Pilot Testing of a Highly Effective Pre-Combustion Sorbent-Based Carbon Capture System

primary project goal

TDA Research Inc. is continuing development of a new sorbent-based pre-combustion carbon capture technology for integrated gasification combined cycle (IGCC) power plants. The process uses an advanced physical adsorbent that selectively removes carbon dioxide (CO_2) from coal-derived synthesis gas (syngas) above the dew point of the gas. The project aims to prove the viability of the new technology by using data collected from the pilot plant tests to complete high-fidelity engineering and cost analyses to calculate the impact of the carbon capture system on the cost of electricity generation at a coal fired IGCC power plant and the potential of the technology to meet the U.S. Department of Energy (DOE) goals of 90% CO_2 capture and 95% purity at a cost of less than $40/tonne CO_2 captured.

Having shown promise under a previously funded DOE project (FE0000469), this sorbent is being evaluated at a larger scale, for longer durations, and under conditions that are more representative of a coal gasification-based application. Current research objectives are to collect performance data for this advanced sorbent, including two 0.1-megawatt-electric (MWe) tests with a fully equipped prototype unit using actual syngas to prove the viability of the new technology; long-term sorbent life evaluation in a bench-scale setup; the fabrication of a pilot-scale testing unit that will contain eight sorbent reactors; and the design of a CO_2 purification subsystem.

technical goals

- Enable pre-combustion CO_2 capture from syngas at 200–250°C and pressures up to 60 bar, with greater than 90% recovery and CO_2 purity of at least 95%, using a functionalized carbon sorbent in a pressure swing adsorption (PSA)-based cycle.
- Improve adsorber reactor design, including the optimized reactor internals and bed geometry through computational fluid dynamics (CFD) analysis and PSA cycle optimization with adsorption modeling.
- Complete pilot-scale field tests on syngas slipstreams at 0.1 MWe equivalent, at design conditions and for extended durations (e.g., greater than 3,000 hours), to demonstrate capability to meet all performance objectives (e.g., CO_2 removal efficiency, hydrogen [H_2] recovery, sorbent life, and performance).
- Validate long-term performance and lifetime of the sorbent through 60,000 cycles with no more than 2% decrease in adsorption capacity over fresh sorbent (enabling projected lifetime of five years for the sorbent).
- Enable improved IGCC plant efficiency (3 to 4 percentage points) over IGCC plants using conventional CO_2 removal technology, thereby improving cost of electricity in coal-based power production.

program area:
Point Source Carbon Capture

ending scale:
Small Pilot

application:
Pre-Combustion Power Generation PSC

key technology:
Sorbents

project focus:
High-Capacity Regenerable Sorbent for Coal IGCC Plants

participant:
TDA Research Inc.

project number:
FE0013105

predecessor projects:
FE0000469

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start date:
10.01.2013

percent complete:
92%

technical content

TDA Research Inc. is designing, constructing, and operating a slipstream 0.1-MWe pilot-scale process for pre-combustion CO_2 capture to assess their novel adsorbent for the selective removal of CO_2 from syngas. The adsorbent consists of a mesoporous carbon grafted with surface functional groups that remove CO_2 via an acid-base interaction. The novel process is based on TDA's high-temperature PSA technology, using the new adsorbent to selectively remove CO_2 from syngas in an IGCC power plant. The integration of the CO_2 separation unit into the IGCC plant is shown in Figure 1.

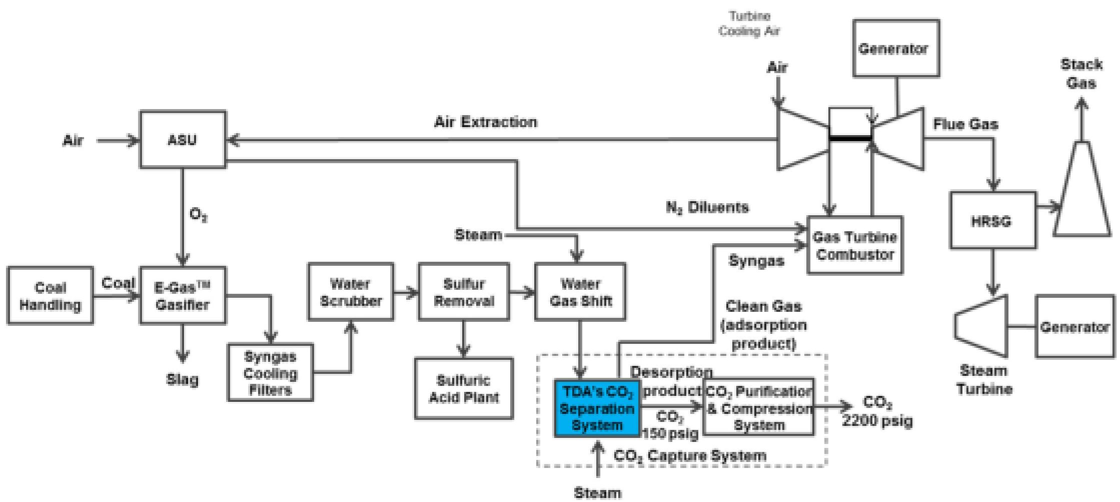

Figure 1: TDA's CO_2 capture system integration in an IGCC power plant.

The CO_2 capture system uses multiple sorbent beds that switch operating modes between adsorption and regeneration. In adsorption mode, which is operated isothermally (temperature of about 240–250°C) and at syngas pressure of about 500 pounds per square inch absolute (psia), the sorbent removes CO_2 via strong physical adsorption. The CO_2 surface interaction is strong enough to allow operation at these elevated temperatures. A detailed breakdown of the carbon capture and storage (CCS) system's operating parameters is given in Table 1.

TABLE 1: SORBENT PROCESS PARAMETERS

Sorbent	Units	Current R&D Value	Target R&D Value
True Density @ STP	kg/m^3	1,314	1,314
Bulk Density	kg/m^3	620	620
Average Particle Diameter	mm	0.42–1.68	0.42–1.68
Particle Void Fraction	m^3/m^3	0.368	0.368
Packing Density	m^2/m^3	4.59E+08	4.59E+08
Solid Heat Capacity @ STP	kJ/kg-K	0.93	0.93
Crush Strength	kg_f	3	3
Manufacturing Cost for Sorbent	$/kg	3.88	3.88
Adsorption			
Pressure	bar	33.8	33.8
Temperature	°C	198	198
Equilibrium Loading	g mol CO_2/kg	1.04	1.04
	g mol CO_2/m^3	645	645
Heat of Desorption	kJ/mol CO_2	-28.5	-28.5
Desorption			
Pressure	bar	10	10
Temperature	°C	195.5	195.5

Equilibrium CO_2 Loading	g mol CO_2/kg	0.005	0.005
	g mol CO_2/m^3	3.22	3.22
Heat of Desorption	kJ/mol CO_2	28.5	28.5
Proposed Module Design		*(for equipment developers)*	
Flow Arrangement/Operation	—	radial-flow fixed bed/cyclic	
Syngas Flowrate	kg/hr	668,083	
CO_2 Recovery, Purity, and Pressure[+]	%/%/bar	90.0% 96.0% 10	
Adsorber Pressure Drop	bar	1.41	
Estimated Absorber/Stripper Cost of Manufacturing and Installation	$\frac{\$}{kg/hr}$	212.8	

[+] CO_2 is recovered at 10 bar from TDA's CO_2 capture system, which is further purified and compressed to 152.7 bar with a final CO_2 purity of 99.96%.

In regeneration mode, also operated isothermally (temperature of about 240–250°C), CO_2 is recovered via combined pressure and concentration swing by contacting the sorbent with a steam purge stream. The operating pressure ranges from 150–158 psia and partial pressure of CO_2 ranges from 0–75 psi. Because the CO_2 is recovered at approximately 150 psia, energy requirement for CO_2 compression for storage is reduced. Also, the isothermal operation eliminates heat/cool transitions, and rapid cycling reduces cycle times and increases sorbent utilization. Because the CO_2 is not bonded via a covalent bond, the energy input to the regeneration is low—only 4.9 kcal/mole of CO_2 removed (comparable to Selexol™). This energy requirement is much lower than that of the chemical absorbents (e.g., sodium carbonate [Na_2CO_3] requires 29.9 kcal/mol) and amine solvents (≈14 kcal/mol). The energy output loss of the IGCC plant is expected to be like that of Selexol's; however, a higher overall IGCC efficiency can be achieved due to higher temperature CO_2 capture.

The pilot plant design includes a gas conditioning unit and a high-temperature PSA-based CO_2 separation unit, as shown in Figure 2. The gas conditioning unit allows for adjustment of the concentration and purity of the syngas. The CO_2 separation unit consists of eight high-temperature sorbent beds. The design of the CO_2 capture skid for the 0.1-MW pilot unit is shown in Figure 3.

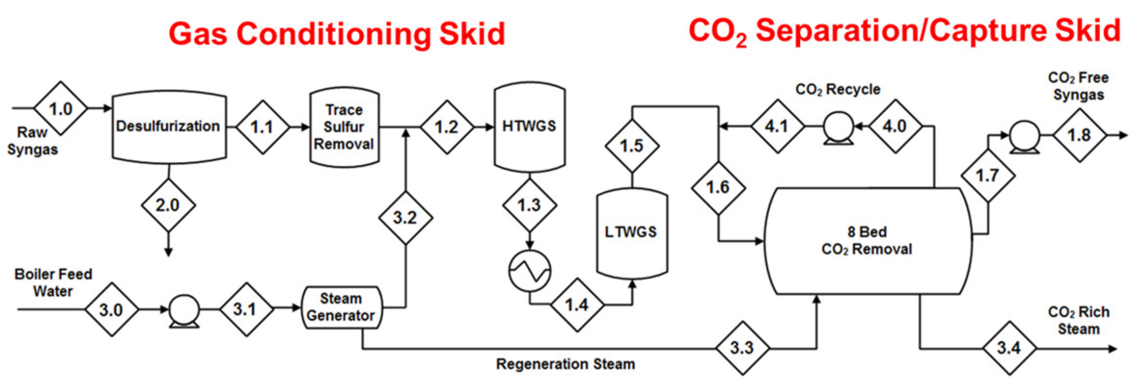

Figure 2: Flow diagram for TDA's pilot test unit.

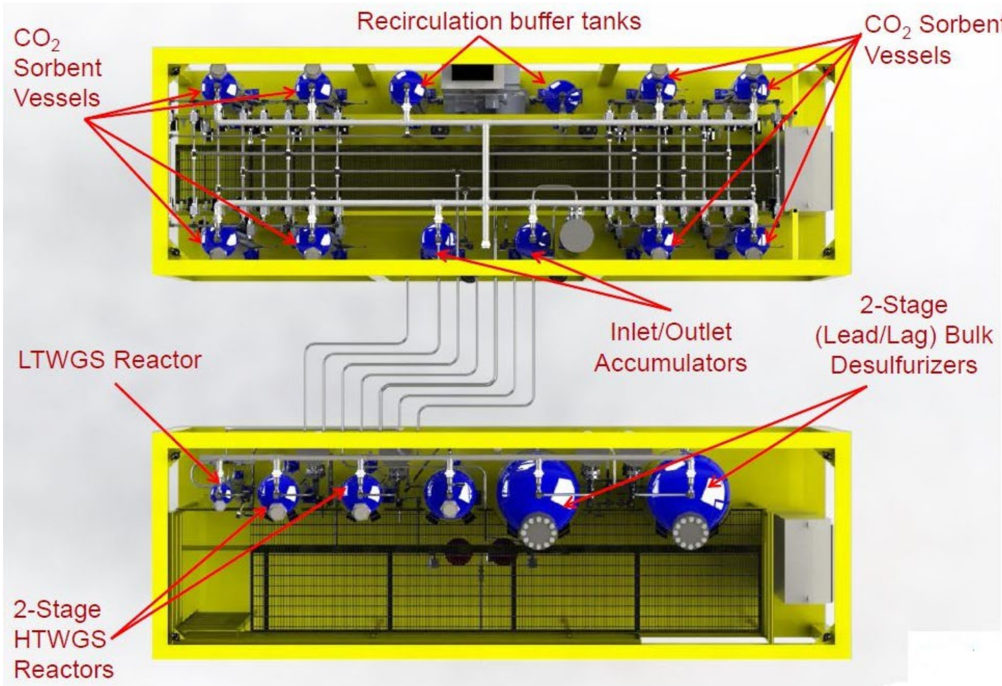

Figure 3: Overhead view of carbon capture skid.

In 2017, TDA's 0.1-MWe pilot-scale eight-bed PSA unit was installed at the National Carbon Capture Center (NCCC; Figure 4) and tested in real coal-derived syngas. The pilot unit ran for 707 hours of continuous operation at up to 97.3% carbon capture at 53 standard cubic feet per minute (SCFM) of syngas flow, exceeding design specifications. The summary results are given in Table 2. This table also shows the upcoming design performance parameters for the Sinopec oxygen-based gasifier testing at considerably increased throughput.

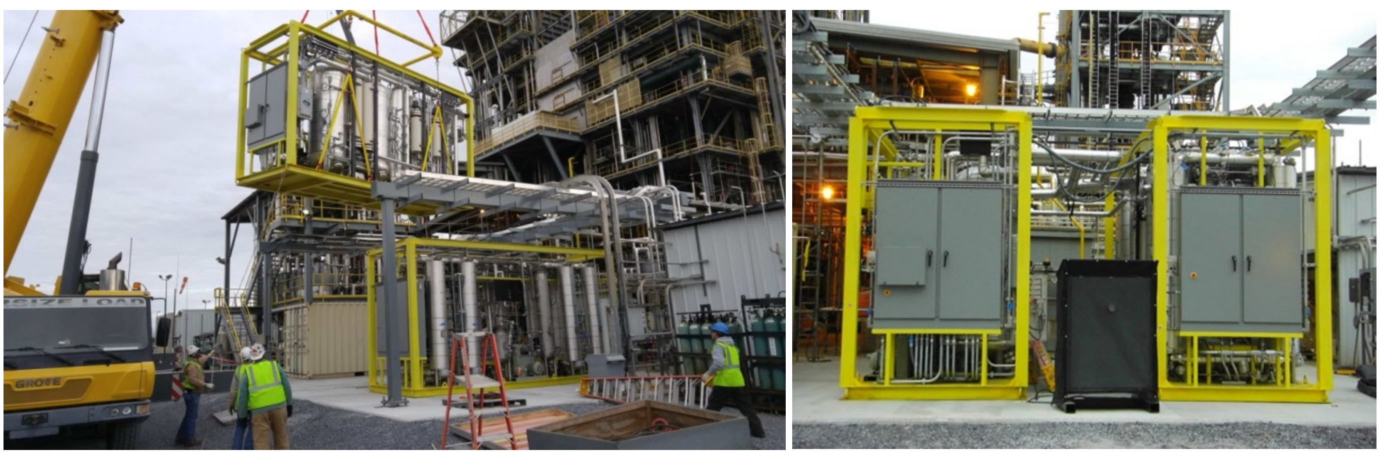

Figure 4: TDA's 0.1-MWe pilot unit installed in the test pad at the NCCC (Wilsonville, Alabama).

TABLE 2: SUMMARY PERFORMANCE RESULTS OF PILOT-SCALE TESTING

	Design NCCC	Actual NCCC	Design Sinopec
Syngas Flow to DeS/WGS Skid (SCFM)	43	53	73
Syngas Flow to DeS/WGS Skid (SCFM)	48	57	100
Steam Added for WGS Reaction (SCFM)	4.1	4.3	27.2
CO_2 Captured (kg/hr)	25	29.6	105.3
Cycle Time (min)	16	8	16
Partial Pressure CO_2 (psi)	29.1	28.8	175.1
Bed Utilization (g CO_2/L-hr)	15.9	18.5	65.8

In 2018 and 2019, TDA shipped, installed, and performed shakedown testing on field units at Sinopec (see Figure 5), which allow oxygen-based gasifier testing at considerably increased throughput.

Very early testing results at 88 SCFM syngas flow have resulted in approximately 85% CO_2 removal efficiency at a rate of approximately 110 kg/hr CO_2.

TDA has also performed preliminary techno-economic analyses (TEAs) of cases assuming application of TDA's sorbent-based CO_2 capture system in IGCC plant cycles, based upon performance data available to date from recent testing. The comparisons involve a baseline of conventional cold-gas cleanup and Selexol acid gas removal, compared to TDA's assumption of warm-gas cleanup combined with the sorbent units for CO_2 capture. Results are summarized in Table 3. Overall, the findings are as follows:

- TDA system achieves higher efficiencies (34.5% and 34.1%) than IGCC with Selexol (32.0% and 31.0%) for E-Gas™ and GE gasifier-based plants.
- Cost of CO_2 capture is calculated as \$31 and \$30/tonne for GE and E-Gas gasifier-based plants, respectively (16–30% reduction against Selexol).
- Cost of CO_2 capture is calculated as \$40 and \$28/tonne for Shell and TRIG gasifier-based plants, respectively (15–28% reduction against Selexol).

Figure 5: Field test units at Sinopec, China.

TABLE 3: PRELIMINARY TECHNO-ECONOMIC COMPARISONS

Gasifier	E-Gas		GE		Shell		TRIG	
Case	1	2	3	4	5	6	7	8
CO_2 Capture Technology	Cold Gas Cleanup Selexol™	Warm Gas Cleanup TDA's CO_2 Sorbent	Cold Gas Cleanup Selexol™	Warm Gas Cleanup TDA's CO_2 Sorbent	Cold Gas Cleanup Selexol™	Warm Gas Cleanup TDA's CO_2 Sorbent	Cold Gas Cleanup Selexol™	Warm Gas Cleanup TDA's CO_2 Sorbent
CO_2 Capture, %	90	90	90	90	90	90	83	83
Gross Power Generated, kW	707,165	669,993	727,416	674,790	672,980	619,054	624,964	616,338
Gas Turbine Power	464,000	425,761	464,000	417,083	464,000	416,147	424,722	413,946
Steam Turbine Power	243,165	244,232	257,250	247,362	208,980	202,907	200,242	202,392
Syngas Expander Power	-	-	6,166	10,345	-	-	-	-
Auxiliary Load, kW	194,495	125,755	193,155	121,834	177,361	112,254	166,998	126,730
Net Power, kW	512,670	544,238	534,262	552,956	495,620	506,800	457,966	489,609
Net Plant Efficiency, % HHV	30.8	34.0	31.9	34.4	30.8	33.4	31.5	34.2
Coal Feed Rate, kg/h	220,557	212,265	222,026	213,013	213,509	201,426	262,700	258,882
Raw Water Usage, GPM/MW	11.0	10.7	11.0	10.8	10.3	11.1	8.2	9.6
Total Plant Cost, \$/kW	3,466	3,063	3,369	3,160	3,901	3,560	3,736	3,328
COE without CO_2 TS&M, \$/MWh	137.3	121.1	133.6	124.0	150.1	138.6	125.5	112.5
COE with CO_2 TS&M, \$/MWh	146.3	129.2	142.2	131.9	159.0	146.8	144.3	129.9
Cost of CO_2 Capture, \$/tonne	43	28	38	29	49	39	40	27

Definitions:

Cost of Carbon Captured – Projected cost of capture per mass of CO_2 captured under expected operating conditions.

Cost of Carbon Avoided – Projected cost of capture per mass of CO_2 avoided under expected operating conditions.

Capital Expenditures – Projected capital expenditures in dollars per unit of energy produced.

Operating Expenditures – Projected operating expenditures in dollars per unit of energy produced.

Cost of Electricity – Projected cost of electricity per unit of energy produced under expected operating conditions.

STP – Standard temperature and pressure (15°C, 1 atmosphere [atm]).

Sorbent – Adsorbate-free (i.e., CO_2-free) and dry material as used in adsorption/desorption cycle.

Manufacturing Cost for Sorbent – "Current" is market price of material, if applicable; "Target" is estimated manufacturing cost for new materials, or the estimated cost of bulk manufacturing for existing materials.

Adsorption – The conditions of interest for adsorption are those that prevail at maximum sorbent loading, which typically occurs at the bottom of the adsorption column.

Desorption – The conditions of interest for desorption are those that prevail at minimum sorbent loading, which typically occurs at the bottom of the desorption column. Operating pressure and temperature for the desorber/stripper are process dependent. Measured data at other conditions are preferable to estimated data.

Pressure – The pressure of CO_2 in equilibrium with the sorbent. If the vapor phase is pure CO_2, this is the total pressure; if it is a mixture of gases, this is the partial pressure of CO_2.

Packing Density – Ratio of the active sorbent area to the bulk sorbent volume.

Loading – The basis for CO_2 loadings is mass of dry, adsorbate-free sorbent.

Flow Arrangement/Operation – Gas-solid module designs include fixed, fluidized, and moving bed, which result in either continuous, cyclic, or semi-regenerative operation.

Estimated Cost – Basis is kg/hr of CO_2 in CO_2-rich product gas; assuming targets are met.

Other Parameter Descriptions:

Chemical/Physical Sorbent Mechanism – Surface functionalized mesoporous carbon removing CO_2 via weak interactions similar to physical adsorption at temperatures above the dew point of the syngas.

Sorbent Contaminant Resistance – The sorbent is highly resistant to contaminants such as hydrogen sulfide (H_2S), carbonyl sulfide (COS), ammonia (NH_3) and trace metals such as mercury (Hg), arsenic (As), etc. If needed, additional functionalities can be incorporated into the sorbent to remove these contaminants simultaneously with CO_2. Results of the 707-hour-long testing with coal-derived syngas with the 0.1-MWe pilot unit at the NCCC in Wilsonville, Alabama, showed excellent resistance to contaminants that could be present in syngas.

Sorbent Attrition and Thermal/Hydrothermal Stability – The sorbent has good thermal/hydrothermal stability; it is stable in nitrogen up to 900°C and in steam stable up to 400°C. The attrition index for the sorbent is estimated to be 0.1% loss per 1,000 hours of operation.

Syngas Pretreatment Requirements – Syngas needs to be shifted to convert carbon monoxide (CO) present into CO_2 and H_2 via water-gas shift (WGS) reaction and sulfur content needs to be reduced to less than 100 parts per million (ppm) before CO_2 removal.

Sorbent Makeup Requirements – The expected life of the sorbent is five years. The annualized sorbent makeup requirement is expected to be 261.5 tonnes on the 550-MWe process plant basis.

Waste Streams Generated – Condensate from cooling the raw CO_2 stream.

Process Design Concept – See Figure 1.

Proposed Module Integration – TDA's CO_2 separation, purification, and compression systems are located downstream of the warm-gas sulfur removal and the WGS processes as shown in Figure 1.

Pressure	Temperature	Composition						
		vol%						ppmv
psia	°F	CO_2	CO	CH_4	N_2	H_2	H_2O	H_2S
497.5	388.4	30.28	0.73	2.04	0.45	39.11	26.59	<10

technology advantages

- Warm-gas CO_2 capture above dew point of syngas leads to more steam in the hydrogen-rich gas entering the turbine.
  - Improved efficiency.
  - Higher mass throughput to gas turbine.
  - Lower-gas turbine temperature, which lowers the need for high-pressure nitrogen (N_2) dilution and lowers nitrogen oxide (NO_X) formation.
- High steam content feed more suited for next-generation hydrogen turbines under development.
- High working capacity and cycle life of sorbent.
- Carbon dioxide recovered at pressure reduces compression costs for storage.
- A weak CO_2 surface interaction allows fast regenerations at lower temperature with minimal or no heat input.
- Short adsorption/regeneration cycles reduce bed size and weight, corresponding to reduced adsorber vessel size and costs.

R&D challenges

- Assuring consistency in sorbent material and minimizing batch-to-batch variation for large-scale manufacture.
- Reducing the use of purge gas during regeneration.
- Confirming resistance to syngas contaminants.

status

Pilot-scale testing at Sinopec was completed in 2020 (testing duration was shortened due to COVID-19 issues). The full TEA has been completed. Further testing is planned to continue in TDA's facilities in Colorado. Decommissioning at Sinopec is underway, and key components are being returned to TDA.

available reports/technical papers/presentations

Altepkin, G.; Jayaraman, A.; Cates, M.; Bruinsma, D.; Kugler, F.; Dippo, J., 2021, "Pilot Testing of a Highly Efficient Pre-Combustion Sorbent-Based Carbon Capture System." TDA Research. Presented at the 2021 Carbon Management and Oil and Gas Research Project Review Meeting. August 13, 2021. *https://netl.doe.gov/sites/default/files/netl-file/21CMOG_PSC_Alptekin_sor.pdf*.

Altepkin, G., 2021, "Pilot Testing of a Highly Efficient Pre-combustion Sorbent-based Carbon Capture System." Quarterly Report #32. Submitted October 30, 2021.

"Pilot Testing of a Highly Efficient Pre-combustion Sorbent-based Carbon Capture System," presented by Gökhan Alptekin of TDA Research, Inc. at the 2019 Carbon Capture, Utilization, Storage, and Oil and Gas Technologies Integrated Review Meeting – Capture and Utilization Sessions, Pittsburgh, Pennsylvania, August 2019. *https://netl.doe.gov/sites/default/files/netl-file/G-Alptekin-TDA-Precombustion-Sorbent.pdf*

"PSA Based CO_2 Capture Above the Dew Point of Synthesis Gas for IGCC Power Plants," presented at the 2017 AIChE Annual Meeting, Minneapolis, MN, November 2017. *https://www.aiche.org/conferences/aiche-annual-meeting/2017/proceeding/paper/628c-psa-based-co2-capture-above-dew-point-synthesis-gas-igcc-power-plants*

"Highly Efficient Warm Gas Carbon Capture System for IGCC Power Plants," presented at the 2016 AIChE Annual Meeting, Minneapolis, MN, November 2016. *https://aiche.confex.com/aiche/2016/webprogram/Paper470738.html*

"Pilot Testing of a Highly Efficient Pre-combustion Sorbent-based Carbon Capture System," presented by Gökhan Alptekin, TDA Research, Inc., 2017 NETL CO_2 Capture Technology Project Review Meeting, Pittsburgh, PA, August 2017. *https://netl.doe.gov/sites/default/files/event-proceedings/2017/co2 capture/2-Tuesday/G-Alptekin-TDA-Evaluation-of-Carbon-Capture-Process.pdf*

"Pilot Testing of a Highly Efficient Pre-Combustion Sorbent-Based Carbon Capture System," presented by Gökhan Alptekin, TDA Research Inc., 2016 NETL CO_2 Capture Technology Project Review Meeting, Pittsburgh, PA, August 2016. *https://www.netl.doe.gov/sites/default/files/event-proceedings/2016/c02 cap review/1-Monday/G-Alptekin-TDA-Sorbent-Based-Carbon-Capture.pdf*

"Pilot Testing of a Highly Efficient Pre-Combustion Sorbent-Based Carbon Capture System," presented by Gökhan Alptekin, TDA Research Inc., 2015 NETL CO_2 Capture Technology Meeting, Pittsburgh, PA, June 2015. *https://netl.doe.gov/sites/default/files/2017-12/G-Alptekin-TDA-Pilot-Test-Efficient-Sorbent-based-Pre-C.pdf*

Alptekin, G., et. al. "A Low Cost, High Capacity Regenerable Sorbent for Pre-Combustion CO_2 Capture," Final Report, September 30, 2012. *http://www.osti.gov/scitech/biblio/1082143*

"Pilot Testing of a Highly Efficient Pre-Combustion Sorbent-Based Carbon Capture System," presented by Gökhan Alptekin, TDA Research Inc., 2014 NETL CO_2 Capture Technology Meeting, Pittsburgh, PA, July 2014. *http://www.netl.doe.gov/File Library/Events/2014/2014 NETL CO2 Capture/G-Alptekin-TDA-Pre-Combustion-Sorbent-Based-Capture.pdf*

"Pilot Testing of a Highly Efficient Pre-Combustion Sorbent-Based Carbon Capture System," Project Kick-Off Meeting, January 2013. *https://www.netl.doe.gov/sites/default/files/2017-12/FE0013105-Kickoff-Pilot-Testing-PreCombustion-CO2Capture-2014-01-16.pdf*

Alptekin, G., Jayaraman, A., Dietz, S., Bonnema, M., Rao, A., "Low Cost, High Capacity Regenerable Sorbent for Precombustion CO_2 Capture," Final Report, September 2012. *https://www.osti.gov/servlets/purl/1082143*

Alptekin, G., "A Low Cost, High Capacity Regenerable Sorbent for CO_2 Capture," presented at the International Colloquium on Environmentally Preferred Advanced Power Generation (ICEPAG), Costa Mesa, CA, February 2012.

Alptekin, G., Jayaraman, A., Dietz, S., and Schaefer, M., "High Capacity Regenerable Sorbent for Pre-Combustion CO_2 Capture," presented at the 28th Annual International Pittsburgh Coal Conference (IPCC), Pittsburgh, PA, September 2011.