Large Pilot Testing of the MTR Membrane Post-Combustion CO_2 Capture Process

primary project goal

Membrane Technology and Research Inc. (MTR) is advancing their innovative membrane-based post-combustion carbon dioxide (CO_2) capture process to the pre-commercial stage of development. The goal of this three-phase project is to design, build, and operate a 150-tonne-per-day (TPD) large pilot capture system at the Wyoming Integrated Test Center (WITC) in Gillette, Wyoming. The membrane large pilot is designed to achieve approximately 70% CO_2 capture from a 10-megawatt-electric (MWe) equivalent slipstream of flue gas. This range of partial capture using membranes offers the lowest cost of capture ($/tonne CO_2). Phases I and II have been completed. Completion of all phases of this project will signify that the MTR membrane capture process is ready to proceed to the demonstration scale.

technical goals

Phase I (Year 1) objectives were to:

- Select a host site and secure cost-share commitments from the selected site.
- Conduct an initial Environmental Information Volume (EIV) and preliminary National Environmental Policy Act (NEPA) review of the test unit at the host site.
- Complete a preliminary design of the pilot system and obtain budgetary estimates from vendors.
- Finalize team commitments and organization for subsequent phases.

Phase II (Year 2) objectives were to:

- Complete required permit processes at the host site.
- Complete an EIV and NEPA review.
- Complete a front-end engineering design (FEED) study and update budgetary estimates and schedule for Phase III.
- Complete an updated techno-economic analysis (TEA) of the process based on the most recent system design and cost information.
- Secure host site and cost-share commitments for Phase III.

Phase III objectives are to:

- Complete construction of the 150-TPD membrane system.
- Install and operate the large pilot system at the host site.

technical content

MTR has developed a new class of membranes, called Polaris™, that have 10 times the CO_2 permeance of conventional gas separation membranes. A tenfold increase in permeance leads to a tenfold decrease in the required membrane area, which substantially reduces the capital cost and footprint of the capture system. These membranes, along with innovative process modifications, address challenges for post-combustion carbon capture.

program area:
Point Source Carbon Capture

ending scale:
Large Pilot

application:
Post-Combustion Power Generation PSC

key technology:
Membranes

project focus:
Large Pilot Testing of Polymer Membrane System

participant:
Membrane Technology and Research, Inc.

project number:
FE0031587

predecessor projects:
FE0026414; FE0007553; FE0005795

NETL project manager:
Sai Gollakota
sai.gollakota@netl.doe.gov

principal investigators:
Richard Baker/Brice Freeman
Membrane Technology and Research, Inc.
richard.baker@mtrinc.com
brice.freeman@mtrinc.com

partners:
The Wyoming Integrated Test Center; Sargent & Lundy; Trimeric Corporation; Electric Power Research Institute

start date:
04.01.2018

percent complete:
55%

Over the past decade, MTR has worked with the U.S. Department of Energy (DOE) to develop these innovations into a cost-effective CO_2 capture process. As a result of these successes, the technology was scaled-up to a 20-TPD (1-MWe) small pilot system that was operated in slipstream tests at the National Carbon Capture Center (NCCC). These activities have brought the MTR technology to the point where it is ready for large pilot evaluation. The large pilot system to be built in this project will be based on the fully validated Gen-1 Polaris membranes. This membrane has been scaled-up to commercial production quantities. In addition to successful use for CO_2 capture in field tests at the NCCC and Babcock & Wilcox Enterprises Inc. (B&W), the Polaris Gen-1 membrane has been used in commercial natural gas and refinery membrane applications.

A simplified version of the process to be used in the pilot plant is shown in the block diagram in Figure 1.

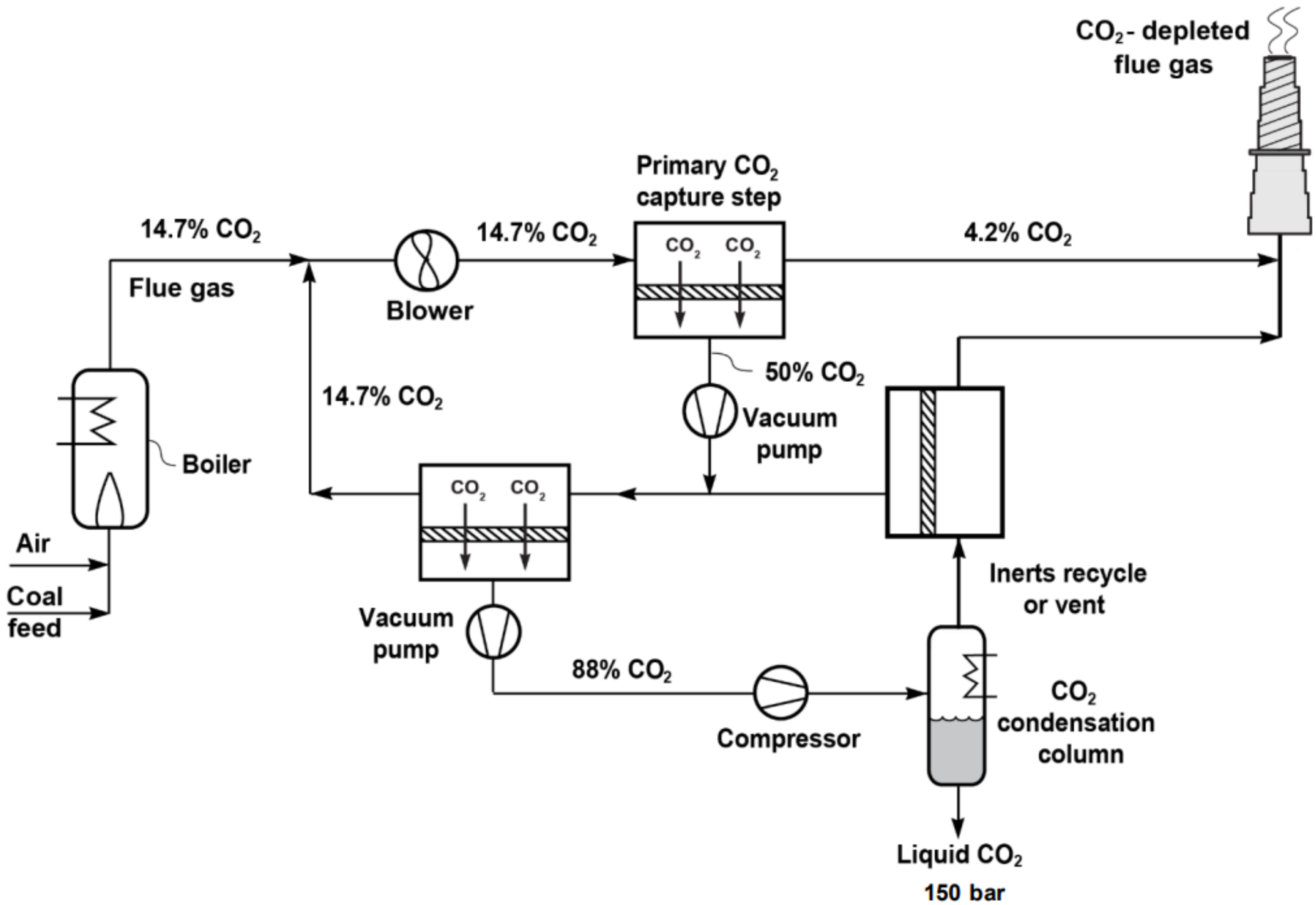

Figure 1: Simplified block diagram of the MTR large pilot CO_2 capture plant to be built.

The large pilot unit will capture approximately 70% of the CO_2 content (150 TPD) from a 10-MWe slipstream of flue gas provided by WITC. The flue gas to be delivered to the unit is at 85°C and contains 12.7% CO_2 and 18% water on average. A blower is used to increase the flue gas pressure to 1.2 bar absolute. The flue gas is then cooled in a direct contact cooler (DCC). A dedicated evaporative cooling tower will produce the cooling water required for the DCC and the various vacuum and compression intercoolers and aftercoolers. The DCC reduces the water content of the gas to 1.5% and increases the CO_2 content to approximately 15%.

The gas leaving the DCC then enters the first-stage membrane modules. The membranes partition the gas into a CO_2-enriched permeate (~50% CO_2) and a CO_2-depleted vent gas (~4% CO_2). The CO_2-depleted flue gas is vented to the atmosphere via a dedicated stack.

The driving force for CO_2 permeation is provided by a vacuum pump, which pulls to about 0.1 bar absolute pressure on the permeate-side of the membrane. From the discharge of the vacuum pump, the CO_2-enriched permeate is compressed to about 1.1 bar and sent to a second-stage membrane, which further enriches the gas to approximately 85% CO_2. The second-stage membrane unit is much smaller than the first one and uses a vacuum pump to provide driving force.

The twice enriched permeate gas from the second membrane stage is compressed to 25 bar. Some of the water in the gas is removed in the inter-stage cooler of the compressor. Most of the water that remains is removed from the compressed gas by cooling to 5°C. A molecular sieve drier is then used to produce bone-dry gas. The dry gas is passed to a low-temperature distillation unit to provide high-purity CO_2. The liquid CO_2 is then pumped to 153 bar as required for enhanced oil recovery (EOR) or storage.

A model of the 150-TPD large pilot membrane skid is shown in Figure 2. The membranes are housed in low-pressure-drop modules, which reduce cost and increase packing density. There are eight modules per stack and six stacks per container skid. The skids are stacked two high, with a total of six containers for the large pilot (five skids for first-stage membrane separation and one skid for second-stage membrane separation). This will be the final form factor for this membrane CO_2 capture technology. The membrane portion of the capture plant has a compact footprint, processing 10 MWe of flue gas in an area of approximately 100 by 100 feet, with a maximum height of 30 feet.

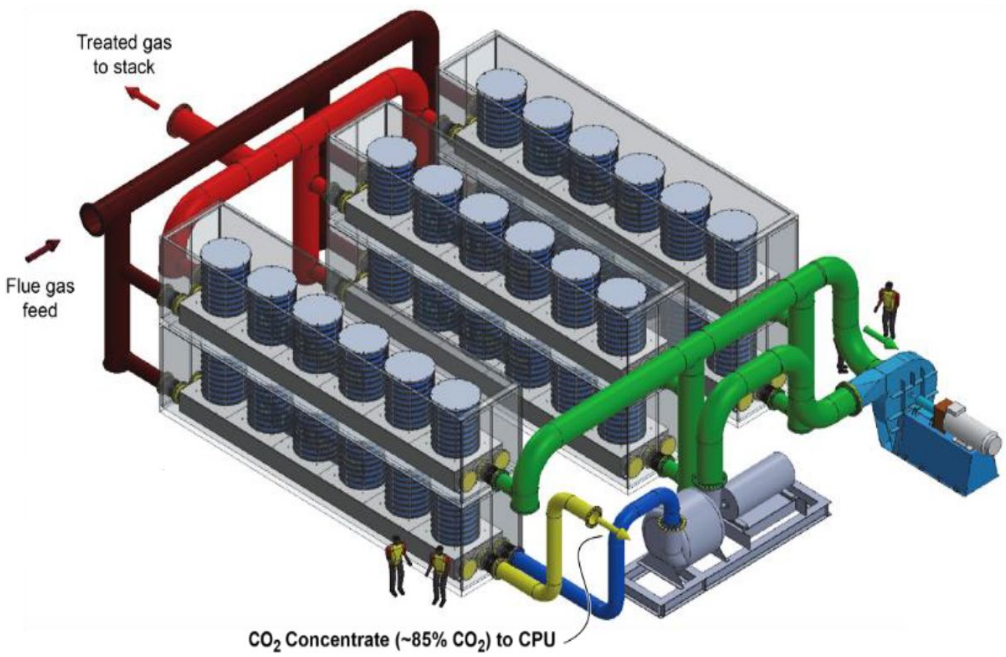

Figure 2: Preliminary general arrangement drawing of the 150-TPD large pilot system to be installed at WITC.

WITC will provide the test site and a significant cost-share contribution for the Phase II and Phase III programs. WITC is located in Gillette, Wyoming, adjacent to the Basin Electric Dry Fork 420-MWe coal power plant. Basin Electric will supply the project with the equivalent of 10 MWe of flue gas. Duct work and fans to deliver flue gas to the test site are in place. Power and water necessary for the project have also been installed. The membrane unit will recover approximately 70% of the CO_2 content of this gas, or approximately 150 TPD. At full-scale, a 70% reduction in CO_2 emissions would bring the remaining CO_2 emissions of a coal power plant to below that of an equivalent-sized natural gas power plant.

All the objectives of the Phase I feasibility study were met. Preliminary engineering drawings for the 150-TPD plant have been prepared. Budget estimates have been obtained for the major equipment items and initial cost estimates for the Phase III construction and operation work have been prepared. A preliminary cost analysis indicates that at the end of the Phase III program, the technology will be ready for scale-up to large demonstrations and CO_2 capture costs in the \$40/tonne CO_2 range will be possible.

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	1.1	1.1
Hours Tested without Significant Degradation	—	11,000 h	11,000 h
Manufacturing Cost for Membrane Material (Module and Skid)	$/m²	50-100	50-100
Membrane Performance			
Temperature	°C	30	30
CO_2 Pressure Normalized Flux	GPU or equivalent	1,000	2,000
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	—	flue gas	flue gas
Proposed Module Design		*(for equipment developers)*	
Flow Arrangement	—	plate-and-frame	
Packing Density	m^2/m^3	1,000	
Shell-Side Fluid	—	N/A	
Flue Gas Flowrate	tons/hr	70.31	
CO_2 Recovery, Purity, and Pressure	%/%/bar	70-75%, 99%, 153 bar	
Pressure Drops Shell/Tube Side	bar	feed: 0.05/sweep: 0.025	

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 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 occurs by a passive, solution-diffusion process. Permeation driving force through the first-stage membrane module is provided by a vacuum pump, which pulls to about 0.1 bar absolute pressure on the permeate-side of the membrane. The second-stage membrane unit is much smaller than the first one, and also uses a vacuum pump to provide driving force.

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, etc., is unknown.

Flue Gas Pretreatment Requirements – Testing at the NCCC showed no additional pretreatment was required downstream of a wet flue gas desulfurization (FGD).

Membrane Replacement Requirements – Greater than three-year membrane lifetime.

Waste Streams Generated – The membrane process will recover greater than 95% of the H_2O in flue gas as liquid. The quality of this H_2O and its potential to be reused in the plant will be studied in future work.

technology advantages

- The process does not use any hazardous chemicals. No new emission streams are produced.
- The membranes developed are 10 times more permeable to CO_2 than conventional membranes, which reduce the required membrane area and capital costs.
- A membrane system does not contain any chemical reactions or moving parts, making it simple to operate and maintain.
- The system is compact and modular.
- The two-stage membrane design allows for high-purity CO_2 combined with high capture rates.
- The low-pressure-drop modules reduce parasitic energy.
- The system is very efficient at partial capture (50 to ~70%).

R&D challenges

- There is a risk that the membranes may be less stable at large scale than anticipated.

status

MTR successfully completed all Phase I and Phase II activities, including an EIV, FEED, and NEPA documentation for the construction and large pilot testing of the MTR membrane post-combustion CO_2 capture process. The environmental permit for construction was obtained from the Wyoming Department of Environmental Quality. MTR finalized the engineering and design documentation and developed near-final contract and financial commitment documents for execution in Phase III. The results of the constructability review in Phase II will be used for procuring the equipment and services for the construction of the large pilot unit in Phase III. The overall design of the 150-TPD large pilot plant was finalized. Preliminary layout drawings for the system at the WITC site were prepared. In addition, MTR completed the design and purchased equipment for the fabrication of the planar module test station to perform performance and leak testing of fabricated modules. The Phase III project team was assembled and a division of responsibilities for the Phase III program was completed, along with an updated schedule and budget.

available reports/technical papers/presentations

Baker, R.W., et al. "Phase III: Large Pilot Testing of the MTR Membrane Post-Combustion CO_2 Capture Process," presented at the 2021 Carbon Management and Oil and Gas Research Project Review Meeting - Point Source Capture - Lab, Bench, and Pilot-Scale Research, August 2021. *https://netl.doe.gov/sites/default/files/netl-file/21CMOG_PSC_Baker.pdf*.

Baker, R.W., et al. "Large Pilot Testing of the MTR Membrane Post-Combustion CO_2 Capture Process," presented at the 2020 NETL Integrated Project Review Meeting - CCUS Integrated Projects, August 2020. *https://netl.doe.gov/sites/default/files/netl-file/20CCUS_Baker.pdf*.

Baker, R.W., et al. "Large Pilot Testing of the MTR Membrane Post-Combustion CO_2 Capture Process," Phase II kickoff meeting presentation, Pittsburgh, PA, October 2019. *https://www.netl.doe.gov/projects/plp-download.aspx?id=10397&filename=Large+Pilot+Testing+of+the+MTR+Membrane+Post-Combustion+CO2+Capture+Process.pdf*.

Baker, R.W., et al. "Large Pilot Testing of the MTR Membrane Post-Combustion CO_2 Capture Process," 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/R-Baker-MTR-Membrane-Testing%20r1.pdf*.

Baker, R.W., et al. "Large Pilot Testing of the MTR Membrane Post-Combustion CO_2 Capture Process," presented at the 2018 NETL CO_2 Capture Technology Project Review Meeting, Pittsburgh, PA, August 2018. *https://netl.doe.gov/sites/default/files/netl-file/R-Baker-MTR-Membrane-Large-Pilot-Testing.pdf*.

Baker, R.W., et al. "Large Pilot Testing of the MTR Membrane Post-Combustion CO_2 Capture Process," Phase I kickoff meeting presentation, Pittsburgh, PA, May 2018. *https://www.netl.doe.gov/projects/plp-download.aspx?id=10402&filename=Large+Pilot+Testing+of+the+MTR+Membrane+Post-Combustion+CO2+Capture+Process.pdf*.