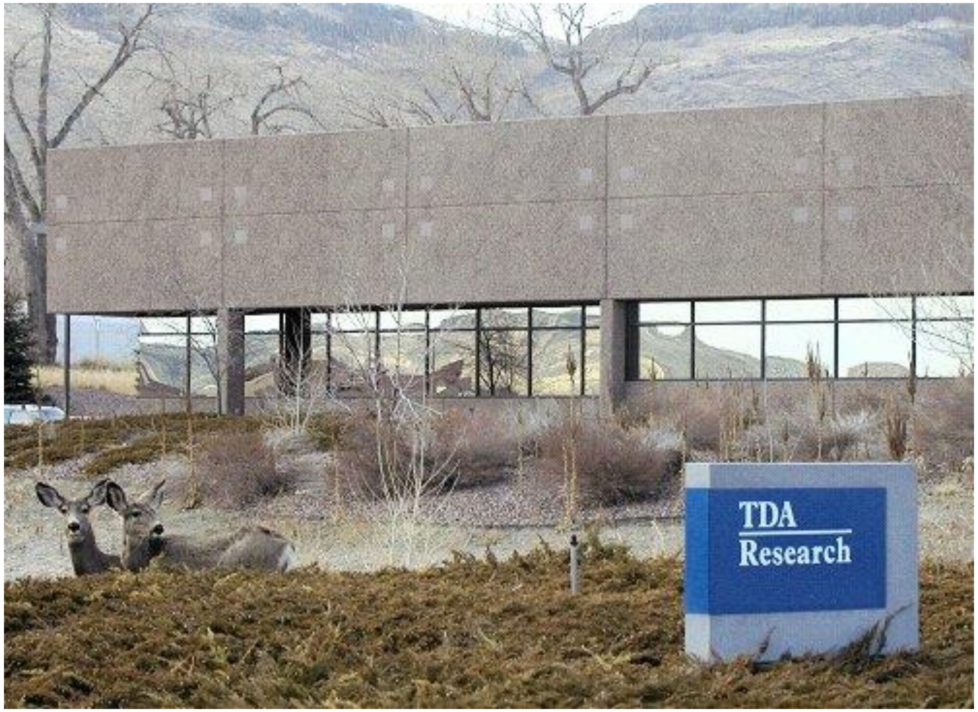
Pilot Testing of a Highly Efficient Pre-combustion Sorbent-based Carbon Capture System (Contract No. DE-FE-0013105)



Gökhan Alptekin

DOE/NETL
Project Kick-off Meeting

Morgantown, WV

January 16, 2013

TDA Research, Inc.

- **Privately Owned / Began operations in 1987**
- **82 full-time technical staff**
  - **Primarily chemists and engineers, more than half with advanced degrees (28 PhDs)**

12345-12355 W 52nd Avenue

22,000 ft^2 offices and labs

Synthetic Chemistry, Catalyst/Sorbent Synthesis and Testing, Machine and Electronics Shops, SEM, TOF Mass Spec

4663 Table Mountain Drive

27,000 ft^2 offices and labs

27 fume hoods, Synthetic Chemistry, Catalytic Process Development

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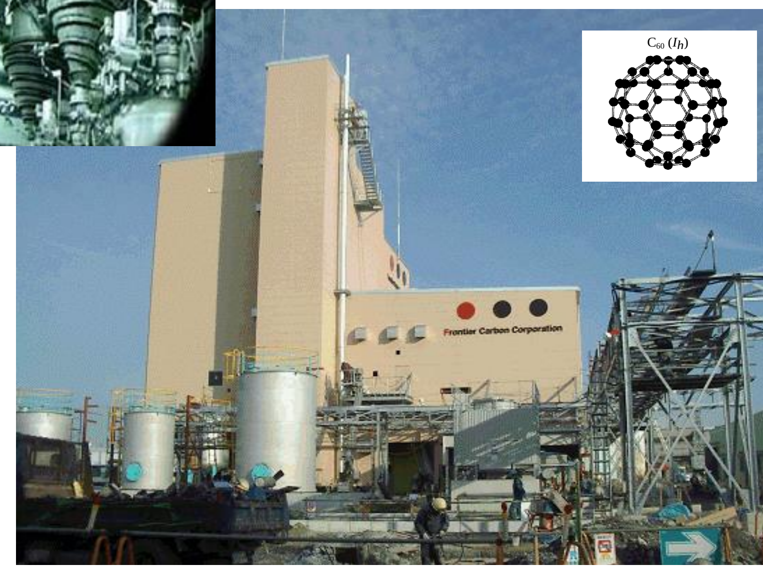
TDA Products - Licences

- **Technologies with high capital investment requirement commercialized via licensing/strategic partnerships**



Direct Oxidation for Bulk Sulfur Removal

Licenses with SulfaTreat DO and GTC (1.3 and 6 ton/day plants at Bakersfield, CA)

Fullerene Synthesis
License with Frontier Carbon
40 ton/year plant in Kitakyushu, Japan TDA built the reactors

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TDA Products – Direct Sales

Ambient Temperature CO Oxidation Catalyst

SuperSoap™

Oligotron™ - Conducting polymers available through Sigma-Aldrich

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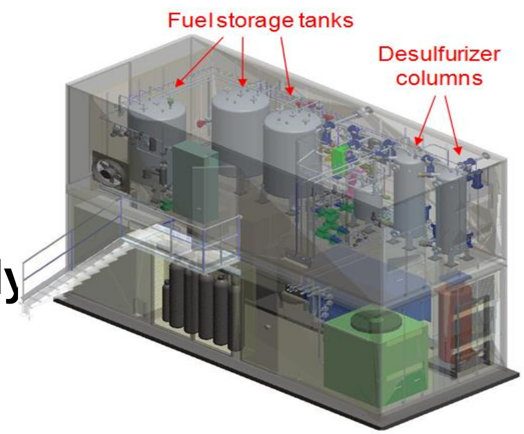
TDA Spin-off - SulfaTrap™ Sorbents



SulfaTrap™ sorbents for stationary/mobile fuel cell applications

- **SulfaTrap™ sorbents desulfurizes various gas streams**
  - Natural gas, LPG, biogas, reformate gas desulfurization, diesel fuel, logistics fuel
- **~50% of fuel cells installed globally (MCFC, SOFC and PEM fuel cells) uses SulfaTrap™ products**

Project Summary

- The overall objective of this work is to develop a new sorbent-based pre-combustion carbon capture technology for Integrated Gasification Combined Cycle (IGCC) power plants
- Demonstrate the techno-economic viability of the new technology by:
  1) Demonstrating pilot-scale 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
  - Concept Demonstration (9 months)
    - 0.1 MW_e Pilot-scale Prototype Fabrication
  - Techno-economic analysis
    - Process simulation supported with Aspen Plus™
    - Engineering design

Project Partners

Project Duration

- Start Date = January 1, 2014
- End Date = September 30, 2017

Budget

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

Potential collaborators

TDA's Approach to CO_2 Capture

- **TDA's CO_2 Capture sorbent consists of 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 measured as 4.9 kcal/mol for TDA sorbent**
  - Selexol ~4 kcal/mol
  - Amine solvents ~14.4 kcal/mol
  - Chemical absorbents 20-40 kcal/mol ($Na_2CO_3 \rightarrow NaHCO_3$ 30 kcal/mol)
- **Net energy loss in sorbent regeneration is similar to Selexol**
  - A much better IGCC efficiency due to high temperature CO_2 capture above the dew point of the synthesis gas
  - Warm gas clean-up improves cycle efficiency 2 to 4%

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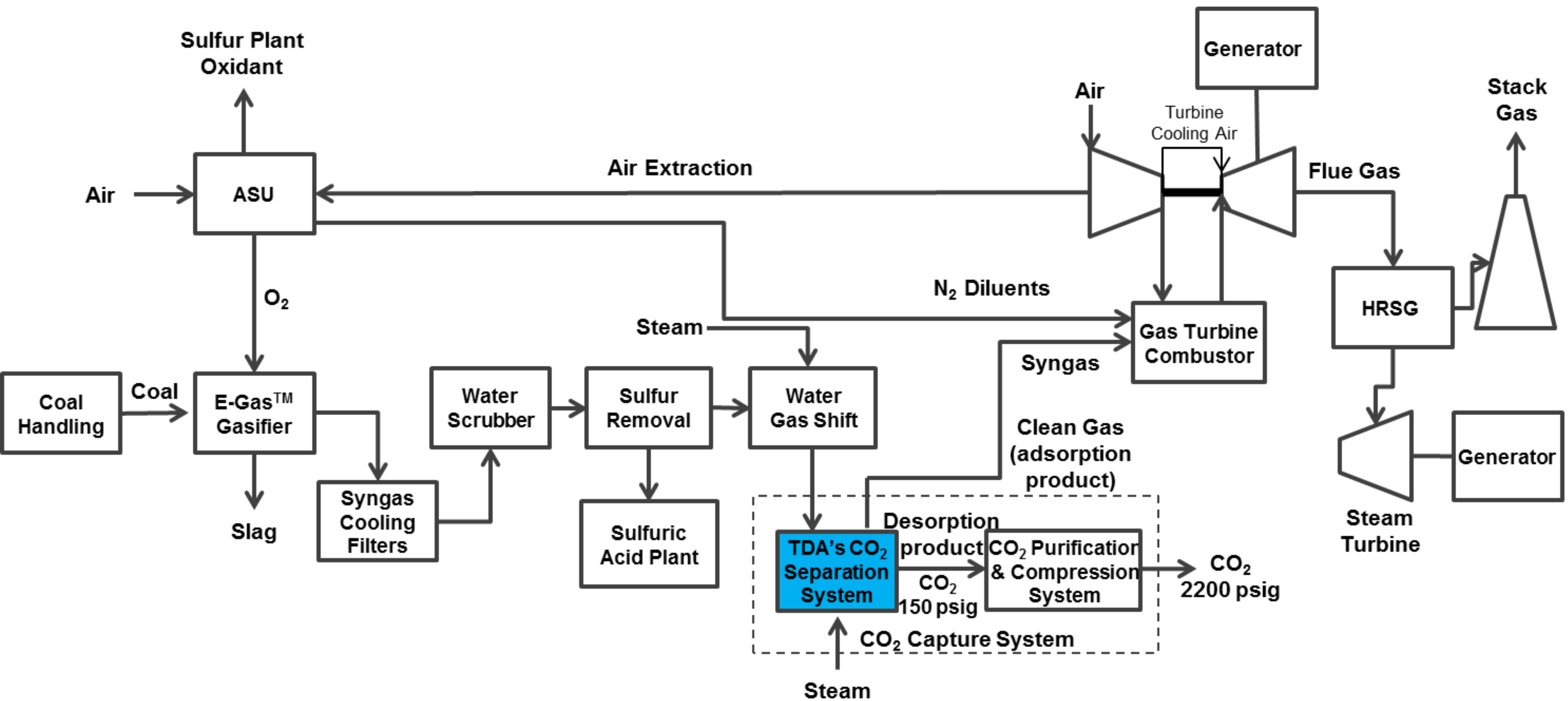
Expected Benefits

- Warm gas CO_2 capture above the dew point of synthesis gas results in more steam entering the gas turbine
  - Higher mass throughput
- Water in the synthesis gas is useful (to a point) as it reduces the gas turbine temperature and prevent NO_X formation
  - Current approaches rely on high pressure N_2 dilution in the gas turbine
  - Reduced need for N_2 in the gas turbine changes the dynamics of the ASU design providing additional benefits
  - Presence of more steam in the gas turbine is also more suited for the next generation hydrogen turbines under-development in the DOE-NETL H_2 turbine program
- Process intensification from eliminating the heat exchangers needed for cooling and re-heating the synthesis gas

IGCC Power Plant with Integrated Warm Gas CO_2 Capture System



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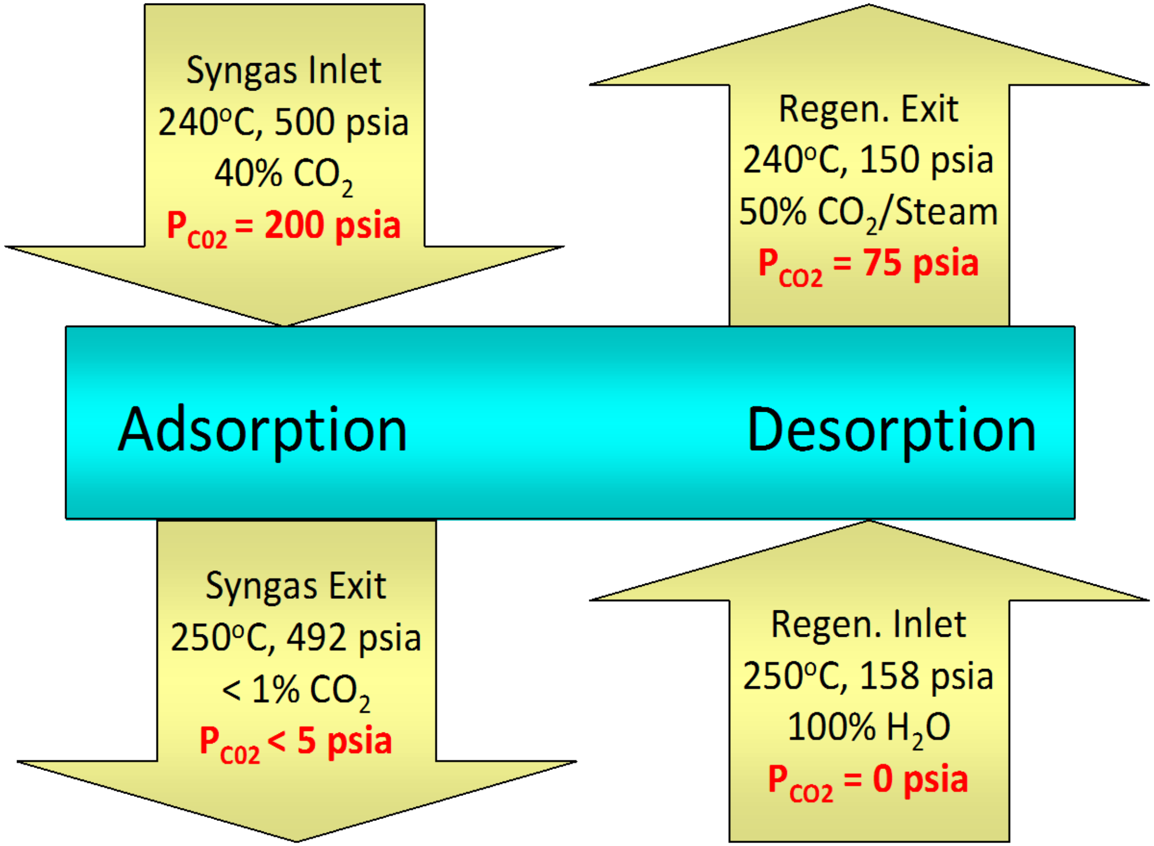
Operating Conditions

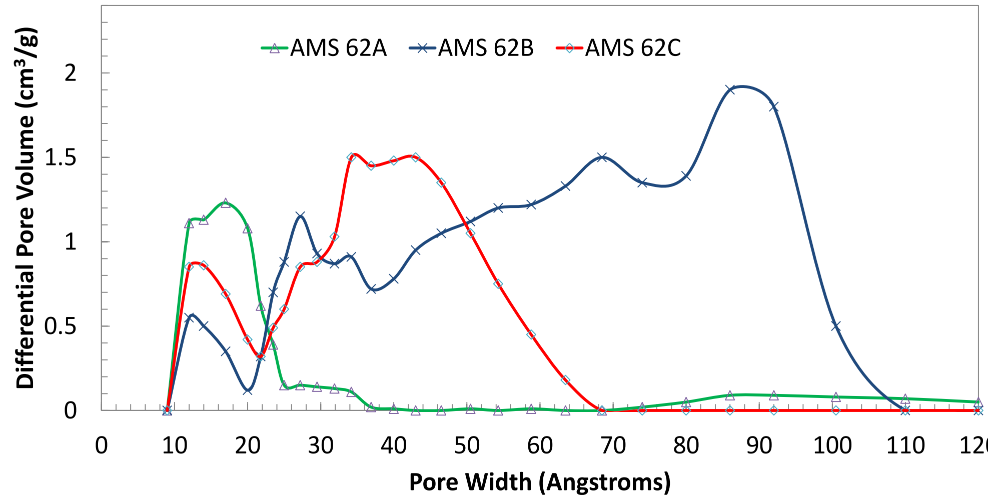
- **Physical adsorbent provides flexibility in regeneration**
  - Temperature swing
  - Pressure swing
  - Concentration swing
  - Any combinations
- **Isothermal operation is critical to eliminate heat/cool transitions which reduces cycle time and increases sorbent utilization**
- **Steam consumption can be significantly reduced if steam purge is carried out at low pressure**



Previous Work
Sorbent Development
DE-FE0000469

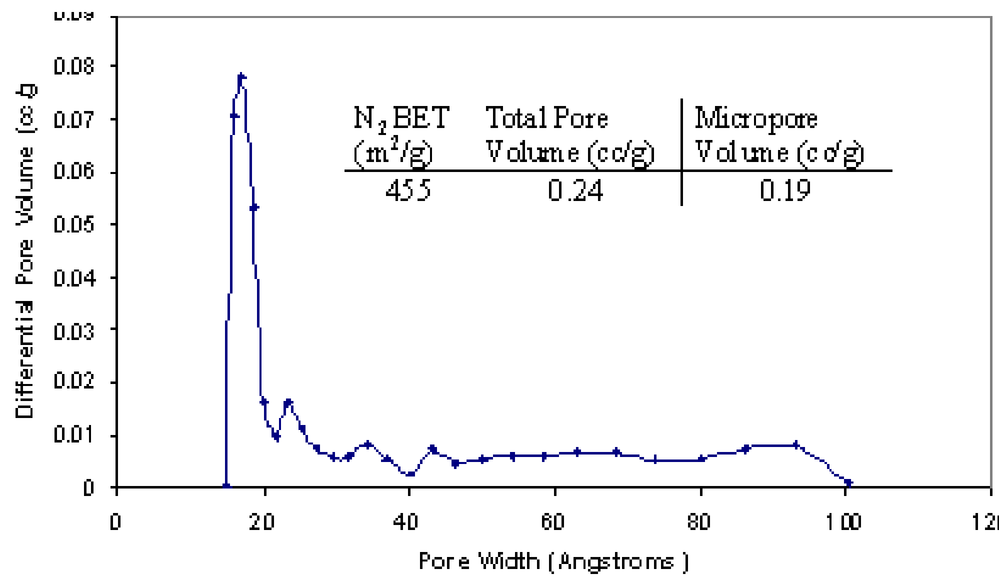
TDA's Sorbent

- **A mesoporous carbon is used to disperse the active phase**
- **The carbon support is previously developed for ultra-capacitors, large pores to achieve liquid transport**



US Pat. Appl. 61/787761, Dietz, Alptekin, Jayaraman "High Capacity Carbon Dioxide Sorbent"

US Pat. Appl. 61/790193, Alptekin, Jayaraman, Copeland "Pre-combustion Carbon Dioxide Capture System Using a Regenerable Sorbent"



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Sorbent Production Scale-up

- **Early samples are prepared using a batch process**
  - 11” diameter
  - Computer controlled
  - 1000°C temp. limit
  - ~5 kg carbon/run
- **60 L sorbent is prepared for field demonstrations**

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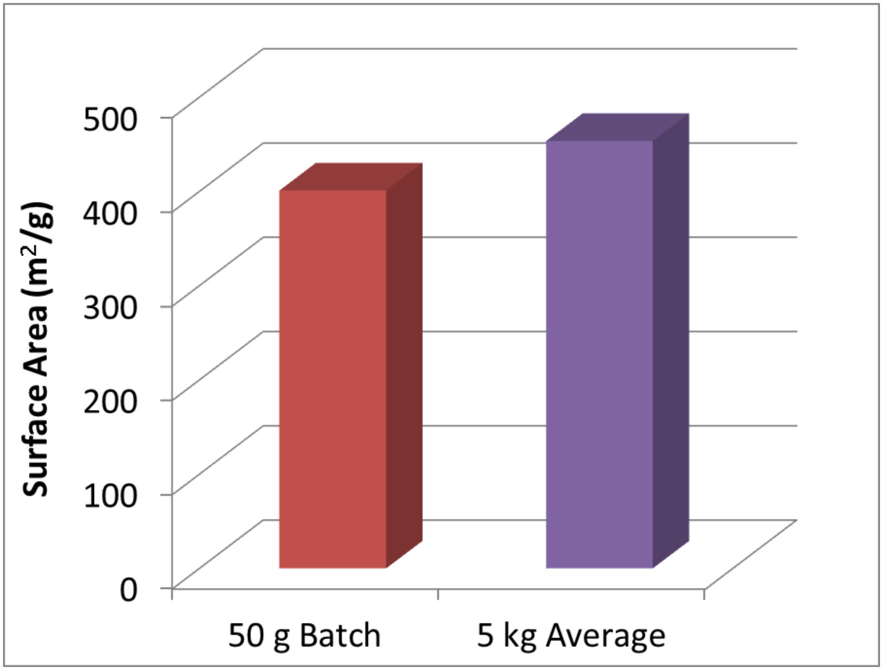
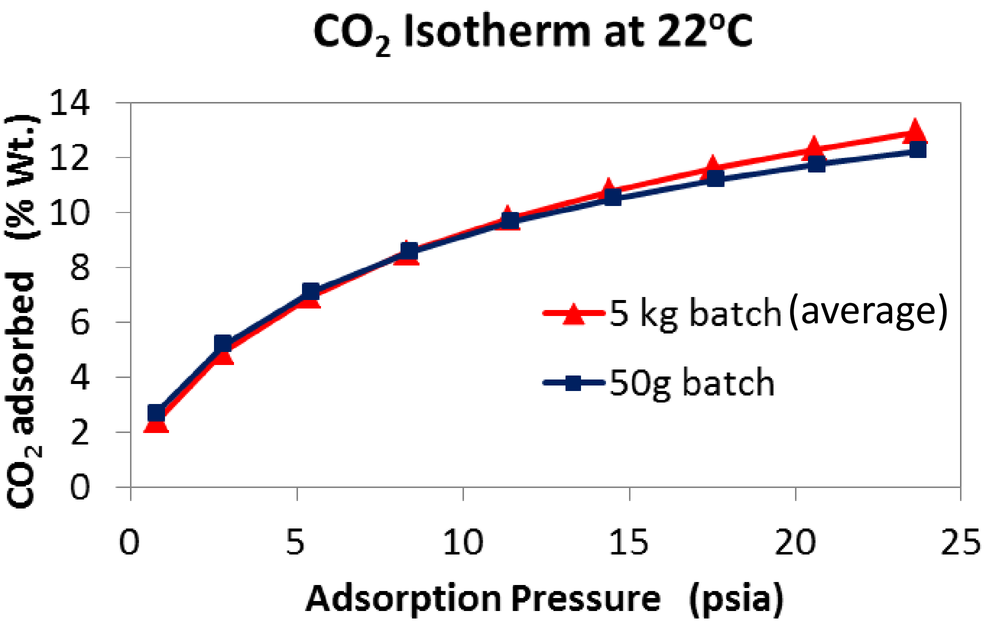
Sorbent Production Scale-up

Surface Area



Low Temperature Isotherm



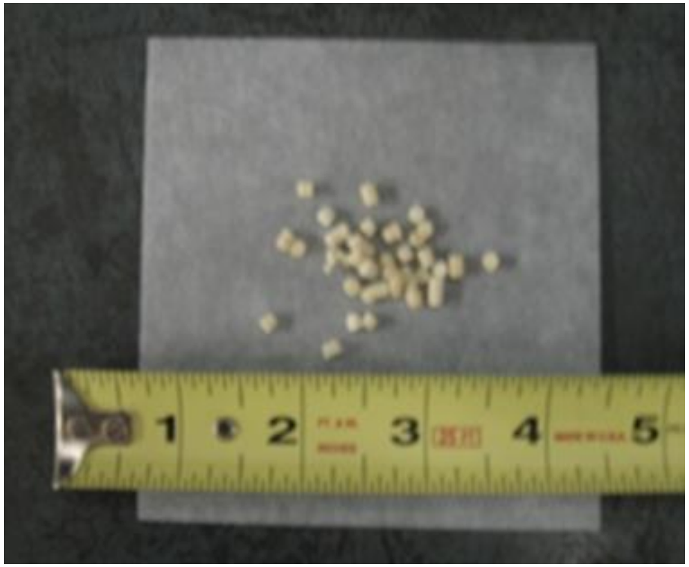
- **The scaled-up sorbent showed surface area and CO_2 capacity similar to the sorbent produced at small batch size**
  - Low temperature isotherms measurements were used for convenience

Improvements in Mechanical Integrity

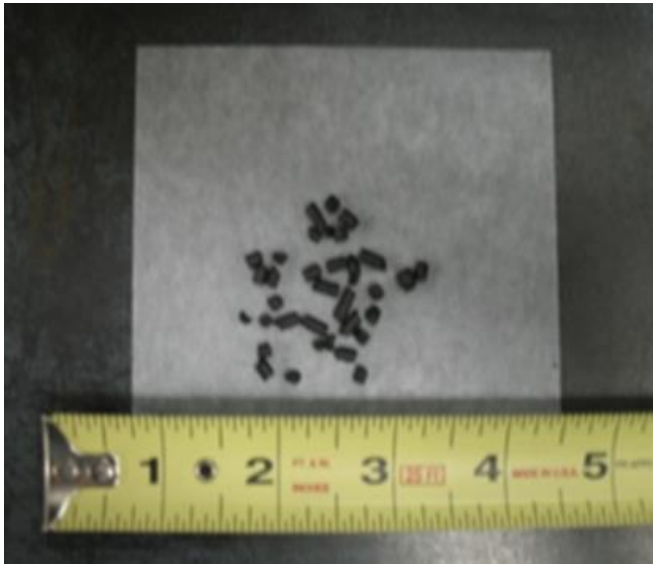
- The crush strength of the pellets are improved to 2.5-3 lb_f/mm (typical range for the commercial samples)

2" screw extruder

Pellets before treatment



Pellets after treatment



- Among the various approaches, forming the pellets prior to carburization provided the highest strength pellets
  - Also provides high yields

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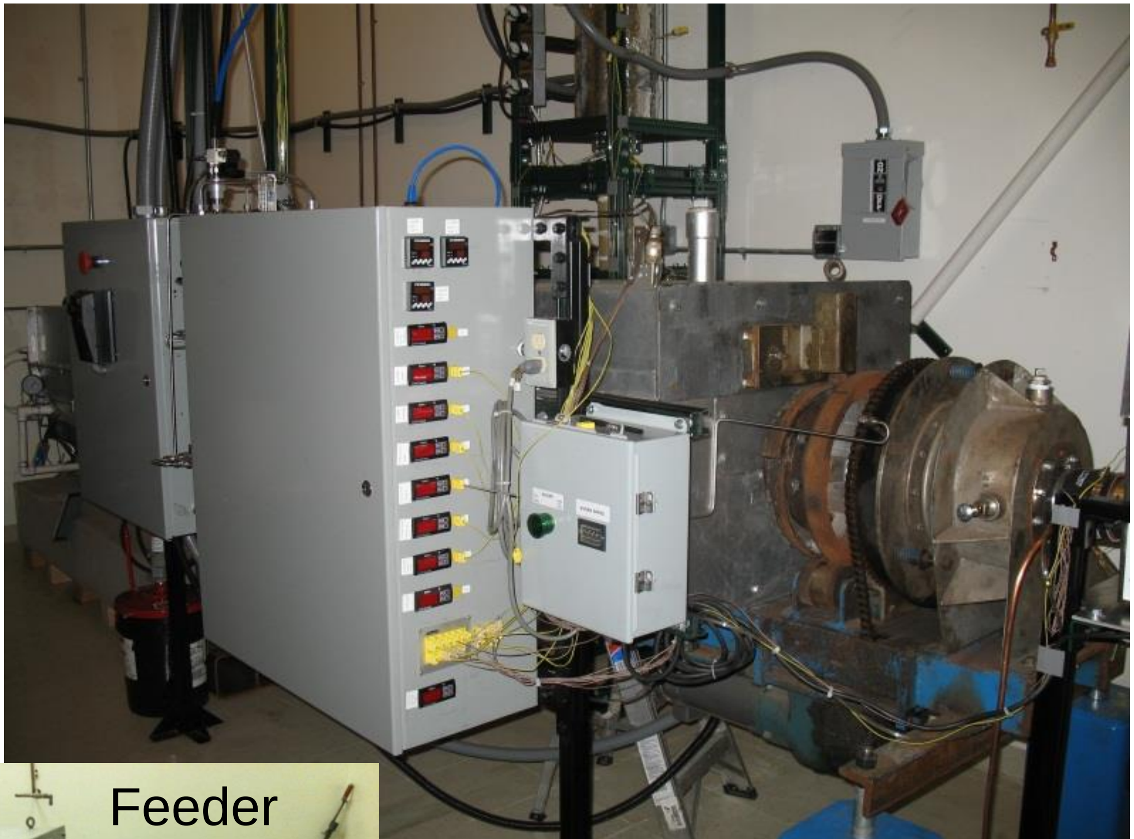
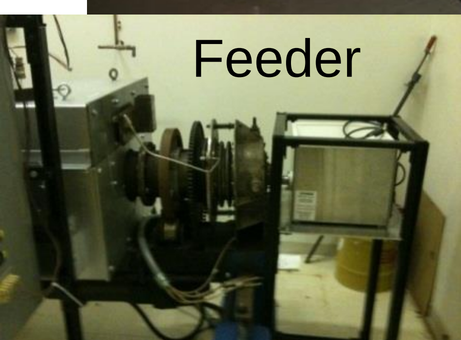
Sorbent Production Scale-up



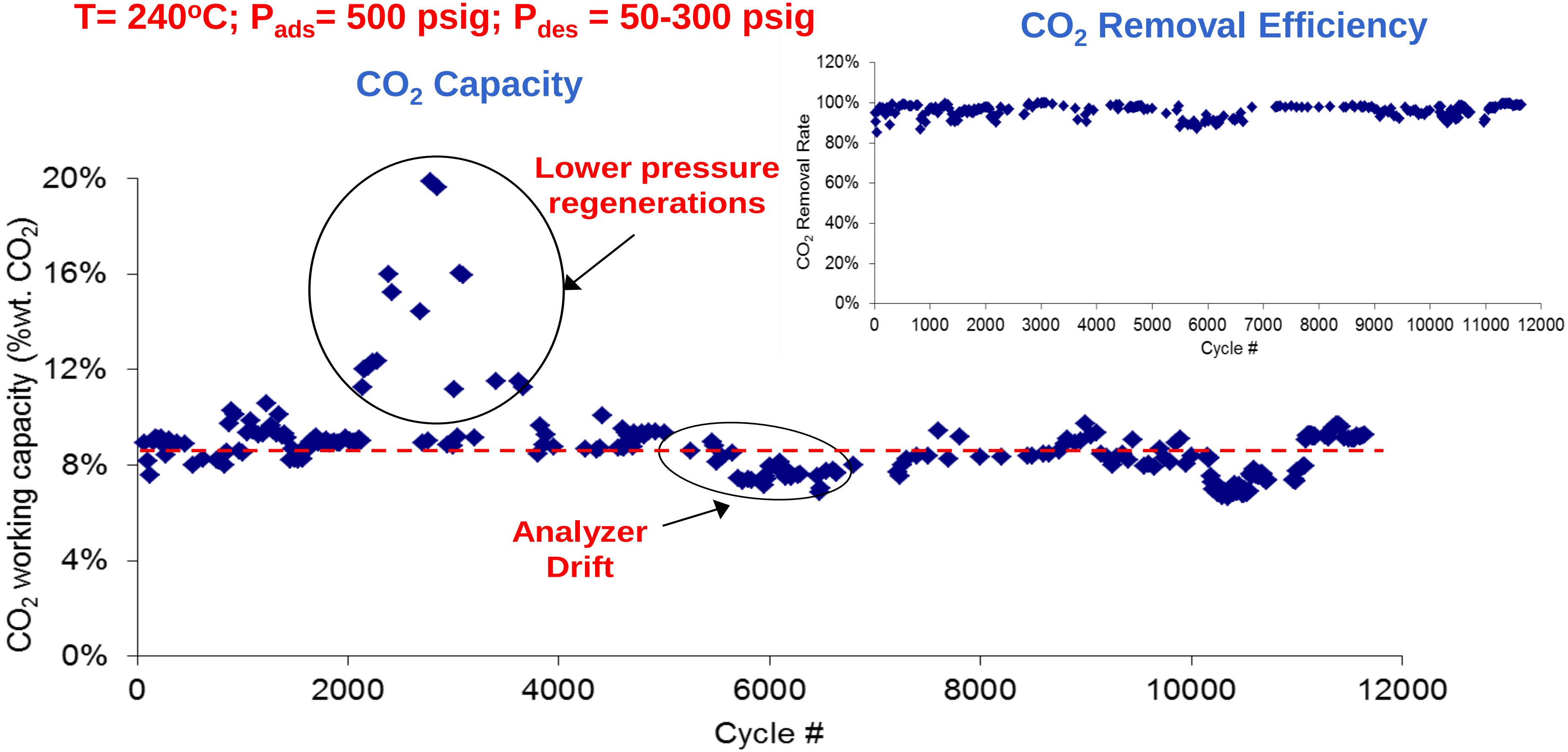


Exhaust treatment

- **A continuous rotary kiln has been installed with production trials started in March 2012**

Multiple Cycle Tests

H_2=32%, CO_2=40%, N_2=3%, CO=1%,H_2O=24%;
T= 240^{o}C; P_{ads}= 500 psig; P_{des} = 50-300 psig



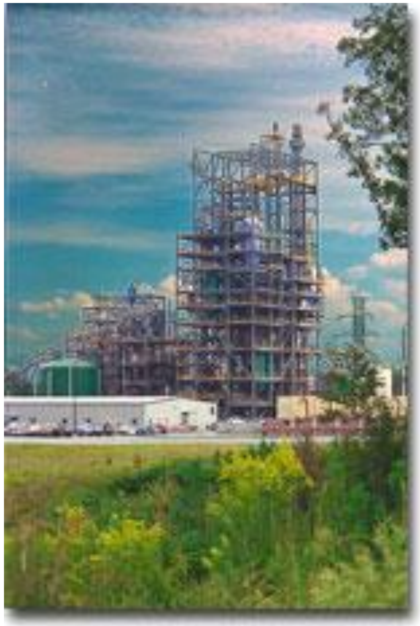
- **Sorbent maintained its CO_2 capacity (8+%wt.) for 12,650 cycles**

Slipstream Demonstrations

- Several test campaigns for proof-of-concept demonstrations were completed at two facilities

Wabash River IGCC Plant, Terre Haute, IN

- Demonstration carried out in September 2012
- Largest single-train gasifier (262 MW)
- Oxy-blown E-Gas^{TM} Gasifier
- Operates on petcoke



National Carbon Capture Center, Wilsonville, AL

- 1^{st} Demonstration carried out in November, 2011
- 2^{nd} Demonstration carried out in April, 2012
- Pilot-scale gasifier
- Air-blown transport gasifier
- Operates on low rank coals

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Test Units – In NEMA-Rated Enclosures

CO_2 Removal Skid

Gas Conditioning Skid

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Field Test Units Installed at NCCC

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Field Test Units at Wabash River IGCC

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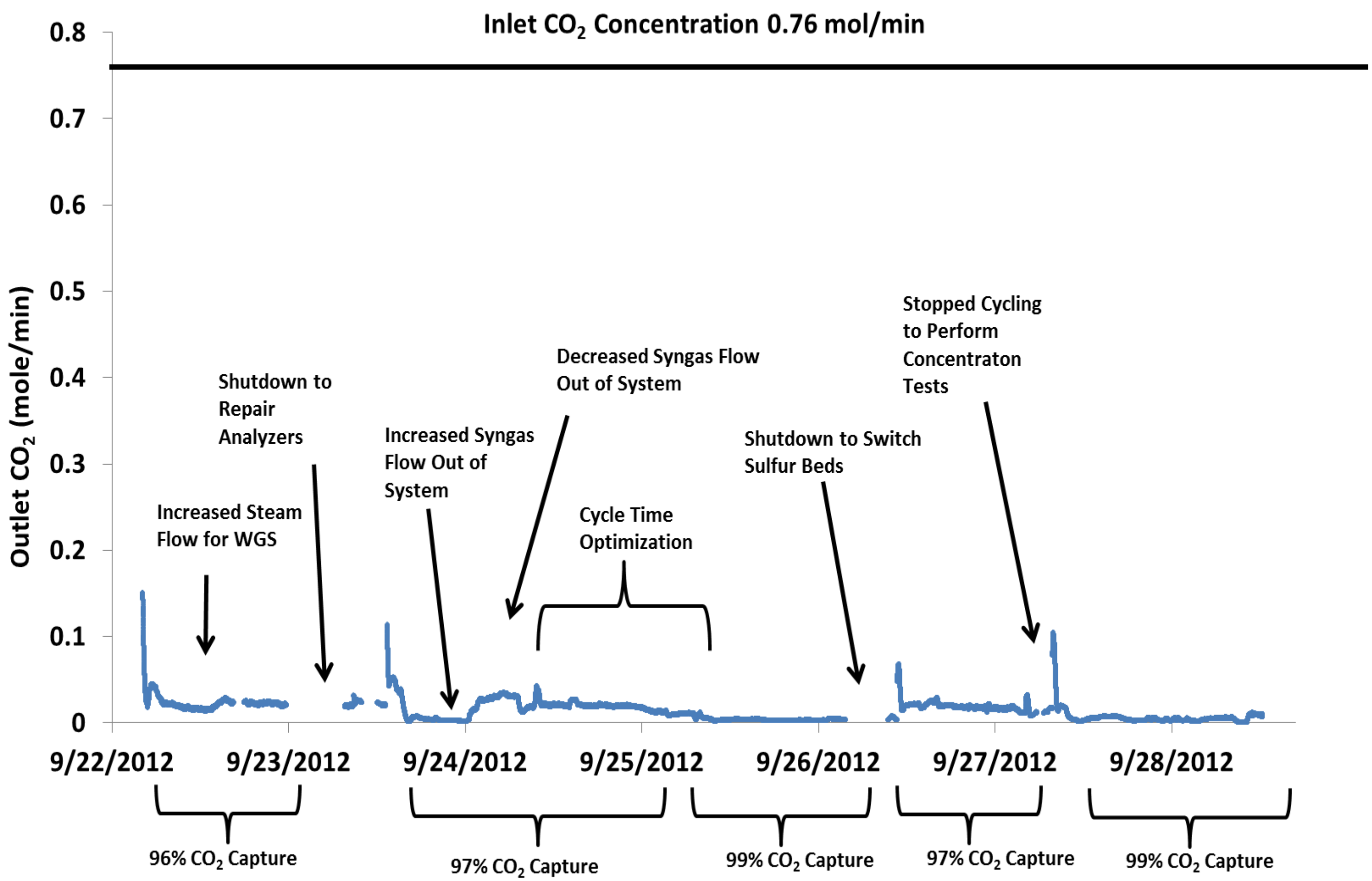
Research

Slipstream Demonstration – Wabash River IGCC Plant



- **Sorbent achieved ~4%wt. CO_2 capacity and 96+% removal efficiency**

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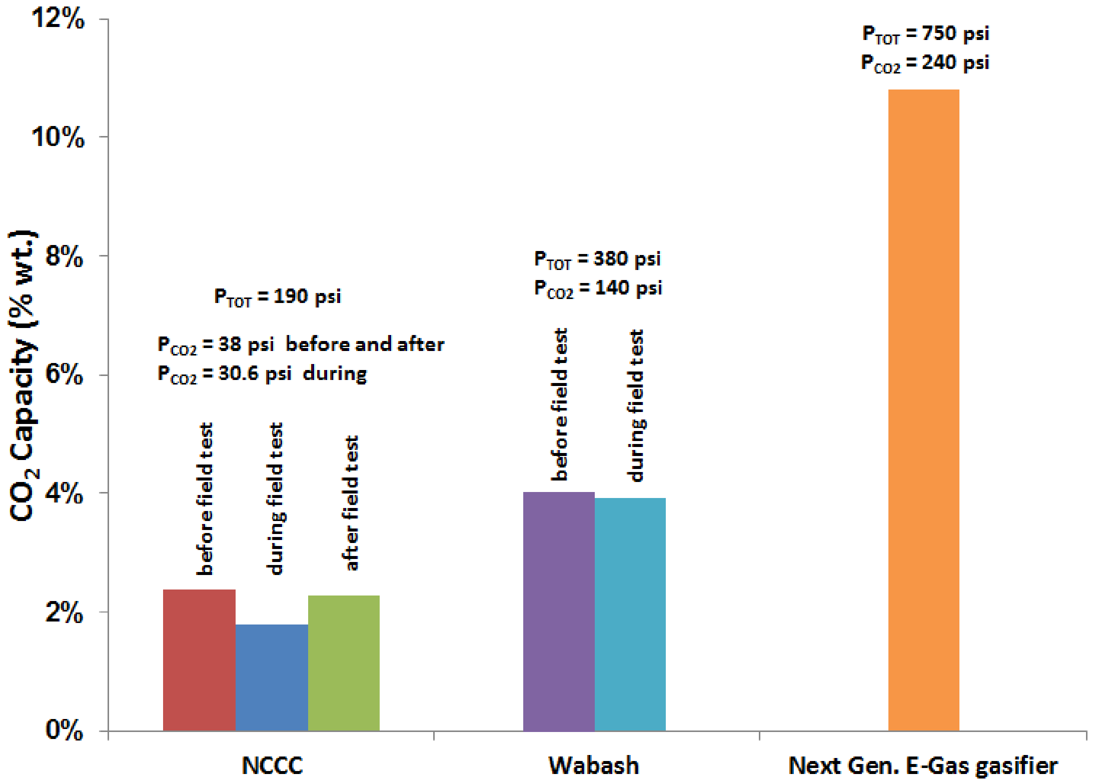
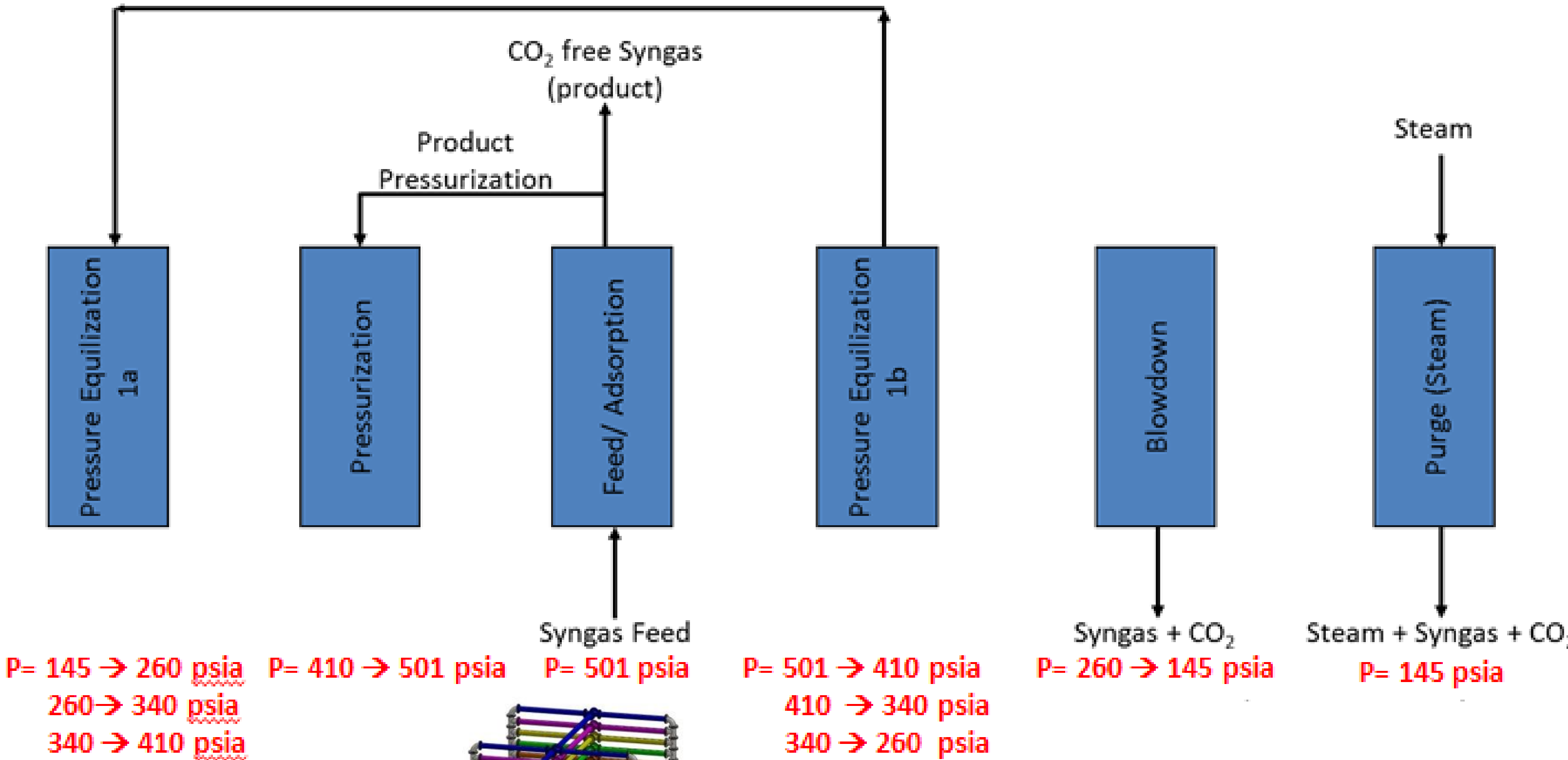
Prototype Performance

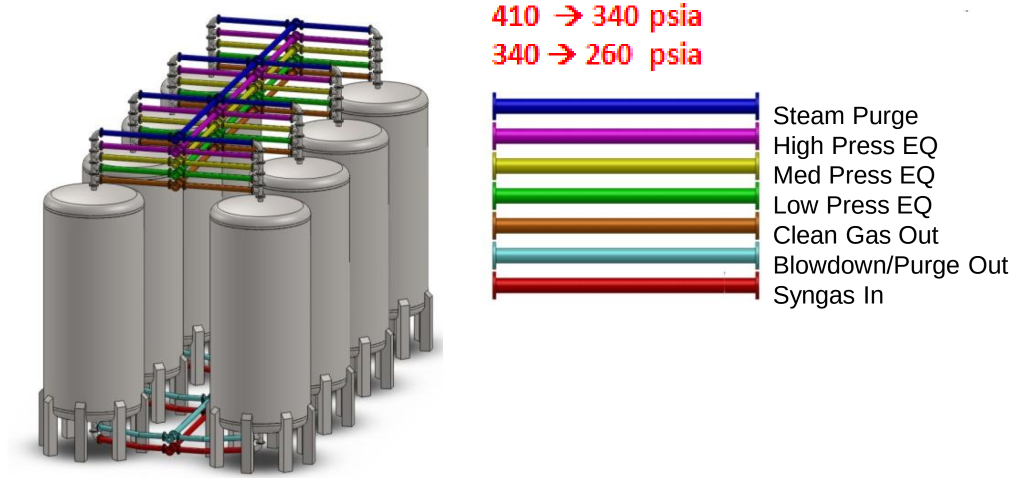


- Sorbent achieved maintained CO_2 capacity before and after the field tests
  - 2.6% wt. CO_2 at P_{CO2} = 38 psi
- At Wabash condition (P_{CO2} = 140 psi) sorbent achieved 4.1% wt. CO_2 capacity
- Next generation E-Gas gasifier is expected to operate at 750 psi (P_{CO2} = 240 psi) and capacity will exceed 10% wt. CO_2

TDA Research

PSA Cycle Design





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PSA Cycle Sequence

- **PSA Cycle Sequence with 8-beds**

	Stage 1		Stage 2		Stage 3		Stage 4		Stage 5		Stage 6		Stage 7		Stage 8	
Time (min)	2		1	1	2		1	1	2		1	1	2		1	1
Bed 1	ADS		EQ1	HOLD	EQ2		EQ3	BD	PURGE		EQ4	HOLD	EQ5		EQ6	PRESS
Bed 2	EQ6	PRESS	ADS		EQ1	HOLD	EQ2		EQ3	BD	PURGE		EQ4	HOLD	EQ5	
Bed 3	EQ5		EQ6	PRESS	ADS		EQ1	HOLD	EQ2		EQ3	BD	PURGE		EQ4	HOLD
Bed 4	EQ4	HOLD	EQ5		EQ6	PRESS	ADS		EQ1	HOLD	EQ2		EQ3	BD	PURGE	
Bed 5	PURGE		EQ4	HOLD	EQ5		EQ6	PRESS	ADS		EQ1	HOLD	EQ2		EQ3	BD
Bed 6	EQ3	BD	PURGE		EQ4	HOLD	EQ5		EQ6	PRESS	ADS		EQ1	HOLD	EQ2	
Bed 7	EQ2		EQ3	BD	PURGE		EQ4	HOLD	EQ5		EQ6	PRESS	ADS		EQ1	HOLD
Bed 8	EQ1	HOLD	EQ2		EQ3	BD	PURGE		EQ4	HOLD	EQ5		EQ6	PRESS	ADS	

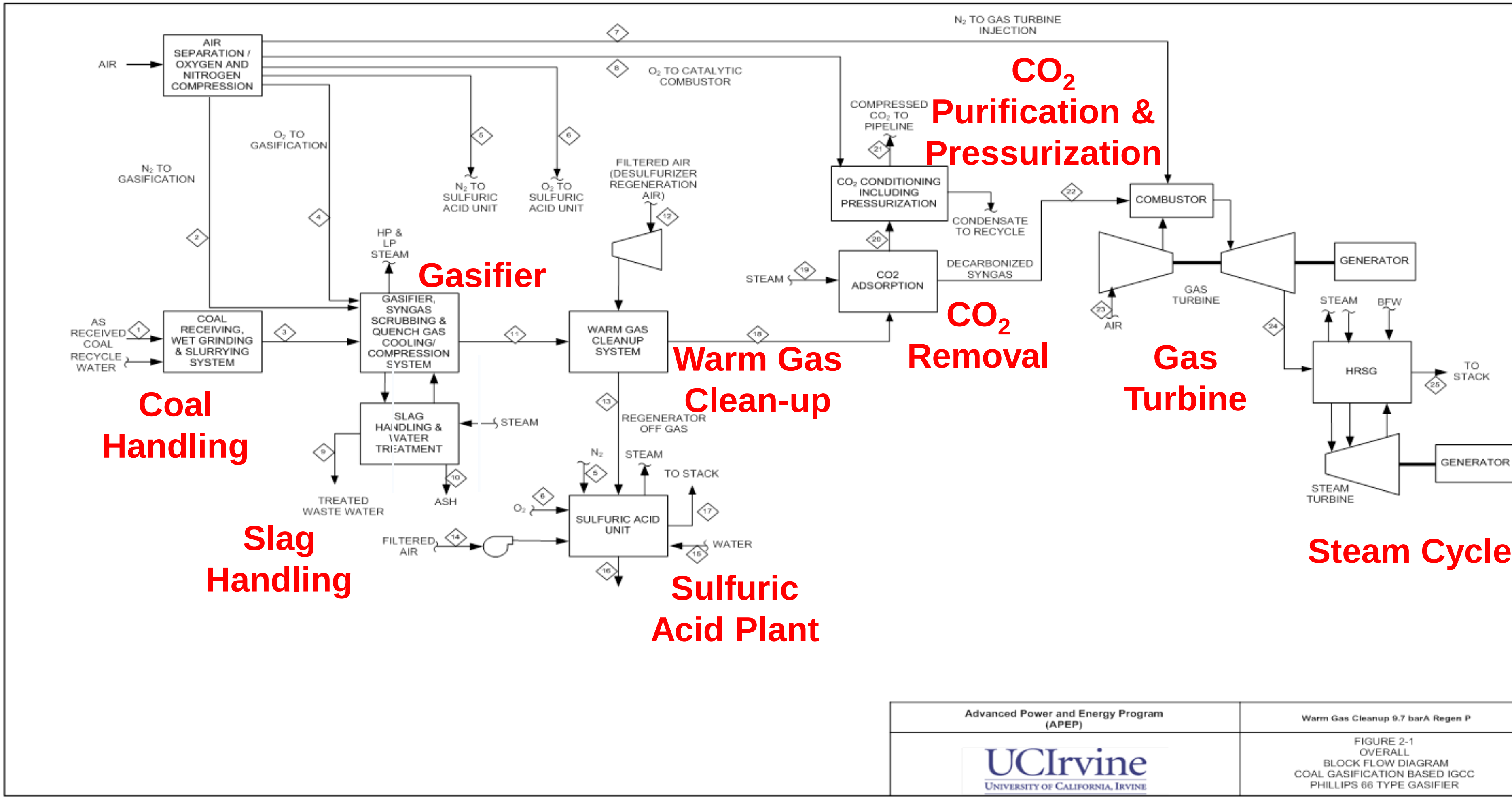
8- bed PSA Cycle Steps:

Step 1 Adsorption at 501 psia (ADS)
Step 2 Pressure Equalization to 420 psia (EQ1)
Step 3 Pressure Equalization to 340 psia (EQ2)
Step 4 Pressure Equalization to 260 psia (EQ3)
Step 5 Blowdown to 145.1 psia (BD)
Step 6 Steam Purge at 145.1 psia (PURGE)
Step 7 Pressure Equalization to 250 psia (EQ4)
Step 8 Pressure Equalization to 330 psia (EQ5)
Step 9 Pressure Equalization to 410 psia (EQ6)
Step 10 Product Pressurization to 501 psia (PRESS)

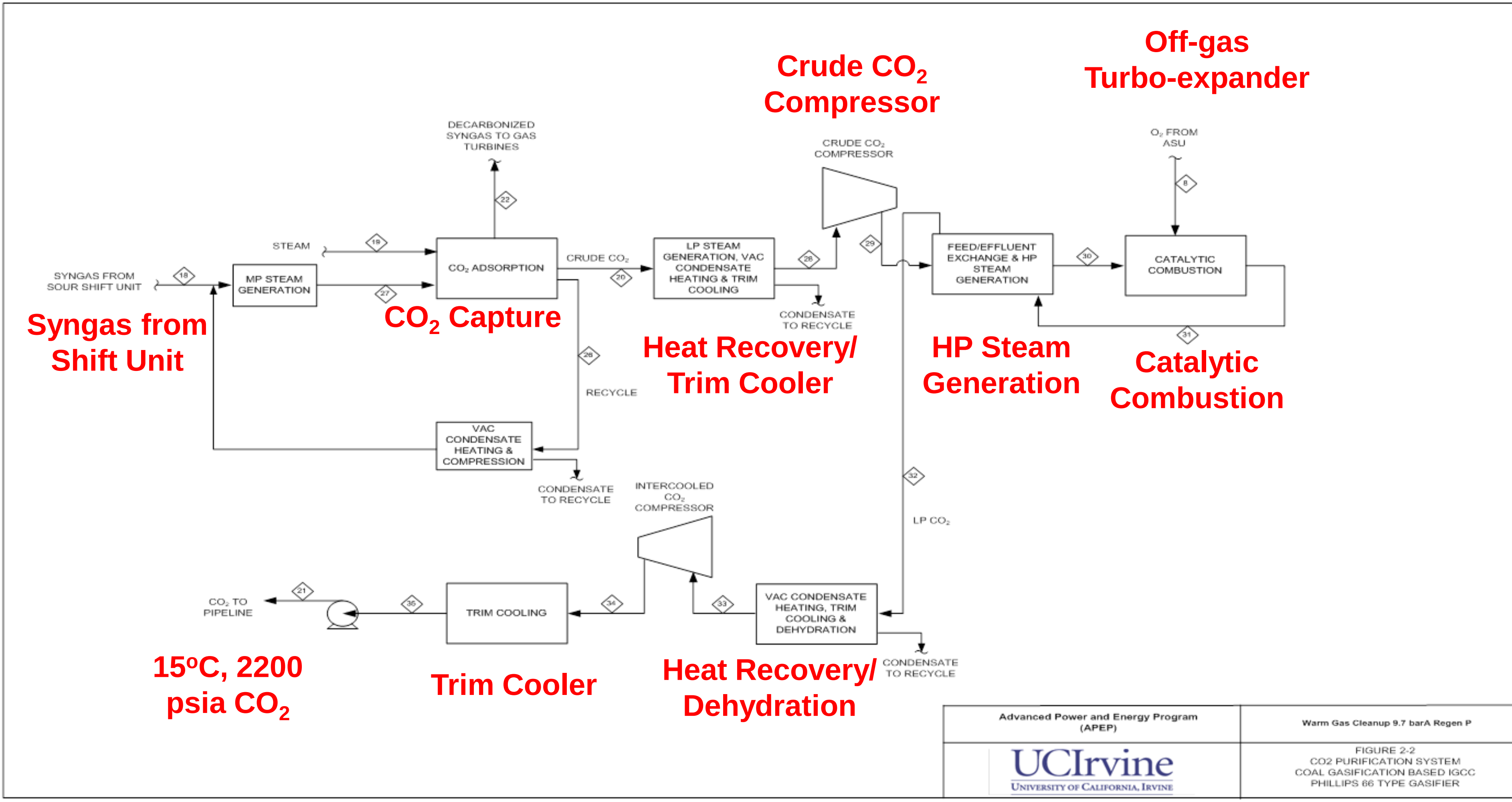
TDA Research

Process Design and Modeling

ASU/N_2 Compression



CO_2 Purification & Compression



TDA Research

UCI System Analysis Results

	Cold Gas Cleanup Selexol™	Warm Gas Cleanup TDA's CO_2 Sorbent
CO_2 Capture, %	90.0	90.0
Gross Power Generated, kWe	691,247	733,028
Gas Turbine Power	464,000	464,000
Steam Turbine Power	227,247	269,028
Auxiliary Load, kWe	175,994	131,163
Net Power, kWe	515,253	601,865
Net Plant Efficiency, % HHV	31.6%	34.0%
Coal Feed Rate, kg/h	216,187	234,867
Raw Water Usage, GPM/MWe	11.8	11.2
Total Plant Cost, $/kWe	2,754	2,418
COE without CO_2 TS&M, $/MWh	99.8	87.8
COE with CO2 TS&M, $/MWh	105.2	92.9

- **IGCC plant with TDA's CO_2 capture system achieves higher efficiency (34.0%) than IGCC with Selexol™ (31.6%)**
- **Cost of per tonne CO_2 avoided is $31.12 for TDA's CO_2 capture system compared $49.50 for cold gas cleanup with Selexol™ technology**

TDA Research

Current Work
Pilot Scale Testing of the CO_2 Capture Sorbent System
DE-FE0013105

Scope of Work – BP1

Budget Period 1 (BP1: 12/30/2013 – 12/31/2014)

- **Develop a Manufacturing Plan and Quality Assurance Plan**
- **Optimize the PSA cycle sequence for the sorbent**
- **Complete a detailed design of the sorbent reactors**
- **Develop a multi-component adsorption model and carry out CFD simulations to support the system design**
- **Complete the detailed design of the 0.1 MWe pilot-scale unit**
  - Acquire approval from the field test sites (NCCC and Sinopec)
- **Provide DOE the full design package for the Pilot Scale CO_2 separation system including detailed vendor quotes**
- **Update process design and simulation**
  - Include any changes in cycle sequence (gas flows, compression needs etc.)

TDA Research

Scope of Work – BP2

Budget Period 2 (BP2: 1/1/2015 – 12/31/2015)

- **Produce sorbent in sufficient quantity to conduct two pilot-scale field tests**
- **Conduct long-term bench-scale performance testing of the sorbent**
  - 20,000 cycles
- **Fabricate a pilot-scale CO_2 separation system**
- **Detailed design of a CO_2 purification sub-system to further treat the separated CO_2 stream**
  - Full-scale design, not to be included into the demonstration
- **Complete a high-fidelity engineering and cost analysis based on vendor quotes**

Scope of Work – BP3

Budget Period 3 (BP3: 1/1/2016 – 12/31/2016)

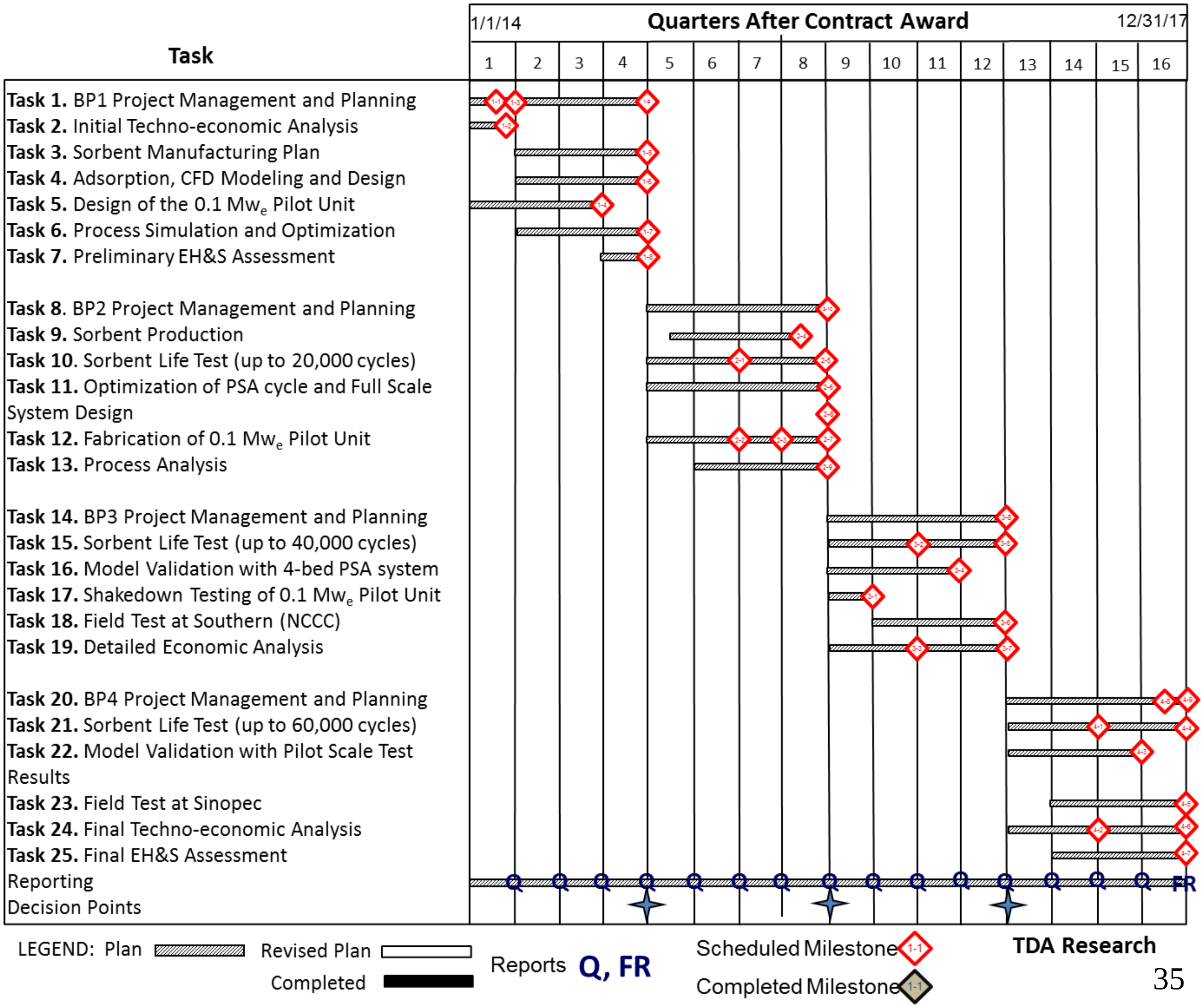
- **Complete the shakedown, troubleshooting and test trials of the pilot-scale unit**
- **Conduct the first pilot-scale field test at the National Carbon Capture Center (NCCC) in Wilsonville, AL**
- **Validation of the Adsorption and CFD Models**
- **Continue the optimization of the PSA cycle scheme**
- **Extend bench-scale sorbent life testing to ~40,000 cycles**
  - Concurrent with the pilot-scale preparations,
- **Validate the adsorption model findings with the first field test results**
- **Improved process design and cost analysis**

Scope of Work – BP4

Budget Period 4 (BP4: 1/1/2017 – 12/31/2017)

- **Transport the pilot-scale slipstream unit to the second field test host site**
- **Complete pilot-scale tests to fully demonstrate the system operation**
- **Complete bench-scale sorbent life testing**
  - 60,000 cycles
- **Complete techno-economic evaluation to accurately estimate the cost of removal of CO_2**
  - Based on DOE/NETL Cost Estimation Guidelines will be prepared
  - Updated with the most recent field test results and cost estimates
- **Complete an Environmental, Health and Safety (EHS) assessment**

Project Schedule



Budget Period 1
12/30/2013 – 12/31/2014

Pilot Scale Testing of the CO_2 Capture Sorbent System
DE-FE0013105

Task 1. BP1 Project Management & Planning

- **Ensure coordination and planning of the project with DOE/NETL and other project participants**
- **Monitor and control the project scope, cost, schedule, and risks**
- **Submit and get approval for the required NEPA documentation**
- **Maintain and revise the Project Management Plan (PMP) and manage and report on activities in accordance with the plan**
- **Update the Project Management Plan as the project progresses**
- **Report progress against milestones, schedule and budget, including any variances**
- **Prepare and deliver required reports and briefings**

Task 2. Initial Techno-Economic Analysis

- **Complete an initial TEA for TDA's CO_2 capture process integrated with an IGCC power plant will be conducted in accordance with Attachment A of the SOPO**
- **Provide the initial TEA as a deliverable to DOE/NETL**

Task 3. Sorbent Manufacturing Plan

- **The production batch size will be set to produce a sufficient quantity of sorbent (~3 m^3) to support and field tests**
  - Large batch sizes using scalable production equipment, including both semi-continuous and continuous equipment
  - Manufacturing Plan
  - Quality Control and Assurance Plan
    - To ensure consistency of the material and minimize any batch-to-batch variations via extensive characterization of each sorbent batch (e.g., surface area, pore size distribution, chemical composition, crush strength)
    - Generate a Product Specification Sheet
- **Task 3.1 Trial Production**
  - Produce sorbent at a nominal 100-Liter batch size (~ 30 batches)
  - The synthesis of the precursor phase will be carried out in batch mode, while a continuous rotary kiln will be used for carburization of the precursor
- **Task 3.2 Manufacturing Plan**
  - TDA will prepare a manufacturing plan that will include specific details on each production step

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Task 4. Adsorption, CFD Modeling and Reactor Housing Design

- **Detailed design of the sorbent reactors, including all valves and manifolds**
- **Task 4.1 Adsorption Model (UOA):**
  - Calculate the concentration distribution across the sorbent bed (via finite-volume based mathematical model in MATLAB) and generate concentration profiles taking surface interactions into account with all syngas constituents
  - The heat effects (due to heat of adsorption) will also be taken into account
  - Various reactor geometries will be modeled to identify the impact of design properties (e.g., bed aspect ratio) on key process parameters (e.g., regeneration time, product purity)
- **The code will feed into a computational fluid dynamics (CFD) model that will provide detailed transient three dimensional (3D) concentration and temperature profiles across the sorbent bed**
- **Task 4.2 CFD Analysis (GTI):**
  - Using code such as FLUENT, local heat and mass transfer processes will be explored to develop axial and radial temperature and concentration profiles
- **The fluid flow and transport phenomena in the reactor will be simulated in a 3D model including the spatial distribution of reactants, sorbents, inerts and products**

TDA Research

Task 4. Adsorption, CFD Modeling and Reactor Housing Design

- **<u>Task 4.3 Engineering Design (TDA):</u>**
  - Based on the adsorption model and CFD simulation results, we will design of the CO_2 sorbent beds for the pilot-scale system
  - Engineering drawings and 3-dimensional layouts for the sorbents beds will be generated
- **Design of the unit will include (at a minimum):**
  - Sorbent vessels
  - Inlet and exit accumulators,
  - All valves and manifolds
    - Needed to complete the cycle sequence with multiple pressure equalizations, product pressurization and back purging steps
- **An accurate cost estimate, including all foundation work, labor and supervision for the installed system will be generated**
- **This input will be utilized to update the cost estimate for the actual system**

Task 5. Design of the Pilot-Scale Unit

- **0.1 MWe pilot-scale field test unit will treat ~2130 SLPM (75 SCFM) of synthesis gas flow**
  - Nominal 109 kg/hr CO_2 capture capability
- **The test unit will be designed to evaluate the technical viability of the concept with actual synthesis gas generated by air- and oxygen-blow gasification systems**
- **The test unit will contain two main skids:**
  - CO_2 Separation Skid
  - Gas Processing Skid
- **Early in the design, design details will be discussed with test sites to ensure it will meet all of the requirements of the facility**
  - Hazard Design Reviews will be conducted for both of the planned field test sites and all required safety pre-cautions will be included into the design

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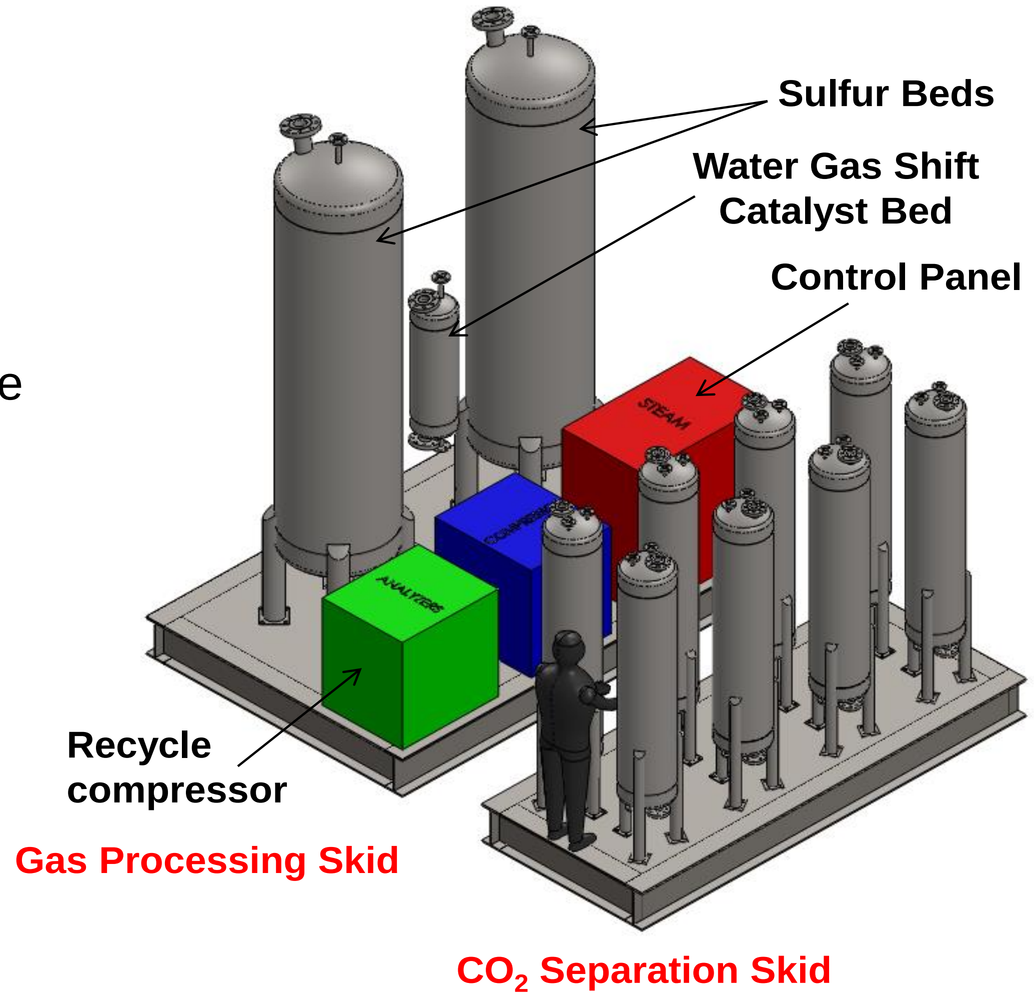
Task 5. Design of the CO_2 Skid

- **CO_2 Separation Skid will consist of:**
  - 8 sorbent reactors
  - Two accumulators (one at the inlet and one at the exit to moderate any pressure and flow fluctuations)
  - Small compressor to recycle of some of the process gases
- **Test unit will include all critical components to enable full evaluation of the PSA cycle sequence**
  - Product purity
  - Product recovery

Task 5. Design of the Gas Processing Skid

- **Gas Processing Skid will control of gas composition feeding into the sorbent reactors**
  - Two lead-lag desulfurization reactors
    - Operated as one-time use expendable beds
  - A multi-stage water-gas-shift (WGS) reactor
    - Commercial catalyst
    - Inter-stage cooling
  - A gas booster to increase the pressure of the H_2 rich product gas to put back into the process to minimize the H_2 loss



TDA Research

Task 6. Process Simulation and Optimization

- **A detailed process design and modeling will be performed using Aspen-Plus™ software**
  - UCI already developed a process model for the high temperature PSA-based carbon capture system to predict system efficiency and cost, and calibrated the model using the results of a DOE/NETL analysis
  - This model will be revised to include the changes in the cycle sequence
  - CO_2 separation system cost will also be revised based on the results of adsorption model and cycle optimization work
- **Detailed sensitivity analysis will also be carried out to identify the optimum operating conditions**
- **Cost analysis will be carried out (with an estimated accuracy of 15%) to check against the Year 1 milestone project review**
  - DOE Guidelines included in Attachment A of the SOPO will be followed

Task 7. Preliminary Environmental, Health and Safety (EH&S) Risk Assessment

- **An assessment of environmental, health and safety risks associated with TDA's CO_2 Capture process will be performed in accordance with the guidelines provided by DOE in the FOA (DE-FOA-000785)**
  - Assess the environmental friendliness and
  - Assess the safety of the proposed system

BP1 – Milestone Log

Mile-stone #	Budget Period	Task/ Subtask No.	Milestone Description	Planned Completion	Actual Completion	Verification Method
			Project Start Date	**12/30/2013**		
1-1	1	1	Updated Project Management Plan (PMP)	2/28/2014		PMP file
1-2	1	2	Complete Initial Techno-economic Analysis	3/20/2014		Topical Report - Initial Techno-economic Analysis
1-3	1	1	Kickoff Meeting at NETL	3/31/2014		Presentation file
1-4	1	5	Complete Pilot Plan Design Package	9/30/2014		Topical Report - Pilot Plant Design Package
1-5	1	3	Complete Sorbent Manufacturing Plan	12/31/2014		Sorbent Manufacturing Plan
1-6	1	4	Complete Adsorption, CFD modeling and CO_2 Reactor Design	12/31/2014		Results update
1-7	1	6	Complete Process Simulation and Optimization	12/31/2014		Results update
1-8	1	7	Complete Preliminary EH&S Risk Assessment	12/31/2014		Preliminary EH&S Risk Assessment Report
1-9	1	1	Annual Review Meeting at NETL	12/31/2014		Presentation file
			Go/No-go Decision Point	**12/31/2014**		

BP1 – Decision Points

- **DOE funding is not authorized beyond Budget Period 1 without the written approval of the Contracting Officer**
- **DOE's decision whether to authorize funding for Budget Period 2 will be specifically based on:**
  - Successful completion of all work proposed in the current Budget Period
  - Satisfactory achievement of applicable success criteria
  - Submission and approval of the Continuation Application

Decision Point	Date	Success Criteria
Go/No-go Decision Point: End of Year 1	12/31/2014	Complete Final Design Package for Pilot Unit with Site Approvals.
		Net plant efficiency better than 2.5% point than Selexol^{TM} based CO_2 capture systems for IGCC power plants.

TDA Research

Budget Period 2
1/1/2015 – 12/31/2015

Pilot Scale Testing of the CO_2 Capture Sorbent System
DE-FE0013105

Task 8. BP2 Project Management & Planning

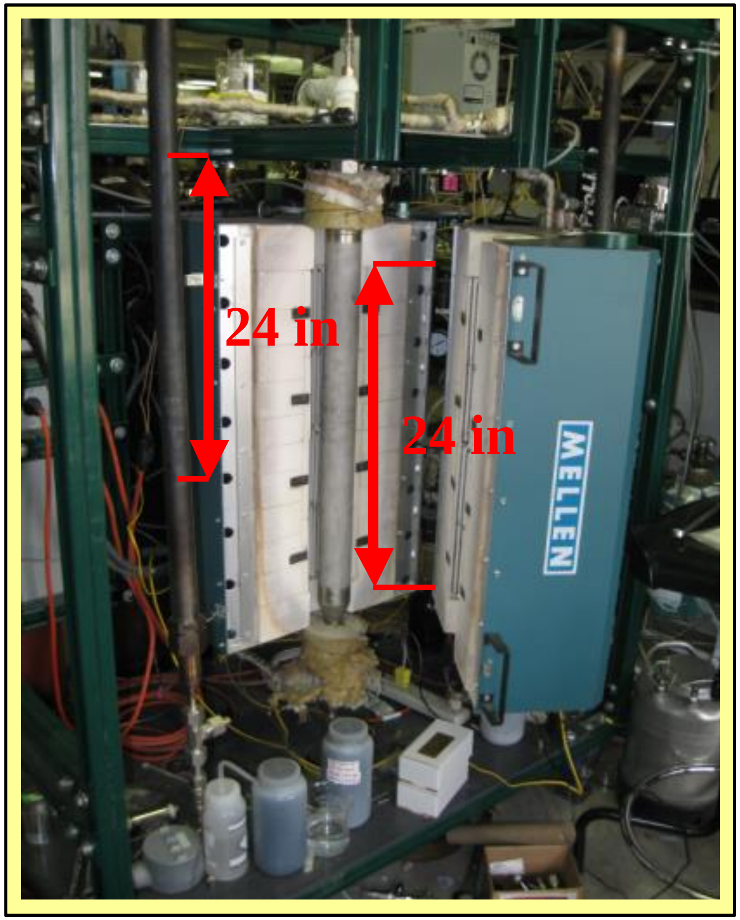
- Ensure coordination and planning of the project with DOE/NETL and other project participants
- Monitor and control the project scope, cost, schedule, and risks
- Submit and get approval for the required NEPA documentation
- Maintain and revise the Project Management Plan (PMP) and manage and report on activities in accordance with the plan
- Update the Project Management Plan as the project progresses
- Report progress against milestones, schedule and budget, including any variances
- Prepare and deliver required reports and briefings

Task 9. Sorbent Production

- **Following the Manufacturing Plan, TDA will prepare sufficient quantity of sorbent for two separate field tests with some extra material (about three m^3)**
- **Each batch of material will be tested in a reactor sized to process 5 SLPM of simulated syngas under a baseline condition to ensure that the sorbent will meet the performance targets**

Task 10. Sorbent Life Test (20,000 Cycles)

- **Bench-scale tests will be conducted to assess sorbent life**
- **Sorbent is estimated to be replaced every 2 years**
  - 52,500 cycles (20 min full cycle)
- **Due to budget and schedule constraints, the planned field test will not be sufficiently long to fully evaluate the sorbent life**
- **In long term durability test sorbent will be evaluated under representative conditions**
  - Simulated syngas flow (~5 SLPM)
  - Single fixed bed



<u>Task 10.1 Cycles up to 10,000</u>

<u>Task 10.2 Cycles up to 20,000</u>

Task 11. Optimization of PSA Cycle and Full Scale System Design

- **We will optimize the cycle sequence to obtain highest product purity and highest H_2 recovery, while maintaining the smallest number of reactors and a minimum sorbent amount**
- **Sophisticated algorithms will be used to optimize a particular adsorption cycle and sub-space of operating parameters (e.g., duration and sequence of steps, pressure levels and flows)**
- **Systematic optimization will minimize the probability of converging on a local minima and allows exploring the entire operational**
- **We will deploy a methodology to optimize the cycle sequence for the following Process Options**
  - Task 11.1 PSA Cycle Scheme & Design for GE Gasifier
  - Task 11.2 PSA Cycle scheme & Design for E-Gas Gasifier
  - Task 11.3 PSA Cycle Scheme & Design for Shell Gasifier
  - Task 11.4 PSA Cycle Scheme & Design for TRIG Gasifier

TDA Research

Task 12. Adsorption, CFD Modeling & Reactor Housing Design

- **Task 12.1 Fabrication of the CO_2 Separation Skid**
  - All components, as well as the fabrication procedures will enable the use of the unit in hazardous environments
  - Unit will be rated for use in Class I Division II environments
- **Task 12.2 Fabrication of the Gas Processing Skid**
  - Unit will be rated for use in Class I Division II environments
- **Task 12.3 Fabrication of Process Control and Automation Module**
  - LabView Control Hardware (or an equivalently capable system) will provide automated operation, data logging and monitoring
  - The control system will fabricated and programmed to allow stand-alone operation with remote monitoring and controls

Task 13. Process Analysis

- **We will continue to increase the accuracy of the process design and cost estimates**
  - Actual operating data will be acquired from the vendors of the critical process equipment
    - Air Separation Unit (ASU) duty specifications will be acquired from vendors, including site conditions, cooling water supply and return conditions, temperature and purity for the O_2 and N_2 streams, steam flow rate and electric power requirement for the given system size
    - Similar inputs will be received from gas turbine manufacturers
  - Similar data will also be obtained from the suppliers all major hardware

BP2 – Milestone Log

Mile-stone #	Budget Period	Task/ Subtask No.	Milestone Description	Planned Completion	Actual Completion	Verification Method
			Project Start Date	**12/30/2013**		
2-1	2	10	Complete up to 10,000 cycles in Sorbent Life Test	6/30/2015		Results update
2-2	2	12	Complete Fabrication of CO_2 Separation Skid	6/30/2015		Results update
2-3	2	12	Complete Fabrication of the Gas Processing Skid	9/30/2015		Results update
2-4	2	9	Complete Sorbent Production	11/30/2015		Results update
2-5	2	10	Complete up to 20,000 cycles in Sorbent Life Test	12/31/2015		Results update
2-6	2	11	Complete Optimization of PSA Cycle and Full Scale System Design	12/31/2015		Results update
2-7	2	12	Complete Fabrication of the Process Control and Automation Module	12/31/2015		Results update
2-8	2	12	Complete Fabrication of 0.1 MWe Pilot Plant Unit	12/31/2015		Results update
2-9	2	13	Complete Process Analysis	12/31/2015		Results update
2-10	2	8	Annual Review Meeting at NETL	12/31/2015		Presentation file
			Go/No-go Decision Point	**12/31/2015**		

BP2 – Decision Points

- **DOE funding is not authorized beyond Budget Period 2 without the written approval of the Contracting Officer**
- **DOE's decision whether to authorize funding for Budget Period 3 will be specifically based on:**
  - Successful completion of all work proposed in the current Budget Period
  - Satisfactory achievement of applicable success criteria
  - Submission and approval of the Continuation Application

Go/No-go Decision Point: End of Year 2	12/31/2015	Complete 20,000 cycles in the life test with less than 2% degradation per 10,000 cycles in sorbent performance.

Budget Period 3
1/1/2016 – 12/31/2016

Pilot Scale Testing of the CO_2 Capture Sorbent System
DE-FE0013105

Task 14. BP3 Project Management & Planning

- Ensure coordination and planning of the project with DOE/NETL and other project participants
- Monitor and control the project scope, cost, schedule, and risks
- Submit and get approval for the required NEPA documentation
- Maintain and revise the Project Management Plan (PMP) and manage and report on activities in accordance with the plan
- Update the Project Management Plan as the project progresses
- Report progress against milestones, schedule and budget, including any variances
- Prepare and deliver required reports and briefings

Task 15. Sorbent Life Test (40,000 Cycles)

- **Continue the cycling of the adsorbent**
- **Task 15.1 Cycles up to 30,000**
- **Task 15.2 Cycles up to 40,000**

Task 16. Model Validation

- **PSA cycle simulation results will be validated using a four-bed PSA system that TDA developed during a previous DOE/NETL project**
  - Sorbent reactors will be modified to reflect the system design that incorporates the desired heat exchange method
- **We will work with GTI to supply actual coal-derived syngas and model results will be validated using the actual data**
  - Measure the axial and radial temperature distributions across the bed
  - CO_2 capacity and removal efficiency to compare against model predictions
- **Approximately 1,000 hours of testing is planned at a synthesis gas feed rate of 0.5 SCFM (~15 SLPM)**
  - Tests to assess the impact of key operating parameters (e.g., temperature, pressure, gas hourly space velocity (GHSV), steam:carbon ratio on sorbent performance

Task 17. Shakedown Testing of the 0.1 MW_e Pilot Unit

- **Integrate the CO_2 Separation Skid and the Gas Processing Skid with the control system**
- **PID loops and other control systems will be tuned to ensure that all critical system parameters can be controlled at the given range**
- **Shakedown and troubleshooting of the integrated system will be carried out with simulated synthesis gas mixtures to test all unit operations**
  - Mostly N_2 and $N_2/CO_2/H_2O$ flows will be used in these tests
- **Shakedown will include verification of:**
  - The operation of the valves, recycle blower and all supporting equipment
  - The programming of the desired cycle sequence
  - The operation of all heaters, steam generator and all other critical system component

TDA Research

Task 18. First Field Test

- **Install the pilot unit at the first field test site (i.e., NCCC, Wilsonville, AL)**
- **Complete a series of shakedown runs (first cold and then hot), to confirm mechanical integrity and the proper functioning of the control systems after the shipment**
  - Prior to accepting synthesis gas
- **Evaluate the sorbent's performance at different operating conditions (e.g., cycle time, temperature)**
- **Evaluate the unit in two separate test campaigns using synthesis gas from the pilot-scale air blown gasifier**
- **Two 750-hour test campaigns (for a total of 1,500 hours) is scheduled**

TDA Research

Task 19. Detailed Economic Analysis

- **A detailed process design and economic analysis will be performed using Aspen-Plus™ software**

Task 19.1 Tune-up IGCC Performance:

- **The results from the adsorption testing and CFD modeling will be incorporated into the Aspen Plus® model**
- **The design of the CO_2 purification system, which will include the catalytic combustor, the dehydration unit and CO_2 compressors will be completed. These results will feed into the engineering design and cost analysis.**

Task 19.2 Detailed Cost Analysis:

- **A higher fidelity system design and cost analysis will be conducted**

BP3 – Milestone Log

Mile-stone #	Budget Period	Task/ Subtask No.	Milestone Description	Planned Completion	Actual Completion	Verification Method
			Project Start Date	**12/30/2013**		
3-1	3	17	Complete Shakedown Testing of 0.1 MWe Pilot Unit	3/31/2016		Results update
3-2	3	15	Complete up to 30,000 cycles in Sorbent Life Test	6/30/2016		Results update
3-3	3	19	Complete Tune-up IGCC Performance	6/30/2016		Results update
3-4	3	16	Complete Model Validation with 4-bed PSA System	9/30/2016		Results update
3-5	3	15	Complete up to 40,000 cycles in Sorbent Life Test	12/30/2016		Results update
3-6	3	18	Complete Field Tests at Southern's PSDF at NCCC	12/30/2016		Topical Report - Field Test Results at PSDF
3-7	3	19	Complete Detailed Economic Analysis for TDA's process integrated with IGCC	12/30/2016		Results update
3-8	3	14	Annual Review Meeting at NETL	12/30/2016		Presentation file
			Go/No-go Decision Point	**12/30/2016**		

BP3 – Decision Points

Go/No-go Decision Point: End of Year 3	12/31/2016	Complete 40,000 cycles in the life test with less than 2% degradation per 10,000 cycles in sorbent performance.
		Complete a minimum of 1,200 hours of testing with Pilot Scale Unit achieving 90% carbon capture under air blown gasification.
		Increase in COE is 20% lower than that of the Selexol™ based CO_2 capture Systems and Cost of CO_2 captured is less than $40/tonne with 95+% CO_2 purity.

TDA Research

Budget Period 4
1/1/2017 – 12/31/2017

Pilot Scale Testing of the CO_2 Capture Sorbent System
DE-FE0013105

Task 20. BP4 Project Management & Planning

- **Ensure coordination and planning of the project with DOE/NETL and other project participants**
- **Monitor and control the project scope, cost, schedule, and risks**
- **Submit and get approval for the required NEPA documentation**
- **Maintain and revise the Project Management Plan (PMP) and manage and report on activities in accordance with the plan**
- **Update the Project Management Plan as the project progresses**
- **Report progress against milestones, schedule and budget, including any variances**
- **Prepare and deliver required reports and briefings**

TDA Research

Task 21. Sorbent Life Test (60,000 Cycles)

Continue the cycling of the sorbent

<u>Task 21.1 Cycles up to 50,000</u>

<u>Task 21.2 Cycles up to 60,000</u>

TDA Research

Task 22. Model Validation Based on Pilot Plant Test

- **The adsorption and CFD models will be updated incorporating the knowledge gained from the first field test**
- **Full-scale reactor designs will be modified using the updated model**

Task 23. Second Field Test

Task 23.1 Transport the Pilot-Scale Unit to Second Site

- **We will decommission, package, transport the pilot unit from NCCC to the second host site**

Task 23.2 Conduct Test at Second Test Site

- **9 nine month test campaign is scheduled using synthesis gas generated from an oxygen-blown gasifier**
- **This include all shakedown runs and parametric tests at different operating conditions**
- **A minimum of 4,000 hours testing is scheduled with continuous steady-state operation**

Task 23.3 Pilot-Test Unit Decommissioning

- **Pilot-scale unit will be decommissioned and the equipment transported to its final disposition/location**

Task 24. Final Techno-Economic Analysis

- **Results from the field tests will be incorporated into the Aspen Plus® model and the IGCC plant performance will be optimized**
- **Cost analysis of the supporting sub-systems will be completed**
  - Costs for will be updated based on the new results
- **These results will feed into the techno-economic analysis, which will be carried out in accordance with the DOE guidelines in Attachment A of the SOPO**
- **Full process simulation for 4 different gasifier types**
  - GE Gasifier
  - E-Gas Gasifier
  - Shell Gasifier
  - TRIG Gasifier

Task 25. Final Technology Environmental, Health and Safety (EH&S) Risk Assessment

- **A detailed assessment of environmental, health and safety risks associated with the TDA's CO_2 capture process will be performed in accordance with the guidelines provided in the DOE FOA (DE-FOA-000785)**

BP4 – Milestone Log

Mile-stone #	Budget Period	Task/ Subtask No.	Milestone Description	Planned Completion	Actual Completion	Verification Method
			Project Start Date	**12/30/2013**		
4-1	4	21	Complete up to 50,000 cycles in Sorbent Life Test	6/30/2017		Results update
4-2	4	24	Incorporate Validated Model Results into Aspen Simulation	6/30/2017		Results update
4-3	4	22	Complete Model Validation with Pilot Scale Test Results and Update System Design	11/30/2017		Results update
4-4	4	21	Complete up to 60,000 cycles in Sorbent Life Test	12/29/2017		Results update
4-5	4	23	Complete Field Test at Sinopec	12/29/2017		Topical Report - Field Test Results at Sinopec
4-6	4	24	Complete Sensitivity and Final Cost Analysis	12/29/2017		Topical Report - Initial Techno-economic Analysis
4-7	4	25	Complete Preliminary EH&S Risk Assessment	12/29/2017		Final EH&S Risk Assessment Report
4-8	4	20	Final Review Meeting at NETL	12/29/2017		Presentation file
4-9	**4**	**20**	**Complete Final Report**	**12/29/2017**		**Final Report**

Decisions Points – Project Completion

Project Completion	12/31/2017	Complete 60,000 cycles in the life test with less than 2% degradation per 10,000 cycles in sorbent performance.
		Complete a minimum of 4,000 hours of testing with Pilot Scale Unit achieving 90% carbon capture with 95% CO_2 purity under oxygen blown gasification.
		Increase in COE is 20% lower than that of the Selexol[TM] based CO_2 capture Systems and Cost of CO_2 captured is less than $40/tonne with 95+% CO_2 purity.

TDA Research

Deliverables

- **Initial Techno-Economic Analysis (Task 2)**
- **Pilot Plant Design Package (Task 5)**
- **Initial EH&S Risk Assessment (Task 7)**
- **Final Techno-Economic Analysis (Task 24)**
  - Prepared in accordance with Attachment A of SOPO
- **Final Technology EH&S Risk Assessment (Task 25)**
  - Prepared in accordance with Attachment B of SOPO
- **Periodic, Topical, and Final reports shall be submitted in accordance to the "Federal Assistance Reporting Checklist“ attached to the proposal**
- **Summary Reports for BP1, BP2 and BP3**
  - Prepared in accordance with the template and instructions for Topical Reports provided in Attachment 3 – Reporting Checklist
- **Reports to include the specific information identified in the FOA (DE-FOA-000785)**

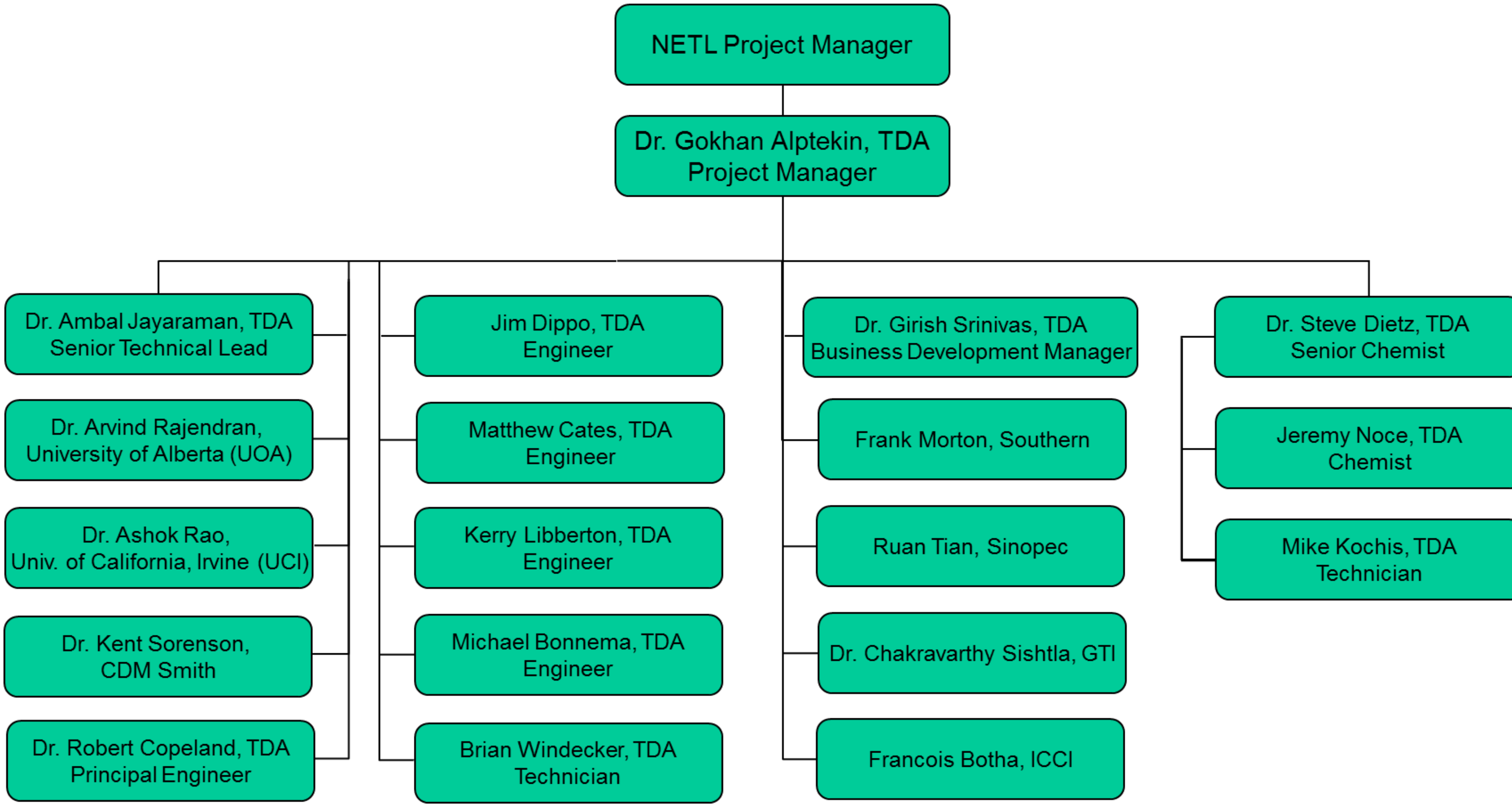
Briefings & Presentations

- **TDA will prepare detailed briefings for presentation to the Project Officer at the Project Officer's facility located in Pittsburgh, PA or Morgantown, WV**
  - Briefings will be given by TDA to explain the plans, progress, and results of the technical effort
  - Briefings will be arranged with the DOE Project Officer, one at project kick-off and one at the end of each BP
  - A final project briefing at the close of the project will also be given
  - TDA will provide and present a technical paper(s) at the DOE/NETL Annual Contractor's Review Meeting and at a National conference

Risk Management

Description of Risk	Probability (Low, Moderate, High)	Impact (Low, Moderate, High)	Risk Management (Mitigation and Response Strategies)
Technical Risks:			
Attrition losses and crush strength of pellets not sufficient	Moderate	High	TDA will use binders to improve strength of the pellets
Slow adsorption kinetics	Low	Moderate	TDA will increase pore size and optimize particle size
Resource Risks:			
Demonstration site availability	Low	Low	TDA will get Southern and Sinopec involved early and get all necessary approvals. As backup we will also look at other options such as the Wabash river IGCC plant that uses an E-Gas™ gasifier.
Prototype Fabrication & Shake down testing	Low	Moderate	We will plan ahead and stay ahead of schedule to give us ample time to deal with any delays or problems
Management Risks:			
Communication & co-ordination	Low	Low	TDA will have regular meetings and teleconferences to keep the entire team involved and informed on the project progress
JDA & NDA between partners executed on time	Low	Moderate	TDA has prior experience with these partners and already have joint Development Agreements in place with most of them (JDA and NDA)

Project Team Organization



TDA Research