Advancing Cleaner Energy

Evaluation of Solid Sorbents as a Retrofit Technology for CO_2 Capture

Cooperative Agreement
Award No. DEFE0004343

March 30, 2016, Rev June 15, 2016

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Project Review

- Overview of Project and Technology
- Project Execution
- Review of Project Objectives and Achievement
- Conclusions

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Project Objective and Goals

- The overall objective was to validate solid sorbent-based post combustion CO_2 capture through pilot testing

- Project Goals:
  - Achieve 90% CO_2 Capture
  - Reduce costs of carbon capture
    Progress towards <35% LCOE Goal
  - Generate a high purity CO_2 stream
  - Successfully scale sorbents

Cooperative Agreement (Award No. DEFE0004343)
American Recovery and Reinvestment Act of 2009
Administered by DOE-NETL: Project Manager Bruce Lani

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Project Participants

- **DOE – NETL**
  - Project Sponsor
- **ADA-ES, Inc.**
  - Project Management
  - Developed Process Concept
  - Sorbent Evaluation & Selection
  - Process Validation Testing
  - Techno-Economic Assessment
  - Primary Cost Share
- **Technip Stone and Webster Process Technology**
  - Detailed Engineering Services
- **Stantec Consulting, Ltd.**
  - Cost Analysis, Plant Integration
- **McAbee Construction**
  - Pilot Fab and Installation
- **EPRI**
  - Technical Advisor
  - Cost Share
  - Independent Performance Evaluation and Techno-Economic Assessment
- **Southern Company**
  - Host Site, Cost Share
- **Luminant**
  - Cost Share
- **Southern Research Institute**
  - Operations personnel
- **Element 1 Engineering**
  - Operations Personnel
- **URS**
  - Operations Personnel
- **National Carbon Capture Center**
  - CEMS

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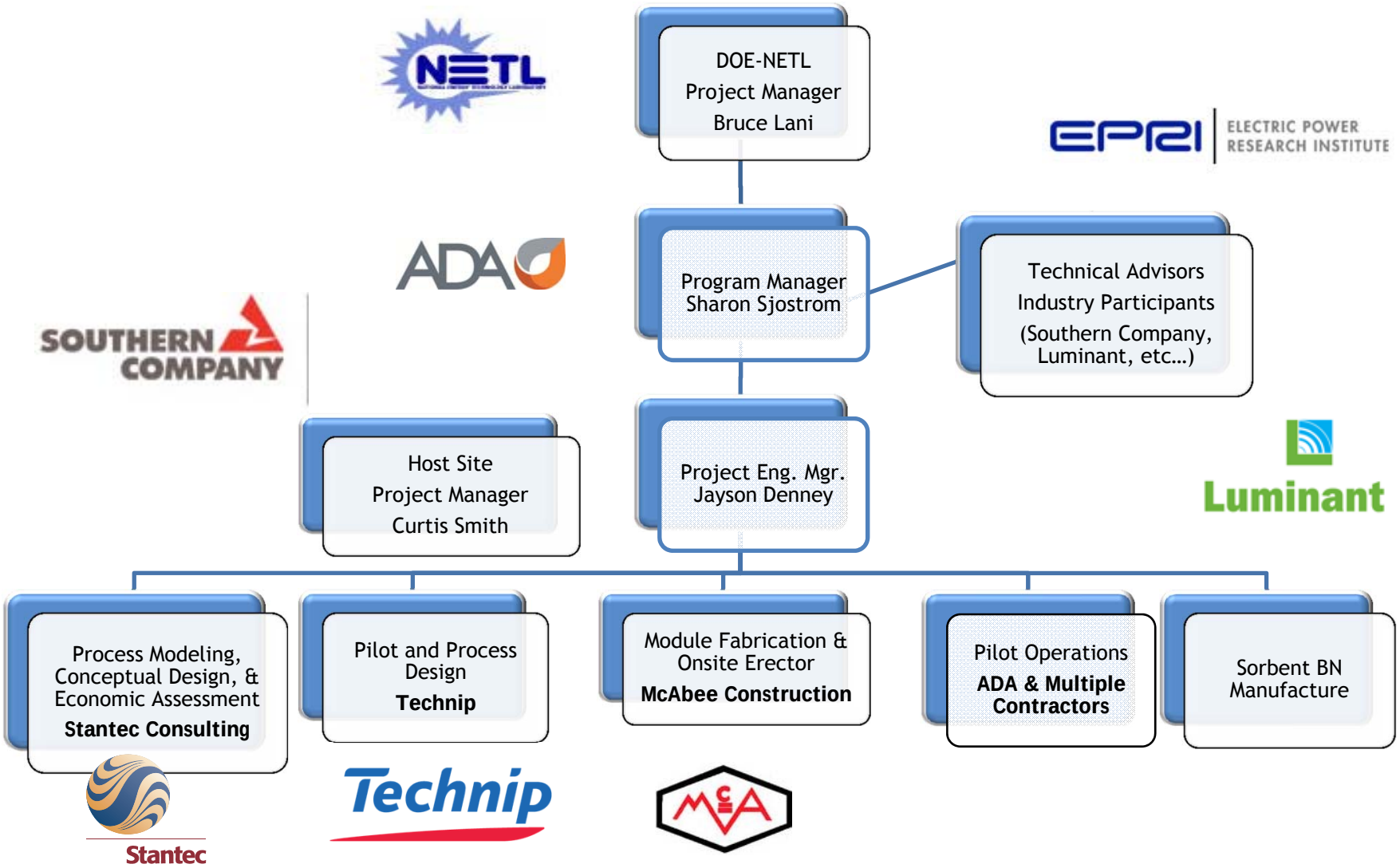
Project Team



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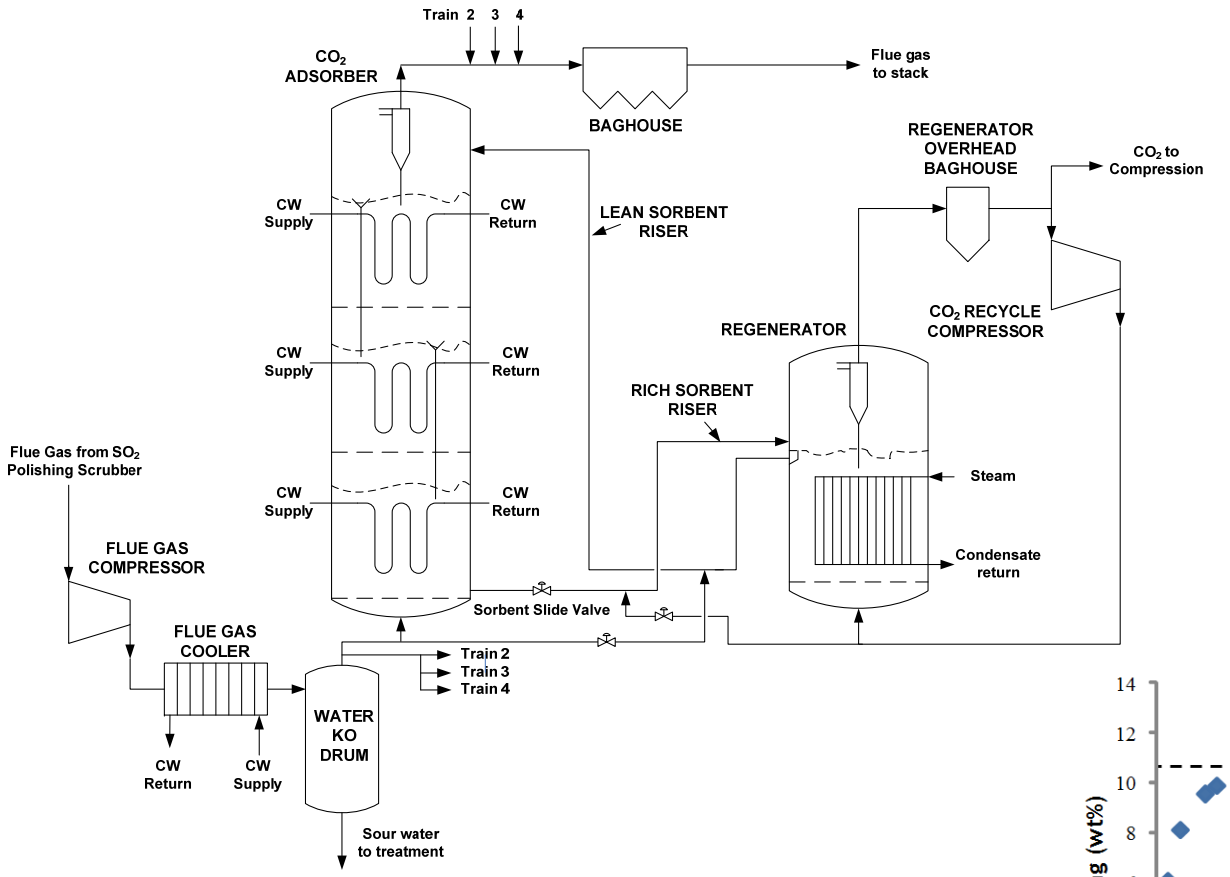
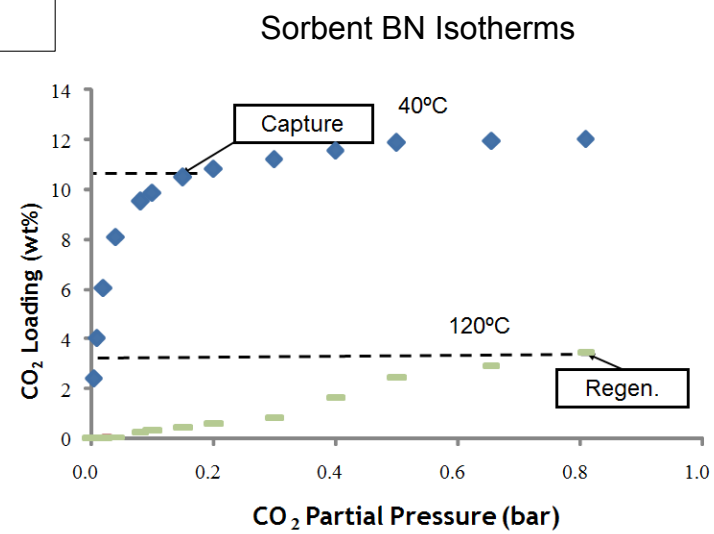
Overview of ADAsorb Process





TSA Process (40°C ←→ 120°C)
Sorbent: Amine-based ion-exchange polymer

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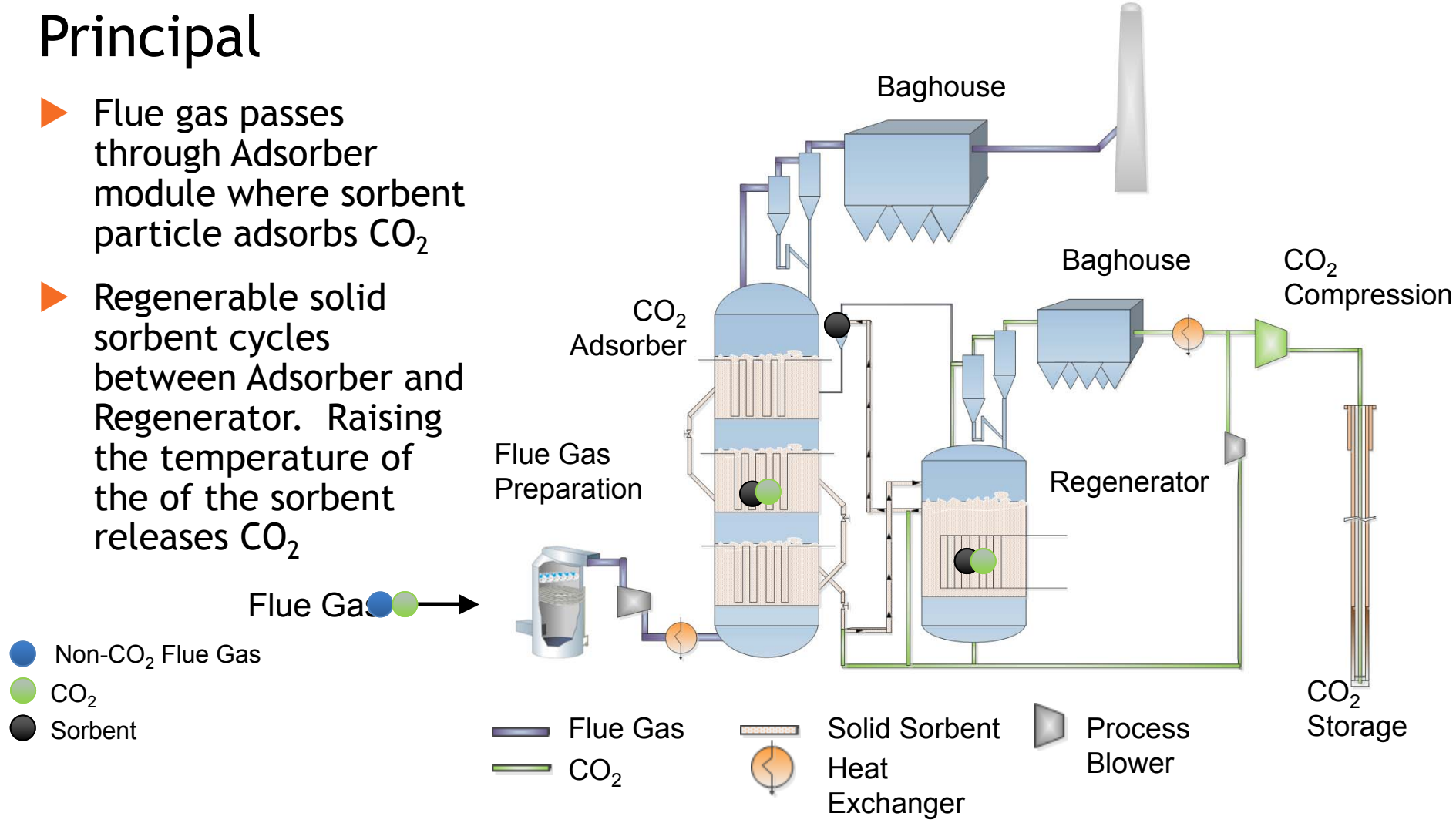
Process Conceptual Design

Principal

- Flue gas passes through Adsorber module where sorbent particle adsorbs CO_2
- Regenerable solid sorbent cycles between Adsorber and Regenerator. Raising the temperature of the of the sorbent releases CO_2



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ADAsorb™ CO_2 Capture Process

Advantages

- Heat transfer
  - Isothermal operation
- Mass transfer favorable
- Proven at the industrial scale
- Approaches counter-current gas/solids contacting
- Process Flexibility
  - Can be applied to cycling plant "load following"

Challenges

- Pressure drop
- Solids circulation
- Sorbent attrition
- Water adsorption
- Heat recovery

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Project Tasks and Timeline Overview

Period 1:
21 months

- Sorbent Selection
- 500 MW Conceptual Design
- Design 1MW Pilot for Validation Testing

Scale down to 1 MW

Manufacture and Construction

- Detailed Engineering
- Manufacture Sorbents
- Fabricate and Install 1 MW pilot
- Commission Pilot

Period 2:
27 months

Period 3:
12 months

- Pilot Testing
- Refine 500 MW Design
- Conduct Techno-economic analysis

Demonstration Phase

Oct '10 – June '12

July '12 – Sep '14

Oct '14 – Sept '15

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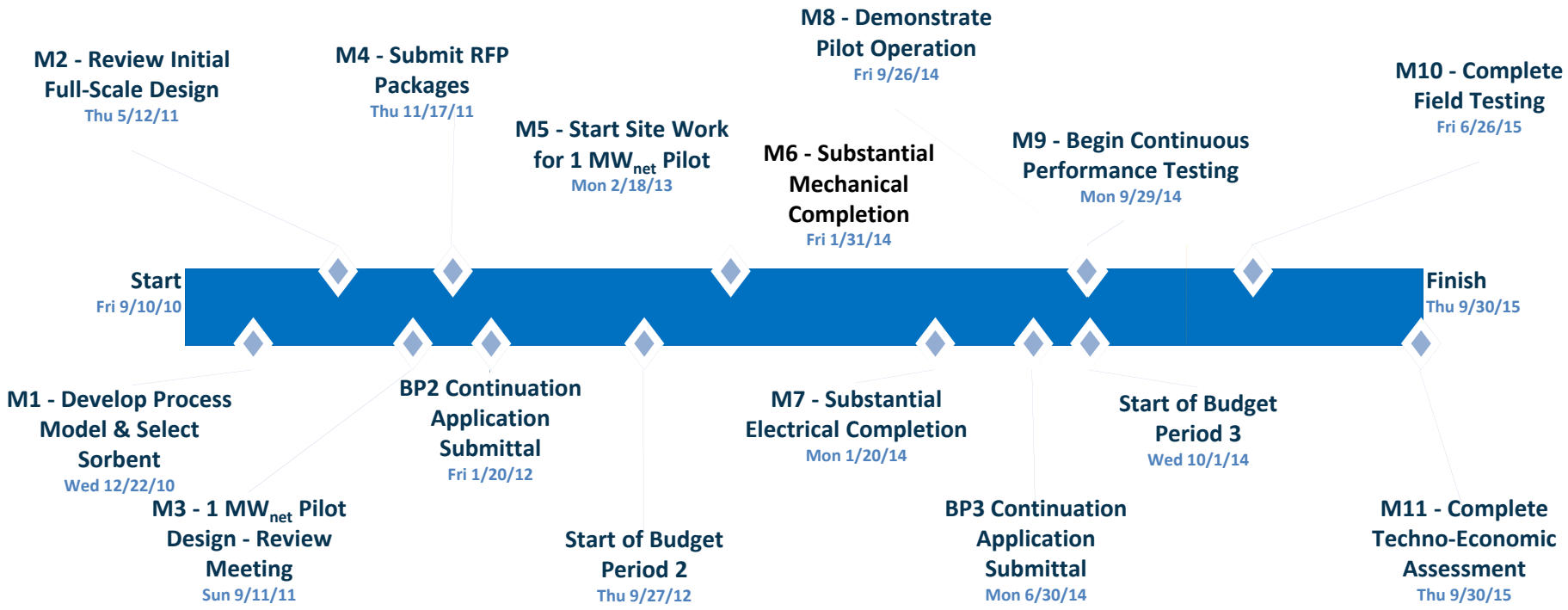
Project Schedule



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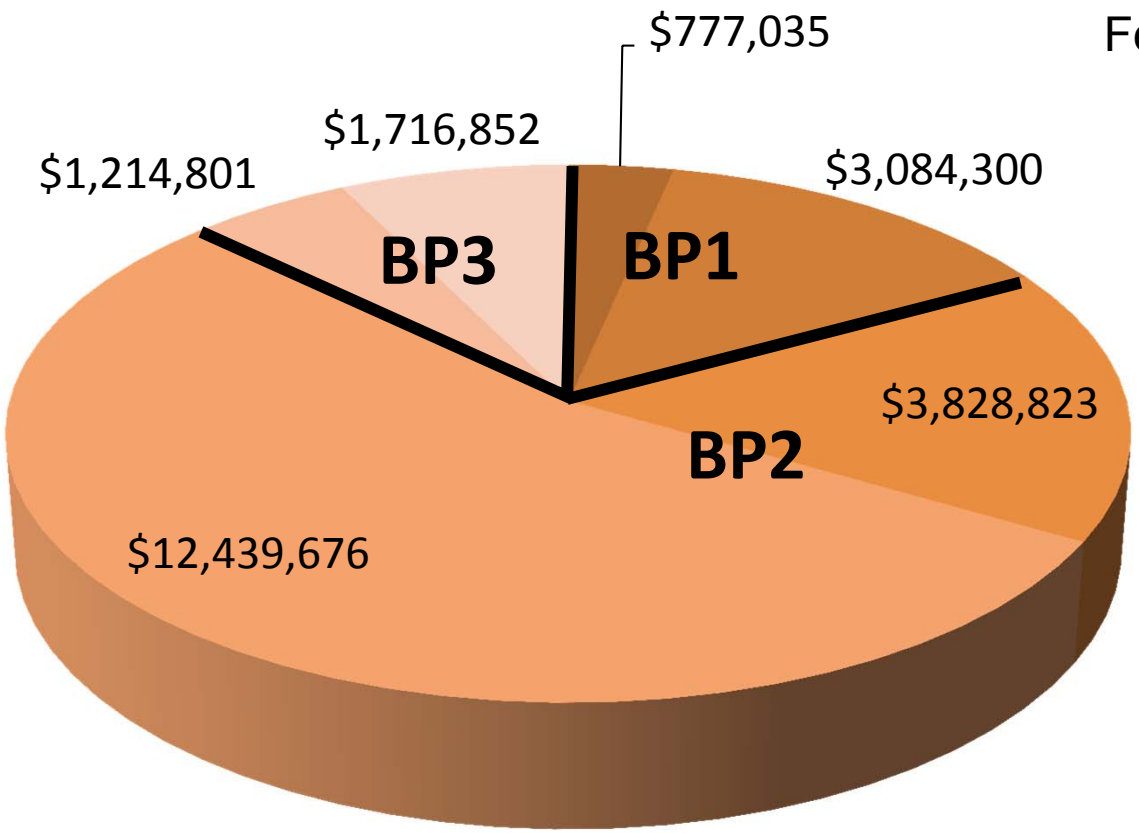
Project Budget

Project Total $23.0M
Cost Share $5.8M
Federal Share $17.2M



- BP1 Cost Share
- BP1 Federal Funds
- BP2 Cost Share
- BP2 Federal Funds
- BP3 Cost Share
- BP3 Federal Funds

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Project Review

- Overview of Project and Technology
- Pre-Construction
  - 500 MW Process Concept
  - Final Sorbent Selection and Characterization
  - 1 MW Pilot Design
- Construction (Budget Period 2)
- Testing and Performance Review (Budget Period 3)
- Review of Project Objectives and Achievement
- Conclusions

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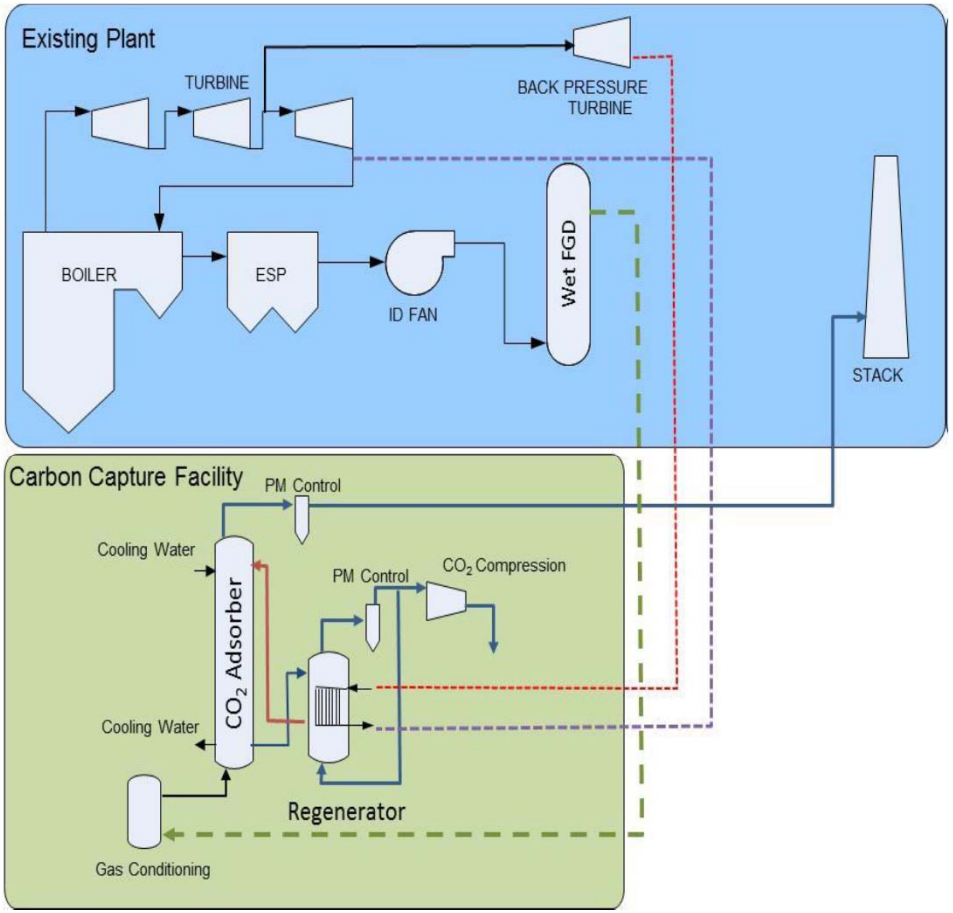
500MW Design Concept

- A 500MW$_{net}$ conceptual power plant incorporating CO_2 capture was designed considering:
  - Capital cost
  - Footprint
  - Pressure drop
  - Gas solids contacting
  - Operability (O&M)
  - Constructability



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500MW Design: Concept Development

Several reactor designs were considered

- **Fixed beds** – stationary systems with internal heat transfer
- **Entrained reactors** – sorbent simultaneously reacts and is conveyed using
- **Moving beds** – densely packed sorbent moves in the opposite direction as the gas
- **Trickle down reactor** – sorbent with significant mobility flows counter current to gas
- **Staged fluidized beds** – a series of fluidized beds in the bubbling regime

Selected for heat and mass transfer characteristics, and industry experience with large-scale commercial, fluidized-bed systems

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500MW Concept – Preliminary TEA

- TEA by Stantec Consulting
  - Solid Sorbent concept resulted in lower LCOE than MEA
  - Largest contributor – capital costs

		Case 10 Methodology – Solid-Sorbent CO_2 Capture Design	Case 10 - PC Subcritical w/ CO_2 Capture (MEA)
Gross Power Output	kWe	650,900	672,700
Total Parasitic Power	kWe	147,702	122,740
Net Power Output	kWe	549,960	549,960
BP Turbine	kWe	46,761	0
Coal Flow Rate	lbm/hr	540,263	614,994
Thermal Input	kWth	1,847,139	2,102,644
CO2 Captured Rate	lbm/hr	1,154,200	1,313,960
Regneration Energy Requirement	Btu/lbm CO_2	1130*	1,530
Raw Water Cons.	1000 gal/day	6,404	8,081
Capital Cost for CO2 Capture	$	215,761,624	302,505,839
LCOE	¢/kWh	14.36	14.77
Incremental Increase in LCOE compared to Case 9	%	**80**	**85**

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Sorbent Selection and Characterization

- Over 250 sorbents were screened
- Narrowed applicable types to supported amine and carbon based sorbents
- Working capacity in a temperature swing process led to the selection of supported amine sorbents for detailed characterization
- Extensive characterization of candidate sorbent
  - CO_2 working capacity
  - Cyclic stability
  - Reaction kinetics
  - Effect of Flue Gas Constituents including SO_2 and Moisture
  - Heat of Reaction
  - Resistance to attrition
  - Physical Characteristics: Particle Size Distribution and Density
  - Sorbent Cost
  - Sorbent fluidization and handling properties
  - Heat Transfer Coefficient

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Sorbent Selection and Characterization

- Supported Amines
  - Pros
    - Higher CO_2 delta loading
    - Demonstrated performance in high moisture environments
  - Concerns
    - Effect of flue gas constituents (SO_2 was specifically a concern, similar to aqueous amine CO_2 capture systems)
    - Some, although not all, supported amines were not cyclically stable
    - Sorbent cost

- Activated Carbons
  - Pros
    - Demonstrated performance in high moisture environments – a small decrease in CO_2 capacity was observed due to moisture, but for many materials the effect was not dramatic
    - Not chemically affected by the presence of SO_2 and other flue gas contaminants
    - Consistent cyclic stability
    - Acceptable sorbent cost
  - Concerns
    - CO_2 delta loading
    - Selectivity and CO_2 purity

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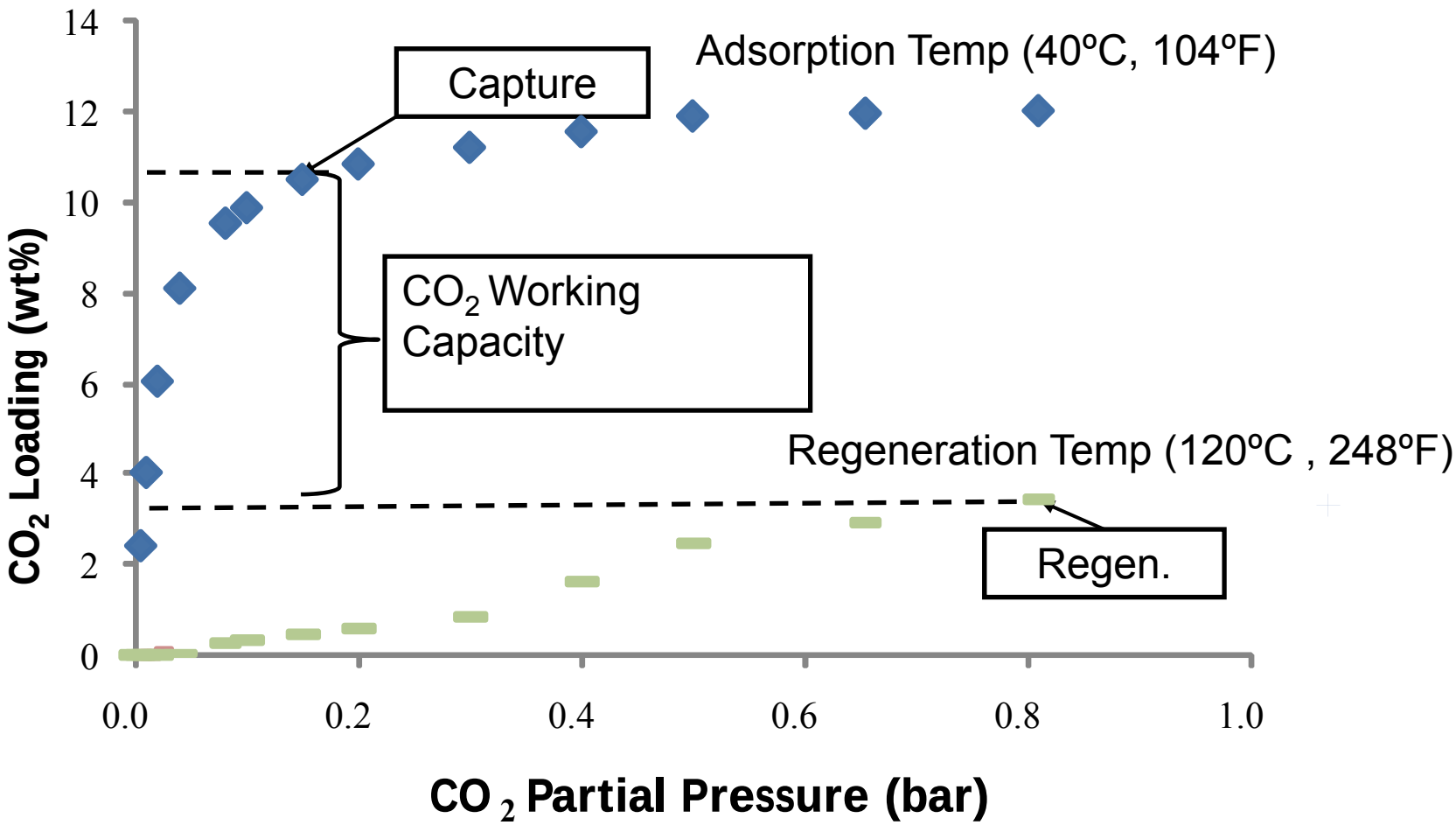
Sorbent Isotherms



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Properties of Sorbent BN

Sorbent BN Modified for Fluidized Bed		
Geldart Classification	A/B Transition	
Sauter Mean Particle Size	158	um
90% size Distribution	80	um
Particle Sphericity	90	unitless
Particle Density	0.71	g/cc
Particle Porosity	0.39	unitless
Bulk Density (Fluffed)	0.38	g/cc
Void Fraction (Fluffed)	0.46	Fraction
Bulk Density (Packed)	0.42	g/cc
Void Fraction (Packed)	0.41	Fraction
Minimum Fluidization Velocity	0.86	ft/s
Particle Aspect Ratio	0.74	unitless
Heat of reaction	82	kJ/mol CO_2

Photo of BN (ion-exchange resin) after larger spherical particles were dried and ground

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Cold-Flow Modeling

- Cold-flow model was designed and fabricated to characterize sorbents in system similar to 1 MW pilot
- Fluidization characterization included:
  - Fluid bed density
  - Bubble volume fraction
  - Entrainment rate
  - Heat transfer coefficient
  - Sorbent size distribution
  - Loop seal ratios
  - Fluidization regime (e.g., bubbling, slugging, fast fluidization, etc.) at different gas velocities
  - Gas velocity required to achieve the desired fluidization regime
  - Quality of fluidization determined both visually, and by means of high frequency ΔP_{bed} fluctuation measurements

Cold-flow model in ADA Process Lab

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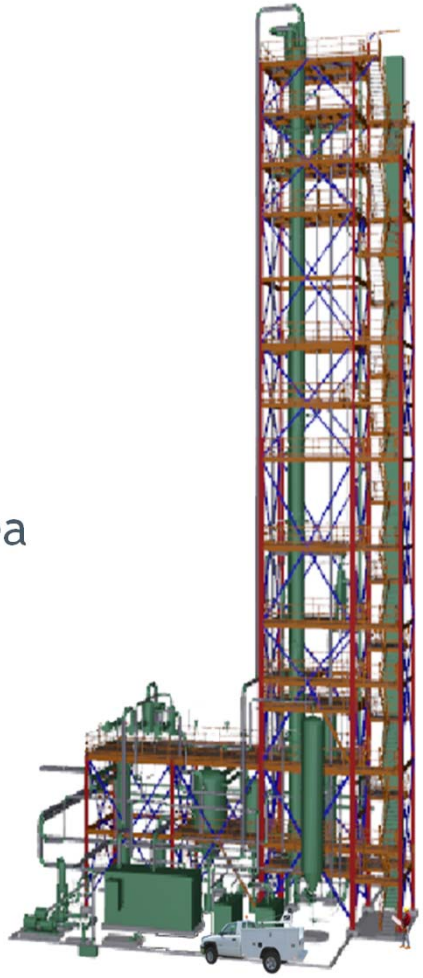
Preliminary Design of 1MW Pilot

- The pilot was designed based on:
  - Properties of the fully characterized sorbent
  - Steam properties at host site
  - Water properties at host site
  - Flue gas composition at host site
  - Geographic considerations of host site
- Considerations:
  - Minimize heated sorbent exposure to oxygen
  - Water temperature effect on cooling coil surface area
  - Minimizing exposure to SO_2
  - Adsorber inlet flue gas temperature
  - Modular construction
  - Minimizing cost



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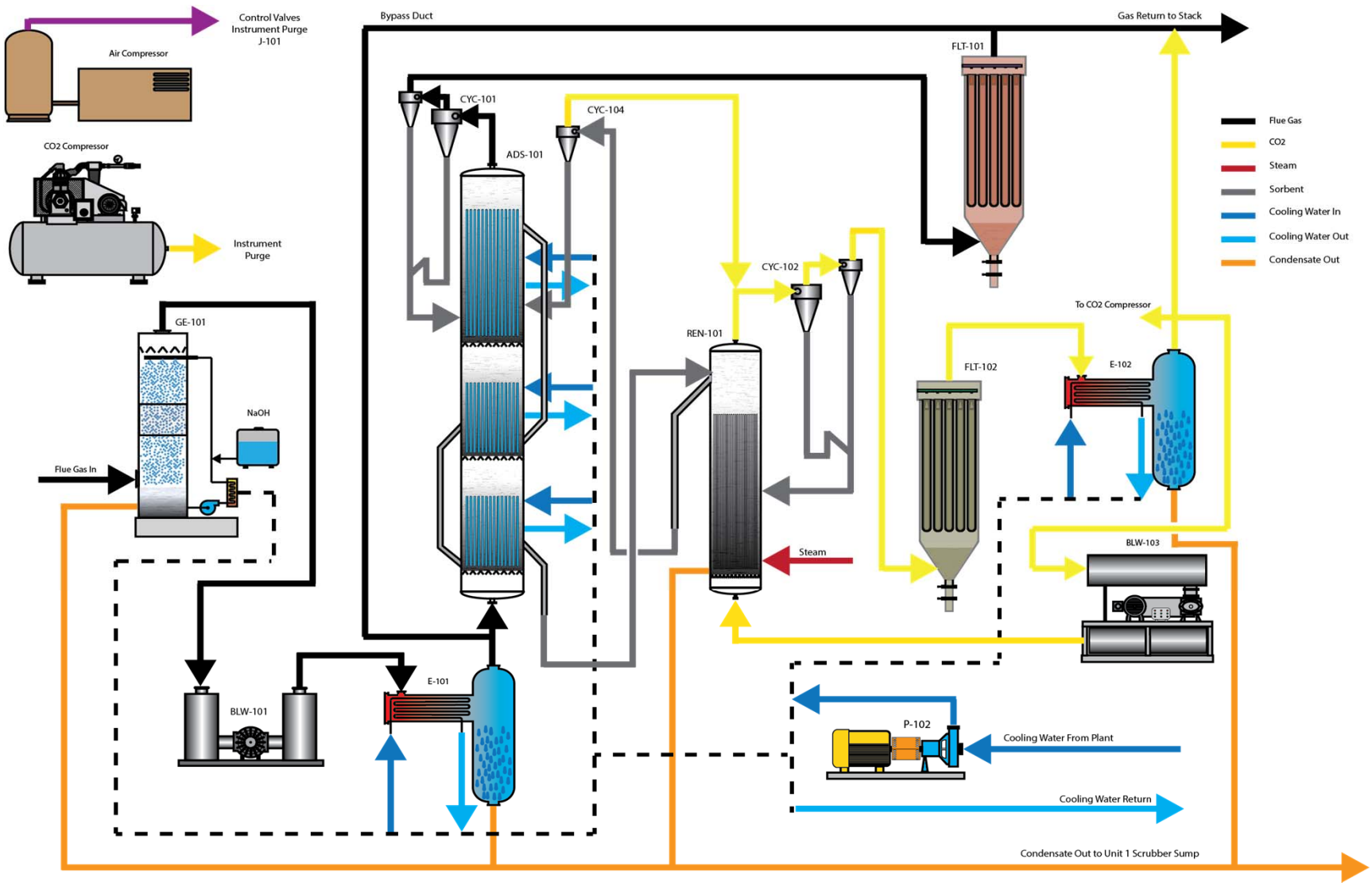
1MW Pilot Process



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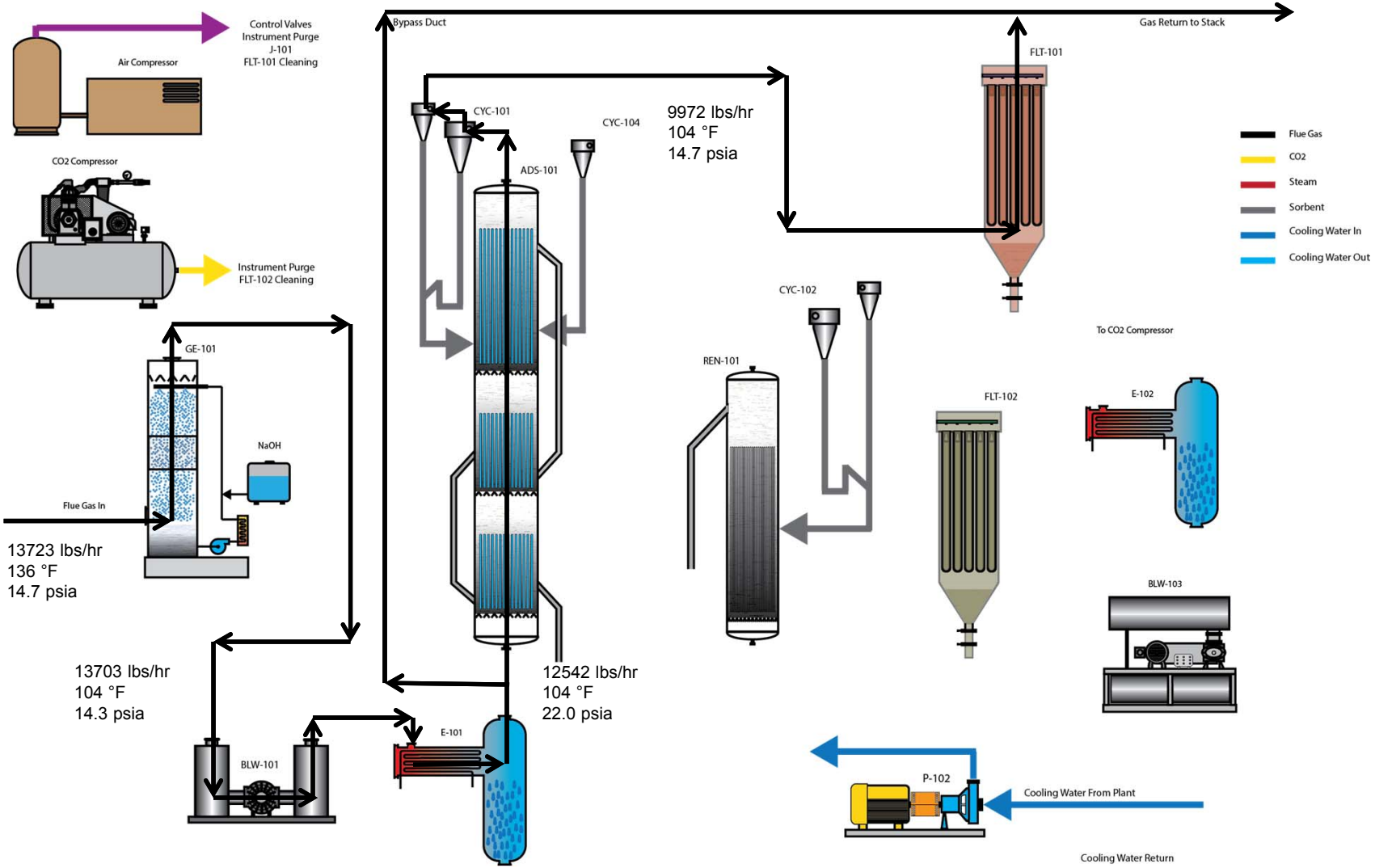
Flue Gas Flow



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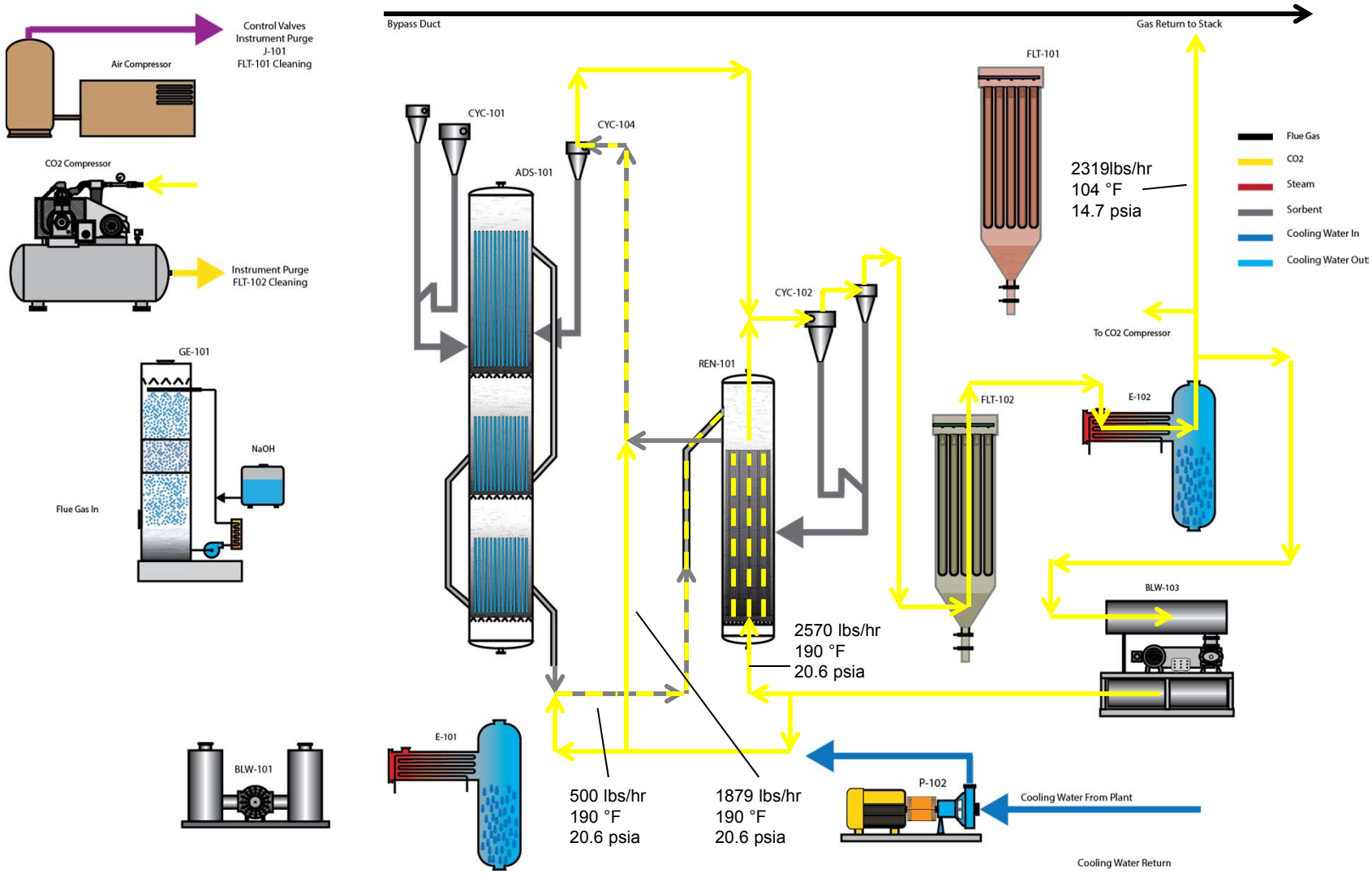
CO_2 Flow



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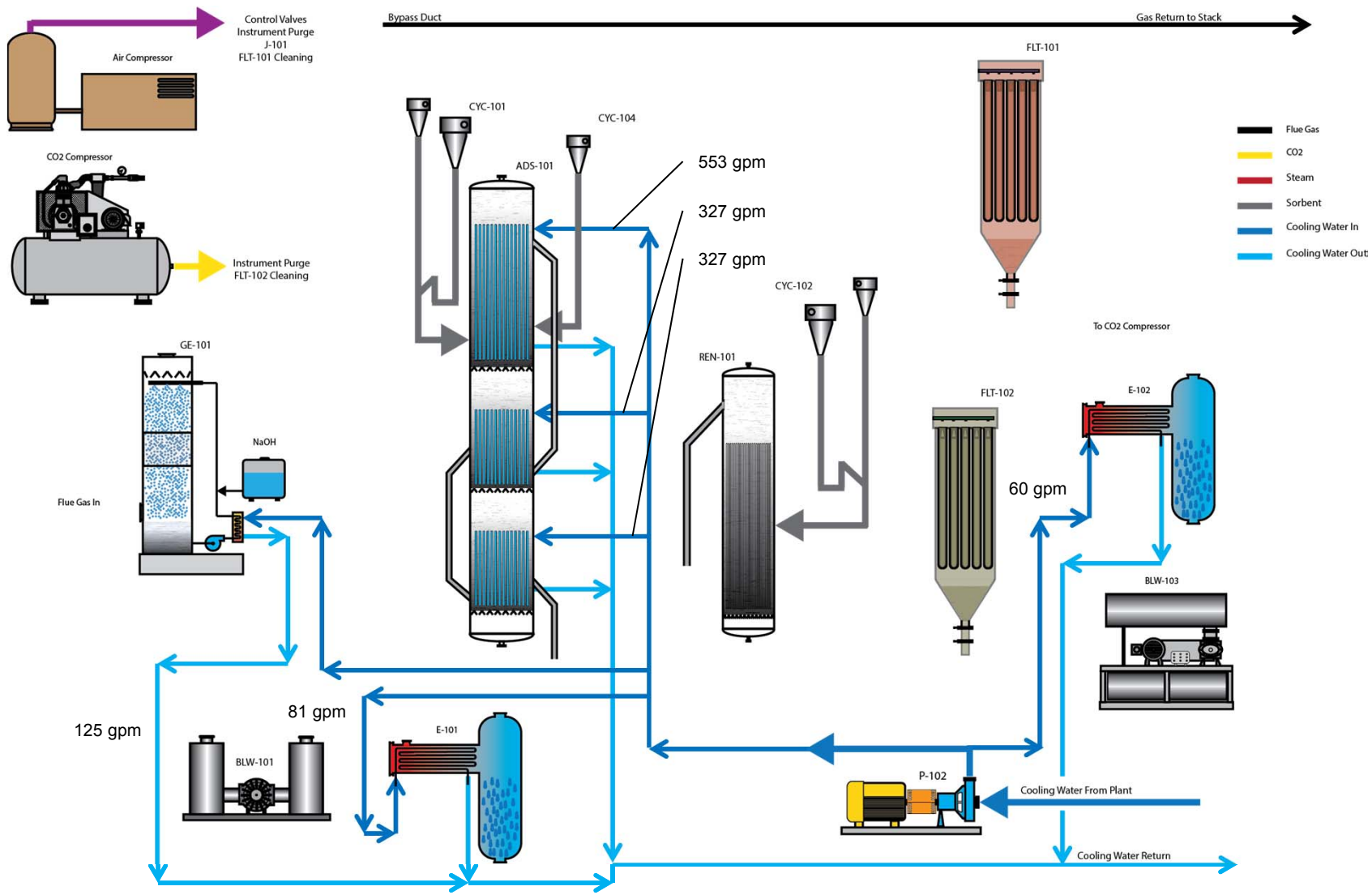
Cooling Water Flow



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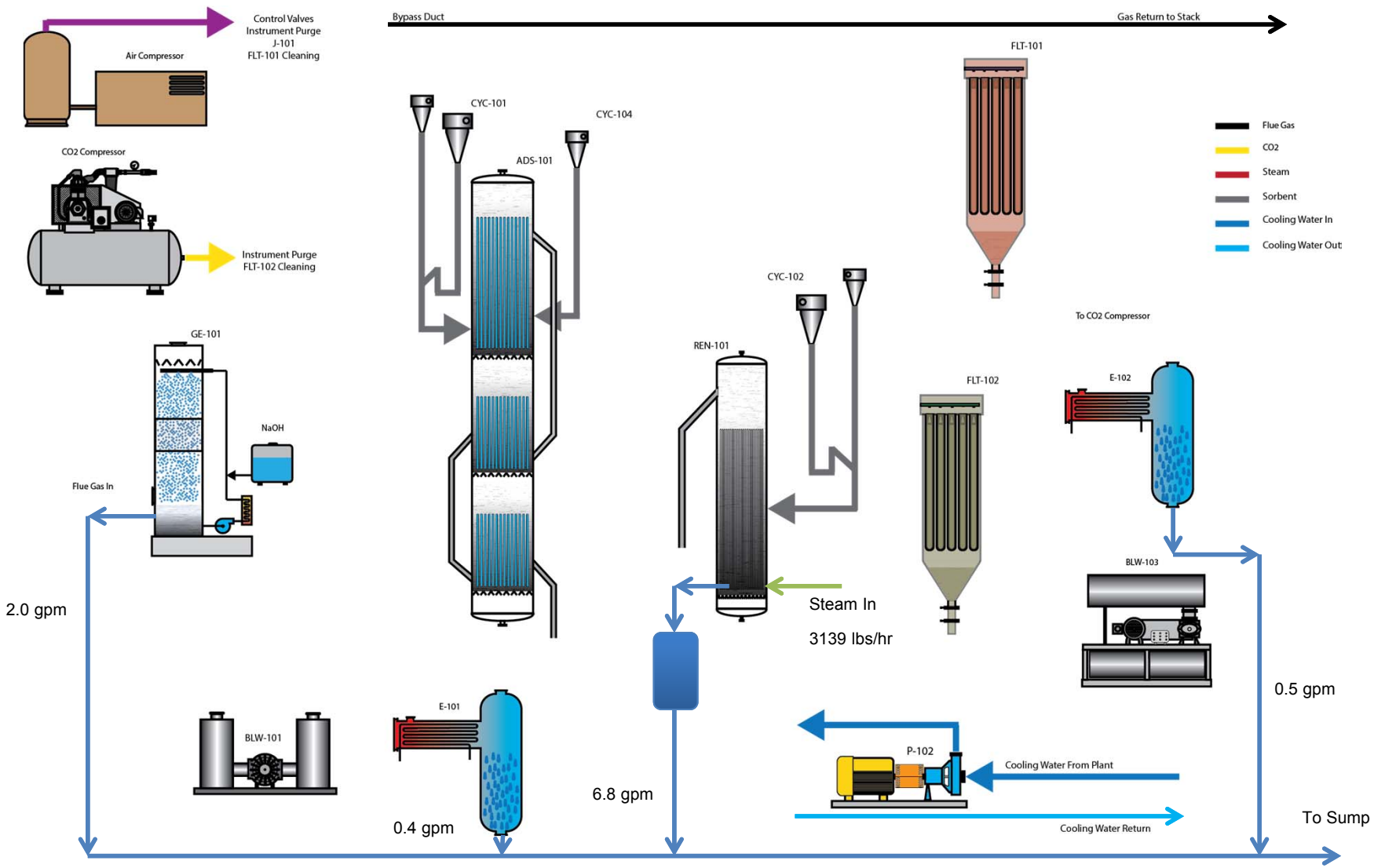
Steam and Waste Water Flow



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Project Review

- Overview of Project and Technology
- Pre-Construction (Budget Period 1)
- Final Design and Construction
  - Detailed Engineering – 1 MW Pilot
  - Manufacture Sorbent
  - Fabricate, Install and Commission Pilot
- Testing and Performance Review (Budget Period 3)
- Review of Project Objectives and Achievement
- Conclusions

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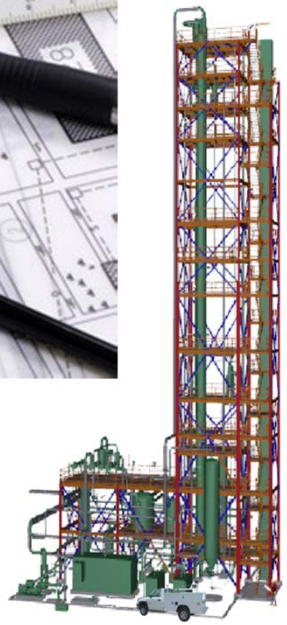
Detailed Engineering of 1MW Pilot

- Detailed engineering was conducted by Technip Stone and Webster Process Technology
  - Process engineering
  - Structural engineering
  - Electrical engineering
  - Detailed drawings
  - Equipment specification
  - 3D modeling
  - HASOP



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Pilot Design Basis

Design Basis			
Flue Gas Flow Rate		1808	acfm
Gas Velocity in Adsorber		4.2	ft/sec
Sorbent Circulation Rate		31107	lb/hr
% CO_2 Captured		90.0%	Weight %
CO_2 Working Capacity		7.0%	gCO_2/g Sorbent
H_2O Working Capacity		1.0%	gH_2O/g Sorbent
Water Usage	Scrubber demister pad	15	gpm
	Cooling for scrubber	125	gpm
	E-101	84	gpm
	Bottom ADS bed	327	gpm
	Middle ADS bed	327	gpm
	Top ADS bed	553	gpm
	E-102	60	gpm
	E-103	6	gpm
CO_2	Fluidizing	343	acfm
	Transfer to REG	67	acfm
	Transfer to ADS	252	acfm
	Total used in Process	662	acfm
	Product	375	acfm
	CO2 Removed witin Adsorber	2172	lbs/hr

Steam	High Pressure	3139	lbs/hr
	lb/lb CO_2	1.4	lb/lb CO2
Density	Bottom ADS bed	15	lbs/cf
	Middle ADS bed	15	lbs/cf
	Top ADS bed	15	lbs/cf
	Regenerator	26	lbs/cf
Temp	Bottom ADS bed	104	F
	Middle ADS bed	104	F
	Top ADS bed	104	F
	Regenerator	248	F
Caustic	Scrubber	2	gpm
Adsorber In	CO2	13.1	%
	O2	5.65	%
	H2O	4.85	%
Adsorber Out	CO2	1.58	%
	O2	6.73	%
	H2O	0.78	%
Regenerator Out	$CO_{2\ (dry)}$	93.4	$\%_{(dry)}$
	O2	0.38	%
	H2O	7.2	%

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Gas Sampling Locations

Gas(es) Sampled	Frequency of Sampling	Analyzer Location	Used for Mass Balance
CO_2,O_2, SO_2	Continuous	Adsorber Inlet	Yes
CO_2,O_2, SO_2	Intermittent	Fluidized Bed Overhead	No
H_2O	Intermittent	Fluidized Bed Overhead	Yes
CO_2,O_2, SO_2	Continuous	Adsorber Outlet	Yes
H_2O	Intermittent	Adsorber Outlet	Yes
CO_2,O_2	Continuous	Regenerator Outlet	Yes
H_2O, O_2	Intermittent	Regenerator Outlet	Yes

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Manufacture and Prepare Sorbent

- Procured 20,000 lbs of raw sorbent
  - At this small quantity sorbent could not economically be manufactured to desired particle size
- Particle size
  - Cold flow modeling was used to determine optimal size distribution
  - Pin milling and screening was used to achieve size distribution
  - Sorbent needed to be less than 12% moisture for milling
- Drying process
  - Raw sorbent is 44% moisture
  - Multiple drying processes were tested
  - Limited to 120°F in ambient oxygen
  - Low temperature fluidized bed drying was implemented

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Fabricate and Install Pilot

- Fabrication and installation was completed by McAbee Construction
  - Modules were fabricated at an offsite fabrication shop and module yard and transported via barge to the host site
  - Onsite foundation and utility work began while the modules were being fabricated
  - Installation and tie in work was completed during the first quarter of 2014

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Pilot Commissioning

- All sub systems of the pilot unit were brought online and verified functional.
- Maximum and minimum flows were verified
- Heating and cooling capabilities were verified
- Measurements and corresponding calculations were verified
- Data logging and display were verified
- Sorbent circulation was verified
- Process control loops were tuned
- HMI control was verified

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Project Review

- Overview of Project and Technology
- Pre-Construction (Budget Period 1)
  - Sorbent, 500 MW Process Concept, 1 MW Pilot Design
- Construction (Budget Period 2)
- Testing and Performance Review
  - Overview of 2014 testing
  - Overview of 2015 testing
- Review of Project Objectives and Achievement
- Conclusions

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Overview of Pilot Operating Periods

	Dates	Comments
Round 1	9/29/14 – 11/11/14	Due to pilot balance of plant issues, only 21 days of operation was possible in 2014 of which **all** performance data generated was subject to static interference • The data generated was usable to identify trends and verified that the process and sorbent were behaving as anticipated • SO_2 scrubber demister pad failure resulted in contamination and failure of the flue gas fluidizing blower • Temperatures below freezing caused pilot shut-down for the winter
Round 2a	4/4/15 – 6/6/15	Scrubber and blower repaired, residual grounding issues resolved, minor modifications and minimal fluidization to cyclone dipleg to increase stability
Round 2b	6/6/15 – 6/26/15	Relatively stable continuous operating period

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Pilot Testing: Evaluated Parameters

- CO_2 delta loading
- H_2O delta loading
- Enthalpy of reaction/adsorption
- Reaction kinetics
  - CO_2 uptake limiting factors in the adsorber
  - CO_2 release limiting factors in the regenerator
- Effective heat transfer coefficients
  - Cooling water requirements
  - Steam requirements
- CO_2 partial pressure in the regenerator
- Reactor pressure drop
- Isothermal operation of the adsorber and regenerator
- Identify sorbent bed height requirements
- Confirm key fluid bed design parameters:
  - Bed density
  - Dipleg density
  - Riser lift gas requirement
  - Standpipe density and aeration gas requirement
- Overall feasibility of using solid sorbent BN for CO_2 capture in ADAsorb™ Pocess

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Pilot Results: June 6 – June 26, 2015

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Review – and Assessment

Pilot performance was limited, primarily due to limits in delta capacity across the adsorber, and sorbent handling issues.

Potential reasons for lower-than-predicted delta CO_2 loading across the adsorber:

- Sorbent Stability: Did sorbent degrade in the pilot?
- Sorbent Kinetics: Are sorbent kinetics slower than expected? Is the residence time in the adsorber sufficient?
- Did the sorbent adsorb CO_2 in the transport line between the regenerator and adsorber?
- Did insufficient regeneration temperature or elevated adsorption temperature in top bed (gas outlet) affect working capacity?

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Sorbent Stability and Sorbent Kinetics

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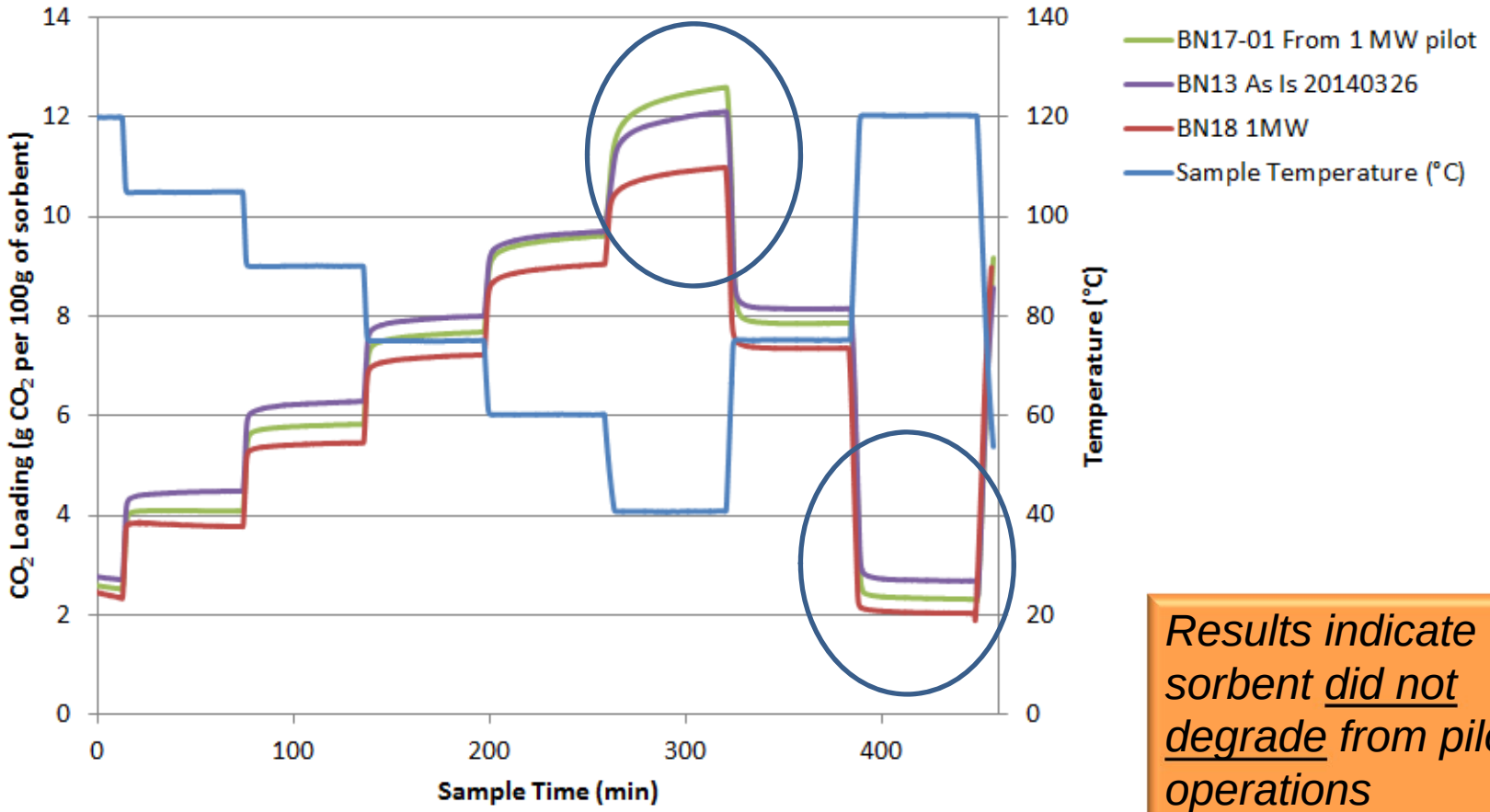
TGA Analysis of Sorbent Performance



Results indicate sorbent <u>did not degrade</u> from pilot operations

- BN 18: sample from the pilot in December, 2014
- BN 17: sample from the pilot in October, 2014
- BN 13: as received fresh sample tested in March, 2014
- Note: Lab data indicates that the material capacity differs from batch to batch, ±20 %

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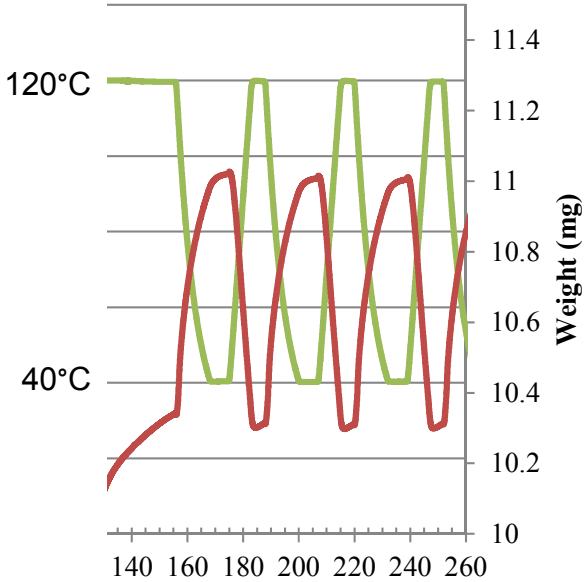
TGA Results and Kinetic Predictions - Updated

Cycling between 40°C/0.15 bar CO_2 and 120°C/0.8 bar CO_2

Condition	Cycle	Time to 80% Capacity Equilibrium (minutes)	Time to 90% Capacity Equilibrium (minutes)	CO_2 Loading (g CO_2/ 100g Fresh Sorbent)	Delta Loading (g CO_2/ 100g Fresh Sorbent)
Desorption	1	17.46	22.78	5.22	
Adsorption		8.27	10.69	12.14	6.92
Desorption	2	6.26	6.98	4.96	
Adsorption		7.30	9.96	12.03	7.07
Desorption	3	5.77	6.74	4.89	
Adsorption		8.16	11.30	11.98	7.08
Desorption	72	7.08	7.83	5.08	
Adsorption		8.29	10.77	11.78	6.71
Desorption	73	6.91	7.08	5.06	
Adsorption		8.47	10.95	11.77	6.72
Desorption	74	7.10	7.79	5.06	
Adsorption		8.75	11.05	11.77	6.72



Results suggest less than 15 minutes should be sufficient to achieve desired working capacity

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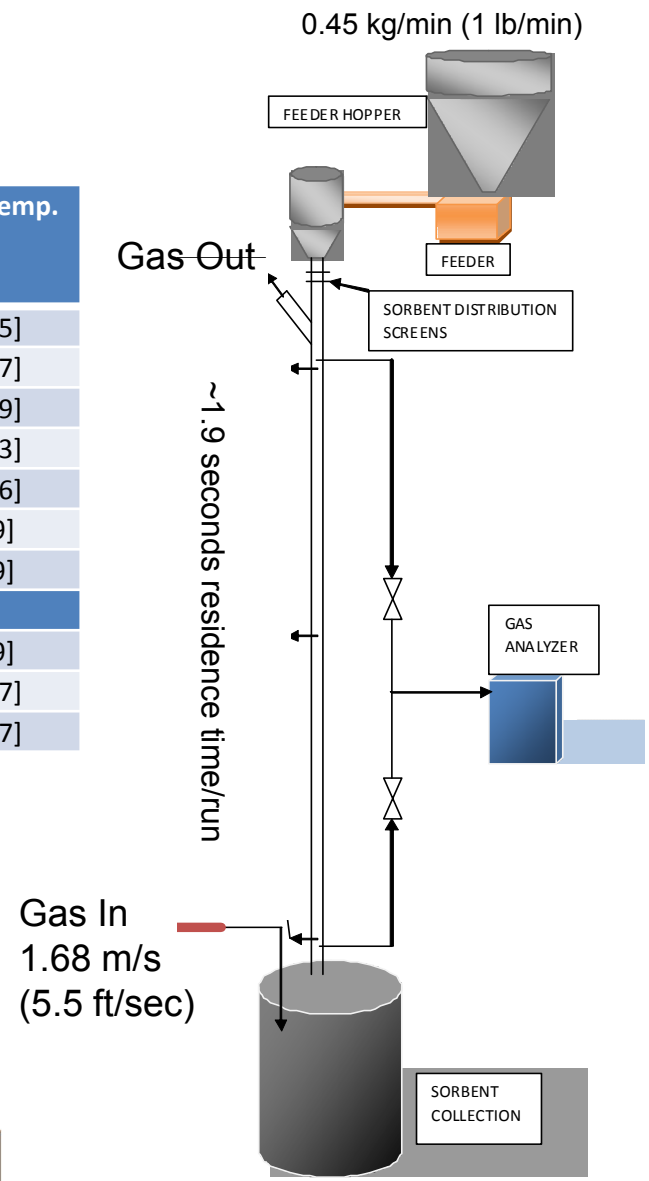
Laboratory Counter-Current Reactor Test

Test Run	Inlet CO_2 Conc. (%)	Outlet CO_2 Conc. (%)	Change in Sorbent Loading During Run (wt CO_2/sorbent, %)	Sorbent Loading at Outlet of Bed (wt CO_2/sorbent, %)	Sorbent Temp. (°C) [(°F)]
1	3.0	1.2	1.6%	1.6%	40 [105]
2	4.5	3.0	1.3%	2.9%	47 [117]
3	5.5	4.5	0.9%	3.8%	43 [109]
4	6.7	5.6	1.0%	4.8%	45 [113]
5	7.2	6.6	0.5%	5.3%	41 [106]
6	8.1	7.4	0.6%	5.9%	37 [99]
7	8.6	8.1	0.4%	6.4%	37 [99]
*Heating and CO_2 Treatment of Sorbent Overnight					
8*	12.5	9.5	2.6%	NA	37 [99]
9	9.2	8.6	0.5%	NA	42 [107]
10	10.3	9.0	1.1%	NA	42 [107]

- Tests conducted in "runs" to simulate longer reactor section
- Run 1 = 90% capture outlet conditions (low CO_2, regenerated sorbent)
- Run 10 = near inlet conditions (high CO_2, loaded sorbent)

Results suggest reaction kinetics are relatively fast



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Working Capacity and Pre-Loading of Sorbent

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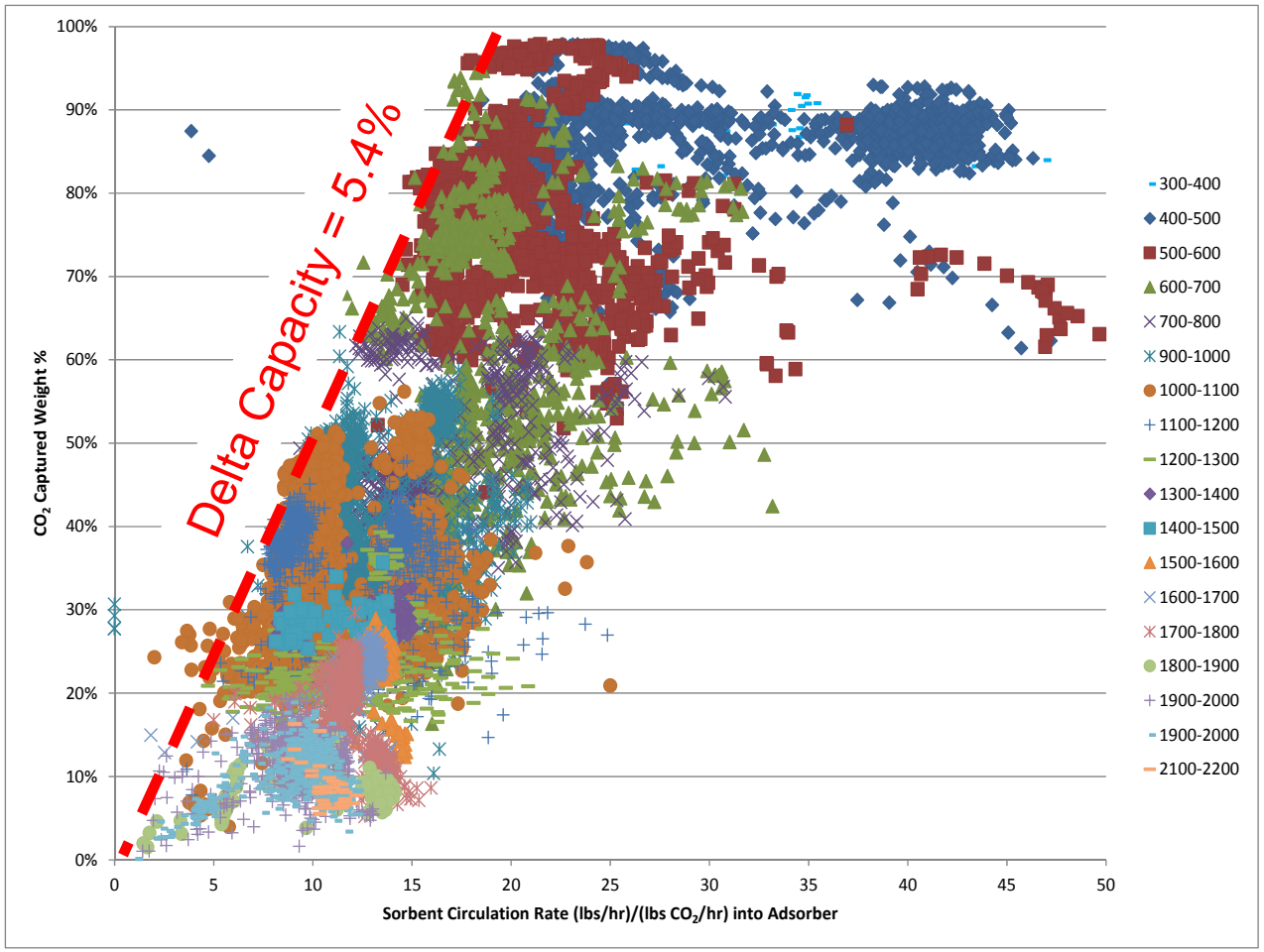
Impact of Mass Ratio on CO_2 Removal

- Large variation in data set at given conditions
- Delta capacity across adsorber limited to ~5.4% CO_2/sorbent



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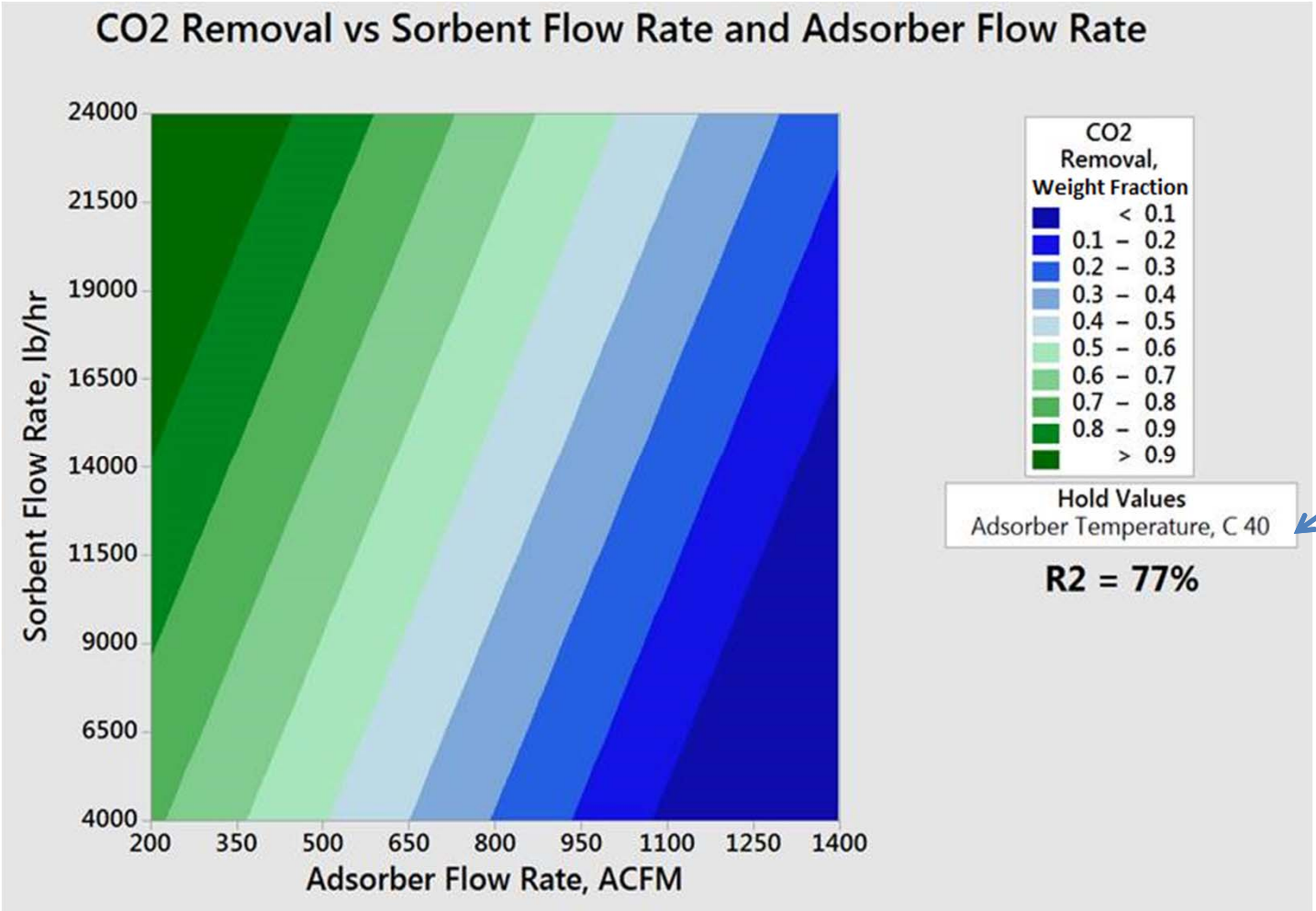
RESULTS: CO_2 Removal Across Adsorber



Representative at 40°C only

The model fits the data with a R^2 value equal to **77%**. At any given adsorber flow rate, an increase in sorbent flow rate produces increased CO_2 removal. The most optimal conditions for CO_2 capture exist at low adsorber flow rates and high sorbent flow rates

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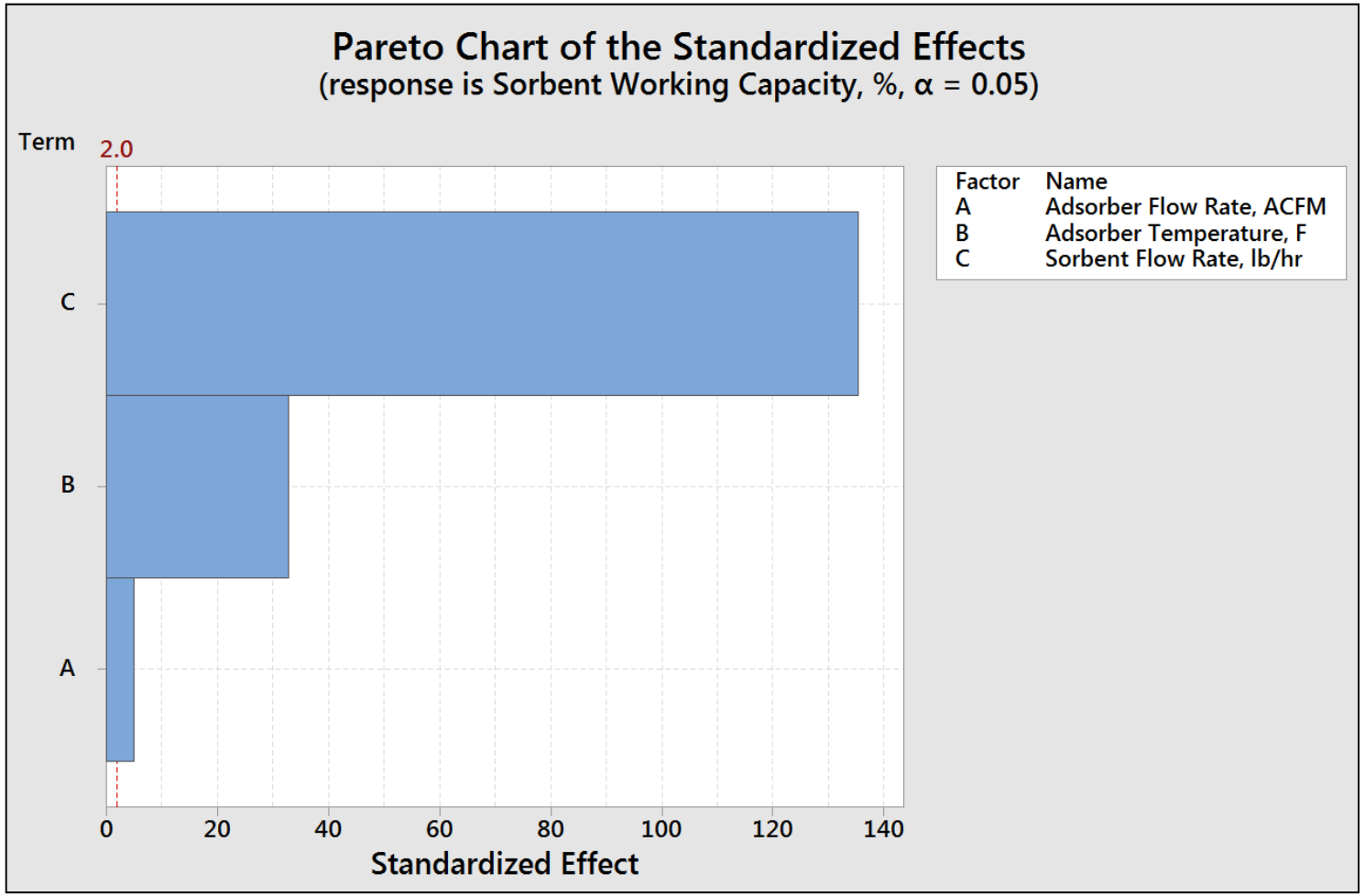
Statistical Model Results: Working Capacity



A *Pareto chart of the effects* determines the magnitude and the importance of an effect. The chart displays the absolute value of the effects and draws a reference line on the chart. Any effect that extends past this reference line is statistically significant. This shows that the **sorbent flow rate has the greatest impact (by an order of magnitude) on working capacity**.

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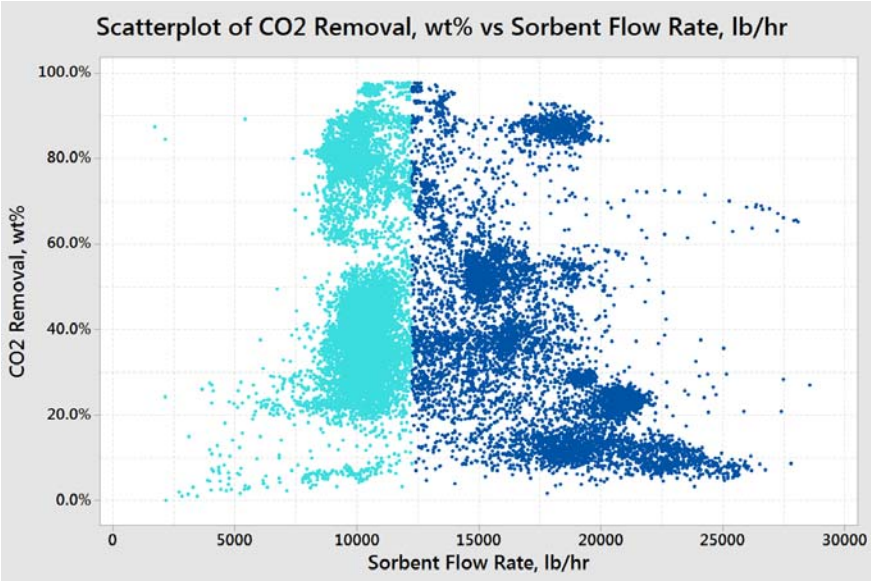
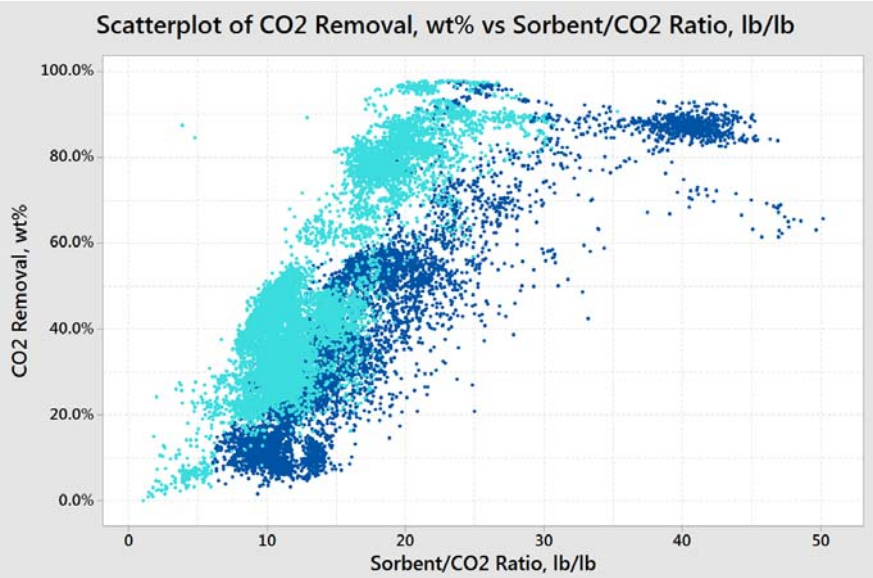
Factors influencing removal – Sorbent flow rate





Lower sorbent flow rates correlate to data representing the sorbent capacity limit for the pilot test

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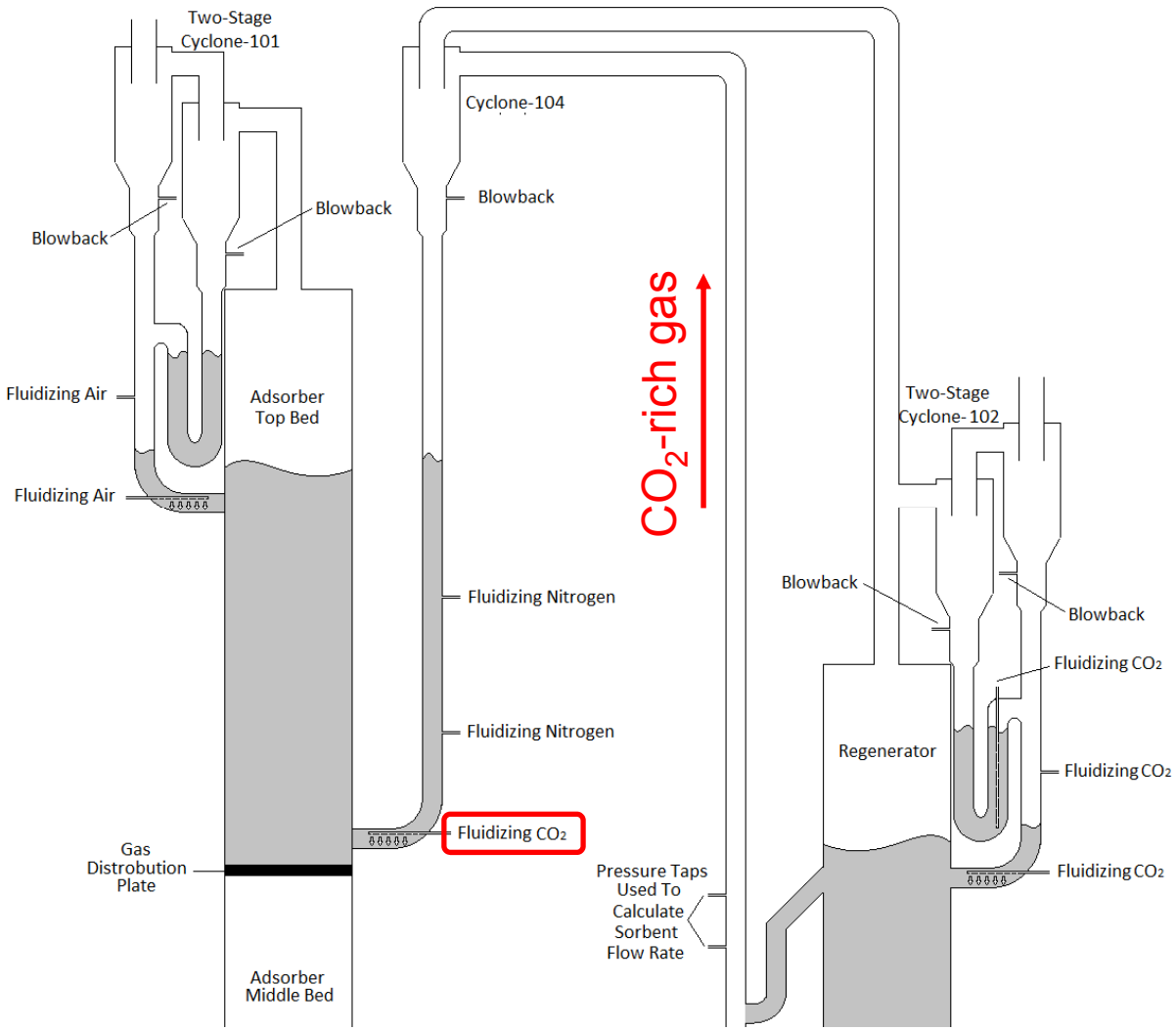
Potential Contributors to CO_2 Pre-loading



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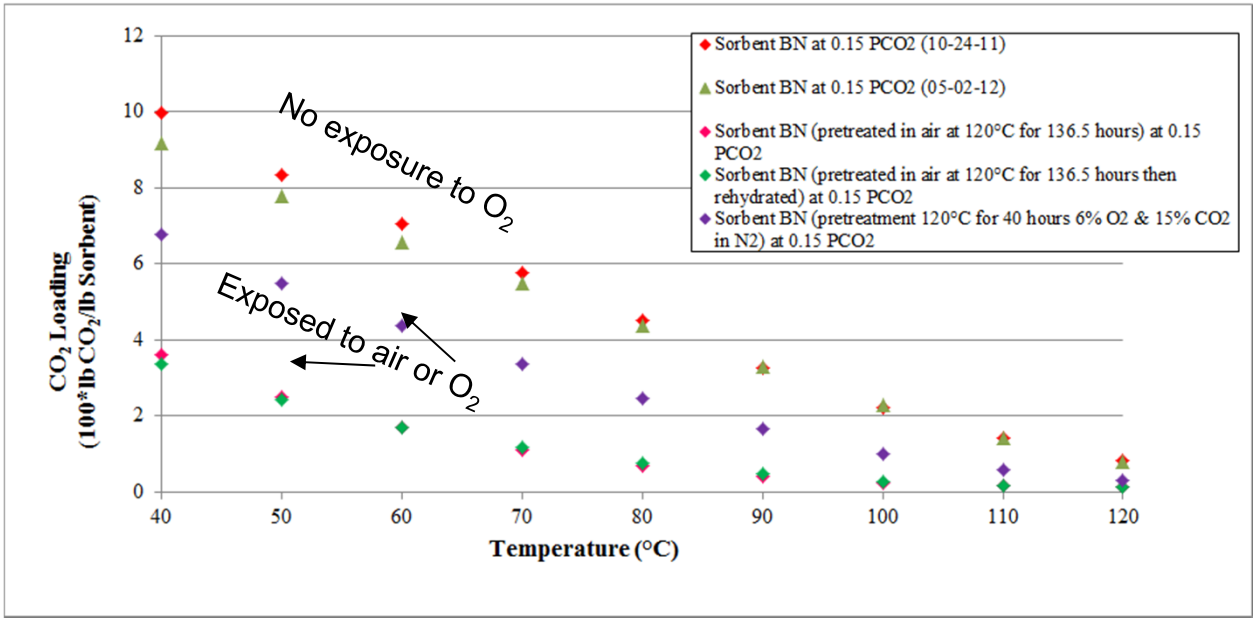
Why Use CO_2-Rich Carrier Gas?

Impact of exposure to oxygen at elevated temperatures on BN performance



- CO_2 was selected as carrier gas to prevent degradation of sorbent at elevated temperatures
- Carrier gas was not maintained at 120°C
  - Intermittent measurements indicate conditions in the transport line between the regenerator and the adsorber were nominally 75°C and 80% to 90% CO_2.
- At 75°C and 0.8 bar partial pressure loading is 8.5 g CO_2/100 g sorbent, compared to 3.43 g CO_2/100 g sorbent at regeneration conditions.

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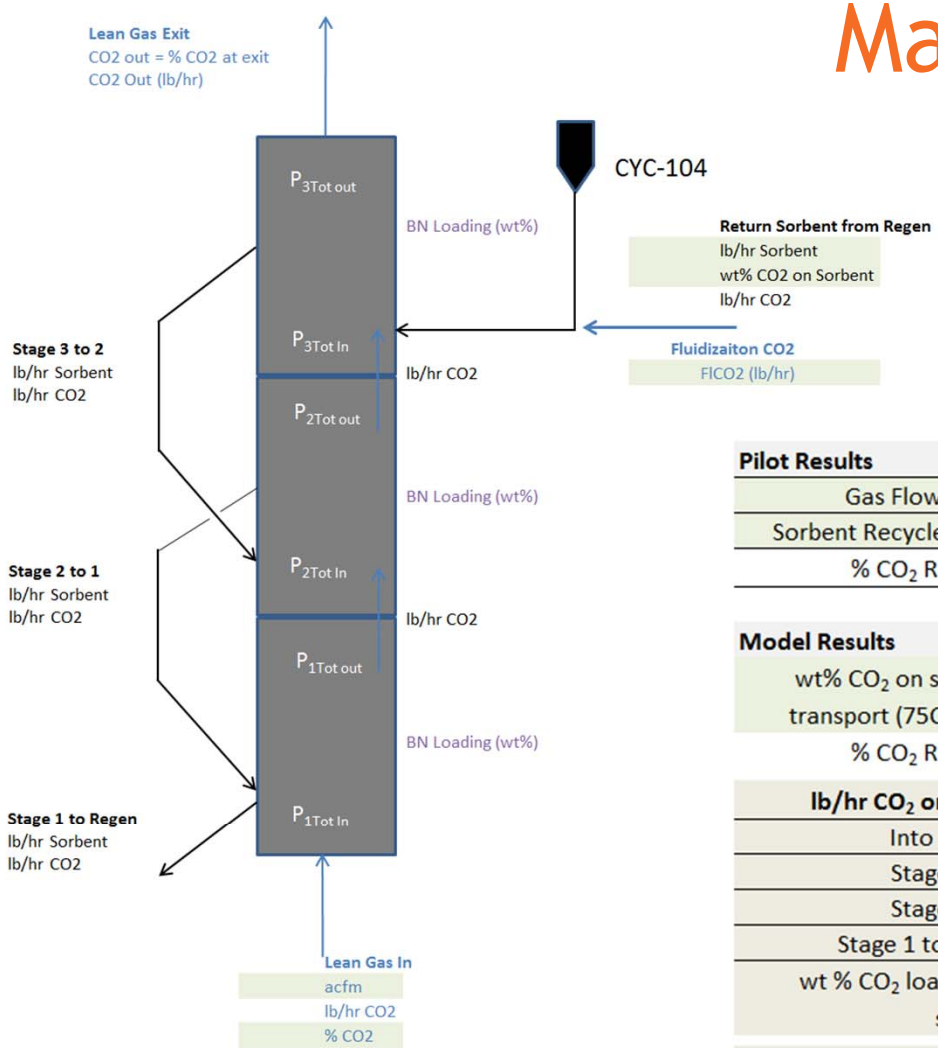
Mass Balance Model



	Case 1	Case 2	Case 3	Case 4	Case 5	Case 5b
Pilot Results						
Gas Flow (acfm)	1600	850	400	380	1808	1808
Sorbent Recycle (lb/hr)	18000	10000	10000	18000	31107	31107
% CO_2 Removal	15	40	80	88		
Model Results						
wt% CO_2 on sorbent, transport (75C, 1 bar)	6.3	6.3	6.3	6.3	6.3	3.47
% CO_2 Removal	42	43	78	83	66	93
lb/hr CO_2 on solids						
Into Stage 3	1134	630	630	1134	1960	1079
Stage 3 to 2	1694	936	701	1158	2520	1239
Stage 2 to 1	1943	1075	839	1216	3096	1969
Stage 1 to Regen	2031	1125	1020	1523	3426	3035
wt % CO_2 loading on sorbent	11.3%	11.3%	10.2%	8.5%	11.0%	9.8%
lb/hr CO_2 in flue gas						
Into Stage 1	1804	958	451	428	2038	2038
Into Stage 2	1716	907	270	121	1708	972
Into Stage 3	1466	768	131	63	1132	242
Exit of Adsorber	932	488	86	64	597	108

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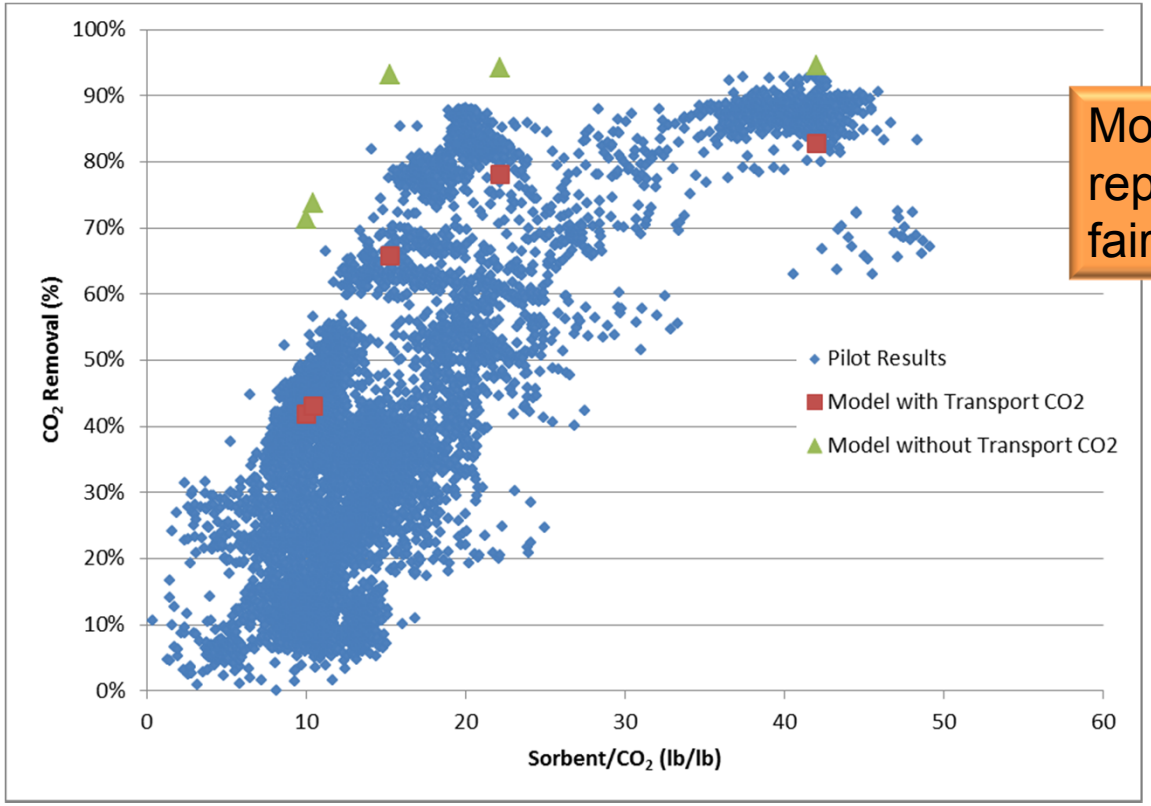
Pilot Results Compared to Model



Model appears to represent pilot results fairly well

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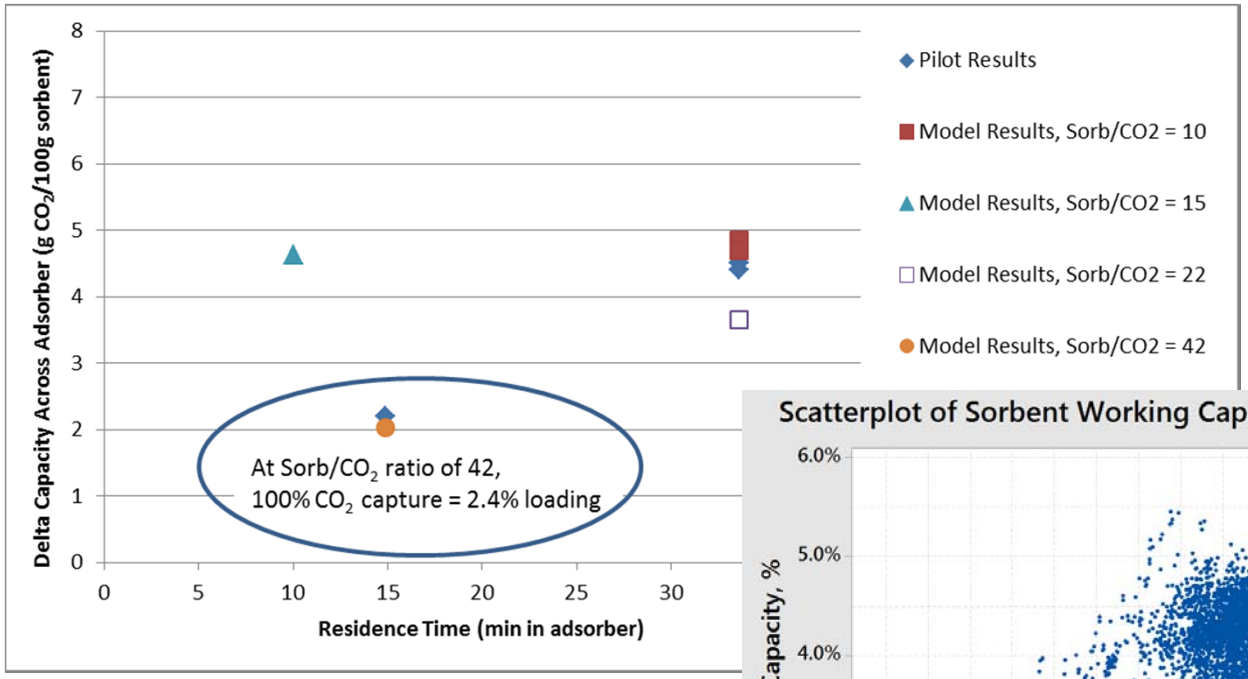
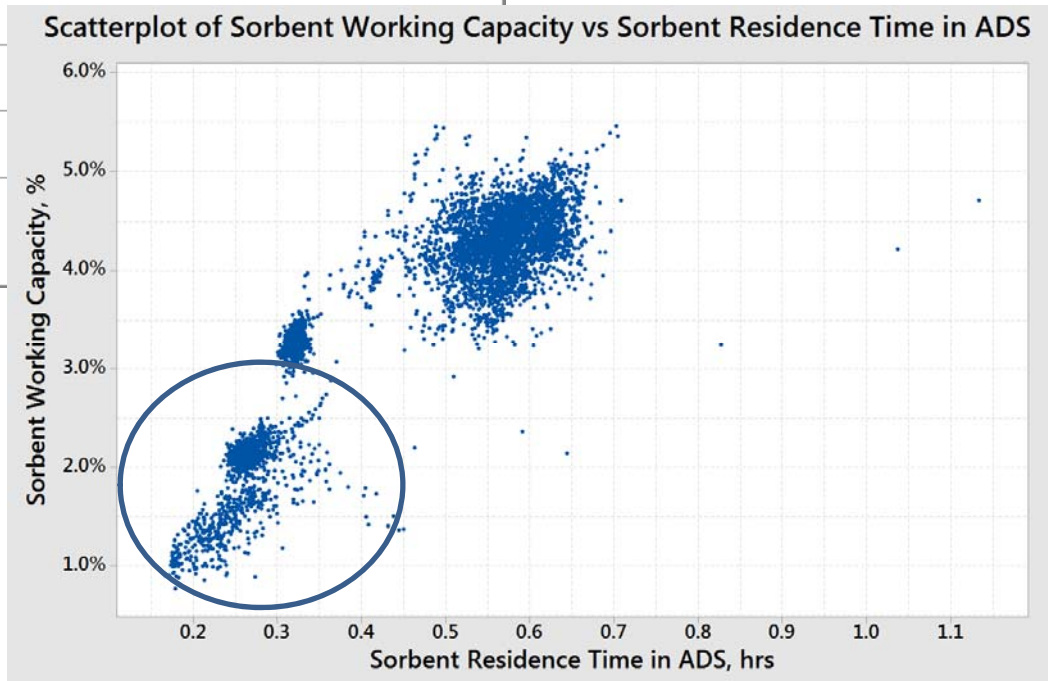
Sorbent Flow, Working Capacity, and Residence Time





Sorbent capacity limited by sorbent/CO_2 ratio, **NOT** adsorption kinetics

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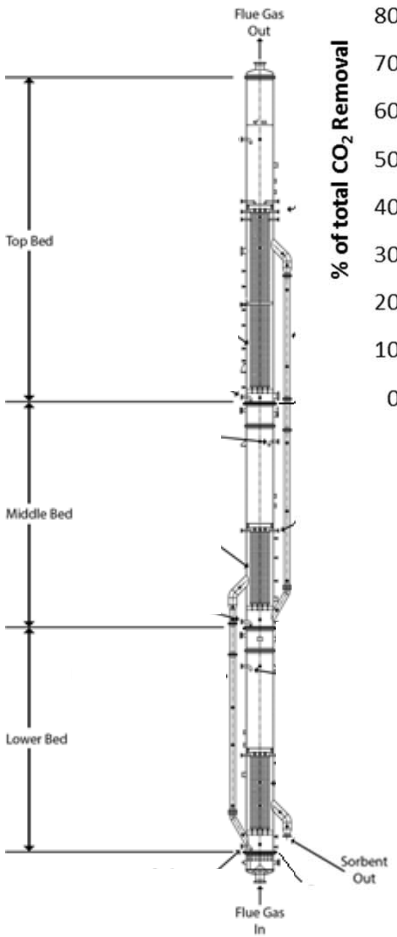
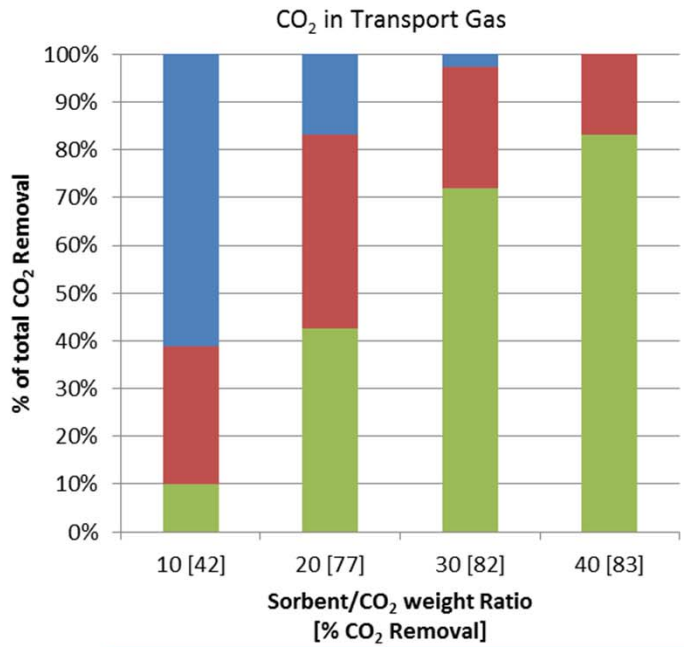
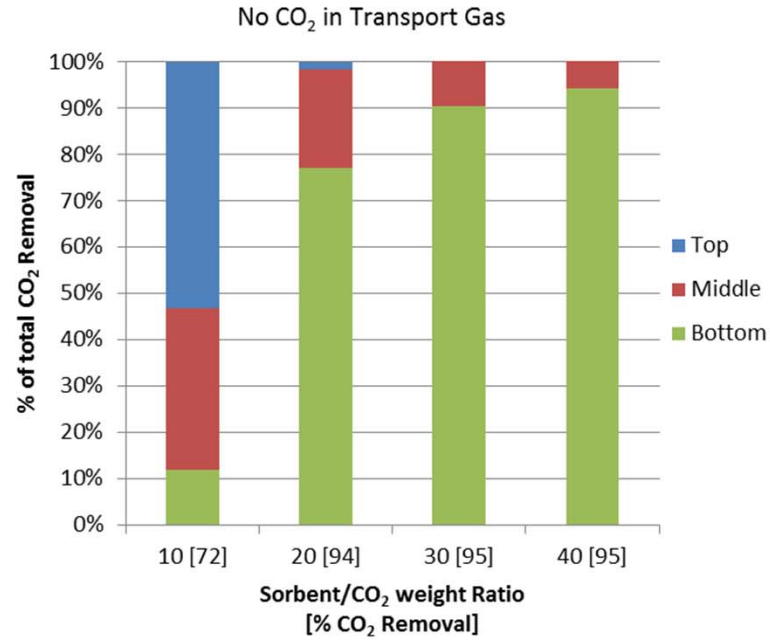
Modeled CO_2 Removal by Stage







- CO_2 in the transport gas limits CO_2 removal from flue gas
- Three stages are <u>required</u> to achieve 90% CO_2 removal at the "lowest" sorbent circulation rate

$$\text{Ads delta } CO_2 \text{ loading} = 1/\left(\frac{\text{sorbent circulation rate}}{\text{incoming } CO_2 * \%\text{ removal}}\right)$$

$$\rightarrow \text{Minimum circulation rate} = \frac{\text{incoming } CO_2 * \%\text{ removal}}{\text{equilibrium delta loading}}$$

Pilot Design: 2038 lb/hr CO_2, Eq. capacity = 0.07 g CO_2/g sorb → min circulation = 26,202 lb/hr
→ 12.8 ratio Sorbent/CO_2

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Regenerator and Adsorber Temperatures

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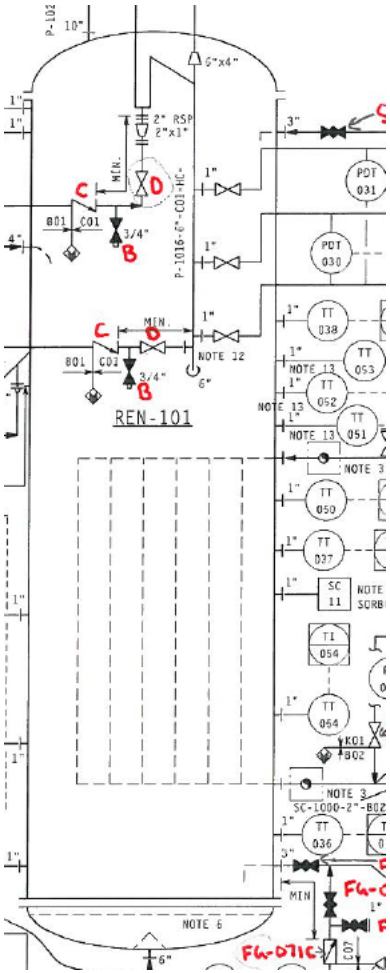
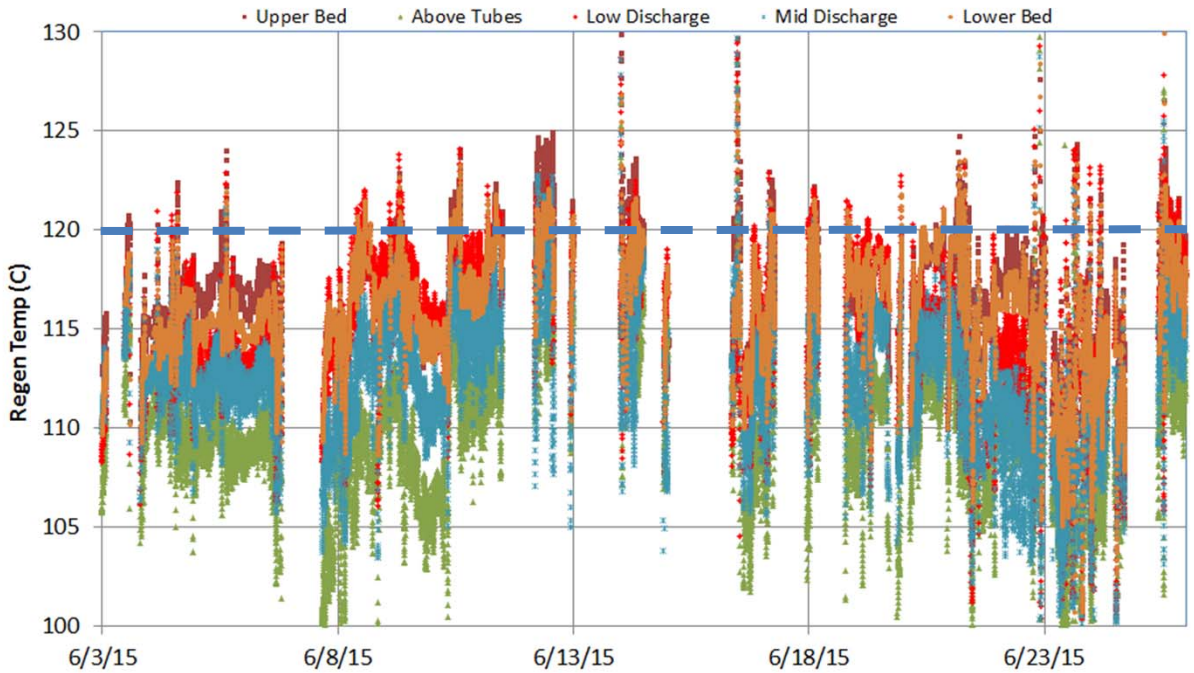
Regenerator Temperatures



Mid-Discharge
Low-Discharge
Above Tubes
Upper Bed
Lower Bed

Design Setpoint: 120°C



Discharge temperature was typically below design

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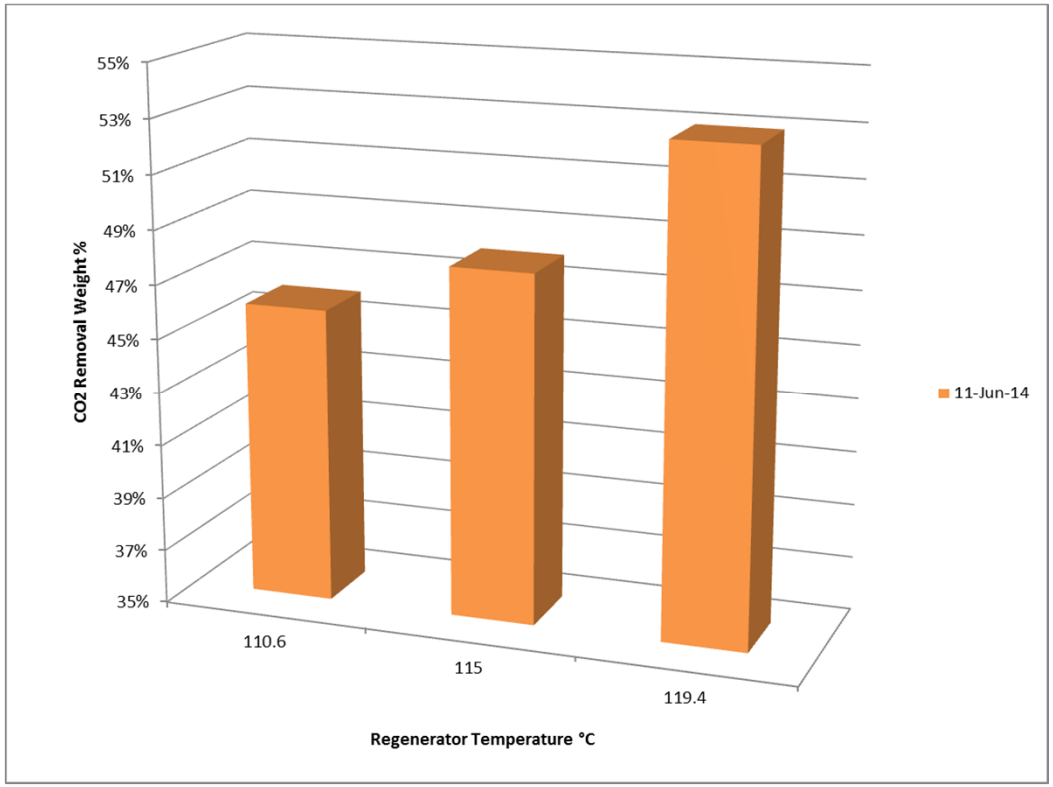
Effect of Regenerator Temperature

- Regenerator temperature has direct effect on CO_2 removal within the adsorber
- Design temperature of 120 °C was chosen because operating above 120 °C has adverse effects on sorbent



Regenerator Temp	CO_2 Removal	Sorbent Circulation	Flue Gas
°C	% mass	lb/hr	acfm
110.5	46%	10,893	457
115.0	48%	10,476	458
119.5	53%	10,141	458

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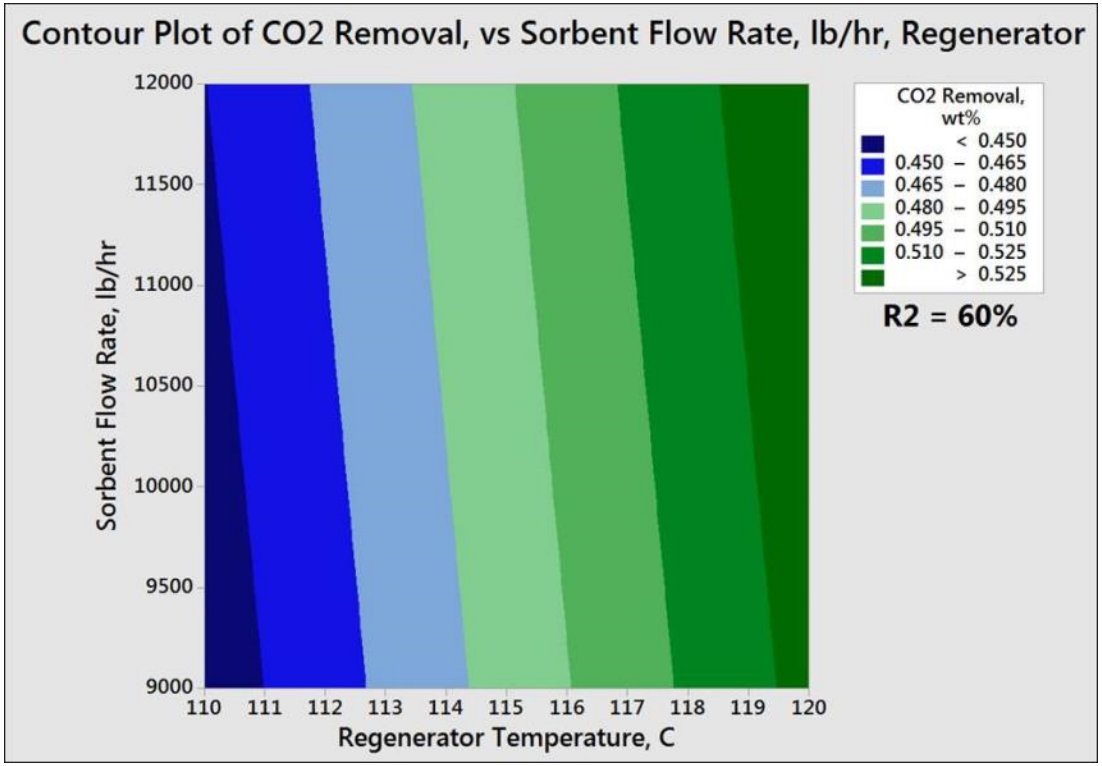

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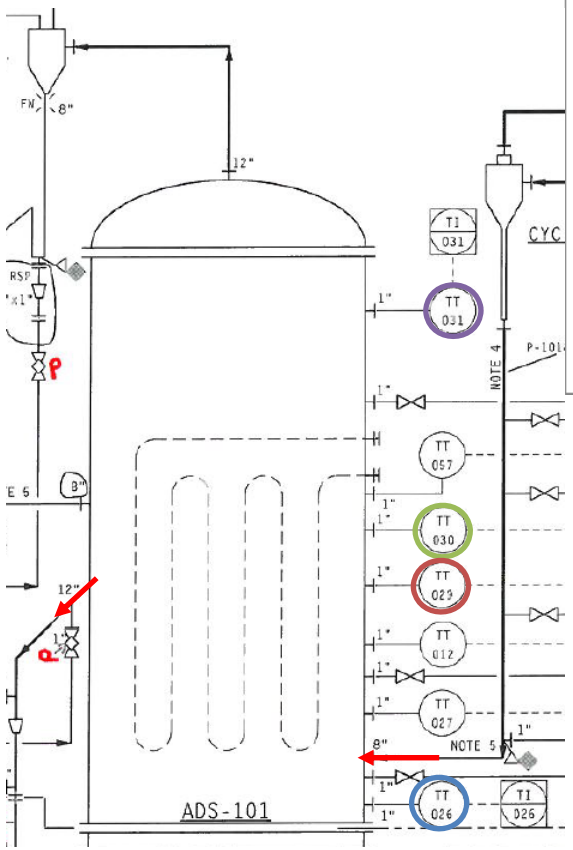
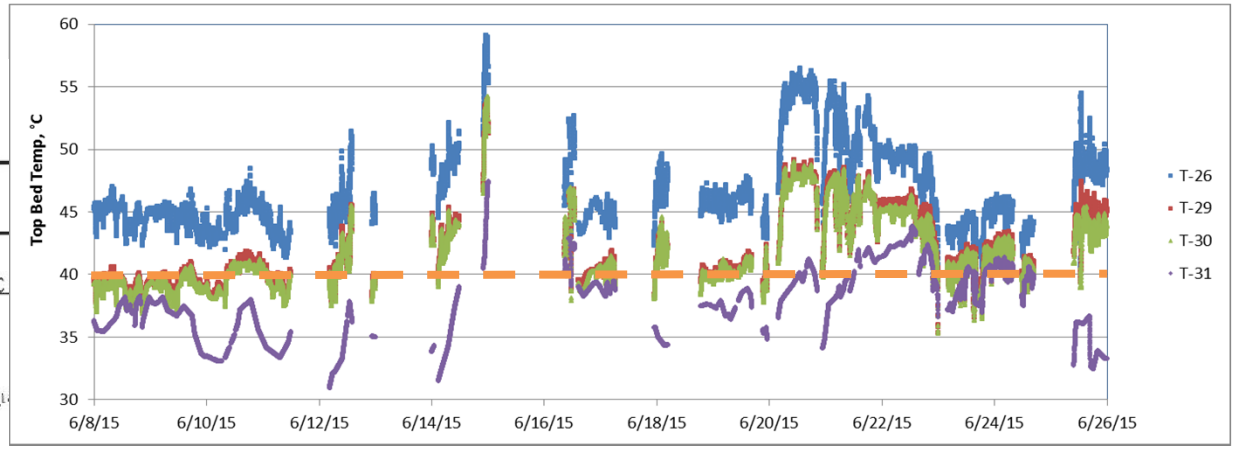
Adsorber Top Bed Temperatures

Design Setpoint: 40°C





Temperature at outlet location was typically at design temperature

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Review of CCSI Insights

The CCSI model predicted an overall removal of CO_2 from the process gas stream of 58.07% and an achieved working load of 4.5 g CO_2 /100 g sorbent, compared to the design condition of 7 g CO_2/100 g sorbent.

- Possible reasons for the poor modeled performance of this process.

  1. Predicted non-isothermal behavior of the regenerator due to strong cooling effect as cool sorbents loaded with CO_2 were introduced, compounded by endothermic reaction during regeneration.
     Predicted solid outlet temperature = 104°C.

     - ADA added a baffle to the regenerator to reduce impact of sorbent addition.
     - Results from testing indicate reduced temperatures, but not as extreme as predicted. Increasing sorbent circulation may increase impact. A cross heat exchanger could mitigate most of this effect.

  2. Slow predicted kinetics of adsorption. *Note that the CCSI team was not provided with all of the kinetic studies conducted by ADA*. The model predicted that the uptake of CO_2 appears to be approaching to 85% of the equilibrium loading. This would suggest that the performance of the adsorber could be improved slightly with faster kinetics or longer residence times, but that improvement might be uneconomical.

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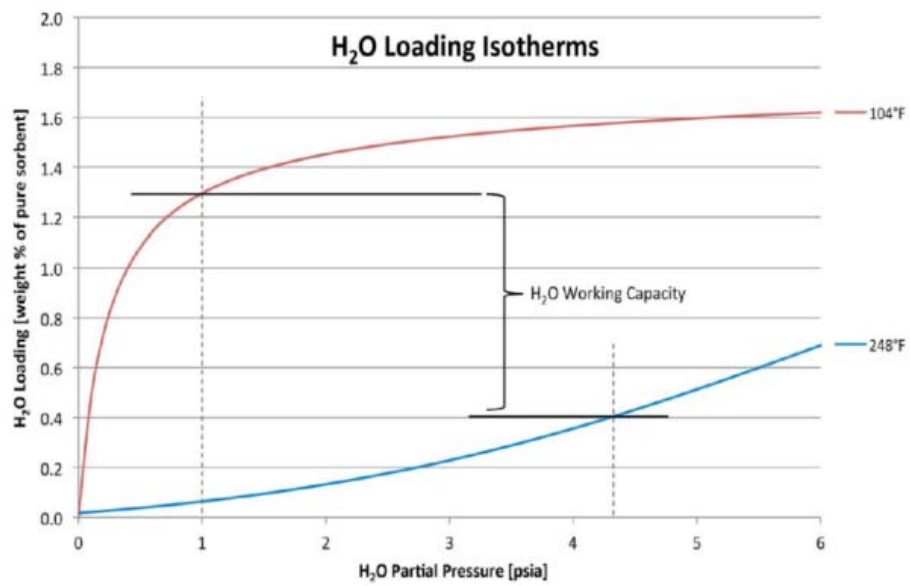
Effects of Moisture

Moisture Working Capacity

- Design basis 1.0%
- Measured 0.3% - 0.9%



	Design	Measured Values						
Flue Gas Flow Rate	1808	1611	779	824	428	415	350	acfm
Sorbent Circulation Rae	31107	18439	15103	10070	13183	9876	17993	lb/hr
% CO_2 Captured	90.0%	13.6%	52.0%	42.0%	94.0%	82.0%	87.0%	Weight %
H_2O Working Capacity	1.0%		0.53%	0.86%	0.28%	0.27%		gH_2O/g Sorbent

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CO_2 Product Purity

- Regenerator outlet stream diluted with more oxygen than expected
- Calculated 55% air in leakage, 45% flue gas carry over
- If air in leakage is eliminated product would have been $92.4\%_{(dry)}$ based on original value of $89.4\%_{(dry)}$
- Pipeline typical requirement is $95\%_{(dry)}$
- Lower than predicted due to lower working capacity

		Design	Measured Values						
	Flue Gas Flow Rate	1808	1611	779	824	428	415	350	acfm
	Sorbent Circulation Rae	31107	18439	15103	10070	13183	9876	17993	lb/hr
	CO_2 Removed witin Adsorber	2172	267	496	439	521	423	390	lbs/hr
Regenerator Outlet	$CO_{2\,(dry)}$	93.4	89	96.8	85.5	88.8	85.5	89.9	$\%_{(dry)}$
	O_2	0.38	1.1	3.2	2.3	1.9	2.4	1.1	%
	H_2O	7.2		8.79	10.85	6.56	6.74		%

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Environmental Testing: Liquid Discharge

- **Liquid discharge samples**
  All condensate locations
  All discharge points
  Collected bi-weekly from both the regenerator and the adsorber
  - Total suspended solids
  - HEM / "Oil and Grease"

Date	Minimum Recordable Limit	6/10/2015	6/10/2015	Units
Location		D-101	Scrubber	
Arsenic	0.05	-	-	mg/L
Barium	0.005	0.01	0.011	mg/L
Cadmium	0.005	-	-	mg/L
Chromium	0.005	-	-	mg/L
Lead	0.02	-	-	mg/L
Mercury	0.0002	-	-	mg/L
Selenium	0.02	0.02	-	mg/L
Silver	0.005	-	-	mg/L
Zink	0.01	0.01	-	mg/L
Total S. Solids	4	8.8	9	mg/L
HEM	6	-	-	mg/L

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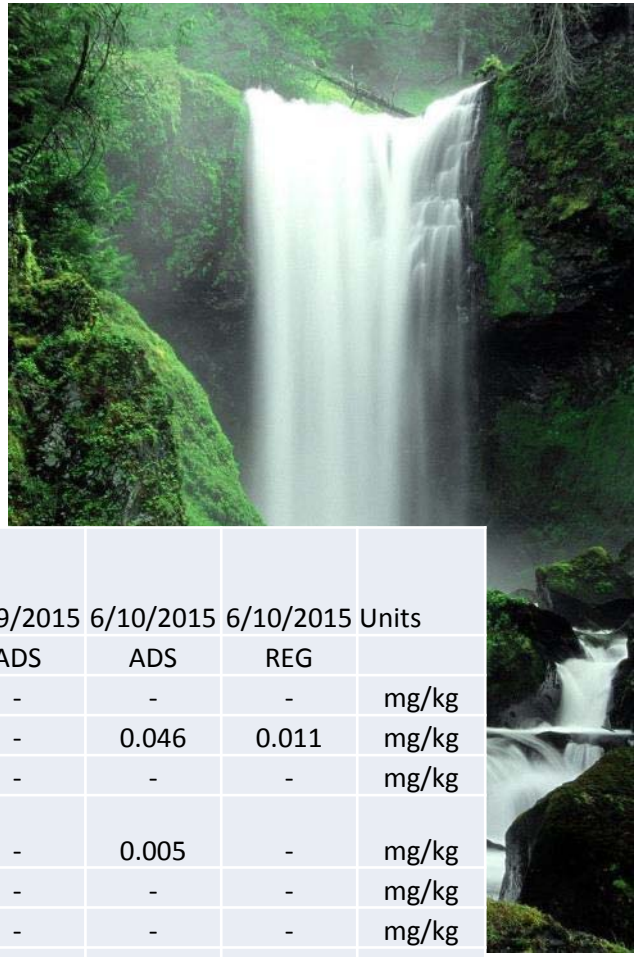
Environmental Testing: Sorbent Samples

- **Sorbent samples**
  Collected bi-weekly from both the regenerator and the adsorber
  - RCRA 8 Metals
  - If over RCRA 8 threshold, test TCLP



Date	Minimum Recordable Limit	10/2/2014	4/8/2015	5/22/2015	5/22/2015	5/26/2015	5/29/2015	6/10/2015	6/10/2015	Units
Location		ADS	ADS	ADS	REG	ADS	ADS	ADS	REG	
Arsenic	5	-	-	-	-	-	-	-	-	mg/kg
Barium	0.5	2.06	-	-	0.528	-	-	0.046	0.011	mg/kg
Cadmium	1	-	-	-	-	-	-	-	-	mg/kg
Chromium	2.5	-	-	-	-	-	-	0.005	-	mg/kg
Lead	2.5	-	-	-	-	-	-	-	-	mg/kg
Mercury	0.05	-	-	-	-	-	-	-	-	mg/kg
Selenium	2.5	-	-	-	-	-	-	-	-	mg/kg
Silver	2.5	-	-	-	-	-	-	-	-	mg/kg

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Review of Techno-Economics

Assuming operating model is representative of performance without the impact of CO_2 in the adsorber-return gas, and handling issues can be resolved, the initial TEA should be representative of costs.

- Capital costs, fuel costs and CO_2 transport, storage, and monitoring costs of the sorbent-based process were lower than those of the MEA case due to the lower thermal input required to operate the CO_2 capture facility.
- The operating and maintenance costs of the sorbent-based CO_2 capture process were higher than those of the MEA process, mostly as a result of a high sorbent cost and consumption for an initial fill.
- The electric requirement for the compression of CO_2 is significant for both aqueous amine and sorbent-based CO_2 capture. However, because the gross power plant with sorbent-based capture is smaller, less CO_2 must be compressed and the related costs are nominally less.
- COE and LCOE of the sorbent-based process were lower than those of the aqueous MEA system due to a lower capital costs, fuel costs, and CO_2 TS&M costs, offsetting higher O&M costs.
- The COE and LCOE were calculated to be 113.3 and 143.6 mills/kWh, respectively.

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Review of Techno-Economics

Description	Unit	Econamine1		Econamine2		Sorbent1		Sorbent2		20-hr Pilot Test	
		BEC as per DOE		BEC based on experience		BEC as per DOE		BEC based on experience		BEC as per DOE	
Gross Power Output	kW_e	672,700		672,700		656,125		656,125		718,738	
Electrical Output – BP Turbine	kW_e	0		0		47,369		47,369		32,525	
Auxiliary Load Summary	kW_e	122,740		122,740		153,534		153,534		201,293	
Net Power Output	kW_e	549,960		549,960		549,960		549,960		549,970	
Thermal Input	kW_{th}	2,102,644		2,102,644		1,865,320		1,865,320		2,383,129	
Coal Flow Rate	lb/hr	614,994		614,995		545,581		545,581		697,032	
Net Plant HHV Efficiency	%	26.2		26.2		29.5		29.5		23.1	
Net Plant HHV Heat Rate	Btu/kWh	13,046		13,046		11,573		11,573		14,785	
CO_2 Capture Profile											
• CO_2 Produced	lb/hr	1,459,838		1,459,838		1,295,067		1,295,067		1,651,831	
• CO_2 Captured	lb/hr	1,313,960		1,313,960		1,165,561		1,165,561		1,486,648	
• CO_2 Emission	lb/hr	145,878		145,878		129,507		129,507		165,183	
Circulating Cooling Water Demand†	gpm	540,000		540,000		399,276		399,276		487,120	
Raw Water Consumption	1000 gal/D	8,081		8,081		6,460		6,460		7,802	
CO_2 Capture Facility											
• Regen. Energy	Btu/lb CO_2	1,530		1,530		1,139		1,139		2,042	
• Total Energy	MMBtu/hr	2,010		2,010		1,328		1,328		3,036	
• Steam Flow	lb/hr	2,219,454		2,219,454		1,429,730		1,429,730		2,709,721	
• Sorbent Amount	lb/hr	N/A		N/A		16,610,220		16,610,220			
Capital Cost											
Bare Erected Cost	$	1,415,831,000		1,931,818,999		1,294,480,737		1,662,613,151		3,377,994,721	
Total Plant Cost	2015$	1,847,389,582		2,613,159,050		1,673,687,989		2,218,697,156		4,724,953,270	
Total Overnight Cost	2015$	2,266,414,272		3,204,167,189		2,071,764,559		2,741,840,062		5,991,041,269	
Total As-Spent Cost	2015$	2,583,712,271		3,652,750,595		2,361,811,597		3,125,697,670		6,355,138,125	
Operating & Maintenance Cost		Initial Cost	Annual Cost	Initial Cost	Annual Cost	Initial Cost	Annual Cost	Initial Cost	Annual Cost	Initial Cost	Annual Cost
Total Fixed Op Costs	$M		61.0		81.2		56.8		71.2		141.3
Total Var. Op. Costs	$M	3.1	42.8	3.1	51.2	13.0	73.2	13.0	62.9		132.0
Fuel Costs	$	99,798,307		99,798,307		87,671,276		88,534,219		113,110,975	
CO_2 TS&M Costs	$	27,112,268		27,112,268		23,815,777		24,050,194		30,675,509	
COE contribution (2015$)	mills/kWh	125.0		160.3		121.8		143.3		283.9	
• Capital Costs	mills/kWh	68.7		97.0		62.8		83.1		181.4	
• Fixed Op. Costs	mills/kWh	14.9		19.9		13.9		17.4		34.5	
• Variable Op. Costs	mills/kWh	10.4		12.5		17.8		15.4		32.9	
• Fuel Costs	mills/kWh	24.4		24.4		21.4		21.6		27.6	
• CO_2 T&SM Costs	mills/kWh	6.7		6.7		5.8		5.9		7.5	
LCOE (2015$)	mills/kWh	158.7		203.2		154.3		181.6		359.9	

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Potential Benefits from Heat Integration

- Evaluation conducted by Lehigh (E.K. Levy) under DE-FE0012914
- 13% reduction in heat rate possible with BN when using a cross heat exchanger to recover the sensible heat of the sorbent, and other heat integration options.
- In general, the capital costs heat integration modifications almost always outweighed the benefits with the exception of a cross heat exchanger

Parameter	Heat Rate	Δ Heat Rate (% from Base Design)	Cost of Electricity ($/MWh)	Δ Cost of Electricity (% from Base Design)	Levelized Cost of Electricity ($/MWh)	Δ Levelized Cost of Electricity (% from Base Design)
Base Design	13364	0.00%	154	0.00%	195	0.00%
FG FWH	13302	-0.46%	170	10.39%	215	10.26%
FG Air	13259	-0.79%	155	0.65%	195	0.00%
Comp FWH	12927	-3.27%	156	1.30%	197	1.03%
Comp REG	12472	-6.67%	150	-2.60%	189	-3.08%
XHTX	12156	-9.04%	148	-3.90%	187	-4.10%
All HI	11625	-13.01%	162	5.19%	205	5.13%
XHTX & Comp REG			147	-4.55%	186	-4.62%

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Project Review

- Overview of Project and Technology
- Pre-Construction (Budget Period 1)
  - Sorbent, 500 MW Process Concept, 1 MW Pilot Design
- Construction (Budget Period 2)
  - Detailed Engineering - Pilot, Manufacture Sorbent, Fabricate, Install and Commission Pilot
- Testing and Performance Review (Budget Period 3)
- Review of Project Key Operational Challenges, Objectives and Achievements
- Conclusions

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Recommendations Based on Pilot Operational Challenges

- Plan for more balance of plant issues on first-of-a-kind pilots than expected
  - Inherent instability of fluidized beds
  - SO_2 scrubber operation and subsequent blower issues
  - Electrical grounding issues
  - Unseasonably cold weather and inadequate freeze protection
  - Supply water contamination
  - Analyzer reliability
  - Insufficient fluidization within transfer lines, sorbent carryover
- Conduct additional lab tests, extrapolate performance, and build in contingency
  - Changes in sorbent behavior at high temperatures
  - Better use of performance models to test assumptions.
  - Limit adsorption in carrier gas lines

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Project Objective and Goals

- The overall objective was to validate solid sorbent-based post combustion CO_2 capture through pilot testing

- Project Goals:
  - Achieve 90% CO_2 Capture
  - Reduce costs of carbon capture
    Progress towards <35% LCOE Goal
  - Generate a high purity CO_2 stream
  - Successfully scale sorbents

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Project Goals – CO_2 Capture

- Achieve 90% CO_2 Capture
  - 90% CO_2 capture was achieved at flow rates less than 1MW equivalent
  - Target flue gas flow rate during 90% capture was ~12500lbs/hr
  - Sustainable flue gas flow rate during 90% capture was ~3000lbs/hr
- Future Development Areas
  - Development of sorbents capable of higher CO_2 delta loading
  - Modify pilot for better high temperature sorbent handling
  - Modify pilot and pilot operation to limit adsorption of CO_2 onto sorbent prior to entering adsorber.

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Project Goals - LCOE

- Reduce costs of carbon capture
  Progress towards <35% LCOE Goal
  - The <u>process technology</u> developed by ADA and the project team functioned as expected after resolving start-up issues and considering adsorption in carrier gas line from regenerator to adsorber.
  - Although the <u>specific sorbent</u> tested in the pilot did not demonstrate the ability to reduce costs for carbon capture compared to MEA during pilot testing, modeling suggests it should with pilot modifications.
  - Sorbent properties were identified that will lead to development of sorbents capable of reduced costs for carbon capture

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Sorbent Properties

- Summary of Sorbent BN performance
  - Predicted CO_2 working capacity was 7%
  - Maximum CO_2 working capacity calculated with pilot operation results is 5.4%
  - Sorbent BN adsorption of CO_2 across adsorber was limited due to adsorption in carrier line between regenerator and adsorber
  - Flowability properties at elevated temperatures lead to sorbent transfer limitations and pluggage in cyclone diplegs
- Future Development and Focus Areas
  - Characterize sorbent flow properties for entire range of expected temperatures
  - Expand analysis of interplay between H_20 and CO_2 capacities and the effect on CO_2 working Capacity
  - Modify pilot and pilot operation to mitigate CO2 adsorption onto sorbent prior to entering adsorber

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Project Goals – Scale Sorbent

- Successfully Scale Sorbents:
  - Over 250 sorbents were screened
  - Multiple sorbents were characterized in detail
  - Manufacturing and processing of the selected sorbent was successfully accomplished
  - Sorbent in quantities needed for pilot demonstration were delivered on time for the pilot demonstration
- Future Development Areas
  - Develop manufacturing which minimizes processing, reduces costs and possibly retains original spherical shape to minimize attrition
  - Identify domestic manufacturer of sorbent

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Project Goals – Product Purity

- Generate High Purity CO_2 Stream
  - A high purity CO_2 stream was generated
  - Target CO_2 Concentration during 90% capture was ~95.0%$_{vol}$ CO_2
  - Sustainable CO_2 Concentration during 90% capture was ~89.4%$_{vol}$ CO_2 +/-5.75%

- Future Development Areas
  - Design consideration for blower air-in leakage will need to be considered

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Overall Conclusions

- A solid sorbent-based post-combustion CO_2 capture TSA process using a 2010-vintage sorbent, produced at large volumes specifically for pilot testing and subsequently modified for testing in a fluidized bed, successfully removed 90% of CO_2 from an incoming flue gas stream from a coal-fired power plant
- Based on pilot results, the sorbent tested at the pilot is competitive with MEA post-combustion capture systems
- Solid sorbents can adsorb CO_2 selectively from coal derived flue gas without concentrating other harmful trace elements such as mercury or selenium
- Laboratory data can be very valuable for design details and predicting performance of larger scale systems

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Additional Slides

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Pilot Design and Actual Performance

		Design	Measured						Units
Flue Gas	Adsorber In	1808	1611	779	824	428	415	350	acfm
Sorbent	Circulation Rate	31107	18439	15103	10070	13183	9876	17993	lb/hr
Sorbent/CO_2 Ratio	ADS Inlet	15.5	9.3	17.1	10.3	25.9	20.0	43.8	lb/lb
CO2 Inlet (%)	ADS Inlet	13%	13%	13%	13%	13%	13%	13%	%
CO_2 % Capture		90.0%	13.6%	52.0%	42.0%	94.0%	82.0%	87.0%	Weight %
CO_2 Working Capacity		7.0%	1.5%	3.3%	4.4%	4.0%	4.3%	2.2%	% CO_2|Sorbent
H_2O Working Capacity		1.0%		0.53%	0.86%	0.28%	0.27%		%H_2O|Sorbent
CO_2	Fluidizing	343	262	267	195	237	229	306	acfm
	Transfer to REG	67	114	90	90	100	90	115	acfm
	Transfer to ADS	252	240	250	254	254	255	213	acfm
Density	Bottom ADS bed	15	15.3	19.8	19.3	20.7	22.4	23.3	lbs/cf
	Middle ADS bed	15	14.2	21.6	20.8	23.9	23.3	24.5	lbs/cf
	Top ADS bed	15	15.7	20.4	20	22.3	22.2	23.5	lbs/cf
	Regenerator	26	18	17.3	19	18.6	18.6	17.5	lbs/cf
Bed Height	Bottom ADS bed	13.3	11.5*	10.5	9	10.5*	7.5	7.8	ft
	Middle ADS bed	13.3	9.5*	7.5	8	8*	6	6	ft
	Top ADS bed	28.9	18*	17	21.5	22.5*	23	17.9	ft
	Regenerator	17	18*	17	16	20.5	15.5	15.9	ft
Temp	Bottom ADS bed	40	40	43	40	42	37	40	C
	Middle ADS bed	40	39	43	41	45	41	44	C
	Top ADS bed	40	43	51	42	43	41	46	C
	Regenerator	120	114	119	118	121	117	119	C
Adsorber In	BLW 101 Outlet	5.9	6.9	6	7	7	6.8	6	psig
	CO_2	13.1	13.1	13.7	13.8	13.8	13.1	14	%
Adsorber Out	ADS Outlet	1.0	1.43	0.38	0.45	0.32	0.32	0.3	psig
	CO_2	1.58	10.4	6.5	7.8	0.9	2.4	1.8	%
Regen Out	$CO_{2\,(dry)}$	93.4	89	96.8	85.5	88.8	85.5	89.9	$\%_{(dry)}$

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