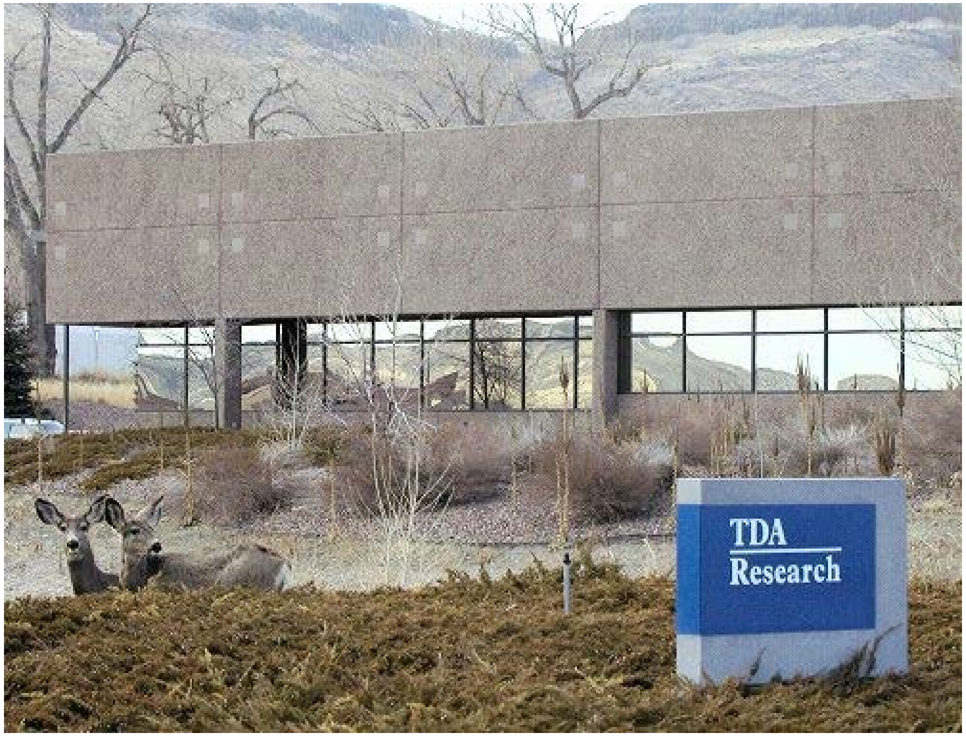
Pilot Testing of a Highly Efficient Pre-combustion Sorbent-based Carbon Capture System (Contract No. DE-FE-0013105)



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DOE/NETL Carbon Capture Meeting

Pittsburgh, PA

August 8, 2016

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 Unit for full-concept evaluation
  - 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

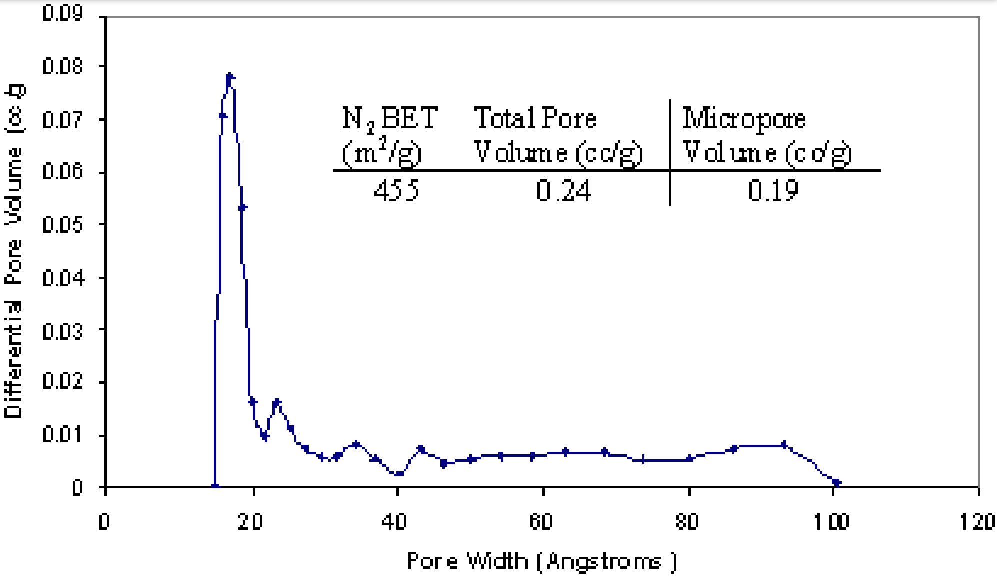
- **Start Date = January 1, 2014**
- **End Date = September 30, 2018**

Budget

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

TDA's Approach

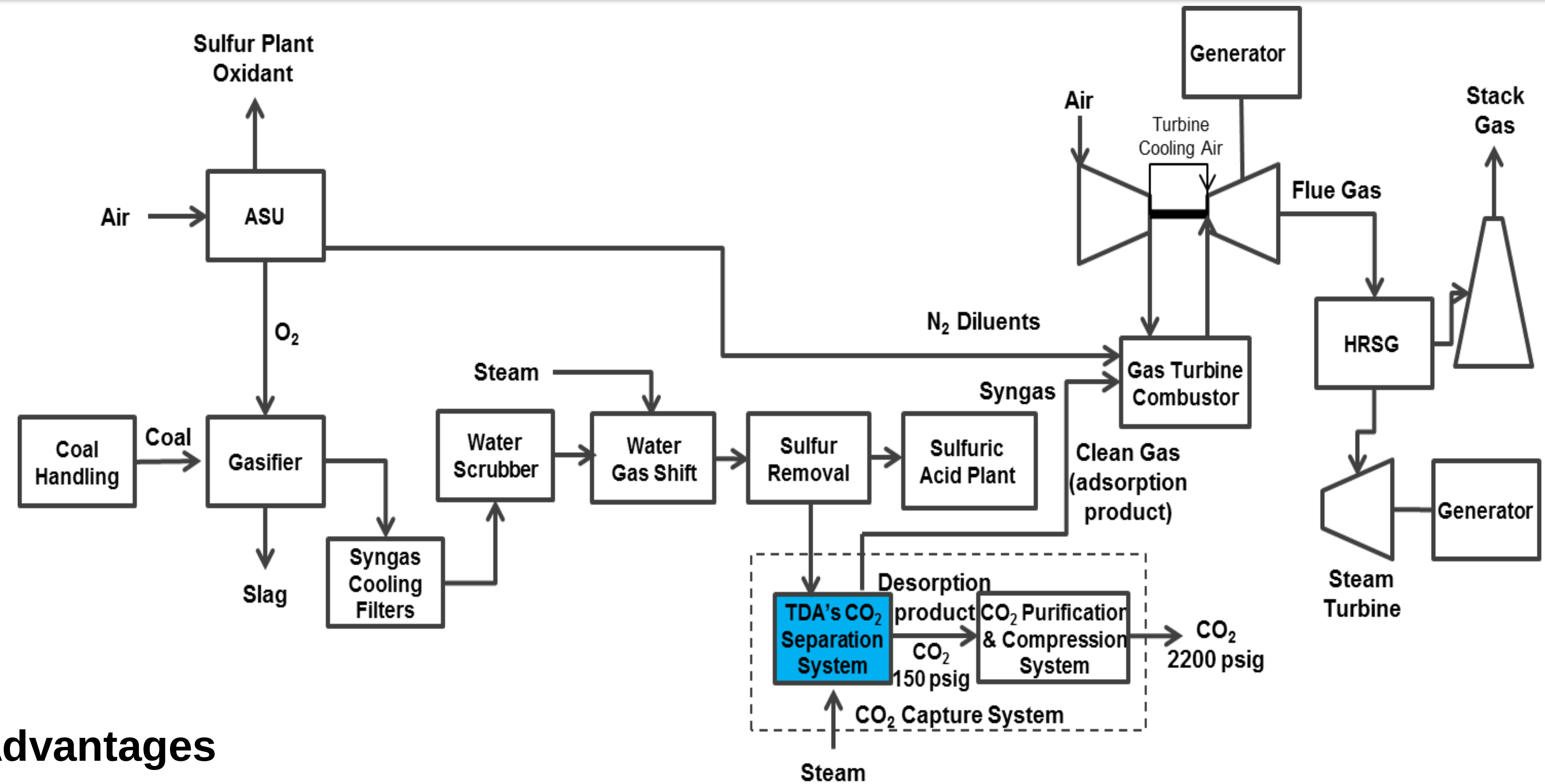
- **TDA's uses a mesoporous carbon modified with surface functional groups that remove CO_2 via strong physical adsorption**
  - CO_2-surface interaction is strong enough to allow operation at elevated temperatures
  - Because CO_2 is not bonded via a covalent bond, the energy input for regeneration 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 Patent 9,120,079, Dietz, Alptekin, Jayaraman "High Capacity Carbon Dioxide Sorbent"
US 6,297,293; US 6,737,445; US 7,167,354
US Pat.App. 61790193, Alptekin, Jayaraman, Copeland "Pre-combustion Carbon 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 and 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

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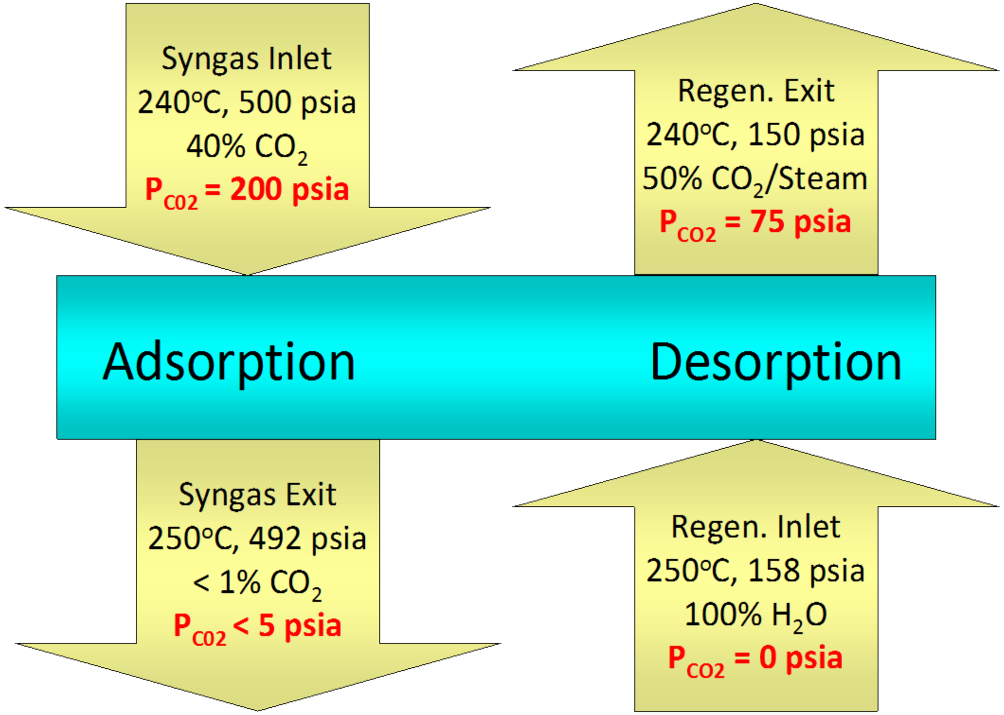
Operating Conditions

- 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

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 as needed
  - H_2 recovery/CO_2 purity
- Long-term performance evaluation
- Evaluations at two sites
  - Field Test #1 at NCCC – Air blown gasification
  - Field Test #2 at Sinopec Yangtzi Petro-chemical Plant, Nanjing, Jiangsu Province, China – Oxygen blown gasification

National Carbon Capture Center

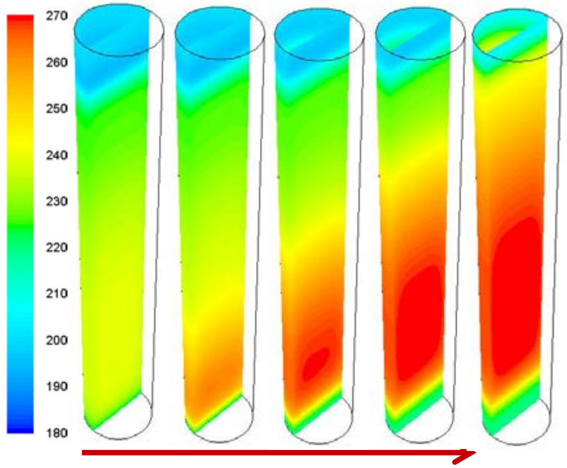
Yangtzi Petro-chemical Plant

Scope of Work – Budget Period #1

<u>Work Completed in BP1</u>

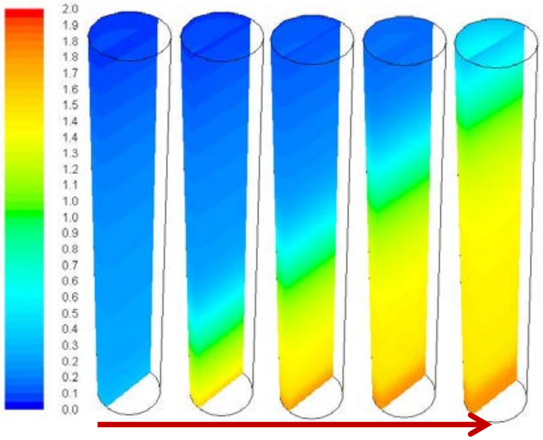
- **Develop a Manufacturing Plan and Quality Assurance Plan**
- **Sorbent production**
- **Develop a multi-component adsorption model for cycle optimization**
- **Design the sorbent reactors**
  - CFD simulations
- **Complete detailed design package for the 0.1 MW_e pilot-scale field test unit**
  - Approval from NCCC and Sinopec
- **Provide the design package to DOE with detailed vendor quotes**
- **Preliminary TEA using DOE guidelines**

Temperature Distribution (°C)



Time (30 sec increment)

CO_2(s) mol-CO_2/kg-sorbent



Time (30 sec increment)

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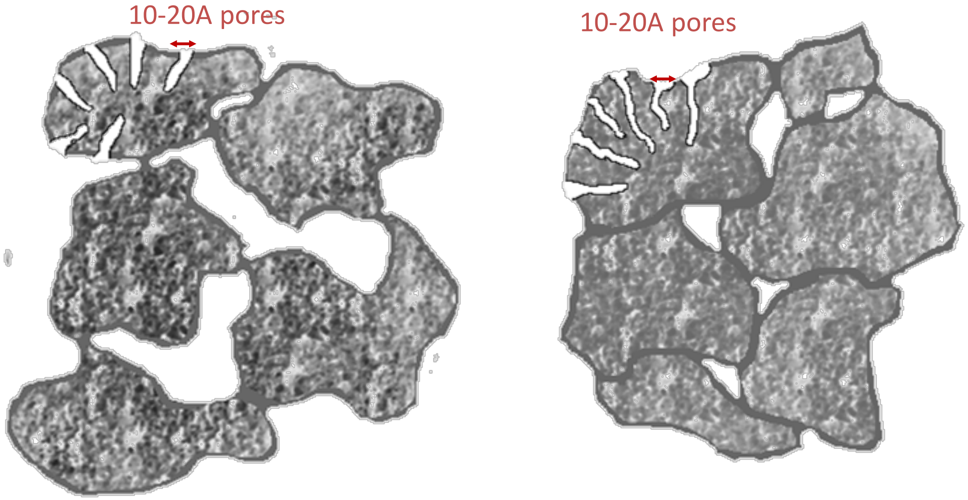
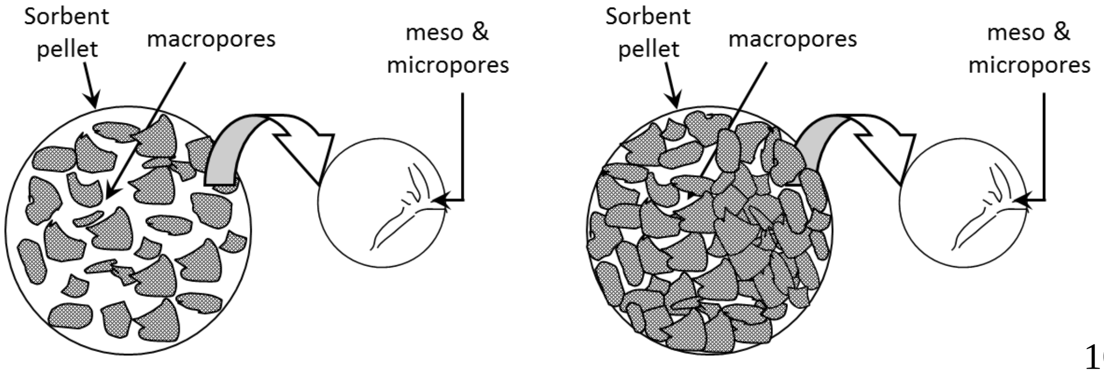
Scope of Work – Budget Period #2

- **Sorbent Production**
  - Completed
- **Sorbent Life Test (up to 20,000 cycles)**
  - To be completed by 09/30/2016
- **Optimize the PSA cycle sequence for Full-scale Unit**
  - To be completed by 09/30/2016
- **Fabrication of the 0.1 MW_e pilot-scale field test unit**
  - To be completed by 09/30/2016
- **Update process design and simulation**
  - Reflect modifications in cycle sequence and sorbent improvement
  - To be completed by 09/30/2016

Improvements in Sorbent



- **Macropore volume is reduced, greatly improving the bulk density and volumetric capacity without significant loss in mass capacity**
  - Smaller reactors and lower capital cost
- **Reduced void volume (ullage space)**
  - Higher product purity at lower purge gas



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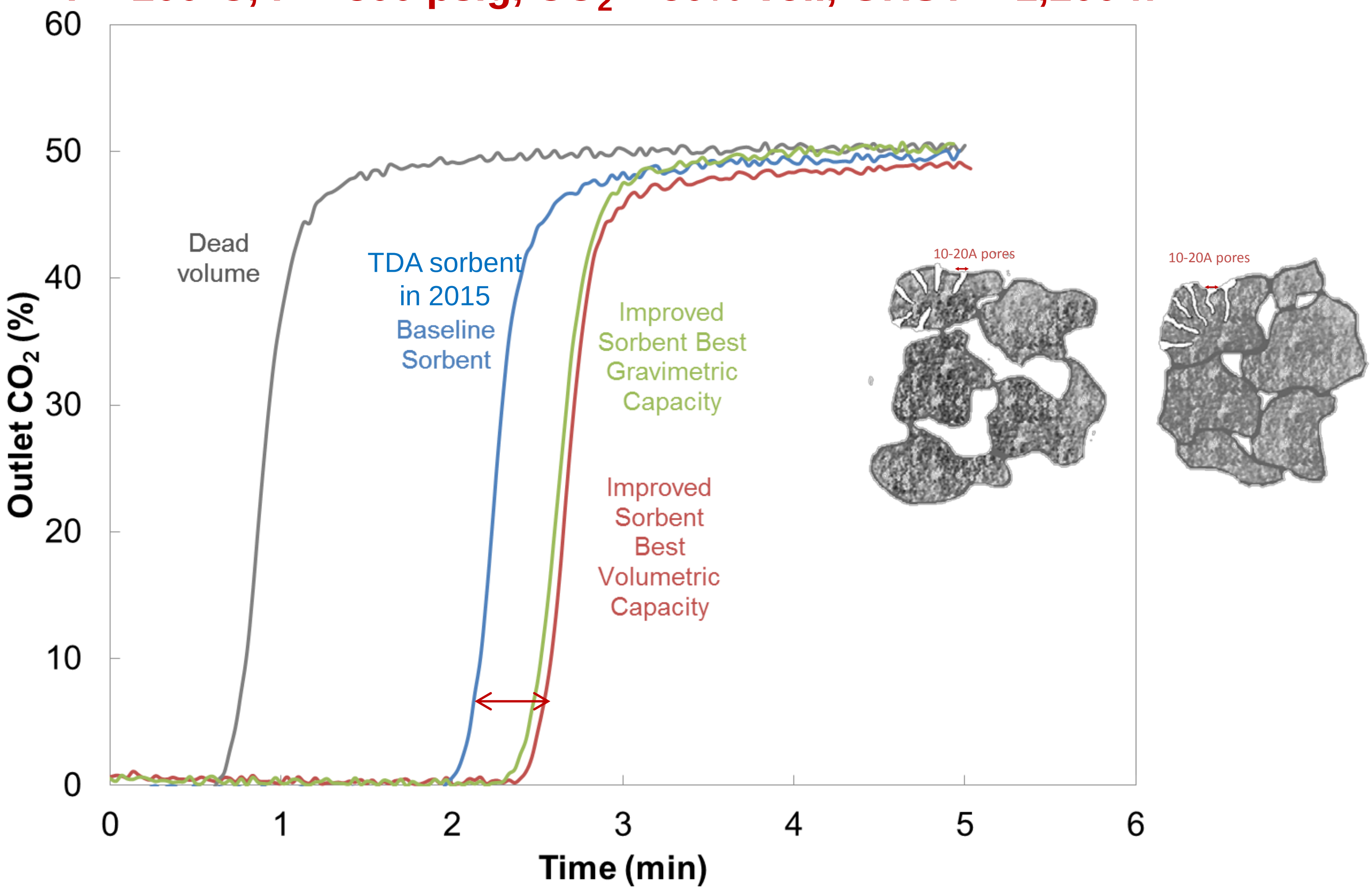
Improvements in Sorbent Performance

T = 200°C, P = 300 psig, CO_2 = 50% vol., GHSV = 1,200 h^{-1}



- **~25% increase in volumetric capacity**

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Sorbent Manufacturing

Screw Extrusion

Continuous rotary kiln

Feeder

Exhaust gas treatment

- Manufacturing Plan and QA Plans are modified to reflect changes
- Sorbent production is completed using high throughput production equipment
- Good agreement batch-to-batch and with-in-batch

TDA Research

Sorbent and Catalyst for Field Tests

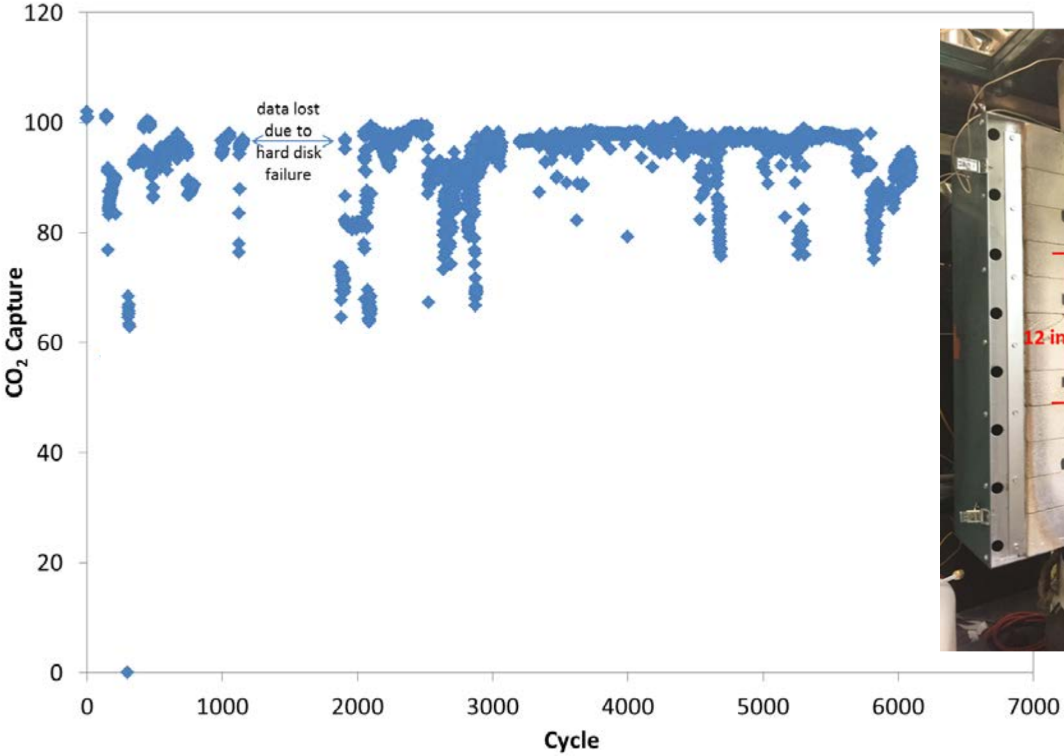
Sulfur Sorbent and WGS Catalyst

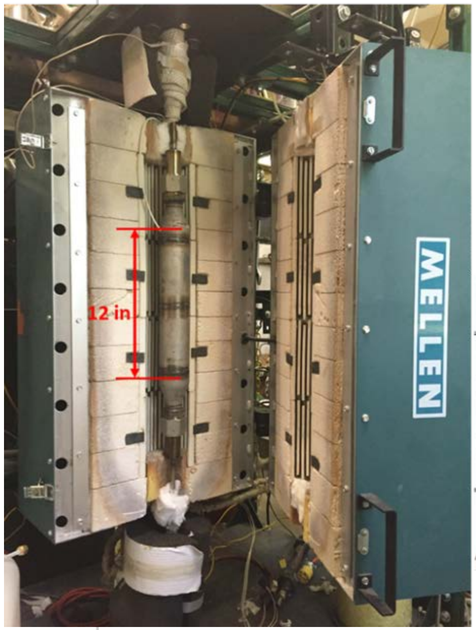
CO_2 Sorbent for Field Tests

- **2 m^3 of TDA's CO_2 sorbent has been produced for use in the field tests**
- **Warm gas Sulfur removal sorbent and High and Low Temperature WGS catalysts have been procured from clariant**

Sorbent Life Tests

T = 200°C, P_{ads} = 500 psig, P_{des} = 75-300 psig, simulated syngas





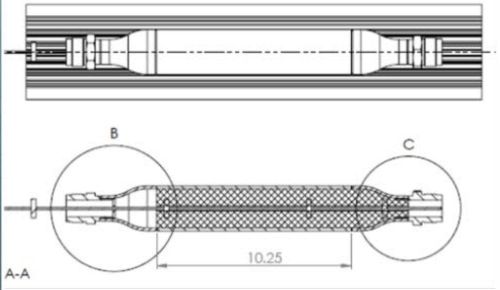
New Reactor for long-term cycling experiments

2in Schedule 40 stainless Steel Reactor

2.07 in Internal Diameter

12 in Heated Bed Length

650 cm^3 Sorbent Bed volume



- **Previously we demonstrated over 11,500 cycles with our baseline formulation**
- **TDA's improved sorbent has so far maintained its performance over 6,000 cycles (60,000 cycles to be completed by end of BP4)**

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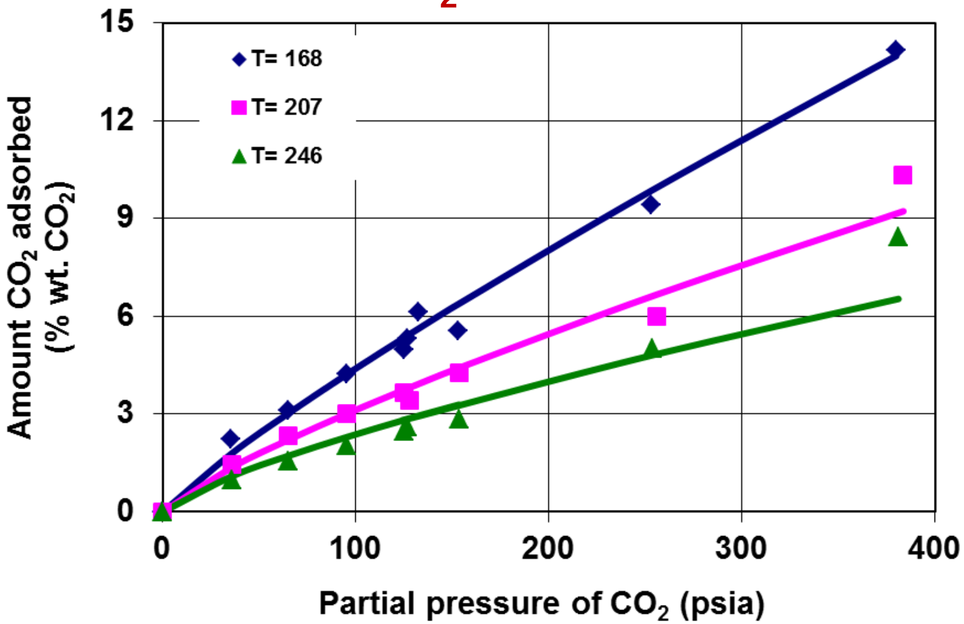
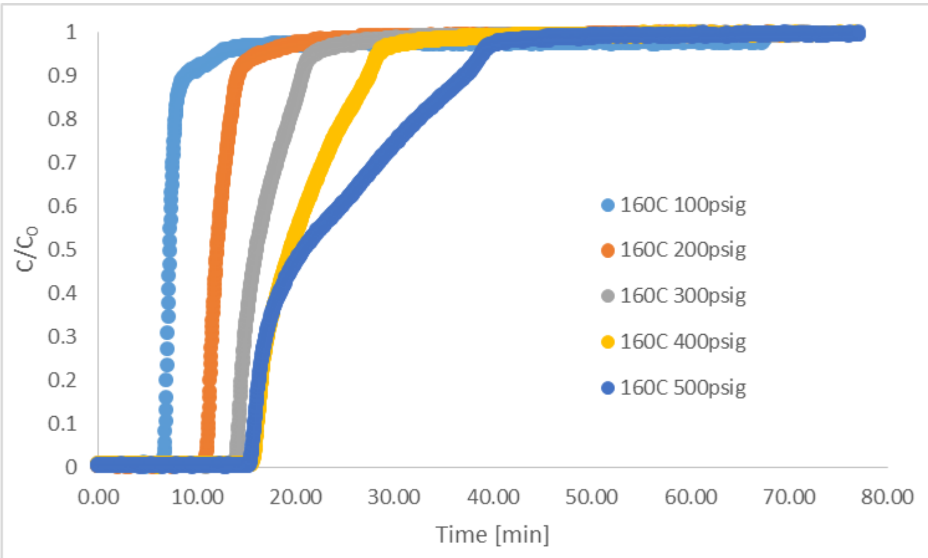
Adsorption Modeling Results

CO_2 isotherms



CO_2 breakthrough



$$q_s = k_1 e^{k_2/T}; B = k_3 e^{k_4/T}; n = k_5 e^{k_6/T}$$

$$q = \frac{q_s B P^n}{1 + B P^n}$$

Langmuir-Freundlich Parameters

q (mol CO_2/kg); P (psia); T (K)

k1	119.03	k4	87.02
k2	139.38	k5	0.34
k3	9.0E-05	k6	421.86

- **CO_2 isotherm and breakthrough models were updated**

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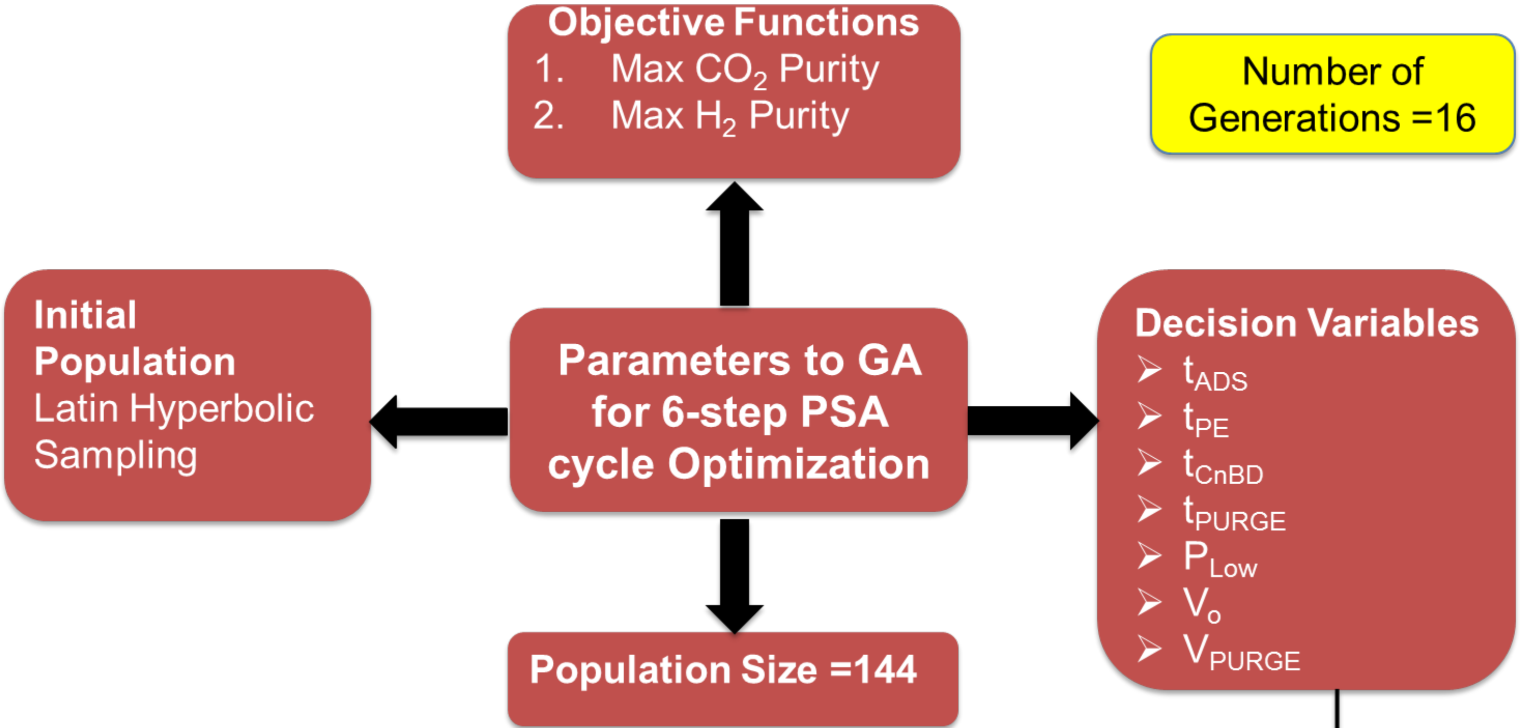
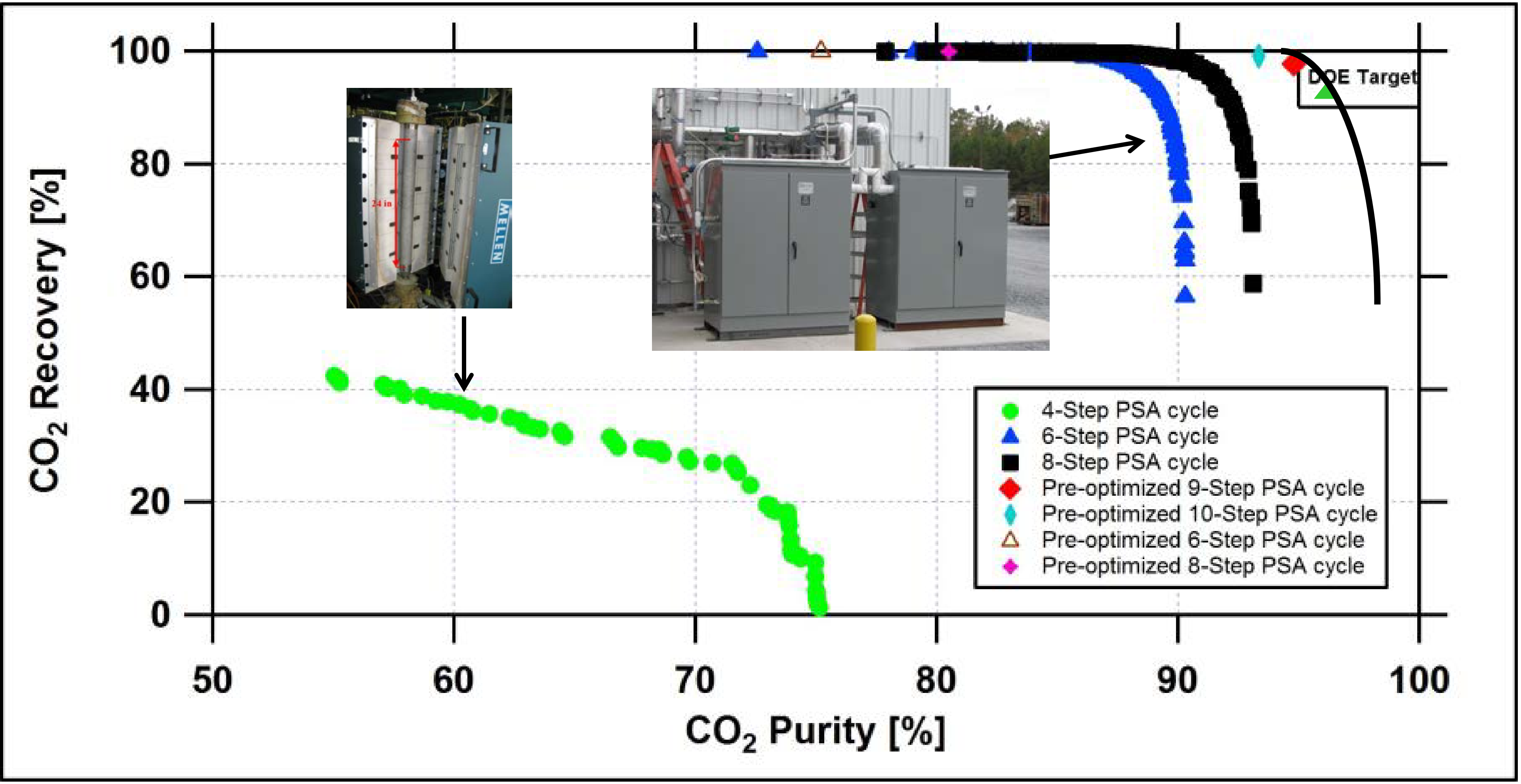
PSA Cycle Optimization



Decision Variables	t_{ADS} (s)	t_{PE} (s)	t_{CnBD} (s)	t_{PURGE} (s)	P_{Low} (bar)	V_o (m/s)	V_{PURGE} (m/s)
LB	20	20	20	10	9.66	0.08	0.1
UB	100	200	200	80	10.35	1.2	1

- **We used a Genetic Algorithm (GA) to optimize the cycle parameters**

Pareto Charts



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Process Cycle Optimization

- **BP1 – PSA Cycle Scheme – 16 min full cycles – 7 min hold time**

	Stage 1	Stage 2	Stage 3	Stage 4	Stage 5	Stage 6	Stage 7	Stage 8
Time (min	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

- **BP2 – PSA Cycle Scheme – 8 min full cycles – 0 min hold time**

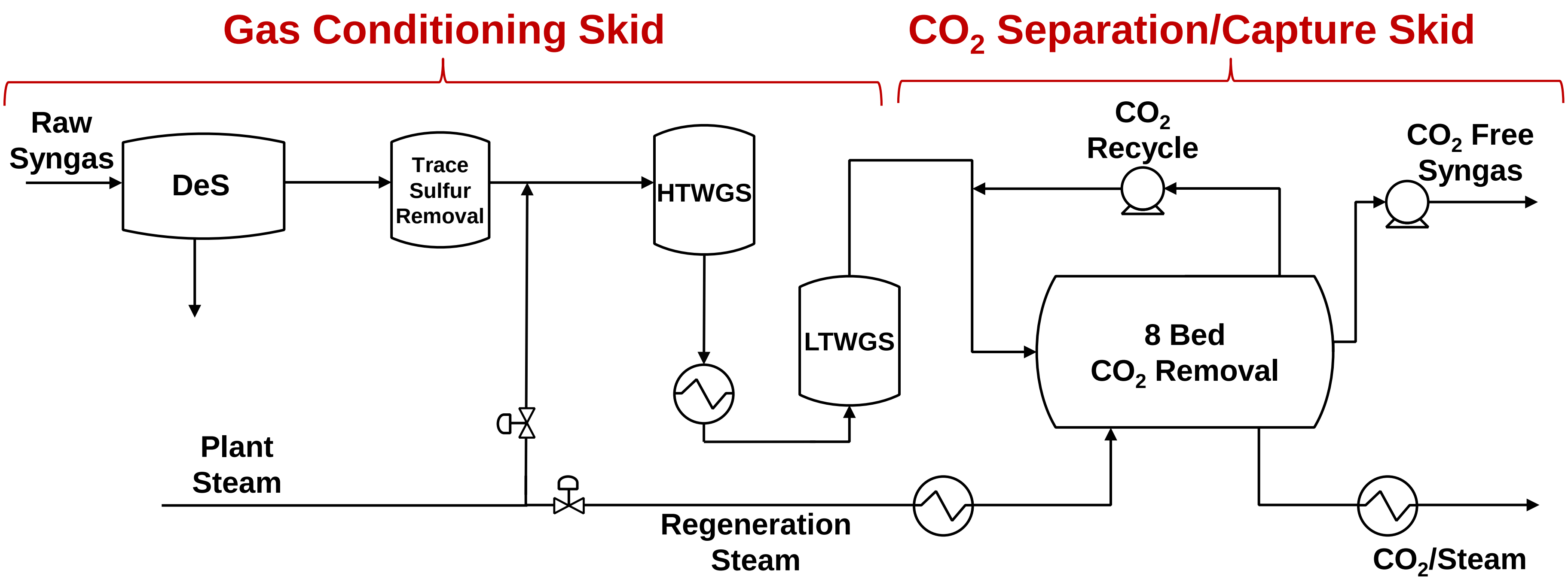
Total Cycle time (8 min) Idle time (0 min)

	Stage 1		Stage 2		Stage 3		Stage 4		Stage 5		Stage 6		Stage 7		Stage 8	
Time (min	1		1		0.5	0.5	0.5	0.5	1		1		0.5	0.5	0.5	0.5
Bed 1	ADS				EQ1D	EQ2D	EQ3D	CoDEP	PURGE				EQ3R	EQ2R	EQ1R	PRESS
Bed 2	EQ1R	PRESS	ADS				EQ1D	EQ2D	EQ3D	CoDEP	PURGE				EQ3R	EQ2R
Bed 3	EQ3R	EQ2R	EQ1R	PRESS	ADS				EQ1D	EQ2D	EQ3D	CoDEP	PURGE			
Bed 4	PURGE		EQ3R	EQ2R	EQ1R	PRESS	ADS				EQ1D	EQ2D	EQ3D	CoDEP	PURGE	
Bed 5	PURGE				EQ3R	EQ2R	EQ1R	PRESS	ADS				EQ1D	EQ2D	EQ3D	CoDEP
Bed 6	EQ3D	CoDEP	PURGE				EQ3R	EQ2R	EQ1R	PRESS	ADS				EQ1D	EQ2D
Bed 7	EQ1D	EQ2D	EQ3D	CoDEP	PURGE				EQ3R	EQ2R	EQ1R	PRESS	ADS			
Bed 8	ADS		EQ1D	EQ2D	EQ3D	CoDEP	PURGE				EQ3R	EQ2R	EQ1R	PRESS	ADS	

- **The faster cycling allows to reduce the bed size by increasing sorbent utilization/productivity**

TDA Research

0.1 MW_e Pilot Unit for Field Tests



	Sinopec	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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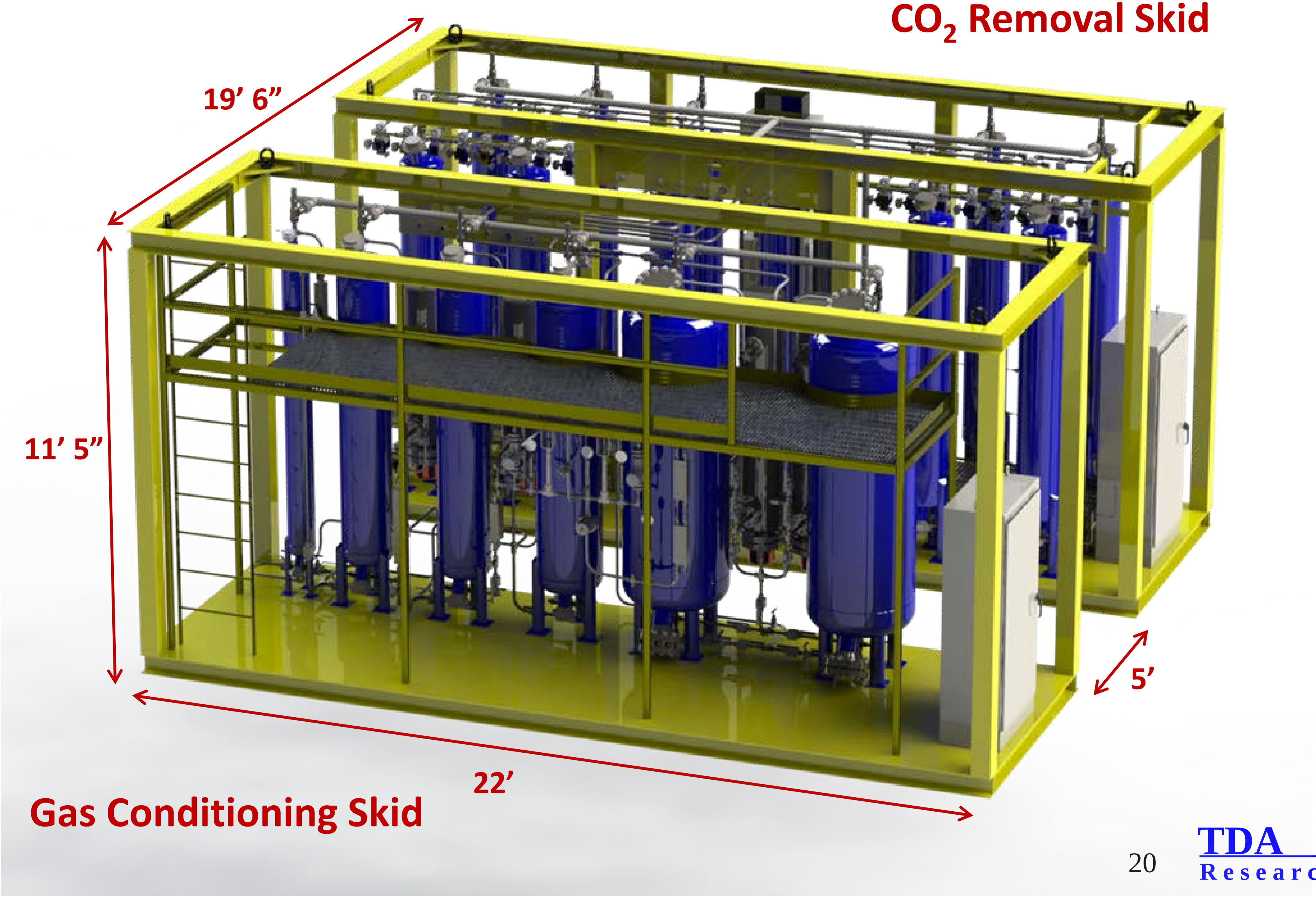
0.1 MW Pilot Unit Design



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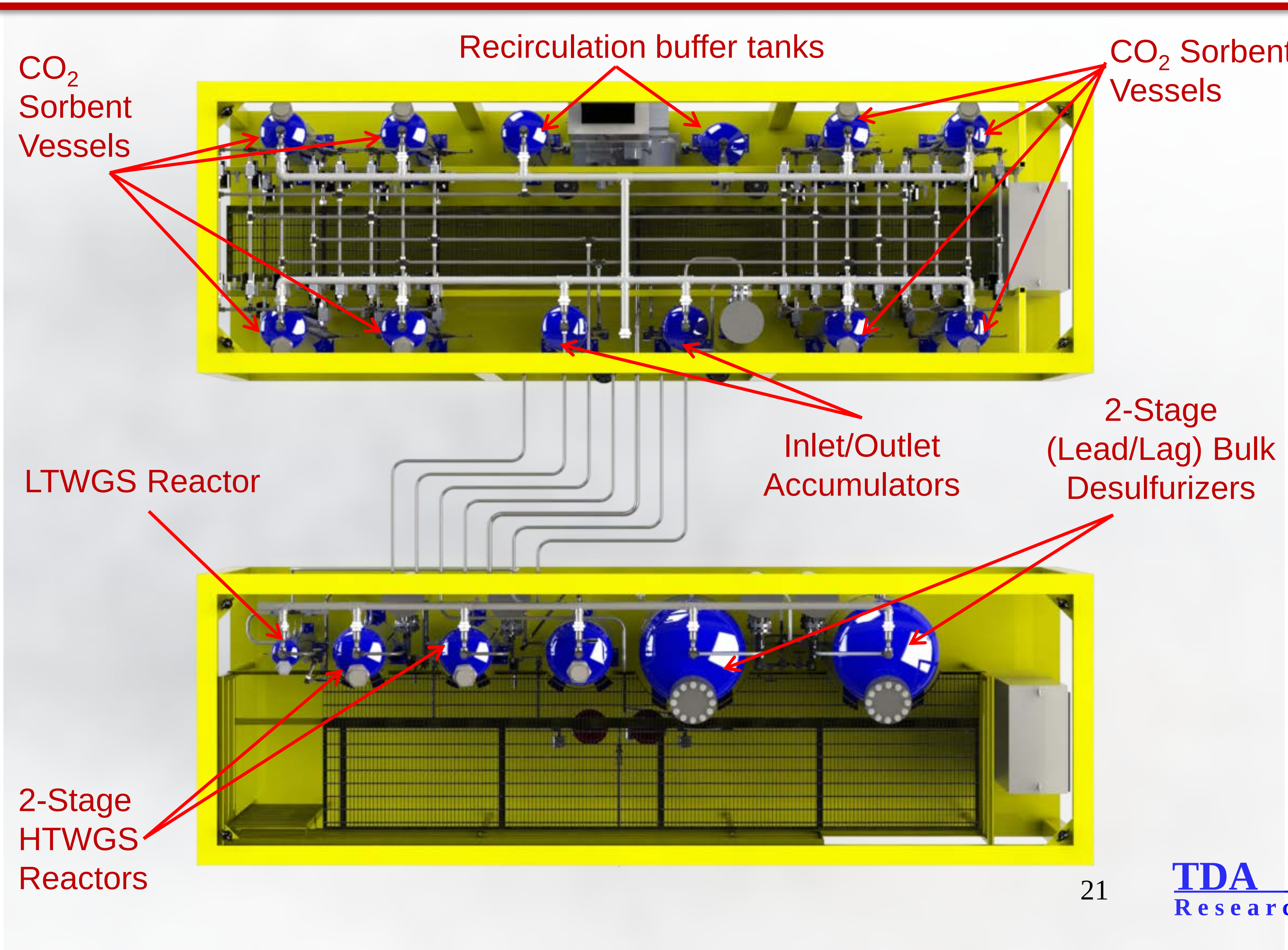
Slipstream Test Skid - Top View



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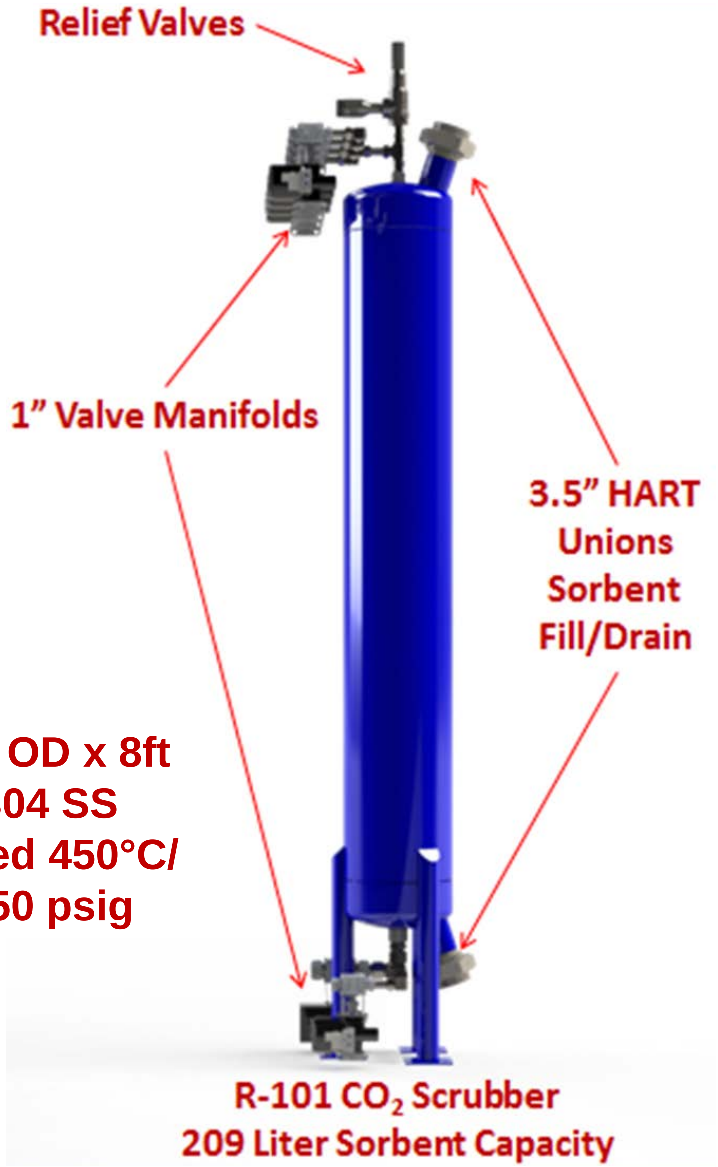
Desulfurization Reactors

32” OD x 9.4 ft
304 SS
1” wall
Rated 450°C/
750 psig

R-1101 Bulk Desulfurizer
1,135 Liter Sorbent Capacity

CO_2 Sorbent Reactors



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

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CO_2 Sorbent Reactors



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CO_2 Removal Skid

- All plumbing work, installations and heat tracing have been completed
- Remaining work is to completion of the insulation and electrical wiring
- Skid completion 8/31/2016

Gas Conditioning Skid

- **Vessel have been mounted and all plumbing work has been completed**
- **Remaining activities (install heat tracing, insulation, electrical) to be completed by 9/15/2016**

Control System/Electrical Wiring

- **Fabrication/installation of control box is complete**
- **Programming is also complete**

TDA Research

E-Gas^{TM} & GE Gasifiers

	E-Gas^{TM} Gasifier		GE Gasifier	
	Case 1	Case 2	Case 3	Case 4
CO_2 Capture Technology	Cold Gas Cleanup Selexol^{TM}	Warm Gas Cleanup TDA's CO_2 Sorbent	Cold Gas Cleanup Selexol^{TM}	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^{TM} (31.2%)**
- **Cost of CO_2 capture is calculated as $38.1 and $36.3 per tonne for GE and E-Gas^{TM} gasifiers, respectively (24-27% reduction against Selexol^{TM})**

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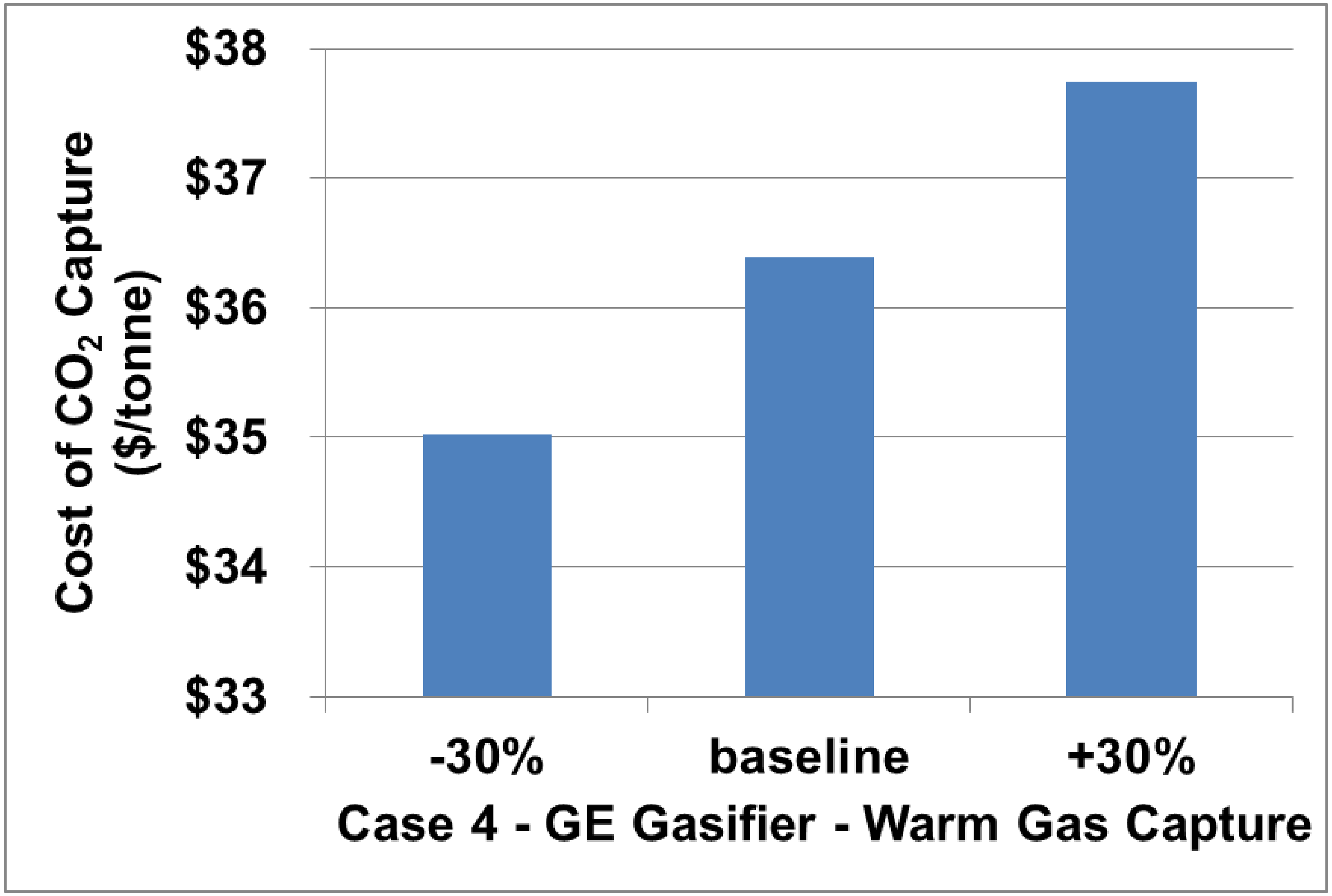
Shell & TRIG Gasifiers

	Shell Gasifier		TRIG Gasifier*	
	Case 5	Case 6	Case 7	Case 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
CO_2 Capture, %	90.0	90.0	90.0	90.0
Gross Power Generated, kWe	683,991	614,090	625,645	606,794
Gas Turbine Power	464,000	411,797	424,616	406,943
Steam Turbine Power	219,991	202,293	201,029	199,851
Auxiliary Load, kWe	179,839	107,813	163,829	120,348
Net Power, kWe	504,152	506,277	461,816	486,446
Net Plant Efficiency, % HHV	**31.10**	**33.33**	**31.80**	**34.00**
Coal Feed Rate, kg/h	215,041	201,426	262,700	258,882
Raw Water Usage, GPM/MWe	9.9	10.8	8.3	9.8
Total Plant Cost, $/kWe	3,884	3,523	3,679	3,347
COE without CO_2 TS&M, $/MWh	149.1	134.9	123.4	112.4
COE with CO_2 TS&M, $/MWh	**157.9**	**143.1**	**142.5**	**129.9**
Cost of CO_2 Capture $/tonne	**57**	**43**	**52**	**40**

* Sub-bituminouis coal to match the previous DOE baseline for this gasifer

- **IGCC plant with TDA's CO_2 capture system achieves higher efficiencies (33.33% and 34.0%) than IGCC with Selexol™ (31.1% and 31.8%)**
- **Cost of CO_2 capture is calculated as $43 and $40 per tonne for Shell and TRIG gasifiers, respectively (23-25% reduction against Selexol™)**

Sensitivity Analysis

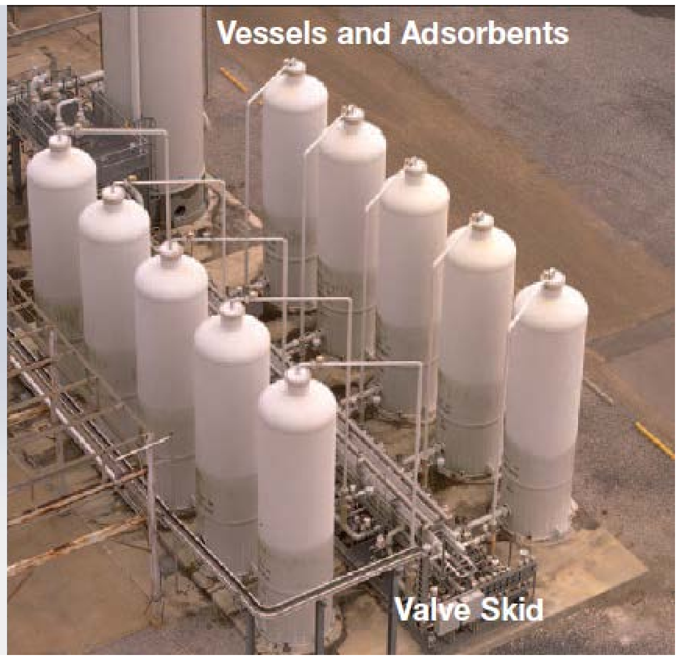


- **Cost of CO_2 Capture changes from $35 to $37.8 per tonne if the capital cost changes from +30% to -30%**

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	34,747
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 syngas flow rate for the based case used in TEA)

TDA Research

Acknowledgements

- **The funding from DOE/NETL under Contract No. DE-FE-0013105 is greatly acknowledged**
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- **Dr. Arvind Rajendran, UOA**
- **Dr. Ashok Rao, UCI**
- **Mr. Scott Machovec and Frank Morton, Southern Co.**
- **Dr. Chen Chaomei, Sinopec**

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