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

Integrated WGSS Pre-combustion Carbon Capture Process
(Contract No. DE-FE-0023684)

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NCCC Review Meeting

October 25, 2016

Project Summary (Pilot Testing)

- **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**

Project Partners

<u>Project Duration</u>

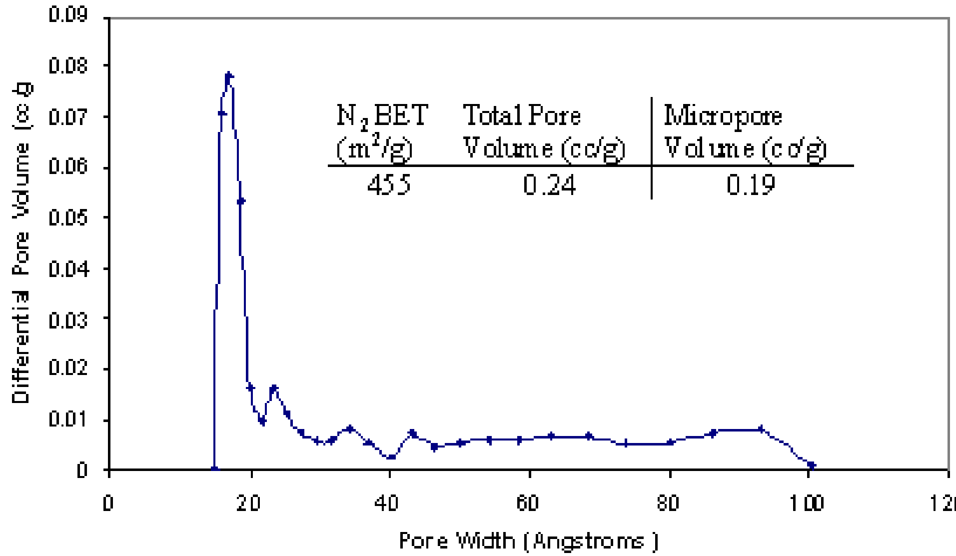
- **Start Date = January 1, 2014**
- **End Date = September 30, 2018**

<u>Budget</u>

- **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**

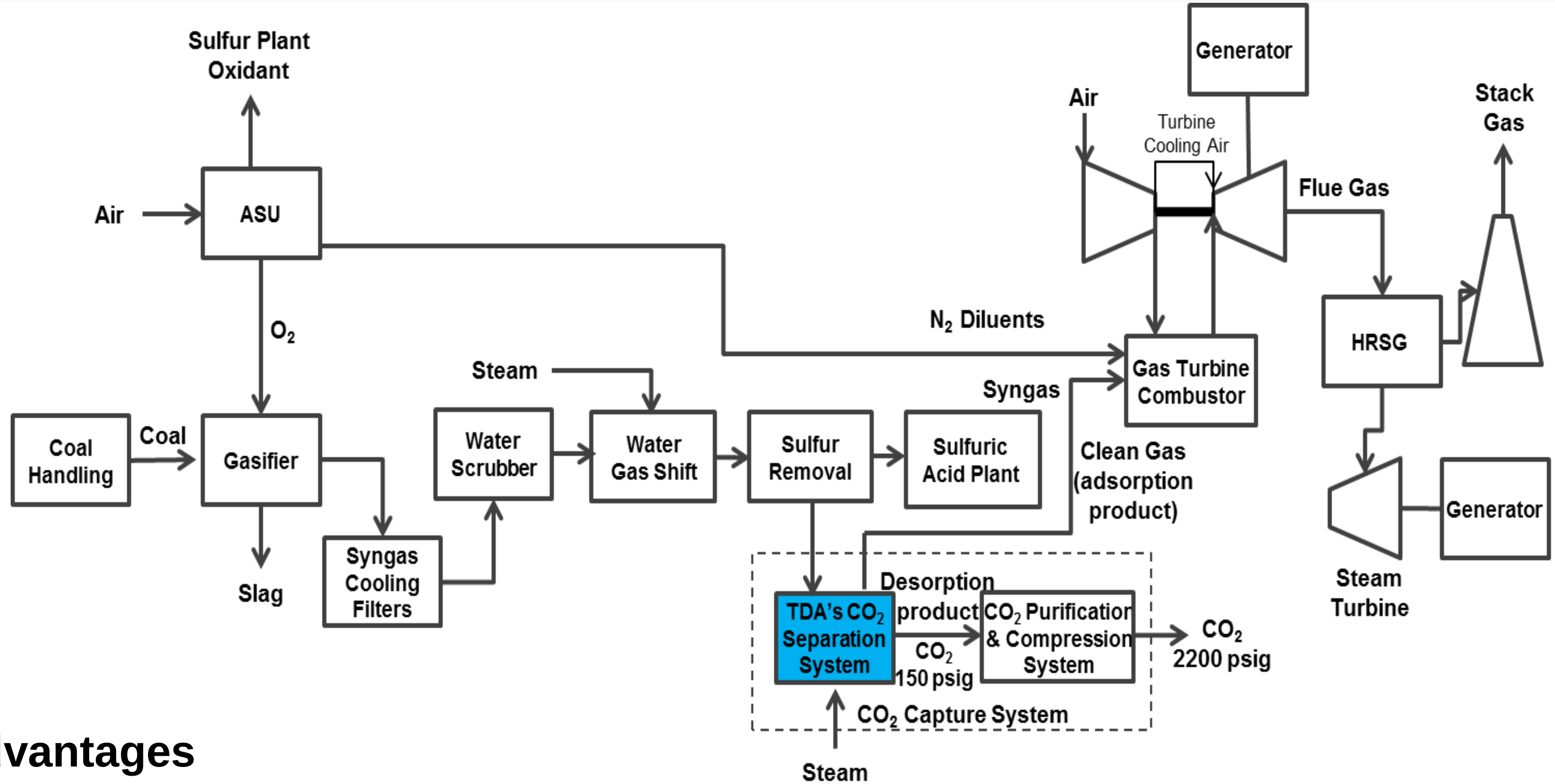


- **Pore size can be finely tuned in the 10 to 100 A range**
- **Mesopores eliminates diffusion limitations and rapid mass transfer, while enables high surface area**

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

TDA Research

Integration to the IGCC Power Plant



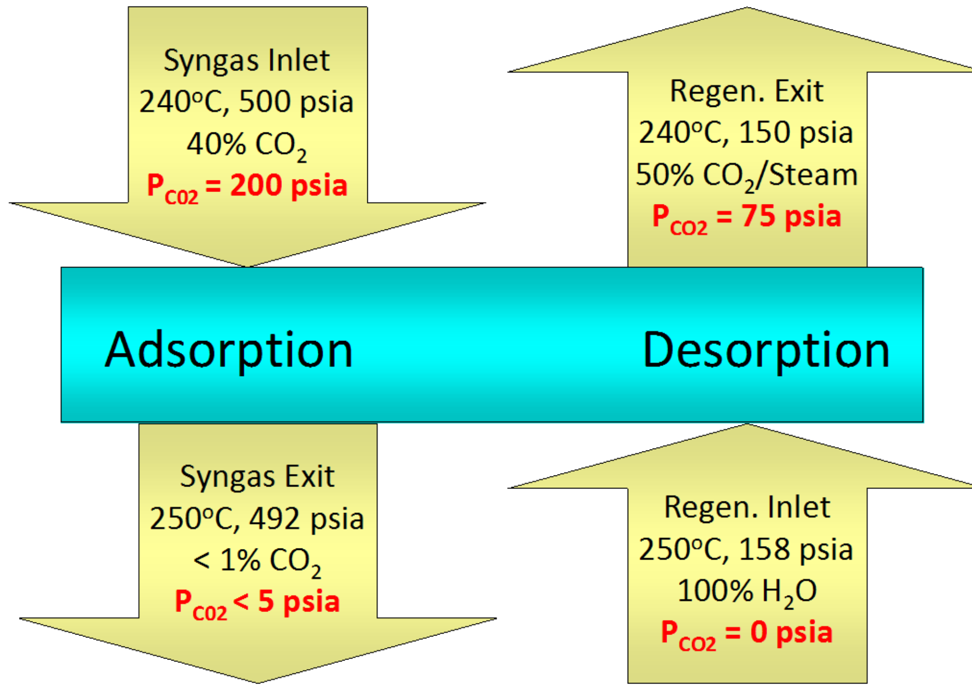
Advantages

- 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

TDA Research

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 Objective

- **0.1 MW_e test in a world class IGCC plant to demonstrate full benefits of the technology**
    - Testing with high pressure, CO_2-rich gas (i.e., oxy-blow gasification)
- **Demonstrate full operation scheme**
    - 8 reactors and all accumulators
    - Utilize product/inert gas purges
    - 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 Yangtzi Petro-chemical Plant, Nanjing, Jiangsu Province, China – Oxygen blown gasification

National Carbon Capture Center

Yangtzi Petro-chemical Plant

TDA Research

Sorbent and Catalyst for Field Tests

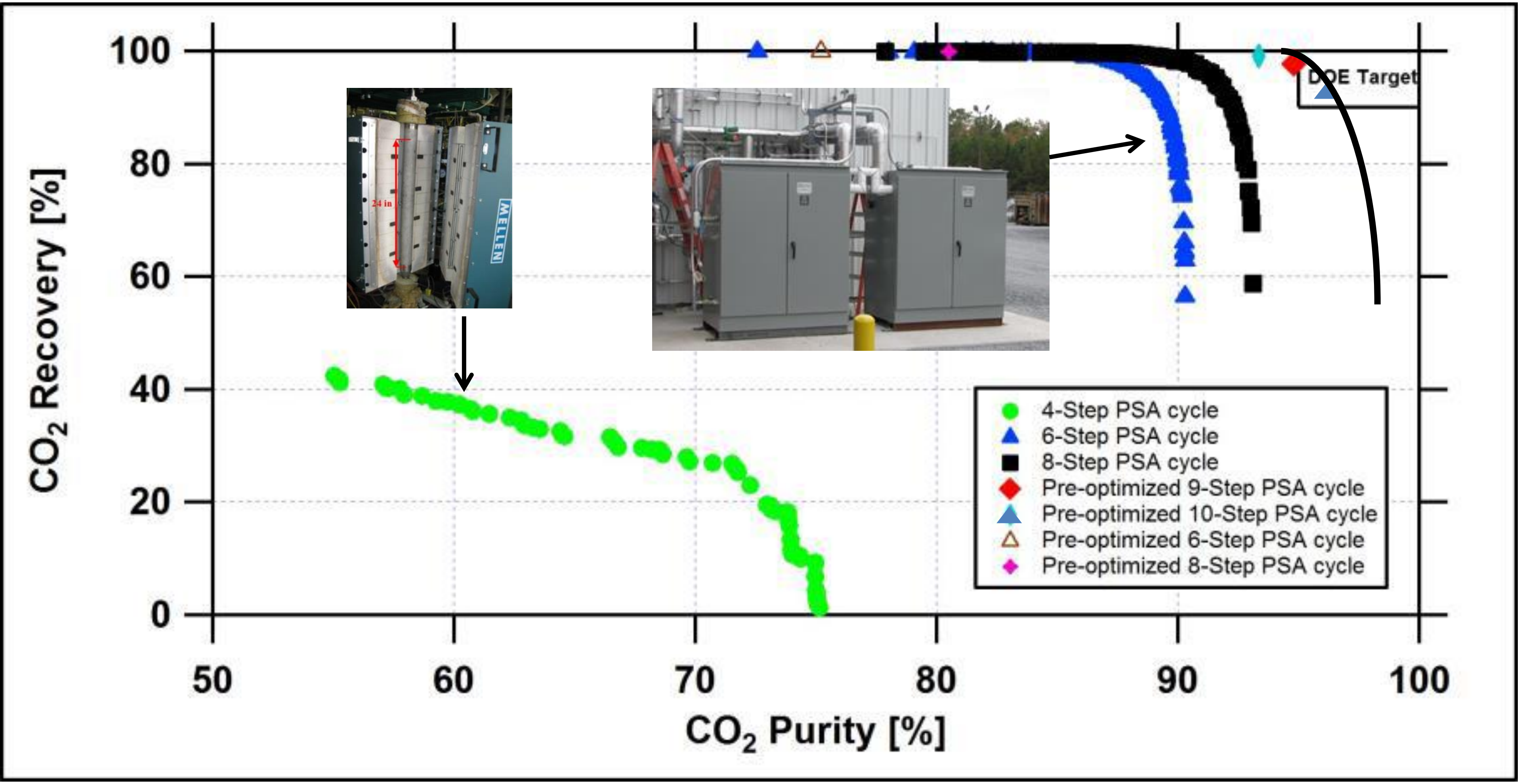
Sulfur Sorbent and WGS Catalyst

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**

TDA Research

Optimized Pareto Curves



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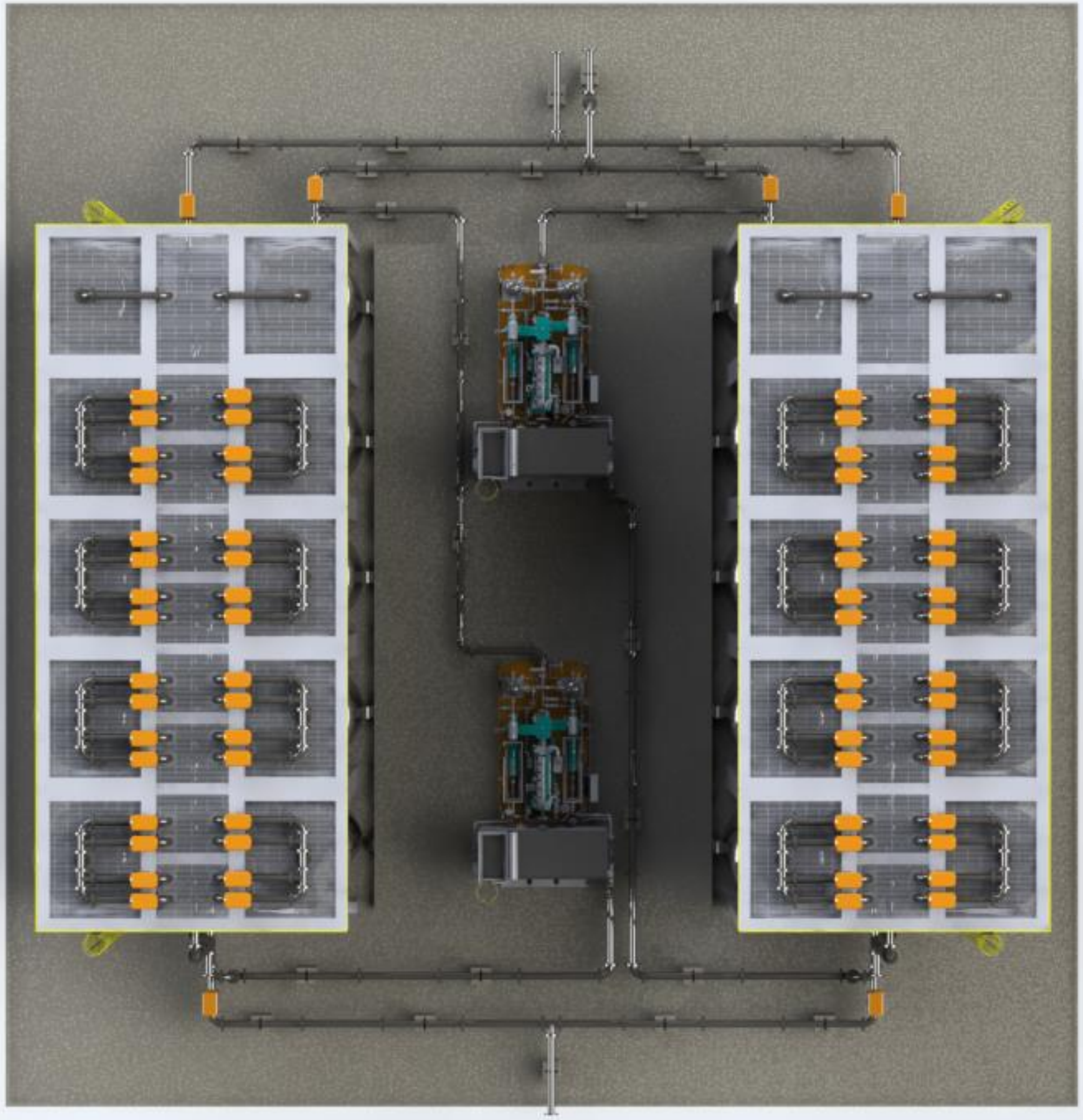
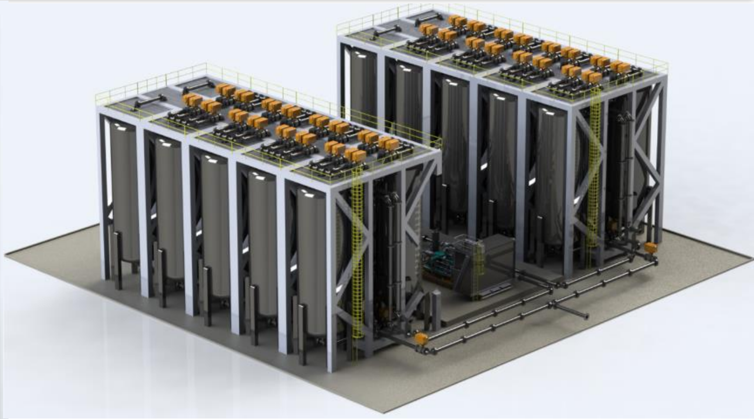
Full-scale System Design





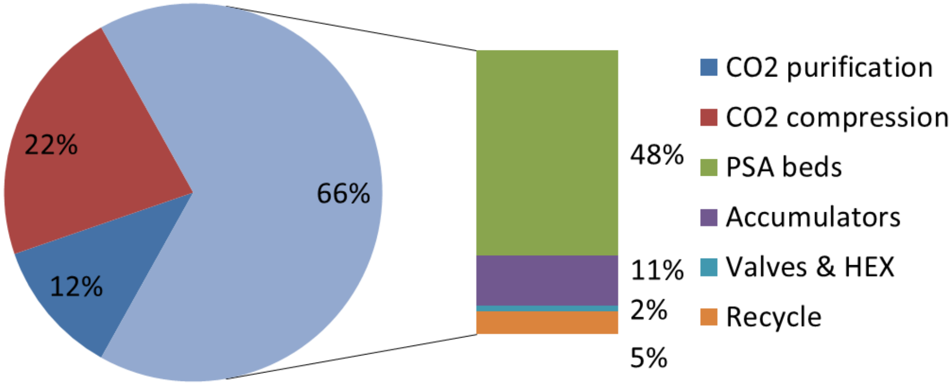
Major Units

- 8 beds x 2 = 16
- 2 accum. X 2 = 4
- Cycling Valves
  - 6 x8 x2 =96
- 2 recycle comp.
- 2 isolation vales x 2 per train = 4

TDA Research

Bed Size & Cost Comparison

\$2011 Cost Basis from	AspenPlus®	AspenPlus®	TDA-Detailed
CO_2 Sorbent formulation	2014	2015	2015
Gasifier Type	E-Gas™	E-Gas™	E-Gas
Case	2	2	2
Syngas Flow, kmol/hr	33,699	33,699	33,699
Syngas Flow, SLPM	12,588,823	12,588,823	12,588,823
Syngas Flow, std m^3/min	12,589	12,589	12,589
CO_2, mol%	30.3%	30.3%	30.3%
CO_2 Removed, kmol/hr	10,211	10,211	10,211
CO_2 Removed, kg/min	7,490	7,490	7,490
Pressure, bar	33.8	33.8	34.3
Design Pressure, psi	538	538	573
Full Cycle Time, min	16	8	8
Adsorption Time, min	2	2	2
Number of 8-bed trains	3	2	2
Number of Beds adsorbing at the same ti	1	2	2
Total Sorbent Needed, m^3	4444.7	2123.1	2123.1
Sorbent per Bed, m3	185.2	132.7	132.7
Cost of CO_2 Capture Unit, \$1,000	118,484	81,890	131,848



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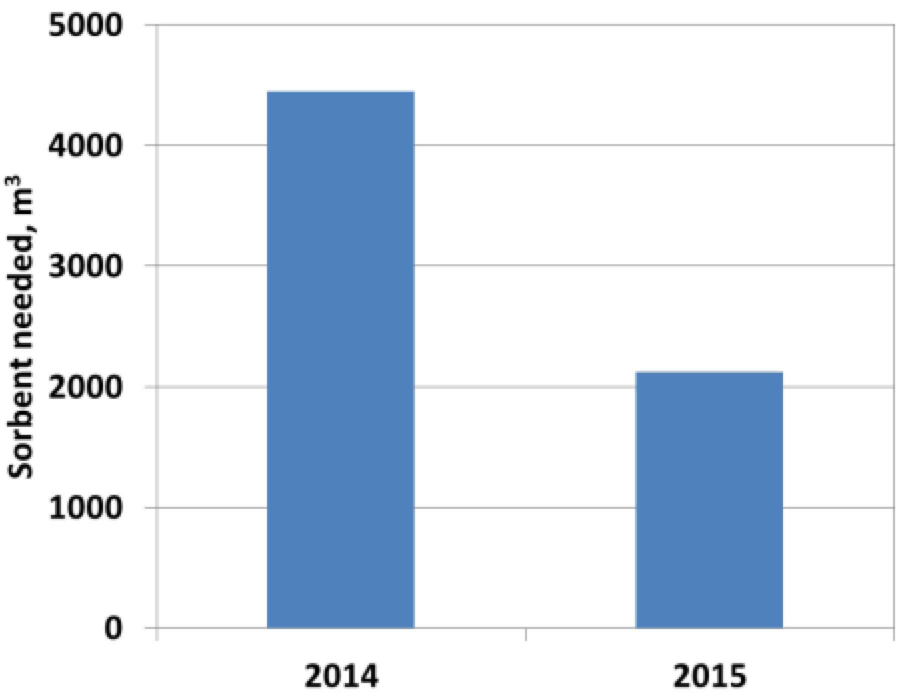
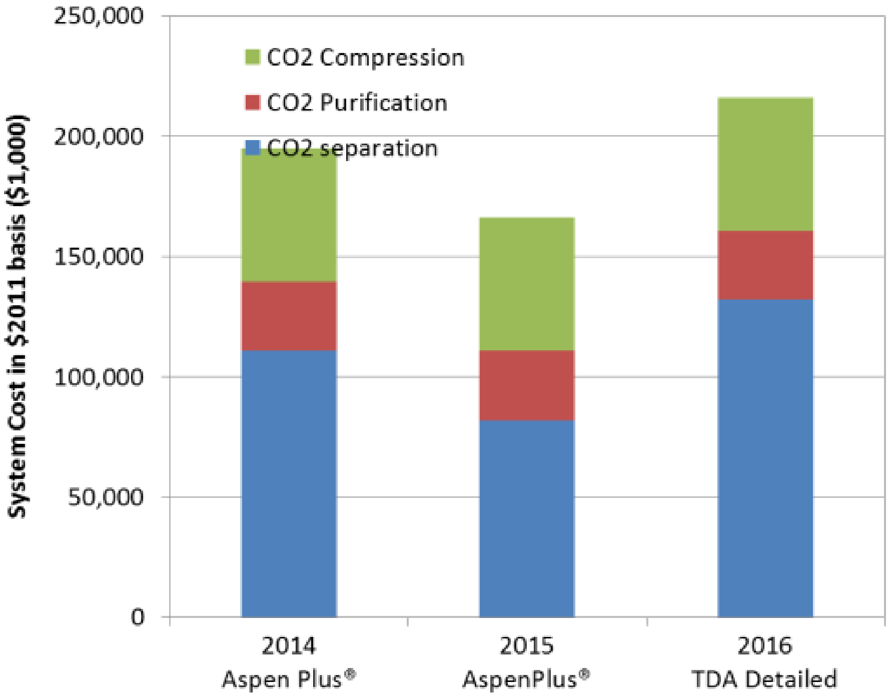
Impact of Process & Materials Improvements in BY2





- **Sorbent performance – resulted from achieving higher density w/o reducing performance**
- **Shorter cycle – 16 min vs. 8 min total cycle time resulted from cycle optimization**

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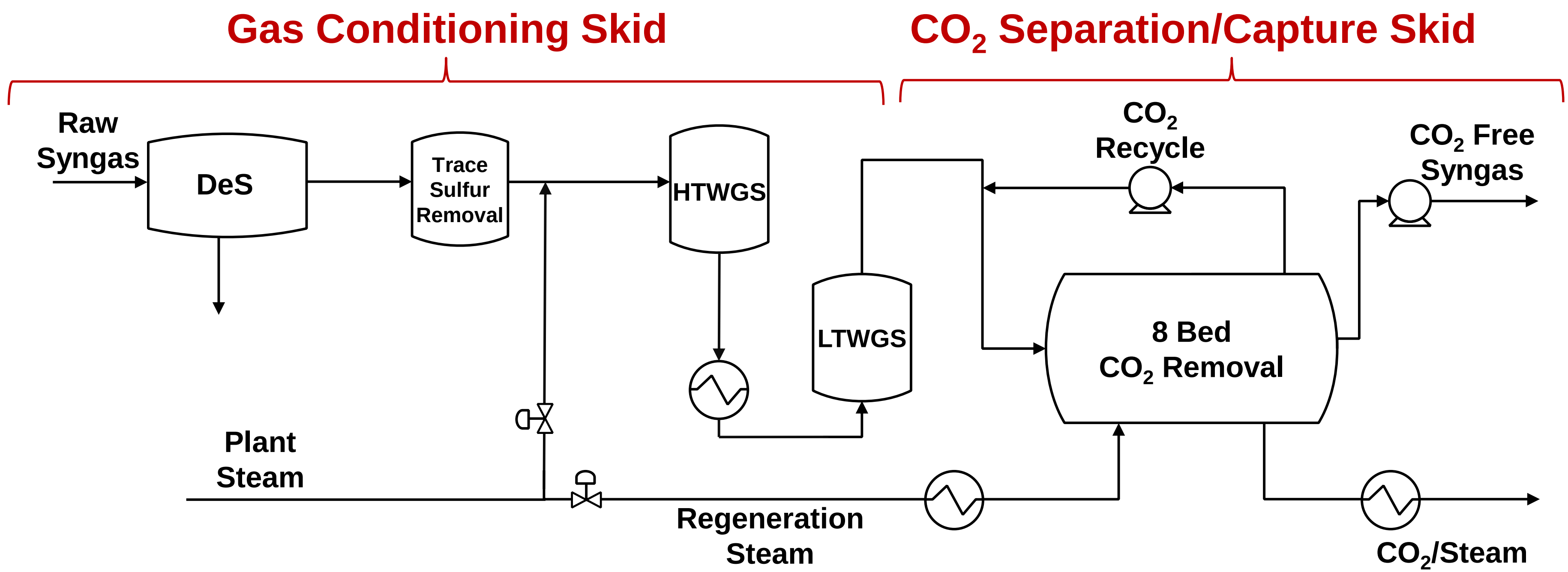
0.1 MW_e Pilot Unit for Field Tests

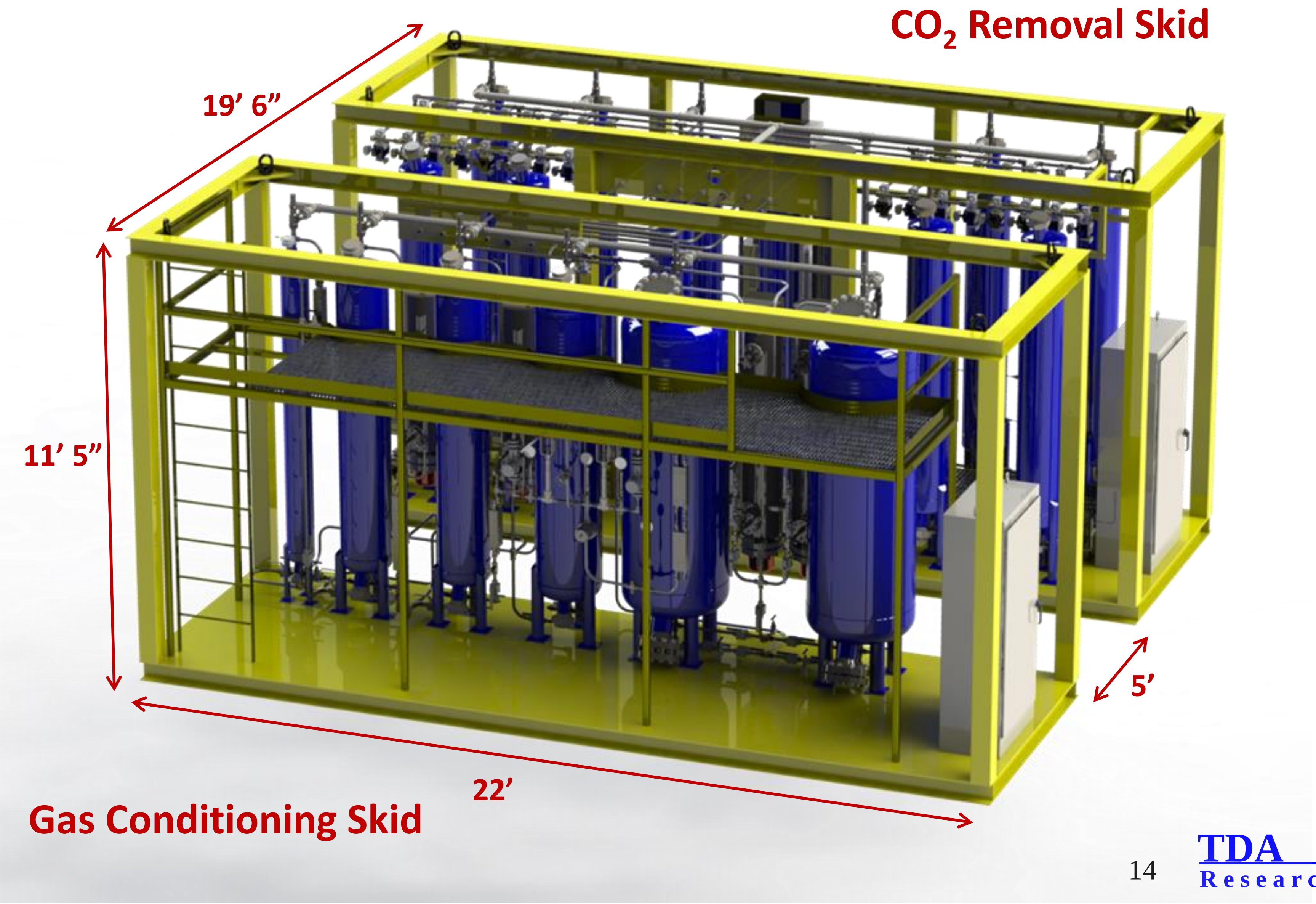


	Sinopec	NCCC - Wilsonville
Syngas flow into CO2 Skid (scfm)	100	100
Syngas flow into DeS/WGS Skid (scfm)	66.3	91.4
Steam added for WGS (scfm)	34.6	8.6
Power Output (MWe)	0.13	0.047
CO2 Captured (kg/hr)	105.5	52.1

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

TDA Research

0.1 MW Pilot Unit Design



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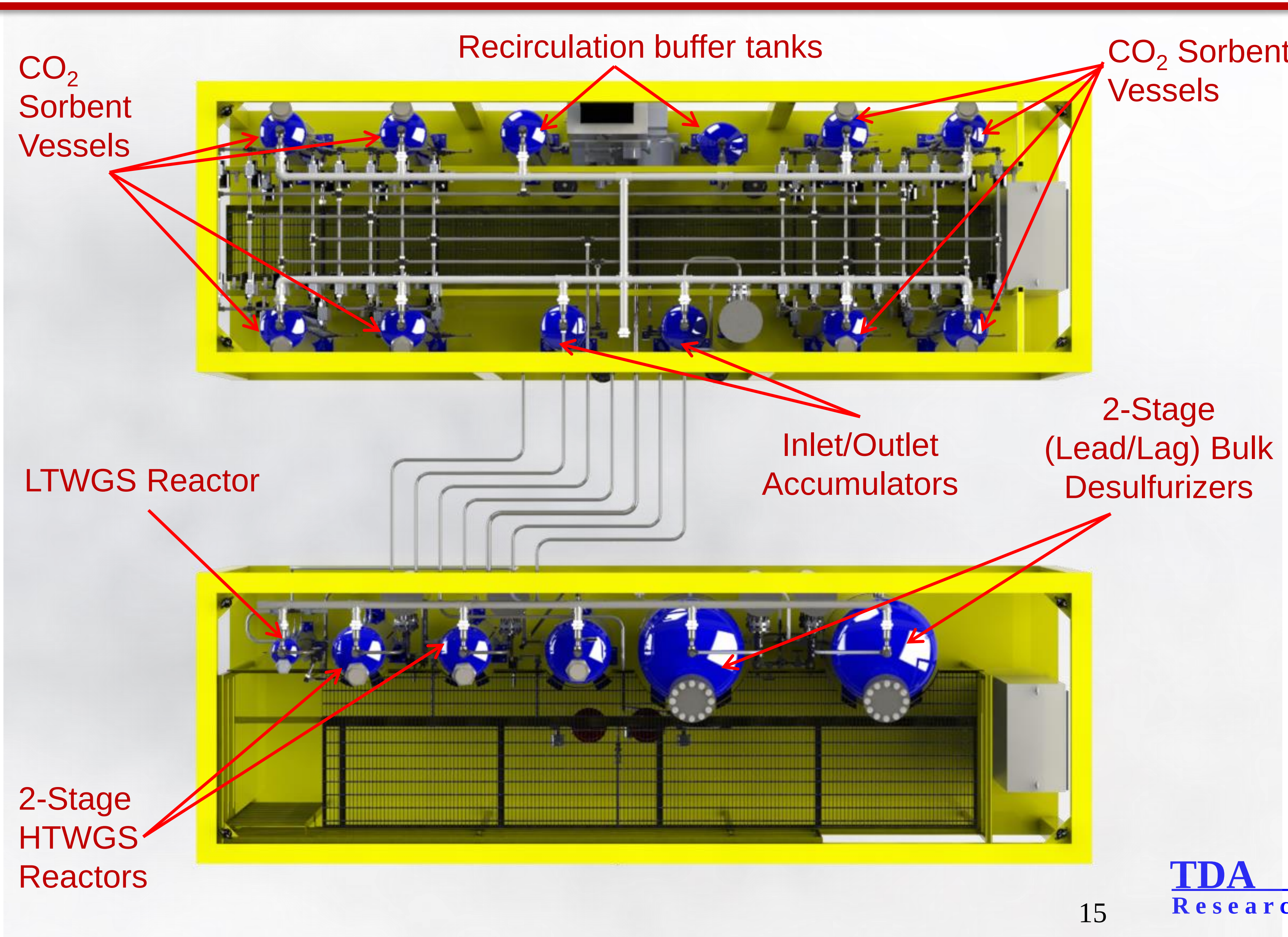
Slipstream Test Skid - Top View



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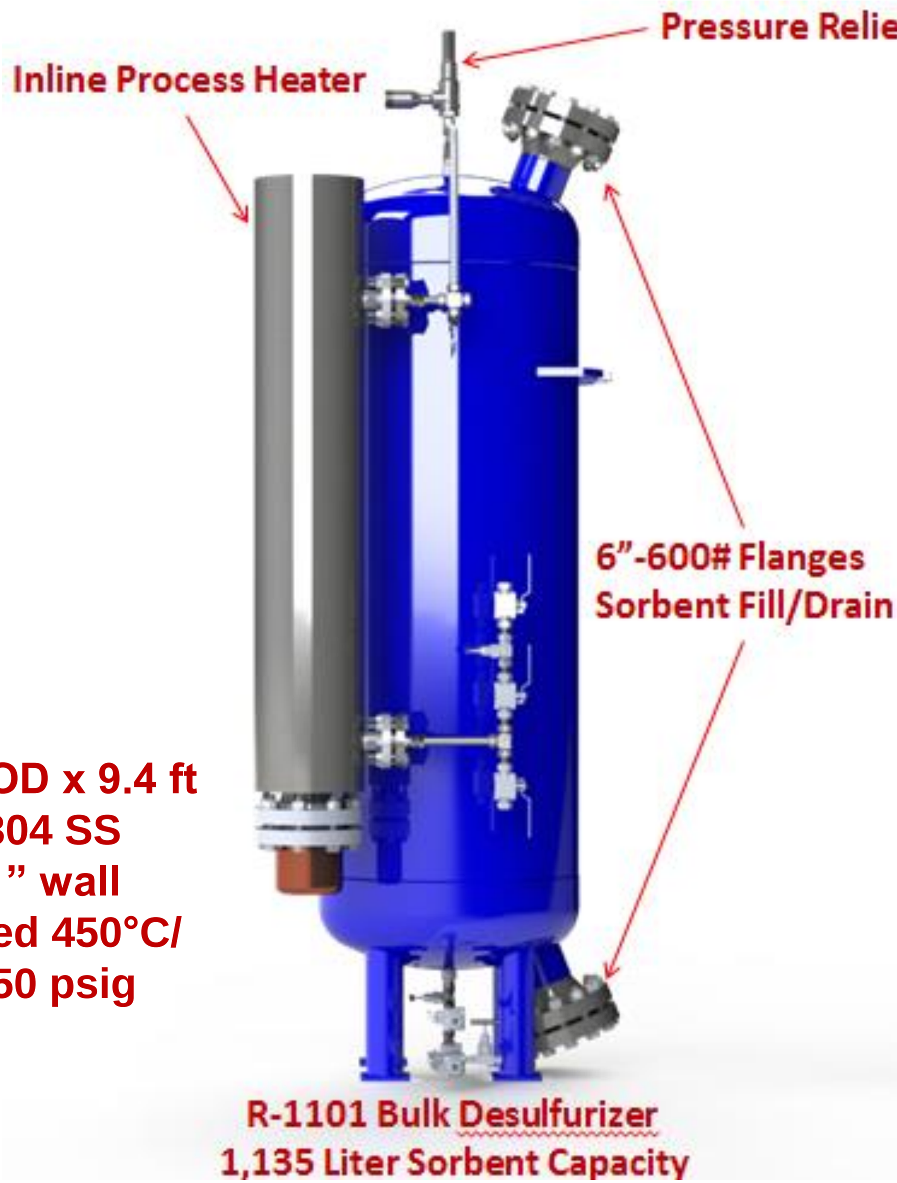
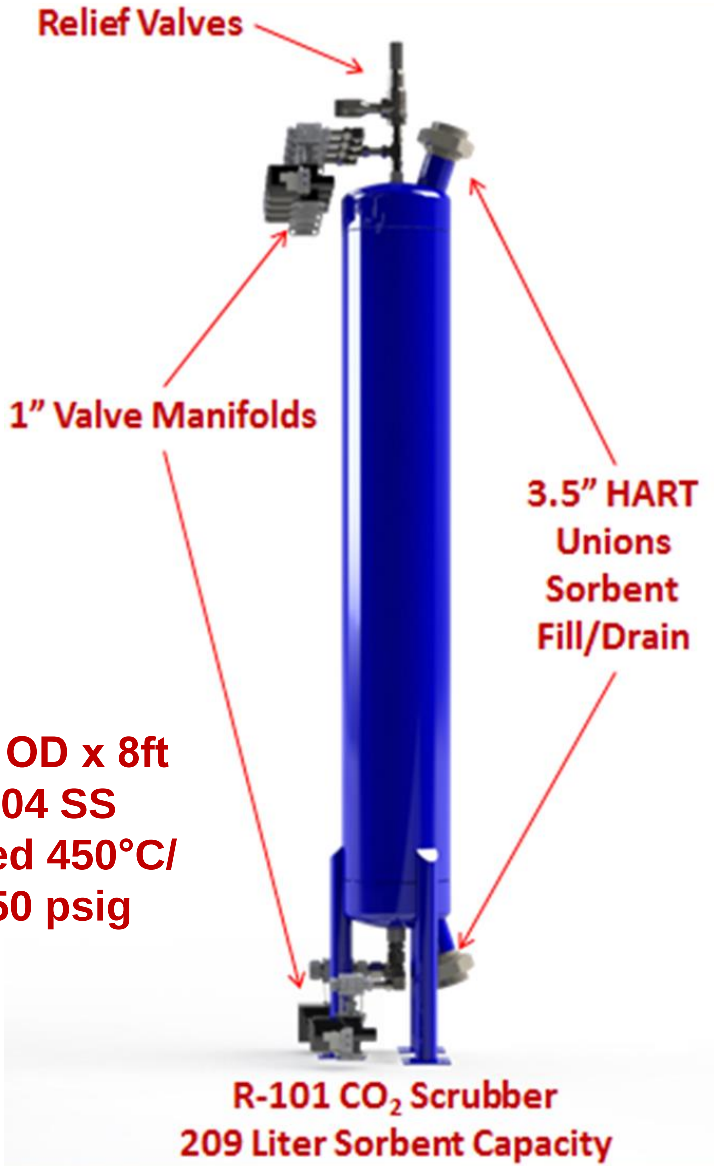
Desulfurization Reactors



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

TDA Research

CO_2 Sorbent Reactors



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

CO_2 Sorbent Reactors

CO_2 Removal Skid

- **All plumbing work, all installations, heat tracing and electrical work have been completed**
- **Skid fabrication completed**

CO_2 Removal Skid

- **All insulation and electrical work on Skid #2 (CO_2 Removal Skid) is complete**
- **Only remaining work is the installation of the gas analyzers**

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Gas Conditioning Skid

- All major plumbing (installations, heat tracing and insulation) is complete
  - Few minor plumbing (connecting gas samples) is remaining
- All electrical work is completed

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Control System/Electrical Wiring

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

Cost Analysis E-Gas™ & GE Gasifiers

Gasifier Type/Make	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	3,042	3,359	3,083
COE without CO_2 TS&M, $/MWh	136.8	120.5	133.0	121.8
COE with CO_2 TS&M, $/MWh	145.7	128.6	141.6	129.7
Cost of CO_2 Captured, $/tonne	**53.2**	**37.4**	**47.3**	**36.1**

- **IGCC plant with TDA CO_2 capture system achieves 34.5% and 34.1 efficiency for GE and E-Gas™ gasifiers, respectively (vs. 31% and 32% with Selexol)**
  - In BP2 Review Meeting, the cost of CO_2 Capture was reported as $37.3 and $38.2 per tonne for GE and E-Gas™ gasifiers (we used higher stress values)
- **Cost of CO_2 capture is calculated as $36.1 and $37.4 per tonne for GE & E-Gas™ gasifiers (vs. 21-29% reduction against Selexol™)**

Project Objectives (Integrated WGS/CO_2 Removal)

- **The project objective is to demonstrate techno-economic viability of an integrated WGS catalyst/CO_2 removal system for IGCC power plants and CTL plants**
  - A high temperature PSA adsorbent is used for CO_2 removal above the dew point of the synthesis gas
  - A commercial low temperature catalyst is used for water-gas-shift
- **Critical Need**
  - Development of an effective heat management system
- **Project Tasks**
  - Design a fully-equipped slipstream test unit with 10 SCFM raw synthesis gas treatment capacity
  - Design and fabricate CFD optimized reactors capable of managing the exothermic WGS reaction while maintaining energy efficiency
  - Demonstrate all critical design parameters including sorbent capacity, CO_2 removal efficiency, extent of WGS conversion as well as H_2 recovery for 2,000 hr using coal synthesis gas

Project Partners - DE-FE0023684

Project Duration

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

Budget

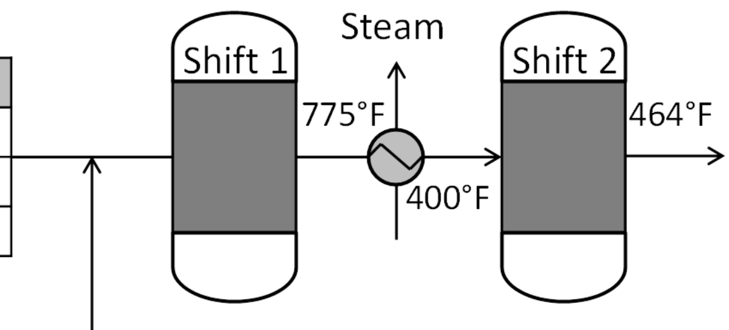
- **Project Cost = $9,929,228**
- **DOE Share = $7,943,382**
- **TDA and its partners = $1,985,846**

Background

- **Conventional IGCC plants use multi-stage WGS reactors with inter-stage cooling**
  - WGS is an equilibrium-limited exothermic reaction
- **Water is supplied at concentrations well above required by reaction stoichiometry to completely shift the CO to CO_2**

H_2O/CO Ratio[1]	
GE	1.1
E-Gas	1.2
Shell	0.8

[1]Prior to shift steam addition



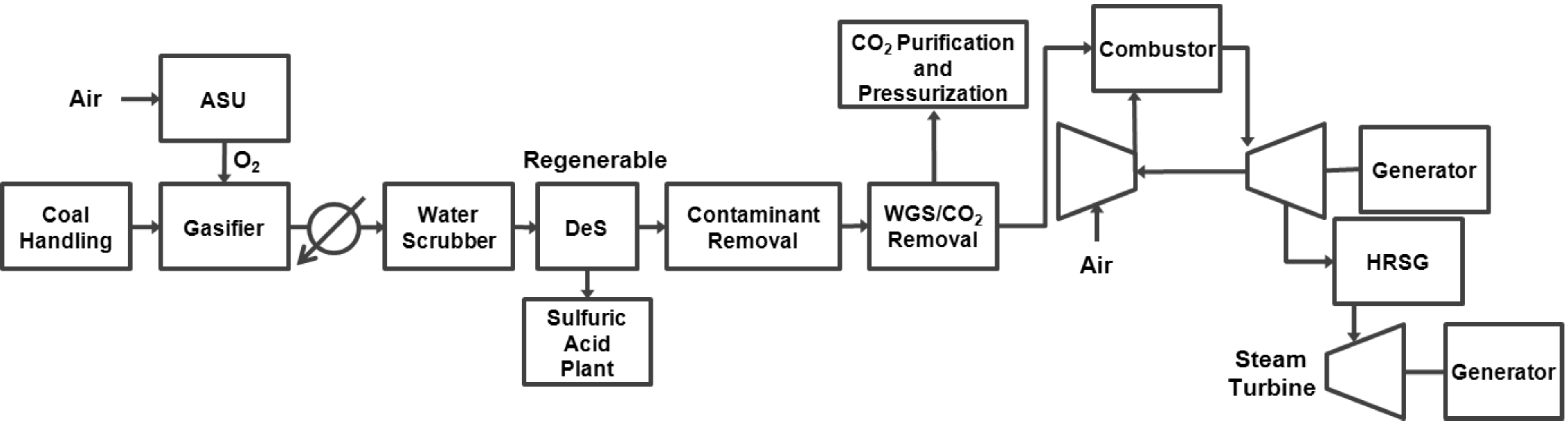
	H_2O/CO added	Energy Value (MW_{th})
GE	0.9	286
E-Gas	1.05	372
Shell	1.0	437

$$H_2O + CO \leftrightarrow CO_2 + H_2$$

3-stage WGS unit is described in the DOE/NETL-2007/1281

- **A high temperature CO_2 adsorbent combined with a LT shift catalyst enables high CO conversion *at low steam:carbon ratios***

Integrated WGS/CO_2 Capture System



- **Reducing the use of excess steam improves power cycle efficiency**
  - Lower energy consumption due to lower energy to raise the steam
- **Process intensification reduces the number of hardware components and cost**

<u>From sorbent's point of view:</u>

- **Less dilution with water increases the CO_2 partial pressure and in turn improves sorbent's working capacity**

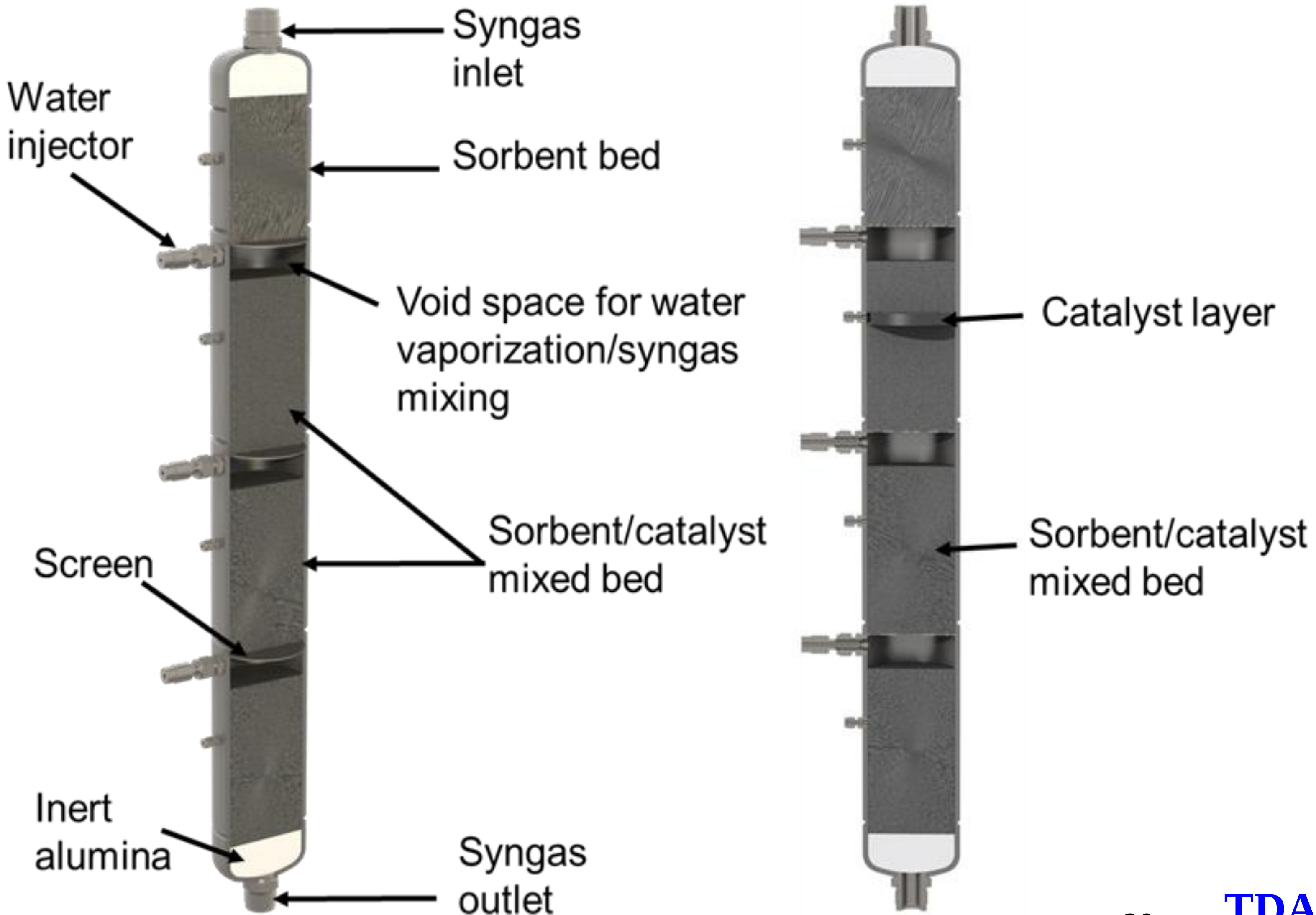
TDA Research

Technology Status/R&D Needs

- **Sorbent is developed under a separate DOE project (DE-FE0000469)**
- **WGS catalyst is commercially available mature technology**
- **Early-stage concept demonstration has already been completed (under DE-FE0007966)**
  - Integrated sorbent/catalyst operation
  - Slipstream test at the NCCC at ~0.2 kg/hr CO_2 removal
  - Pointed out the need to incorporate effective heat management
- **A larger-scale (10 kg/hr CO_2 removal) test will be carried out at the Wabash River IGCC plant (under DE-FE-00012048)**
- **Key R&D need is the design/development of a high fidelity prototype to fully demonstrate the concept using actual coal-derived synthesis gas**
  - Early-stage prototype demonstration of an integrated system with heat management is also under progress (under DE-FE-00012048)

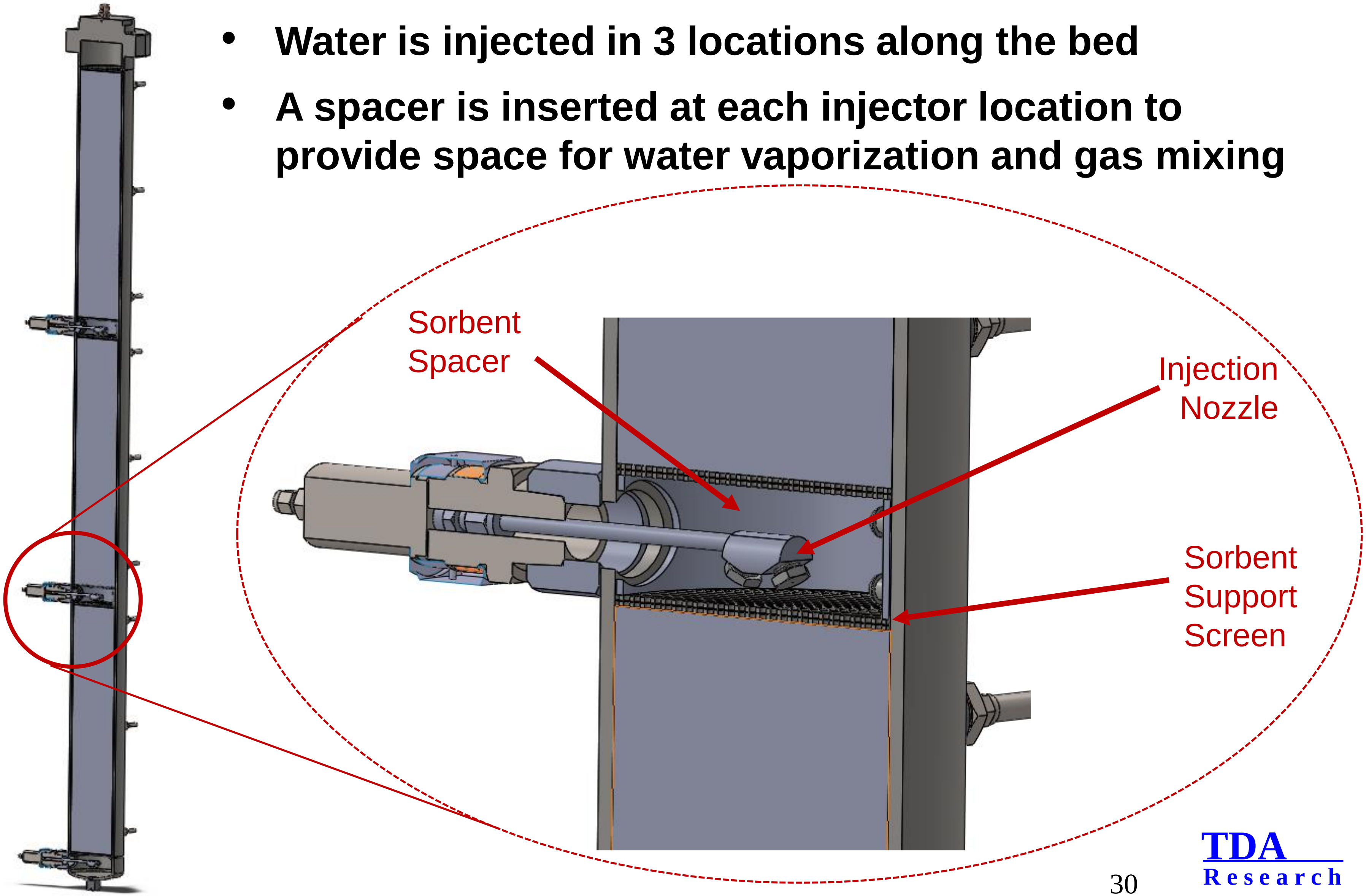
TDA Research

Reactor Design w/ Water Injectors



Water Injection System

- **Water is injected in 3 locations along the bed**
- **A spacer is inserted at each injector location to provide space for water vaporization and gas mixing**



TDA Research

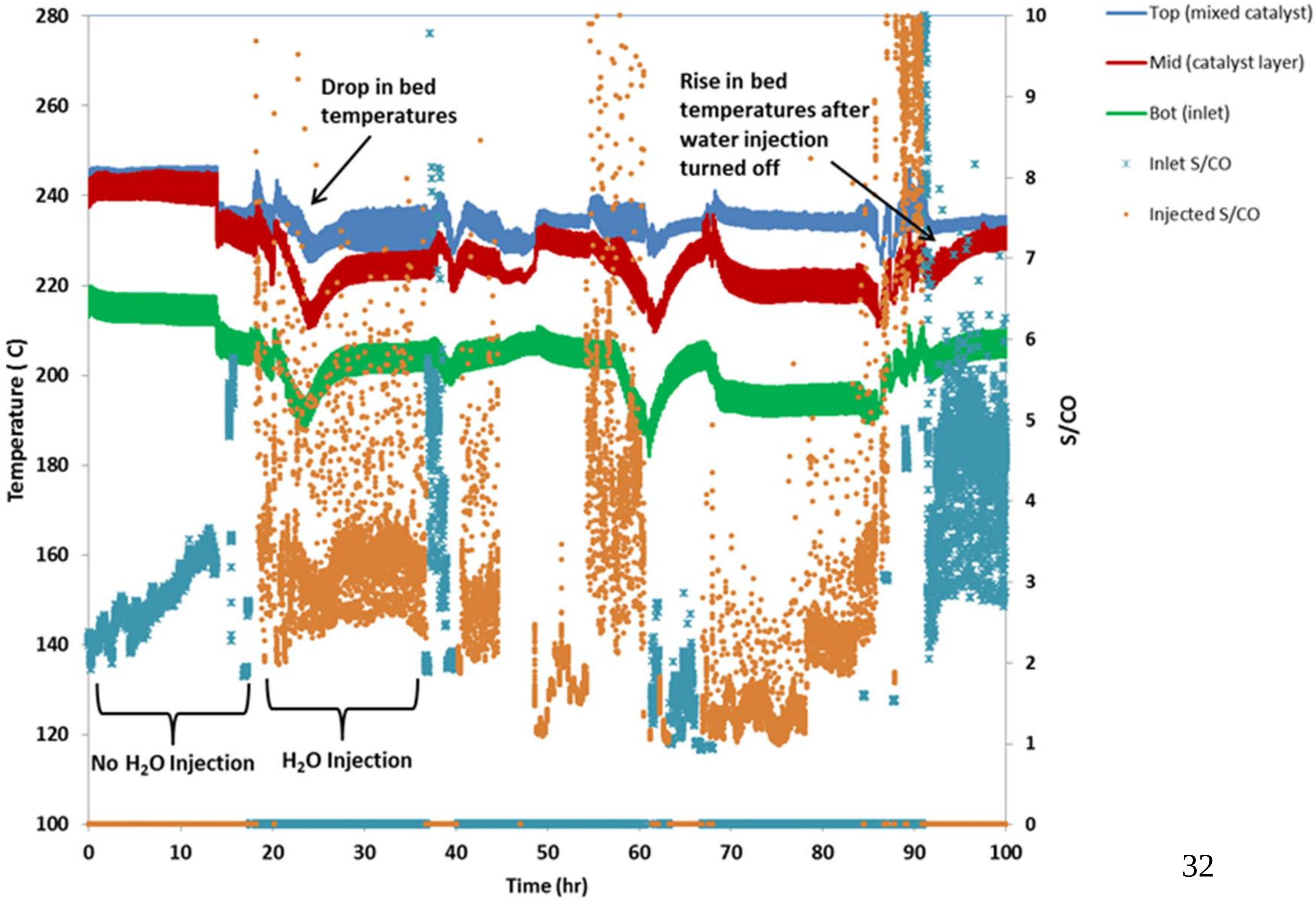
Previous Testing at NCCC

- Testing during the G3 & G4 campaigns using at 1 SCFM scale validated the impact of water injection on bed temperature and CO conversion
- An existing setup qualified for NCCC operation was modified
- We completed over 650 hours testing during which key aspects have been demonstrated
  - CO conversion, overall carbon capture, bed temperature and water injection functionality

TDA Research

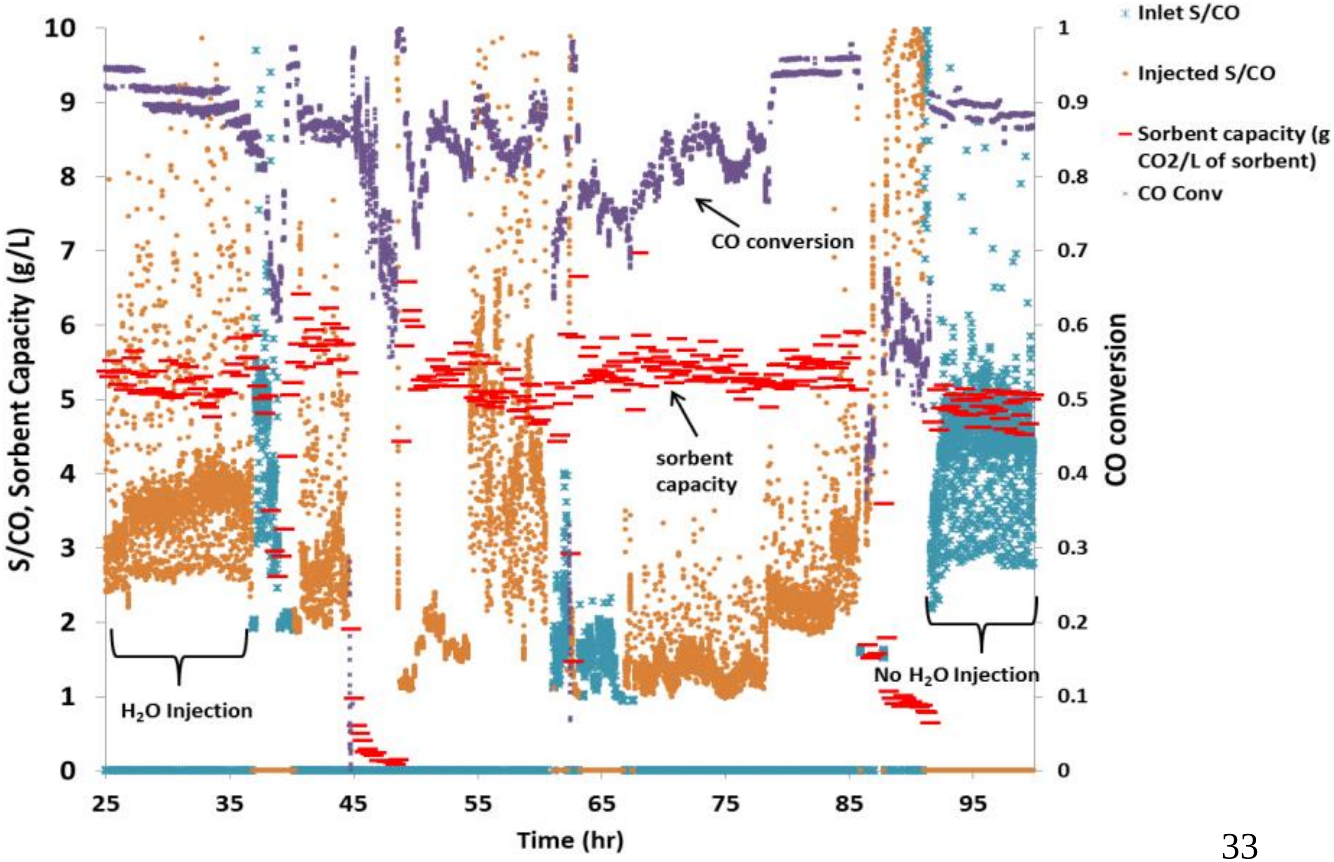
Effects of Water Injection - Temperature

- **Bed temperatures were maintained as much as 20ºC lower by direct injection of water while maintaining steam to CO ratio of 2-3**



Effect of H_2O Injection – CO Conversion

- At the same steam:CO ratio, 90% CO conversion was achieved during water injection compared to 88% with steam added upstream of the reactors
- With water injection, the sorbent capacity averaged at 5.5 gCO_2/L while without water injection it averaged 4.8 gCO_2/L



Process Simulation and Analysis

IGCC plant with E-Gas^{TM} Gasifier operating on Bituminous Coal

#	CO_2 Capture	Notes	Steam/ Water Addition	Overall Steam:CO Ratio	Net Efficiency % HHV
1	Conventional Technology	Reference IGCC Case with Steam addition to 1st WGS reactor feed	Steam	2.25	31.04
2A	TDA/PSA Technology	Steam addition to 1st WGS reactor feed; no water injection into 2nd WGS reactor (not combined with PSA)	Steam	2.25	33.81
2	TDA/Advanced Technology	No steam addition to 1st WGS reactor feed; water injection into combined WGS+PSA reactor	Water	1.50	34.30
2-1	TDA/Advanced Technology	No steam addition to 1st WGS reactor feed; no water injection into combined WGS+PSA reactor	None	1.24	34.55 (87% carbon capture)
2-3	TDA/Advanced Technology	No 1st WGS reactor & water injection into combined WGS+PSA reactor	Water	2.21	33.73

- **Reducing Steam:CO ratio to 1.50 with water addition to Integrated WGS/CO_2 Removal Reactor (2nd stage) provides a net plant efficiency of 34.30%**
  - **0.5% point improvement over TDA's previous technology**

TDA Research

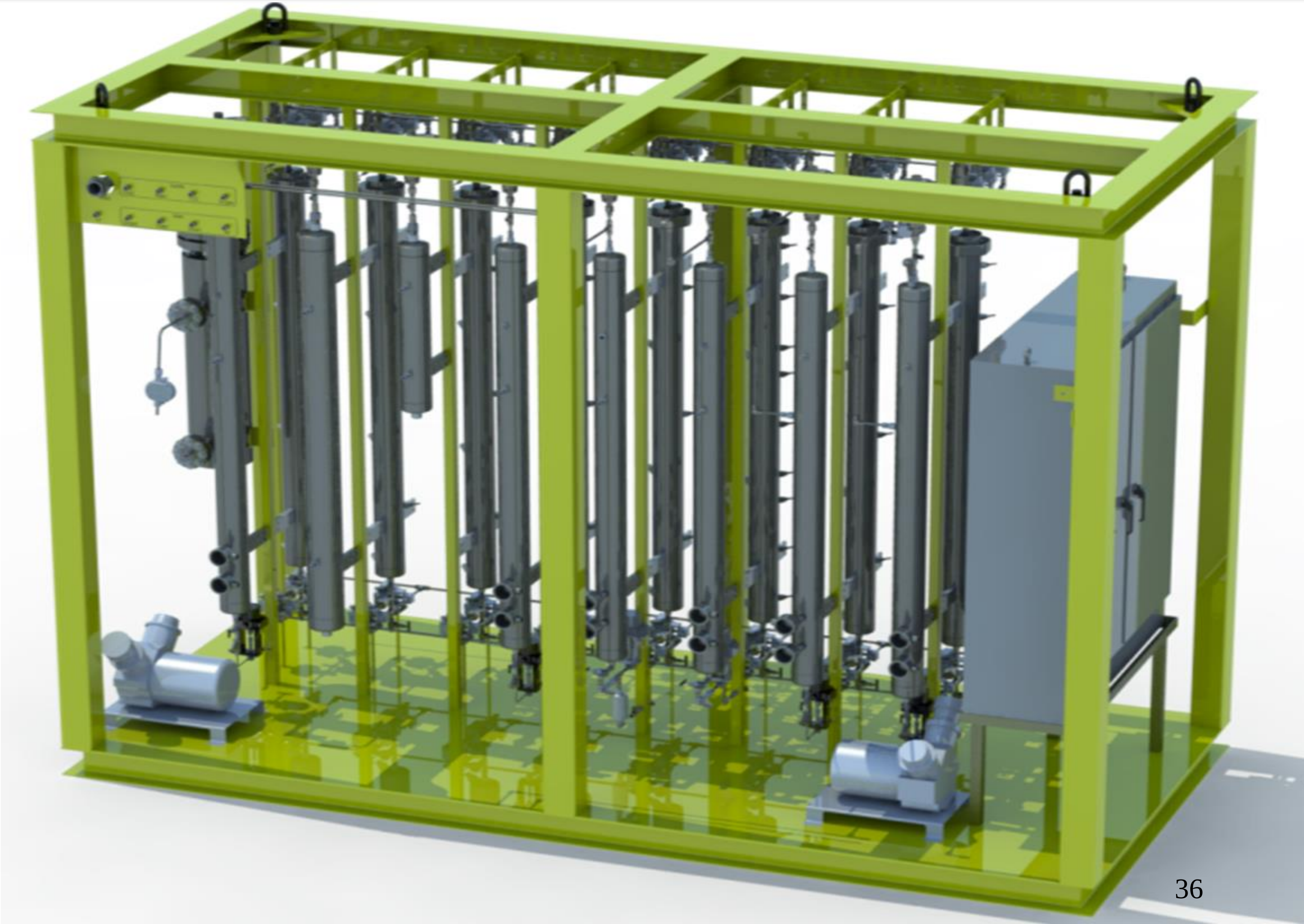
Combined WGS & CO_2 Capture

Gasifier Type/Make	E-Gas			Shell		
Case	1	2	2* (WGS/CO_2)	5	6	6* (WGS/CO_2)
CO_2 Capture Technology	Cold Gas Cleanup Selexol™	Warm Gas Cleanup TDA's CO_2 Sorbent	Warm Gas Cleanup TDA's CO_2 Sorbent	Cold Gas Cleanup Selexol™	Warm Gas Cleanup TDA's CO_2 Sorbent	Warm Gas Cleanup TDA's CO_2 Sorbent
CO_2 Capture, %	90	90	90	90	90	90
Gross Power Generated, kW	710,789	670,056	693,542	672,576	619,214	633,849
Gas Turbine Power	464,000	425,605	427,980	464,000	416,396	417,077
Steam Turbine Power	246,789	244,450	265,562	208,576	202,817	216,772
Syngas Expander Power	-	-	-	-	-	-
Auxiliary Load, kW	194,473	124,138	138,741	176,753	111,347	124,552
Net Power, kW	516,316	545,917	554,801	495,823	507,867	509,298
Net Plant Efficiency, % HHV	31.0	34.1	34.7	30.8	33.4	33.5
Coal Feed Rate, kg/h	220,549	212,265	212,265	213,397	201,426	201,426
Raw Water Usage, GPM/MW	10.9	10.3	10.0	9.9	10.8	10.4
Total Plant Cost, $/kW	3,464	3,042	2,990	3,893	3,535	3,520
COE without CO_2 TS&M, $/MWh	136.8	120.5	118.8	149.6	135.7	135.7
COE with CO_2 TS&M, $/MWh	145.7	128.6	126.7	158.4	143.8	143.9
Cost of CO_2 Captured, $/tonne	**53.24**	**37.37**	**35.81**	**57.16**	**44.24**	**44.25**

- **Combined WGS/CO_2 capture provides improved plant efficiency of 34.7% Vs 34.1% and also lowers the cost of CO_2 capture to $35.8 per tonne from $37.4 for E-Gas™ Case**
- **For Shell Gasifier Case the improvement in net plant efficiency is marginal**

TDA Research

Integrated WGS/CO_2 Capture Test Skid



Project Status

- The skid will be ready for the G6 NCCC Gasification Run (Fall of 2017)
- Skid and vessel fabrication will be completed by late November 2016
- Fully equipped test skid to be completed by Spring 2017
- Prior to testing at NCCC, a testing w/ Praxair is planned to demonstrate integrated operation with the OTM system
  - OTM based ASU enables high gasifier efficiency (handling high CH_4 syngas), TDA system enables carbon capture