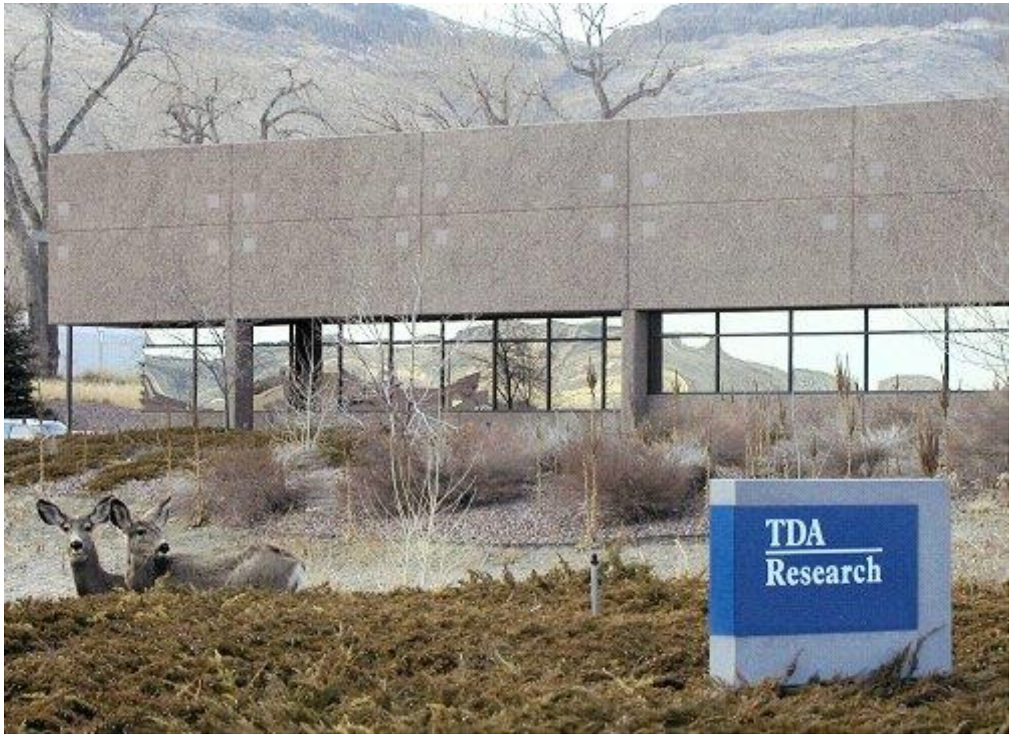
Low Cost Air Separation Process for Gasification Applications
Contract No. DE-FE-0026142



Gökhan Alptekin
Ambal Jayaraman

DOE Project Kickoff Meeting

December 7, 2015

TDA Research Inc. • Wheat Ridge, CO 80033 • www.tda.com

Project 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 (min 12,500 cycles)
  - Design of a fully-equipped sub-scale 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

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Project Partners

Project Duration

- **Start Date = October 1, 2015**
- **End Date = March 31, 2017**

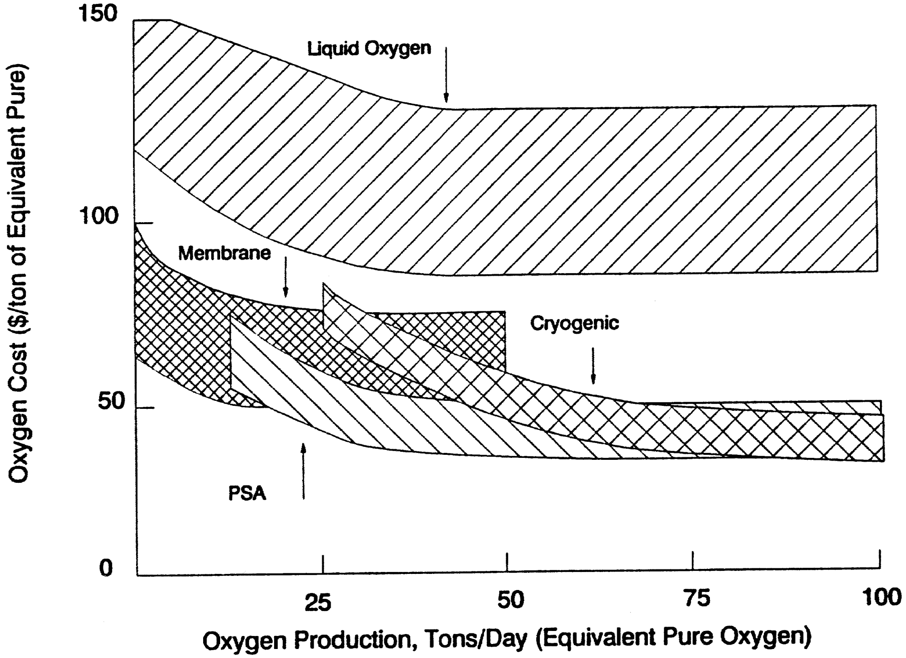
Budget

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

Introduction

- **Oxygen-blown gasifiers provide smaller size and higher efficiency**
  - Substantially lower NO_x and improve gas purity with the removal of N_2
- **ASU is one of the largest cost items in an IGCC plant (consumes 5% of plant power and constitutes ~15% of plant cost)**
- **The cryogenic air separation is the choice of technology at large-scale**
  - 600 MW gasifier 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

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Air Separation Sorbent

- **A unique sorbent is used for an oxidation-reduction (redox) process**
- **Unlike conventional chemical looping combustion sorbents that also work via a similar redox process, the metal oxide phase phase auto-reduces by changing process conditions (i.e., by changing T, P, oxygen partial pressure)**
  - The metal changes oxidation state without needing to directly contact a reducing gas (e.g., CH_4, H_2, CO, syngas) or fuel
  - The auto-reduction releases oxygen, which can be recovered as a pure product

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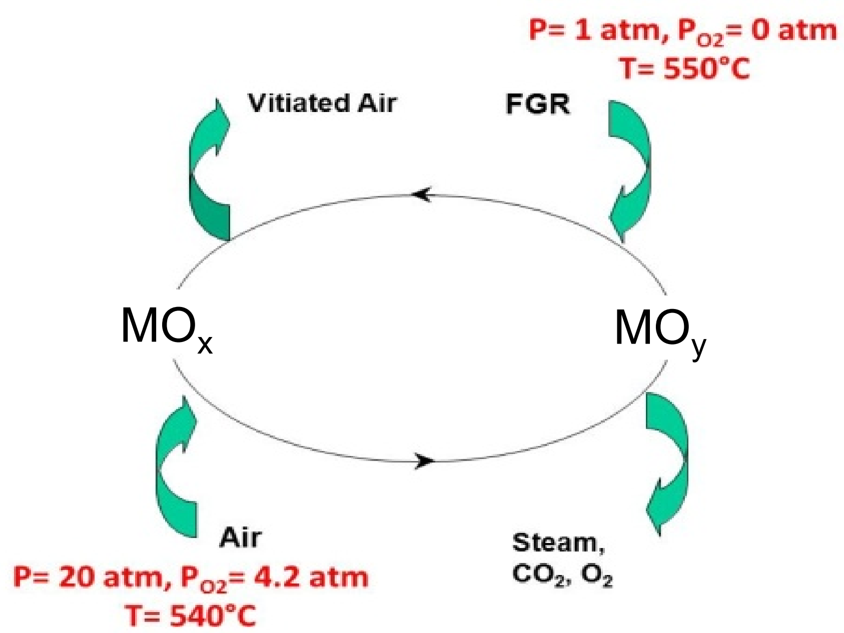
Separation Process

- **Sorbent removes some (25-30%) but not all the O_2 from high pressure gas**
  - Vitiated high pressure is further heated and expanded to recover the energy value
- **Regeneration is carried out using warm sweep gas (FGR or superheated steam)**
  - Partial pressure difference assisted with temperature swing (in case of the IGCC application) will cause the release of oxygen



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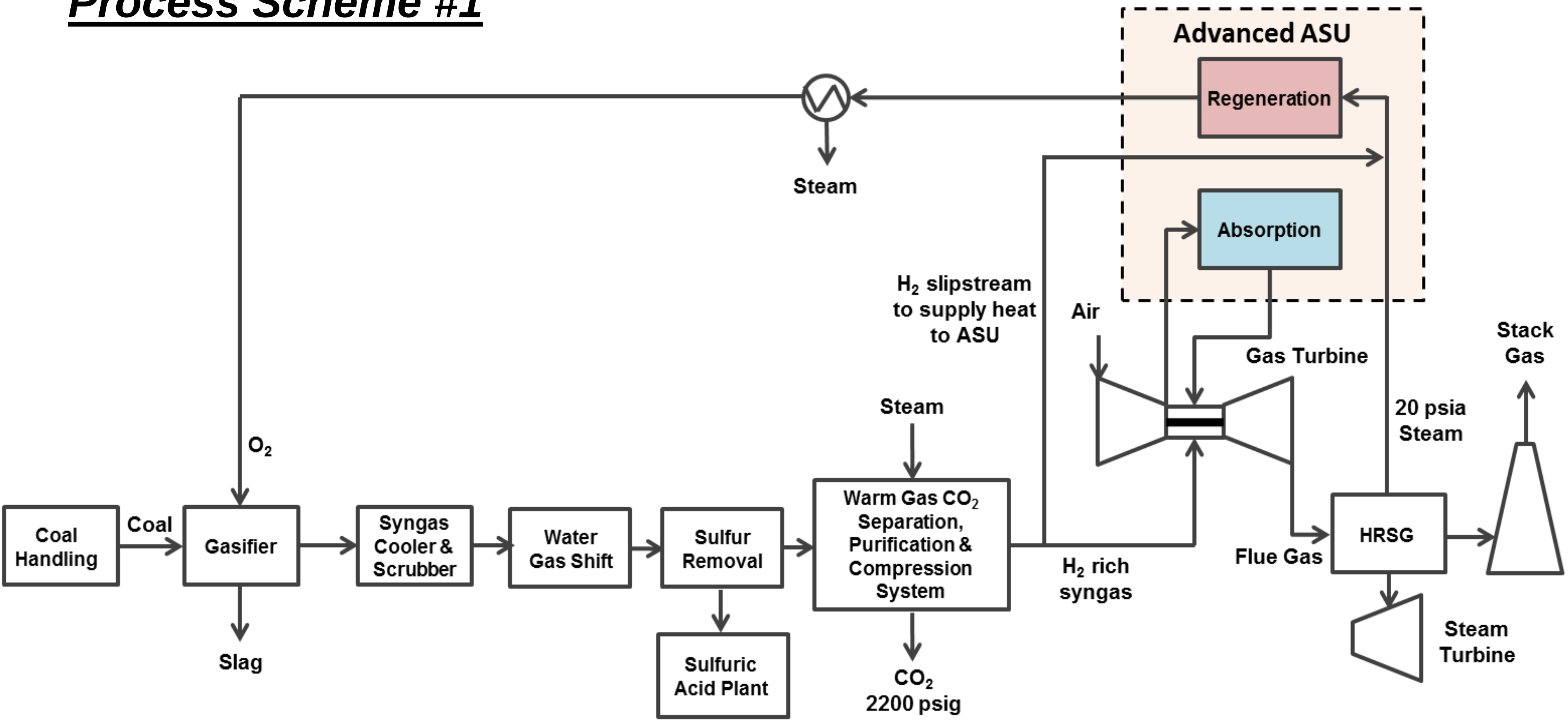
Integrated with IGCC Power Plant

Process Scheme #1



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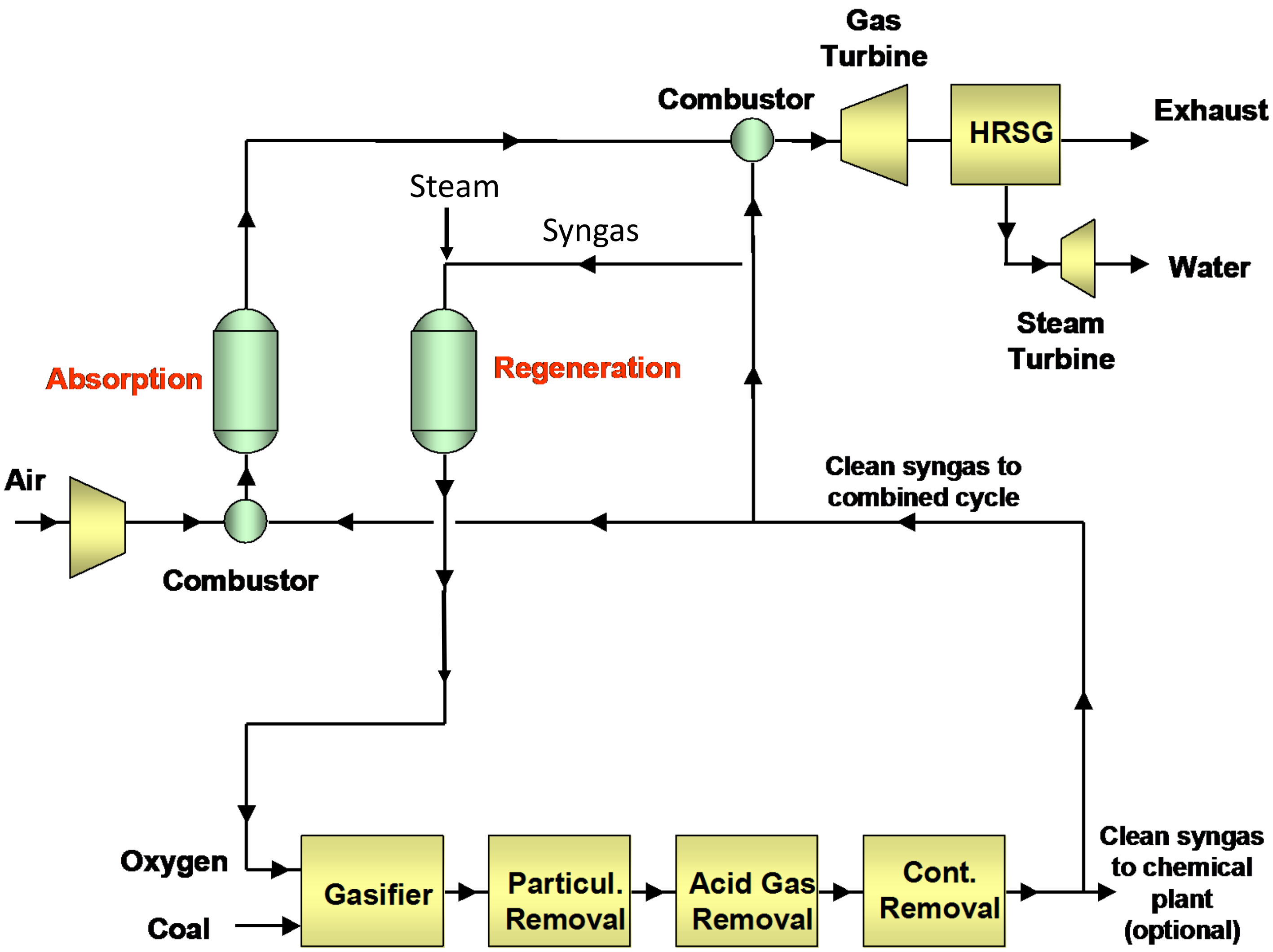
Integration to the IGCC/CTL Plant



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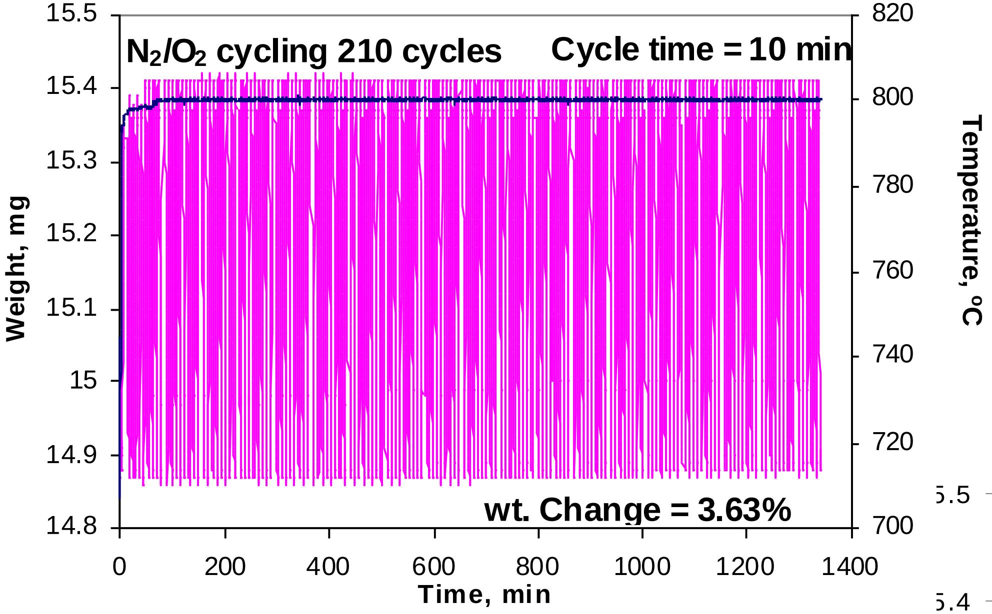
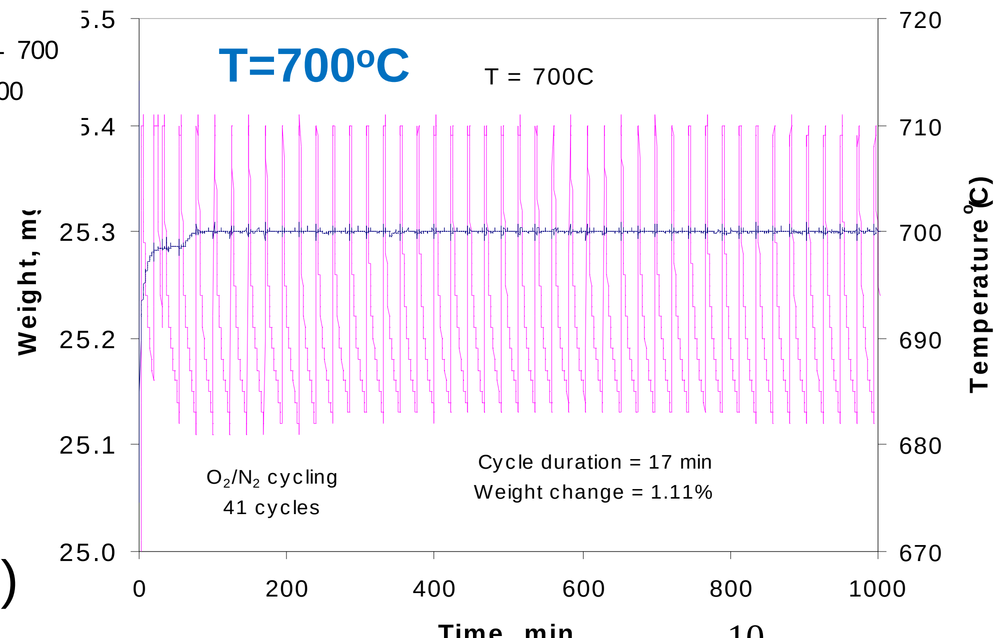
Early Results in TGA

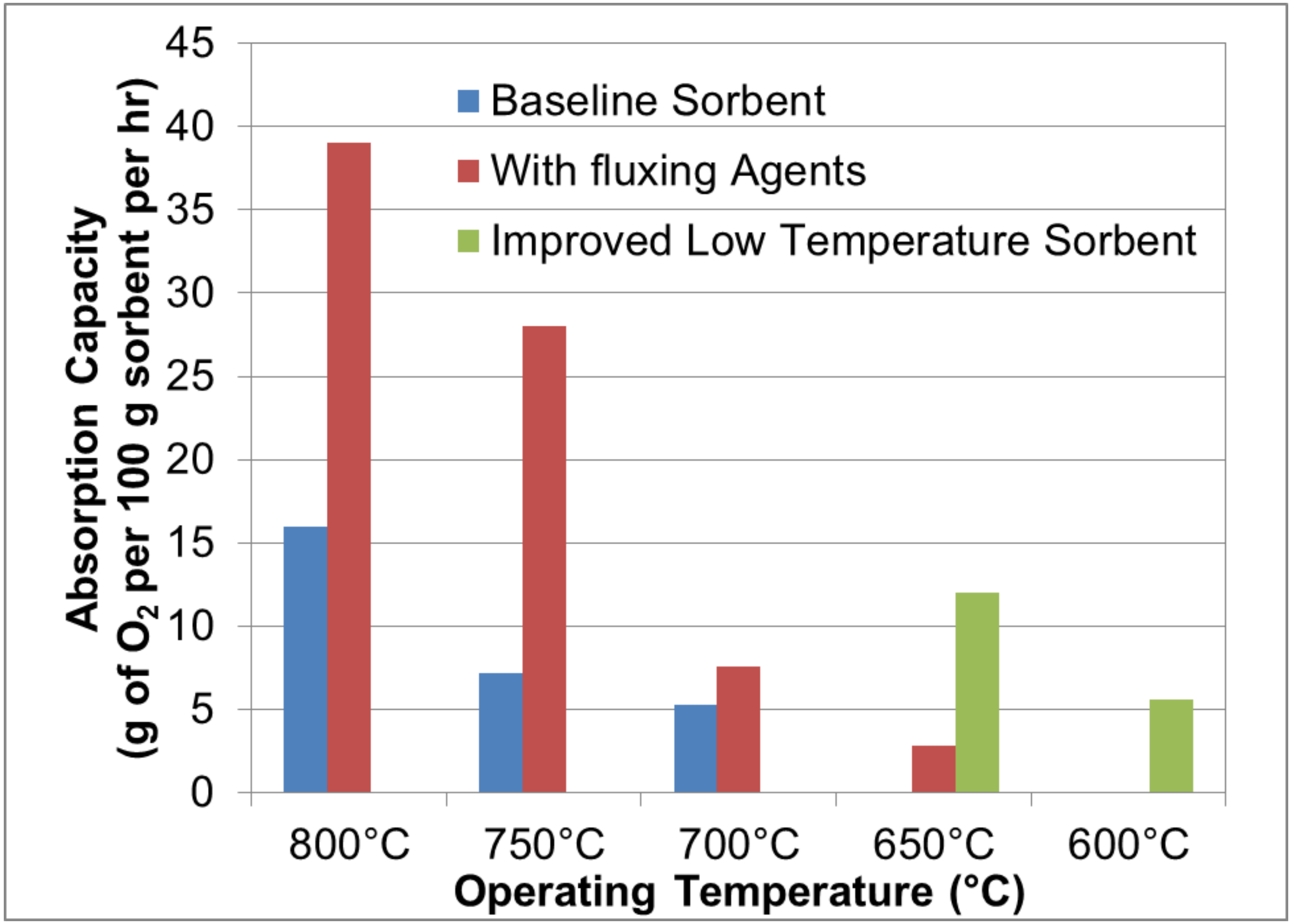


- **Similar trends at 700ºC**
- **Lower capacity if the same cycle time is maintained due to slower kinetics during regeneration**

- **Sorbent can be regenerated by concentration swing**
  - Switching from pure O_2 to pure N_2
- **Higher capacity at 800ºC**
  - 3.63% wt. O_2 loading at 800ºC (10 min full cycle time)



Sorbent Optimization



- **Oxygen release was documented over a wide range of temperatures**

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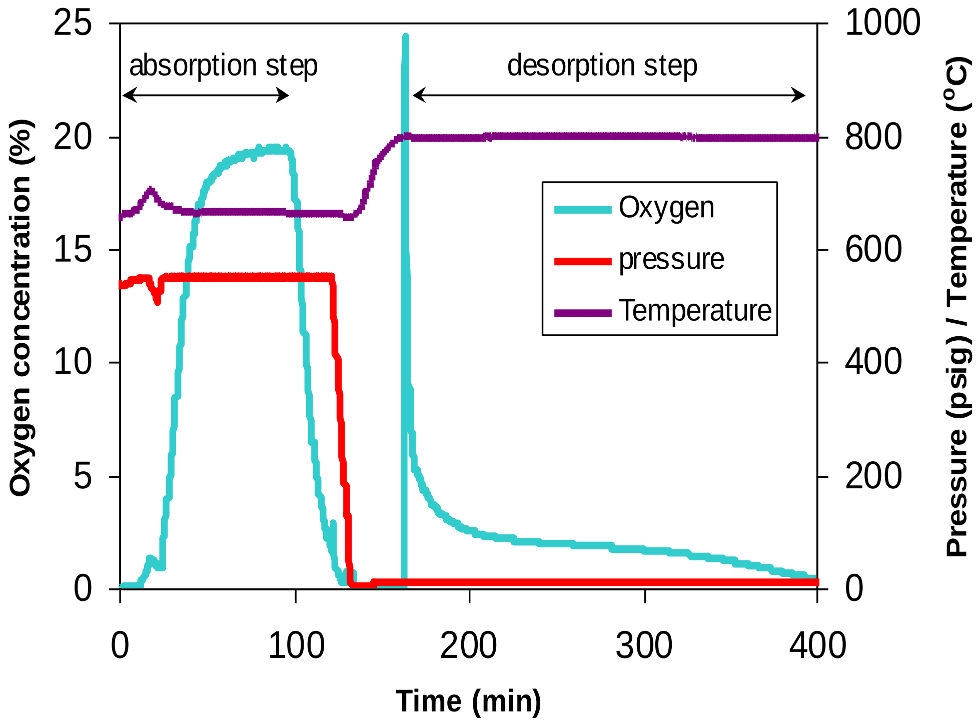
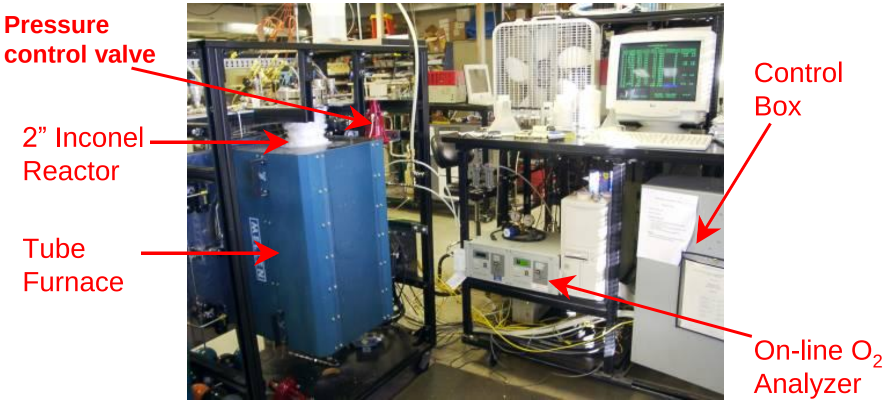
Flow Experiments in Small & Large Reactors





- **Oxygen release was documented over a wide range of reactor configurations**

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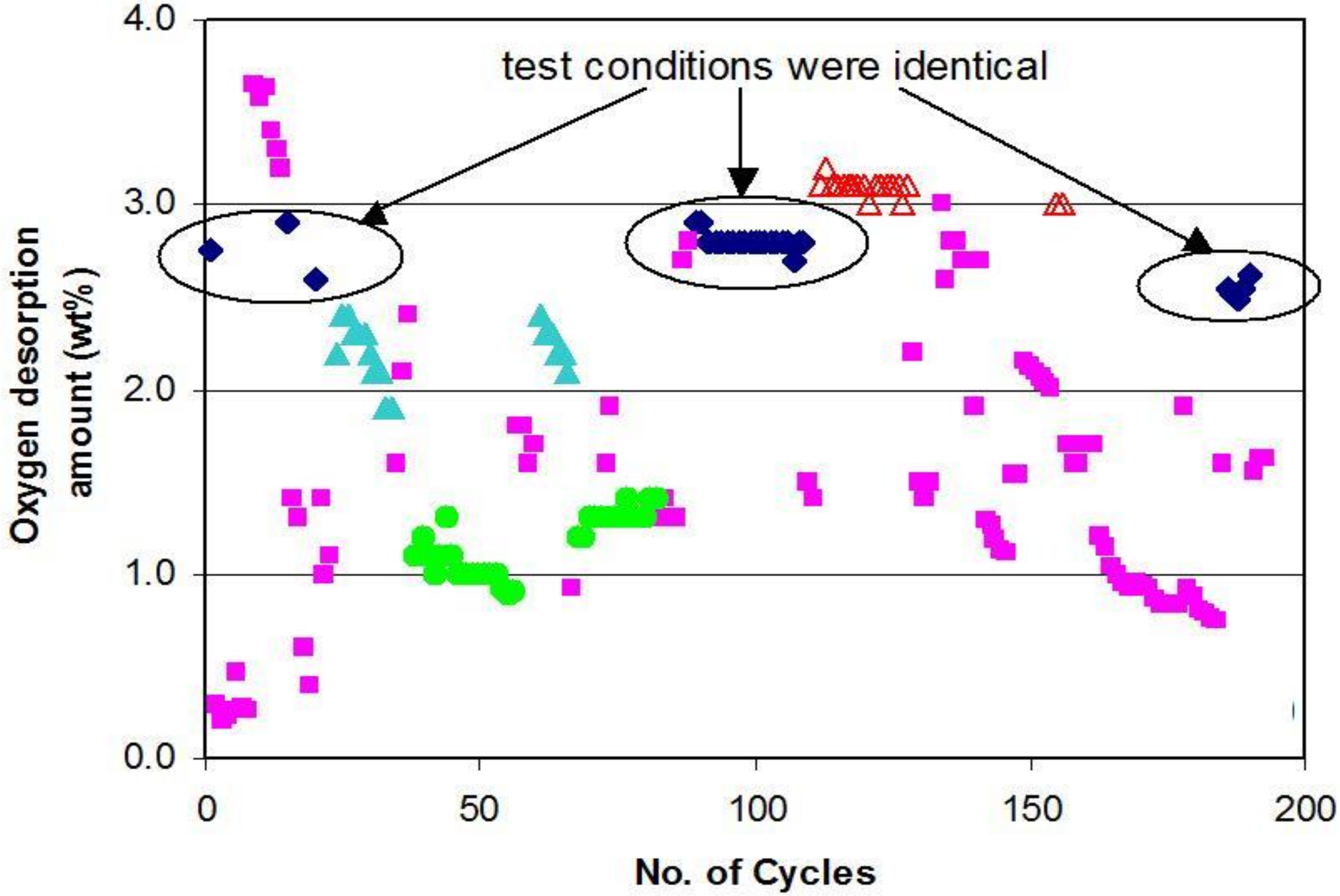
Long-term Durability



- **Sorbent maintained performance for 200 cycles**

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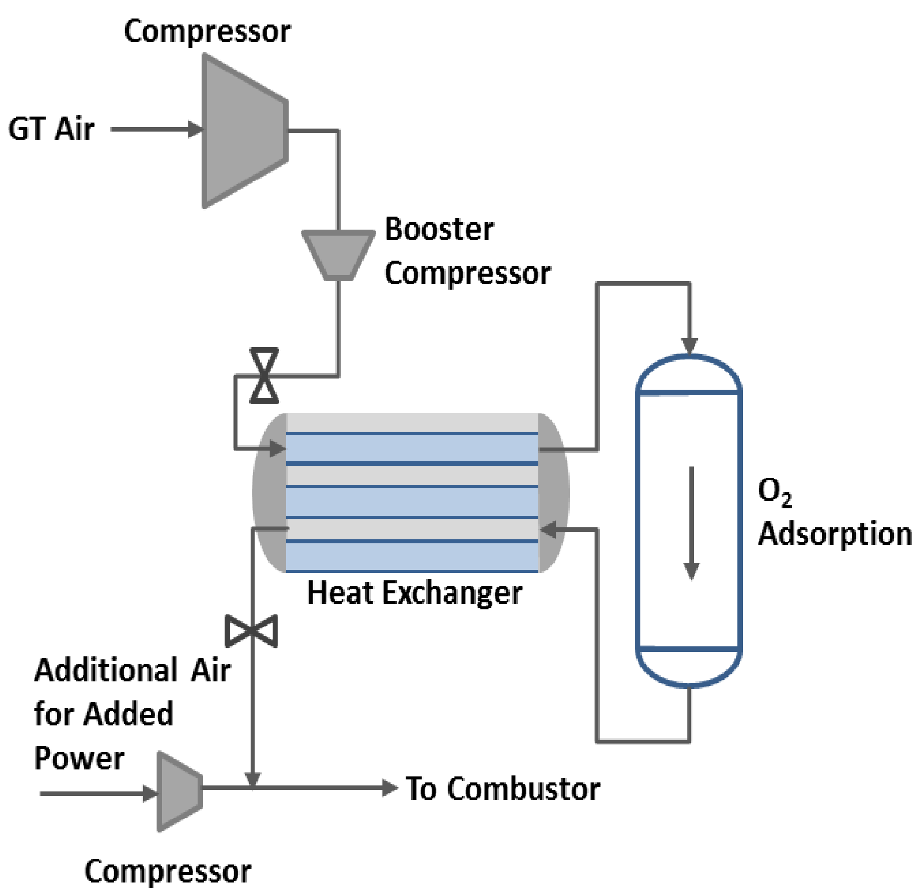
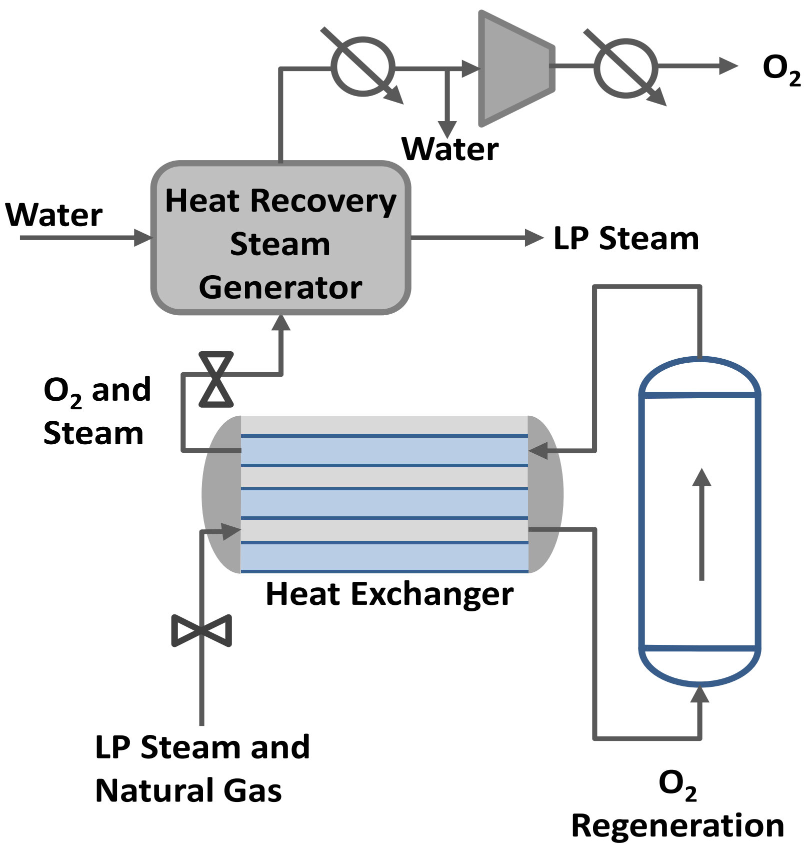
System Design

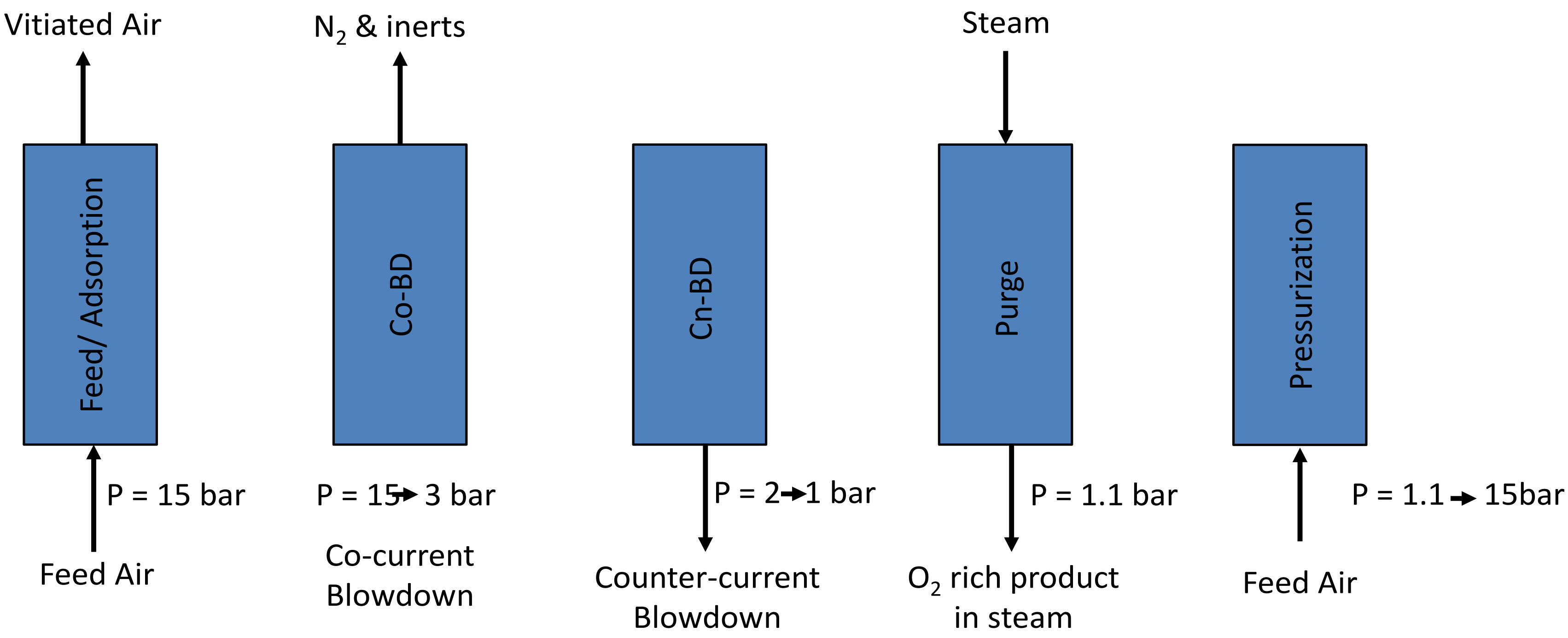


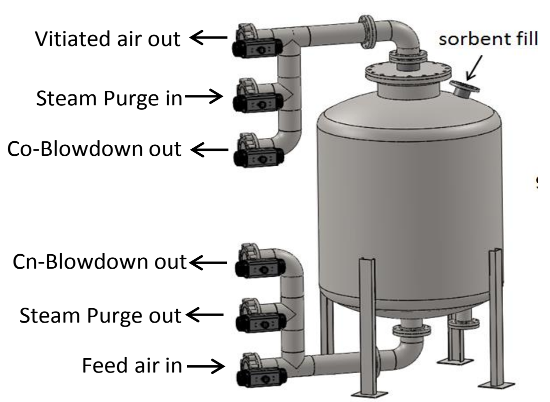
Absorption Process



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>
</table>

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IGCC without CO_2 Capture

GE Gasifier

TDA Steam Plant Changes	
Scaled up Steam Plant	292,692
Steam extration	-43,351
LP steam Generated	11,194
Methane expander	540
Net Steam Power	261,075

Auxiliary Power	
GT Air Boost	584
Added Air Compressor	60,617
O2 Compressor	10,260
Internal O2 Compressor	10,981
Net Axilary Load changes	82,441

Power Summary	
Gas Turbine Power, kW	515,395
Sweet Gas Expander, kW	7,500
Stem Turbine, kW	261,075
Total Power, kW	783,970
Auxiliary Load, kW	109,771
Net Power, kWe	674,199
Net Plant Efficiency %, HHV	40.43%

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Preliminary Process Analysis

IGCC without CO_2 Capture (GE Gasifier – DOE Case 1)

- **New sorbent-based ASU can increase the plant efficiency to 40.4%, in comparison to 39% with the same plant equipped with cryogenic separation**
- **Cost of electricity (COE) on a $2011 basis is expected to be $93.2 per MWhr (versus $101.2 per MWhr with cryogenic ASU)**

IGCC with CO_2 Capture (GE Gasifier – DOE Case 2)

- **New sorbent-based ASU could reduce the cost of CO_2 captured on a $ 2011 basis, for both the conventional Selexol-based and TDA's warm gas CO_2 capture technology to $38.8/tonne and $29.3/tonne respectively**

Assumption = Cost of the new ASU is the same as cryogenic plant

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Research

Vision for Commercialization

- **Slipstream to pilot-scale demonstrations to increase technical maturity from TRL = 4 to TRL = 6**
- **Develop a complete technology package for licensing**
  - **Intellectual Property**
  - **Process Design Package**
  - **Sorbent Manufacturing**






- **Privately Owned / Began operations in 1987**
- **Two facilities in Wheat Ridge and Golden, CO**
  - **50,000 ft^2 of office and lab space**
- **82 full-time technical staff**
  - **More than half with advanced degrees (28 PhDs)**

Project Structure

<u>October 1, 2015 – March 31, 2017</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 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**

Task 1. Project Management & Planning

- Undertake necessary activities to 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, and report progress against milestones, schedule and budget, including any variances
- Prepare and deliver required reports and briefings

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Task 2. Sorbent Production Scale-up

- In our current project (DE-FE-0024060), we are optimizing the sorbent formulations

In the new project

- We will scale up the production using high throughput production equipment in our production facility in Golden, CO.
- 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
- Each batch will be extensively characterized using physical and chemical analysis methods (e.g., surface area, chemical composition, crush strength)
- Generate a Product Specification Sheet
- We will evaluate each batch of material in a bench-top reactor to quantify O_2 capacity and oxidation/auto-reduction reaction kinetics

Task 3. Sorbent Life Test

- We will carry out bench-scale tests to assess sorbent life for 12,500 cycles
- We anticipate sorbent replacement in every 2 years, which corresponds to 17,520 cycles (based on 3 fixed-bed reactors going over 60 minute full cycle)
- The proposed testing will provide sufficiently long for us to be able to assess the long term durability of the sorbent under representative conditions

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Task 4. Adsorption, CFD Modeling and Reactor Housing Design

- **Detailed design of the sorbent reactors**
- **<u>Task 4.1 Adsorption Model:</u> (University of Alberta)**
  - To calculate the concentration distribution across the sorbent bed
  - Finite-volume based mathematical model in MATLAB) will be used to generate concentration profiles taking the surface interactions into account with all synthesis gas 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 regeneration time, product purity etc.
- **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**
- **<u>Task 4.2 CFD Analysis:</u> (Gas Technology Institute)**
  - 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 first simulated in a 3D model including the spatial distribution of reactants, sorbents, inerts and products**

Task 4. Adsorption, CFD Modeling and Reactor Housing Design

- **<u>Task 4.3 Engineering Design:</u>**
  - Based on the adsorption model and CFD simulation results, the design of the O_2 sorbent beds for the pilot-scale system will be completed
  - Engineering drawings and 3-dimensional layouts will be generated
- **Design of the air separation system will include (at a minimum) the sorbent beds, inlet and exit accumulators, all valves and manifolds needed for the system to complete the cycle sequence with multiple pressure equalizations, product pressurization and back purging steps**
- **An accurate cost estimate for the unit, including all foundation work, labor and supervision for the installed system will be generated**
- **This input will be utilized to update the overall system cost estimate (and COE)**

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Task 5. Optimization of Cycle Sequence

- **University of Alberta will assist in the optimization of the cycle sequence to ensure highest product O_2 purity, while maintaining the smallest number of reactors/sorbent amount and minimum energy penalty**
  - Operating parameter space to be scanned is large (e.g., duration and sequence of steps, pressure levels and flows)
    - Sophisticated algorithms are needed to identify the sub-space within for a high performing process
  - Dr. Rajendran's group at UOA developed methods that combine stochastic optimization with detailed simulations to evaluate the potential of a particular adsorption cycle
  - Systematic optimization will minimize the probability of converging on to local minima and allows exploring the entire operational space in a reasonable time

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

- **We will design a fully functional proof-of-concept prototype unit that has the ability to produce 1 kg/hr oxygen on a continuous basis**
  - Unit will have the capability to fully demonstrate the efficacy of the sorbent (e.g., capacity) as well as to allow us to assess the effective operation of cycle sequence (e.g., O_2 purity and recovery)
- **Based on the test data from our current work, we will design the unit to treat 12 Nm^3/hr air flow rate**
- **O_2 Separation Skid will consist of 3 sorbent reactors, 2 accumulators to moderate pressure fluctuations, all valves and manifolds, as well as a small compressor/blower that will push the gas through the system**
- **The proposed test unit will allow us to fully demonstrate the cycle with all steps in the sequence (e.g., pressure equalizations, pressurization with ambient air, co-current depressurization, etc.)**

Task 7. Fabrication of the 1 kg/hr Oxygen Generation Unit

- **Based on the final design approved after HAZOP analysis we will first fabricate a single reactor and evaluate it under simulated conditions to validate the adsorption models and the design**
  - Series of parametric tests will be carried out to assess the impact of key operating parameters on sorbent performance as well as on model predictions
- **All components will be designed and fabricated at the ASME standards following good engineering practices**
- **We will use LabView Control Hardware for automated operation that will allow stand-alone operation, with remote monitoring and controls that enables system operation for extended periods without the full attendance of TDA personnel**
- **We will then complete the fabrication of the complete unit**

Task 8. Testing of the Prototype Unit

- We will first complete the shakedown tests
- We will tune all PID loops and other control systems to ensure that all critical system parameters can be controlled at the given range
- We will evaluate the operation of the valves and all supporting equipment to ensure that the desired cycle sequence.
- We will carry out a series of parametric tests to identify the optimum operating conditions and then measure steady-state performance for a minimum of 1,000 h

Task 9. Techno-economic Analysis (TEA)

- **TDA, in collaboration with University of California, Irvine will perform a detailed process design and modeling of the Low Cost Air Separation System using Aspen-Plus^{TM} software**
  - Model will be calibrated using the results of a DOE/NETL analysis
  - Revise the model results with the most recent test data and optimized reactor design for two different types of gasification systems (GE and E-Gas)
  - Compare the performance of these systems against those using conventional cryogenic air separation systems when integrated with both cold and warm gas CO_2 capture systems
  - Sensitivity analysis will also be carried out to identify the optimum operating conditions for the unit
  - Preliminary cost analysis will be carried out (with an estimated accuracy of 15%) following DOE Guidelines for Carbon Capture
- **Task 9.1 TEA for GE Gasification System**
- **Task 9.2 TEA for E-Gas Gasification System**

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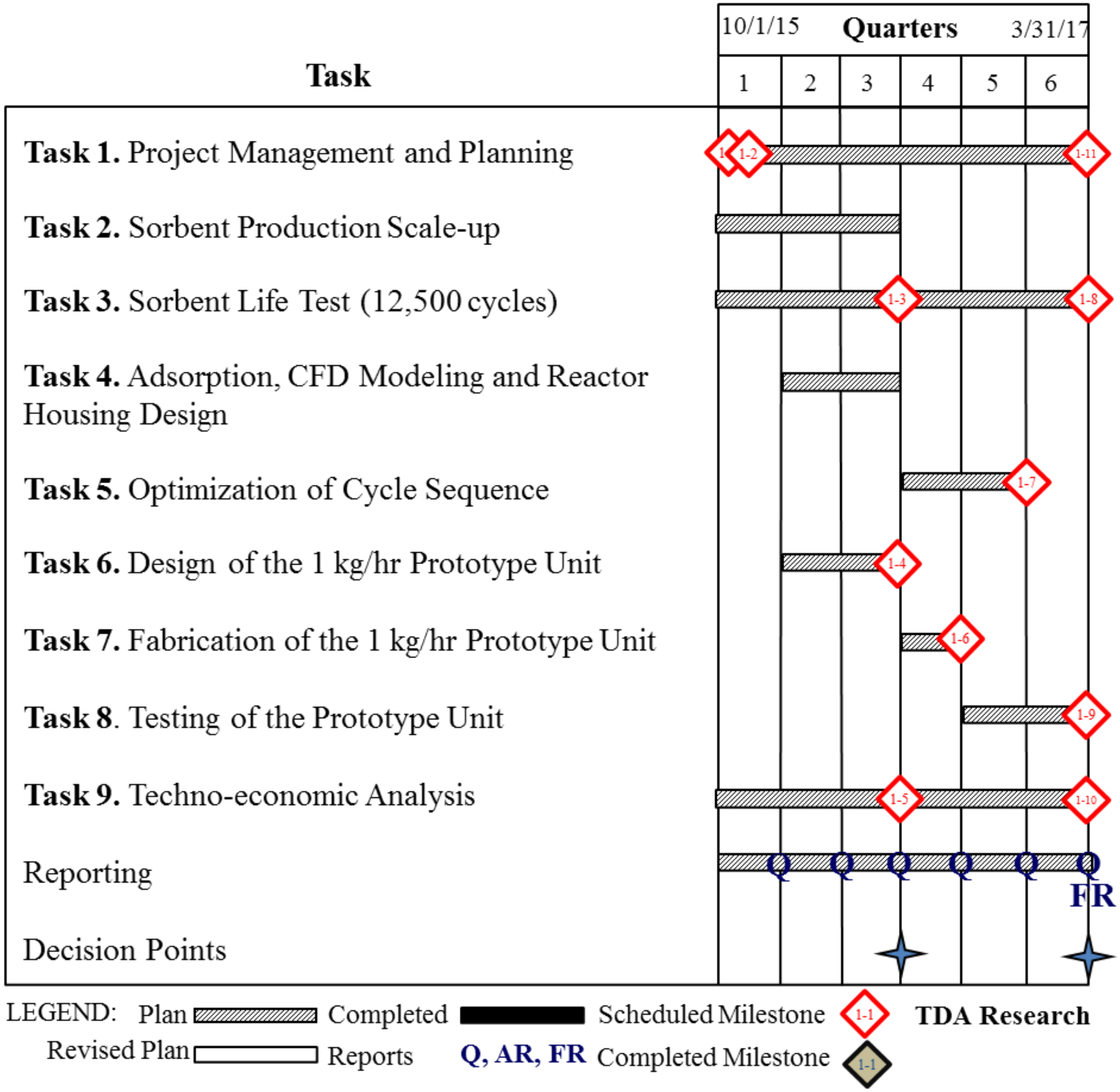
Deliverables

- **TDA will provide Periodic, Topical, and Final reports shall be submitted in accordance with the attached "Federal Assistance Reporting Checklist“**
- **Comprehensive Decision Point Reports will be submitted for each Decision point**
- **TDA will also provide DOE with the recommendations and proposed scale-up strategy for next stage of technology demonstration**
- **List of Deliverables:**
  - Preliminary Techno-economic Analysis Report
  - Prototype Unit Test Results
  - Final Techno-economic Analysis Report

Project Schedule



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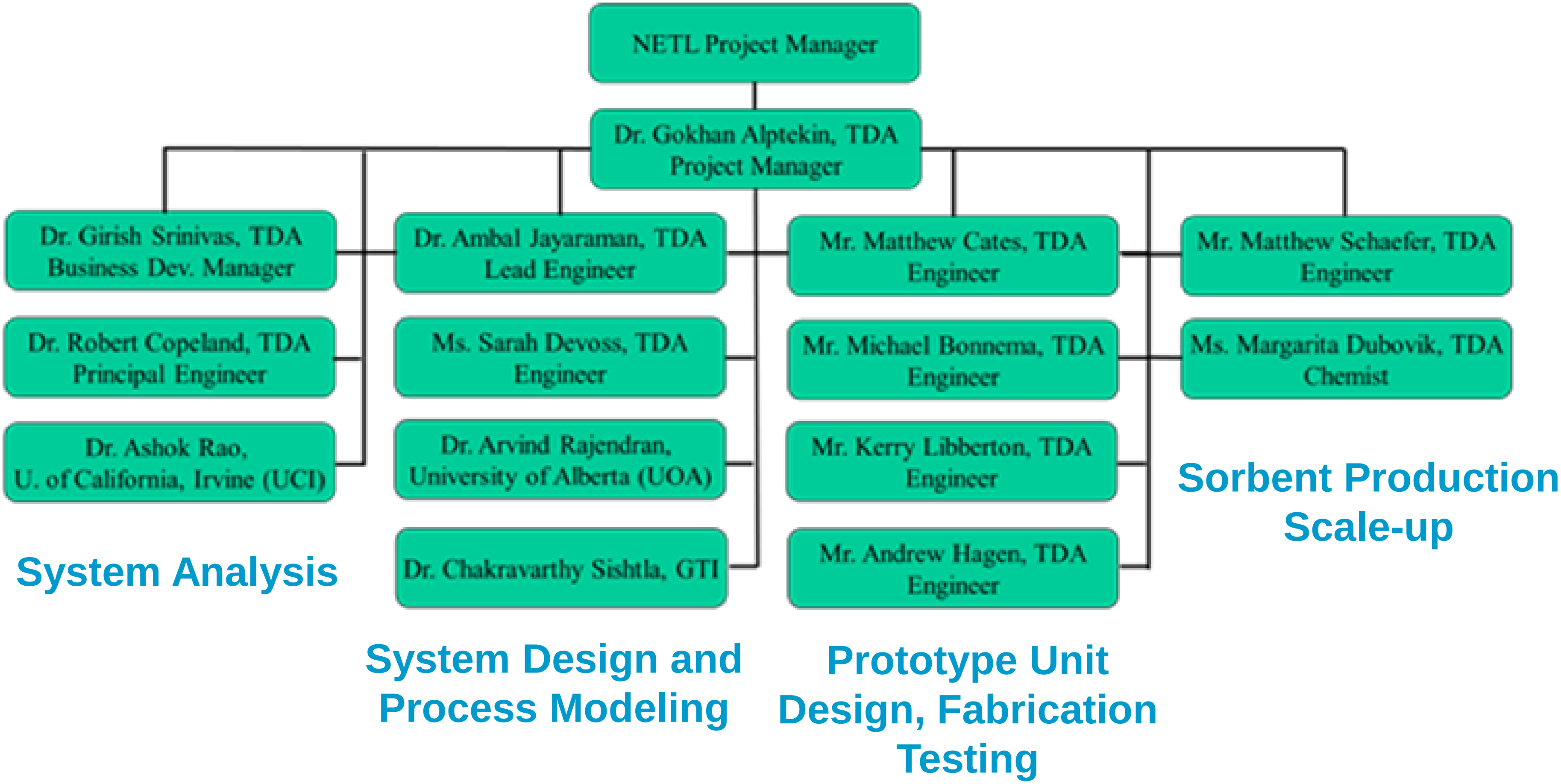
Project Milestones

Budget Period	ID	Task Number	Title	Planned Completion Date	Verification Method
			Anticipated Project Start Date	10/1/2015	
1	1-1	1	Update (PMP)	11/1/2015	PMP file
1	1-2	1	Kickoff Meeting	12/1/2015	Presentation file
1	1-3	3	Complete 6,000 Cycle Life Test	6/30/2016	Results update
1	1-4	6	Complete Prototype Unit Design	6/30/2016	Design Package
1	1-5	9	Complete Preliminary TEA	6/30/2016	Topical Report #1
			Go/No-go Decision Point	6/30/2016	
1	1-6	7	Complete Fabrication of the Prototype Unit	9/30/2016	Results update
1	1-7	5	Complete Cycle Sequence Optimization	12/30/2016	Results update
1	1-8	3	Complete 12,500 Cycles in Sorbent Life Test	3/31/17	Results update
1	1-9	8	Complete 500 hrs of Testing with the Prototype Unit	3/31/2017	Topical Report #2
1	1-10	9	Complete Final TEA	3/31/2017	Topical Report #3
1	1-11	1	Final Review Meeting	3/31/2017	Presentation file

Project Budget

	Budget Period 1 (10/1/15 - 3/31/2017)			
Recipient	**DOE funds**	**Cost Share**	**Total**	**Cost Share (%)**
TDA Research	$1,042,612	$280,564	$1,323,176	21.2%
Gas Technology Institute	$80,024	0	$80,024	0.0%
University of Alberta	$79,574	$19,882	$99,456	20.0%
University of California, Irvine	$77,790	$19,554	$97,344	20.1%
Total	$1,280,000	$320,000	$1,600,000	20.0%

Project Management Plan



Risk Management

Description of Risk	Probability	Impact	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 solid diffusion rates	Low	Moderate	TDA will include low temperature flux agents and promoters that increase solid diffusion rates and optimize pore size and particle size
High temperature reactor designs resulting in high costs and complex schemes	Low	High	TDA will be looking designs that would have a low impact on the capital costs
Resource Risks			
High temperature reactor design fabrication & testing	Low	Moderate	We will plan ahead and stay ahead of schedule to give us ample time to deal with 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	Low	Moderate	TDA has prior experience with UOA, GTI and UCI so we will be able to get the JDA and NDA executed on time