Bench-Scale Development of a Transformative Membrane Process for Pre-Combustion CO_2 Capture (DE-FE0031632)

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Project Kickoff Meeting
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Presentation Outline

- Project overview
- Technology background
  - Pre-combustion CO_2 capture process with membranes
  - Composite membrane and module development pathway
  - Previous MTR pre-combustion field tests at NCCC
- Project objectives
- Project approach / work plan
- Wrap up

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Project Overview

Award name: Bench-Scale Development of a Transformative Membrane Process for Pre-Combustion CO_2 Capture (DE-FE0031632)

Project period: 10/1/18 to 9/30/21

Funding: $2.0 million DOE; $0.5 million cost share ($2.5 million total)

DOE program manager: Bruce Lani

Participants: MTR, Susteon, Energy & Environmental Research Center (EERC)

Project scope: Optimize Gen-2 Proteus membrane and develop modules capable of operation at 200°C; demonstrate membrane module performance processing coal-derived syngas during field test at EERC; optimize integration of membrane processes into IGCC with carbon capture

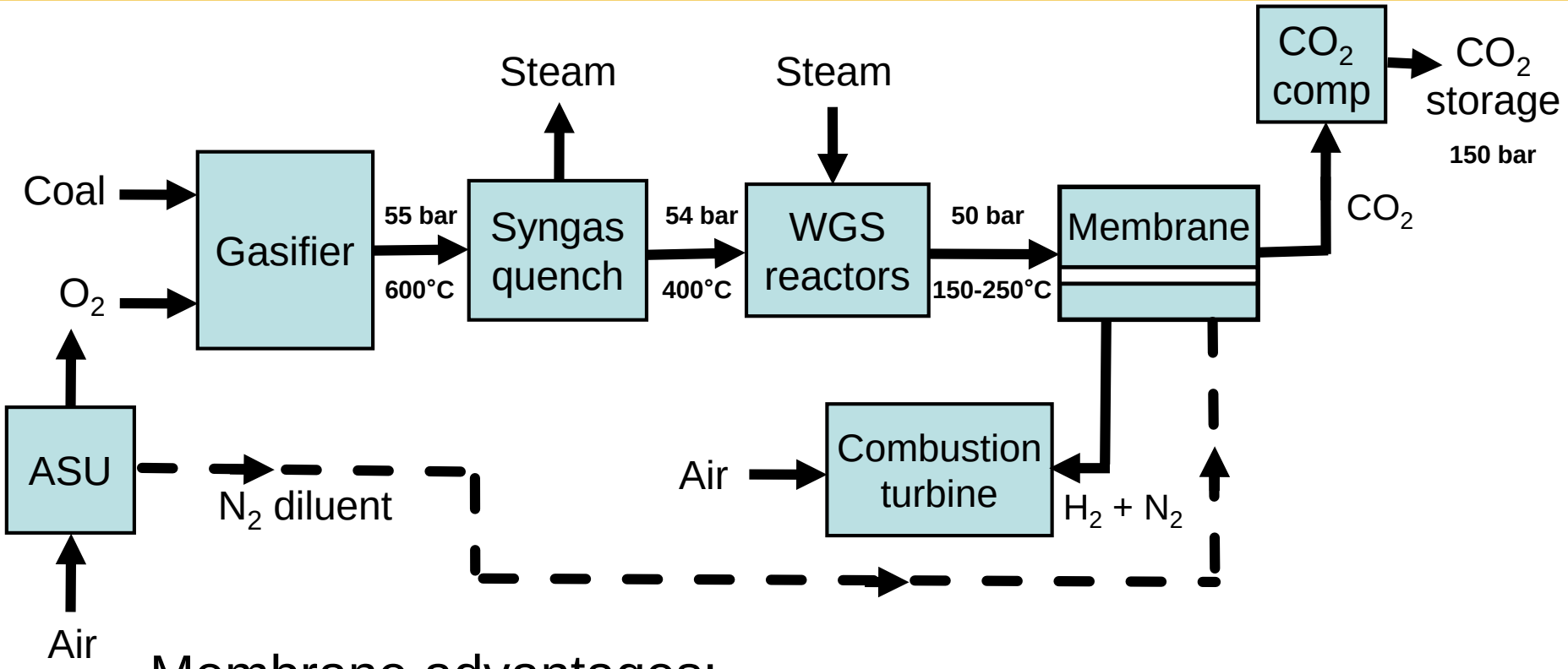
Project plan: The project is organized in three phases:

- **Budget Period 1/Year 1** – Gen-2 Proteus membrane optimized and scaled up, high temperature module components identified
- **Budget Period 2/Year 2** – Gen-2 Proteus modules tested at MTR; fabricate field test skid
- **Budget Period 3/Year 3** – Install skid and conduct field test at EERC, analyze results, update TEA with field test performance and optimized membrane process design

Roles of Participants

- MTR – project lead and liaison with DOE; responsible for membrane and module development; skid design, construction, installation and operation; will lead data analysis and all reporting to DOE
- Susteon – process optimization studies for integration of MTR's membrane capture process in IGCC and assist in TEA
- EERC – host site for field test in Budget Period 3/Year 3 of project; with MTR, will coordinate system installation, operation, decommissioning, and data analysis

Technology Background: Pre-Combustion CO_2 Capture with Membranes



Membrane advantages:

- Can operate warm/hot to reduce the need for heat exchange
- CO_2 is maintained at pressure; less compression compared to standard AGR
- Water goes with fuel gas; reduces CO_2 dehydration costs

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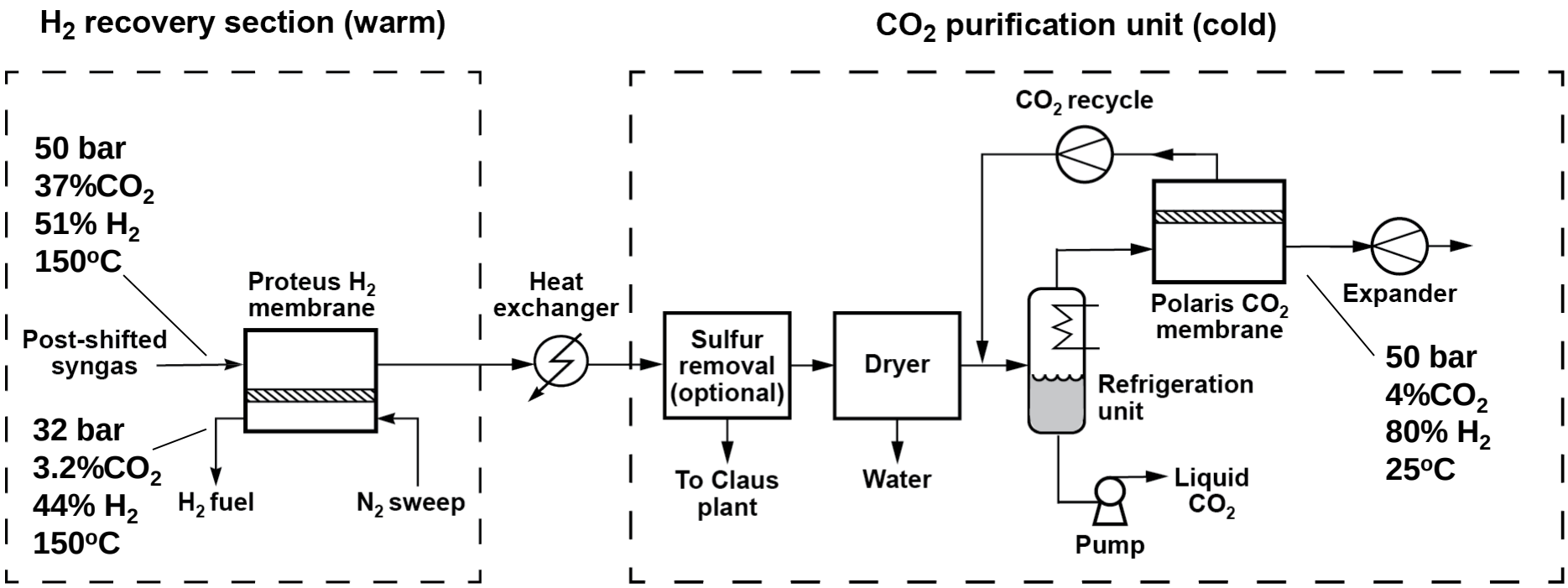
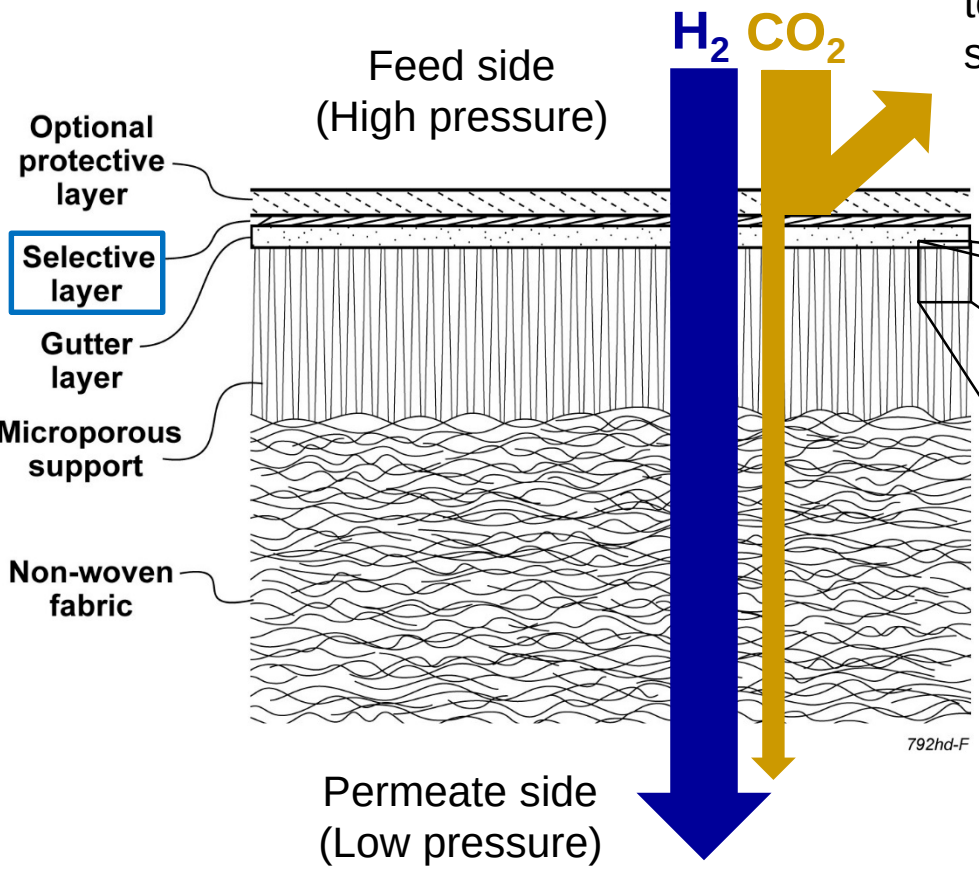
Background: MTR Dual Membrane Process for Pre-Combustion Capture

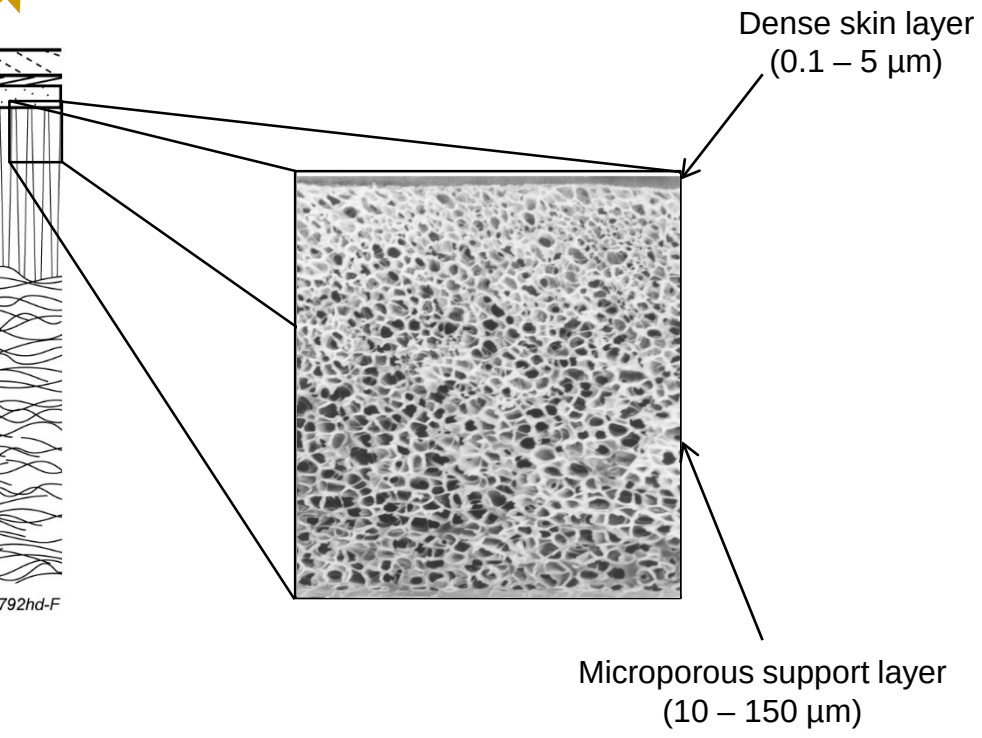


- Collaborated with Jim Black at DOE NETL and Peter Kabatek at WorleyParsons to analyze MTR process
- Compared to GE Gasifier with 2-stage Selexol (Case 2 of DOE Bituminous Baselines Study), MTR process shows 27 MW_e net power improvement and 7.4% lower COE with Gen-1 Proteus membrane properties
- Both warm (H_2 membrane) and cold (CO_2 membrane) portions of process tested at NCCC

Background: Proteus Multi-Layer Composite Structure

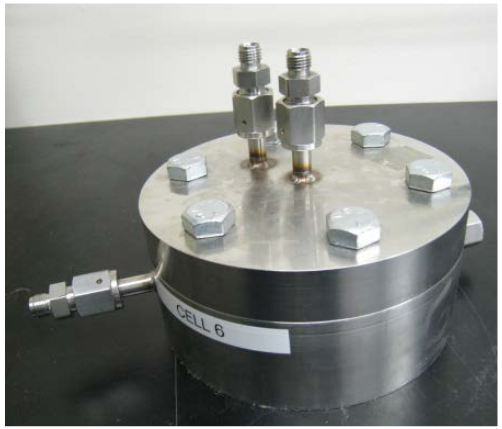
Very thin selective layers (100-500 nm) needed to obtain high flux required for industrial separations



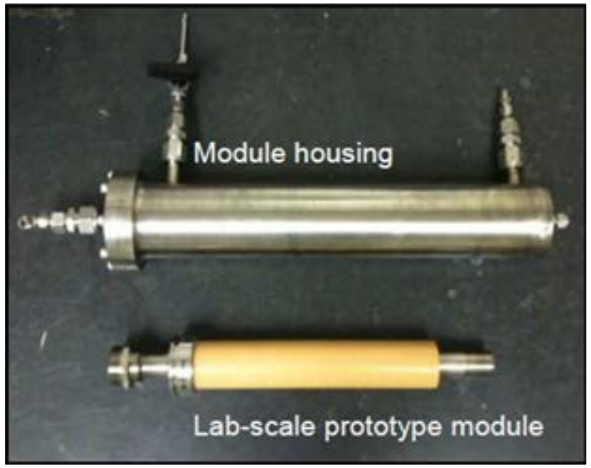


Background:
Stages of Membrane Development

1) <u>Membrane Stamps</u>
Area: 0.0030 m^2
Flow: 1 lb/h



2) <u>Lab-scale Module</u>
Area: 0.130 m^2
Flow: 10 lb/h



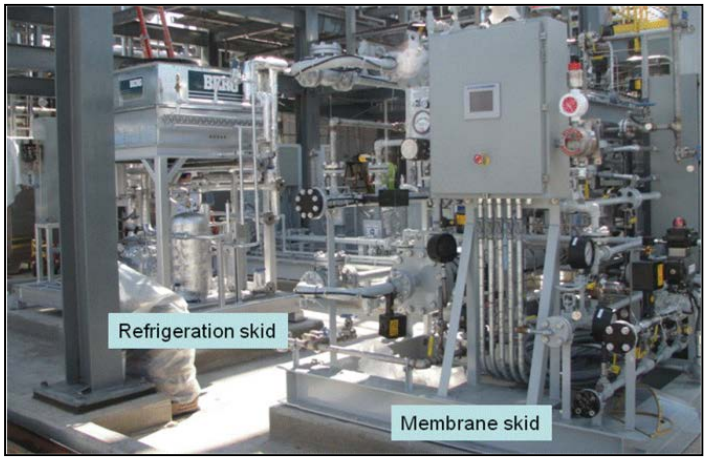
3) <u>Semi-commercial Module</u>
Area: 1 - 4 m^2
Flow: Bench-scale (50 lb/h)

4) <u>Commercial Module</u>
Area: 20 – 50 m^2
Flow: Field Demonstration (500 lb/h)

Background:
MTR/DOE Pre-Combustion Testing at NCCC

Bench-scale module test skid

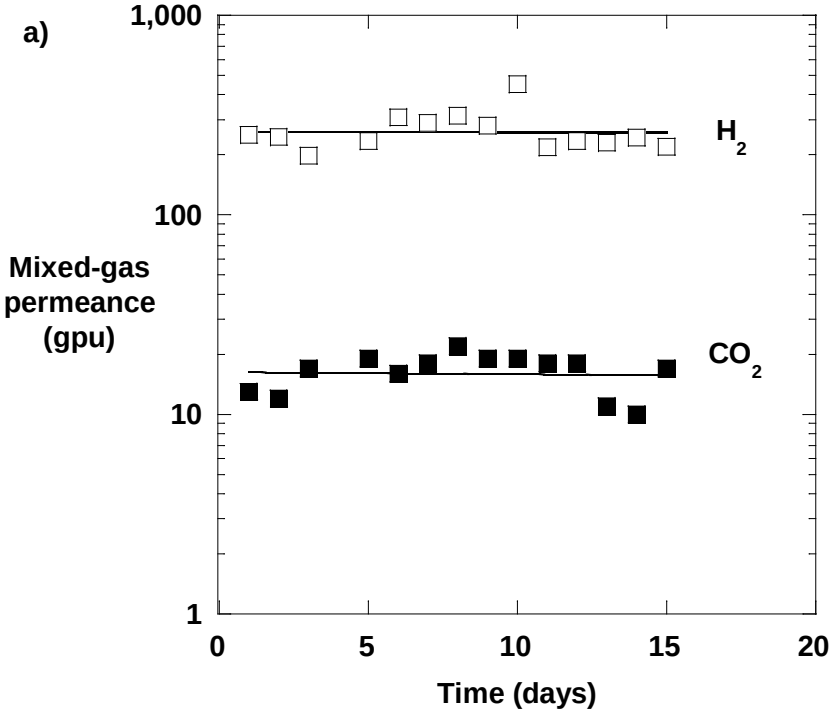
Pilot-scale liquid CO_2 skid



- Pre-Combustion field tests at NCCC supported by DOE funding
  - DE-FE0001124 (9/15/09 to 9/14/11)
  - DE-FE0006138 (10/1/10 to 6/30/13)
- Polaris CO_2-selective membrane (Cold Section)
  - Semi-commercial modules (2009 – 2013): 4,400 hours
  - Commercial modules (2012 – 2013): 800 hours
- Gen-1 Proteus H_2-selective membrane (Warm Section)
  - Membrane stamps and lab-scale modules (2009 – 2016): 5,500 hours
  - Semi-commercial modules (2013 – 2017): 3,625 hours
- Over 14,000 cumulative hours of testing at NCCC

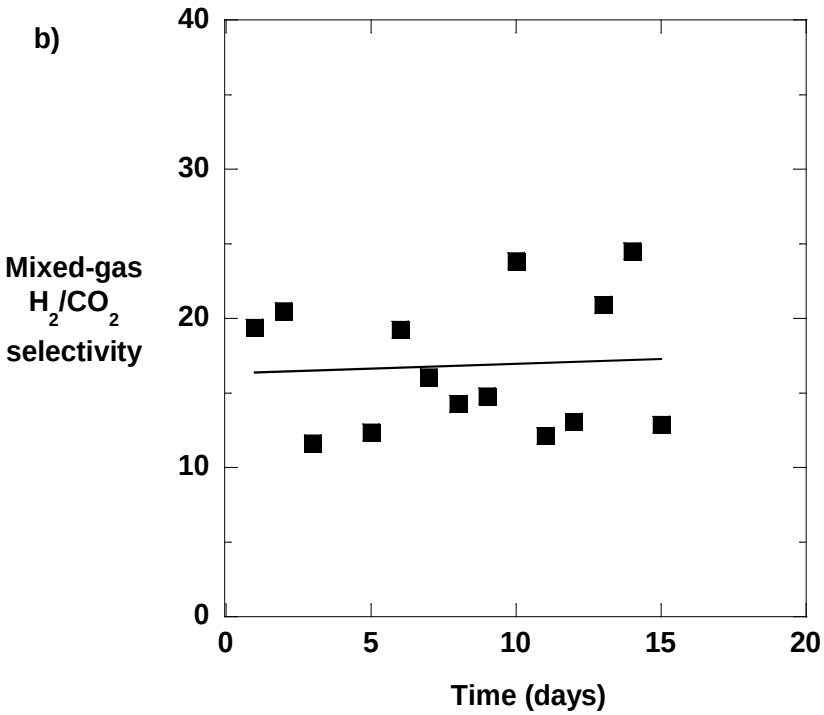
Background: Gen-1 Proteus Stamp Data NCCC Data at 135°C

Membrane Stamp Permeance



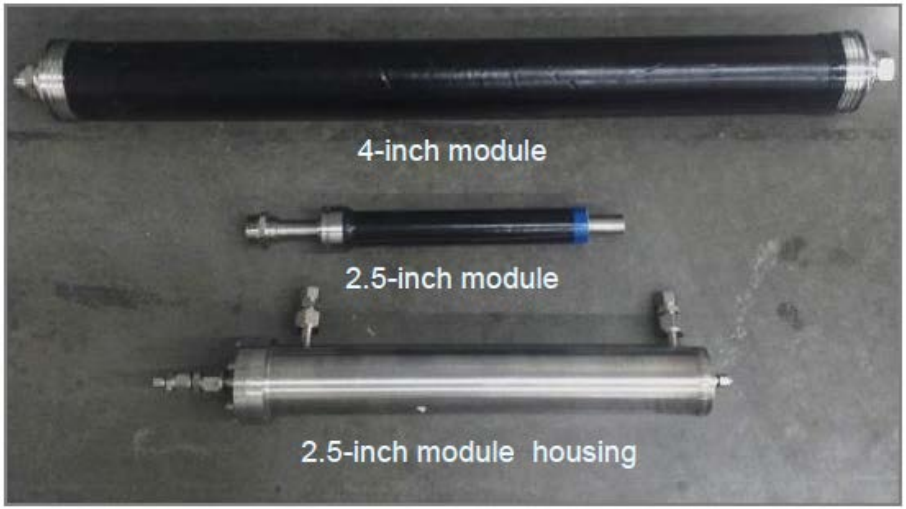
- Gen-1 Proteus temperature limit: 150°C
- Average H_2 permeance: 230 gpu
- Average H_2/CO_2: 15

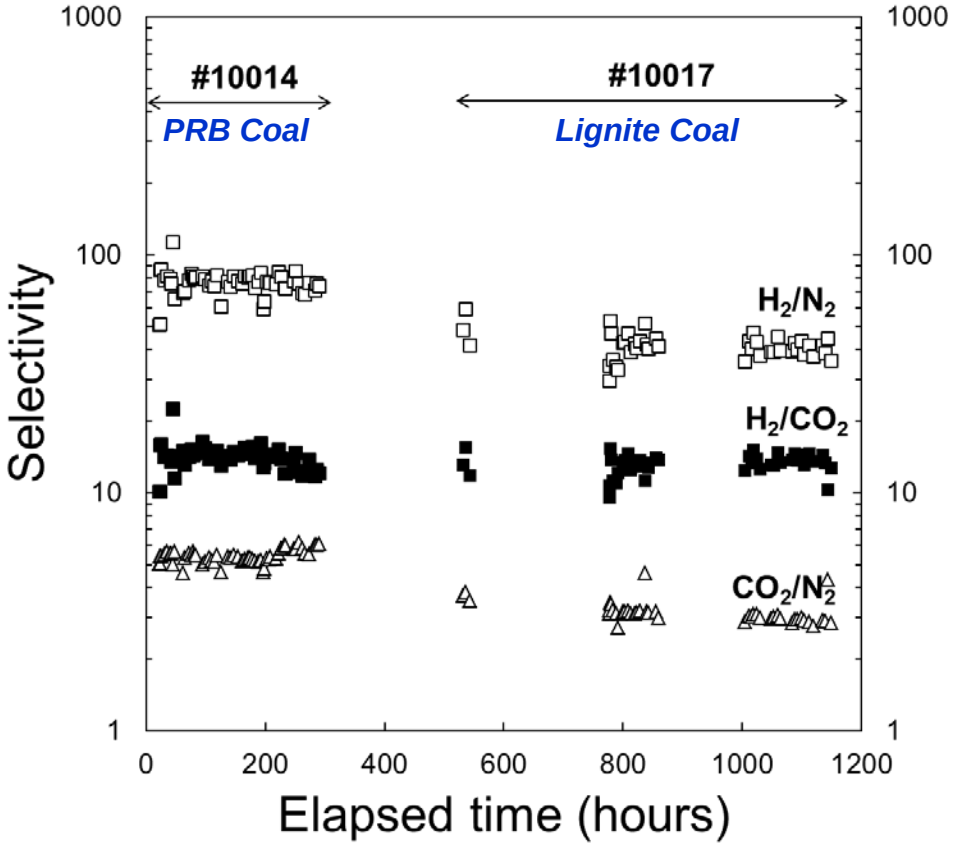
Membrane Stamp Selectivity



Background: Recent Gen-1 Proteus Semi-Commercial Module Results from NCCC

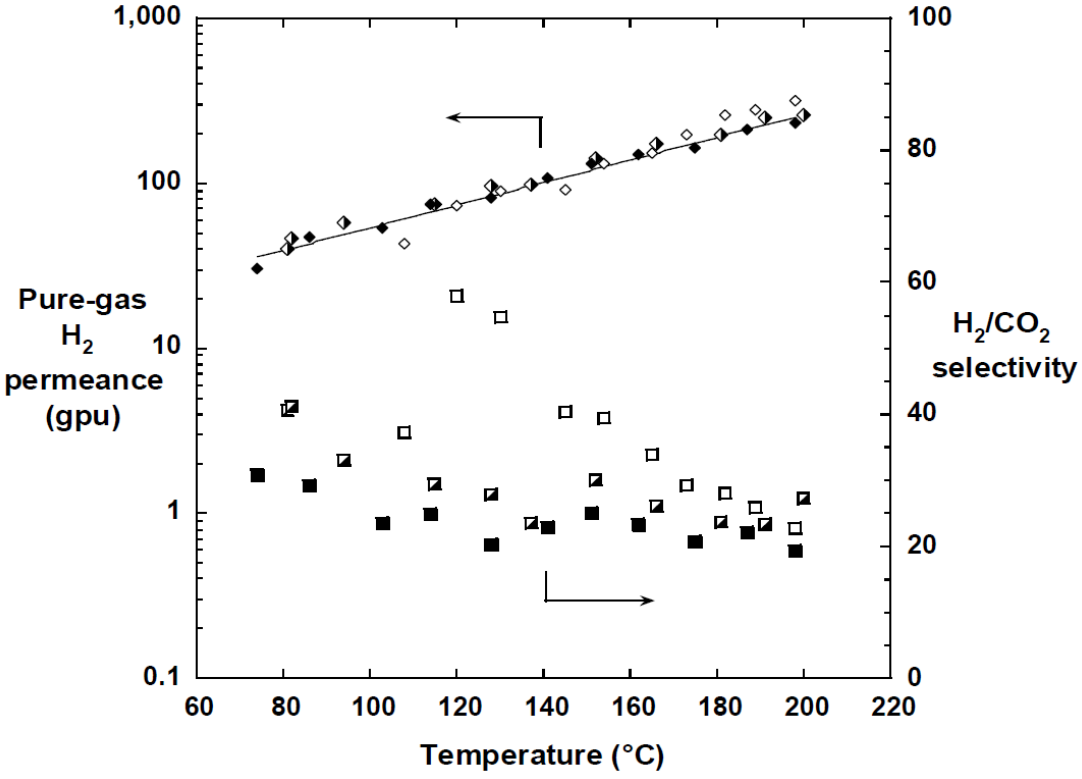
- Average H_2/CO_2: 15
- Iterative refinements in module design and components led to improved performance
- Gen-1 Proteus modules also used in industrial pilot systems for:
  - H_2 recovery in bio-waste to ethanol process
  - Syngas ratio adjustment in gas to liquids process





Gen-2 Proteus Membrane Stamp MTR Lab Data

Membrane Stamp Pure-Gas Temperature Cycling



- H_2 permeance and H_2/CO_2 selectivity measured at 50 psig
- Three temperature cycles up to 200°C
- Membrane stamp stable at all temperatures
- H_2 permeance increases with temperature, up to ~300 gpu
- No H_2 permeance hysteresis, no membrane damage
- H_2/CO_2 selectivity averages ~30

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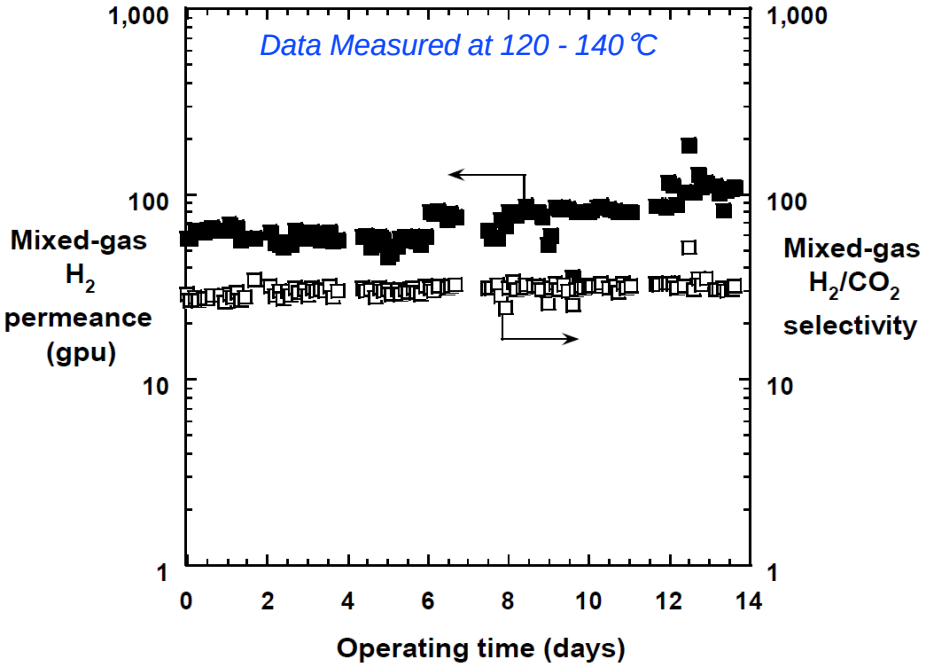
Preliminary Gen-2 Proteus Stamp Data from NCCC

Field Test Conditions at NCCC

- Shifted syngas: ~13% H_2, 13% CO_2, 70% N_2, 2.5% CO, 1.5% CH_4
- Feed: 300 – 800 ppmv H_2S, 165-180 psig, 120 - 140°C
- 50 lb/h syngas to main MTR skid, 1 lb/hr slipstream to stamp cell



NCCC Field Test Stamp Results

- Membrane stamps were stable up to 200°C
- H_2/CH_4, H_2/N_2, H_2/CO selectivities were all > 100
- H_2/H_2S selectivity > 50
- Average H_2/CO_2 selectivity = 32
- Findings consistent with lab results

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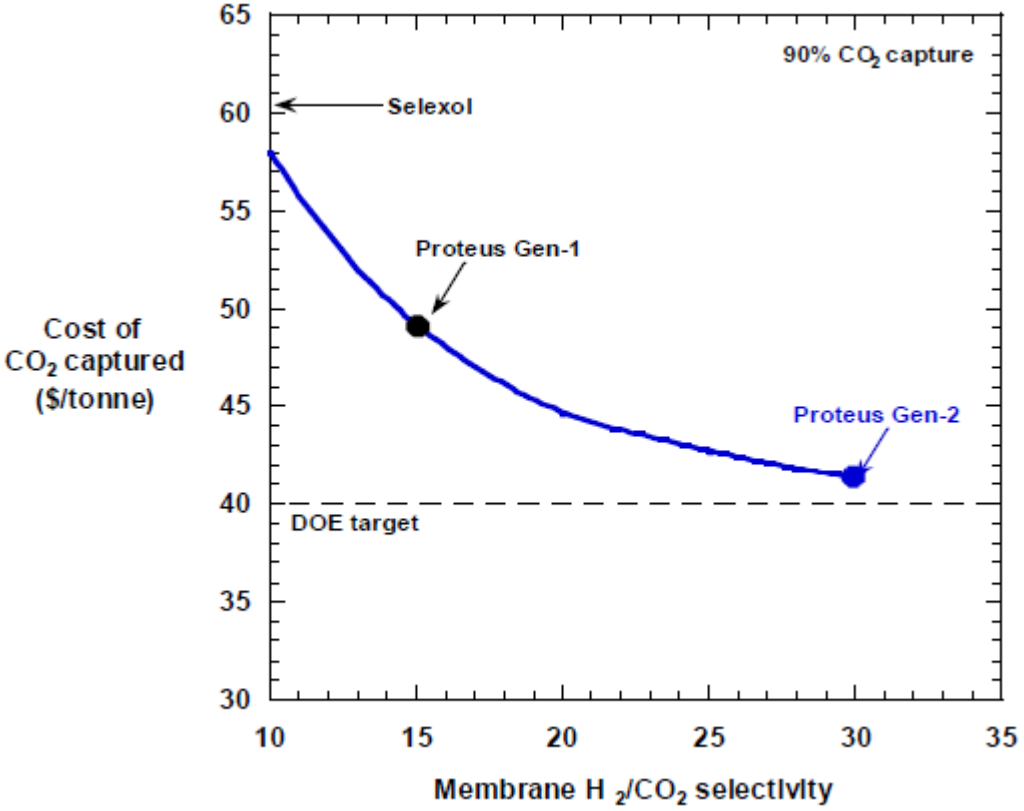
MTR Dual Membrane Process Preliminary Cost and Sensitivity Study



- Methodology from DOE Bituminous Baselines Study with updated costs used
- Improvements in H_2 permeance or selectivity would further reduce costs
- Potential for lower capture costs with alternative process designs to be investigated in this project

Assumptions Used in the Membrane Process Cost Analysis

System Parameter	Value
Process contingencies^	20%
Project contingencies	20%
Installation cost multiplier: all equipment	1.6
Membrane skid cost	$300/m^2
Compression equipment cost	$500/kW
Refrigeration equipment cost	$500/kW

Project Objectives

- Optimize and scale-up Gen-2 Proteus membrane
- Develop high temperature Gen-2 Proteus membrane modules for use in coal gasification environments
- Design, fabricate, and operate bench-scale membrane module skid at a EERC field test with coal-derived syngas
- Move the Gen-2 Proteus membrane pre-combustion capture technology from TRL 4 to TRL 5
- With project partner Susteon, evaluate sulfur treatment options and optimize alternative membrane process designs for integration into an IGCC plant
- Update TEA incorporating field test performance data and optimized membrane process design for pre-combustion CO_2 capture

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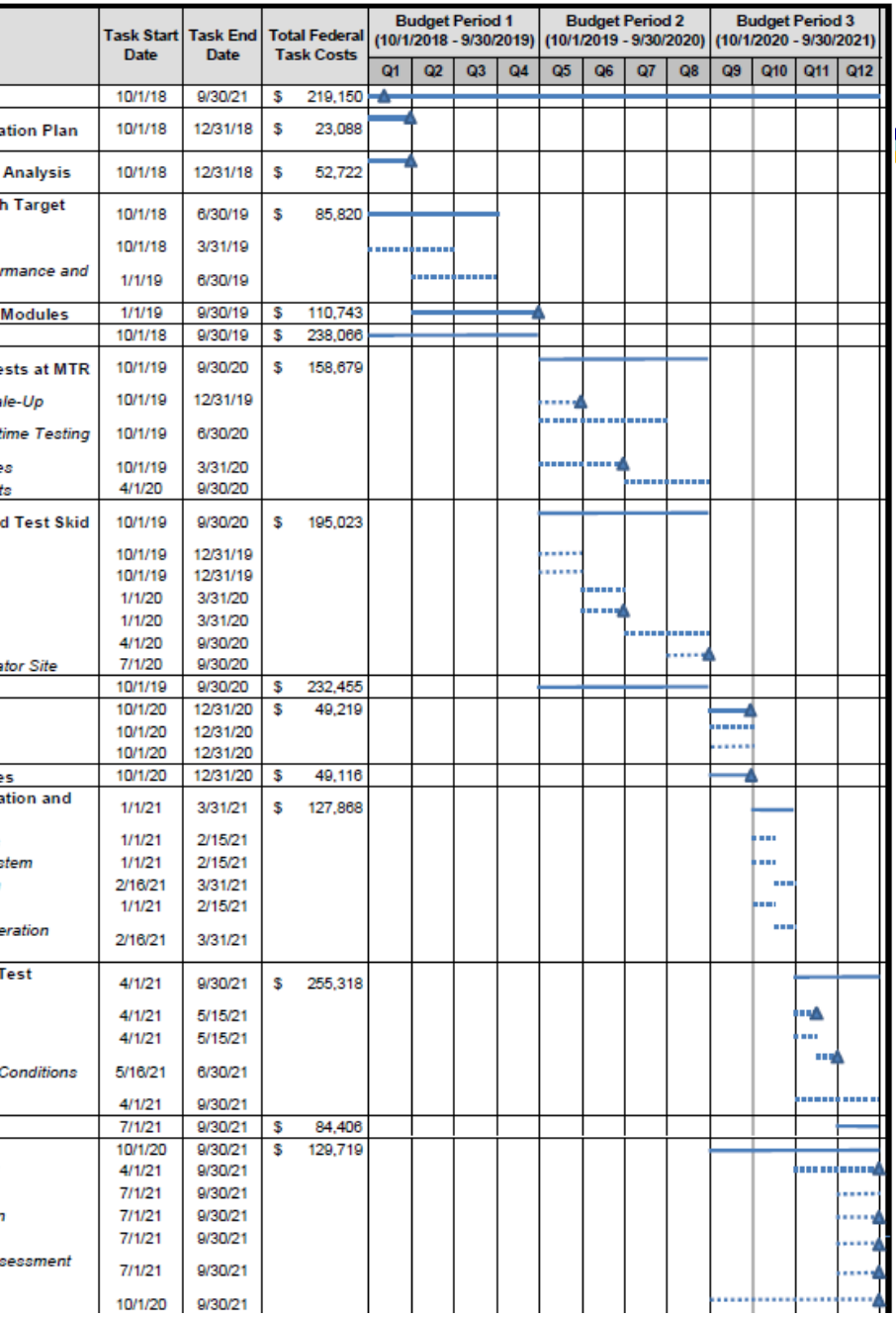
Project Gantt Chart

Task	Project Tasks	Task Start Date	Task End Date	Total Federal Task Costs
M1	Project Management and Planning	10/1/18	9/30/21	$ 219,150
1	Prepare Preliminary Technology Maturation Plan	10/1/18	12/31/18	$ 23,088
2	Prepare Preliminary Techno-Economic Analysis	10/1/18	12/31/18	$ 52,722
3	Prepare Gen-2 Proeteus Membrane with Target Performance	10/1/18	6/30/19	$ 85,820
3.1	*Optimize Gen-2 Proteus Membrane*	10/1/18	3/31/19	
3.2	*Evalaute Gen-2 Proteus Membrane Performance and Lifetime*	1/1/19	6/30/19	
4	Fabricate Prototype High Temperature Modules	1/1/19	9/30/19	$ 110,743
5	Evaluate Alternative Process Designs	10/1/18	9/30/19	$ 238,066
6	Prototype High Temperature Module Tests at MTR	10/1/19	9/30/20	$ 158,679
6.1	*Gen-2 Proteus Membrane Production Scale-Up*	10/1/19	12/31/19	
6.2	*Continued Gen-2 Proteus Membrane Lifetime Testing*	10/1/19	6/30/20	
6.3	*Prepare Lab-Scale Gen-2 Proteus Modules*	10/1/19	3/31/20	
6.4	*High Temperature Lab-Scale Module Tests*	4/1/20	9/30/20	
7	Design and Fabricate Bench-Scale Field Test Skid	10/1/19	9/30/20	$ 195,023
7.1	*Prepare Preliminary Design*	10/1/19	12/31/19	
7.2	*Review EERC Site Specifications*	10/1/19	12/31/19	
7.3	*HAZOP review and Finalize Design*	1/1/20	3/31/20	
7.4	*Select Vendors and Fabricator*	1/1/20	3/31/20	
7.5	*Fabricate Skid*	4/1/20	9/30/20	
7.6	*Factory Acceptance Test (FAT) at Fabricator Site*	7/1/20	9/30/20	
8	Optimize Process Designs	10/1/19	9/30/20	$ 232,455
9	Host Site Preparations	10/1/20	12/31/20	$ 49,219
9.1	*Prepare EERC Host Site*	10/1/20	12/31/20	
9.2	*Ship Bench-Scale Test System to EERC*	10/1/20	12/31/20	
10	Prepare Bench-Scale Field Test Modules	10/1/20	12/31/20	$ 49,116
11	Bench Scale Membrane System Installation and Shakedown	1/1/21	3/31/21	$ 127,868
11.1	*Tie-In All Utility and Process Connections*	1/1/21	2/15/21	
11.2	*Install Gen-2 Proteus Modules in Test System*	1/1/21	2/15/21	
11.3	*Installation of Heat Tracing and Insulation*	2/16/21	3/31/21	
11.4	*Develop A Preliminary Test Plan*	1/1/21	2/15/21	
11.5	*Job Site Safety Practices Review and Operation Training*	2/16/21	3/31/21	
12	Operate Bench-Scale Membrane Field Test System	4/1/21	9/30/21	$ 255,318
12.1	*System Commissioning*	4/1/21	5/15/21	
12.2	*Finalize Test Plan*	4/1/21	5/15/21	
12.3	*Operation of Test System Under Syngas Conditions*	5/16/21	6/30/21	
12.4	*Analyze System Performance*	4/1/21	9/30/21	
13	Decommissioning Activities	7/1/21	9/30/21	$ 84,406
14	Prepare Project Reports	10/1/20	9/30/21	$ 129,719
14.1	*Prepare Final Techno-economic Analsysi*	4/1/21	9/30/21	
14.2	*Final State Point Data Table Updated*	7/1/21	9/30/21	
14.3	*Prepare Final Technology Maturation Plan*	7/1/21	9/30/21	
14.4	*Technology Gap Analysis Completed*	7/1/21	9/30/21	
14.5	*Environmental Health and Safety Risk Assessment Completed*	7/1/21	9/30/21	
14.6	*Final Report Prepared*	10/1/20	9/30/21	



Key Task 1: Gen-2 Proteus Development

- Membrane
  - Optimize selective layer and other composite membrane components on small scale
  - Tune coating parameters on R&D roll-to-roll fabrication equipment
  - Produce membrane on existing MTR commercial roll-to-roll equipment
  - Verify membrane performance at all scales with pure gas and simulated gas mixtures under syngas conditions
- Membrane module
  - Screen component candidates with exposure tests
  - Down select components and prepare dummy modules
  - Pressure and temperature cycle tests with dummy modules
  - Prepare modules with different configurations and test performance under mixed-gas conditions

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Key Task 2: Membrane Process Integration into IGCC

- Optimize membrane integration
  - Within syngas clean-up train with emphasis on sulfur and CO_2 separation
  - Within overall IGCC or chemical plant
- Optimization will use performance and cost metrics to achieve DOE CO_2 capture performance goals
- Results from optimization will be used for field test planning and development and preparation of final TEA

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Key Task 3: EERC Field Test

- MTR to design skid and oversee fabrication
  - EERC to provide input based on site specifications and participate in HAZOP
  - Skid will have local control of pressure (feed and permeate), temperature, and flow
- MTR along with DOE, Susteon, and EERC will develop a test plan
  - Parametric testing to develop purity vs. recovery performance window
- MTR will assist EERC in installation, pre-commissioning, test operation, and decommissioning activities
- Susteon will assist in analysis of results
  - Final TEA will be based on filed test performance and data

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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.	Budget Period 1				$582,671	$145,668	$728,339
2.	Budget Period 2				$658,612	$164,653	$823,265
3.	Budget Period 3				$758,717	$203,920	$962,637
4.							
5.	Totals				$2,000,000	$514,241	$2,514,241

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	$171,626	$167,081	$183,827		$522,534
	b. Fringe Benefits	$0	$0	$0		$0
	c. Travel	$6,696	$6,945	$19,766		$33,407
	d. Equipment	$0	$75,000	$0		$75,000
	e. Supplies	$12,000	$12,000	$5,000		$29,000
	f. Contractual	$194,766	$228,077	$381,390		$804,233
	g. Construction	$0	$0	$0		$0
	h. Other	$0	$0	$5,000		$5,000
	i. Total Direct Charges (sum of 6a-6h)	$385,088	$489,103	$594,983		$1,469,174
	j. Indirect Charges	$343,251	$334,162	$367,654		$1,045,067
	k. Totals (sum of 6i-6j)	$728,339	$823,265	$962,637		$2,514,241
7.	Program Income					$0

Key Project Milestones

Milestone Number and Task	Milestone Title	Planned Completion Date	Actual Completion Date	Variance Comment	Verification Method (if complete; e.g., summary report, quarterly progress report)
Budget Period 1 / Year 1					
4 (Task 4)	Components for High-Temp Modules Identified	9/30/19	TBD	N/A	Quarterly Progress Report
Budget Period 2 / Year 2					
6 (Task 6.3)	Lab-scale Gen-2 Proteus Modules Prepared	3/31/20	TBD	N/A	Quarterly Progress Report
7 (Task 7.3)	Finalize Bench-Scale Test System Design	3/31/20	TBD	N/A	Quarterly Progress Report
8 (Task 7.6)	Bench-Scale Test System Passes FAT at Fabricator Site	9/30/20	TBD	N/A	Quarterly Progress Report
Budget Period 3 / Year 3					
12 (Task 12.3)	Baseline and Parametric Performance Tests Completed at EERC	6/30/21	TBD	N/A	Quarterly Progress Report
13 (Task 14.1)	Complete Final Techno-Economic Analysis Report	9/30/21	TBD	N/A	Topical Report to be included in the Final Report

Project Success Criteria

- Budget Period 1 (Year 1)
  - Complete preliminary TEA showing potential to reduce the cost of capture by more than 30% compared to Selexol
  - Scale-up production of Gen-2 Proteus to meet project needs. Membrane will have average H_2/CO_2 = 30, within 10%
  - 200°C module components identified
- Budget Period 2 (Year 2)
  - Prototype Gen-2 Proteus modules made, pass QC tests (H_2/CO_2 within 10% of membrane roll), and are tested under simulated syngas conditions
  - Field test skid passes FAT at fabricator and ready to ship to EERC
  - Membrane integration optimization design completed
- Budget Period 3 (Year 3)
  - Parametric and steady state field test operations completed at EERC. System performance is consistent with modeling predictions and modules show no signs of performance degradation under syngas conditions
  - Updated TEA is completed confirming the potential of the MTR process to reduce the cost of capture by more than 30% compared to Selexol
  - Complete a technology gap analysis to determine components or systems that should be the focus of future development efforts

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Current Project Status

- Project started October 1, 2018
- Technology maturation plan and initial techno-economic analysis on track to be completed by end of December
- Working with vendors for module component samples for initial exposure tests at new operating conditions
- New MTR hire will start in January to assist in membrane and module development
- Susteon is reviewing Polaris and Proteus data and developing heat and mass balances of various process designs

Summary

- Project is just underway with initial effort focused on finalizing subcontracts, technology maturation plan, initial TEA, and information exchange with Susteon
- Primary project goal will be field testing at EERC of Gen-2 Proteus membrane modules to bring this technology from TRL-4 to TRL-5
- Secondary goal will be to optimize integration of a membrane process within syngas cleanup to meet overall DOE performance goals for pre-combustion CO_2 capture

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Acknowledgements

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  - Bruce Lani
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  - Raghubir Gupta
  - Brian Turk
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  - David Dunham
  - Mike Swanson
  - Joshua Stanislowski