

# Large Pilot Testing of the MTR Membrane Post-Combustion CO<sub>2</sub> Capture Process

## primary project goals

The overall goal of this project is to bring Membrane Technology and Research, Inc.'s (MTR) innovative membrane-based post-combustion carbon dioxide (CO<sub>2</sub>) capture process to the final pre-commercial stage of development. The recipient's plan in this three-phase project is to design, build, and operate a 140 tonne-per-day (TPD) large pilot capture system at the host site for the project, the Wyoming Integrated Test Center (WITC) in Gillette, Wyoming. The membrane large pilot will be designed to achieve ~70% CO<sub>2</sub> capture from a 10 megawatt electricity (MWe) equivalent slipstream of flue gas. This range of partial capture using membranes offers the lowest cost of capture (\$/tonne CO<sub>2</sub>). 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 (completed in year 1) included selection of the host power plant, securing financial commitments, conducting an environmental review, updating design and budget, and finalizing team commitments and organization for subsequent phases.
- Phase II (year 2) focuses on the detailed design portion of the program, including a complete front-end engineering and design (FEED) study, National Environmental Policy Act (NEPA) review, and finalized project cost projections.
- Phase III (years 3 to 6 if chosen from down-select) includes construction, installation, and operation of the large pilot system.

## technical content

MTR has developed a new class of membranes, called Polaris™, that have 10 times the CO<sub>2</sub> 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.

Over the past decade, MTR has worked with the U.S. Department of Energy (DOE) to develop these innovations into a cost-effective CO<sub>2</sub> 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

### technology maturity:

Large Pilot-Scale, Actual  
Flue Gas (140 TPD)

### project focus:

Large Pilot Polymer  
Membrane System

### participant:

Membrane Technology and  
Research, Inc.

### project number:

FE0031587

### predecessor projects:

FE0005795  
FE0026414  
FE0007553

### 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:

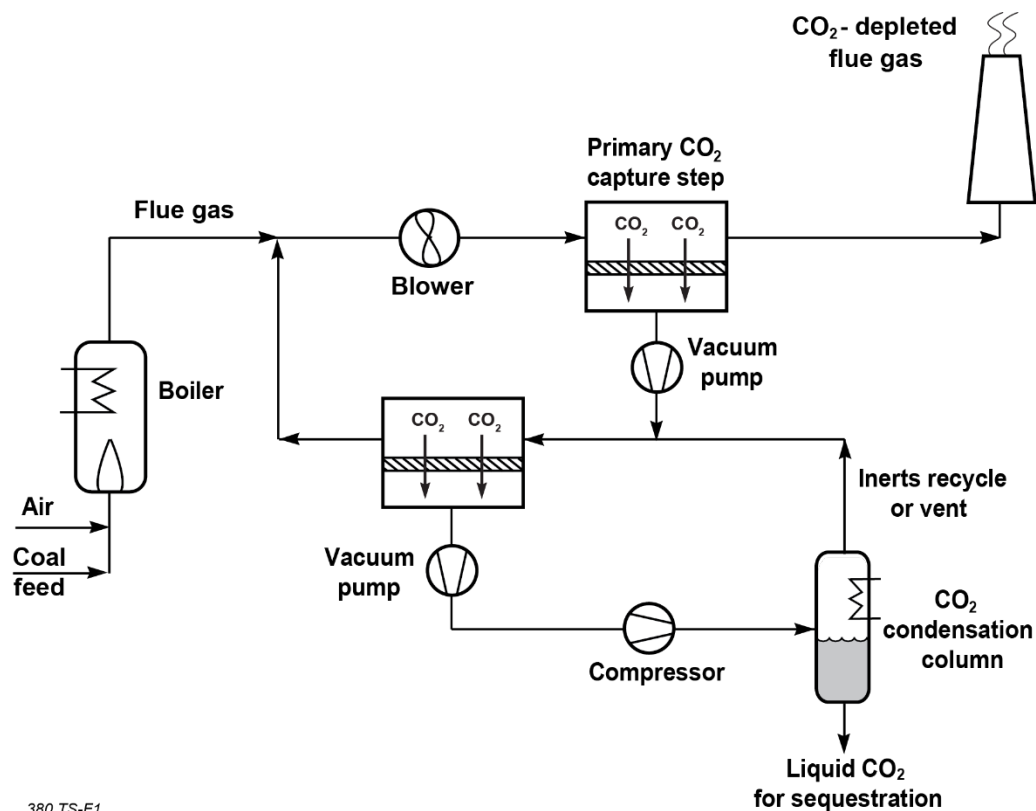
04.01.2018

### percent complete:

55%

to successful use for CO<sub>2</sub> capture in field tests at 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.



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Figure 1: Simplified block diagram of the MTR large pilot CO<sub>2</sub> capture plant to be built.

The large pilot unit will capture ~70% of the CO<sub>2</sub> content (140 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<sub>2</sub> 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<sub>2</sub> content to ~15%.

The gas leaving the DCC then enters the first-stage membrane modules. The membranes partition the gas into a CO<sub>2</sub>-enriched permeate (~50% CO<sub>2</sub>) and a CO<sub>2</sub>-depleted vent gas (~4% CO<sub>2</sub>). The CO<sub>2</sub>-depleted flue gas is vented to the atmosphere via a dedicated stack.

The driving force for CO<sub>2</sub> 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<sub>2</sub>-enriched permeate is compressed to about 1.1 bar and sent to a second-stage membrane, which further enriches the gas to ~85% CO<sub>2</sub>. The second-stage membrane unit is much smaller than the first one, and also 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<sub>2</sub>. The liquid CO<sub>2</sub> is then pumped to 153 bar as required for enhanced oil recovery (EOR) or storage.

A model of the 140-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. This will be the final form factor for this membrane CO<sub>2</sub> 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.

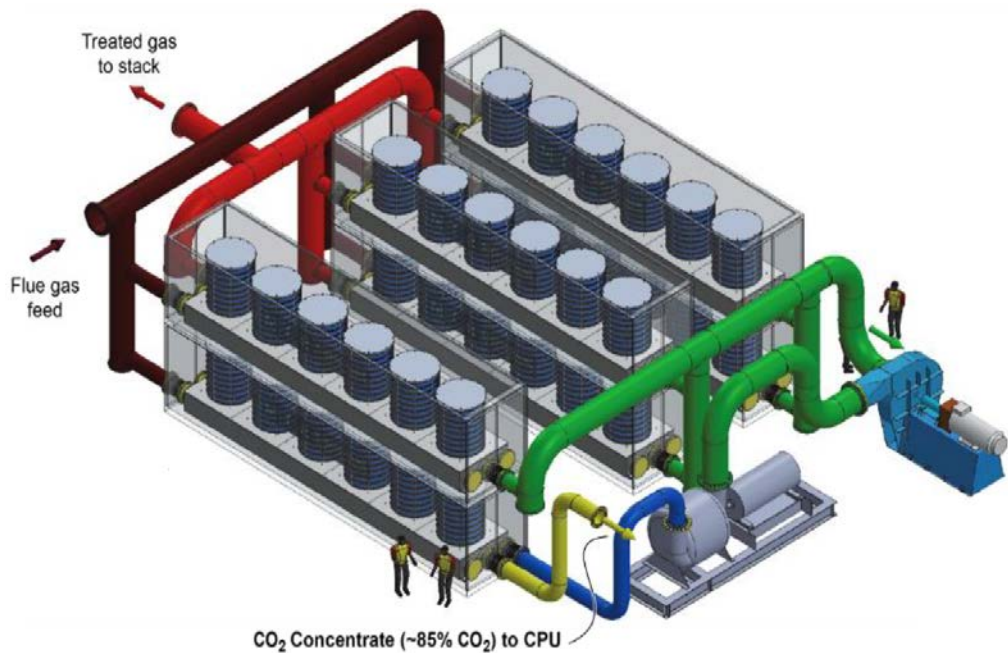


Figure 2: Preliminary general arrangement drawing of the 140-TPD large pilot system to be installed at WITC.

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 ~70% of the CO<sub>2</sub> content of this gas, or ~140 TPD. At full-scale, a 70% reduction in CO<sub>2</sub> emissions would bring the remaining CO<sub>2</sub> emissions of a coal power plant to below that of an equivalent-sized natural gas power plant.

All of the objectives of the Phase I feasibility study were met. Preliminary engineering drawings for the 140-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<sub>2</sub> capture costs in the \$40/tonne CO<sub>2</sub> 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)	\$/m <sup>2</sup>	50-100	50-100

**Membrane Performance**

Temperature	°C	30	30
CO <sub>2</sub> Pressure Normalized Flux	GPU or equivalent	1,000	2,000
CO <sub>2</sub> /H <sub>2</sub> O Selectivity	—	0.3	0.3
CO <sub>2</sub> /N <sub>2</sub> Selectivity	—	50	50
CO <sub>2</sub> /SO <sub>2</sub> 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 <sup>2</sup> /m <sup>3</sup>	1,000
Shell-Side Fluid	—	N/A
Flue Gas Flowrate	tons/hr	70.31
CO <sub>2</sub> 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<sup>-6</sup> cm<sup>3</sup> (1 atmosphere [atm], 0°C)/cm<sup>2</sup>/s/cm mercury (Hg). For non-linear materials, the dimensional units reported should be based on flux measured in cm<sup>3</sup> (1 atm, 0°C)/cm<sup>2</sup>/s with pressures measured in cm Hg. Note: 1 GPU = 3.3464 × 10<sup>-6</sup> kg mol/m<sup>2</sup>-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<sub>2</sub>-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<sub>2</sub>O), oxygen (O<sub>2</sub>), and sulfur dioxide (SO<sub>2</sub>). The effect of trace contaminants, such as Hg, etc., is unknown.

**Flue Gas Pretreatment Requirements** – Testing at 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<sub>2</sub>O in flue gas as liquid. The quality of this H<sub>2</sub>O and its potential to be reused in the plant will be studied in future work.

## technology advantages

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- The process does not use any hazardous chemicals. No new emission streams are produced.
- The membranes developed are 10 times more permeable to CO<sub>2</sub> 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<sub>2</sub> 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

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

## status

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The overall design of the 140-TPD large pilot plant was finalized. Preliminary layout drawings for the system at the WITC site were prepared. Based on the final design, a table listing the expected cost of all the major equipment items was prepared. This information formed the basis of a preliminary estimate of the Phase III schedule and budget. The Phase II project team was assembled and a division of responsibilities for the Phase II and Phase III programs was completed. Finally, WorleyParsons finalized the preliminary environmental information volume (EIV) for the pilot system at WITC.

## available reports/technical papers/presentations

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Baker, R.W., et al. "Large pilot Testing of the MTR Membrane Post-Combustion CO<sub>2</sub> Capture Process," Phase II kickoff meeting presentation, Pittsburgh, PA, October 2019. <https://www.netl.doe.gov/projects/plp-download.aspx?id=17214&filename=MTR%20Ph2%20DOE%20Kickoff%20Mtg%20100119.pdf>.

Baker, R.W., et al. "Large pilot Testing of the MTR Membrane Post-Combustion CO<sub>2</sub> Capture Process," presented at the 2018 NETL CO<sub>2</sub> Capture Technology Project Review Meeting, Pittsburgh, PA, August 2018. <https://www.netl.doe.gov/projects/plp-download.aspx?id=13129&filename=R-Baker-MTR-Membrane-Large-Pilot-Testing.pdf>.

Baker, R.W., et al. "Large pilot Testing of the MTR Membrane Post-Combustion CO<sub>2</sub> Capture Process," Phase I kickoff meeting presentation, Pittsburgh, PA, May 2018. <https://www.netl.doe.gov/projects/plp-download.aspx?id=13128&filename=MTR-Kickoff-Presentation-Public-FE0031587-FOA1788.pdf>.