Engineering-Scale Design and Testing of Transformational Membrane Technology for CO_2 Capture

primary project goal

Gas Technology Institute (GTI) is advancing the Ohio State University's (OSU) transformational membrane-based carbon dioxide (CO_2) capture technology through engineering-scale testing on actual coal-derived flue gas at the Wyoming Integrated Test Center (ITC). The amine-containing CO_2-selective membranes developed under U.S. Department of Energy (DOE)-funded projects (FE0031731; FE0026919; FE0007632) consist of a thin selective layer coated on a polymer support and exhibit high CO_2 permeance and very high selectivity of CO_2 over nitrogen (N_2). The superior performance is based on a facilitated transport mechanism, in which a reversible CO_2 reaction with fixed-site and mobile amine carriers enhances the CO_2/N_2 separation. The objectives of this project are to fabricate commercial-size membrane modules; design and install a 1-megawatt-electric (MWe) CO_2 capture system at ITC; conduct parametric testing with one- and two-stage membrane processes at varying CO_2 capture rates (60–90%); perform continuous testing at steady-state operation for a minimum of two months; and gather the data necessary for further process scale-up.

technical goals

- Design and build an engineering-scale CO_2 capture system using OSU's transformational membrane in commercial-size membrane modules.
- Conduct tests on coal flue gas at ITC and demonstrate a continuous, steady-state operation for a minimum of two months. Gather the data necessary for process scale-up.
- Complete initial detailed techno-economic analysis (TEA) and detailed design of the engineering-scale system.
- Complete construction of the engineering-scale system and install it at ITC.
- Complete engineering-scale testing and analysis, achieve 95% CO_2 purity, and validate a capture cost of \$30/tonne of CO_2 captured and cost of electricity (COE) at least 30% less than DOE baseline approach.

technical content

OSU has developed a transformational membrane in commercial-size—a spiral-wound membrane module shown in Figure 1. The novel CO_2-selective membranes are synthesized by formulating amine-containing polymer into a thin-film composite membrane configuration (Figure 2). The polymer selective layer, typically 100–200-nm thick, carries out the CO_2/N_2 separation. The highly gas-permeable nanoporous support layer provides the mechanical strength necessary for use in a separation module.

program area:
Point Source Carbon Capture

ending scale:
Small Pilot

application:
Post-Combustion Power Generation PSC

key technology:
Membranes

project focus:
Membrane Technology for Coal-Fired Power Plants

participant:
Gas Technology Institute

project number:
FE0031946

predecessor projects:
FE0007632; FE0026919; FE0031731

NETL project manager:
Andrew O'Palko
andrew.opalko@netl.doe.gov

principal investigator:
Shiguang Li
Gas Technology Institute
shiguang.li@gastechnology.org

partners:
Ohio State University; Trimeric Corporation; Wyoming Integrated Test Center

start date:
10.01.2020

percent complete:
15%

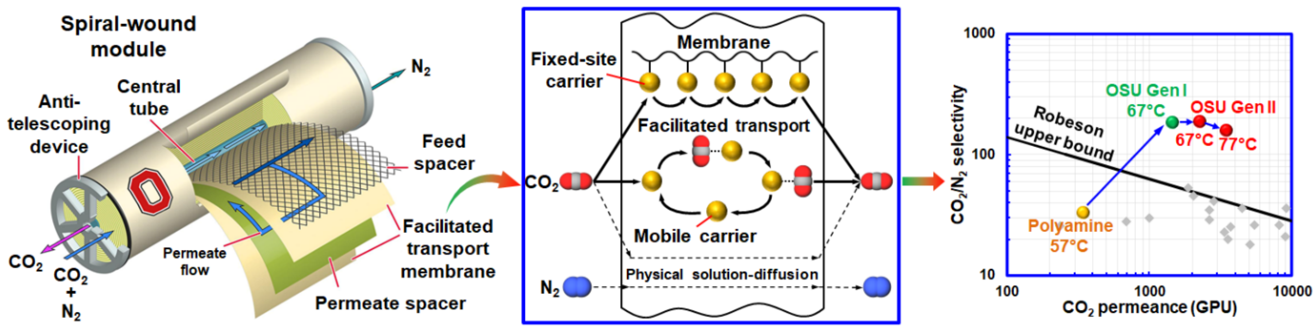

Figure 1: Diagrams of the membrane module (left), transport mechanism (middle), and performance (right).

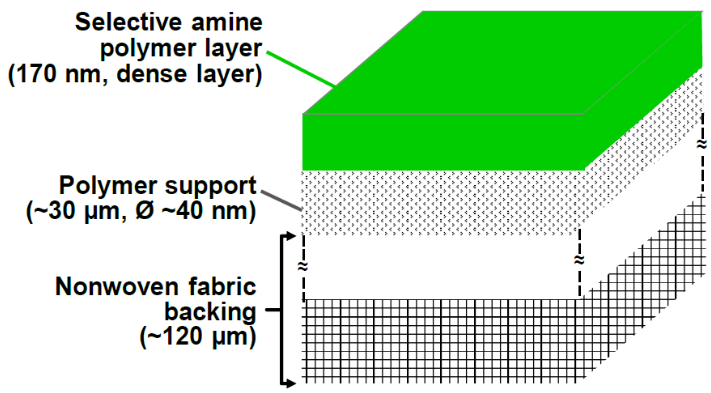

Figure 2: Schematic of the thin-film composite membrane.

In the presence of a transmembrane partial pressure difference, as illustrated in Figure 1 (middle), CO_2 molecules from the feed side dissolve in the selective layer via the reaction with the amine carriers ($CO_2 + R\text{-}NH_2 + H_2O \rightleftharpoons R\text{-}NH^+ + HCO_3^-$). The reaction product (HCO_3^-) diffuses across the membrane and eventually is converted back to the CO_2 molecules via the reverse reaction and released on the low-pressure side.

The fixed-site carrier is covalently bound to the polymer, and the mobile carrier exists as nonvolatile amino acid salt. Thus, the carriers stay in the membrane. The permeation of N_2 is extremely slow due to the lack of reactive diffusion. The disparate permeation rates result in a high CO_2 permeability and a high CO_2/N_2 selectivity, which are usually more than three-fold of those shown by membranes relying on size or condensability discrimination through the solution-diffusion mechanism.

The project is to design and build a nominal 1-MWe engineering-scale unit (approximately 20 tonnes per day [TPD]) using this transformational membrane with commercial-size modules and test it with coal-fired flue gases at ITC, located at Basin Electric Power Cooperative's Dry Fork Station, seven miles north of Gillette, Wyoming. The testing goal is to capture 60–90% CO_2 of the feed CO_2 with approximately 95% CO_2 purity. The test system will proceed in two modes—a single-stage process that is anticipated to be preferred for the lower CO_2 capture rates and an innovative retentate recycle two-stage process for the higher CO_2 capture rates (Figure 3). The data will be used in the TEA to determine the optimum configuration to meet DOE's programmatic goals.

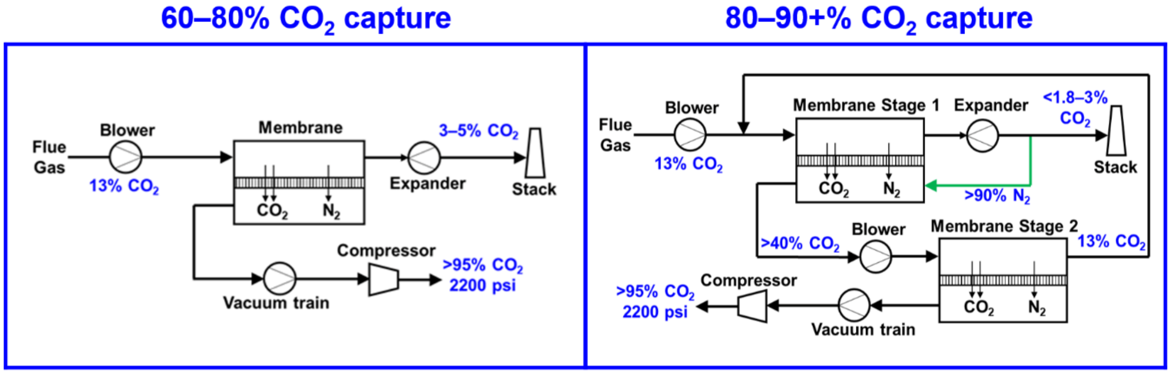

Figure 3: Flow diagrams of a one-stage membrane process to achieve 60–80% capture (left) and an innovative process to achieve >80% capture (right).

TABLE 1: MEMBRANE PROCESS PARAMETERS

Materials Properties	Units	Current R&D Value	Target R&D Value
Materials of Fabrication for Selective Layer	—	amine-containing polymer	
Materials of Fabrication for Support Layer	—	polyethersulfone on non-woven fabric	
Nominal Thickness of Selective Layer	nm	170	170
Membrane Geometry	—	flat sheet	flat sheet
Max Trans-Membrane Pressure	bar	4	4
Hours Tested without Significant Degradation	—	2,500	2,500
Manufacturing Cost for Membrane Material	$/m^2	20	20
Membrane Performance			
Temperature	°C	77	77
CO_2 Pressure Normalized Flux	GPU or equivalent	3,500	3,500
CO_2/H_2O Selectivity	—	1	1
CO_2/N_2 Selectivity	—	160	160
Type of Measurement	—	mixed gas	mixed gas
Proposed Module Design		*(for equipment developers)*	
Flow Arrangement	—	spiral-wound, countercurrent	
Packing Density	m^2/m^3	ca. 2,000	
Permeate-Side Fluid	—	vacuum or retentate recycle	
Flue Gas Flowrate	ft^3/min	30.9	
CO_2 Recovery, Purity, and Pressure	%/%/bar	60–90 >95 1	
Pressure Drops Shell/Tube Side	psi/m	1.5/1.5	
Estimated Module Cost of Manufacturing and Installation	$\frac{\$}{m^2}$	21.2	

Definitions:

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 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^{-10} 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 de-sulfurized flue gas.

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 (CO_2-rich) or retentate (flue gas) stream.

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

Flue Gas Assumptions – Unless noted, flue gas pressure, temperature, and composition leaving the FGD (wet basis) should be assumed as:

Pressure	Temperature	Composition						
		vol%					ppmv	
		CO_2	H_2O	N_2	O_2	Ar	SO_X	NO_X
14.79 psia	135°F	12.46	14.97	68.12	3.64	0.81	42	74

Other Parameter Descriptions:

Membrane Permeation Mechanism – Facilitated transport for amine-containing selective layer.

Contaminant Resistance – Resist up to 3 parts per million volume (ppmv) SO_2 and NO_2, respectively.

Flue Gas Pretreatment Requirements – Removal of particulates; SO_2 and NO_2 polishing to 3 ppmv.

Membrane Replacement Requirements – Estimated approximately four years.

Waste Streams Generated – Nitrogen with water, about 1% CO_2, and minor impurities.

Process Design Concept – Flowsheet diagrams shown in Figure 3.

Proposed Module Design – See Figure 1 (left).

TABLE 2: POWER PLANT CARBON CAPTURE ECONOMICS (90% CAPTURE)

Economic Values	Units	Current R&D Value	Target R&D Value
Cost of Carbon Captured	\$/tonne CO_2	40.3	40.0
Capital Expenditures	\$/MWhr	19.8	20.0
Operating Expenditures	\$/MWhr	10.5	12.0
Cost of Electricity	\$/MWhr	100.5	100.4

TABLE 3: POWER PLANT CARBON CAPTURE ECONOMICS (70% CAPTURE)

Economic Values	Units	Current R&D Value	Target R&D Value
Cost of Carbon Captured	\$/tonne CO_2	33.6	30.0
Capital Expenditures	\$/MWhr	10.6	10.5
Operating Expenditures	\$/MWhr	6.8	7.0
Cost of Electricity	\$/MWhr	85.9	86.0

Definitions:

Cost of Carbon Captured – Projected cost of capture per mass of CO_2 captured 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.

Calculations Basis – "Cost and Performance Baseline for Fossil Energy Plants Volume 1: Bituminous Coal and Natural Gas to Electricity, Rev. 4" report (*https://www.netl.doe.gov/energy-analysis/details?id=3745*).

Scale of Validation of Technology Used in TEA – Bench-scale testing.

Qualifying Information or Assumptions – A direct contact cooler is not needed to condition the flue gas since the membrane is operated at 77°C. The purchased equipment cost for the turbo expander is $300/kWe based on literature data.

technology advantages

- Simplicity of membrane design leads to low-cost membranes.
- High CO_2 selectivity due to facilitated transport mechanism.
- Sensitivity study suggests that the COE at 70% CO_2 capture can be ca. 30% less than the DOE baseline approach.

R&D challenges

- Membrane stability in the presence of high-level contaminants, such as SO_2 and nitrogen oxide (NO_X).
- Corrosion or particulates fouling of membrane system equipment.

status

OSU has successfully developed their Gen II membrane, which has CO_2 permeance of 3,500 GPU and CO_2/N_2 selectivity of 160. Long-term stability was confirmed on simulated flue gas for the OSU Gen II membrane and on simulated and actual flue gas at the National Carbon Capture Center (NCCC) for the OSU Gen I membrane. The TEA based on bench-scale data suggests the membrane can achieve ca. 30% reduction in COE for a 70% CO_2 capture rate with a one-stage process compared with the DOE baseline approach and ca. $40/tonne for a 90% CO_2 capture rate with an innovative two-stage process. Current efforts are focusing upon designing an engineering-scale CO_2 capture system using OSU's transformational membrane and process for field testing at ITC. Fabrication and testing of prototype membrane and commercial-sized membrane modules are currently underway.

available reports/technical papers/presentations

Shiguang Li, Yang Han, Winston Ho, Travis Pyrzynski, Weiwei Xu, Howard Meyer, and John Marion, "Engineering Scale Design and Testing of Transformational Membrane Technology for CO_2 Capture," Project kickoff meeting presentation, Pittsburgh, PA, July 2021. *http://www.netl.doe.gov/projects/plp-download.aspx?id=11034&filename=Engineering+Scale+Design+and+Testing+of+Transformational+Membrane+Technology+for+CO2+Capture.pdf*.

Shiguang Li, Yang Han, Winston Ho, Travis Pyrzynski, Weiwei Xu, and Howard Meyer, "Engineering Scale Design and Testing of Transformational Membrane Technology for CO_2 Capture," NETL Carbon Management Research Project Review Meeting, Pittsburgh, PA, August 2021. *https://netl.doe.gov/sites/default/files/netl-file/S-Li%2C-GTI-Transformational-Membrane-Testing.pdf*