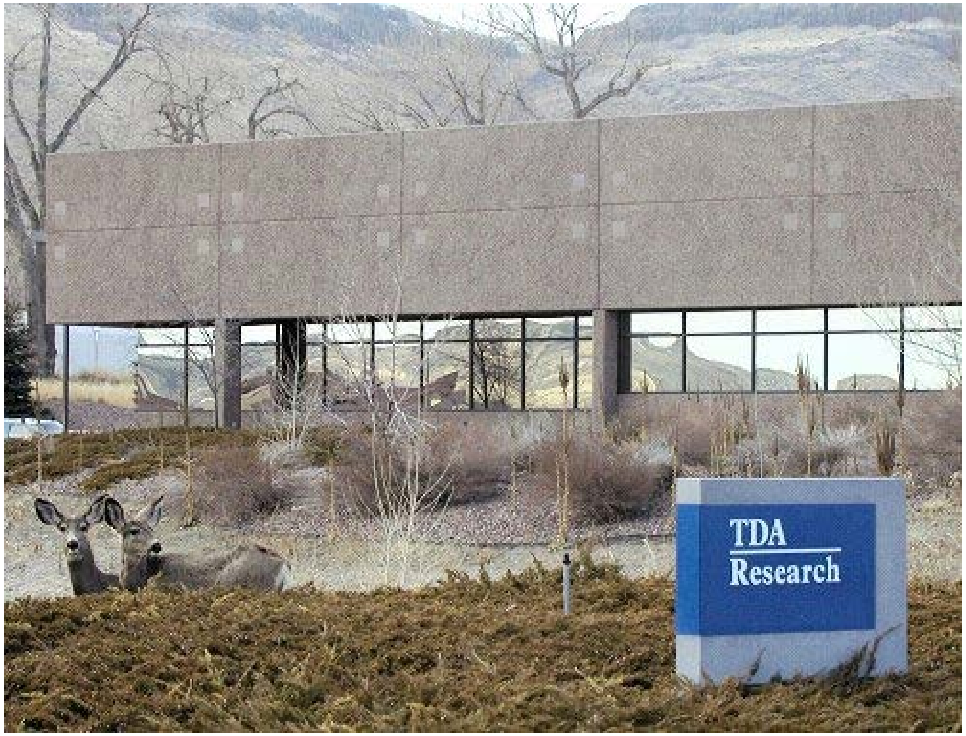
Pilot Testing of a Highly Efficient Pre-combustion Sorbent-based Carbon Capture System (Contract No. DE-FE-0013105)



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2018 DOE/NETL CO_2 Capture Technology 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 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

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Project Partners

Project Duration

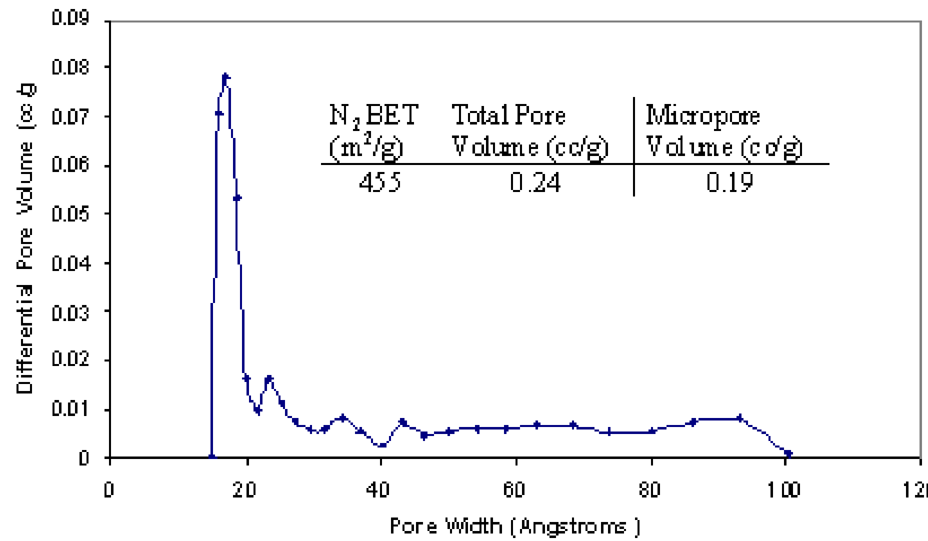
- **Start Date = January 1, 2014**
- **End Date = September 30, 2019**

Budget

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

TDA's Approach

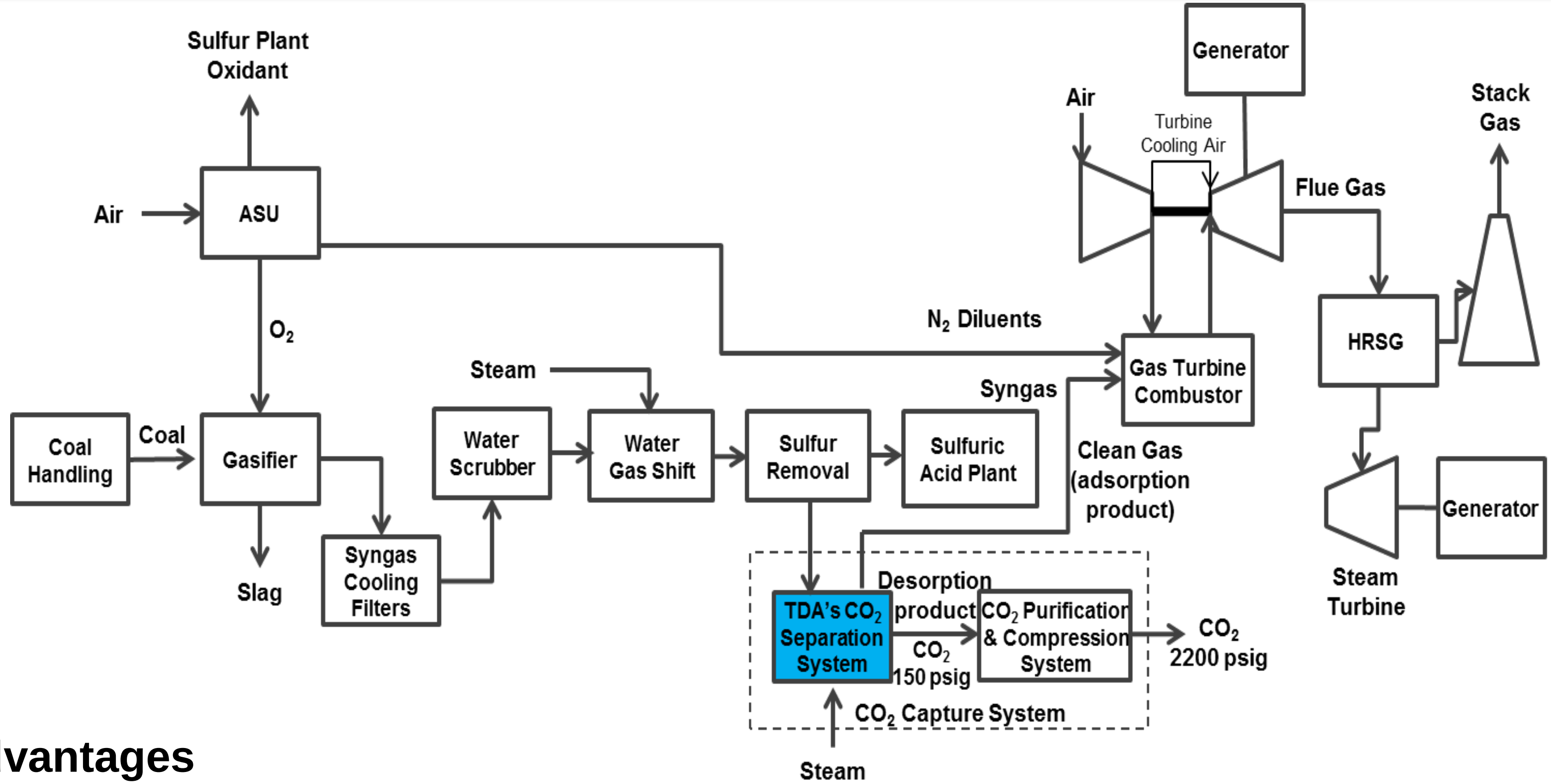
- **TDA's uses a mesoporous carbon modified with surface functional groups that remove CO_2 via strong physical adsorption**
  - CO_2-surface interaction is strong enough to allow operation at elevated temperatures
  - Because CO_2 is not bonded via a covalent bond, the energy input for regeneration is low
- **Heat of CO_2 adsorption is 4.9 kcal/mol for TDA sorbent**
  - Comparable to that of Selexol's
- **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"

Integration to the IGCC Power Plant

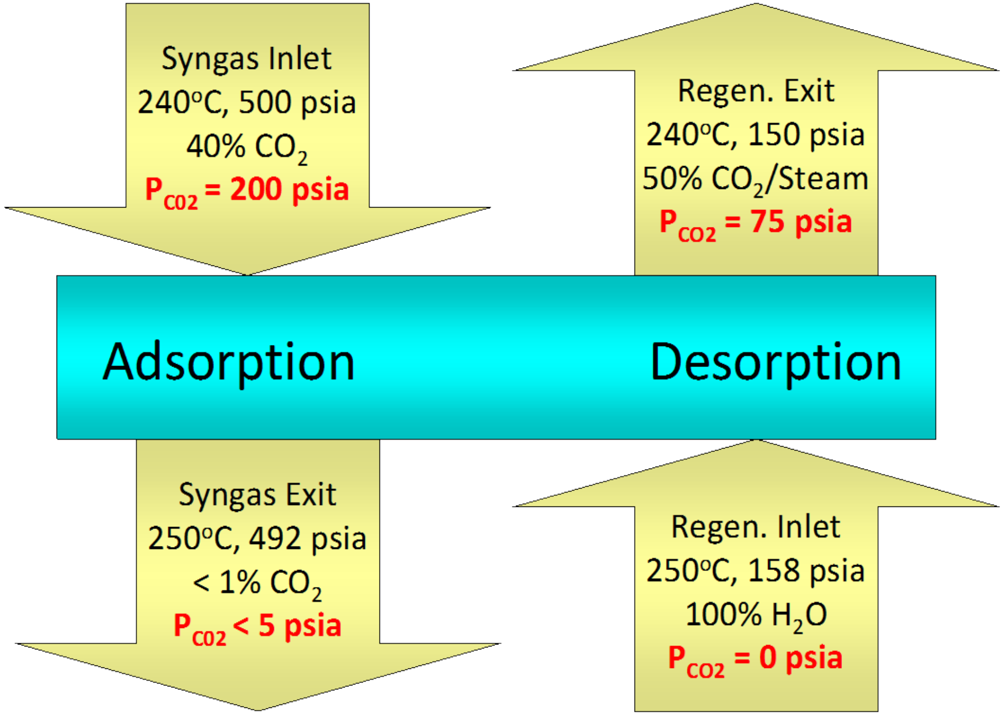


Advantages

- 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

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
- **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 Chemicals Petro-chemical Plant, Nanjing, Jiangsu Province, China – Oxygen blown gasification

National Carbon Capture Center

Sinopec/Yangtzi Chemicals Petro-chemical Complex

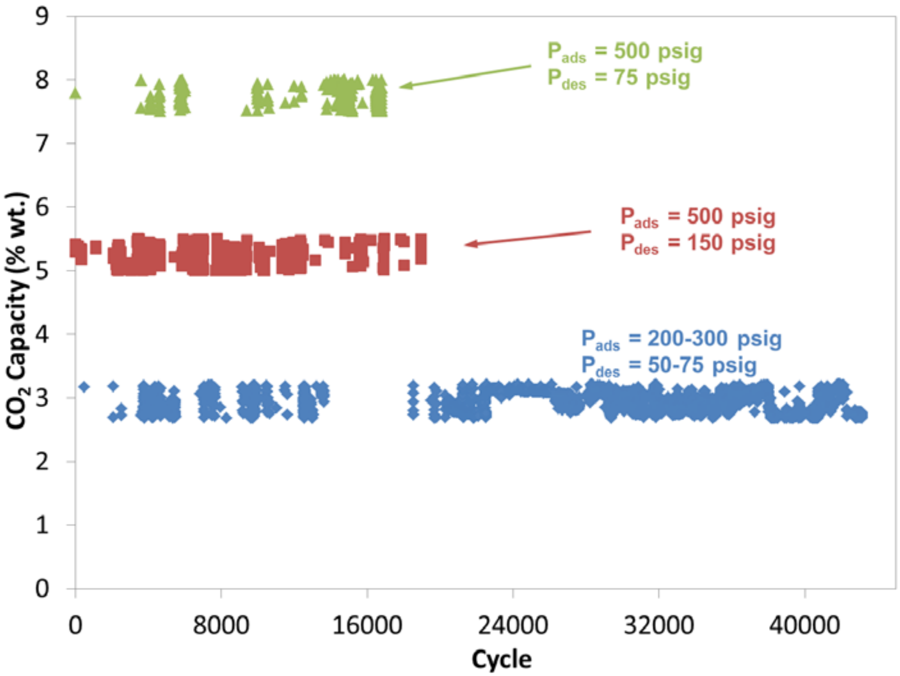
Sorbent and Catalyst for Field Tests

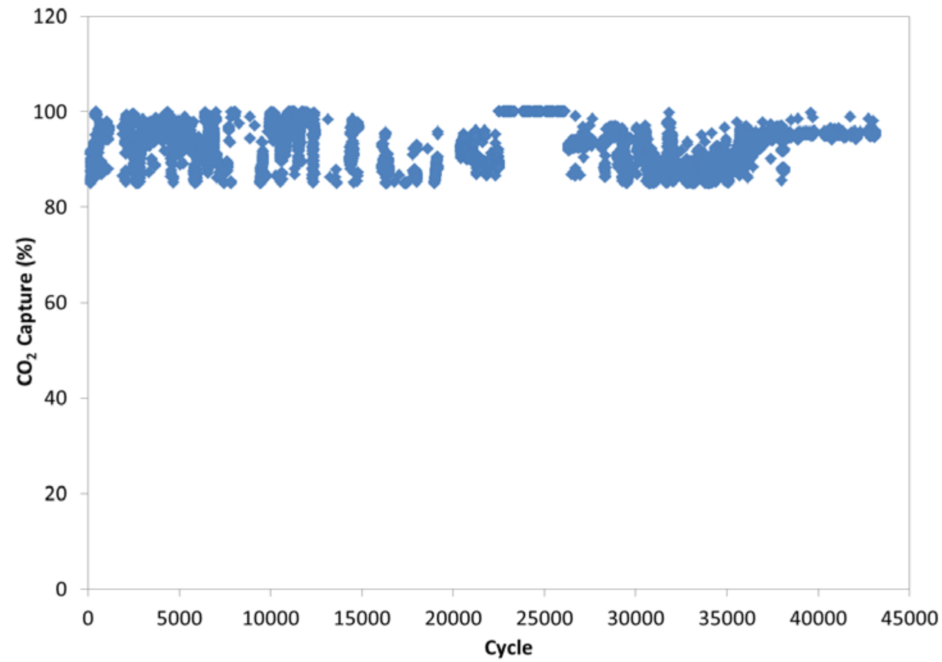
Sulfur Sorbent and WGS Catalyst

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**

Long-term Sorbent Evaluation





	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 scale-up sorbent shows stable performance over 42,000 cycles**
- **60,000 cycles will be completed by December 30, 2018**

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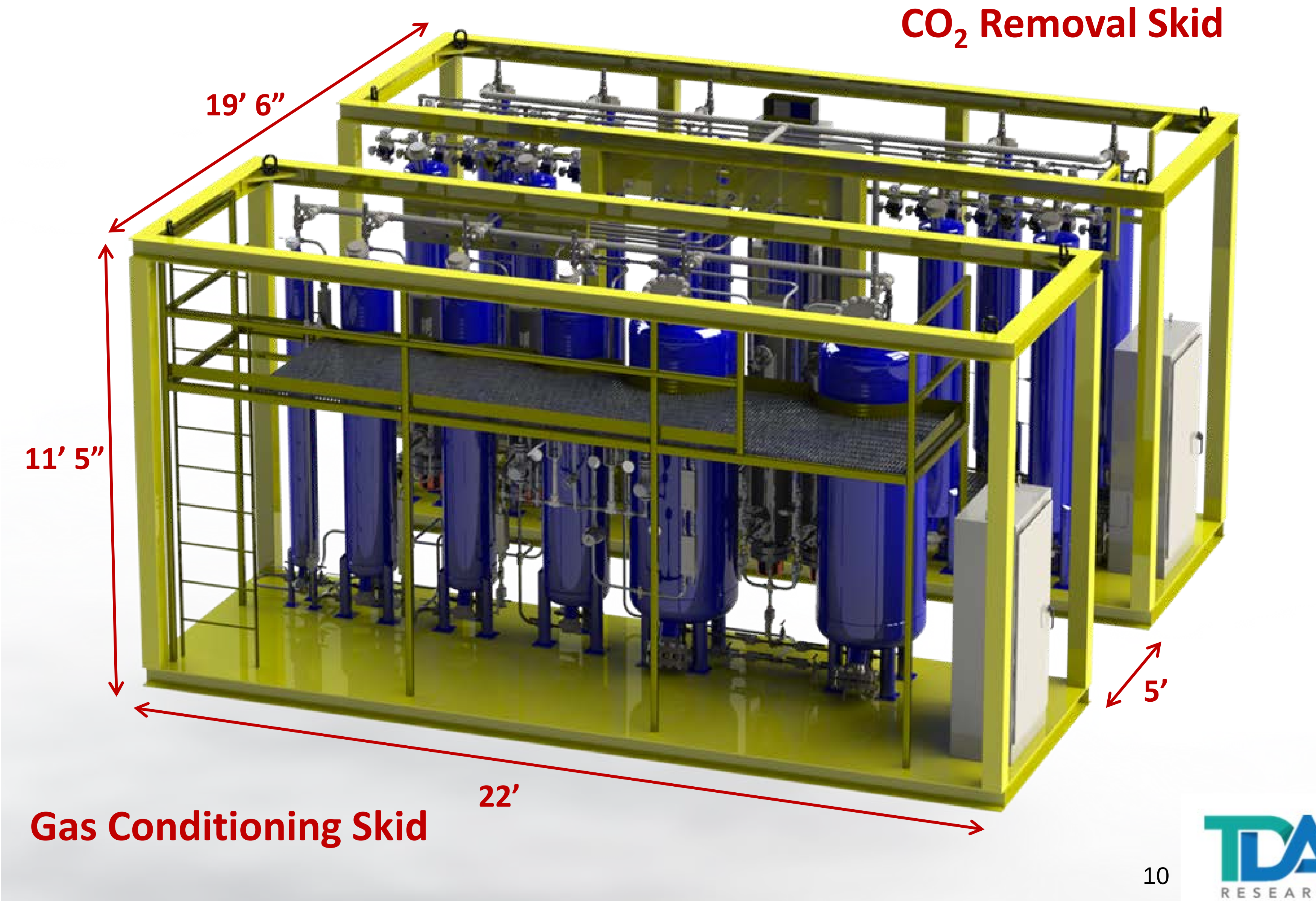
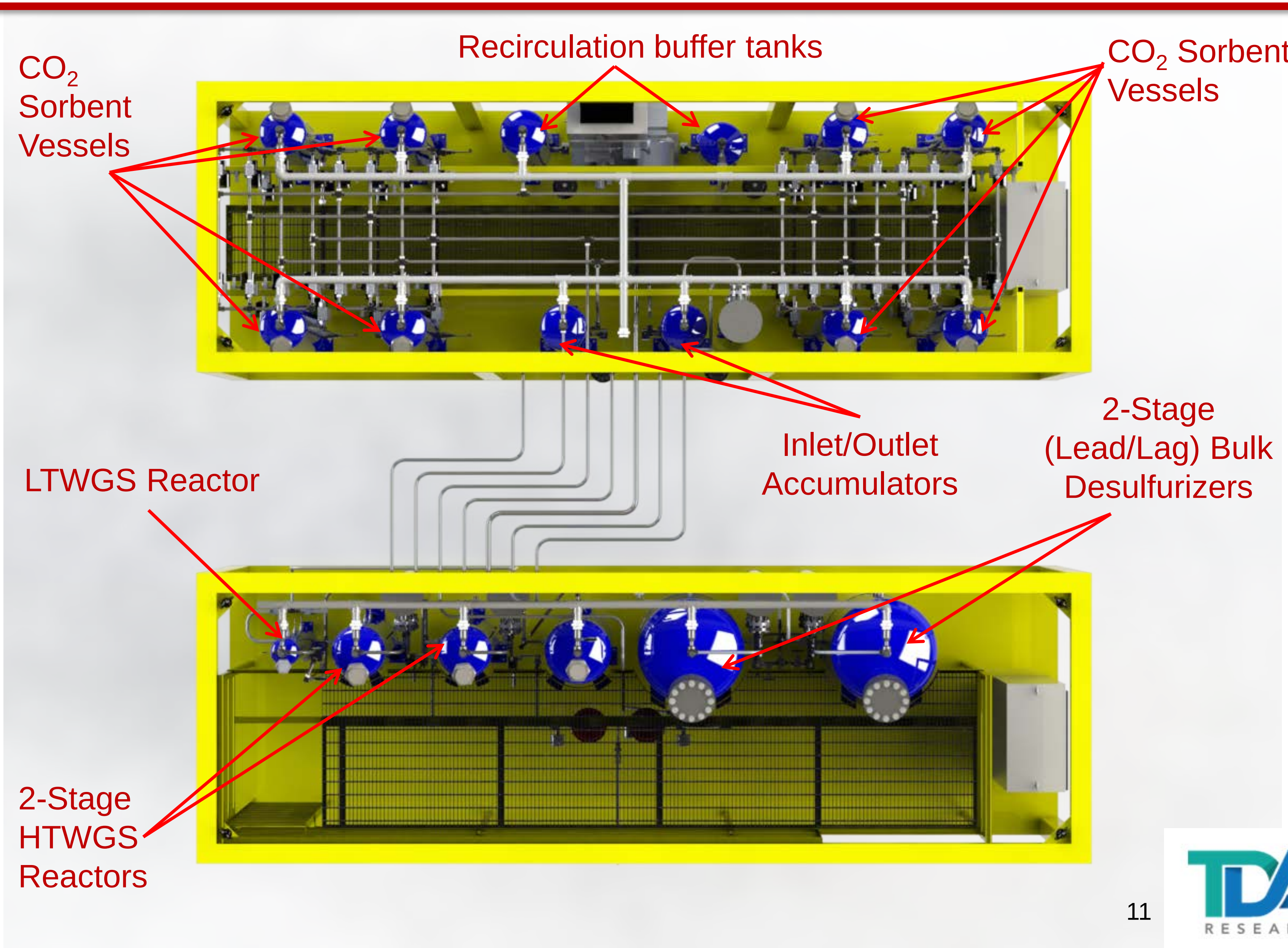
0.1 MW Pilot Unit Design



Slipstream Test Skid - Top View



Field Test Units

- **Completed the fabrication of the Field Evaluation units in September 2016**
- **All troubleshooting and shakedowns are completed in December 2016**

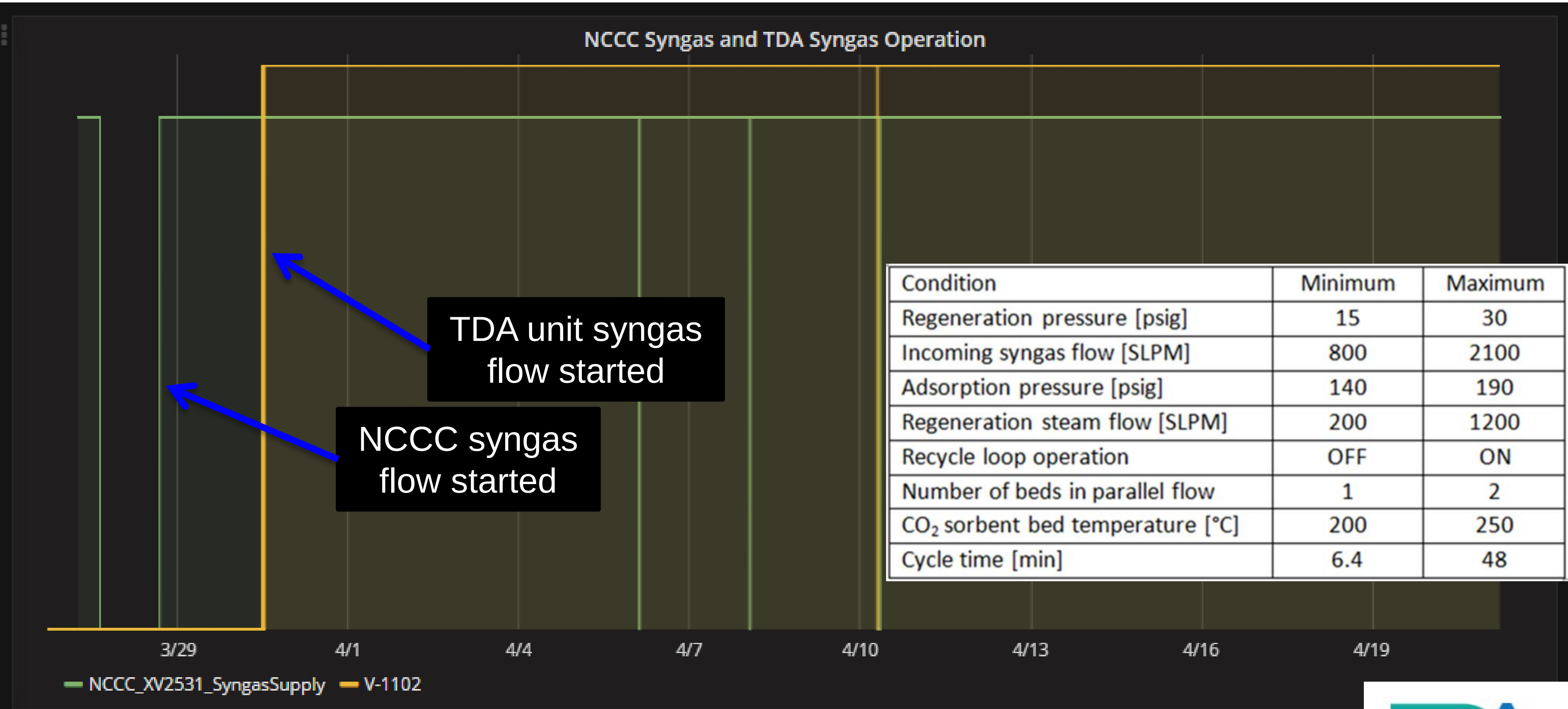
Field Unit Installation at NCCC

Field Test Unit Installed at NCCC

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

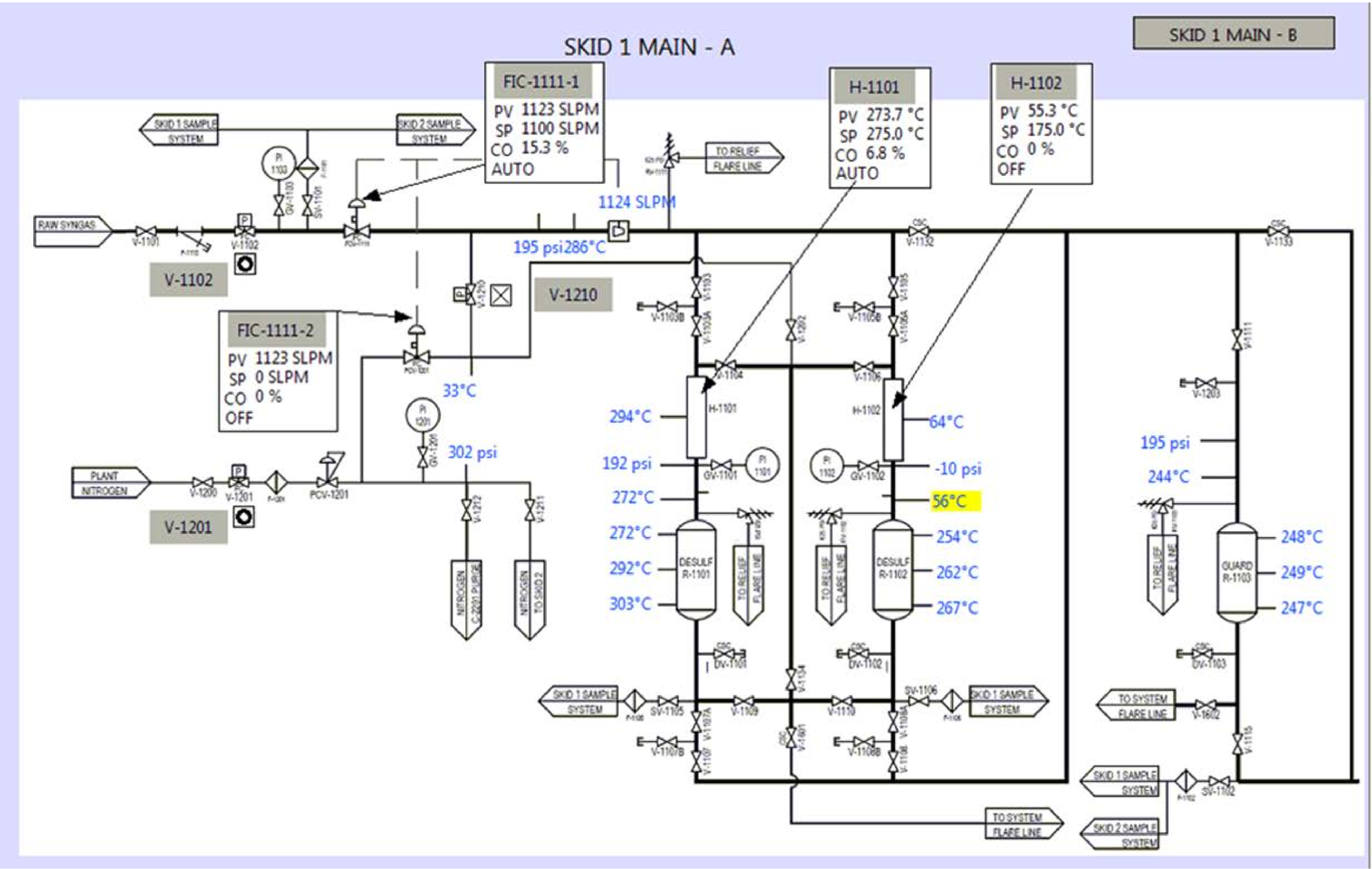
Operation with Synthesis Gas

- **NCCC started synthesis gas flow on 3/28/17 at 18:00**
- **TDA started the operation of its unit on 3/30/17 at 15:30**
- **Both systems are operating well without any interruptions**

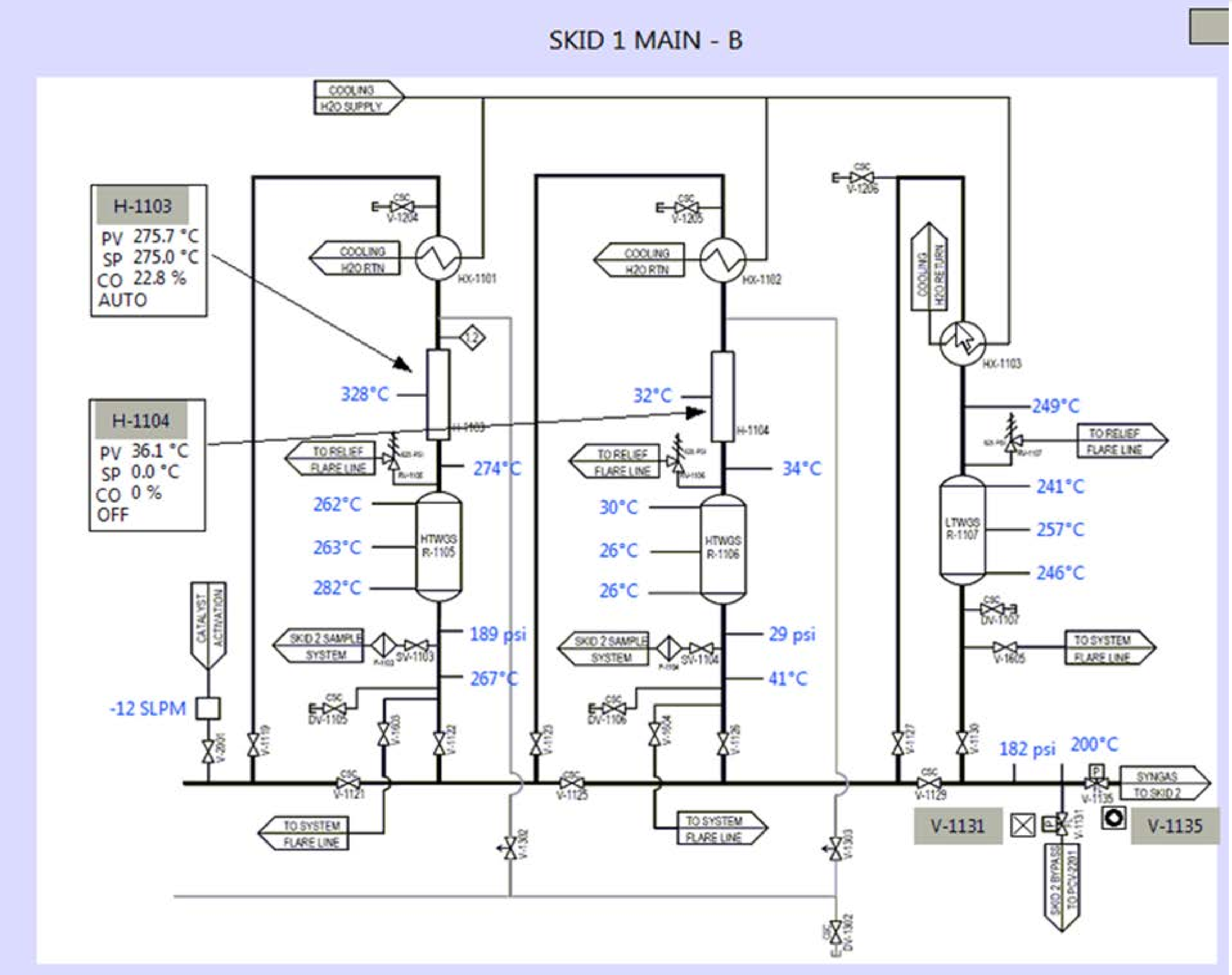


Condition	Minimum	Maximum
Regeneration pressure [psig]	15	30
Incoming syngas flow [SLPM]	800	2100
Adsorption pressure [psig]	140	190
Regeneration steam flow [SLPM]	200	1200
Recycle loop operation	OFF	ON
Number of beds in parallel flow	1	2
CO_2 sorbent bed temperature [°C]	200	250
Cycle time [min]	6.4	48

Sulfur Removal Skid Conditions



WGS Reactors Operating Conditions



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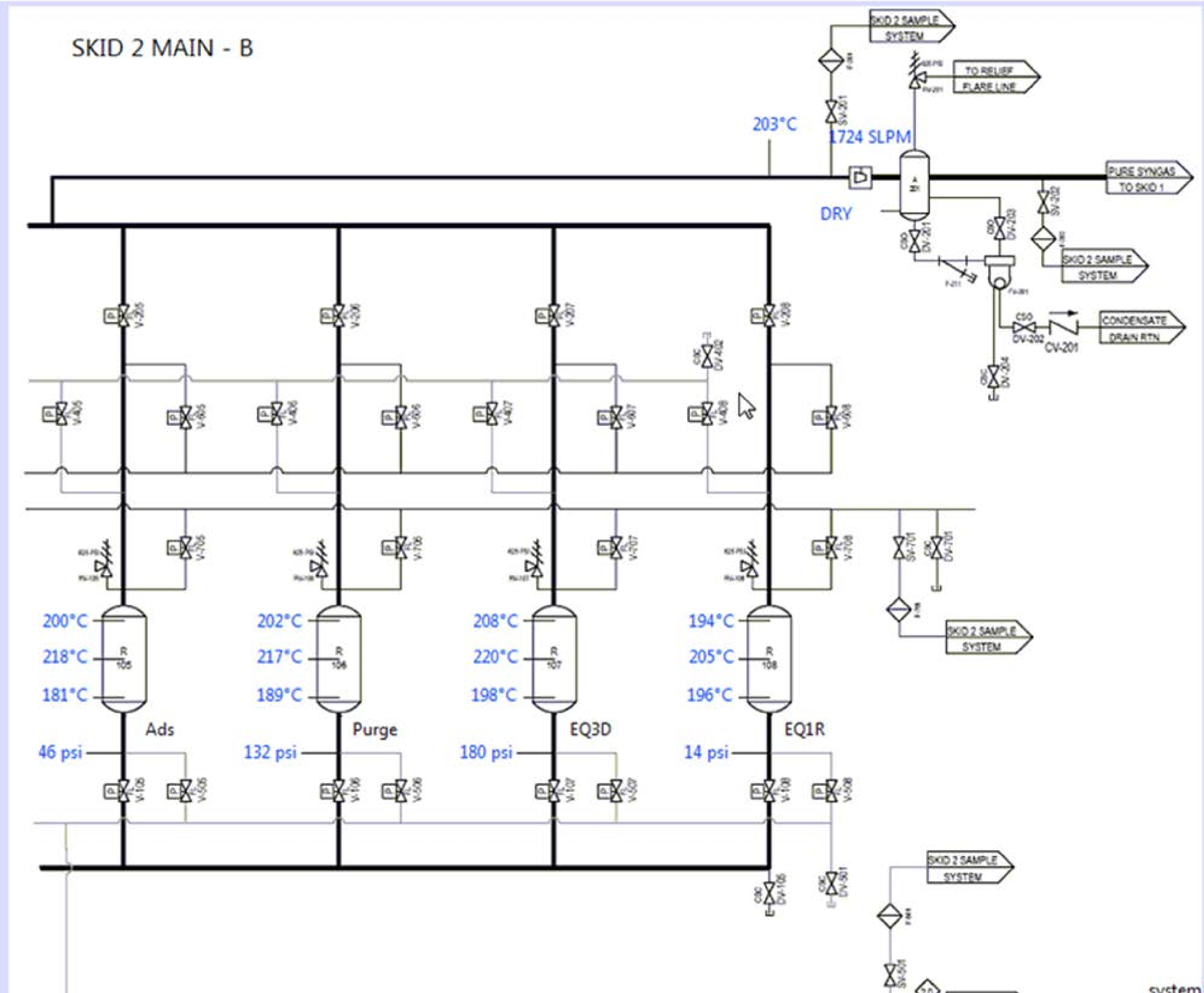
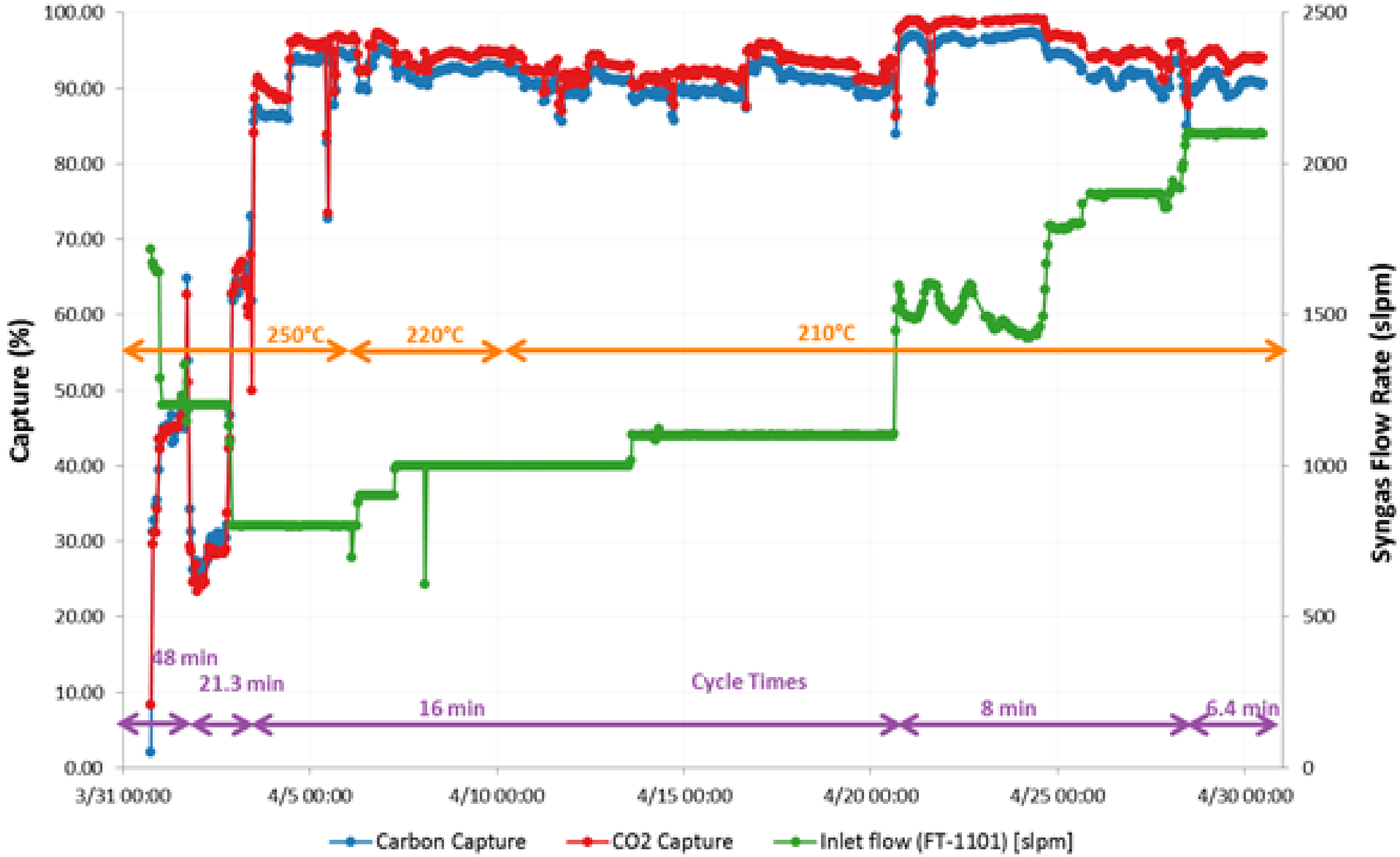
PSA System Operating Conditions



system

Test Summary



- **707 hrs of continuous operation at 90+% carbon capture**
  - **97.3% capture @ 1,500 SLPM; 93% @ 1,800 SLPM; 90% @ 2,100 SLPM**
  - **Design flow at NCCC operating conditions was 1,360 SLPM (48 SCFM)**

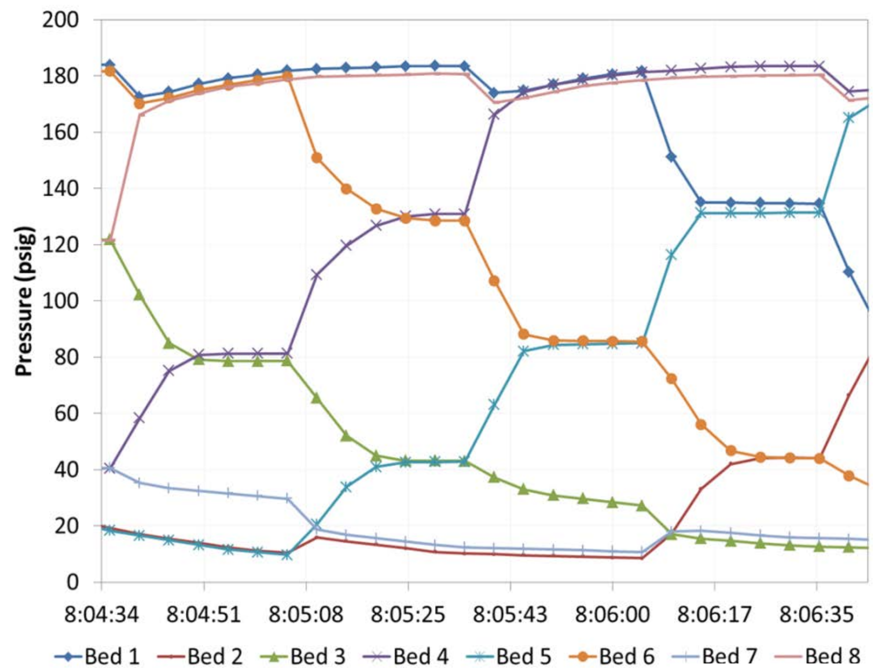
Cycle Scheme with Parallel Flows

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

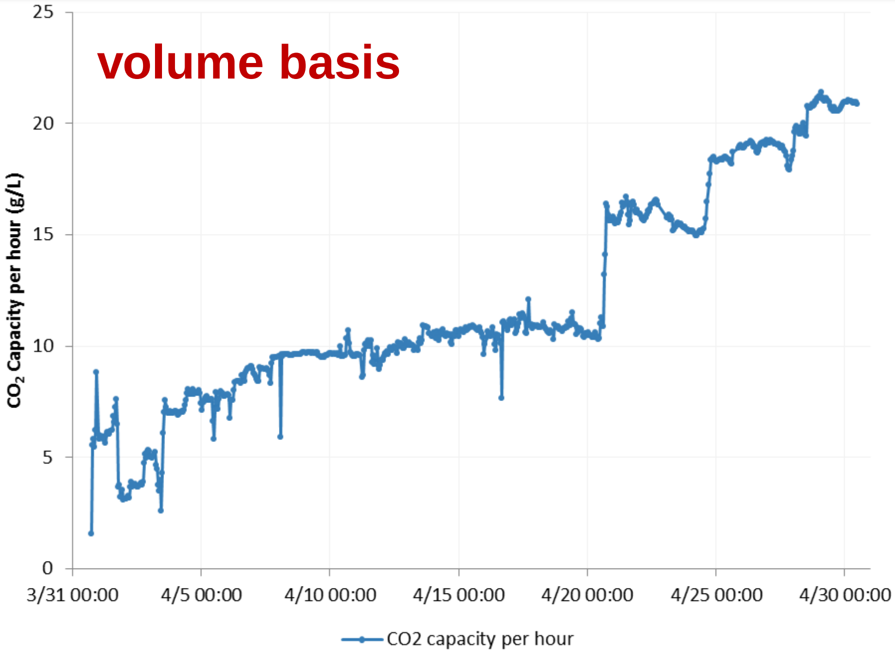
Total Cycle time (8 min) Idle time (0 min)

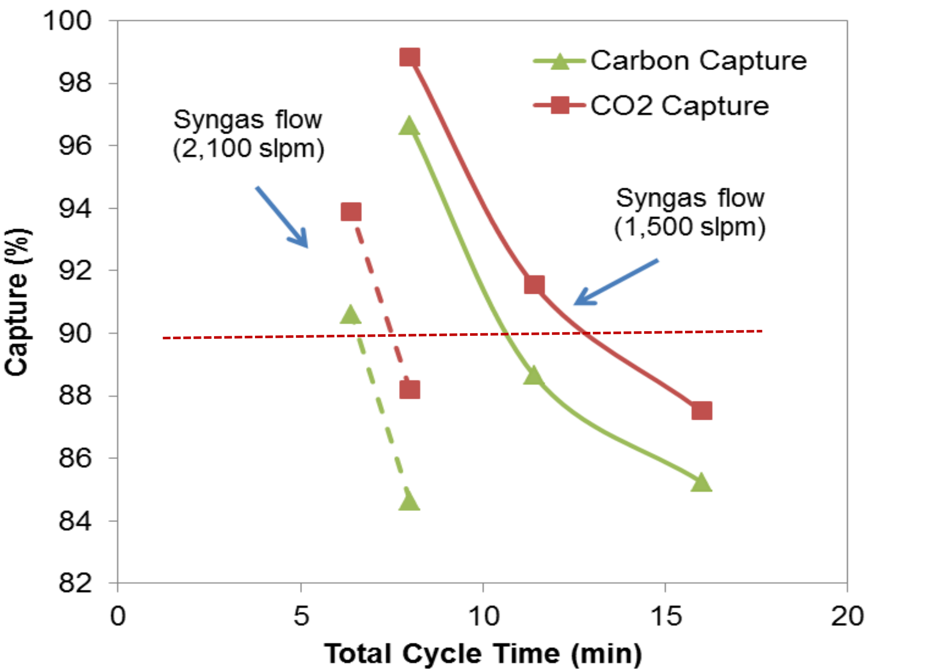
	Stage 1		Stage 2		Stage 3		Stage 4		Stage 5		Stage 6		Stage 7		Stage 8	
Time (mir	1		1		0.5	0.5	0.5	0.5	1		1		0.5	0.5	0.5	0.5
Bed 1	ADS				EQ1D	EQ2D	EQ3D	CoDEP	PURGE				EQ3R	EQ2R	EQ1R	PRESS
Bed 2	EQ1R	PRESS	ADS				EQ1D	EQ2D	EQ3D	CoDEP	PURGE				EQ3R	EQ2R
Bed 3	EQ3R	EQ2R	EQ1R	PRESS	ADS				EQ1D	EQ2D	EQ3D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

- **Optimized cycle scheme uses parallel flows through two beds during adsorption and purge steps**
  - Space velocity is half of the BP1 cycle scheme
  - Eliminated any hold time and minimized time for supporting steps
  - Reduces the pressure drop and allows higher syngas flow
- **Tested parallel flow scheme in NCCC field tests and showed 50% higher bed utilization**



Working Capacity of the Sorbent





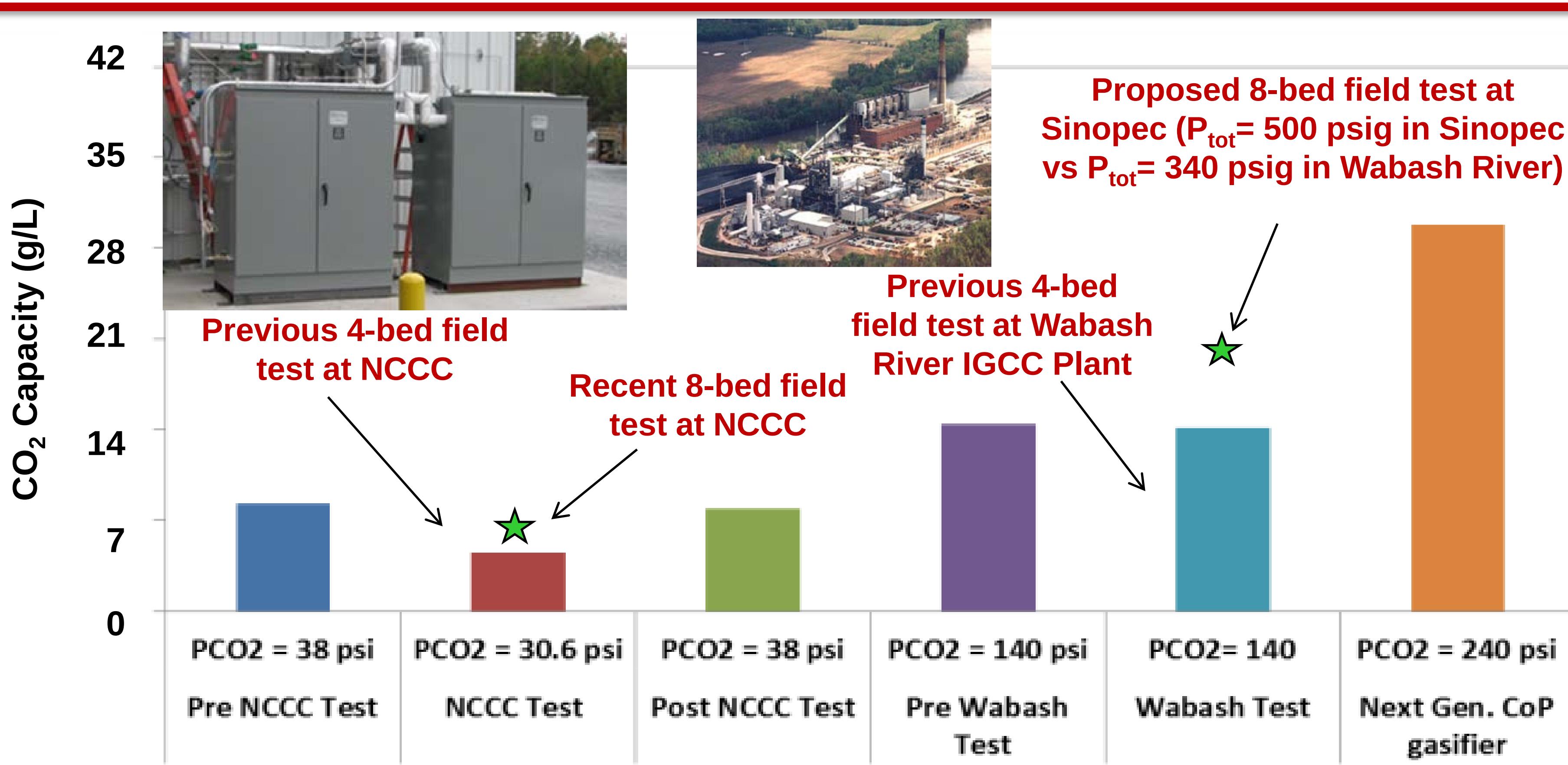
- **Sorbent's working capacity increased during the course of the test by:**
  - **Lowering the cycle time**
  - **Increasing syngas flow rate (main increase made possible by having parallel beds in adsorption and purge steps)**
- **Pressure drop through the gas conditioning skid prevented flowing more than 2,100 SLPM of syngas through the PSA skids**
  - For Sinopec test, we modified the system to further increase the flow

Summary

	Design		Actual				
	Sinopec	NCCC	NCCC				
PSA Cycle Scheme	BP1		BP1	BP2			
Temperature (°C)	216	207	210	210	210	210	210
Pressure (psig)	532	181	190	180	180	160	150
Syngas flow into DeS/WGS Skid 1 (scfm)	73	44	42	42	53	67	74
Syngas flow into CO2 Skid 2 (scfm)	100	48	45	45	57	71	78
Steam added for WGS (scfm)	27.2	4.1	2.7	2.7	4.3	4.3	4.3
CO_2 Captured (kg/hr)	105.3	25.4	18.0	19.8	25.2	29.5	33.3
Cycle time (min)	16	16	16	16	8	8	6.4
Beds Adsorbing in parallel	1	1	1	2	2	2	2
PCO2 (psi)	175.1	29.0	30.4	28.8	28.8	25.6	24
CO2 capture (%)			94%	89%	99%	93%	94%
Carbon Capture (90%)	90%	90%	91%	86%	96%	90%	91%
Bed Utilization (g CO2/L/hr)	65.8	15.9	11.3	12.4	15.8	18.5	20.8

- **We successfully operated the 8-bed PSA unit with real coal derived syngas**
- **Test unit achieved ~30% higher CO_2 capture than the design performance**
  - High dP in the gas conditioning skid limited even higher performance
  - Modifications were competed to achieve higher flows in Sinopec test

Bed Capacity Comparison



- Sorbent/PSA system maintained slightly higher CO_2 capacity than the earlier field tests at NCCC at ~60X scale
- At Sinopec we expect to achieve higher capacity than in the previous oxy-fired gasification tests at Wabash River IGCC power plant

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Status of Sinopec Testing

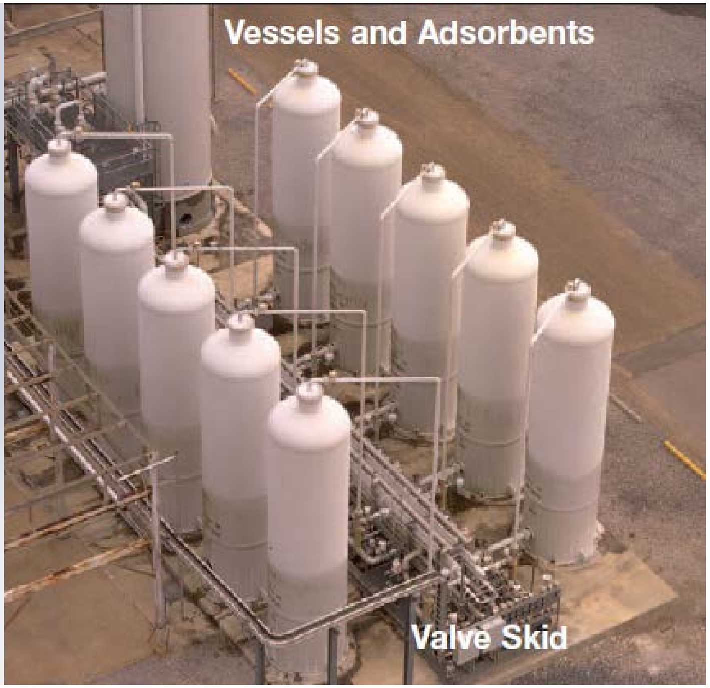
- 2 skids and 2 containers (containing sorbents, catalyst, analyzers, supplies, toolboxes) are shipped to China in December 2017
- Both skids and one of the containers were delivered to the site on April 2018
- One skid held up due to the hazardous nature of the WGS catalyst
- Skid contents will be procured locally; troubleshooting will start in Oct. 2018

Nanhua Plant Syngas Supply	
Composition	**mol%**
H_2	32.493
CO	0.546
CO_2	24.715
H_2S	0.083
COS	0
C1	0.021
N_2	0.128
AR	0.05
NH_3	0.069
HCN	0
HCL	0
H_2O	41.895
温度 Temperature, C	265.6
压力 Pressure, MPaG	4

Reactor Design

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

TDA Design

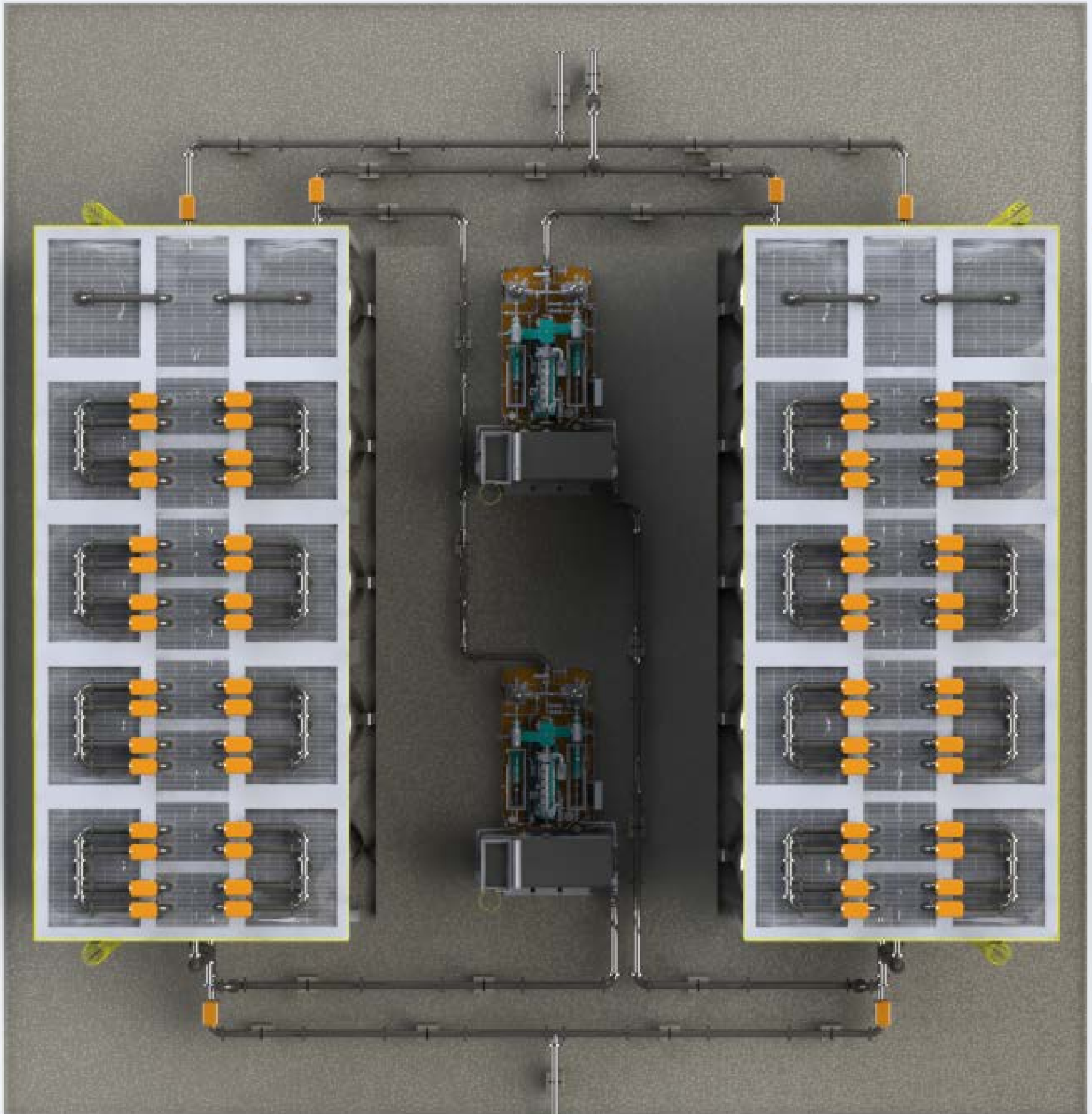


Source: Honeywell/UOP

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

E-Gas™ & GE Gasifiers

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%)**
- **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™)**

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Shell & TRIG Gasifiers

Gasifier	Shell		TRIG	
Case	5	6	7	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	90	83	83
Gross Power Generated, kW	672,576	619,214	621,595	617,159
Gas Turbine Power	464,000	416,396	424,616	413,635
Steam Turbine Power	208,576	202,817	196,979	203,524
Syngas Expander Power	-	-	-	-
Auxiliary Load, kW	176,753	111,347	163,837	124,104
Net Power, kW	495,823	507,867	461,808	493,056
Net Plant Efficiency, % HHV	30.8	33.4	31.5	34.5
Coal Feed Rate, kg/h	213,397	201,426	262,700	258,882
Raw Water Usage, GPM/MW	9.9	10.8	8.3	9.6
Total Plant Cost, $/kW	3,893	3,612	3,728	3,353
COE without CO_2 TS&M, $/MWh	149.6	140.2	124.7	113.0
COE with CO_2 TS&M, $/MWh	158.4	148.4	143.6	130.3
Cost of CO_2 Capture, $/tonne	47	40	39	28

- **IGCC plant with TDA's CO_2 capture system achieves higher efficiencies (33.4% and 34.5%) than IGCC with Selexol™ (30.8% and 31.5%)**
- **Cost of CO_2 capture is calculated as $40 and $28 per tonne for Shell and TRIG gasifiers, respectively (15-28% reduction against Selexol™)**

TDA RESEARCH

Acknowledgements

- DOE/NETL funding under the DE-FE-0013105 project
- Project Manager, Andy O’Palko
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