Commercial-Scale Front-End Engineering Design Study for Membrane Technology and Research's Membrane Carbon Dioxide Capture Process

primary project goal

Membrane Technology and Research, Inc. (MTR) is conducting a front-end engineering design (FEED) study for an ~400-megawatt-electric (MWe) membrane-based carbon dioxide (CO_2) capture system installed at Basin Electric's Dry Fork Station in Gillette, Wyoming. The project builds on prior work in advancing MTR's membrane capture technology through small pilot testing and a pre-FEED study.

technical goals

- Complete FEED study of MTR capture process applied to the 400-MWe Dry Fork Station.
- Complete an environmental review of full-scale MTR membrane capture at Dry Fork Station.
- Provide a path to commercialization (detailed costs and construction plan) for a full-scale membrane capture plant based on actual equipment costs with a reliability of ±15%.

technical content

The project team is performing a FEED study of MTR's membrane CO_2 capture technology applied at commercial-scale as the next step in the development of the process, after the successful completion of small pilot testing and execution of a full-scale pre-FEED study. The study includes an estimate of the cost and performance of a first-of-its-kind commercial-scale membrane capture plant and a plan for its construction. The plant is being designed to capture approximately 5,600 tonnes per day (TPD) of CO_2 (approximately 2.0 million tonnes/year of CO_2), representing 70% of the Dry Fork Station power plant's CO_2 emissions. The system incorporates the innovative high-performance Polaris™ membrane packaged in low-pressure-drop membrane modules. Earlier research has shown that the MTR process has the potential to capture CO_2 from coal-fired flue gas at the U.S. Department of Energy (DOE) capture cost target of less than $40/tonne CO_2.

A preliminary process flow diagram of the membrane capture process to be examined in the FEED study is shown in Figure 1.

program area:
Point Source Carbon Capture

ending scale:
FEED

application:
Post-Combustion Power Generation PSC

key technology:
Membranes

project focus:
Polaris™ Polymeric Membrane-Based Process Retrofit to Coal Plant

participant:
Membrane Technology and Research, Inc.

project number:
FE0031846

predecessor projects:
FE0026414
DE-NT0005312
FC26-07NT43085
FE0005795
FE0007553
FE0013118

NETL project manager:
Carl Laird
carl.laird@netl.doe.gov

principal investigator(s):
Tim Merkel and Brice Freeman
Membrane Technology and Research, Inc.
tim.merkel@mtrinc.com
brice.freeman@mtrinc.com

partners:
Sargent & Lundy (S&L); Basin Electric; Trimeric Corporation; Electric Power Research Institute (EPRI); Efficient Fuel Additives (EFA)

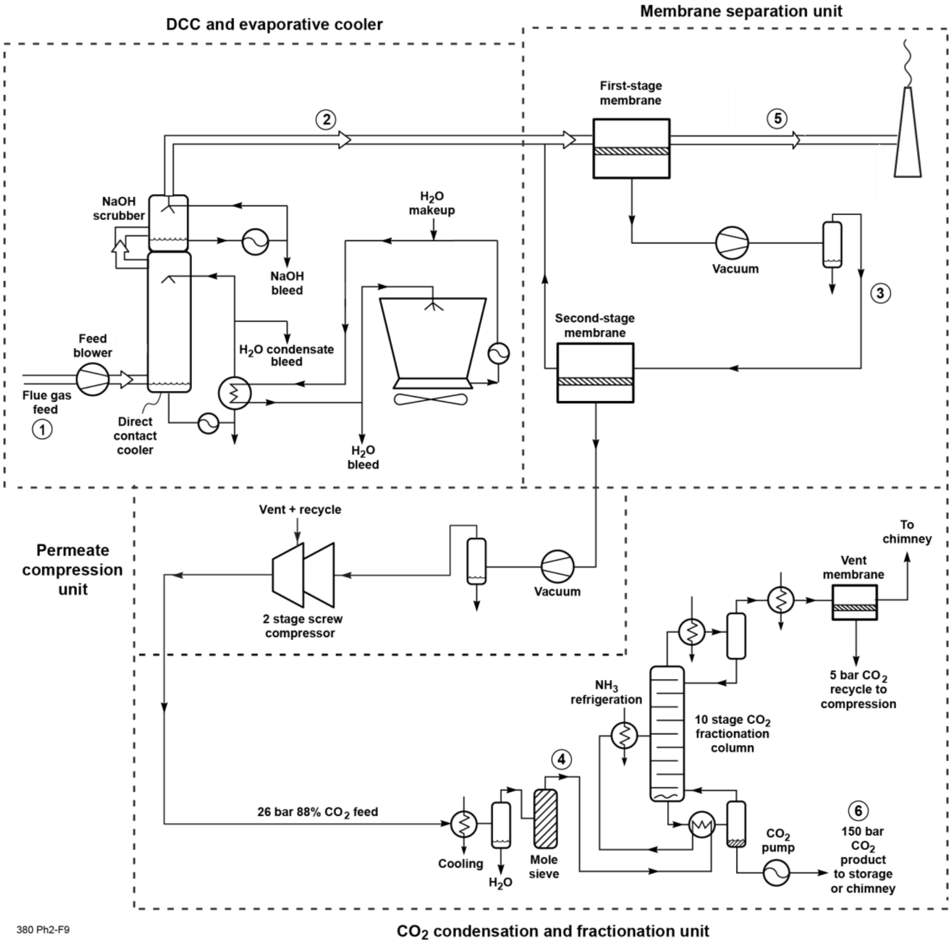

Figure 1: Preliminary design for full-scale membrane capture plant.

Compared to other industrial membrane applications, the main challenge of membrane technology for post-combustion CO_2 capture is the low partial pressure of CO_2 in flue gas, resulting in a large membrane area being required due to the small driving force for separation. MTR has developed two innovations that address this problem:

- A new class of membranes called Polaris that exhibit 10 times the CO_2 permeance of conventional gas separation membranes, leading to a large decrease in required membrane area and reduced capital cost.
- A low-pressure-drop, low-cost membrane module design. The pressure differentials, and therefore the energy required, to circulate gas through the module is a fraction of that measured in conventional modules.

Single-stage membrane designs are unable to produce high-purity CO_2 combined with high CO_2 capture rates because the system performance is limited by the small pressure ratio across the membrane. MTR's multi-stage membrane process design (Figure 2) addresses the pressure ratio constraint to efficiently capture 50 to 75% of the CO_2 in flue gas. First, the combustion flue gas enters a primary capture module, which produces a permeate containing ~55 to 60% CO_2. This gas is then treated by a second membrane stage to further enrich the CO_2 stream to greater than 85% CO_2. The CO_2-rich permeate from the second-stage module is dehydrated and compressed.

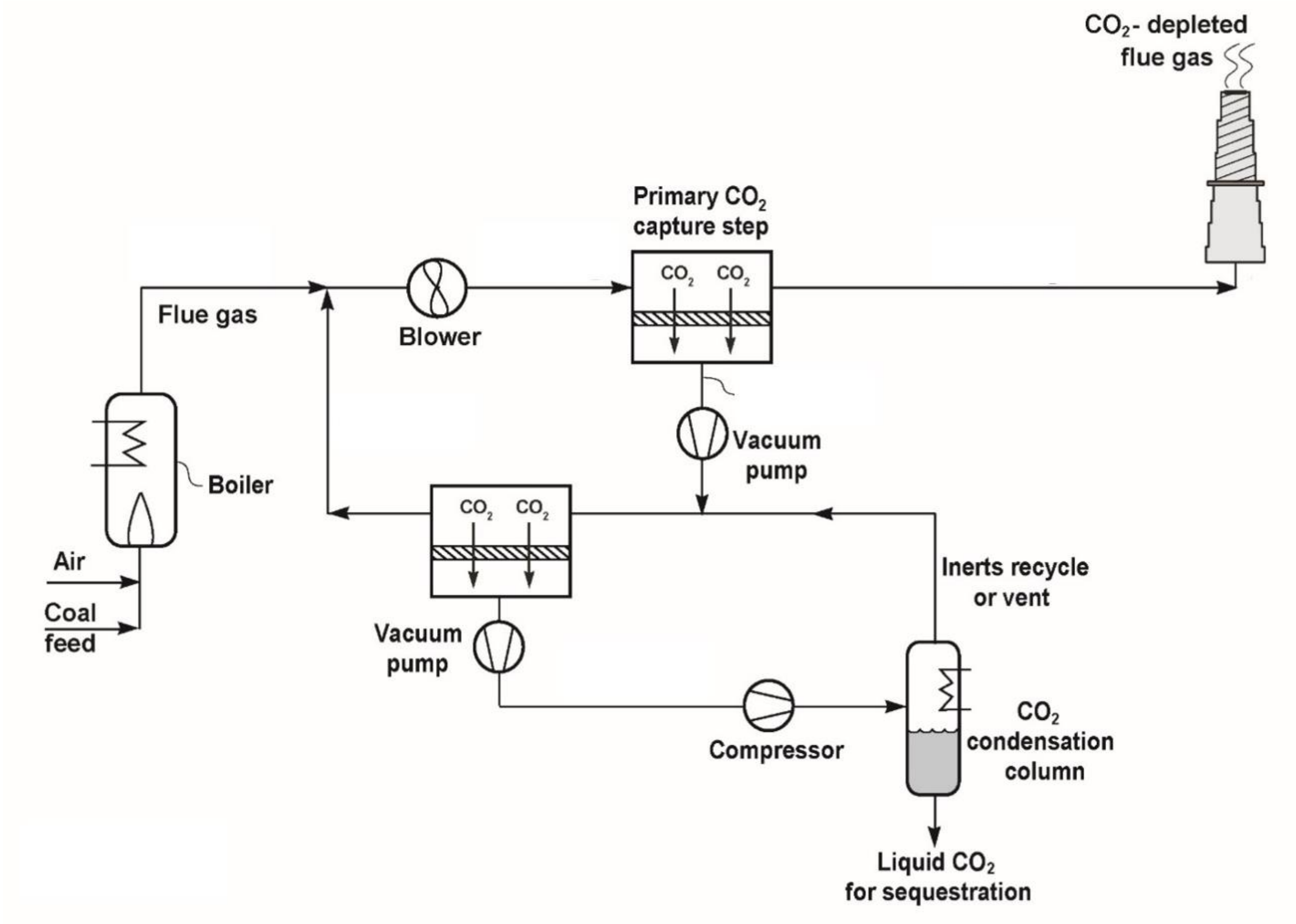

Figure 2: MTR CO_2 capture process.

MTR's Polaris membrane was first developed in a previous DOE-funded project, DE-NT43085. Polaris exhibits high CO_2 permeance and high CO_2/nitrogen (N_2) selectivity for post-combustion flue gas applications. The thin-film composite membrane utilizes hydrophilic polymers. Commercial Polaris membranes offer a step-change improvement over typical commercial CO_2-selective membranes used for natural gas treatment, with an average CO_2 permeance of 1,000 gas permeation units (GPU) and a CO_2/N_2 selectivity of 50. Recent studies have improved membrane performance, demonstrating a CO_2 permeance of 3,000 GPU at lab-scale. The combination of these membranes with novel module and process innovations greatly reduces the projected cost of CO_2 capture.

Membranes packed into spiral-wound modules are widely used in commercial membrane installations today. Spiral-wound modules are robust, resistant to fouling, and economical; they are used in 95% of the reverse osmosis (RO) desalination industry and more than 70% of the membrane market for CO_2 removal from natural gas. Figure 3 shows the general design features of a spiral-wound membrane module. The module consists of a permeate collection tube with a spiral formation of permeate spacers and feed spacers, which allow the flue gas and separated CO_2 to flow through the device. The process parameters for the Polaris membranes in a spiral-wound module configuration are shown in Table 1.

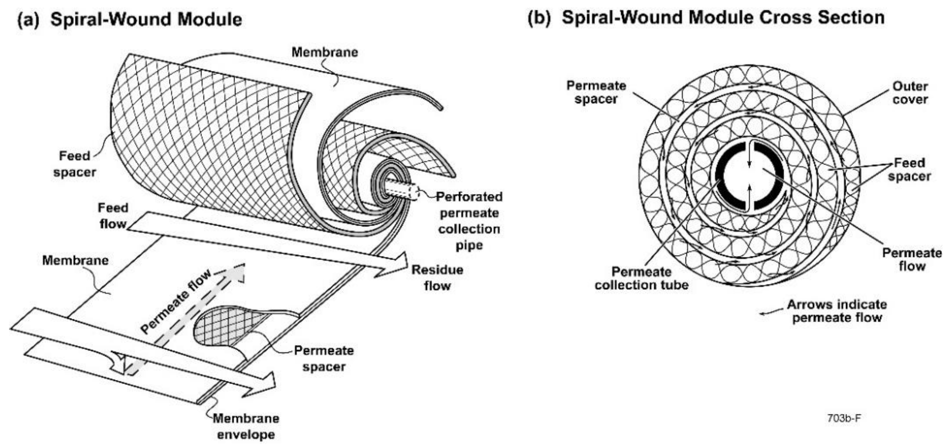

Figure 3: Schematic diagram of a spiral-wound membrane module.

TABLE 1: MEMBRANE PROCESS PARAMETERS IN SPIRAL-WOUND MODULE CONFIGURATION

Materials Properties	Units	Design Value
Materials of Fabrication for Selective Layer	—	proprietary polymer
Materials of Fabrication for Support Layer	—	proprietary polymer
Nominal Thickness of Selective Layer	µm	<1
Membrane Geometry	—	spiral
Max Trans-Membrane Pressure	bar	70
Hours Tested without Significant Degradation	—	11,000
Manufacturing Cost for Membrane Material	$\$/m^2$	10
Membrane Performance		
Temperature	°C	30
CO_2 Pressure Normalized Flux	gpu or equivalent	1,000
CO_2/H_2O Selectivity	—	0.3
CO_2/N_2 Selectivity	—	30
CO_2/SO_2 Selectivity	—	0.5
Type of Measurement	—	Mixed gas
Module Design		
Flow Arrangement	—	crossflow and countercurrent
Packing Density	m^2/m^3	1,000
Shell-Side Fluid	—	N/A
Flue Gas Flow rate	kg/hr	
CO_2 Recovery, Purity, and Pressure	%/%/bar	90% / >96% / 140
Pressure-Drops Shell/Tube Side	bar	0.1
Estimated Module Cost of Manufacturing and Installation	$\frac{\$}{m^2}$	50

Under a previous DOE-funded project, DE-FE0005795, a membrane skid designed to capture 1 tonne of CO_2 per day from a 7,000-standard-m^3/day (250,000 standard cubic feet per day [scfd]) flue gas slipstream was installed and tested at the National Carbon Capture Center (NCCC; Figure 4). The skid held up to eight (four crossflow and four countercurrent sweep), 8-inch-diameter Polaris membrane modules. The system accumulated more than 11,000 hours of operation with flue gas testing spiral-wound modules in both steps of the MTR process: a capture step operating with permeate vacuum and a selective-recycle step that uses air sweep to provide driving force for CO_2 removal. The test demonstrated membrane operation in commercial-scale modules and determined typical membrane lifetimes under coal combustion flue gas operating conditions.

Figure 4: Membrane skid used for 1-TPD bench-scale slipstream testing at NCCC.

Scale-up of the Polaris capture system from the 1-TPD bench-scale unit to a 20-TPD small pilot system using commercial-scale membrane components was also completed in FE0005795. The 20-TPD system is a two-level design, with membrane modules located on the upper level, and all rotating and associated equipment on the lower level. Like the 1-TPD unit, the 20-TPD unit was designed for slipstream operation at NCCC and is shown in Figure 5.

Figure 5: 20-TPD small pilot system installed at NCCC.

Pilot-scale operation of the previous 1-MWe (20-TPD) membrane CO_2 capture system, integrated with a Babcock & Wilcox (B&W) 0.6-MWe coal-fired research boiler, was performed in the DOE-funded project DE-FE0026414 to determine how various membrane parameters impact the performance of a boiler system. Operation of the integrated membrane-boiler system involves the recycling of CO_2-laden air back to B&W's boiler via a countercurrent sweep membrane. A modest reduction in boiler efficiency due to recycled CO_2 was measured (1.8%) at 90% capture, showing that the selective-recycle process is feasible and the impact on boiler performance is relatively small.

While previous tests have shown that recycle to the boiler is feasible, operation at ~70%+ capture without recycle is often of interest, because it offers lower capture costs and still reduces coal plant emissions to less than that of a natural gas power plant. Therefore, the current FEED study focuses on a two-stage membrane system that captures 70% of the CO_2 in the flue gas without selective recycle and concentrates the gas to about 85% CO_2. A CO_2 purification unit is then used to produce greater than 99% CO_2 at 150 bar. For the full-scale capture plant, container-sized skids will be used as the basic modular building block. An evaluation of the most efficient arrangement of the membrane capture skids is being conducted in the FEED study.

MTR applied an alternative approach to membrane packing to develop planar modules optimized for low-pressure operation. Testing of the small pilot-scale 20-TPD system at NCCC and B&W incorporated this novel large-area membrane module designed by MTR in project DE-FE0007553. A single planar membrane module element has the equivalent membrane area of five 8-inch spiral-wound membrane modules. Figure 6 shows the plate-and-frame module design. The simple, straight flow path of the new module design results in a pressure-drop that is almost four times lower than that measured for the spiral-wound module, as shown in Figure 7, resulting in energy and cost savings. At full-scale, this reduced pressure-drop represents about a 10-MWe savings in fan power. The planar module skids are projected to cost $50/m^2 of membrane at full commercialization stage. Process parameters for the Polaris membranes in a planar module configuration are shown in Table 2.

Figure 6: Prototype plate-and-frame module during testing at NCCC.

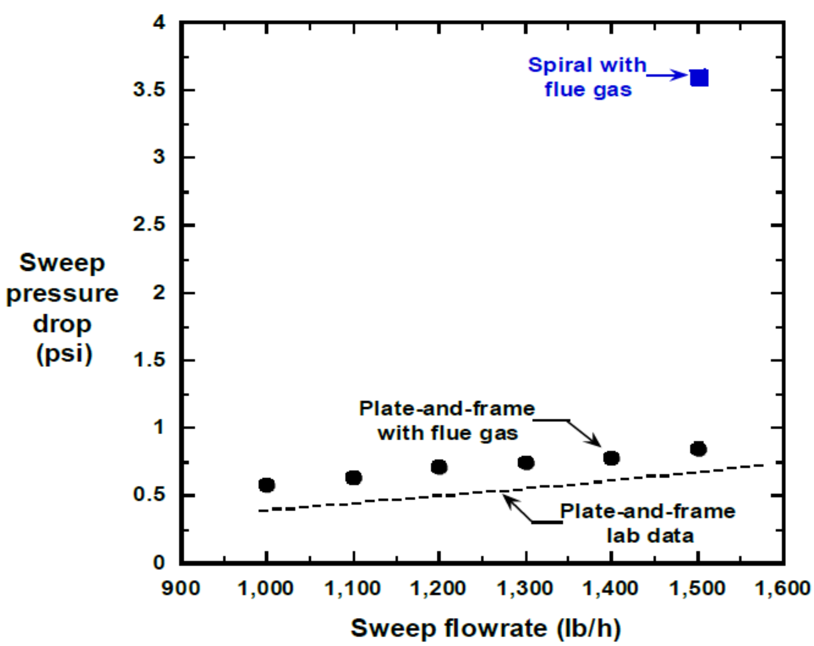

Figure 7: Measured pressure-drop in plate-and-frame module, compared to spiral-wound module.

TABLE 2: MEMBRANE PROCESS PARAMETERS IN PLATE-AND-FRAME MODULE CONFIGURATION

Materials Properties	Units	Design Value
Materials of Fabrication for Selective Layer	—	proprietary polymer
Materials of Fabrication for Support Layer	—	proprietary polymer
Nominal Thickness of Selective Layer	µm	<1
Membrane Geometry	—	plate-and-frame
Max Trans-Membrane Pressure	bar	2
Hours Tested without Significant Degradation	—	1,500
Manufacturing Cost for Membrane Material	$\$/m^2$	30
Membrane Performance		
Temperature	°C	30
CO_2 Pressure Normalized Flux	gpu or equivalent	1,700
CO_2/H_2O Selectivity	—	0.5
CO_2/N_2 Selectivity	—	30
CO_2/SO_2 Selectivity	—	0.5
Type of Measurement	—	Mixed gas
Module Design		
Flow Arrangement	—	crossflow, partial countercurrent
Packing Density	m^2/m^3	1,000
Shell-Side Fluid	—	N/A
Flue Gas Flow rate	kg/hr	
CO_2 Recovery, Purity, and Pressure	%/%/bar	70% / >96% / 150
Pressure-Drops Shell/Tube Side	bar	0.1
Estimated Module Cost of Manufacturing and Installation	$\frac{\$}{m^2}$	50

Further improvements to the membrane module design to reduce fabrication costs resulted in a module prototype based on injection-molded, fiber-reinforced thermoplastics. The modules are designed to fit one on top of another to create a module stack, which is placed on a container-sized skid, as shown in Figure 8. The large membrane capture system will consist of multiple container-sized membrane module skids that will be prefabricated using advanced, high-volume manufacturing and shipped to the plant site. This approach minimizes expensive site assembly and installation work and enhances fabrication quality. The FEED study is evaluating and quantifying savings based on the modular construction approach.

Figure 8: Containerized plate-and-frame membrane module stacks.

MTR also previously evaluated a hybrid membrane-absorption process system combining Polaris membranes and an amine solvent-based capture system under DOE-funded project DE-FE0013118. The integrated system combines MTR's plate-and-frame sweep module with a CO_2 capture system developed by the University of Texas at Austin (UT-Austin) that uses a piperazine (PZ) solvent and advanced high-temperature/high-pressure regeneration. This hybrid design requires significantly less membrane area for a two-step CO_2 capture process, compared to MTR's all-membrane process. In the hybrid design, MTR's Polaris membrane recycle stage enriches flue gas from ~13 to ~20% CO_2 and a 5 molal PZ advanced flash stripper with cold-rich bypass is optimized to take advantage of the higher CO_2 concentration. Both series and parallel configurations were considered with the hybrid design, as shown in Figure 9. Process modeling of MTR's plate-and-frame skid integrated with UT-Austin's Separations Research Program (SRP) 0.1-MWe pilot plant showed that a hybrid-parallel configuration offers a lower cost of capture than the series configuration. However, the benefits of a hybrid system do not outweigh the costs. The estimated economics data, including cost of capture, is shown in Table 3.

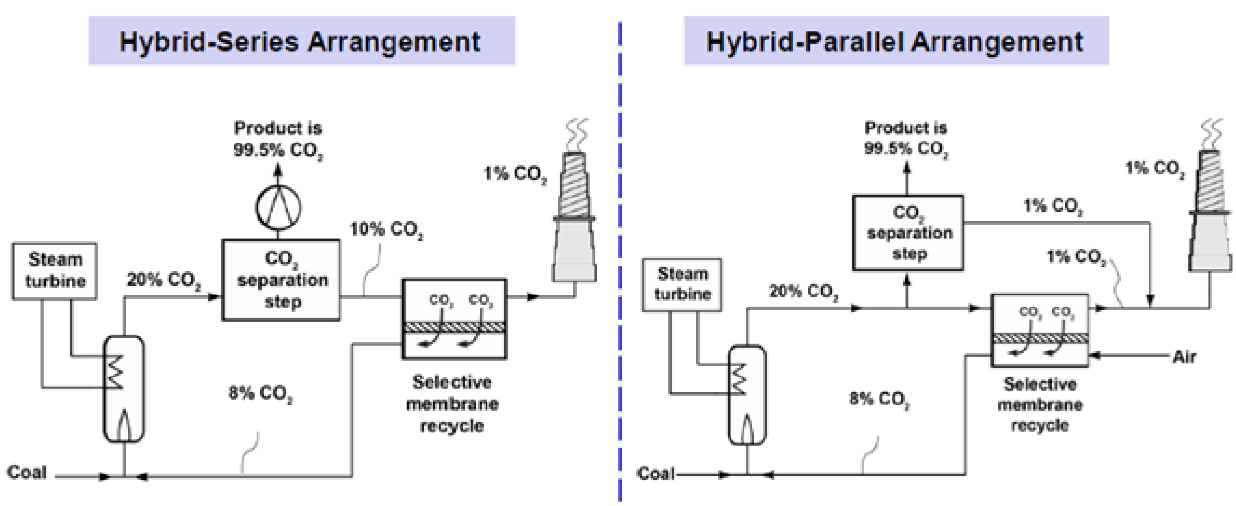

Figure 9: Two hybrid configurations for membrane-absorption CO_2 capture process.

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	54	43
Cost of Carbon Avoided	\$/tonne CO_2	n/a	n/a
Capital Expenditures	\$/MWhr	18.4	23.9
Operating Expenditures	\$/MWhr	25.9	22.2
Cost of Electricity	\$/kWhr	0.05	0.05

MTR is also currently working on three additional DOE-sponsored projects related to this study. DE-FE0031587 is a three-phase project for the design, construction, and operation of a large-scale pilot system to treat 10 MWe of flue gas at Wyoming's Integrated Test Center, with support from Basin Electric's Dry Fork Station power plant. The Phase I feasibility program and the Phase II FEED study are complete and the project is now in Phase III. The National Environmental Policy Act (NEPA) review and Environmental Information Volume (EIV) that were completed in Phase I can be leveraged in this FEED project. The second project recently completed (DE-FE0031589) is a pre-FEED study led by the Electric Power Research Institute (EPRI), in collaboration with MTR, Nexant, and Bechtel, to evaluate a full-scale (640-MWe) membrane capture technology applied to Duke Energy's East Bend Station. The general configuration from the pre-FEED capture plant design is being used as the starting point for the Dry Fork Station FEED study. In project DE-FE0031591, MTR and its partners are scaling-up the next-generation Polaris membranes and modules to a final form optimized for commercial use, and validating their performance in an engineering-scale field test at Technology Centre Mongstad.

The Dry Fork Station power plant is an ideal location for installation of a membrane CO_2 capture system due to:

- High CO_2 content (~15% on dry basis) in the flue gas increases efficiency of membrane capture system.
- Cool, dry climate allows cooling water operation at ~25°C, resulting in an energy savings of 25 MWe/tonne of CO_2 captured.
- Dry Fork Station generates electricity at a low cost, which is important for a capture process powered only by electricity.
- CO_2 utilization opportunities with nearby oil fields and CO_2 pipeline.

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 desulfurized 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 flue gas desulfurization (FGD) unit (wet basis) should be assumed as:

Pressure	Temperature	Composition						
		vol%					ppmv	
psia	°F	CO_2	H_2O	N_2	O_2	Ar	SO_x	NO_x
14.7	135	13.17	17.25	66.44	2.34	0.80	42	74

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., was examined in the field tests at NCCC and no major issues were found.

Flue Gas Pretreatment Requirements – The greatest concern of species present in flue gas is that particulate matter will foul the membranes, reducing module lifetimes. The field tests at NCCC treated post-FGD flue gas, and in extended testing (more than 13,000 hours), fouling was not a significant issue.

Membrane Replacement Requirements – The target membrane module lifetime is 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 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.

Process Design Concept – See Figure 1.

technology advantages

- The Polaris membranes developed are more than 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 membrane material has a high tolerance to wet acid gases and is inert to O_2.
- The membrane system has a flexible footprint and low energy cost.
- The membrane capture system can recover water from flue gas.
- The use of an existing air stream to generate a CO_2 partial-pressure gradient in the countercurrent sweep membrane stage reduces the need for compressors or vacuum pumps, thus reducing the overall energy cost.
- The recycled CO_2 from the air sweep to the boiler increases the CO_2 partial-pressure driving force for separation in the initial CO_2 separation step (either membrane or absorption/stripper unit), reducing total system cost.

R&D challenges

- Uncertainty in vacuum pumps and compression equipment efficiency and stability treating flue gas.
- Potential performance problems with the CO_2 purification equipment.
- Scale-up of advanced Polaris membranes that exhibit a CO_2 permeance of 3,000 GPU to reduce the capital cost of the membrane system.

status

MTR has completed all preliminary process design work for the capture plant. All operating parameters have been defined and all vendor equipment has been selected. In addition, a waste management plan has been finalized, and the detailed equipment arrangement within the plant is currently being developed. The remaining balance of plant and building designs, as well as cost estimates, are also under development.

available reports/technical papers/presentations

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