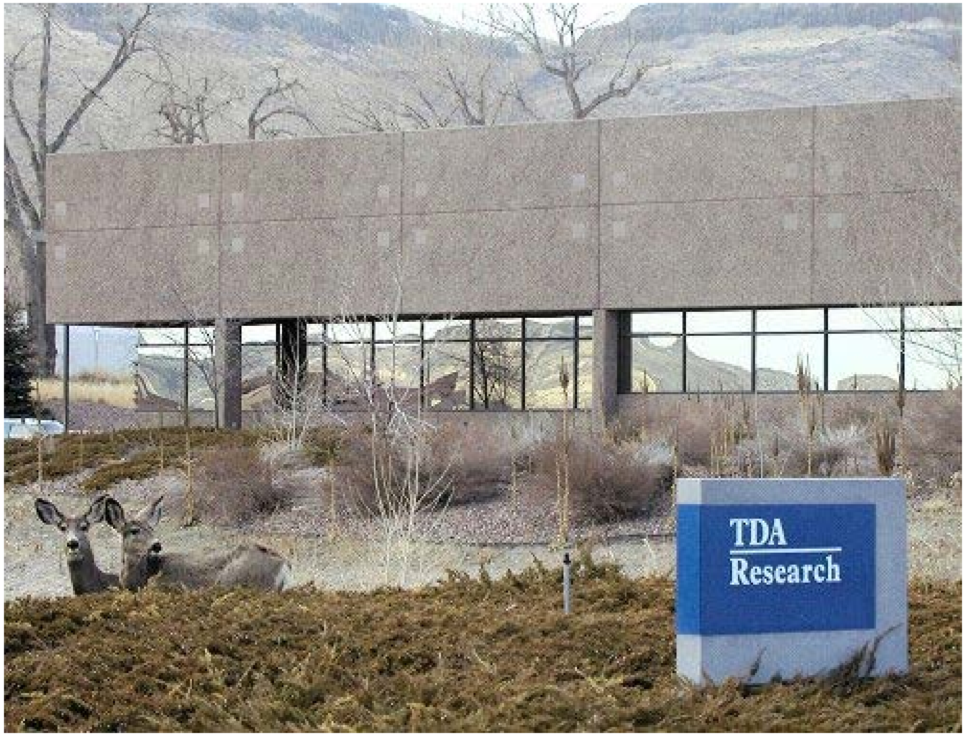
Pilot Testing of a Highly Efficient Pre-combustion Sorbent-based Carbon Capture System (Contract No. DE-FE-0013105)



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DOE/NETL Carbon Capture Meeting
Pittsburgh, PA
June 25, 2015

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

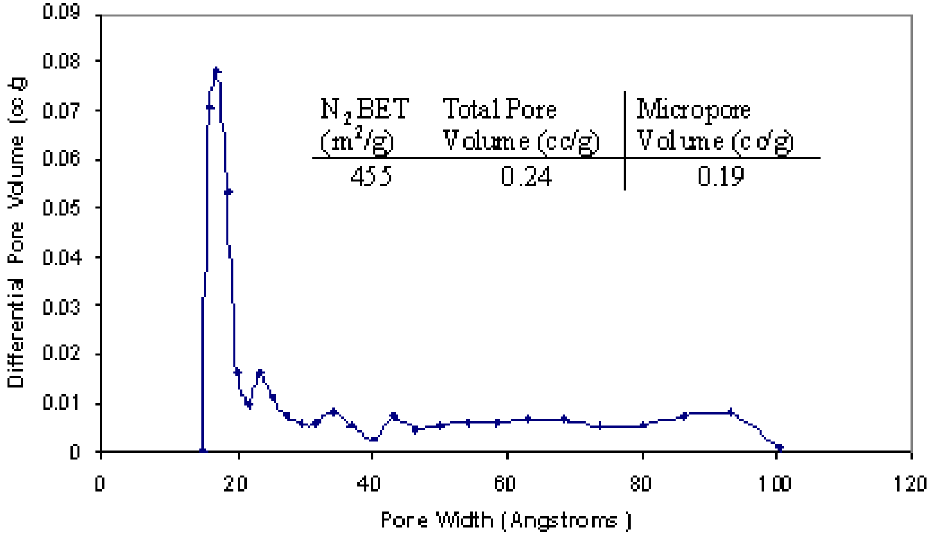
- **Start Date = January 1, 2014**
- **End Date = September 30, 2017**

Budget

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

TDA's Approach

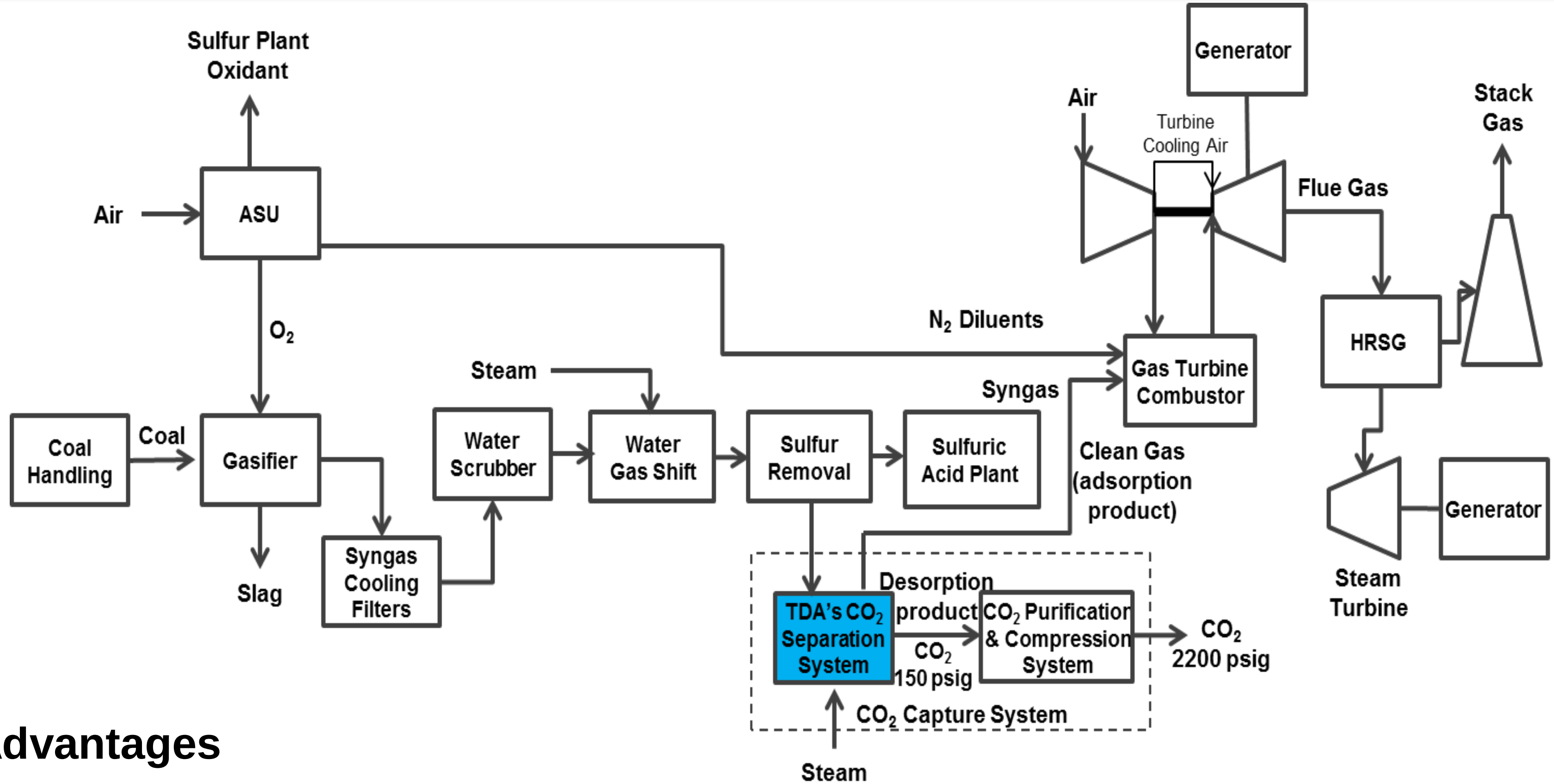
- **TDA's uses a mesoporous carbon modified with surface functional groups that remove CO_2 via strong physical adsorption**
  - CO_2-surface interaction is strong enough to allow operation at elevated temperatures
  - Because CO_2 is not bonded via a covalent bond, the energy input for regeneration is low
- **Heat of CO_2 adsorption is 4.9 kcal/mol for TDA sorbent**
  - Comparable to that of Selexol
- **Net energy loss in sorbent regeneration is similar to Selexol, but a much higher IGCC efficiency can be achieved due to high temperature CO_2 capture**



- **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**

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"

Integration to the IGCC Power Plant



- **Advantages**
  - **Higher mass throughput to the gas turbine – higher efficiency**
  - **Lower GT temperature – Reduced need for HP N_2 dilution and lower NO_X formation**
  - **Elimination of the 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**

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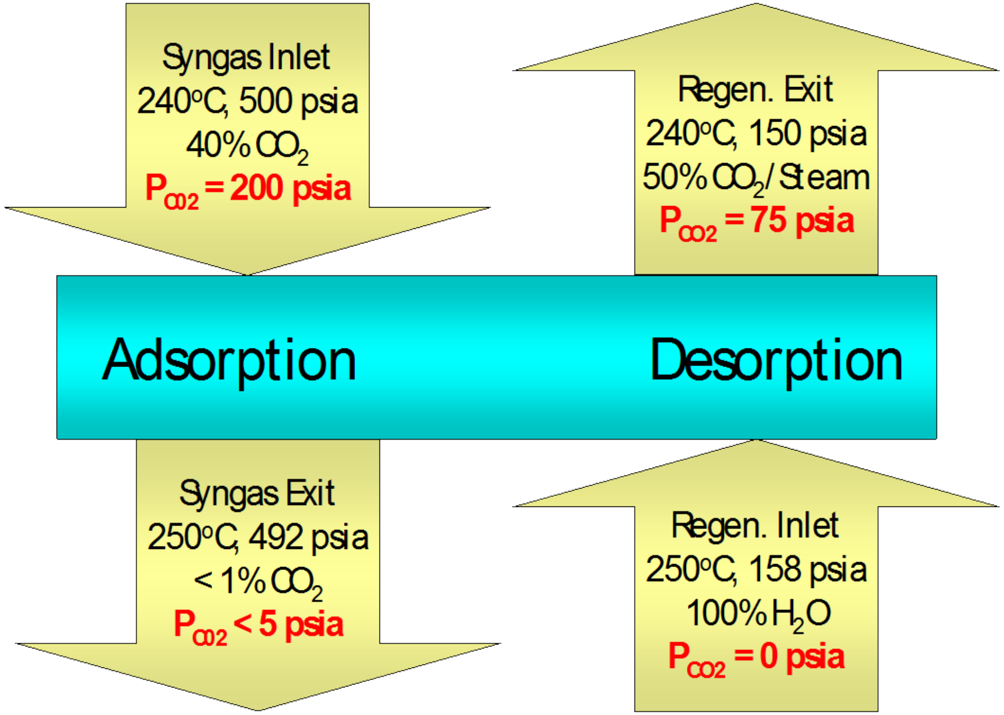
Operating Conditions

- **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**

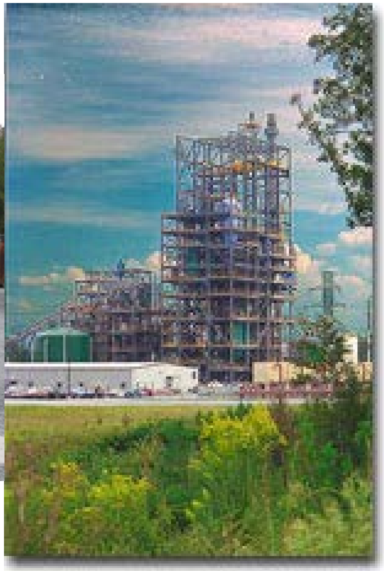


Source: Honeywell/UOP

Early Slipstream Evaluations

National Carbon Capture Center, Wilsonville, AL

- 1st Test in November, 2011
- 2nd Test in April, 2012
- Pilot-scale air blown TRIG gasifier



Wabash River IGCC Plant, Terre Haute, IN

- Testing carried out in September 2012
- Largest single-train Gasifier (262 MW)
- Oxy-blown E-Gas^{TM} Gasifier
- Operates on petcoke

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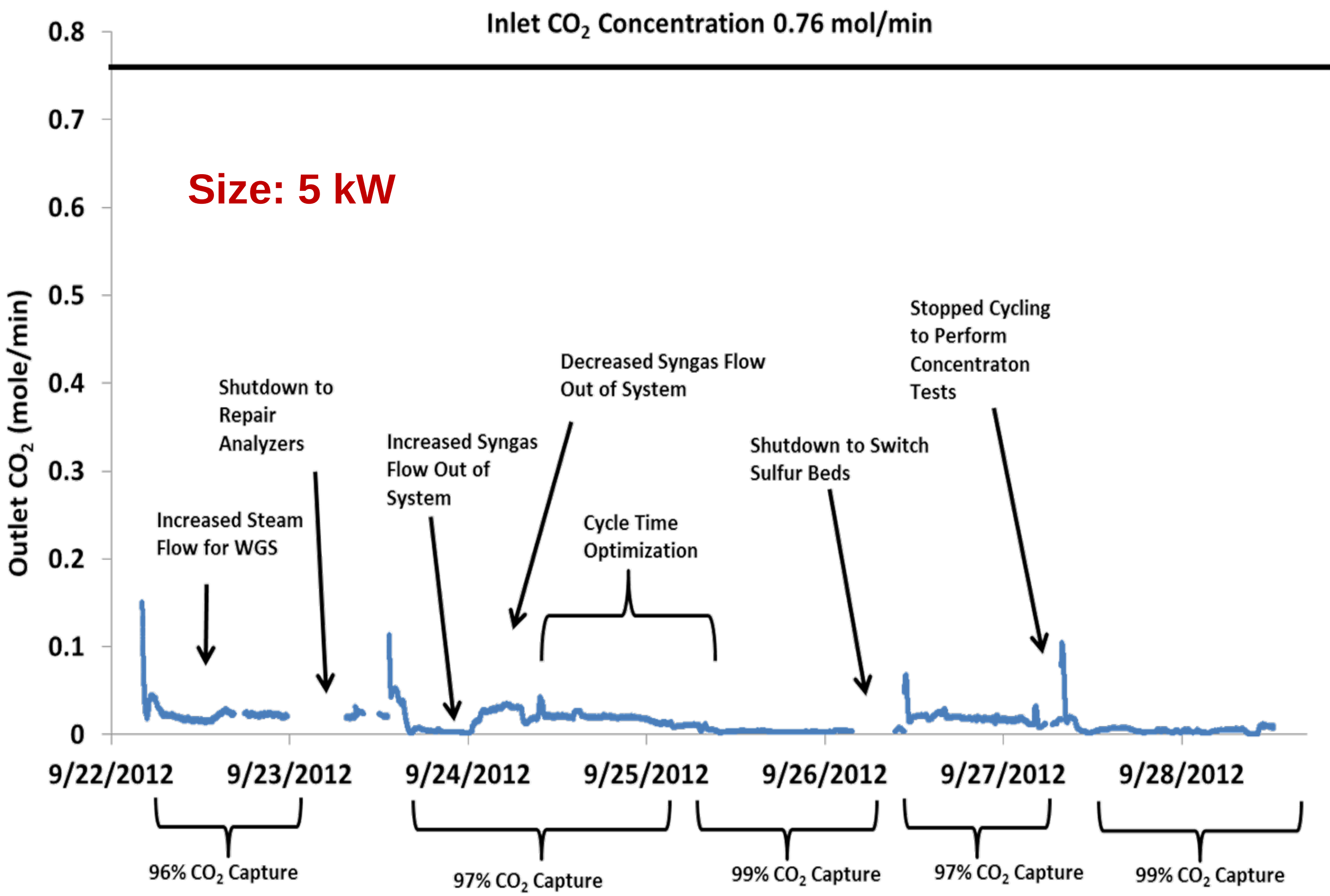
Early Slipstream Demonstration – Wabash River IGCC Plant



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

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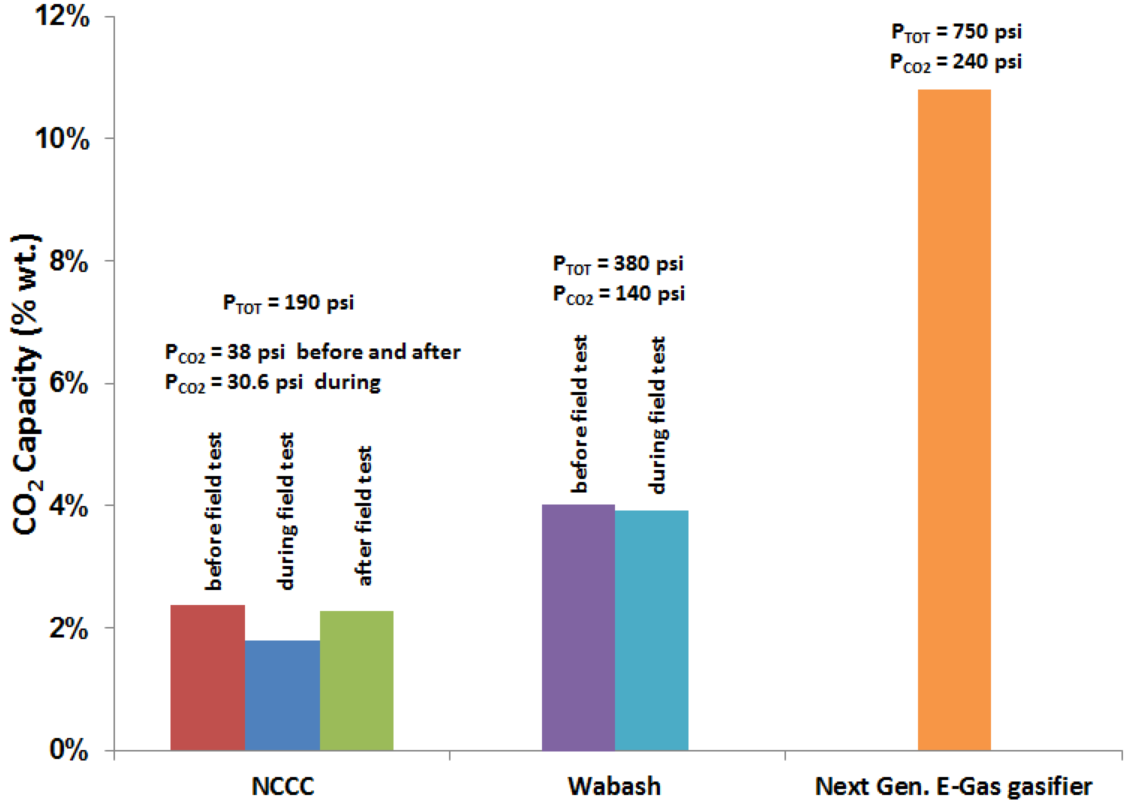
Prototype Performance



- **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**

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Primary Objective

- **0.1 MW test 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**
  - **H_2 recovery/CO_2 purity**
- **Long-term performance**
- **Evaluations at various sites using coal-derived synthesis gas**
  - **Field Test #1 at NCCC – Air blown gasification**
  - **Field Test #2 at Sinopec Yangzi Petro-chemical Plant, Nanjing, Jiangsu Province, China – Oxygen blown gasification**

9 million t/a crude oil processing
$10 billion USD worth chemicals production

- **650 kt/a ethylene**
- **1.4 million t/a aromatics**
- **1.05 million t/a purified terephthalic acid**
- **870 kt/a plastics**
- **300 kt/a ethylene glycol**
- **210 kt/a butadiene**

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Scope of Work – Budget Period #1

- **Develop a Manufacturing Plan and Quality Assurance Plan**
- **Sorbent production**
- **Optimize the PSA cycle sequence**
  - Multi-component adsorption model
- **Design the sorbent reactors**
  - Multi-component adsorption model
  - CFD simulations
- **Complete detailed design of the 0.1 MW_e pilot-scale field test unit**
  - Provide the design package to test sites (NCCC and Sinopec) for approval
- **Provide the design package to DOE with detailed vendor quotes**
- **Update process design and simulation**
  - Modifications in cycle sequence (gas flows, compression needs etc.)
  - Preliminary TEA following DOE guidelines

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Manufacturing and QA Plans

Screw Extrusion

Continuous rotary kiln

Feeder

Exhaust gas treatment

- **Manufacturing Plan and QA Plans are finalized using high throughput pilot production equipment**
- **A continuous rotary kiln (12 lb/hr capacity) was used in preparing 20+ batches**
- **Good agreement batch-to-batch and with-in-batch**

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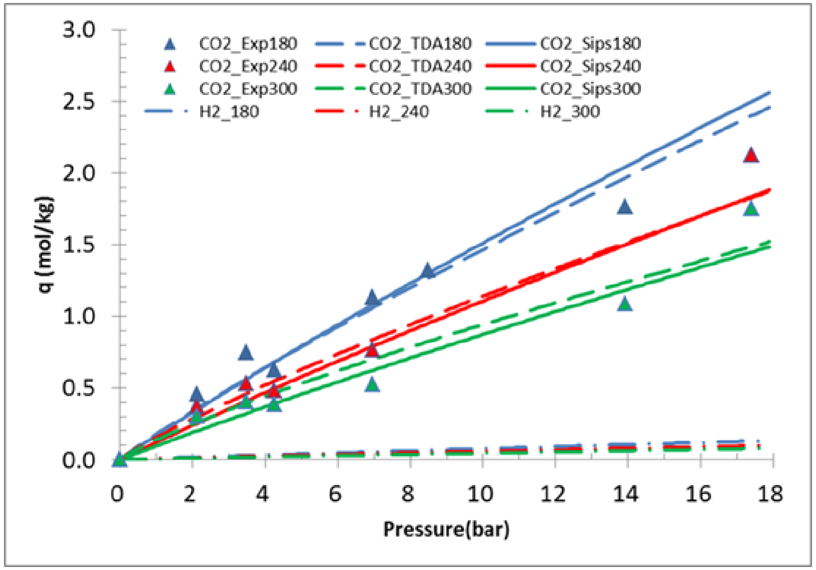
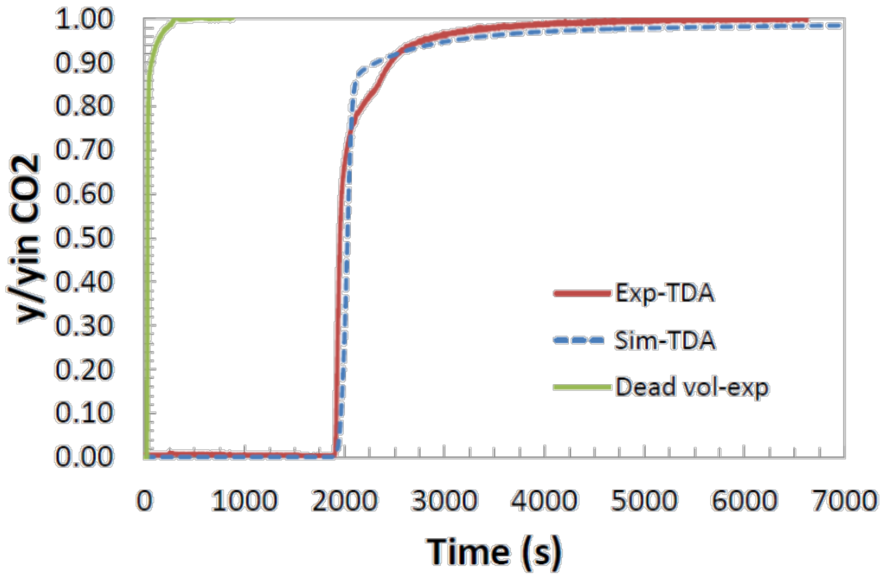
Adsorption Modeling Results

CO_2 & H_2 isotherms



CO_2 breakthrough modeling



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

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

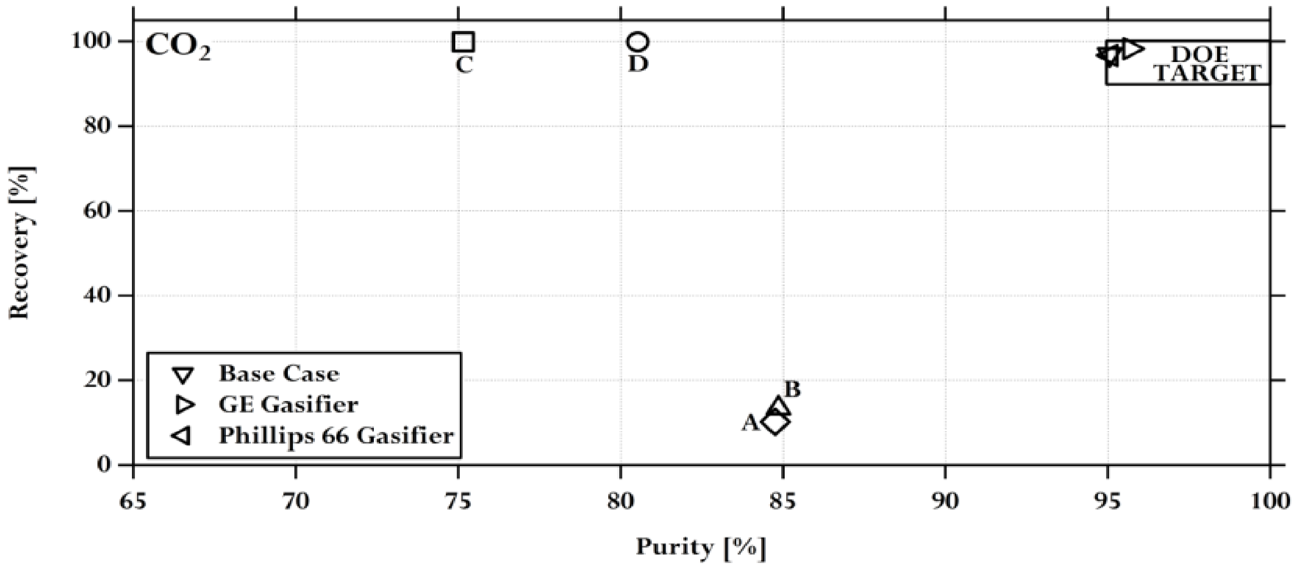
$$s_i = s_{1,i} \operatorname{atan}(s_{2,i}(T - T_{ref})) + s_{ref,i}$$

Sipps Isotherm Model Parameters

	ω_i (mol/kg)	φ_i (kJ/mol)	θ_i (1/Pa)	$\emptyset_i$ (kJ/mol)	$s_{1,i}$	$s_{2,i}$	$s_{ref,i}$	T_{ref} (K)
CO_2	3.74	-7.87	26.9*10^{-09}	-2.05	0.136	0.110	0.760	281
H_2	6.6	0	0.70*10^{-09}	-9.83	0	0	0.956	273

- **CO_2 isotherm and breakthrough modeling have been completed**

Process Cycle Optimization



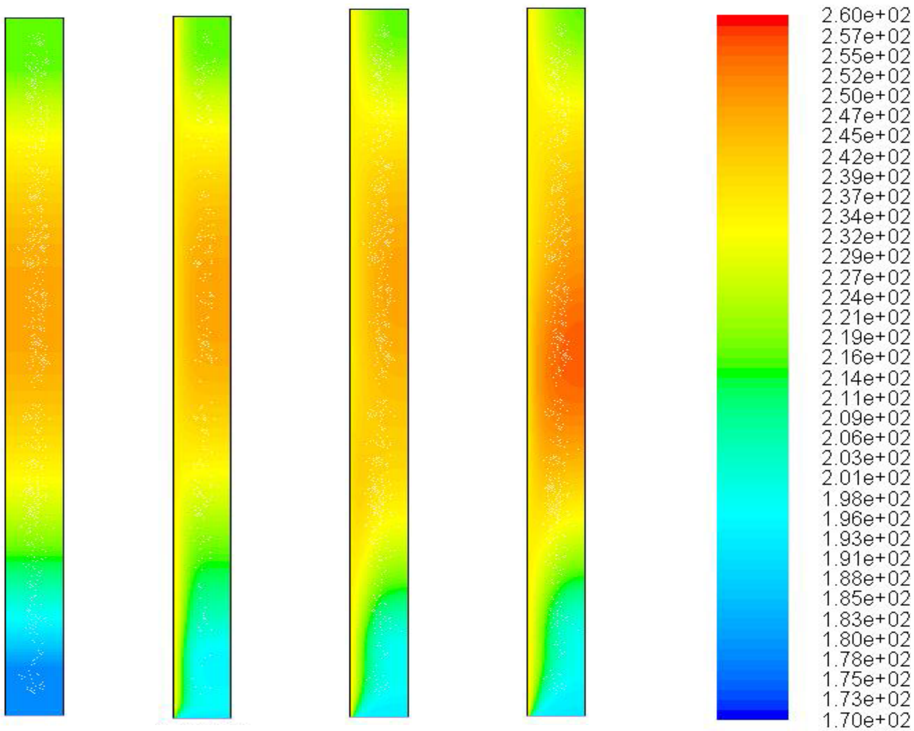
- **DOE Target of 90% CO_2 Capture & 95% purity (dry basis) were achieved for 8-bed configuration with multiple pressure equalizations and steam purge**

	Stage 1	Stage 2	Stage 3	Stage 4	Stage 5	Stage 6	Stage 7	Stage 8
Time (mir	2	1 / 0.5 / 0.5	0.5 / 0.5 / 1	0.5 / 0.5 / 1	2	0.5 / 1.5	0.5 / 0.5 / 1	1 / 0.5 / 0.5
Bed 1	ADS	HOLD / EQ1D / HOLD	Hold / EQ2D / Hold	EQ3D / CoDEP / BD	PURGE	EQ3R / HOLD	Hold / EQ2R / Hold	Hold / EQ1R / PRESS
Bed 2	Hold / EQ1R / PRESS	ADS	HOLD / EQ1D / HOLD	Hold / EQ2D / Hold	EQ3D / CoDEP / BD	PURGE	EQ3R / HOLD	Hold / EQ2R / Hold
Bed 3	Hold / EQ2R / Hold	Hold / EQ1R / PRESS	ADS	HOLD / EQ1D / HOLD	Hold / EQ2D / Hold	EQ3D / CoDEP / BD	PURGE	EQ3R / HOLD
Bed 4	HOLD	Hold / EQ2R / Hold	Hold / EQ1R / PRESS	ADS	HOLD / EQ1D / HOLD	Hold / EQ2D / Hold	EQ3D / CoDEP / BD	PURGE
Bed 5	PURGE	EQ3R / HOLD	Hold / EQ2R / Hold	Hold / EQ1R / PRESS	ADS	HOLD / EQ1D / HOLD	Hold / EQ2D / Hold	EQ3D / CoDEP / BD
Bed 6	EQ3D / CoDEP / BD	PURGE	EQ3R / HOLD	Hold / EQ2R / Hold	Hold / EQ1R / PRESS	ADS	HOLD / EQ1D / HOLD	Hold / EQ2D / Hold
Bed 7	EQ2D / Hold	EQ3D / CoDEP / BD	PURGE	EQ3R / HOLD	Hold / EQ2R / Hold	Hold / EQ1R / PRESS	ADS	HOLD / EQ1D / HOLD
Bed 8	HOLD / EQ1D / HOLD	Hold / EQ2D / Hold	EQ3D / CoDEP / BD	PURGE	EQ3R / HOLD	Hold / EQ2R / Hold	Hold / EQ1R / PRESS	ADS

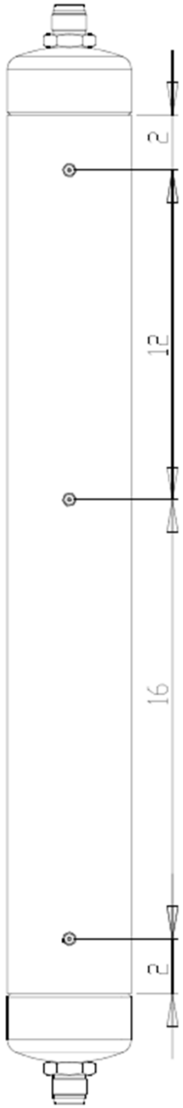
CFD Modeling

- **First a 2-D model was developed**
- **Temperature simulation results are consistent with the testing results on the adsorption side**

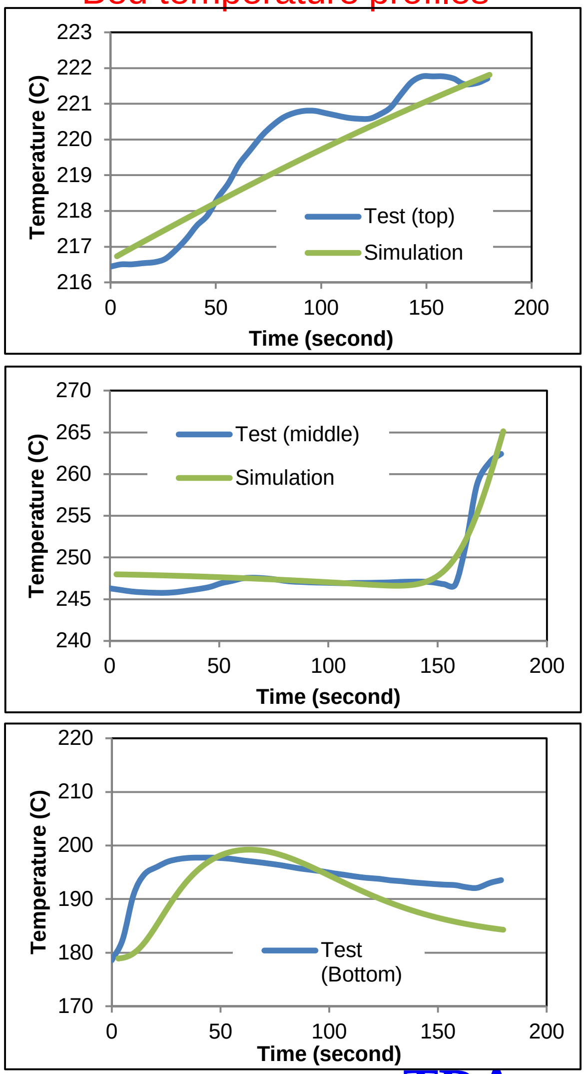
$CO_2(gas) \rightarrow CO_2(s)$



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



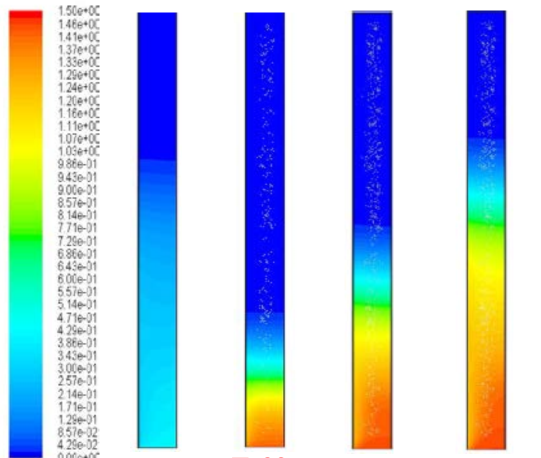
Bed temperature profiles



2-D Concentration Distributions

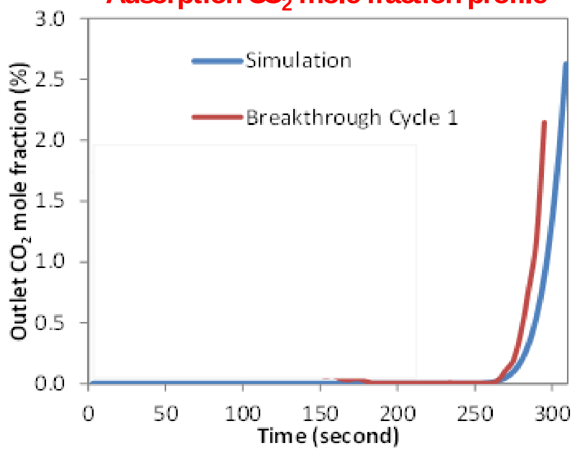
Adsorption process

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



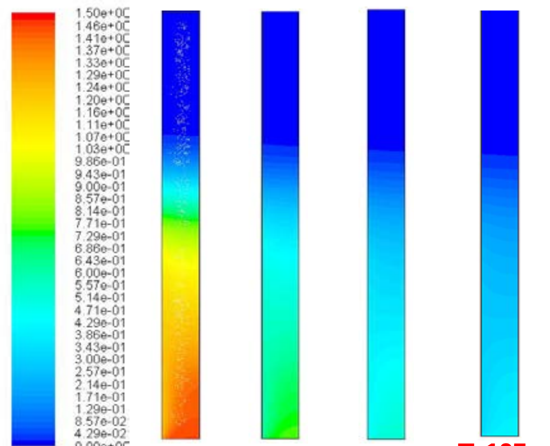
T=0 s T=60 s T=120 s T=180 s

Adsorption CO_2 mole fraction profile



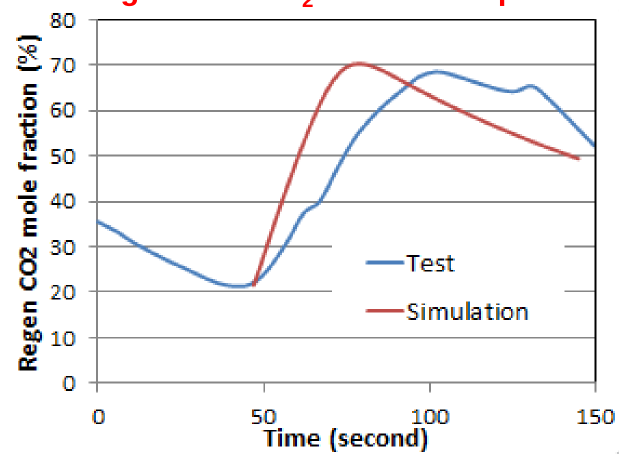
Desorption process

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



T=0 s T=35 s T=70 s T=105 s

Regeneration CO_2 mole fraction profile



- **Simulation results for CO_2 concentrations are consistent with test results**

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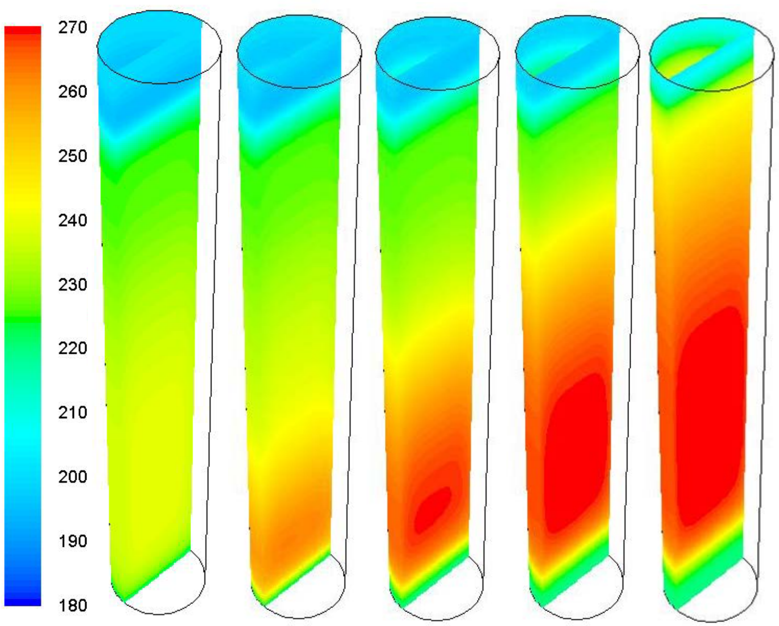
3-D CFD Modeling for 0.1 MW_e Unit

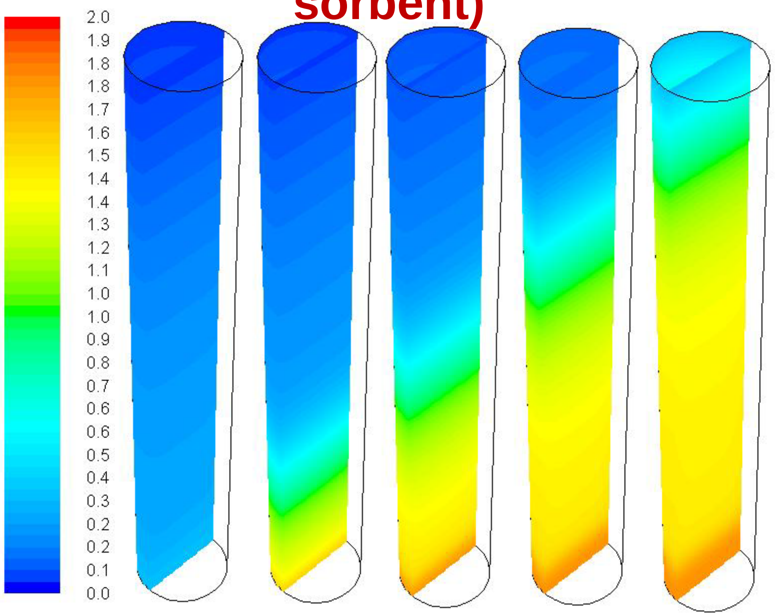
- **GTI extended the model predictions for the 8-bed 0.1 MW_e Pilot PSA Unit**
- **The temperature rise in the 8-bed system is expected to be within 35°C without any active heat management**
  - No need for any additional heat managements in the PSA beds

Temperature Distribution (°C)



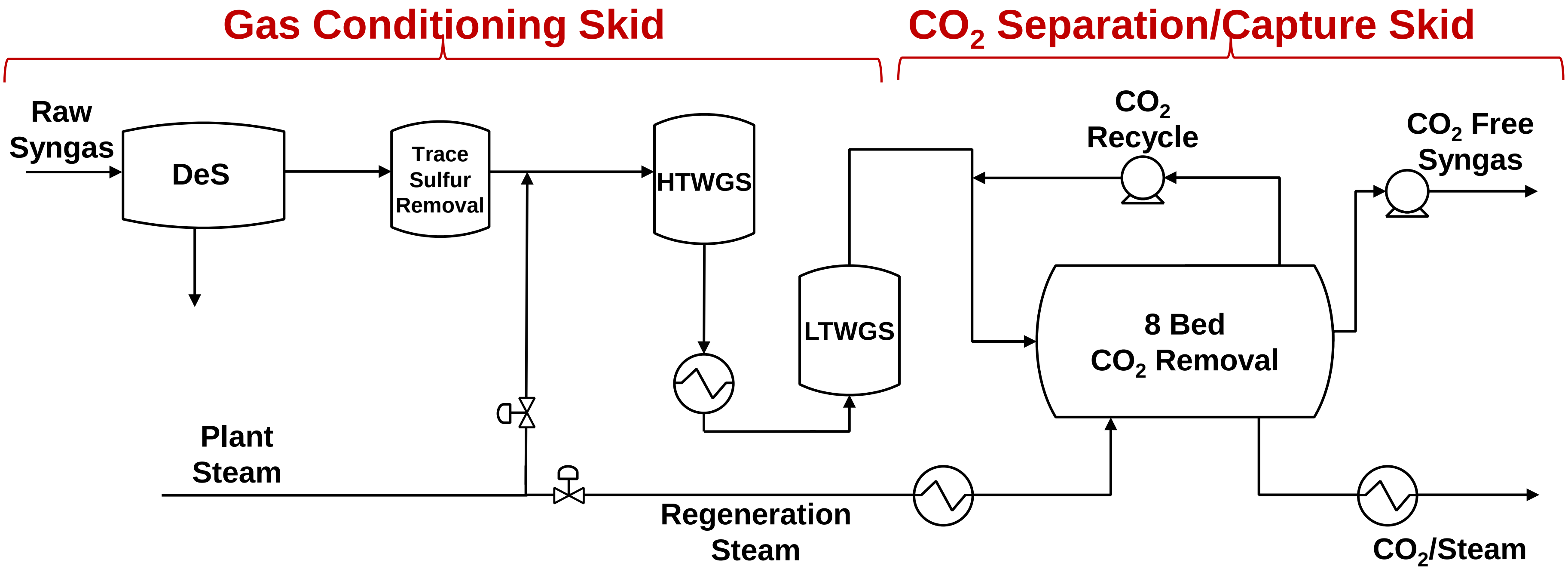
Time (30 sec increment)

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



Time (30 sec increment)

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

- **Evaluation will focus on critical sub-systems (CO_2 purification is excluded)**

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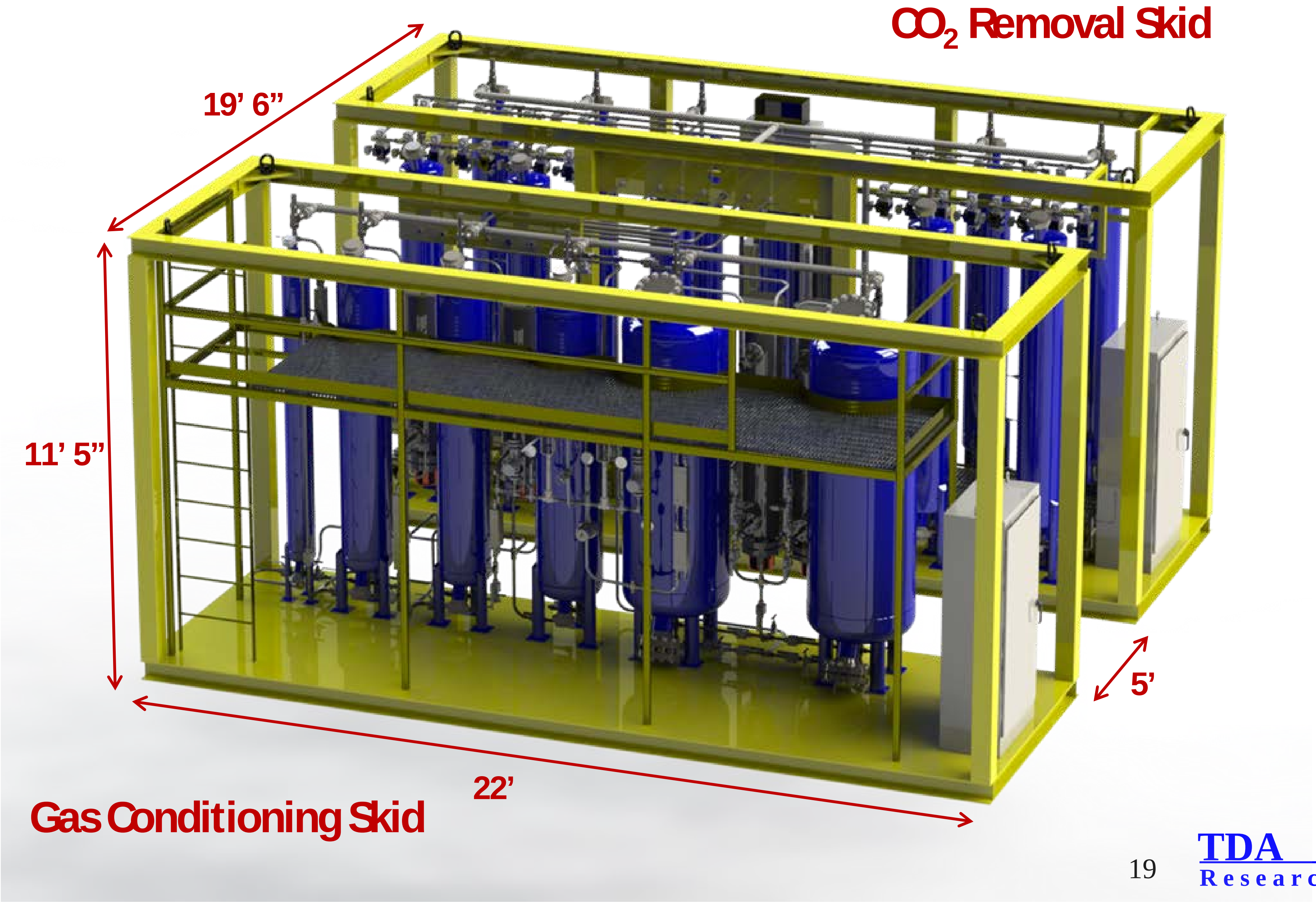
0.1 MW Pilot Unit Design



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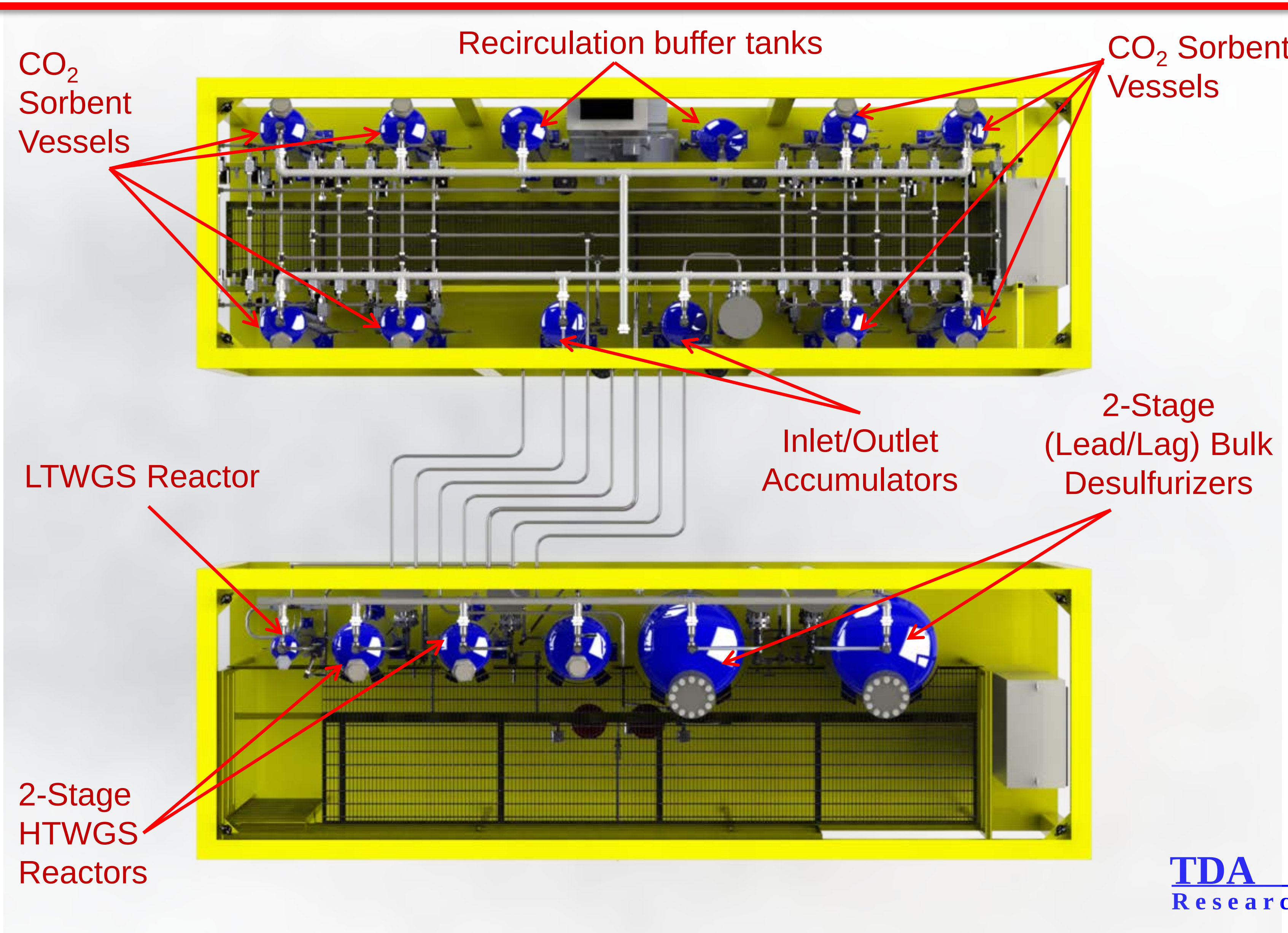
Reactor Design and Optimization



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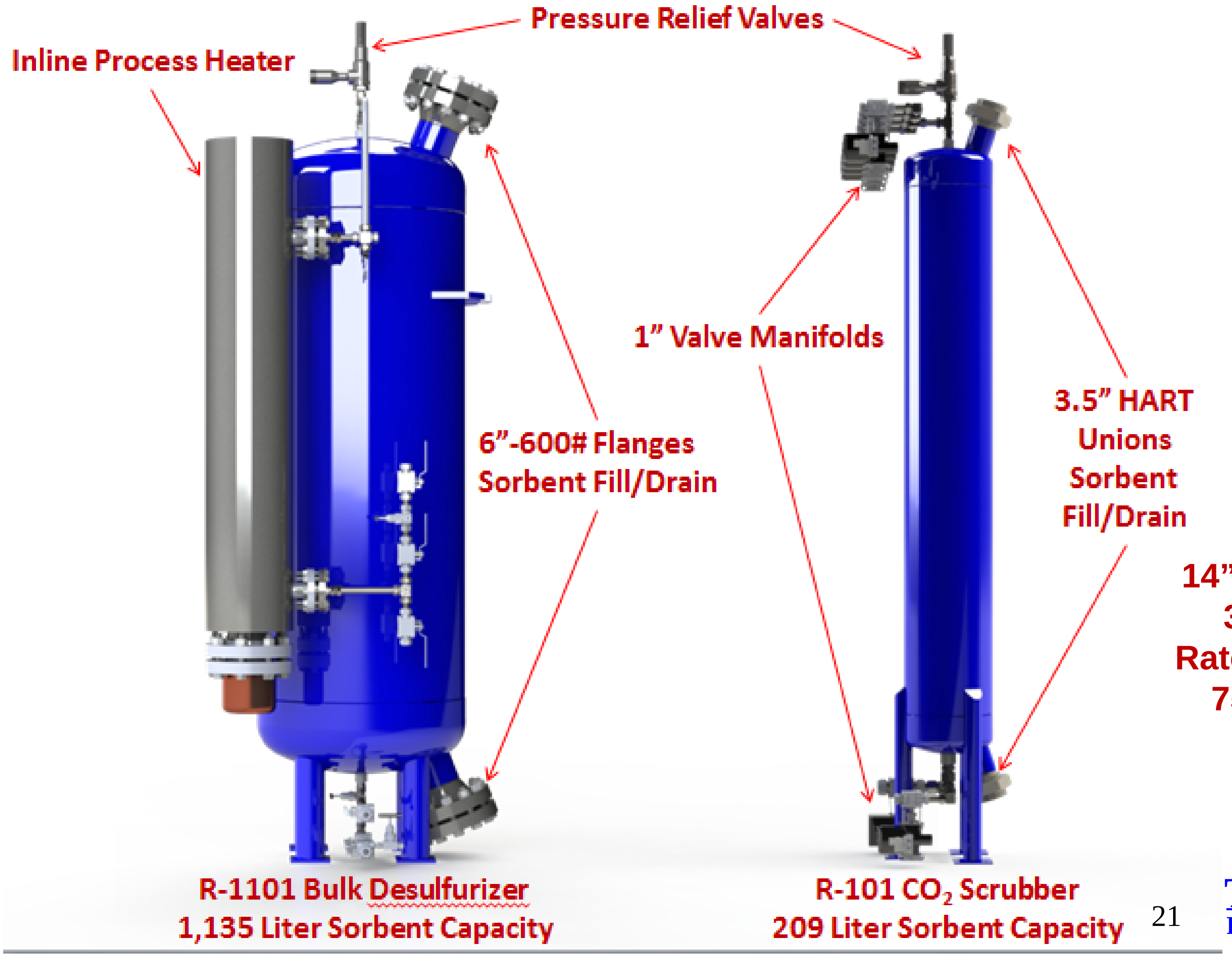
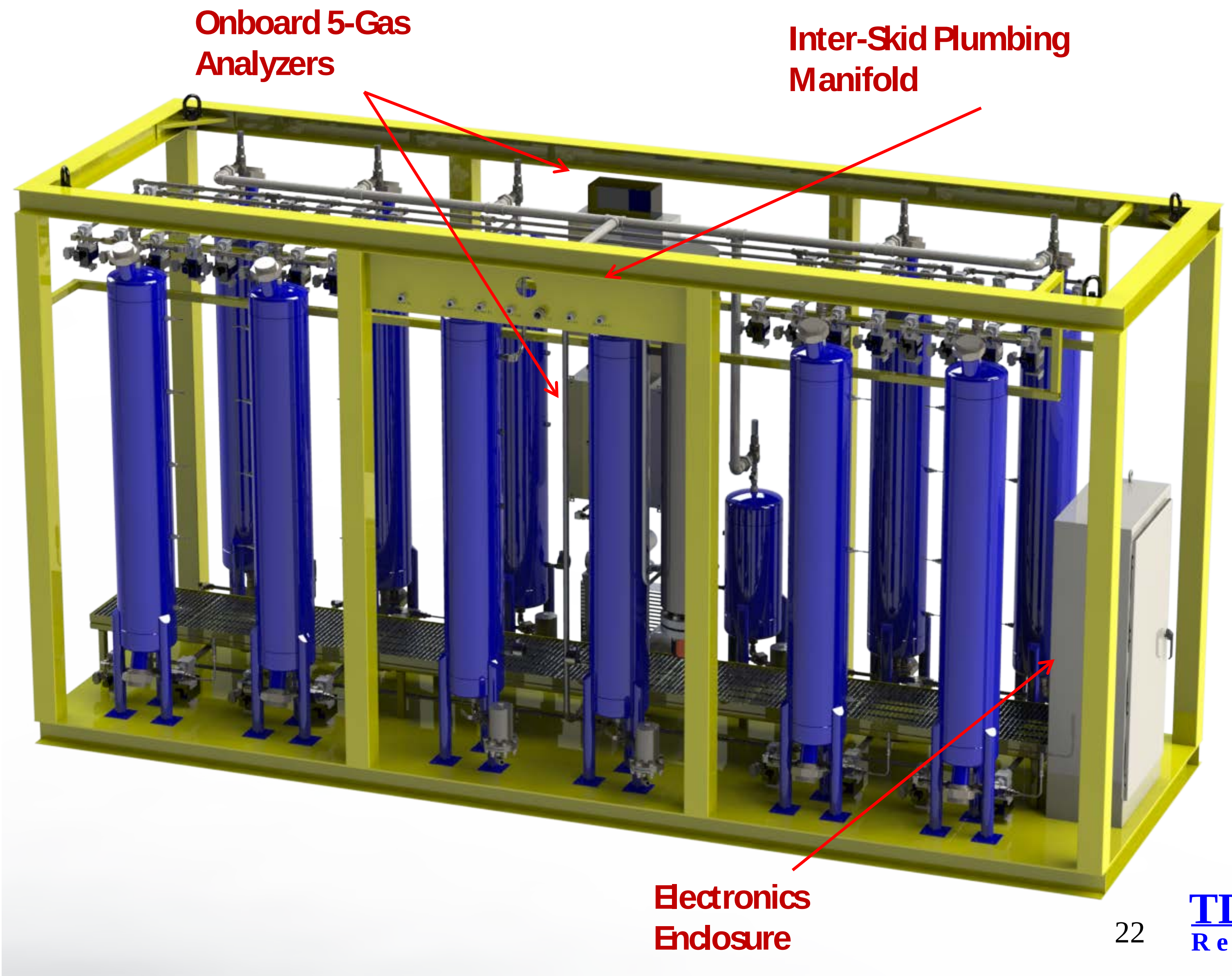
Reactor Design and Optimization



14" OD x 8ft
304 SS
Rated 450°C/
750 psig

Reactor Design and Optimization



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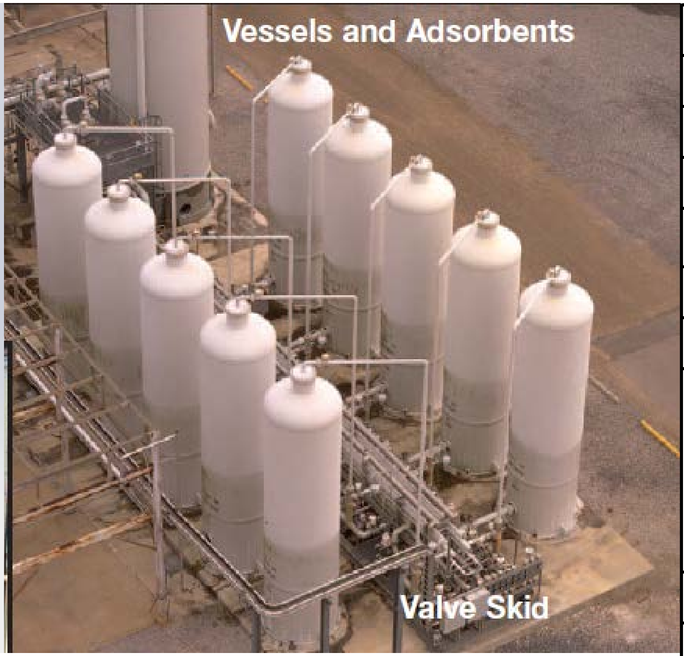
Reactor Design Concepts

- 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	34,708
Sorbent needed, kg	781,132
Cycle time, min	8
Ads. GHSV, h^{-1}	1,115
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 ~770,000 m^3/hr syngas flow rate for the based case used in TEA)

TDA Research

System Analysis Results

	E-Gas™ Gasifier		GE Gasifier	
	Case 1	Case 2	Case 3	Case 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, %	90.0	90.0	90.0	90.0
Gross Power Generated, kWe	716,419	659,244	727,370	667,263
Gas Turbine Power	464,000	418,911	464,000	411,132
Steam Turbine Power	252,419	240,333	263,371	256,131
Auxiliary Load, kWe	194,924	119,583	192,927	115,576
Net Power, kWe	521,496	539,661	534,443	551,686
Net Plant Efficiency, % HHV	31.20	33.70	32.00	34.30
Coal Feed Rate, kg/h	221,463	212,166	221,584	213,013
Raw Water Usage, GPM/MWe	10.8	10.8	10.9	10.5
Total Plant Cost, $/kWe	3,427	3,061	3,387	3,109
COE without CO_2 TS&M, $/MWh	135.4	121.2	133.5	122.1
COE with CO_2 TS&M, $/MWh	144.2	129.4	142.1	130.1
Cost of CO_2 Capture $/tonne	51.98	38.08	47.89	36.34

- IGCC plant with TDA's CO_2 capture system achieves higher efficiency (33.7%) than IGCC with Selexol™ (31.2%)
- Cost of CO_2 capture is calculated as $38.1 and $36.3 per tonne for GE and E-Gas™ gasifiers, respectively (24-27% reduction against Selexol™)

TDA Research

Acknowledgements

- The funding from DOE/NETL under Contract No. DE-FE-0007580 is greatly acknowledged
- Technical Monitor, Elaine Everitt, DOE/NETL
- Dr. Chuck Shistla and Andy Hill, GTI
- Dr. Arvind Rajendran, UOA
- Dr. Ashok Rao, UCI
- Dr. Liu Fangtao, Sinopec
- Dr. Francois Botha and Dr. Debalina Dasgupta, ICCI

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