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

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2020 DOE/NETL Carbon Capture Technology Review Meeting

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Project Summary

- The objective is to develop a new sorbent-based pre-combustion capture technology for Integrated Gasification Combined Cycle (IGCC) power plants
- 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
    - ✓ Performance validation via long-term cycling tests
  - ✓ Reactor Design
    - ✓ CFD Analysis and PSA cycle optimization/adsorption modeling
  - ✓ Fabricate a Pilot-scale Prototype for Demonstration
  - ✓ Evaluations at various sites using coal-derived synthesis gas
  - ✓ Techno-economic analysis
    - ✓ High fidelity engineering analysis and process simulation

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Project Partners

Project Duration

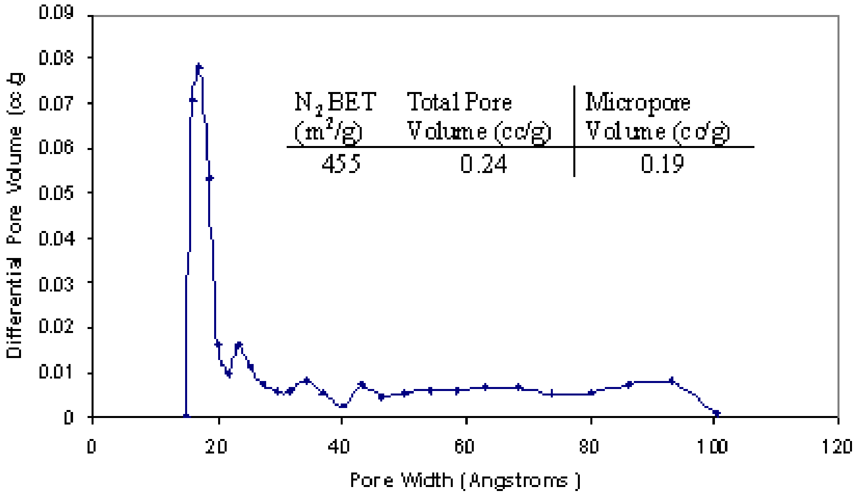
- **Start Date = January 1, 2014**
- **End Date = March 31, 2021**

Budget

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

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"

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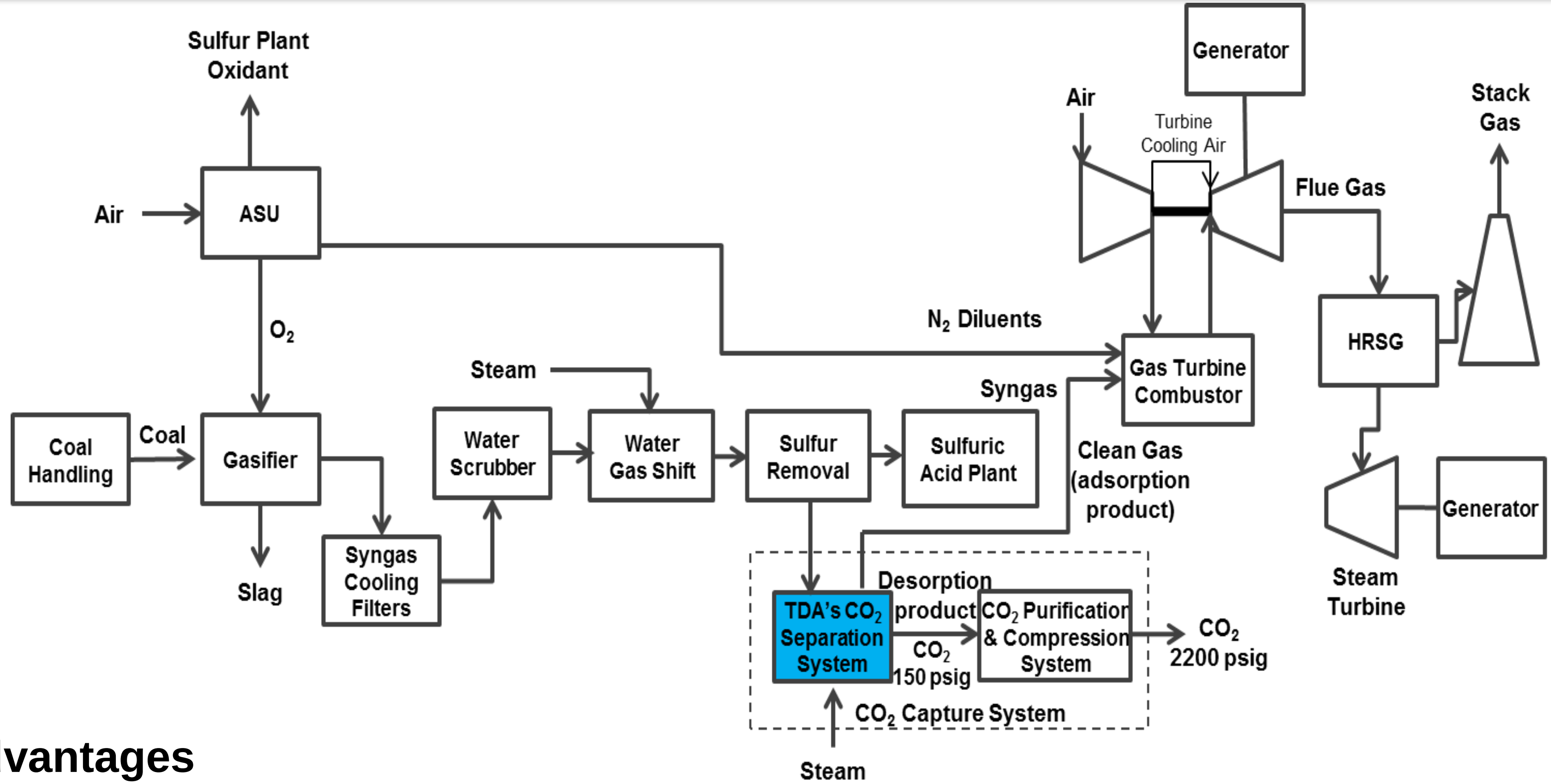
Integration to the IGCC Power Plant

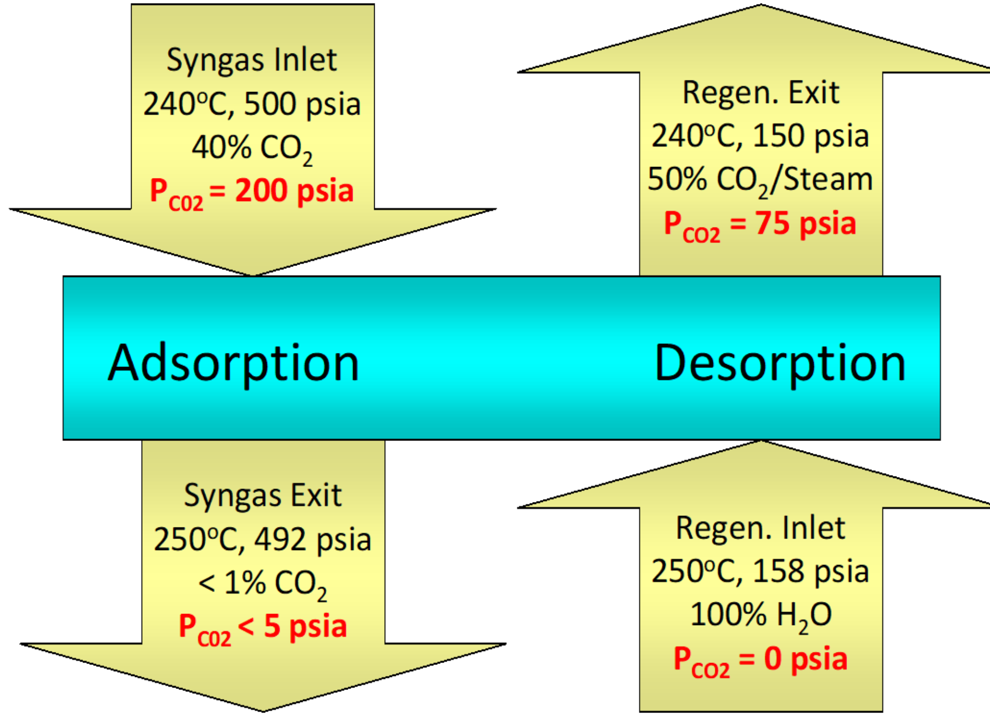


Advantages

- 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

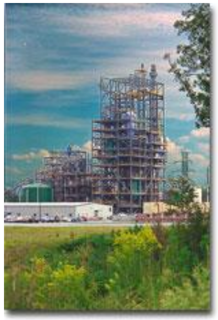


Source: Honeywell/UOP

Technology Maturation Timeline





2008	2011	2013	2014	2017	2018	2019
Bench-scale tests	0.5-1 kW tests at NCCC	0.5-1 kW tests at Wabash River IGCC	Sorbent Scale-up IP secured	0.1 MW tests at NCCC	Integrated with WGS Tests with Praxair	0.1 MW Tests at Sinopec/ Yangtze Chemicals Nanhua Plant

Primary Focus

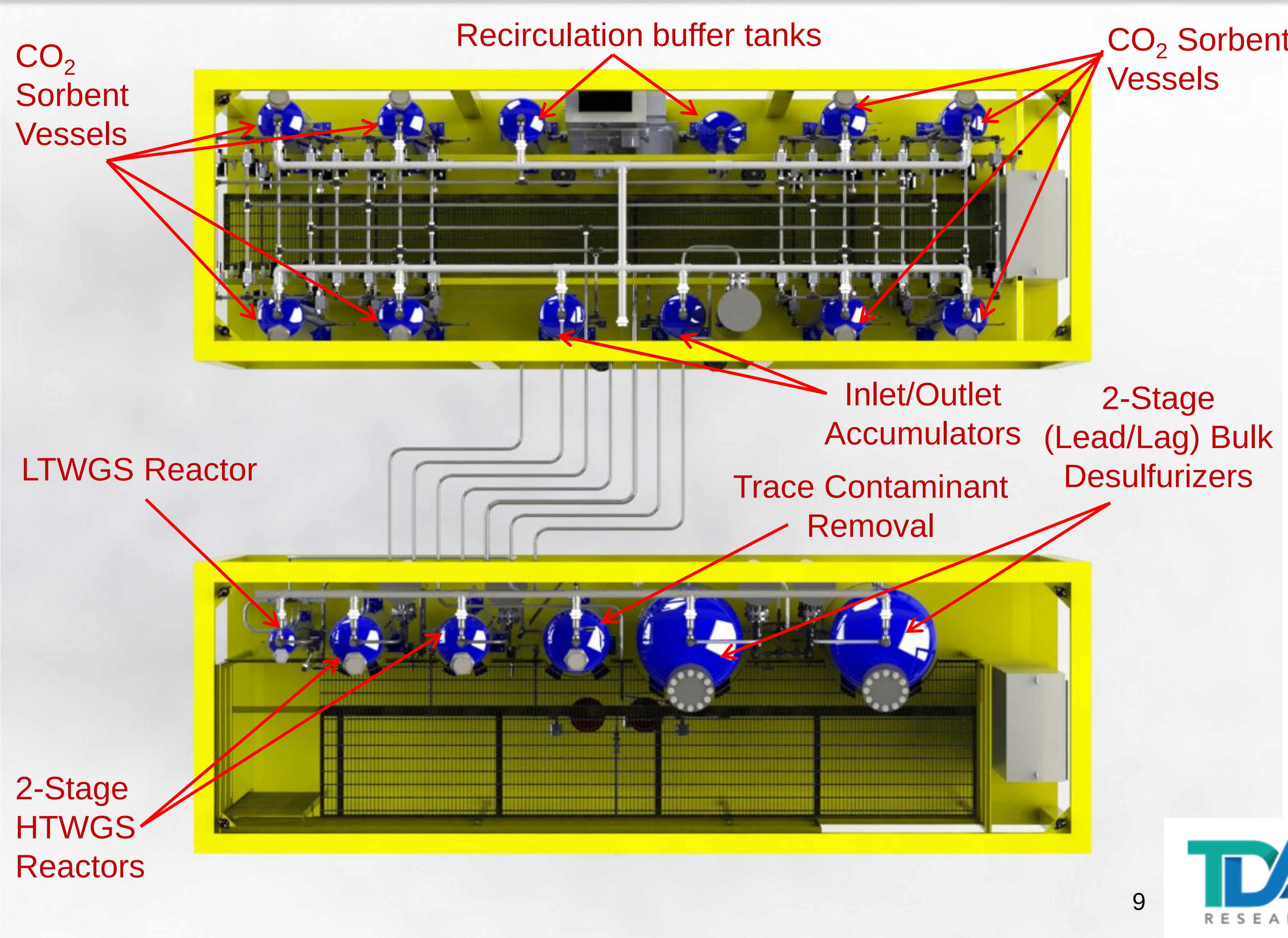
- **0.1 MW_e evaluation in a world class IGCC plant to demonstrate full benefits of the technology**
    - **Testing with high pressure gas**
- **Demonstrate full operation scheme**
    - 8 reactors and all accumulators
    - Utilize product/inert gas purges
    - H_2 recovery/CO_2 purity
- **Evaluations 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 Complex

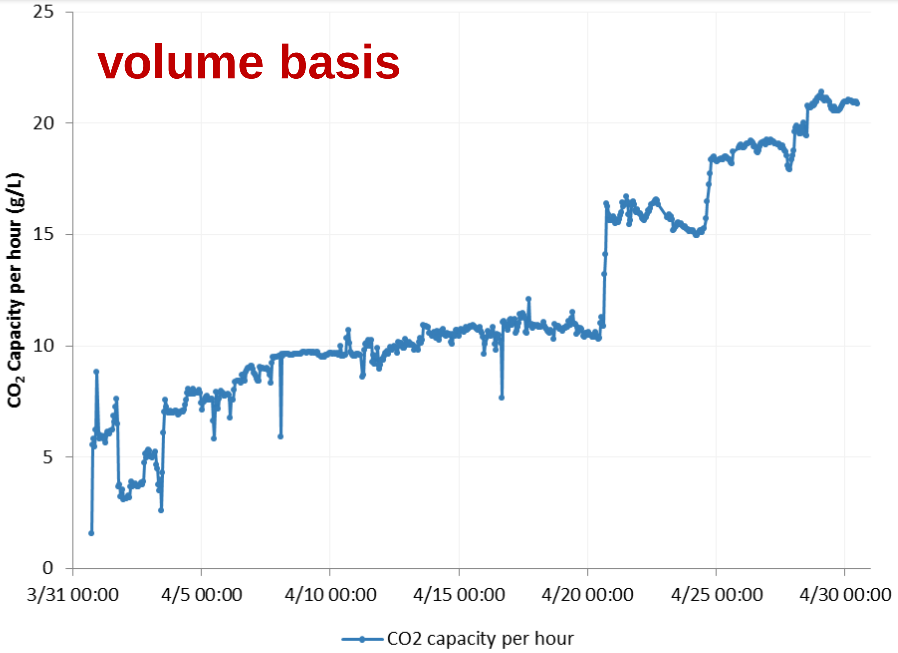
Slipstream Test Skid - Top View

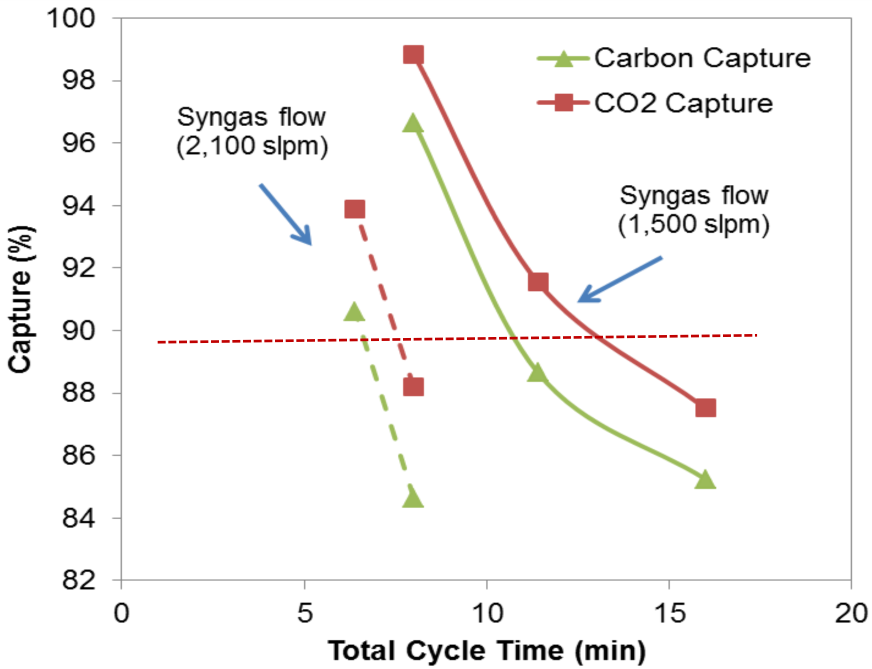


Field Test Unit Installed at NCCC

- **Fabrication is completed in 2016**
- **Installation with all the hook-ups were completed in March 2017**
- **Testing initiated in April 2017**

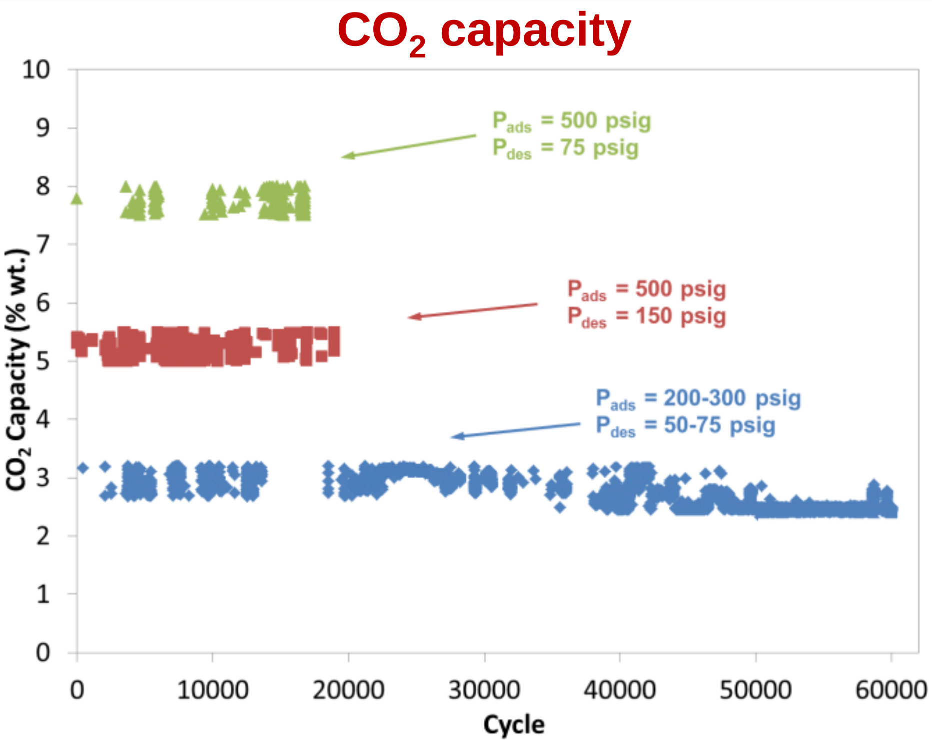
Working Capacity of the Sorbent

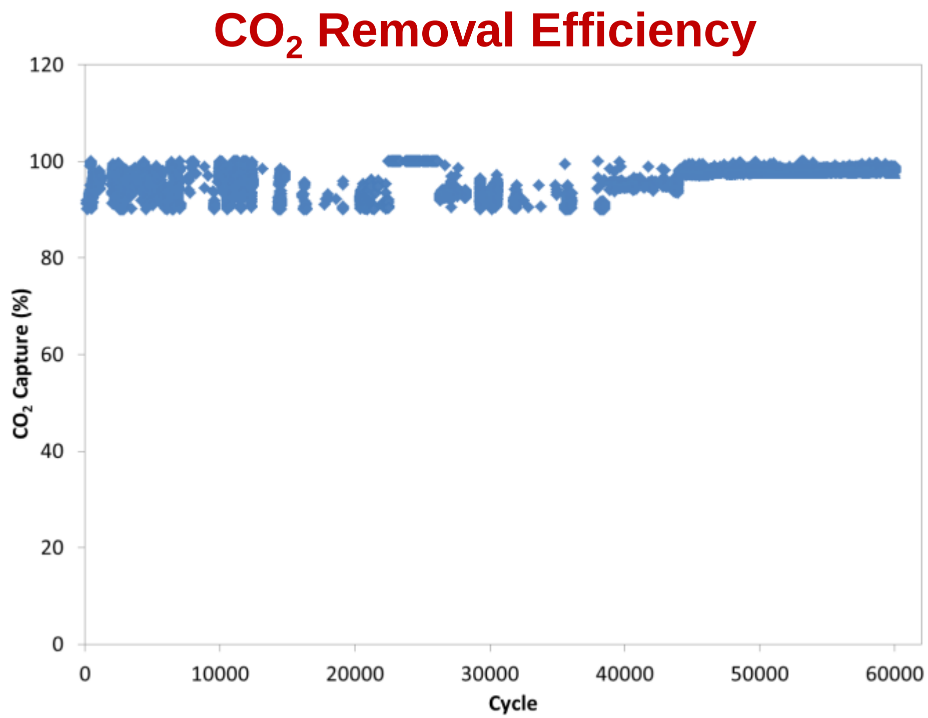




- **A successful 30 day (707 hrs) evaluation was completed at NCCC**
  - **Design flow at NCCC operating conditions was 1,420 SLPM (50 SCFM)**
  - **97.3% capture @ 1,500 SLPM**
  - **93% @ 1,800 SLPM**
  - **90% @ 2,100 SLPM**
- **Pressure drop through the gas conditioning skid prevented flowing more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

Sorbent Evaluations – Multiple Cycles





	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**

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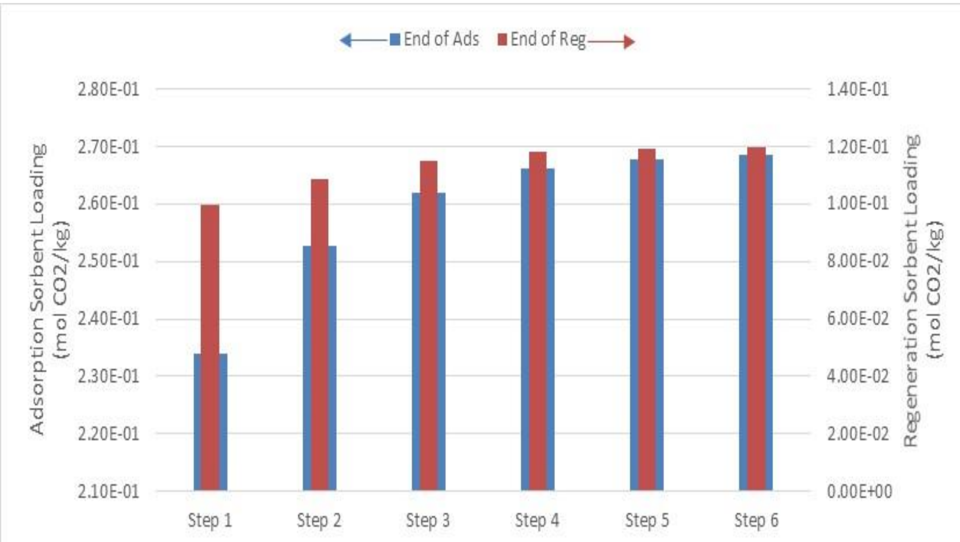
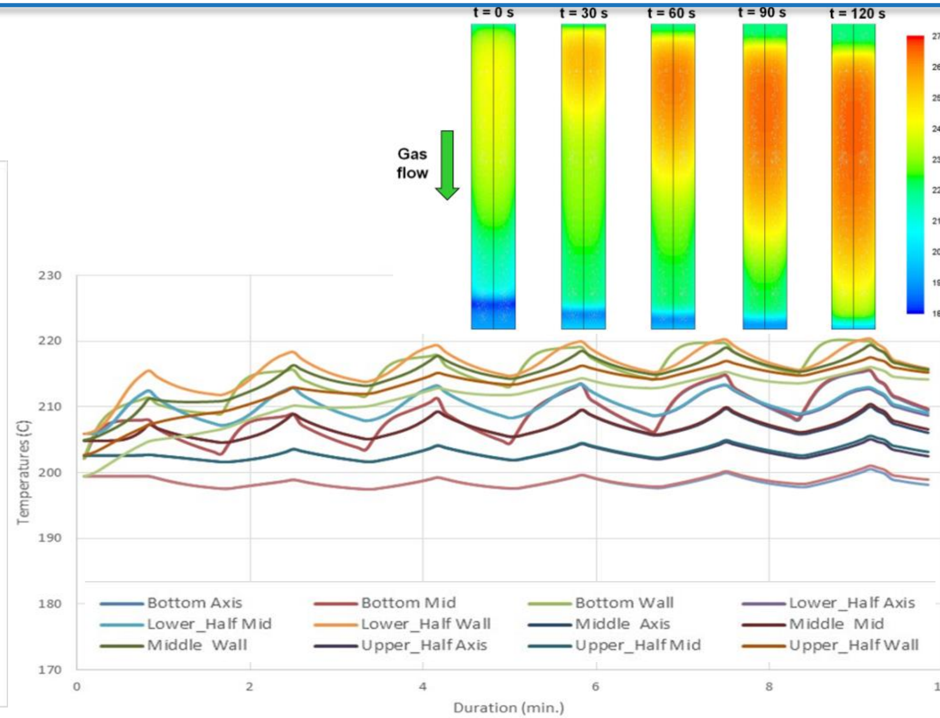
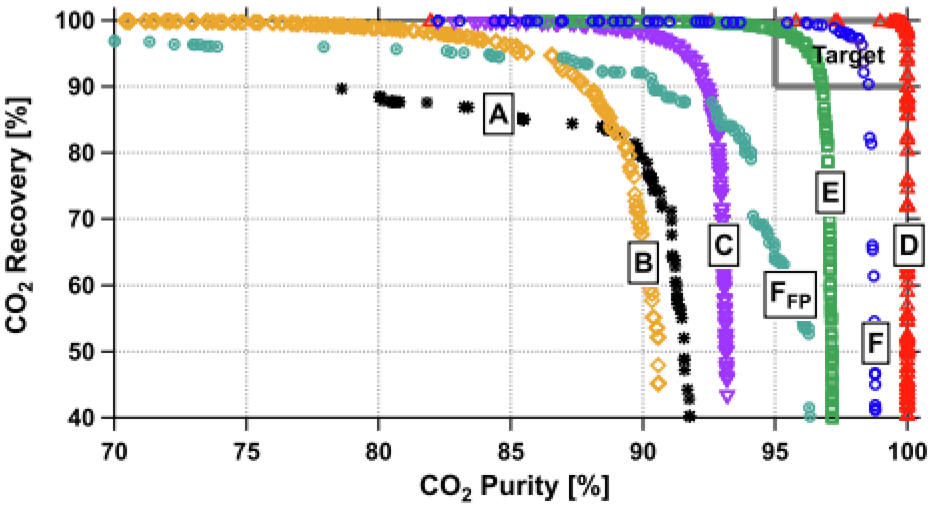
CFD Model Tuning

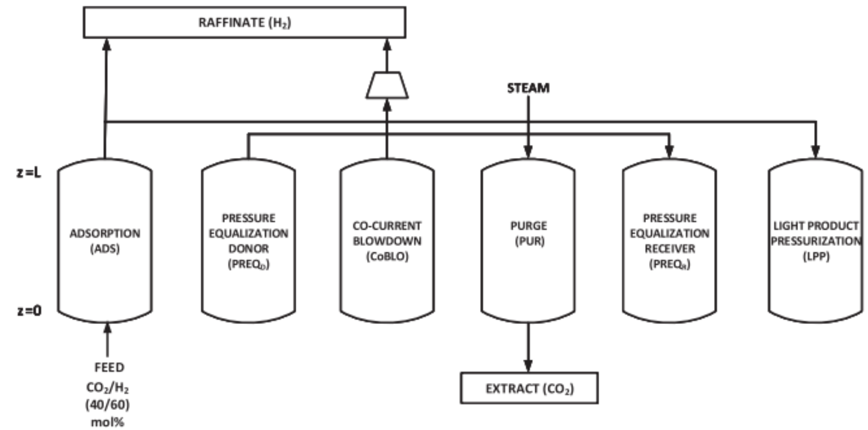




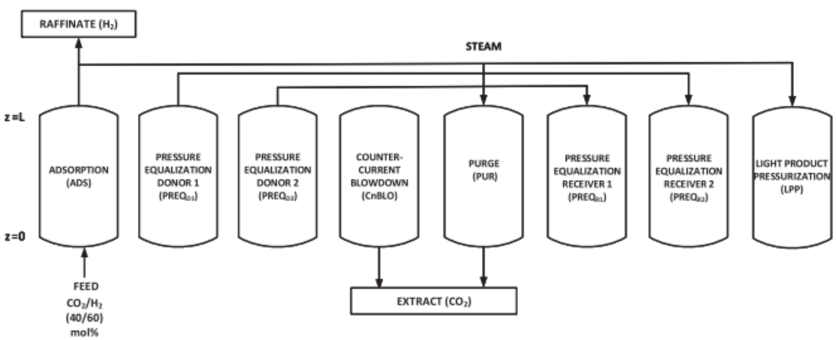
- **Working with GTI, we developed a CFD model to support reactor design**
- **The model was tuned using the data from 1 kW and 0.1 MW systems evaluated at Wabash River IGCC Plant and NCCC field tests**
- **CFD simulations reached steady state in 6 cycles and the working capacity matched the data sets**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

Cycle Optimization

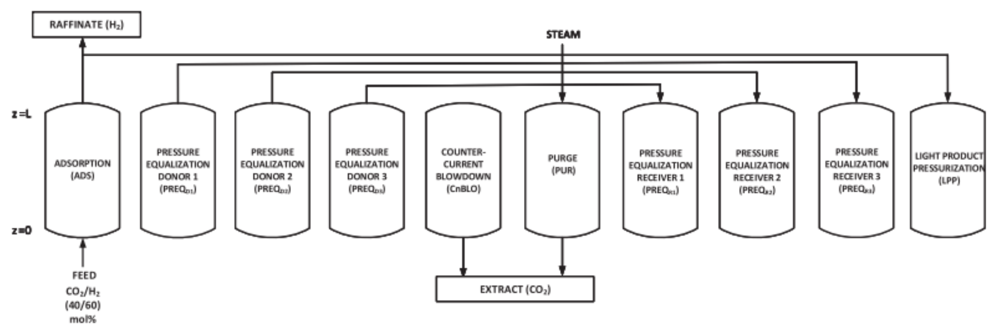




D. 6-step PSA cycle with CoBLO, purge, PREQ & LPP



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



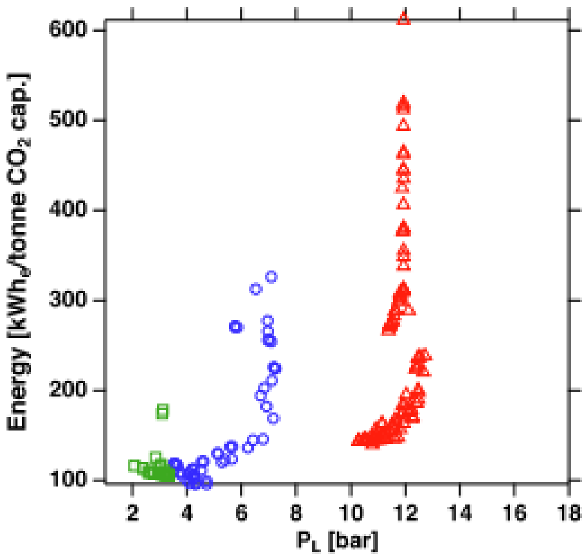
F. 10-step PSA cycle with CnBLO, purge, three PREQ & LPP

Applied Energy, Volume 254, 15 November 2019, 113624

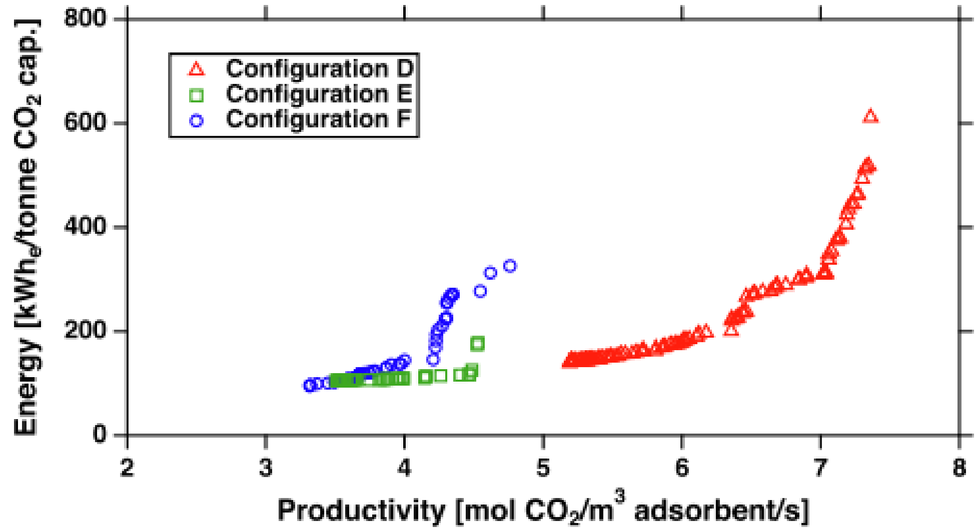
- **Cycle Schemes D, E and F that use pressure equalizations and co-current blowdown met DOE targets of 90% capture and 95% CO_2 purity**

Minimization of Energy Penalty

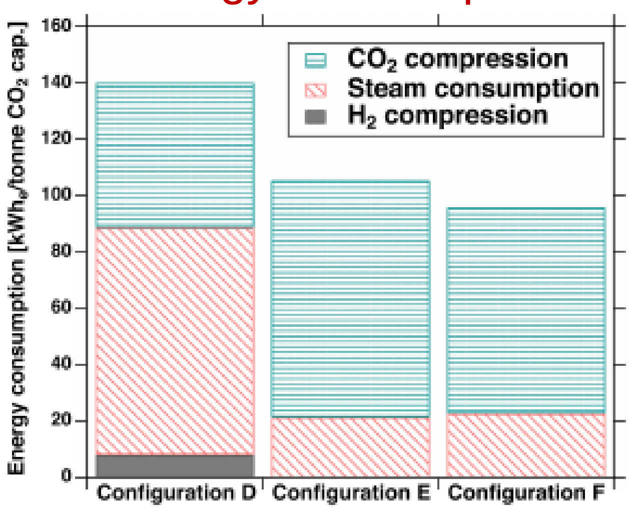
CO_2 Recovery Pressure



Sorbent Productivity/Bed Size Factor



Energy Consumption



- Configuration F: 10-step PSA cycle with three pressure equalizations: 95.7 kWh/tonne of CO_2 captured at productivity of 3.3 mol $CO_2/m^3/s$
- Configuration D: 6-step PSA cycle with one pressure equalization and a co-current blowdown: 140 kWh/tonne of CO_2 captured at productivity of 5.2 mol $CO_2/m^3/s$
- OPEX/CAPEX trade-off is being evaluated for a fully optimized PSA cycle

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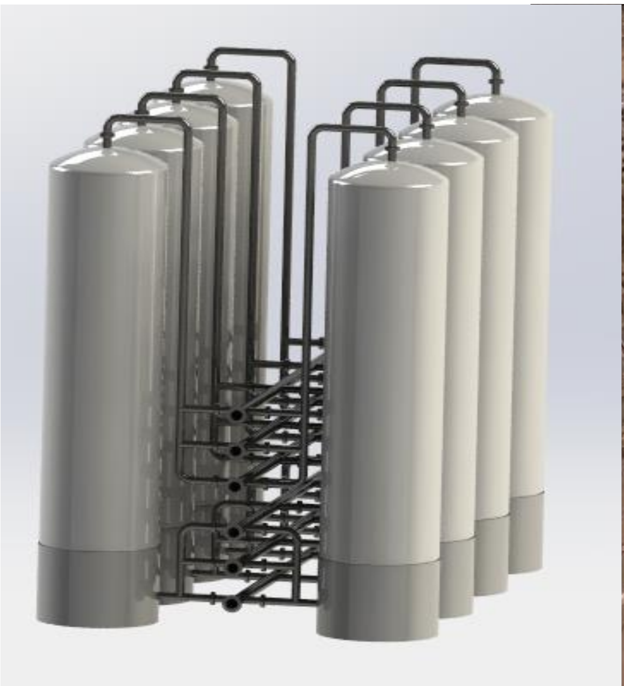
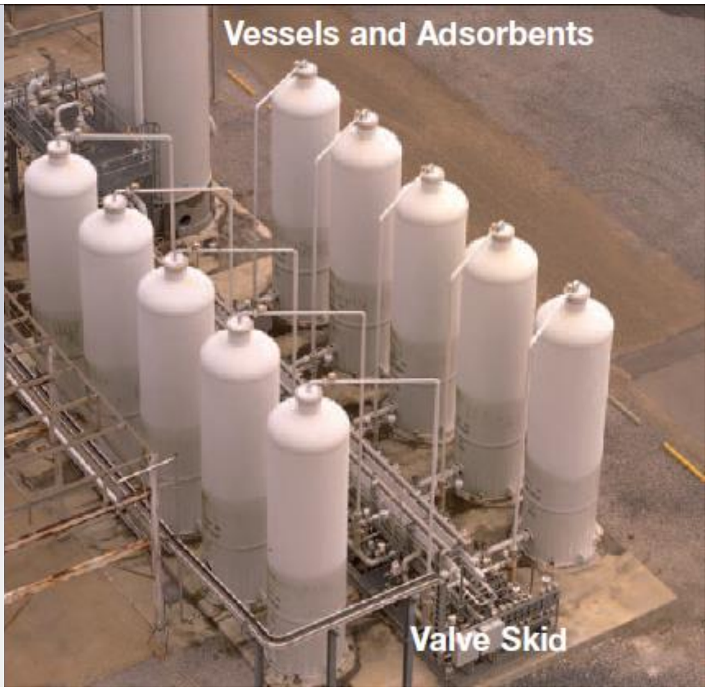
Reactor Design

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



TDA Design

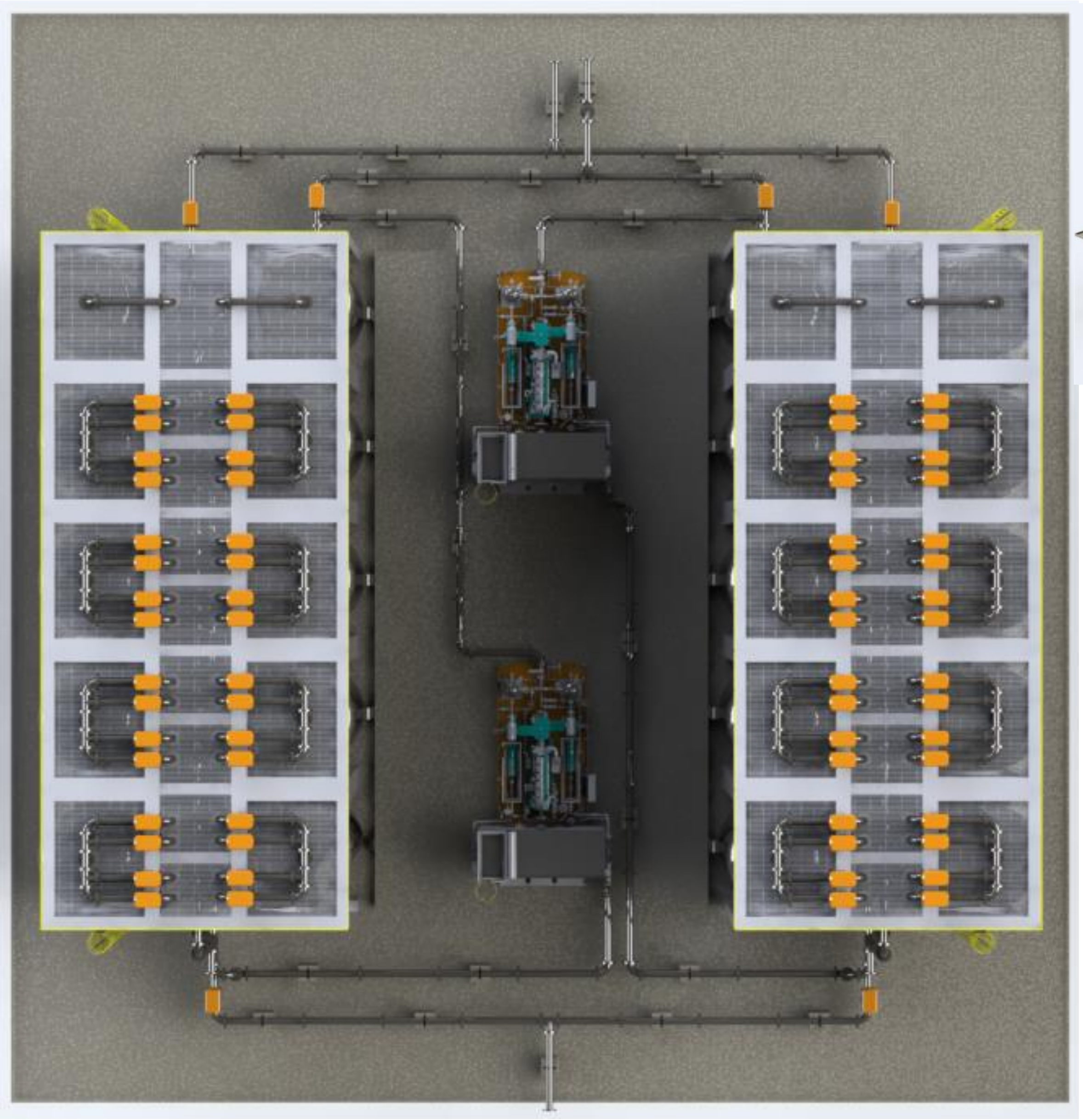


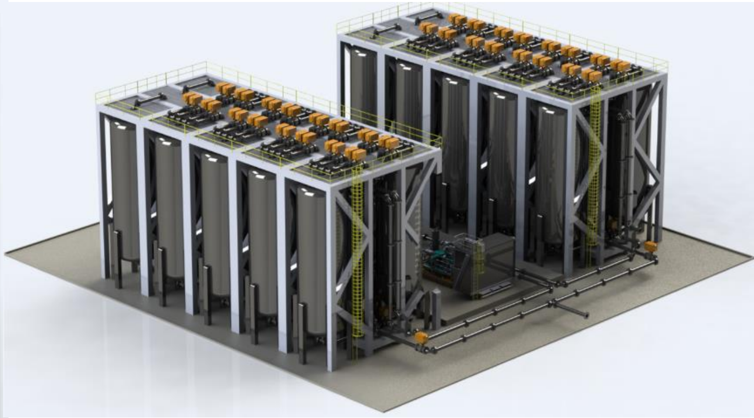
Source: Honeywell/UOP

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

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Techno-economic Analysis

Gasifier	E-Gas		GE	
Case	1	2	3	4
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
CO_2 Capture, %	90	90	90	90
Gross Power Generated, kW	710,789	670,056	727,633	674,331
Gas Turbine Power	464,000	425,605	464,000	417,554
Steam Turbine Power	246,789	244,450	257,657	246,746
Syngas Expander Power	-	-	5,977	10,031
Auxiliary Load, kW	194,473	124,138	192,546	120,661
Net Power, kW	516,316	545,917	535,087	553,671
Net Plant Efficiency, % HHV	31.0	34.1	32.0	34.5
Coal Feed Rate, kg/h	220,549	212,265	221,917	213,013
Raw Water Usage, GPM/MW	10.9	10.3	10.7	10.5
Total Plant Cost, $/kW	3,464	3,102	3,359	3,212
COE without CO_2 TS&M, $/MWh	136.8	122.3	133.0	125.5
COE with CO_2 TS&M, $/MWh	145.7	130.4	141.6	133.4
Cost of CO_2 Capture, $/tonne	43	30	37	31

- **IGCC plant with TDA's CO_2 capture system achieves higher efficiencies (34.5% and 34.1%) than IGCC with Selexol™ (32.0% and 31.0%) for the E-Gas™ and GE gasifiers**
- **Cost of CO_2 capture is calculated as $31 and $30 per tonne for GE and E-Gas™ gasifiers, respectively (16-30% reduction against Selexol™)**
- **Cost of CO_2 capture is calculated as $40 and $28 per tonne for Shell and TRIG gasifiers, respectively (15-28% reduction against Selexol™)**

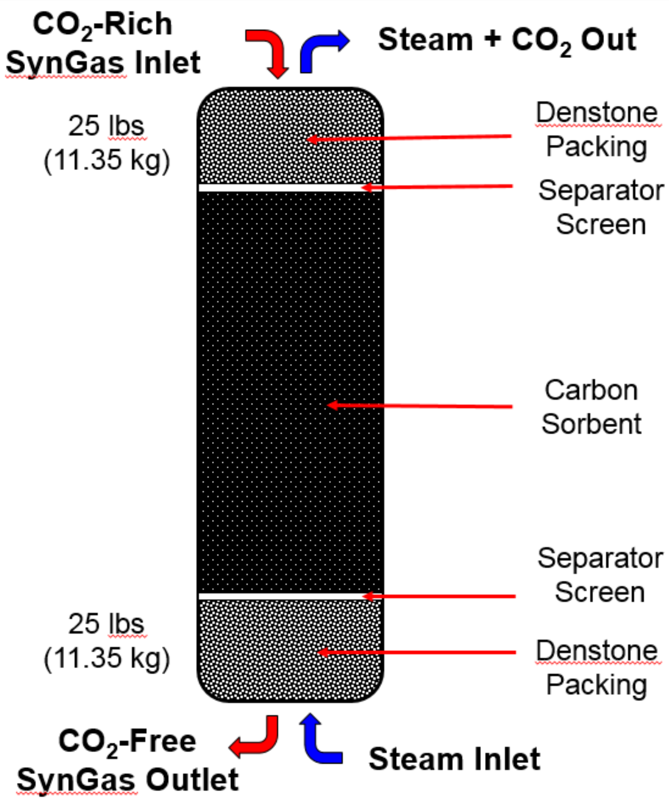
Sinopec Field Test Update

- Both skids and one of the containers were late to the site
- One skid held up due to the hazardous nature of the WGS catalyst and regulations on some of the power equipment
- Catalyst, transformer, fiber optic cable etc. were procured locally

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**
- **An existing super-structure at the new site added complexity to installation**
  - Skids were pipe rolled over berm and into place
  - Vessels were loaded manually via socks and buckets

Carbon Bed Filling



Filter separator

Denstone deltaP beads on top of the column

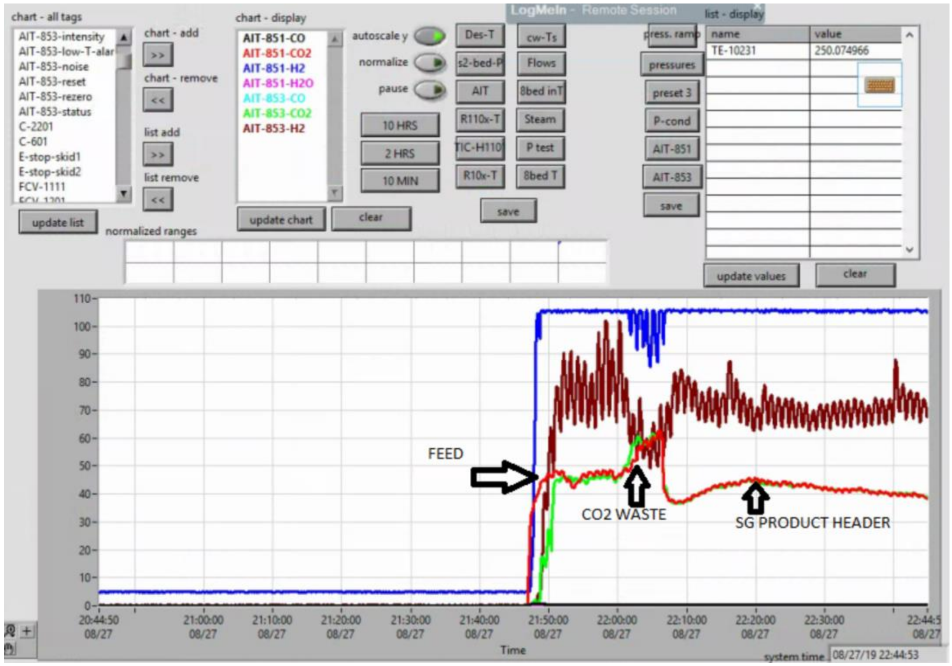
Sorbent loading using socks

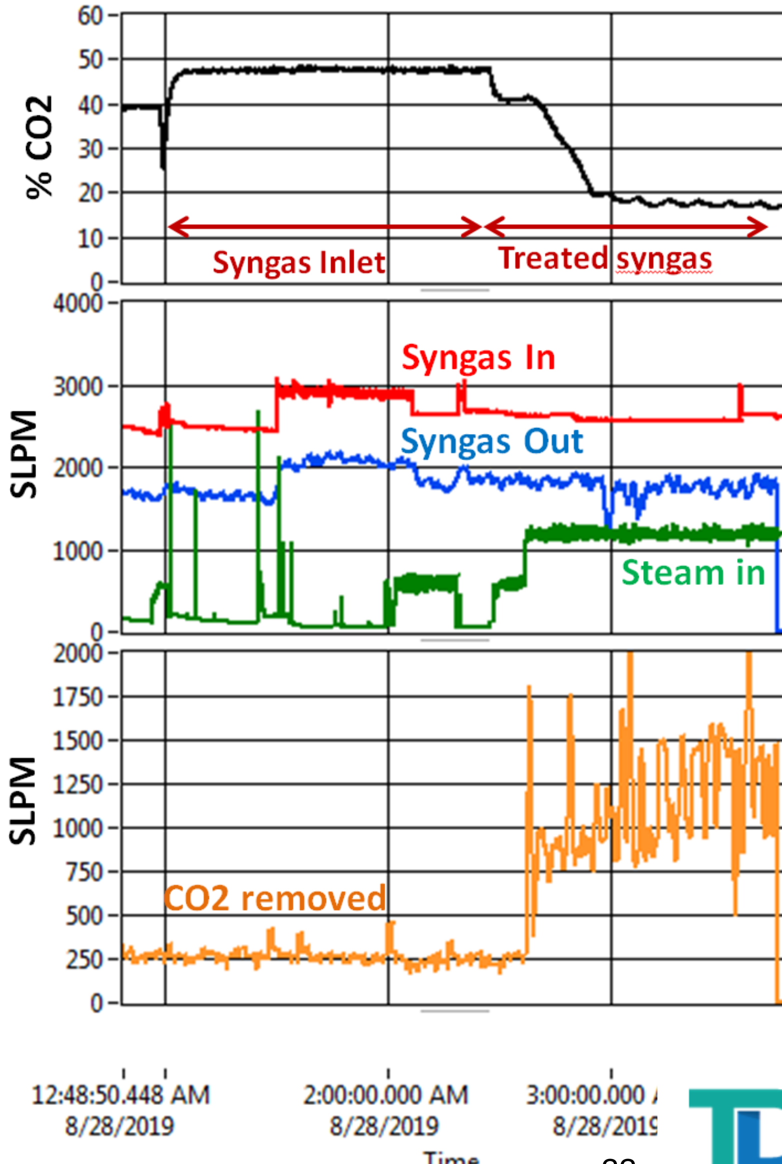
- **Stainless mesh screens and Denstone deltaP media are added to the beds (not available in NCCC tests)**
  - The inert ceramic beads eliminated some of the dead volume in the reactor top and bottom
  - Heavy Denstone beads also limits material movement in the bed during cycling

Pilot Plant Installed at Sinopec

TDA Research

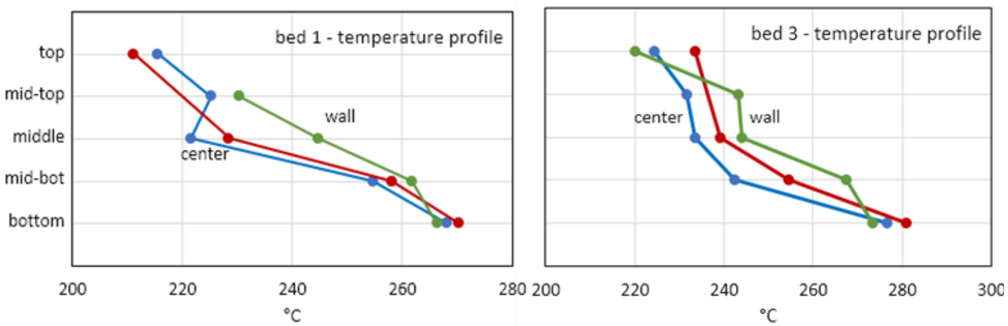
Early Results

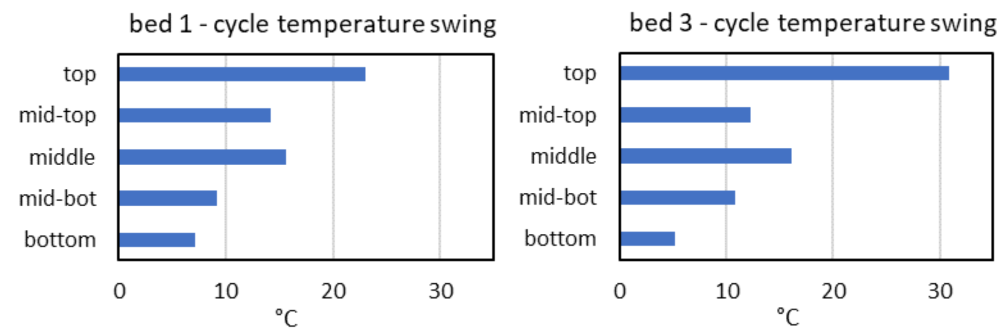


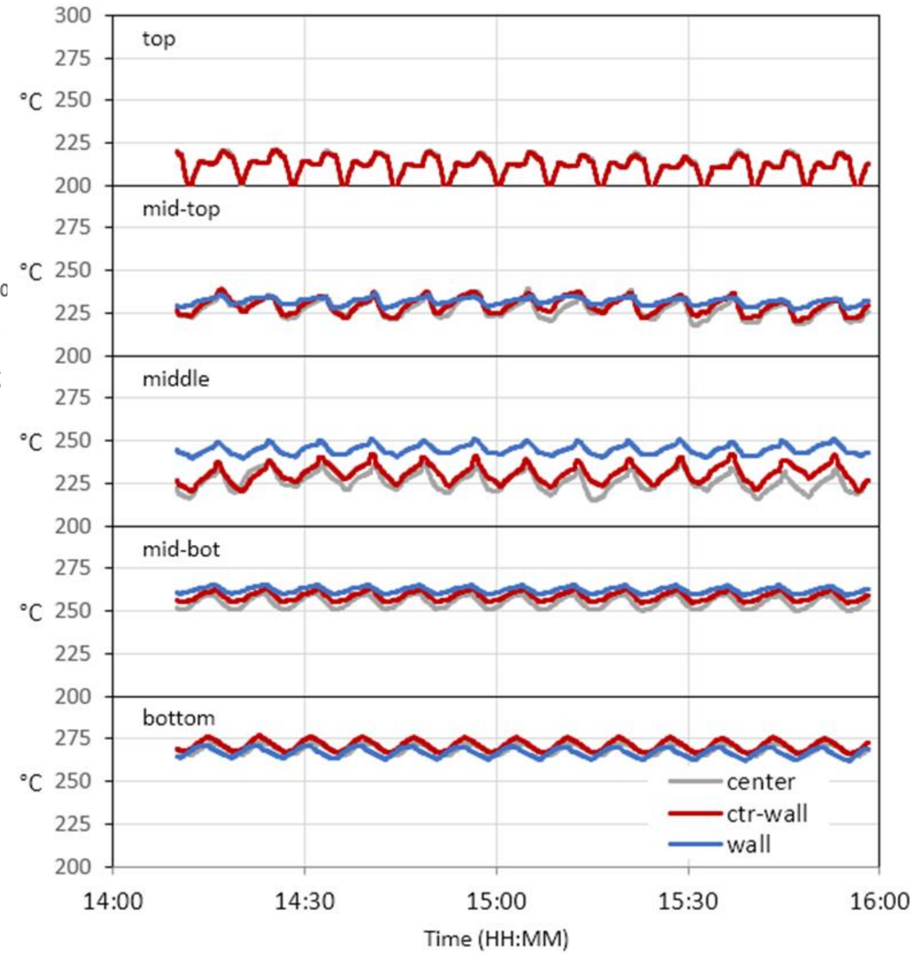


- **Testing started on 8/27/2019 at 21:50 MST**
- **High syngas flow, high T, low P during start-up to avoid water/tar condensation in the system**
- **2500 SLPM Syngas Flow**
- **~85% CO_2 removal efficiency**
- **~110 kg/hr CO_2 removal rate**

Bed Temperatures

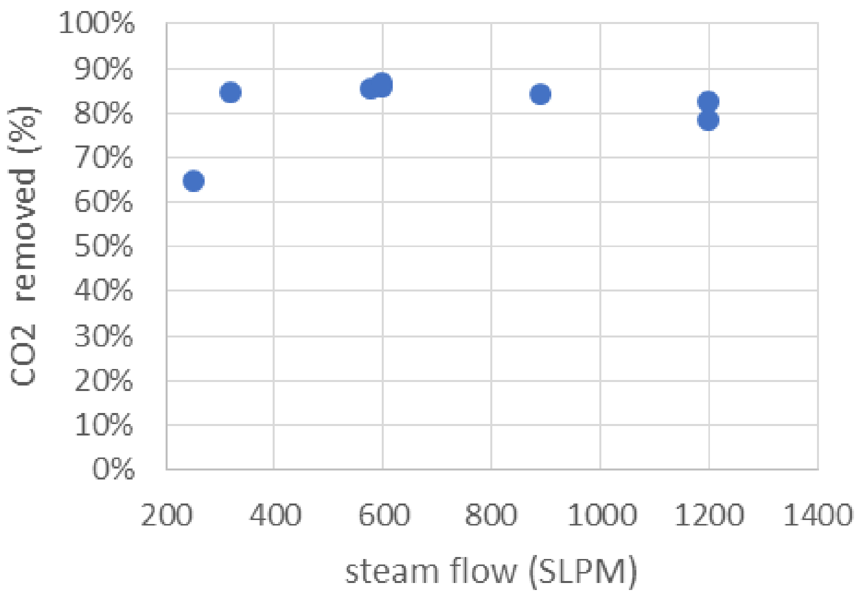


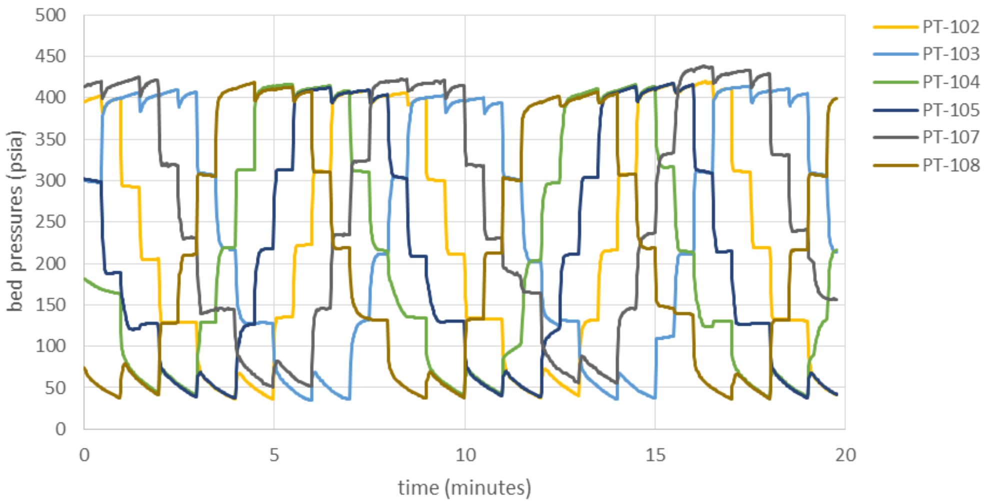




- **Bed temperature gradients were as expected**
- **Larger gradients in the syngas inlet ends, while smaller gradients at the CO_2 free syngas end**
- **DeltaT of ~20-30°C was as predicted in the CFD simulations at GTI**

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 (35 kg/hr CO_2 at NCCC)
- **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
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%
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%
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**

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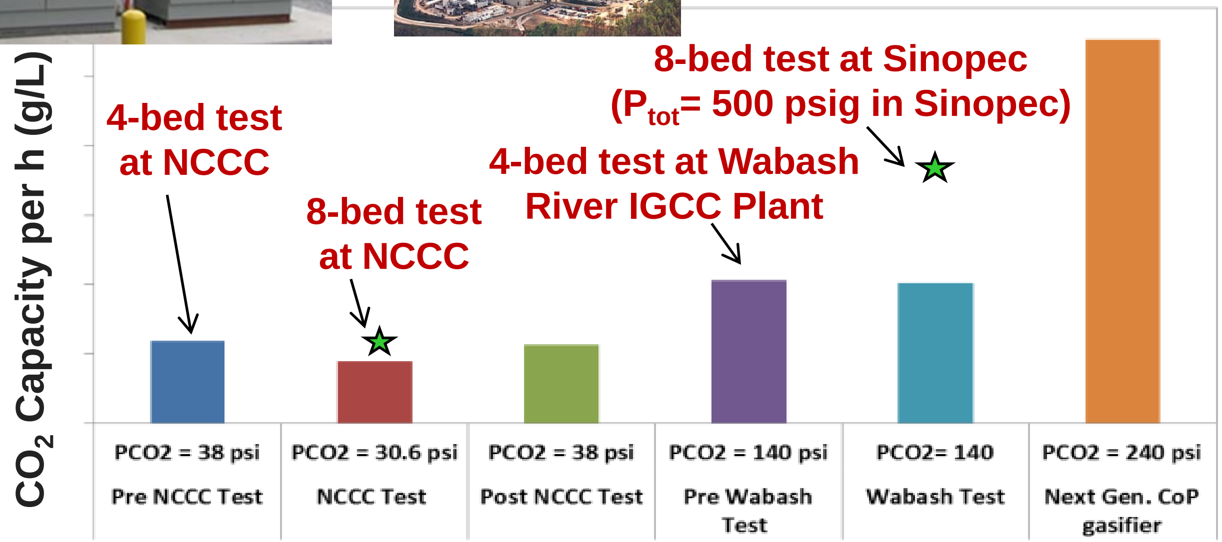
Sorbent Performance Summary



- **Sorbent/PSA system maintained slightly higher CO_2 capacity than the earlier field tests at NCCC at ~60X scale**
- **At Sinopec we achieved a much higher capacity than in the previous oxy-fired gasification tests at Wabash River IGCC power plant**
- **Total Pressure – 340 vs 500 psia**

Acknowledgements

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- Frank Morton, NCCC