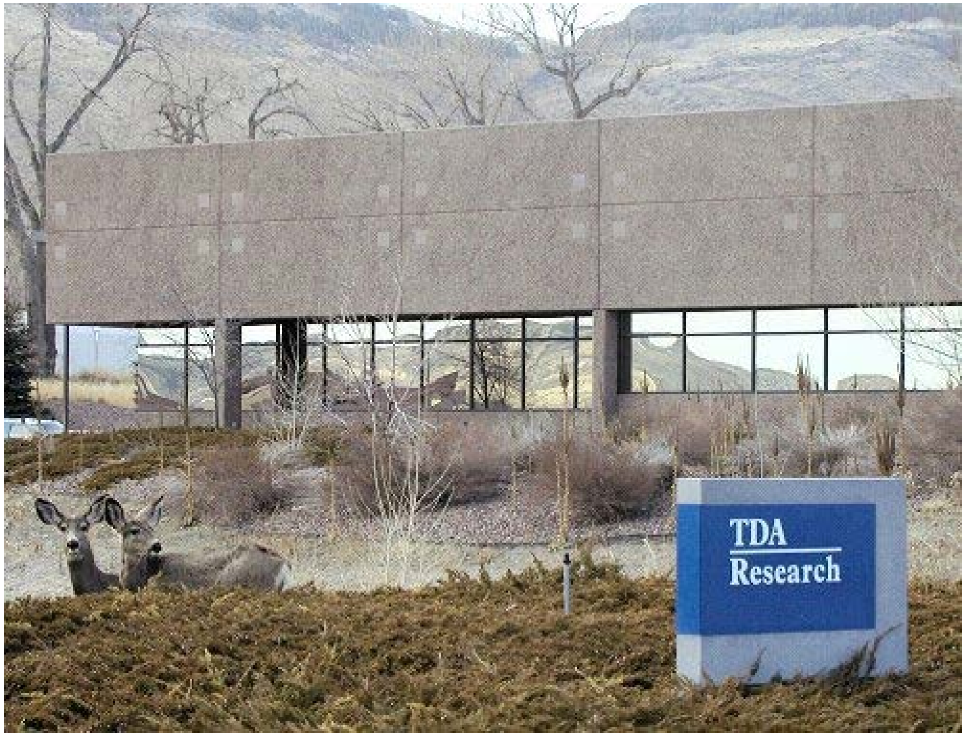
Pilot Testing of a Highly Efficient Pre-combustion Sorbent-based Carbon Capture System (Contract No. DE-FE-0013105)



Gökhan Alptekin, PhD

Ambal Jayaraman, PhD

Matt Cates

Mike Bonnema

Jim Dippo

David Gribble

Byron Wall

2017 CO_2 Capture Technology Meeting

August 22, 2017

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) Assessing the technical feasibility in 0.1 MW_e pilot-scale 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

<u>Project Duration</u>

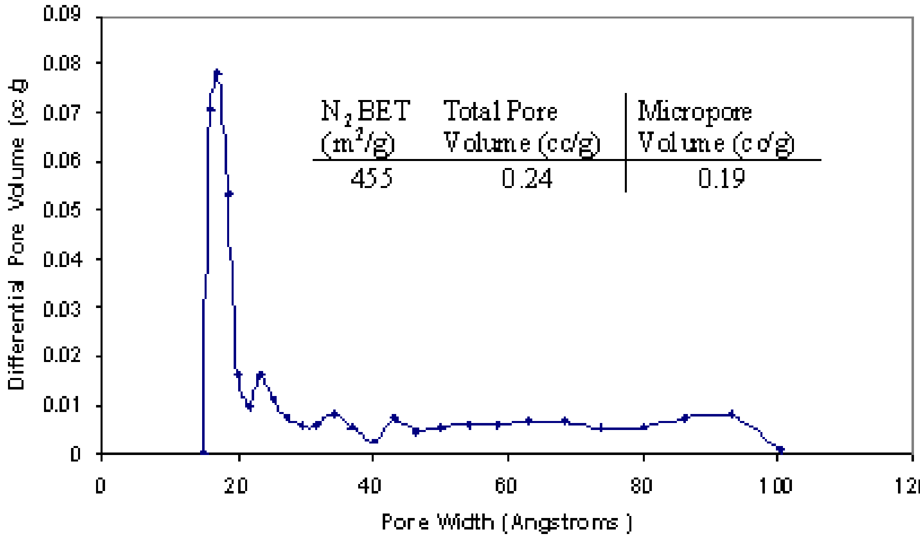
- **Start Date = January 1, 2014**
- **End Date = September 30, 2018**

<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'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**

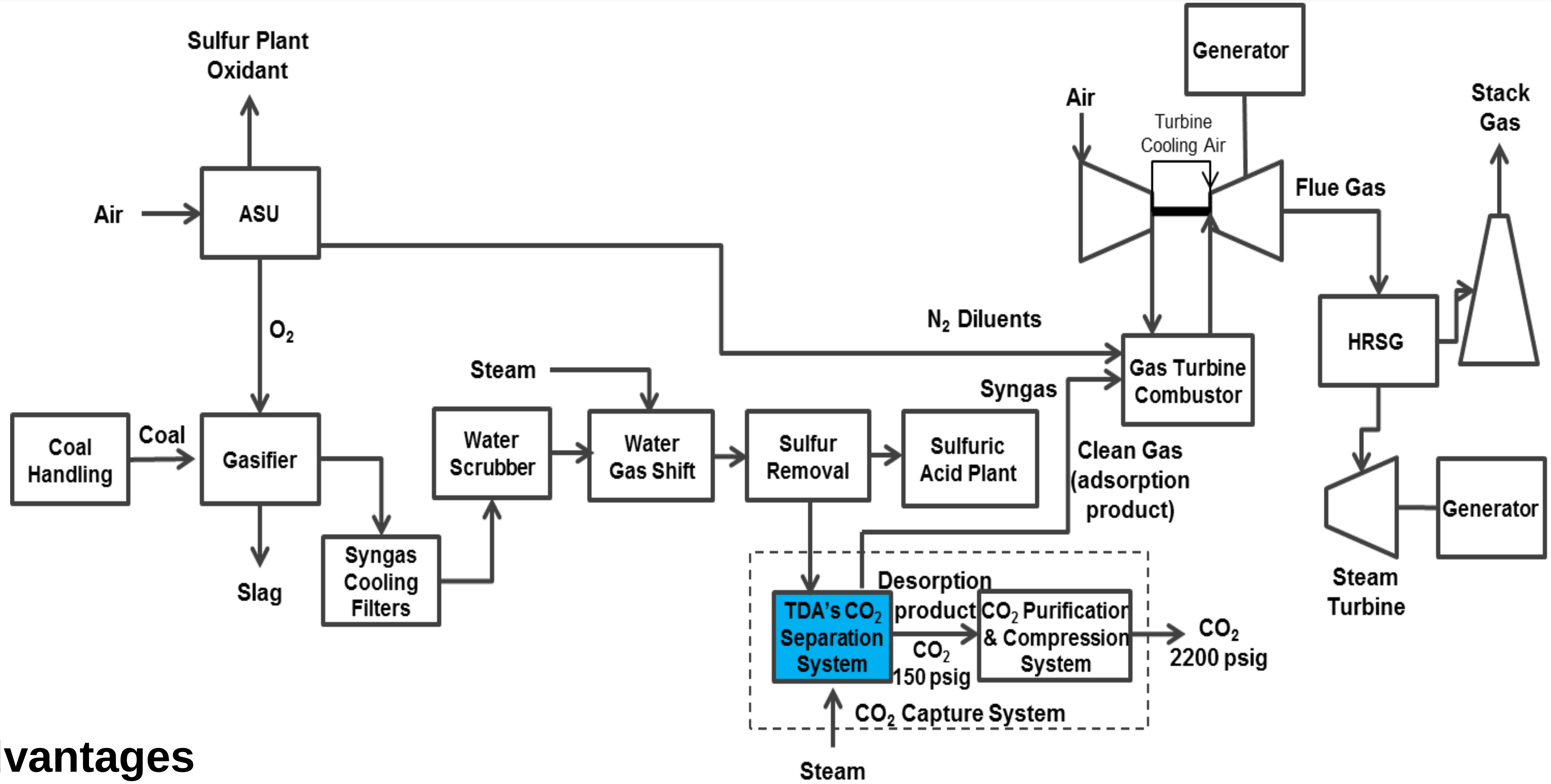


N_2 BET (m^2/g)	Total Pore Volume (cc/g)	Micropore Volume (cc/g)
455	0.24	0.19

- **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

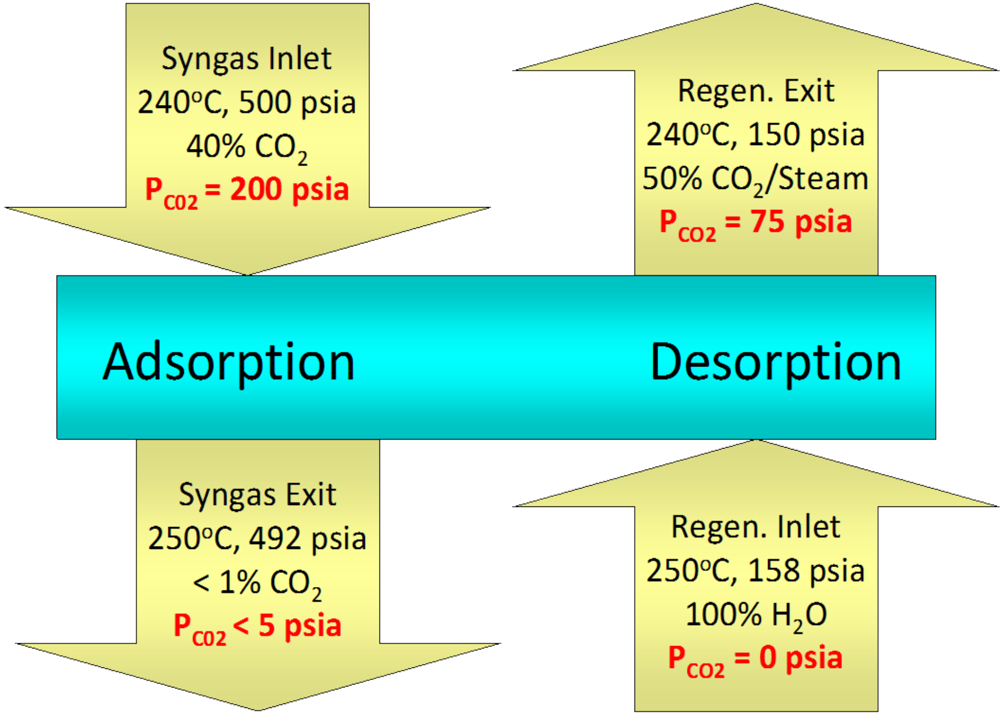


Advantages

- 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

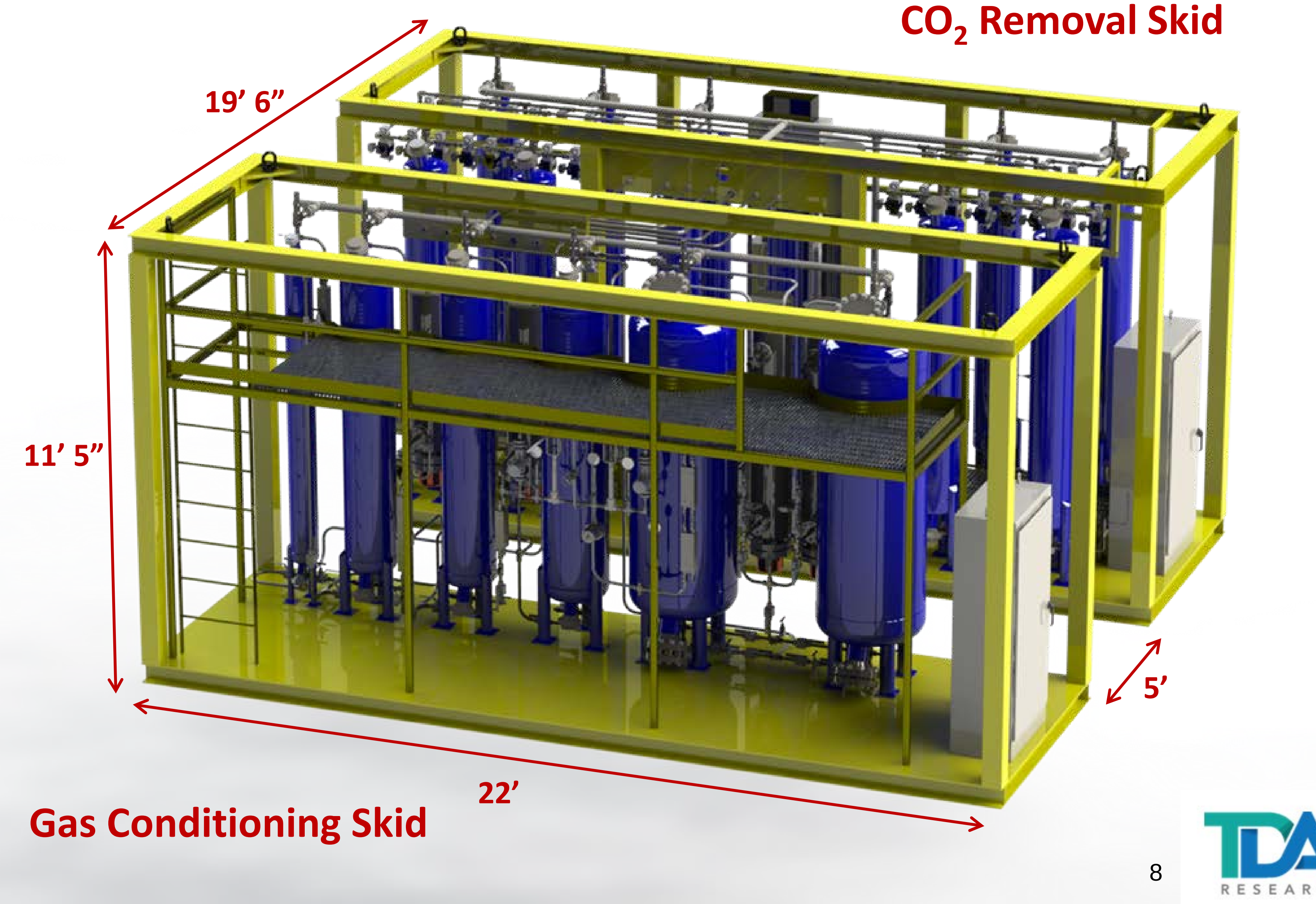
Primary Focus

- **0.1 MW_e evaluation in a world class IGCC plant to demonstrate full benefits of the technology**
- **Demonstrate full operation scheme**
  - All reactors and accumulators
  - Utilize product/inert gas purges
  - H_2 recovery/CO_2 purity
- **Long-term performance tests using synthesis gas from an oxy-blown gasifier**
- **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

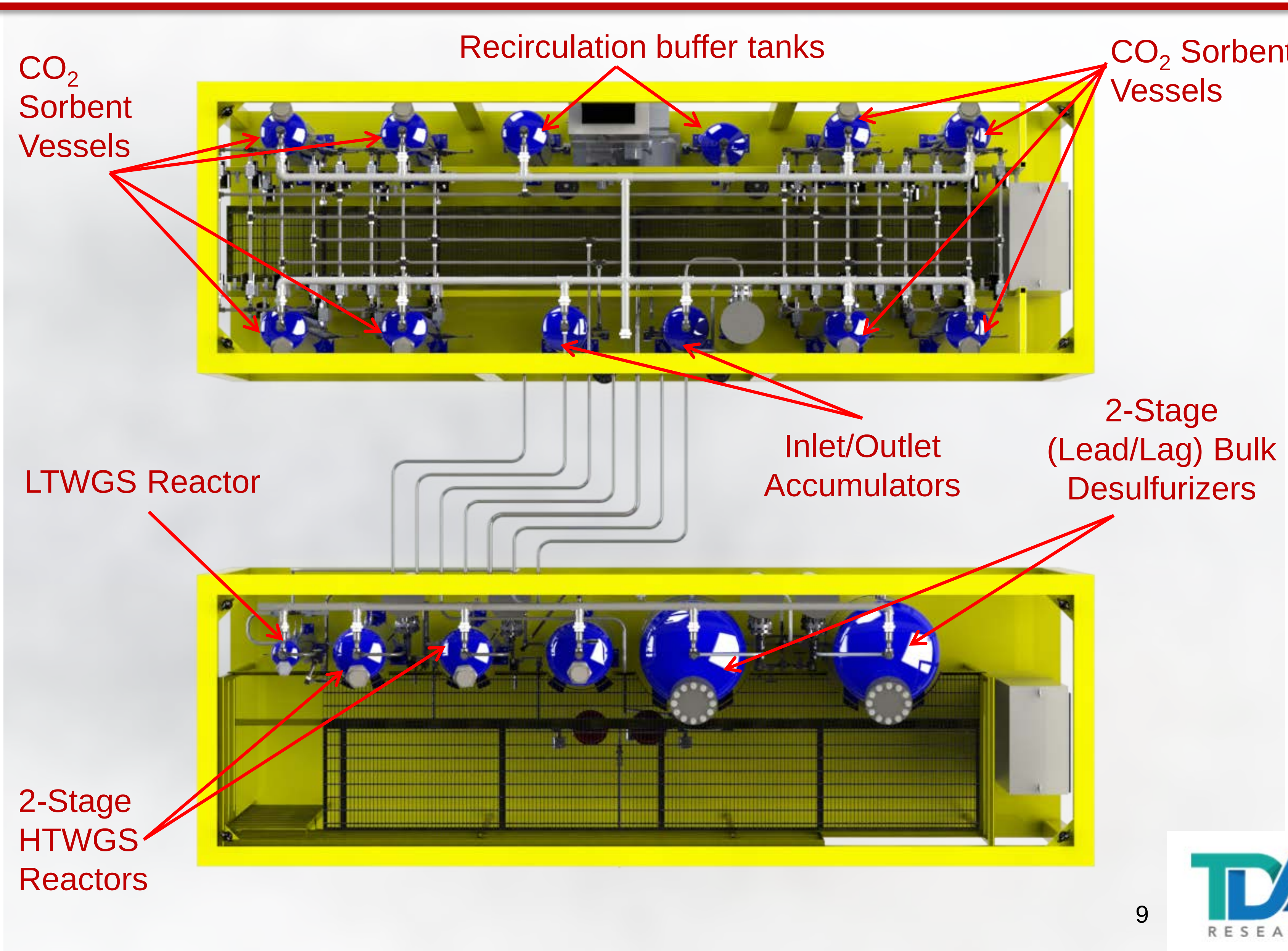
National Carbon Capture Center

Sinopec/Yangtzi Chemicals Petro-chemical Complex

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**

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**

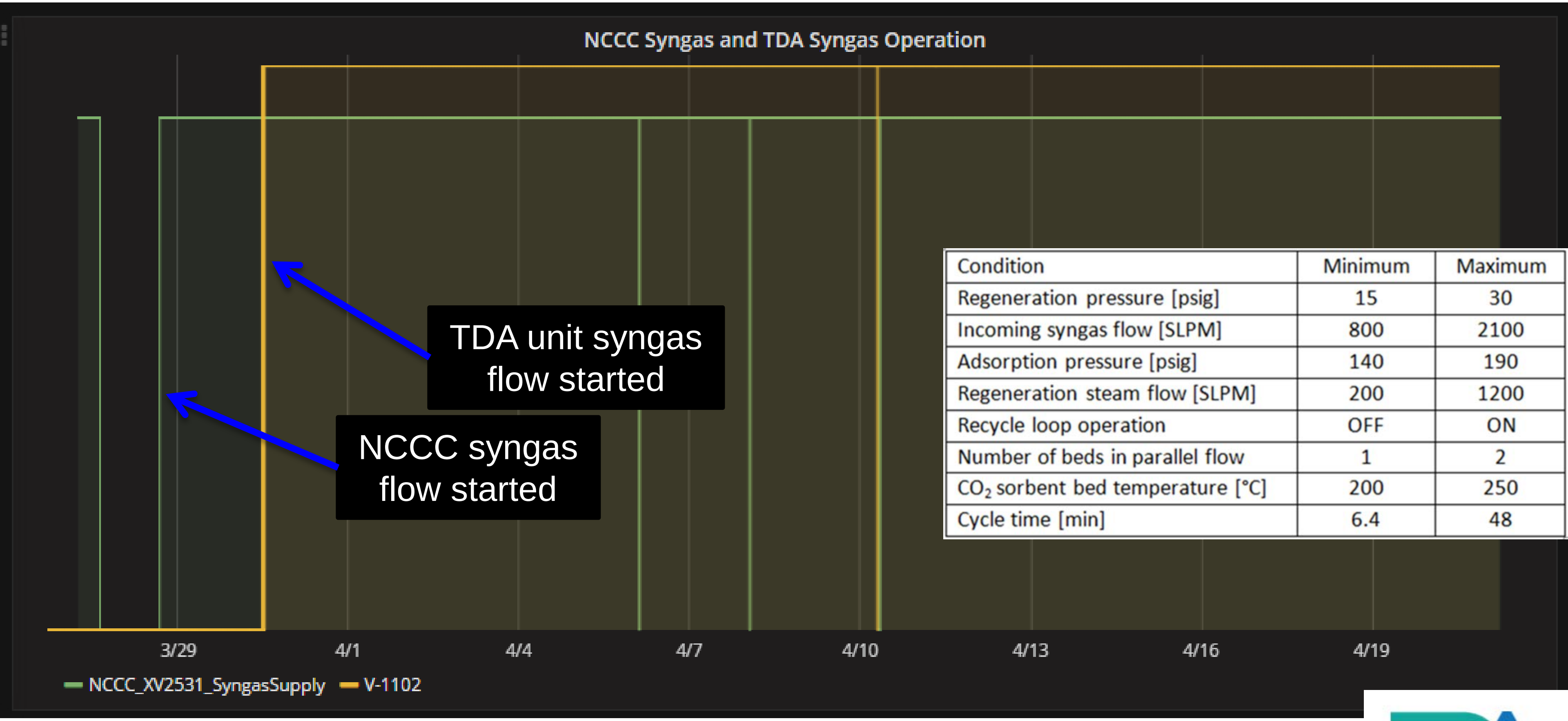
Field Unit Installation at NCCC

Field Test Unit Installed at NCCC

- **Installation with all the hook-ups were completed in March 2017**
- **Testing started on March 30, 2017**

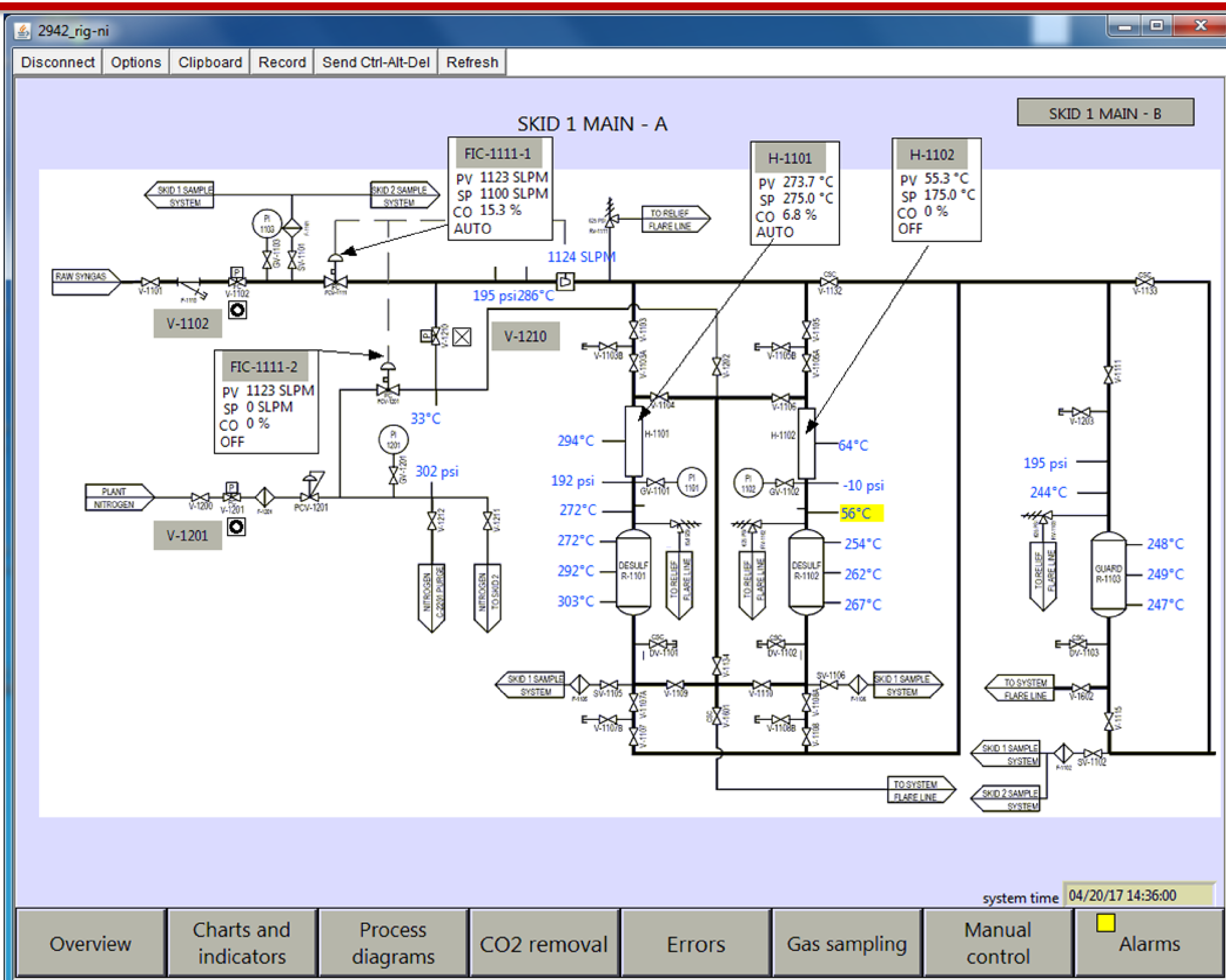
Operation with Synthesis Gas

- **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**



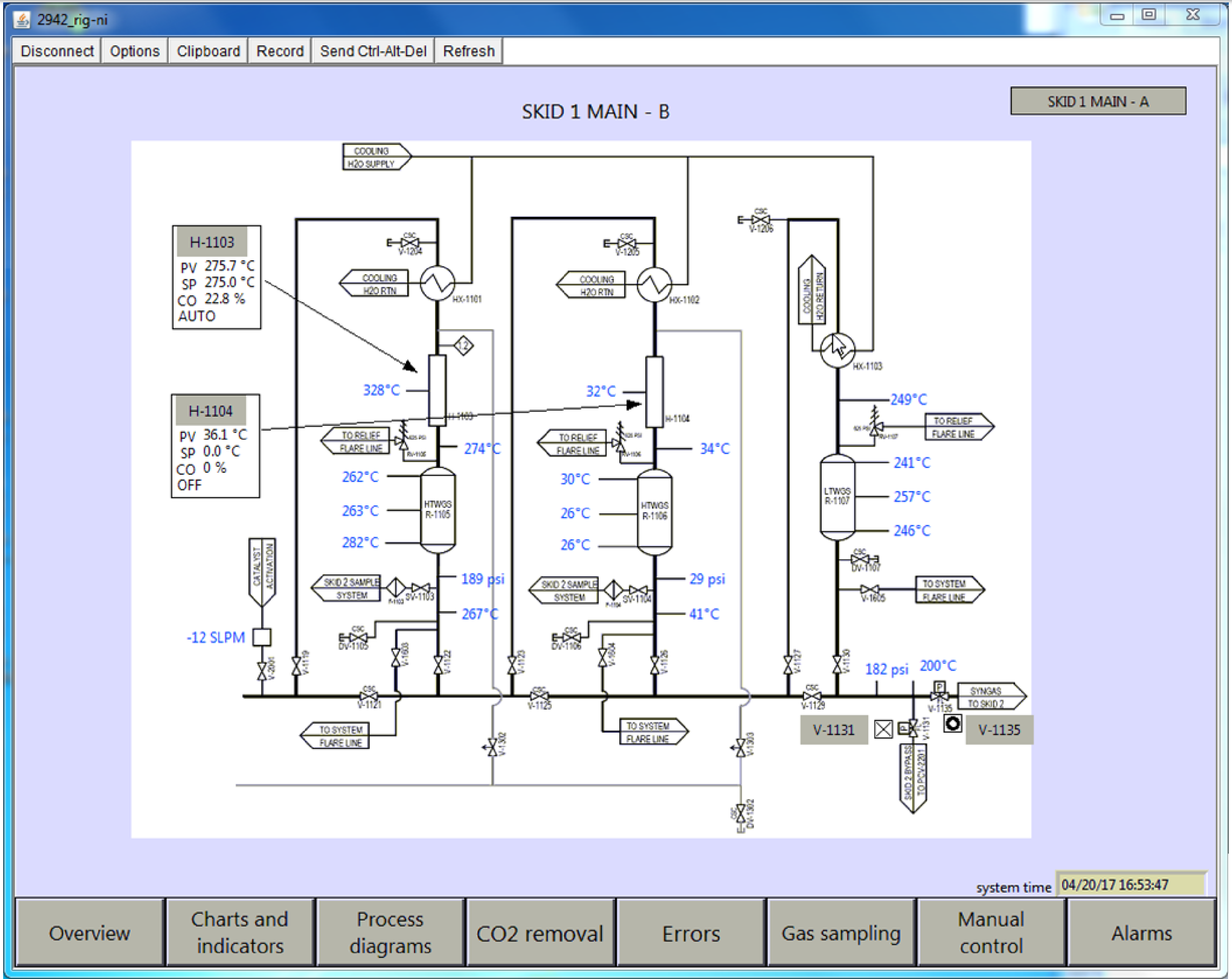
Condition	Minimum	Maximum
Regeneration pressure [psig]	15	30
Incoming syngas flow [SLPM]	800	2100
Adsorption pressure [psig]	140	190
Regeneration steam flow [SLPM]	200	1200
Recycle loop operation	OFF	ON
Number of beds in parallel flow	1	2
CO_2 sorbent bed temperature [°C]	200	250
Cycle time [min]	6.4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

Sulfur Removal Skid Conditions

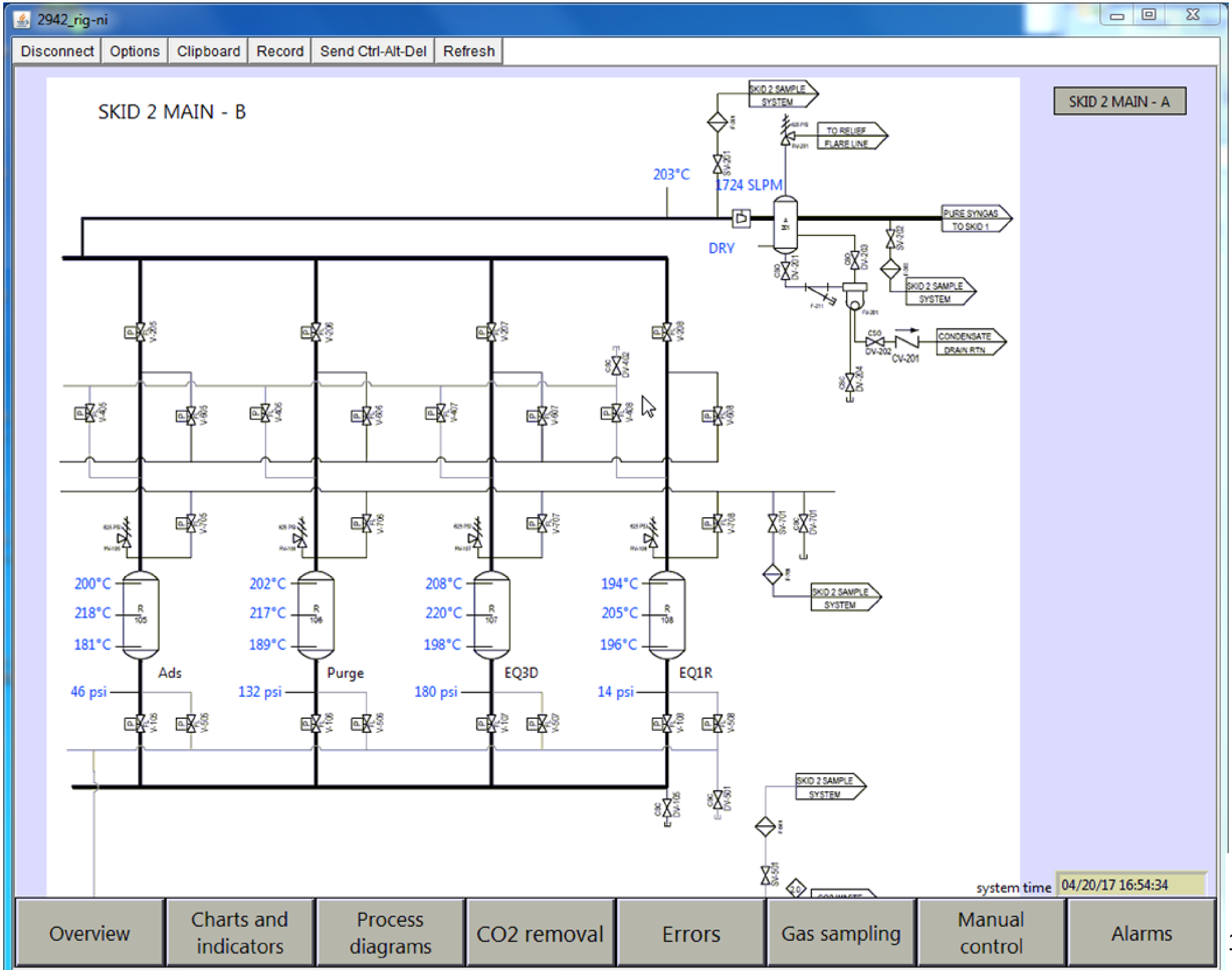


TDA RESEARCH

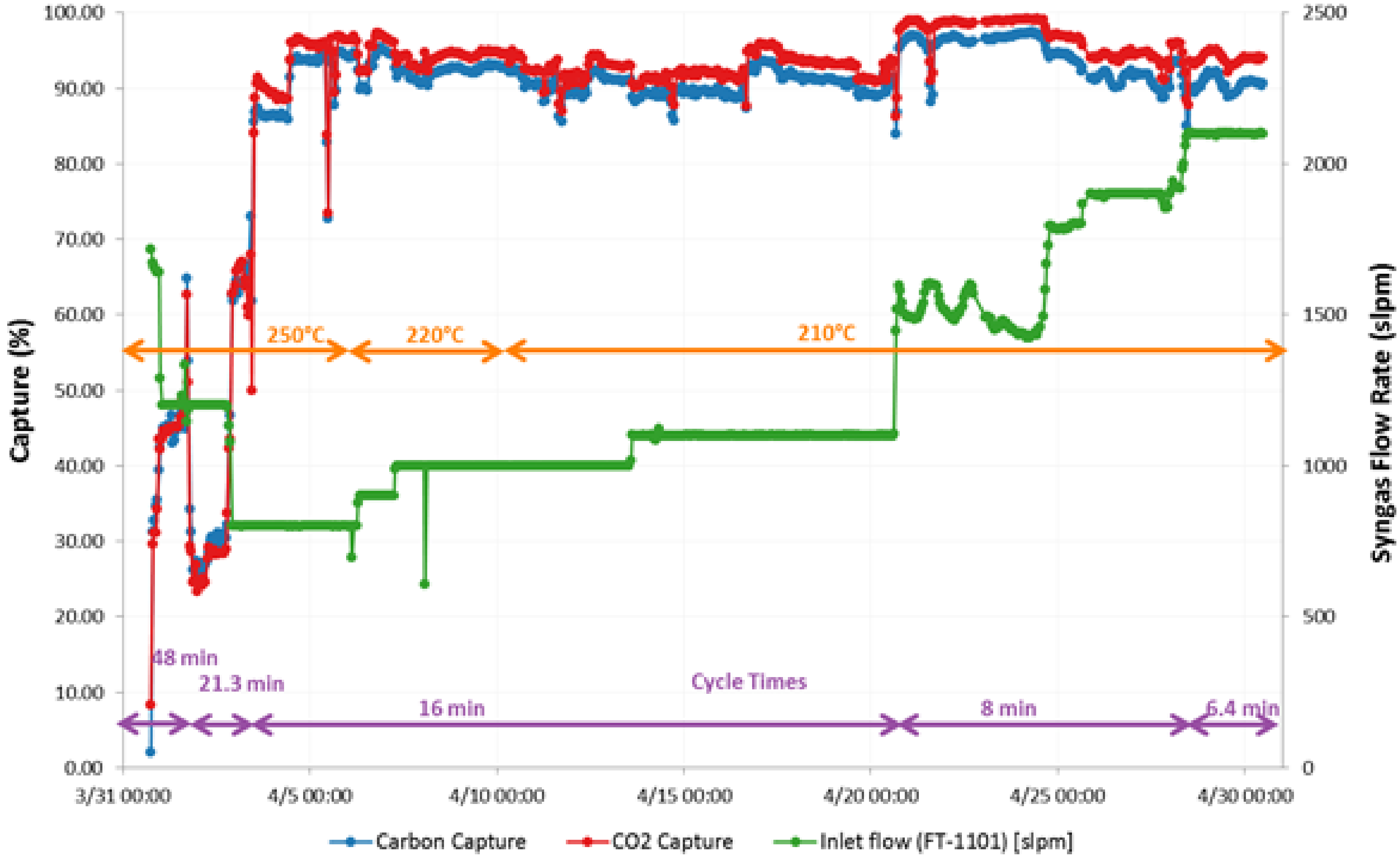
WGS Reactors Operating Conditions



PSA System Operating Conditions

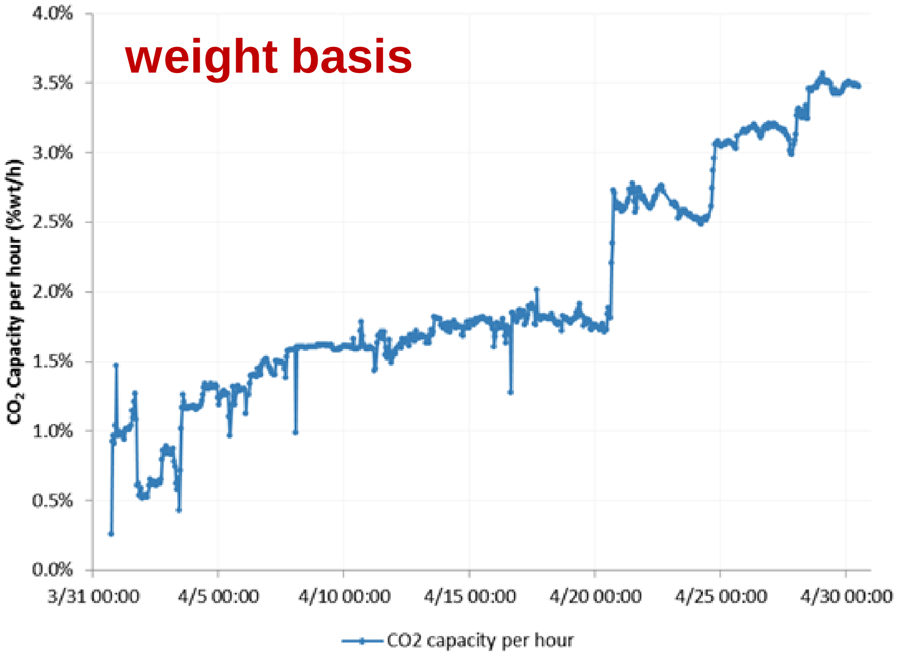


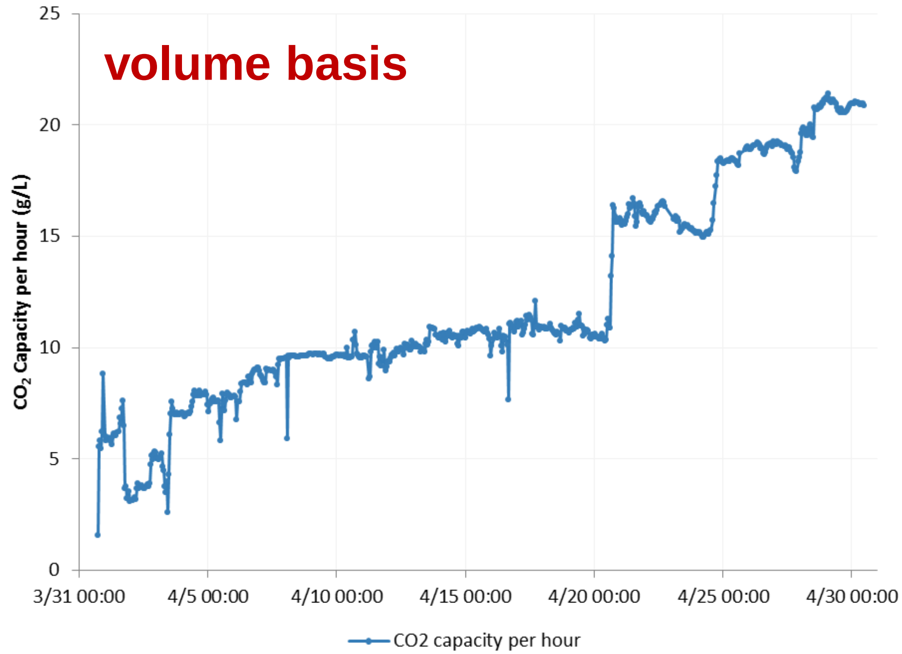
Test Summary



- **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)**

Working Capacity of the Sorbent





- **Sorbent's working capacity increased during the course of the test by:**
  - Reducing 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**
  - In the next field test at Sinopec we will change our flow control valve to further increase the flow

TDA RESEARCH

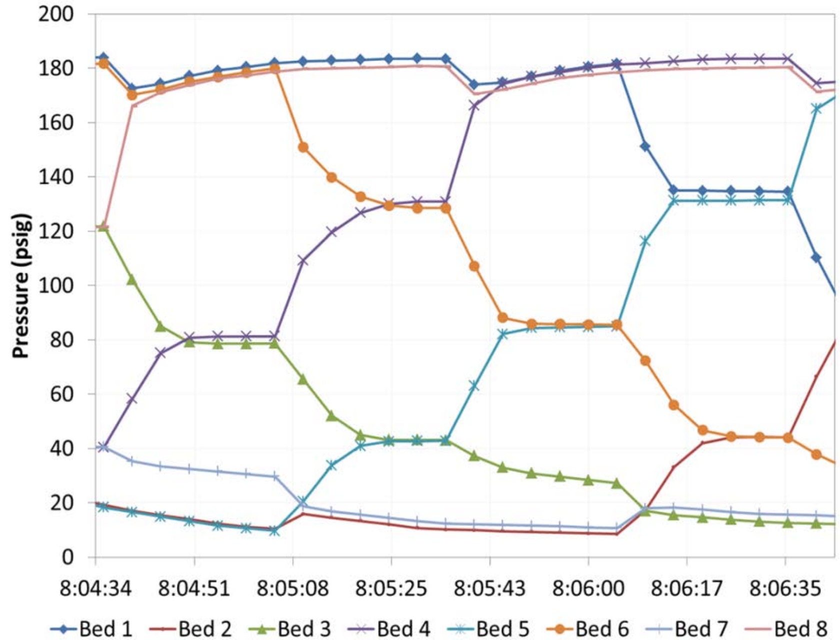
Cycle Scheme with Parallel Flows

- **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 (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	

- **Optimized cycle scheme uses parallel flow 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 at NCCC and showed 50% higher bed utilization**

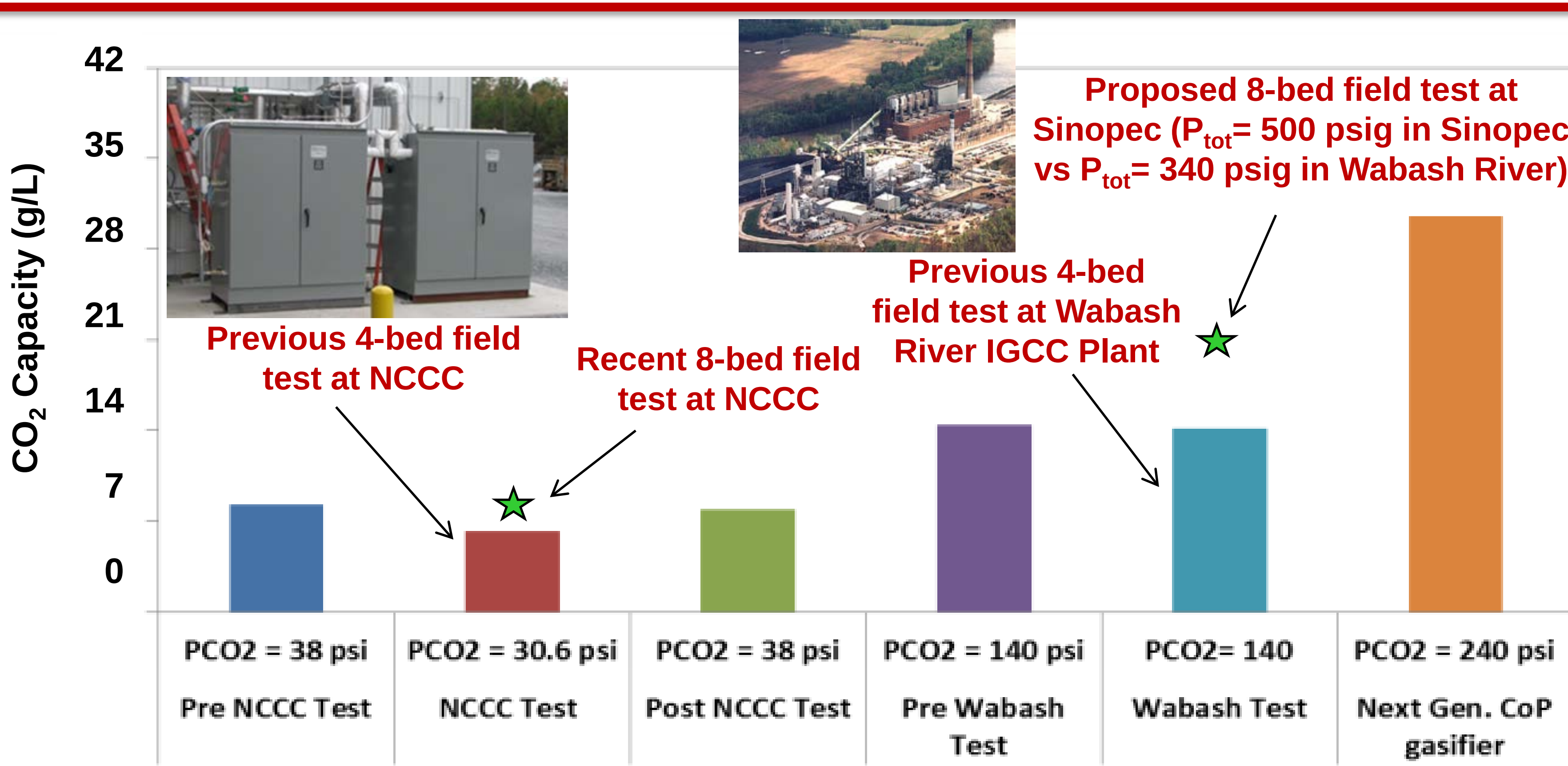


Summary

	Design		Actual
	Sinopec	NCCC	NCCC
Syngas Flow to DeS/WGS Skid (SCFM)	73	43	53
Syngas Flow to CO_2 PSA Skid (SCFM)	100	48	57
Steam Added for WGS RxN (SCFM)	27.2	4.1	4.3
CO_2 Capture (kg/hr)	105.3	25	29.6
Cycle Time (min)	16	16	8
PCO_2 (psi)	175.1	29.1	28.8
Bed Utilization (g CO_2/L-hr)	65.8	15.9	18.5

- **We successfully operated the 8-bed PSA unit with real coal derived syngas**
- **Test unit achieved ~17% higher CO_2 capture than the design performance**
  - Due to improvements in cycle scheme and sorbent capacity
- **High pressure drop caused by the gas conditioning skid limited even higher performance**
- **Minor system modifications are scheduled for September 2017 to achieve higher flows in Sinopec test (while the pressure drop will not be as much as we observed at NCCC)**

Bed Capacity Comparison

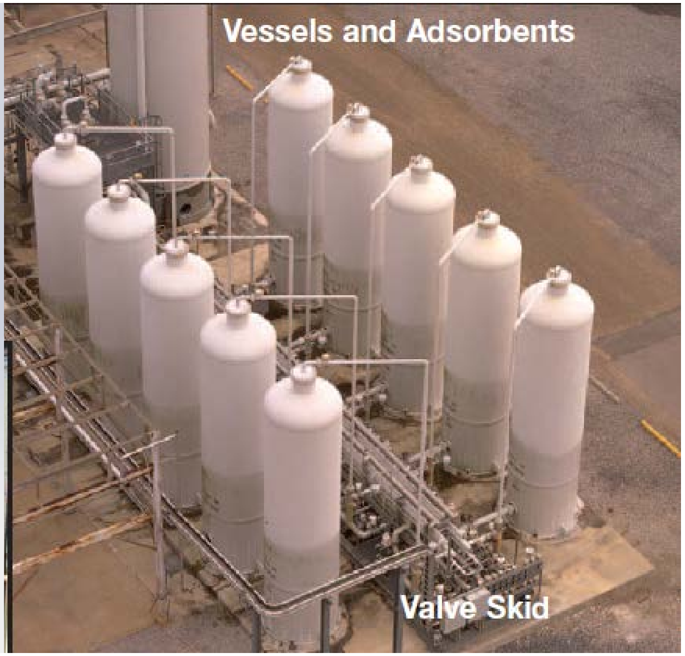


- Sorbent maintained higher CO_2 capacity than the earlier NCCC field tests at ~60X scale
- At Sinopec the system is expected to achieve significantly higher capacity than it had achieved in the previous oxy-fired gasification tests at Wabash River IGCC power plant

Reactor Design

- Different reactor concepts have been evaluated
- Multiple train vertical reactor configuration with internal flow distribution is selected for final design

TDA Design

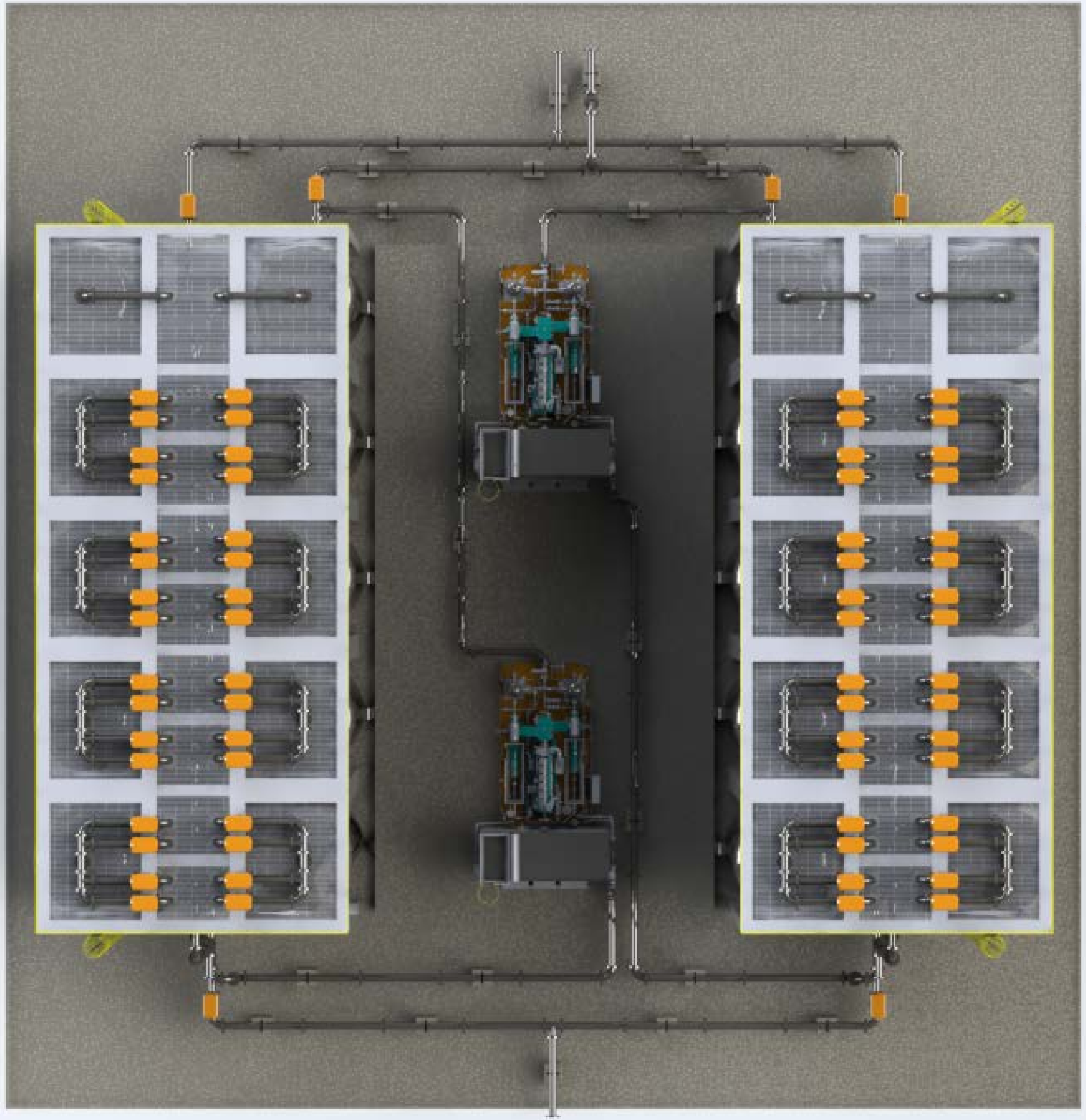


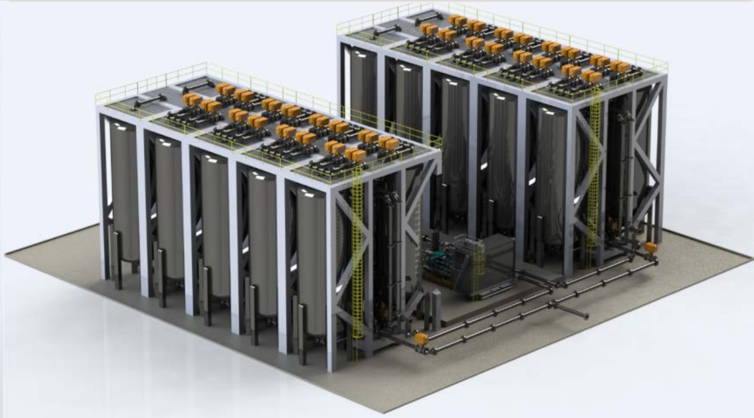
Source: Honeywell/UOP

GE Gasifier	
Syngas flow, kmol/h	34,747
Sorbent needed, kg L	1,115,903 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 Length, ft Vessel wall thickness, in	 14 30.1 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)

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^{TM} & GE Gasifiers

Gasifier	E-Gas		GE	
Case	1	2	3	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	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^{TM} (32.0% and 31.0%)
- Cost of CO_2 capture excluding TS&M is calculated as $31 and $30 per tonne for GE and E-Gas^{TM} gasifiers, respectively (16-30% reduction against Selexol^{TM})
- DOE target of $40 per tonne is reached even with TS&M included

TDA RESEARCH

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 provided the DE-FE-0013105 project is greatly acknowledged
- Project Manager, Andy O’Palko