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Development and Testing of a High-Temperature PBI Hollow-Fiber Membrane Technology for Pre-Combustion CO_2 Capture

Project Review (FE0031633)

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NATIONAL ENERGY TECHNOLOGY LABORATORY

PBI PERFORMANCE PRODUCTS, INC.

Project Team

Enerfex, Inc.

Energy Commercialization, LLC

UK Center for Applied Energy Research

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Technology Background

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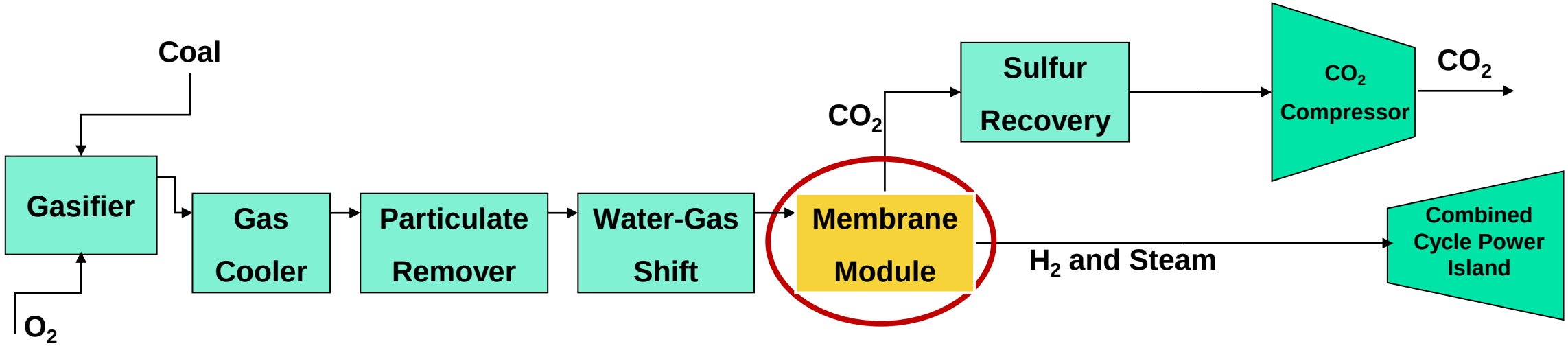
Membranes for Pre-Combustion CO_2 Capture

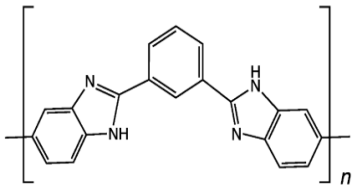
Advantages of High-Temperature Membranes for Separation of CO_2



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

Preliminary TEA

Developed by Enerfex

Preliminary TEA has been updated to correspond to Rev. 4 of Cost & Performance Baseline document

Case Name	IGCC-B1A Baseline No Capture	IGCC-B5B [1] Baseline CO_2 Capture	SRI PBI 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	46
H_2 GPU	n/a	n/a	215
CO_2 capture	n/a	95.18%	89.12%
CO_2 purity	n/a	99.08%	95.80%
H_2 recovery	n/a	99.46%	99.04%
HHV plant efficiency	43.00%	33.70%	34.47%
LHV plant efficiency	44.60%	35.00%	35.74%
COE w/o T&S ($/MWh)	$105.80	$144.20	$135.39
COE w/ T&S ($/MWh)	$105.80	$152.30	$143.49
% Increase in LCOE	0.00%	43.95%	35.63%

% Increase in Cost of Electricity (COE)

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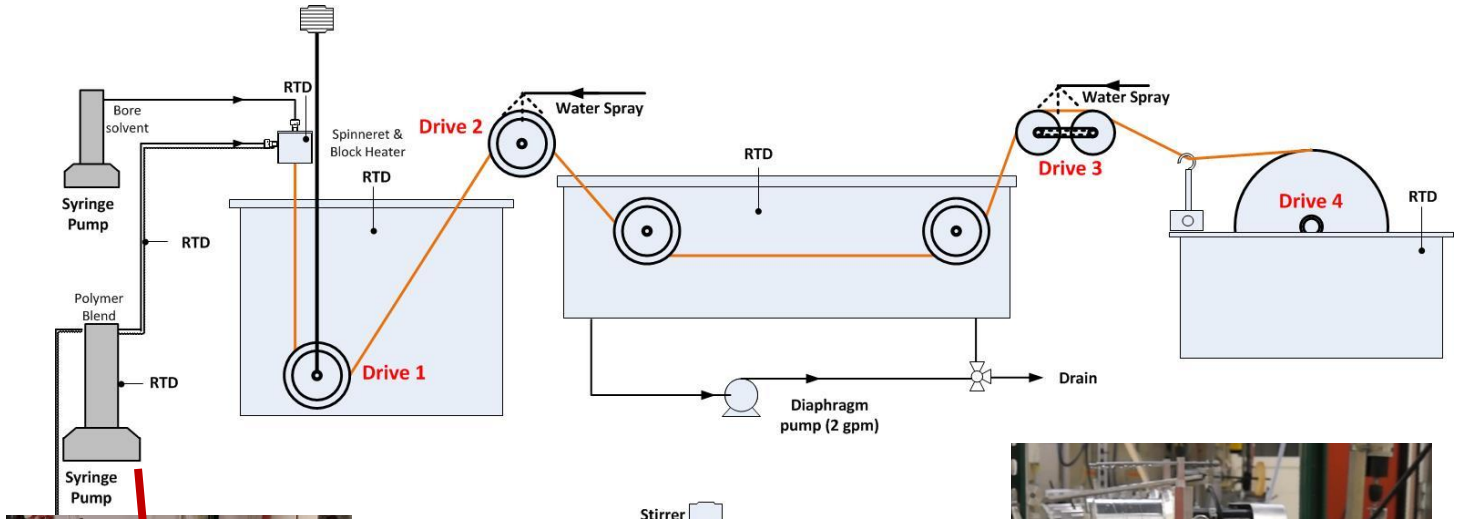
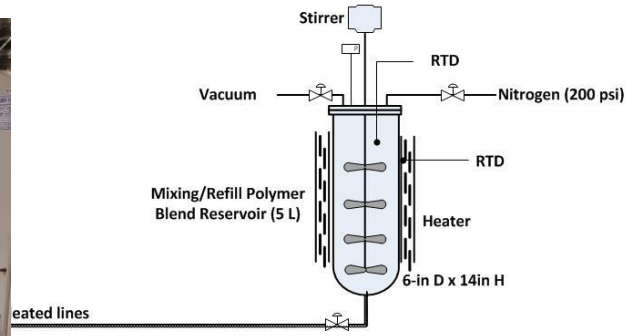
[1] Cost and Performance Baseline for Fossil Energy Plants Volume 1: Bituminous Coal and Natural Gas to Electricity, Rv4-1, September 24, 2019

SRI Fiber Spinning Lines

1st line installed in 2015
2nd line installed in 2019





Syringe Pumps

Drives and Motors

Fiber Optimization:

- Air gap
- Solvents
- Non-solvents
- Roller speed

→ Wall thickness, Pore size, Substructure, Dense layer thickness

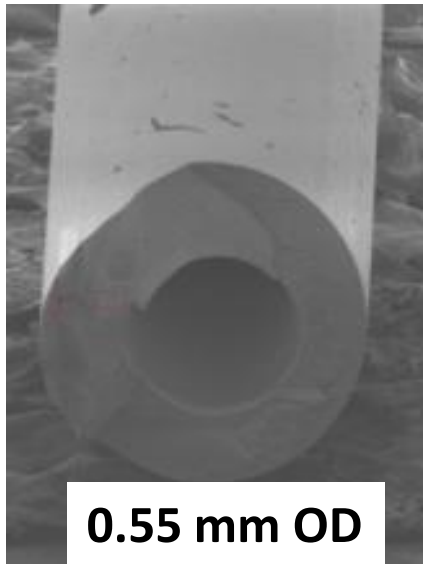
Variety of Applications:

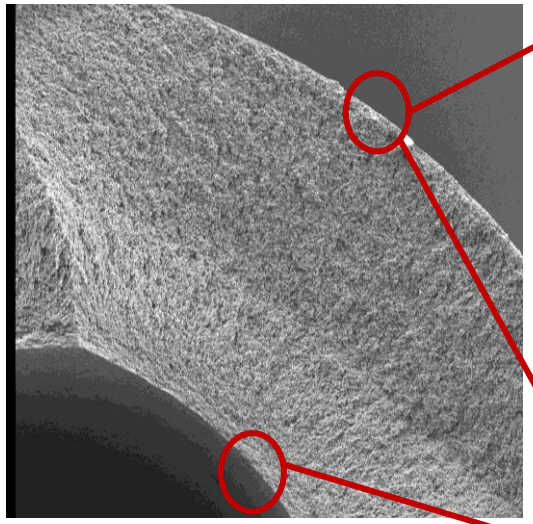
- Gas Separations[1]
- Reverse Osmosis (RO)[2]
- Ultra Filtrations (UF)[3]

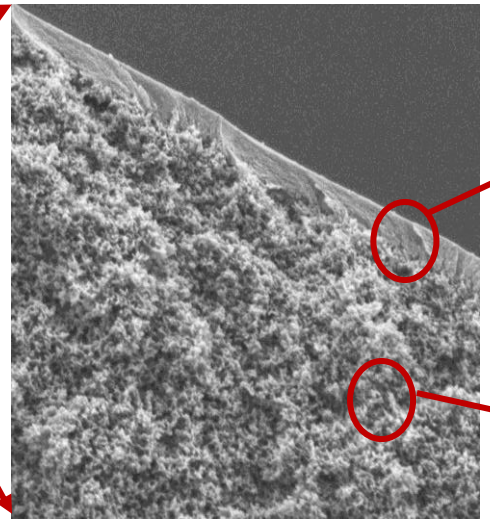
1. Xiao et al. (2018), Membranes, 2018, 8(4), 113;
2. Wales et al. (2021), Membranes, 2021, 11(6), 430;
3. Xiao et al. (2021), Desal and Water Treatment, 2021, 69-78, 229

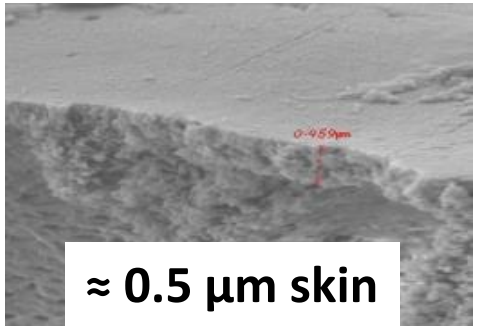
Fabrication of Fibers with Good Reproducibility

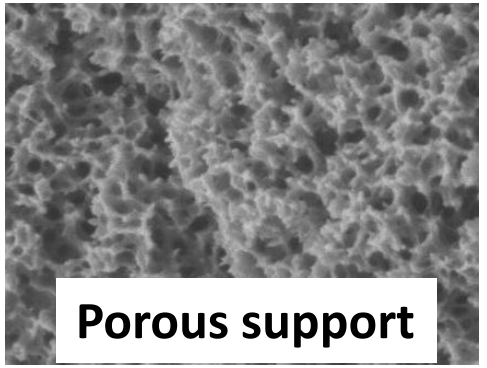
Quality Control is the KEY to success when scaling up

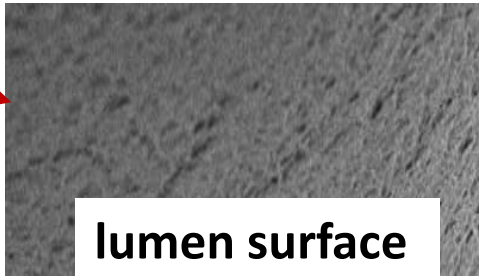












SRI Fiber Production – VERY GOOD REPRODUCIBILITY:

- Dense (skin) Layer: 0.3 – 0.5 µm
- OD: 450 – 650 µm
- ID: 120 – 250 µm
- Spun > 500 km

} **Tunable**

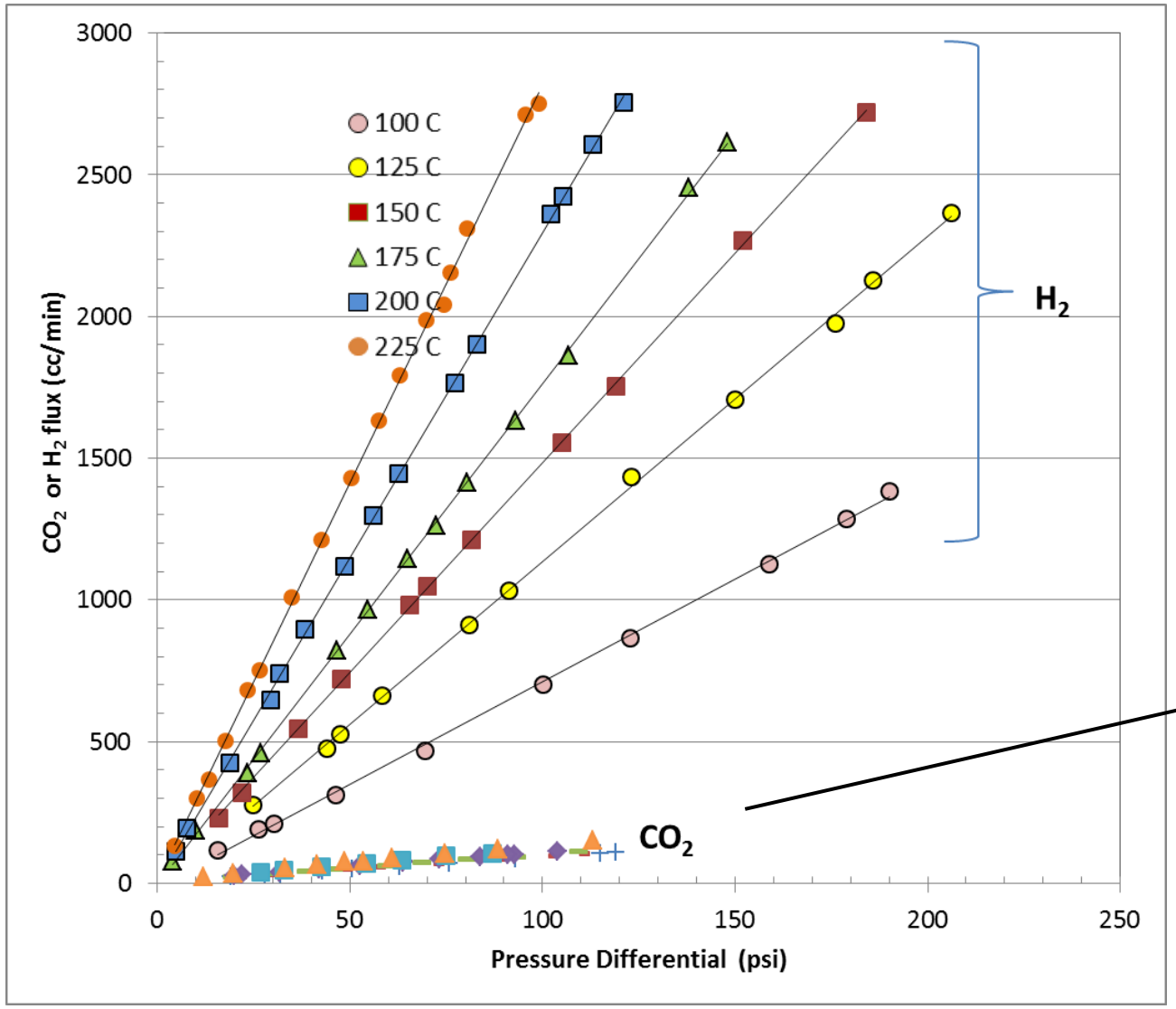
Achievements:

- Dense-layer thickness reduced from 1 µm to < 0.3 µm (Gen-1)
- Fiber diameter reduced from 1 mm to less than 600 µm

Gen-2:

- 0.5 µm dense layer
- Reduce defect, improve reproducibility

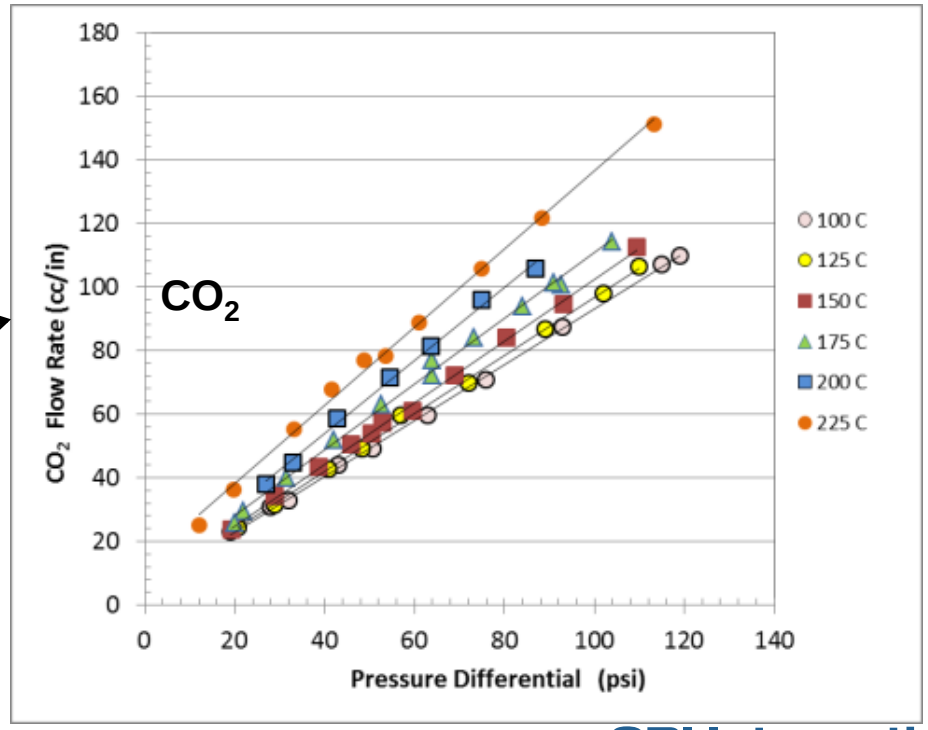
PBI Fiber Withstands High Pressures & Temperatures



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	

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



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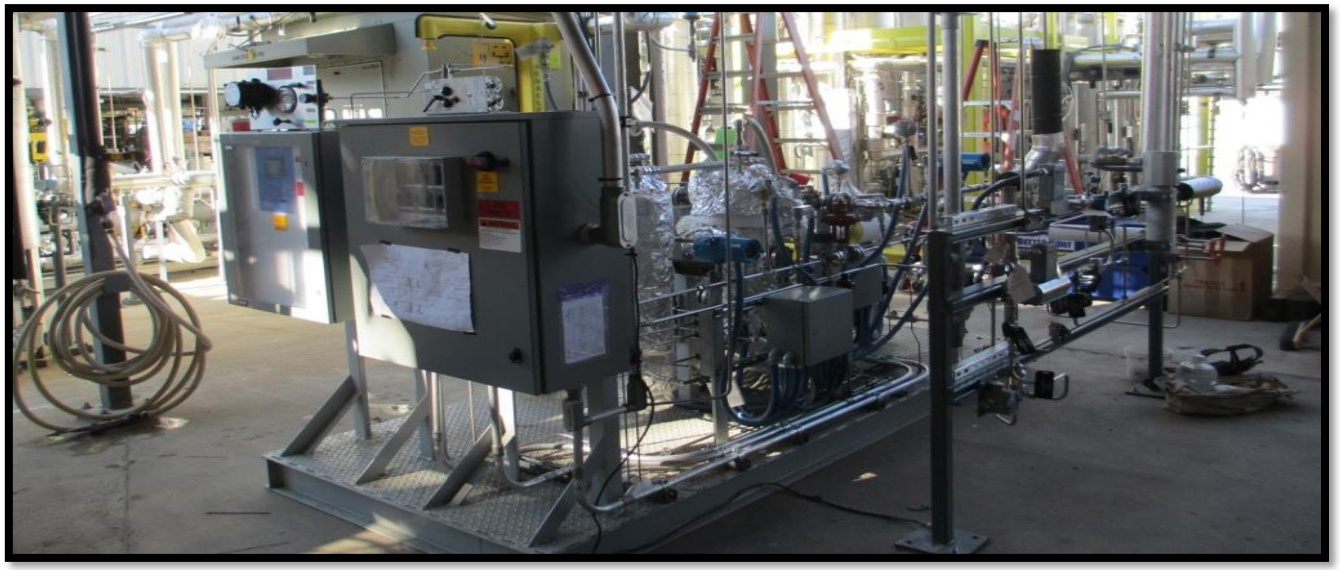
Critical Asset: Membrane Testing Skid

Installed and Tested at the NCCC



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

- Test campaign at NCCC conducted in April 2017 (50 kWth scale)
- Skid was removed from the host-site and returned to SRI in March 2018 for inspection and modification
- Upgraded skid is used in current work

Sample test matrix

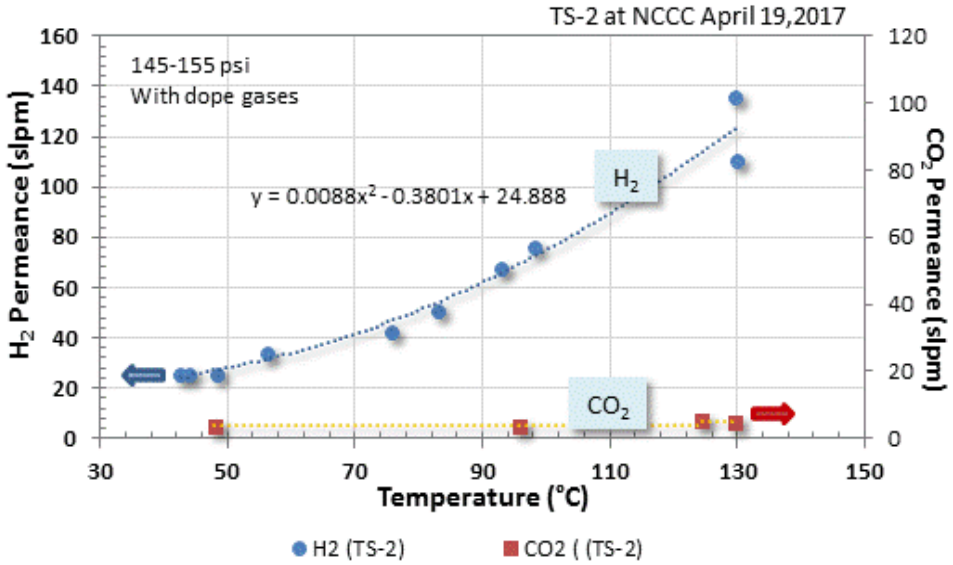
Test Parameter	Range	Unit
Temperature	80 to 215	°C
Pressure	50 to 170	psig
Gas composition	Variable	slpm
Stage cut	0.2-0.7	
H_2 in syngas	12 to 50	%
CO_2 in syngas	5 to 40	%

600 hours of performance data collected from PBI skid at NCCC

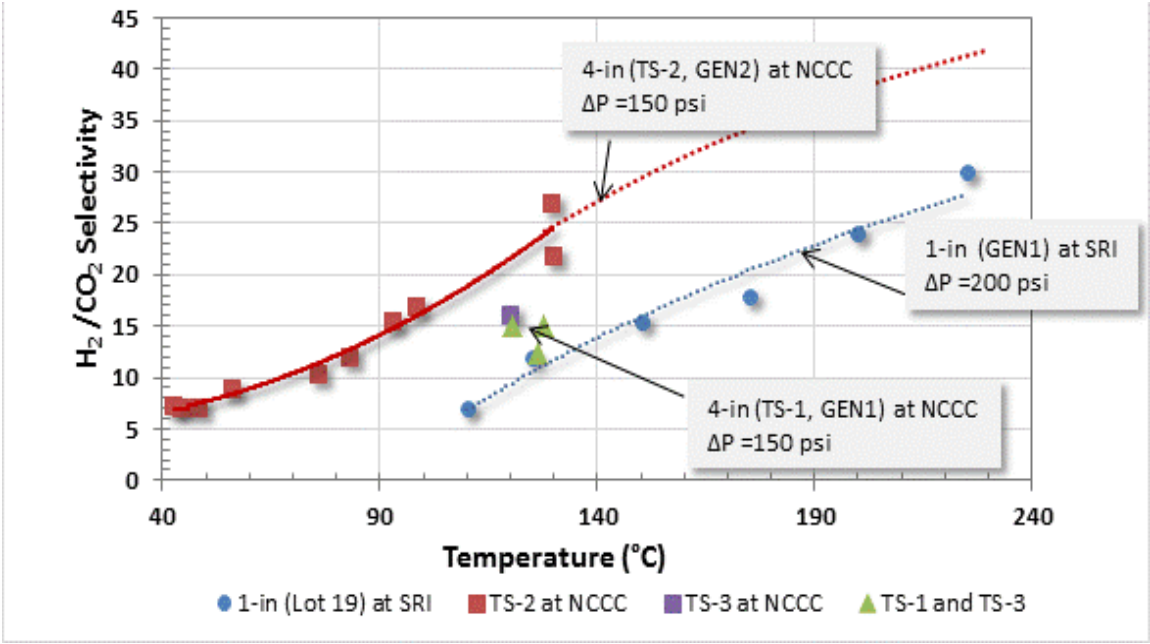
Test Results at NCCC

Air-blown Gasifier

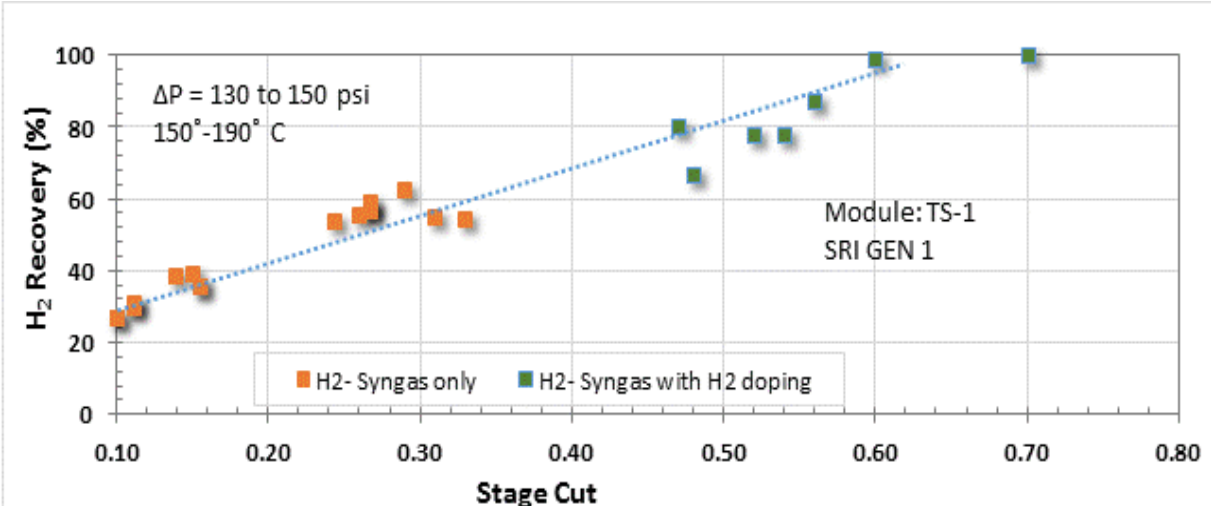
- Tunable fiber spinning process can be tailored to higher flux (GEN-1) or higher selectivity (GEN-2)
- Modules tested at NCCC:
  - Membrane element TS-1 consisting of SRI GEN-1 fibers (GPU~150, H_2/CO_2 selectivity ~ 25 at 150˚C) for ~ 500 hr
  - Membrane element TS-2 consisting of SRI GEN-2 fibers (GPU ~ 100 , H_2/CO_2 selectivity ~ 40 at 200˚C, 200 psi) for ~ 48 hr



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.



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



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

Current Project Details

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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 06/30/22
  - Expecting modification to PoP

Funding:

- U.S. Department of Energy: $2.007 million
- Cost share: $0.505 million (20.1%)
- Total: $2.512 million

NETL Project Manager:

- Krista Hill
- Andrew Jones (former)

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 TEA

Energy Commercialization

- Commercialization analysis

UKy CAER

- Gasifier facility test site

Project Objectives

- Demonstrate that PBI based hollow fiber membranes provide a pathway to achieving DOE's pre-combustion capture targets
  - Targets: 90% CO2 capture and 95% purity
    - >99% H2 recovery
    - 30% reduction in COE
  - Field test fiber skid (50 kWth) with actual syngas feed stream from an **OXYGEN BLOWN** gasifier
  - Evaluate Techno-economics based on field test results
- Leverage assets and knowledge generated from previous projects
  - Spin >100 km of SRI PBI fibers
  - Improved potting and module construction
  - Modifications/improvements to fiber skid
  - Test skid utilized for testing (50 kWth) at the NCCC on an AIR BLOWN gasifier

Project Tasks

Budget Period 1 (10-01-2018 → 03-31-2020)

Task #	BP	Task	Status
1	1	Project Management and Planning	Completed
1	1	Preliminary Technology Maturation Plan Program Management Plan Preliminary TEA	Completed
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	Completed
3	1	Modeling - Modeling of the Module arrangement - Modeling of the skid performance - Preliminary TEA	Completed

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 from the skid	>90% complete
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)	In progress
6	2	Skid Decommissioning - Skid decommissioning and Transport - Skid Postmortem and Storage	Not Started

Current project work update

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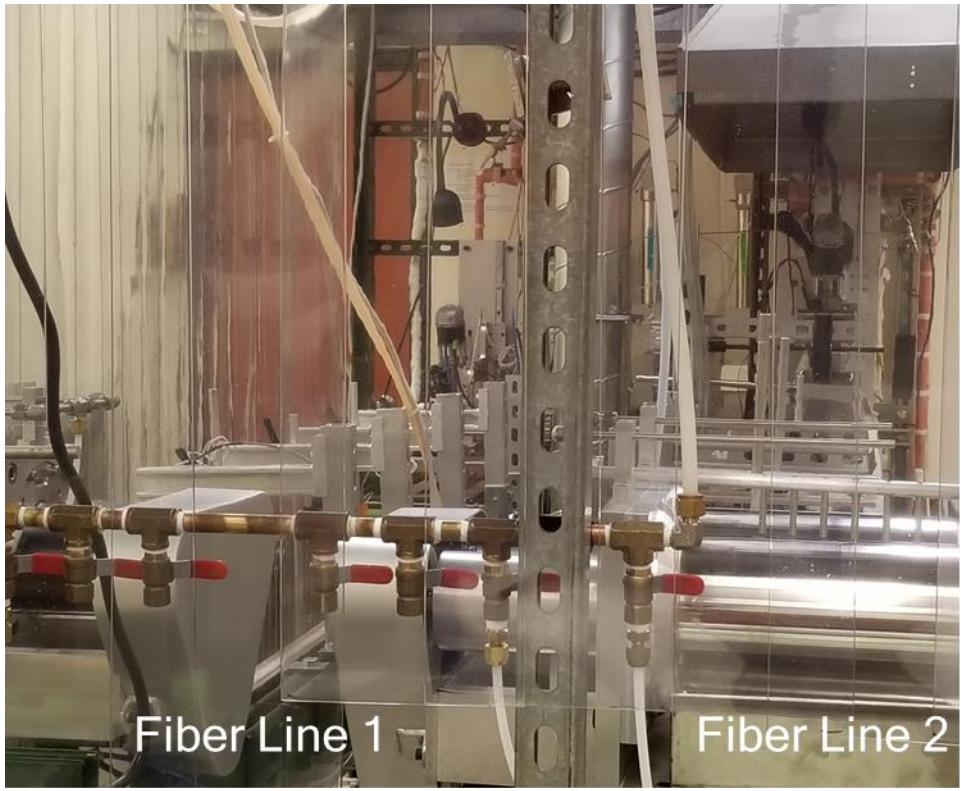
Fiber spinning and potting

Budget Period 1



Fiber spinning capacity doubled with addition of Line 2 in 2019

Spun 150 km of fibers (BP-1)

Potted 160+ cartridges (old + new style), BP-1&2

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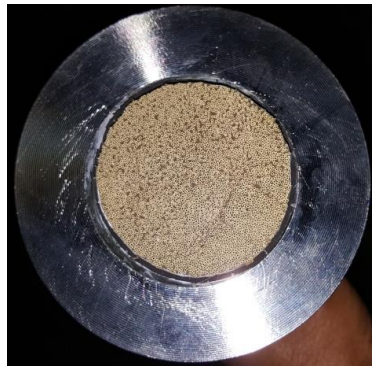
Fiber Skid Modifications/Improvements

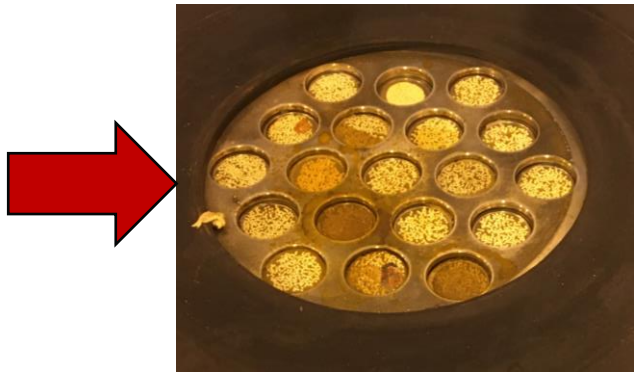
Budget Period 1 – Ensure maximum up-time at UK-CAER (max data collection)

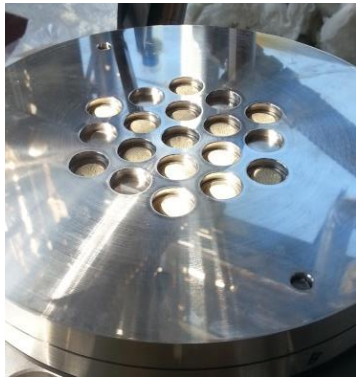
Converted 2x existing modules:

- ~6.5 m^2 each
- Only need to replace damaged cartridge
- Faster replacement than repairing the 4-inch bundle



4-inch





19x modular

Installed 2x new modules:

- ~4 m^2 each
- Faster module swapping than converted modules
- Reduce gas bypass
- Designed to allow sweep gas

2x-new modules

19x modular

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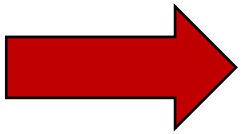
Fiber Skid Modifications/Improvements

Budget Period 1

Refurbished existing Skid:

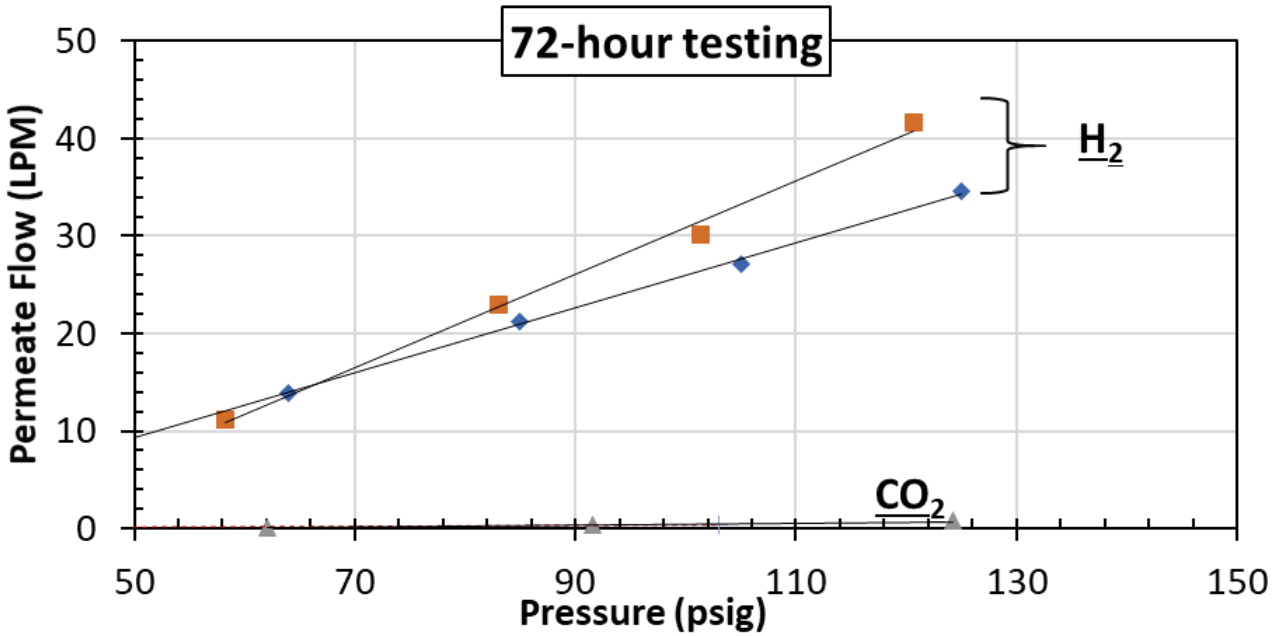


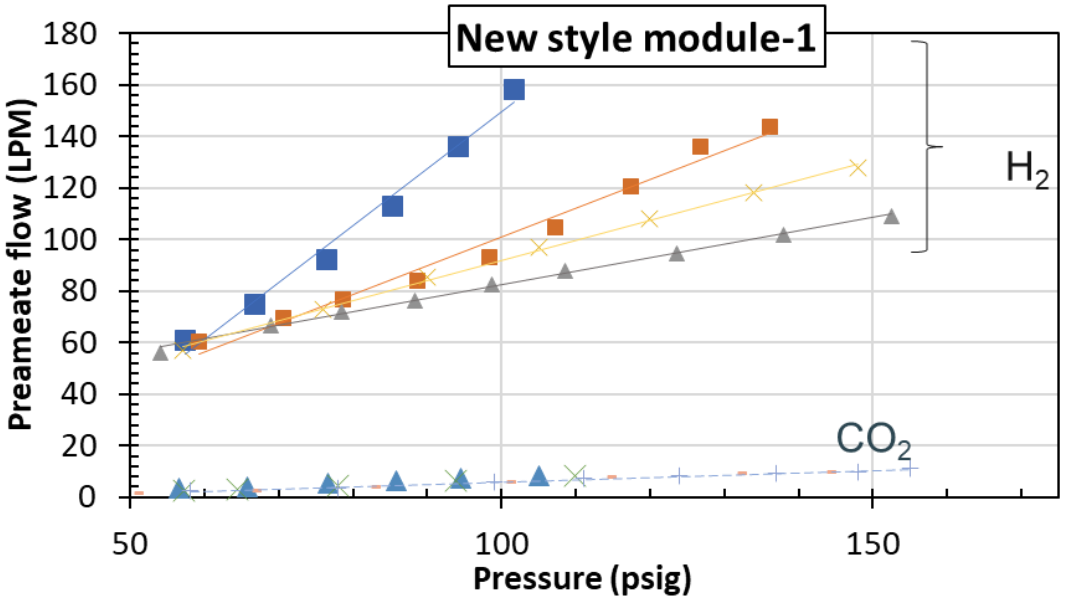
Skid Acceptance Testing

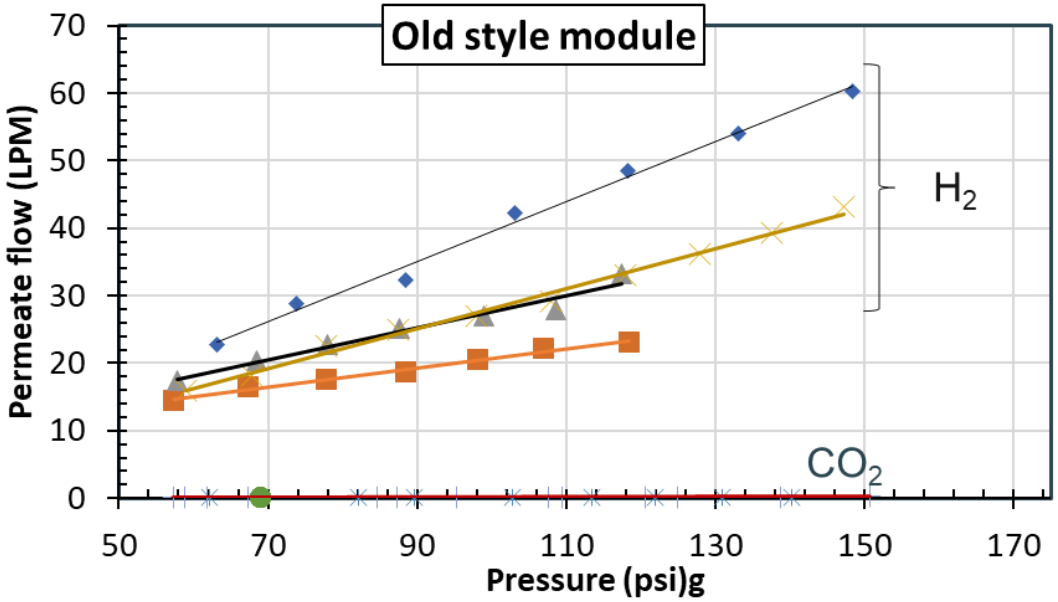
Budget Period 2

Performance met expectations:

- Over 150 hours of Skid testing at SRI
- Over 150 membrane cartridges tested in skid
- Longer testing up to 72 hours for single run
- Selectivity: 19 – 50
- GPUs: 130 (150 °C)







Skid shipping & installation at UK CAER

Budget Period 2

+ Installed at UK CAER July 2021
  - 1st trip: September 2021
  - 2nd trip: November 2021
  - 3rd trip: June 2022

Cartridges prepped for shipping

Skid inside Container

Skid Container being lifted onto trailer

Gas lines going from CAER facility into Container

UK-CAER Pilot Facility

Gasification Unit

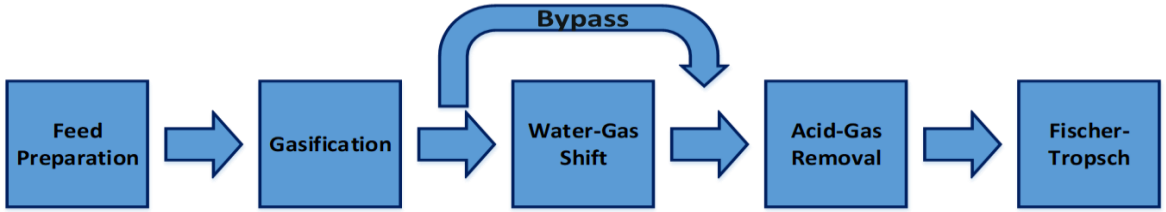
- Multi-burner, entrained flow, oxygen blown, slagging type
- 1 ton/day coal consumption
- Syngas production rate: ~80 m^3/hr
- H_2/CO: ~.80

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 (°C)	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

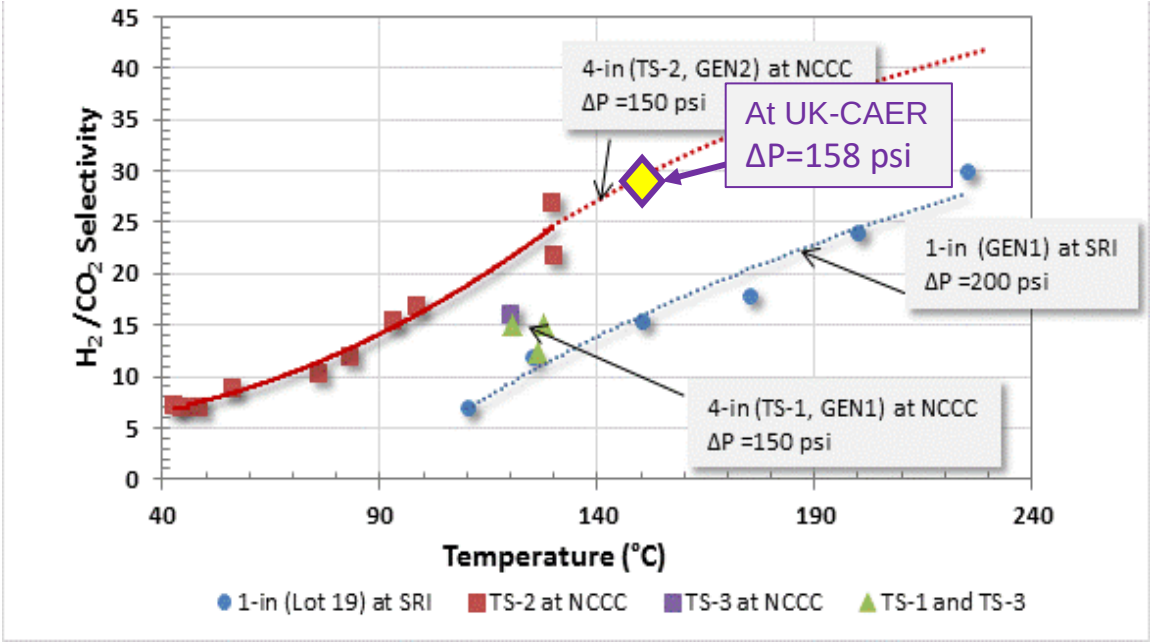
Compressor

Test Results at UK-CAER

Budget Period 2

Syngas type	H_2%	CO_2%	CO%	N_2%	H_2S%
Natural gas	20 - 22	20 - 21	26 - 27	20 - 22	0
Coal	22 - 30	30 - 40	21 - 31	11 - 17	0.3 - 0.4

Feed to skid	1st trip	2nd trip	3rd trip	All trips
Hours on nitrogen	82	175	447	694
Hours on syngas (natural gas)	14	19	22	53
Hours on syngas (coal)	2	18	31	51
Total hours on syngas	16	36	53	105
Total time hot and pressurized	98	211	500	809



Date	Pressure (psig)	Temperature (C)	Feed (L/min)	Permeate (L/min)	Stage cut (Per./feed)	H_2/CO_2
6/27/2022	162	142	9.48	2.72	0.3	22.7
6/27/2022	153	142	26.26	7.87	0.3	25.6
6/27/2022	161	143	16.97	4.52	0.27	23.5
6/27/2022	158	147	23.66	6.46	0.27	26.8

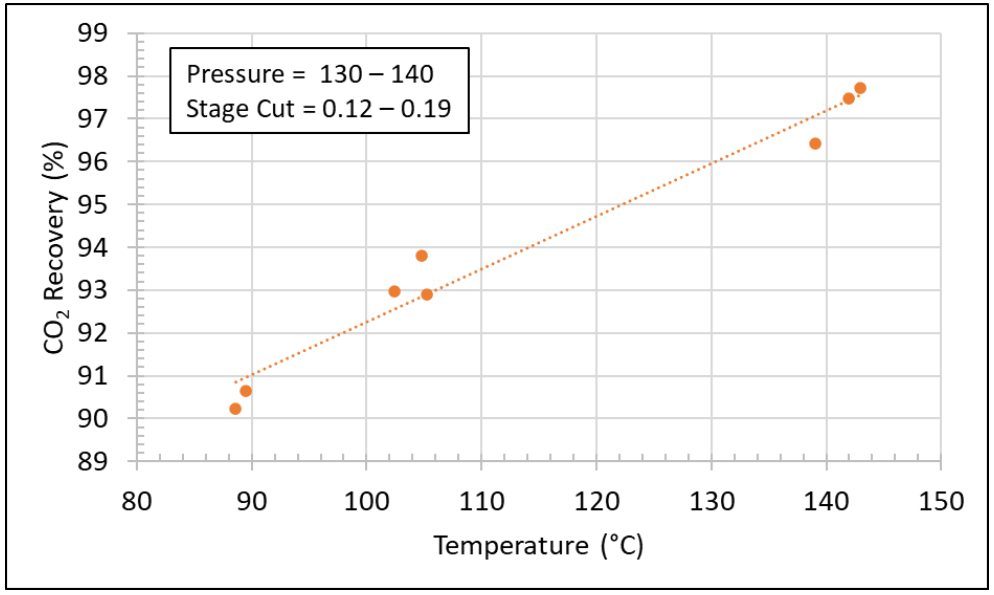
Test Results at UK-CAER

Budget Period 2

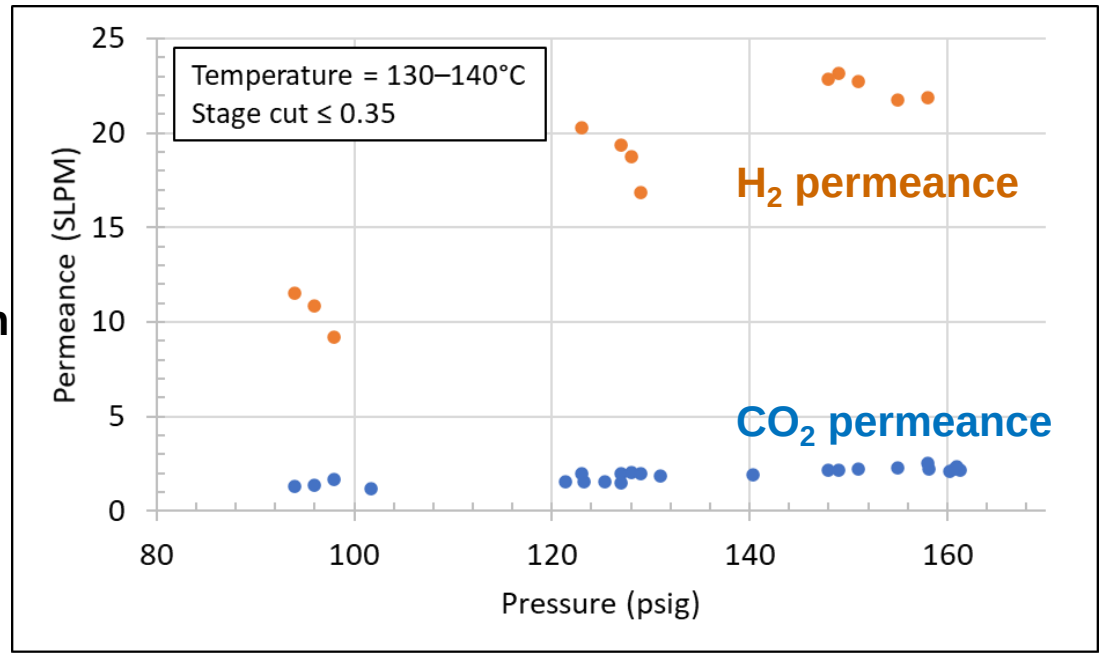
Performance on real syngas at UK-CAER agrees with results on simulated syngas at SRI.

Selectivity increases with temperature (strongest effect) and pressure

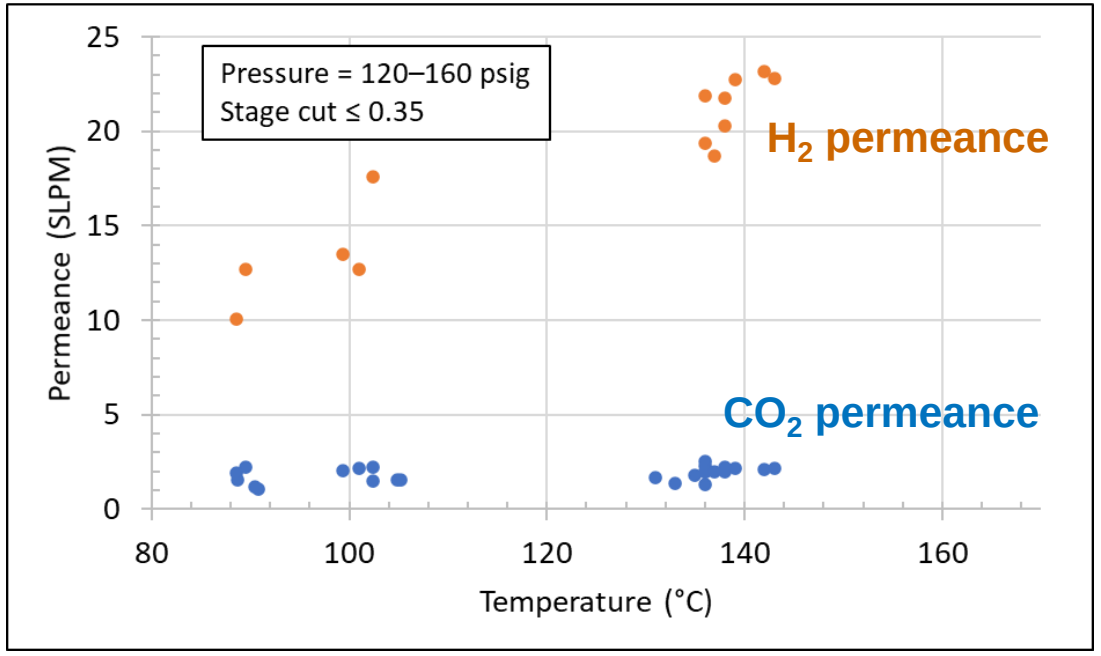
High CO_2 recovery that increases with temperature



Effect of pressure on H_2 and CO_2 permeance



Effect of temperature on H_2 and CO_2 permeance



Technology Maturation

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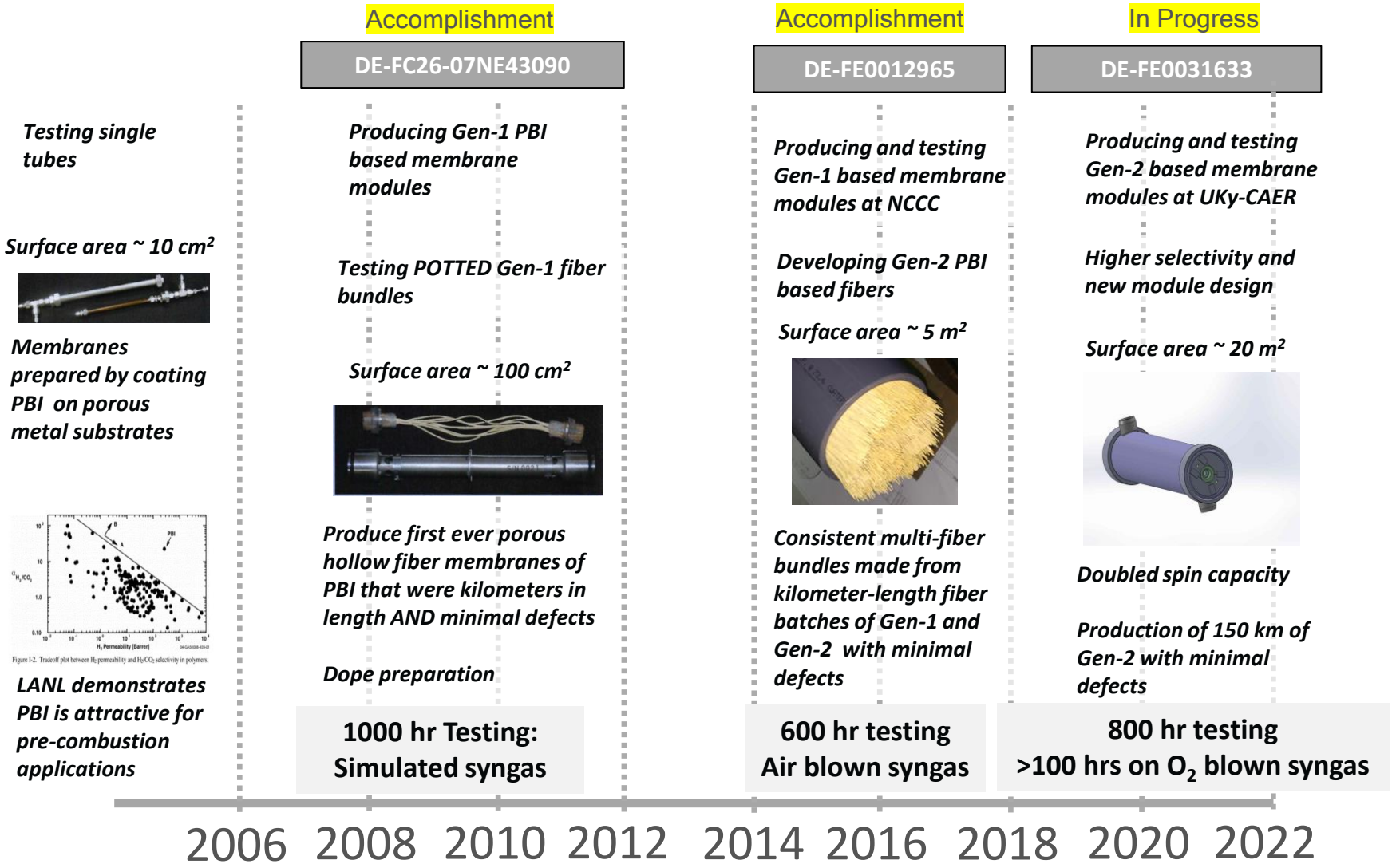
DOE Funding Critical to Technology Maturation

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



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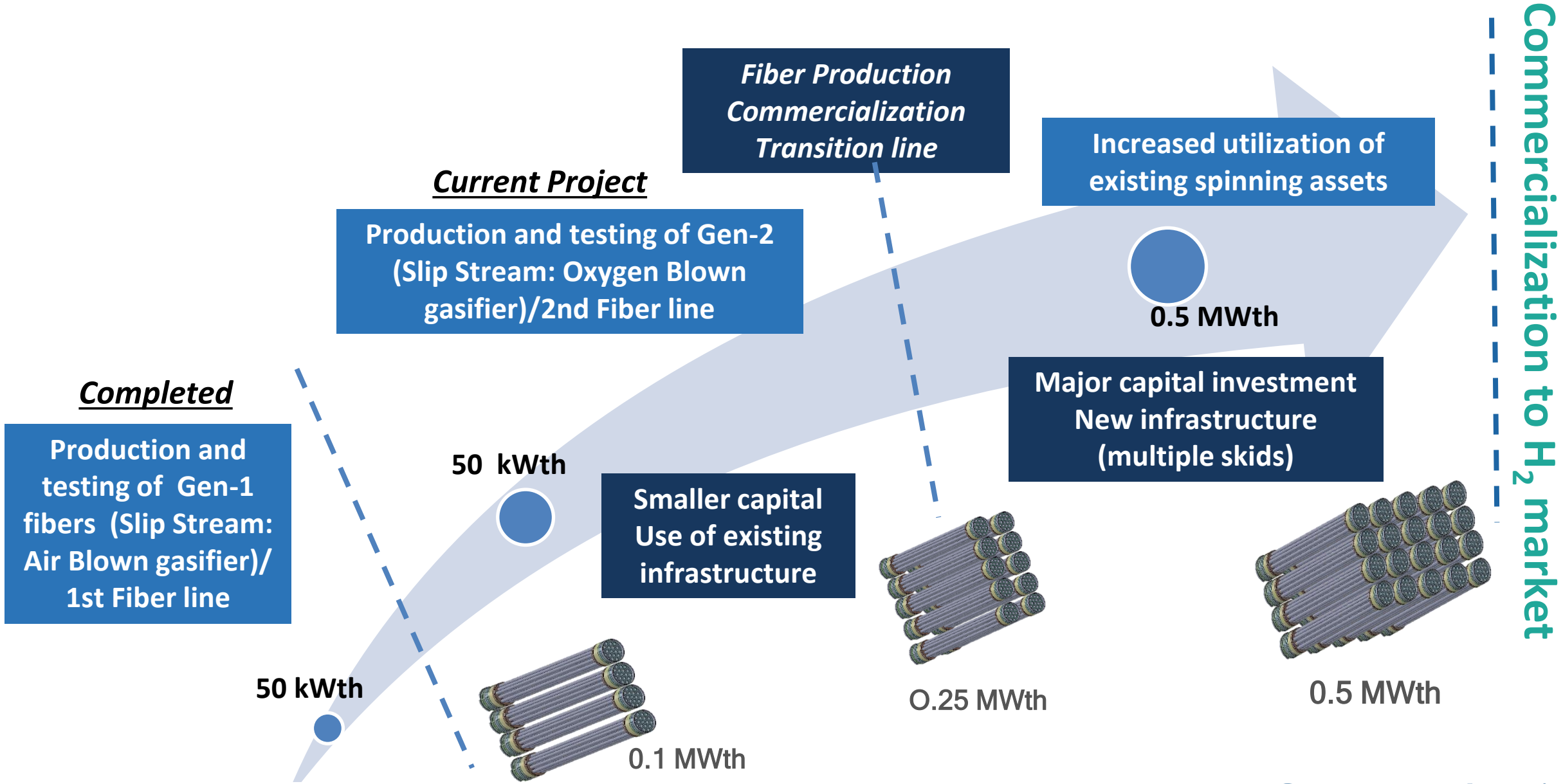
Roadmap to Small and Large Pilot Scale



US Patent 9,321,015 Issued on April 26, 2016

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Acknowledgements

+ Krista Hill, Dan Hancu, Andrew Jones, Jose Figueroa, Lynn Brickett, and others at NETL

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

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

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Thank you

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