Initial Engineering Design of a Post-Combustion CO_2 Capture System for Duke Energy's East Bend Station Using Membrane-Based Technology

primary project goal

The Electric Power Research Institute, Inc. (EPRI) produced an initial engineering design and cost estimate of a first-of-a-kind (FOAK), full-scale, membrane-based post-combustion carbon dioxide (CO_2) capture system retrofit to an existing U.S. coal power plant. The capture technology was provided by Membrane Technology and Research (MTR), and the power plant was Duke Energy's East Bend Station (EBS) located on the Ohio River in Kentucky. The primary objective was to develop a design that would minimize the impact on the power plant by disrupting as little of the existing facilities as possible, minimizing the cost of each tonne of captured CO_2 while also maintaining the net 600-megawatt (MW) output of EBS. This was to be done by optimizing the percentage of CO_2 captured from the coal-fired power plant (expected to be somewhere between 45 and 75% of the total CO_2 in the flue gas). The initial phase was also to examine options for integrating waste heat from the new combustion turbine (CT) with the existing coal plant to improve the thermal efficiency of the coal-fired unit. Once an optimal configuration was selected, an engineering design, sufficient in detail to support a +/-30% capital cost estimate, was to be generated, along with a techno-economic analysis (TEA).

technical goals

- Develop, review, and approve a design basis document for EBS.
- Develop a steam cycle model of an existing power plant and benchmark existing performance.
- Optimize the configuration of the membrane CO_2 capture system, including a decision on the level (percentage) of capture for the design that offers the lowest cost on a $/tonne of CO_2 captured basis.
- Evaluate options for supplying auxiliary power to the CO_2 capture system.
- Develop a complete process design package of the membrane-based CO_2 capture system.
- Define retrofit modifications required to integrate the membrane-based process into EBS and conduct a hazard identification (HAZID)/constructability review of a retrofitted capture facility.
- Complete a TEA for the retrofitted power plant.

technical content

For this retrofit design project, second-generation Polaris™ membranes from MTR and an optimized level of CO_2 capture were used to reduce capture costs, toward a goal of $30/tonne CO_2. These second-generation Polaris™ membranes have double the CO_2 removal capacity of the original membrane and were packaged in low-pressure-drop modules optimized for high-volume flue gas treatment. Prototypes of these modules had been validated in prior field trials that confirm

program area:
Point Source Carbon Capture

ending scale:
Pre-FEED

application:
Post-Combustion Power Generation PSC

key technology:
Membranes

project focus:
Polymeric Membrane-Based Process Retrofit Pre-FEED Study

participant:
Electric Power Research Institute, Inc.

project number:
FE0031589

predecessor projects:
N/A

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start date:
04.06.2018

percent complete:
100%

large energy and cost savings. Targeting a lower degree of capture for this proposed project will obtain a post-combustion CO_2 capture system that provides the lowest cost on a $/tonne CO_2 captured basis. Membrane-based post-combustion CO_2 capture systems achieve an optimal cost in the range of 45 to 75% capture.

Duke Energy's EBS was the host site for the retrofit study (Figure 1). EBS is a 600-MW-net coal-fired power plant located on a 1,600-acre site along the Ohio River in Boone County, Kentucky. Duke originally envisioned having multiple 600 megawatt-electric (MWe) units at this site, but only one unit was built. As a result, there is an abundance of space around the existing facility, which will facilitate the addition of the CO_2 capture plant.

Figure 1: Duke Energy's East Bend Station 600-MWe coal-fired power plant.

The proposed design for the EBS post-combustion CO_2 capture system is shown in Figure 2. It is a two-stage membrane system that accomplishes 60% CO_2 capture from the base plant's exhaust, with no boiler recycle.

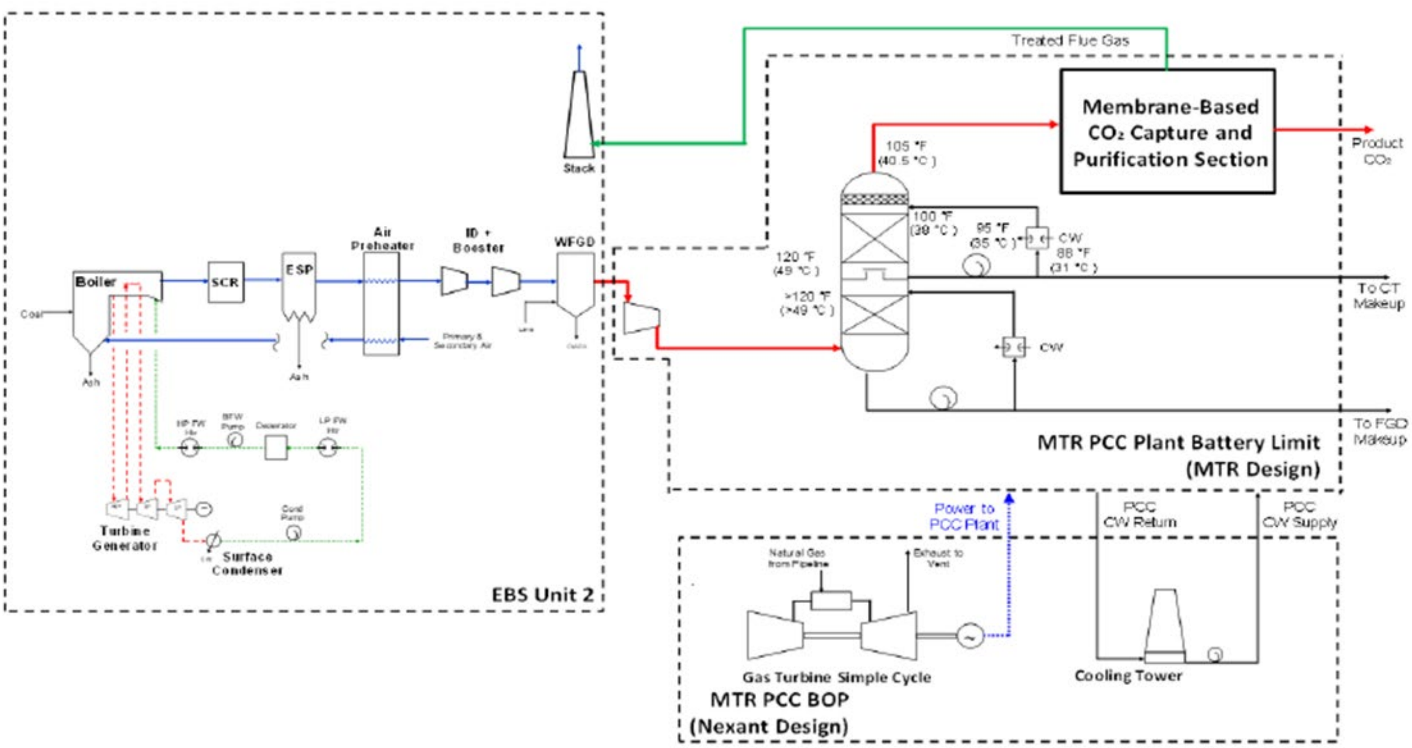

Figure 2: Proposed design for the East Bend unit.

Unlike solvent post-combustion CO_2 capture systems, there is no steam requirement for the membrane system. However, power is required to drive the membrane system's fans, blowers, vacuum compressors, pumps, and CO_2 compressors. To make up for the increased auxiliary load imposed by the post-combustion CO_2 capture system, and to minimize the disruption to the existing power plant, the addition of a natural gas-fired CT power plant to the EBS site was investigated. Various design parameters for the membrane system are shown in Table 1.

Four integration options were considered to provide power to the optimized membrane system retrofit:

1. New natural gas-fired simple cycle (maintain original net output).
2. New combined cycle (maintain original net output).
3. New simple cycle with additional waste heat recovery unit sized to supplying steam to power plant feedwater heaters.
4. Auxiliary power supplied from existing station (decrease net output).

Option 1 with the MTR post-combustion CO_2 capture plant supported by a single gas turbine simple cycle (GTSC) power island was determined to be the best arrangement for this project. It was found to provide:

- The lowest upfront cost of all the external power options considered.
- A phased implementation of feedwater pre-heat if required later (phase in Option 3 if required).
- Enough temperature and heat available for future EBS high-pressure feedwater preheating, if desired.
- Potential for future retrofit with full-size heat recovery steam generator (HRSG) for additional power export if New Source Review (NSR) regulations are relaxed.
- A well-established commercial operation history.

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 (coal)	11,000 (coal)
Manufacturing Cost for Membrane Material	$/m²	50-100	50-100
Membrane Performance			
Temperature	°C	30	30
CO_2 Pressure Normalized Flux	GPU or equivalent	1,600	1,600
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	—	Actual flue gas	Actual 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	kg/hr	2,661,428	
CO_2 Recovery, Purity, and Pressure	%/%/bar	50-70%, >99%, 153 bar	
Pressure Drops Shell/Tube Side	bar	feed: <0.05/sweep: 0.025	

The final proposed membrane process equipment and plant layout detail is shown in Figure 3, and detailed cost of CO_2 data is shown in Table 2.

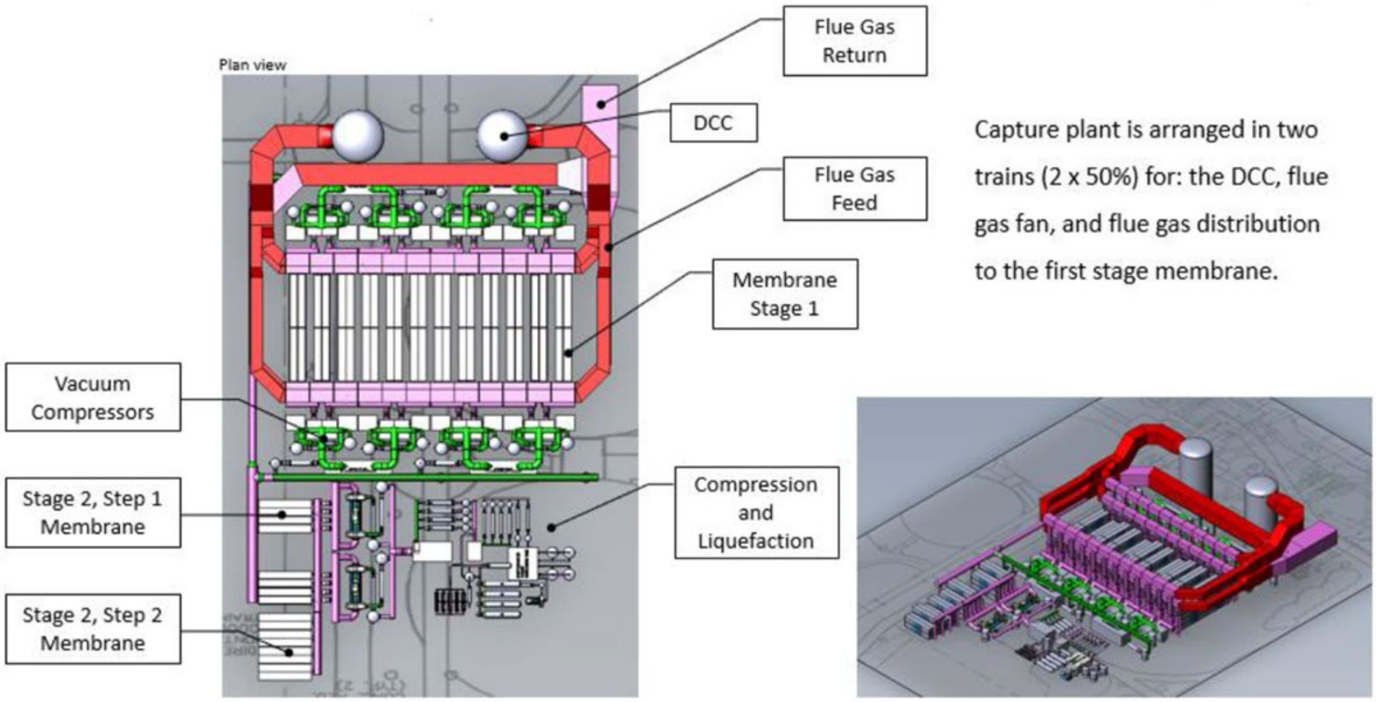

Figure 3: Final proposed membrane process equipment and layout.

TABLE 2: POWER PLANT CARBON CAPTURE ECONOMICS

Economic Values	Units	Current R&D Value	Target R&D Value
Cost of Carbon Captured (1)	$/tonne CO_2	75	~30
Cost of Carbon Avoided	$/tonne CO_2	112	n/a
Capital Expenditures	$/MWhr	24	n/a
Operating Expenditures	$/MWhr	28	n/a
Cost of Electricity (2)	$/MWhr	52	n/a

Notes:
(1) Current R&D value based on final pre-FEED study results for specific FOAK East Bend retrofit. (Target R&D value based on initial proposal goal.)
(2) Additional first-year cost of electricity (COE) based on 90% capacity factor.

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).

HAZID – Hazard Identification study, which was conducted to assess the safety of the post-combustion capture facility at EBS. The study was conducted based on process flow diagrams developed as a part of the previous TEA.

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 – Very fine particulates flow through the membrane channels and are discharged to the stack. Nitrogen oxides (NO_X) will not harm the membranes. The sulfur oxides (SO_X) that reach the membrane will not harm it. Some trace elements may reach the membrane. Their effect on the post-combustion CO_2 capture system is unknown.

Flue Gas Pretreatment Requirements – The flue gas desulfurization (FGD) system at EBS will remove SO_X, hydrogen chloride, soluble salts, and particulate matter (PM). EBS is also equipped with an electrostatic precipitator that will remove PM.

Membrane Replacement Requirements – Membrane modules will nominally be replaced every three years.

Waste Streams Generated – The post-combustion CO_2 capture system will generate liquid waste streams in the form of water condensate streams. Experience from test campaigns show that these streams are acidic and will either need to be pH-corrected prior to discharge or be combined and managed with other liquid waste streams present at the host power plant. Disposition and possible re-use of the condensates at EBS (e.g., as FGD makeup water) will be investigated as part of this design study. The current industry practice for membrane plants is to landfill the spent membrane elements. As part of the environment, health, and safety (EH&S) evaluation, the project team will review federal and state regulations regarding solid waste steams to determine if any flue gas contaminates entrained in the spent modules may require special handling or disposal. MTR's current understanding is that no special disposal measures are needed.

technology advantages

- The process does not use any hazardous chemicals. No new emission streams are produced.
- Reduces coal plant CO_2 emissions to those of a natural gas-fired plant.
- Utilizes MTR's second-generation Polaris™ membranes with CO_2 permeance two times that of their first-generation membrane technology.
- No modifications to existing plant steam cycle; potential to avoid NSR.
- Simple passive operation; no degradation caused by flue gas SO_X and NO_X.
- Compact modular system design.

R&D challenges

- Minimizing the cost of each tonne of CO_2 captured while maintaining current net output of the 600-MWe station.
- Efficiently supplying auxiliary power to the capture system at low cost.
- Upgrading the electrical interconnection to handle larger loads and avoid tripping the generator.

status

The project was completed, and a final report was delivered in September 2020. Four options for supplying power to the membrane system with a few variations therein were proposed and investigated, and a natural gas-powered simple-cycle configuration was selected as the option best suited for the study. An overall CO_2 capture rate of 52% (including emissions from the new GT system) was observed. The CO_2 system imposed an efficiency penalty of about 6.9 points (32.1% baseline to 25.2% with capture), resulting in a net cost of electricity increase of around $50–60/MW-hr (5–6 cents/kW-hr). Detailed results were made available in the final report.

available reports/technical papers/presentations

Dillon, D.," Initial Engineering Design of a Post-Combustion CO_2 Capture System for Duke Energy's East Bend Station Using Membrane-Based Technology," presented at the 2019 NETL Carbon Capture, Utilization, Storage and Oil and Gas Technologies Integrated Review Meeting, Pittsburgh, PA, August 2019. *https://netl.doe.gov/sites/default/files/netl-file/D-Dillon-EPRI-East-Bend-Membrane.pdf*.

Bhown, A., "Initial Engineering Design of a Post-Combustion CO_2 Capture System for Duke Energy's East Bend Station using Membrane-Based Technology," presented at the 2018 NETL CO_2 Capture Technology Project Review Meeting, Pittsburgh, PA, August 2018.

Dillon, D., "Initial Engineering Design of a Post-Combustion CO_2 Capture System for Duke Energy's East Bend Station using Membrane-Based Technology," Kick-off meeting presentation, Pittsburgh, PA, June 2018.

Dillon, D.; Chu, R.; Elliot, W.; Freeman, B.; McKaskle, R., "Initial Engineering Design of a Post-Combustion CO_2 Capture System for Duke Energy's East Bend Station Using Membrane-Based Technology," Final Project Report. Report Number: DOE-EPRI-31589. September 2020. *https://www.osti.gov/biblio/1686164*.