COMBINED SORBENT/WGS-BASED CO_2 CAPTURE PROCESS WITH INTEGRATED HEAT MANAGEMENT FOR IGCC SYSTEMS

Cooperative agreement # DE-FE0026388
Kickoff Meeting Presentation

Principal Investigators: Dr. Andrew Lucero and Dr. Santosh Gangwal

DOE FPM: Isaac "Andy" Aurelio

October 27, 2015

Agenda

- Attendee Introductions
- Project Overview (25 minutes)
- Break (5 minutes)
- Project Details (60 minutes)
  - Task Description
  - Schedule
  - Milestones and Deliverables
  - Plans and Progress
- Open Discussion (30 minutes)

Project Overview

- Project Objectives
- Sponsors and Participant Roles
- Technology Description
- Budget Summary
- Specific Project Objectives
- Major Milestones and Success Criteria
- Deliverables

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Overall Project Objectives

Project Objective: Conduct laboratory-scale research to develop a combined magnesium oxide (MgO)-based CO_2 sorbent/water gas shift (WGS) reactor that offers high levels of durability, simplicity, flexibility and heat management ability.

Project Goal: The ultimate goal is to develop a process to capture 90% of the CO_2 for integrated gasification combined cycle (IGCC) applications and reduce the cost of electricity by 30% over IGCC plants employing conventional methods of CO_2 capture.

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Project Sponsors and Participant Roles

- **Sponsors and Funding**:
  - DOE/NETL $1,962K
  - Southern Research $491K
- **Project Duration**: 36 months, Oct. 1, 2015- Sept. 30, 2018
- **Participants and Roles**:
  - **Southern Research**: Overall project management, lab-scale reactor system design and commissioning, CO_2 sorbent preparation and testing with simulated coal-derived syngas, WGS catalyst performance verification, hybrid sorbent/WGS reactor testing, and process/technical modeling and evaluation
  - **IntraMicron**: Laboratory scale heat exchange reactor loading
  - **Nexant**: Economic evaluation support

INTRAMICRON

Nexant

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Process Chemistry

$MgO\ (s) + CO_2\ (g) \leftrightarrow MgCO_3\ (s)$

$MgO\ (s) + H_2O\ (g) \leftrightarrow Mg(OH)_2\ (s)$

$Mg(OH)_2\ (s) + CO_2\ (g) \leftrightarrow MgCO_3\ (s) + H_2O\ (g)$

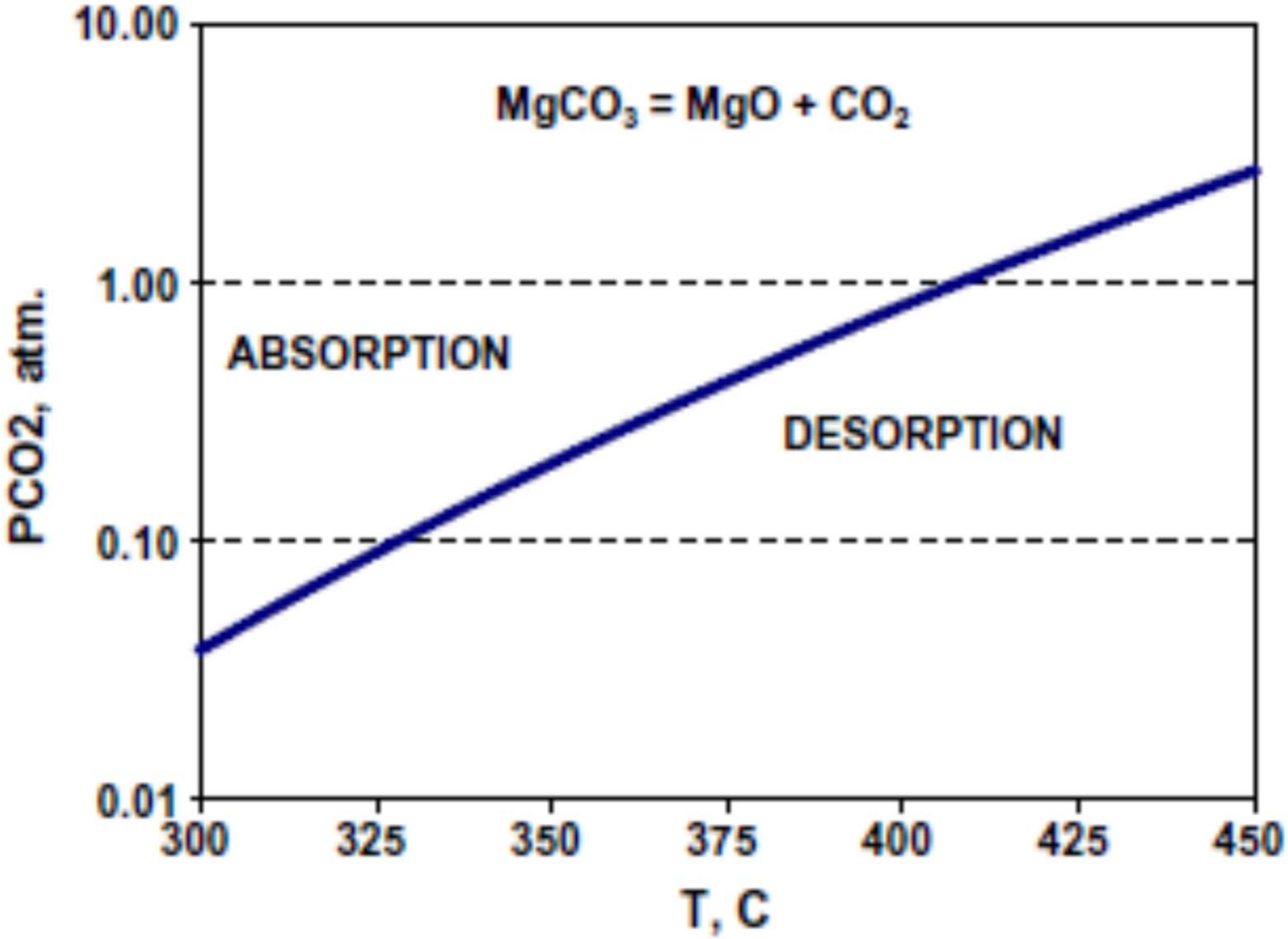
$CO\ (g) + H_2O\ (g) \leftrightarrow CO_2\ (g) + H_2\ (g)$

Major Operations for Commercial IGCC with CO_2 Capture

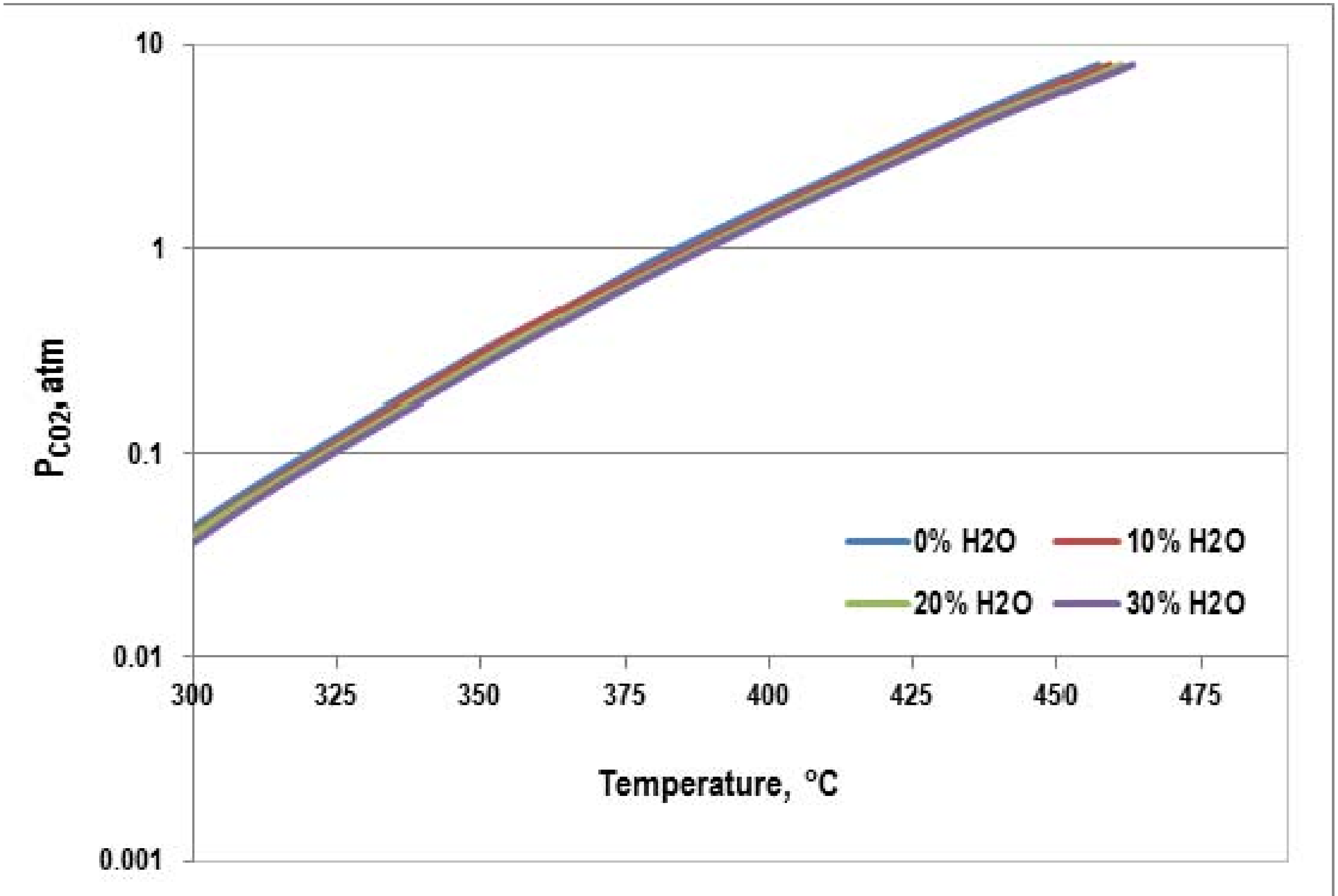
- Gasification
- Particulate Removal
- Contaminant Removal (Tar, NH_3, S)
- Water-gas Shift
- CO_2 Capture
- Power Generation

Process Intensification to Combine WGS/CO_2 Capture

MgO/CO_2 Equilibrium



$Mg(OH)_2/MgO/CO_2$ Equilibrium



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Simultaneous CO_2 Capture/WGS Reactor

- WGS reaction is equilibrium limited
- CO_2 capture onto solid drives WGS equilibrium towards CO_2
- Helps to achieve 90% capture of CO and CO_2

Candidate MgO based CO_2 Sorbents and WGS Catalyst

- DOE/NETL sorbent [Sirivardane 2008, 2013]
- Aramco-RTI [Hamad E.Z. et al. 2013]
- Mg-Al Hydrotalcite [commercially available PURALOX MG70, van Selow et al., 2009]
- Mg-Al Hydrotalcite [Hanif et al., 2014]
- SR-CC-1 (Stabilized high-capacity nanostructured MgO/$Mg(OH)_2$ -Southern Research)
- Commercial WGS catalyst

Budget Period Durations and Funding

Budget Period	Dates	Months	Funding	
			DOE	SR
1	10/1/2015 - 9/30/2016	12	$628,906	$157,227
2	10/1/2016 - 3/31/2018	18	$943,442	$235,860
3	4/1/2018 - 9/30/2018	6	$389,843	$97,461

Specific Project Objectives (BP1)

- Budget Period 1 objectives are:
  - Design, construct, and operate a laboratory test system
  - Select the two best CO_2 sorbents from promising ones developed by Southern Research and other research centers based on adsorption/regeneration experiments in simulated syngas
  - Substantiate that one or more of the CO_2 sorbents maintains capacity and that the sorbent can be regenerated
  - Substantiate that CO_2 sorbents can be sufficiently regenerated in the presence of nearly pure CO_2
  - Substantiate that a commercial WGS catalyst maintains activity after being subjected to pressure and temperature swings needed for CO_2 sorption and desorption
  - Develop a preliminary CO_2 capture/WGS reactor model, and develop a preliminary estimate of the cost of electricity with the integrated technology

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Specific Project Objectives (BP2, BP3)

- Budget Period 2 objectives are:
  - Design, construct, and commission an integrated CO_2 capture/WGS reactor with advanced integrated heat management
  - Evaluate the selected sorbents over multiple cycles using 3 different combinations of sorbent and WGS catalyst
  - Develop a detailed integrated CO_2 capture/WGS reactor model that can be utilized to predict the performance of the integrated reactor system and update the predictions for cost of electricity for IGCC applications.
- Budget Period 3 objectives are:
  - Experimentally evaluate the integrated sorption/WGS reactor technology for extended periods (1000 cycles) using the best sorbent identified from previous experiments
  - Develop an Initial Technical and Economic Feasibility study to evaluate the technology for potential to meet energy performance goals of 90% CO_2 capture rate with 95% CO_2 purity at a cost of electricity 30% less than baseline capture approaches.

Major Milestones and Success Criteria

- BP1: Simulated Syngas Sorbent and WGS Tests
  - Sorbent capacity of 1.5 mmol/g for at least 1 sorbent with less than 0.5% degradation for 100 cycles
  - Go/No-Go: 90% CO_2 capture, 97% approach to equilibrium conversion of CO to CO_2, potential for 30% reduction in cost of electricity
- BP2: Combined CO_2 Capture/WGS Catalyst Testing with Integrated Heat Management
  - One sorbent achieves 2.0 mmol/g in combined CO_2 capture/WGS reactor
  - 90% Removal of CO+CO_2 in combined CO_2 capture/WGS reactor over 100 cycles
  - Go/No-Go: 90% CO_2 capture, 97% conversion of CO to CO_2, potential for 30% reduction in cost of electricity
- BP3: Extended Tests Sorbent/Catalyst Durability for 1000 Cycles
  - < 0.5% loss in sorbent capacity over 500 cycles and > 97 conversion of CO to CO_2 over 1000 cycles in combined CO_2 capture/WGS reactor
  - Initial TEA to confirm potential to meet cost targets

Deliverables

- Deliverables per Federal Assistance Reporting Checklist
- Supplemental deliverables as specified in SOPO
- Presentation at CO_2 Capture Technology Meeting
- Task 1: Update Project Management Plan
- Task 2.2.2: Draft Test Plan for Sorbent Parametric Tests
- Task 2.3: Draft Test Plan for WGS Experiments
- Task 2: Continuation Report Describing Experimental Results, Updated State Point Data Table and Initial Modeling
- Task 3.2: Draft Test Plan for Integrated CO_2 Capture/WGS Experiments
- Task 3: Continuation Report Describing Experimental Results, Updated State Point Data Table, and Modeling for Integrated CO_2 Capture/WGS Experiments

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Project Details

- Task Description and Overall Schedule
- Task Details
- Major Deliverables
- Success Criteria and Go/No-Go Decision Points
- Milestone Lists and Verification Methods
- Plans for Q1
- Progress to Date
- Summary

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Task Description and Overall Schedule

Task	Description	Dates
1.0	Project Management and Planning	10/1/2015 – 9/30/2018
2.0	Simulated Syngas Sorbent and WGS Tests (BP1 – 12 months)	10/1/2015 – 9/30/2016
2.1	Lab Skid Design and Fabrication	
2.2	Sorbent Parametric Experiments	
2.3	Commercial Catalyst WGS Experiments	
2.4	Initial Process Modeling	
3.0	Combined CO_2 Capture/WGS Catalyst Heat Exchange Reactor Testing (BP2 – 18 months)	10/1/2016 – 3/31/2018
3.1	Reactor Design and Fabrication	
3.2	CO_2 Capture/WGS Parametric Tests	
3.3	Detailed Reactor Modeling	
4.0	Extended Tests: CO_2 Capture/WGS Catalyst Durability for 1000 Cycles (BP3 – 6 months)	4/1/2018 – 9/30/2018
5.0	Initial Technical and Economic Feasibility Study (BP3 – 6 months)	4/1/2018 – 9/30/2018

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Task 1. Project Management

- Revised Project Management Plan (PMP) upon award; updated periodically as necessary
- Regular updates to/discussions with project participants for coordination/scheduling
- Kick-off meeting upon award; additional Project Review Meetings as appropriate
- Quarterly Technical, Financial, and Other Reports to DOE/NETL per FARC
- Papers at CO_2 Capture Review Meeting and national conferences e.g. the Pittsburgh Coal Conference
- Final Technical/Scientific Report

Task 2. Simulated Syngas Sorbent and WGS Tests

- Lab Skid Design and Fabrication - Design and fabrication of separate laboratory scale pressure and temperature swing CO_2 adsorber and WGS reactors for testing using simulated GE and TRIG syngas.
- Sorbent Parametric Experiments - Selection of two best MgO-based sorbents from promising ones developed by Energy Research Center of Netherlands (or other selected promising hydrotalcite from literature), NETL, IIT, RTI, and Southern Research based on adsorption/regeneration T, P experiments in simulated syngas, Sorbent characterization, operating condition optimization, sorbent activity, durability, and regenerability
- Commercial Catalyst WGS Experiments - Commercial WGS catalyst performance confirmation and durability with simulated syngas under optimal sorbent conditions
- Initial Process Modeling - Combined mass transfer and reaction model for CO_2 adsorption combined with WGS; development of optimum combination of WGS catalyst and sorbent within reactor based on experimental data, preliminary cost estimate for go-no/go decision

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Task 3. Combined CO_2 Capture/WGS Catalyst Testing with Integrated Heat Management

- Reactor design and fabrication - Integrated heat exchange reactor design incorporating both WGS catalyst and selected CO_2 sorbents in optimal combination, fabrication, and integration into laboratory skid.
- CO_2 capture/WGS parametric tests - Parametric experiments with the two selected sorbents combined with WGS catalyst in heat exchange reactor and integrated heat removal to confirm optimum operating conditions for sorption, WGS, and regeneration with 90% CO_2 capture. Selection of best sorbent for long term test.
- Detailed Reactor Modeling - Detailed mass transfer, heat transfer, and WGS reactor model and updated cost estimate

Task 4. Extended Tests: CO_2 Capture/Catalyst Durability for 1000 Cycles

- 1000 cycle test for the best sorbent in Task 3 integrated with WGS to evaluate its long term durability.
- Targets to demonstrate less than 0.5% capacity loss after 500 cycles following stabilization, 90% CO_2 capture, and maintenance of >97% CO conversion to CO_2 over 1000 cycles.

Task 5. Initial Technical and Economic Feasibility Study

- Integrate reactor model into process model and update cost estimates.
  - Multiple reactors to allow for CO_2 capture, regeneration, and pressure equalization.
  - The entire IGCC warm capture PSA/WGS process will be included in an Aspen Plus™ economic estimate based on the data developed in the project.

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Major Deliverables

- Updated PMP
- Continuation reports prior to the end of budget periods 1 and 2.
  - Experimental results, working capacity, and operating conditions presented in progress reports per SOPO requirements
  - State point data table
- Final Report
  - Scale-up strategy to move toward commercialization
  - High level technical and economic feasibility
- FARC technical, cost, and administrative reports

Success Criteria and Go/No-Go Decision Points

Decision Point	Date	Success Criteria
Go/No-Go BP1; Separate CO_2 Capture and WGS Experiments	9/30/2016	90% CO_2 capture, 97% approach to equilibrium conversion of CO to CO_2, potential for 30% reduction in cost of electricity
Go/No-Go BP2; Combined CO_2 Capture and WGS Experiments	3/30/2018	90% CO_2 capture, 97% conversion of CO to CO_2, potential for 30% reduction in cost of electricity

BP1 Milestone List and Verification Method

Milestone No.	BP No.	Task No.	Milestone Description	Planned Completion	Actual Completion	Verification Method
1	1	1	Updated PMP	10/31/2015	10/31/2015	Updated PMP File to DOE
2	1	1	Kickoff Meeting with DOE NETL	12/15/2015	10/27/2015	Presentation File - This meeting serves as the first quarterly review meeting
3	1	2	Draft Test Plan for Parametric Sorbent Experiments	1/15/2016		File submittal to DOE
4	1	2	CO2 capacity of 1.5 mmol/g for at least 1 sorbent with < 0.5% loss of capacity over 100 cycles	7/20/2016		Letter report to DOE documenting analysis of laboratory data.
5	1	2	Draft Test Plan for WGS Experiments	7/20/2016		File submittal to DOE
6	1	2	Continuation report describing experimental results and initial process modeling	9/14/2016		Draft Report describing experimental results and initial process modeling
7	**1**	**2**	**Project Briefing; Discuss Go/No-Go**	**9/30/2016**		**90% CO_2 capture, 97% approach to equilibrium conversion of CO to CO_2, potential for 30% reduction in cost of electricity**

BP2, BP3 Milestone List and Verification Method

Milestone No.	BP No.	Task No.	Milestone Description	Planned Completion	Actual Completion	Verification Method
8	2	3	Draft Test Plan for integrated CO2 Capture/WGS	2/17/2017		File submittal to DOE
9	2	3	One sorbent achieves 2.0 mmol/g in combined adsorber reactor	6/30/2017		Letter report to DOE documenting analysis of laboratory data.
10	2	3	90% Removal of CO+CO_2 in combined CO_2 capture/WGS reactor over 100 cycles	1/15/2018		Letter report to DOE documenting analysis of laboratory data.
11	2	3	Continuation report describing experimental results and modeling	3/15/2018		File submittal to DOE
12	**2**	**3**	**Project Briefing; Discuss Go/No-Go**	**3/30/2018**		**90% CO_2 capture, 97% conversion of CO to CO_2, potential for 30% reduction in cost of electricity**
12	3	4	Following stabilization, < 0.5% loss in sorbent capacity over 500 cycles	6/4/2018		Letter report to DOE documenting analysis of laboratory data.
13	3	4	> 97 conversion of CO to CO_2 over 1000 cycles in combined reactor	8/6/2018		Letter report to DOE documenting analysis of laboratory data.
14	3	1	Final Project Briefing	9/21/2018		File submittal to DOE
15	3	1	Final Report	12/20/2018		File submittal to DOE

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Plans for Q1

- Project kickoff, updated PMP, Nexant subcontract
- Select and prepare or obtain at least one literature sorbent as baseline
- Synthesize and characterize at least one sorbent for experiments beginning Q2
- Design, construct, and commission lab-scale reactor skid for CO_2 capture and WGS experiments

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Progress to Date

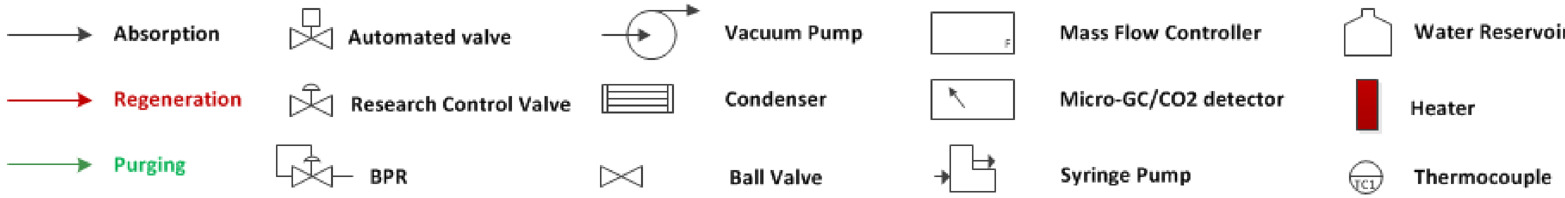
- Revisited recent MgO sorbent literature
- Selected improvements to SR-CC-1 sorbent based on literature
- Design and procurement for lab-scale CO_2 capture reactor in progress
  - Design based on anticipated cycle conditions
  - Sufficient flexibility in design to cover a range of pressure, temperature, space velocity, syngas composition, and regeneration procedure

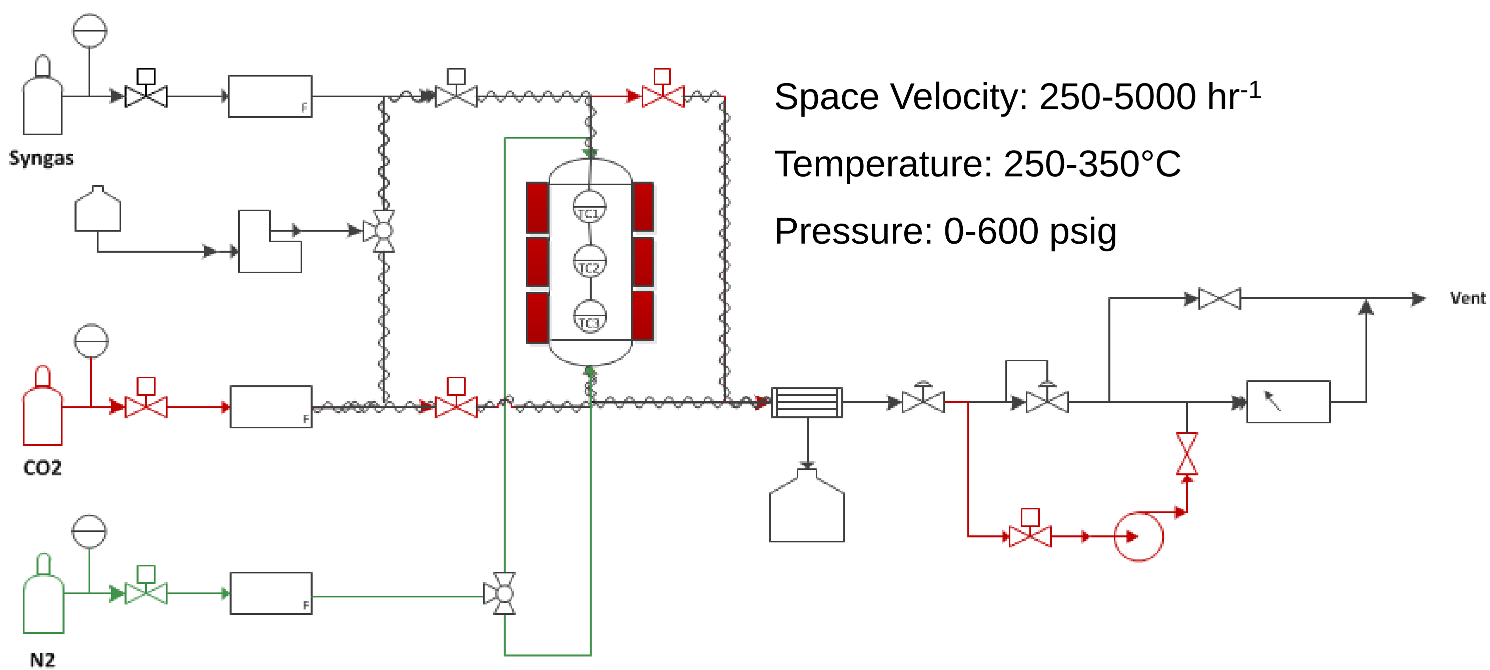
Progress on Lab-scale CO_2 Capture Reactor Design

- Adsorption reactor sized
- Simulated syngas and shifted gas composition determined
- Preliminary adsorption conditions determined (275-325°C, 40 atm, 250-5000 hr^{-1})
- Automated control strategy formulated for the CO_2 adsorption/desorption cycle
- Reactor equipment, including MFCs, a syringe pump, a backpressure regulator, and a mico-GC ordered for project use

Absorbent Reactor Sizing		
	inch	cm
Reactor Diameter	0.50	1.27
Reactor Thickness	0.05	0.12
Reactor Length	18.00	45.72
	$inch^3$	cm^3
Reactor Volume	2.28	37.42

CO_2 Capture Reactor Design





Space Velocity: 250-5000 hr^{-1}

Temperature: 250-350°C

Pressure: 0-600 psig

- Pressure Swing Adsorption System (0-600 psig)
- Precise Temperature/Pressure Control
- Sorbent Regeneration via Pressure Swing/Vacuum
- Automated Adsorption/Desorption Cycle
- Reverse Gas flow During Desorption

CO_2 Capture/Sorbent Regeneration Cycle

- **<u>Step 1 (Reactor Conditioning):</u>** Reactor is brought to 325°C and pressurized in flowing steam and N_2 to 600 psig
- **<u>Step 2 (CO_2 Capture):</u>** Simulated syngas (or shifted syngas) then replaces N_2 into the reactor for CO_2 capture; gas composition including CO_2 concentration is continuously monitored using a micro-GC and a continuous CO_2 analyzer
- **<u>Step 3 (Purge):</u>** Purge following CO_2 breakthrough
- **<u>Step 4 (Sorbent Regeneration):</u>** Pressure and/or temperature swing regeneration after desired length of purge.
- **Repeat Step 1 through Step 4 for next cycle!**

GE syngas and shifted GE syngas (O_2 blown)*

GE Syngas	
Mole, %	
H_2	34.16
CO	35.79
CO_2	13.66
N_2	0.8
CH_4	0.12
H_2O	13.58
He	0.86
H_2S	0.7300
HCl	0.0800
COS	0.0200
NH_3	0.2100
Tar	0.0000

Adding Steam

350 °C, 600 psi

Shifted GE Syngas		
Mole, %	50% CO shifted	70% CO shifted
H_2	44.9	44.5
CO	16.0	11.6
CO_2	27.1	28
N_2	0.7	0.6
CH_4	0.1	0.1
H_2O	9.8	13.8
Ar	0.8	0.7
H_2S	0.6	0.6
HCl	0	0
COS	0.02	0.02
NH_3	0	0
Tar	0	0

*DOE Baseline IGCC Report

TRIG syngas and shifted TRIG syngas (air blown)*

TRIG Syngas		
Mole, %	Air Blow	O_2 Blow
H_2	11.7	27.0
CO	17.5	34.3
CO_2	8.5	16.1
N_2	50.5	0.5
CH_4	2.6	5.1
H_2O	7.8	15.5
He	0.5	0.8
H_2S	0.0250	0.0451
HCl	0.0089	0.0177
COS	0.0026	0.0051
NH_3	0.2718	0.5410
Tar	0.1000	0.3005

350 °C, 600 psi

Adding Steam

Shifted TRIG Air Blow Syngas		
Mole, %	50% CO shifted	70% CO shifted
H_2	19.0	20.7
CO	8.9	4.8
CO_2	15.9	17.9
N_2	48.8	44.1
CH_4	2.5	2.3
H_2O	4.4	9.8
Ar	0.5	0.4
H_2S	0.024	0.022
HCl	0	0
COS	0.002	0.002
NH_3	0	0
Tar	0	0

*Kemper Demonstration Project

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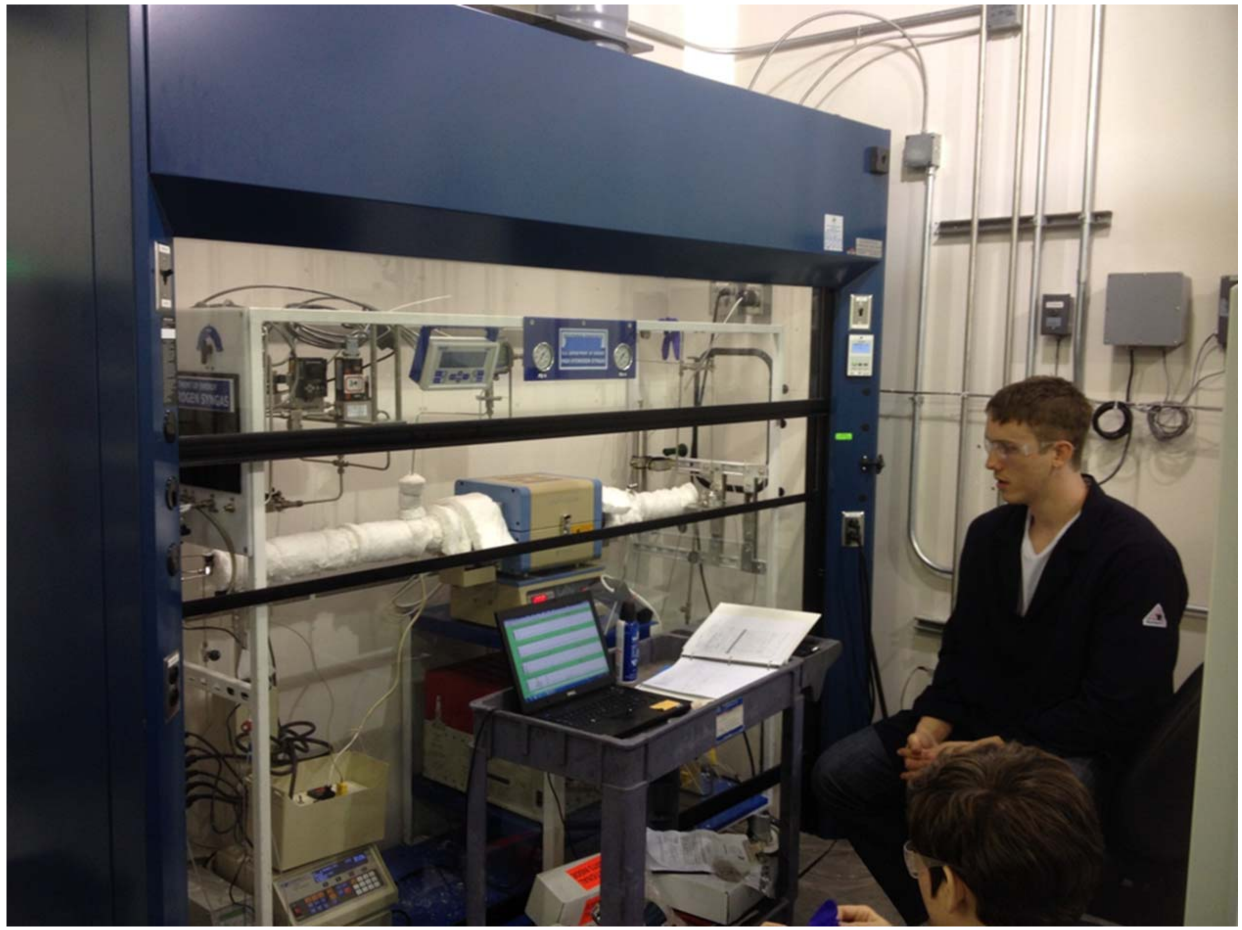
Example Lab-Scale FT Process

- Lab-scale FT reactor can operate as fixed catalyst bed or with small MFEC
- Simulated syngas
- Near continuous offgas analysis with online GC

Example: Lab-Scale Steam Reformer Process

- Lab scale steam reforming with fixed catalyst bed
- Adjust temperature, pressure, space velocity
- Online GC for offgas analysis
- Walk-in hood simplifies experiments with high concentrations of H_2S



Summary

- Southern is developing a novel hybrid CO_2 capture/WGS reactor with integrated heat management utilizing process intensification approaches and technological innovations to reduce the costs of pre-combustion CO_2 separation in IGCC facilities

- Upon successful completion of the project, the technology will be developed to the point that it is ready for closed-loop testing at the bench-scale (TRL 5) with actual coal-derived syngas.

- Data and modeling tasks planned will confirm that a commercial process based on this technology is a potential pathway to meet DOE energy performance goals of 90% CO_2 capture, 95% CO_2 purity, and potential for 30% reduction in cost of electricity compared to baseline CO_2 capture approaches.

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Open Discussion

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Introduction to Southern Research

- Established in 1941 as an independent, not-for-profit (501-c-3) center for scientific research and development
- Headquartered in Birmingham, Alabama; 8 locations in Southeastern US; 500 employees
- Serves both Government and private industry clients
- Revenue ~$80 million from contract research/services and licensing of IP derived from internal technology development
- Research divisions:
  - Engineering
  - Energy and Environment
  - Drug Discovery
  - Drug Development

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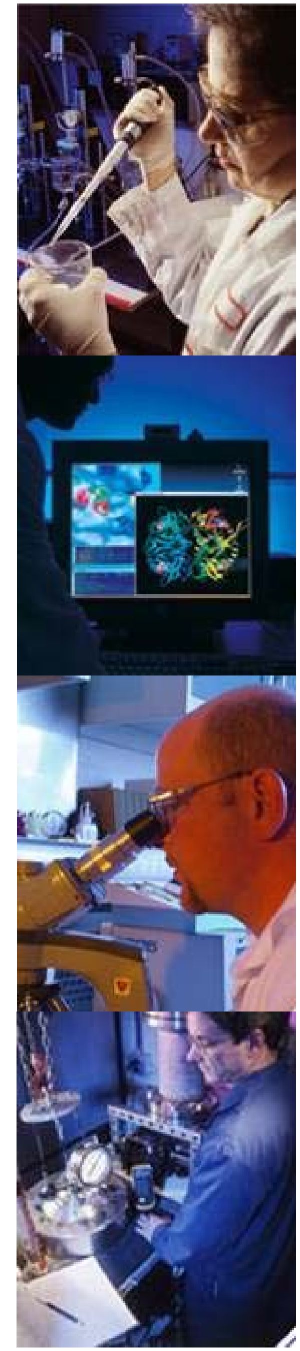
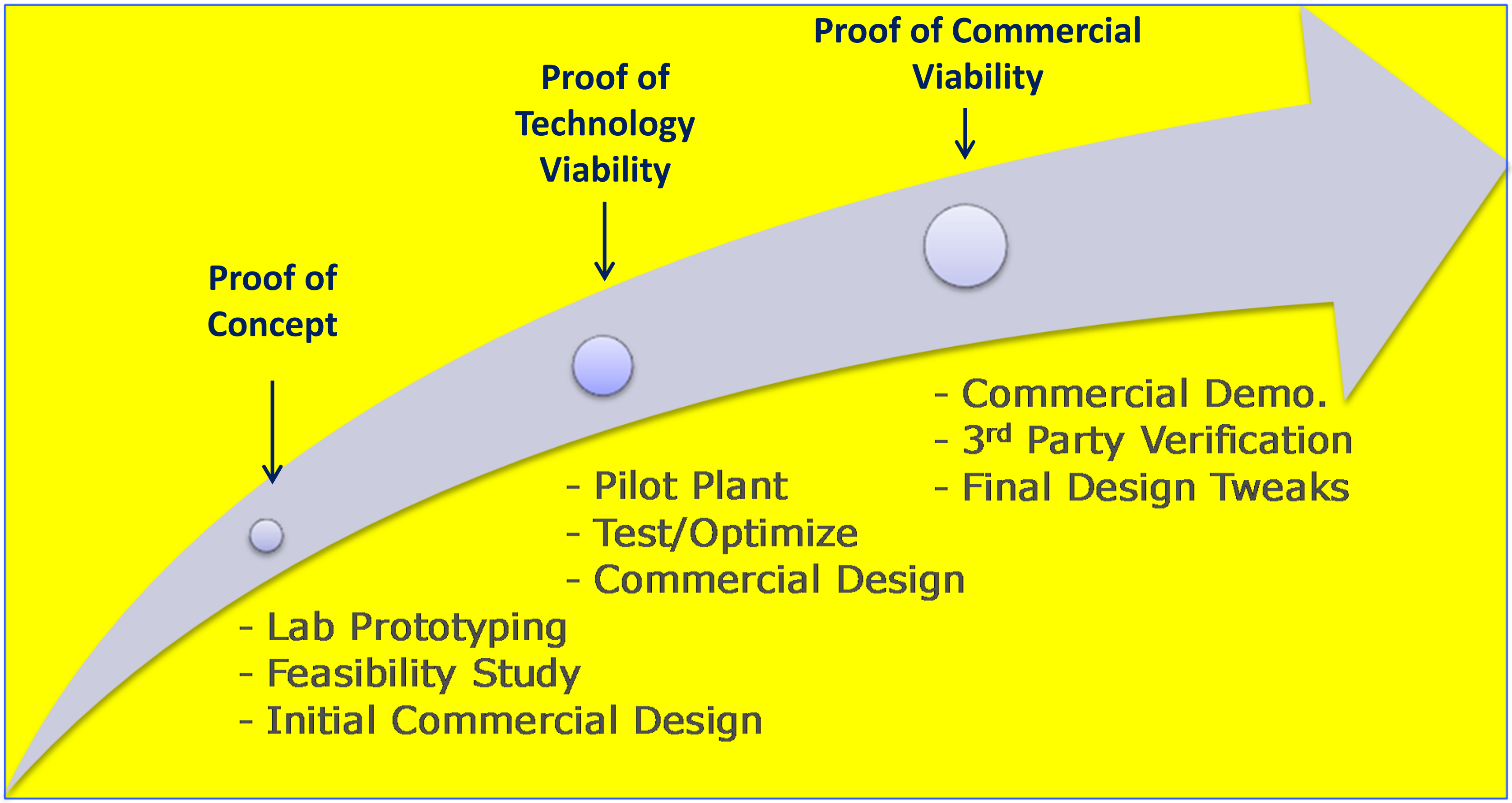


Energy and Environment
Durham, North Carolina

- Established in 2007 for alternative energy-related process research (biomass, coal, solar, waste heat) with a $30+ million investment
- Conducts lab, bench and pilot scale R&D/technology development
- Also provides contract services to private technology developers
- Capabilities include a 30,000 ft^2 high bay pilot plant, complete lab facility for process development, full interconnects, 30+ experienced PhD/MS/BS engineers and operators, 24/7 operations, Autocad and Aspen Modeling
- Pilot plant experience >30,000 hrs




SR Supports The Full Pathway to Energy Technology Commercialization



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Project Examples

- **Lab-Scale Projects**
  - Hydrogen production using palladium membranes
  - Direct liquefaction of biomass
  - High temperature syngas reforming
  - Biomass sugar conversion to acrylonitirile
  - CO2 capture using functionalized amines
- **Bench-Scale Projects**
  - Autothermal reforming
  - Thermochemical energy storage for solar plants
  - Coal and biomass feeding against high pressure without lockhoppers
  - Selective FT catalyst testing
  - Water cleanup from shale fracturing operations
- **Pilot-Scale Projects**
  - Conventional FT synthesis
  - Biomass gasification (gasifiers range from 2 to 4 ton/day, fixed and fluidized bed)
  - MSW gasification and conversion to power and liquid fuel
- **Field Demonstration Projects**
  - Thermal oxidizer- based microturbine for converting very low BTU gas to power
  - Solar-energy based adsorption chiller
  - Engine waste heat conversion to power using an organic Rankine cycle system
  - Slipstream testing of coal/biomass to liquids