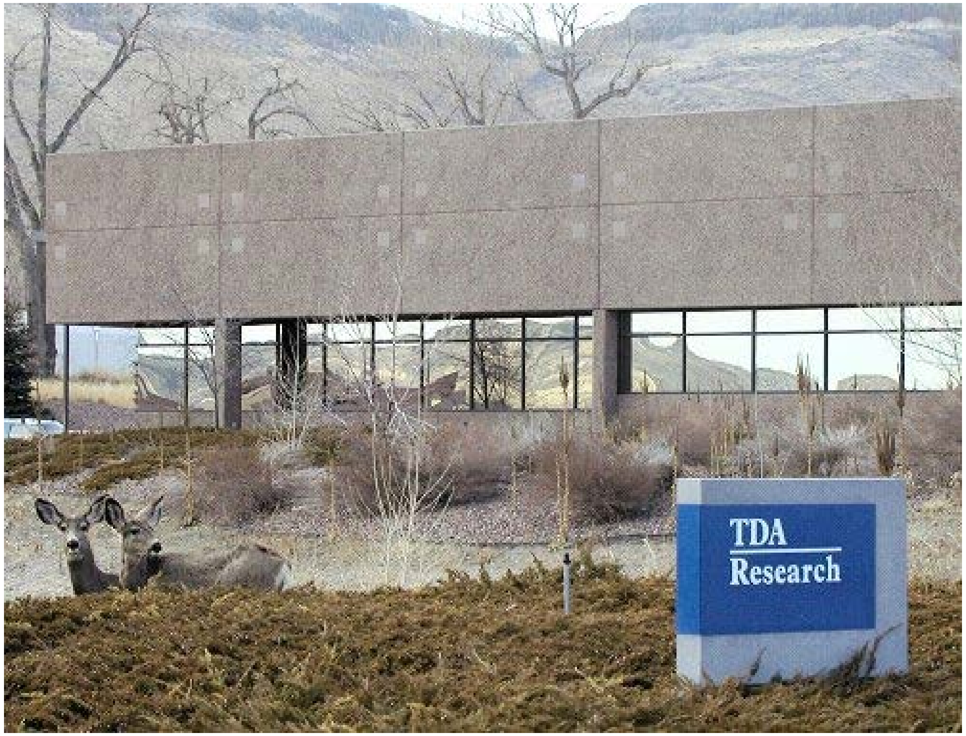
Pilot Testing of a Highly Efficient Pre-combustion Sorbent-based Carbon Capture System (Contract No. DE-FE-0013105)



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2019 DOE/NETL CO_2 Capture Technology Meeting

August 28, 2019

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/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

TDA RESEARCH

Project Partners

Project Duration

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

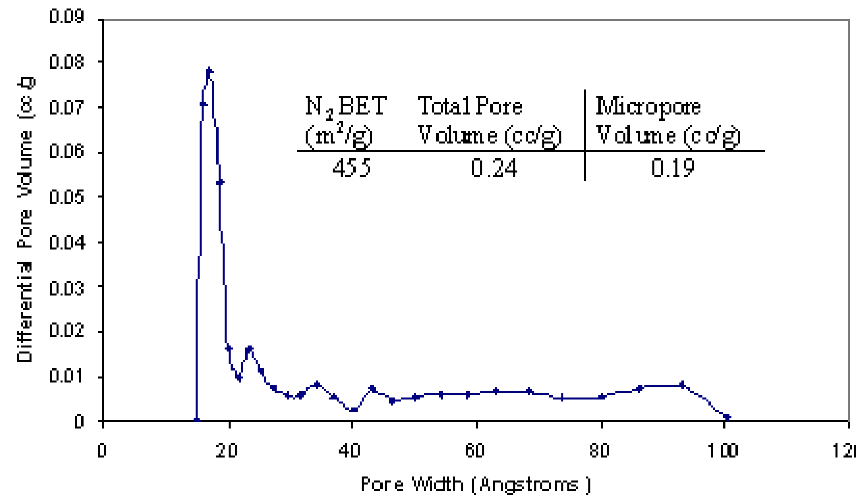
Budget

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

* 12 month no cost time extension is requested from DOE

TDA's Sorbent

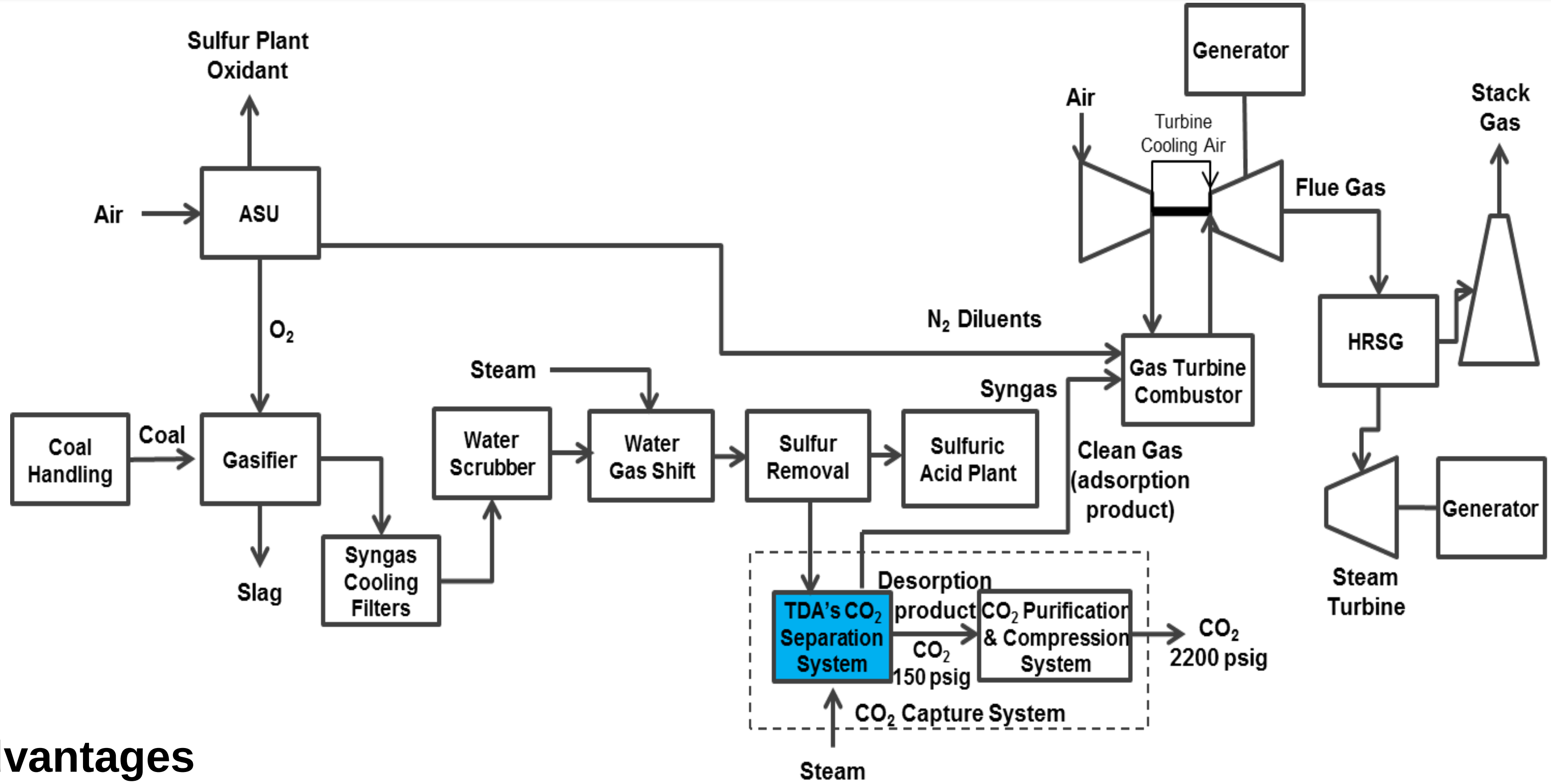
- **TDA's uses a mesoporous carbon with surface functional groups that remove CO_2 via strong physical adsorption**
  - CO_2-surface interaction is strong enough to allow operation at elevated temperatures
  - Because CO_2 is not bonded via a covalent bond, energy input for regeneration is low
- **Heat of CO_2 adsorption is 4.9 kcal/mol for TDA sorbent**
  - Net energy loss in sorbent regeneration is similar to Selexol; much higher IGCC efficiency can be achieved due to high temperature CO_2 capture
- **Favorable material properties**
  - Pore size is tuned to 10 to 100 A
  - Mesopores eliminates diffusion limitations



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 CO_2 Capture System Using a Regenerable Sorbent"

TDA Research

Integration to the IGCC Power Plant

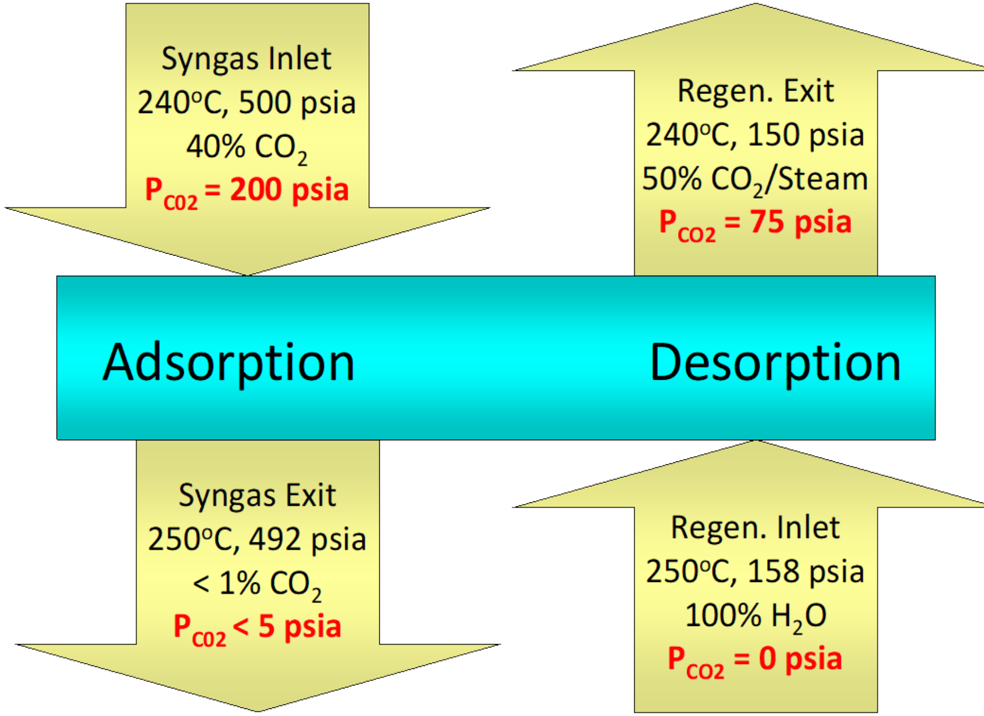


Advantages

- 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

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

Technology Maturation Timeline








2008	2011	2013	2014	2017	2018	2019
Bench-scale tests	0.5-1 kW tests at NCCC	0.5-1 kW tests at Wabash River IGCC	Sorbent Scale-up IP secured	0.1 MW tests at NCCC	Integrated with WGS Tests with Praxair	0.1 MW Tests at Sinopec/ Yangtze Chem. Nanhua Plant

Primary Focus

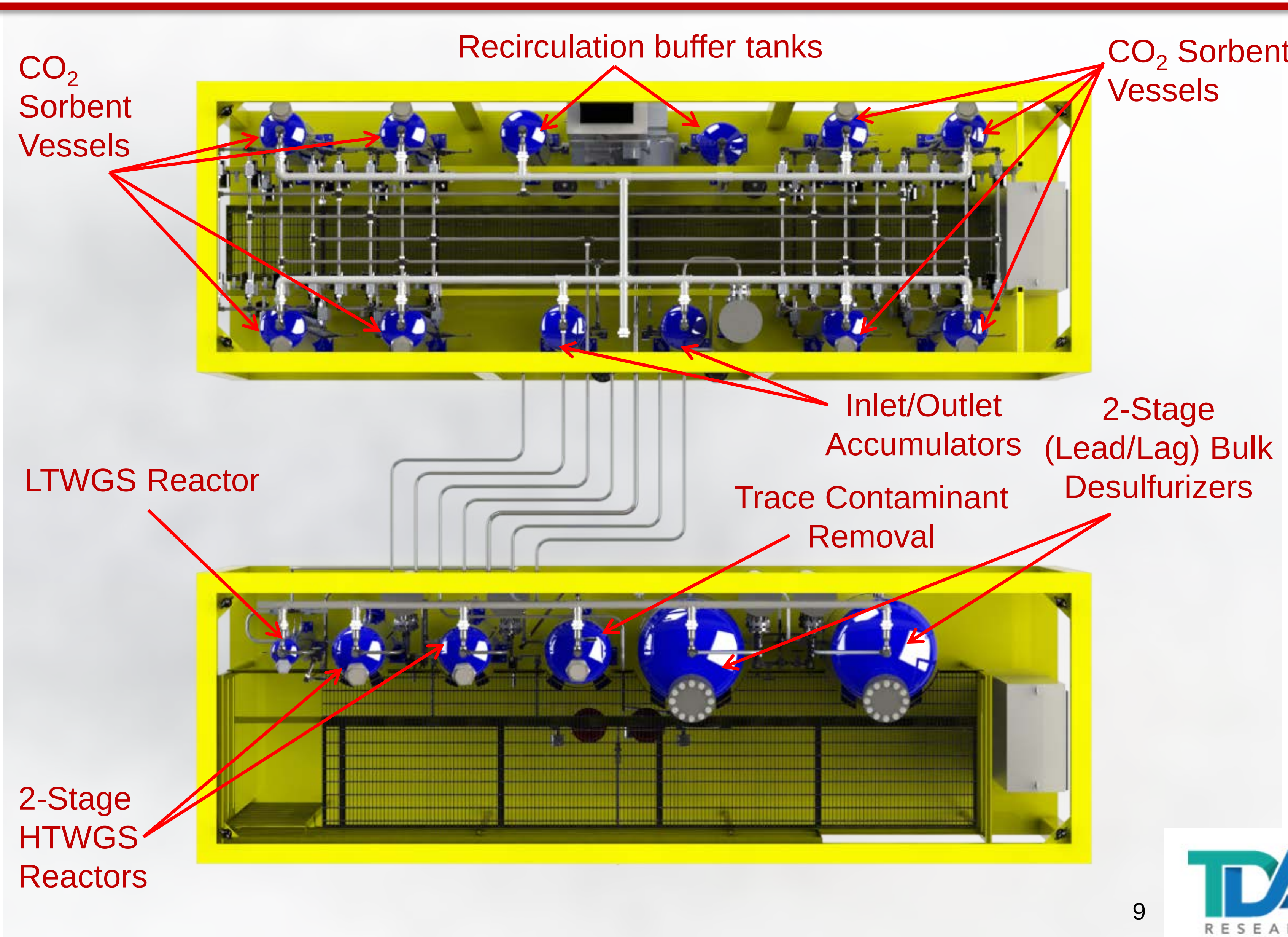
- **0.1 MW_e evaluation in a world class IGCC plant to demonstrate full benefits of the technology**
  - **Testing with high pressure gas**
- **Demonstrate full operation scheme**
  - 8 reactors and all accumulators
  - Utilize product/inert gas purges
  - H_2 recovery/CO_2 purity
- **Evaluations at various sites using coal-derived syngas**
  - Field Test #1 at NCCC – Air blown gasification
  - Field Test #2 at Sinopec Nanhua Petro-chemical Plant, Nanjing, Jiangsu Province, China – Oxygen blown gasification

National Carbon Capture Center

Nanhua Plant Syngas Supply	
Composition	**mol%**
H2	32.493
CO	0.546
CO2	24.715
H2S	0.083
COS	0
C1	0.021
N2	0.128
AR	0.05
NH3	0.069
HCN	0
HCL	0
H2O	41.895
温度 Temperature, C	265.6
压力 Pressure, MPaG	4

Sinopec/Yangtzi Chemicals Petro-chemical Complex

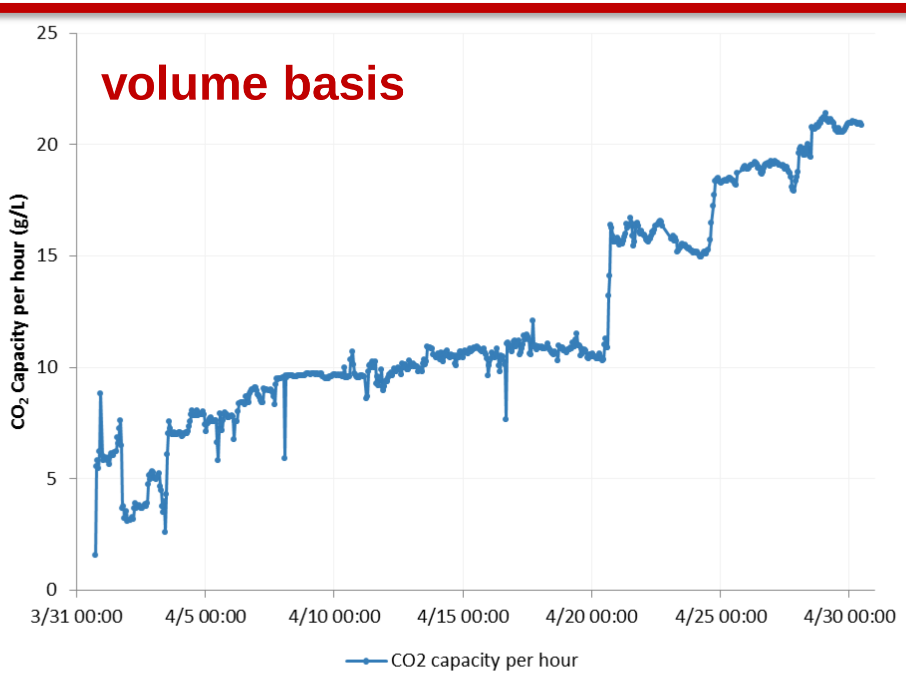
Slipstream Test Skid - Top View

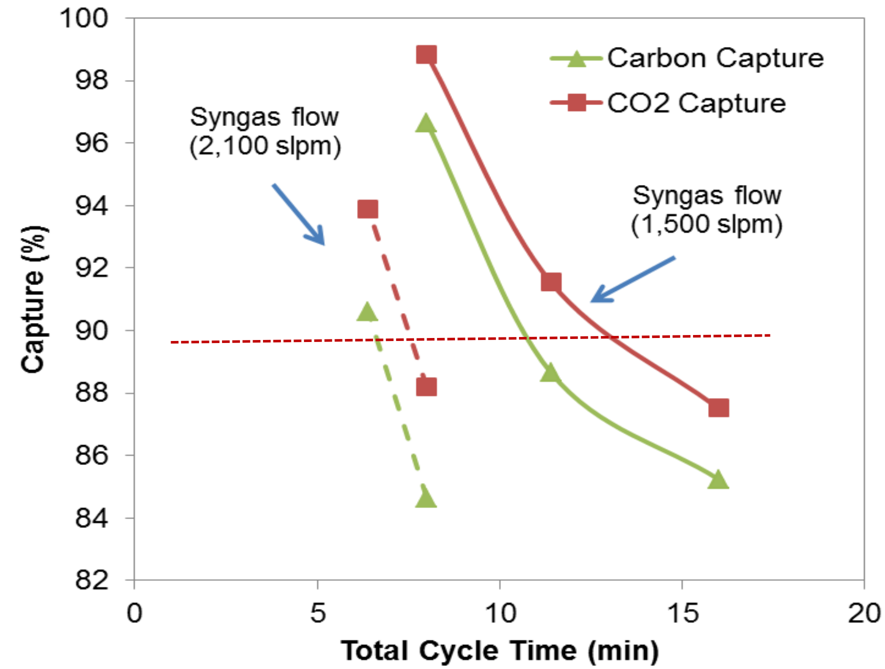


Field Test Unit Installed at NCCC

- **Fabrication is completed in 2016**
- **Installation with all the hook-ups were completed in March 2017**
- **Testing initiated in April 2017**

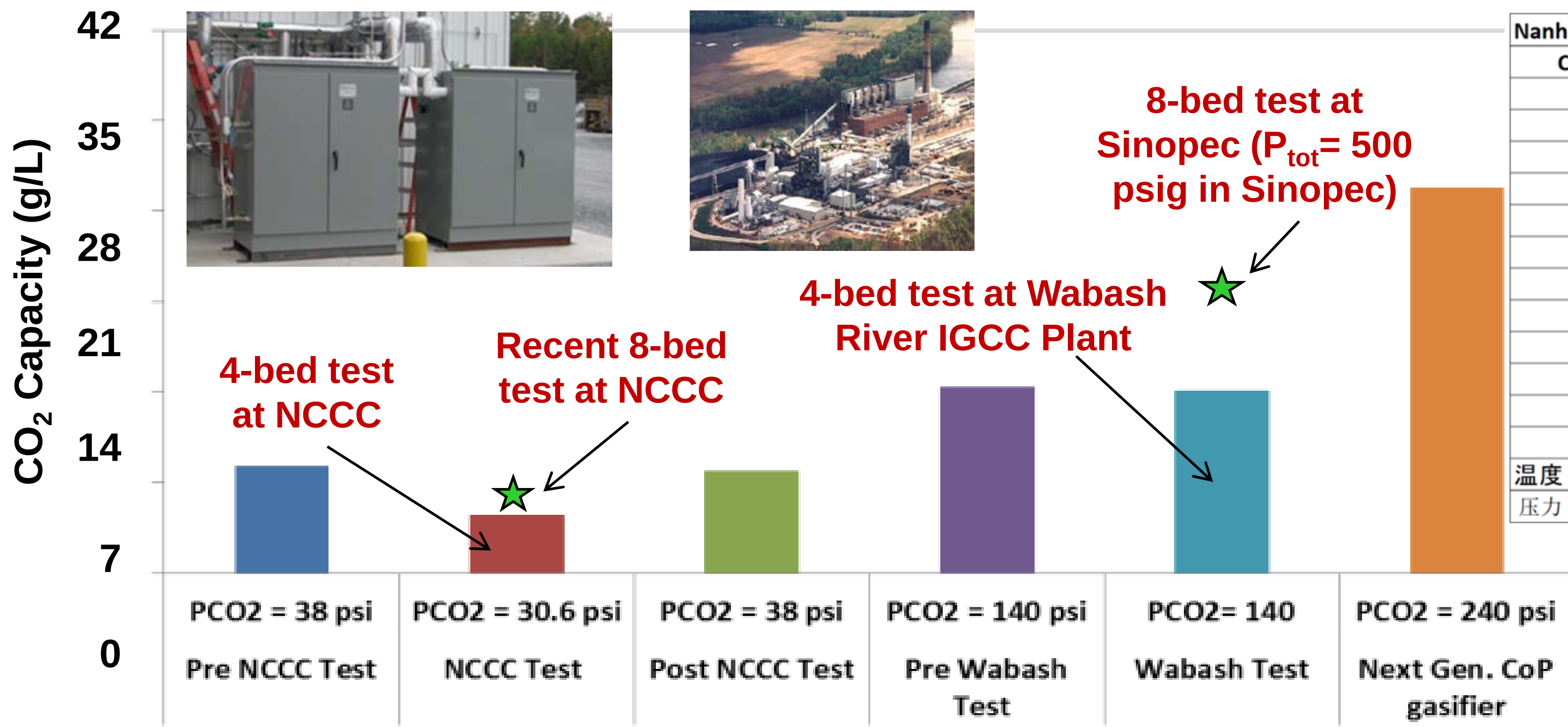
Working Capacity of the Sorbent





- A successful 30 day (707 hrs) evaluation was completed at NCCC
  - Design flow at NCCC operating conditions was 1,420 SLPM (50 SCFM)
  - 97.3% capture @ 1,500 SLPM
  - 93% @ 1,800 SLPM
  - 90% @ 2,100 SLPM
- Pressure drop through the gas conditioning skid prevented flowing more than 2,100 SLPM of syngas through the PSA skids

Sorbent Performance



Nanhua Plant Syngas Supply	
Composition	mol%
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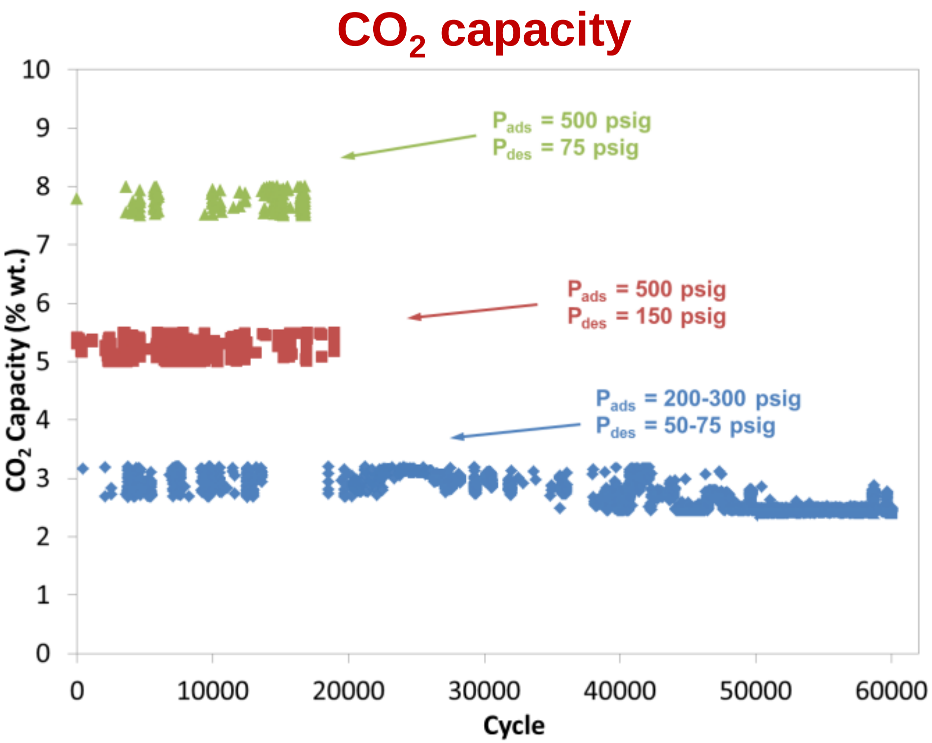
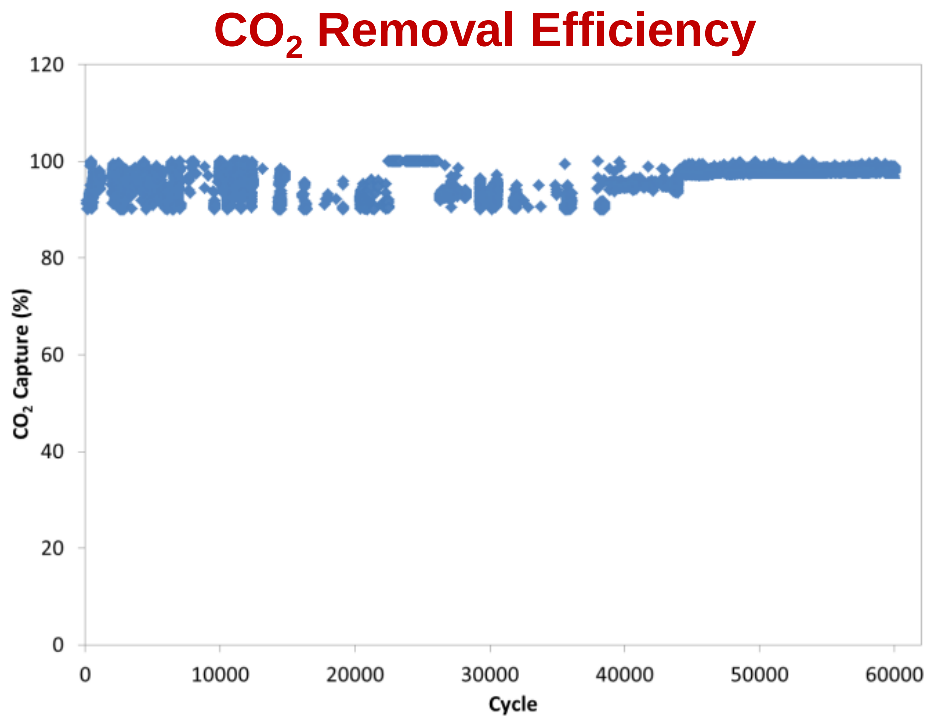
CO2	24.715
H2S	0.083
COS	0
C1	0.021
N2	0.128
AR	0.05
NH3	0.069
HCN	0
HCL	0
H2O	41.895
温度 Temperature, C	265.6
压力 Pressure, MPaG	4

- **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**
- **Total Pressure – 340 vs 500 psia**
  - CO_2 Partial pressure <2X due to lower N_2 content and high syngas P

Sorbent Evaluations – Multiple Cycles



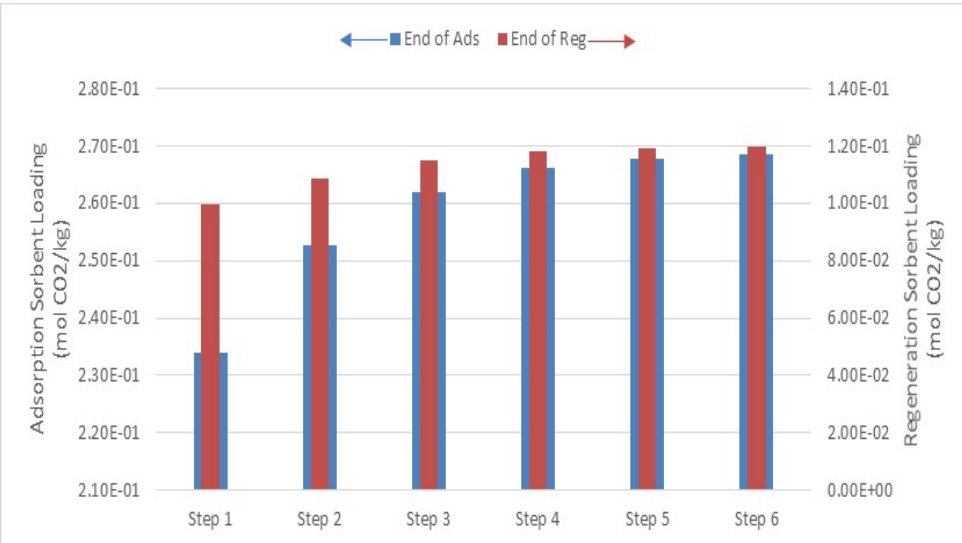


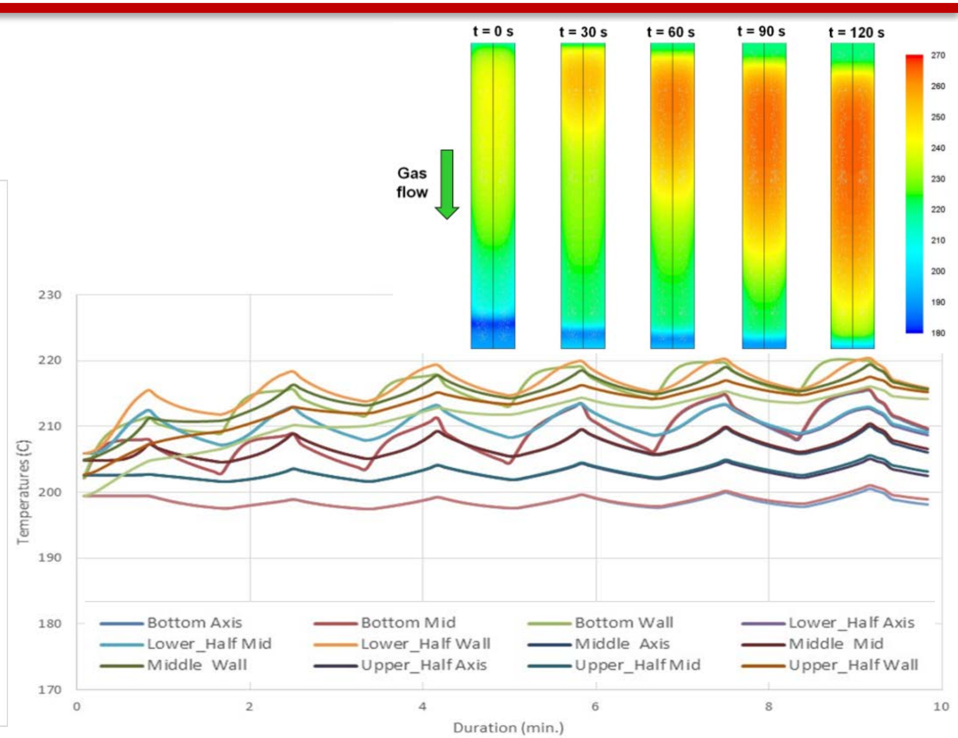
	Synthesis Gas	Simulated Gas	Steam Purge
Temperature	200°C	200°C	200°C
Pressure	500 psig	200-500 psig	50-300 psig
	Composition		
H_2	42.8%	53.4%	50.0%
CO_2	30.0%*	30.0%	-
H_2O	26.6%	26.6%	50.0%+
CO	0.6%	-	-

+ adjusted for purge with 100% steam at 150 psia

- **Long-term cycling of the scaled-up sorbent has been completed with stable performance over 60,000 cycles**

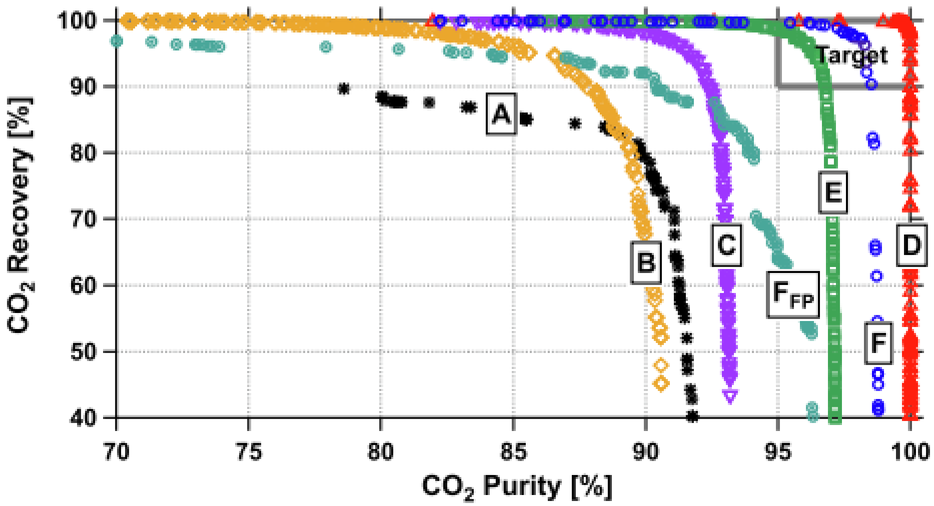
CFD Model Tuning

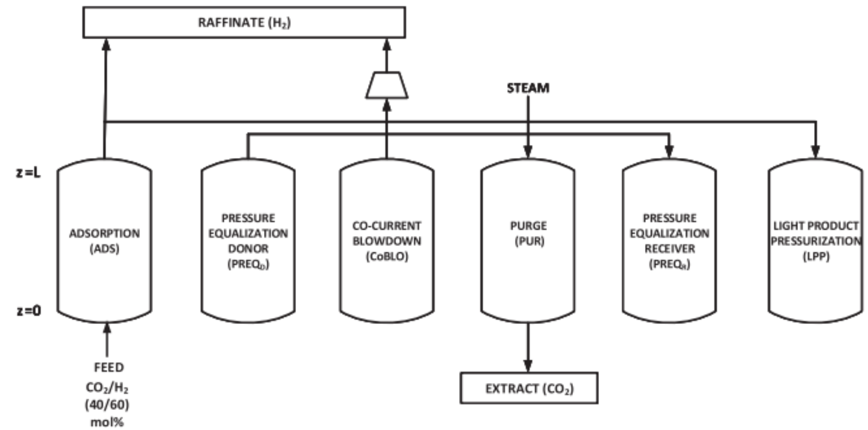




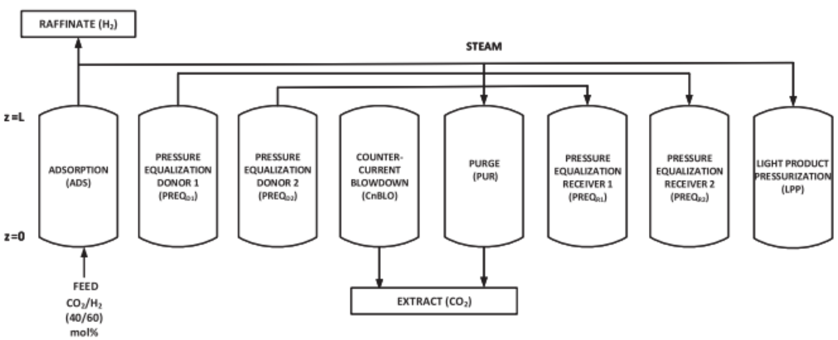
- **Working with GTI, we developed a CFD model to support reactor design**
- **The model was tuned using the data from 1 kW and 0.1 MW systems evaluated at Wabash River IGCC Plant and NCCC field tests**
- **CFD simulations reached steady state in 6 cycles and the working capacity matched the data sets**
- **CFD model will be further tuned using data from Sinopec field datasets**

Cycle Optimization

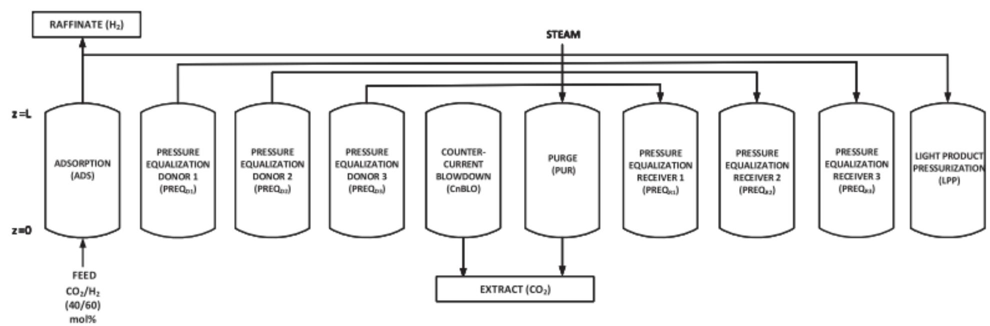




D. 6-step PSA cycle with CoBLO, purge, PREQ & LPP



E. 8-step PSA cycle with CnBLO, purge, two PREQ & LPP



F. 10-step PSA cycle with CnBLO, purge, three PREQ & LPP

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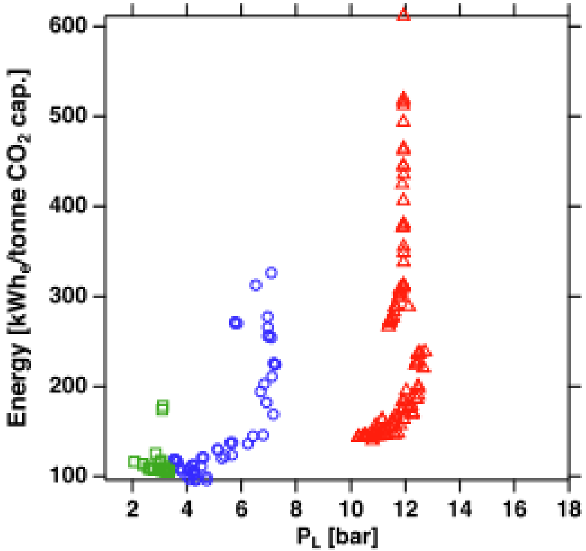
- **Cycle Schemes D, E and F that use pressure equalizations and co-current blowdown met DOE targets of 90% capture and 95% CO_2 purity**

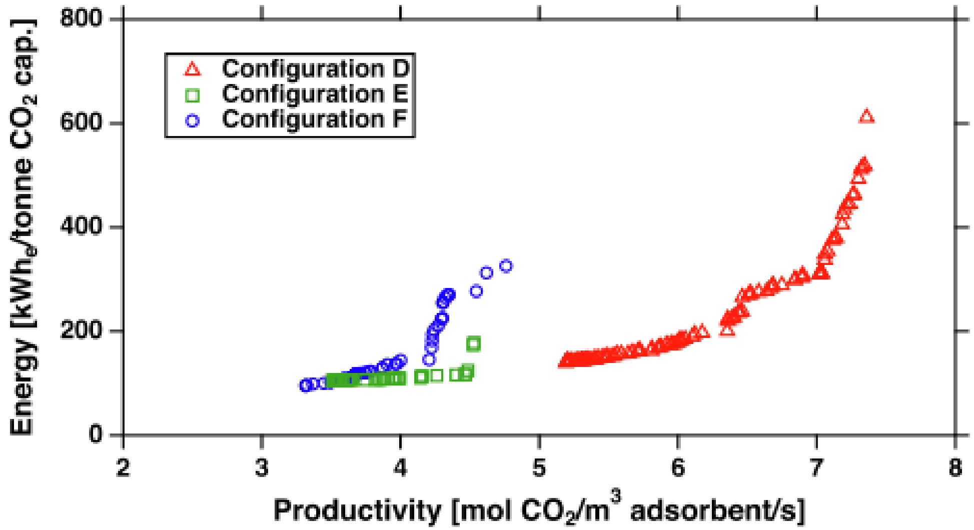
RESEARCH

Minimization of Energy Penalty

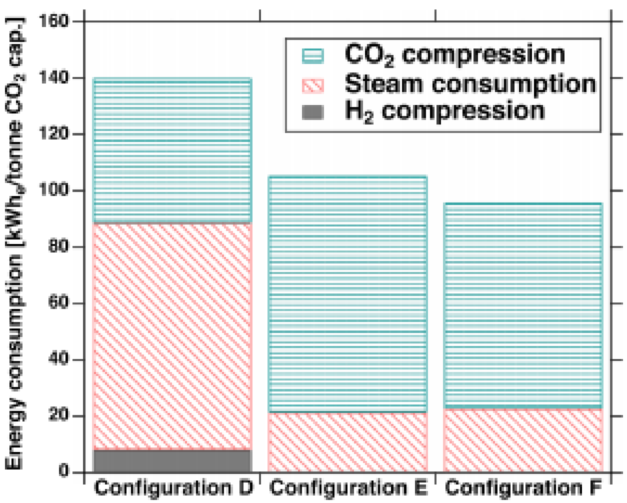
CO_2 Recovery Pressure



Sorbent Productivity/Bed Size Factor



Energy Consumption



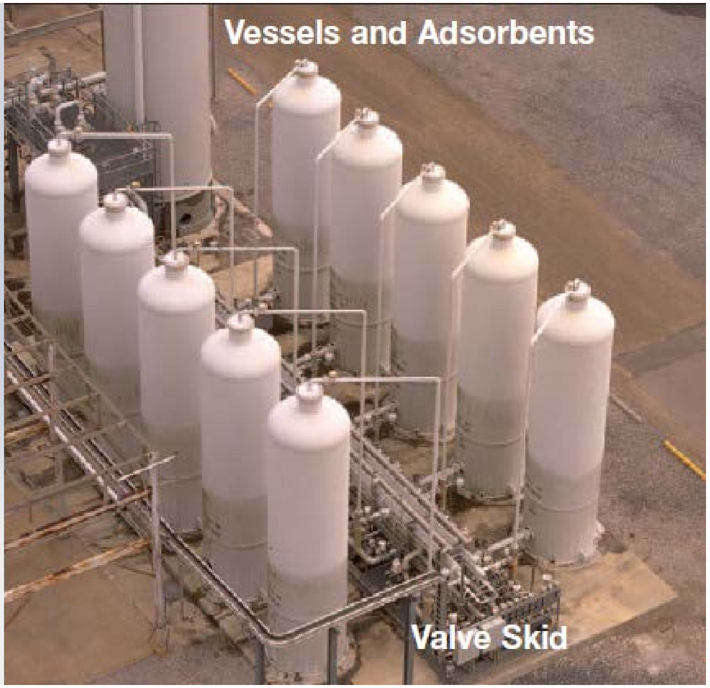
- Configuration F: 10-step PSA cycle with three pressure equalizations: 95.7 kWh/tonne of CO_2 captured at productivity of 3.3 mol $CO_2/m^3/s$
- Configuration D: 6-step PSA cycle with one pressure equalization and a co-current blowdown: 140 kWh/tonne of CO_2 captured at productivity of 5.2 mol $CO_2/m^3/s$
- OPEX/CAPEX trade-off is being evaluated for a fully optimized PSA cycle

TDA RESEARCH

Reactor Design

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

TDA Design

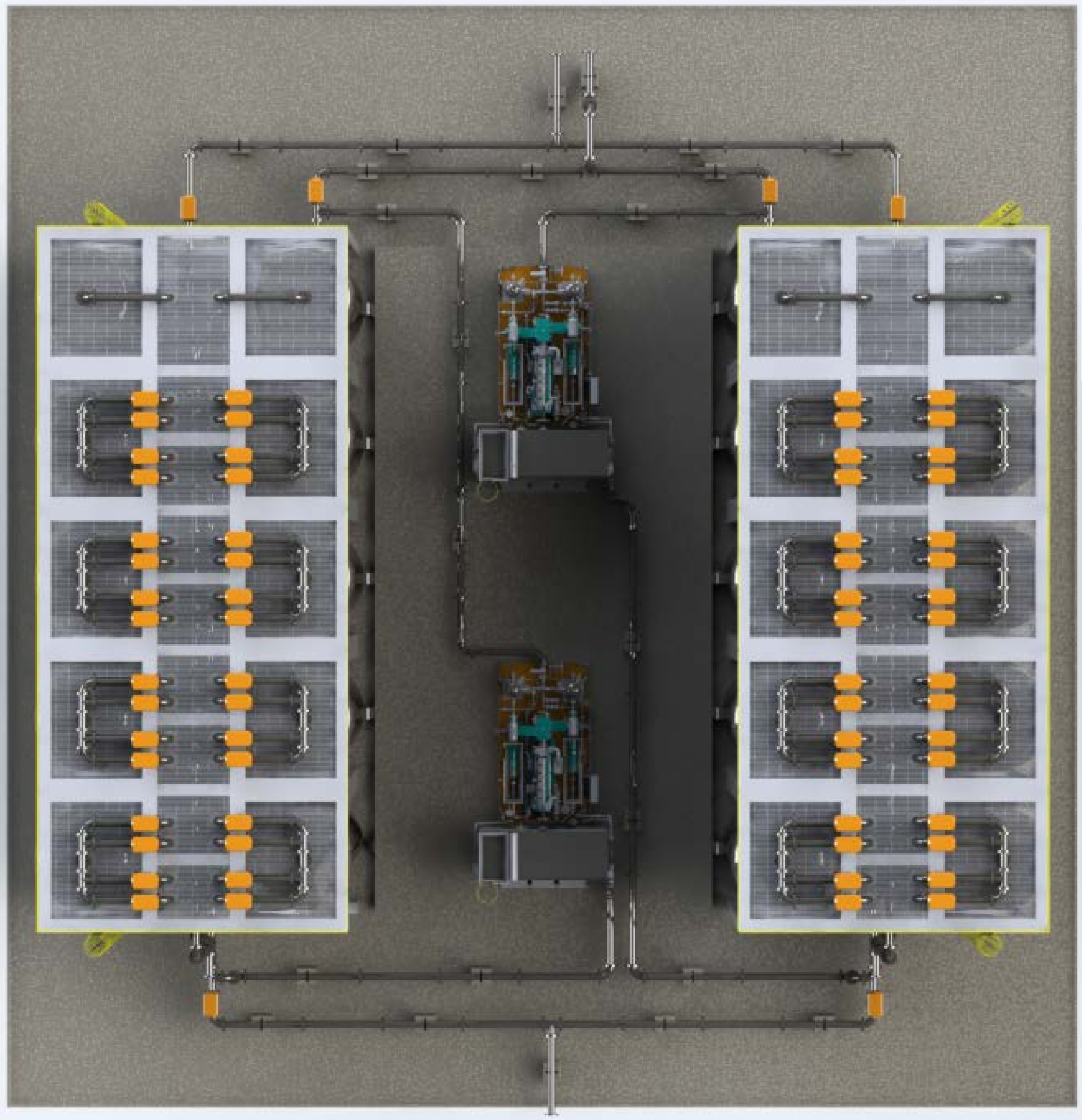


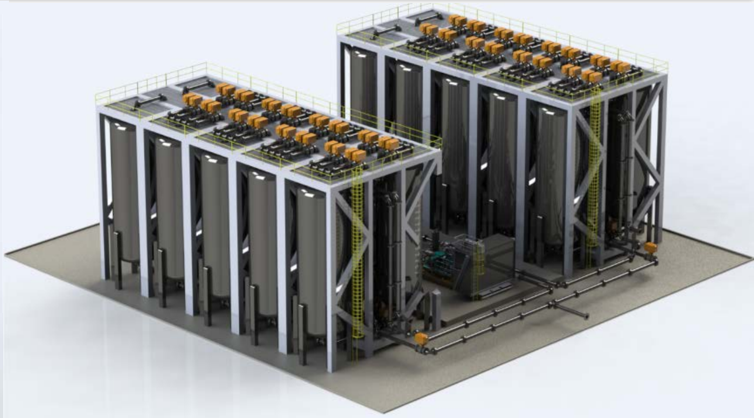
Source: Honeywell/UOP

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

Techno-economic Analysis

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%) for E-Gas™ and GE gasifiers**
- **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™)**
- **Cost of CO_2 capture is calculated as $40 and $28 per tonne for Shell and TRIG gasifiers, respectively (15-28% reduction against Selexol™)**

Sinopec Field Test Update

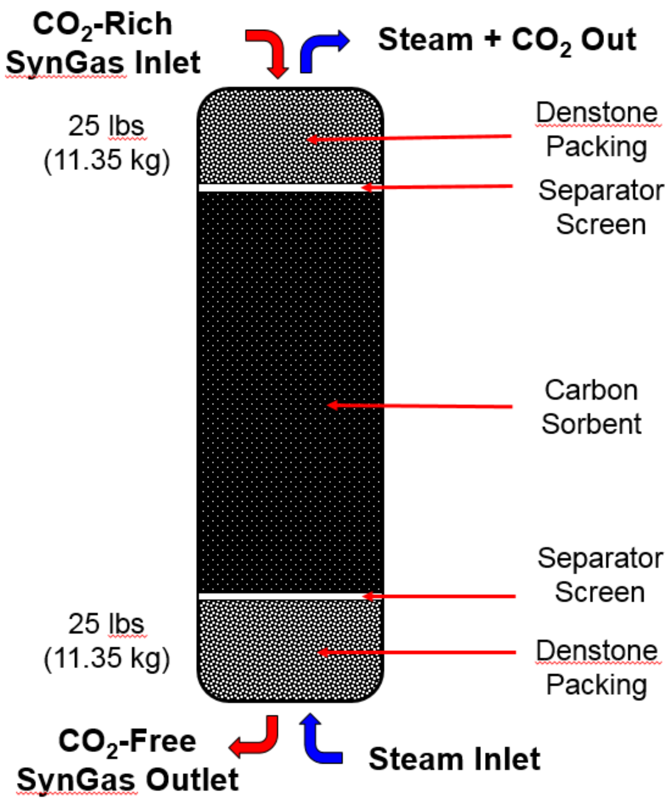
- 2 skids and 2 containers (containing sorbents, catalyst, analyzers, supplies, toolboxes) are shipped to China in December 2017
- Both skids and one of the containers were delivered to the site on April 2018
- One skid held up due to the hazardous nature of the WGS catalyst and regulations on some of the power equipment
- Catalyst, transformer, fiber optic cable etc. were procured locally

TDA RESEARCH

Installation Work at Sinopec

- **Because of the delays getting all equipment to site, the test setup had to be moved to a different location in the plant**
- **An existing super-structure at the new site added complexity to installation**
  - Skids were pipe rolled over berm and into place
  - Vessels were loaded manually via socks and buckets

Carbon Bed Filling



Filter separator

Denstone deltaP beads on top of the column

Sorbent loading using socks

- **Stainless mesh screens and Denstone deltaP media are added to the beds (not available in NCCC tests)**
  - The inert ceramic beads eliminated some of the dead volume in the reactor top and bottom
  - Heavy Denstone beads also limits material movement in the bed during cycling

Pipework and Utility Connections





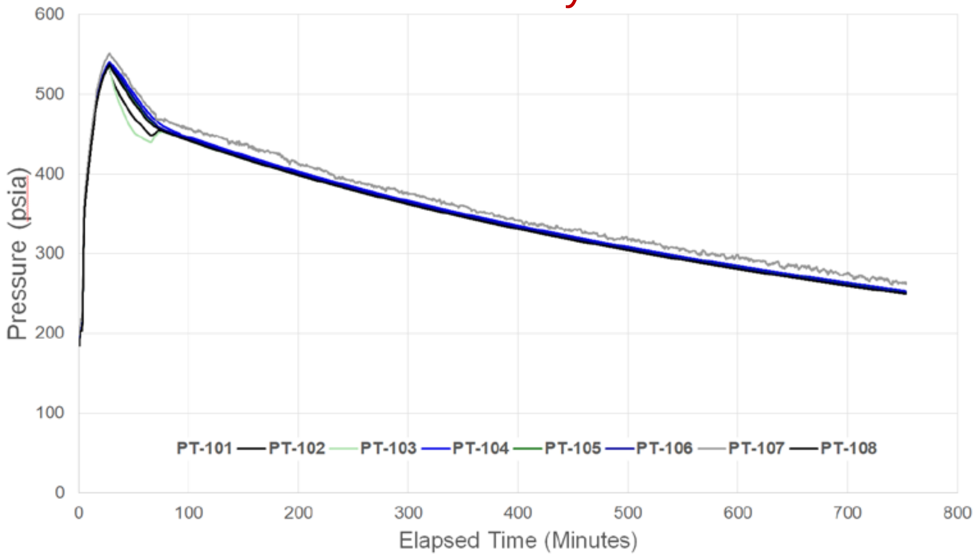
- **Sinopec completed all needed site modifications and installations in the plant**
  - **Syngas Inlet Line – 120 m insulated line**
  - **Syngas Return Line – 120 m insulated line (high emphasis on reserving as much H_2 as possible)**
  - **Exhaust/flare lines – 120 m**
  - **High and Low P nitrogen – 100 m**
  - **Instrument air – 100 m**
  - **Cooling water lines inlet and return – 15 m**
  - **Electrical connections – 400 m**
    - **400VAC to 480VAC transformer procured from China was installed**
  - **Fiber optic lines from the control room to the skid PC – 450 m**

Pilot Plant Installed at Sinopec

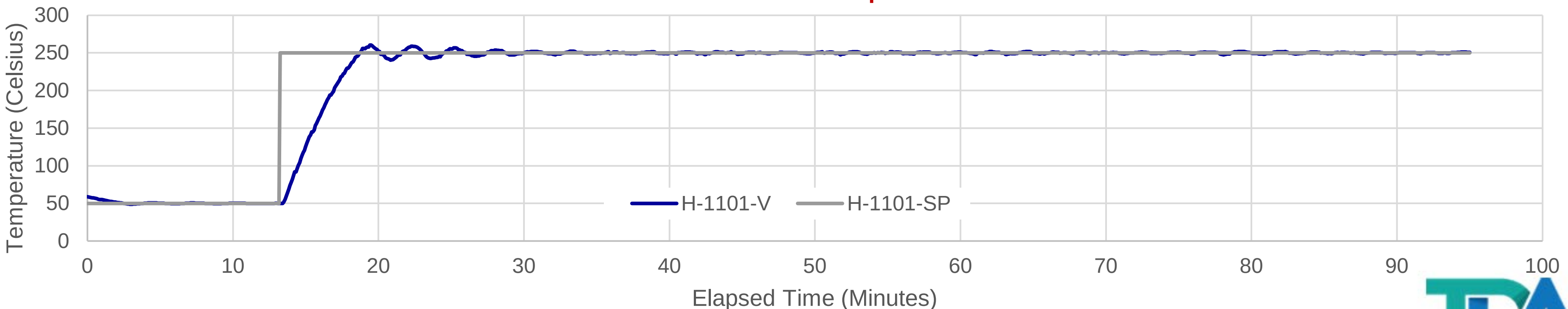
Shakedown Tests

- **All leak checks were completed**
  - **Long road trip from NCCC Alabama to Los Angeles, ocean travel to Shanghai, followed by another road trip to Nanjing**
  - **Skids were lifted several times China (one improperly despite having a specified lift plan)**
- **Pressure decay testing was performed at 4.0 MPag**
- **All heaters, heated lines were tested**

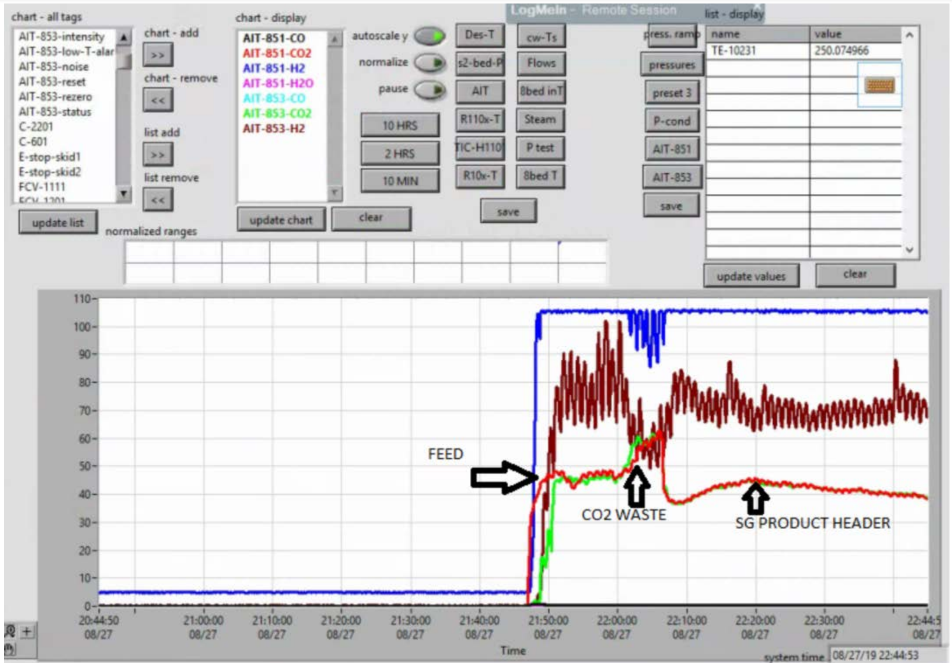
Pressure decay tests

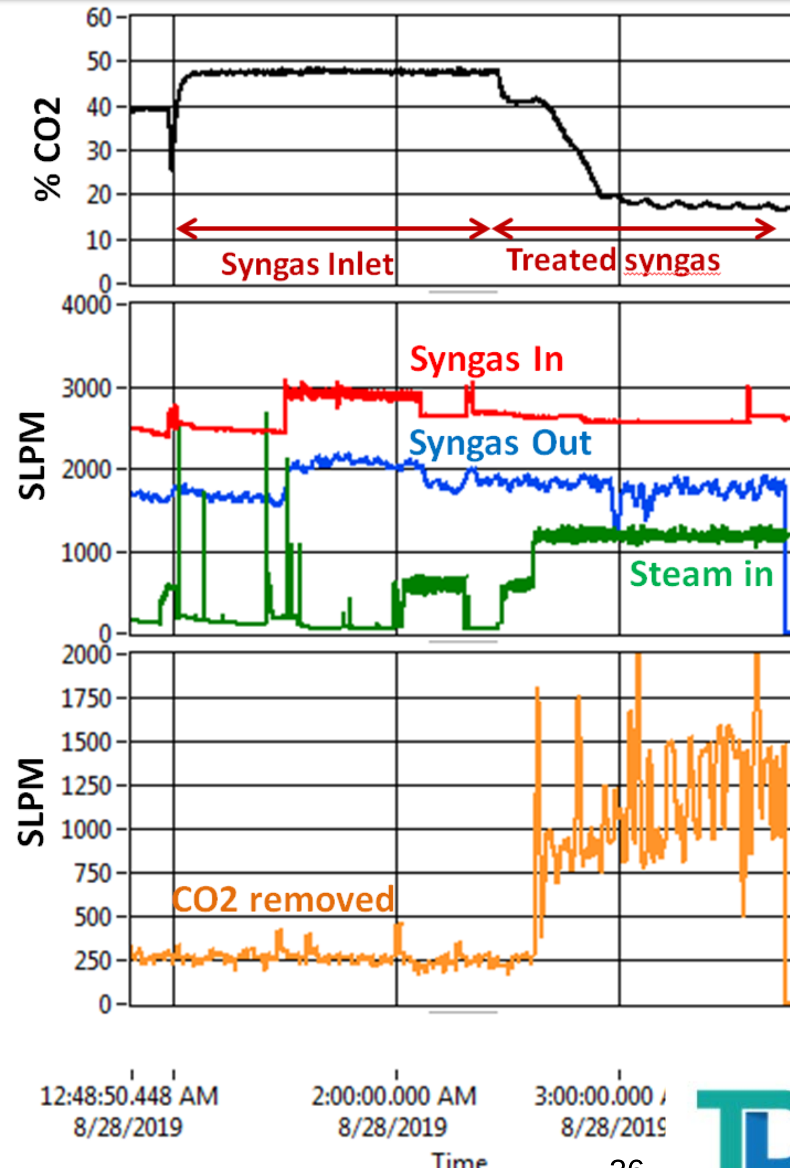


Heater tune-up tests



Very Early Results





- **Testing started on 8/27/2019 at 21:50 MST**
- **High syngas flow, high T, low P during start-up to avoid water/tar condensation in the system**
- **2500 SLPM Syngas Flow**
- **~85% CO_2 removal efficiency**
- **~110 kg/hr CO_2 removal rate**

TDA RESEARCH

Next Steps

- A fiber optic cable with adapters to Ethernet at both ends will be installed to allow monitoring the equipment from the USA and for data transfer
  - The distance from the skids to the control room is roughly 400m
- Training of plant personnel is underway
- Within 2-3 weeks of routine operation, TDA will let Sinopec/Yangtze employees to run the unit (basic maintenance etc.)
- 6 to 9 month evaluation is planned

Acknowledgements

- DOE/NETL funding under the DE-FE-0013105 project
- Project Manager, Andy O'Palko
- Chuck Shistla, GTI
- Ashok Rao, UCI
- Arvind Rajandran, UOA
- Frank Morton, NCCC
- Chen Chaomei and Ruan Tian, Sinopec
- Yang Xujie, Yangtze Petrochemicals Nanhua Plant