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THE UNIVERSITY OF NORTH DAKOTA

Evaluation of Carbon Dioxide Capture From Existing Coal Fired Plants by Hybrid Sorption Using Solid Sorbents

UND & Envergex LLC

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Presentation Overview

- Project and Technology Overview
- Budget Period 1
  - Technical Summary
  - Project schedule and associated milestones
  - Decision points and success criteria
- Budget Period 2
  - Technical Summary
  - Project schedule and associated milestones
  - Decision points and success criteria
- Budget Period 3
  - Technical Summary
  - Project schedule and associated milestones
  - Decision points and success criteria
- Next Steps
  - STTR Phase II – E-CACHYS™ project

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Project Objectives

- The overall objective of this project was to scale-up and demonstrate a hybrid solid sorbent technology for carbon dioxide (CO_2) capture and separation from coal combustion-derived flue gas.
  - Improve current state-of-the-art (amine scrubbing) by developing a novel sorbent-based, post-combustion CO_2 capture technology
  - Achieve at least 90% CO_2 removal from coal combustion flue gas
  - Demonstrate progress toward DOE target of less that 35% increase in levelized cost of electricity (LCOE) for plant with CO_2 capture
  - Develop key information on sorbent and process effectiveness

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Capture of **C**O_2 by **Hy**brid **S**orption (CACHYS™)

- Novel solid sorbent technology
  - reduction of energy for sorbent regeneration,
  - utilization of novel process chemistry,
  - contactor conditions that minimize sorbent-CO_2 heat of reaction and promote fast CO_2 capture, and
  - low-cost method of heat management

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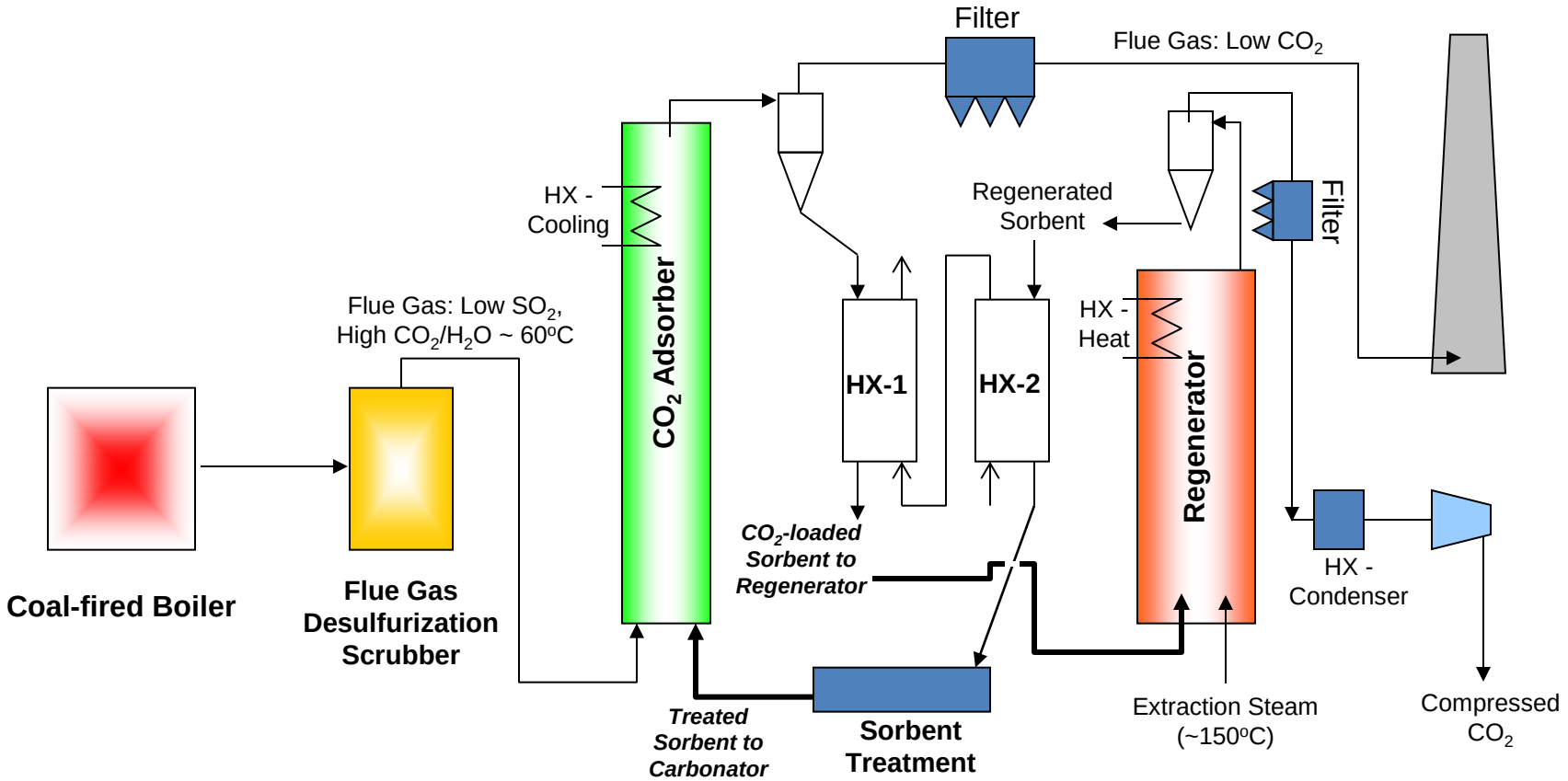
CACHYS™ Hybrid Sorption Process



- Sorbents prepared from bulk commodity materials – low cost target
- Key component – alkali carbonate salt
- Reacts with CO_2 to form adduct. Reversible with the addition of heat
- Additive/process conditions - enhances adsorption kinetics and reduces regeneration energy

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Project Team

- US Department of Energy - NETL
- UND Institute for Energy Studies
- Envergex LLC
- Lignite Energy Council
- ALLETE Group
  - Minnesota Power
  - BNI Coal
- SaskPower
- Barr Engineering
- Solex Thermal Science

Project Work Scope

BP1: Tasks 1-3 BP2: Tasks 1, 3-6 BP3: Tasks 1, 7-8

Task 1: Project Management and Planning

Coordination and planning of the project

Task 2: Initial Technology and Economic Feasibility Study

Initial evaluation of the technical and economic feasibility of the CACHYS™ concept

Task 3: Determination of Hybrid Sorbent Performance Metrics

Defining the envelope of optimum process conditions using hybrid sorbent for CO_2 capture

Task 4: Bench-Scale Process Design

Design of the bench-scale CACHYS™ system

Task 5: Bench-Scale Process Procurement and Construction

Procurement of components and construction of the bench-scale CACHYS™ system

Task 6: Initial Operation of the Bench-Scale Unit

Shakedown testing of the bench-scale CACHYS™ system

Task 7: Bench-Scale Process Testing

Parametric and continuous testing of the bench-scale CACHYS™ system

Task 8: Final Process Assessment

Environmental Health & Safety assessment and final technical and economic feasibility study

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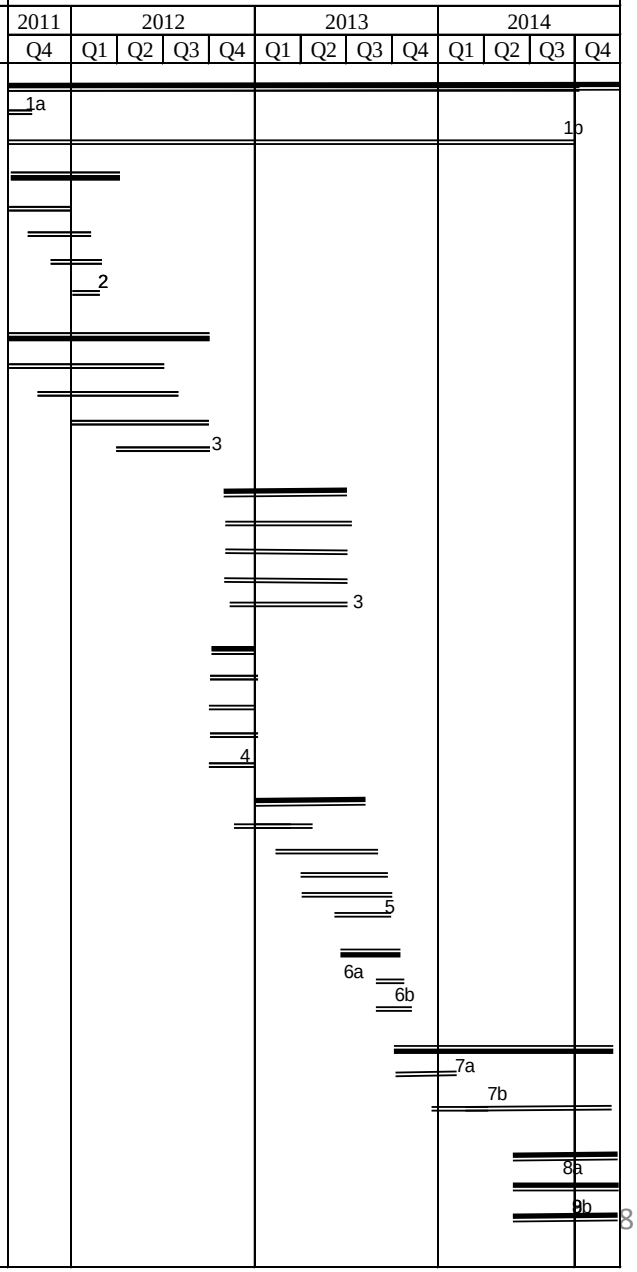
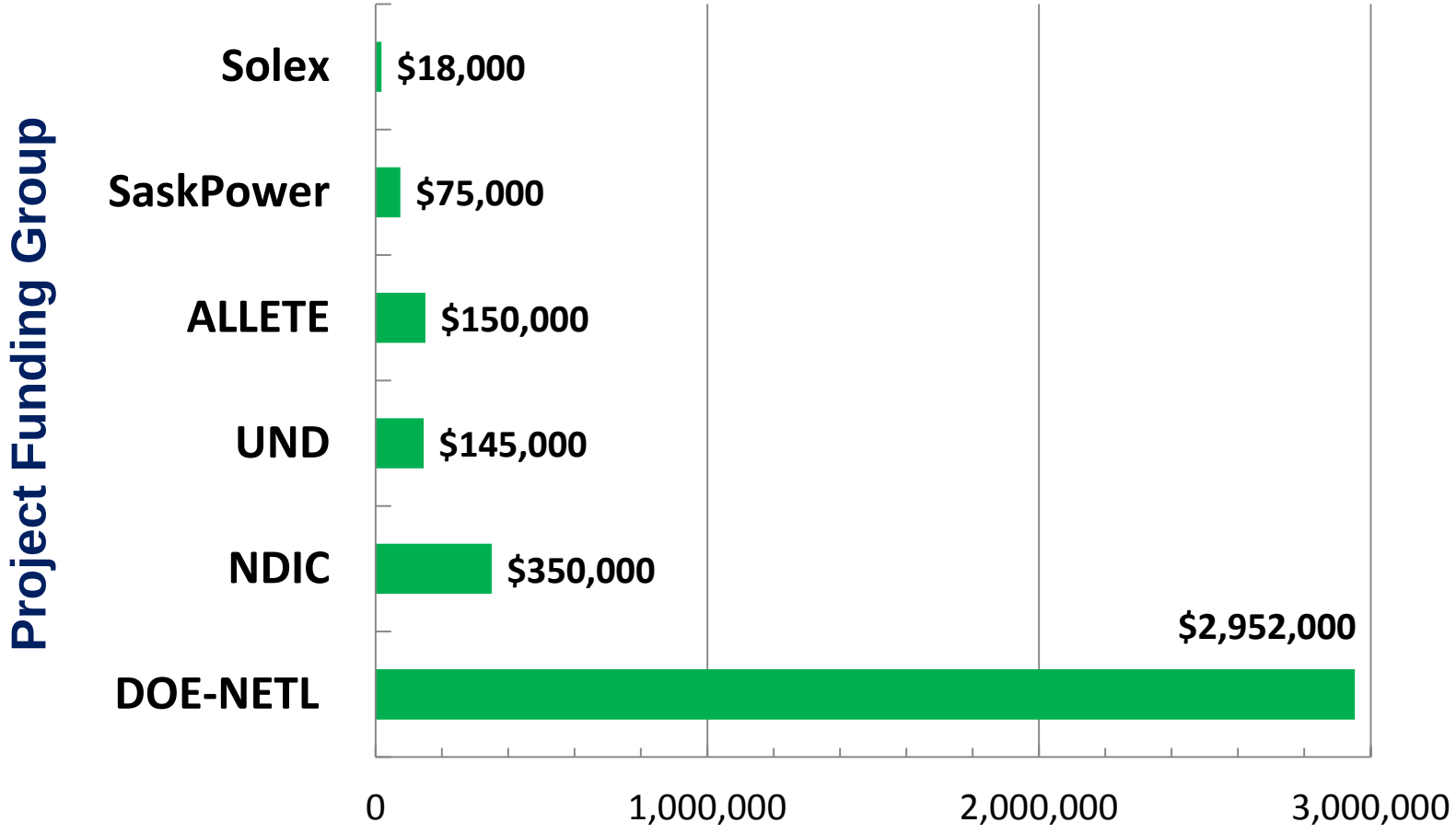
Resource Loaded Schedule

BUDGET PERIOD	TASK/ SUBTASK	TASK DESCRIPTION	PLANNED START	PLANNED COMPLETION	Total
1, 2, 3	**1**	**Project Management Plan**	**10/1/2011**	**12/31/2014**	616,681
	1.1	Project Management and Planning	10/1/2011	11/1/2011	
	1.2	Briefings and Reports			
1	**2**	**Initial Technology and Economic Feasibility Study**	**10/1/2011**	**8/15/2012**	444,261
	2.1	Detailed Process Description	10/1/2011	1/15/2012	
	2.2	Process Modeling and Equipment Design	11/1/2011	7/17/2012	
	2.3	Equipment Design	12/1/2011	7/17/2012	
	2.4	Preliminary Technical and Economic Analysis	1/1/2012	8/16/2012	
1	**3**	**Determination of Hybrid Sorbent Performance Metrics**	**10/1/2011**	**9/30/2012**	292,457
	3.1	Sorbent Formulation and Selection	10/1/2011	7/31/2012	
	3.2	Bench-scale Testing of Sorbents Using Pressurized TGA/DSC	11/15/2011	8/31/2012	
	3.3	Determiniation of Sorben Physical Properties	1/1/2012	9/30/2012	
	3.4	Fixed-Bed Reactor Testing	4/1/2012	9/30/2012	
2	**3**	**Determination of Hybrid Sorbent Performance Metrics**	**10/1/2012**	**8/1/2013**	373,966
	3.1	Sorbent Formulation and Selection	10/1/2012	8/8/2013	
	3.2	Bench-scale Testing of Sorbents Using Pressurized TGA/DSC	10/1/2012	8/8/2013	
	3.3	Determiniation of Sorben Physical Properties	10/1/2012	8/8/2013	
	3.4	Fixed-Bed Reactor Testing	10/1/2012	8/8/2013	
2	**4**	**Bench-Scale Process Design**	**10/1/2012**	**12/31/2012**	292,457
	4.1	Bench-Scale Adsorber Design	10/1/2012	12/31/2012	
	4.2	Bench-Scale Regenerator Design	10/1/2012	12/31/2012	
	4.3	Additional Cycling and Sorbent Transport Testing	10/1/2012	12/31/2012	
	4.4	Recycle Sorbent Feed System Design	10/1/2012	12/31/2012	
2	**5**	**Bench-Scale Process Procurement and Construction**	**12/1/2013**	**10/28/2013**	627,560
	5.1	Bench-Scale Process Procurement	12/1/2013	3/31/2013	
	5.2	Bench-Scale Adsorber Construction	4/1/2013	10/15/2013	
	5.3	Bench-Scale Regenerator Construction	4/15/2013	10/15/2013	
	5.4	Bench-Scale Process Installation and Integration	6/15/2013	10/15/2013	
2	**6**	**Initial Operation of the Bench-Scale Unit**	**8/1/2013**	**10/31/2013**	213,412
	6.1	Bench-Scale Shakedown Procurement	8/1/2013	8/31/2013	
	6.2	Bench-Scale Process Optimization	9/1/2013	10/31/2013	
3	**7**	**Bench-Scale Process Testing**	**11/1/2013**	**11/30/2014**	556,578
	7.1	Bench-Scale Parametric Testing	11/1/2013	4/2/2014	
	7.2	Bench-Scale Continuous Testing	3/1/2014	11/30/2014	
3	**8**	**Final Process Assessment**	**7/1/2014**	**12/31/2014**	272,628
	8.1	Process Environmental Health and Safety Assessement	7/1/2014	12/31/2014	
	8.2	Final Technical and Economic Feasibility Study	7/1/2014	12/31/2014	
		Total			3,690,000



Budget – Funding Sources



Total Funds = $3.69 Million

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Success Criteria and Decision Points

Decision Point	Basis for Decision/Success Criteria
Completion of Budget Period 1	Successful completion of all work proposed in Budget Period 1.
	Demonstrate a sorbent CO_2 equilibrium capacity of greater than 70 gm of CO_2/kg of sorbent
	Demonstrate a heat of sorption of 80 kJ/mole of CO_2 or less
	Submission of a Topical Report – Preliminary Technical and Economic Feasibility Study
	Submission and approval of a Continuation Application in accordance with the terms and conditions of the award.
Completion of Budget Period 2	Successful completion of all work proposed in Budget Period 2.
	Submission of a bench-scale engineering design package
	Complete construction of an integrated bench-scale CACHYS™ system
	Submission of a test matrix for the bench-scale parametric testing campaign
	Submission and approval of a Continuation Application in accordance with the terms and conditions of the award.
End of Project	Successful completion of all work proposed.
	Adsorber -- Achieve capture levels in sorbent of 7g CO_2/100g sorbent
	Adsorber – Achieve 90% CO_2 Capture
	Regenerator – Minimize heat of regeneration <80 kJ/mole
	Regenerator -- Maximize Desorption of CO_2 ~ 80% desorption
	Integrated System- run on a continuous basis for 3 weeks (1-week increments)
	Submission of a Topical Report - Final Technical and Economic Feasibility Study
	Submission of a Topical Report – Preliminary EH&S Assessment
	Submission of a Final Report

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BUDGET PERIOD 1

Task 1 - Project Management and Planning

Subtask 1.1 – Project Management and Planning

- The Project Management Plan submitted at the initiation of the project and was revised to include Barr Engineering
- Project meetings and conference calls including UND and selected subcontractors held weekly to biweekly.

Subtask 1.2 – Briefings and Reports

- A project kick-off meeting at NETL in Pittsburgh was held on November 21, 2011.
- Gave presentation at CO_2 Capture Technology Conference held in Pittsburgh during July 2012.

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Task 2 - Initial Technology and Economic Feasibility Study

- Subtask 2.1 – Detailed Process Description
- Subtask 2.2 – Process Modeling and Equipment Design
- Subtask 2.3 – Equipment Design
- Subtask 2.4 – Preliminary Technical and Economic Analysis

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Accomplishments and Key Findings Summary (I)

- Initial Technical and Economic Feasibility (550MW$_e$)
  - Total O&M $28,290,000
  - Capital Charge $102,504,000
  - Total Cost (annualized) $130,794,000
  - CO_2 Captured 3,614,000 Tons
  - Cost of CO_2 Capture $36.19/ton
  - Cost of Electricity Increase 40%

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Task 3 - Determination of Hybrid Sorbent Performance Metrics

- Subtask 3.1: Sorbent Formulation and Selection
- Subtask 3.2: Lab-scale testing of sorbents using TGA/DSC
- Subtask 3.3: Determination of Sorbent Physical Properties
- Subtask 3.4: Fixed-Bed Reactor Testing

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Sorbent Screening and Energetics Determination

- Sorbent formulation and selection
- Thermogravimetric analyzer/differential scanning calorimeter (TGA/DSC) used to determine sorbent capacity, kinetics and sorption energetics

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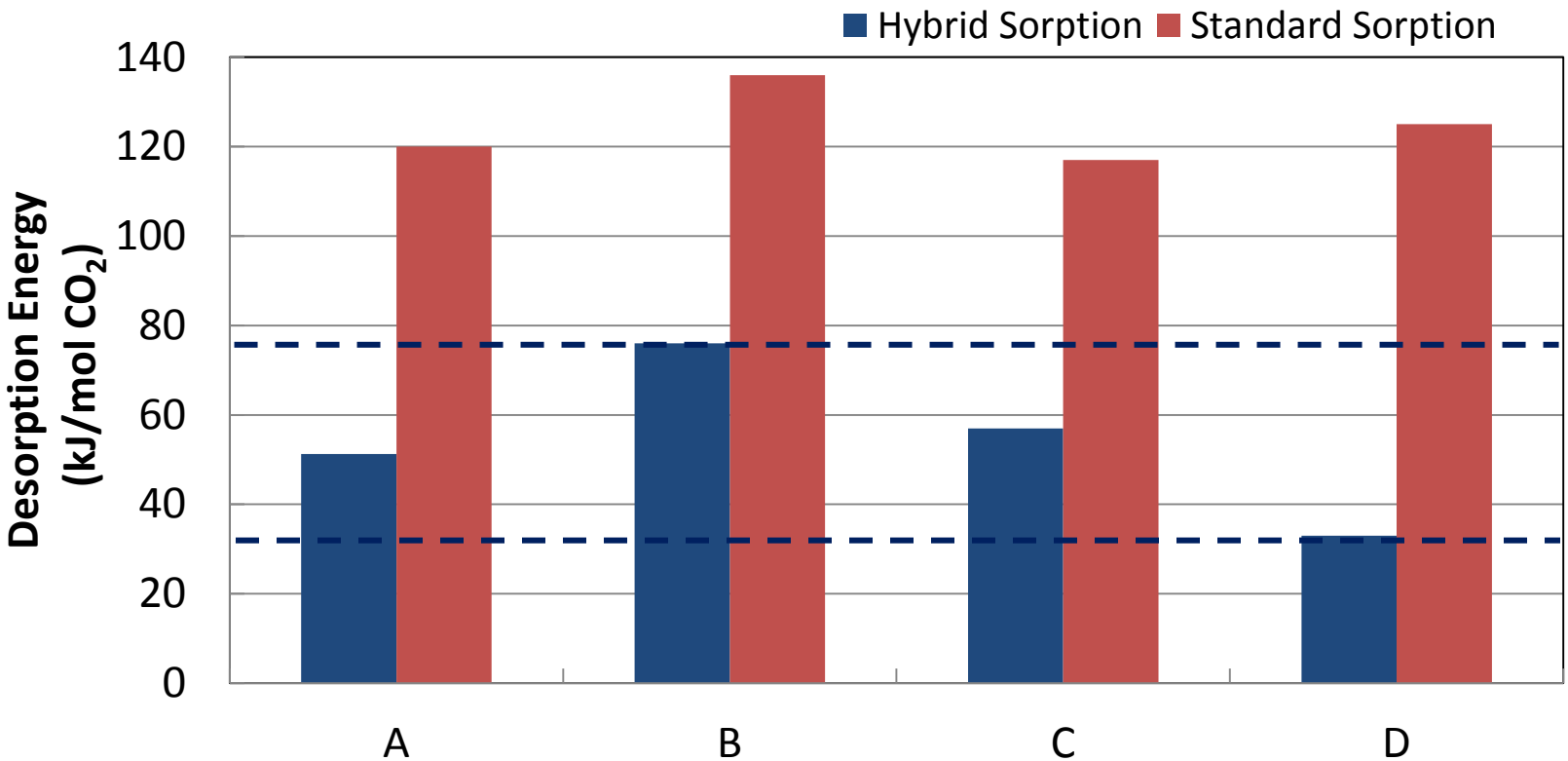
TGA/DSC Desorption Energy Data



- Desorption energy ~ 30-75 kJ/mol CO_2
- Below target of 80kJ/mol CO_2 and significantly lower than standard carbonate process (130 kJ/mol CO_2)

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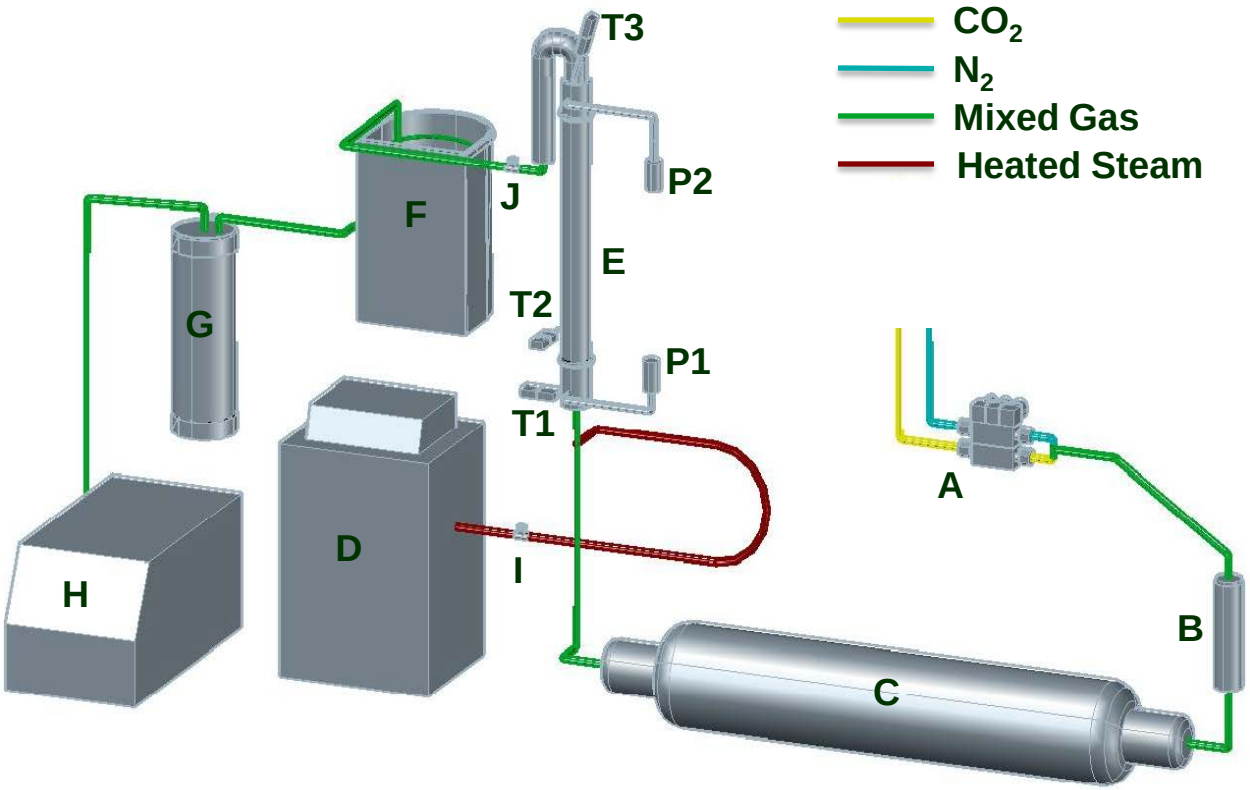
Fixed-Bed Reactor Testing



	Components
A	Mass Flow Controllers
B	Bubbler
C	Air Preheater
D	Steam Generator
E	Reactor
F	Condenser
G	Water Knockout Drum
H	5 Gas Analyzer
I	Manual Steam Control #1
J	Manual Steam Control #2
T1	Thermocouple – Air In
T2	Thermocouple – Reactor Wall
T3	Thermocouple – Air Out
P1	Pressure Transducer (Bottom)
P2	Pressure Transducer (Top)

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Accomplishments and Key Findings Summary (II)

- Sorbent Performance
  - Eight sorbent formulations tested with two support materials
    - CO_2 adsorption capacity ranged from 7.1 to 9.2 g CO_2/100 g sorbent
    - Heat of Adsorption: -40 to -80 kJ/mol CO_2
    - Desorption Energy: 30 to 75 kJ/mol CO_2
  - Two Sorbents down selected for multi-cycle testing
    - HCK-4 sorbent: Average capacity of 7.1 g/100 g sorbent
      - 35 wt% active component with moderate surface area support
    - HCK-7 sorbent: Average capacity of 9.2 g/100 g sorbent (as high as 10 g/100g)
      - 35 wt% active component with higher surface area and high strength support

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Decision Points and Success Criteria

Decision Point	Basis for Decision/Success Criteria
Completion of Budget Period 1 Year 1	1. Successful completion of all work proposed in Budget Period 1
	2. Demonstrate sorbent CO_2 equilibrium capacity of greater than 70 g of CO_2/kg of sorbent - **CACHYS™ sorbents have capacities that range from 70 to 100 g CO_2/kg sorbent.**
	3. Demonstrate a heat of sorption of 80 kJ/mole of CO_2 or less - **desorption energies ranged from 30 to 75 kJ/mole of CO_2**
	4. Submission of a Topical Report – Preliminary Technical and Economic Feasibility Study - **submitted and accepted**
	5. Submission/approval of a Continuation Application to DOE – **submitted and accepted**

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BUDGET PERIOD 2

Task 1 - Project Management and Planning

Subtask 1.1 – Project Management and Planning

- The Project Management Plan revised to include the use of funding not spent in Budget Period 1 to conduct additional testing of sorbent formulations and construct a sorbent dryer
- Project meetings and conference calls including UND and selected subcontractors held weekly to biweekly.
- 1-month no-cost extension was granted due to delays in procurement/installation of bench-scale test system components

Subtask 1.2 – Briefings and Reports

- Three presentations were made that included:
  - "Evaluation of Carbon Dioxide Capture From Existing Coal Fired Plants by Hybrid Sorption Using Solid Sorbents (CACHYS™)" presented at EUEC 2013 Conference in Phoenix, Arizona on January 30, 2013,
  - "CO_2 Capture using Hybrid Sorption with Solid Sorbents," presented at the Clearwater Clean Coal Conference, June 2-6, 2013, Clearwater, Florida.
  - Project Update at NETL Carbon Capture Technology Conference in Pittsburgh July 8-11, 2013.
- Project was peer reviewed at the FY13 Carbon Capture Peer Review held in Pittsburgh on March 13, 2013.

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Task 3 – Determination of Sorbent Performance Metrics

- ***Additional multi-cyclic testing and characterization of down-selected sorbents***

- Testing of additional sorbent formulations and support materials

- Construction of a larger-scale sorbent dryer

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Fixed Bed Reactor: Multi-cycle Sorbent Testing

- 100 cycles with down-selected sorbents, HCK-4 & HCK-7
- Gather key information on sorbent performance
  - Attrition resistance
  - Determine capacity with continuous cycling
  - Determine optimal operating conditions
- HCK-4 Results
  - Statistical analysis showed all factors were significant
  - Capacity at optimal process conditions: 8.3 g CO_2/100 g Sorbent
  - No apparent loss in sorbent capacity
  - Little attrition through 75 cycles – measurable attrition between 75 and 100 cycles
- HCK-7 Results
  - Statistical analysis showed all factors were insignificant
  - Average capacity: 8.9 g CO_2/100 g Sorbent
  - No apparent loss in sorbent capacity
  - Little attrition through 100 cycles

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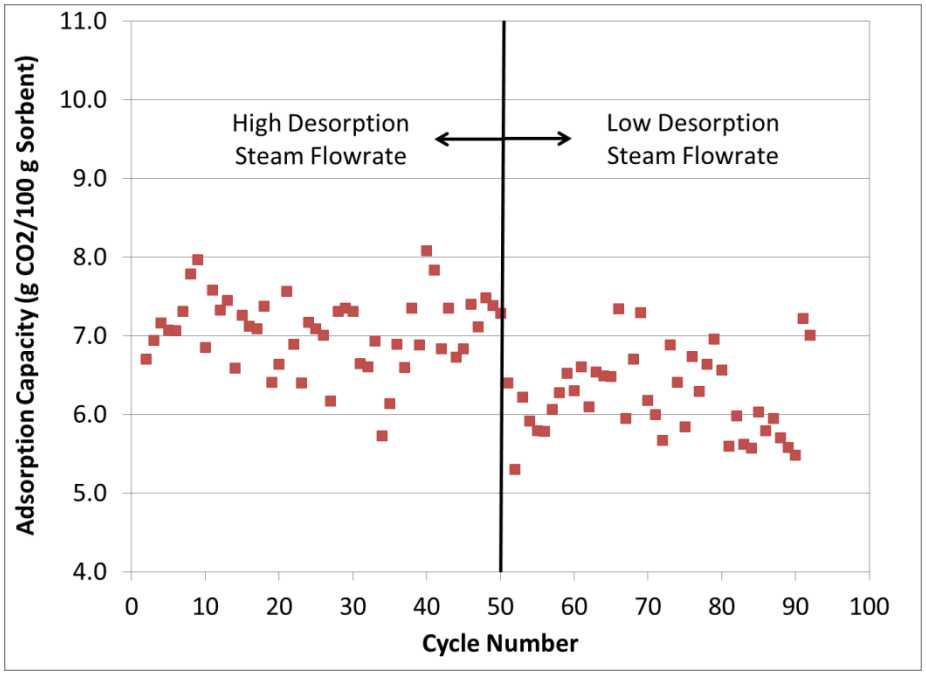
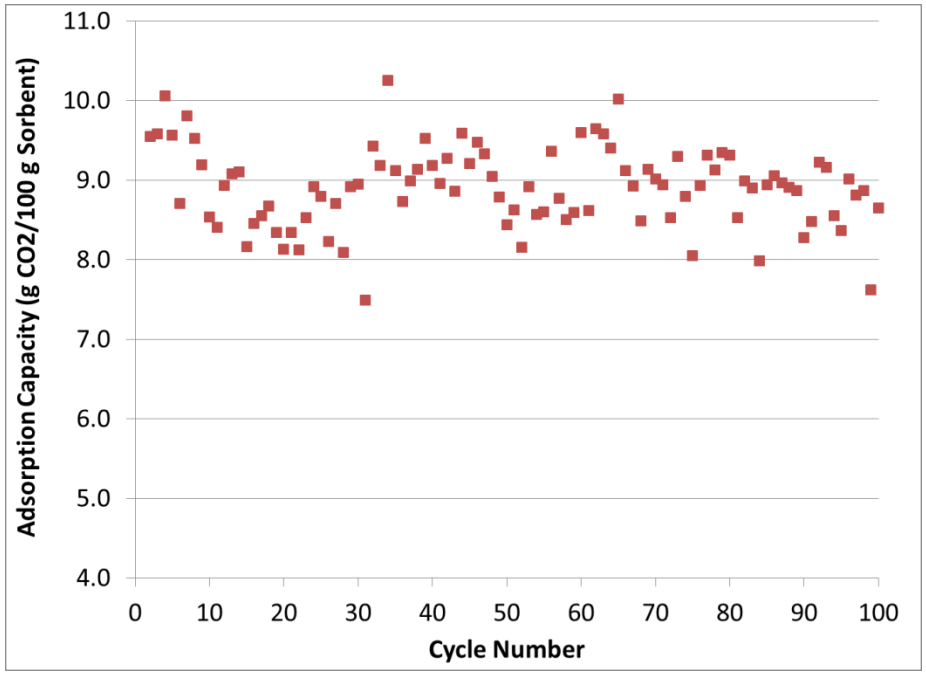
Fixed Bed Reactor: Multi-cycle Sorbent Testing

HCK-4



HCK-7



- Both sorbents exceeded goal of 7.0 g CO_2/100g of sorbent and maintained capacity over the 100 cycle tests

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Technical Approach and Project Scope
Budget Period 2 (10/1/12 – 10/31/13)

- Tasks 4-6: Process design of bench scale system as well as construction and shakedown testing of adsorption and desorption system
- This work conducted by UND, Solex Thermal and Envergex LLC with support from Barr Engineering

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Task 4: Bench-Scale System Design

CO_2 Capture Using 30 acfm Flue Gas from UND's Steam Plant

- Gas Conditioning System
  - Fabric Filter
  - Wet Packed Bed SO_2 Scrubber
- Adsorber System
  - FD/ID Fans
  - Circulating Fluidized Bed
  - Cyclones for Bulk Solids Separation
  - Fabric Filters for Fines Separation
- Regenerator System
  - Pre-heater Unit
  - Regenerator Unit
  - Cooler Unit
- Regenerator Off-Gas System
  - Particulate Filter
  - Steam Condensers

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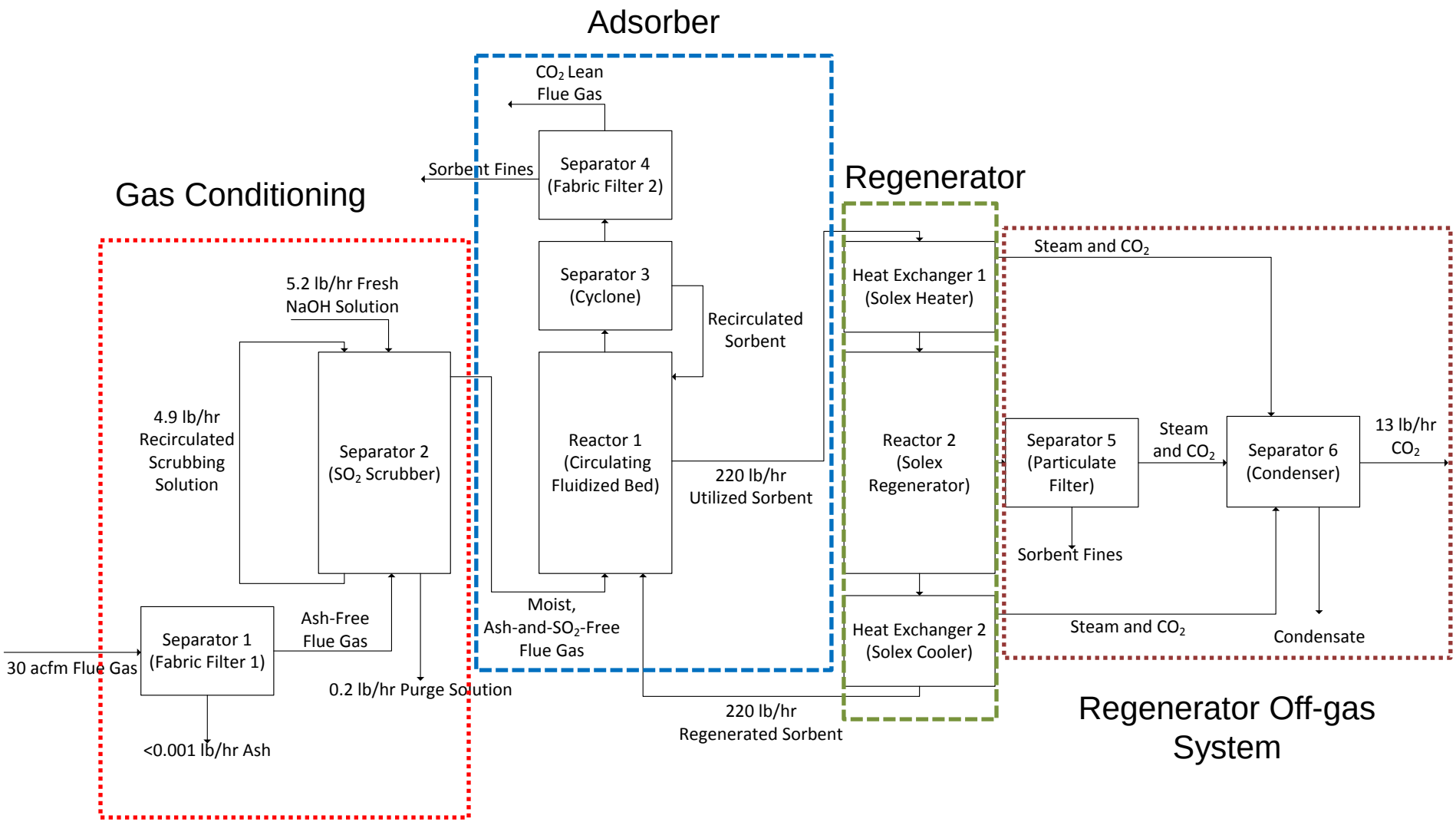
Bench-Scale Design: Block Flow Diagram



Integration at UND steam plant

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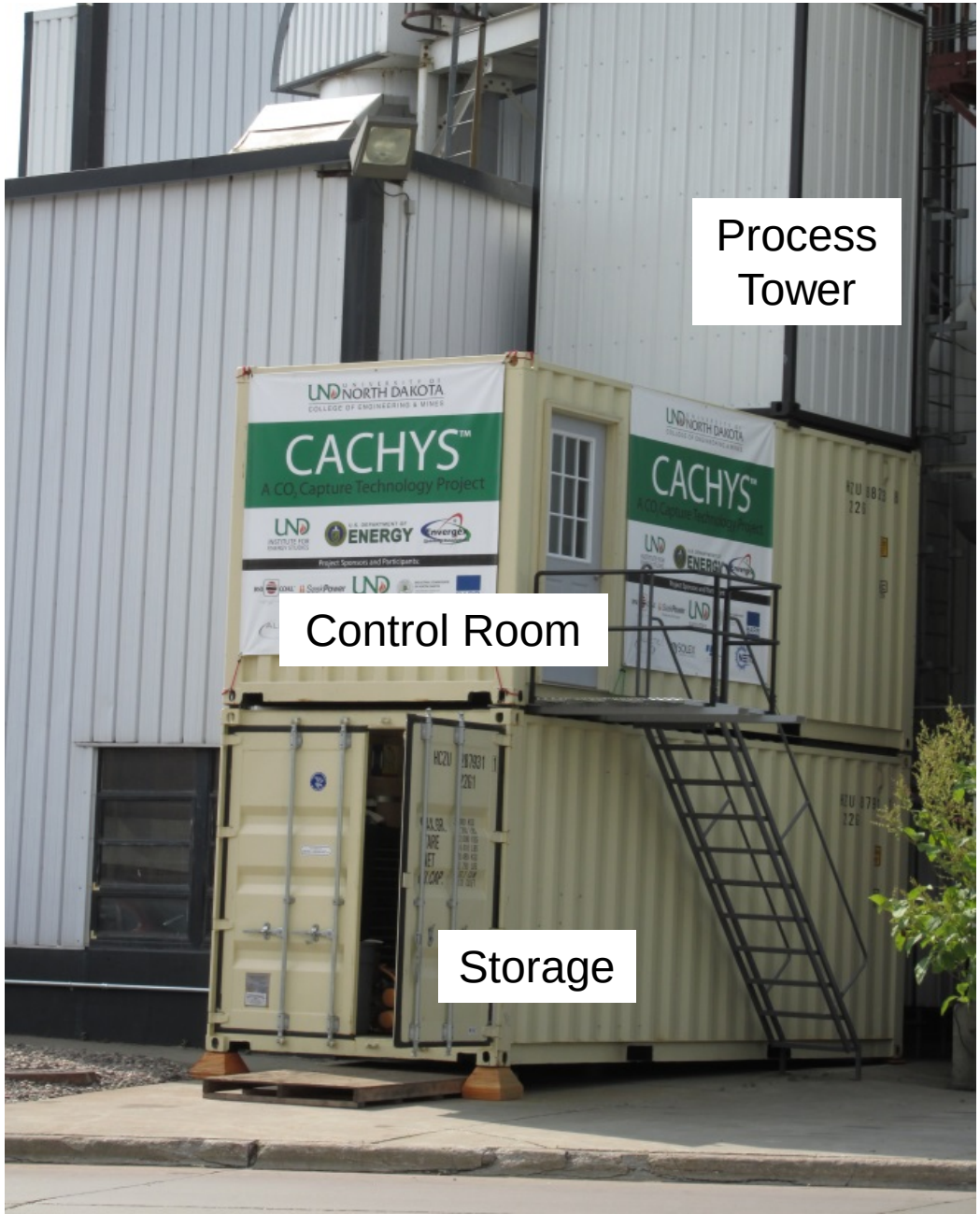
Bench-Scale Facility Process Housing



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Gas conditioning system

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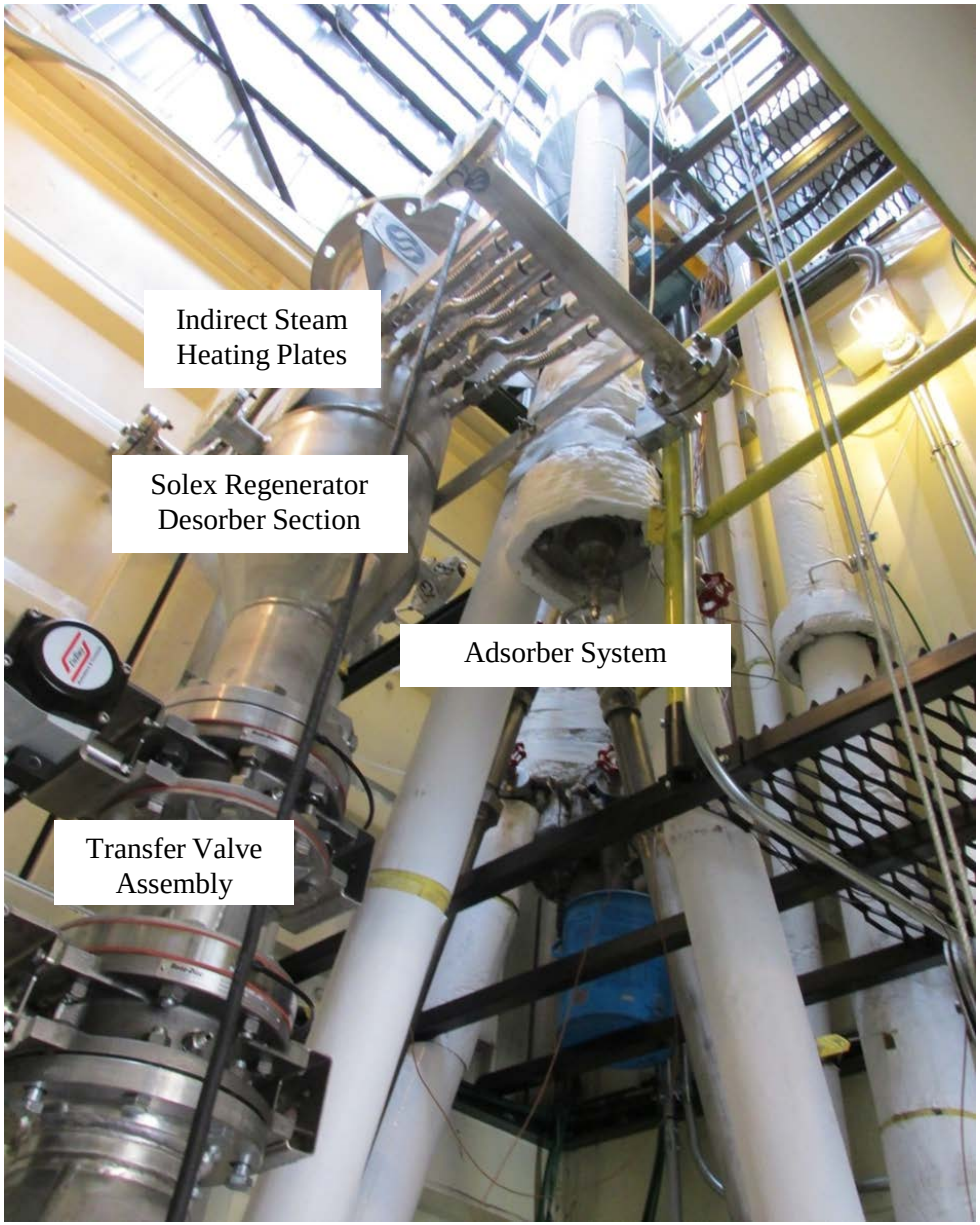
View of the adsorber system and installation of the Solex Regenerator system



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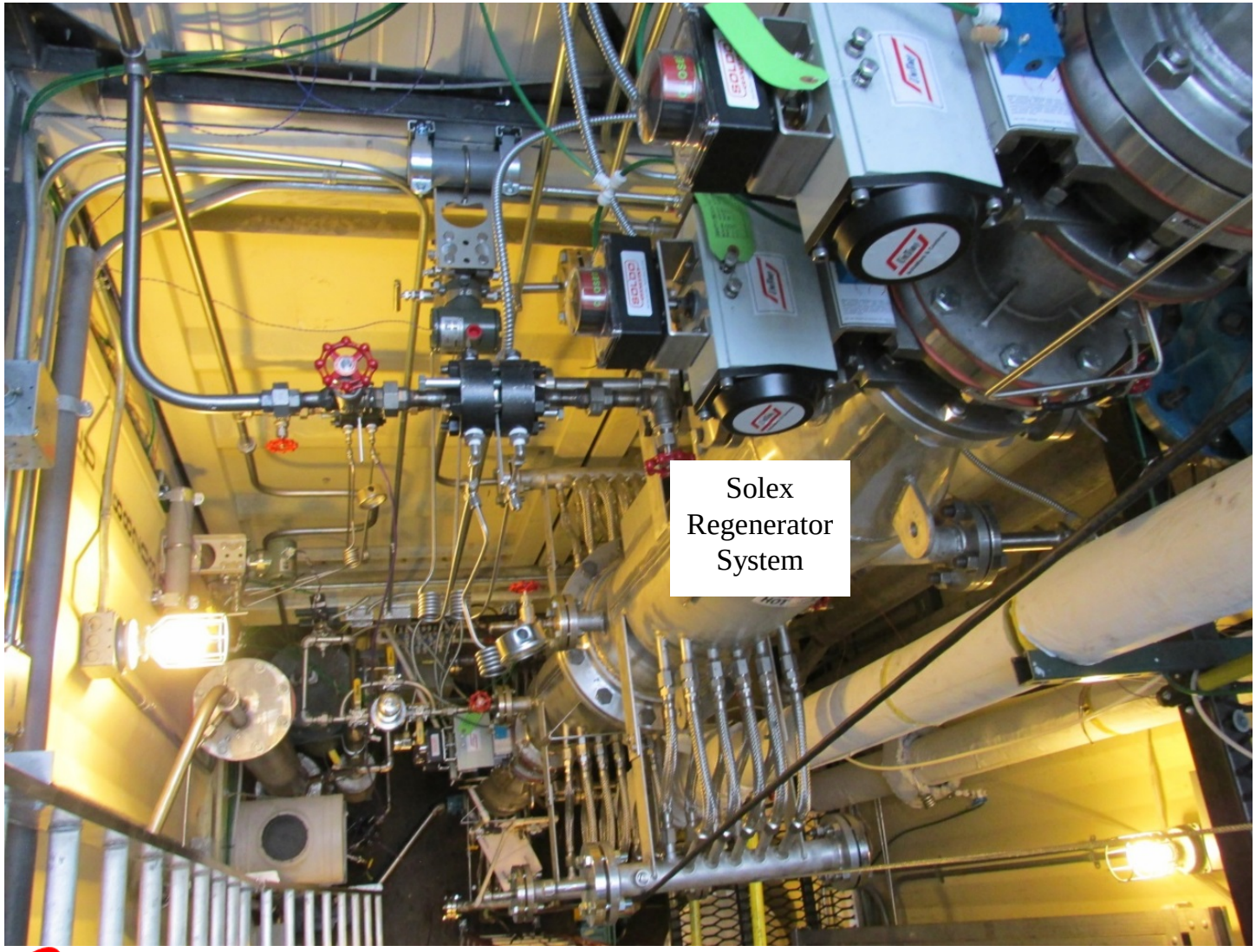
Solex Regenerator and Associated Piping



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Task 6. Shake Down Testing

- Bench-Scale Shakedown Testing
  - Phase I -- testing the flue gas sampling and conditioning system
  - Phase II -- testing the adsorber
  - Phase III – testing the regenerator

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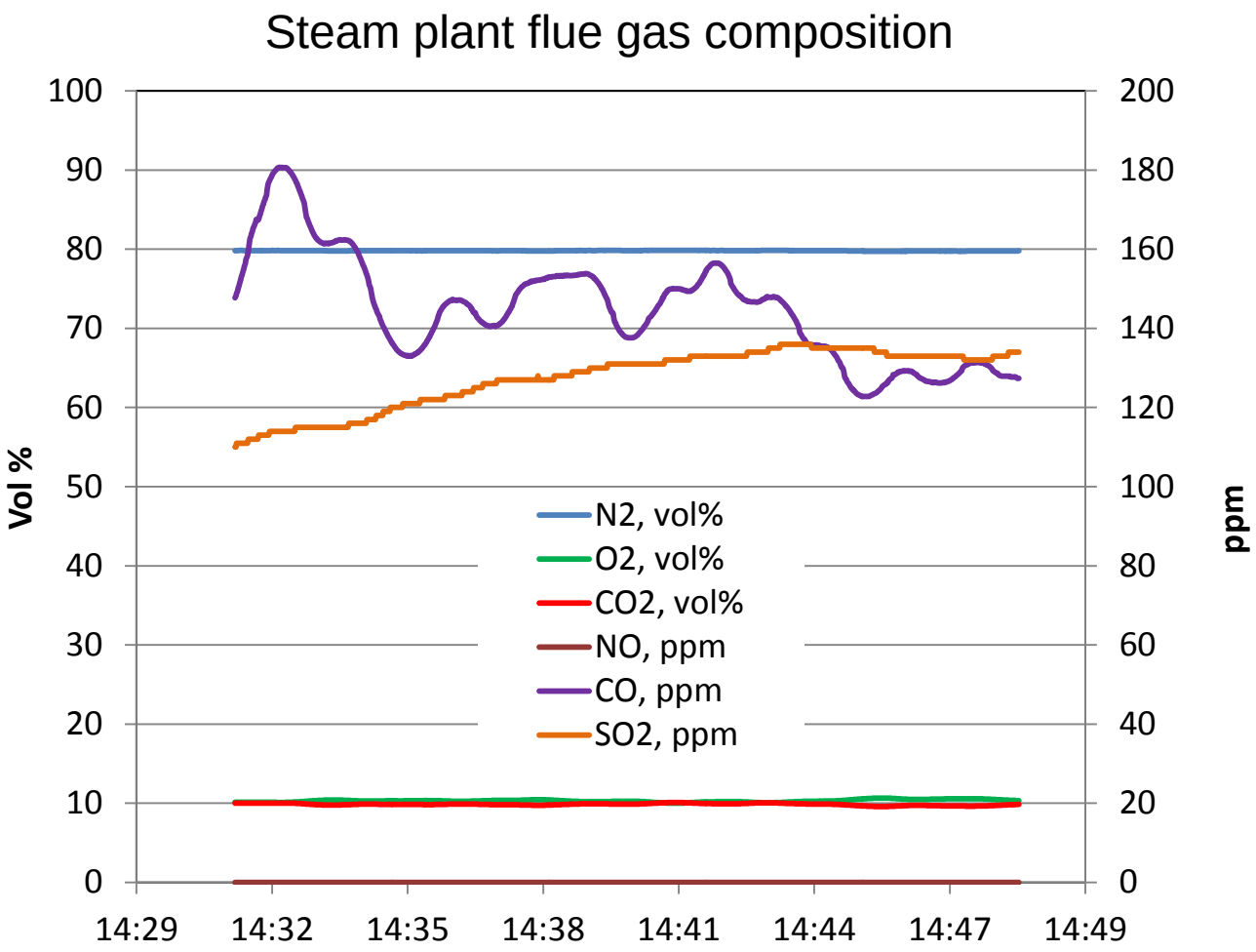
Shakedown – Flue Gas Sampling and Conditioning



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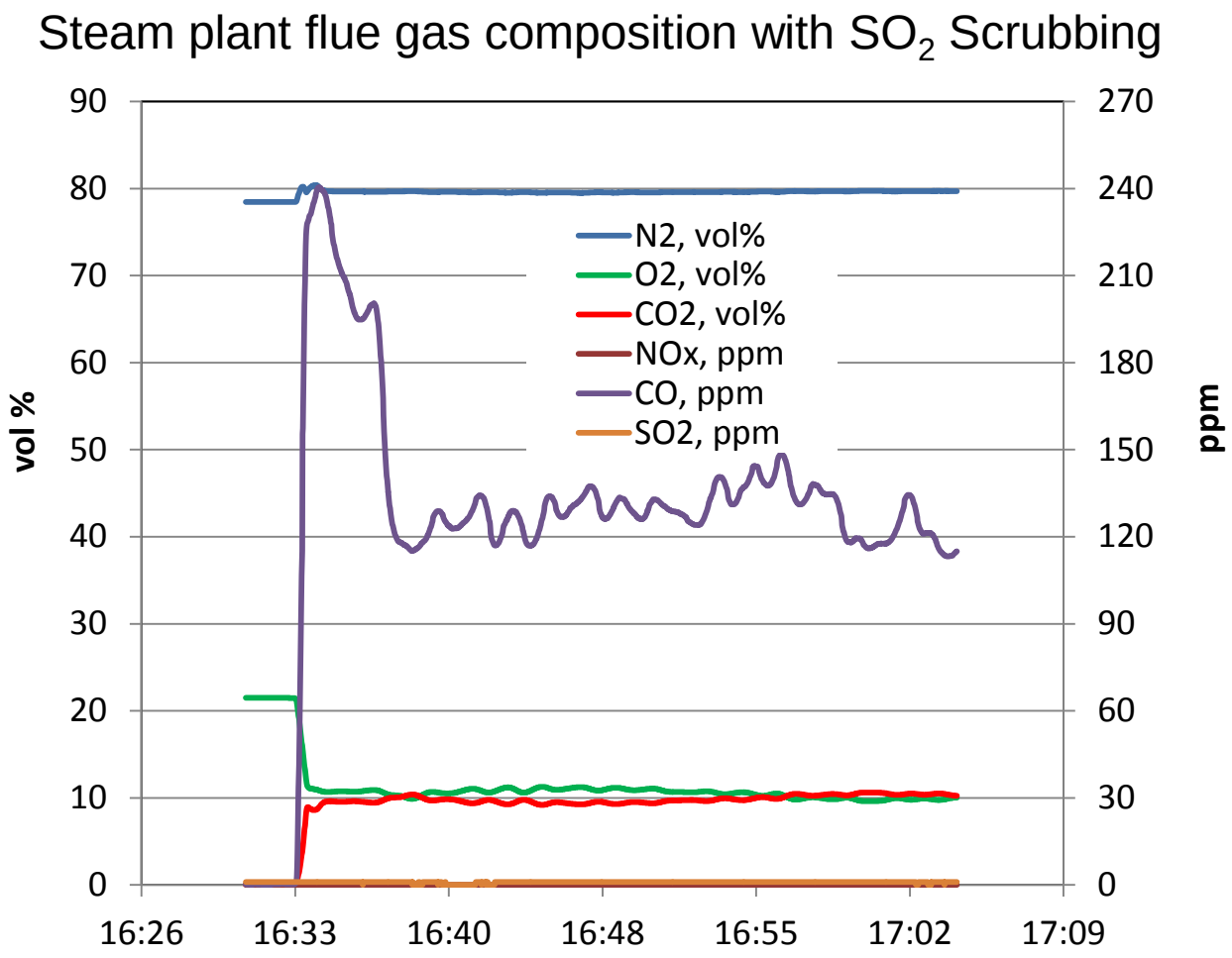
Shakedown – Flue Gas Sampling and Conditioning



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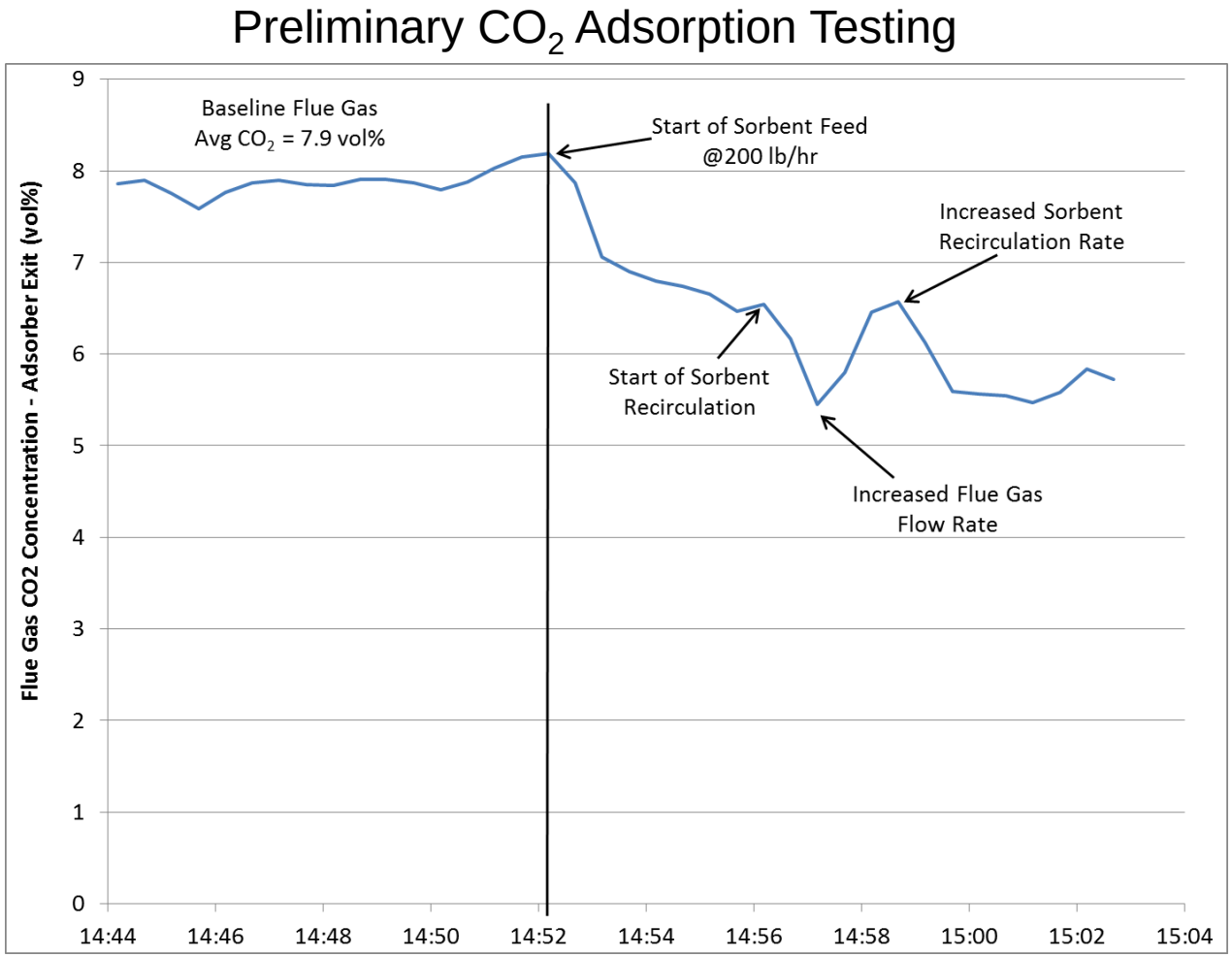
Shakedown- testing the adsorber



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Shakedown– testing the regenerator

- Tested and confirmed operation of pneumatic sorbent transport system between adsorber and regenerator
- Programmed cycling of transfer valves
- Confirmed operation of sorbent level sensors
- Confirmed operation of moving sorbent through regenerator
- Confirmed ability to heat sorbent and release CO_2

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Decision Points and Success Criteria

Decision Point	Basis for Decision/Success Criteria
Completion of Budget Period 2 Year 2	1. Successful completion of all work proposed in Budget Period 2.
	2. Submission of a bench-scale engineering design package – **Design package was provided**
	3. Complete construction of a bench-scale CACHYS™ system – **Completed construction and conducted component shakedown**
	4. Submission of a test matrix for the bench-scale testing campaign – **Detailed test plan submitted**
	5. Submission/approval of a Continuation Application to DOE

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BUDGET PERIOD 3

Work Plan for Budget Period 3

- **Task 1 - Project Management and Planning**
  - Subtask 1.1 – Project Management and Planning
  - Subtask 1.2 – Briefings and Reports
- **Task 7- Bench-Scale Process Testing**
  - Subtask 7.1. Bench-Scale Parametric Testing
  - Subtask 7.2 – Bench-Scale Continuous Testing
- **Task 8 - Final Process Assessment**
  - Subtask 8.1 Process Environmental Health and Safety Assessment
  - Subtask 8.2 Final Technical and Economic Feasibility Study
  -

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Task 1 - Project Management and Planning

Subtask 1.1 – Project Management and Planning

- The Project Management Plan was revised to reflect the 1-month extension applied to BP2. The PMP was later revised to reflect the 3-month extension that was applied to BP3 as well as to better identify success criteria for BP3.
- Project meetings and conference calls including UND and subcontractors were held at least on a biweekly basis during the course of the project.

Subtask 1.2 – Briefings and Reports

- During this reporting period, UND and Envergex made two presentations associated with the work conducted on this project.
  - Thirteenth Annual Conference on Carbon Capture, Utilization & Storage in Pittsburgh, PA, April 28 – May 1, 2014. The title of the paper was "CO_2 Capture Using Hybrid Sorption with Solid Sorbents (CACHYS™)," by Srivats Srinivasachar, Dan Laudal, and Steve Benson.
  - Project Update at the NETL CO_2 Capture Technology Meeting held in Pittsburgh, PA on July 29-August 1, 2014.

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Task 7 – Bench-scale Testing

- Subtask 7.1 – Bench-scale Parametric Testing
  - Component Testing
    - Additive injection – Effect of Hybrid Sorption
    - Regenerator
    - Adsorber
  - Integrated System
  - HCK-4 sorbent used for bench-scale tests

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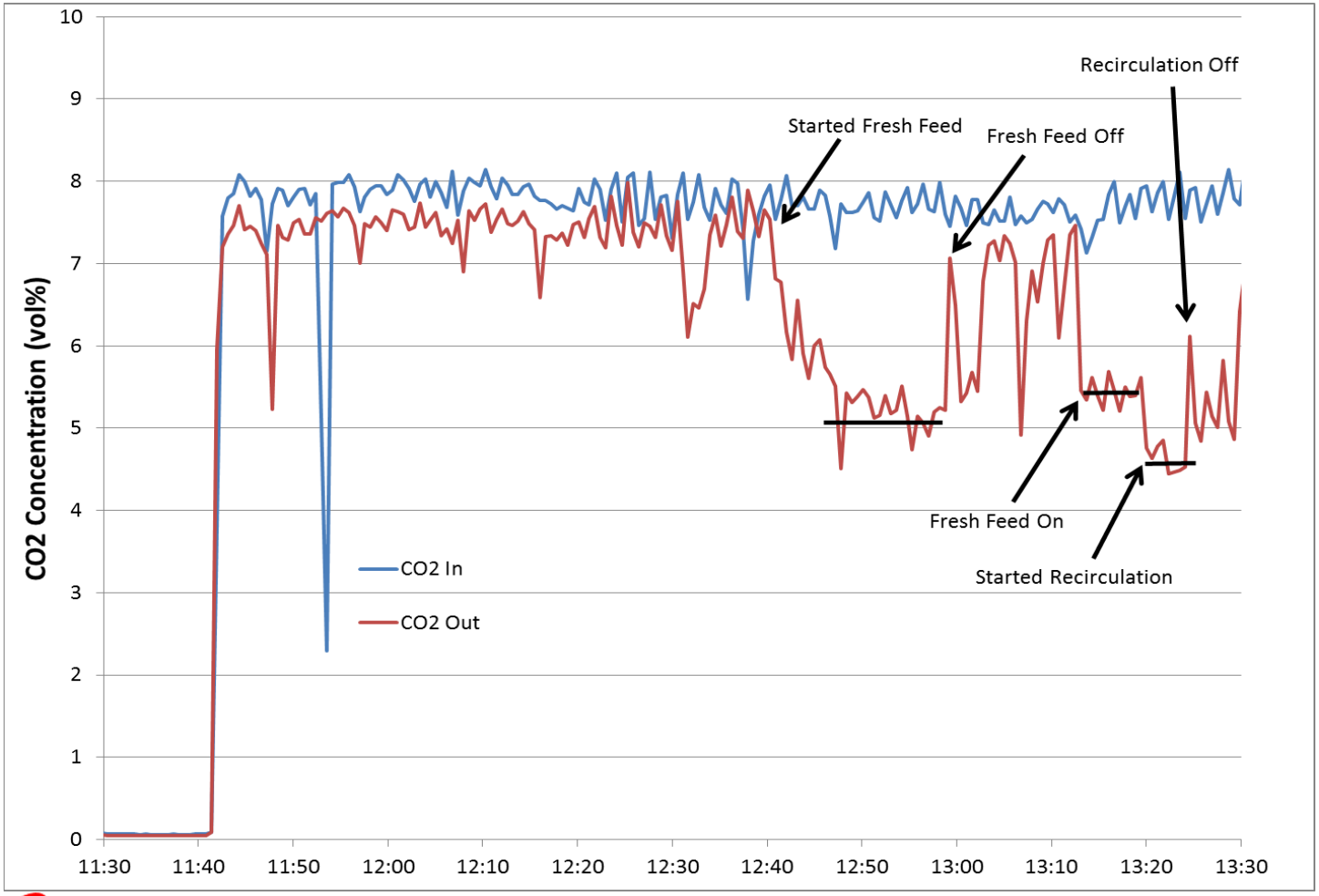
Initial Hybrid Sorption Testing



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Effect of Hybrid Sorption

- Hybrid sorption increased amount of CO_2 captured by 2-3X compared to adsorption conducted at the same conditions without additive injection (standard carbonate sorption)

- Capture of up to 44% was achieved with a low recirculation rate, a partially utilized sorbent (30-40%) and with half the gas residence time that is possible with the bench-scale system

- Hybrid sorption helps to control adsorber temperatures. Minimal increases in bed temperature were observed when initiating fresh/recirculated sorbent feeds when compared to very large temperature gradient (> 45°C) that was observed without hybrid sorption

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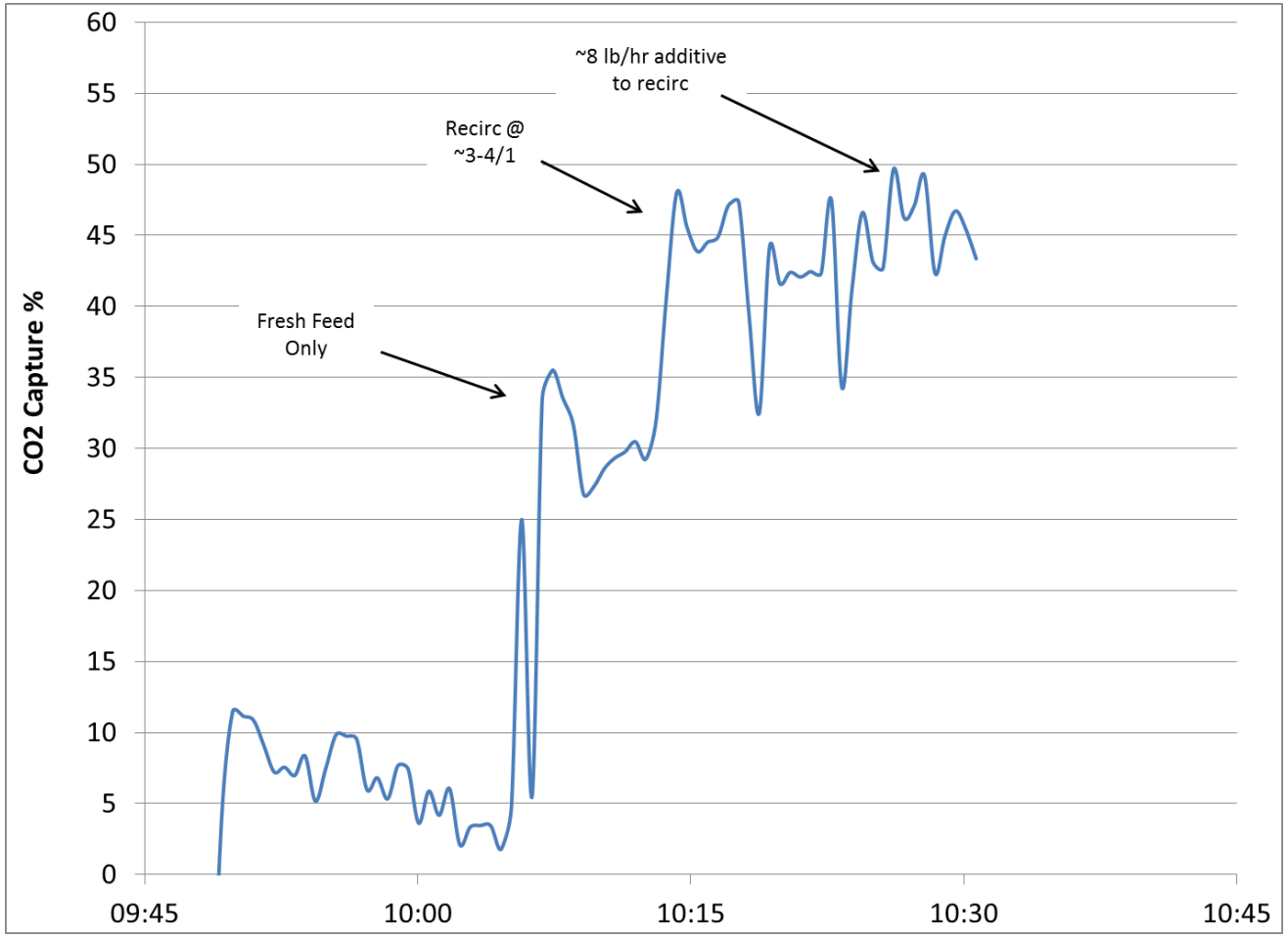
Parametric Testing – Adsorber

Preloaded sorbent – single bed operation



- Recirculation increased capture substantially
- Minimal effect of online additive addition

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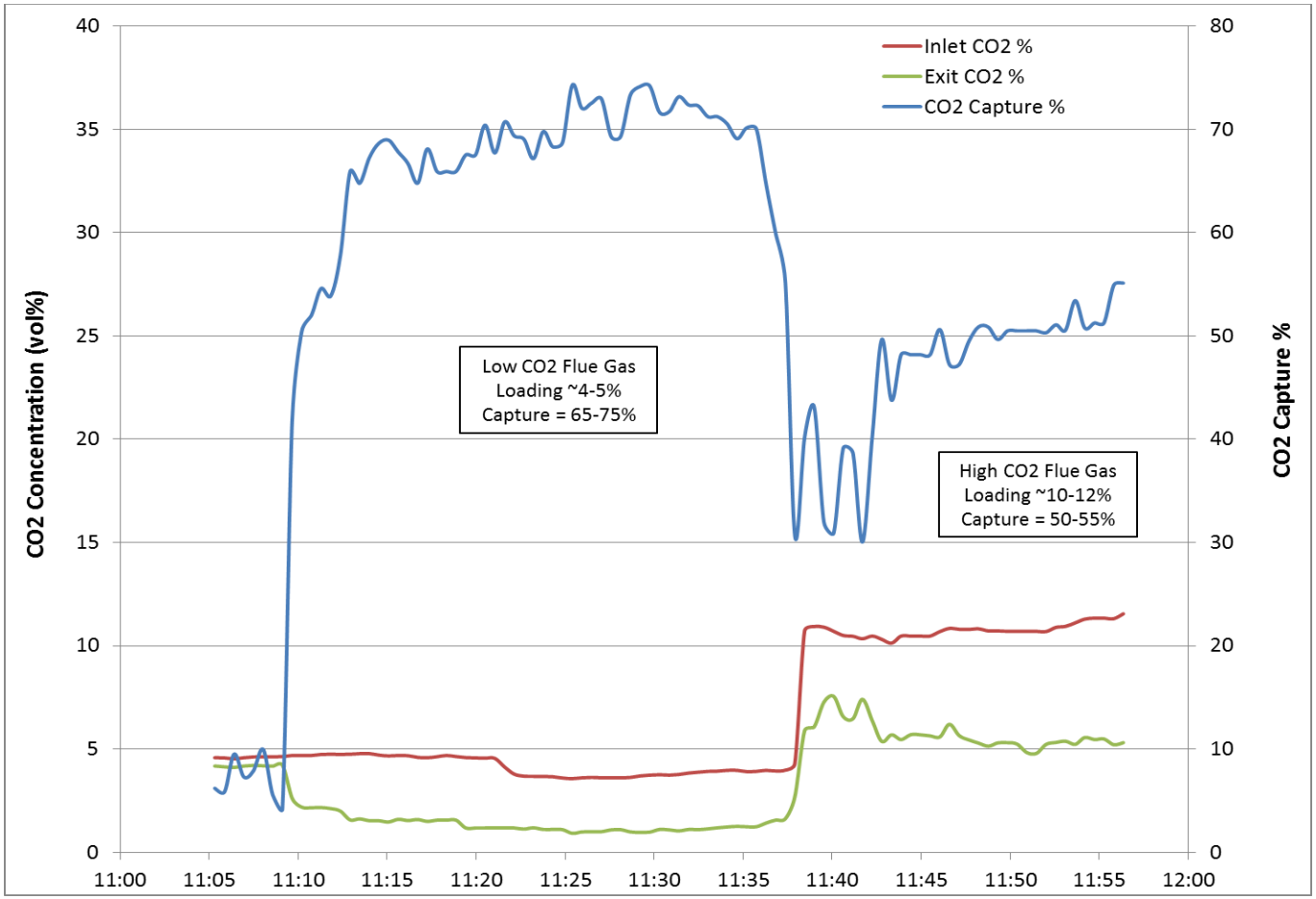
Parametric Testing – Adsorber

Preloaded sorbent – single bed operation – multiple flue gas CO_2 loadings



- Although capture % was higher with low inlet CO_2 flue gas loading, the ***amount*** of CO_2 captured was higher during the high inlet CO_2 loading operation
- Indicates the importance of driving force for capture

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Parametric Testing – Adsorber

Preloaded sorbent – single bed operation – multiple flue gas CO_2 loadings

	Fresh Feed	Ads. Exit 11:17	Ads. Exit 11:30	Ads. Exit 11:57
Active Component Utilization, %	20-22	30.92	38.37	28.97
Gas Balance				
Average Capture %	-	**67.0**	**72.0**	**50.1**
Inlet CO_2 %	-	4.7	3.7	10.8
FG Flow, scfm	-	34.0	34.0	31.8
lb/hr CO_2 Captured	-	**7.4**	**6.2**	**12.0**

- **Low active component utilization post adsorption indicates potentially insufficient gas/sorbent contacting time**

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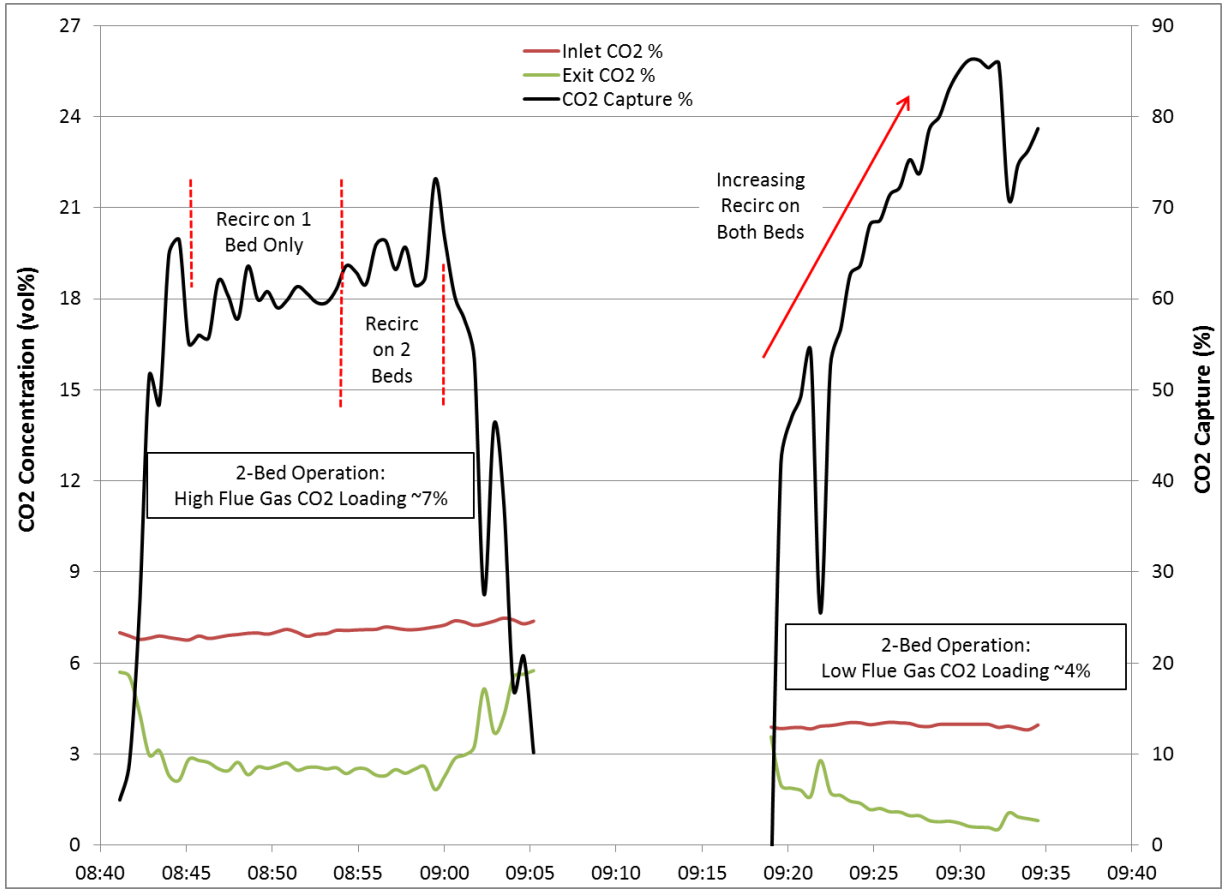
Parametric Testing – Adsorber

Preloaded sorbent – two bed operation

- multiple recirculation rates - multiple flue gas CO_2 loadings



- **Achieved ~85% capture, but this mode of operation was very difficult to sustain for long periods**

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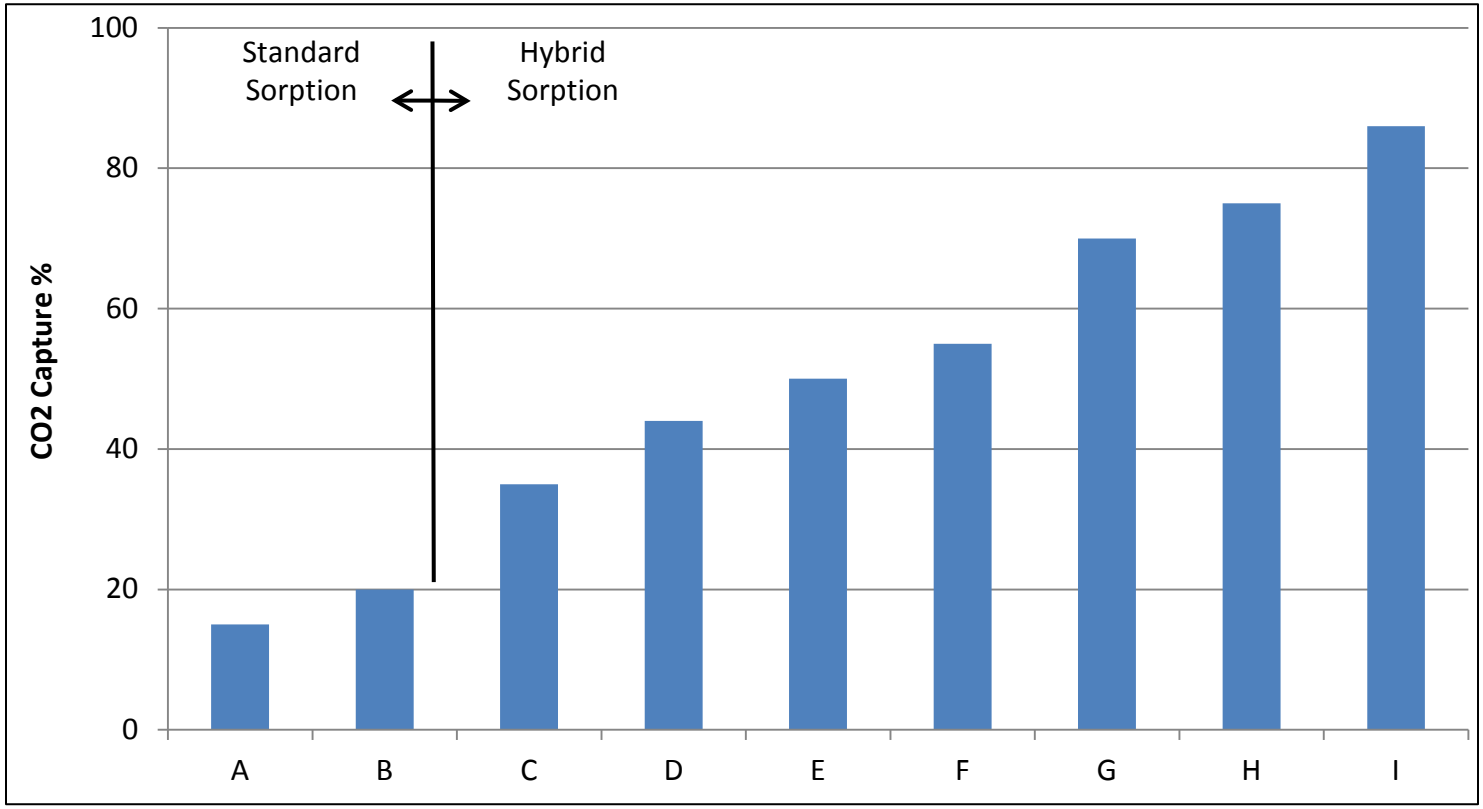
Parametric Testing – Adsorber Summary



A	Zero Additive	D	Sorbent Recirculation	G	Increased Gas Res. Time
B	Sorbent Recirculation	E	Increased Additive Loading	H	Decreased Flue Gas CO_2
C	Sorbent with Additive	F	Increased Fresh Feed	I	Increased Gas Res. Time

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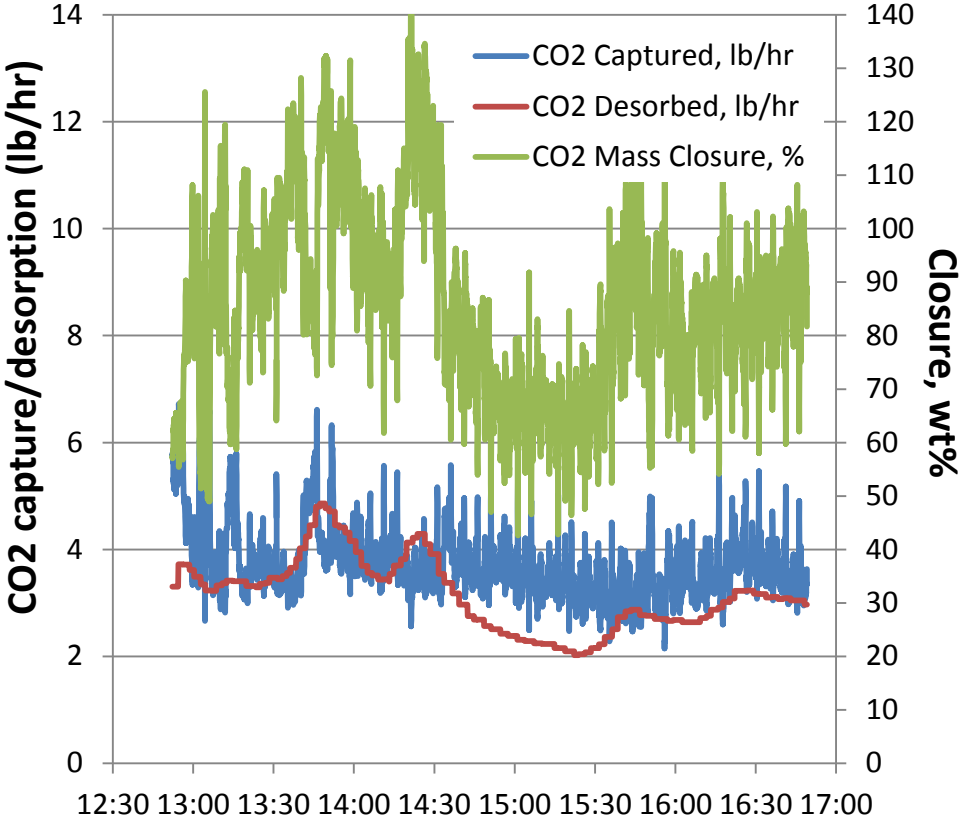
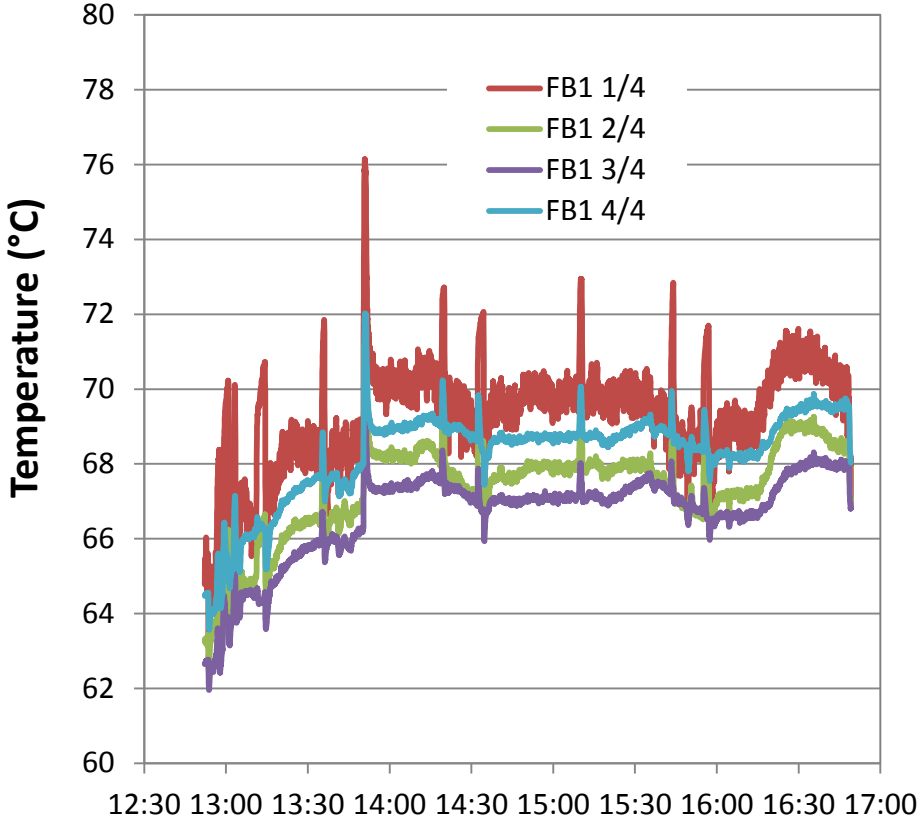
Parametric Testing - Integrated System

Single bed adsorber operation without recirculation

Flue gas supplied by propane-fired furnace





- Achieved reasonable CO_2 mass closures over an extended period
- Very good control of the exothermic heat of reaction in the adsorber

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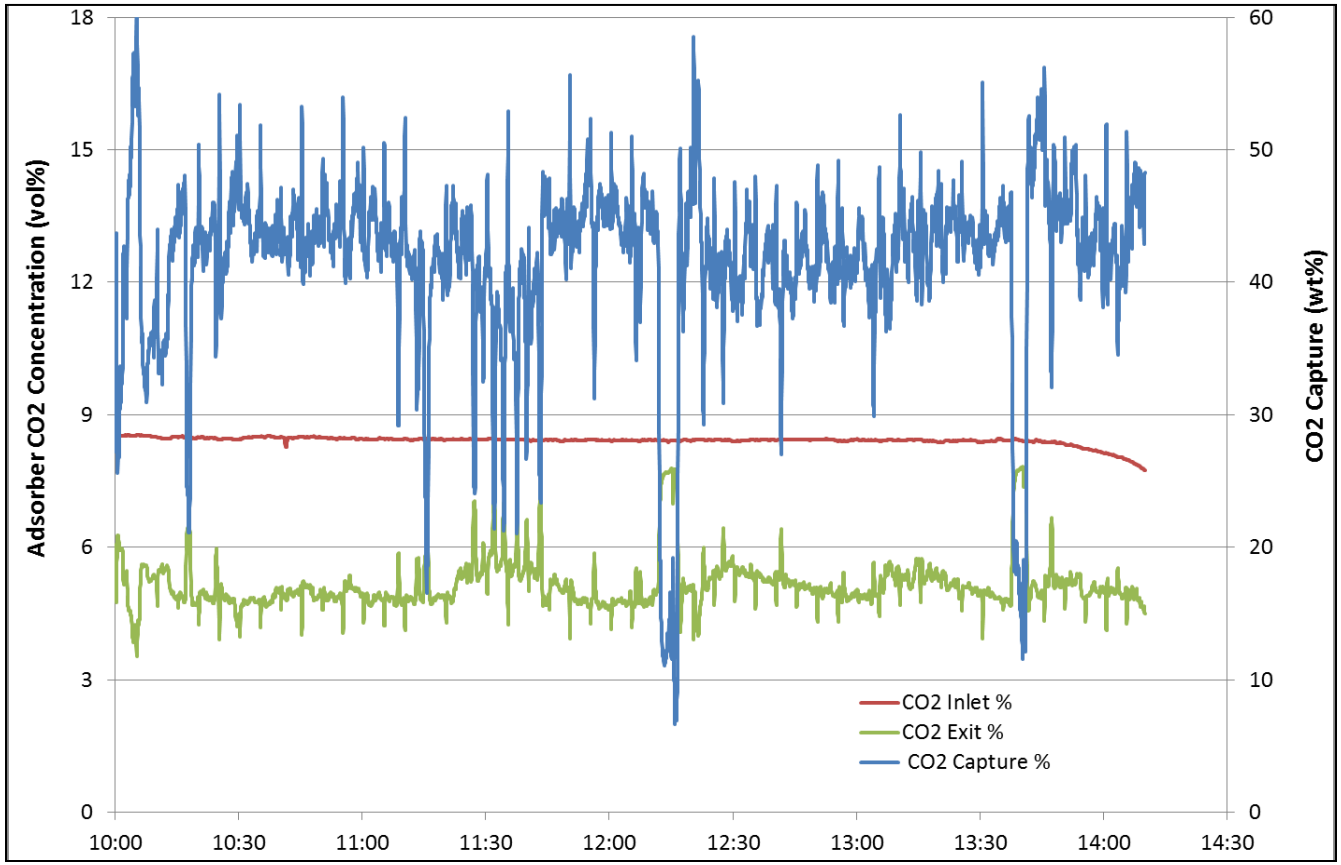
Parametric Testing - Integrated System

Single bed adsorber operation with recirculation
Flue gas supplied by propane-fired furnace



- **Sustainable capture of 40-50% @ 8% CO_2 in flue gas**
- **Working capacity of 1-2.5 wt% during this test: Data suggests additional gas/sorbent contacting time is required**

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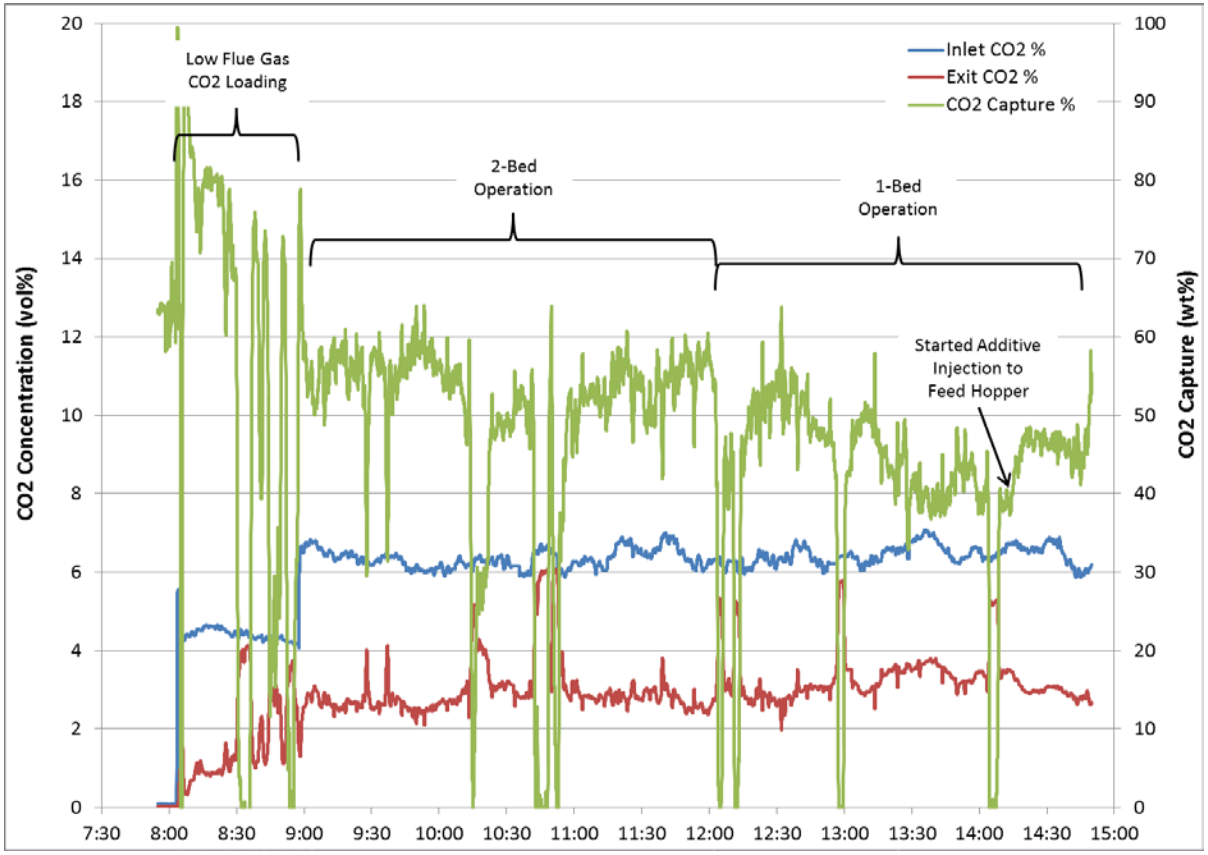
Continuous Integrated Testing

-Adsorber with one and two bed operation



- Relatively small reduction in capture from two-bed to one-bed operation indicates that ***gas/sorbent contact time***, rather than gas residence time is too low
- Online additive injection in large diameter hopper is much simpler – measurable increase in capture- additive injection successful

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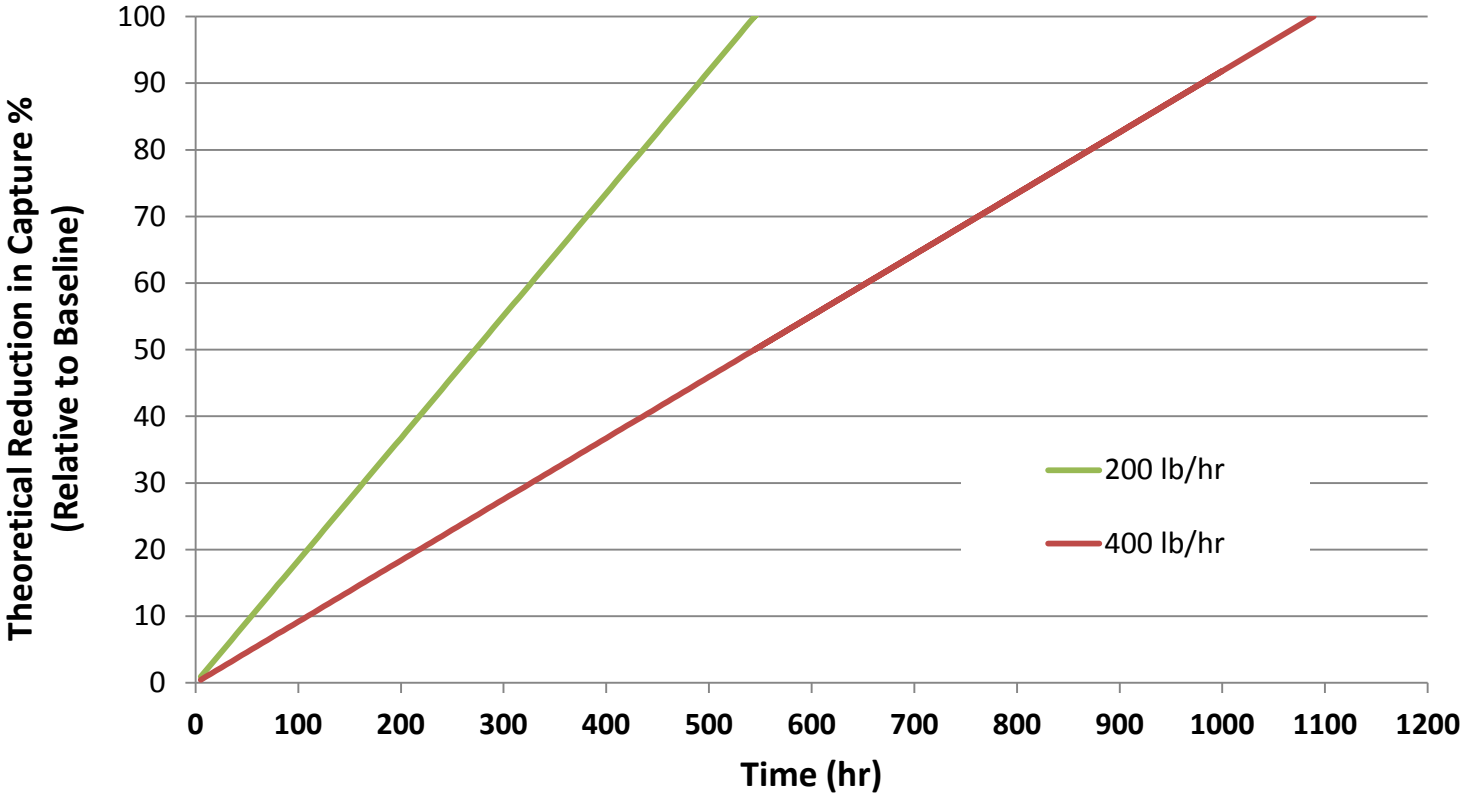
Continuous Integrated Testing

High SO_2 Test - Confirmed ~100% reaction of SO_2 with CACHYS™ sorbent



- In the bench-scale test system, reaction of SO_2 with CACHYS™ sorbent would have a "detectable" effect on capture performance only after about 50-100 hours of exposure to 200 ppm SO_2

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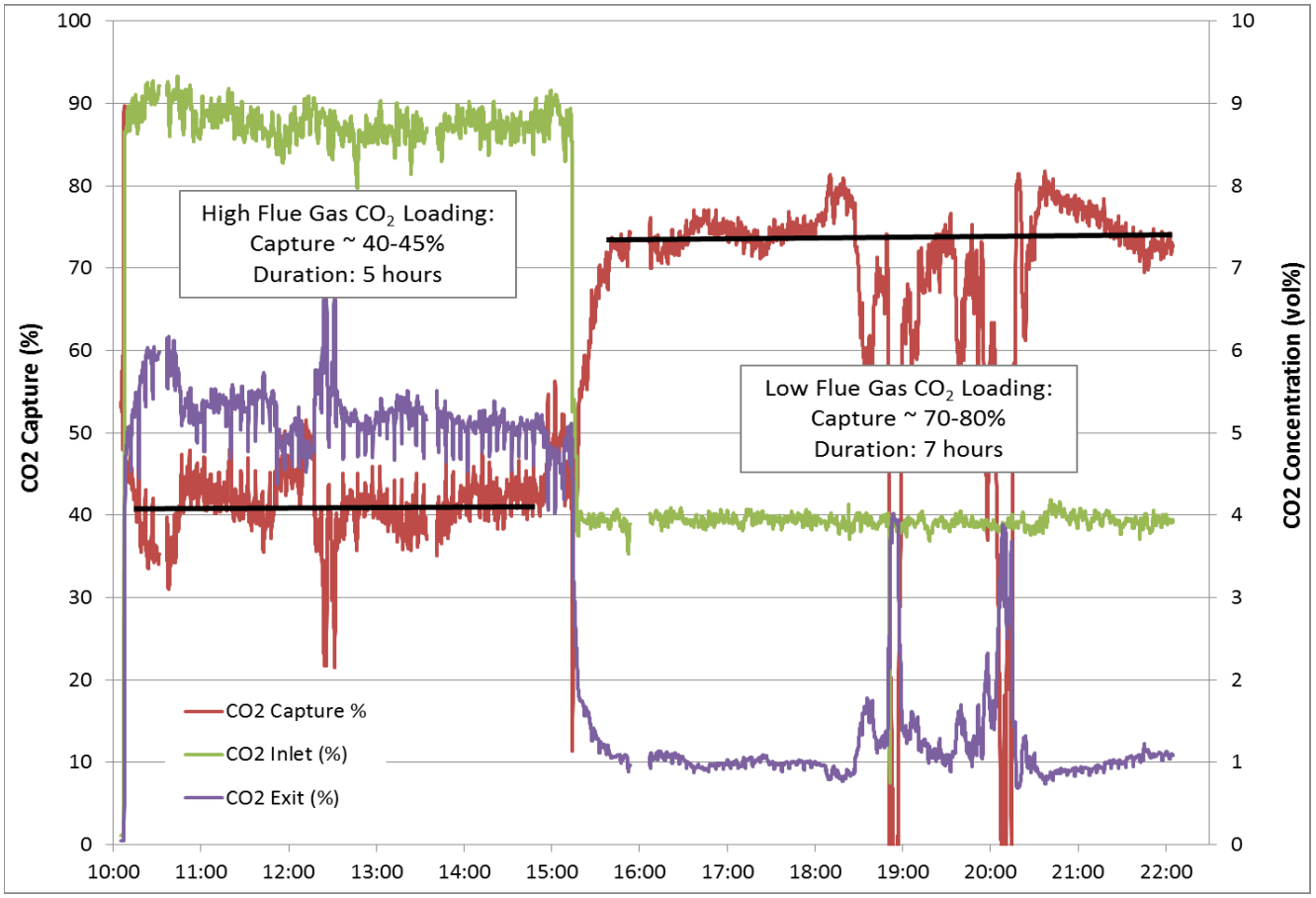
Continuous Integrated Testing

Achieved 12 hours of sustainable CO_2 capture



- Longest duration achieved during test program – ***minimal operational issues***

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Summary of Bench-scale Testing

- Parametric testing confirmed the benefits of hybrid sorption
  - Reaction kinetics were improved over "dry" sorption (2-3X)
  - Direct steam had a large impact on the desorption rate
- Maximum CO_2 capture was achieved using a 2-bed configuration
  - 85% capture at 4% flue gas CO_2 loading
  - 65-70% capture at 7% flue gas CO_2 loading
- Sustainable (~7 hours) capture of 70-80% at 4% flue gas CO_2 loading
- Sustainable (~5 hours) capture of 40-45% at 8% flue gas CO_2 loading

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Summary of Bench-scale Testing

- Higher recirculation rates will be required to attain 90% capture at 7wt% working capacity
- Isolation/segregation of sorbent regeneration and sorbent cooling is required to improve working capacity by preventing CO_2 re-adsorption in the cooler
- Process operation reliability was affected predominantly by sorbent flow stoppage in regenerator
- Substrate physical characteristics are a critical aspect of an effective sorbent
  - A second sorbent type, HCK-31, was evaluated in the bench-scale system, but poor flowability resulted in severe plugging
  - Function of distribution of the active component

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Task 8 – Final Process Assessment

- Subtask 8.1 – Process Environmental Health and Safety Assessment
- Subtask 8.2 – Final Technical and Economic Feasibility Study

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Subtask 8.1 – Process Environmental Health and Safety Assessment

- Conducted by Barr Engineering with support from UND & Envergex
- There is minimal environmental, health and safety risk with the CACHYS™ technology due to the use of relatively benign materials with essentially zero volatility
- Main sources of emissions/waste are particulate filters and sorbent waste stream
  - 4.2 tons/hour of sorbent waste due to sulfation/attrition: Equates to about 2000 adsorption/desorption cycles or about 0.23 years of useful life.
  - < 200 tons/year of particulate emissions from process fabric filters
- Sorbent waste stream due to sulfation can be reduced through installation of an SO_2 pre-scrubber (as assumed for Case 12)
- Sorbent waste stream due to attrition could also be reduced through an
  - Equipment design which accommodates finer particle sizes, thus increasing sorbent lifetime

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Subtask 8.2 – Final Technical and Economic Feasibility Study

- Capital Cost
- Operating Cost

- **<u>NOTE:</u>**
  - **This document considers data for a desorption energy of 80 kJ/mol CO_2, as a conservative value**
  - **A second document, which uses data for 40 kJ/mol CO_2, is also available, and is considered the expected performance**

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Capital Cost

Category	Cost (million $ - 2014)	$/kW	Cost (million $ - 2007)	$/kW
Bare Erected Cost	$294.5	$530	263.3	475
EPC Cost	126.4	230	113.0	205
Process Contingency	120.9	220	108.1	196
Project Contingency	157.5	286	140.8	255
Total CO_2 Capture Plant Cost	$696.3	$1,266	625.1	$1,113

- Capital cost was calculated only for the CO_2 capture section of plant and does not include the increase in size of the main power plant

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Operating Cost

Category	Cost per year (million 2014 USD)	Cost per year (million 2007 USD)
Personnel	3.00	2.50
Maintenance Materials	1.25	1.15
Sorbent*	46.9	41.9
Sorbent Recovery	0	0
Total	51.2	45.6

- Operating cost for CO_2 capture section of plant only
- Increased operating cost of main section of power plant - increased fuel firing for same net MW_e output not included
- Assumes 4.2 tons/hr of sorbent makeup which is due to sorbent attrition with ~50% sulfated sorbent (45 ppmv SO_2 inlet → 2.1 tons/hr)
- Sorbent losses due to sulfation can be lowered significantly (e.g. 5 X) by using pre-scrubber

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Levelized Cost of Electricity

	Base Case FOA Appendix 3	Case 11 DOE Report	Case 12 FOA Appendix 3	CACHYS™ FOA Appendix 3	% Increase Over Base Case FOA Appendix 3
Electricity (mills/kWh)	64.0	74.7	132.3	119.4	86.6
Steam ($/1,000 lb)	5.83	NA	12.15	9.10	56.1

Cost of electric power (mills/kWh) = 0.3073 x (total power loss in MWe) + 64

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Cost of Carbon Dioxide Capture

	CACHYS - Cost Per Year (2014$)	CACHYS – Cost per Year (2007$)	Case 12 – Cost Per Year ($)
Total O&M (million $)	51.15	45.6	17.3
Capital Charge (million $)	121.85	108.9	155.92
Total Cost (million $)	173.0	154.5	173.2
	Tons Per Year		
CO_2 Captured	4,058,070	4,058,070	4,501,692
	Cost Per Ton ($)		
Cost of CO_2 Capture	42.63	38.06	38.48

- Cost of capture includes only CO_2 section of plant capital and operating costs *for* ***both*** CACHYS and Case 12
- Projected costs of capture will be about $20-25/ton CO_2 higher with inclusion of increase in capital and operating costs for larger-sized main plant

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Summary of Sensitivity Cases

Sensitivity Case	Parameter Adjusted	Cost of CO_2 Capture—$/ton (2007$)
Base Case	None	38.06
Value Engineering	5% capital cost reduction	36.77
Spent Sorbent Recovery	Sorbent waste flow reduced 50%	33.65
Process and Project Contingency	Total contingency reduced to 43%	32.21

- All values are calculated for each case being compared to base case
- Contingency assumptions for CACHYS as an early development stage technology has a large impact on economics

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Comparison of Initial and Final TEA with Case 12

Parameter	CACHYS™ Initial TEA	CACHYS™ Final TEA	Econoamine DOE Case 12
Net Heat Duty (MMBtu/hr)	547.6	903.0	2,335
Auxiliary Power Requirements (kW)	55,000	63,676	65,490
Net Plant Efficiency	34.6	30.56	28.4
Total Plant Cost (million $)	672.8	625.1 (2007$)	890.9
Total Plant Cost ($/kW)	1,004	1,113	1,620
Total O&M Cost (million $/year)	33.9	45.6 (2007$)	17.3
Electricity Cost (mils/kWh)	89.5	119.4	132.28
Cost of CO_2 Capture	36.2	38.06 (2007$)	38.5

- Main negative impact on LCOE in Final TEA due to high heat of regeneration assumption
- Plant, O&M cost, and cost of capture is for CO_2 plant section only

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Milestones for Budget Period 3

ID	Task	Title/Description	Planned Completion Date	Actual Completion Date	Verification Method
o	7	Complete parametric testing of the bench-scale CACHYS™ process components	4/2/2014	9/15/2014	Results reported in the quarterly report
p	7	Complete continuous testing of the integrated bench-scale CACHYS™ process for one month	9/30/2014	12/5/2014	Results reported in the quarterly report
q	8	Complete Preliminary EH&S Assessment	12/31/2014	12/31/2014	Topical Report file
r	8	Complete Final Technical and Economic Feasibility Study	12/31/2014	12/31/2014	Topical Report file
F	1	Draft Final report	1/31/2015	1/31/2015	Draft Final Report file

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Decision Points and Success Criteria for Budget Period 3

Decision Point	Basis for Decision/Success Criteria
End of Project	Successful completion of all work proposed.
	Adsorber -- Achieve capture levels in sorbent of 7g CO_2/100g sorbent-***Bench scale testing had working capacity of up to 2.5 wt%***
	Adsorber – Achieve 90% CO_2 Capture - ***Maximum capture of 85% achieved at 4% CO_2 in flue gas – Maximum capture of 70% at 7% CO_2 in flue gas – Sustainable capture (7 hours) of 70-80% at 4% CO_2 in flue gas – Sustainable capture (5 hours) of 40-45% capture @ 8% CO_2 in undiluted flue gas***
	Regenerator – Minimize heat of regeneration <80 kJ/mole – ***Unable to measure due to inaccurate steam/condensate flow meters, but strong evidence existed that verified underlying mechanism for low heat of regeneration***
	Regenerator -- Maximize Desorption of CO_2 ~ 80% desorption – ***Bench scale testing showed sustainable active component utilization of ~20% after desorption (i.e. 80% desorption)***
	Integrated System- run on a continuous basis for 4 weeks (1-week increments) – ***24 hour operations were not possible due to equipment limitations: A 15 hour test (12 hours of CO_2 capture) was completed with minimal operational difficulty***
	Submission of a Topical Report - Final Technical and Economic Feasibility Study – **Submitted**
	Submission of a Topical Report – Preliminary EH&S Assessment – **Submitted**
	Submission of a Final Report – **Submitted**

Technology Shortcomings/Challenges

- Sorbent flowability in regenerator system – significant challenges throughout testing
- Bench-scale system was unable to provide reliable operation with recirculation rates that would be required to achieve 90% capture
- Sorbent attrition is clearly a potential issue which must be addressed, especially considering the high cost of sorbent replacement

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Recommendations for Future R&D to overcome shortcomings/challenges

- Sorbent Flowability
  - Installation of active cleaning mechanism in critical areas
- Sorbent/Gas Contacting Time
  - Modification of the sorbent recirculation system to provide higher rates
- Sorbent Attrition
  - Investigation of higher strength substrates

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Project Highlights – Key Accomplishments

- Demonstrated heat of regeneration 30-75 kJ/mol and process conditions necessary to achieve low energetics
- High sorbent capacity of 7-10 wt% in fixed bed tests – Expected to be achievable with higher recirculation rates in the bench-scale system
- Excellent chemical stability – 100 cycle test showed no detectable loss in performance.
- Sorbent (HCK-4) reactivity was maintained over the entire bench-scale test program
- Constructed bench-scale system and performed ~ 200 hours of testing
  - Testing culminated with demonstration of reliable operability over a 15-hour period with sustainable capture rates
- Demonstrated the benefits of hybrid sorption at the bench-scale: faster kinetics, temperature control in adsorber, low energy of desorption
- Capture of up to 85% achieved at the bench-scale at 4% CO_2 in flue gas
- Capture of up to 70% achieved at the bench-scale at 7% CO_2 in flue gas

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Future Plans

- E-CACHYS™
  - Developed as part of a DOE SBIR/STTR Phase I grant
  - Goal to increase sorbent capacity by 2x CACHYS™ sorbents
  - Capacity targets were achieved while maintaining other benefits of hybrid sorption
  - Phase II application was recently submitted to DOE and has been awarded

- Phase II SBIR/STTR
  - Develop improved sorbent manufacturing methodologies
  - Modification of the existing bench-scale facility to accommodate improved sorbent
  - Develop an improved hybrid sorption technology that will further reduce the cost of CO_2 capture

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