SRI International

Project Review (FE0031633)

DEVELOPMENT AND TESTING OF A HIGH-TEMPERATURE PBI HOLLOW-FIBER MEMBRANE TECHNOLOGY FOR PRE-COMBUSTION CO_2 CAPTURE

Presented by Elisabeth Perea

Advanced Technology and Systems Division

SRI International

Project Team

NATIONAL ENERGY TECHNOLOGY LABORATORY

PBI PERFORMANCE PRODUCTS, INC.

Enerfex, Inc.

Energy Commercialization, LLC

UK Center for Applied Energy Research

August 26-30, 2019 • Convention Center• Pittsburgh, Pennsylvania

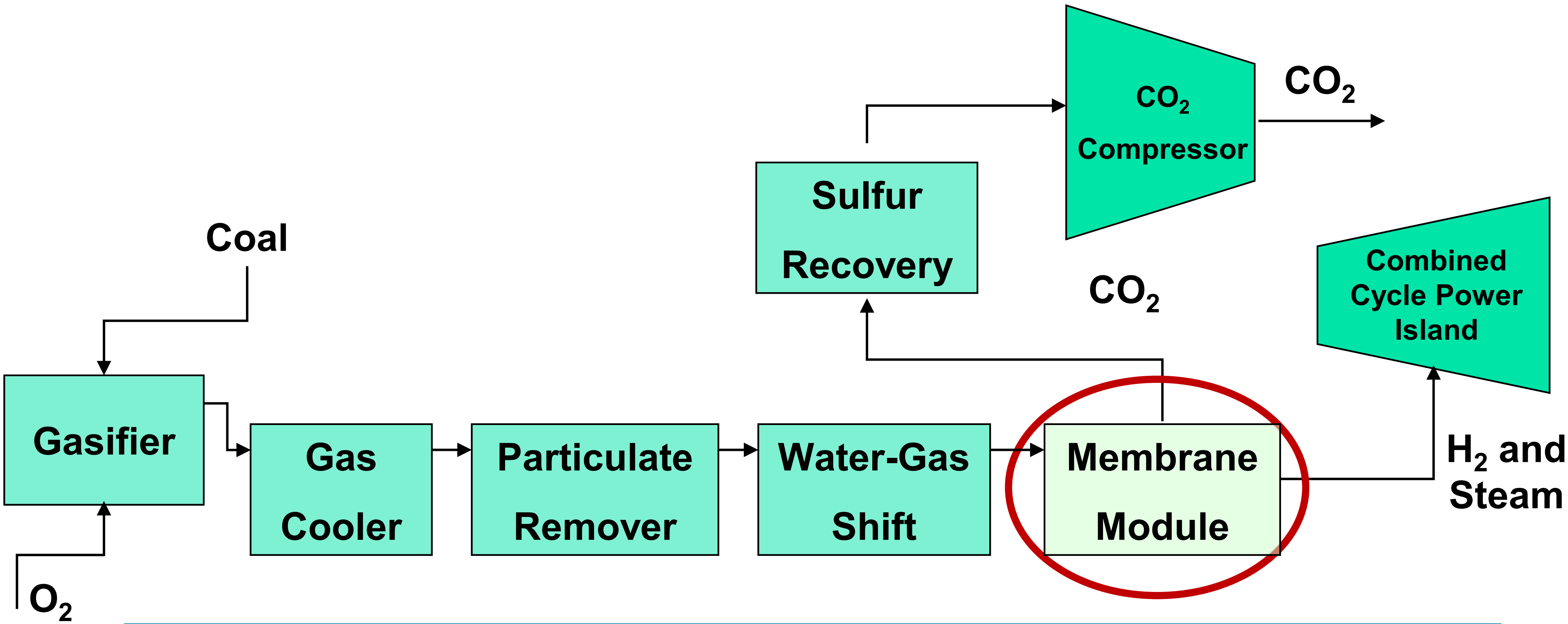
Disclaimer

This presentation includes an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

Technology Background

Membranes for Pre-Combustion CO_2 Capture

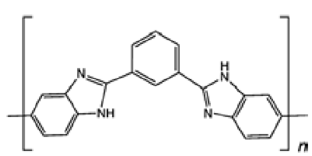
Advantages of High-Temperature Membranes for Separation of CO_2



Note: PBI hollow fiber membrane (HFM) is a H_2O and H_2 transporting membrane

Advantages of Membrane-Based Separation

- Reduced costs for syngas cooling
- Reduced CO_2 compression costs
- Emission free, i.e., no solvents
- Decreased capital costs
- Low maintenance
- Modular



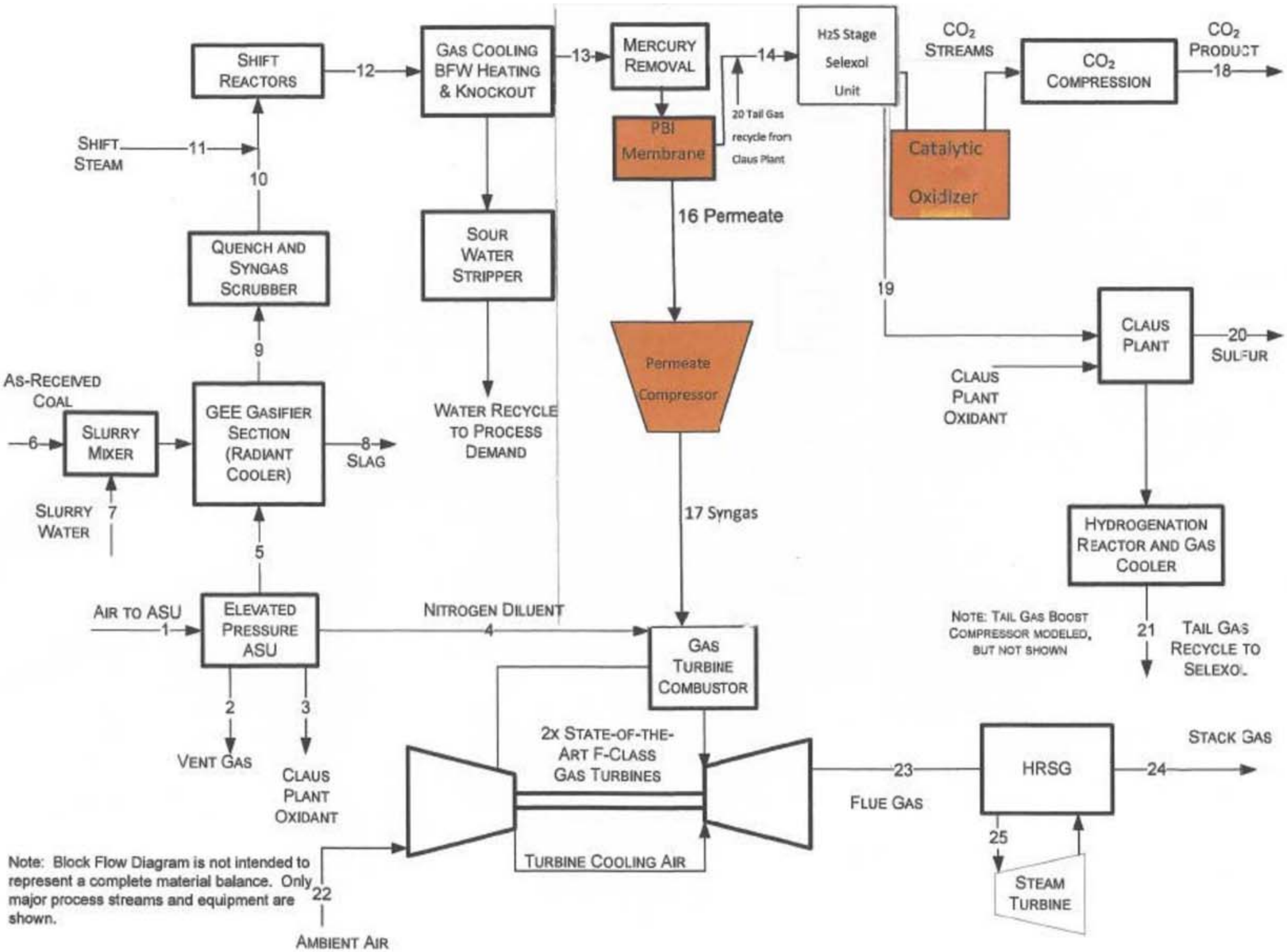
m-Polybenzimidazole (m-PBI)

Characteristics of PBI Membranes

- Attractive combination of throughput (permeance) and separation (selectivity)
- Thermally stable up to ~ 300°C and sulfur tolerant
- Tested up to 225°C with simulated gases and with real syngas

PBI Membrane Integration

Modification of Case B5B, GEE IGCC with CO_2 Capture



Techno Economic Analysis

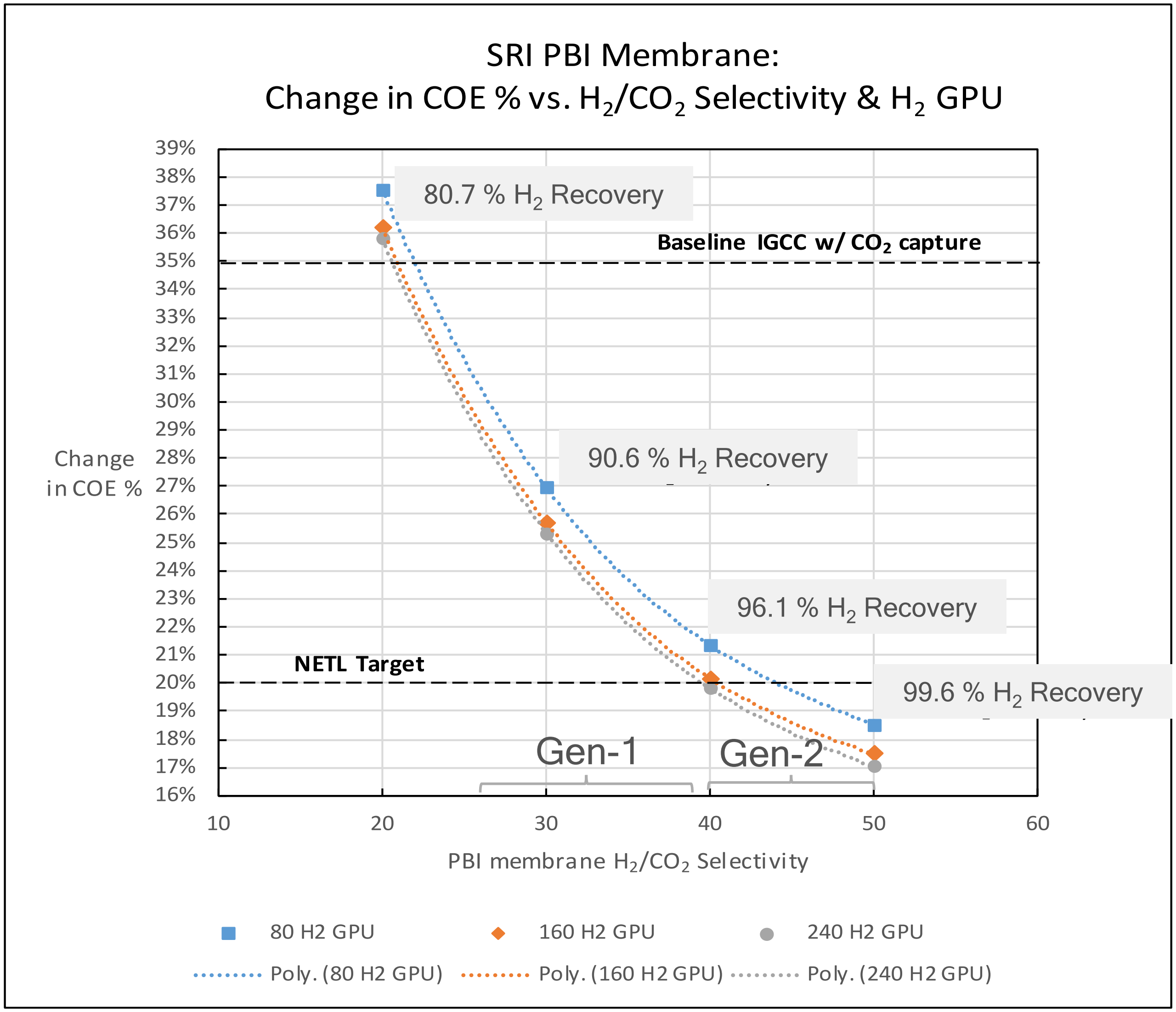
Developed by Enerfex

Case Name	IGCC-B1A Baseline No Capture	IGCC-B5B [1] Baseline CO_2 Capture	Gen-1 Membrane CO_2 Capture	Gen-2 Membrane CO_2 Capture
CO_2 removal	No	Selexol	PBI membrane	
CO_2 purification	No		Yes	
Sulfur removal	Sulfinol	Selexol		
Performance and Economic Summary				
H_2/CO_2 Selectivity	n/a	n/a	40	50
H_2 GPU	n/a	n/a	80	80
CO_2 capture	n/a	92.25%	90.0%	90.0%
CO_2 purity	n/a	99.48%	95.6%	95.6%
H_2 recovery	n/a	99.98%	96.1%	99.6%
HHV plant efficiency	42.1%	32.6%	32.6%	34.4%
LHV plant efficiency	43.7%	33.8%	33.8%	35.6%
COE w/o T&S ($/MWh)	$107	$135	$121	$118
COE w/ T&S ($/MWh)	$107	$144	$130	$127
% Increase in COE	0.0%	34.9%	21.3%	18.5%

[1] Cost and Performance Baseline for Fossil Energy Plants Volume 1b: Revision 2b, July 31, 2015

COE vs H_2/CO_2 Selectivity and H_2 GPU

90% CO_2 Capture



Reduced CO_2 Capture Options:

- 40 selectivity and 100 GPU recovers 99% H_2 with 88% CO_2 capture
- 25 selectivity and 150 GPU recovers 99% H_2 with 82 % CO_2 capture

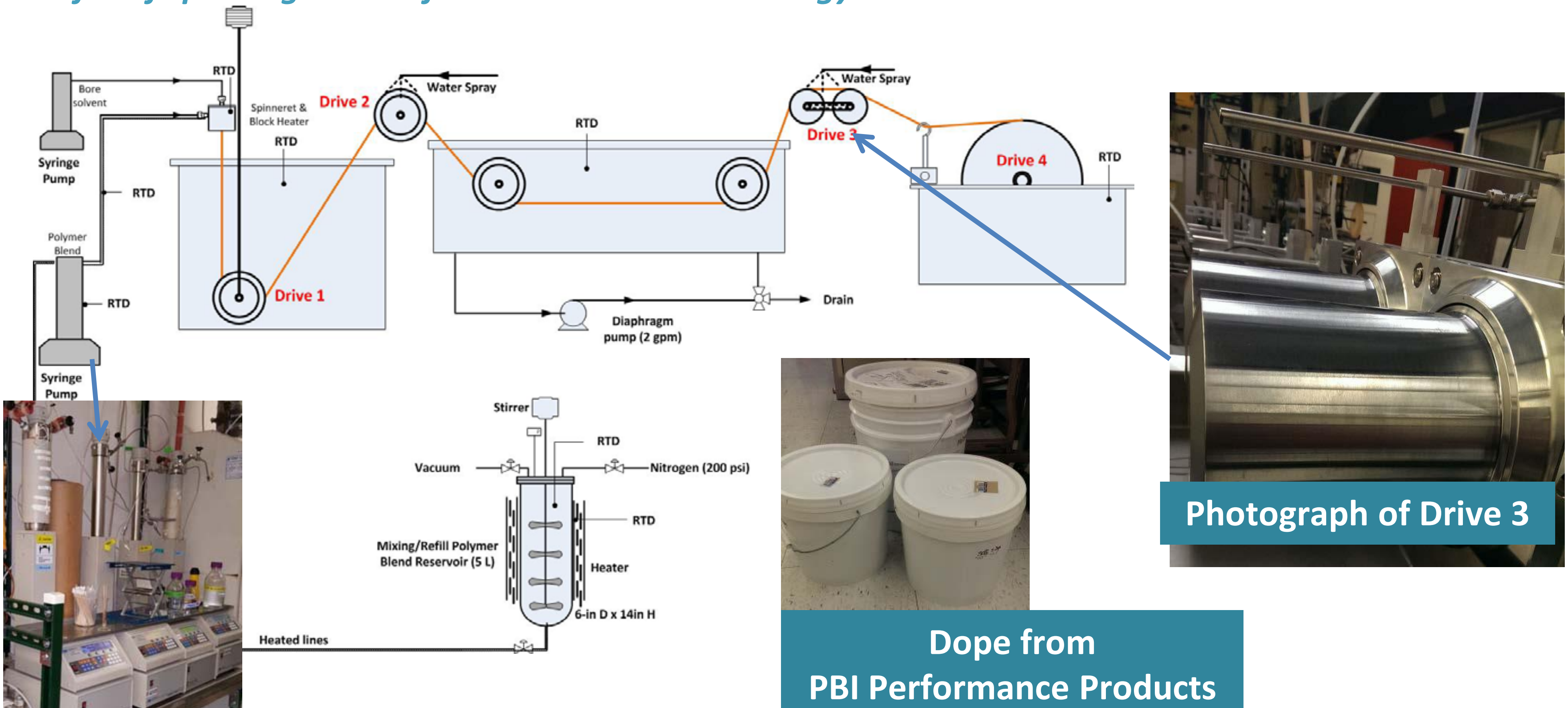
T= 225°C, Pressure ratio= ~12

Illustration of the reduction in COE in moving from Gen- 1 to Gen-2 performance.

Advancements in Spinning Kilometer Lengths of Asymmetric PBI Hollow Fibers with Minimal Defects

First Spinning Line Installed at SRI in 2015

Transfer of spinning hollow fibers critical to Technology Maturation



Dope from
PBI Performance Products

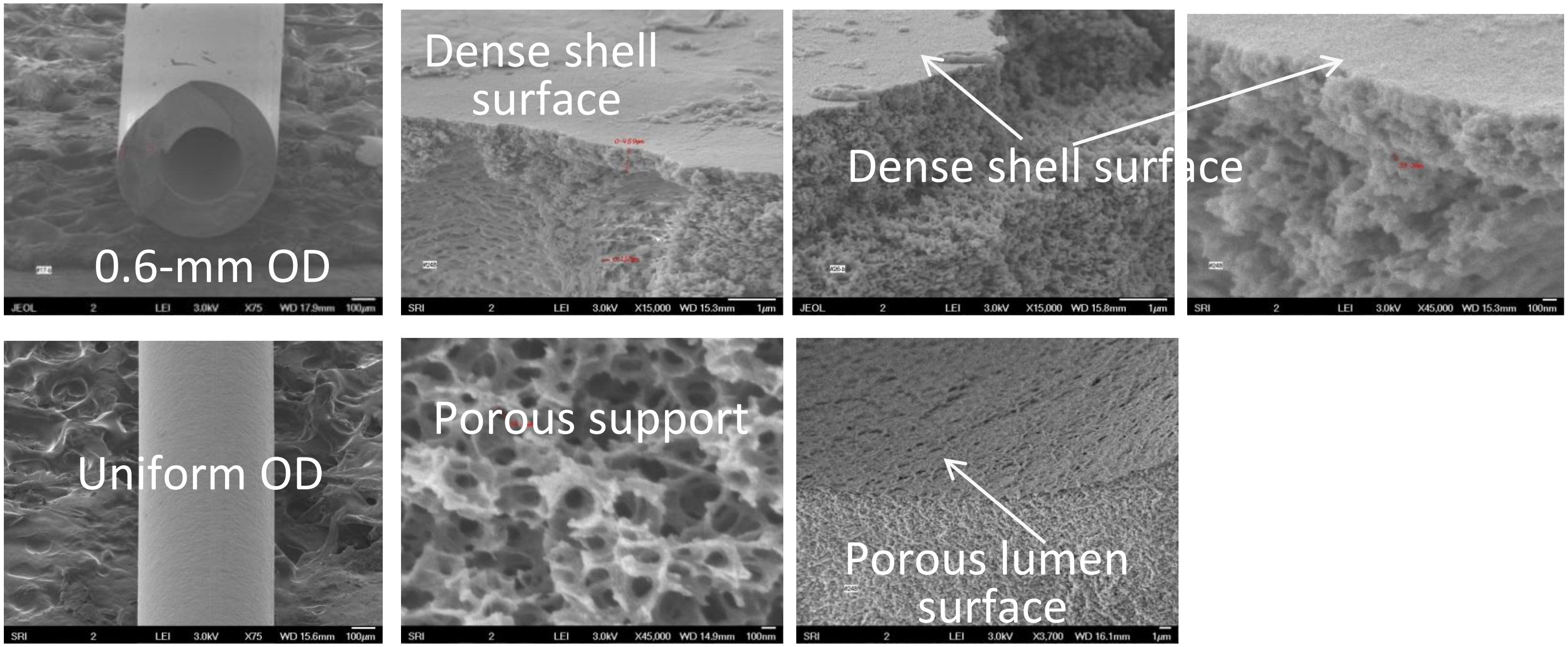
Photograph of Drive 3

The new spinning line was crucial for developing an improved and robust spinning process that can be transferred to industry. The line enabled:

- Use of multiple coagulation solvents
- Increased productivity (1 gal reservoir)
- Process monitoring and data collection
- Precise flow controls and draw ratios
- Optimization of fiber diameter
- Optimization of the fiber dense-layer thickness

Fabrication of Fibers with Good Reproducibility

Quality control is the KEY to success when scaling-up

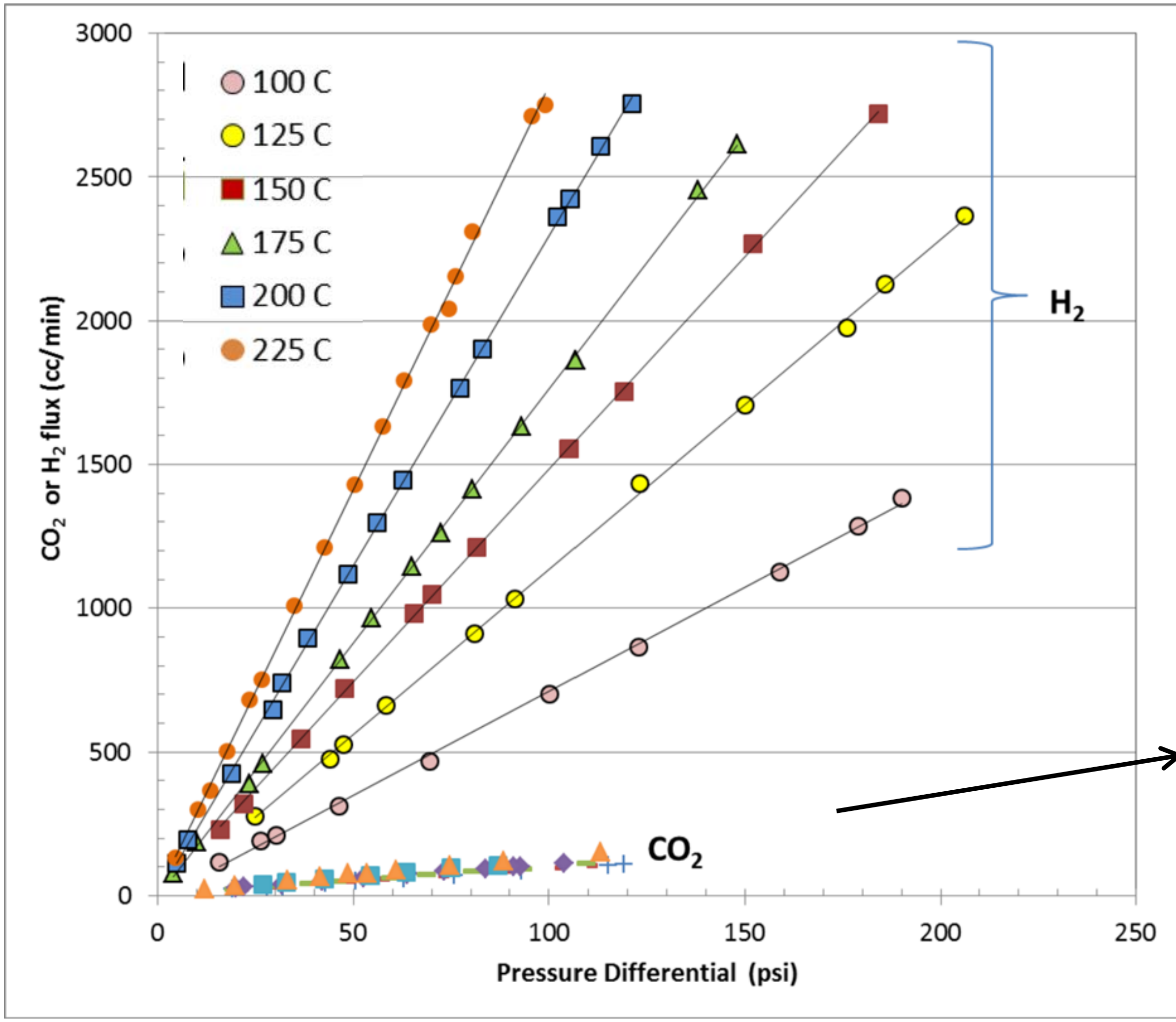


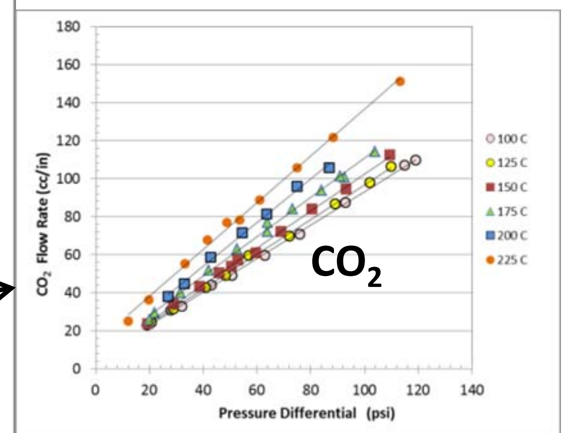
- Developed protocols for spinning < 0.3-µm dense layer hollow-fiber membranes with membrane OD 450 to 650 µm. *ABOVE*: ~ 0.1-µm fibers with ~ 600-µm OD.
- Tested more than 100 fiber bundles (1-in) for fiber-spinning optimization of OD and dense layer
- Fabricated Gen-1 hollow-fiber membrane with a very thin, dense layer (< 0.3 µm) in kilometer lengths with <u>very good reproducibility</u>
- Spun > 100 km of Gen-1 fibers for both Generon and SRI modules (4-in)

Achievements:
- **Dense-layer thickness reduced from 1 µm to < 0.3 µm**
- **Fiber diameter reduced from 1 mm to less than 600 µm**

Gen-2:
0.5 µm dense layer
Reduced defect potential

PBI Fiber Withstands High Pressures & High Temperatures





Mixed Gases

	Selectivity
H_2/CO_2	40
H_2/N_2	98
H_2/CO	103
H_2/H_2S	>200
225 ˚C and 200 psi ΔP	

Observation: H_2/CO_2 selectivity increases with temperature up to 225 ° C.

Fabrication of Large Modules at SRI: 4-inch

Photograph of 5000 fibers (5 m^2) arranged for potting at SRI

4-in sleeve for fiber potting

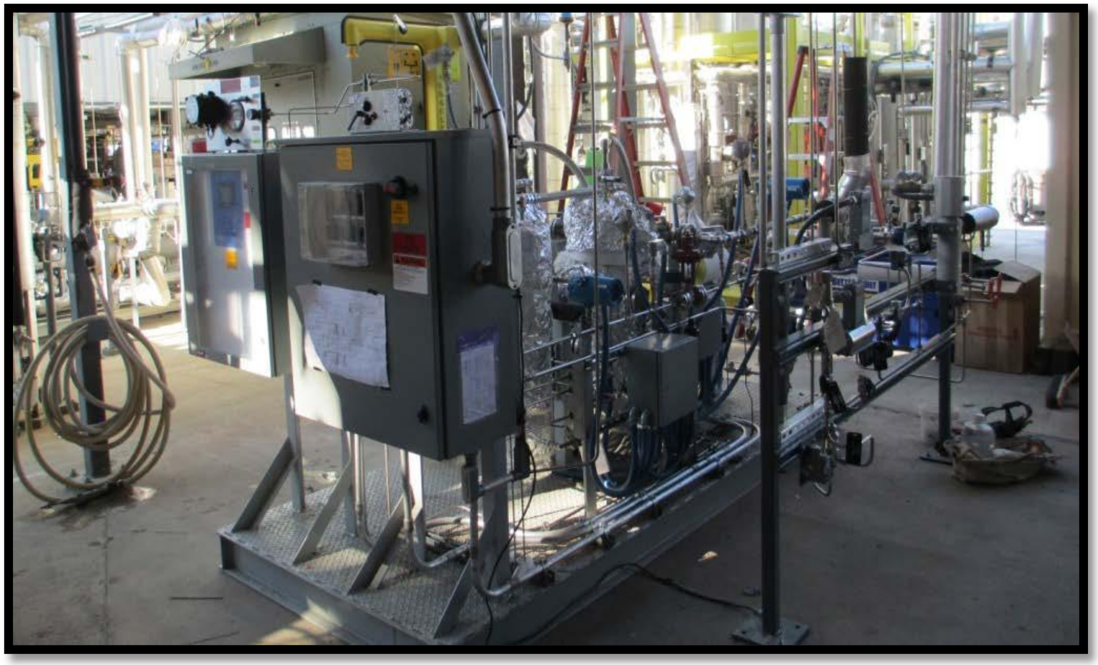
Potted 4-in fiber module cross-section (early design)

SRI fiber modules are designed for:

-Easy fabrication
-Easy handling
-Easy drop-in replacement

Critical Asset: Membrane Testing Skid

Installed and Tested at the NCCC



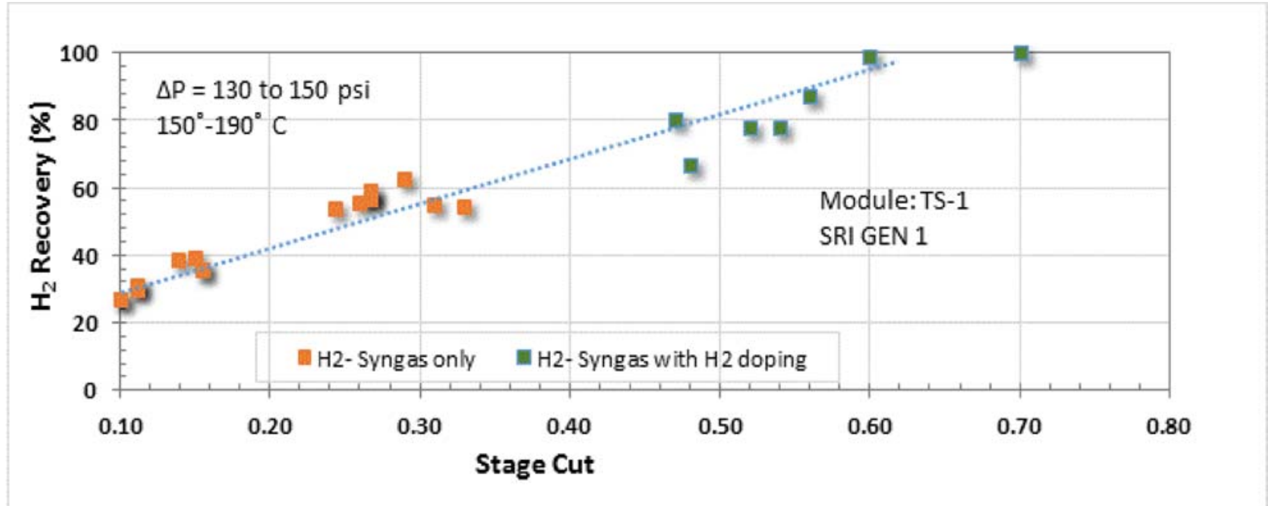
Photograph of the skid installed at the NCCC (April 2017)

Photograph of the skid installed at SRI (December 2018)

- PBI membrane skid transferred to the NCCC in March 2017
- Test campaign at NCCC conducted in April 2017 at 50 kWth scale
- Skid was removed from the host-site and returned to SRI in March 2018 for inspection and preservation
- Skid will be used in current work

Test Results at NCCC

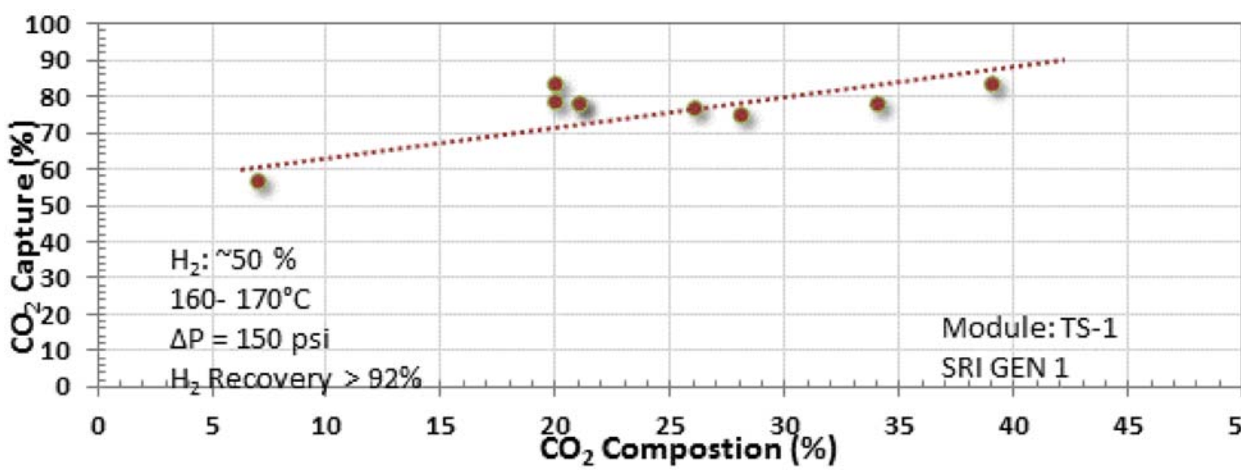
Air-blown Gasifier



Observed hydrogen recovery with varying stage cuts in the temperature range 150˚ – 190˚C and pressure differentials of 130 to 150 psi for the syngas-only condition and for syngas with doped with H_2

Sample parametric matrix

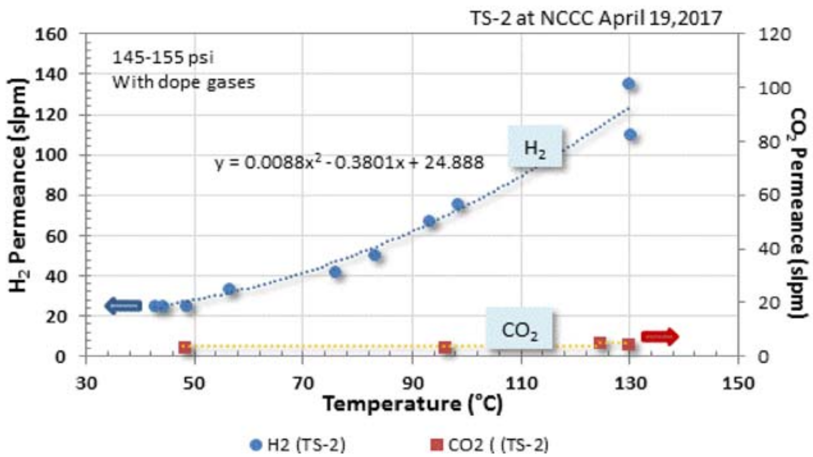
Test Parameter	Range	Unit
Temperature	80 to 215	°C
Pressure	50 to 170	psig
Gas composition	Variable	slpm
Stage cut	0.2-0.7	
H_2 in syngas	12 to 50	%
CO_2 in syngas	5 to 40	%



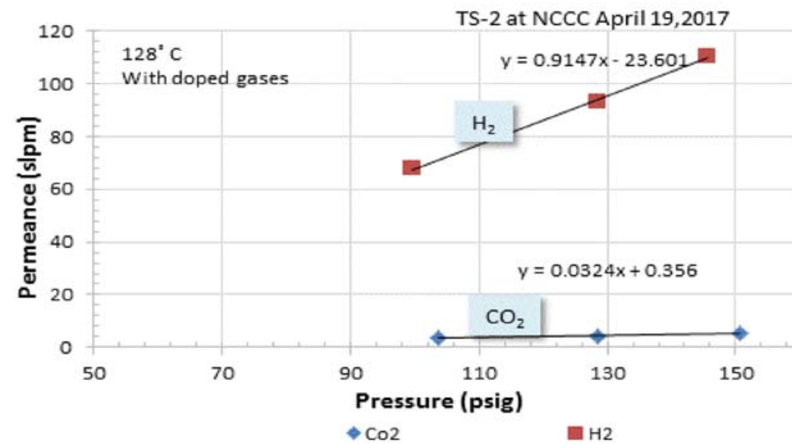
Observed CO_2 capture with varying feed CO_2 composition under fixed hydrogen composition at the temperature range 150 – 190˚C and a pressure differential ~ 150 psi for the TS-1 membrane

600 hours of performance data collected from PBI skid

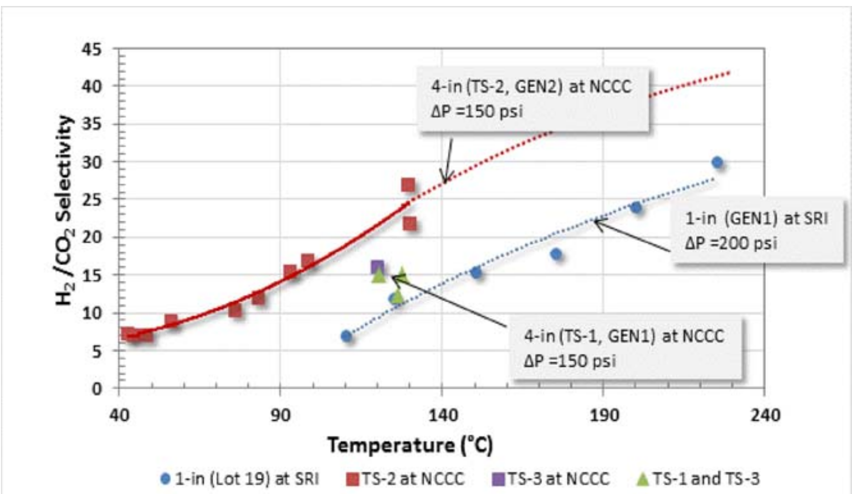
Gen-2 at NCCC: Temperature and Pressure Effect on Permeance



Measured H_2 and CO_2 permeances at the NCCC for the TS-2 (GEN-2) module at varying temperatures under a pressure differential of 145 to 155 psi.



Measured H_2 and CO_2 permeances at the NCCC for the TS-2 (GEN-2) module with varying pressures at 128˚C



Comparison of measured H_2/CO_2 selectivity for GEN-1 and GEN-2 modules

Modules tested at NCCC:

- Membrane element TS-1 consisting of SRI GEN-1 fibers (GPU~150, H_2/CO_2 selectivity ~ 25 at 150˚C) for ~ 500 hr
- Membrane element TS-2 consisting of SRI GEN-2 fibers (GPU ~ 100 , H_2/CO_2 selectivity ~ 40 at 200˚C, 200 psi) for ~ 48 hr

Performance of GEN-2 at SRI: GPU ~ 80, H_2/CO_2 selectivity ~ 50 at 200˚C, 200 psi)

PBI Gen-2 Offers Significant Advantages over PBI Gen-1

Current Project Details

Project Budget and Team for DE-FE0031633

- **Cooperative agreement grant with U.S. DOE Period of Performance**:
  - BP1: 10-1-2018 to 03-31-20
  - BP2: 04-01-20 to 09-30-21
- **Funding**:
  - U.S. Department of Energy: $2.007 million
  - Cost share: $0.505 million (20.1%)
  - Total: $2.512 million
- **NETL Project Manager**:
  - Andrew Jones

NETL

- Funding and technology oversight

SRI

- Gen-2 PBI membrane Spinning
- Module fabrication
- Skid installation & testing

PBI Performance Products, Inc.

- PBI Dope and industry perspective

Enerfex, Inc.

- Membrane system modeling and Techno-economic analysis

Energy Commercialization

- Commercialization analysis

UKy CAER

- Gasifier facility test site

- Current Spending: $222,527 (as of 27 July 2019)

Project Objectives

- Demonstrate that Gen-2 PBI based hollow fiber membranes provide a pathway to achieving DOE's pre-combustion capture targets
  - Bench-scale testing (50 kWth) of Gen-2 with actual syngas feed stream from an OXYGEN BLOWN gasifier
  - Evaluate Techno-economics based on bench-scale test results

- Leverage assets and knowledge generated from previous projects
  - PBI Hollow fiber membrane spinning line
  - Potting of fibers
  - Construction of modules based on PBI fibers
  - Test skid utilized for testing Gen-1 (50 kWe) at the NCCC on an AIR BLOWN gasifier
  - Production of Gen-2 fibers with improved selectivity over Gen-1

Project Tasks

Budget Period 1

Task #	BP	Task	Status
1	1	Project Management and Planning	On going
1	1	Preliminary Technology Maturation Plan Program Management Plan Preliminary TEA	Submitted
1	1	Installation of Partner Agreements and Sub-awards	Completed
2	1	Modification of the 50 kWth Test Unit - Refurbish and upgrading of the existing skid system - Fabrication of Gen-2 Fibers - Module design and installation of the Modules (4 to 6-in diameter) - Membrane performance testing at SRI - HAZOP and PI&D Review at CAER	Started
3	1	Modeling - Modeling of the Module arrangement - Modeling of the skid performance - Preliminary TEA	Started

Project Tasks

Budget Period 2

Task #	BP	Task	Status
4	2	Operation of the Test Unit at a Field -Skid Transport and Installation at the Site - Development of a test plan - Operation of the skid and data collection - Analysis of the data form the skid	Not Started
5	2	EH&S, TEA and other Related Reports - Techno-Economic Analysis - Update the State Point Data Table - Technology Gap Analysis - Preparation of Technology Maturation Plan - Environmental Health and Safety Assessment (EH&S)	Not Started
6	2	Skid Decommissioning - Skid decommissioning and Transport - Skid Postmortem and Storage	Not Started

Project Milestone Plan

Budget Period 1

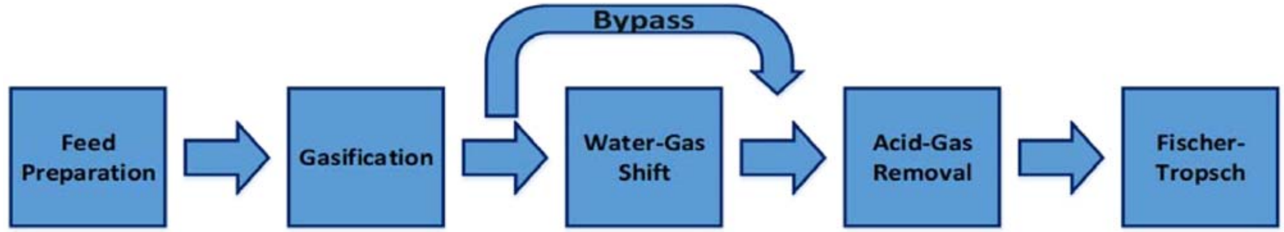
Task/ Subtask	Milestone Description	Planned Completion	Status	Verification Method
1	Updated PMP	10/31/2018	Completed	PMP file
1	Kick-off Meeting	1/31/2019	Completed	Presentation file
1	Technology Maturation Plan	12/31/2018	Completed	TMP file
3.3	Completion and submission of preliminary TEA	12/31/2018	Completed	Topical report
2.1 to 2.3	Complete the production of at least 100 km of Gen-2 fibers that provide a H_2/CO_2 selectivity of about 40 and H_2 permeance of 80-120 GPU at > 150°C at a 150 psi pressure differential	11/30/2019	Started	Results reported in QR
2.1	Completion of the updated Basic Engineering Design package for modification of 50 kWth skid	12/30/2019	Started	Results reported in QR
2.1 to 2.4	Completion of bench skid acceptance testing for 50 hrs at SRI and achieve H_2/CO_2 selectivity > 35	3/31/2020	Not started	Results reported in QR

We are on schedule to complete the project milestones

Project Tasks and Schedule

BP1: 18 months BP2:18 months			BP1								BP2				
			10/1/18	1/1/19	4/1/19	7/1/19	10/1/19	1/1/20	4/1/20	7/1/20	10/1/20	1/1/21	4/1/21	7/1/21	12/31/21
Task	Start Date	End Date	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12	
Development and Testing of a High Temperature PBI Hollow Fiber Membrane Technology for Pre-Combustion CO2 Capture	**10/1/2018**	**9/30/2021**													
Task 1.0 (BP1 & BP2) - Project Management and Planning	**10/1/2018**	**9/30/2021**													
Subtask 1.1 - Project coordination and reporting	10/1/2018	9/30/2021													
Subtask 1.2 - Preparation and Submission of Continuation Report	3/1/2021	3/31/2020													
Milestones			a b c					f,h							
Task 2.0 (BP1): Modification of the 50 Kwth Test Unit for the Field Test	**10/1/2018**	**3/31/2020**													
Subtask 2.1 - Refurbish and upgrading of the existing skid system	10/1/2018	8/31/2019													
Subtask 2.2 - Fabrication of SRI Generation 2 (GEN 2) Fibers	1/1/2019	3/31/2020													
Subtask 2.3 - Module design and installation of the Modules (4 to 6-in diameter)	4/1/2019	3/31/2020													
Subtask 2.4 - Membrane performance testing at SRI	1/1/2019	3/31/2020													
Subtask 2.5 - HAZOP and PI&D Review at CAER	4/1/2020	3/31/2020													
Milestones								d,e							
Task 3.0 (BP1) -Modeling	**10/1/2018**	**3/31/2020**													
Subtask 3.1 - Modeling of the Module arrangement	1/1/2019	3/31/2020													
Subtask 3.2 - Modeling of the skid performance	4/1/2019	3/31/2020													
Subtask 3.3 - Preliminary TEA	10/1/2018	12/31/2018													
Milestones								g							
Task 4.0 (BP2) - Operation of the Test Unit at a Field Site	**4/1/2020**	**9/30/2021**													
Subtask 4.1 -Skid Transport and Installation at the Site	4/1/2020	3/31/2021													
Subtask 4.2 - Development of a test plan	10/1/2020	12/31/2020													
Subtask 4.3 - Operation of the skid and data collection	1/1/2021	3/31/2021													
Subtask 4.4 - Analysis of the data form the skid	1/1/2021	6/30/2021													
Milstones											j	i	k		
Task5.0 (BP2) - EH&S, TEA and other Related Reports	**1/1/2021**	**9/30/2021**													
Subtask 5.1 - Techno-Economic Analysis	1/1/2021	6/30/2021													
Subtask 5.2 - Update the State Point Data Table	7/1/2021	9/30/2021													
Subtask 5.3 - Technology Gap Analysis	7/1/2021	9/30/2021													
Subtask 5.4 - Preparation of Technology Maturation Plan	10/1/2018	12/31/2018													
Subtask 5.5 - Environmental Health and Safety Assessment (EH&S)	7/1/2021	9/30/2021													
Submit the State Point Data Table	9/1/2021	9/30/2021													
Submit the Technology Gap Analysis	9/1/2021	9/30/2021													
Submit the Technology Maturation Plan	9/1/2021	9/30/2021													
Milestones													l	m,n,o,p	
Task 6.0 (BP2) - Skid Decommissioning	**9/1/2021**	**9/30/2021**													
Subtask 6.1 - Skid decommissioning and Transport															
Subtask 6.2 - Skid Postmortem and Storage															
Milestones															q,r
Project Reviews															
Final Report Submission	10/1/2021	12/31/2021													

UKy-CAER Pilot Facility



Gasification Unit

- Multi-burner, entrained flow, oxygen blown, slagging type
- 1 ton/day coal consumption
- Syngas production rate: ~80 m^3/hr
- H_2/CO: ~.80

Water-Gas Shift

- Packed bed
- Sulfur tolerant sour shift catalyst
- H_2/CO: up to 11/1

Syngas Compressor

- Metal Diaphragm Compressor
- 450 psi max outlet pressure

Gasifier

Gasifier Operating Parameters	
Temperature (℃)	1350
Pressure (MPag)	0.1
CWS Solid (%)	53.0
Syngas (vol%)	
H_2	24.51
N_2	2.93
CO	28.94
CO_2	40.89
H_2O	2.54
H_2S	0.18
COS	0.02

WGS

Compressor

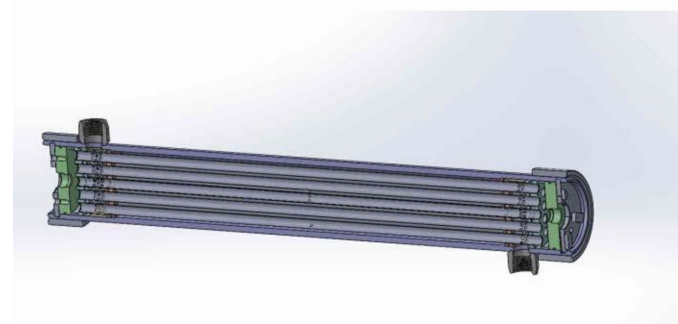
Current project work update

Improved Module Design

Reliable fiber module performance enables maximum collection of high-quality data at UKy-CAER

Previous tube sheet module design

New tube sheet module design



Fast module swapping and reduced gas bypass

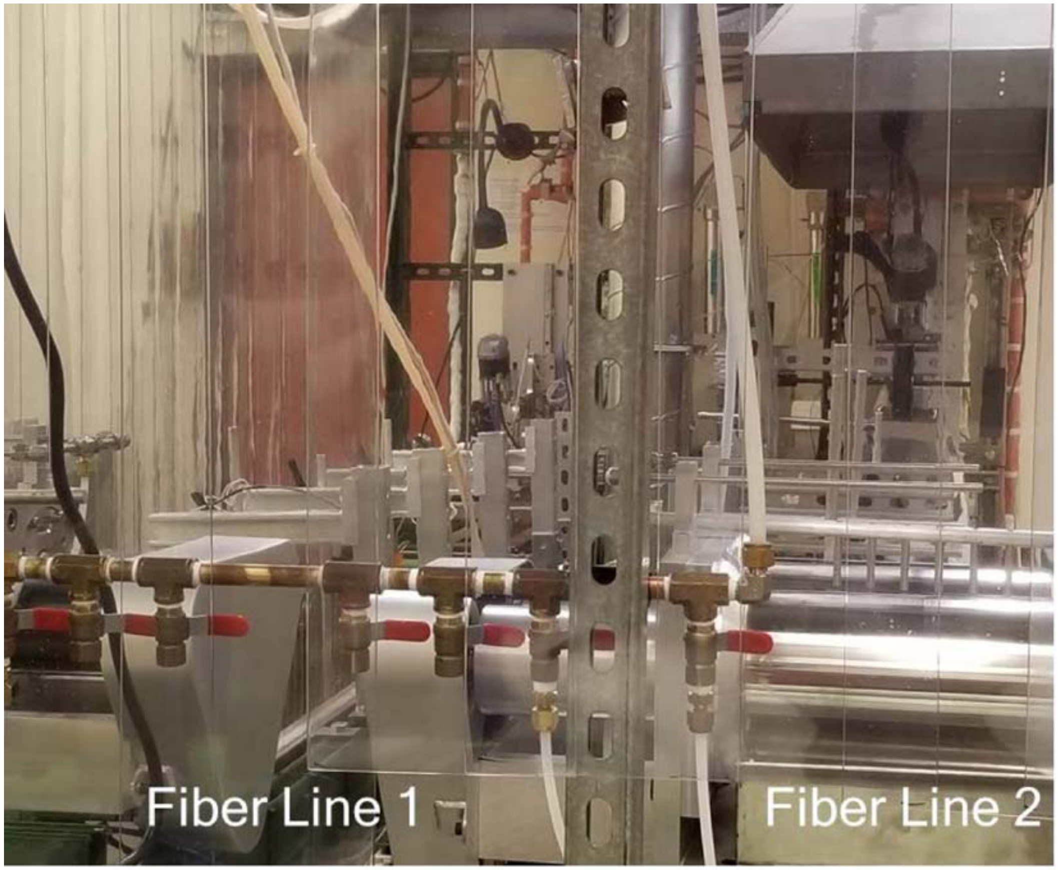
In Progress: Production of Gen-2 Fibers

Reproducible spinning process to provide abundant hollow fibers for installation in skid

>10 km Gen-2 fibers produced to date

A Second Spinning Line Installed at SRI in 2019

Transfer of spinning hollow fibers critical to Technology Maturation



Photographs of the new fiber spinning line. Line 1 is the old line, and Line 2 is the newly installed line.

Fiber Spinning Capacity Doubled

Technology Maturation

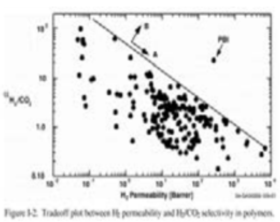
DOE Funding: Critical to Technology Maturation

DOE enabled "first-of a kind" hollow fiber membranes of PBI in kilometer lengths

Testing single tubes

Surface area ~ 10 cm²

Membranes prepared by coating PBI on porous metal substrates



LANL demonstrates PBI is attractive for pre-combustion applications

Accomplishment

DE-FC26-07NE43090

Producing Gen-1 PBI based membrane modules

Testing POTTED Gen-1 fiber bundles

Surface area ~ 100 cm²

Produce first ever porous hollow fiber membranes of PBI that were kilometers in length AND minimal defects

Dope preparation

High temperature potting

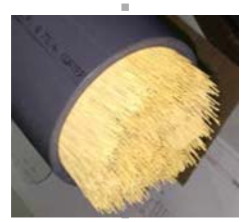
Accomplishment

DE-FE0012965

Producing and testing Gen-1 based membrane modules at NCCC

Developing Gen-2 PBI based fibers

Surface area ~ 5 m²



Consistent multi-fiber bundles that are kilometers in length of Gen-1 and Gen-2 with minimal defects

In Progress

DE-FE0031633

Producing and testing Gen-2 based membrane modules at UKy-CAER

Higher selectivity and new module design

Surface area ~ 20 m²

Doubled spin capacity

Production of 100 km of Gen-2 with minimal defects

2006 2008 2010 2012 2014 2016 2018 2020 2022

Acknowledgements

- Andrew Jones, Jose Figueroa, Elaine Everitt, Lynn Brickett, and others at NETL

- Indira Jayaweera (Principal Investigator), and the rest of the SRI team: Srini Bhamidi, Regina Elmore, Xiao Wang, William Olson, Gopala Krishnan, Milad Yavari, Palitha Jayaweera and Chris Lantman

- Richard Callahan (Enerfex, Inc.)
- Kevin O'Brien (Energy Commercialization, LLC)
- Greg Copeland and Mike Gruende (PBI Performance Products)
- Kunlei Liu and his team (UKy- CAER)
- John Jensvold and his team (Generon IGS)
- The staff at the NCCC

SRI International

Contact:

Dr. Indira Jayaweera

indira.jayaweera@sri.com

1-650-859-4042

Thank You

Headquarters
333 Ravenswood Avenue
Menlo Park, CA 94025
+1.650.859.2000

Additional U.S. and
international locations

www.sri.com