Scale-Up Testing of Advanced Polaris Membrane CO_2 Capture Technology

DE-FE0031591

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Final Project Review Meeting
January 27, 2023

Presentation Outline

- Background/review of prior results
- Project overview/objectives
- Results of project activities
  - Design and scale up of Gen-2 Polaris planar module stacks
  - Field test at Technology Centre Mongstad (TCM)
  - Post-field test analysis and TEA
- Project summary and next steps

Why Membranes for CO_2 Capture?

- No chemical handling, emissions, or disposal issues / easier permitting
- Simple passive operation; modular technology with flexible footprint
- Relatively low water usage
- Uses only electricity, so can be powered by renewables
- Near instantaneous response; high turndown possible
- Capture cost decreases for higher CO_2 content streams
- Challenges: need for low pressure drop module and high performance membrane

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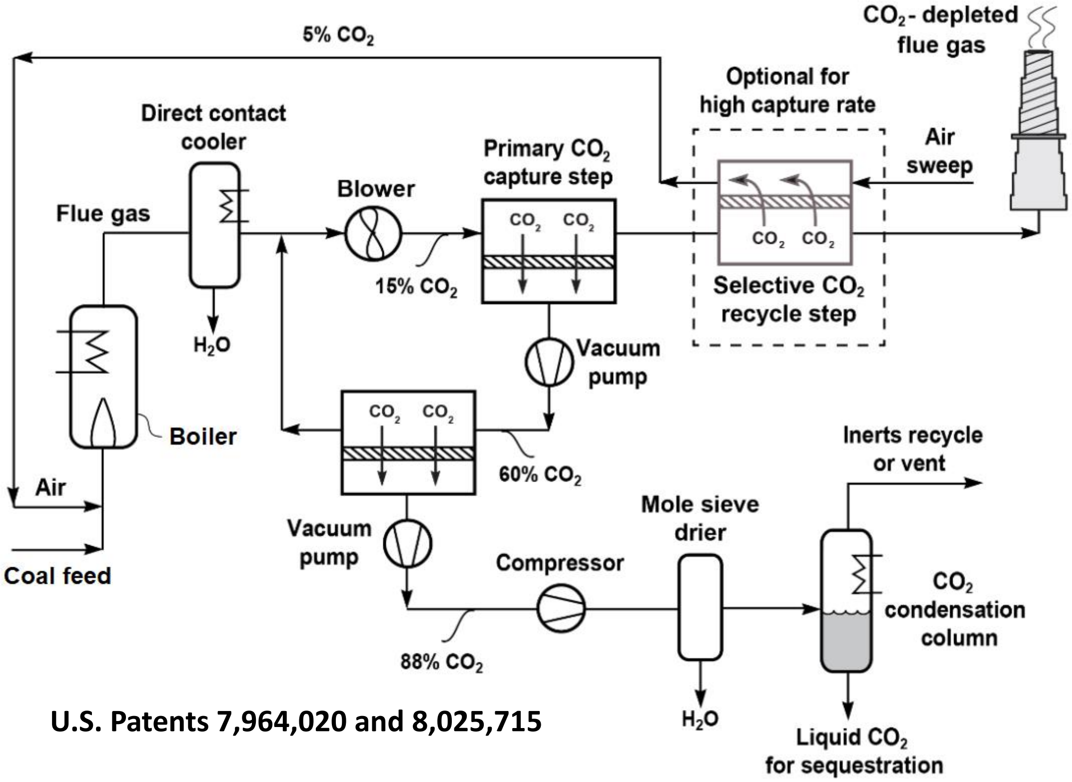
Background: MTR CO_2 Capture Process



U.S. Patents 7,964,020 and 8,025,715

- Selective recycle can be used to reduce capture costs at high capture rates if it can be tolerated by the combustion process
- Prior work with B&W showed it is technically possible for coal, but many operators prefer end-of-pipe solution
- More interest for selective recycle in industrial cases – cement, steel, waste-to-energy

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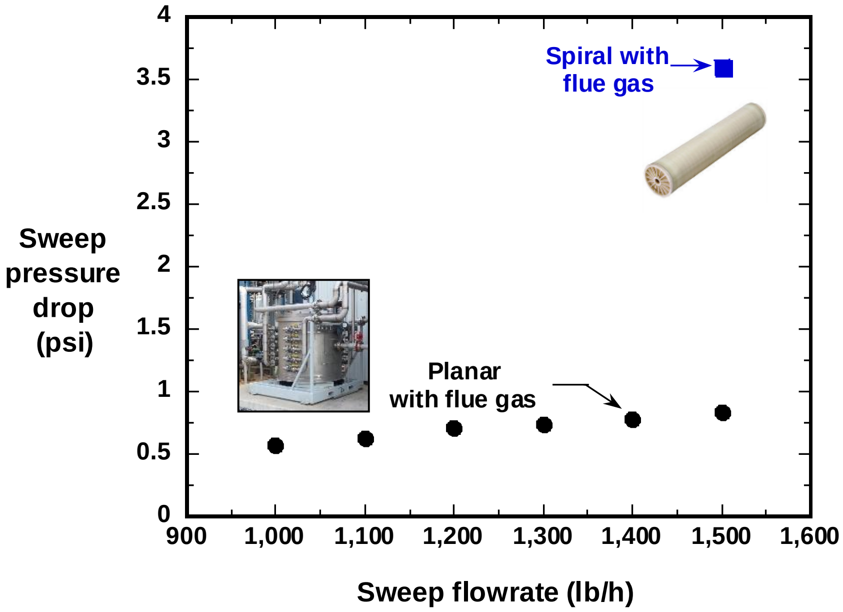
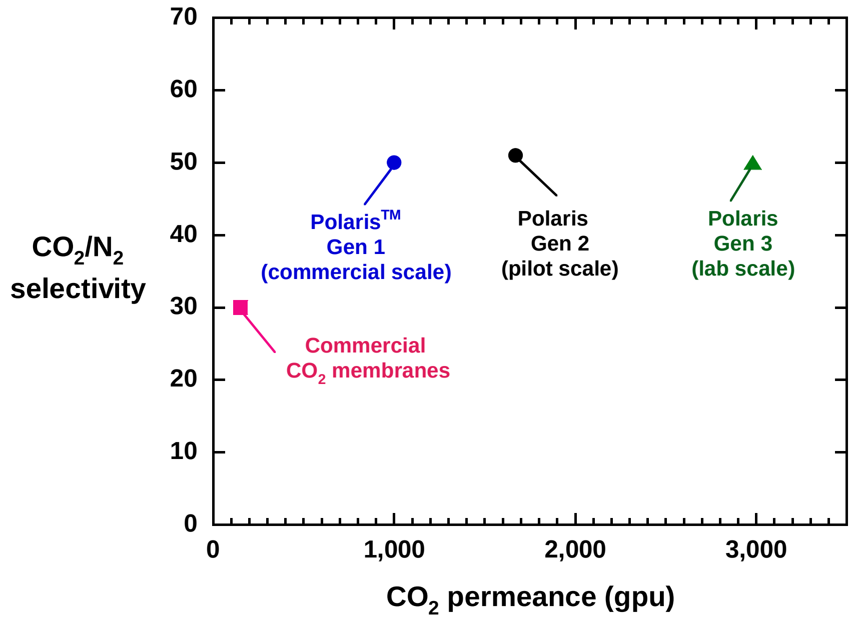
Background: Membrane and Module Improvements

Planar Modules



Polaris™ Membranes



- Moving from Gen 1 to Gen 2 Polaris cuts membrane area by ~50% (~$10/tonne CO_2)
- Lower pressure drop of new modules saves 15 MW_e fan power on 500 MW_e system

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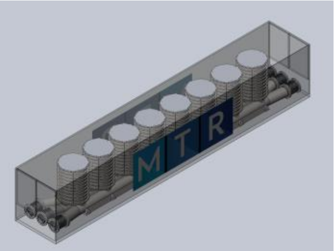
Membrane Module Development Timeline

	Semi-commercial Module / Lab-Scale System	Commercial Module / Bench-Scale System	Prototype Module / Small Pilot System	Advanced Module Stack/ Small Pilot System	Final Form Factor / Large Pilot System
TRL Level	5	5	6	6	7
Field Test Location	APS, NCCC	APS, NCCC	NCCC, B&W, UT-Austin	TCM	WITC
Field Test Dates	2009 – 2013	2010 - 2015	2015 - 2018	2021-2022	2023-2025







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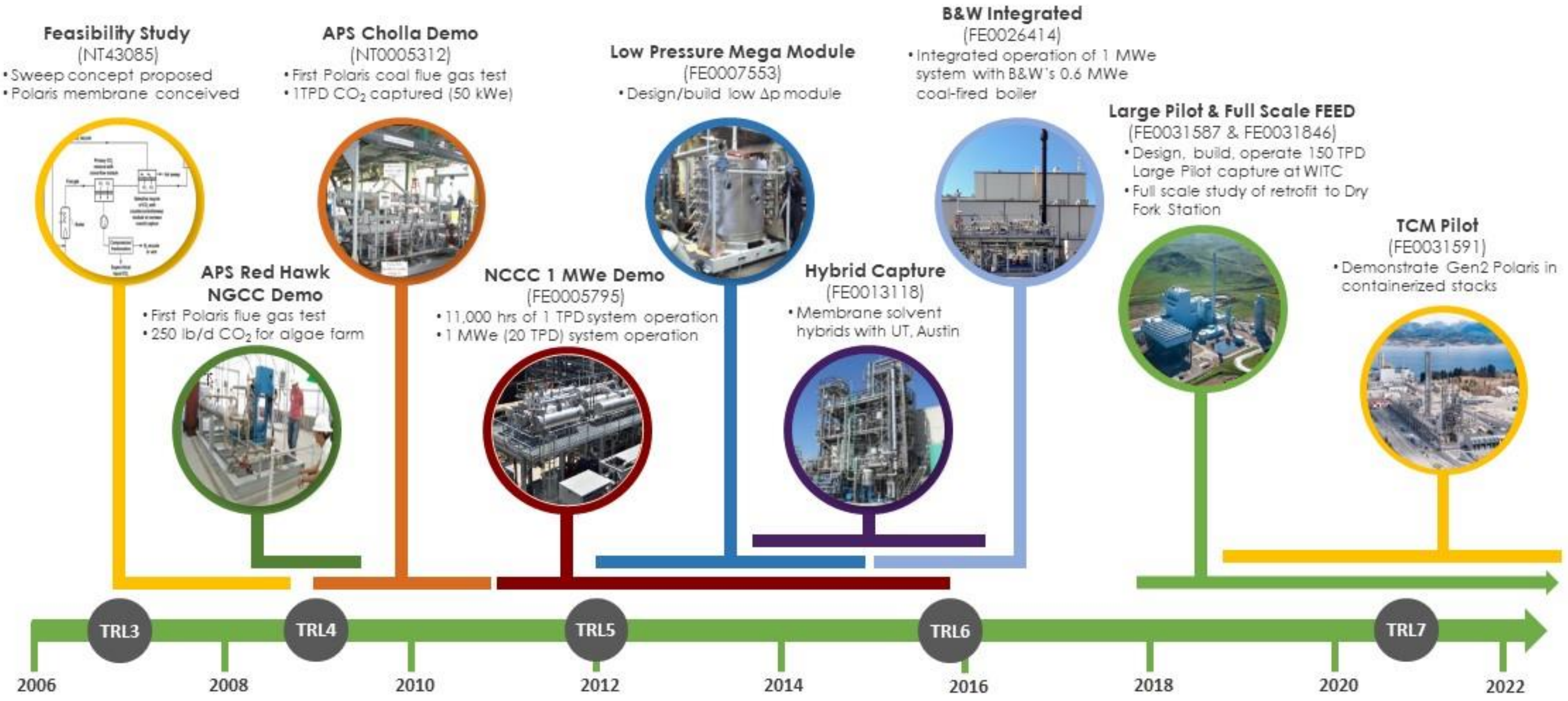
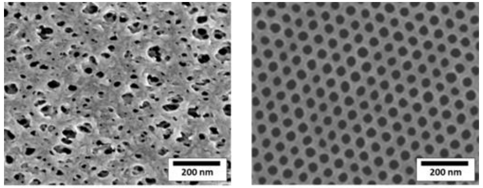
Technology Development Timeline



This Project in Context

Self-Assembly Isoporous Supports (DE-FE31596; Hans Wijmans)

- Transformational new membrane (TRL 3 – 4)
- Reduces membrane area and energy use



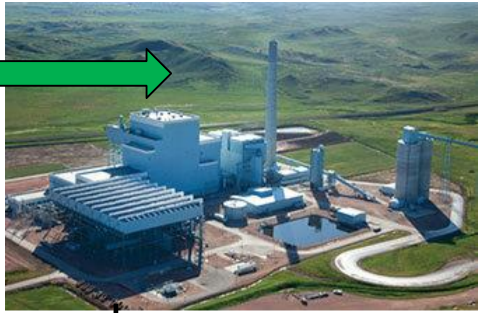
Surface of Conventional Support   Surface of Isoporous Support

Pilot Testing at TCM, Norway (DE-FE0031591; Tim Merkel)

- Gen 2 Polaris™ membrane
- Low pressure-drop modules
- Containerized skid, 10 TPD pilot scale

Large-Pilot Testing at Wyoming ITC (DE-FE31587; Brice Freeman)

- Phase I – Design 150 TPD pilot; secure host site
- Phase II – FEED and permitting
- Phase III – Fabricate, install and operate (TRL 7 – 8)



2018 2019 2020 2021 2022 2023 2024 2025

Project Overview

Award name: Scale-Up and Testing of Advanced Polaris Membrane CO_2 Capture Technology (DE-FE0031591)

Project period: 8/1/18 to 1/31/23

Funding: $8.2 million DOE; $2.6 million cost share ($10.8 million total)

DOE program manager: Isaac “Andy” Aurelio (BP1 & 2), Andy O’Palko (BP3)

Participants: MTR, TCM, Trimeric, CCSI2

Project scope: Design, build, and operate a system at TCM with Gen 2 Polaris modules

Project plan: The project is organized in three phases:

- **Phase 1** – Design system, fabricate membrane modules
- **Phase 2** – Build and install system at TCM
- **Phase 3** – Operate system, analyze results, decommissioning

Role of Participants

- MTR (Tim Merkel, Jay Kniep, Thomas Hofmann) – project lead and liaison with DOE; responsible for membrane system design, construction, installation and operation; will lead data analysis and all reporting to DOE
- TCM (Kjetil Hantveit, Blair McMaster) – host site for the field test; with MTR, will coordinate system installation, operation, and data analysis
- Trimeric (Ray McKaskle, Darshan Sachde, Anne Ryan) – Responsible for membrane capture process techno-economic analysis (TEA)

Project Objectives

- Scale-up Gen 2 Polaris membrane packaged in low-pressure-drop, low-cost module stacks and test at TCM
- Demonstrate "containerized" skid as final form factor for future large-scale systems; reduce scale up risk
- Test pilot system (~10 TPD) over range of CO_2 capture rates and feed CO_2 content for TEA input
- Update overall process TEA (Trimeric)

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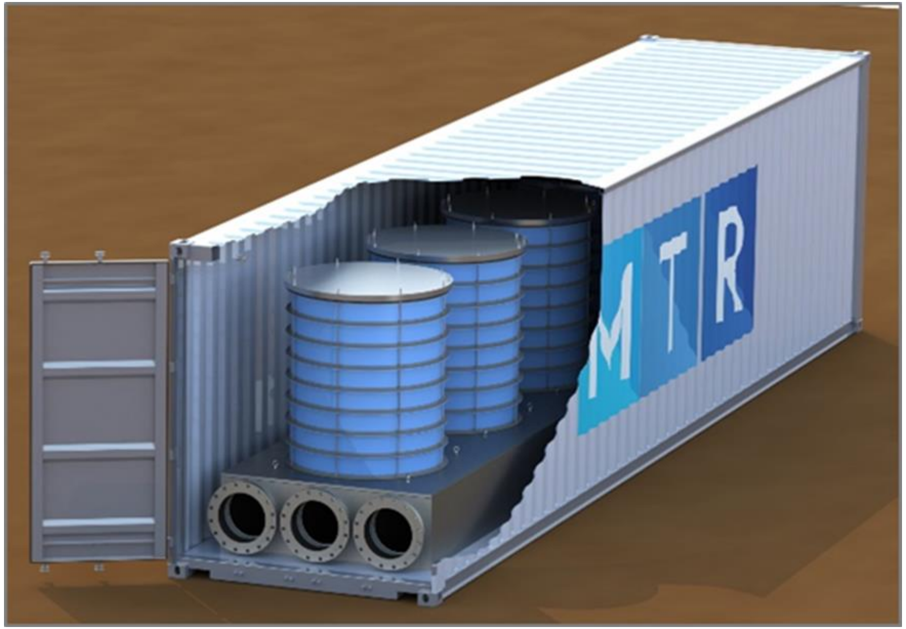
Key Objective: Module-Scale Up

Plate-and-Frame Prototype with Gen-1 Polaris
(Tested at NCCC/B&W/UT-Austin 2015-18)

Verified low-pressure drop in field testing

Containerized Module Stacks with Gen-2 Polaris
(2021/22 TCM Field Test)

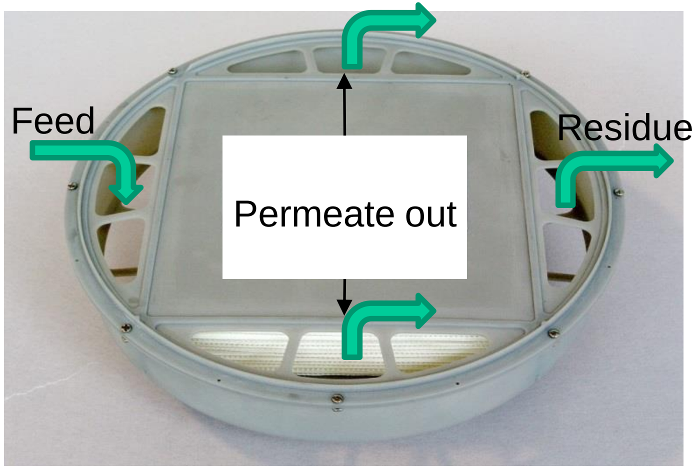


Low pressure drop, plus optimized flow distribution and reduced cost (valves, etc)

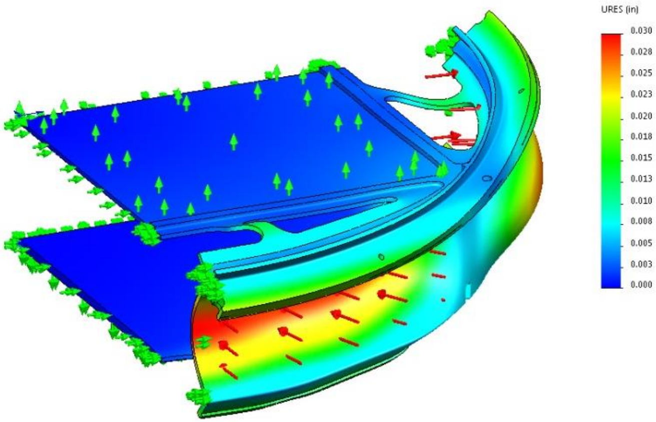
New Planar Membrane Module Design

- New planar module design will reduce pressure drop and is amenable to low cost materials of construction / automated assembly
- Modules will be stackable with 8 modules per stack
- CFD has been performed to determine velocity profiles, minimize pressure drop, and ensure mechanical stability

1/6th Scale Housing made by 3D printing



Housing Deformation Under Load



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Module Fabrication at MTR

Membrane module stack trimming system

Module test apparatus

- Gen 2 Polaris produced on commercial roll-to-roll equipment
- Membrane stacks were assembled and passed QC testing at MTR prior to installation on the test system

Module Stack Assembly/QC Testing

- Gen-2 Polaris membrane was made in 600 ft rolls on commercial roll-to-roll equipment
- All membrane was subjected to pure gas quality control testing prior to module fabrication
- Individual membrane modules were subjected to vacuum decay and pure gas quality control testing
- Module stacks were shipped to system fabricator (PRI), installed on system and leak tested immediately prior to sending to TCM

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TCM Site Preparations

View of TCM with 3rd site in foreground

- Technology Centre Mongstad (TCM) is a world-leading site for evaluation of carbon capture technologies
- TCM began development of the "3rd" site for testing emerging capture technologies in 2019
- TCM assisted MTR with installation of the pilot system at the site in spring/summer 2021, and with operation in fall 2021/winter 2022

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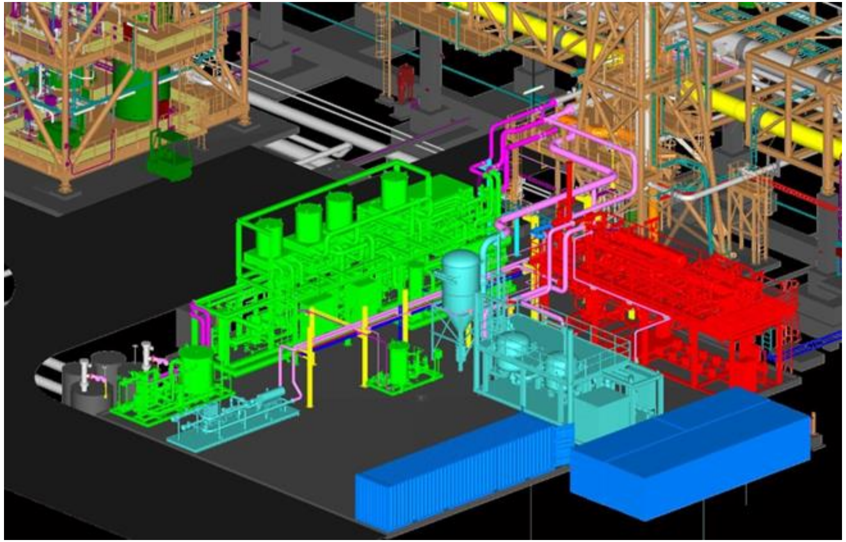
TCM Site Preparations

3rd site with MTR and TDA skids

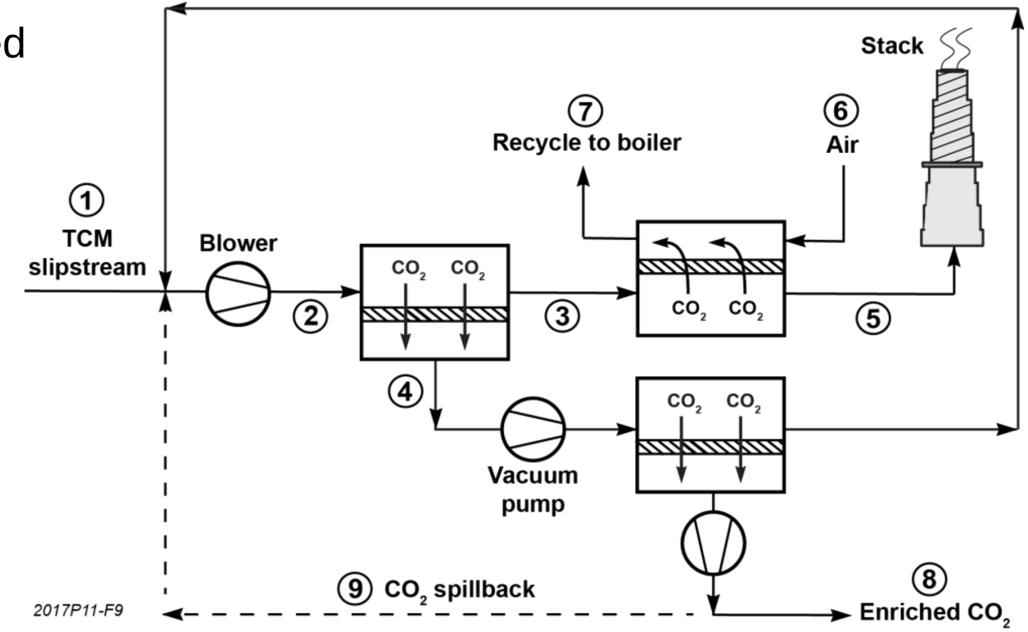


Close up view of 3rd site foundation

- MTR membrane and TDA hybrid systems were the first capture technologies to be tested at TCM's Site for Emerging Technologies

MTR Test System Design

- 2 stage membrane system with air sweep step (stream 6) and varying feed CO_2 content using recycle (stream 9)
- TCM slipstream flow rate of 800 to 2,400 Nm^3/h
- 50% to 90+% CO_2 capture rates possible
- Tests the membrane portion of the capture process, but not the CO_2 purification unit (CPU)
- HAZOP and P&ID review with TCM occurred in September 2019 in Colorado



Test Plan for TCM Campaign

- Received input from DOE, TCM and CCSI2 team on test plan
  - Adjustable parameters: flue gas flow rate, temperature, sweep air flow rate, and CO_2 concentration to 1st stage membrane
  - Will use these variables to explore capture rates from 50% to 90+% and CO_2 feed content from 14% to ~25%

- TCM Field Test Key Performance Indicators
  - Demonstrate CO_2 capture rates up to 50% without air sweep step
  - Demonstrate CO_2 capture rates up to 80% with air sweep step
  - CO_2 purity in the 2nd Stage permeate reaches 80%
  - Module pressure-drops (feed-to-residue and sweep-side) are < 2 psi (13.8 kPa)

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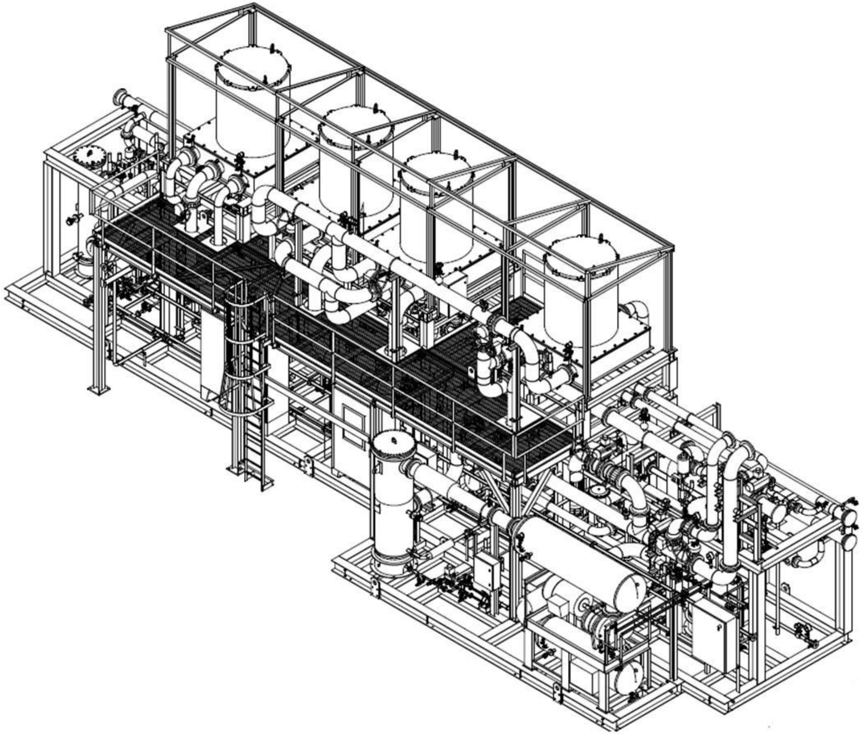
MTR System General Arrangement

- Membrane “container” with 4 stacks on top floor (full container would be 6-8 stacks); blower/pumps on bottom floor
- Factory Acceptance Test (FAT) of system completed in March 2021
- Skids shipped to Norway in spring 2021, and installed at TCM in summer 2021



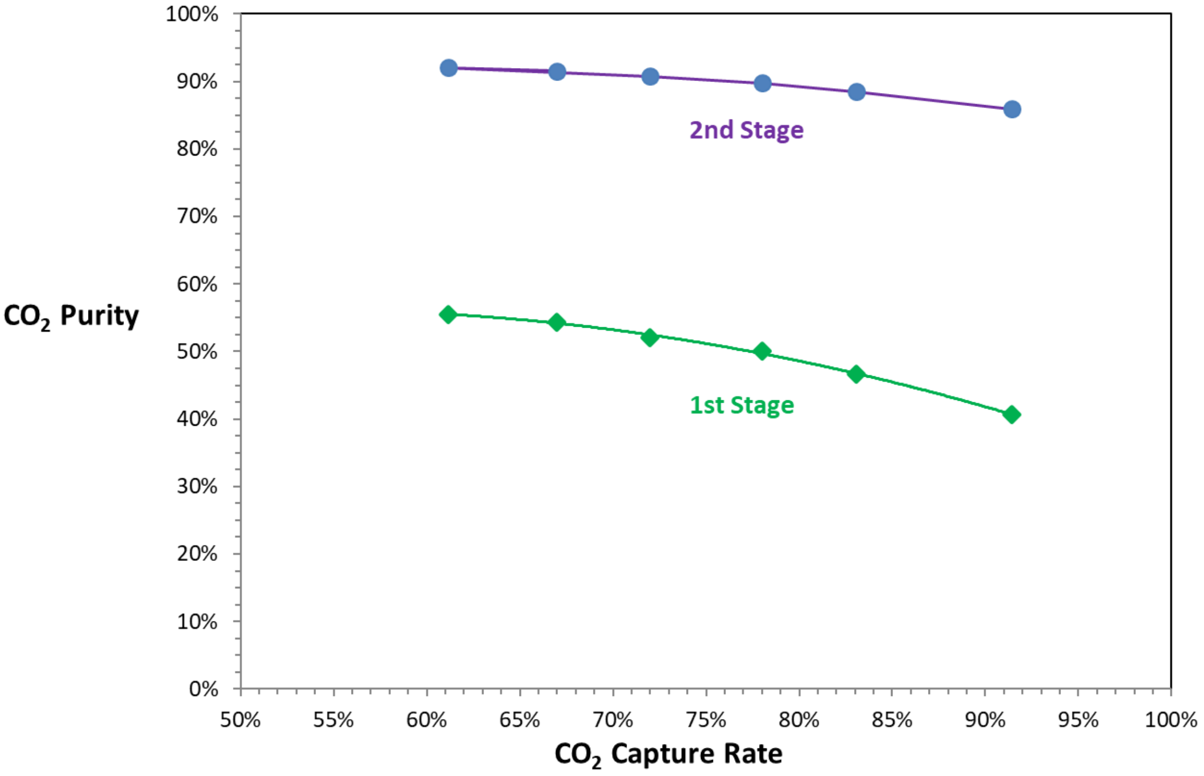
MTR System Installation

- MTR arrived at TCM in mid-May 2021 to coordinate installation plans
- TCM obtained travel exemptions from the Norwegian government for all MTR personnel
- Main skids arrived at TCM in late May
- All smaller skids and containers were on-site by mid-June
- Up to 4 MTR personnel were on-site during installation activities

MTR System at TCM

- MTR system was first commissioned on flue gas on July 28, 2021
- A few initial issues with pumps, valves, heat tracing, etc
- Parametric testing started in late September
- In total, 2,200 hours on TCM RFCC flue gas
- Included one new module stack installed in early Jan 2022 to evaluate a new flow field design

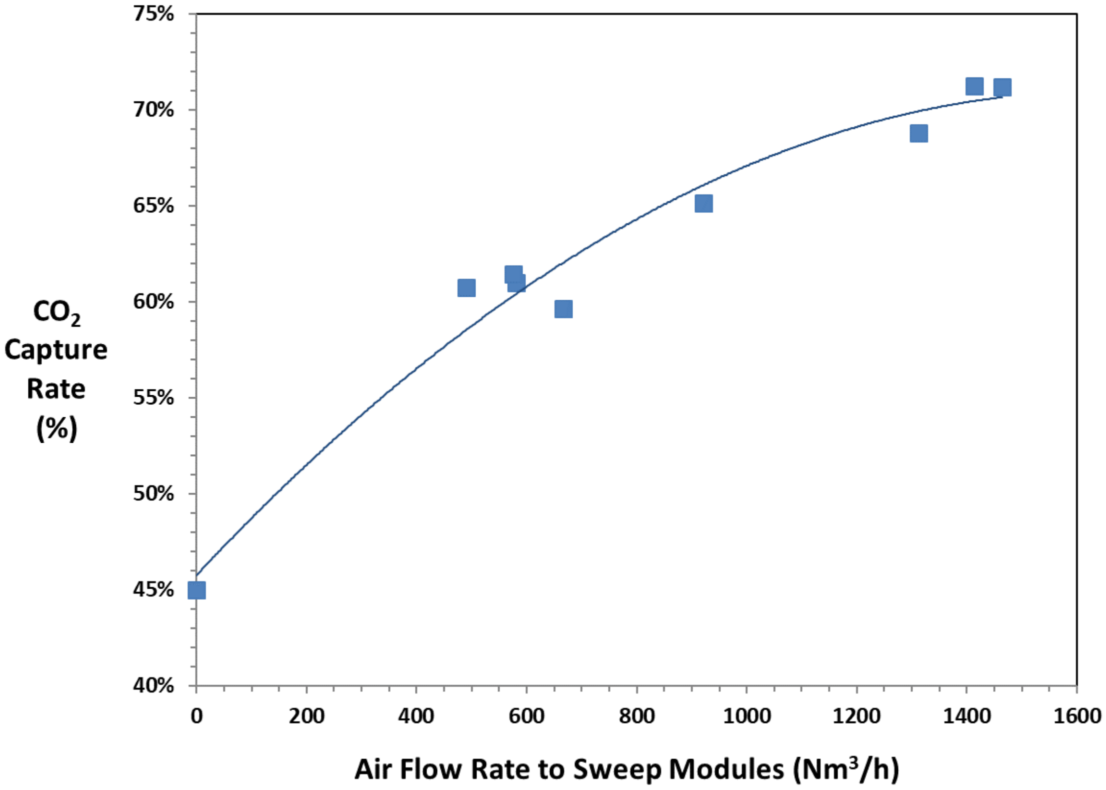
TCM Test Data: Purity/Recovery



- With ~14% CO_2 feed gas, a single stage membrane produces 40-55% CO_2 and a second stage produces >85% CO_2
- There is a typical tradeoff between capture rate and CO_2 purity with higher capture rate producing lower purity
- In a complete system, the second stage permeate would be sent to the CPU for liquefaction producing >99.9% CO_2 ready for pipelines

Feed = ~14% CO_2 flue gas

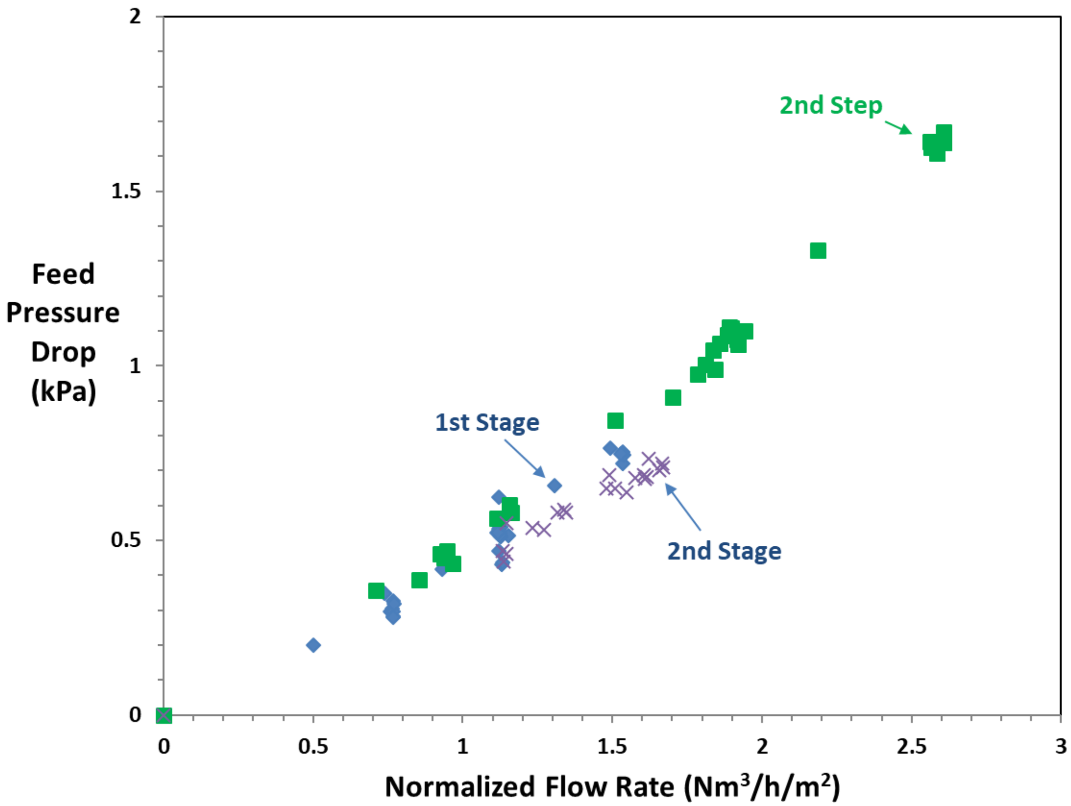
TCM Test Data: Effect of Air Sweep



- Air sweep on a 2nd step membrane module can be used to increase capture rate at a relatively low cost
- The TCM campaign was slipstream testing, so the CO_2-laden air was measured and vented; in a real system, it would be recycled to the combustion process
- The impact of CO_2 in air on combustion would need to be evaluated for each application

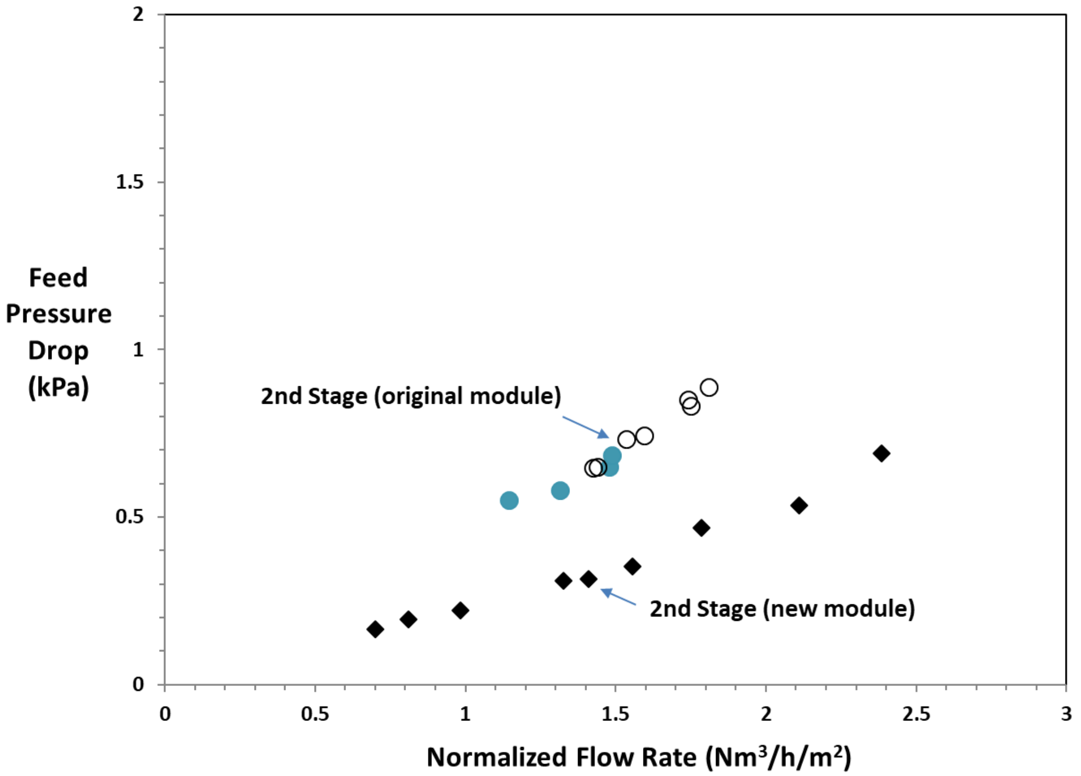
Feed = 1800 Nm^3/h of ~14% CO_2 flue gas

TCM Test Data: Pressure Drop



- A key feature of the planar modules developed by MTR is lower pressure drop compared to other module configurations
- Lower pressure drop means less fan power is needed to push gas through the membrane modules
- The target pressure drop for each step in the TCM unit is <2 psi (<13.8 kPa); actual performance is a fraction of this value!
- Data for different modules falls on a single trendline indicating good flow distribution

TCM Test Data: Improved Module Design



- During the TCM campaign, a new module configuration was installed on Stage 2 for the final 2 months of operation
- It shows even lower pressure drop with equal throughput
- It offers further energy savings (Opex) or smaller size (Capex) at same power usage

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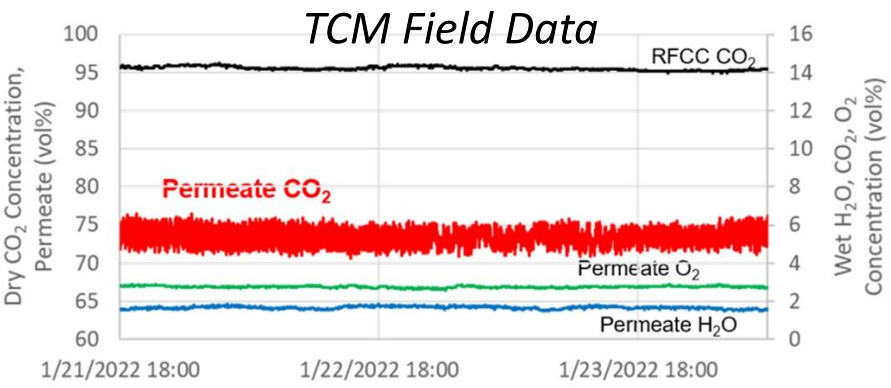
Stable Performance for Polaris Tested at TCM



- After testing at TCM, modules were returned to MTR for evaluation
- Within uncertainty in measurements, performance is unchanged from original QC values measured at MTR before testing at TCM

- Modules tested on the TDA Hybrid system (all stainless steel components) showed stable performance over 8+ months of TCM field operation

Module ID	Normalized Performance (Final/Initial)	
	CO_2 Permeance	CO_2/N_2
13240	94%	96%
13236	94%	122%
13245	110%	118%
13244	92%	93%

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Decommissioning and Current Test System Status

- Testing at TCM finished March 1, 2022
- Decommissioning of the system was completed in June 2022

- The system was initially transported to the port of Bergen for temporary storage
- The system is best suited for use at an industrial capture in Europe (due to electrical and other standards)

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TEA of MTR CO_2 Capture Process

- NETL Baseline Repot Rev 4 was used as the design basis
- Benchmark cases
  - Case B12A (without capture)
  - Case B12B (capture with Shell CANSOLV)
- Trimeric led all key components of TEA
  - MTR supplied H&MB and skid costing for membrane unit operations
- 70% CO_2 capture rate chosen because FOA was flexible and at the time (2018), interested in lower capex bulk removal
  - Note that TCM testing included >90%, which is current focus
- Draft TEA report submitted to DOE in early December
  - Revised TEA report submitted to DOE in mid-January

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Summary TEA Results

Case	Cost of Capture (no TS&M) $/tonne CO_2	Change vs. MTR Base Case	LCOE $/MWh	Change vs. MTR Base Case	CO2 Capture and Compression Total Plant Cost $MM
B12B (90% capture)	**$45.63**	**-**	**$105.20**	**-**	**$826**
MTR Base Case (70% capture)	**$48.50**	**-**	**$96.55**	**-**	**$667**
MTR PEC (-20%)	$42.95	-11.4%	$92.90	-3.8%	$534
MTR PEC (+20%)	$54.05	+11.4%	$100.22	+3.8%	$801

- MTR capture cost estimate is slightly higher than B12B, although within the 20% uncertainty in purchased equipment cost (PEC)
- Future analysis to include: impact of Gen 3 membrane (cement study showed reduction of ~$8/tonne), impact of less stringent CO_2 purity (CPU is 26% of PEC and 13% of total energy), impact of higher CO_2 content (industrial cases) and higher capture rates

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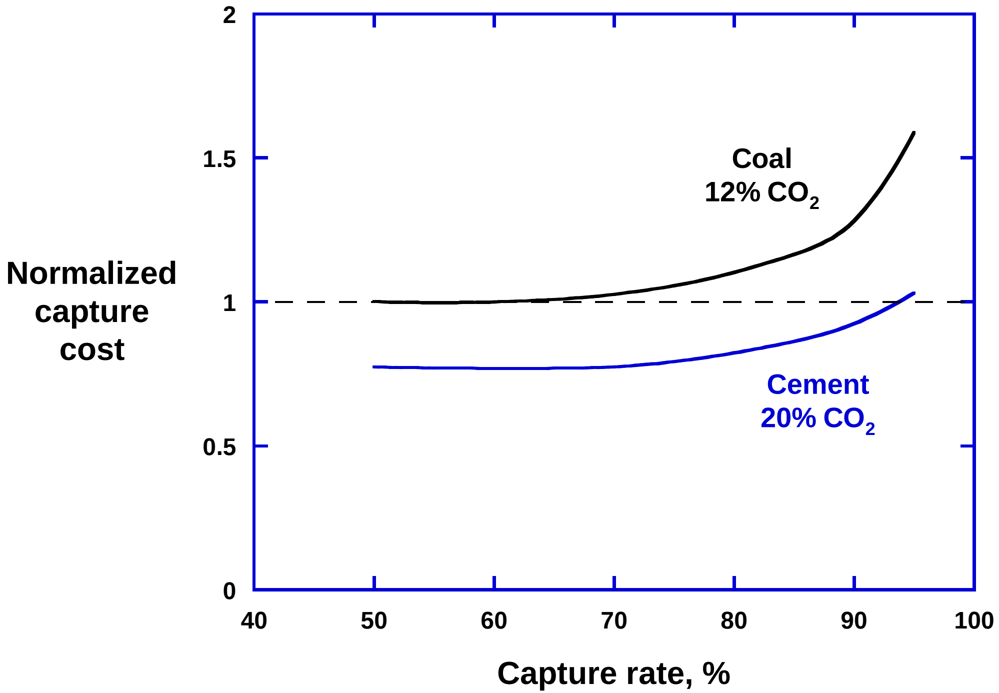
Impact of Capture Rate and Feed CO_2 Content on Costs



Capture cost is normalized to 60% capture from coal using Polaris Gen2 membranes

- As part of pre-FEED study on Cemex Balcones cement plant, 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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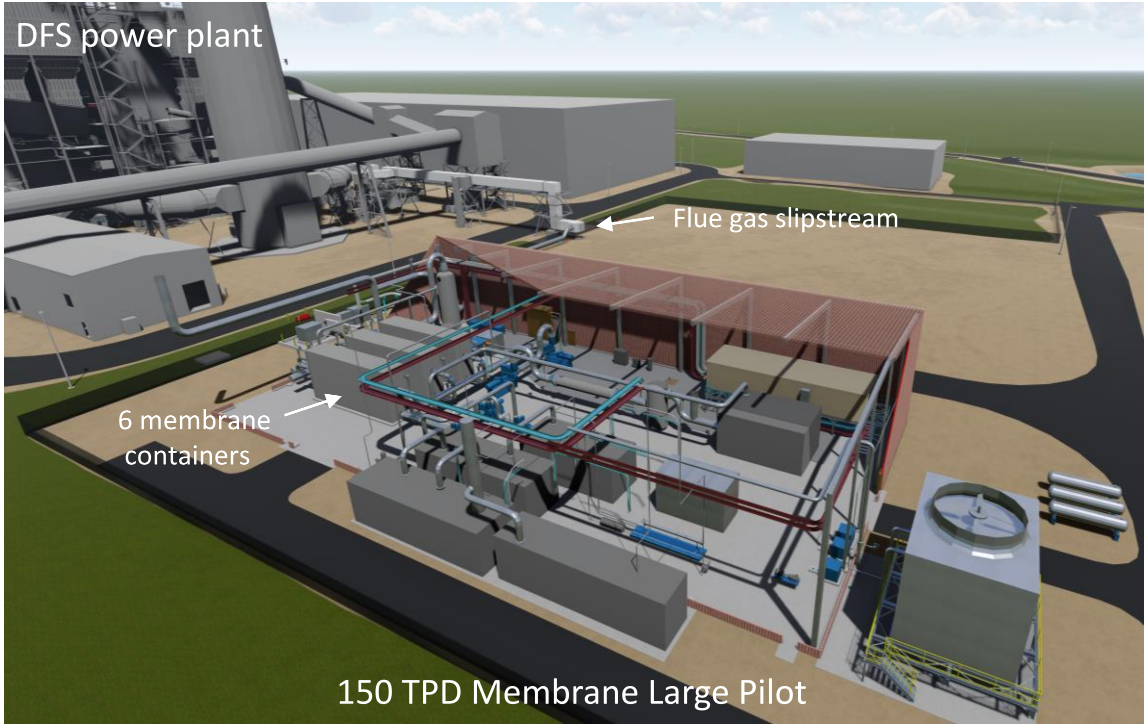
Next Steps: Large Pilot System (DE-FE0031587)

Conceptual Drawing of MTR Large Pilot at WITC



- The modular membrane capture approach demonstrated at TCM will be used on the larger 150 TPD system under construction at the Wyoming Integrated Test Center (WITC) - Dry Fork Station (DFS) power plant

Large Pilot Modules

- The planar module stacks validated at TCM are now being made from fiber-reinforced plastic
- Dramatic cost reduction
- Designed for high-volume manufacturing
- Tested for compatibility with flue gas / acid condensate → no corrosion

New module housing emerging from molding machine

First delivery of module stacks to MTR

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Summary

- A planar module test system was designed, built, installed and operated at the new TCM Site for Emerging Technologies
- ~6 months of testing was focused on varying capture rates and evaluating different module configurations; completed in March 2022
- Performance confirmed expected purity/recovery tradeoff and low pressure drop of planar modules; this test experience was important to reduce scale up risk for future large pilot
- Lessons learned from testing included need to protect membranes from capture system corrosion; component and membrane material solutions
- TEA showed that MTR capture cost was similar (within uncertainty) to Case B12B; higher feed CO_2, less stringent CO_2 purity, and better membrane will reduce capture costs, particularly at higher capture rates

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TCM-Specific Lessons Learned

- Long distance travel is expensive, particularly airfare. Schedule on-site support for longer duration intervals (4 – 6 weeks).
- Invest in remote PLC monitoring software and cloud storage of field test data. This will aid in real time troubleshooting support and system viewing from various locations.
- CRADA process with CCSI2 is lengthy, start ASAP.
- Test system skid design should be modular (shipping container dimensions) to avoid unnecessary shipping costs.
- Contact local transport company (BRING) early in process for customs and transport within Norway.
- Test system VAT payments can be avoided by an ATA Carnet. Carnet paperwork must be completed prior to skids leaving US port.
- Norwegian lifting requirements are more rigorous than US standards. All lifting plans and lifting lug design will need to be approved by the appropriate Norwegian entity. Recommend subcontracting this work to a Norwegian engineering company (Oceaneering) that is familiar with local codes.

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