MTR CARBON CAPTURE

Membrane Hybrid Process for Deep Decarbonization of Industry

(DE-FE0032462)

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Membrane Technology and Research, Inc.

Project Kickoff Meeting

January 29, 2025

Presentation Outline

- Project overview
- Technology background
- Project objectives
- Project approach/work plan
- Wrap up

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Project Overview

Award name: Membrane Hybrid Process for Deep Decarbonization of Industry (DE-FE0032462)

Project period: 12/1/24 to 11/30/28

Funding: $7.0 million DOE; $2.6 million cost share ($9.6 million total)

DOE program manager: Andy O'Palko

Participants: MTR, St. Marys Cement, Sargent & Lundy, Trimeric, TDA

Project scope: Conduct a 3 tonnes CO_2/day pilot test of MTR's CO_2 capture hybrid process applied to the St. Marys Cement plant in Charlevoix, MI

Project plan: The project is organized in three budget periods:

- **Budget Period 1** – Design (12 months)
- **Budget Period 2** – Fabricate System/Site Preparation (18 months)
- **Budget Period 3** – Install/Operations/Decommissioning/Reporting (18 months)

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Roles of Participants

- **MTR** – project lead and liaison with DOE; responsible for membrane skid design, fabrication, installation, and operation; coordinate all activities; will lead data analysis and all reporting to DOE
- **St. Marys Cement** – host site for the 6-month field test at their Charlevoix, MI cement plant; will aid in site engineering design and support all activities at site
- **Sargent & Lundy** – Manage site engineering design and preparation work, system installation, and decommissioning activities
- **TDA** – sorbent technology developer; lead design and fabrication of sorbent skid; support system operation, analysis, and various project reports
- **Trimeric** – support and prepare project initial TEA, final TEA, and EH&S risk assessment reports

MTR Carbon Capture Development History

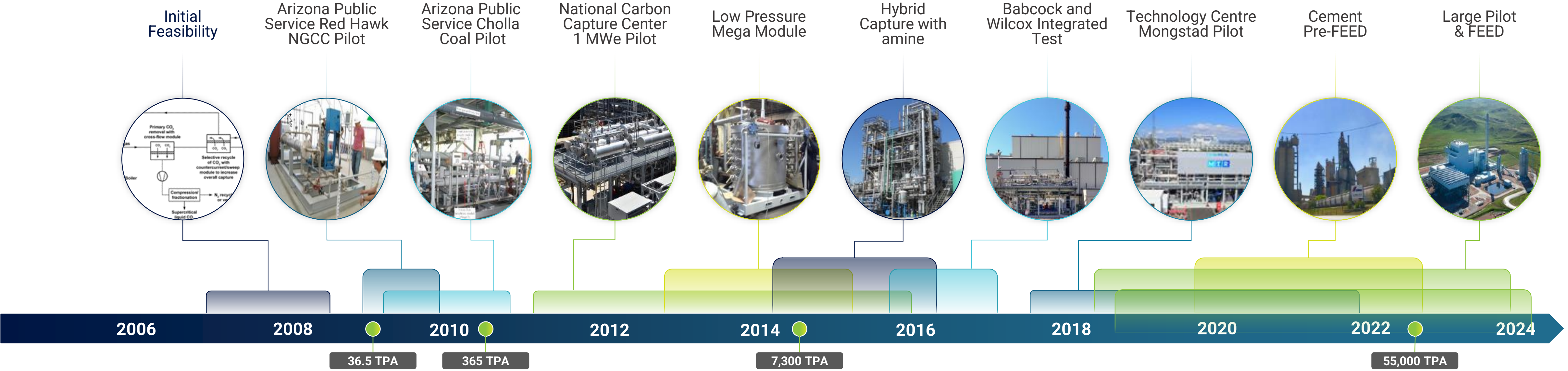
15 Year
Relationship with DOE

20+
DOE Awards Won

>$140mm
Total Funding Received from U.S. Government Agencies

- Support from the DOE has helped bring MTR's capture technology from early concept to the point of commercialization
- Over this time, the membrane capture system capacity has been scaled up by more than 3 orders of magnitude

Development Timeline

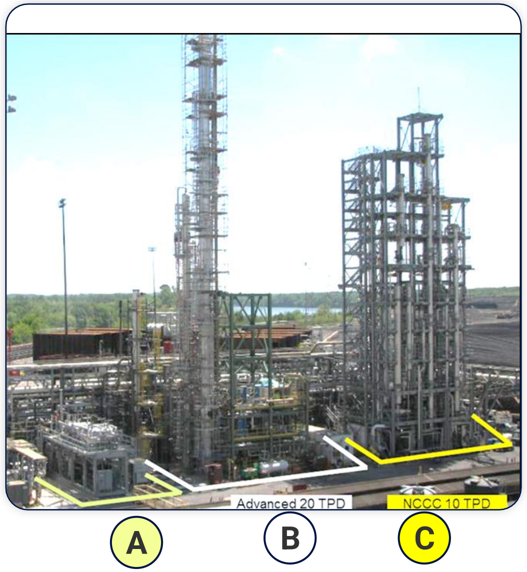


Membrane Advantages for Carbon Capture

Key Advantages

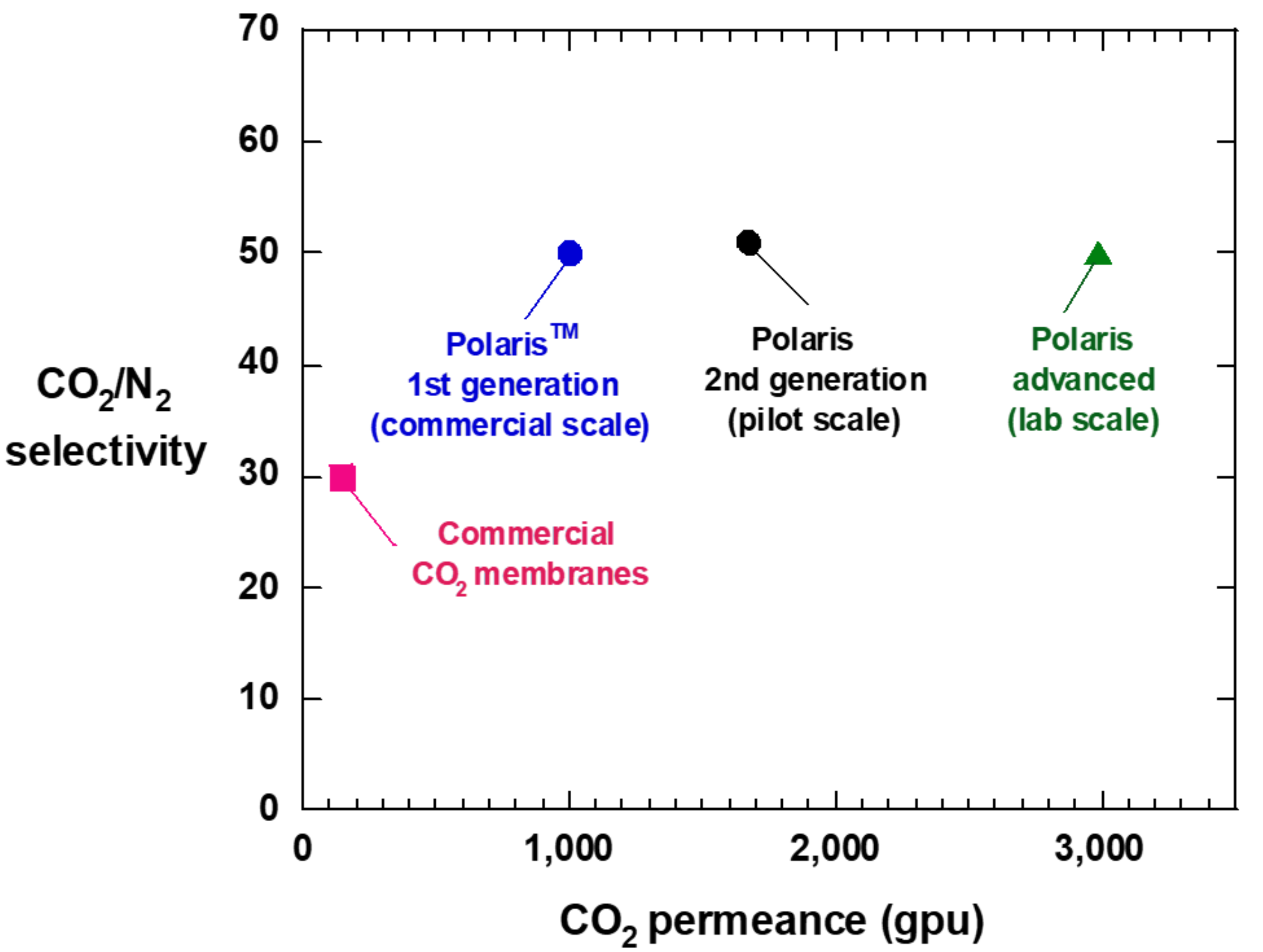
- **A clean approach to carbon capture**: No chemical handling, emissions or disposal issues / easier permitting than typical solvent systems
- Recovers water from flue gas; ideal for arid locations
- A modular technology with a flexible footprint – without tall, heavy towers – that is easily scalable
- Uses only electricity, so can be powered by renewables; no fossil fuel for steam required
- Offer high turndown and rapid response times, making membranes ideal for load following or intermittent industrial processes

Pilot Test at US National Carbon Capture Center



- A — MTR 20 TPD System
- B — Advanced Amine 20 TPD System
- C — Standard Amine 10 TPD System

MTR Polaris™ Membranes are Very Permeable



1 gpu = 10^{-6} cm^3(STP)/(cm^2 s cmHg)= 3.35 x 10^{-10} mol/(m^2 s Pa)

- Original Polaris about 10X more permeable than prior commercial membranes for CO_2 / natural gas separations
- 1^{st} generation Polaris now used commercially in shale gas and refinery applications
- Gen-2 Polaris demonstrated at TCM field test and WITC Large Pilot
- Ongoing research shows even better performance at lab scale; potential for future optimization
- No membrane research in this project; the best membrane available will be used in field test

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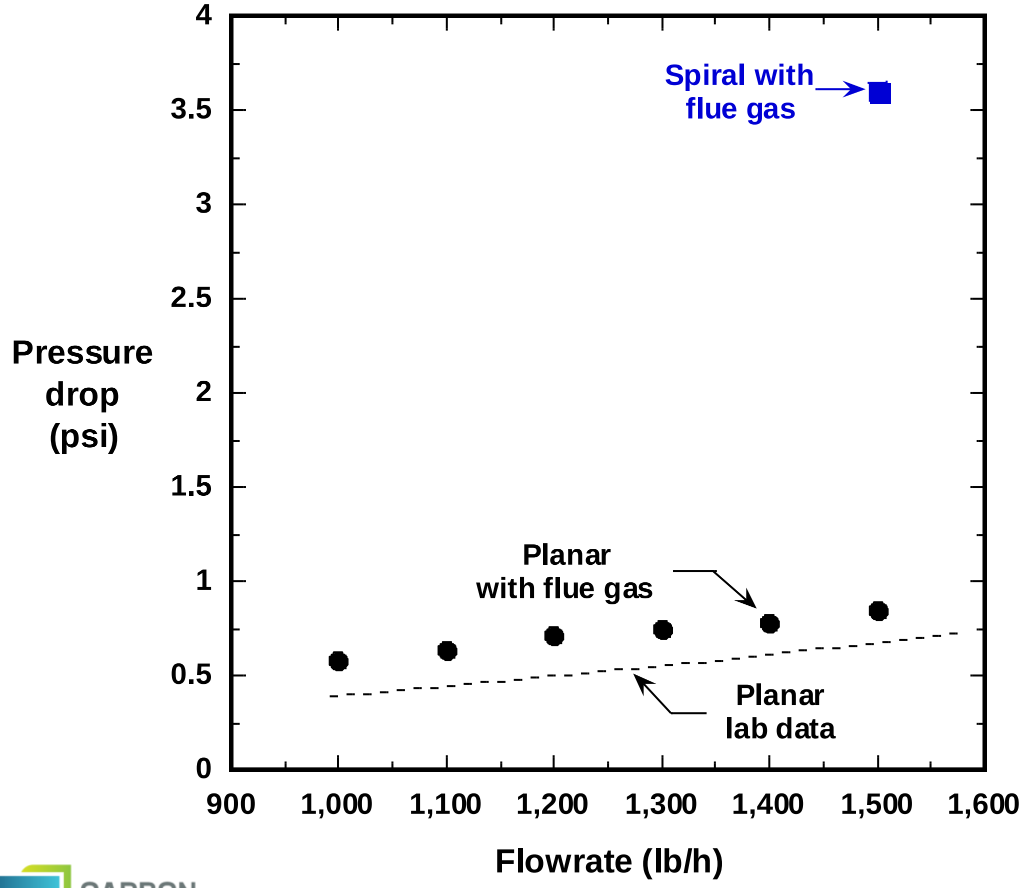
Background: Planar membrane module development

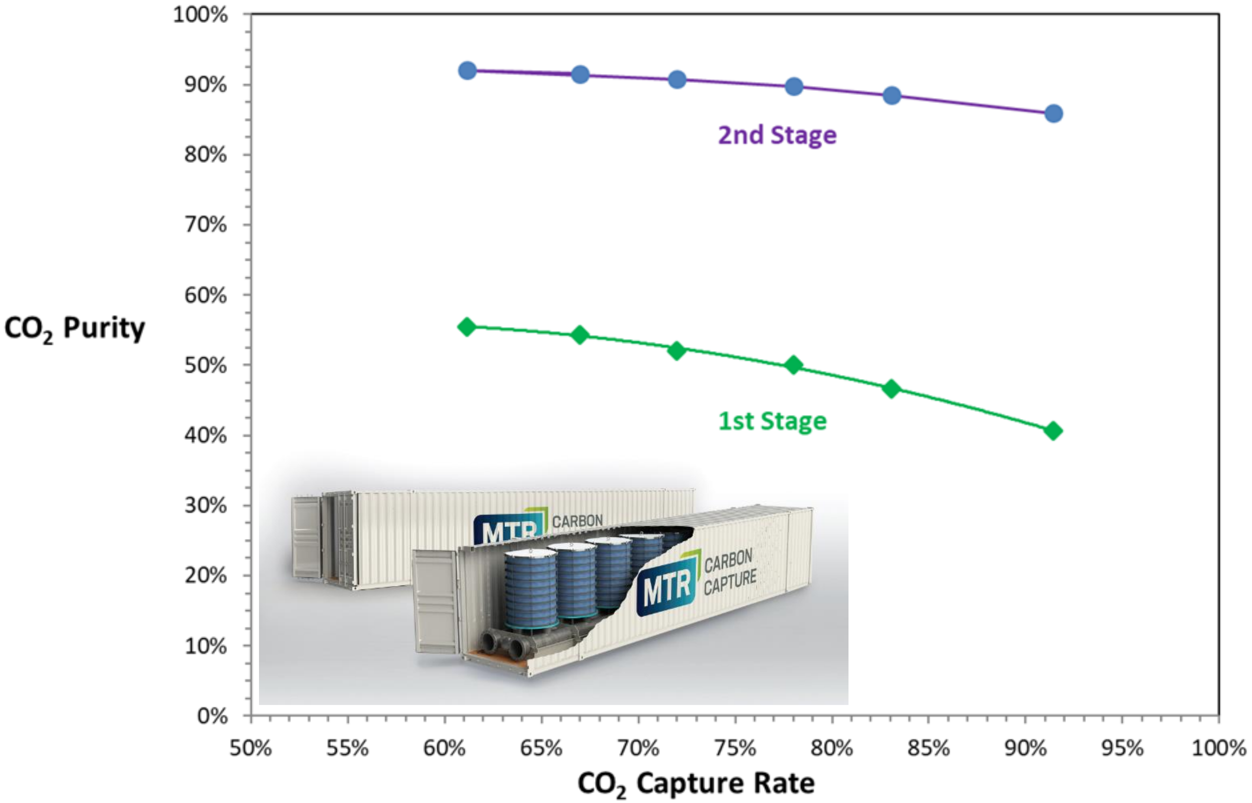
- Prototype planar module performance at NCCC validated reduced pressure-drop
  - Energy savings of ~10 MW_e at full-scale



- Injection molding module design has led to low-cost, high-volume production

Background: Field test results with "containerized" modules

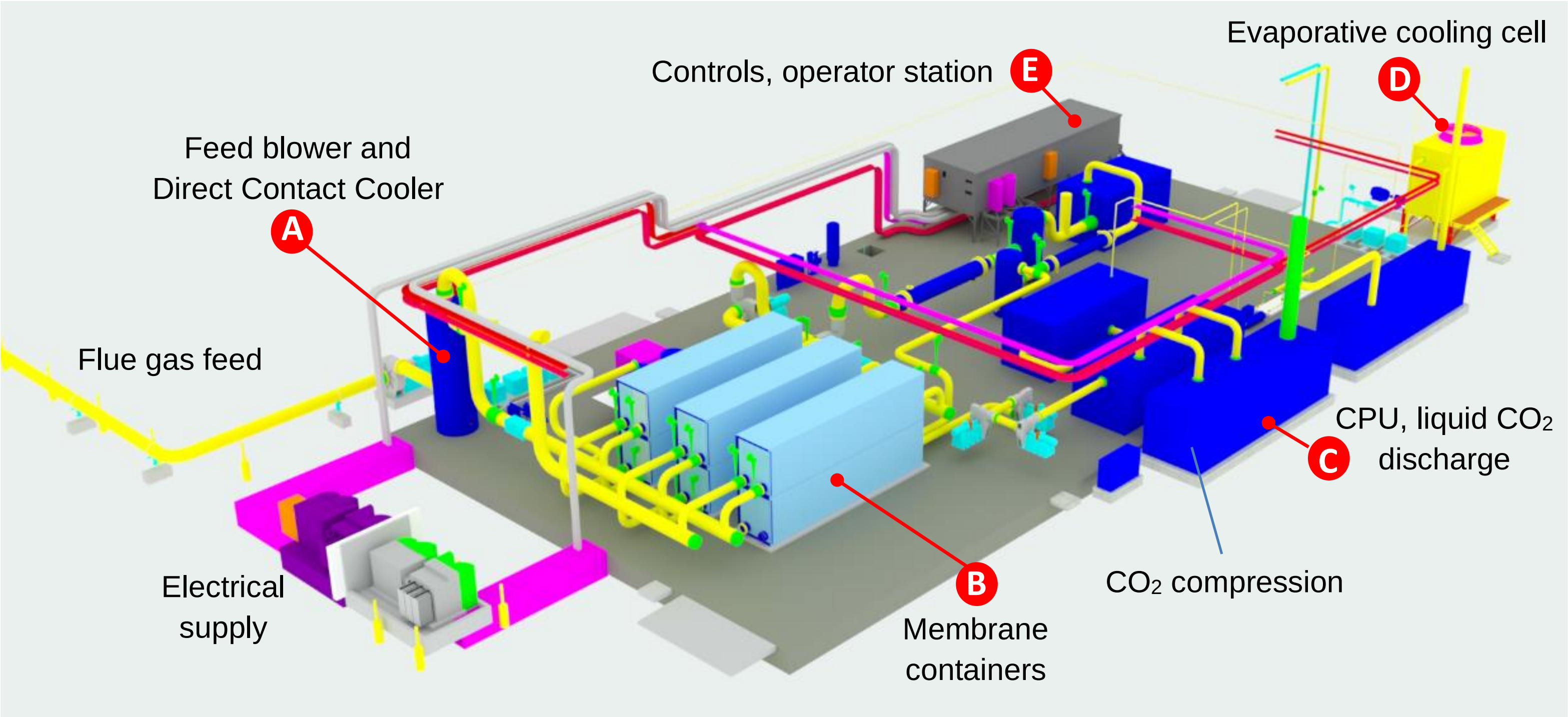
- Test system at TCM in Norway used a single container of membrane stacks
- Larger systems will use multiples of this unit building block



- 2-stage membrane system produces > 85 mol% CO_2 at 90% capture
- Observed module pressure drop (<0.15 psi) significantly lower than target (~1.5 psi)

Background: MTR Large Pilot at Wyoming Integrated Test Center

Conceptual Drawing of MTR Large Pilot at DFS



Most equipment are inside a building for weather protection

- $85 million pilot plant
- Uses 6 membrane containers capturing 150 tonnes/day
- Will demonstrate the complete capture process including liquefaction of CO_2
- System mechanical completion was achieved in November 2024
- Currently operating at design conditions; 90% CO_2 capture case and parametric testing to follow

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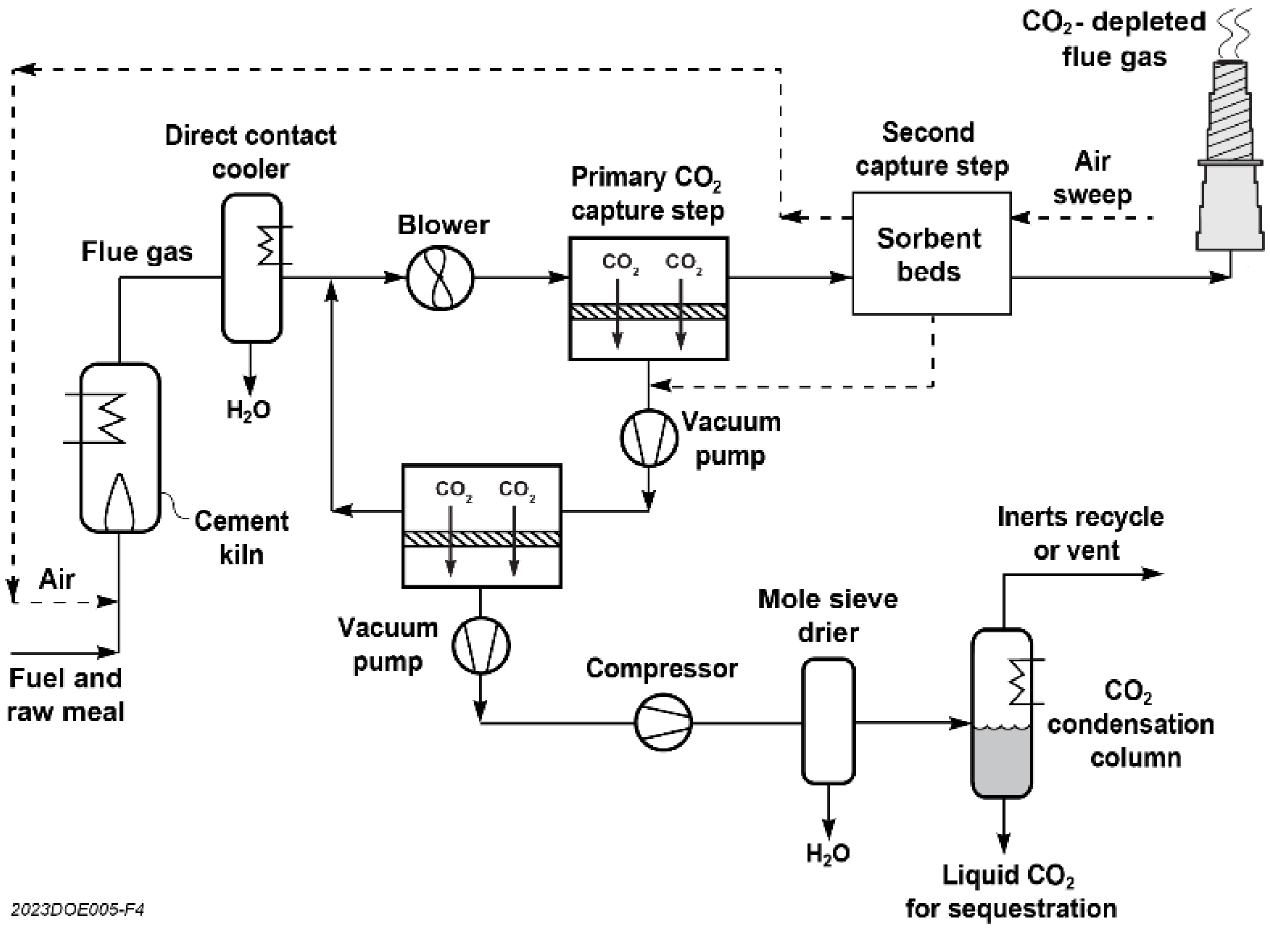
MTR/TDA hybrid process for CO_2 capture

- MTR two stage CO_2 capture process will be utilized along with TDA sorbent to achieve high (>95%) capture rates
- Process design relaxes removal requirement of the primary CO_2 capture step and allows the membrane to do efficient bulk removal
- Sorbent is cost-effective at removing additional CO_2 from a cleaner, CO_2-diluted membrane residue
- TDA and MTR extensively analyzed and field-tested the sorbent air-sweep recycle option in a previous small pilot project (DE-FE00031603)
- 6-month field test in Budget Period 3 will include parametric testing to identify the optimal hybrid configuration, quantify co-capture benefits, and evaluate system dynamic response
- Performance data from the hybrid field test will be used in the project final TEA report



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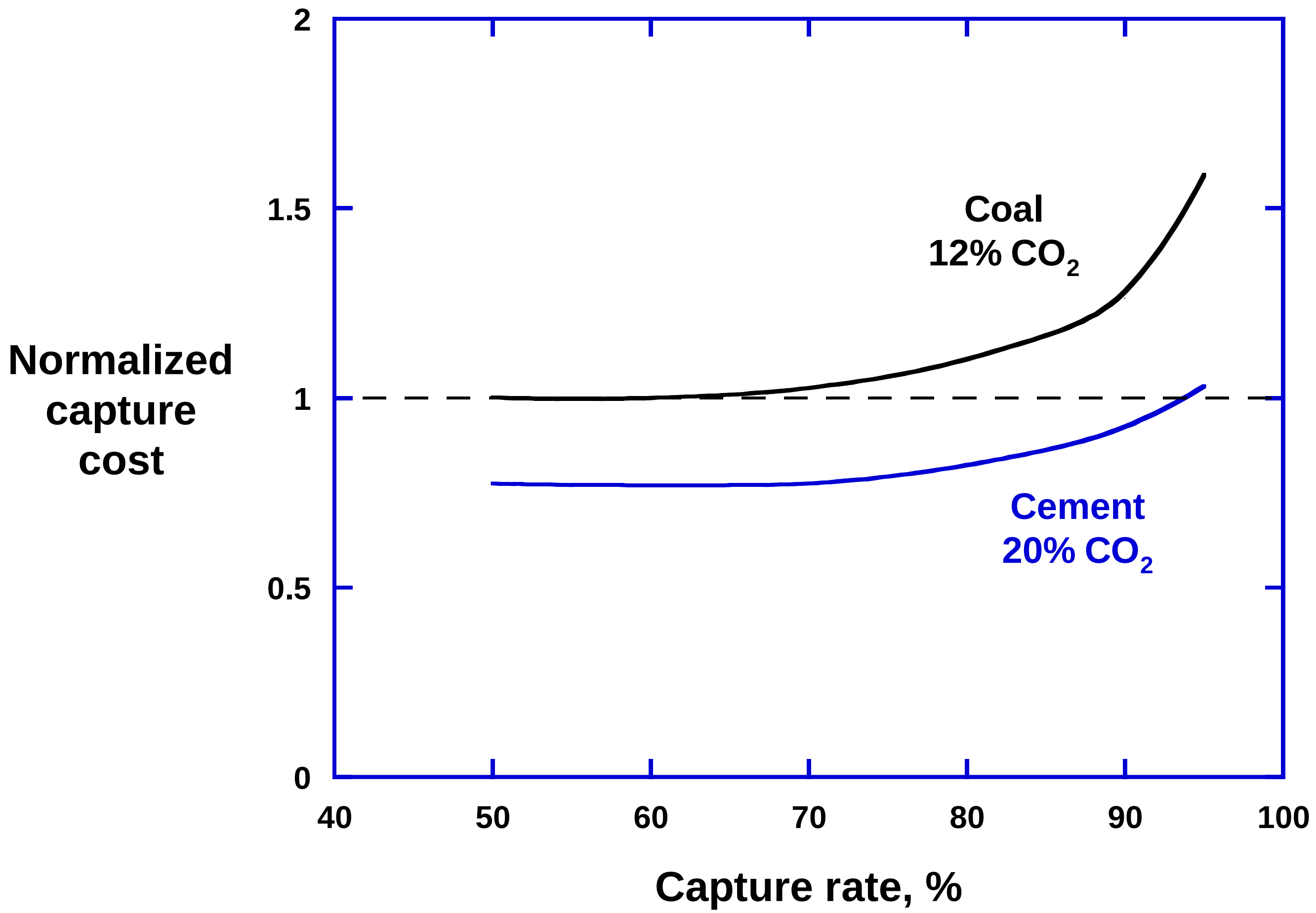
Membranes are well-suited for industrial emitters



Capture cost is normalized to 60% capture from coal using Polaris Gen-2 membranes

- As part of pre-FEED study on Cemex Balcones cement plant (DE-FE0031949), sensitivity analysis was performed to set capture rate targets
- Capture cost is ~20% lower for cement compared to coal (if factors other than CO_2 content fixed)
- Membrane cost is less sensitive to capture rate for higher feed CO_2 content; higher capture is more affordable for cement or other high CO_2 content industrial sites

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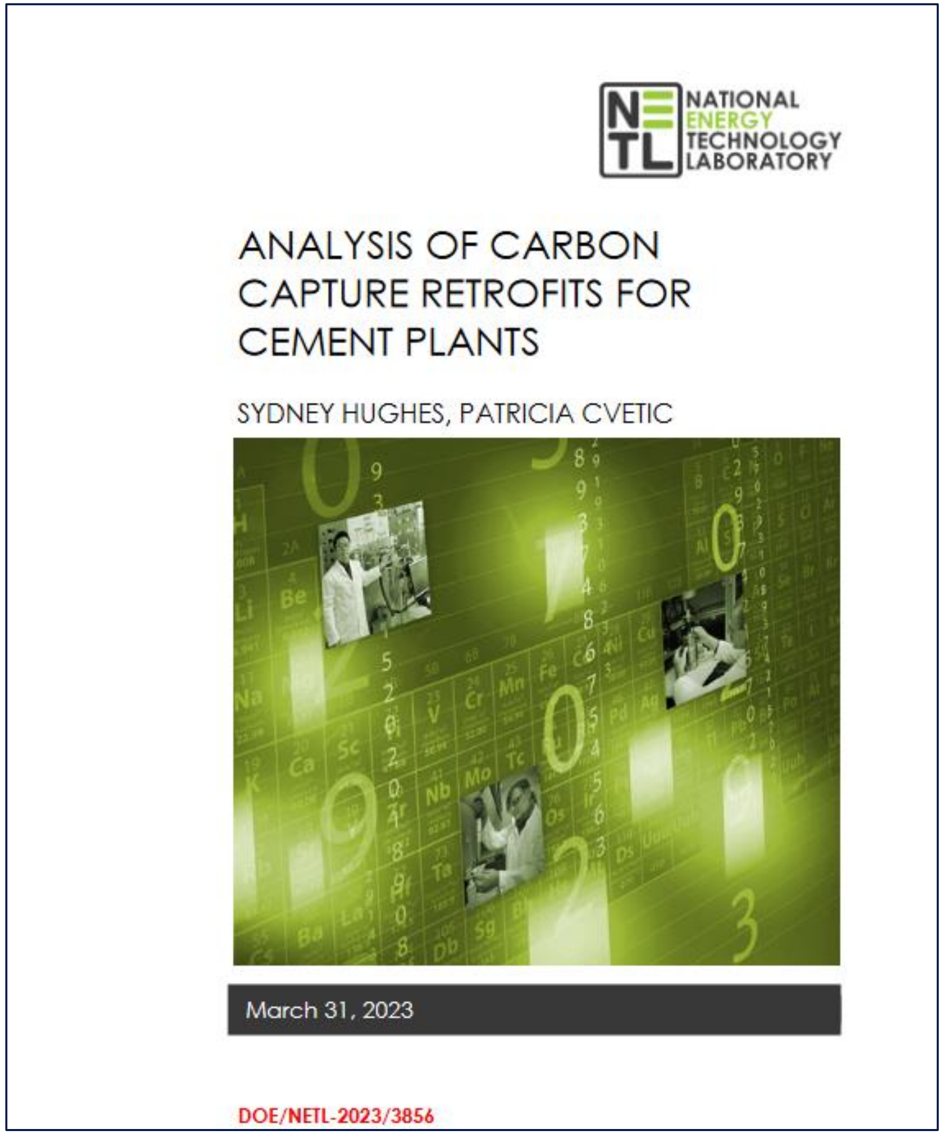
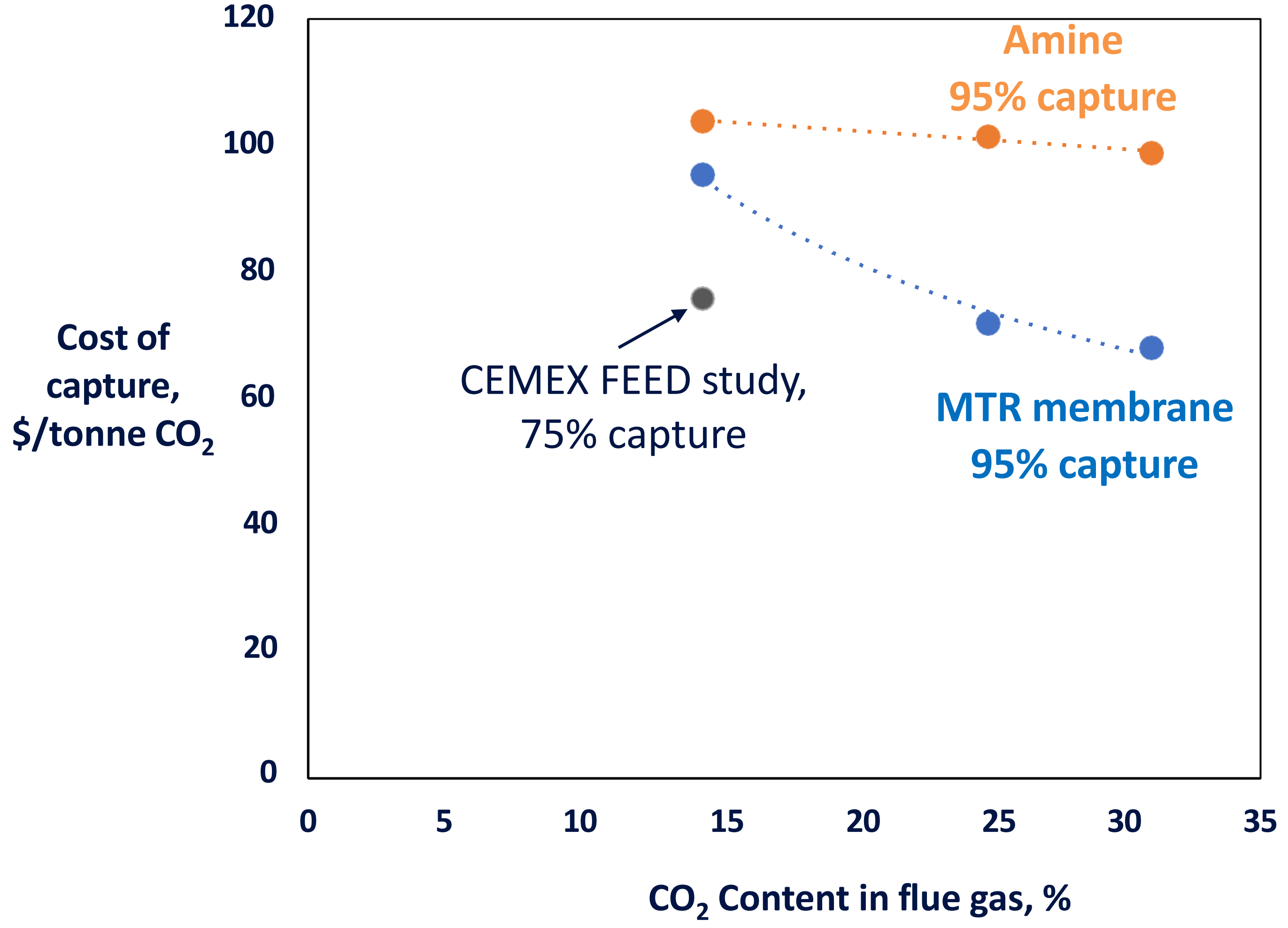
MTR process comparison with recent DOE cement study



- Recently, DOE published study on costs of capture from cement plants using amine absorption (Cansolv)
- MTR Balcones costs were adjusted to DOE study conditions (95% capture, Nov 2022 dollars, $67.28/MWh, etc) for better comparison
- DOE examined 3 feed CO_2 contents: 14.5%, 25%, and 31%; lowest content is close to Balcones
- Advanced Gen 3 MTR membranes used in calculations

MTR process cost comparison with DOE baseline



- Both technologies show a decreasing capture cost as feed CO_2 content increases
- However, membrane costs decrease faster resulting in significant savings (~30%) at CO_2 content >20%
- Membrane environmental advantages: DOE study shows amine uses ~400 gal water/ tonne CO_2 captured; membrane < 50 gal/tonne

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Project Objectives

- Design, fabricate, and operate membrane-sorbent hybrid small pilot system at St. Marys Cement Charlevoix, MI plant
- Complete 6-month field test showcasing hybrid process ability to efficiently capture >95% of the CO_2 emissions from a 3 TPD flue gas slipstream
- Quantify the co-capture benefits of the hybrid process operating on cement flue gas
- Update TEA incorporating field test performance data and optimized hybrid process design for post-combustion CO_2 capture from cement plants

Project Gantt Chart

Project Tasks	Task Participants	Task Start Date	Task End Date	Budget Period One 12/1/2024 - 11/30/25	Budget Period Two 12/1/25 - 5/31/27	Budget Period Three 6/1/27 - 11/30/28
				Q1 Q2 Q3 Q4	Q5 Q6 Q7 Q8 Q9 Q10	Q11 Q12 Q13 Q14 Q15 Q16
Task 1. Project Management and Planning		**12/1/2024**	**11/30/2028**			
Task 1.1. Project Management Plan	MTR	*12/1/2024*	*12/31/2024*			
Task 1.2. Technology Maturation Plan	MTR	*12/1/2024*	*2/28/2025*			
Task 2. Initial Techno-Economic Analysis		**12/1/2024**	**5/31/2025**			
Task 2.1. Initial Techno-Economic Analysis Report	Trimeric/MTR/TDA	*12/1/2024*	*3/31/2025*			
Task 1.2. Presentation of Initial TEA and Process Models	MTR/TDA/Trimeric	*3/1/2025*	*5/31/2025*			
Task 3. Design and Engineer Hybrid Test System		**12/1/2024**	**11/30/2025**			
Task 3.1. Preliminary Design	MTR/TDA/S&L	*12/1/2024*	*5/31/2025*			
Task 3.2. Review Host Site Specifications	MTR/TDA/S&L/SMC	*3/1/2025*	*5/31/2025*			
Task 3.3. HAZOP Review and Finalize Design	MTR/TDA/S&L/SMC	*6/1/2025*	*11/30/2025*			
Task 4. Host Site Engineering Design Work	S&L/MTR/TDA/SMC	**12/1/2024**	**11/30/2025**			
Task 5. Make Membrane Rolls with Target Performance	MTR	**12/1/2024**	**11/30/2025**			
Task 6. Field Test Membrane Module and Sorbent Preparation		**12/1/2025**	**5/31/2027**			
Task 6.1. Low Pressure Drop Field Test Modules	MTR	*12/1/2025*	*11/30/2026*			
Task 6.2. Sorbent Production	TDA	*12/1/2025*	*5/31/2027*			
Task 7. Fabricate Hybrid Test System		**12/1/2025**	**5/31/2027**			
Task 7.1. Select Vendors and Fabricators	MTR/TDA	*12/1/2025*	*5/31/2026*			
Task 7.2. Fabricate Skids	MTR/TDA	*6/1/2026*	*2/28/2027*			
Task 7.3 Factory Acceptance Test (FAT) at Fabricator Site	MTR/TDA	*3/1/2027*	*5/31/2027*			
Task 7.4. Installation of Membrane Modules at Fabricator Site	MTR/TDA	*3/1/2027*	*5/31/2027*			
Task 8. Host Site Preparations		**12/1/2025**	**5/31/2027**			
Task 8.1. Skid Foundation	S&L/SMC	*12/1/2025*	*5/31/2026*			
Task 8.2. Prepare Electrical and Water Utilities	S&L/SMC	*6/1/2026*	*2/28/2027*			
Task 8.3. Prepare Process Connections	S&L/SMC	*12/1/2026*	*5/31/2027*			
Task 8.4. Shipment of Hybrid Test Skids to Field Test Site	MTR/TDA/SMC	*3/1/2027*	*5/31/2027*			
Task 8.5. Develop Preliminary Test Plan	MTR/TDA/SMC	*3/1/2027*	*5/31/2027*			
Task 9. Hybrid Test System Installation and Pre-Commissioning		**6/1/2027**	**8/31/2027**			
Task 9.1. Hybrid Test System Mechanical Installation	S&L/MTR/TDA/SMC	*6/1/2027*	*8/31/2027*			
Task 9.2. Utility Connections	S&L/SMC	*6/1/2027*	*8/31/2027*			
Task 9.3. Process Line Connections	S&L/SMC	*6/1/2027*	*8/31/2027*			
Task 9.4. Load Sorbent in Test System Vessels	TDA/S&L/SMC	*6/1/2027*	*8/31/2027*			
Task 9.5. Pre-Commissioning Operations	MTR/TDA	*6/1/2027*	*8/31/2027*			
Task 10. Operate Hybrid Test System		**9/1/2027**	**5/31/2028**			
Task 10.1. System Commissioning	MTR/TDA	*9/1/2027*	*11/30/2027*			
Task 10.2. Finalize Test Plan	MTR/TDA/SMC	*9/1/2027*	*10/15/2027*			
Task 10.3. Operation of Hybrid Test System	MTR/TDA	*12/1/2027*	*5/31/2028*			
Task 10.4. Analyze System Performance	MTR/TDA	*9/1/2027*	*5/31/2028*			
Task 11. Decommissioning and Site Clean-Up	S&L/MTR/TDA/SMC	**6/1/2028**	**8/31/2028**			
Task 12. Prepare Project Reports		**12/1/2027**	**11/30/2028**			
Task 12.1 Final Techno-Economic Analysis	Trimeric/MTR/TDA	*12/1/2027*	*8/31/2028*			
Task 12.2 Technology EH&S Risk Assessment	Trimeric/MTR/TDA	*12/1/2027*	*8/31/2028*			
Task 12.3 Final Technology Maturation Plan	MTR	*12/1/2027*	*8/31/2028*			
Task 12.4. Final State Point Data Table	MTR/TDA	*12/1/2027*	*8/31/2028*			
Task 12.5 Final Report	MTR	*3/1/2028*	*11/30/2028*			

Host Site: St. Marys Cement Charlevoix Plant (Charlevoix, MI)

St. Marys Cement is a part of Votorantim Cimentos' US operations

- Year of Installation: 1967/upgraded 2017
- Volume of Production
  - 2,054 kt cement/year
  - 1,911 kt clinker/year
- Products
  - Slag Cement
  - Portland Cement Type III
  - Masonry Cement Type M, N, and S
  - Blended Hydraulic Cement Type IL
- Markets Served
  - Michigan, Illinois, Wisconsin, Indiana, Ohio, Canada

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Small Pilot location at SMC Charlevoix site has been determined

- Location will minimize distance from plant and utility connections
- All project tasks at site will not disrupt normal plant operation

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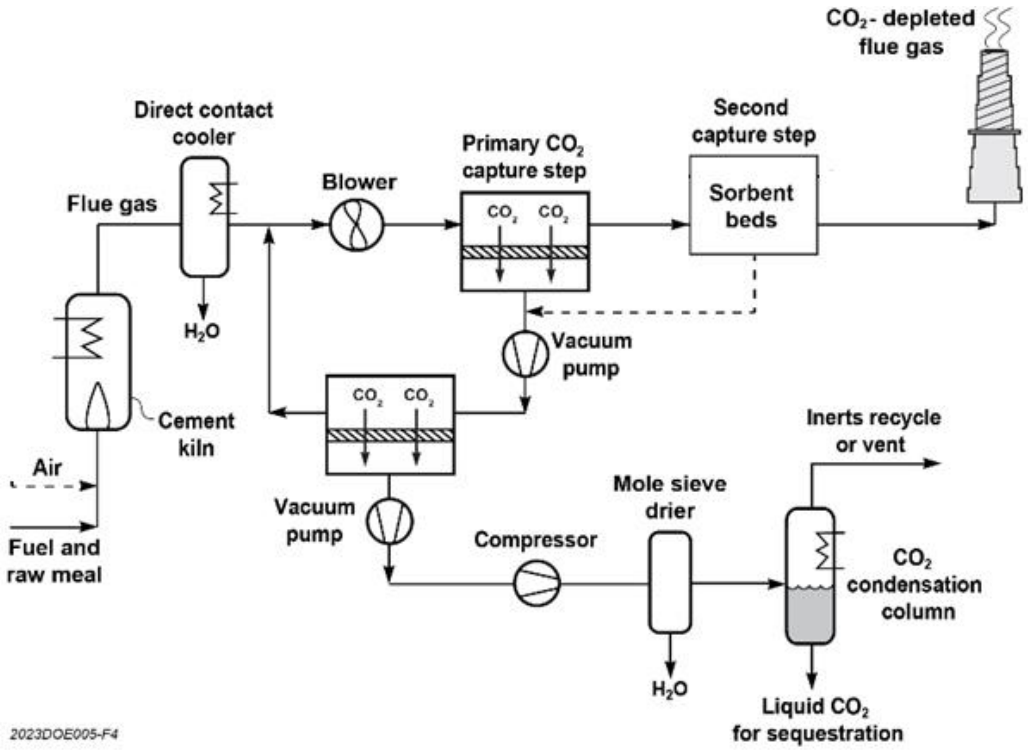
Initial Hybrid Test Plan

Test plan will be further developed with input from TDA and CCSI2

- Vary capture rate of membrane and sorbent steps
- Vary overall capture rate of hybrid process
- Vary tie-in point of enriched CO_2 stream from sorbent step back to membrane process
- Run dynamic tests (startup/shutdown, load change) to document hybrid system response time
- Based on parametric test data, select optimum condition for long term steady state test
- Quantify co-capture benefits



Budget Summary

Section A - Budget Summary							
	Grant Program Function or Activity	Catalog of Federal Domestic Assistance Number	Estimated Unobligated Funds		New or Revised Budget		
			Federal	Non-Federal	Federal	Non-Federal	Total
	(a)	(b)	(c)	(d)	(e)	(f)	(g)
1.	Fossil Energy and Carbon Management	81.089			$845,614	$282,689	$1,128,303
2.	Fossil Energy and Carbon Management	81.089			$4,860,251	$1,911,705	$6,771,956
3.	Fossil Energy and Carbon Management	81.089			$1,294,032	$427,758	$1,721,790
4.							$0
5.	Totals		$0	$0	$6,999,898	$2,622,152	$9,622,050

Section B - Budget Categories					
6. Object Class Categories	Grant Program, Function or Activity				Total (5)
	(1) Budget Period 1	(2) Budget Period 2	(3) Budget Period 3	(4)	
a. Personnel	$133,637	$126,877	$180,486		$441,000
b. Fringe Benefits	$0	$0	$0		$0
c. Travel	$12,776	$23,440	$49,716		$85,932
d. Equipment	$0	$2,250,000	$0		$2,250,000
e. Supplies	$35,000	$125,000	$0		$160,000
f. Contractual	$679,616	$3,967,885	$1,105,616		$5,753,117
g. Construction	$0	$0	$0		$0
h. Other	$0	$25,000	$25,000		$50,000
i. Total Direct Charges (sum of 6a-6h)	$861,029	$6,518,202	$1,360,818	$0	$8,740,049
j. Indirect Charges	$267,274	$253,754	$360,972		$882,001
k. **Totals** (sum of 6i-6j)	$1,128,303	$6,771,956	$1,721,790	$0	$9,622,050
7. Program Income					$0

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Key Project Milestones

Milestone Number	Task/ Subtask No.	Milestone Description	Planned Completion Date (*)	Verification Method
Phase 1 / Budget Period 1 (12/1/2024 – 11/30/2025)				
4	3.3	Finalize Test System Design	11/30/25	Quarterly Report
Phase 2 / Budget Period 2 (12/1/2025 – 5/31/2027)				
9	7.3	Test Skids Passes Factory Acceptance Tests (FAT) at Fabricator Sites	5/15/2027	Quarterly Report
10	8	St. Marys Cement Field Test Site Preparation Work Completed	5/15/2027	Quarterly Report
11	8.4	Field Test Skids Arrive at St. Marys Cement Field Test Site	5/31/2027	Quarterly Report

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Key Project Milestones

Milestone Number	Task/ Subtask No.	Milestone Description	Planned Completion Date (*)	Verification Method
Phase 3 / Budget Period 3 (6/1/2027 – 11/30/2028)				
14	10.3	Field Test Campaign Completed	5/31/2028	Quarterly Report
16	12.1	Complete Techno-Economic Analysis	8/31/2028	Topical Report

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Current Project Status

- Project started December 1, 2024
- MTR finishing up activities to get subrecipient contracts in place and POs issued to vendors
- Initial technology maturation plan on track to be completed by end of February
- Trimeric, MTR, and TDA held initial TEA meeting in early January. All project partners currently working on various tasks for the report
- Test system and plant preparation design meetings with all project partners to start next week
- MTR and St. Marys Cement completed Host Site Agreement in late December (project deliverable)

Summary

- Project is just underway with initial effort focused on finalizing subcontracts, technology maturation plan, initial TEA, and completing the host site agreement with St. Marys Cement
- Test system and plant design work to ramp up in the coming weeks
- Primary project goal will field testing at SMC Charlevoix cement plant of a membrane-sorbent hybrid system at high (>95%) capture rates
- This project will determine the optimal hybrid process design, quantify co-capture benefits of the capture technology, and de-risk scale-up of this technology for CO_2 capture from cement plants

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Acknowledgements

- U.S. Department of Energy, National Energy Technology Laboratory
  - Andy O'Palko
  - Mike Fasouletos
  - Ron Munson
  - Dan Hancu

- Project partners