Update on Pilot Unit of Sorbent Based Post-Combustion CO_2 Capture
Project # DE-FE0012870

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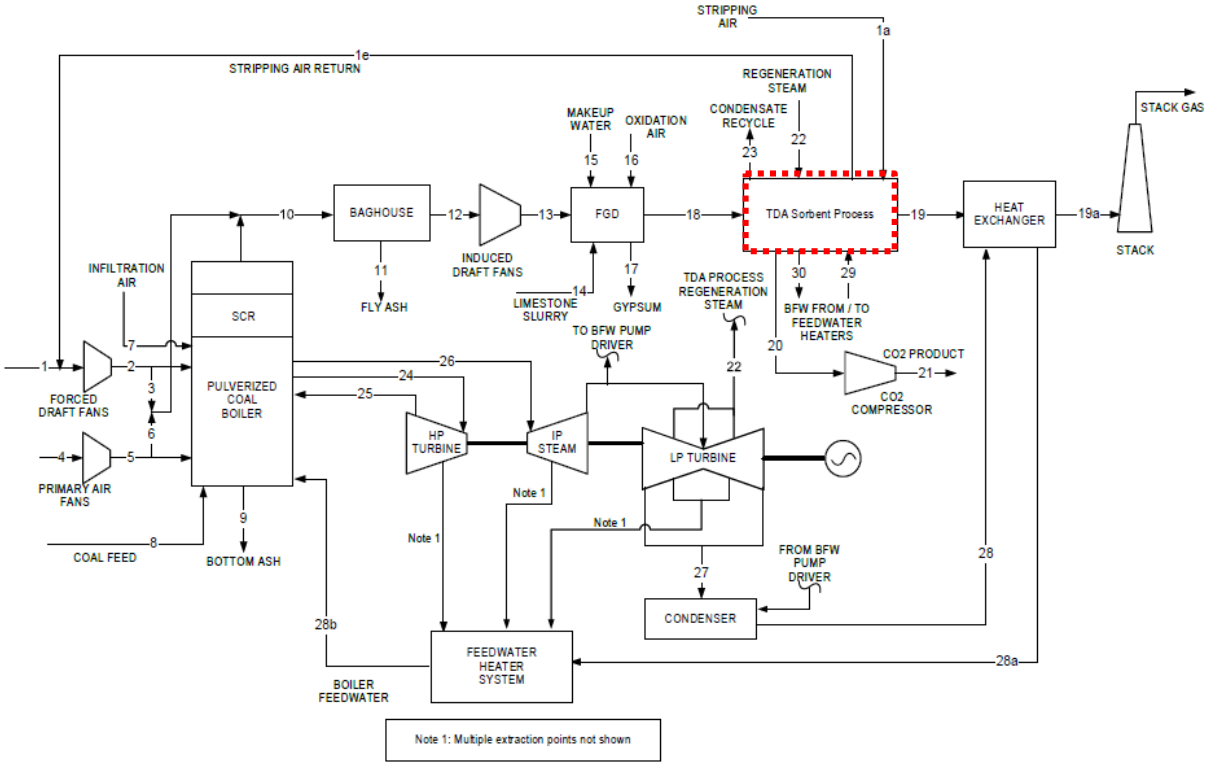
Project Objectives

- The objective is to develop solid sorbent capture technology that captures CO_2 at less than $40 per tonne without TS&M.
- Demonstrate alkalized alumina sorbent technology under realistic conditions at 0.5 MW_e (~10 tpd) scale in National Carbon Capture Center (NCCC) to collect data necessary for scale up to next level plant.



TDA CO_2 Capture on Supercritical 550 MW plant

Project Scope

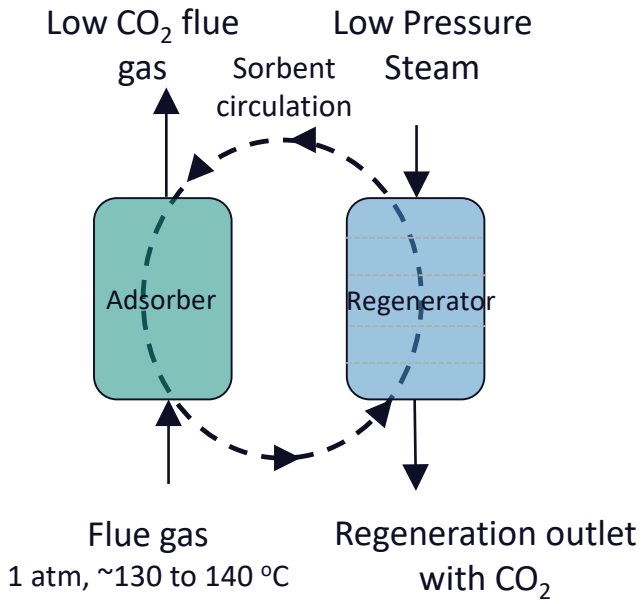
DoE Project DE-FE0012870
Funding - Total Project $6,480,377

- **Budget Period 1: Optimization & Design**
- **Budget Period 2: Construction & Installation**
  - Pilot Unit Construction
  - Sorbent Production Scale-up and Quality Assurance
  - Pilot Unit Installation
- **Budget Period 3: Shakedown & Operation**

TDA's Approach

TDA Research has developed:

- A low-cost, alkalized alumina adsorbent
- A CO_2 capture process designed specifically for this sorbent (A unique CO_2 capture process to run adsorption and regeneration at near isothermal conditions)
- Multiple patents on the process



Advantages over moving bed

- Moving bed had expensive conveyors, although the beds would be smaller
- Selected Multiple fixed bed design
  - ✓ Basic duct work
  - ✓ Low cost construction
  - ✓ Simple bed design
  - ✓ Eliminates parasitic power needed to move the sorbent
- Lower overall cost than moving beds

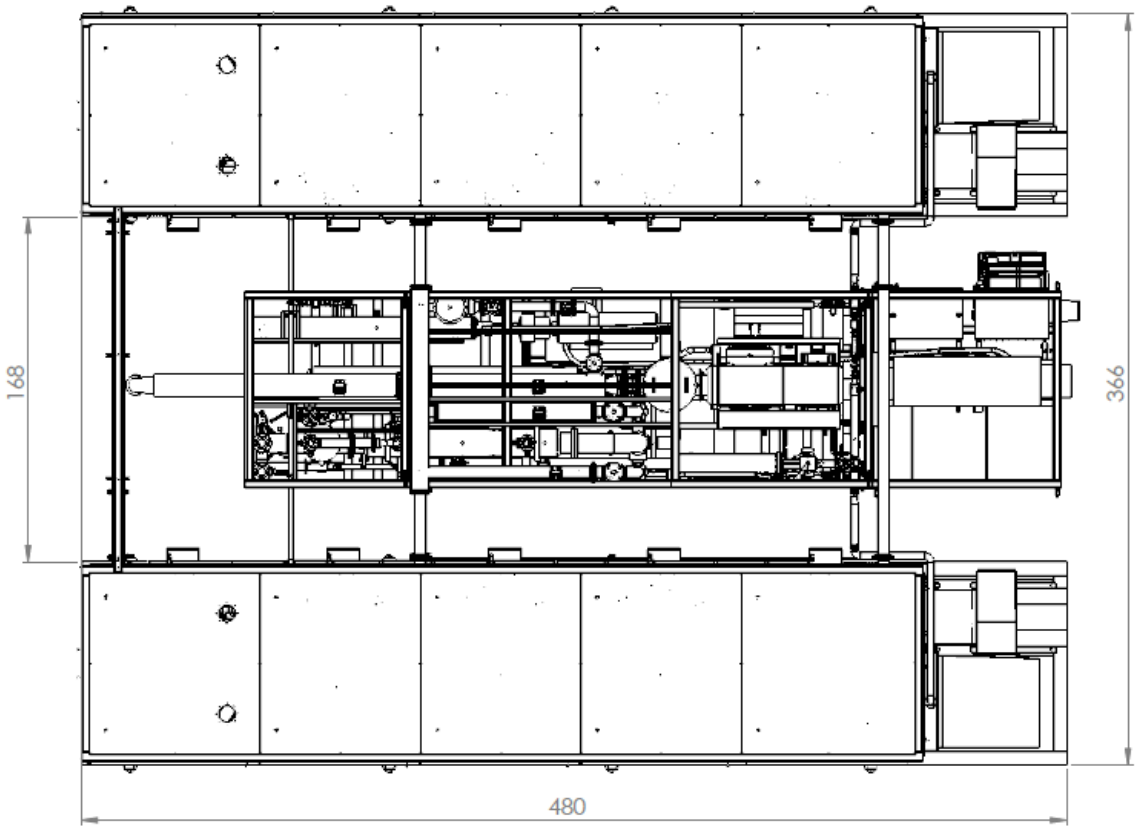
Pilot Unit System
0.5 MW Demonstration

2 Sorbent Bed Trailers

- Sorbent trailers house 10 sorbent beds (5 in each trailer) and manifold piping
- Each trailer is insulated and heated to provide an isothermal environment

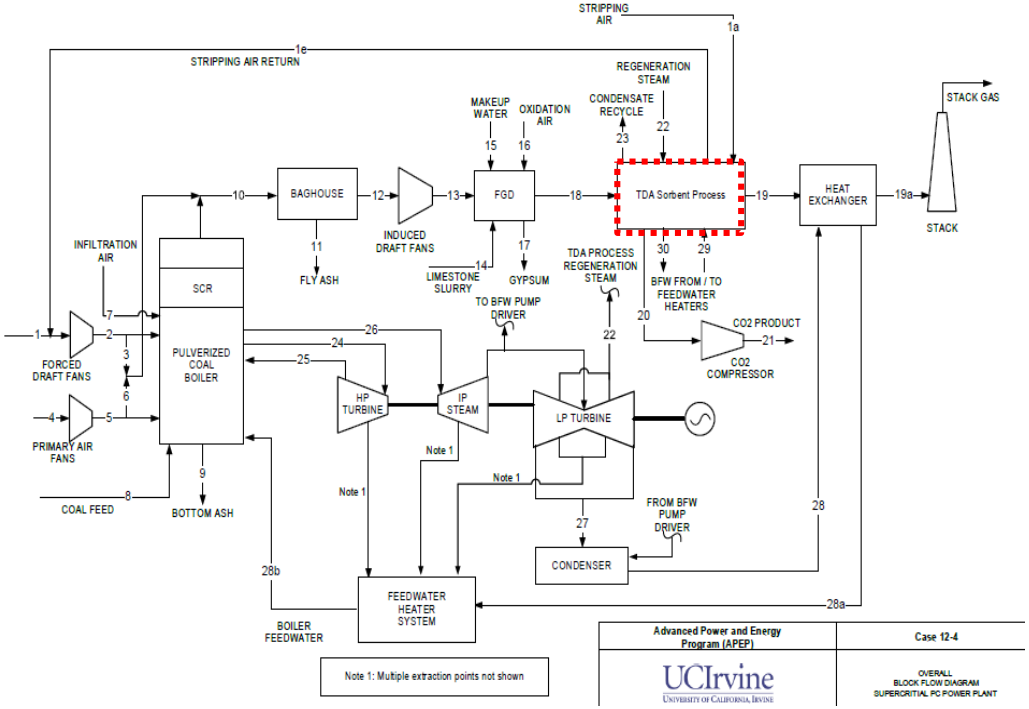
Service Unit/Instrument Trailer

- Pressure, temperature, and flow control for process gases
- Each process gas routed to both sorbent bed trailers
- Houses the control system and all electrical components for power allocation
- A full suite of on-board analyzers to evaluate system performance



Preliminary Techno-Economic Analysis

- Integration with greenfield supercritical 550 MW coal fired power plant
  - CO_2 feed 13%
- 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 on Improved Process

- Based on experimental data (SV, steam usage) for optimized process
- Boiler Feed Water used to heat flue gas (coal derived heat)
- Included costs of 10 beds, air blower, and condenser on air purge outlet
- **Optimized design system demonstrated in bench-scale experiments has $41.2/tonne CO_2 capture without TS&M and $58/tonne CO_2 avoided**

CO_2 Capture Technology	No Capture Case 11	Amine Capture Case 12	TDA Case 3	TDA Case 4
Carbon Captured,%	0	90	90	90
Steam Turbine Power, KWe	580,400	662,800	658,313	658,848
Total Auxiliary Consumption, KWe	30,410	112,830	108,003	108,848
Net Power Output, KWe	550	550	550	550
% Net Plan Efficiency, HHV	39.3	28.4	29.51	29.85
As-received coal feed, kg/h	185,759	256,652	247,258	244481
Natural Gas Feed, kg/h	0	0	0	0
Raw Water Withdrawal, min^3/min	20.1	38.1	34	33.8
1 rst year cost of electricity (COE), $/MWh, 2007$	58.9	100.9	92.8	94.7
1 rst year CO_2 capture cost w/o TS&M, $/tonne, 2007$	-	42.1	38.0	37.0
1 rst year CO_2 capture cost w/o TS&M, $/tonne, 2011$		**46.9**	**42.4**	**41.2**
1 rst year CO_2 avoided cost w/o TS&M, $/tonne, **2011$**		68.0	59.1	58.0

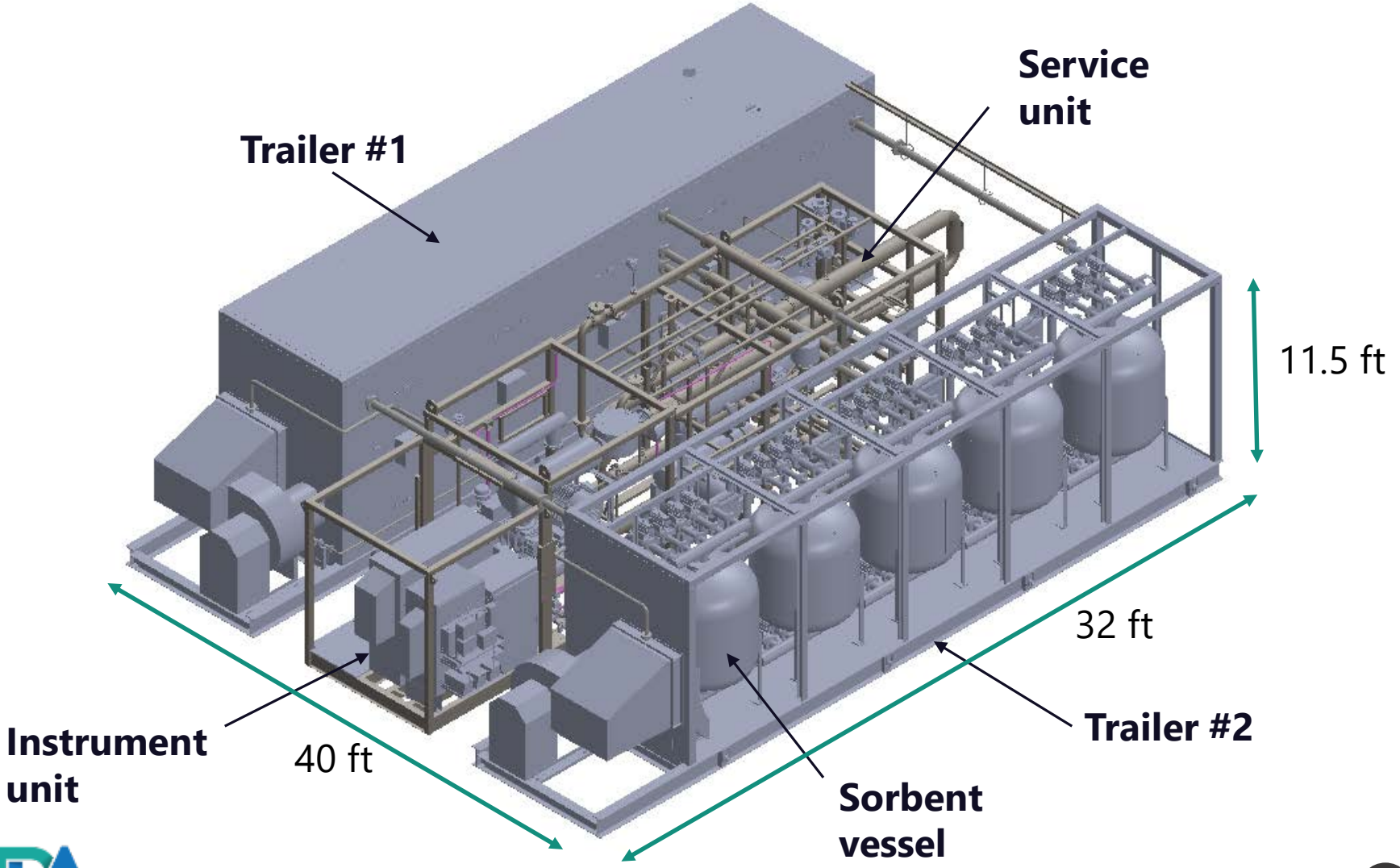
CEPCI(2011)/CEPCI(2007) = 585.7/525.4 = 1.11

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

CO_2 Capture cost = $41.2/ tonne, $2011

Pilot Unit Construction

Pilot Unit Skids



Fabrication of Pilot Unit

- Sorbent Trailers and Gas conditioning units were fabricated by Spring Fabrication, Inc. (200,000 sq. ft. facility, 220 employees) in Colorado Springs.

- Instrument control unit was fabricated at TDA.

Fabrication of Pilot Unit

Sorbent Trailers

Fabrication of Pilot Unit

Sorbent Trailers

Fabrication of Pilot Unit

The instrument and control cabinets made by TDA

High Voltage Power Enclosure

Fabrication of Pilot Unit

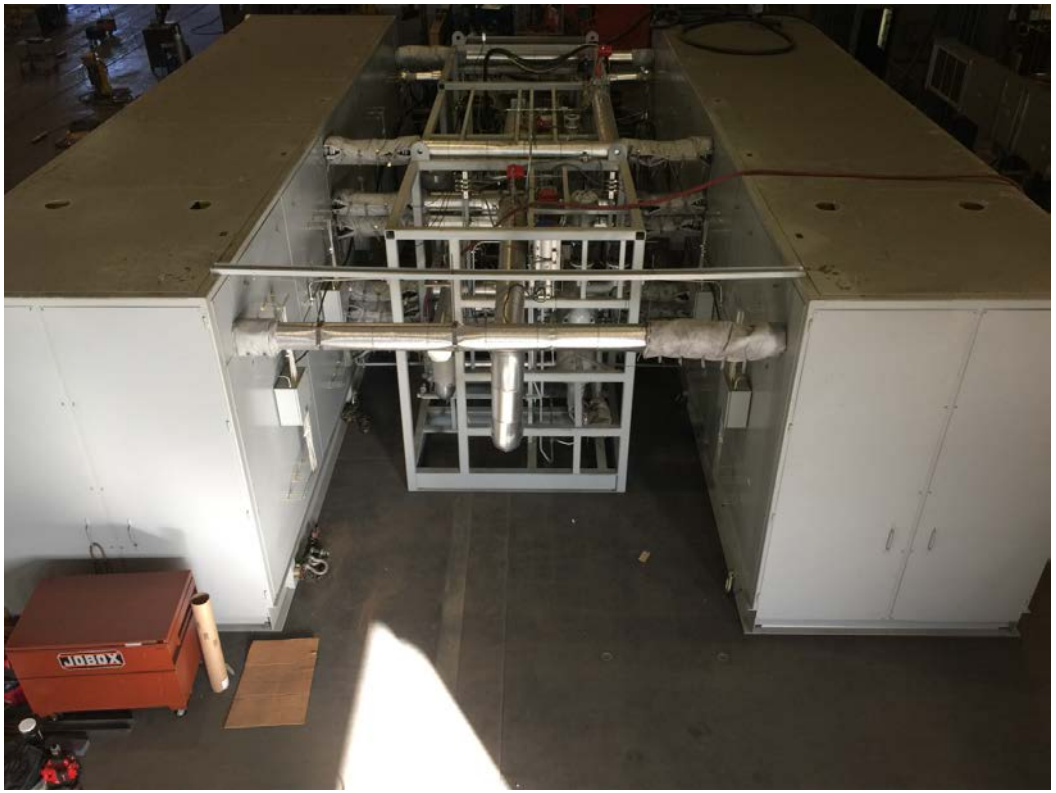
Skids set in place at Fabrication shop for FAT testing

Factory Acceptance Testing

Tests successfully completed:

- ✓ Turn on/off heaters, blowers
- ✓ Verify and control each pneumatic valve on the reactors and service unit
- ✓ Check analyzer signals to the control box
- ✓ Cycle the whole system with basic cycling program
- ✓ Confirmed beds hold pressure

Utility used: 480 V power, 90 psig shop air



Max Phillips and Greg McKinnon from Southern CO visited during FAT on October 11, 2017

Test Plan

- The primary objective of the pilot unit field tests is to demonstrate the technical merits of this sorbent-based CO_2 capture process. Flue gas = 5000 lb/hr for 0.5 MW.
- Optimize cycle parameters to achieve the following goals:
  - Minimize the amount of regeneration steam used
  - Maximize the flue gas flow rate through the TDA system
  - Minimize purge gas flow
- We will also evaluate the process under both coal derived flue gas and simulated natural gas conditions (diluted flue gas).
- Demonstrate cyclic operation at steady state using the optimized adsorption cycle scheme.
- Evaluation at 90% capture and less than 90% capture rate.

Sorbent Production and Testing

- Sorbent was made by Porocel in Little Rock, AR
- Production was conducted over 3 weeks
- 22 supersacks and 135 bags (45 lbs) produced

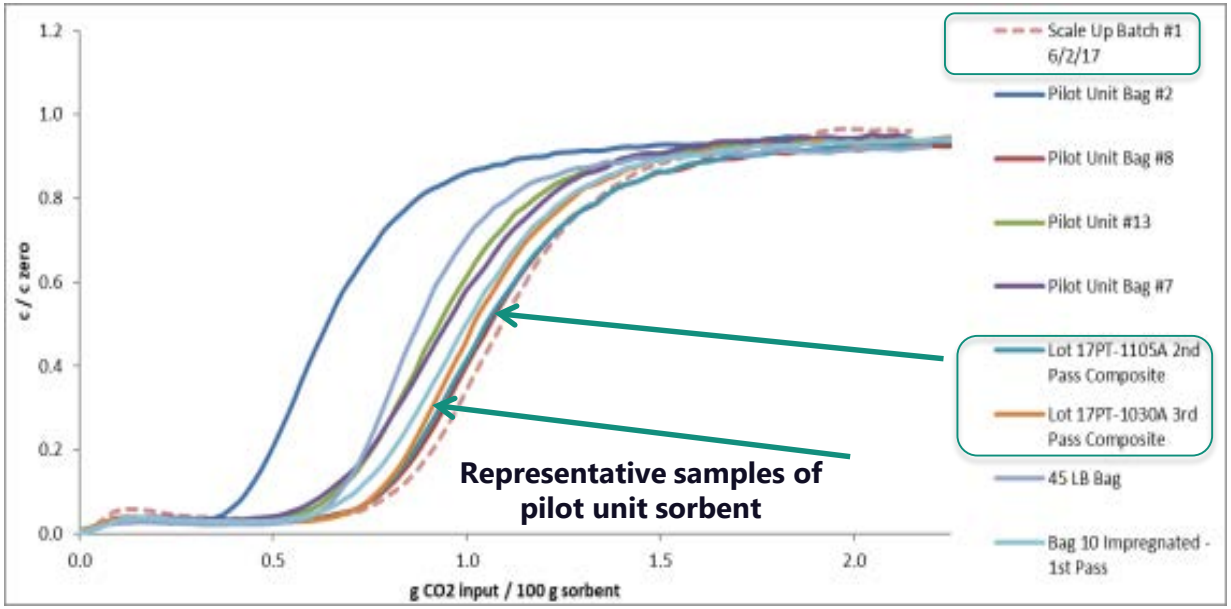
Pilot Unit Sorbent Characterization

Batch number	Bulk density (g/ml)	BET Surface Area (m^2/g)	BJH Adsorption Cumulative Pore Volume of pores (cm^3/g)	Adsorption Average Pore Diameter (nm)
Pilot Unit	0.84	99.3	0.3	12.0
Batch 1 (Scale up batch)	0.728	84.3	0.214	10.15
TDA-812 (Laboratory Sorbent)	0.616	145	0.53	10.3

- Physical properties were within expected range

- Material scaled up on 6" extruder is denser
- Sorbent delivered to NCCC in early November 2017

Single Bed Adsorption Breakthrough

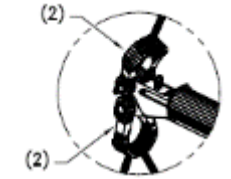


- Samples of multiple bags and composites of all bags were evaluated at TDA
- Sorbent performance of composite samples were similar to previous scale up batch made at Porocel (Batch #1)

Skid Installation

Four trucks shipped the three skids plus connecting piping and instruments from Colorado to Alabama in October 2017

Lift Plan



A DETAIL A
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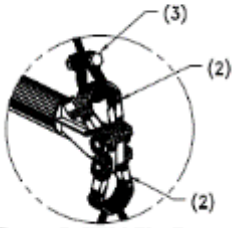

B DETAIL B
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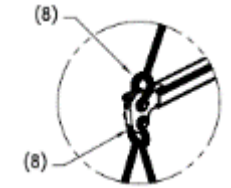
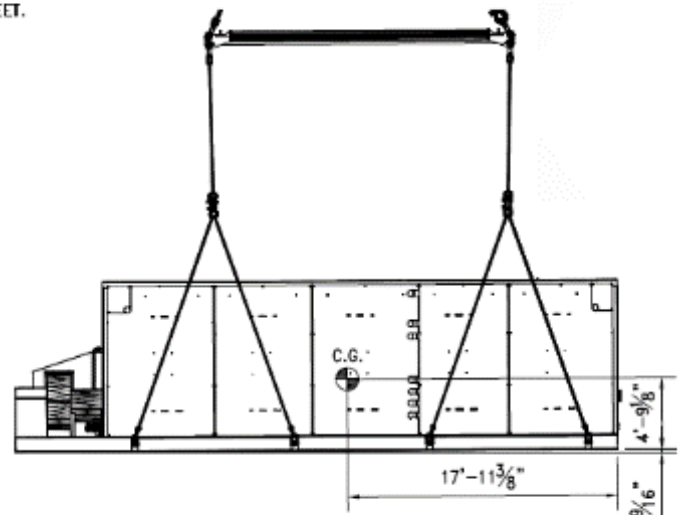


C DETAIL C
SCALE: N.T.S.

1 ELEVATION VIEW
SCALE: N.T.S.

RIGGING WEIGHT TABULATION *Sorbent Bed Trailer Unit-1 to Crane*				
#	Item	Wt.	Qty.	Total Wt.
1	1½" Φ EIP IWRC, 20' Long, 60" Bridle, 36 Ton Bridle Capacity	125	2	250
2	75t Wide Body Shackle, Crosby G-2160 or Equivalent	100	4	400
3	35t Shackle, Crosby G-2130 or Equivalent	53	1	53
4	90 Ton Tandemloc 8" End Cap Spreader Bar, 20'-0" Eye to Eye	1,235	1	1,235
5	1¼" Φ EIP IWRC, 10' Long, 60" Bridle, 25 Ton Bridle Capacity	54	4	216
6	25 Ton G&R Plant Maint. 10'-16' Adj. Spreader Bar, 10' Eye to Eye	290	2	580
7	1" Φ EIP IWRC, 15' Long, 60" Bridle, 16 Ton Bridle Capacity	42	8	336
8	17t Shackle, Crosby G-2130 or Equivalent	19	16	304
	Rigging Weight Contingency	1,000	1	1,000
	Total Rigging Weight (LBS)			**4,374**
	Rigging Capacity - 36 Tons			

TOTAL LIFT WEIGHT = 46,500 LB + 4,374 LB = 50,874 LB



2 SIDE VIEW
SCALE: N.T.S.

3 END VIEW
SCALE: N.T.S.

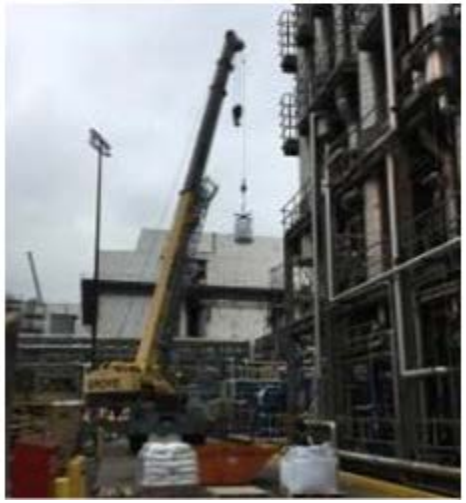
Pilot Unit installed at Pilot Bay #2 at the NCCC PC4 per approved lift plan

Installation at NCCC

Sorbent Loading

Sorbent Loading at NCCC

Sorbent dispenser with a shut-off valve.



- NCCC assisted in sorbent loading by providing the crane and labor to remove and reinstall pilot unit panels and vessel headers. November 2017

System Integration

System Integration

- NCCC completed inter-connection for the flue, steam, cooling water, drain lines, pneumatic air, electrical and signal connections.
- TDA reinstalled pneumatic valve boxes to operate vessel mounted shut-off valves.
- TDA reinstalled all analyzers and instruments contained within the analyzer cabinet and terminated the heat tracing on all sample lines to keep gas samples in the gas phase.
- TDA vacuumed out bottom valve headers for dust collected from sorbent loading.

Shakedown

- A pre-operation safety review on site at NCCC conducted on January 9, 2018.
- The control system was powered up and run in 24-hour mode.
- The following items have been checked out: manual control for the blowers and heaters, open/close for all the pneumatic valves, the PID control for 13 heat tracing zones, safety monitoring, reactor sequencing, real-time data processing and historical data log.
- Issues related to hard freeze in January were addressed.
- AC unit for electronics box was damaged and was shipped back to manufacturer for repaired.
- Gaston 5 plant shutdown end of February through mid March due to low loading. No steam or flue gas were available during this time.

Additional Sorbent Evaluation

- We used the time during AC repair and flue gas shutdown to further evaluate the pilot unit sorbent.
- We found the scaled-up sorbent degraded significantly during extended cycling .
- This degradation is not acceptable and had not happened with any earlier sorbent batches.

Sorbent	CO_2 loading, wt%	CO_2 capture rate
Batch 1	0.82	89.3%
Pilot Batch	0.31	66.0%

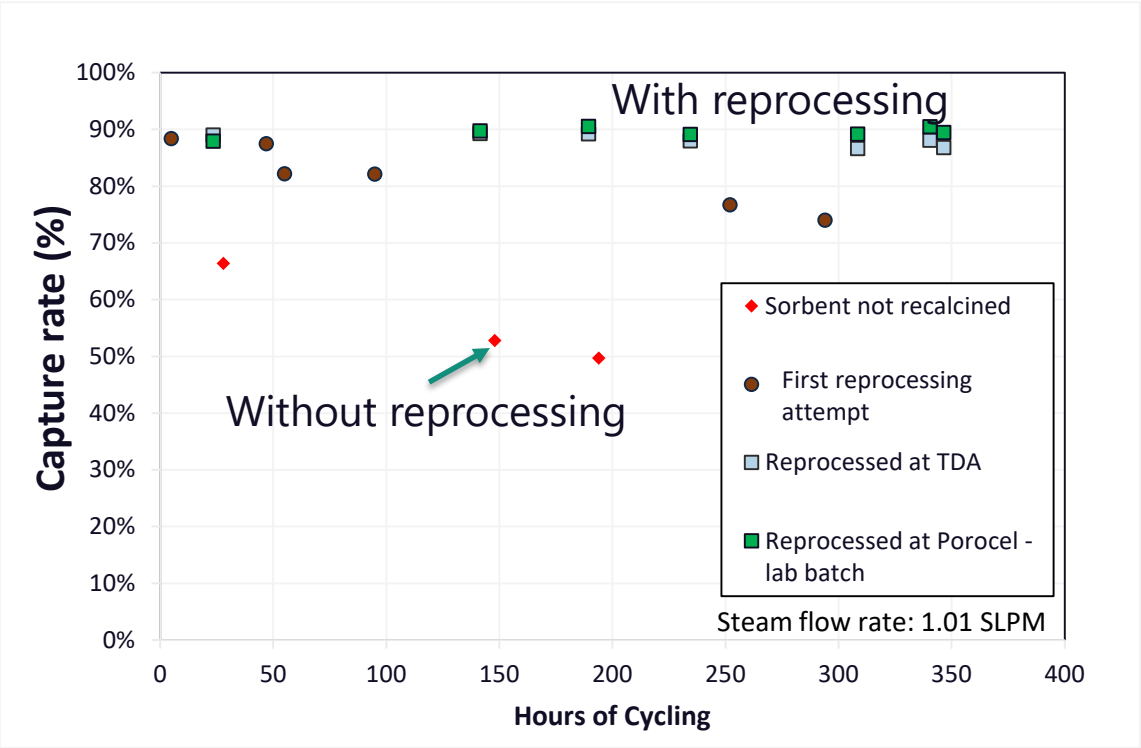
- Additional characterization determined the sorbent was not fully calcined. Humidity had impacted QA/QC checks.

TDA Bench-scale test unit

- ✓ Ten 400 cc Fix Bed Reactors with continuous Adsorption and Regeneration
- ✓ Automated control

Sorbent Reprocessing

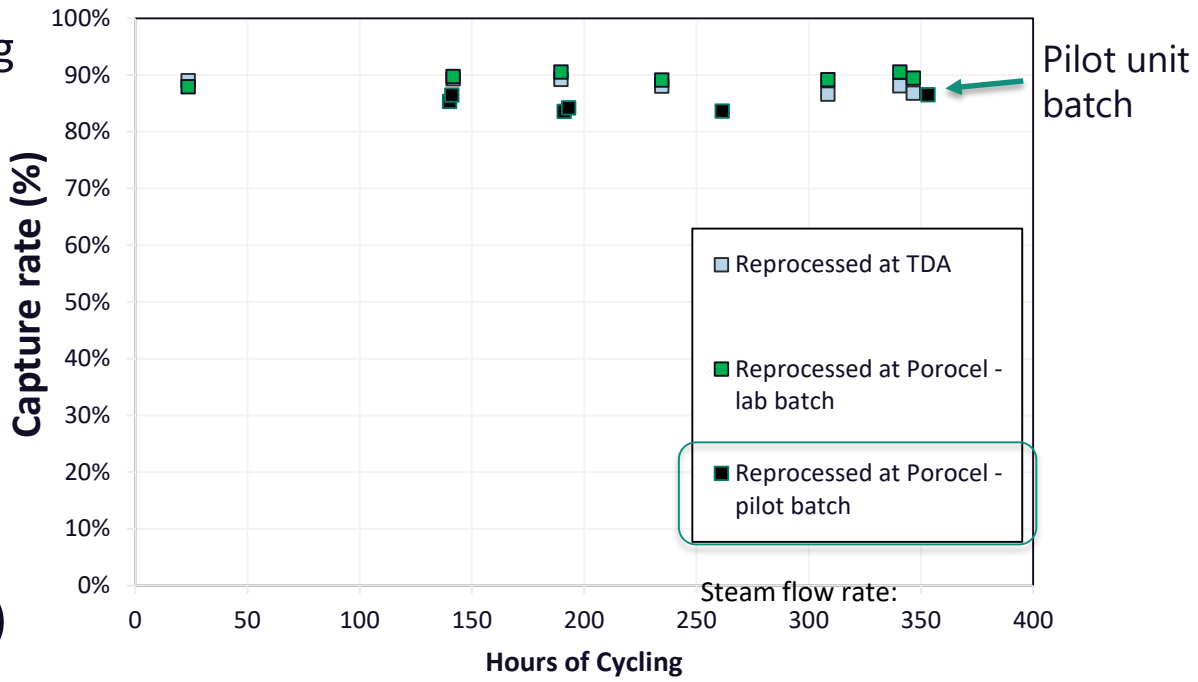
- Laboratory testing demonstrated that the sorbent could be reprocessed to achieve good performance and stability
- Experiments were conducted to develop the best reprocessing method
- Reprocessing demonstrated in laboratory testing at TDA and Porocel
- Lab batch validated in cycling tests
- Sorbent was unloaded by J.V. Industrial Companies and returned for retreatment



Pilot Unit Sorbent Reprocessing and Testing

- Pilot unit sorbent successfully reprocessed by the manufacturer in late June 2018
- Sorbent was evaluated at TDA for 350 hours of cycling
  - Performance stabilized by reprocessing

- Some loss of sorbent was unavoidable in reprocessing (breakage during removal, loss in handling, shrinkage in retreatment etc.)
- Reprocessed sorbent was loaded into 8 beds at the pilot unit
- 2 beds filled with modified commercial alkalized alumina (lower performing)



Current Status

- Sorbent reloaded mid-July 2018 and system closed up
- Shakedown continued until NCCC Gaston U5 shutdown on July 25, 2018
- Aug 17 - November 1 outage planned at NCCC
- Pilot Unit Operation to start in November
  - Parametric testing
  - Steady state testing

National Carbon Capture Center located at the E.C. Gaston power plant (Wilsonville, Alabama)

Summary

- Pilot-Unit construction and FAT testing completed.
- Pilot-Unit sorbent produced.
- System delivered and installed at NCCC. Sorbent loaded into 10 reactors.
- System integrated into NCCC site at Pilot Bay #2.
  - NCCC completed inter-connection for the flue, steam, cooling water, drain lines, pneumatic air, electrical and signal connections.
- Shakedown performed in January/February 2018. NCCC shutdown late February (no steam/flue gas).
- Pilot-Unit Sorbent batch showed expected performance initially. Extended cycling test run at TDA showed that the sorbent had poor stability.
- The sorbent was unloaded, reprocessing conditions defined, and the sorbent was successfully retreated by the manufacturer.
- The sorbent is reloaded at NCCC. Work will continue when current outage is completed November 2018.

Acknowledgements

- Project funding provided under DoE Contract # DE-FE0012870
- DoE: Andy O'Palko and Lynn Brickett
- NCCC: Tony Wu