MTR MEMBRANE TECHNOLOGY & RESEARCH

Scale-Up and Testing of Advanced Polaris Membranes at TCM (DE-FE0031591)

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Carbon Management Research Project Review Meeting
Capture from Power Generation / Pilot-Scale Research
August 16, 2022

Project Overview

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

Project period: 8/1/18 to 9/30/22

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

DOE program manager: Bruce Lani (BP1), 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

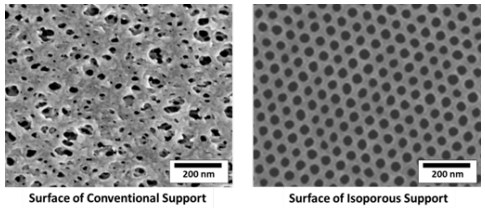
Project plan: The project is organized in three phases:

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

Background: This Project in Context

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

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



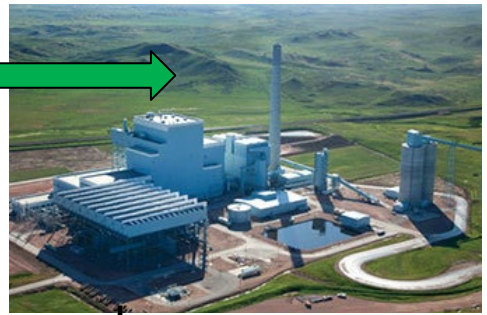
Surface of Conventional Support | Surface of Isoporous Support

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)

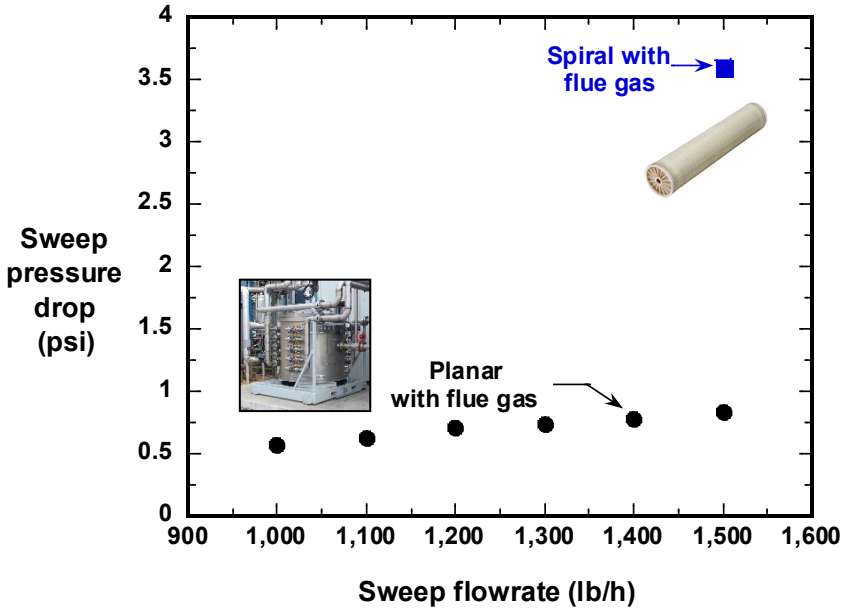
- Phase I – Design 150 TPD pilot; secure host site
- Phase II – FEED and permitting
- Phase III – Fabricate, install and operate (TRL 7 – 8)



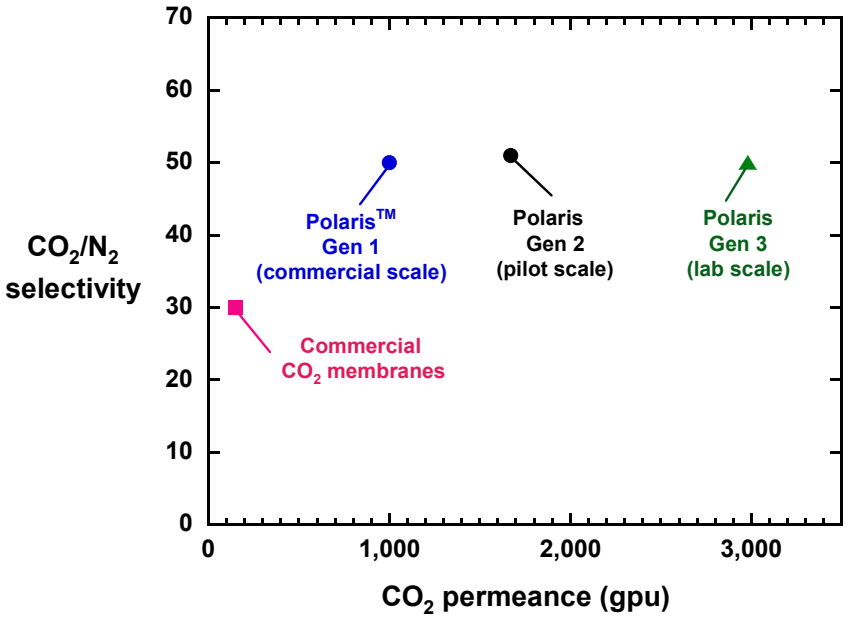
2018 2019 2020 2021 2022 2023 2024 2025

Background: Membrane and Module Improvements

Planar Modules



Polaris™ Membranes



- Moving from Gen 1 to Gen 2 Polaris cuts membrane area by ~50% (~$12/tonne CO_2)
- Lower pressure drop of new modules saves 10 MW_e fan power on 500 MW_e system

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
- Test pilot system (~10 TPD) over range of CO_2 capture rates and feed CO_2 content for TEA input
- Update overall process TEA

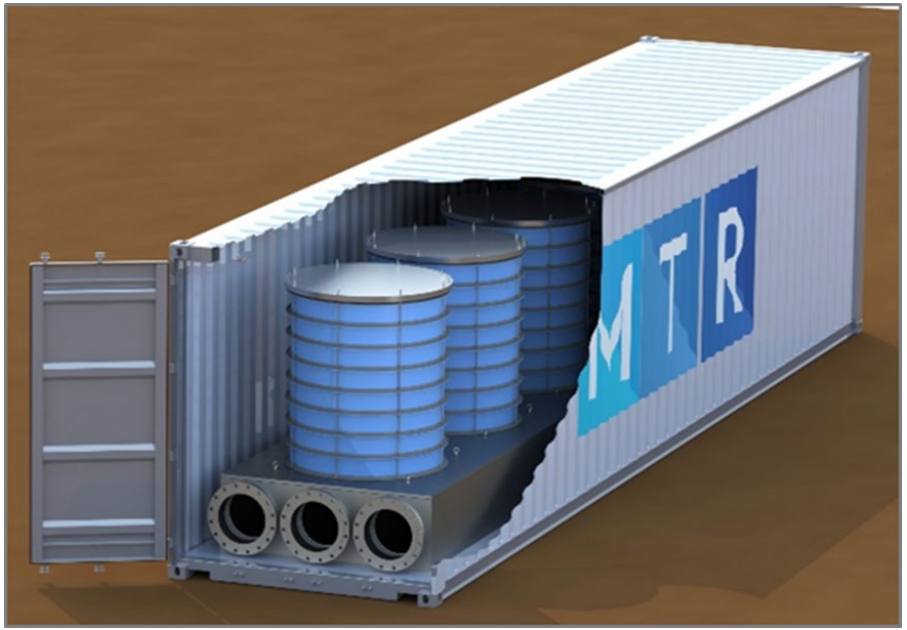
MTR

Primary 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

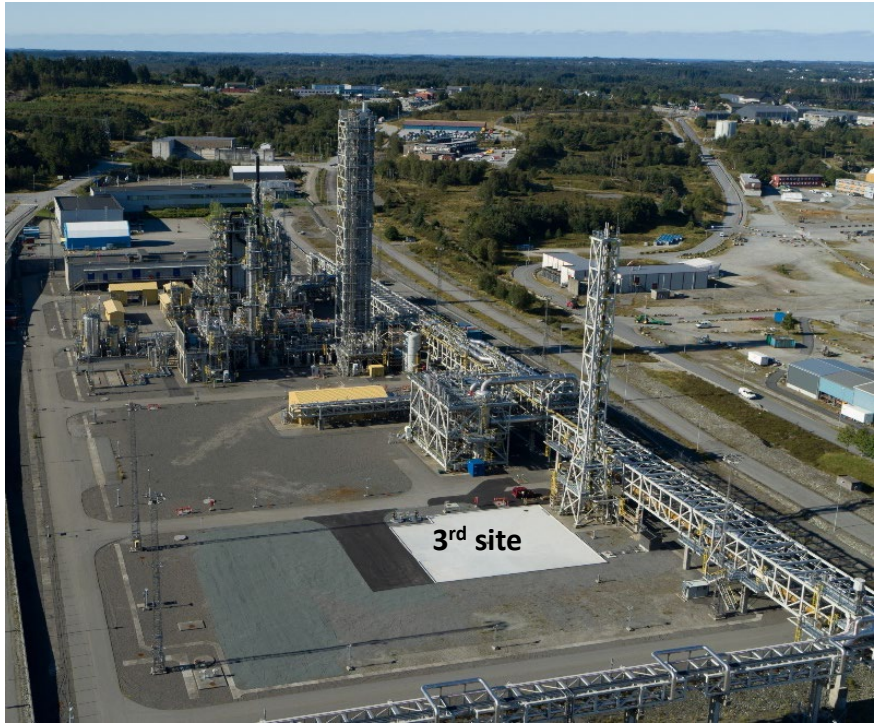
Containerized Module Stacks with Gen-2 Polaris
(2021/22 TCM Field Test)



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

TCM Site Preparations

View of TCM with 3rd site in foreground

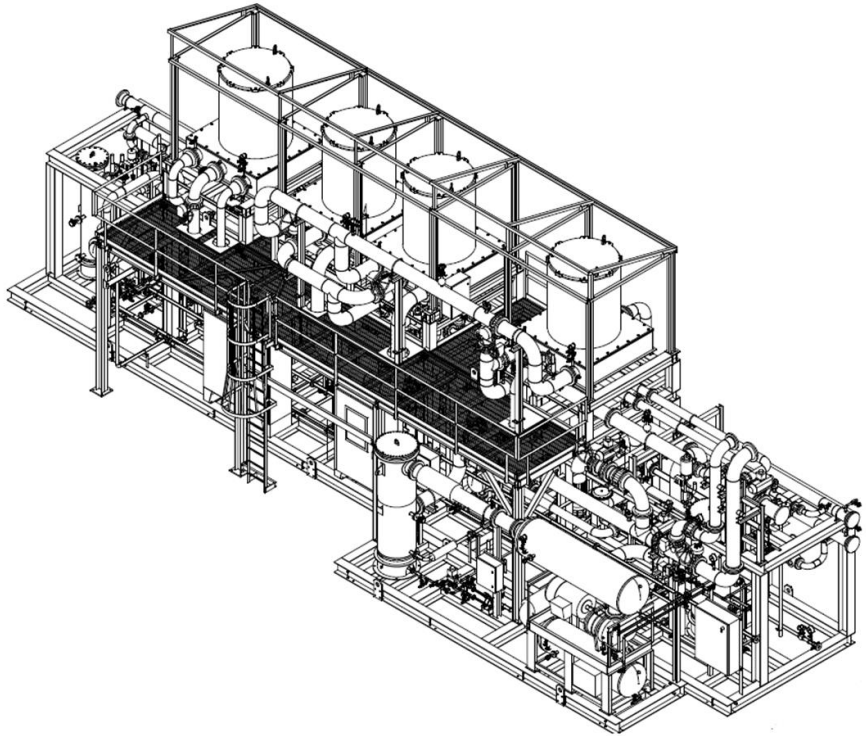


- Technology Centre Mongstad (TCM) is a world-leading site for evaluation of carbon capture technologies
- TCM began development of the “3rd” site for testing of emerging capture technologies in 2019
- TCM assisted MTR with installation of the pilot system at the site in spring/summer 2021, and with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

MTR

MTR System General Arrangement

- Membrane system general arrangement drawings finalized in BP2 (June 2020)
- 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

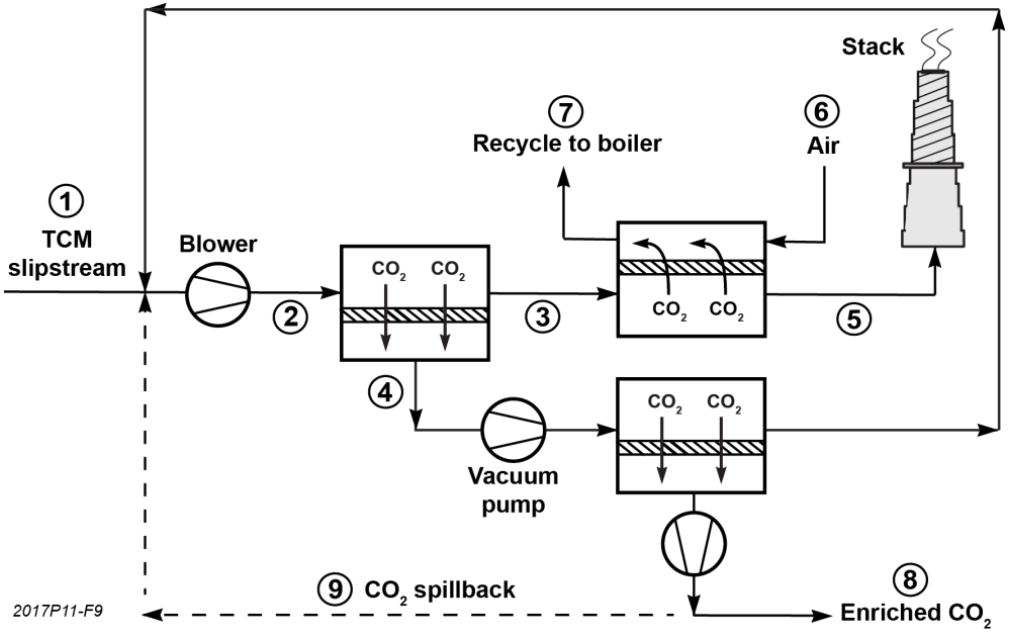


MTR System at TCM

- System has a single membrane container. Future larger systems will have multiples of this unit building block

Test System Design

- 2 stage 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)

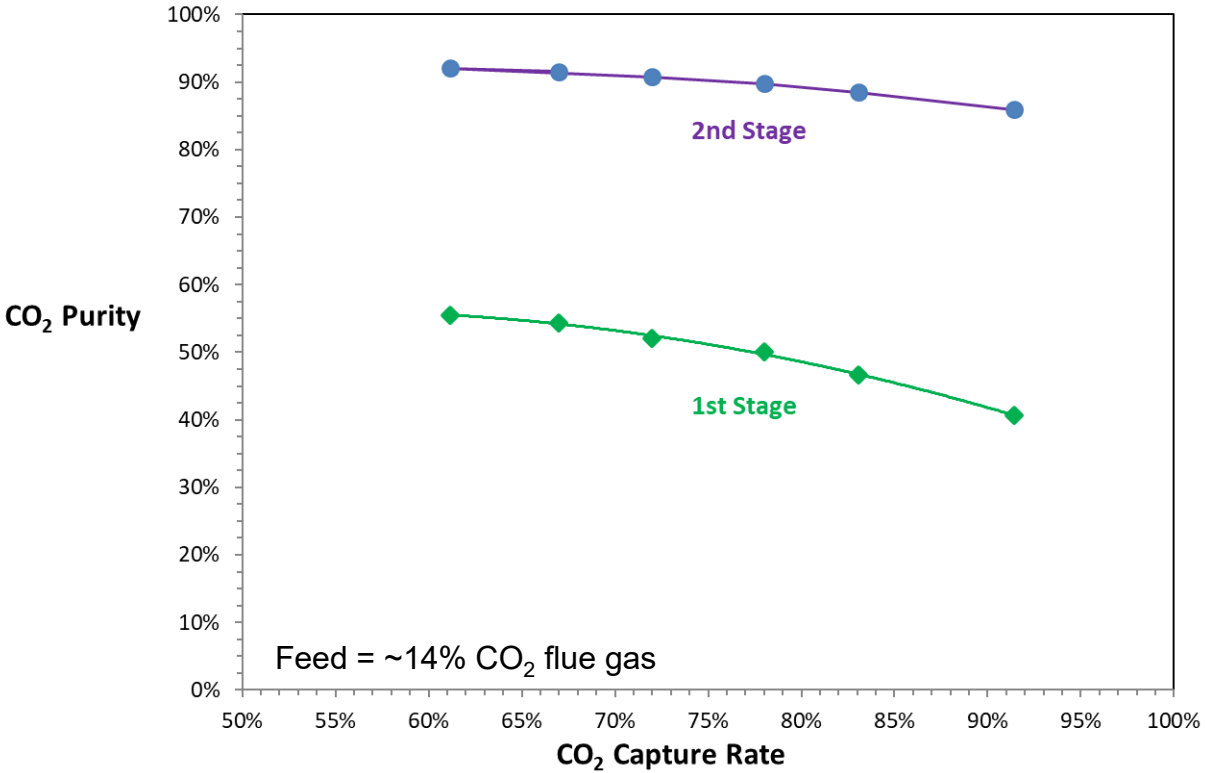


Test Plan for TCM Campaign

- Received input from DOE, TCM and CCSI2 team on test plan
  - Adjustable test parameters included: flue gas flow rate, sweep air flow rate, and CO_2 concentration to 1st stage membrane
  - Used these variables to explore capture rates from 50% to >90% and to evaluate pressure drop in planar modules
  - Two different module configurations with different pressure drop characteristics were examined
  - Metal coupon testing of membrane generated streams also conducted: carbon steel, Ni plated CS, 304 SS, 316 SS, Al 6061, etc

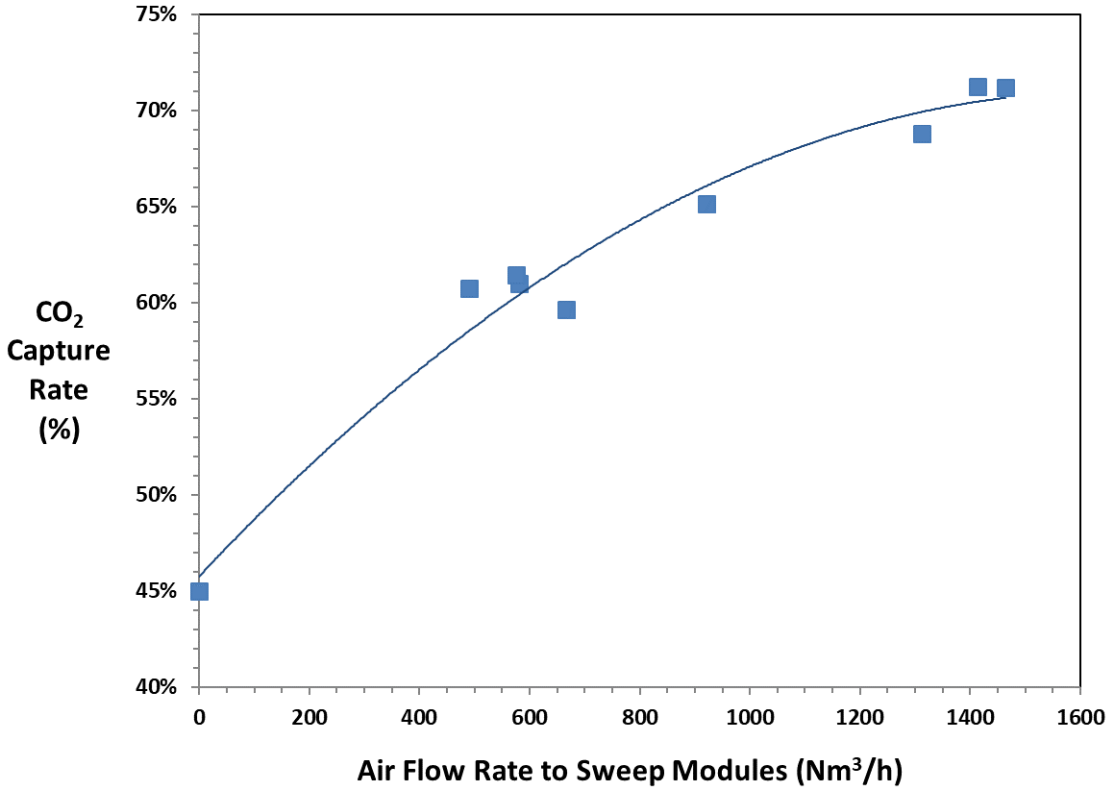
MTR

TCM Test Data: Purity/Recovery



- With ~14% CO_2 feed gas, a single stage membrane produces 40-55% CO_2 and a second stage yields >85% CO_2
- Purity/recovery tradeoff is typical membrane behavior; details are useful for future system design
- In a complete system, the second stage permeate would be sent to the CPU for liquefaction producing >99.9% CO_2 ready for pipelines

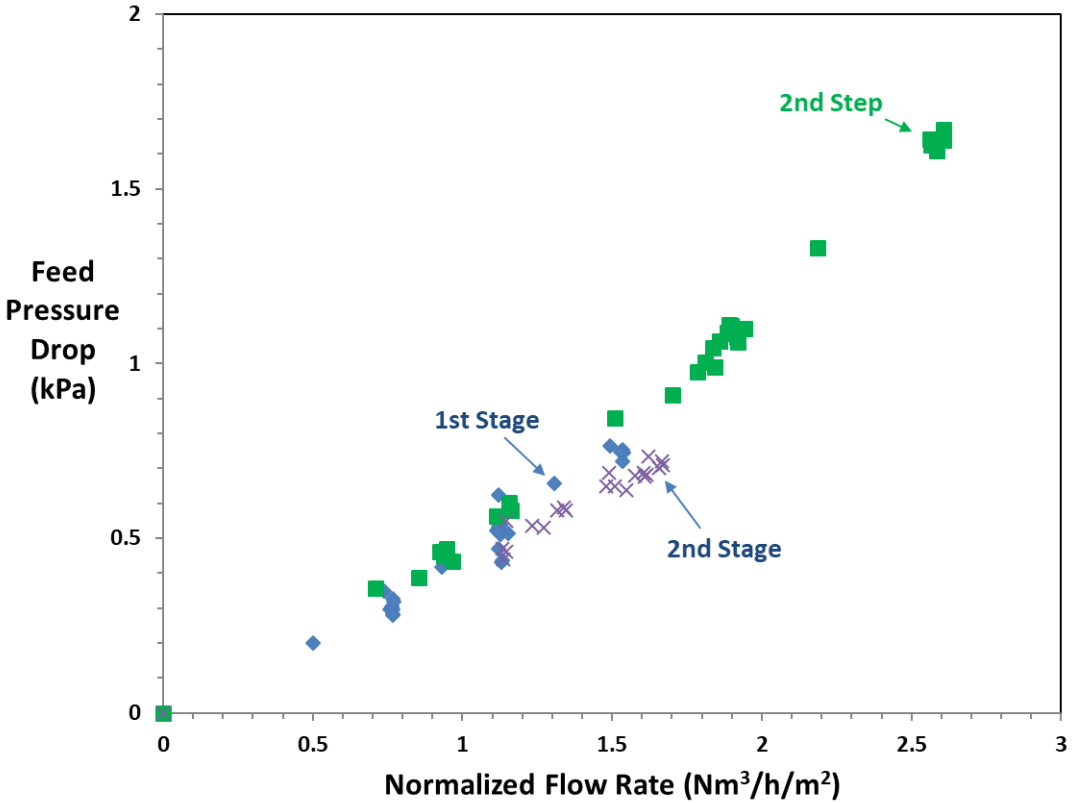
TCM Test Data: Effect of Air Sweep



- Air sweep on a 2nd step membrane module can be used to increase capture rate at 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
- Results are consistent with prior sweep testing at B&W and NCCC

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

TCM Test Data: Pressure Drop



- A key feature of the MTR planar modules 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
- Pressure drop used in TEA is 1.5 psi (10.4 kPa); actual performance is much lower!
- Data for different modules falls on a single trendline indicating good flow distribution

Current Project Status

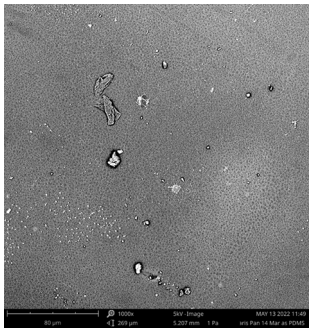
- Testing at TCM finished March 1, 2022
- Decommissioning of the system was completed in June
- The system is now being stored at the port of Bergen awaiting future industrial test opportunities

- Currently, we are working on the project TEA with Trimeric
- This study, as well as the technology gap analysis and the EH&S reports, are on schedule for Sept 30 completion

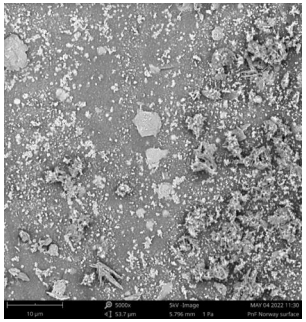
Lessons Learned

- Because of supply chain issues, module housings were aluminum instead of plastic or stainless steel (prior systems)
- After running at TCM, housings showed significant aluminum sulfate corrosion presumably due to water + SO_2 condensate

Fresh Polaris



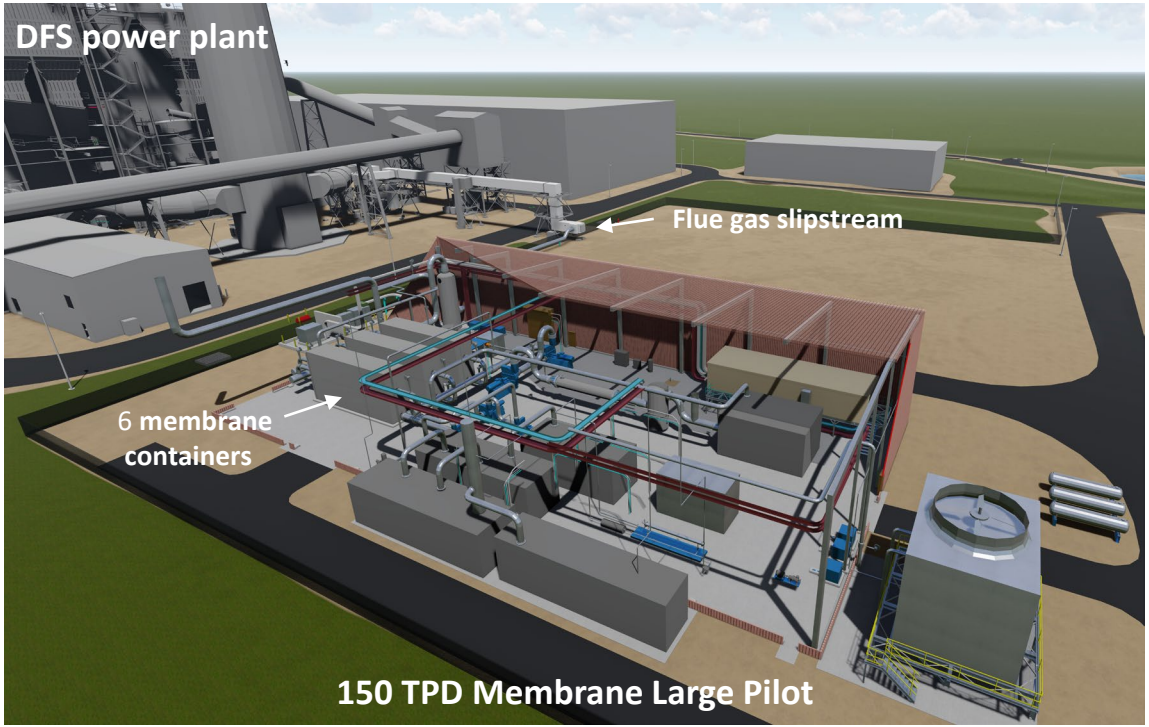
After TCM Testing



- Surface analysis of membranes (SEM/EDS, XPS, ICP-MS) confirmed the presence of aluminum and ammonium (bi)sulfate, which lowered membrane permeance
- Running in parallel at TCM, the TDA/MTR hybrid system with all SS housings showed no membrane fouling;
- Also, a new module installed mid-campaign with fouling-resistant Polaris formulation was unaffected by the corrosion

Next Steps

Conceptual Drawing of MTR Large Pilot at WITC



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

Summary

- A planar module test system was designed, built, installed and operated at the new TCM 3rd site
- ~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
- Lessons learned included need to protect membranes from capture system corrosion; component and membrane material solutions
- Project is nearing completion with TEA and other reports on schedule for Sept 30 end date

Acknowledgements

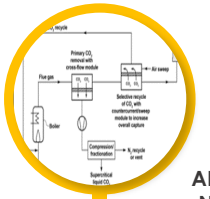
This material is based upon work supported by the Department of Energy under Award Number DE-FE0031591.

Disclaimer

EXTRA SLIDES

Background: Development Timeline

Feasibility Study
(NT43085)
- Sweep concept proposed
- Polaris membrane conceived

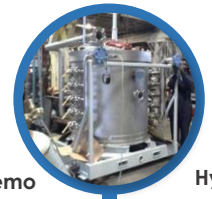


APS Cholla Demo
(NT0005312)
- First Polaris coal flue gas test
- 1TPD CO_2 captured (50 kWe)

APS Red Hawk NGCC Demo
- First Polaris flue gas test
- 250 lb/d CO_2 for algae farm

NCCC 1 MWe Demo
(FE0005795)
- 11,000 hrs of 1 TPD system operation
- 1 MWe (20 TPD) system operation

Low Pressure Mega Module
(FE0007553)
- Design/build low Δp module



Hybrid Capture
(FE0013118)
- Membrane solvent hybrids with UT, Austin

B&W Integrated
(FE0026414)
- Integrated operation of 1 MWe system with B&W's 0.6 MWe coal-fired boiler

Large Pilot & Full Scale FEED
(FE0031587 & FE0031846)
- Design, build, operate 150 TPD Large Pilot capture at WITC
- Full scale study of retrofit to Dry Fork Station

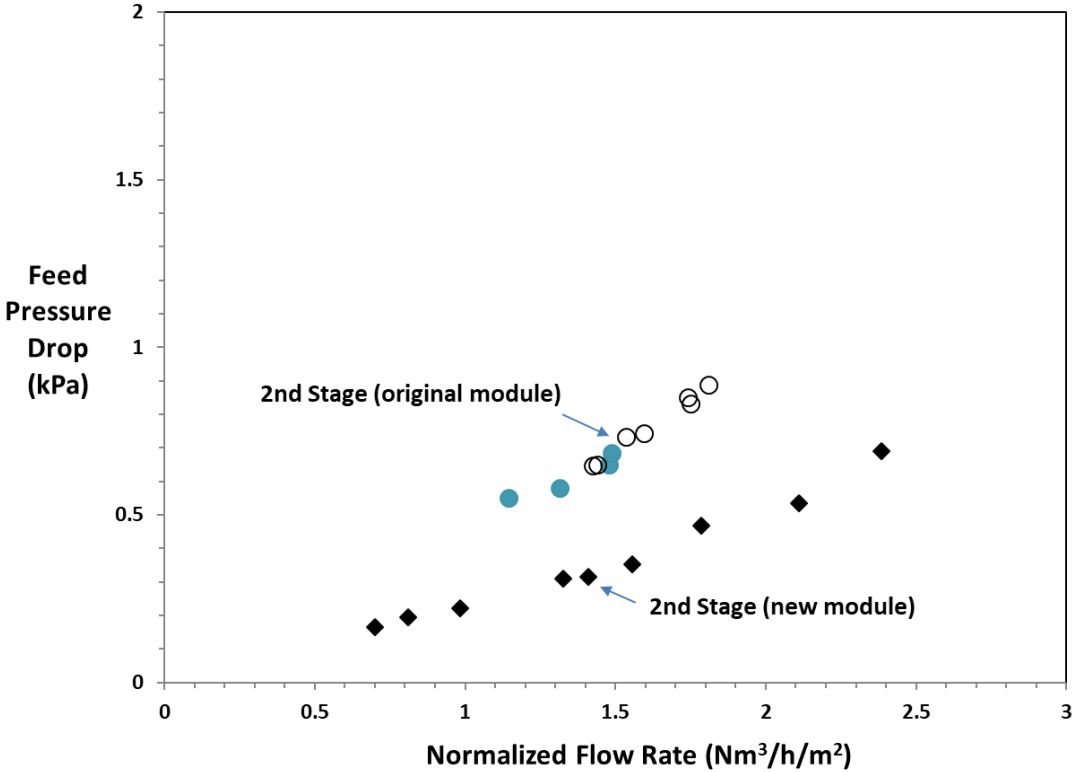
TCM Pilot
(FE0031591)
- Demonstrate Gen2 Polaris in containerized stacks

TRL3 2006 | TRL4 2008 | 2010 | TRL5 2012 | 2014 | TRL6 2016 | 2018 | TRL7 2020 | 2022

Presentation Outline

- Project overview
- Background and objectives
- Progress to date
- Future plans
- Summary

TCM Test Data: Pressure Drop 2



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

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, Sundus Akhter) – host site for the field test; with MTR, will coordinate system installation, operation, and data analysis
- Trimeric (Ray McKaskle) – Responsible for membrane capture process techno-economic analysis (TEA)

Budget Period 3 Milestones

Milestone Number	Task/ Subtask No.	Milestone Description	Planned Completion Date (*)	Verification Method
Phase 3 / Budget Period 3				
11	8.1	Test System Commissioned on Flue Gas	7/31/21	Quarterly Report
12	8.3	Parametric Tests Completed, Long Term Performance Testing Begins	12/31/21	Quarterly Report
13	8.4	Long Term Performance Testing Completed	2/28/22	Quarterly Report
14	10	Complete Techno-Economic Analysis Report	9/30/22	Topical Report
15	11	Complete Technology Gap Analysis Report	9/30/22	Topical Report
16	12	Complete Environmental Health and Safety Risk Assessment Report	9/30/22	Topical Report
17	M1	Submit Final Report	12/31/22	Final Report

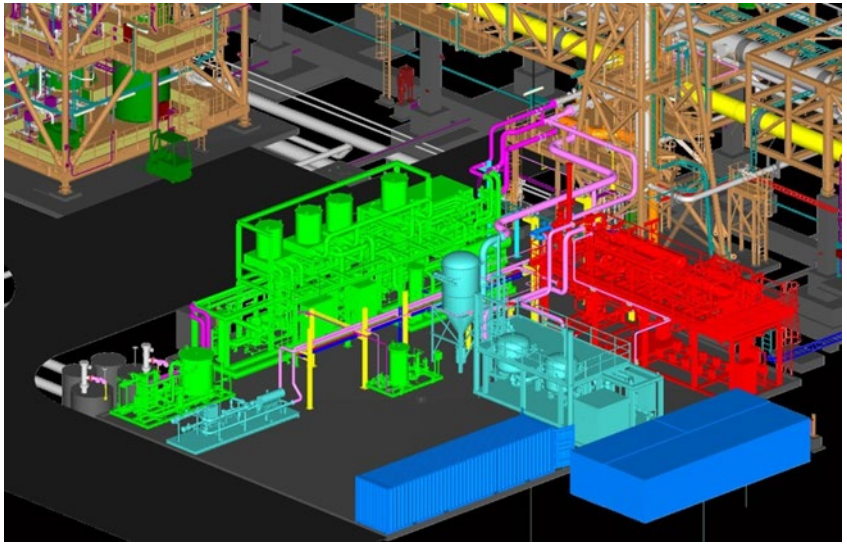
Budget Period 3 Scope of Work

- Main objective of BP3 is operation of the test system; tasks include:
  - Task 8: Operate Membrane Test System
  - Task 9: Decommissioning and Site Clean-Up
  - Task 10: Refine Techno-Economic Analysis
  - Task 11: Technology Gap Analysis
  - Task 12: Environmental Health and Safety Risk Assessment
- BP3 budget: $2,614,694
  - $1,333,694 Federal, $1,281,000 Cost Share

MTR

TCM Site Preparations

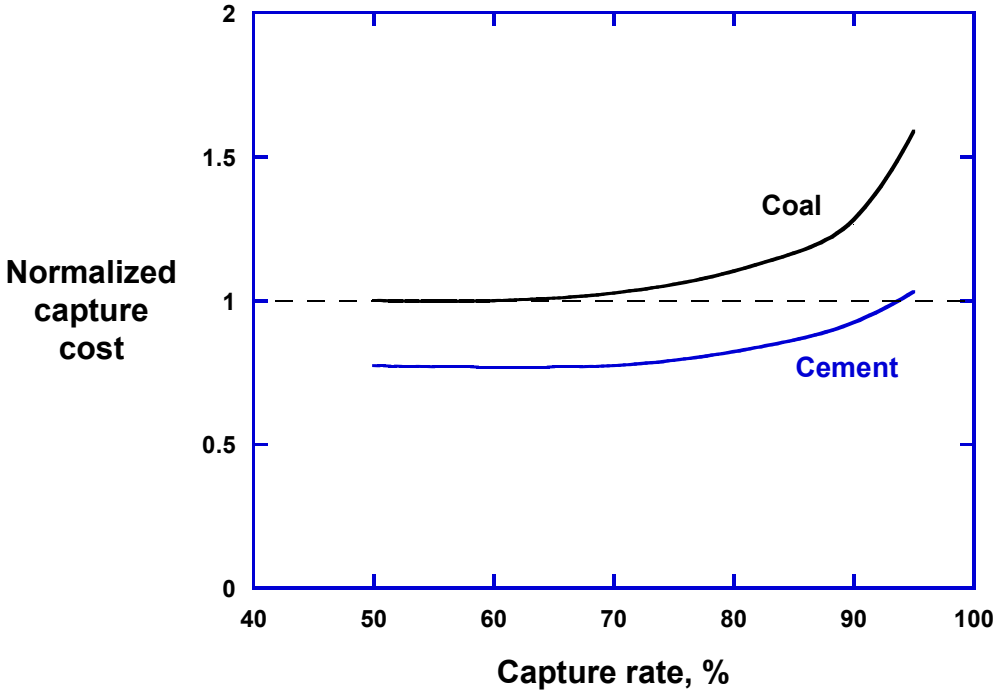
3rd site with MTR and TDA skids



Close up view of 3rd site foundation

- TCM approved development of the “3rd” site for testing of emerging technologies in 2019
- The site was ready for system installation by Fall 2020

Capture Cost vs Rate and CO_2 Content



Capture cost is normalized to 60% capture from coal using today's Polaris membranes

- TEA will quantify the impact of capture rate and CO_2 content on costs
- Membrane costs are sensitive to the feed CO_2 content
- Minimum cost is about 20% lower for cement compared to coal
- Membrane cost is less sensitive to capture rate for higher feed CO_2 content; higher capture is more affordable for cement

Primary 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

Planar Module Stacks with Gen-2 Polaris

(2021 TCM Field Test)

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

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