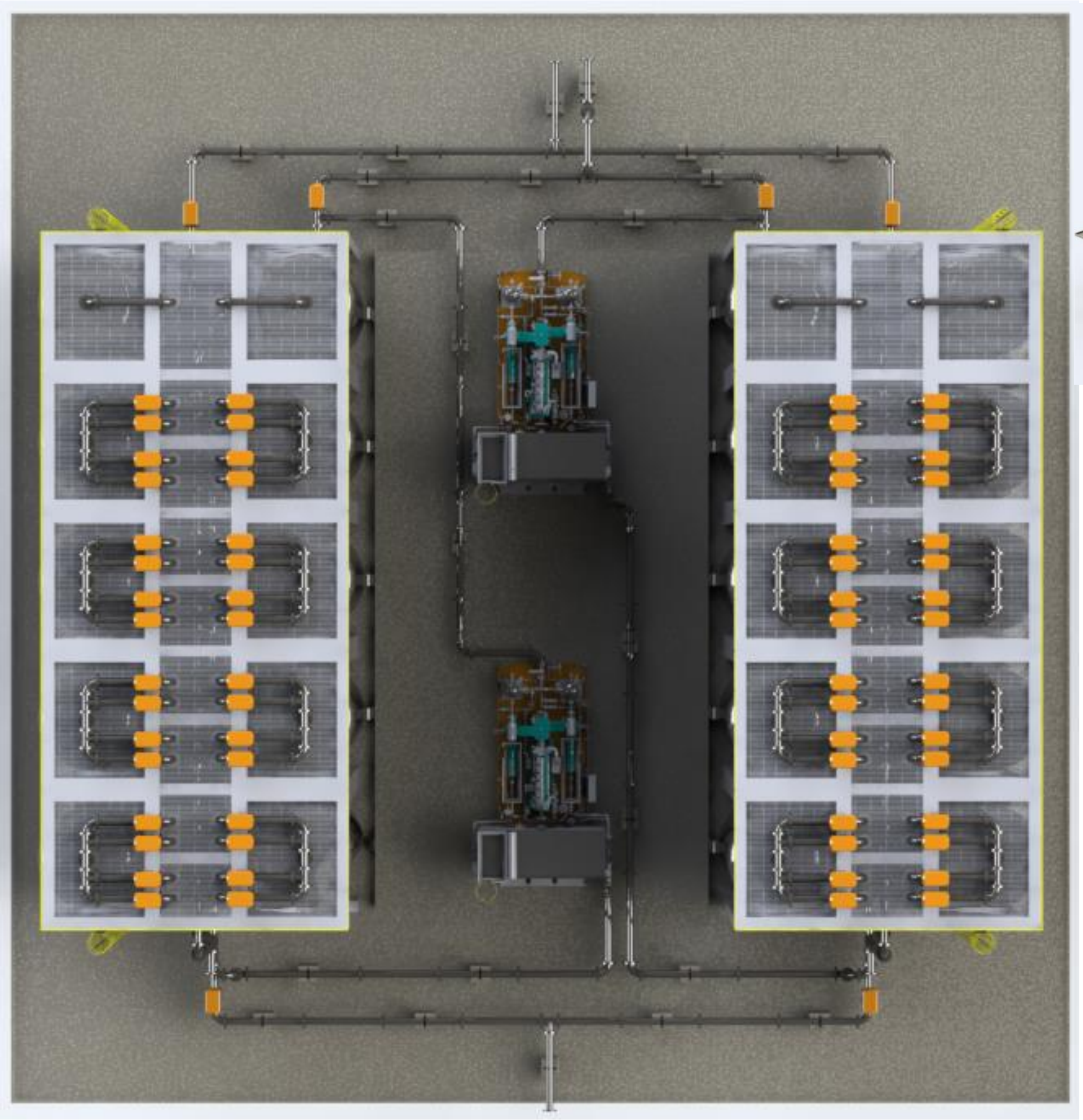


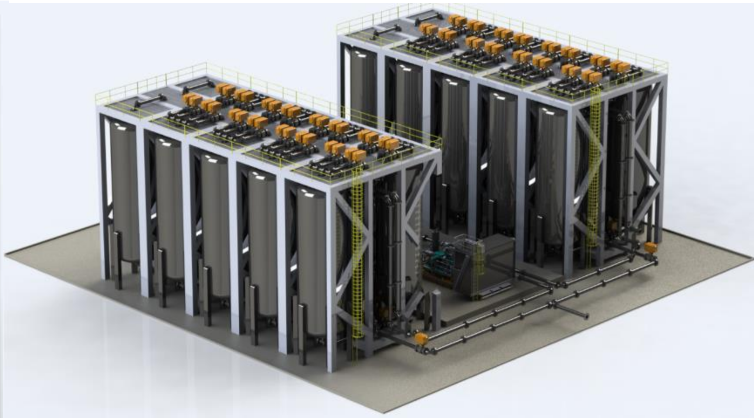
Source: Honeywell/UOP

GE Gasifier	
Syngas flow, kmol/h	34,747
Sorbent needed, kg	1,115,903
L	1,859,838
Cycle time, min	8
Ads. GHSV, h^{-1}	1,117
Total Beds	16
Bed. Volume, L	116,240
Bed Dimensions	
Diameter, ft	14
Length, ft	30.1
Vessel wall thickness, in	5.0
L/D	2.30
Particle size, in	1/8
Bed Pressure drop, psid	3.6

- **World-class PSA systems used in H_2 purification produces up to 400,000 m^3/hr H_2 (compared to ~780,000 m^3/hr flow rate used in TEA base case)**

Full-scale System Design





Major Units

- 8 beds x 2 = 16
- 2 accumulator X 2 = 4
- Cycling Valves
  - 6 x 8 x 2 = 96
- 2 recycle compressors
- 2 isolation vales x 2 per train = 4

Techno-economic Analysis

Gasifier	E-Gas		GE		Shell		TRIG	
Case	1	2	3	4	5	6	7	8
CO_2 Capture Technology	Cold Gas Cleanup Selexol™	Warm Gas Cleanup TDA's CO_2 Sorbent	Cold Gas Cleanup Selexol™	Warm Gas Cleanup TDA's CO_2 Sorbent	Cold Gas Cleanup Selexol™	Warm Gas Cleanup TDA's CO_2 Sorbent	Cold Gas Cleanup Selexol™	Warm Gas Cleanup TDA's CO_2 Sorbent
CO_2 Capture, %	90	90	90	90	90	90	83	83
Gross Power Generated, kW	707,165	669,993	727,416	674,790	672,980	619,054	624,964	616,338
Gas Turbine Power	464,000	425,761	464,000	417,083	464,000	416,147	424,722	413,946
Steam Turbine Power	243,165	244,232	257,250	247,362	208,980	202,907	200,242	202,392
Syngas Expander Power	-	-	6,166	10,345	-	-	-	-
Auxiliary Load, kW	194,495	125,755	193,155	121,834	177,361	112,254	166,998	126,730
Net Power, kW	512,670	544,238	534,262	552,956	495,620	506,800	457,966	489,609
Net Plant Efficiency, % HHV	30.8	34.0	31.9	34.4	30.8	33.4	31.5	34.2
Coal Feed Rate, kg/h	220,557	212,265	222,026	213,013	213,509	201,426	262,700	258,882
Raw Water Usage, GPM/MW	11.0	10.7	11.0	10.8	10.3	11.1	8.2	9.6
Total Plant Cost, $/kW	3,466	3,063	3,369	3,160	3,901	3,560	3,736	3,328
COE without CO_2 TS&M, $/MWh	137.3	121.1	133.6	124.0	150.1	138.6	125.5	112.5
COE with CO_2 TS&M, $/MWh	146.3	129.2	142.2	131.9	159.0	146.8	144.3	129.9
Cost of CO_2 Capture, $/tonne	43	28	38	29	49	39	40	27

- **IGCC plant with TDA's CO_2 capture system achieves higher efficiencies (34.4% and 34.0%) than IGCC with Selexol™ (31.9% and 30.8%) for E-Gas™ and GE gasifiers**
- **Cost of CO_2 capture is calculated as $29 and $28 per tonne for GE and E-Gas™ gasifiers, respectively (24-35% reduction against Selexol™)**
- **Cost of CO_2 capture is calculated as $40 and $28 per tonne for Shell and TRIG gasifiers, respectively (20-33% reduction against Selexol™)**

TDA RESEARCH

Acknowledgements

- DOE/NETL funding under the DE-FE-0013105 project
- Project Manager, Andy O’Palko
- Chuck Shistla, GTI
- Ashok Rao, UCI
- Arvind Rajendran, UOA
- Frank Morton, NCCC