Bench-Scale Testing of a High-Efficiency, Ultra-Compact Process for Pre-Combustion CO_2 Capture

primary project goal

The main objective is to scale-up and field-validate the technical feasibility of the University of Southern California's (USC) membrane- and adsorption-enhanced water-gas shift (WGS) process that employs a carbon molecular sieve (CMS) membrane reactor (MR), followed by an adsorption reactor (AR), for pre-combustion carbon dioxide (CO_2) capture. The project begins at Technology Readiness Level (TRL) 4, as the system prototype has already been validated in the laboratory on simulated syngas (under predecessor project FE0026423). The project aims to end at TRL 5, via scaling-up of the prototype system and its testing on actual syngas at the University of Kentucky (UKy). Project tasks include designing, constructing, assembling, and validating the bench-scale experimental MR-AR system; preparing suitable membranes, adsorbents, and catalysts needed for the bench-scale system; and deploying the unit at UKy and testing system performance using real syngas. Results are to be used to complete an updated process techno-economic analysis (TEA) and environmental, health, and safety (EH&S) risk assessment.

technical goals

- Demonstrate CO_2 capture from actual coal gasification syngas at a bench-scale syngas flow rate of 50.7 to 253 kg/day, at a temperature of 250°C, at a pressure of 25 atmosphere [atm], and for 500 hours of testing.
- Increase stability of membranes and adsorbents in the process system in terms of degradation by syngas constituents, with an interim target of less than 30% decline in performance over 500 hours of testing at typical syngas conditions.
- Hydrogen (H_2) permeance greater than 1 m^3/m^2.hr.bar for the H_2-selective membrane, with a target range for H_2/carbon monoxide (CO) selectivity exceeding 80.
- Sorbent working capacity greater than 2.5 weight % CO_2; sorbent attrition rate less than 0.2.
- Demonstrate progress (TRL 4 to TRL 5) toward enabling an MR-AR system in a 550-megawatt-electric (MWe) integrated gasification combined cycle (IGCC) plant, capable of CO_2 capture with greater than 95% purity, while reducing the cost of electricity (COE) by 30% over IGCC plants employing conventional methods of CO_2 capture.

technical content

The working hypothesis of this project is that the conventional WGS unit found in an IGCC plant (for shifting the syngas toward primarily H_2 and CO_2) and the downstream conventional amine absorption unit for capturing the CO_2 from the shifted syngas could be replaced in whole by a unique membrane- and adsorption-enhanced WGS reactor system (previously developed for H_2 production via methane steam reforming) that allows for in situ preferential H_2 permeation and

program area:
Point Source Carbon Capture

ending scale:
Bench Scale

application:
Pre-Combustion Power Generation PSC

key technology:
Hybrid

project focus:
Combined Membrane Reactor and Adsorption Reactor System

participant:
University of Southern California

project number:
FE0031737

predecessor projects:
FE0026423

NETL project manager:
Katharina Daniels
katharina.daniels@netl.doe.gov

principal investigator:
Theodore Tsotsis
University of Southern California
tsotsis@usc.edu

partners:
Media and Process Technology Inc.; University of California Los Angeles; University of Kentucky Research Foundation

start date:
06.01.2019

percent complete:
92%

simultaneous CO_2 adsorption. The reactor system is depicted, in the context of a typical IGCC power plant cycle, within the blue border-surrounded process block in Figure 1.

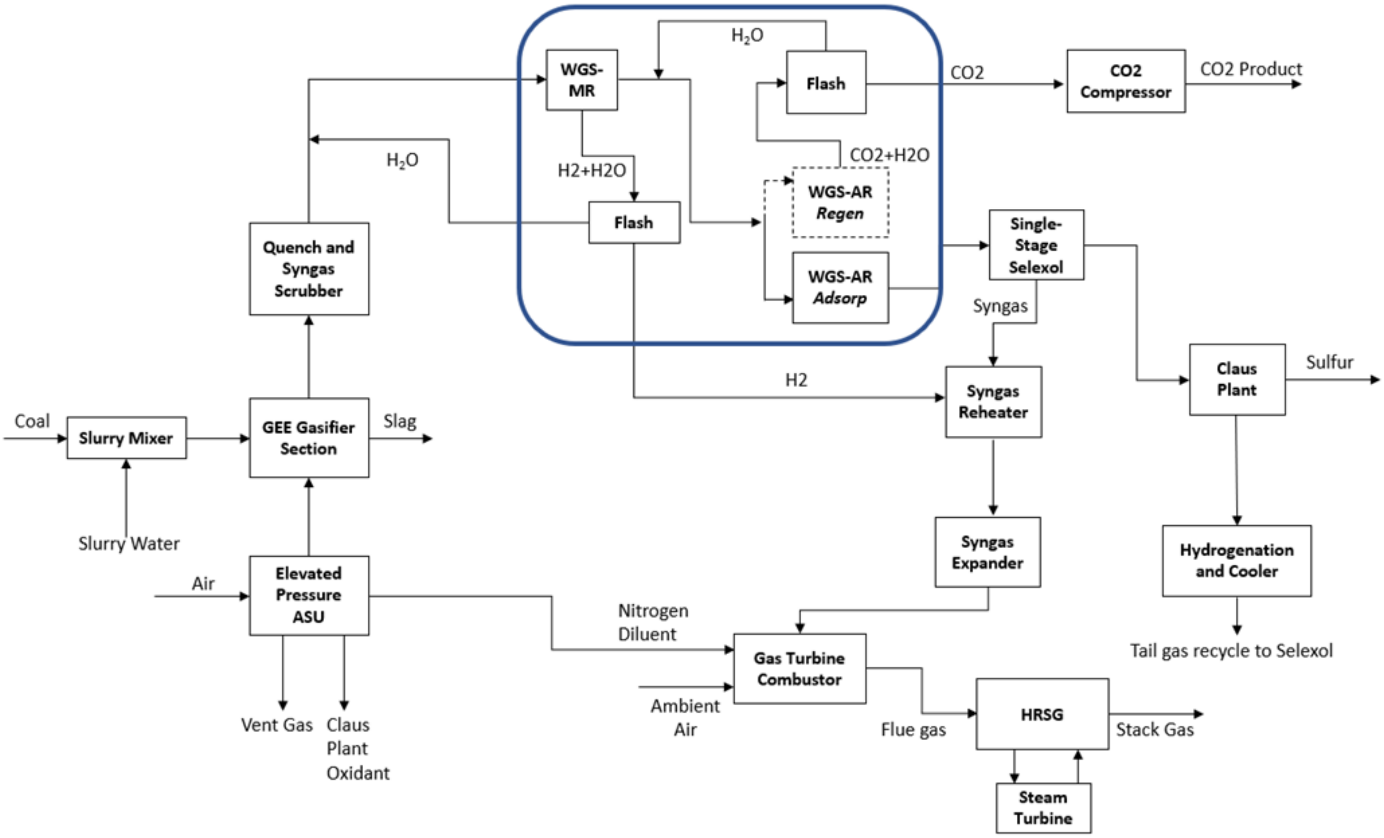

Figure 1: MR and AR system in the context of an IGCC plant process.

The system combines an MR and AR in tandem to continuously produce a pure H_2 product (while attaining greater than 99% CO conversion) until the adsorbent (in the AR unit) is saturated. The AR unit must then be taken off-stream and regenerated via steam-enhanced temperature swing adsorption (TSA). This unique reactor configuration can, therefore, be viewed as a hybrid MR-AR system with TSA cycling. Compared to conventional WGS followed by CO_2 capture using a conventional amine process, the MR-AR system is more efficient and compact. Furthermore, the use of a TSA rather than a pressure-swing CO_2 recovery step (as commonly practiced in AR systems) allows the recovery of CO_2 at higher pressures aiding system efficiency.

The combined MR-AR process is shown in more detail in Figure 2. Here, the syngas first passes into the MR vessel, consisting of WGS catalyst packed around an array of membrane tubes. The tubes are CMS-based membranes on ceramic support, which are highly selective to H_2. The MR permeate consists of high-purity H_2. As the H_2 is withdrawn from the MR vessel, the WGS reaction equilibrium is pushed toward further H_2 production. Retentate/rejected gases are passed to an array of ARs operating in a periodic manner, whereby at any given time some ARs are fed retentate gases and operate in reaction/adsorption mode, while the remaining ARs are fed steam and operate in a TSA regeneration mode. The ARs contain additional WGS catalyst, in addition to CO_2 sorbent. In this technology, hydrotalcite (HTC) is utilized as the CO_2 sorbent. This co-location of the WGS reaction and CO_2 separation functions in the AR allows traditional WGS reaction equilibrium limitations to be overcome, thus enabling enhanced shifting of the syngas to occur until most of the carbon as CO is converted into CO_2 and adsorbed. This results in a relatively pure H_2 gas exiting the AR at high pressure when the ARs operate in reaction/adsorption mode, while a high-pressure steam/CO_2 mixture exits the ARs when they operate in regeneration mode. In summary, the process configuration combining the MR and AR in tandem provides significant process flexibility, efficient high-pressure and high-purity H_2 production, and CO_2 recovery.

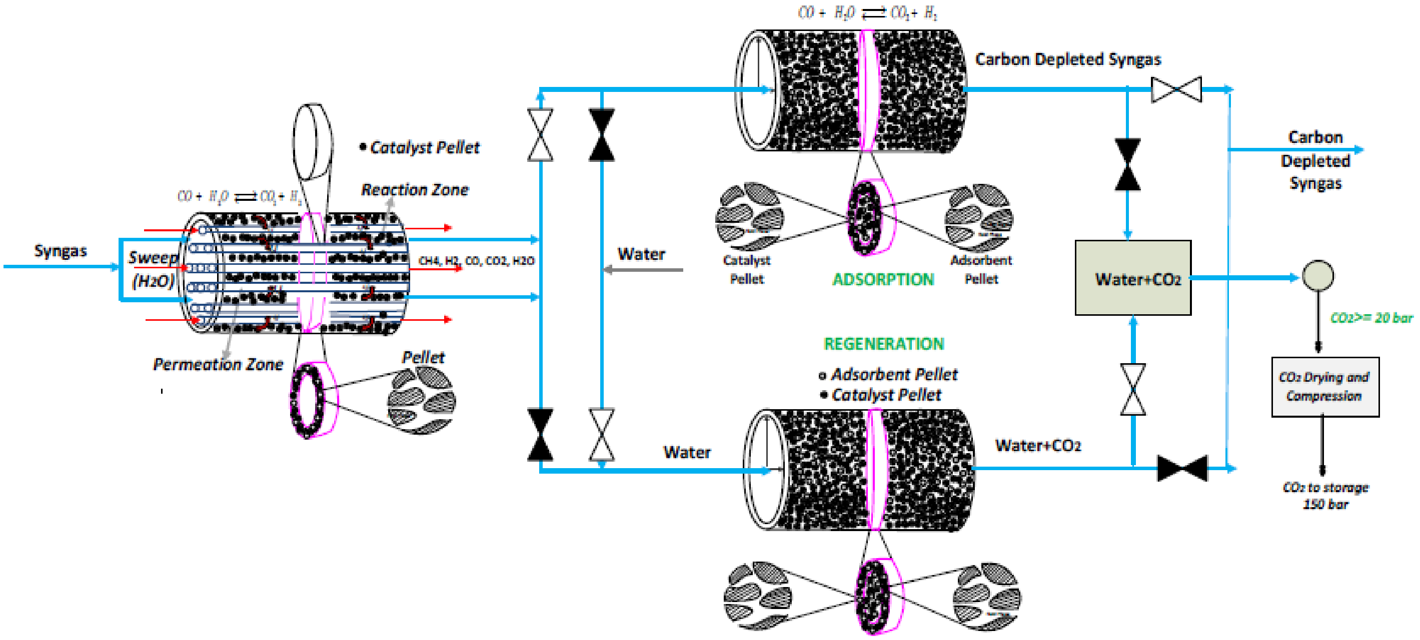

Figure 2: MR-AR process.

The HTC sorbent mentioned previously is an anionic clay magnesium (Mg)/aluminum (Al)-layered double hydroxide, as depicted in Figure 3. It has a relatively high CO_2 capacity over a wide range of temperatures and pressures; can be easily prepared by precipitation of Mg/Al from solution in sodium hydroxide (NaOH); and is unaffected by hydrogen sulfide (H_2S) and simulated tars at anticipated operating temperature, thereby conferring process stability.

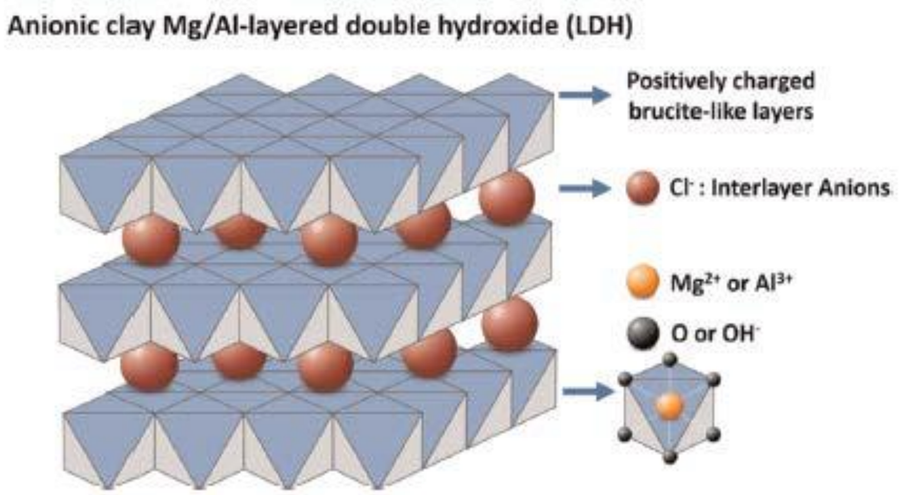

Figure 3: Hydrotalcite (HTC) adsorbent.

The main accomplishments and findings of the USC team's predecessor project included the following:

- CMS membranes were prepared and tested over the full range of expected operating temperatures (up to 300°C) and pressures (10 to 25 bar). Performance targets for H_2 permeance (350 to 550 gas permeation units [GPU]) and H_2/CO selectivity of greater than 80 were met.
- HTC sorbent was prepared, and adsorption/desorption kinetics and working capacity measured at expected operating conditions of 300 to 450°C and pressure up to 25 bar. A performance target for working capacity of greater than 3 weight % CO_2 was met.
- Kinetics of a commercially available sour-shift WGS catalyst were measured at expected operating conditions. This information is essential in modeling and in preparing a TEA of the MR-AR process.

- An MR-AR system operating run of greater than 500 hours was carried out on simulated syngas at a flow rate of less than 0.9 kg/day in a lab-scale integrated experimental apparatus. This effectively advanced the MR-AR technology to TRL 4. Also, the membranes, sorbents, and catalysts were shown to be robust at expected operating conditions.
- Preliminary TEA study results comparing an MR-AR integrated system to a baseline Selexol system (both in the IGCC context) show substantial reductions in required compression work and WGS catalyst requirements. The overall COE target of 30% lower cost than the baseline COE would be closely approached or met given known performance parameters and assumptions.

It should be noted that there are several major points of departure of the case of MR-AR within an IGCC power plant context from the baseline IGCC case. These become important in process performance and cost analysis:

1. The WGS reaction occurs in the MRs and ARs alongside H_2 removal (in the MRs) and CO_2 removal (in the ARs).
2. The amount of steam used in the MR-AR technology serves not only as a reactant but also as a sweep agent to separate the WGS reaction products.
3. A single-stage Selexol unit is needed for H_2S removal, as opposed to a dual-stage Selexol unit for H_2S and CO_2 removal in the baseline case.
4. Steam is used as diluent in the combustion turbine, as opposed to nitrogen (N_2) in the baseline case.

All four of the above items are beneficial from cost, efficiency, and environmental impact viewpoints. The simultaneously reactive-separative nature of the MR-AR units intensifies the kinetic and equilibrium behavior of the WGS reaction, thus resulting in lower catalyst use. It also delivers separate, high-pressure H_2 and CO_2 streams, thus improving process efficiency, economics, and environmental impact through reduced H_2/CO_2 compression costs and reduced Selexol solvent losses/emissions from the single-stage Selexol unit used in MR-AR for H_2S removal compared to the dual-stage Selexol unit used in the baseline. Although, in the MR-AR process, water is used as a WGS reactant, sweeping agent, and H_2 combustion diluent, net water consumption in the MR-AR is only marginally higher than that of the baseline case. This is the result of heat/power/water integration strategies, which additionally result in the availability of N_2 or possible sales that significantly improve process economics, and can also potentially reduce environmental impact, by reducing the possibility of nitrous oxide (NO_X) emissions in H_2 turbine combustion. The use of N_2 as raw material for ammonia (NH_3) production and the current commercialization of NH_3 as an H_2 transport medium greatly enhance the marketability of the MR-AR technology.

Bench-scale testing was sited at UKy's Center for Applied Energy Research (CAER) to enable testing on actual coal-derived syngas from CAER's entrained-flow coal gasifier. The bench-scale unit utilizes 30-inch membrane tubes in 2-inch outer diameter modules for the MR; the process parameters for which are shown in Table 1, while those of the sorbent are shown in Table 2. Test campaigns totaling 500 hours are planned, enabling determination of performance at this larger scale, affording an opportunity to evaluate membrane, catalyst, and sorbent stability over time. The performance data will allow improved TEA of the MR-AR system.

TABLE 1: MEMBRANE PROCESS PARAMETERS

Materials Properties	Units	Current R&D Value	Target R&D Value
Materials of Fabrication for Selective Layer	—	carbon molecular sieve (CMS)	
Materials of Fabrication for Support Layer	—	alumina	
Nominal Thickness of Selective Layer	µm	2–3	2–3
Membrane Geometry	—	tubular	tubular
Maximum Trans-Membrane Pressure	bar	>82 bar	>82 bar
Hours Tested without Significant Degradation	—	>16,000 hours in lab, >1,000 hours at NCCC	—
Manufacturing Cost for Membrane Material	$/m^2	<1,500	<750
Membrane Performance			
Temperature	°C	250–300	250–300
H_2 Pressure Normalized Flux	GPU or equivalent	500	900
H_2/H_2O Selectivity	—	2–4	>3
H_2/CO_2 Selectivity	—	.200	>200
H_2/H_2S Selectivity	—	>100	>100
Sulfur Tolerance	ppm	>10,000	>10,000

Type of Measurement	—	mixed gas		mixed gas
Proposed Module Design				
Flow Arrangement	—		co/counter-current or cross-flow	
Packing Density	m^2/m^3		>450	
Shell-Side Fluid	—		Permeate	
Syngas Gas Flowrate	kg/hr		—	
CO_2 Recovery, Purity, and Pressure	%/%/bar	90	95	>60
H_2 Recovery, Purity, and Pressure	%/%/bar	>80	>90	Up to 20
Pressure Drops Shell/Tube Side	bar		—	
Estimated Module Cost of Manufacturing and Installation	$\frac{\$}{kg/hr}$		1,500	

TABLE 2: SORBENT PROCESS PARAMETERS

Sorbent	Units	Current R&D Value		Target R&D Value
True Density @ STP	kg/m^3	2,849–3,066		2,849–3066
Bulk Density	kg/m^3	1,322–1,423		1,322–1,423
Average Particle Diameter	mm	0.6–0.8		2–3
Particle Void Fraction	m^3/m^3	0.536		0.536
Packing Density	m^3/m^3	0.406		0.406
Solid Heat Capacity @ STP	kJ/kg-K	0.5–0.65		0.5–0.65
Crush Strength	kg_f	N/A		10-15
Manufacturing Cost for Sorbent	$/kg	—		—
Adsorption				
Pressure	bar	25		>25
Temperature	°C	250–300		250–300
Equilibrium Loading	g mol CO_2/kg	~3		~3
Heat of Adsorption	kJ/mol CO_2	~10 kJ/mol		~10 kJ/mol
Desorption				
Pressure	bar	25		>25
Temperature	°C	400–450		<400
Equilibrium CO_2 Loading	g mol CO_2/kg	0.1-0.2		<0.1
Heat of Desorption	kJ/mol CO_2	—		—
Proposed Module Design			*(for equipment developers)*	
Flow Arrangement/Operation	—		See Figure 2	
Flue Gas Flowrate	kg/hr		—	
CO_2 Recovery, Purity, and Pressure	% / % / bar	>90	95	25
Adsorber Pressure Drop	bar		—	
Estimated Adsorber/Stripper Cost of Manufacturing and Installation	$\frac{\$}{kg/hr}$		—	

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.

Membrane Geometry – Flat discs or sheets, hollow fibers, tubes, etc.

Pressure Normalized Flux – For materials that display a linear dependence of flux on partial pressure differential, this is equivalent to the membrane's permeance.

GPU – Gas permeation unit, which is equivalent to 10^{-6} cm^3 (1 atm, 0°C)/cm^2/s/cm mercury (Hg). For non-linear materials, the dimensional units reported should be based on flux measured in cm^3 (1 atm, 0°C)/cm^2/s with pressures measured in cm Hg. Note: 1 GPU = 3.3464×10^{-6} kg mol/m^2-s-kPa (SI units).

Type of Measurement – Either mixed or pure gas measurements; target permeance and selectivities should be for mixture of gases found in pre-conditioned syngas.

Flow Arrangement – Typical gas-separation module designs include spiral-wound sheets, hollow-fiber bundles, shell-and-tube, and plate-and-frame, which result in either cocurrent, countercurrent, crossflow arrangements, or some complex combination of these.

Packing Density – Ratio of the active surface area of the membrane to the volume of the module.

Shell-Side Fluid – Either the permeate (H_2-rich) or retentate (syngas) stream.

STP – Standard temperature and pressure (15°C, 1 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.

Desorption – The conditions of interest for desorption are those that prevail at minimum sorbent loading. 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.

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

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

Flow Arrangement/Operation – See Figures 1 and 2.

Estimated Cost (Sorbent + Membrane) – Basis is kg/hr of CO_2 in CO_2-rich product gas; assuming targets are met (see Table 3).

Other Parameter Descriptions:

Membrane Permeation Mechanism – Molecular sieving.

Contaminant Resistance – Resists all chemical contaminants in gasifier off-gas including H_2S, NH_3, heavy metals, organic vapors, tars, etc., based on bench-scale testing conducted at the National Carbon Capture Center (NCCC).

Syngas Pretreatment Requirements – Particulate removal should be practiced.

Membrane Replacement Requirements – Not known presently but assumed to be five to 10 years. More than 16,000 hours of laboratory thermal stability testing has been demonstrated with no failure. More than 1,000 hours of live syngas testing at NCCC has been conducted with no failure.

Waste Streams Generated – None.

Process Design Concept – See Figure 1.

Proposed Module Integration – See below.

Entering Module	Pressure psia.	Temperature °F	Composition						
			vol%						ppmv
			CO_2	CO	CH_4	N_2	H_2	H_2O	H_2S
MR	800	440-540	0.1089	0.2823	0.0010	0.0055	0.2689	0.3190	5700
AR	800**	440-540*	0.2480	0.1466	0.0009	0.0055	0.2590	0.3253	5700

* Species compositions shown for inlet temperature of 440°F; **To match the exit gasifier conditions.

TABLE 3: POWER PLANT CARBON CAPTURE ECONOMICS

Economic Values	Units	Current R&D Value	Target R&D Value
Cost of Carbon Captured	\$/tonne CO_2	9.2—37.4 (Yes-No N_2 sold) 63.2 (B5B Baseline)	N/A
Cost of Carbon Avoided	\$/tonne CO_2	23.1—66.4 (Yes-No N_2 sold) 91.7 (B5B Baseline)	N/A
Capital Expenditures	\$/MWhr	56.9—60.4 (No-Yes N_2 sold) 74.2 (B5B Baseline)	N/A
Operating Expenditures	\$/MWhr	26.3—28.0 (No-Yes N_2 sold) 30.4 (B5B Baseline)	N/A
Cost of Electricity	\$/MWhr	89.1—109.8 (Yes-No N_2 sold) 135.4 (B5B Baseline)	94.8

technology advantages

- Improved WGS efficiency: hybrid concept process allows the simultaneous removal from the reacting phase and recovery of both H_2 and CO_2, resulting in significant reaction rate enhancement over the conventional WGS system.
- Significantly reduced catalyst weight usage requirements: reaction rate enhancement (over conventional WGS) permits operation at lower weight of catalyst/inlet molar flow rate of CO (W/F_{CO}), thus resulting in significant catalyst savings.
- No syngas pretreatment required given use of sour-shift catalyst and use of CMS membranes, which have demonstrated stability to all gaseous contaminants present in coal-derived syngas.
- Efficient H_2 production and superior CO_2 recovery and purity: the synergy of the MR and AR units satisfies the CO_2 recovery/purity, carbon utilization (CO conversion), and H_2 recovery/purity goals.

R&D challenges

- Heat management in reactors.
- Process integration with IGCC.
- Particulate matter needs to be controlled to reduce its potential impact on the reactor units.
- Scale-up and integration issues, given the large number of reactor modules needed to service a 550-MWe plant.

status

Design and construction of the bench-scale unit for testing at UKy CAER has been completed. All utility connections have also been completed, and testing is currently underway. Schematics, photographs, and system description were provided in quarterly reports.

available reports/technical papers/presentations

"Bench-Scale Testing of a High Efficiency, Ultra-Compact Process for Pre-Combustion CO_2 Capture," presentation by Theo Tsotsis, University of Southern California, 2020. Budget Period 1 Report Meeting. November 2020.

"*A High Efficiency, Ultra-compact Process for Pre-combustion CO_2 Capture*," presentation by Theo Tsotsis, University of Southern California, 2019 Carbon Capture, Utilization, Storage, and Oil and Gas Technologies Integrated Review Meeting - Capture and Utilization Sessions, August 2019. *https://netl.doe.gov/sites/default/files/netl-file/T-Tsotsis-USC-Ultracompact-Capture.pdf*.

"*Bench-Scale Testing of a High Efficiency, Ultra-Compact Process for Pre-Combustion CO_2 Capture*," NETL Project Kickoff Meeting Presentation, May 2019. *https://www.netl.doe.gov/projects/plp-download.aspx?id=15394&filename=USC%20Bench%20MR-AR%20Kickoff_May%202019.pdf*.

"*A High Efficiency, Ultra-compact Process for Pre-combustion CO_2 Capture*," Final Report submitted to the U.S. Department of Energy, National Energy Technology Laboratory. DOE Award Number DE-FE0026423, University of Southern California, April 2019. *https://www.osti.gov/servlets/purl/1526847*.

Karagöz, S., Tsotsis, T.T., and Manousiouthakis, V.I., "Multi-scale Modeling and Simulation of a Novel Membrane Reactor (MR)/Adsorptive Reactor (AR) Process," In Press, *Chemical Engineering & Processing: Process Intensification,* 137, 146, 2019.

Karagöz, S., Tsotsis, T.T., and Manousiouthakis, V.I., "Energy Intensification of H_2 Generation and CO_2 Capture/Utilization by Carrying-out the Water Gas Shift Reaction in an Adsorptive Reactor: Multiscale Dynamic Modeling and Simulation," *AIChE J.,* 2019.doi: 10.1002/aic.16608.

Pichardo, P., Karagöz, S., Ciora, R., Tsotsis, T.T., and Manousiouthakis, V.I., "Technical Economic Analysis of an Intensified Integrated Gasification Combined Cycle (IGCC) Power Plant Featuring a Sequence of Membrane Reactors," *J. Membrane Sci.,* 579, 266, 2019.

Garshasbi, A., Chen, H., Cao, M., Karagöz, S., Ciora, R.J., Liu, P.K.T, Manousiouthakis, V.I., and Tsotsis, T.T., "Membrane-based Reactive Separations for Process Intensification during Power Generation", Catalysis Today, 331, 18, 2019.

Pichardo, P., Karagöz, S., Ciora, R., Tsotsis, T.T., and Manousiouthakis, V.I., "Techno-Economic Analysis of an Intensified Integrated Gasification Combined Cycle (IGCC) Power Plant Featuring a Combined Membrane Reactor - Adsorptive Reactor (MR-AR) System," DOI: 10.1021/acs.iecr.9b02027, *Ind. Eng. Chem. Res.,* 2019.

Karagöz, S., Tsotsis, T.T., and Manousiouthakis, V.I., "Multi-scale Model based Design of Membrane Reactor/Separator Processes for Intensified Hydrogen Production through the Water Gas Shift Reaction," In Press, Int. *J. Hydrogen Energy.*

Garshasbi, A., Karagöz**,** S**.,** Chen, H., Cao, M., Pichardo, P., Ciora, R., Liu, P.K.T, Manousiouthakis, V., and Tsotsis, T.T., "Membrane-Based Reactive Separations for Process Intensification During the Power Generation," Presentation at the 25th International Symposium on Chemical Reaction Engineering, May 20-23, 2018, Florence, Italy.

Chen, H., Garshasbi, A., Karagöz**,** S**.,** Cao, M., Pichardo, P., Ciora, R., Liu, P.K.T, Manousiouthakis, V., and Tsotsis, T.T., "Carbon Molecular Sieve-Based Reactive Separations for Power Generation Applications," Presentation at the 15th International Conference on Inorganic Membranes, June 18-22, 2018, Dresden, Germany

Tsotsis, T., Manousiouthakis, V., Ciora, R., "A High Efficiency, Ultra-Compact Process for Pre-combustion CO_2 Capture (FE0026423)," Presented at the CO_2 Capture Technology Meeting, August 13-17, 2018, Pittsburgh, PA.

Karagöz S., Tsotsis, T., Manousiouthakis, V.I., "Process Intensification of Hydrogen Production Systems," Session 185ag Interactive Session: Systems and Process Design, presented at AIChE Annual Meeting, Pittsburgh, PA, 10-29-2018.

Karagöz S., Tsotsis, T., Manousiouthakis, V.I., "Effectiveness Factor Phenomena for the Transition between PBR and MR via Coupled Heat and Mass Transfer," Session 360g Process Intensification by Enhanced Heat and Mass Transfer, presented at AIChE Annual Meeting, Pittsburgh, PA, 10-30-2018.

Chen, H., Cao, M., Karagöz, S., Zhao, L., Manousiouthakis, V., and Tsotsis, T.T., “Experimental and Numerical Study of an Intensified Water-Gas Shift (WGS) Reactor Process Using a Membrane Reactor (MR)/Adsorptive Reactor (AR) Sequence,” Paper 464b, presented at the AIChE Annual Meeting, Pittsburgh, PA, 10-31-2018.

Karagöz, S., Da Cruz, F.E., Tsotsis, T.T., and Manousiouthakis, V.I., “Multi-Scale Membrane Reactor (MR) Modeling and Simulation for the Water Gas Shift Reaction,” *Chemical Engineering & Processing: Process Intensification*, 133, 245, 2018.

Chen, H., Cao, M., Manousiouthakis, V.I., and Tsotsis, T.T., “An Experimental Study of an Intensified Water-Gas Shift Reaction Process Using a Membrane Reactor/Adsorptive Reactor Sequence,” *Ind. Eng. Chem. Res.,* 57, 13650, 2018.

Karagöz S., Tsotsis, T., Manousiouthakis, V., “Modeling and Simulation of a Hybrid Adsorptive-Membrane Reactor (HAMR) for Intensification of the Water-Gas Shift (WGS) Reaction Process,” Presentation at 2017 AIChE Conference, October 29 - November 3, Minneapolis, MN.

Karagöz S., Tsotsis, T., Manousiouthakis, V., “A Parametric Study of the Adsorption/Desorption Steps for an Adsorptive Reactor (AR) Intensifying the Water Gas Shift (WGS) Reaction,” Presentation at 2017 AIChE Conference, October 29-November 3, Minneapolis, MN.

Karagöz S., Tsotsis, T., Manousiouthakis, V., “Comparative Study of a Hybrid Adsorptive-Membrane Reactor (HAMR) with a Membrane Reactor/Adsorptive Reactor Sequence,” Presentation at the 2017 AIChE Conference, October 29-November 3, Minneapolis, MN.

Pichardo, P., Karagöz, S., Tsotsis, T.T., Ciora, R., Manousiouthakis, V. “Technical Economic Analysis of an Intensified Integrated Gasification Combined Cycle Plant Design Featuring Membrane and Adsorptive Reactors,” Presentation at 2017 AIChE Conference, October 29-November 3, Minneapolis, MN.

Chen, H., Cao, M., Karagöz, S., Manousiouthakis, V., and Tsotsis, T.T., “Experimental and Numerical Study of an Intensified Water-Gas Shift (WGS) Reaction Process Using a Membrane Reactor (MR)/Adsorptive Reactor (AR) Sequence,” Presentation at the 2017 AIChE Conference, October 29-November 3, Minneapolis, MN.

Garshasbi, A., Chen, H., Cao, M., Karagöz, S., Ciora, R.J., Liu, P.K.T, Manousiouthakis, V.I., and Tsotsis, T.T., “Membrane-Based Reactive Separations in Power Generation,” Presentation at ICOM 2017, San Francisco, CA, 29 Jul-4 Aug, 2017.

Tsotsis, T., Manousiouthakis, V., Ciora, R., “A High Efficiency, Ultra-Compact Process for Pre-combustion CO_2 Capture (FE0026423),” Presented at the CO_2 Capture Technology Meeting, August 2017, Pittsburgh, PA.

Garshasbi, A., Chen, H., Cao, M., Karagöz, S., Ciora, R.J., Liu, P.K.T, Manousiouthakis, V.I., and Tsotsis, T.T., “Membrane-Based Reactive Separations for Process Intensification During Power Generation,” Key-note Presentation at the ICCMR13, Houston, TX, July 10-13, 2017.

Tsotsis, T., Manousiouthakis, V., Ciora, R., “A High Efficiency, Ultra-Compact Process for Pre-Combustion CO_2 Capture,” BP1 Project Review Meeting Presentation, Pittsburgh, PA, March 2, 2017.

Tsotsis, T., Manousiouthakis, V., Ciora, R., “A High Efficiency, Ultra-Compact Process for Pre-combustion CO_2 Capture (FE0026423),” Presented at the CO_2 Capture Technology Meeting, August 8-12, 2016, Pittsburgh, PA.

Lowd, J., Tsotsis, T., Manousiouthakis, V., Ciora, R., “Experimental and Theoretical Studies of CO_2 Adsorption on Hydrotalcite,” Presentation at 2016 AICHE Conference, November 13-18, San Francisco, California.

Karagöz S., Tsotsis, T., Manousiouthakis, V., “Study of Adsorptive Reactor (AR): Dynamic Multi-Scale (Catalyst/Adsorbent/Reactor Scale) Modeling and Simulation,” Presentation at 2016 AICHE Conference, November 13-18, San Francisco, California.

Karagöz S., Tsotsis, T., Manousiouthakis, V., “Multi-Scale (Pellet-Reactor Scale) Membrane Reactor Modeling and Simulation: Low Temperature and High-Pressure Water-Gas Shift Reaction,” Presentation at 2016 AICHE Conference, November 13-18, San Francisco, California.

Tsotsis, T., Manousiouthakis, V., Ciora, R., “A High Efficiency, Ultra-Compact Process for Pre-Combustion CO_2 Capture,” Project Kickoff Presentation, Pittsburgh, PA, Nov. 16, 2015.