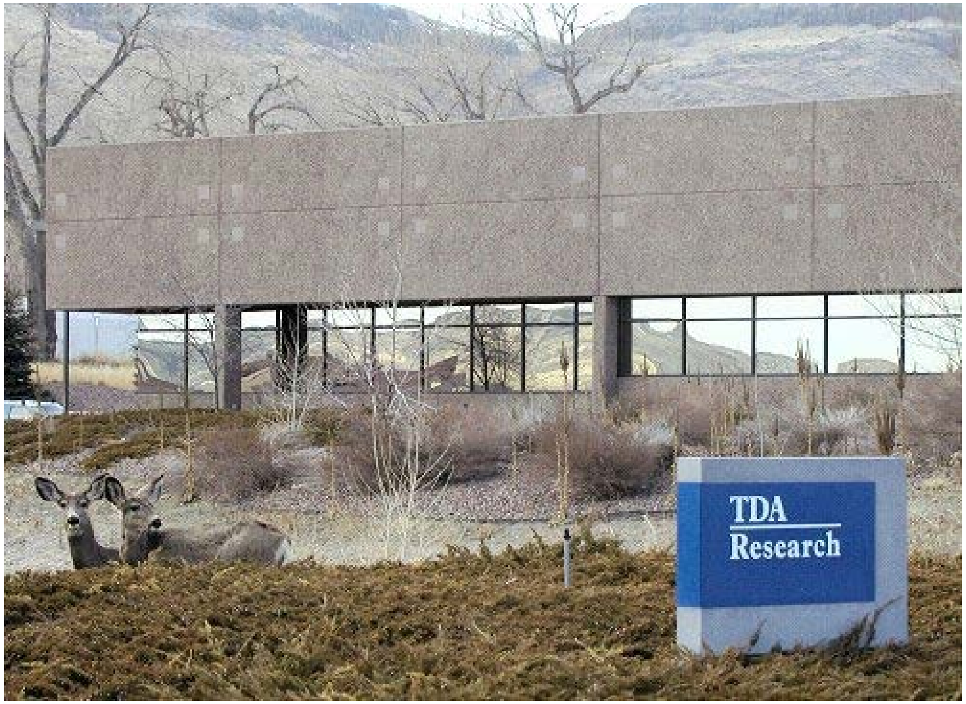
Pilot Testing of a Highly Efficient Pre-combustion Sorbent-based Carbon Capture System (Contract No. DE-FE-0013105)



Gökhan Alptekin, PhD
Ambal Jayaraman, PhD
Matt Cates
Mike Bonnema
Jim Dippo
David Gribble
Kerry Libberton

DOE/NETL Carbon Capture Meeting
Pittsburgh, PA
August 1, 2014

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

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 with 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

Project Partners

Project Duration

- **Start Date = January 1, 2014**
- **End Date = September 30, 2017**

Budget

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

TDA's Approach to CO_2 Capture

- TDA's sorbent consists of a mesoporous carbon modified 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, the energy input for regeneration is low
- Heat of CO_2 adsorption is measured as 3.8 to 4.9 kcal/mol for TDA sorbent
  - Selexol ~4 kcal/mol
  - Amine solvents ~14.4 kcal/mol
  - Chemical absorbents 20-40 kcal/mol ($Na_2CO_3 \rightarrow NaHCO_3$ 30 kcal/mol)
- Net energy loss in sorbent regeneration is similar to Selexol
  - A much better IGCC efficiency due to high temperature CO_2 capture above the dew point of the synthesis gas
  - Warm gas clean-up improves cycle efficiency 2 to 4%

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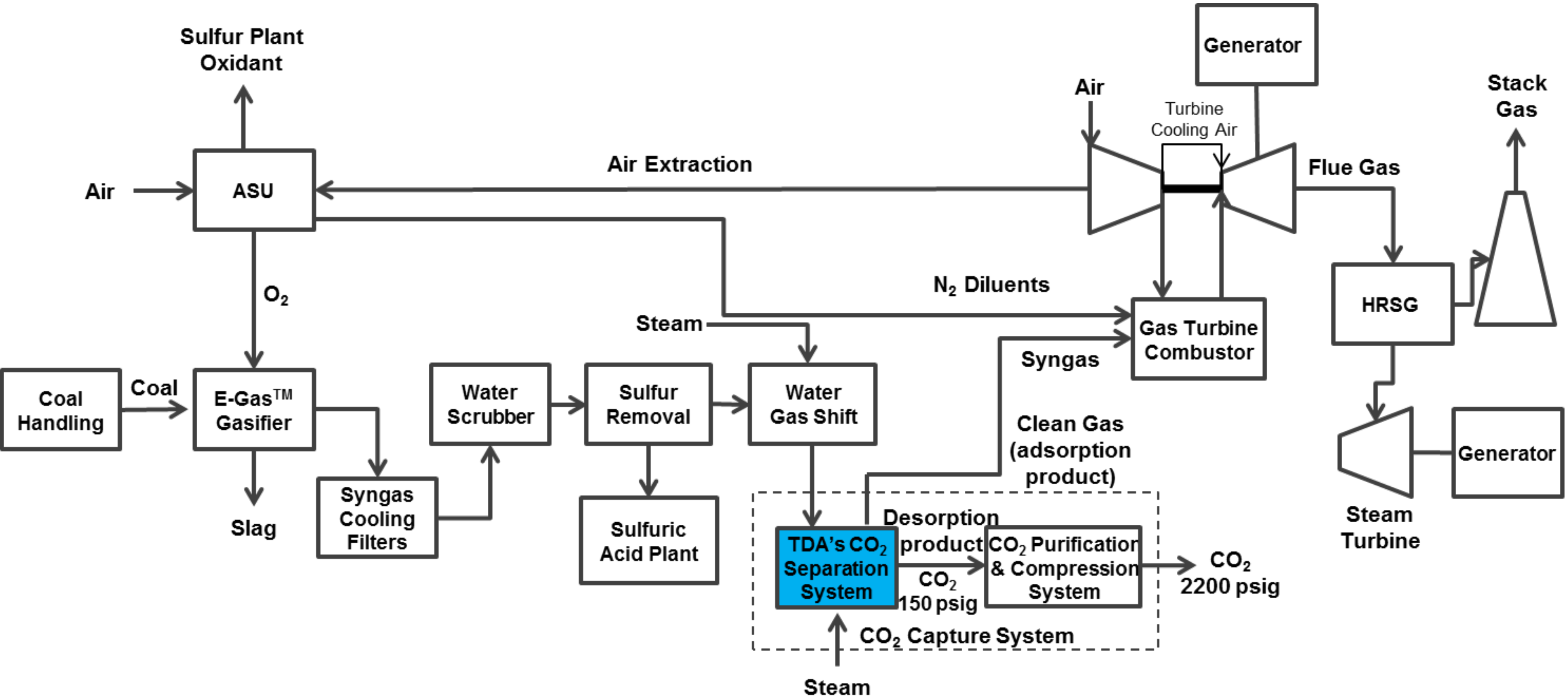
Benefits of Warm Gas Clean-up

- **Warm gas CO_2 capture above the dew point of syngas results in more steam in the H_2 rich (CO_2 free) gas entering the gas turbine**
  - Higher mass throughput to the gas turbine
  - Lower gas turbine temperature
    - Significantly reduces the need for high pressure N_2 dilution in GT
    - Lower NO_X formation
- **High steam content feed is also more suited for the next generation hydrogen turbines under development in the DOE/NETL H_2 turbine program**
- **Simpler process**
  - Elimination of the heat exchangers needed for cooling and re-heating the synthesis gas
  - Elimination of gray water treatment problem
- **Potential higher efficiency via integrated WGS/Carbon Capture Process**

IGCC Power Plant with Integrated Warm Gas CO_2 Capture System



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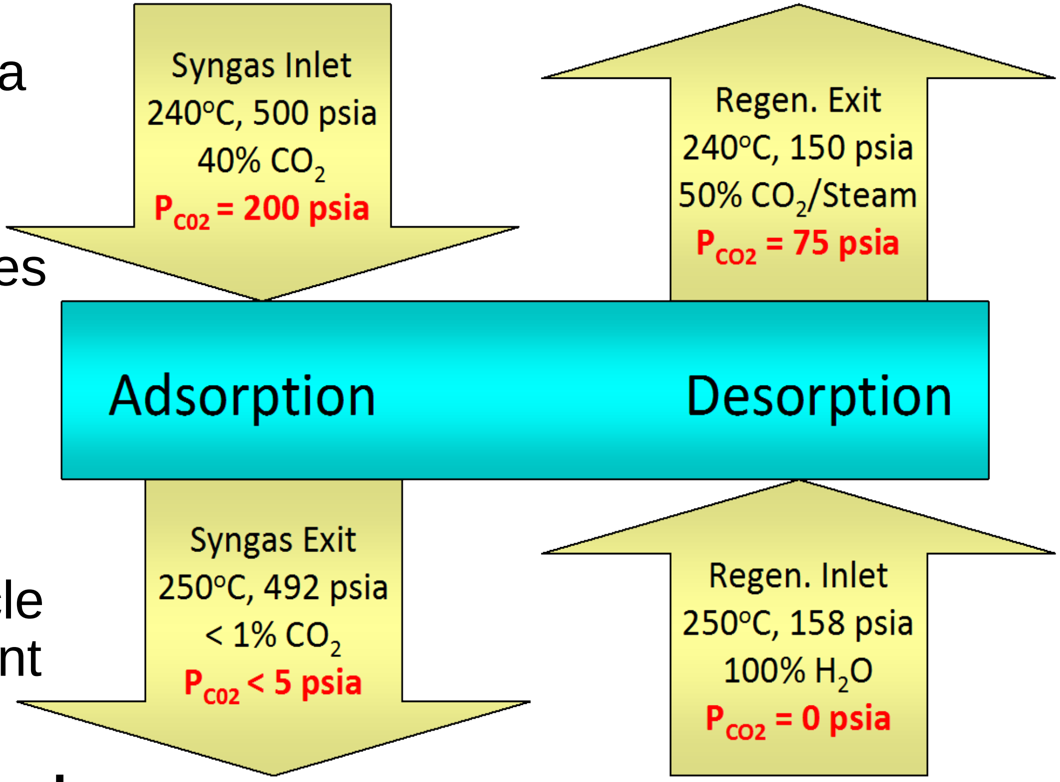
Operating Conditions

- **CO_2 recovery via a combined pressure and concentration swing**
  - CO_2 recovery at ~150 psia reduces energy need for CO_2 compression
  - Small steam purge enables purity requirements
- **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**



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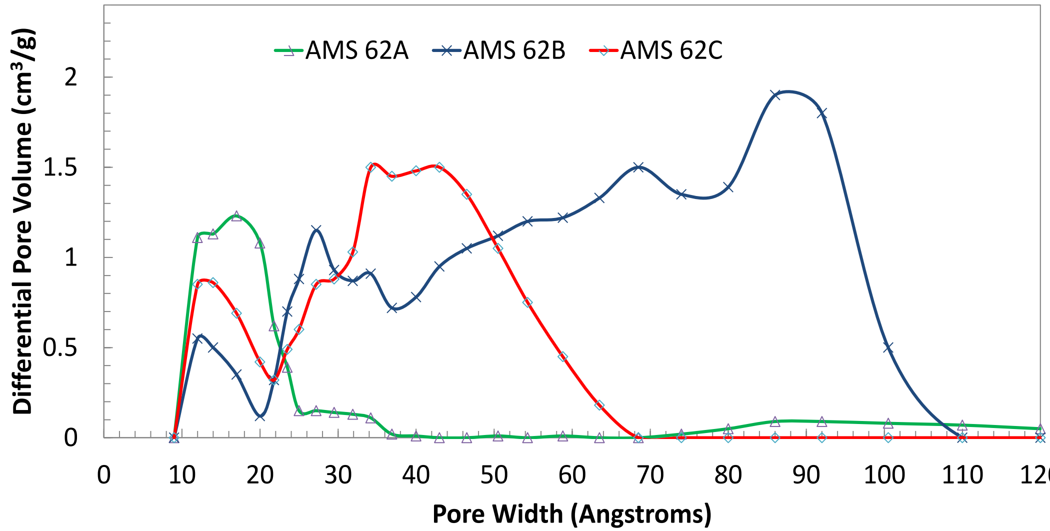
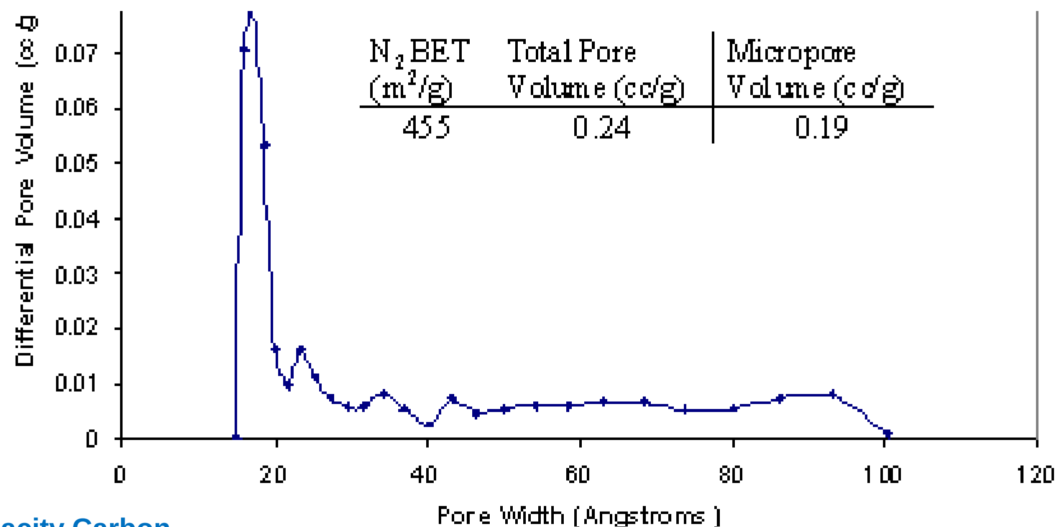
TDA’s Sorbent

- A mesoporous carbon is used to disperse the active sorbent phase
- Pore size can be finely tuned in the 10 to 100 A range
- Mesopores eliminates diffusion limitations and rapid mass transfer, while enables high surface area
- The preparation process also enables us to introduce various surface groups active for removing different compounds





US Pat. Appl. 61787761, Dietz, Alptekin, Jayaraman “High Capacity Carbon Dioxide Sorbent”
US Pat. Appl. 61790193, Alptekin, Jayaraman, Copeland “Pre-combustion Carbon Dioxide Capture System Using a Regenerable Sorbent”

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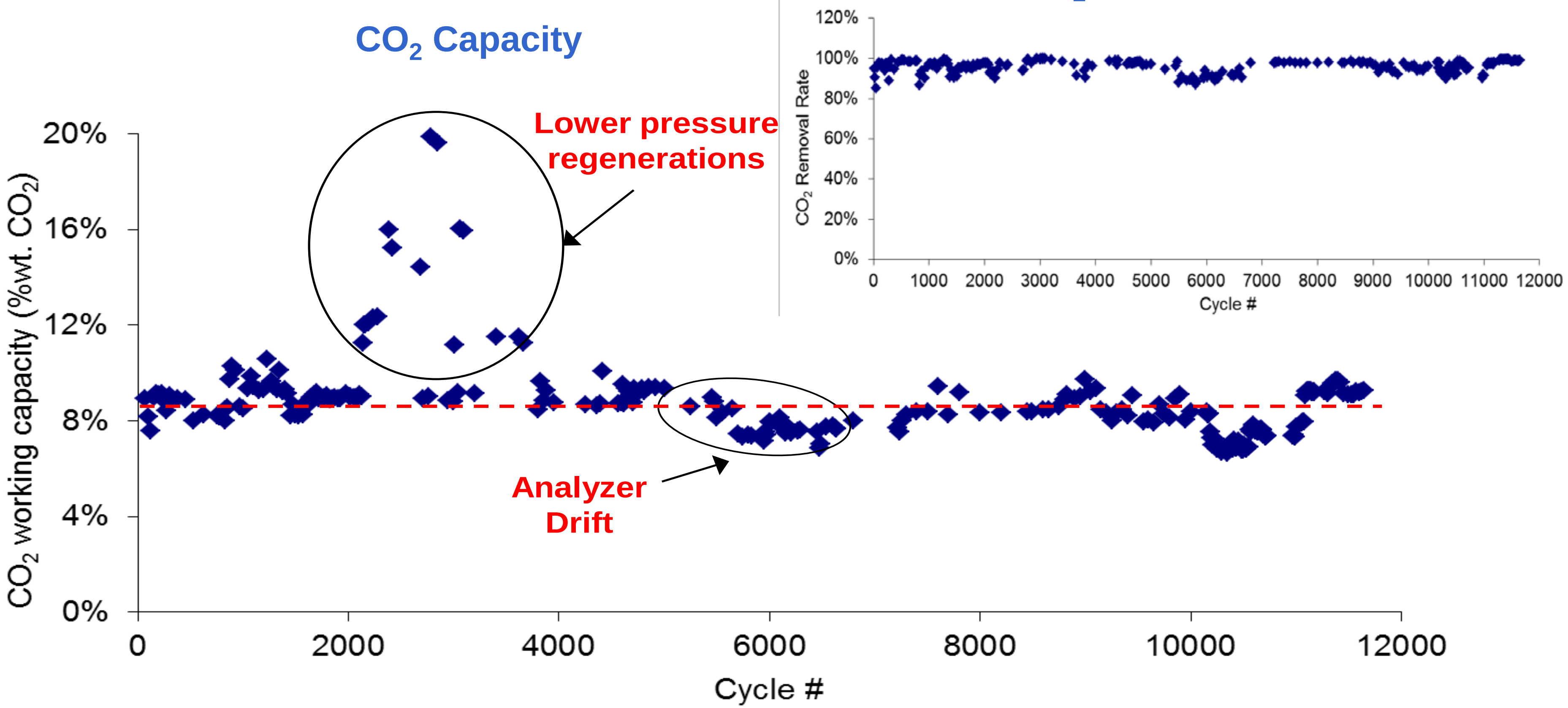
Multiple Cycle Tests – Bench-scale

H_2=32%, CO_2=40%, N_2=3%, CO=1%,H_2O=24%;
T= 240°C; P_{ads}= 500 psig; P_{des} = 50-300 psig

CO_2 Removal Efficiency

CO_2 Capacity



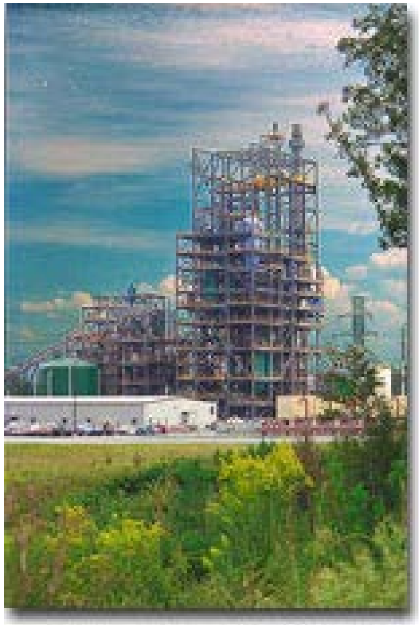
- **Sorbent maintained its CO_2 capacity (8+%wt.) for 12,650 cycles**

Slipstream Demonstrations

- **Several for proof-of-concept tests were completed at two different facilities**

<u>Wabash River IGCC Plant, Terre Haute, IN</u>

- **Demonstration carried out in September 2012**
- **Largest single-train Gasifier (262 MW)**
- **Oxy-blown E-Gas™ Gasifier**
- **Operates on petcoke**



<u>National Carbon Capture Center, Wilsonville, AL</u>

- **1st Demonstration carried out in November, 2011**
- **2nd Demonstration carried out in April, 2012**
- **Pilot-scale air blown TRIG gasifier**
- **Operates on low rank coals**

Test Units – In NEMA-Rated Enclosures

CO_2 Removal Skid

Gas Conditioning Skid

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Field Test Units Installed at NCCC

Field Test Unit at Wabash River IGCC

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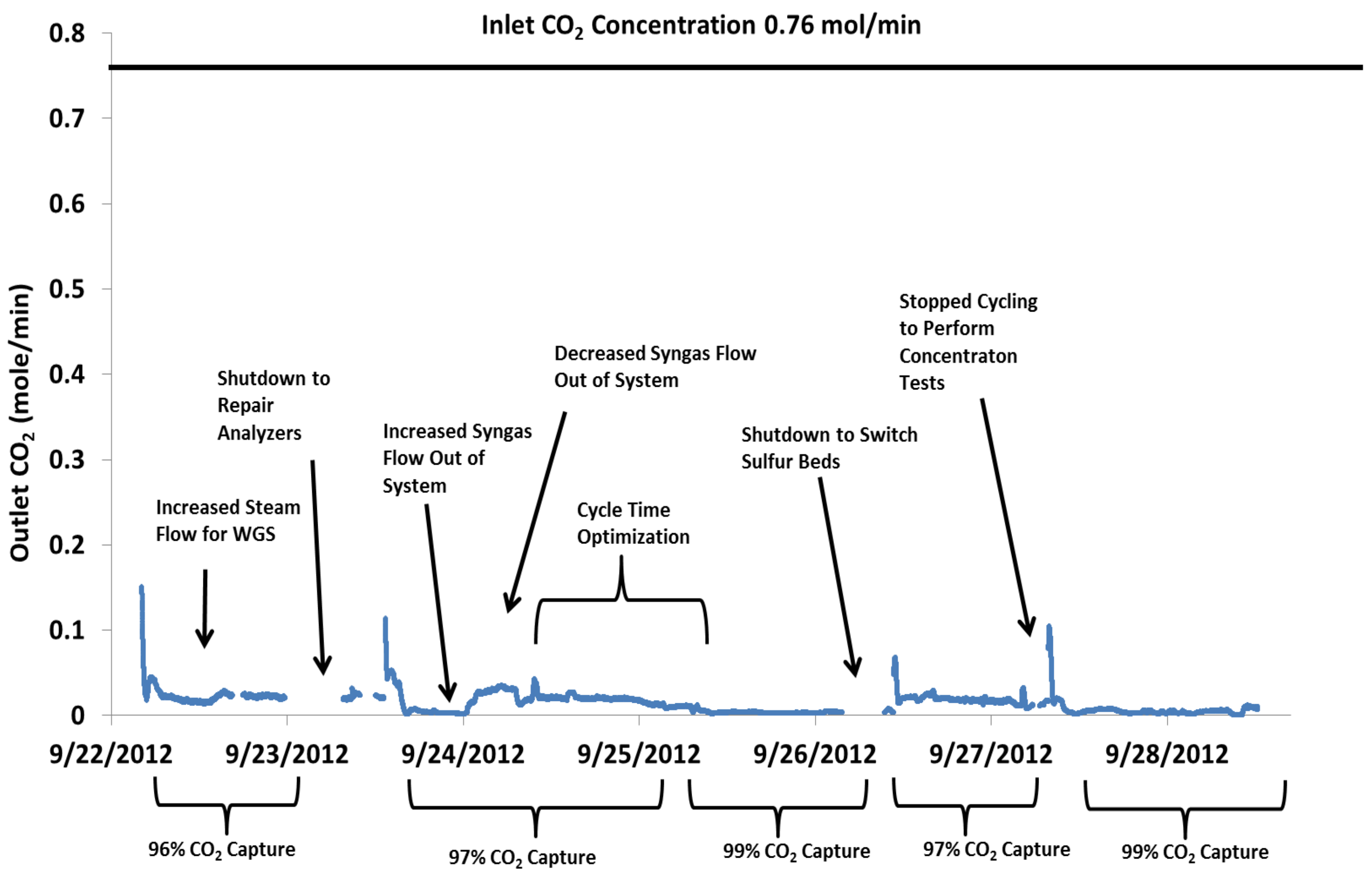
Slipstream Demonstration – Wabash River IGCC Plant



- **Sorbent achieved ~4%wt. CO_2 capacity and 96+% removal efficiency**

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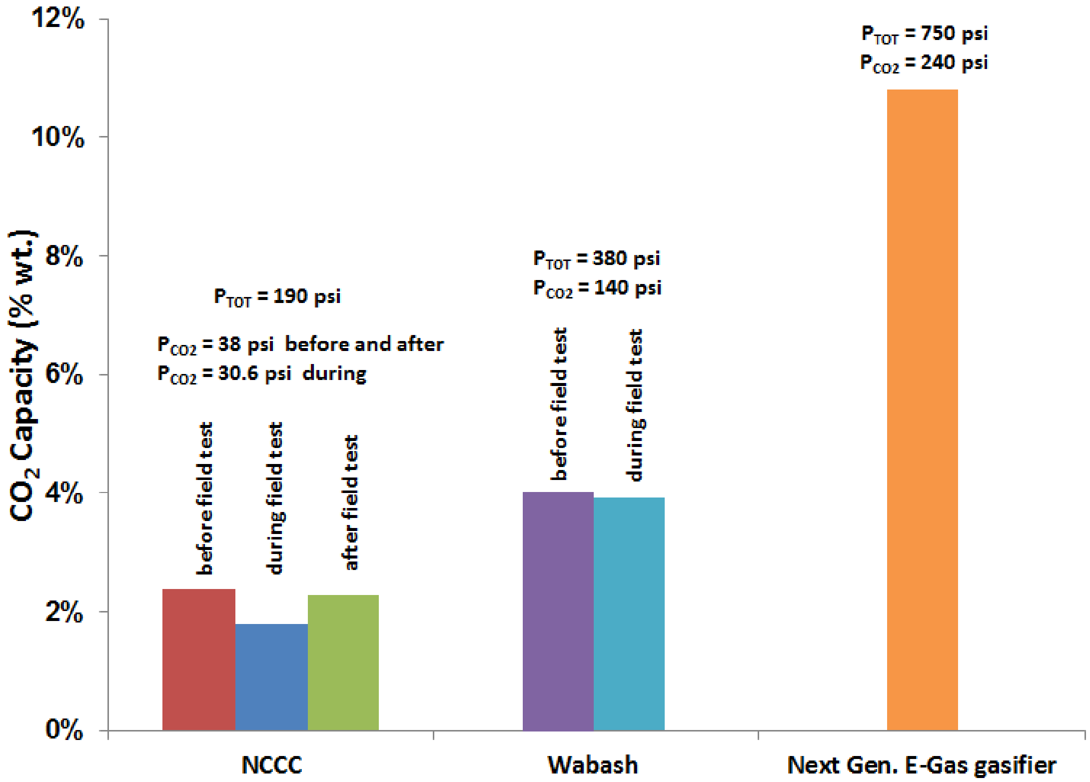
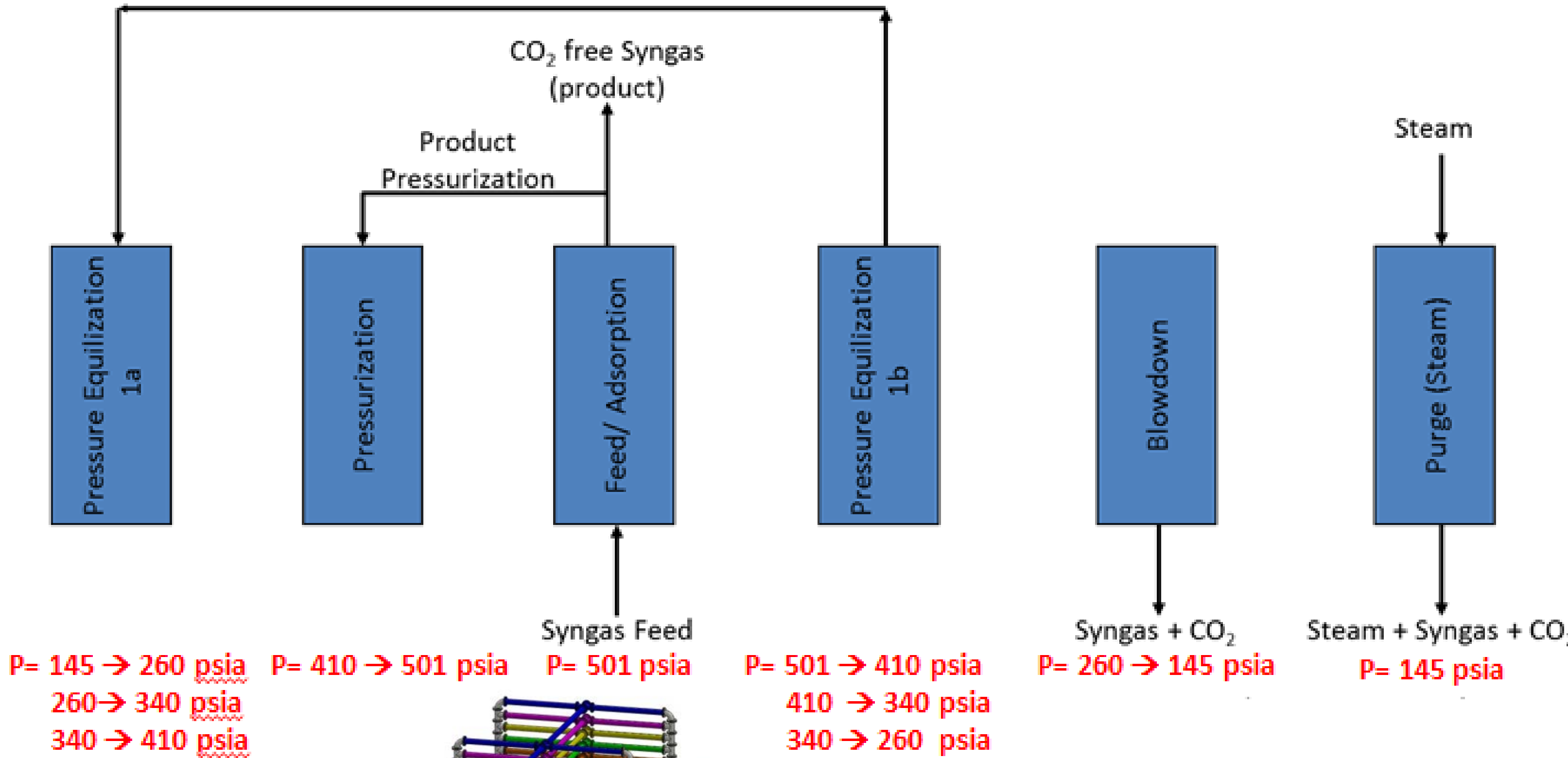
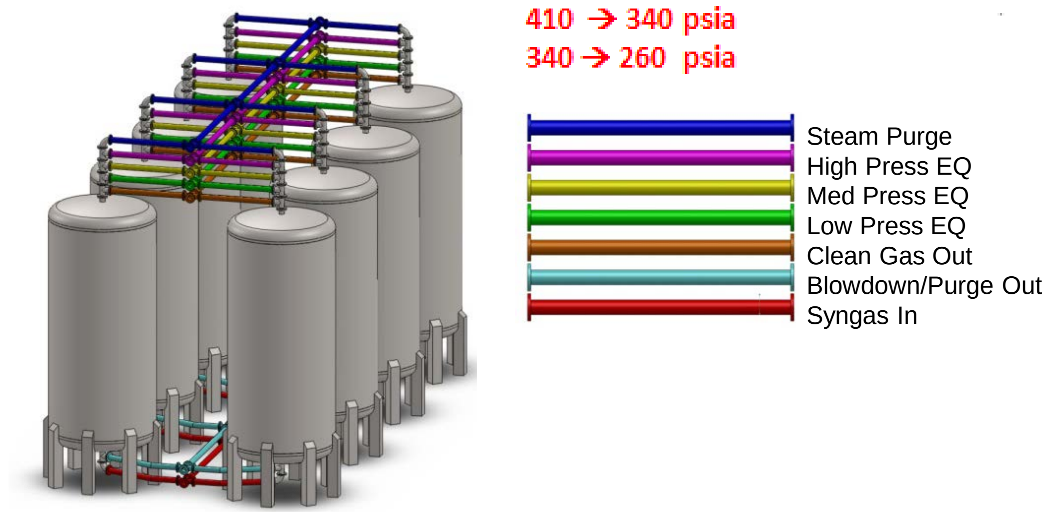
Prototype Performance



- **Sorbent achieved maintained CO_2 capacity before and after the field tests**
  - **2.6% wt. CO_2 at P_{CO2} = 38 psi**
- **At Wabash condition (P_{CO2} = 140 psi) sorbent achieved 4.1% wt. CO_2 capacity**
- **Next generation E-Gas gasifier is expected to operate at 750 psi (P_{CO2} = 240 psi) and capacity will exceed 10% wt. CO_2**

PSA Cycle Design





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System Analysis Results

	Cold Gas Cleanup Selexol™	Warm Gas Cleanup TDA's CO_2 Sorbent
CO_2 Capture, %	90.0	90.0
Gross Power Generated, kWe	691,247	733,028
Gas Turbine Power	464,000	464,000
Steam Turbine Power	227,247	269,028
Auxiliary Load, kWe	175,994	131,163
Net Power, kWe	515,253	601,865
Net Plant Efficiency, % HHV	**31.6%**	**34.0%**
Coal Feed Rate, kg/h	216,187	234,867
Raw Water Usage, GPM/MWe	11.8	11.2
Total Plant Cost, $/kWe	2,754	2,418
COE without CO_2 TS&M, $/MWh	99.8	87.8
COE with CO2 TS&M, $/MWh	**105.2**	**92.9**

- **IGCC plant with TDA's CO_2 capture system achieves higher efficiency (34.0%) than IGCC with Selexol™ (31.6%)**
- **Cost of per tonne CO_2 avoided is $31.1 for TDA's warm gas CO_2 capture technology compared $49.5 for cold gas cleanup with Selexol™**

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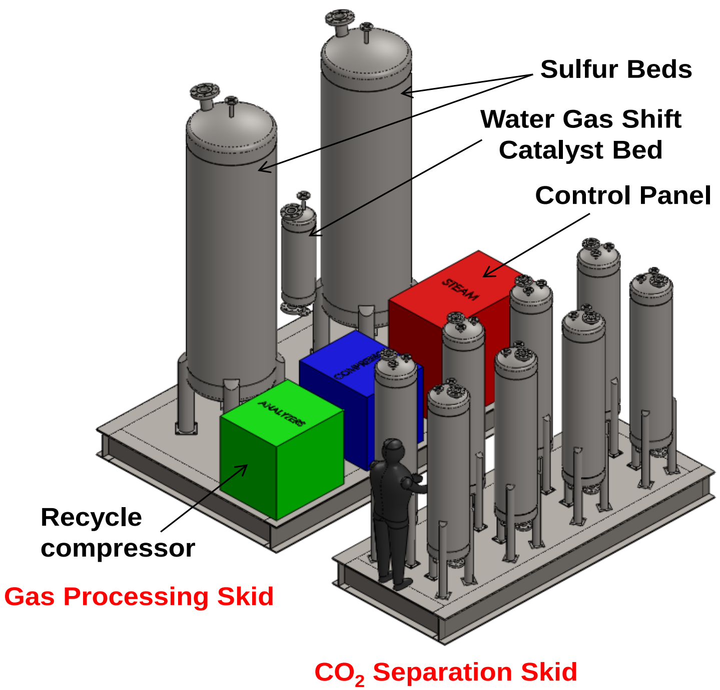
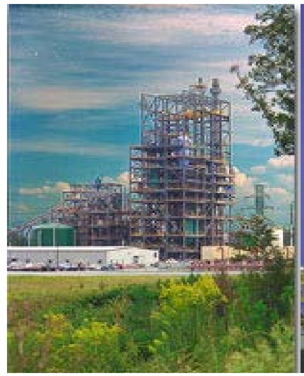
Specific Objectives





- Testing with <u>high pressure</u> syngas
  - Long-term performance
  - H_2 recovery/CO_2 purity
- 0.1 MW test with Sinopec (world class petcoke-IGCC or CTL plant)
- High fidelity system design and economic analysis

Scope of Work – BP1

Budget Period 1 (BP1: 12/30/2013 – 12/31/2014)

- **Develop a Manufacturing Plan and Quality Assurance Plan**
- **Optimize the PSA cycle sequence for the sorbent technology**
- **Complete a detailed design of the sorbent reactors**
- **Develop a multi-component adsorption model and carry out CFD simulations to support the system design**
- **Complete the detailed design of the 0.1 MWe pilot-scale field test unit**
  - Provide the design package to test sites for approval (NCCC and Sinopec)
- **Provide DOE the full design package for the Pilot Scale CO_2 separation system including detailed vendor quotes**
- **Update process design and simulation**
  - Modifications in cycle sequence (gas flows, compression needs etc.)

Manufacturing and QA Plans

Screw Extrusion

Continuous rotary kiln

Exhaust gas treatment

Feeder

- **Manufacturing plan was drafted based on high throughput pilot production equipment**
- **A continuous rotary kiln (with 12 lb/hr production capacity) was used in preparing 20+ batches**
- **Good agreement batch-to-batch and with-in-batch**

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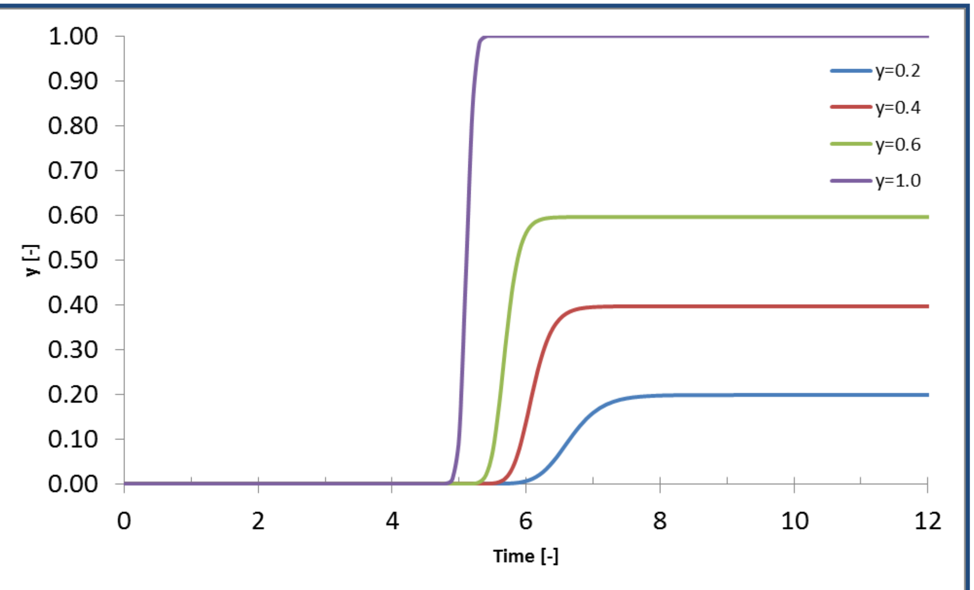
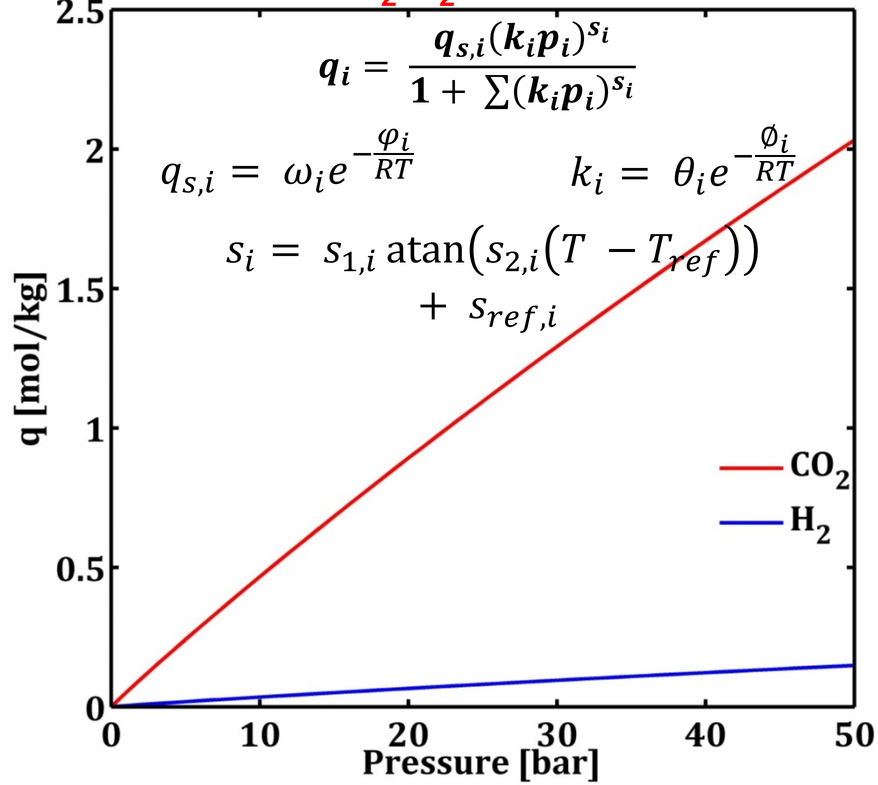
Adsorption Modeling – Cycle Design

Single Component Breakthrough Profiles (CO_2) at 240˚C



Binary isotherm for 40/60 mixture of CO_2/H_2 at 240˚C



$$q_i = \frac{q_{s,i}(k_i p_i)^{s_i}}{1 + \sum(k_i p_i)^{s_i}}$$

$$q_{s,i} = \omega_i e^{-\frac{\varphi_i}{RT}} \qquad k_i = \theta_i e^{-\frac{\phi_i}{RT}}$$

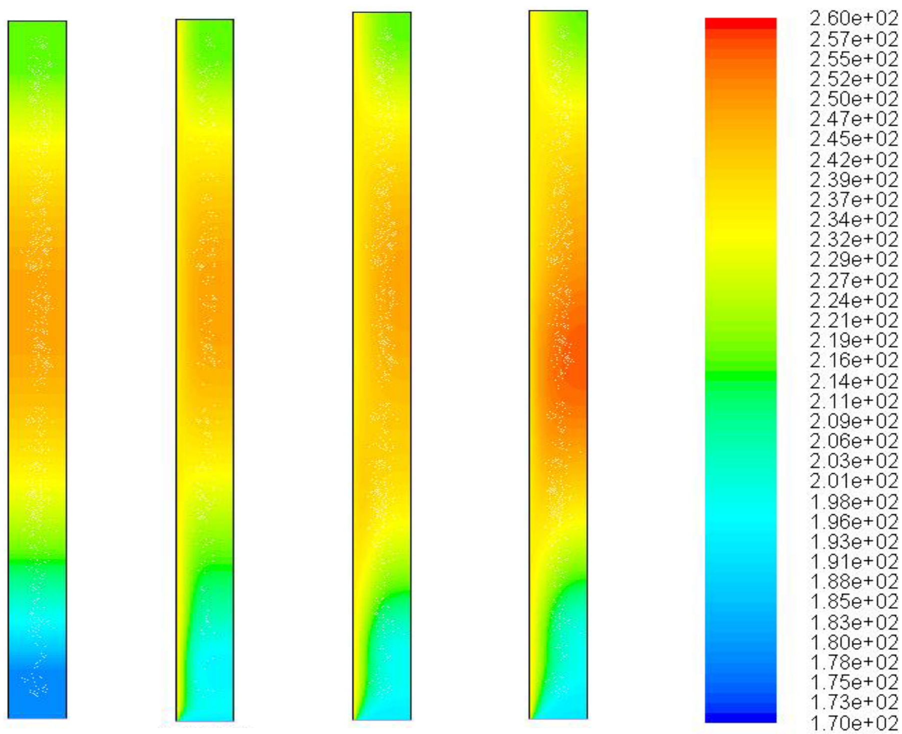
$$s_i = s_{1,i}\,\mathrm{atan}\big(s_{2,i}(T - T_{ref})\big) + s_{ref,i}$$

	ω_i (mol/kg)	φ_i (kJ/mol)	θ_i (1/Pa)	ϕ_i (kJ/mol)	$s_{1,i}$	$s_{2,i}$	$s_{ref,i}$	T_{ref} (K)
CO_2	3.74	-7.87	26.9x10^{-09}	-2.05	0.136	0.110	0.760	281
H_2	6.6	0	0.70x10^{-09}	-9.83	0	0	0.956	273

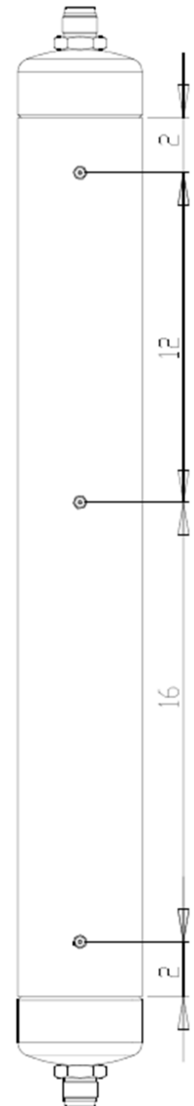
2-D Model Validation - Adsorption

- **Temperature simulation results are consistent with the testing results on the adsorption side**

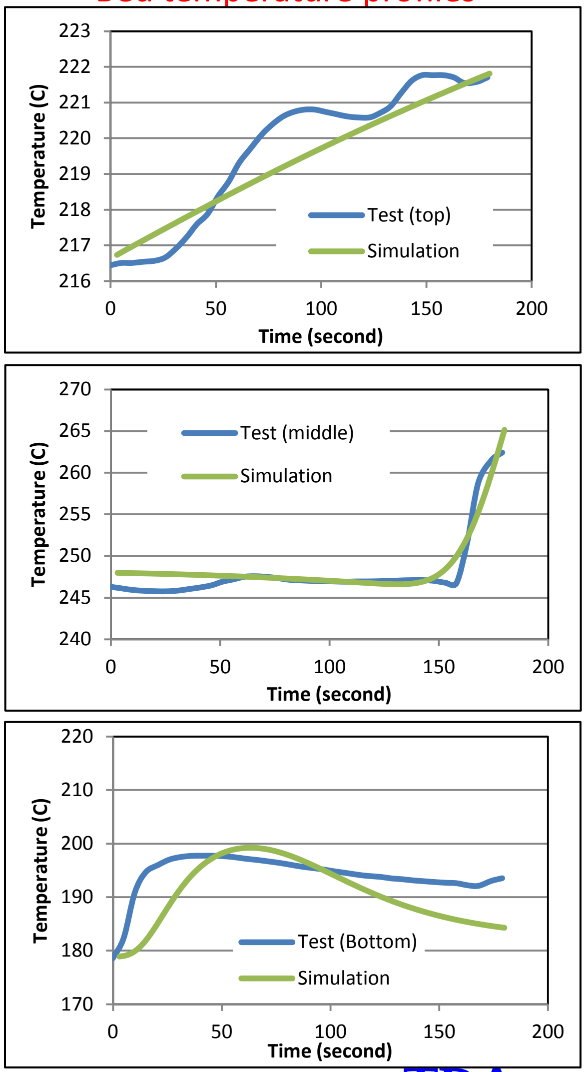
$CO_2(gas) \rightarrow CO_2(s)$



T=0 s T=60 s T=120 s T=180 s (end of adsorption)



Bed temperature profiles



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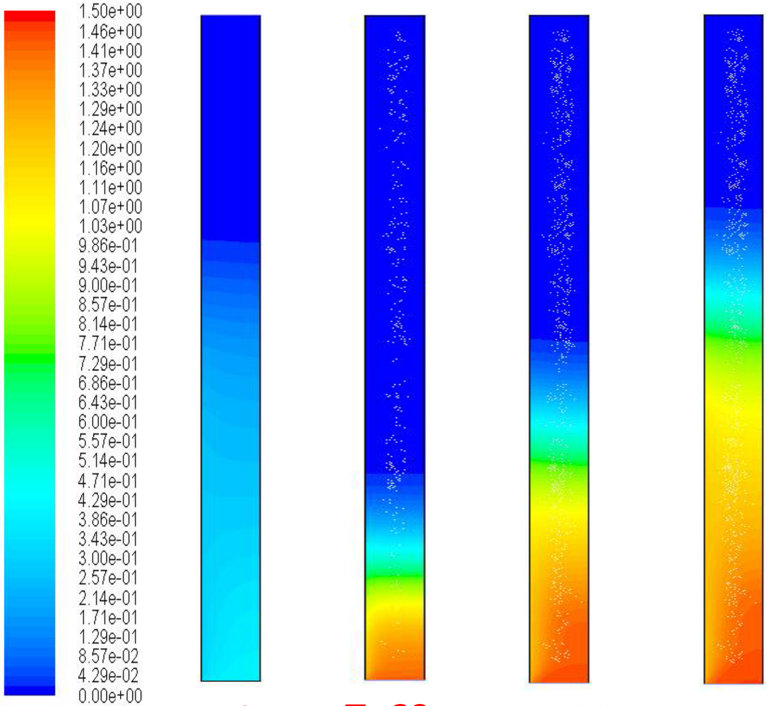
2-D Concentration Distributions

Adsorption process

$CO_2(gas) \rightarrow CO_2(s)$

$CO_2(s)$ distributions (mol-CO_2/kg-sorbent)

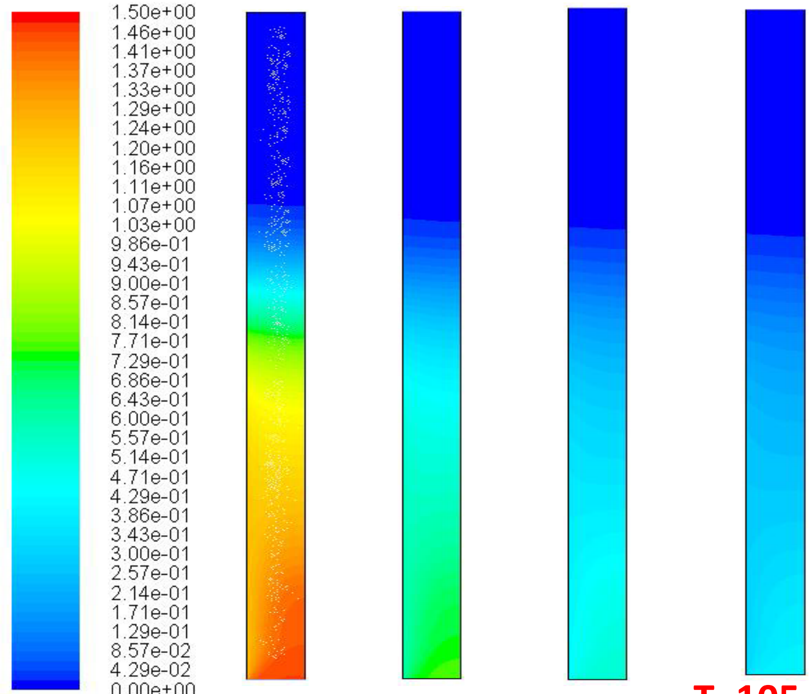


T=0 s | T=60 s | T=120 s | T=180 s (end of adsorption)

Desorption process

$CO_2(s) \rightarrow CO_2(gas)$

$CO_2(s)$ distributions (mol-CO_2/kg-sorbent)



T=0 s | T=35 s | T=70 s | T=105 s (end of desorption)

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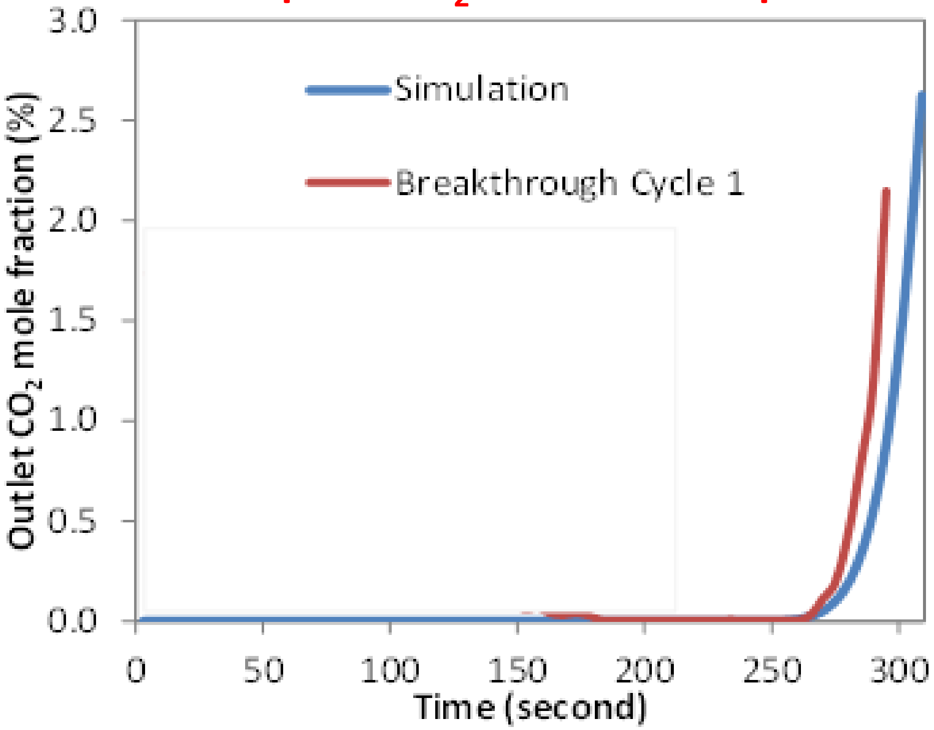
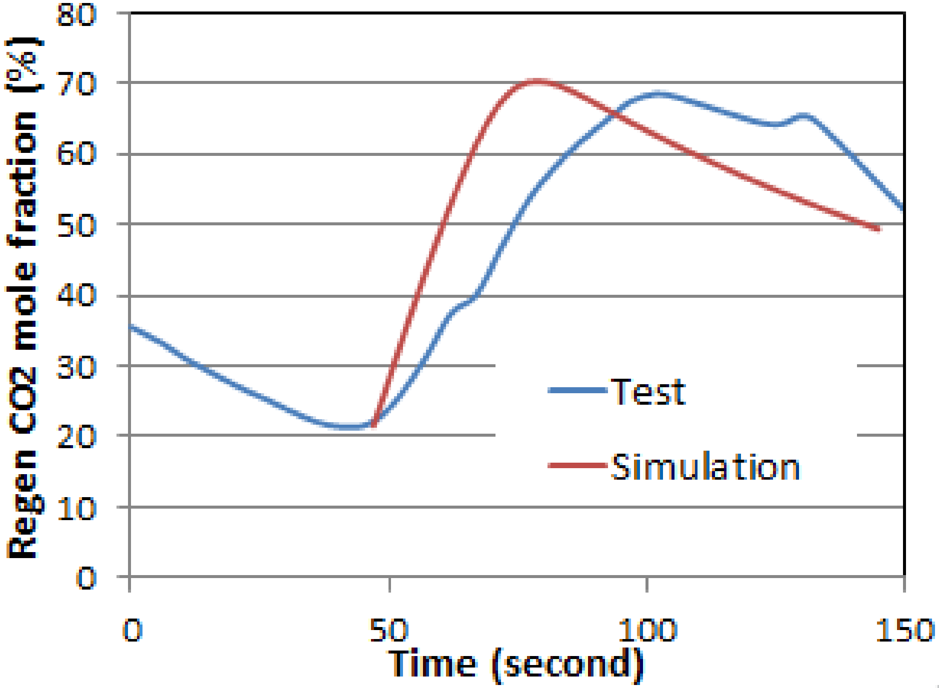
2D Model Validation – CO_2 Concentration

- **Adsorption and regeneration stream CO_2 concentrations are consistent with the testing results**

Adsorption CO_2 mole fraction profile

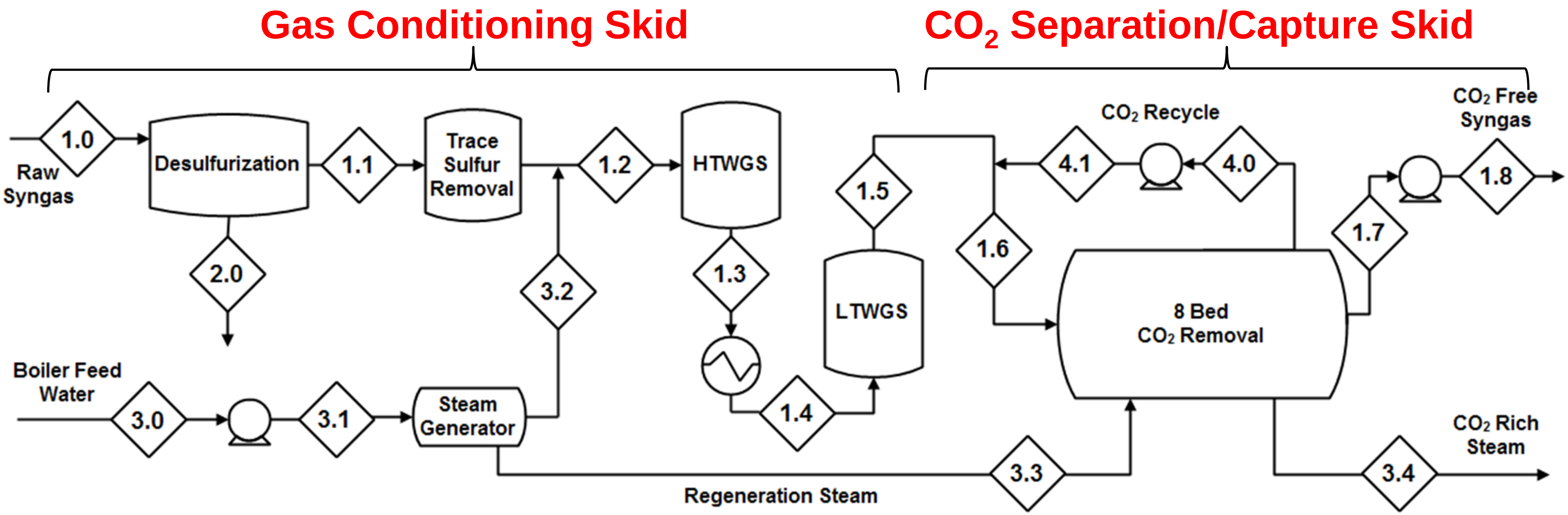


Regeneration CO_2 mole fraction profile



- **3-D model development validation is underway**
- **4-bed demo unit was shipped to GTI data to support validation tests using coal-derived synthesis gas**

Design of the Pilot Testing Unit



	Wabash River IGCC	NCCC - Wilsonville
Syngas flow into CO2 Skid (scfm)	100	100
Syngas flow into DeS/WGS Skid (scfm)	66.3	91.4
Steam added for WGS (scfm)	34.6	8.6
Power Output (MWe)	0.13	0.047
CO2 Captured (kg/hr)	105.5	52.1

- **Proof-of-concept evaluation of critical sub-system components (CO_2 purification system is excluded)**

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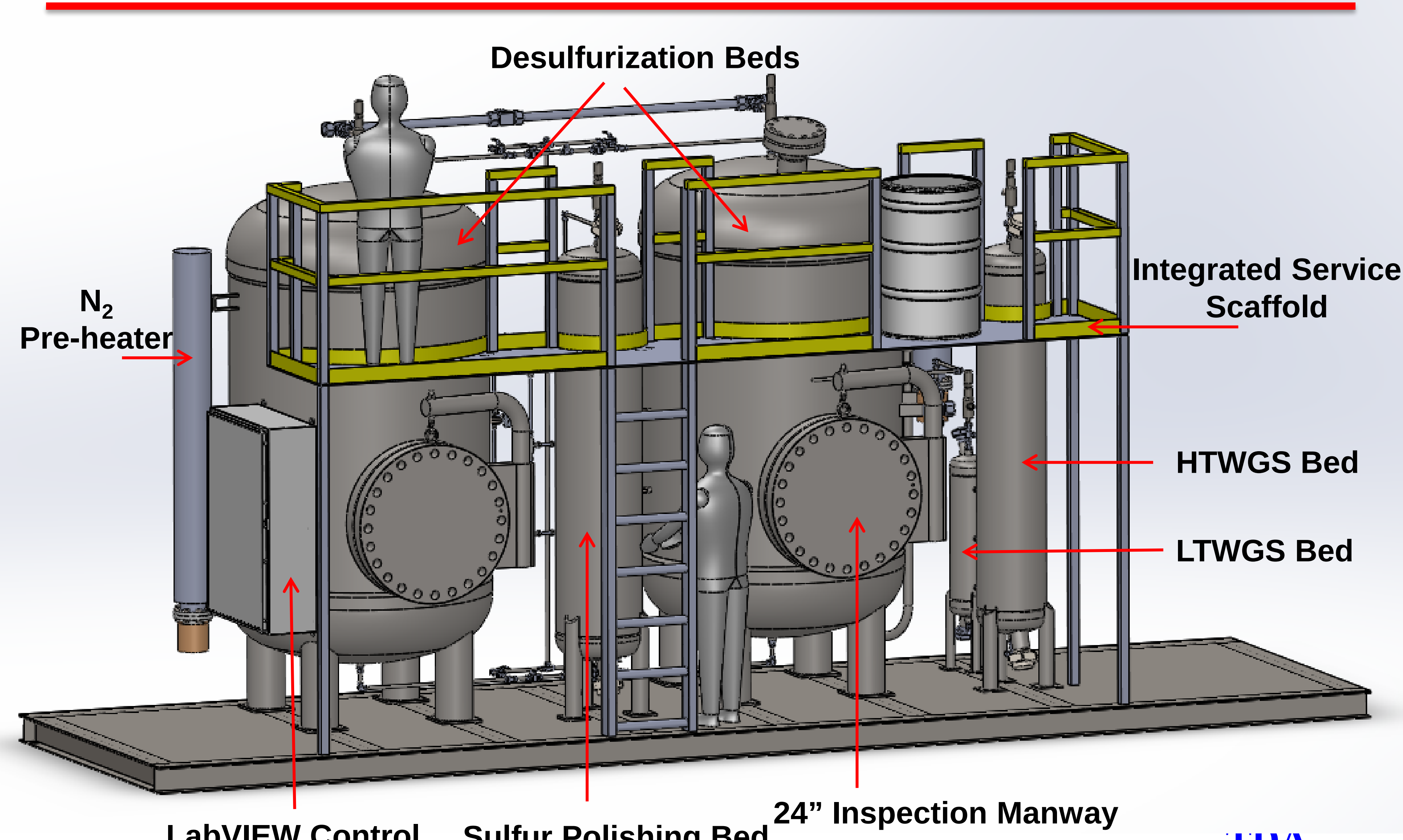
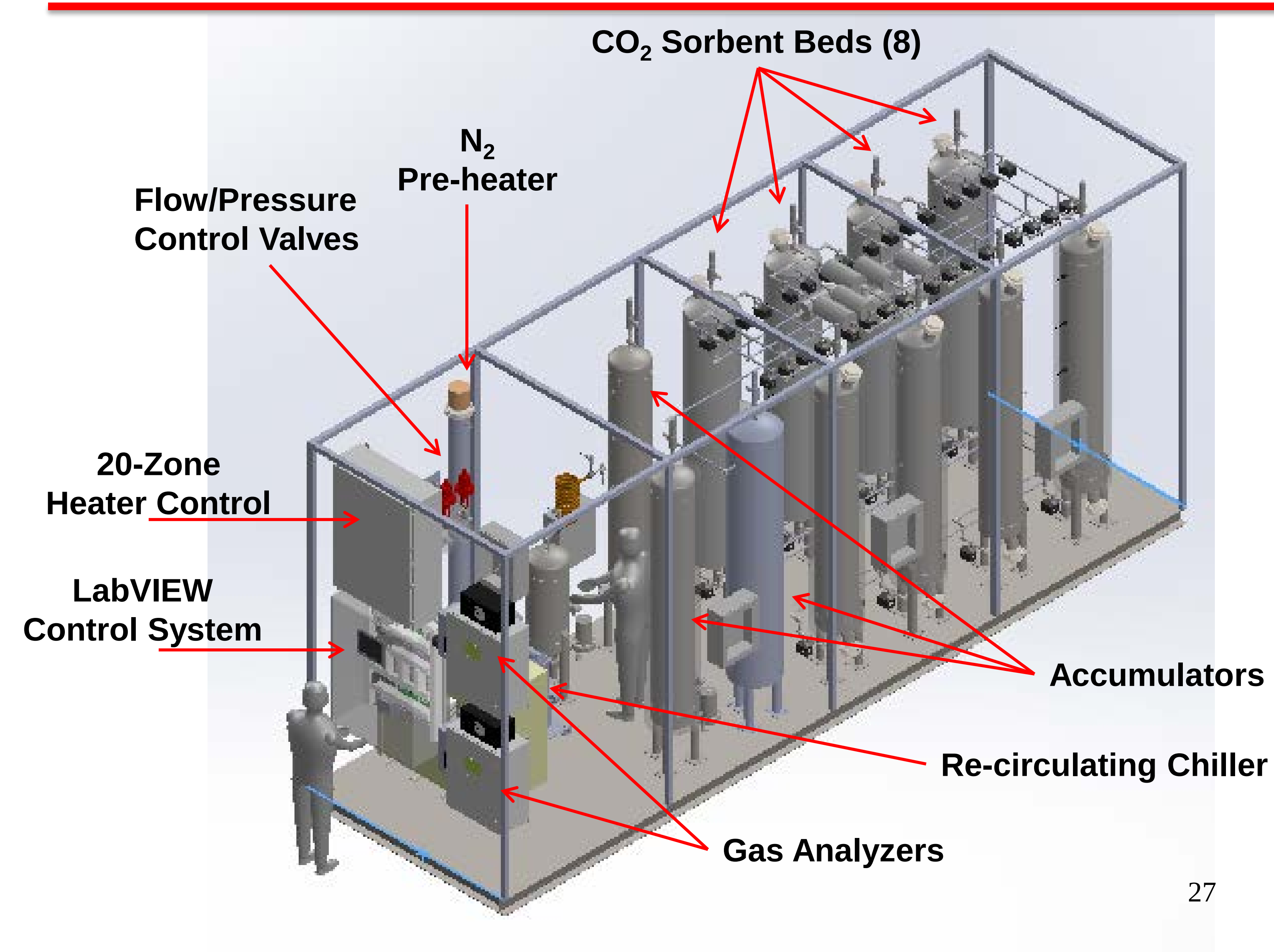
Gas Conditioning Skid



CO_2 Separation Skid



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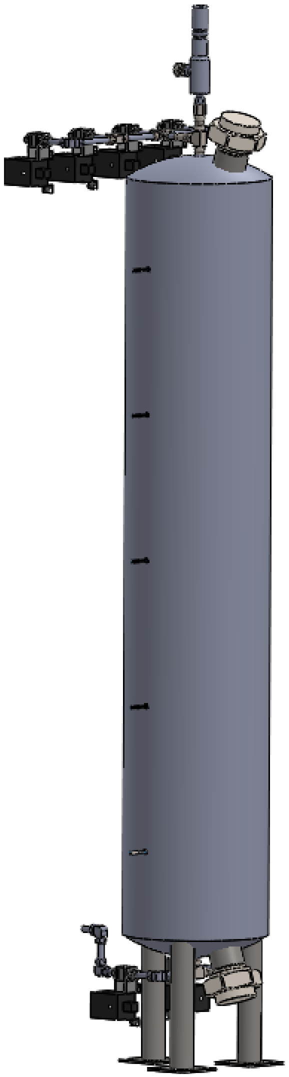
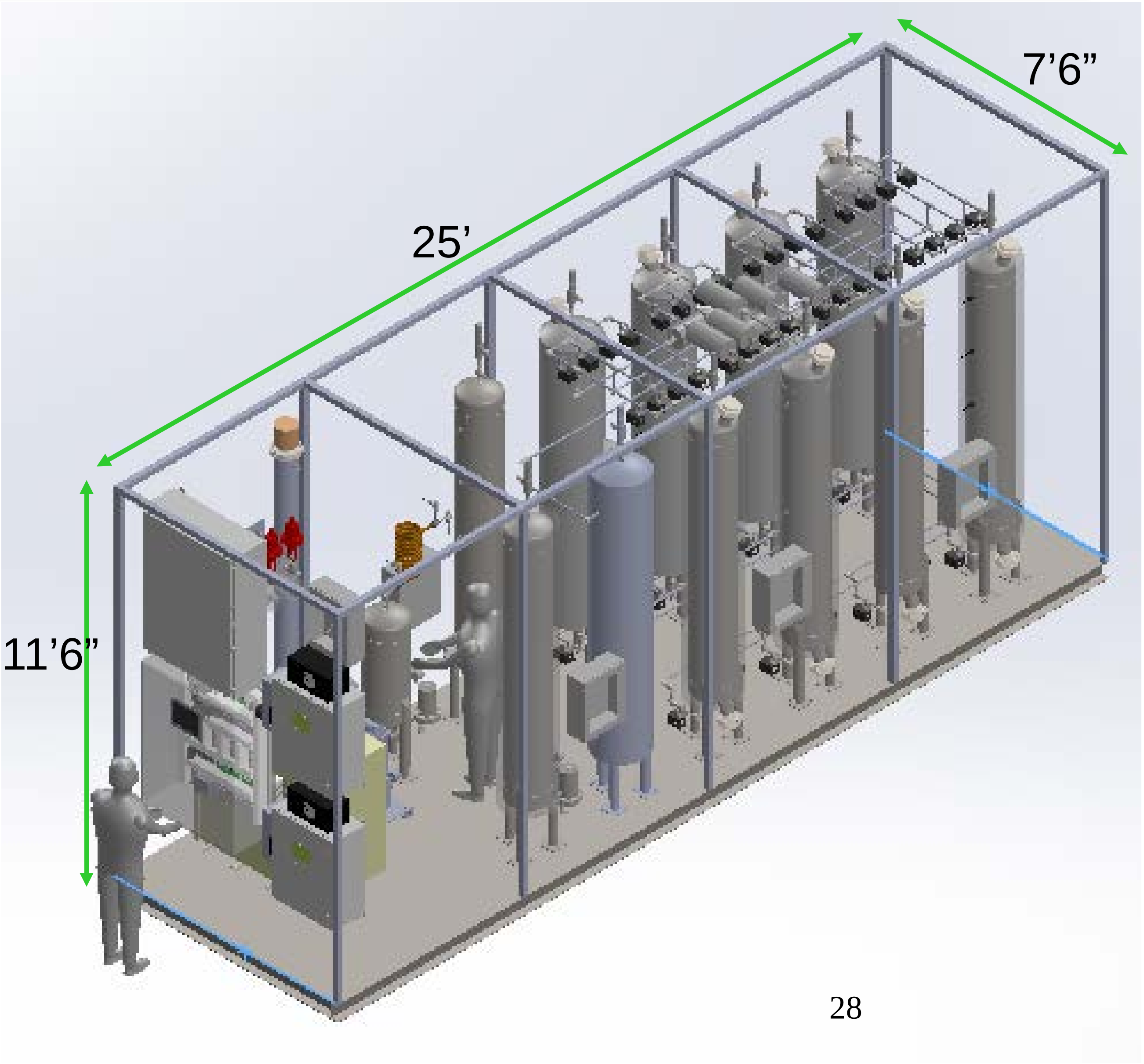
CO_2 Separation Skid



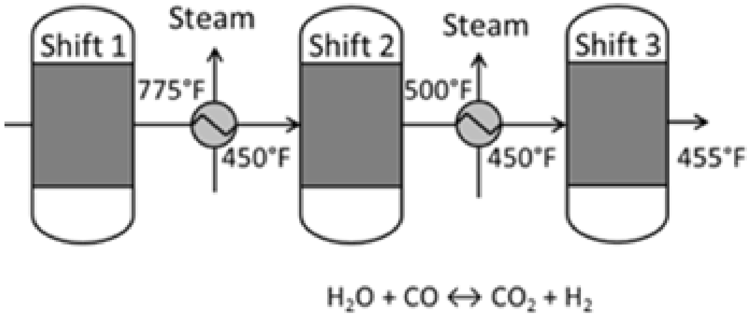
14” OD x 8ft
200 L
304 SS
Rated 450°C/
750 psig



Process Simulation

- **TEA is being updated based on the new Cost Guidelines provided by DOE**
- **TEA is being updated using the GE gasification technology**
- **Process improvements are under consideration**
- **Integrated WGS/CO_2 capture**
  - DE-FE-00012048

Steam:CO ratio = 2.0
3-stage WGS unit as described in the DOE/NETL-2007/1281



Steam:CO ratio = 1.15
2-stage WGS unit

CO_2 Capture Technology	Cold Gas Cleanup Selexol™	Warm Gas Cleanup TDA's CO_2 Sorbent	
		PSA	WGS/PSA
CO_2 Capture, %	90.0	90.0	90.0
Gross Power Generated, kWe	703,700	720,322	767,147
Gas Turbine Power	464,000	464,000	464,000
Steam Turbine Power	239,700	256,322	303,147
Auxiliary Load, kWe	190,090	130,656	157,304
Net Power, kWe	513,610	589,665	609,843
Net Plant Efficiency, % HHV	31.0	33.8	34.5
Coal Feed Rate, kg/h	219,635	231,379	234,444
Raw Water Usage, GPM/MWe	11.3	10.8	10.3

* DOE Study DOE/NETL-2010/1397 Rev2a

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