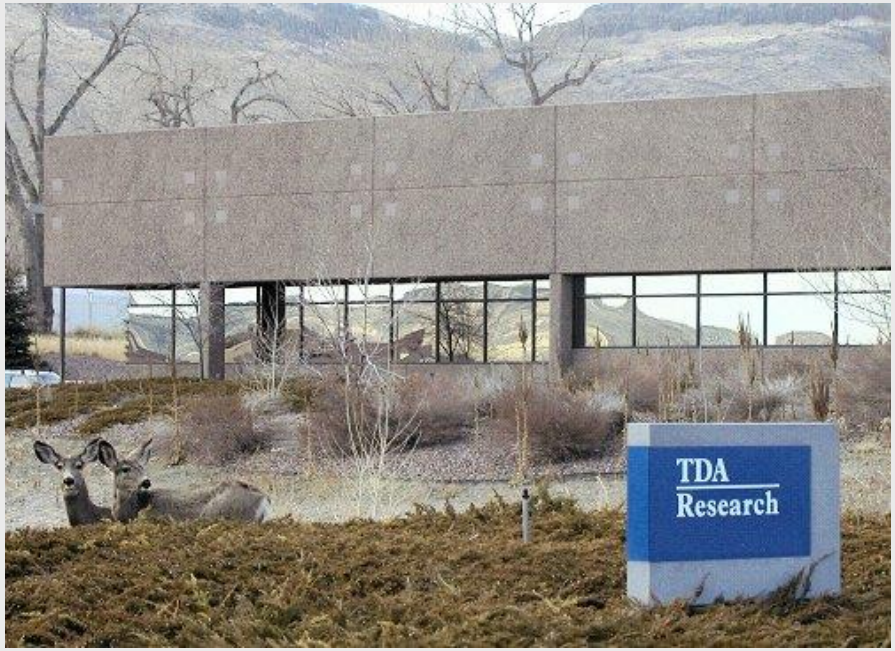
Post-Combustion CO_2 Capture with Low Cost Solid Sorbent Slipstream Testing

Project # DE-FE0012870



2016 NETL CO_2 Capture Technology Meeting

August 9, 2016

Dr. Jeannine Elliott

Dr. Bob Copeland

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

Project Objectives

- The objective is to develop solid sorbent capture technology that captures CO_2 at less than $40 per tonne w/o TS&M
- Demonstrate TDA's sorbent technology under realistic conditions at 0.5 MW_e (~10 tpd) scale to collect data necessary for scale up to next level plant
- Major Project Tasks
  - Design, construction, and operation of slipstream test unit to capture CO_2 from flue gas at the National Carbon Capture Center (NCCC)
- Successful project completion will move the technology along the commercialization road map towards slipstream demonstrations and multi MW installations by 2020-2025

National Carbon Capture Center

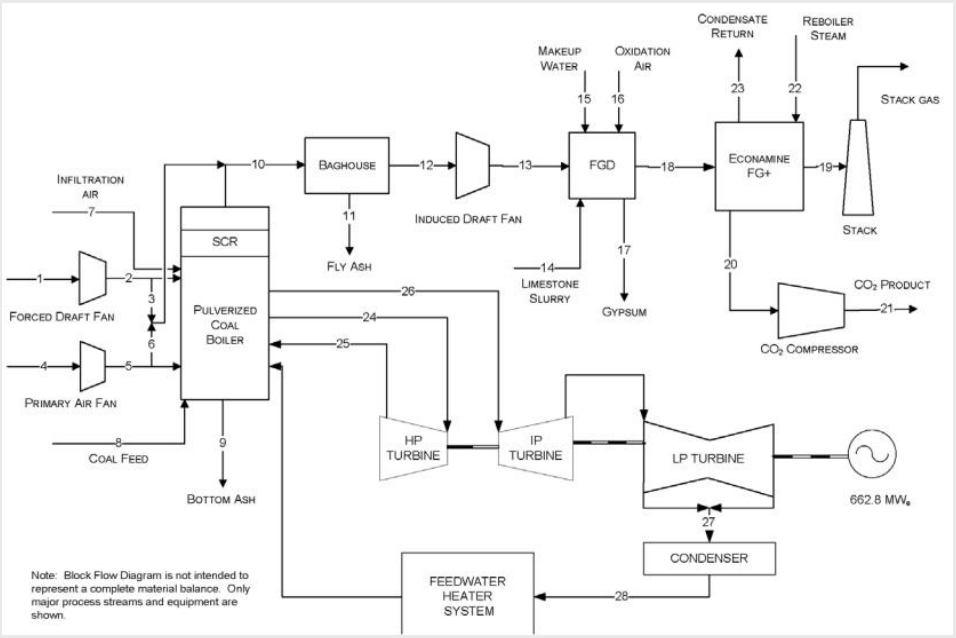
DoE Project DE-FE0012870
Funding - Total Project $6,480,377

TDA Research

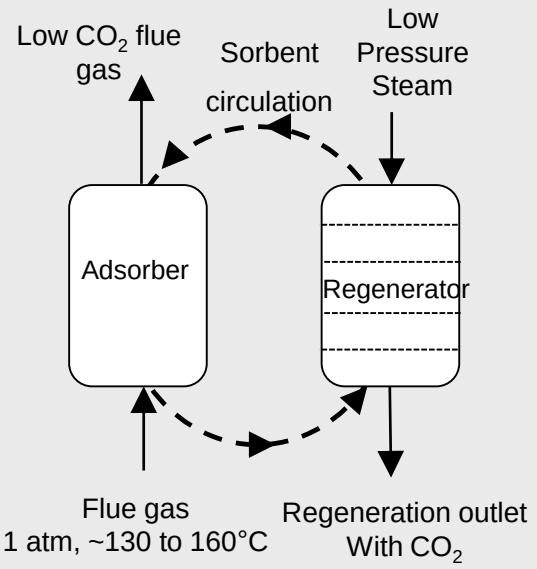
TDA's Approach

TDA Research has developed:

- A low-cost, solid alkalized alumina adsorbent, and
- A CO_2 capture process designed around this process



TDA CO_2 Capture on Supercritical 550 MW plant



- Moving bed had expensive conveyors, although the beds would be smaller
- New multiple fixed bed design
  - Basic duct work
  - Low cost construction
  - Simple bed design
  - Eliminates power lost when moving the sorbent
- Lower overall cost than moving beds

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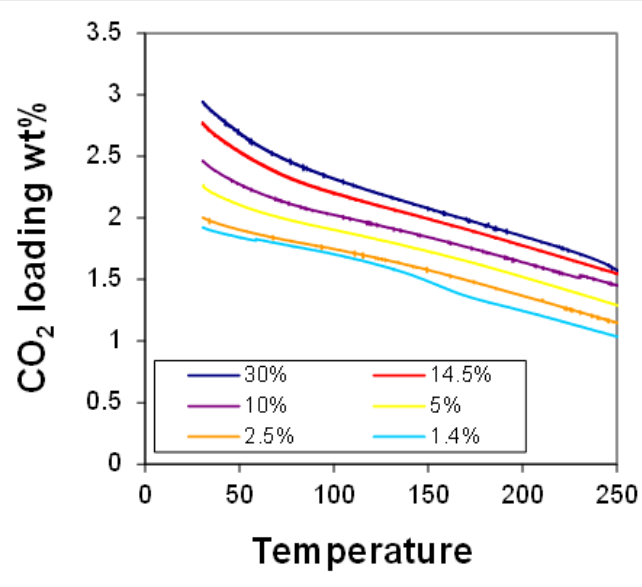
TDA's Post Combustion CO_2 Capture

- **Process advantages:**
  - Low cost sorbent material
  - Regenerates with low pressure (inexpensive) steam
  - Operates at near isothermal conditions, ambient pressure
  - Does not require heat recovery from the solid sorbent
  - Uses counter-current operation to:
    - Maximize capture efficiency
    - Maximize sorbent loading

- **Patents filed July 2014**
  - Pending U.S. and PCT applications
  - Two applications have received notices of allowance



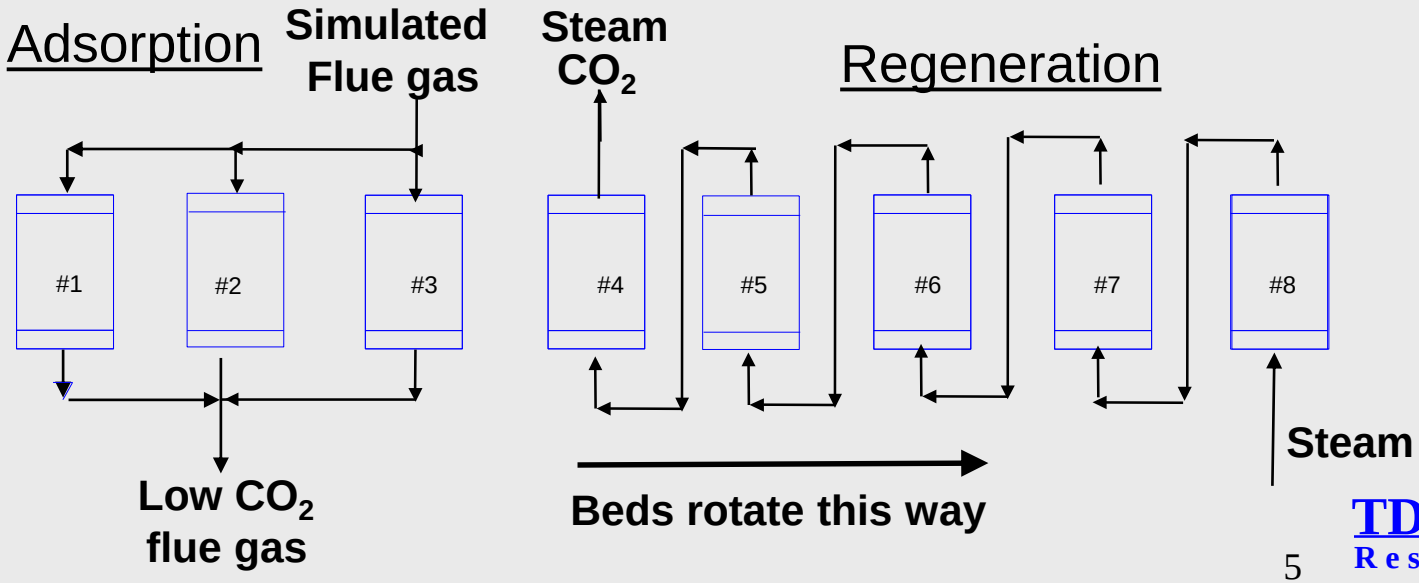
Heat of adsorption

Heat of adsorption ranges from 3 kcal/mole at higher CO_2 concentrations of 10-14%, to 10.3 kcal/mole at CO_2 concentrations of 1-5%

Simulated Moving Bed Process

- **Slipstream project builds on previous DoE funded research**
  - Contract #DE-NT0005497
  - $1,714,846 Project
- **Investigated capture process in single fixed bed reactor**
- **Demonstrated continuous CO_2 capture in 8 bed bench-scale unit**

Demonstrated in field testing with coal derived flue gas at Western Research Institute (Laramie, WY)



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Project Scope

- **Budget Period 1: Optimization & Design**
  - April 2014 to Feb 2016
- **Budget Period 2: Construction & Installation**
  - March 2016 to May 2017
- **Budget Period 3: Operation**
  - June 2017 to Aug 2018

Progress to Date

- Redesigned a bench-scale apparatus to test and optimize the design of the slip stream unit we plan to build and test
- Preliminary TEA carried out by University of California Irvine UCI (Nov 2014). Further analysis of improved (and demonstrated) process (Jan 2016) gave a CO_2 capture cost of $38.7/tonne, which meets DoE's goal of capturing CO_2 at <$40/tonne without TS&M
- Preliminary EHS report submitted June 26, 2015
- Formal Process Hazard Analysis (PHA) on September 29-30, 2015, facilitated by the Process Improvement Institute
- Completed Design Package for 0.5 MW_e Pilot Unit and submitted it to DoE on Feb 10, 2016.
- Budget Period 1 Review March 7, 2016
- Sorbent continues to advance in sorbent scale up
- Further evaluation of process design trade-offs with improved sorbent
- Subcontract awarded for pilot unit construction to Springs Fabrication, Inc.

Budget Period 1 Tasks

- **Task 1: Project Management**
- **Task 2: Preliminary Techno-Economic Analysis**
  - based on integration with a nominal 550 MW_e greenfield supercritical plant
- **Task 3. Pilot Plant Design Optimization**
  - Process experiments to finalize process design
  - Basic Process Specification and Design
- **Task 4. Pilot Plant Detailed Design and Engineering**
  - Design a 0.5 MW_e pilot plant to capture 10 tons per day of CO_2,
  - Perform an initial Environmental, Health and Safety (EH&S) study
  - Hazard Review
- **Task 5. Determine Slipstream Unit Construction Cost**
  - Develop a firm cost estimate for the slipstream unit

Design Optimization

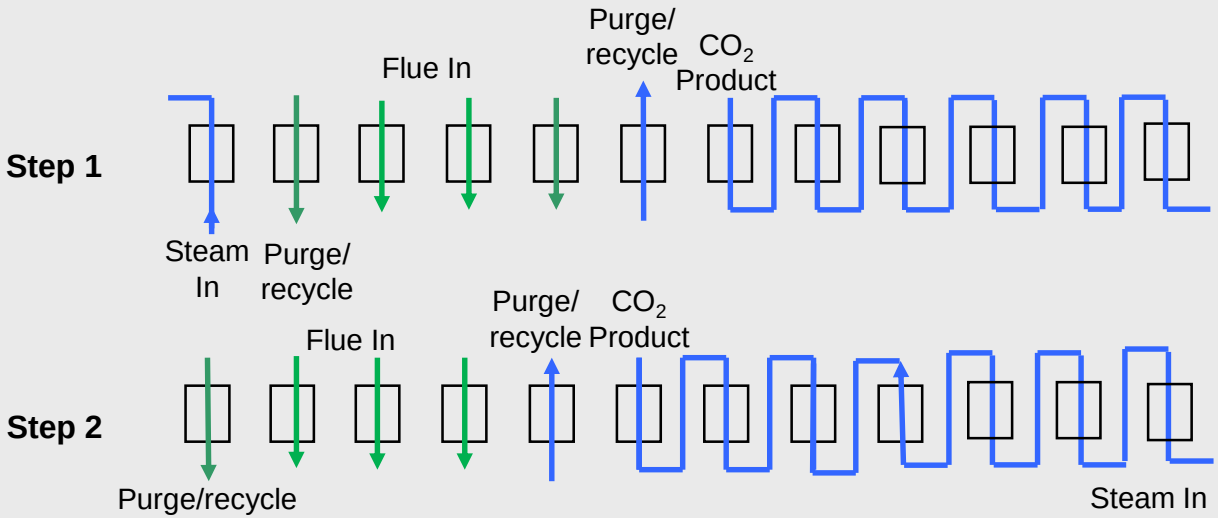
- **Process optimization in bench-scale unit conducted to determine optimum flow/cycling logic for pilot unit**
  - Previous 8 bed apparatus had limited ability to simulate recycle options
- Multiple design improvements, modifications, and experimental tests

Previous 8 bed bench-scale unit

- The bench-scale experimental data for the optimal process was used for the preliminary TEA and as design basis for pilot unit

Multiple Bed Process Design

- **Multiple Fixed Bed Contactor**
  - Provides counter-flow contact between the solids and gases
- **Beds cycle between adsorption and regeneration functions**
- **Gas flows in parallel through adsorption beds and in series across regeneration beds**



- System expanded to 12 bed to increase stages and evaluate transition steps
- Separate control for transition

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Features & Benefits of Multi-Bed Design

- Previous TDA bench-scale apparatus had 8 beds and limited ability to simulate recycle step options
- Bench-scale unit was rebuilt with 12 bed apparatus to allow evaluation of improved flow patterns and better simulation of slip stream unit/ commercial system

Feature	Advantage	Benefit
12 beds (vs. 8 beds)	Additional regeneration stages	• Additional stripping for same steam usage • Beds needed for transition steps • Trade-off of adding more beds
Steam saver recycle with controlled flow and timing	Steam recycled back to regeneration side to rehydrate bed can be optimized in controlled manner	• Steam usage decreased • Steam saver can now be tuned for maximize benefit
Purge	Additional regeneration	• Higher capture rate • Less steam usage
Adsorption Breakthrough recycle	Effluent flue in last adsorption bed recycle back to feed to keep capture up	• This recycle option was not available in previous bench-scale apparatus

- TDA collected data to evaluate optimized process conditions and performance of recycles/purge steps

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Flow Pattern Comparison Testing

- **Collected data to evaluate optimized process conditions and performance of recycles/purge steps**
  - Optimum number of beds in adsorption and regeneration
  - Flow pattern options: steam saver, air strip, and breakthrough recycle
  - Flow direction up and down for steam saver and air strip
  - Time/flow for steam saver step
- **Experimental results used in TEA**

Expanded Bench-scale Apparatus

Higher capture rate with same steam use with use of transition Steps

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Preliminary Techno-Economic Analysis

- Integration with greenfield supercritical 550 MW coal fired power plant
  - Cost and Performance Baseline for Fossil Energy Plants (Black 2010) Case 12
- Analysis followed DoE guidelines
- Work performed with University of California at Irvine (UCI)
  - Dr. Ashok Rao of Advanced Power and Energy Group developed ASPEN model around process and determine cost of CO_2 capture
- TEA performed at start of BP1 based on performance at end of previous project (Contract #DE-NT0005497) and after process improvement in BP1

TEA on Improved Process

- Based on experimental data (SV, steam usage) for expanded process
- Boiler Feed Water used to heat flue gas (coal derived heat)
- Included costs of 12 beds, air blower, condenser on air purge outlet, boost flue gas for breakthrough recycle
- Very recent data shows further optimization of sorbent and process which we are analyzing in additional TEA

CO_2 Capture Technology	No Capture Case 11	Amine Capture Case 12	TDA
Carbon Captured,%	0	90	90
Steam Turbine Power, KWe	580,400	662,800	658,003
Total Auxiliary Consumption, KWe	30,410	112,800	108,003
Net Power Output, KWe	550	550	550
% Net Plan Efficiency, HHV	39.3	28.4	29.51
As-received coal feed, kg/h	185,759	256,652	247,258
Natural Gas Feed, kg/h	0	0	0
Raw Water Withdrawal, min^3/min	20.1	38.1	34
1 rst year cost of electricity (COE), $/MWh, 2007$	58.9	100.9	92.8
1 rst year CO_2 capture cost w/o TS&M, $/tonne, 2007$	-	42.1	34.7
1 rst year CO_2 capture cost w/o TS&M, $/tonne, 2011$		**46.9**	**38.7**

$$Cost\ of\ CO_2\ Captured = \frac{(COE_{With\ CC} - COE_{Without\ CC})}{CO_2\ Captured}$$

CO_2 Capture cost = $38.7/ tonne (2011 $)

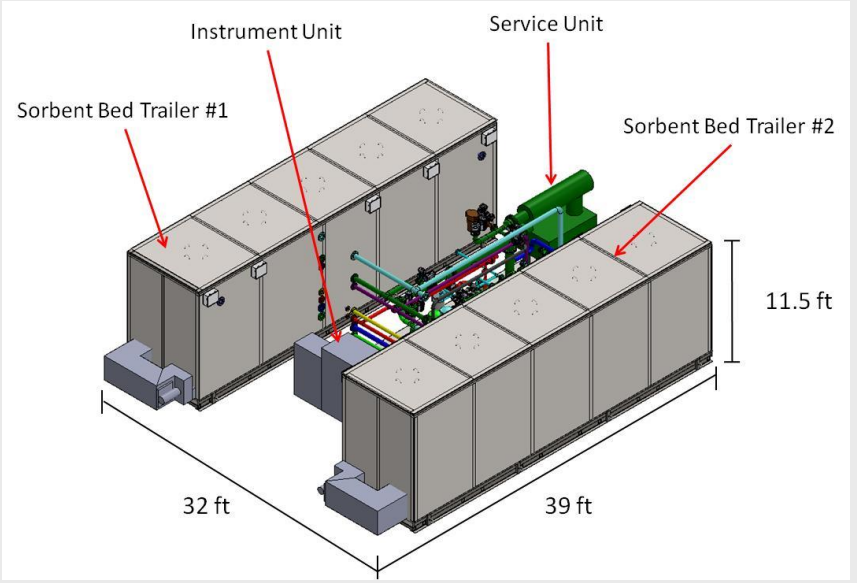
- **Design system (demonstrated in bench-scale experiments) meets DoE goal of CO_2 capture < $40/tonne without TS&M**

TDA Research

Pilot Unit

- **0.5 MW_e slip stream test with 5000 lb/hr of flue gas**
- Adsorber/Regeneration Contractor is a multiple fixed bed unit
- Sorbent is regenerated by steam
- Adsorber/Regenerator operates near isothermal (adiabatically) at 120 to 140°C with about 17 psia steam
- Operation pressure is near atmospheric pressure
- Coal flue gas: 12.14% CO2, 13.3% H_2O and 5.2% O_2
- Designed based on bench-scale experimental data

4 Skid Mounted Units:
- **Two sorbent bed trailers**
- **Service unit** (heat exchangers, blowers, flow metering, exhaust coolers)
- **Instrument unit** (control system and gas analysis



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Pilot Unit Design

2 Sorbent Bed Trailers

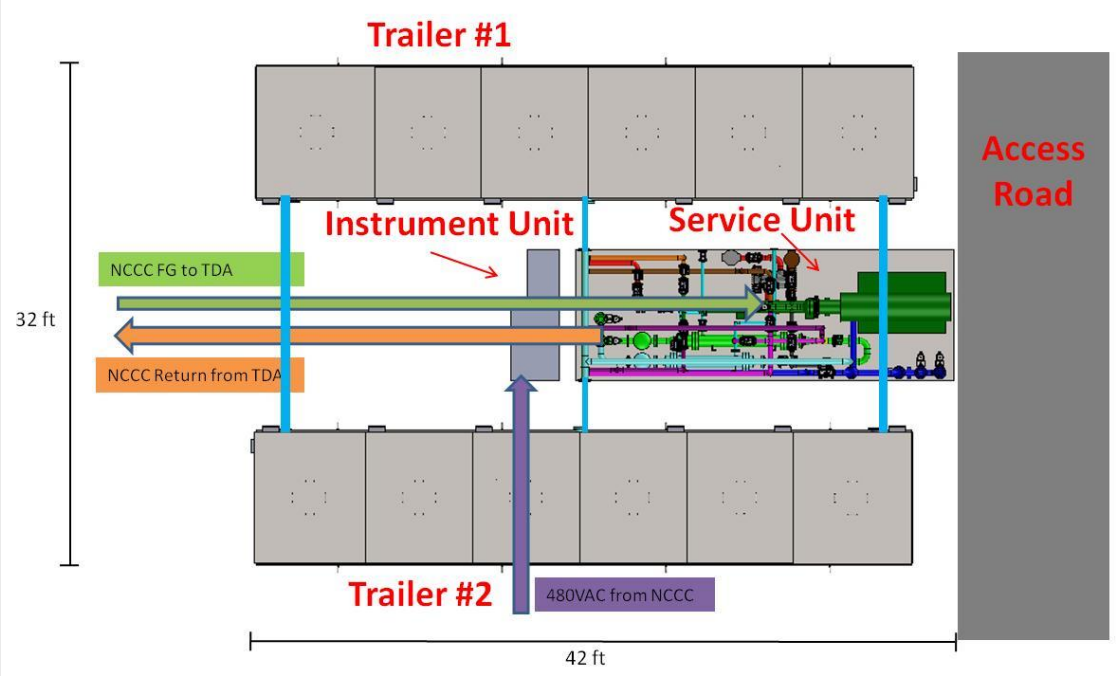
- Sorbent trailer houses sorbent beds and manifold piping
- Each trailer is insulated and heated to provide an isothermal environment within

1 Service Unit Trailer

- Pressure, temperature and flow control for each process gas
- Each process gas routed to both sorbent bed trailers

1 Instrument Unit

- Houses the control system and all electrical components for power allocation
- A full suite of on-board analyzers to evaluate system performance



System was planned to be located at NCCC Post-Combustion Pilot Bay #3

- **Computational fluid dynamics (CFD) calculations to analyze flow paths and pressure drops through the sorbent beds.**
- **Design package submitted to DoE**

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Preliminary EHS

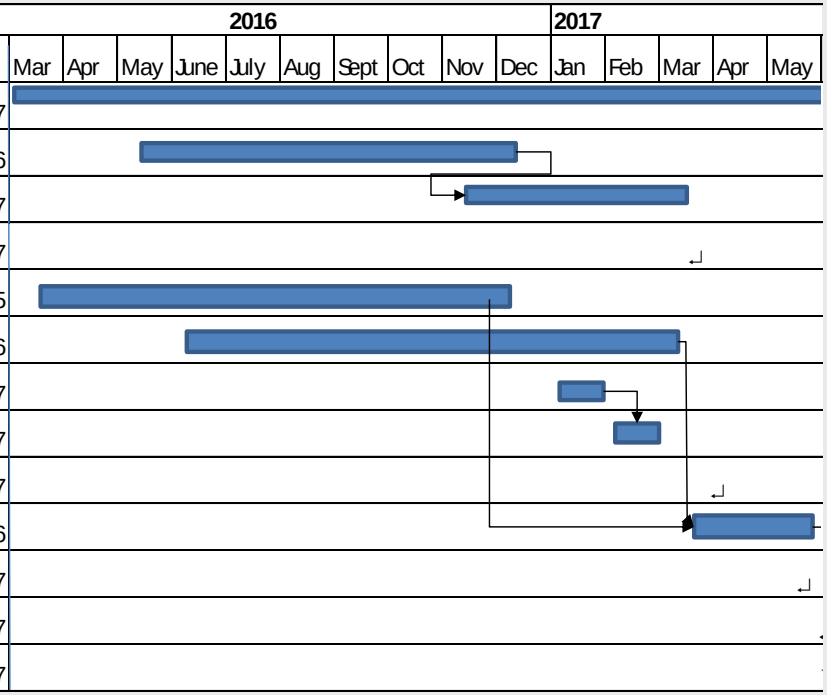
- A preliminary EH&S study was completed (June 2015) on the pilot plant operation and sorbent production.
- The sorbent is comprised of low hazard materials, primarily inorganic compounds. All are solids at ambient temperatures, and have low NFPA ratings for health, fire, and reactivity risk
- The sorbent production process does not utilize any toxic or hazardous materials.
- Sorbent loading and unloading will be conducted in accordance with all relevant regulations with appropriate PPE to manage dust exposure.

HAZOP Review

- Before finalizing the Pilot Unit's PI&Ds, TDA conducted a preliminary Hazard Review with NCCC on May 12, 2015.
- A detailed Failure Modes and Effect Analysis (FMEA) was also carried out at TDA to identify safety vulnerabilities and correct them in the design
- A formal Process Hazard Analysis (PHA) was conducted on September 29-30, 2015.
  - Facilitated by Process Improvement Institute, Inc. with the National Carbon Capture staff in attendance
  - Used HAZOP analysis along with the What-If? methodology
  - All recommendations incorporated into Pilot Unit design

Budget Period 2

Task Name	Start	Finish
Task 1. Project Management	3/1/2016	5/30/2017
Task 6.1 Sorbent Production	5/1/2016	12/1/2016
Task 6.2 Sorbent QA/QC Testing	11/1/2016	3/15/2017
Milestone 6-1: Sorbent scale-up QA/QC		3/15/2017
Task 7.1 Fabrication of Adsorber Unit	3/1/2015	10/1/2015
Task 7.2 Fabrication of other Modules	6/1/2015	1/1/2016
Task 8.1 Finalize Slip stream Test Plan	1/1/2016	2/1/2017
Task 8.2 Operator Training	2/1/2016	3/1/2017
Milestone 8-1: Finalize Test Plan		4/1/2017
Task 9. Appartus Integration at host site	3/15/2016	3/15/2016
Milestone 9-1: Installation of Pilot Unit		5/15/2017
Milestone 9-2: Year 1 Annual Review		5/20/2017
Go/ No go Decision Point	5/31/2017	5/31/2017



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Budget Period 2 Tasks

- **Task 6. Sorbent Production Scale-up and Quality Assurance**
  - Scale-up production of the sorbent to 30,000 lbs
    - Two producers had competitive prices for sorbent production
  - Sorbent is alkalized alumina - not exotic material
  - Sorbent QA/QC testing at TDA in bench-scale unit
  - Sorbent will be tested under proposed test conditions
  - Evaluation of optimum steady state conditions
- **Task 7. Procurement of Components and Fabrication of Units**
  - Construction of four skid-mounted units
  - Fabricator constructing skid structure, manifolds and beds on two sorbent trailers. Instrument unit will be built at TDA
  - Beds fabrication will be inspected prior shipment, control system shakedown on cold system, 30 days FAT testing

Budget Period 2 Tasks

- **Task 8. Finalize Test Plan**
  - Operating conditions and key parameter parametric conditions selected
  - Operator training
- **Task 9. Pilot Plant Installation at NCCC**
  - Units transported to NCCC
  - Skid Units installed
  - Beds filled with sorbent
  - Tie-ins with NCCC

Sorbent Production

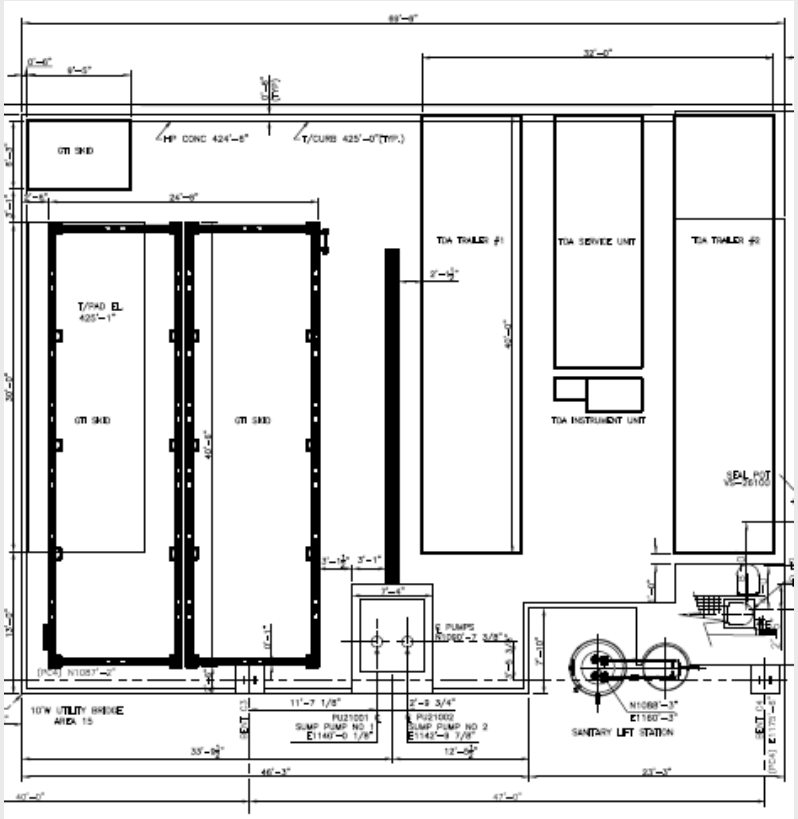
- Contacted five companies about toll production of the sorbent
- Sorbent production cost ranged from $6.5/lb to $20/lb
- Based on discussions with the manufacturers, this sorbent could be made for $2/lb when the technology is commercialized and installed across the power plant sector
- Intermediate scale-up to 100 lb batches planned for September 2016, and then full production scale-up

Continued Progress

- During sorbent production scale-up research, the sorbent performance has continued to advance
- We evaluated the improved sorbent and compared the trade-off with steam usage and process complexity
  - TDA analysis showed the breakthrough recycle process step does not benefit overall process economics
  - Increase in SV with some increase in regeneration steam usage looks promising
- Four additional cases with UCI to define sensitivity of capital, operating cost and regeneration steam usage

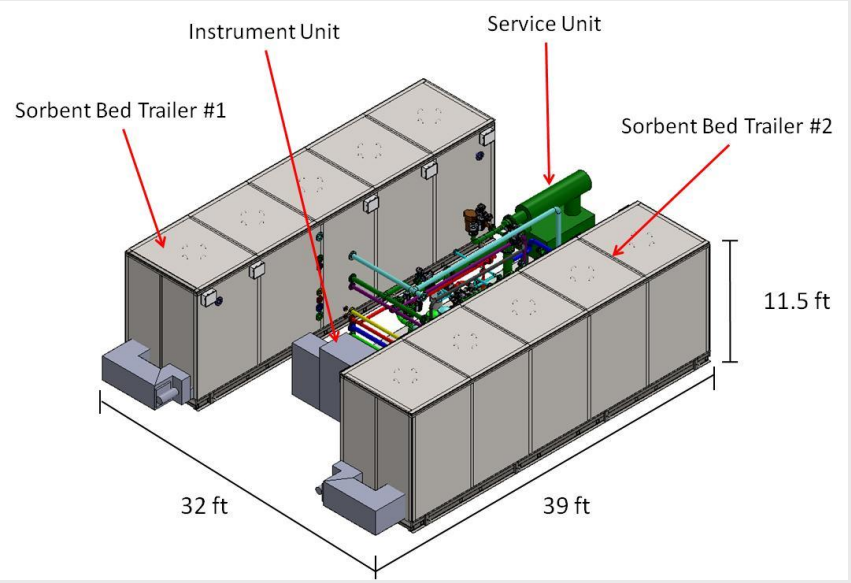
Slipstream Unit Construction

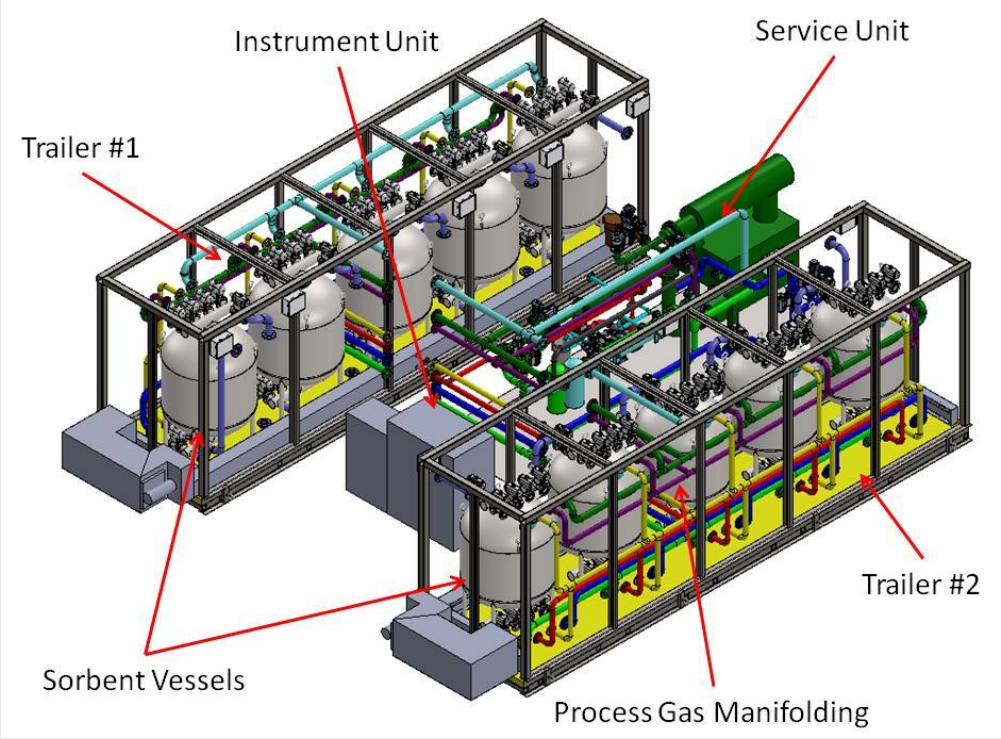
- Sorbent Trailers and Gas conditioning units are being fabricated by Spring Fabrication, Inc. in Colorado Springs
- Instrument control unit is being fabricated at TDA



System now planned to be located at NCCC Pilot Bay #2 ~42’ x 35’

Pilot Unit Skids





- Pilot Unit operates at ambient pressure with near isothermal operation at 140°C

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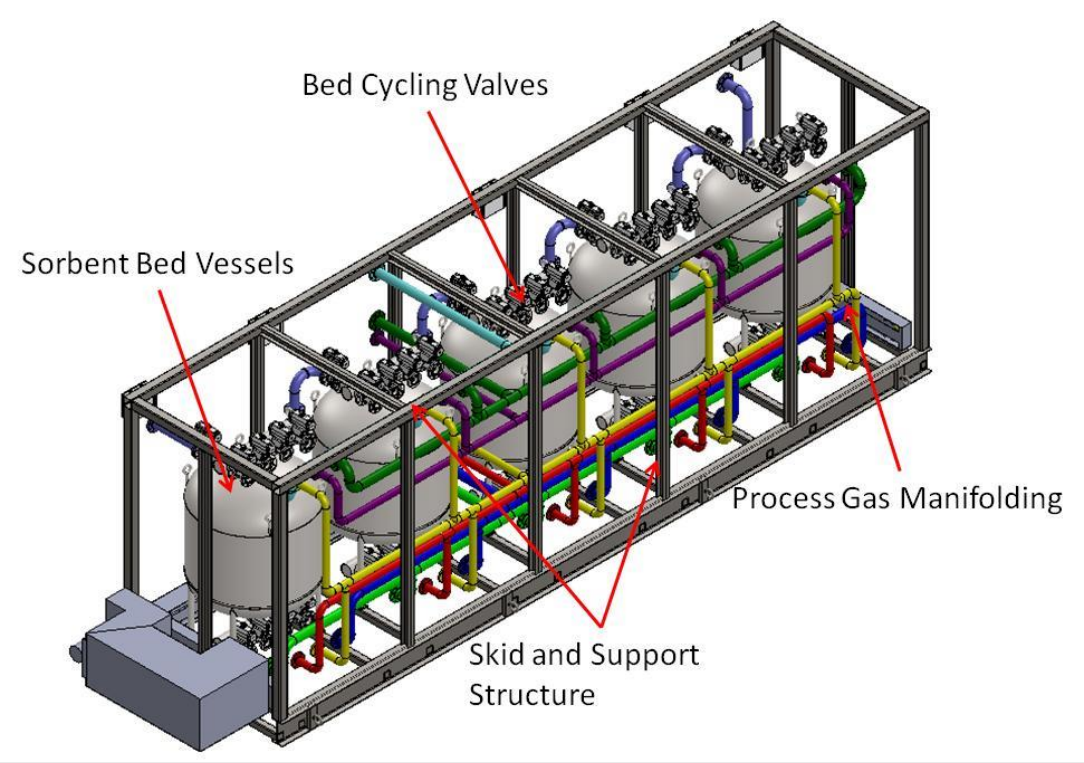
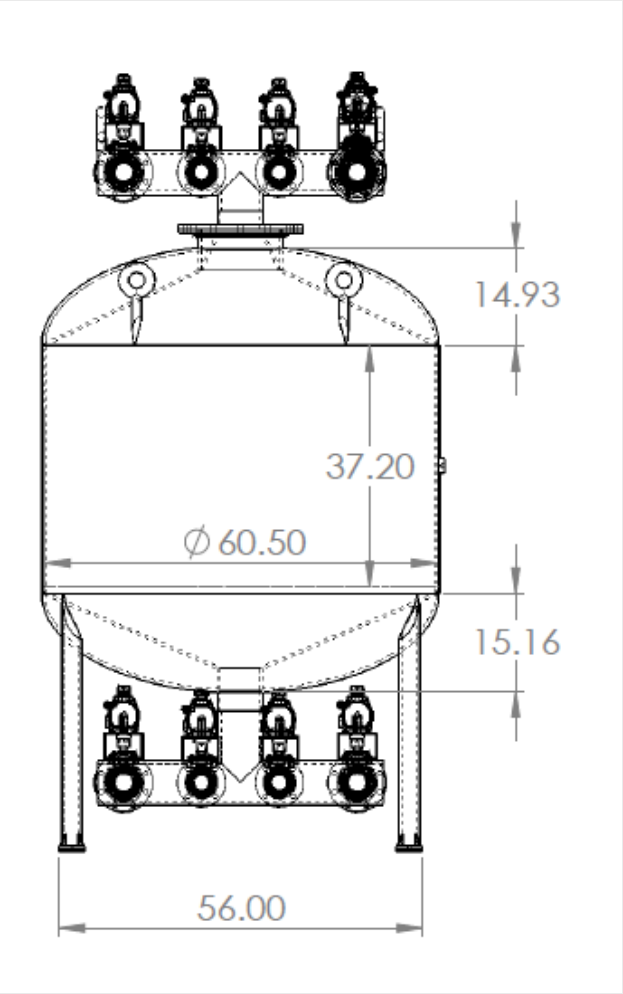
Sorbent Trailer





- Two Sorbent Trailers (8.5 ft x 33 ft) each contain five cylindrical packed sorbent beds

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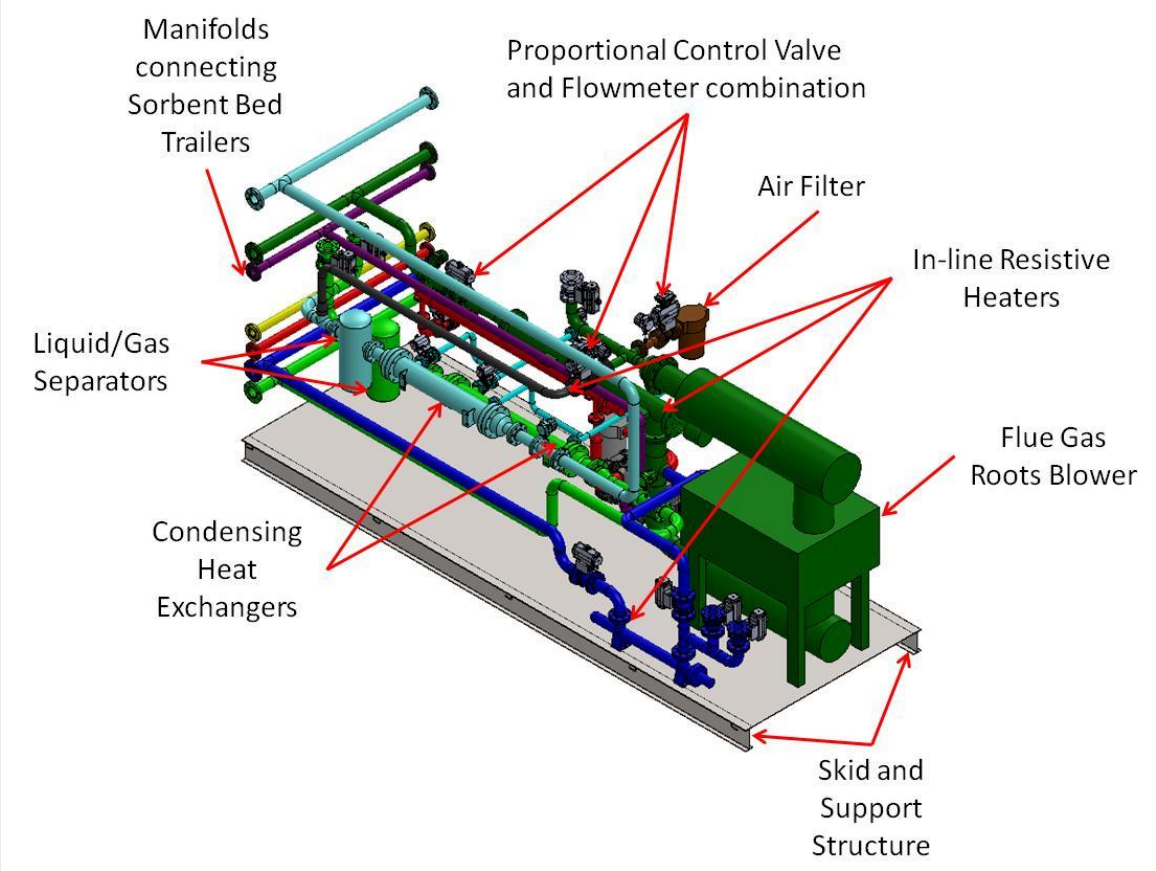
Service Unit

- **Service Unit controls the flow, pressure and temperature of the flue gas and steam to the sorbent beds.**



Service Unit Skid (23 ft x 8ft)

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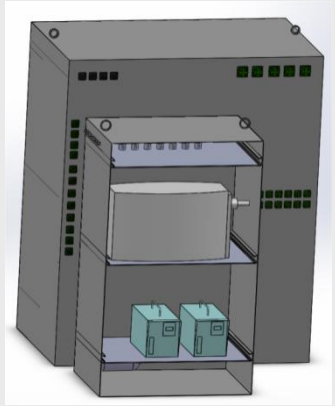
Instrument Unit

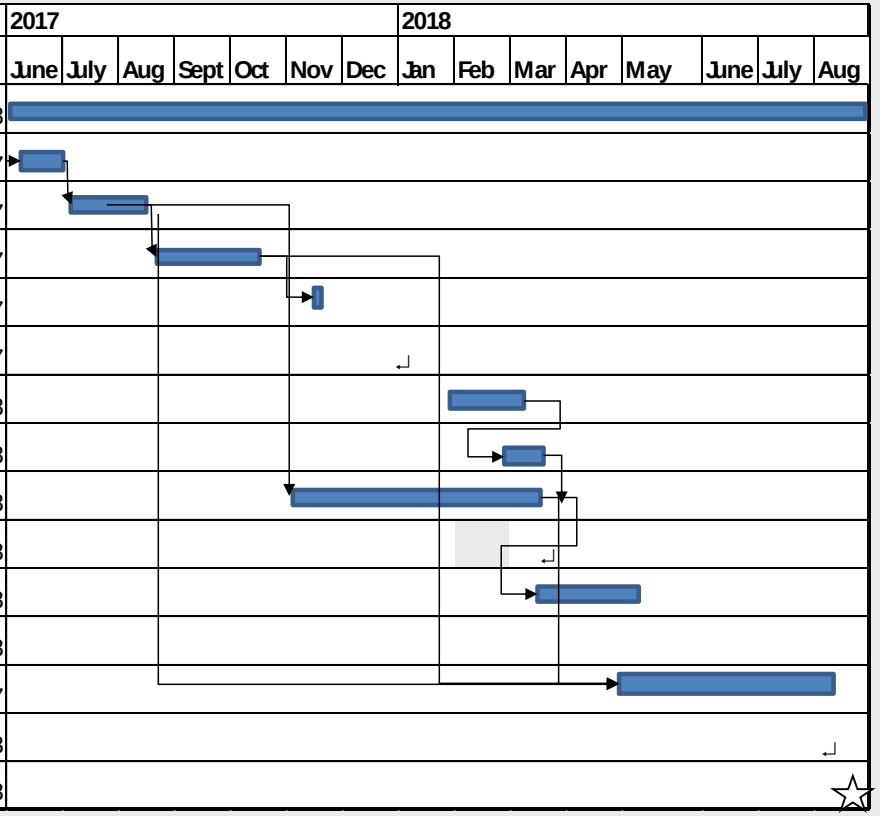
- The instrument unit contains the control system, operator interface, and equipment for gas analysis.
- To calculate capture rate and sorbent loading we will continuously sample the flue feed, flue effluent and product stream
  - Measure total flow and gas composition



- We can also monitor the concentration of individual sorbent beds with a mass spectrometer to tune performance and optimize system operation

Budget Period 3 Schedule

Task Name	Start	Finish
Task 1. Project Management	6/1/2017	8/31/2018
Task 10. Shakedown of Pilot-Unit	6/1/2017	6/30/2017
Task 11.1 Parametric Testing	7/1/2017	8/15/2017
Task 11.2 Steady State Testing	8/15/2017	10/15/2017
Task 11.3 Decommisssioning	11/1/2017	12/15/2017
Milestone 11-1: Complete Pilot-scale Test		12/31/2017
Task 12.1 Characterization of Sorbent	1/15/2018	3/1/2018
Task 12.2 Sorbent Cost & Replacement	2/1/2018	3/1/2018
Task 13 Slip Stream Testing Data Analysis	9/1/2016	3/1/2018
Milestone 13-1: Update Table of State		3/1/2018
Task 14. Final EH&S Study	3/1/2016	5/1/2018
Milestone 14-1: Complete EH&S Analysis		5/1/2018
Task 15. Update Techno-Economic Analysis	4/1/2017	8/15/2017
Milestone 15-1: Complete Updated TEA		8/15/2018
Milestone 15-2: Year 3 Annual Review		8/31/2018



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Budget Period 3 Tasks

- **Task 10. Shakedown of slipstream unit.**
- **Task 11. Operation of Slipstream Unit**
  - Demonstrate this process in slipstream testing at the NCCC under both parametric and steady state conditions using coal derived flue gas.
- **Task 12. Post-Testing Sorbent Analysis**
  - Characterize physical and chemical properties of sorbent after testing
  - Determine Sorbent cost, useful life and replacement rate
- **Task 13. Slipstream Testing Data Analysis**
  - Data from the pilot plant test will be used to develop recommendations for the next level of scale up

Budget Period 3 Tasks

- **Task 14. Update EH&S Study**
  - Update based on results of slipstream test
  - Review CO_2 capture process and sorbent manufacturing
- **Task 15 Update Techno-Economic Analysis**
  - Incorporate performance data from slipstream test into TEA and update results
  - Determine cost of electricity for TDA's sorbent based CO_2 capture process
  - Compare to current state of the art technology
  - Work performed with UCI

Summary

- TDA has improved the multiple fixed bed CO_2 Capture process
  - New flow process demonstrated experimentally in our bench-scale apparatus
- Preliminary TEA showed Capture Cost of $38.7/tonne
- Experimental results form design based for 0.5 MW Pilot Unit
- Detailed design, HAZOP Review and Preliminary EHS review completed.
- Strong technical and economic merit established for conducting pilot unit test at NCCC
- Project is in Budget Period 2, focused on sorbent scale-up and fabrication

Acknowledgements

- Project funding provided under DoE Contract # DE-FE0012870
- Andy O'Palko
- Lynn Brickett