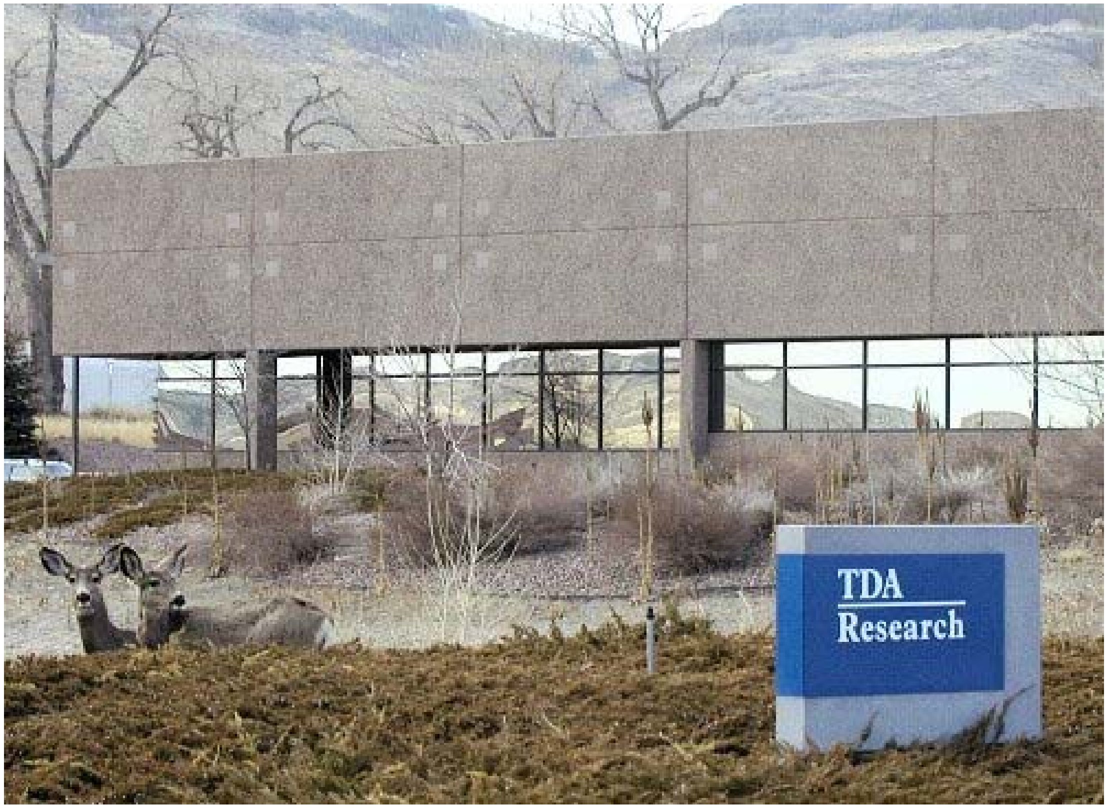
Low Cost Air Separation Process for Gasification Applications



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2017 Gasification Systems Project Review

DE-FE0026142
October 1, 2015 – March 31, 2018

March 20, 2017

Project Goals and Objective

- **The project objective is to demonstrate techno-economic viability of a new air separation technology that can be integrated into the coal gasification processes**
- **A high temperature chemical absorbent selective for O_2 removal is the key for the process**
  - Early proof-of-concept demonstrations in an SBIR Phase II project and NETL project (DE-FE-0024060) proved high oxygen uptake and stable performance
- **Project Tasks**
  - Sorbent production scale-up
  - Bench-top demonstration of life (minimum 12,500 cycles)
  - Design of a fully-equipped prototype unit to fully demonstrate the concept at the bench-scale (1 kg/hr O_2 production rate)
  - Concept demonstration
  - Process design & cost analysis by Aspen Plus^{TM} simulations
    - IGCC power generation and CTL

Project Partners

DEPARTMENT OF ENERGY · UNITED STATES OF AMERICA

TDA RESEARCH

UNIVERSITY of CALIFORNIA • IRVINE

UNIVERSITY OF ALBERTA

gti

<u>Project Duration</u>

- **Start Date = October 1, 2015**
- **End Date = March 31, 2018**

<u>Budget</u>

- **Project Cost = $1,600,000**
- **DOE Share = $1,280,000**
- **TDA and its partners = $320,000**

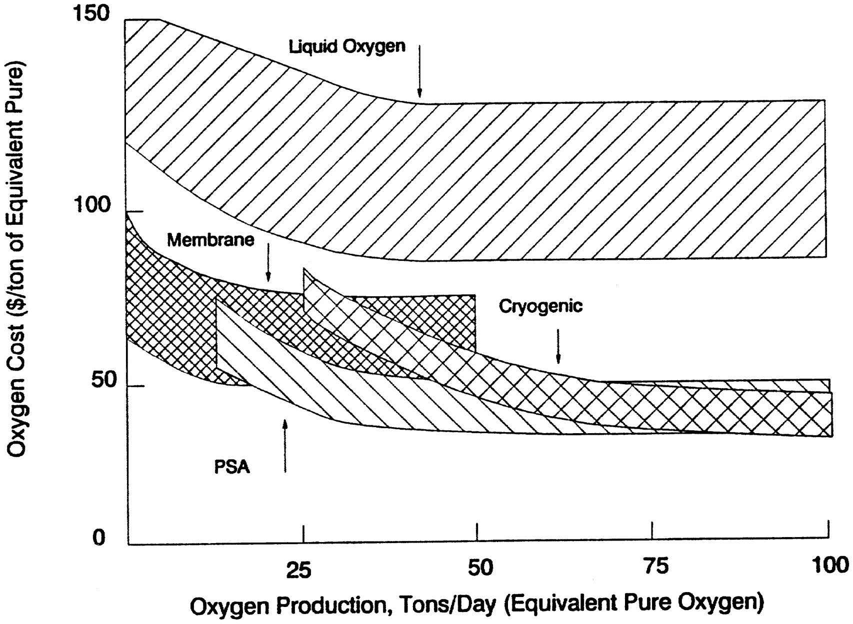
Presentation Outline

- Background
- TDA's Approach
- System Design
- Bench-Scale Results
- Modeling Results
- Prototype Unit Design
- Techno-economic Analysis
- Future Plans

Background

- **Oxygen-blown gasifiers provide smaller size and higher efficiency**
  - Substantially lower NO_x generation in IGCCs
  - Improved gas purity with the removal of N_2 in CTL processes
- **ASU is one of the largest cost items in a gasification plant (consumes over 5% of plant power and constitutes ~15% of plant cost)**
- **Cryogenic air separation is the choice of technology at large-scale**
  - 600 MW IGCC plant requires ~170 ton O_2/day
- **Cryo-separation is highly energy intensive due to the thermal inefficiencies inherent in the low operating temperatures**

Source: Air Products and Chemicals, Inc.



Source: Kobayashi, 2002

TDA's Approach

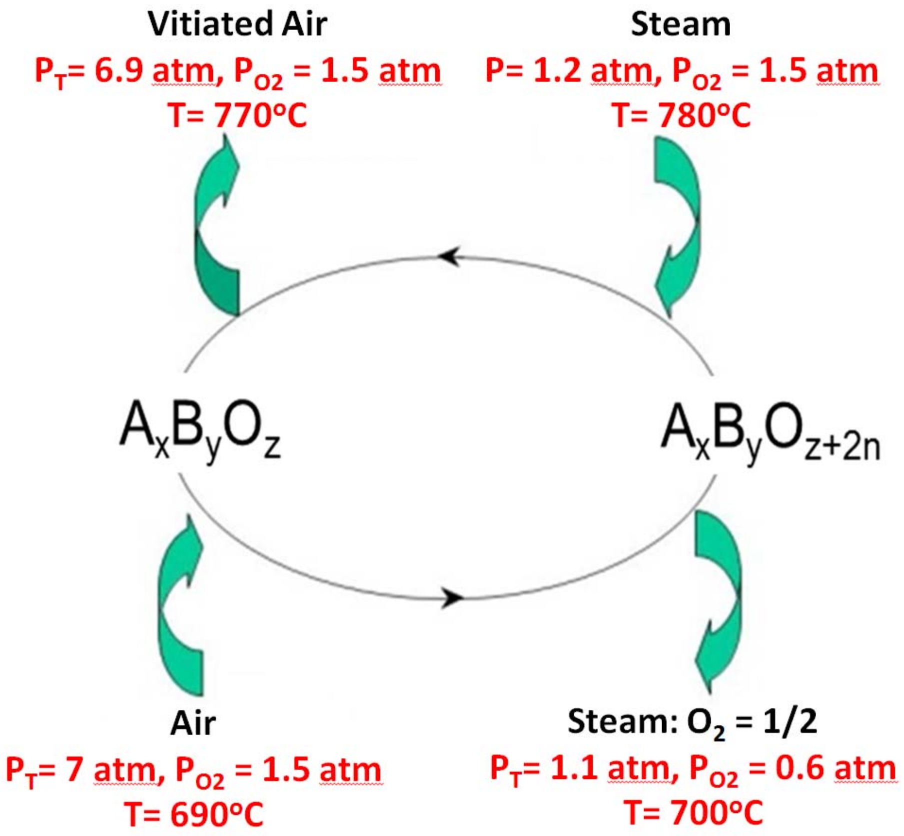
- **TDA's process uses a unique sorbent material to carry out an oxidation-reduction (redox) process**

$$A_xB_yO_z + nO_{2(g)} \leftrightarrow A_xB_yO_{z+2n}$$

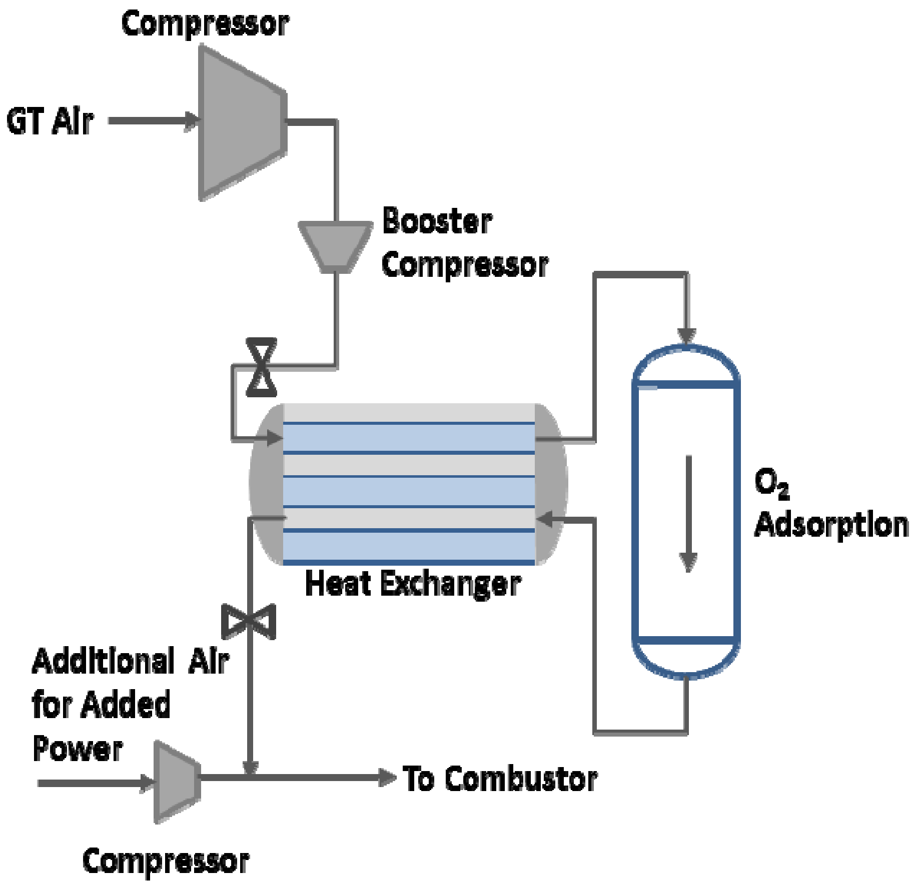
- **Unlike conventional chemical looping combustion sorbents that also work via a similar redox cycle, the oxygen in our sorbent is released by changing process conditions**
- **The oxidized metal oxide phase is "meta-stable" and auto-reduces by changing T, P, oxygen partial pressure**
  - The auto-reduction releases oxygen, which can be recovered as a pure product
  - No use of reducing gases (e.g., CH_4, H_2, CO, syngas) which will consume oxygen

Separation Process

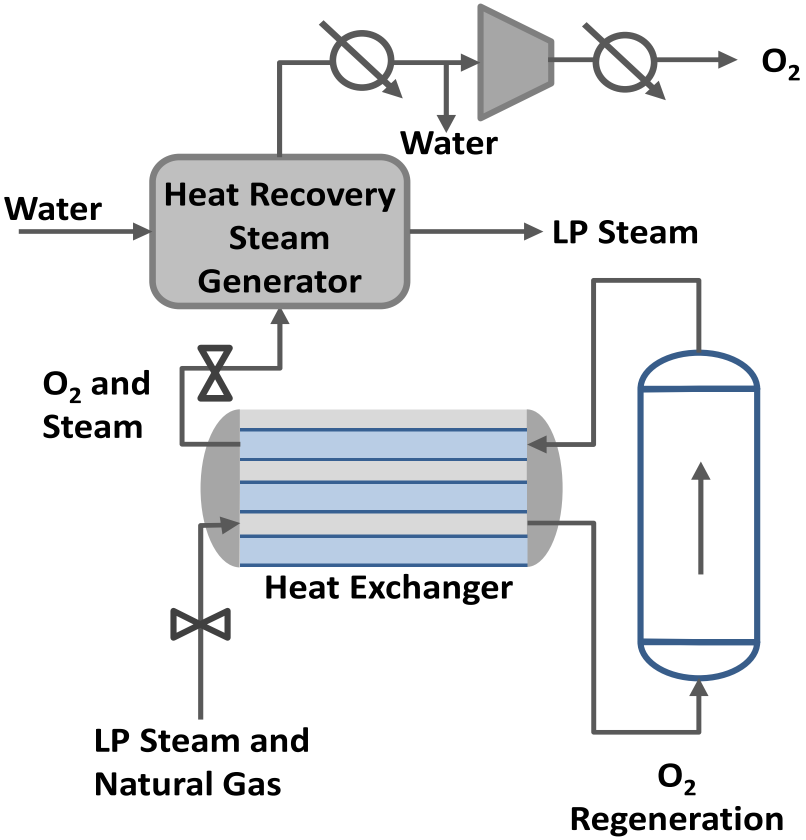
- **Sorbent removes the oxygen from the high pressure air**
    - 90-95% of the oxygen is selectively removed
    - The vitiated high pressure air (that is mostly N_2) is utilized in a gas turbine after boosting the pressure
- **Regeneration is carried out at low pressure close to ambient pressure using a warm sweep gas (superheated steam) <u>ideally</u> under isothermal conditions**
    - The combined pressure swing and concentration swing (i.e., the partial pressure difference) is used to drive O_2 from the sorbent
- **Temperature swing assisted Pressure swing and Vacuum swing are feasible but not economical**



System Design

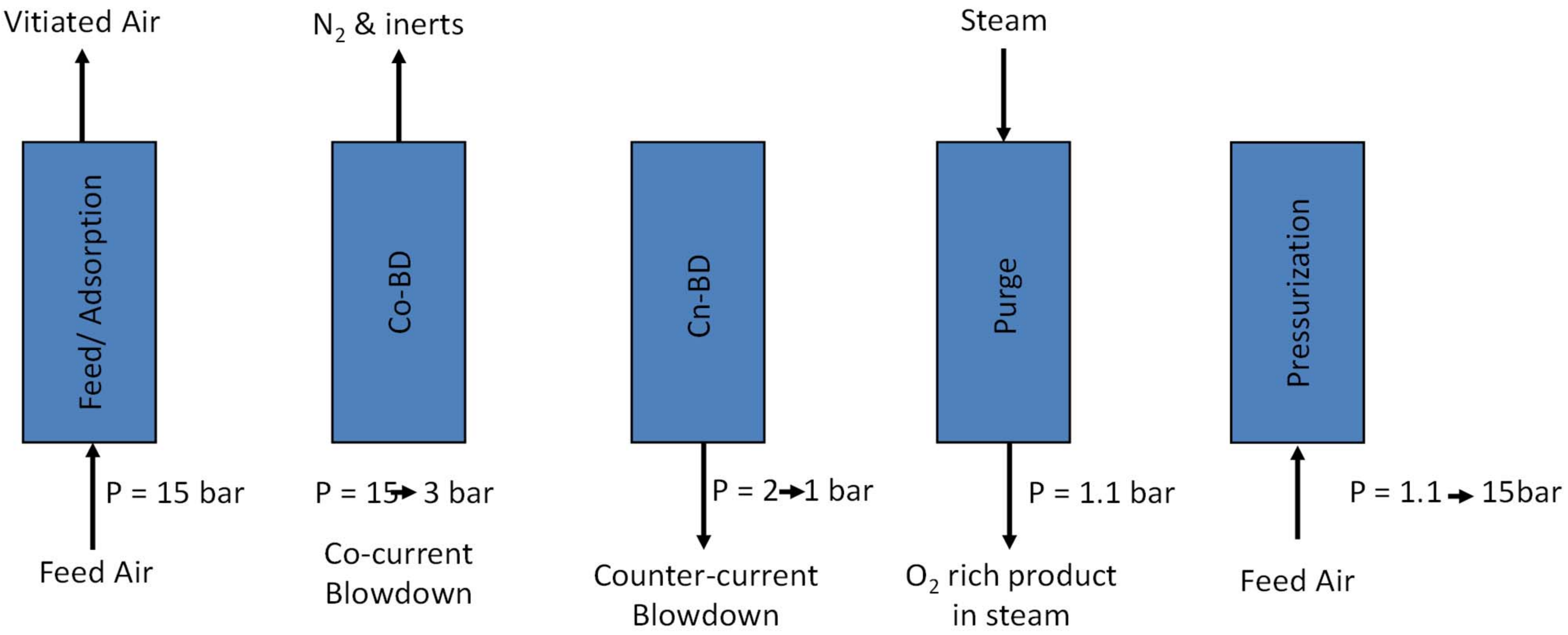


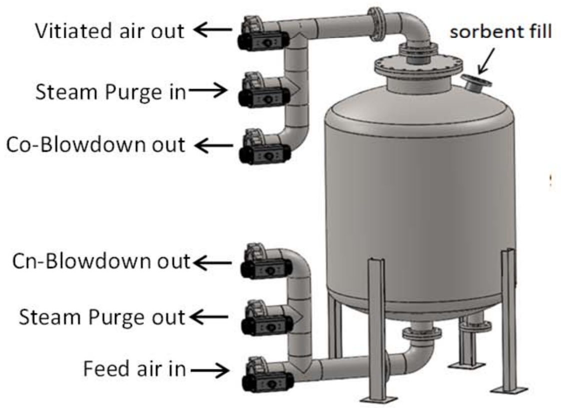
Absorption Process



Regeneration Process

Cycle Sequence





<table>
<tr><td>Bed 1</td><td colspan="3">Adsorption</td><td>Co-BD</td><td>Cn-BD</td><td colspan="3">Purge</td><td>Press</td></tr>
<tr><td>Bed 2</td><td colspan="2">Purge</td><td>Press</td><td colspan="3">Adsorption</td><td>Co-BD</td><td>Cn-BD</td><td>Purge</td></tr>
<tr><td>Bed 3</td><td>Co-BD</td><td>Cn-BD</td><td colspan="3">Purge</td><td>Press</td><td colspan="3">Adsorption</td></tr>
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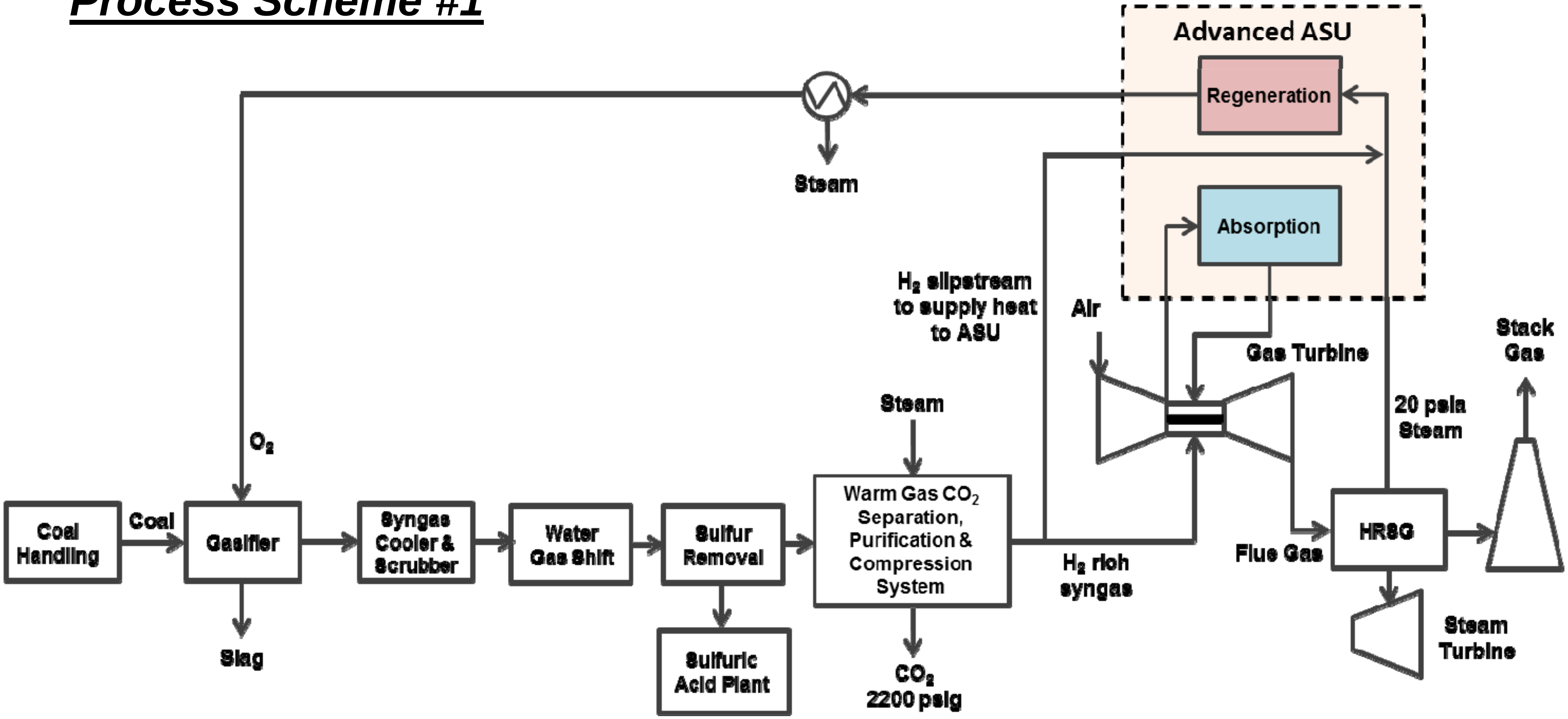
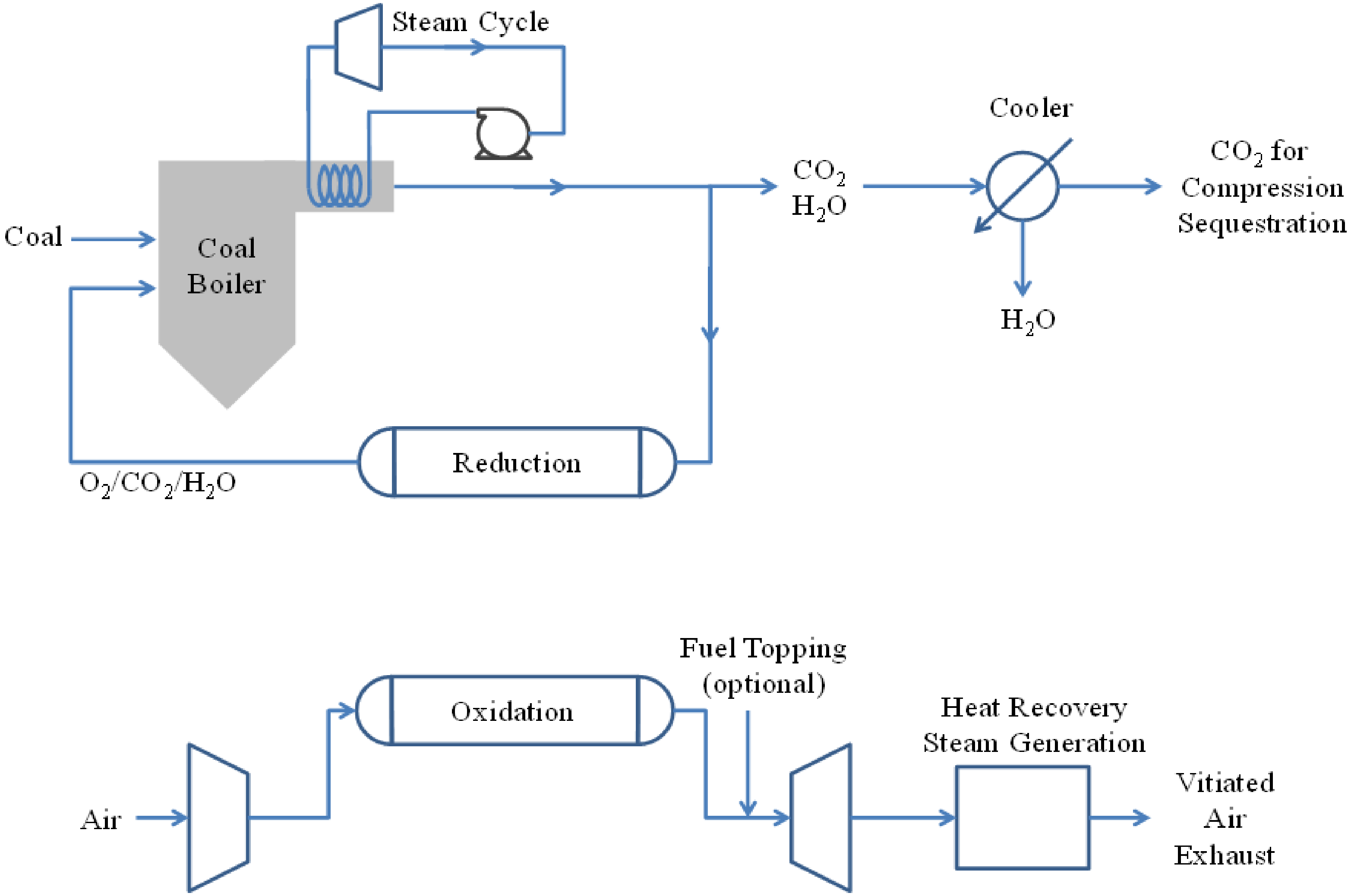
Integrated with IGCC Power Plant

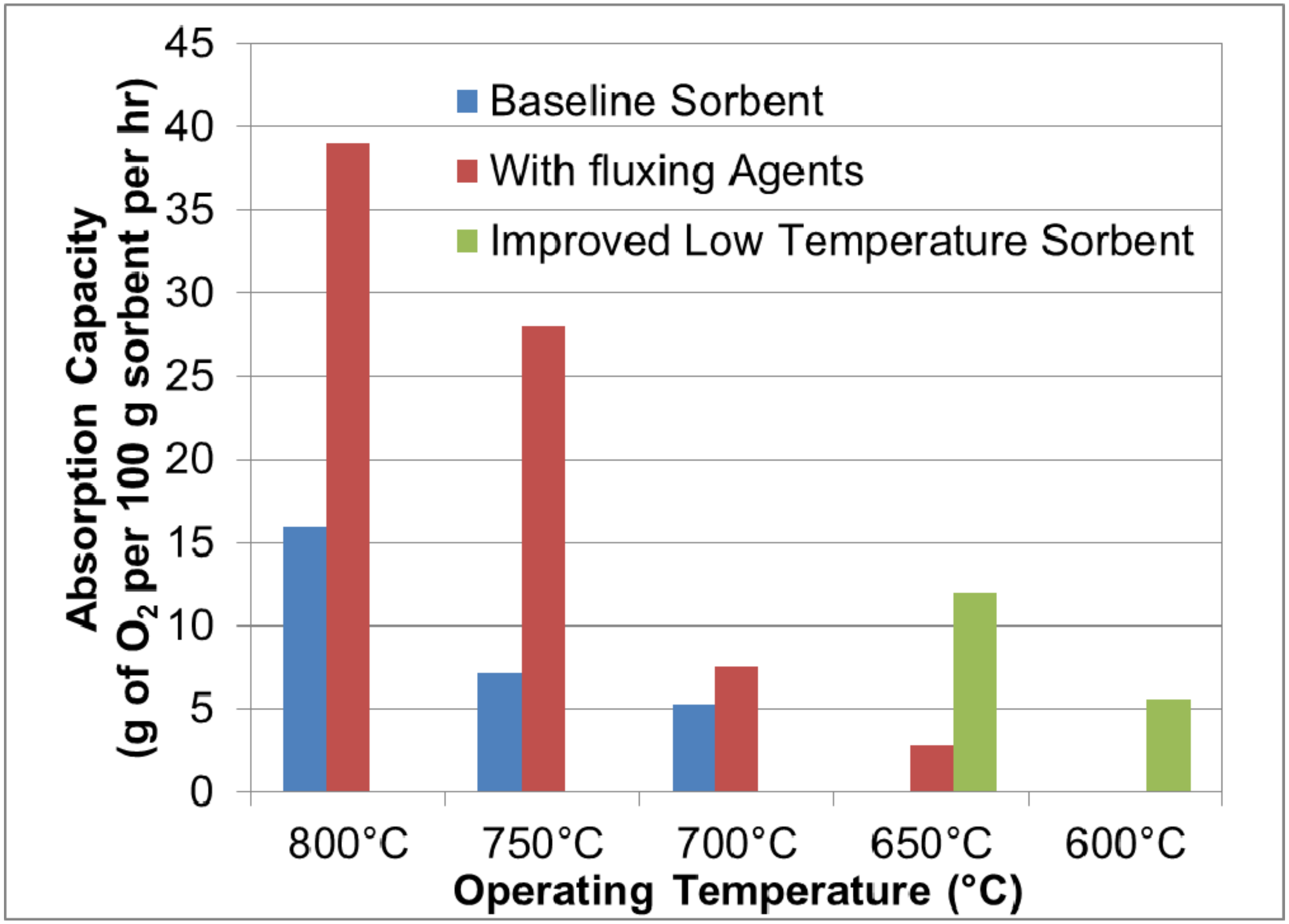
Process Scheme #1



Integration to Oxy-Combustion



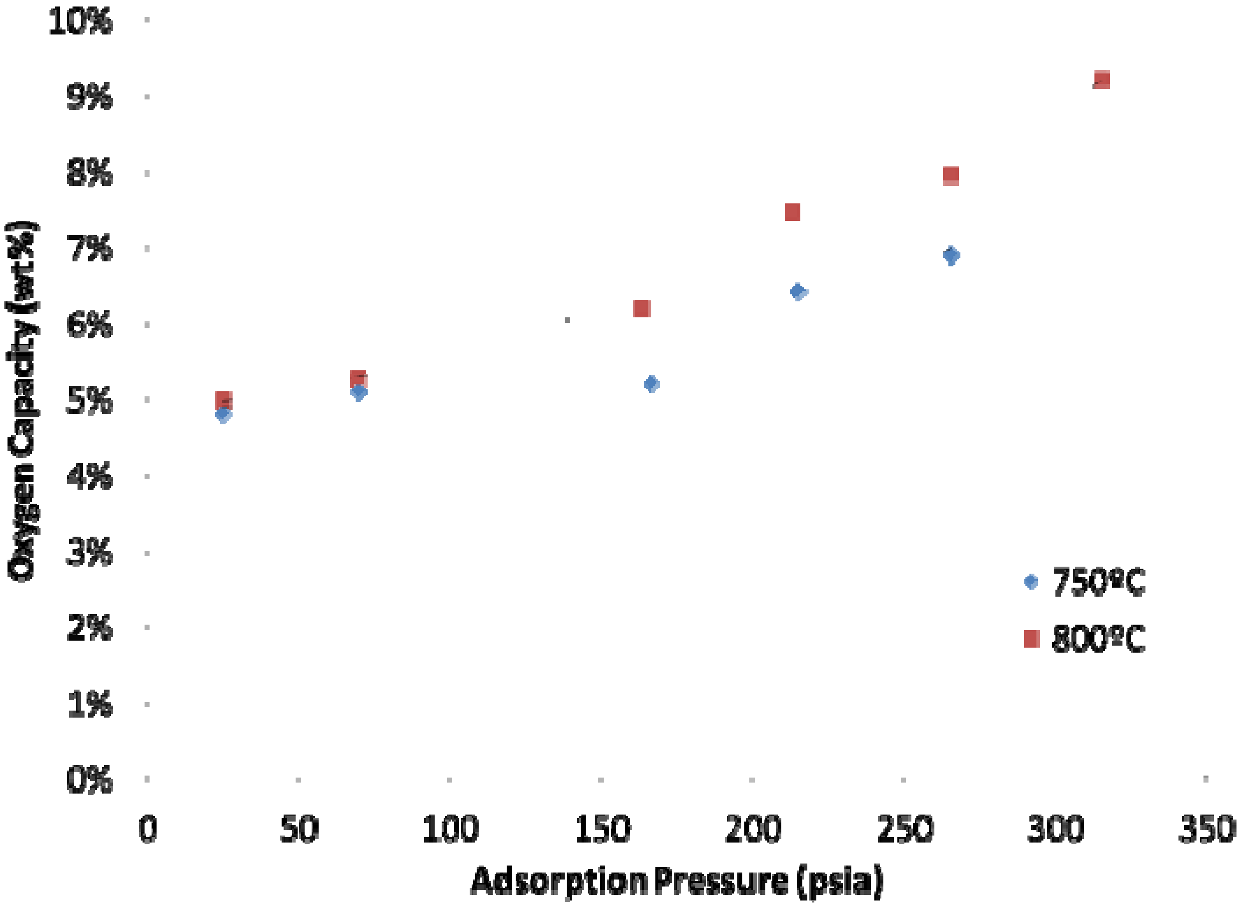
Sorbent Optimization



- **Oxygen release was documented over a wide range of temperatures**
  - Early work (DE-FE0024060) focused on improving activity at lower temperatures

Impact of Pressure

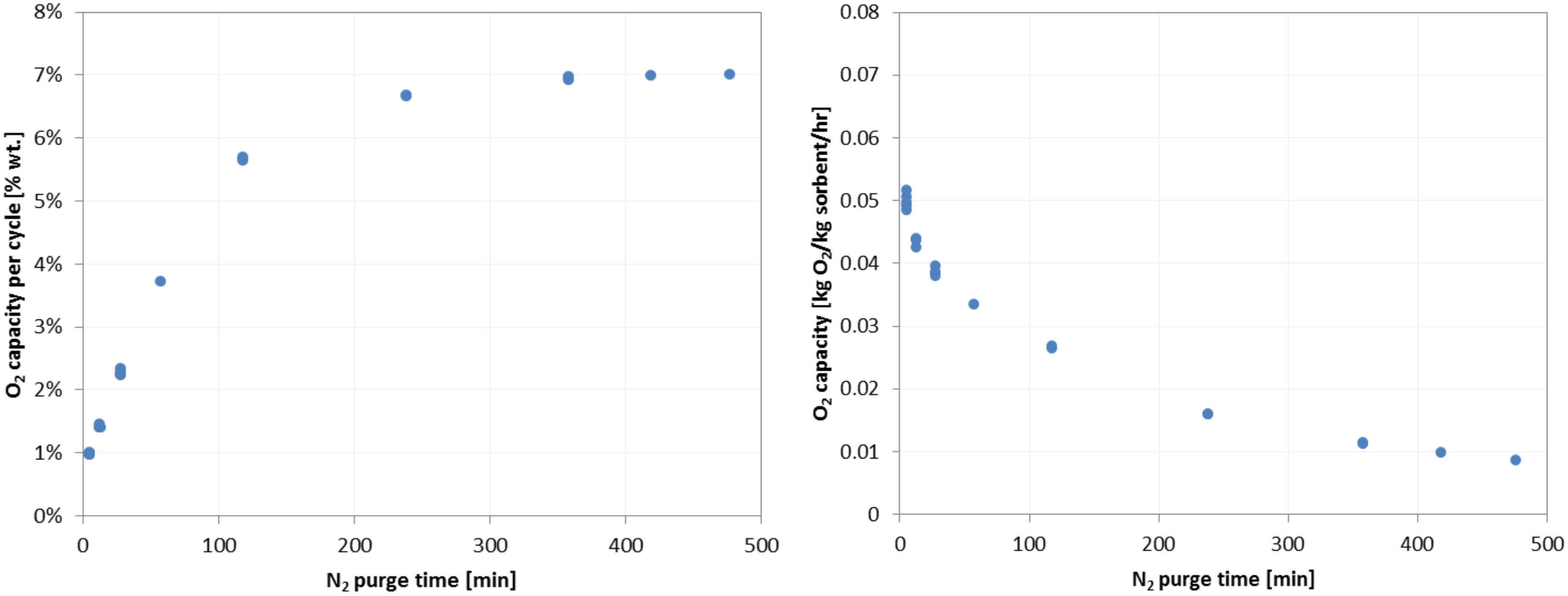
GHSV = 500 h^{-1}, T = 750, 800°C, P_{abs} = 12-253 psig, P_{des} = 12 psig



- **Capacity increases at higher adsorption pressure**

Impact of Cycle Time

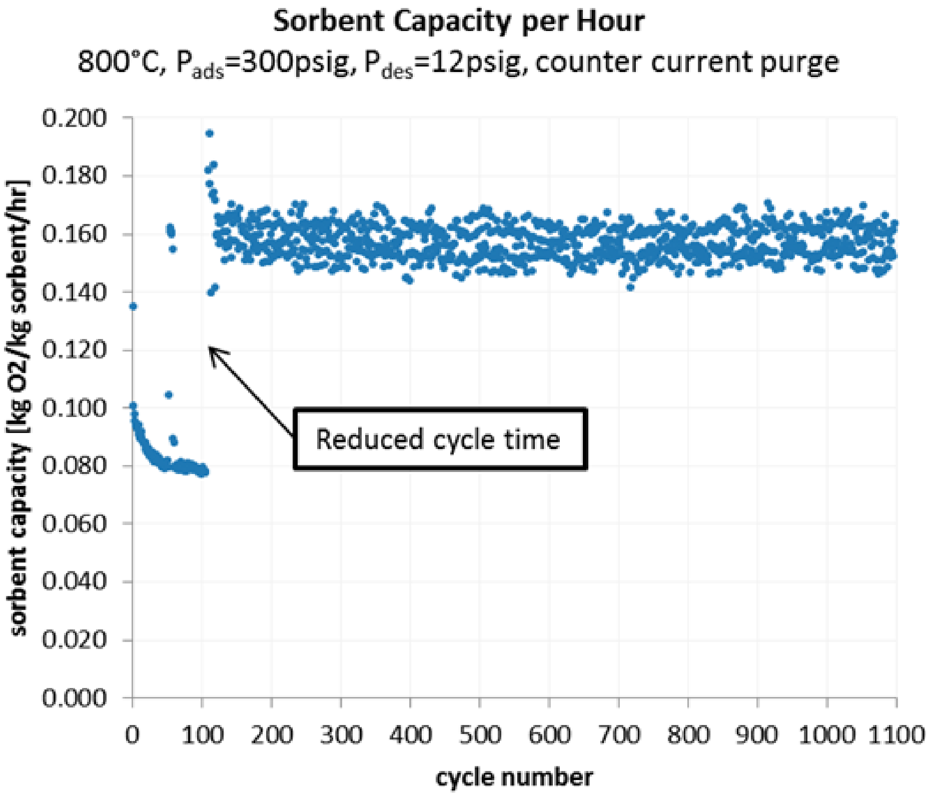
GHSV = 500 h^{-1}, T = 800°C, P_{abs} = 150 psig, P_{des} = 12 psig



- **Shorter cycles provided the best sorbent utilization or hourly working capacity**

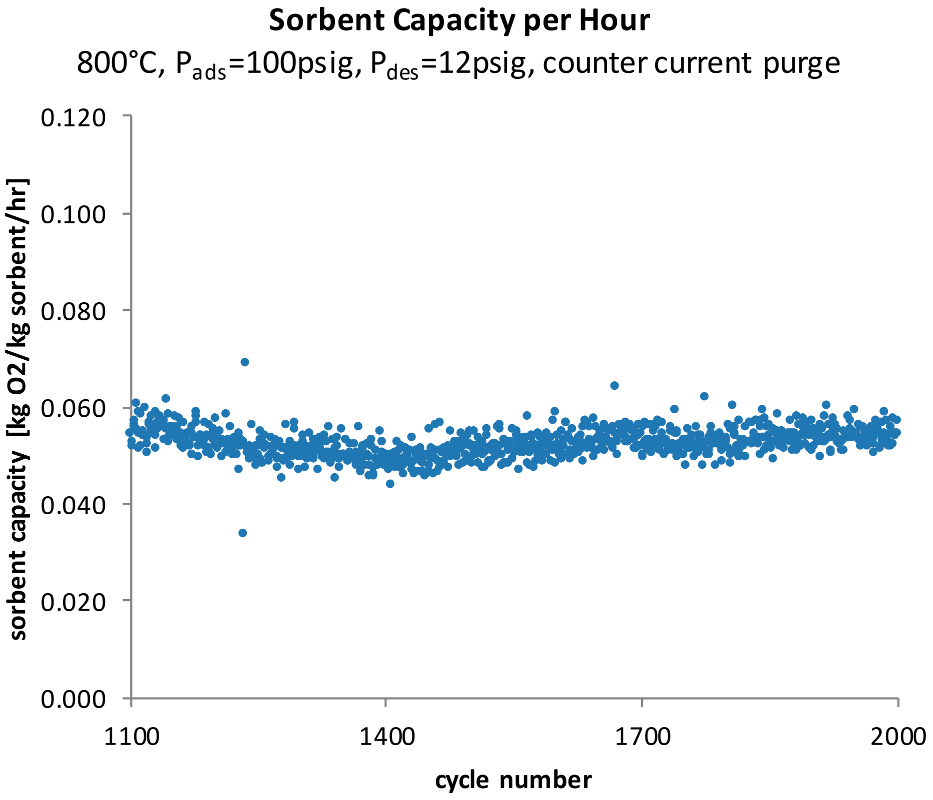
Sorbent Working Capacity

GHSV = 500 h^{-1}, T = 800°C, P_{abs} = 300 or 150 psig, P_{des} = 12 psig



Sorbent Capacity per Hour

800°C, P_{ads}=300psig, P_{des}=12psig, counter current purge



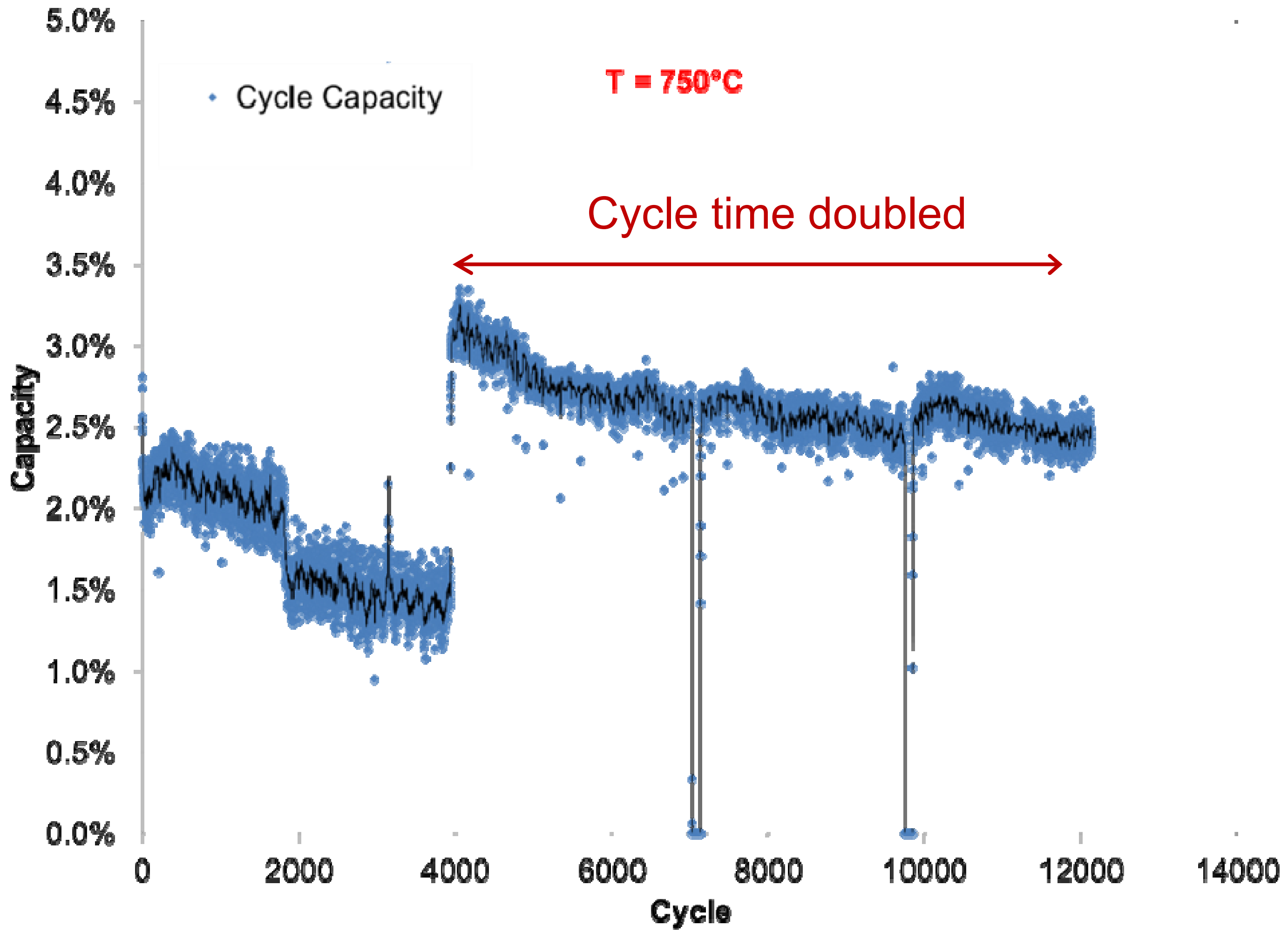
Sorbent Capacity per Hour

800°C, P_{ads}=100psig, P_{des}=12psig, counter current purge

Adsorption pressure [psig]	Sorbent Capacity		Cycles completed
	Per cycle [kg O2/kg sorbent/cycle]	Per hour [kg O2/kg sorbent/hr]	
300	2.54%	0.157	1000
100	0.52%	0.052	500

- **Higher pressures in the IGCC condition provides three times higher working capacity**

Multiple Cycle Tests



T = 750°C

Cycle time doubled

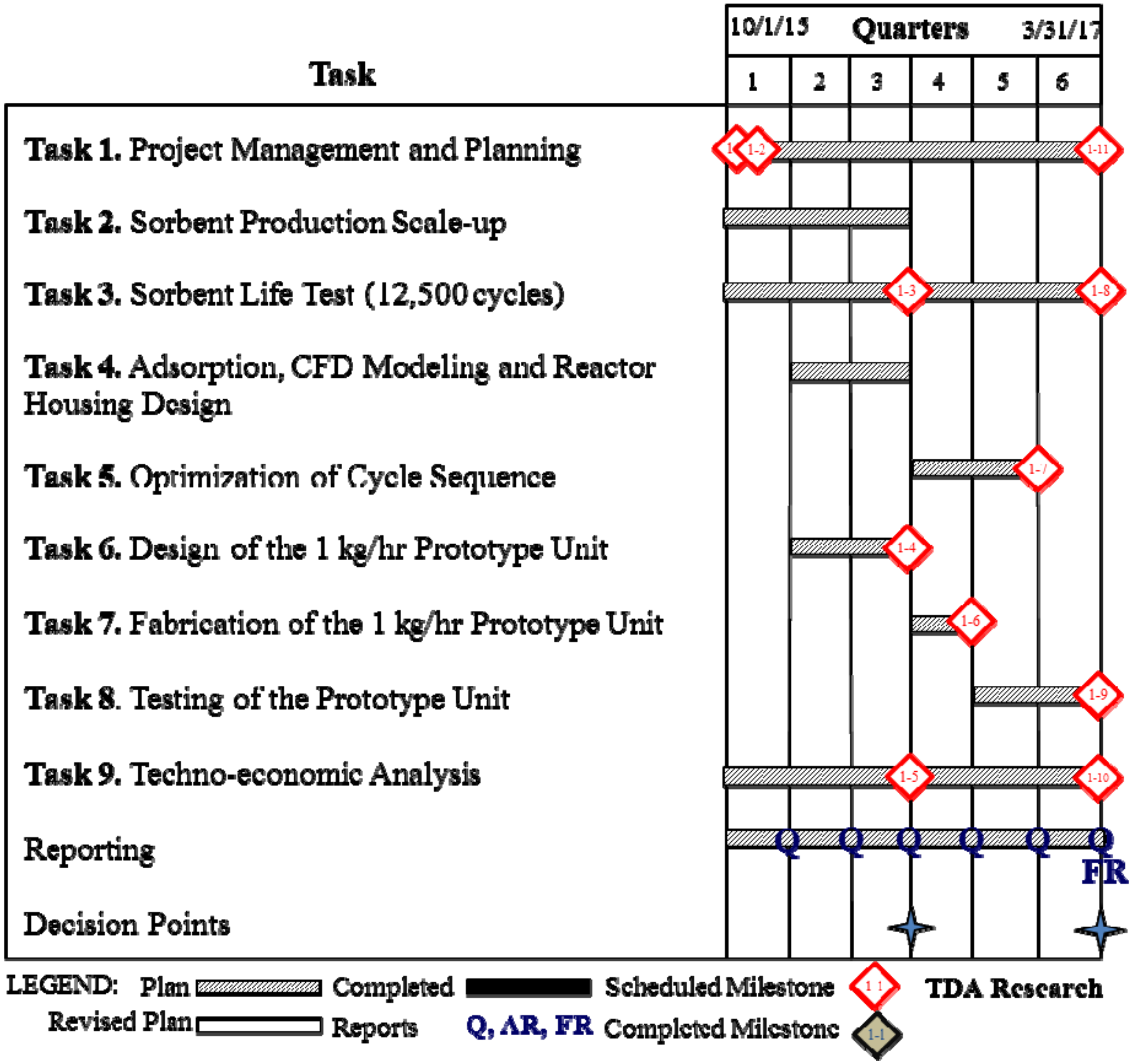
- **Sorbent showed a stable cyclic capacity of over 2.5% wt. O_2 at 750°C**

Project Structure - DE-FE0026142

<u>October 1, 2015 – March 31, 2018</u>

- Task 1. Project Management and Planning
- Task 2. Sorbent Production Scale-up
- Task 3. Sorbent Life Test (12,500 cycles)
- Task 4. Adsorption, CFD Modeling and Reactor Housing Design
- Task 5. Optimization of Cycle Sequence
- Task 6. Design of Prototype Unit (1 kg/hr O_2 Output)
- Task 7. Fabrication of the Prototype
- Task 8. Proof-of-Concept Demonstrations with the Prototype Unit
- Task 9. Techno-economic Analysis

Project Schedule



Task

Task 1. Project Management and Planning

Task 2. Sorbent Production Scale-up

Task 3. Sorbent Life Test (12,500 cycles)

Task 4. Adsorption, CFD Modeling and Reactor Housing Design

Task 5. Optimization of Cycle Sequence

Task 6. Design of the 1 kg/hr Prototype Unit

Task 7. Fabrication of the 1 kg/hr Prototype Unit

Task 8. Testing of the Prototype Unit

Task 9. Techno-economic Analysis

Reporting

Decision Points

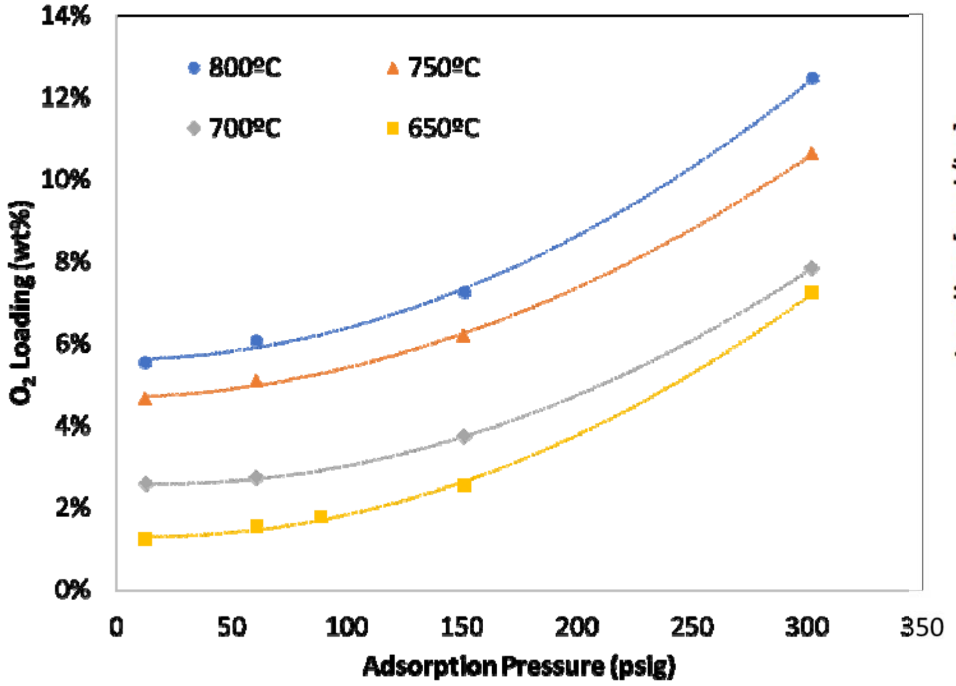
LEGEND: Plan ▨ Completed ■ Scheduled Milestone ◇ TDA Research
Revised Plan □ Reports **Q, AR, FR** Completed Milestone ◆

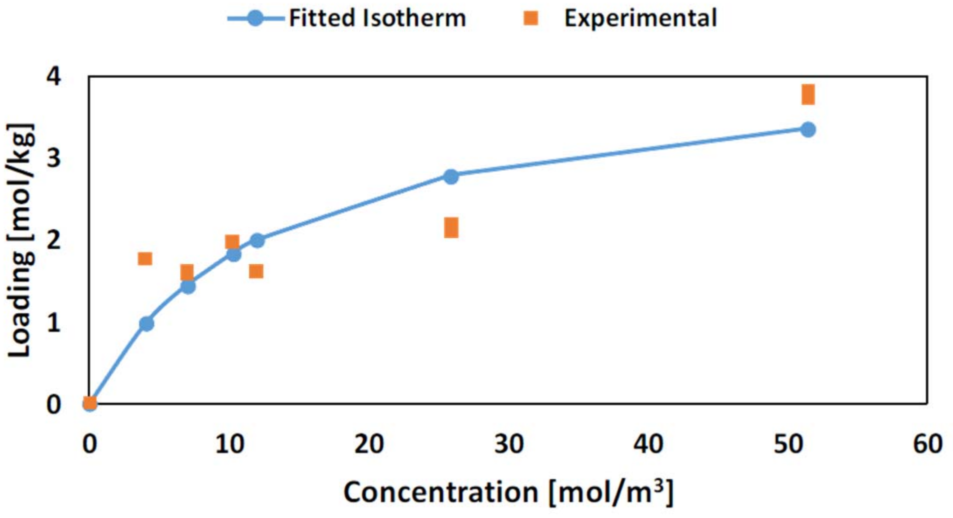
Sorbent Production Scale-up

- **Early work batch size 0.1 to 0.5 kg**
- **Current batch size 1 to 10 kg**
- **Target batch size (End of Task 2) 100 kg**
  - The scale-up work is carried out at TDA's pilot production facility Golden, CO using high throughput production equipment

- **We will develop a Manufacturing and Quality Assurance Plans to ensure consistency in the sorbent material within each batch and minimize any batch-to-batch variations**

Absorption Equilibrium Model



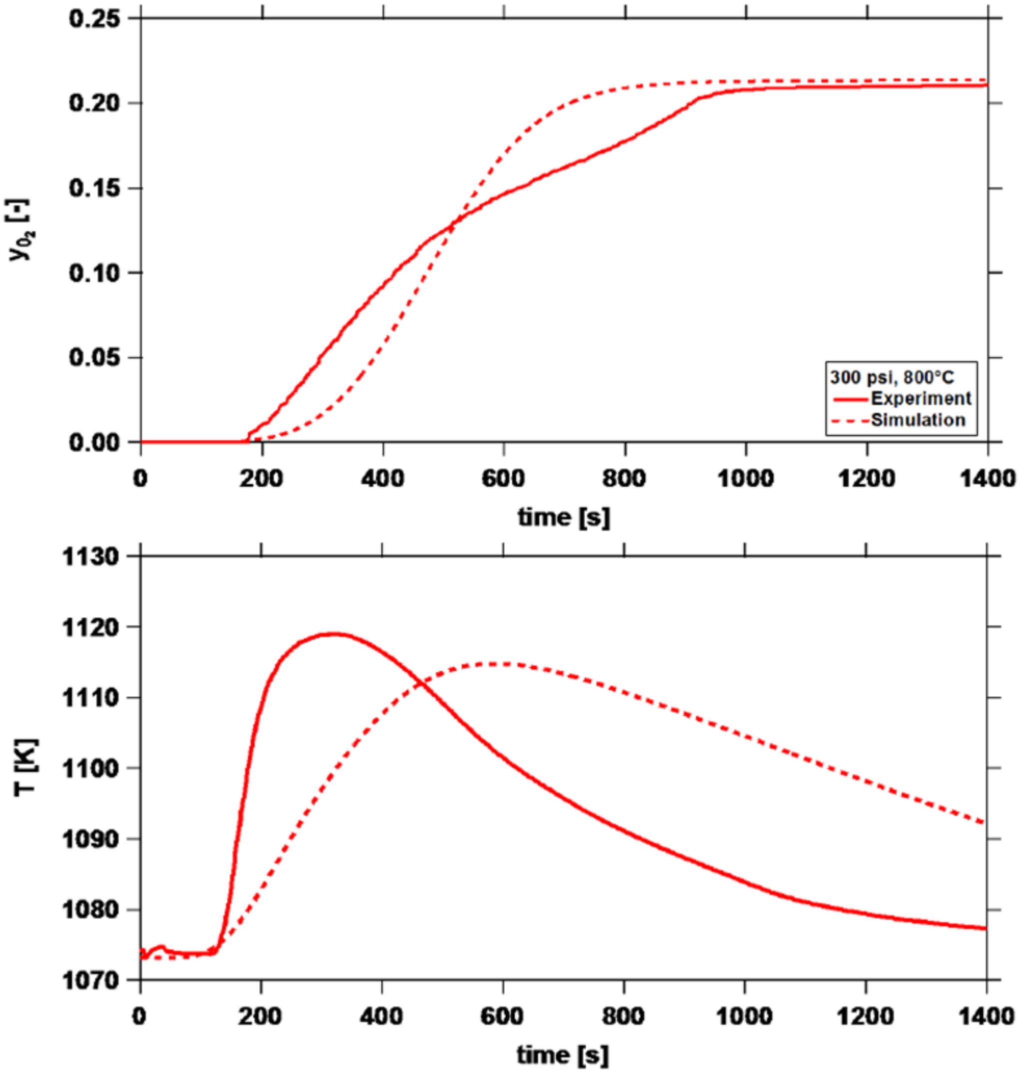


q_s [mol/kg]	b_o [m^3/mol]	-ΔU [J/mol]
4.245963	0.00453	25122.97

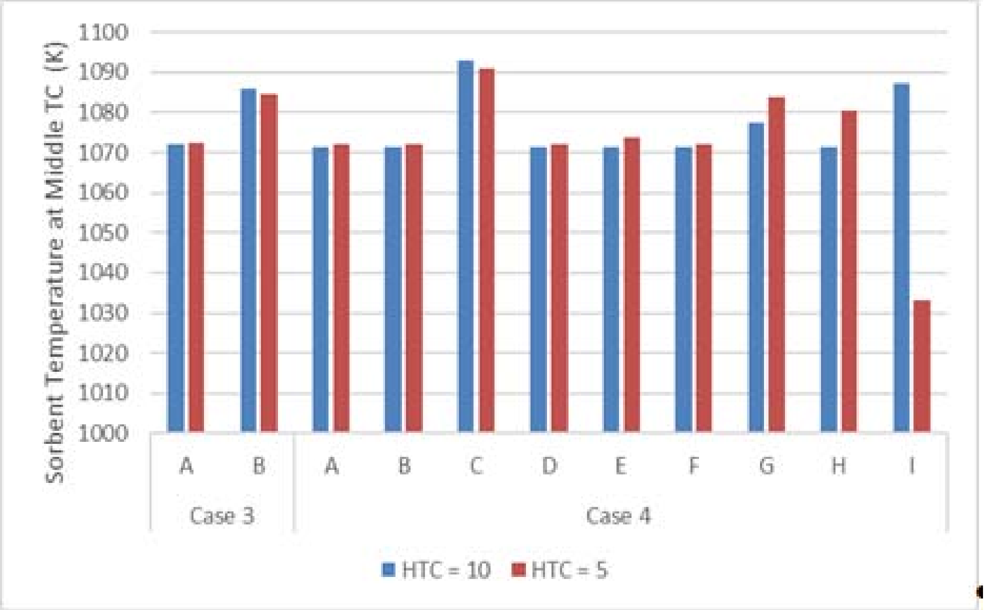
- The sorbent achieves very high equilibrium capacity above 6% wt. at a low temperature of 650°C
- In these tests we ensured complete regenerations between each data point to obtain the maximum possible capacity
- An predictive model is being built by University of Alberta

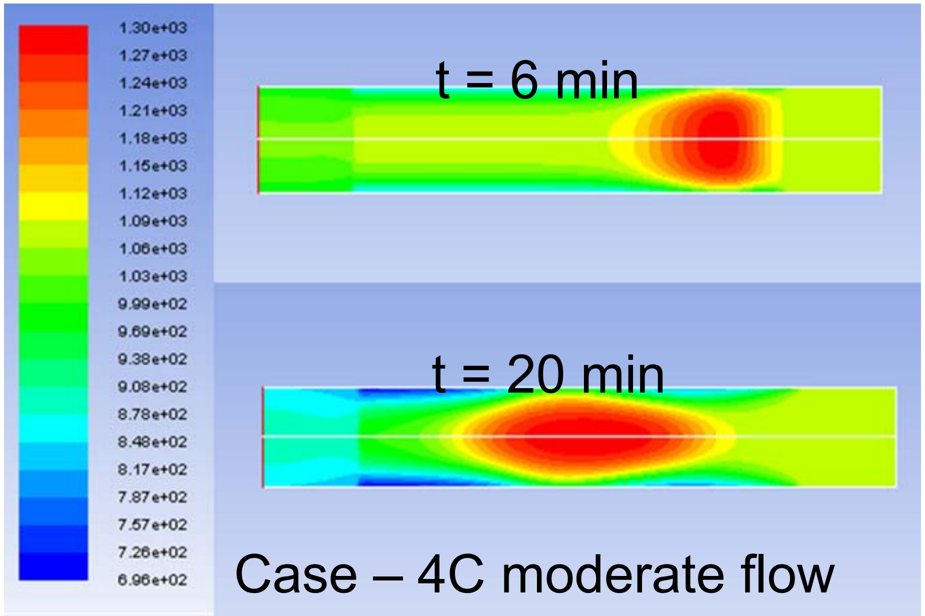
Breakthrough Simulations

- **Equilibrium isotherms were modeled using a simple Langmuir Isotherm**
- **Isotherm model parameters were used to simulate the breakthrough curves**
- **These simple models were able to replicate the heat effects and the average breakthrough time**
- **These models are now being refined for use in cycle optimization**



CFD Modeling

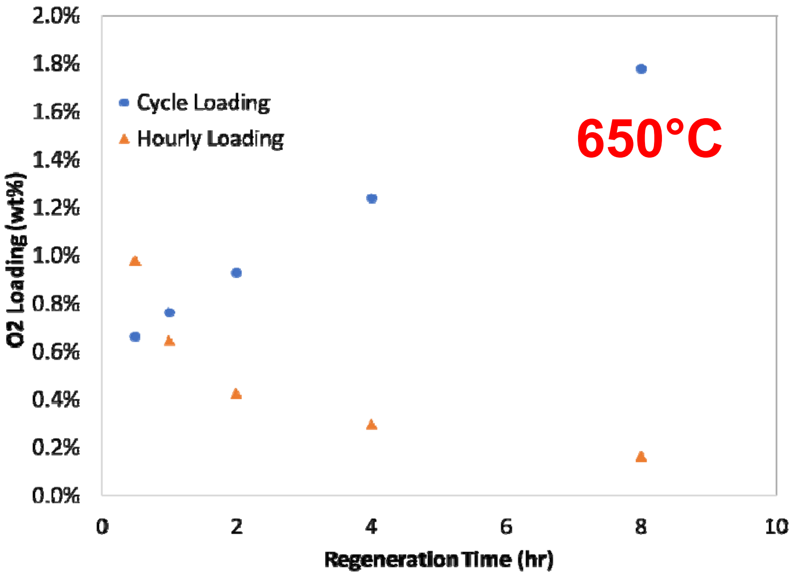


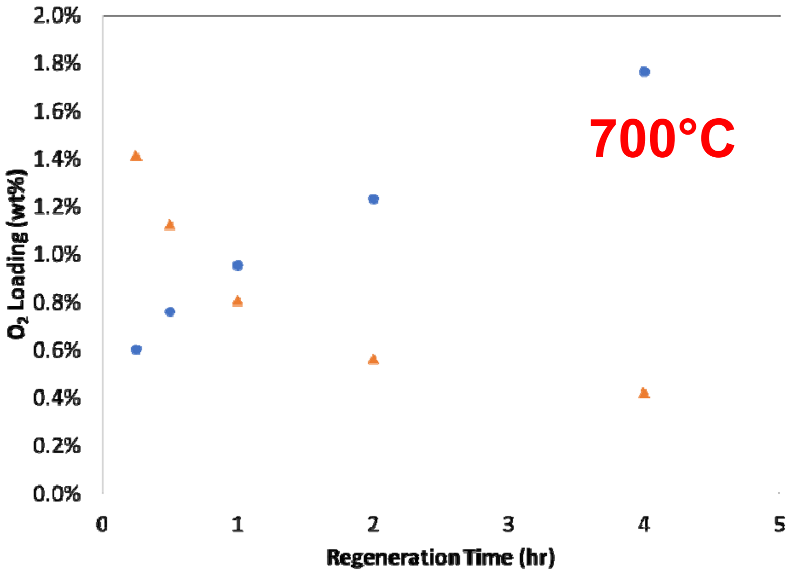


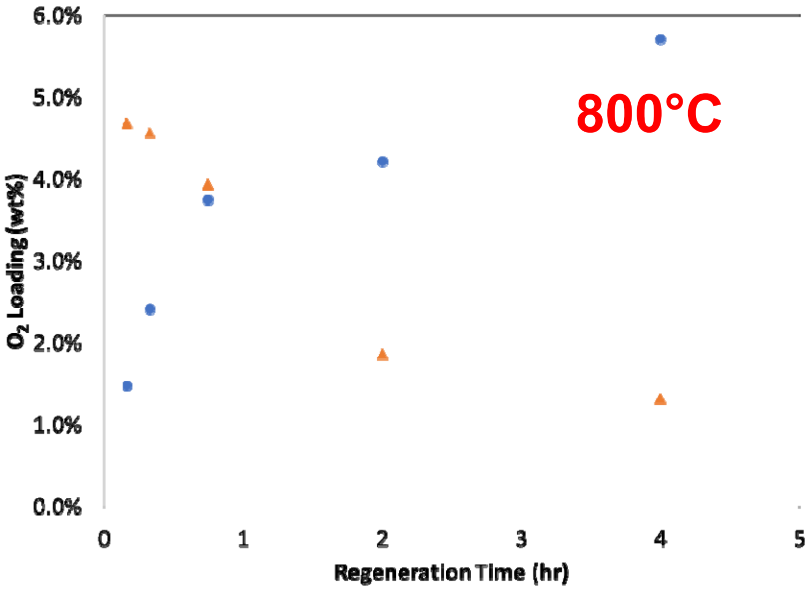
Case – 4C moderate flow

- **To assist with the reactor design, GTI is carrying out CFD modeling work**
  - Model calibrations based on the bench-scale results are completed
  - The lab measurements and model predictions indicate modest temperature increase due to the reaction exotherm (the temperature rise between 60-110°C is predicted based on operating conditions)
- **The model results is used in the design of the 1 kg/hr prototype**
  - It will now be used for full-scale system

Working Capacity, Low Absorption P

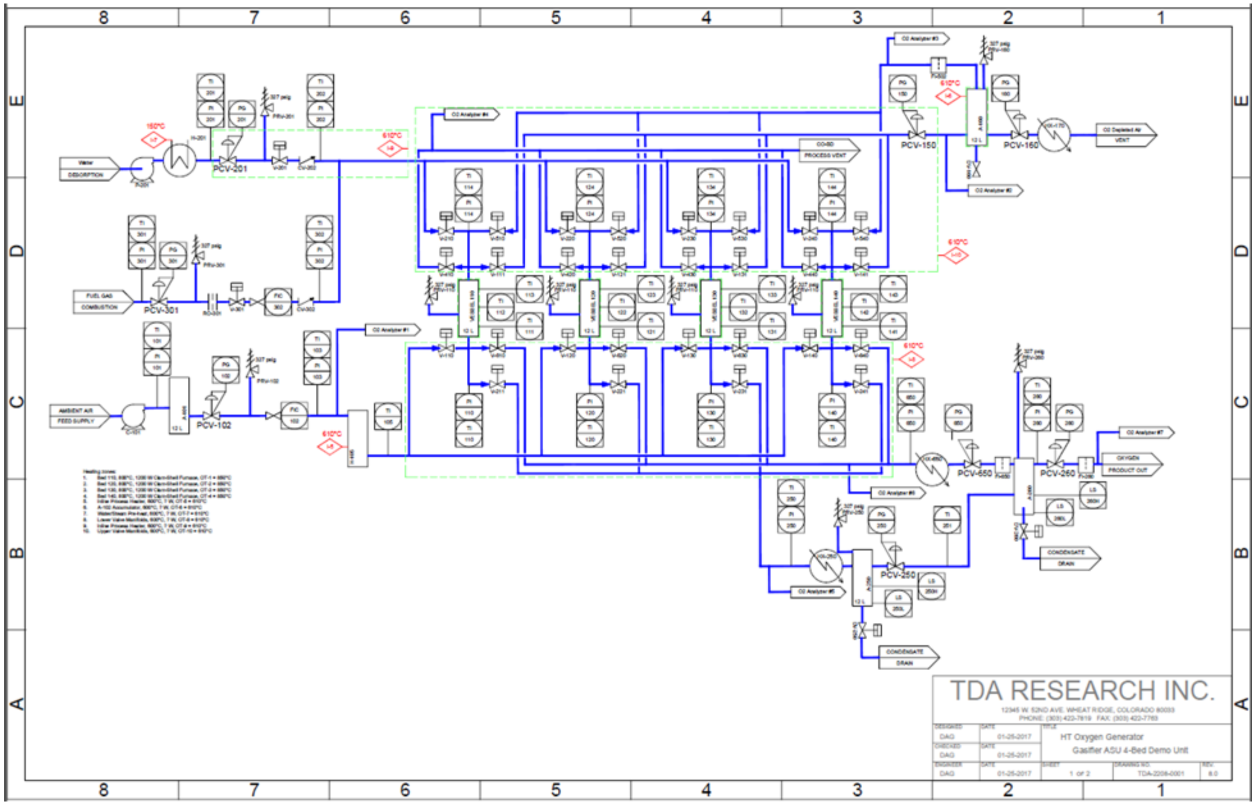


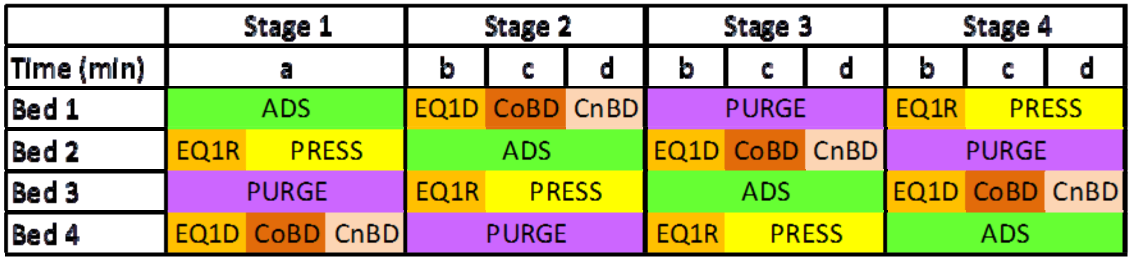




- **Sorbent achieves a high hourly working capacity at short cycle times**
  - Less than 20 min
- **Hourly working capacity**
  - 4.6% wt. O_2 at 800°C
  - 1.4% wt. O_2 at 700°C
  - 1% wt. at 600

Prototype Unit – P&ID





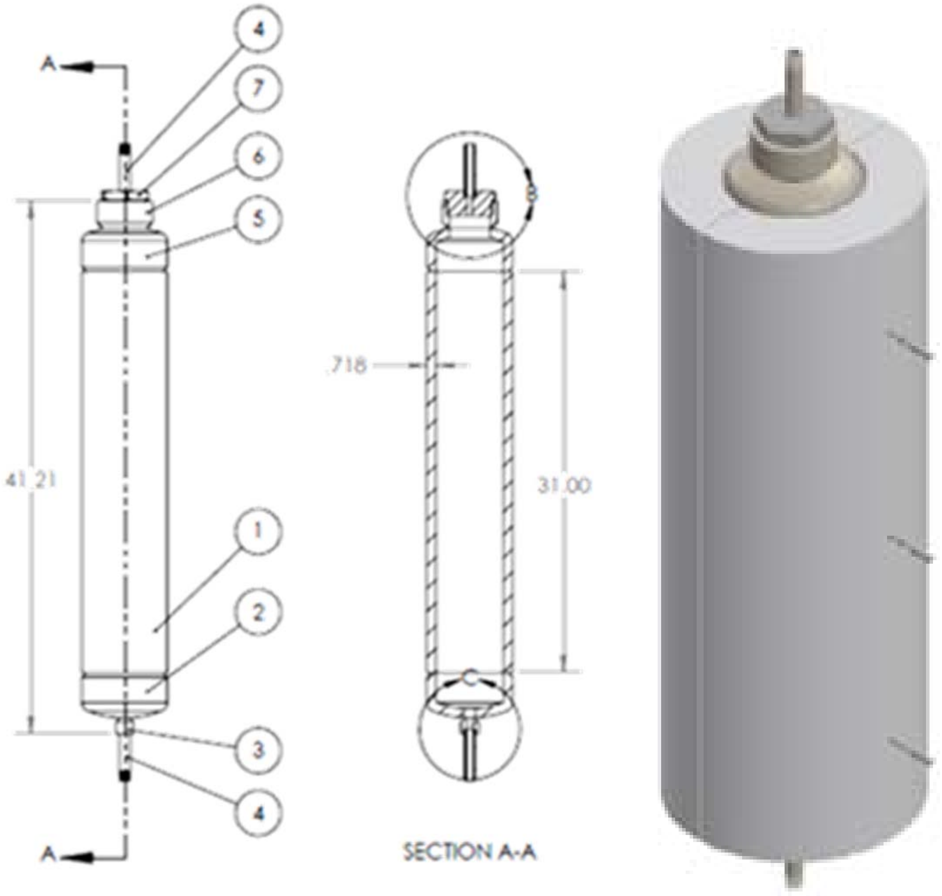
	Stage 1	Stage 2			Stage 3			Stage 4		
Time (min)	a	b	c	d	b	c	d	b	c	d
Bed 1	ADS	EQ1D	CoBD	CnBD	PURGE			EQ1R	PRESS	
Bed 2	EQ1R PRESS	ADS			EQ1D	CoBD	CnBD	PURGE		
Bed 3	PURGE	EQ1R	PRESS		ADS			EQ1D	CoBD	CnBD
Bed 4	EQ1D CoBD CnBD	PURGE			EQ1R	PRESS		ADS		

- **We designed a 4-bed high temperature PSA system**

Reactor Design

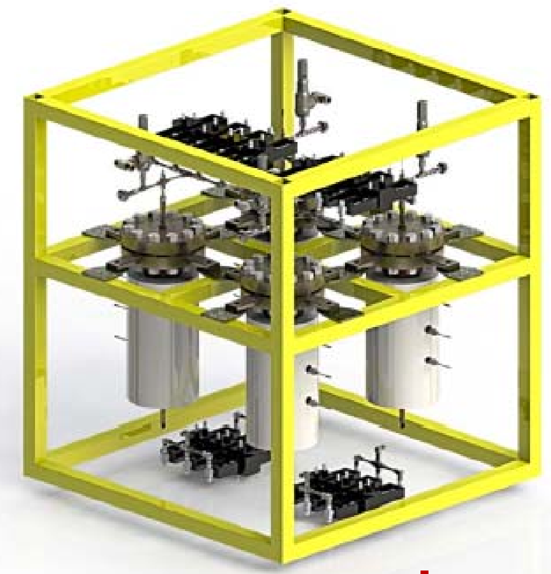
Vessel Sizing for 1 kg/hr O_2

O_2 Product Rate	1	kg/h
O_2 Product Rate	16.7	g/min
Sorbent Capacity	1.57%	wt. O2
Sorbent density	0.793	kg/L
Cycle time	30	min
Sorbent needed	31.8	kg
Total Sorbent Volume	40.2	L
Sorbent Volume (1 Bed)	10	

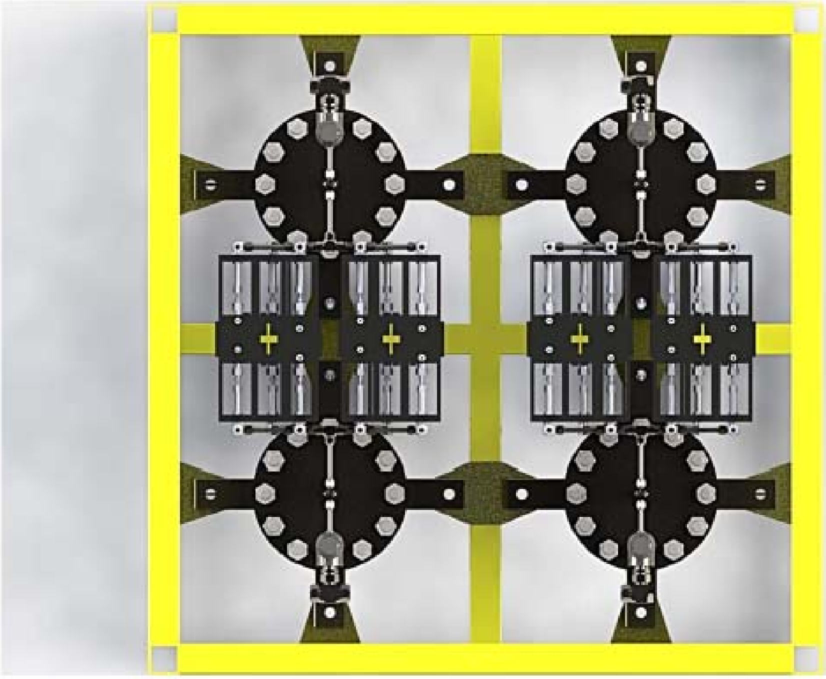


- **6” diameter 36” height vessels to house 12L (0.4 CF) sorbent**
  - Incoloy HT is chosen for the material with a design temperature of 850°C and pressure of 300 psig

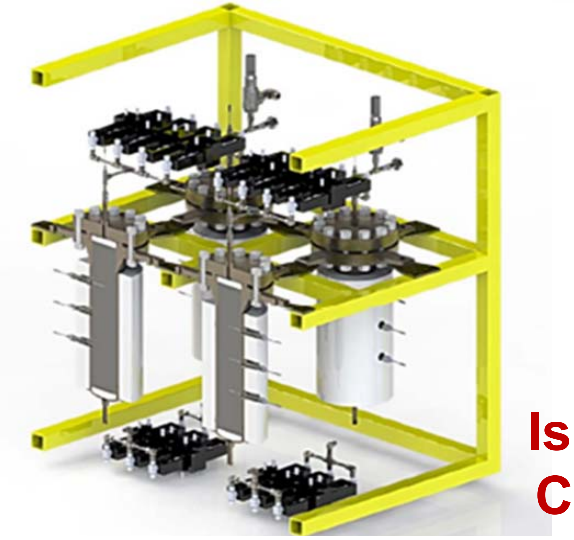
Prototype Unit Layout



Isometric View



Top View



Isometric Cut-view

- The design is completed
- All component identified and ordered

Techno-economic Analysis (TEA)

- **TDA in collaboration with University of California, Irvine is carrying out a high fidelity process design and economic analysis**
- **TDA's ASU unit provides significant improvement in overall plant performance: an increase in the net plant efficiency from 32% to 33.74% for an IGCCC power plant equipped with a cold gas cleanup system (compared to a cryogenic ASU)**
- **The efficiency also improvement for the IGCC power plant with warm gas cleanup system**
  - 35.09% vs 34.46%
- **The 1st year Cost of Electricity (COE) and the Cost of CO_2 Capture are also lower for the TDA ASU that for the cryogenic ASU**
- **Cost of CO_2 capture goes from \$47 to \$43 per tonne for cold gas capture and from \$41 to \$39 per tonne for warm gas capture**
- **The efficiency benefits are also demonstrated for a supercritical pulverized coal oxy-combustion power plant**
  - Net plant efficiency increased from 29.3% (for a cryogenic ASU) to 30.7% (TDA ASU)

Process Techno-economic Analysis

Case		Case 1A		Case 1B	Case 2
Type Plant	IGCC – Cold Gas Cleanup -Selexol^{TM} GE Gasifier		IGCC – Warm Gas Cleanup –TDA Sorbent - GE gasifier		SCPC – Oxy-combustion
ASU Technology	Cryogenic	TDA Sorbent	Cryogenic	TDA Sorbent	TDA Sorbent
CO_2 Capture, %	90	90	90	90	99.5
Gross Power Generated, kWe	727,370	736,376	674,331	735,358	817,314
Gas Turbine Power	464,000	464,000	417,554	464,000	-
Steam Turbine Power	257,403	263,488	246,746	260,809	731,607
Syngas/Air Expander	5,968	8,888	10,031	10,549	85,707
Auxiliary Load, kWe	192,927	170,247	120,661	142,079	267,314
Net Power, kWe	534,443	566,129	553,671	593,279	550,000
Net Plant Efficiency, % HHV	32.00	33.74	34.46	35.09	30.7
Coal Feed Rate, kg/h	221,584	222,570	213,013	224,161	224,159
Raw Water Usage, GPM/MWe	10.92	9.35	10.55	10.51	13.92
Total Plant Cost, $/kWe	3,359	3,232	3,212	3,175	3,849
COE without CO_2 TS&M, $/MWh	133	128	126	124	140
COE with CO_2 TS&M, $MWH	142	136	134	132	151
Cost of CO_2 Capture, $/tonne	47	43	41	39	-

Future Work

- TDA will complete the fabrication and testing of the 1 kg/hr prototype unit demonstrating the high temperature air separation process
- The results will allow us to further validate the CFD and absorption cycle models
- The performance results will also be used to revise the process models being developed by UCI
- Revise our estimates for the cost of CO_2 capture for GE and E-Gas gasifier based IGCC power plants and oxy-combustion coal fired power plant