Scale-Up and Testing of Advanced Polaris Membrane CO_2 Capture Technology

primary project goal

Membrane Technology and Research Inc. (MTR) will design, build, and operate an advanced Polaris™ membrane carbon dioxide (CO_2) capture system at the Technology Centre Mongstad (TCM) using actual flue gas from a refinery catalytic cracker, which simulates coal flue gas. This test system will validate recent membrane technology advancements and mitigate risk in future scale-up activities. The overall MTR membrane process will show the potential to meet the 2030 U.S. Department of Energy (DOE) target of $30/tonne CO_2 captured from coal-fired power plants. This project will demonstrate a cost-effective advanced membrane process to capture CO_2 from flue gas through slipstream tests at TCM using commercial-scale components. Results from this field test will provide performance data to allow a thorough technical and economic evaluation of the proposed membrane process. Successful completion of this project will signify readiness to proceed to the next step—testing a larger proof-of-concept advanced membrane system on the scale of 10–25 megawatts-electric (MWe).

technical goals

- Design the membrane test system and complete host site preparations.
- Fabricate commercial-scale membranes and low-pressure-drop membrane modules.
- Fabricate membrane test system skid, with membrane modules incorporated into skid, and install system at TCM.
- Conduct a minimum six-month field test, including three months of steady-state operation and parametric tests that focus on verifying system performance at partial capture rates that minimize capture costs.
- Evaluate optimal integration of advanced compression into the membrane capture process, including cost estimates.
- Complete a techno-economic analysis (TEA) and environmental, health, and safety (EH&S) assessment of the membrane capture technology.

technical content

In this project, no additional membrane development is required. A previously validated second-generation (Gen-2) membrane will be scaled-up to commercial manufacturing equipment. It is expected that this production scale-up process will produce cost savings through bulk materials usage and application of automated manufacturing equipment.

The goal of this project is to scale-up advanced Polaris Gen-2 membranes and modules to a final form optimized for commercial use, and to validate their transformational potential in an engineering-scale field test at TCM. This program will expand on work conducted by MTR over the past decade with DOE support to develop efficient membrane CO_2 capture technology. This effort has produced the MTR Polaris class of membranes and a patented selective recycle process design that lowers the cost of capture.

program area:
Point Source Carbon Capture

ending scale:
Large Pilot

application:
Post-Combustion Power Generation PSC

key technology:
Membranes

project focus:
Polymeric Membranes for Coal-Fired Power Plants

participant:
Membrane Technology and Research, Inc.

project number:
FE0031591

predecessor projects:
FE0005795
FE0026414

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partners:
Technology Centre Mongstad; Dresser-Rand; Trimeric Corporation; WorleyParsons/Advisian

start date:
08.01.2018

percent complete:
80%

Over the course of this development effort, key improvements made included higher-permeance membranes, low-pressure-drop modules, and a process design that optimizes the efficiency of capture.

The Polaris Gen-2 membranes have demonstrated 70% higher CO_2 removal capacity compared to the original membrane in bench-scale tests at the National Carbon Capture Center (NCCC) (Figure 1). They will be packaged into new modules designed for low-pressure flue gas treatment. Prototypes of these modules have been validated in prior field trials that confirm large energy and cost savings. Assemblies of these modules will be fitted into a standard container that represents the final form factor for this technology, with future commercial systems simply utilizing large numbers of this modular repeat unit.

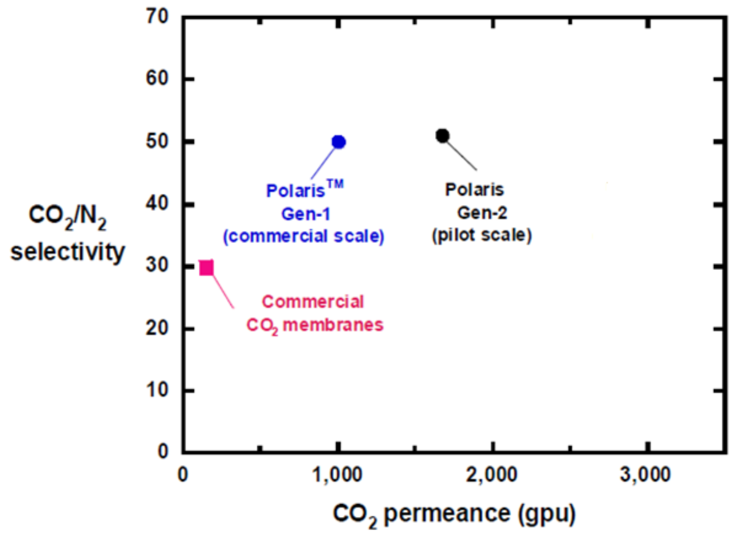

Figure 1: A CO_2/N_2 trade-off plot showing data for two generations of MTR Polaris membrane. Data are pure-gas values at room temperature.

These step-change material and device advances will be incorporated into a system design that takes advantage of the inherent efficiency of membranes for bulk separations. Capture costs can be minimized by operating at partial capture rates (50–80%), while still reducing coal plant CO_2 emissions to that of a gas-fired power plant or less. Finally, the pairing of Polaris Gen-2 membrane technology with advanced compression technology will be investigated. This technology combination was previously featured in the DOE Pathways Study as an attractive way to reach future cost targets.

In addition to an advanced membrane material, this project will also utilize a new type of low-pressure-drop module. This plate-and-frame module, in addition to its relatively compact size, had about four times lower pressure-drop as prior spiral modules during field testing at NCCC under the same conditions (Figure 2), resulting in large energy savings.

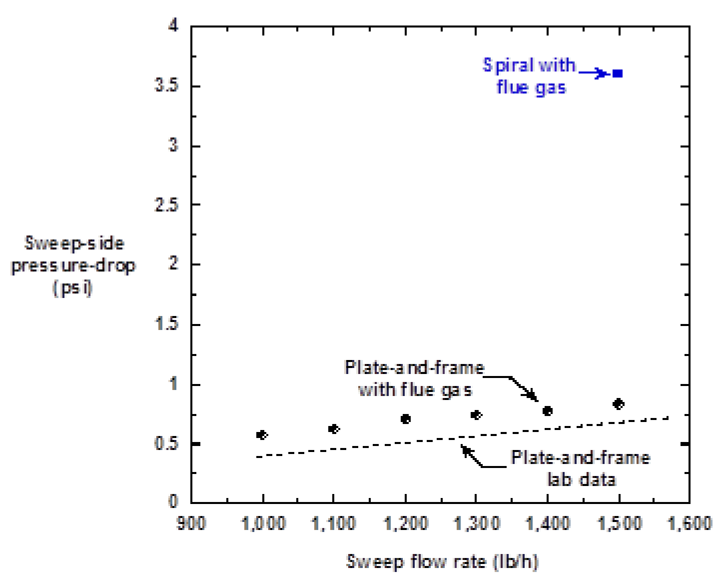

Figure 2: Difference in pressure-drop between spiral and plate-and-frame modules in NCCC field tests.

To reduce the cost of the membrane modules, MTR plans to fabricate them from structural plastics. During this project, a mold flow analysis was completed for the new module design. With this analysis, any issues with the mold design can be identified prior to actual fabrication of the mold and the molding company can determine how to operate their machinery with the MTR mold. Various process parameters were profiled and optimized, including temperature, pressure, number of gates, and gate locations.

Using the mold flow analysis, MTR, along with the domestic mold fabricator and custom plastics injection molding companies, finalized a mold design. A detailed drawing of the new planar stack containing eight membrane modules is shown in Figure 3. The process parameters for these membranes are shown in Table 1.

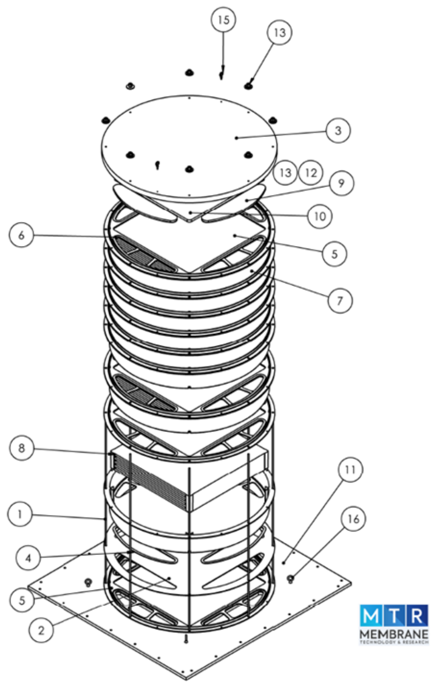

Figure 3: Detailed drawing of a membrane module stack containing eight membrane modules.

TABLE 1: MEMBRANE PROCESS PARAMETERS

Materials Properties	Units	Current R&D Value	Target R&D Value
Materials of Fabrication for Selective Layer	—	proprietary polymer	
Materials of Fabrication for Support Layer	—	proprietary polymer	
Nominal Thickness of Selective Layer	µm	<1	<1
Membrane Geometry	—	flat sheet	flat sheet
Max Trans-Membrane Pressure	bar	70	70
Hours Tested without Significant Degradation	—	>11,000 (real coal)	>13,000 (real and simulated coal)
Manufacturing Cost for Membrane Material	$/m^2	50	20
Membrane Performance			
Temperature	°C	30	30
CO_2 Pressure Normalized Flux	GPU or equivalent	1,700	1,700
CO_2/H_2O Selectivity	—	0.3	0.3
CO_2/N_2 Selectivity	—	50	50
CO_2/SO_2 Selectivity	—	0.5	0.5

Type of Measurement	—	mixed gas	mixed gas
Proposed Module Design		*(for equipment developers)*	
Flow Arrangement	—	plate-and-frame (crossflow and countercurrent)	
Packing Density	m^2/m^3	1,000	
Shell-Side Fluid	—	N/A	
Flue Gas Flow rate	kg/hr	2,676	
CO_2 Recovery, Purity, and Pressure	%/%/bar	75, >85, 1 (test system conditions)	
Pressure Drops Shell/Tube Side	bar	feed: <0.05/sweep: 0.05	

Figure 4 shows a simple process flow diagram for the MTR engineering-scale system to be installed at TCM. A slipstream of flue gas is sent to the membrane system (stream 1). After passing through a feed blower, the flue gas (stream 2) goes to the first membrane step, where a vacuum on the permeate is used to remove CO_2. The membrane permeate (stream 4) is sent to a second-stage CO_2 purification unit (stream 5). Some of this purified CO_2 can be routed through a spillback line (stream 9) to the front of the membrane system to increase the concentration of CO_2 in the feed from 13 to ~20%. In this way, the feed to the membrane system will mimic the fully integrated case without having to recycle CO_2 to the boiler. With this spillback option, the 20% CO_2 membrane feed contains about 1 MWe worth of CO_2. The partially treated flue gas that leaves the first membrane step (stream 3) is then sent to the sweep membrane unit. Air (stream 6) flows on the permeate-side of these membranes and removes additional CO_2 from the flue gas. The CO_2-enriched air (stream 7) would be sent to the boiler in integrated operation, but here it is just vented after analysis. Finally, the cleaned flue gas (stream 5) flows to the stack.

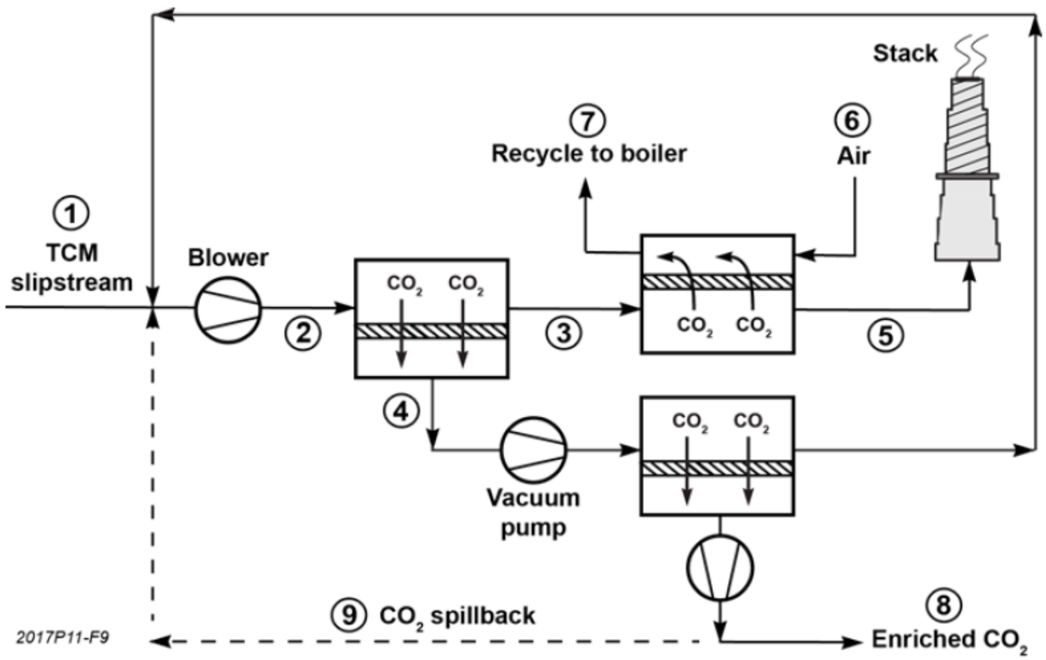

Figure 4: Simplified process flow diagram for the MTR skid operating at TCM.

Finally, the economics data for the developed membranes is shown in Table 2.

TABLE 2: POWER PLANT CARBON CAPTURE ECONOMICS

Economic Values	Units	Current R&D Value	Target R&D Value
Cost of Carbon Captured	\$/tonne CO_2	54	43
Cost of Carbon Avoided	\$/tonne CO_2	97	80

Capital Expenditures	\$/MWhr	23.9	18.4
Operating Expenditures	\$/MWhr	25.9	22.2
Cost of Electricity	\$/MWhr	50	50

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 atmosphere [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 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 concurrent, 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.

Other Parameter Descriptions:

Membrane Permeation Mechanism – Permeation through the Polaris membrane occurs by the passive solution-diffusion mechanism.

Contaminant Resistance – The membranes are known to be unaffected by water (H_2O), oxygen (O_2), and sulfur dioxide (SO_2). The effect of trace contaminants, such as Hg, arsenic, etc., is still under investigation. Polaris modules exposed to coal-fired fuel gas at NCCC for more than a year had no reduction in performance.

Flue Gas Pretreatment Requirements – When placed downstream of existing power plant flue gas emission treatment unit operations to remove particulates (nitrogen oxide [NO_X] and SO_2). The MTR Polaris post-combustion CO_2 capture membrane process design does not require additional pretreatment.

Membrane Replacement Requirements – MTR has installed hundreds of commercial membrane systems in the petrochemical, refinery, and natural gas industries over the past 30 years. The membrane module lifetime is estimated to be three years, which is at the conservative end of the typical industrial gas separation module lifetime of three to five years.

Waste Streams Generated – The MTR capture process will produce a dry, CO_2-depleted flue gas stream routed to the stack and a liquid stream containing much of the moisture in the flue gas (because the MTR membrane captures water as well as CO_2). Prior studies have determined that this water can be recycled to existing flue gas desulfurization (FGD) blowdown wastewater treatment.

technology advantages

- Polaris Gen-2 membranes have a CO_2 permeance approximately 70% higher than Gen-1 and nearly 20 times that of conventional membranes.
- There are no hazardous chemicals or emissions in the membrane process.
- The plate-and-frame membrane module minimizes pressure-drop.
- A simple system allows for low-cost partial capture, while a novel two-step design efficiently captures CO_2 at high removal rates.
- The CO_2 recycle increases feed concentration, reducing membrane area and energy requirements.
- High turndown and rapid response to dynamic conditions are possible.
- The membrane module stack reduces module space and cost, which translates into additional cost savings in the system due to reduced ductwork and system complexity.

R&D challenges

- Optimizing CO_2 capture rate to minimize capture cost.
- Long-term stability of Gen-2 membranes.
- High-permeance membrane is required to lower capital cost.
- Pressure-drops must be minimized to reduce energy losses.
- Balance of plant equipment cost and efficiency, particularly for rotating equipment, are critical to system performance.
- Scale-up and integration issues (and operational complications from multiple vacuum pumps and valves, and complicated ductwork in multiple flow banks) likely given the large number of membranes needed to service a 550-MWe plant.

status

The test system at TCM was fully commissioned at the end of July 2021. All budget period 2 objectives were completed, and full testing has begun. Project duration was extended to ensure at least six months of full-scale testing. The current system can capture 75% of CO_2 emissions with a CO_2 purity of more than 90%.

available reports/technical papers/presentations

Merkel, T., 2021, "Scale-Up Testing of Advanced Polaris Membrane CO_2 Capture Technology." Quarterly Progress Report to NETL. October 29, 2021.

Casillas, C.; Hicks, D.; Huang, I.; Hofmann, T.; Kniep, J.; Merkel, T.; Paulaha, C.; Salim, W.; Westling, E., 2021, "Scale-Up and Testing of Advanced Polaris Membranes at TCM (DE-FE0031591)." Presented at the 2021 Carbon Management and Oil & Gas Research Project Review Meeting. Pittsburgh, PA. August 12, 2021. *https://netl.doe.gov/sites/default/files/netl-file/21CMOG_PSC_Merkel.pdf*.

Merkel, T., et al. "Scale-Up and Testing of Advanced Polaris Membrane CO_2 Capture Technology," presented at the 2019 NETL CO_2 Capture Technology Project Review Meeting, Pittsburgh, PA, August 2019. *https://netl.doe.gov/sites/default/files/netl-file/T-Merkel-MTR-Advanced-Polaris-Membrane-r1.pdf*

Merkel, T., et al. "Scale-Up and Testing of Advanced Polaris Membrane CO_2 Capture Technology," Project Kickoff Presentation, Pittsburgh, PA, September 2018. *https://www.netl.doe.gov/sites/default/files/netl-file/FE0031591-Project-Kickoff-092418.pdf*.

Merkel, T., et al. "Scale-Up and Testing of Advanced Polaris Membrane CO_2 Capture Technology," presented at the 2018 NETL CO_2 Capture Technology Project Review Meeting, Pittsburgh, PA, August 2018. *https://www.netl.doe.gov/sites/default/files/netl-file/T-Merkel-MTR-Advanced-Polaris-Membrane.pdf*.