SRI International

Project Review (FE0031633)

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

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Integrated Systems and Solutions (InSyS) Division

SRI International

Project Team

NATIONAL ENERGY TECHNOLOGY LABORATORY

PBI PERFORMANCE PRODUCTS, INC.

Enerfex, Inc.

Energy Commercialization, LLC

Center for Applied Energy Research

August 12-17, 2021 • Carbon Management and Oil and Gas Research Project Review Meeting • Virtual Session

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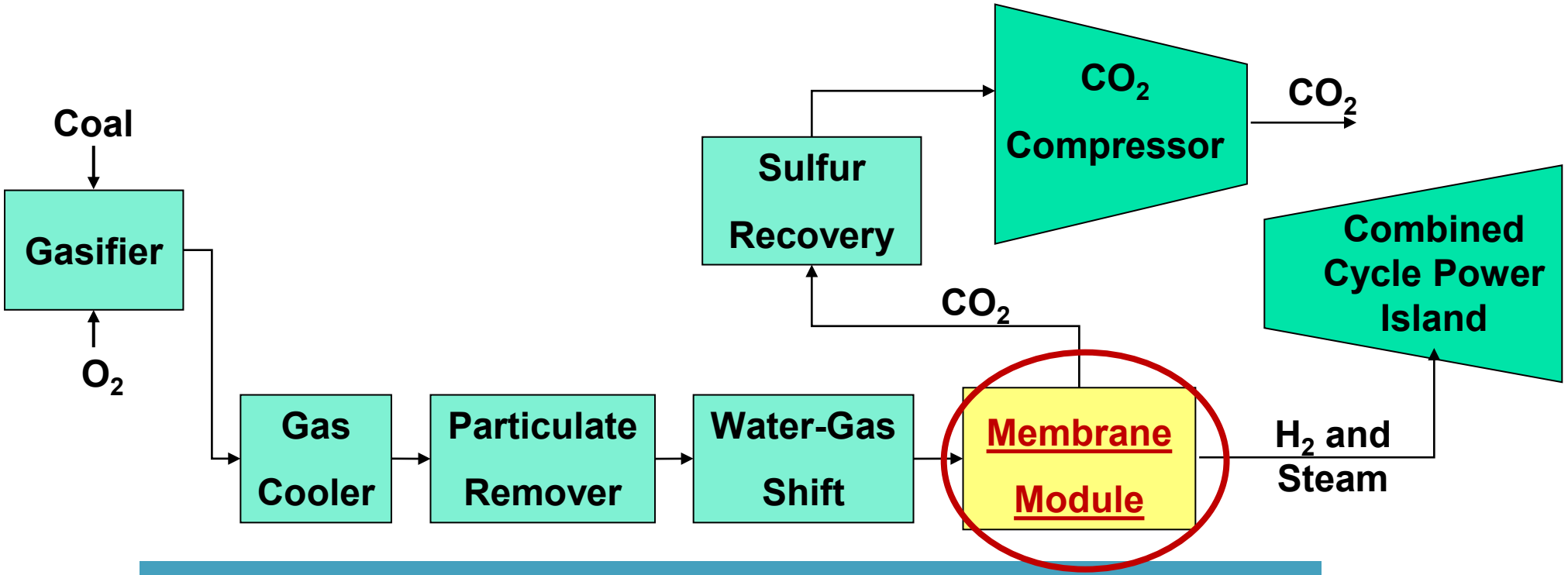
Technology Background and Previous Projects

Membranes for Pre-Combustion CO_2 Capture

Advantages of High-Temperature Membranes for Separation of CO_2



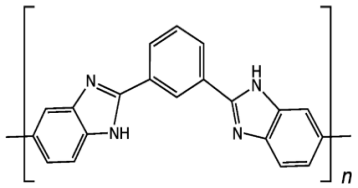
Note: PBI hollow fiber membrane (HFM) is a H_2O and H_2 transporting

Characteristics of PBI Membranes

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

Advantages of Membrane-Based Separation

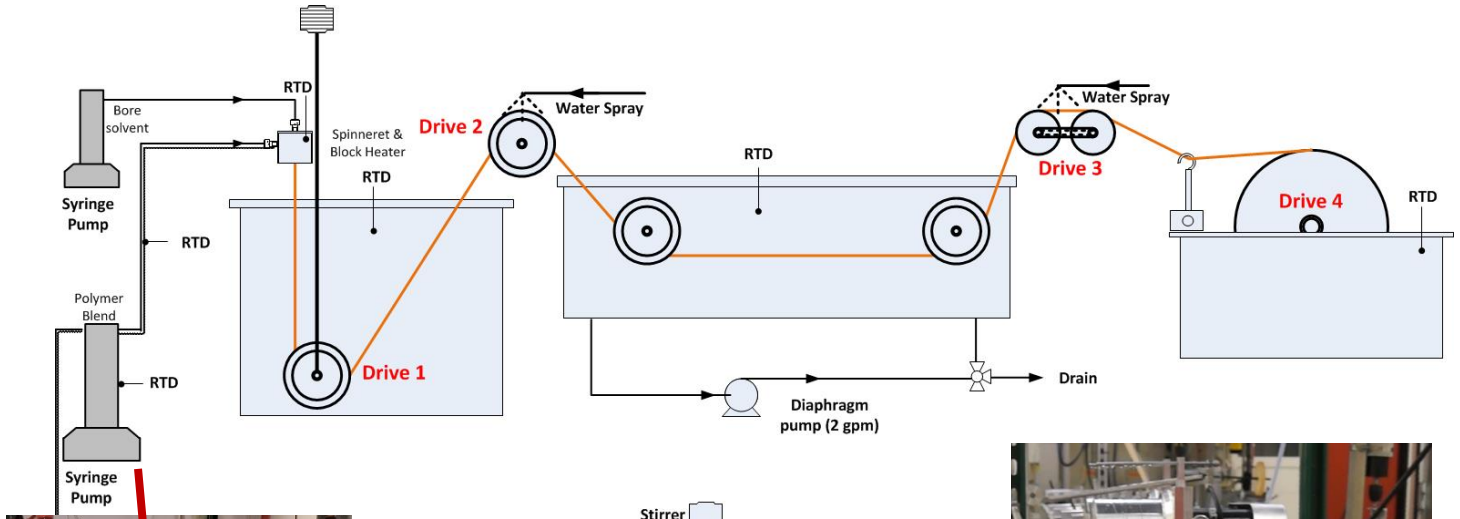
- Reduced costs for syngas cooling
- Reduced CO_2 compression costs
- Emission free, i.e., no solvents
- Decreased capital costs
- Low maintenance
- Modular



m-Polybenzimidazole (m-PBI)

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

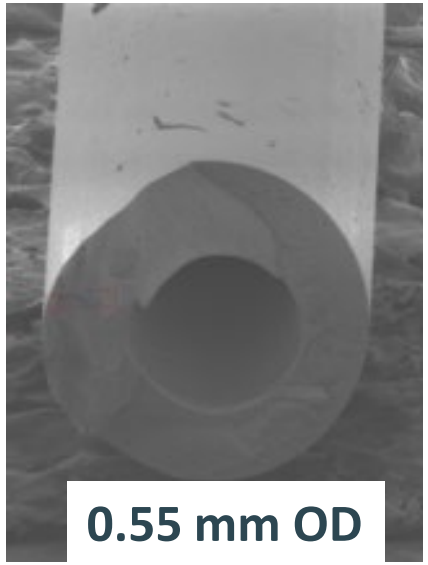
Variety of Applications:

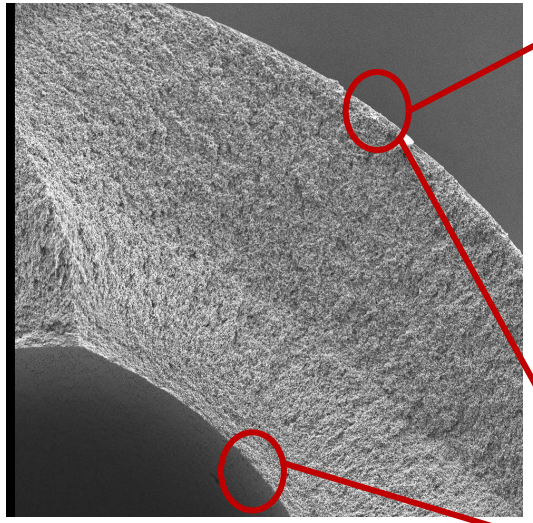
- Gas Separations[1]
- Reverse Osmosis (RO)[2]
- Ultra Filtrations (UF)[3]

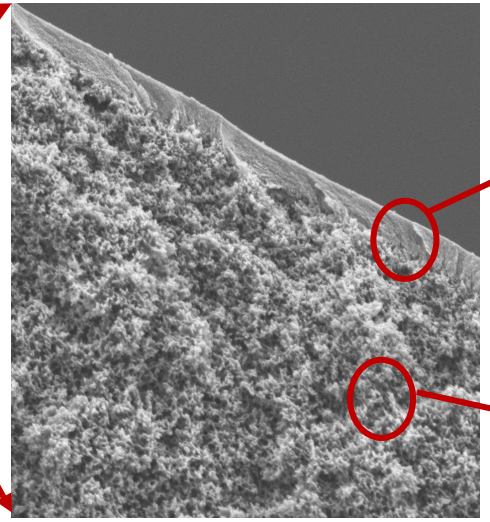
1. Xiao et al. (2018), Membranes, 2018, 8(4), 113;
2. Wales et al. (2021), Membranes, 2021, 11(6), 430;
3. Xiao et al. (2021), Desal and Water Treatment, 2021, 69-78, 229

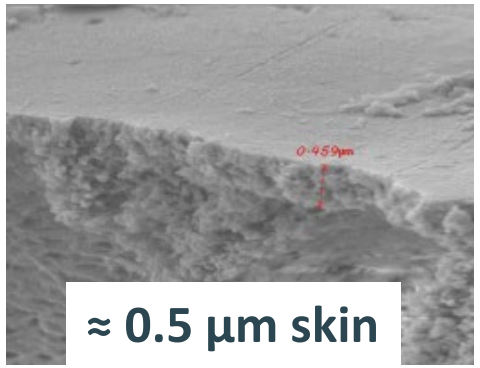
Fabrication of Fibers with Good Reproducibility

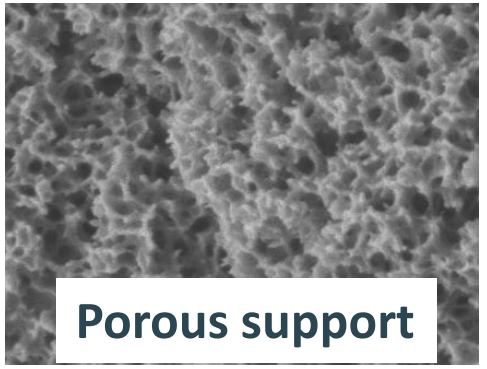
Quality Control is the KEY to success when scaling up











SRI Fiber Production – VERY GOOD REPRODUCIBILITY:

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

Tunable

- Spun > 500 km

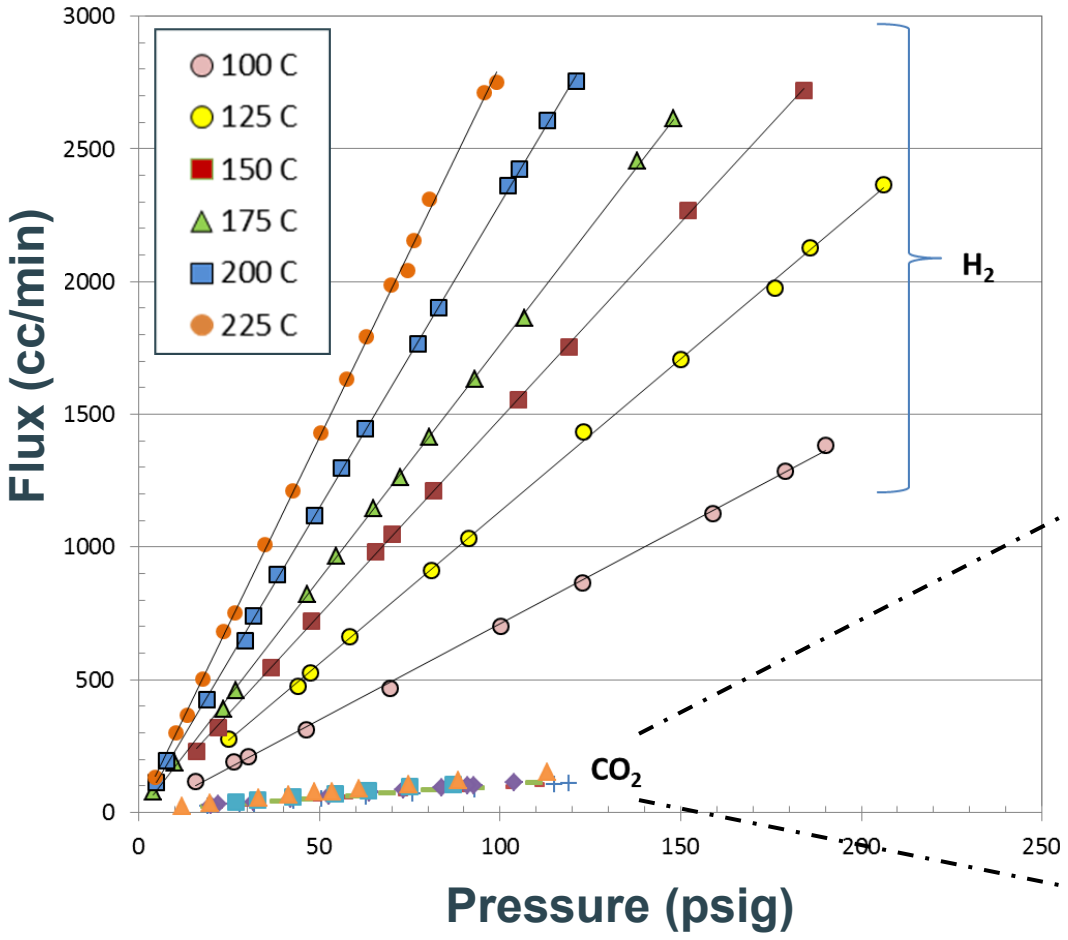
Achievements:

- 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:

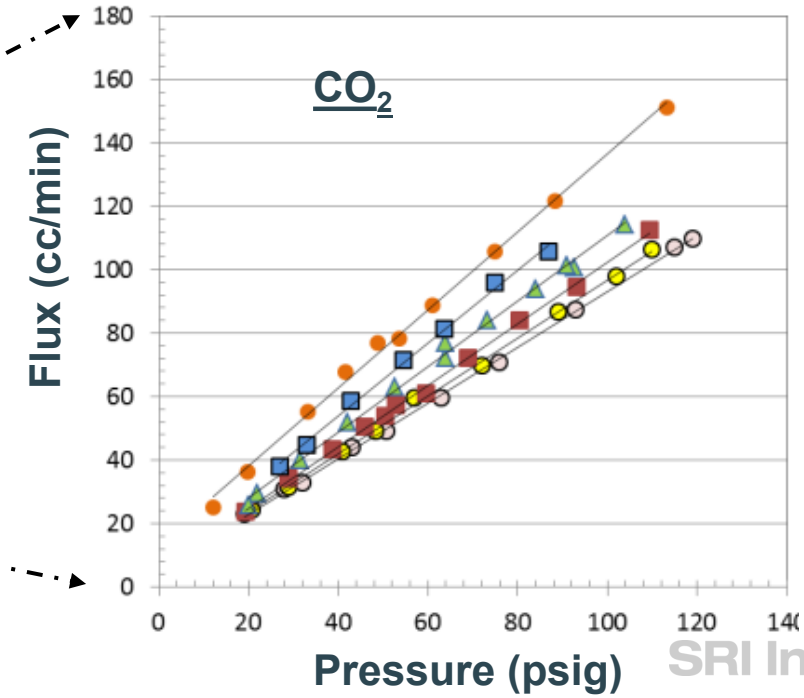
- 0.5 µm dense layer
- Reduce defect, improve reproducibility

PBI H_2/CO_2 Selectivity Increases with Temperature and Pressure



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	

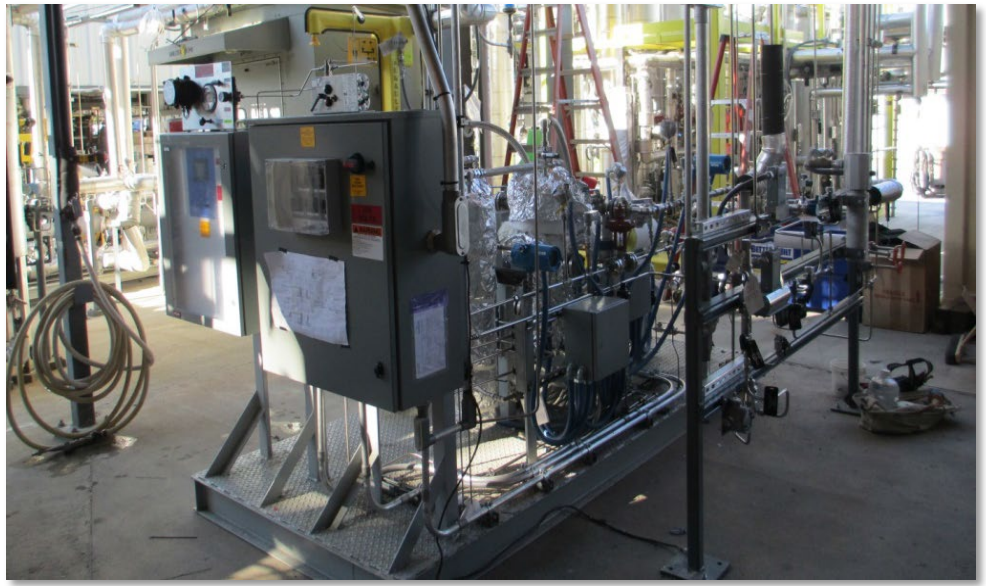


Critical Asset: Membrane Testing Skid

Field Tested at the National Carbon Capture Center (NCCC)

5,000 fibers (5 m^2) arranged for potting

4-inch modules (~5,000 fibers)



Skid installed at the NCCC (April 2017)

<u>50 Kilowatt-Thermal Demonstration</u>:

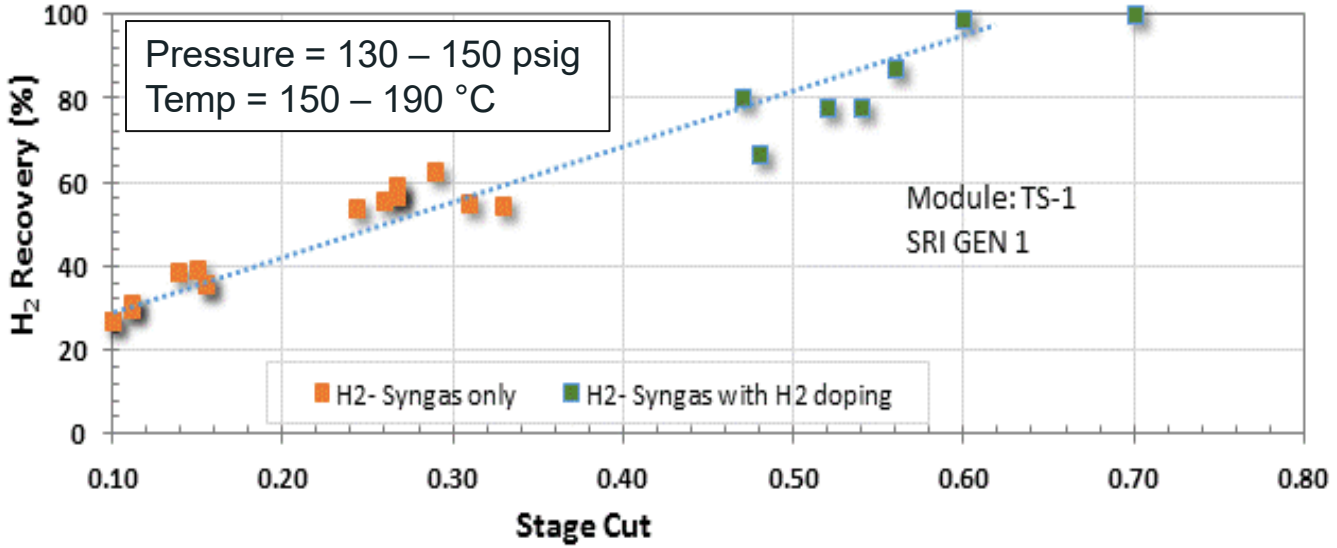
- PBI membrane skid transferred to NCCC in March 2017
- Tested in April 2017 (>600 hours)
- Returned to SRI in March 2018
- Used in current work (with upgrading)

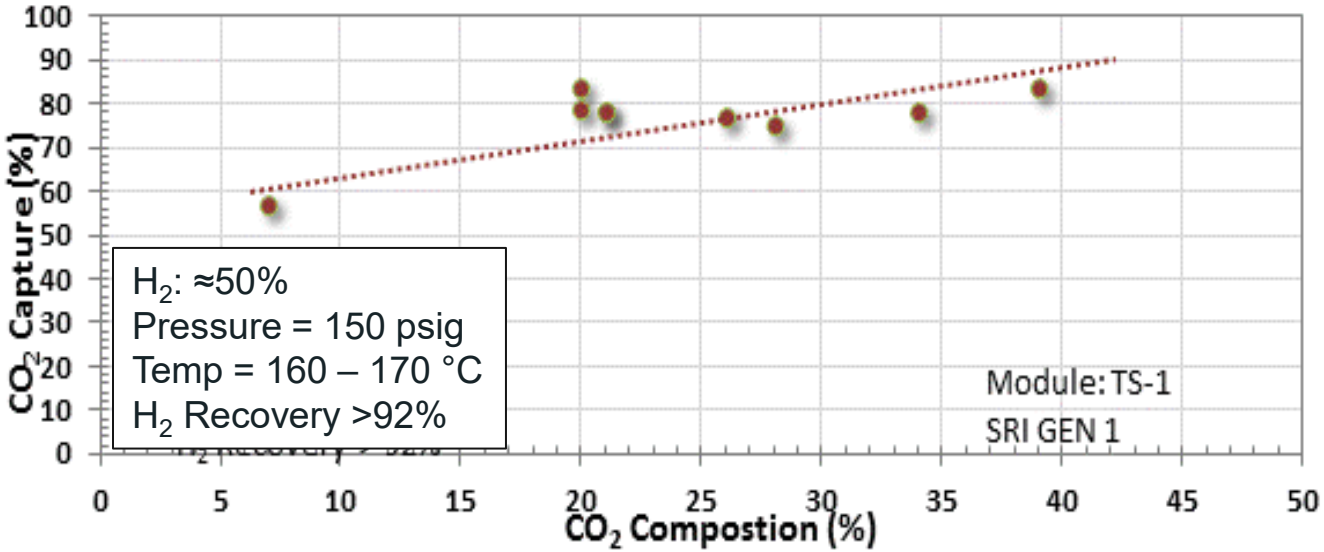
Results from NCCC Field Test

Air-Blown Gasifier

Sample parametric matrix

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

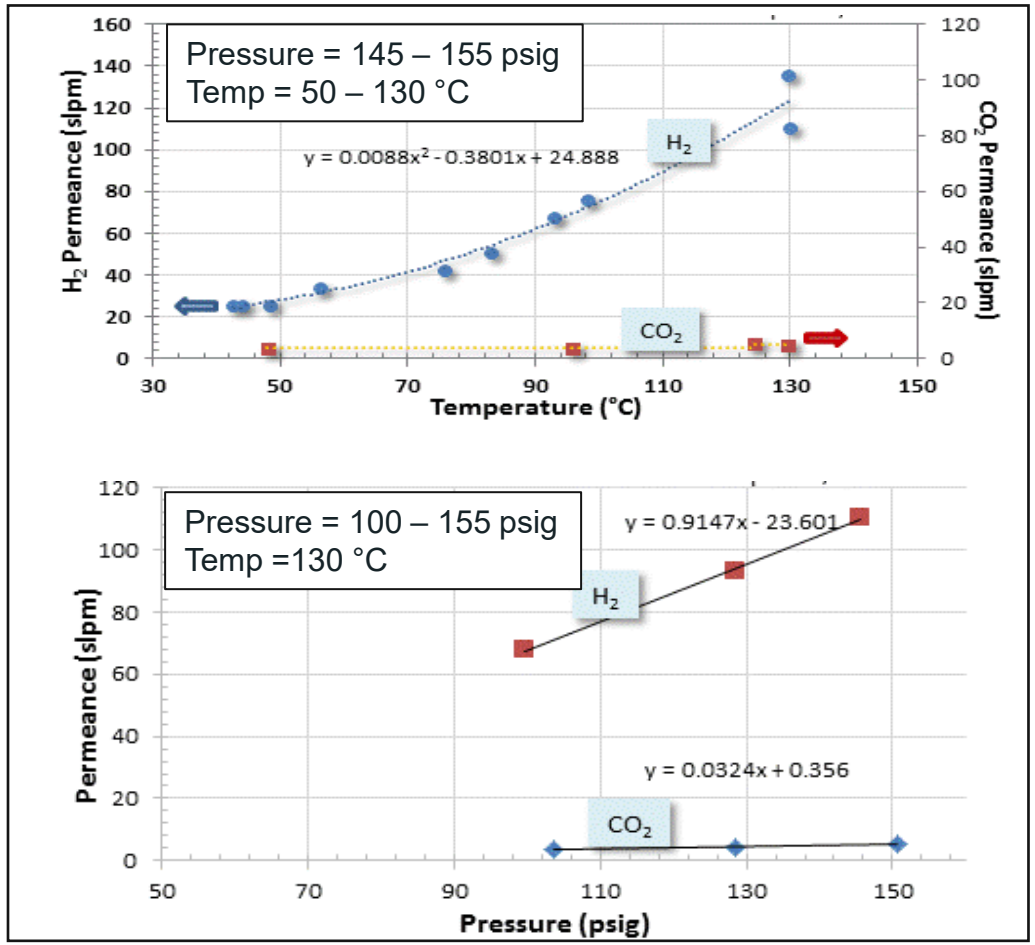




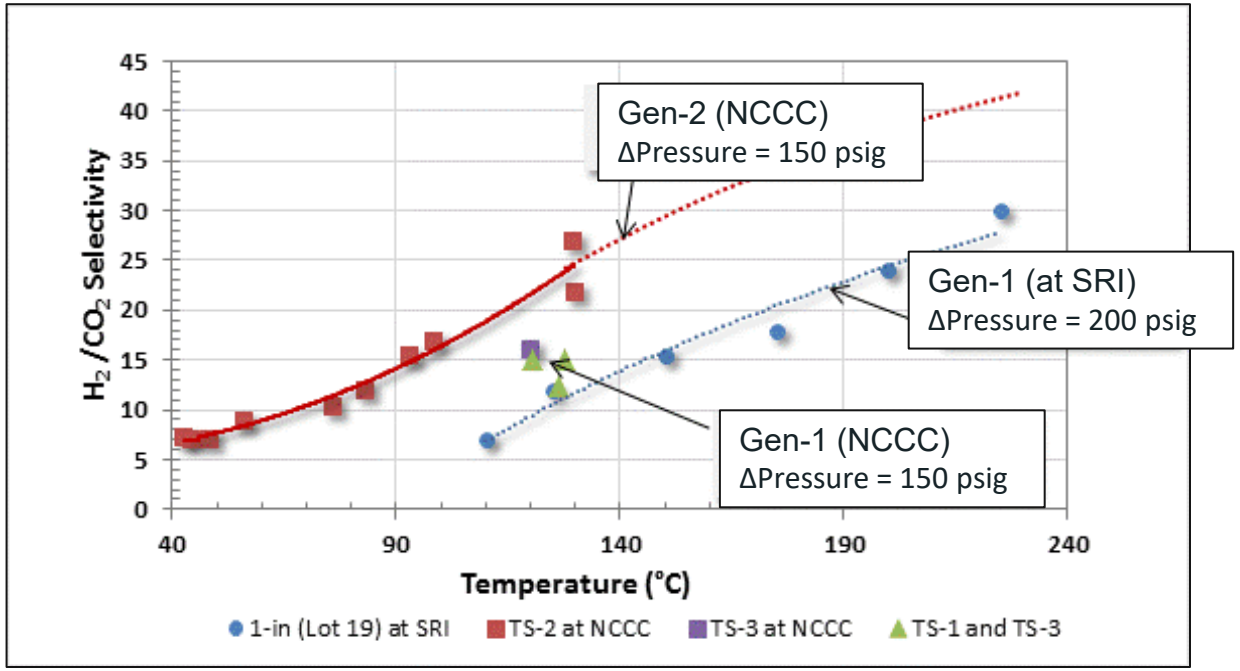
600 Hours of Data Collected

Gen-2 Results from NCCC Field Test

Air-Blown Gasifier



H_2 and CO_2 permeances as a function of temperature (top), function of pressure (bottom)



Gen-1 and Gen-2 selectivities as a function of pressure

<u>Selectivity of PBI Gen-2 > PBI Gen-1</u>:

- Gen-2 has better selectivity than Gen-1

  40 compared to 25
- Gen-1 has higher flux (150 GPU compared to 100 GPU
- Selectivity is more important than Flux (TEA)

TEA

Developed by Enerfex

Case Name	IGCC-B1A Baseline No Capture	IGCC-B5B [1] Baseline CO_2 Capture	SRI PBI GEN-1 Membrane CO_2 Capture	SRI PBI 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%	90.04%	90.02%
CO_2 purity	n/a	99.48%	95.62%	95.57%
H_2 recovery	n/a	99.98%	96.10%	99.64%
HHV plant efficiency	42.10%	32.60%	32.61%	34.39%
LHV plant efficiency	43.70%	33.80%	33.81%	35.65%
COE w/o T&S ($/MWh)	$107.10	$135.30	$120.76	$117.74
COE w/ T&S ($/MWh)	$107.10	$144.50	$129.96	$126.94
% Increase in COE	0.00%	34.92%	21.34%	18.52%

% Increase in Cost of Electricity (COE)

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

Current Project Details

Objectives

<u>Demonstrate that Gen-2 PBI based HFM provide a pathway to achieve DOE's pre-combustion capture targets</u>:

- Targets: 90% CO_2 capture and 95% purity
  >99% H_2 recovery
  30% reduction in COE
- Field test 50 kWth fiber skid
- University of Kentucky Center for Applied Energy Research (UK-CAER), Oxygen Blown Gasifier
- Techno-Economic Analysis from field data

<u>Leverage assets, technology, and knowledge from previous projects</u>:

- Spin 100 km of SRI PBI fibers
- Improved potting and module construction
- Modifications/improvements to fiber skid

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:

- 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 Techno-economic analysis

Energy Commercialization

- Commercialization analysis

UKy CAER

- Gasifier facility test site

Project Objectives and 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 100 km of SRI PBI Fibers - Module design and installation of the Modules (4 to 6-in diameter) - Membrane performance testing at SRI - HAZOP and PI&D Review at UK-CAER	Competed
3	1	Modeling - Modeling of the Module arrangement - Modeling of the skid performance - Preliminary TEA	Completed

Project Objectives and Tasks

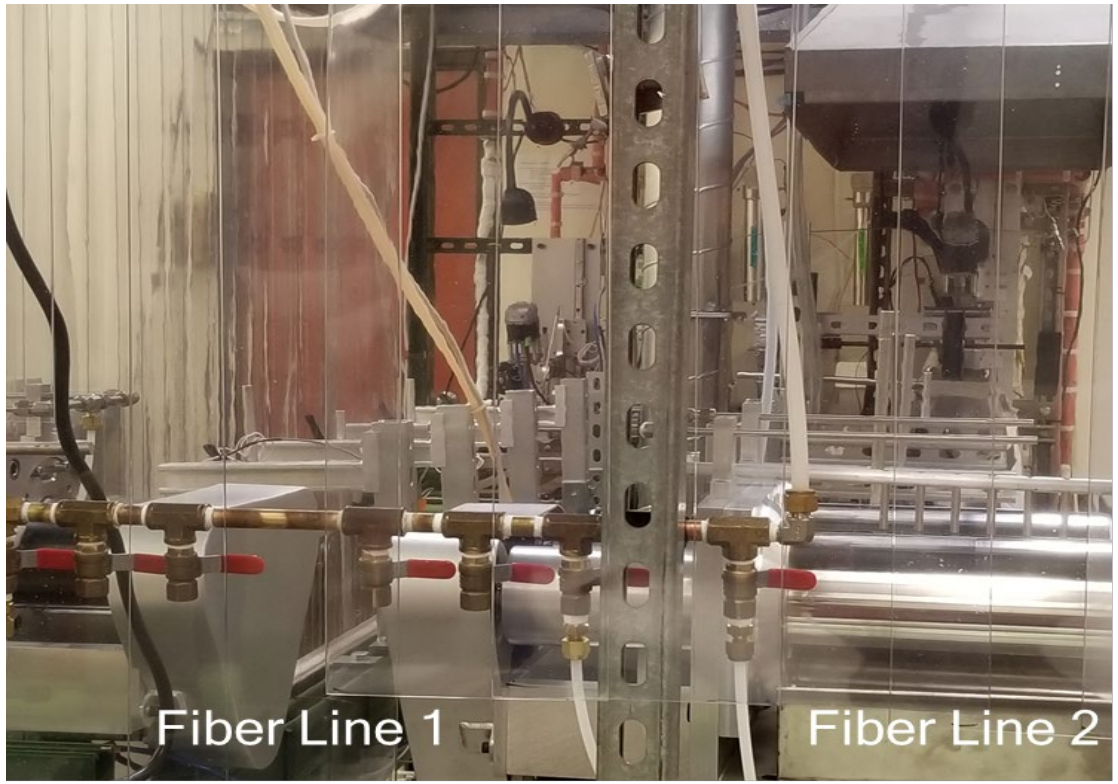
Budget Period 2 (04-01-2020 → 09-30-2021)

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	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 (Post-UK CAER)
6	2	Skid Decommissioning - Skid decommissioning and Transport - Skid Postmortem and Storage	Not Started (Post-UK CAER)

2nd Spinning Line Installed in 2019

Budget Period 1

New = Fiber Line 2 (right):

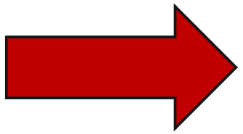


Spin 150 km of fibers (BP-1):

Fiber Skid Modifications/Improvements

Budget Period 1

Refurbished existing Skid:



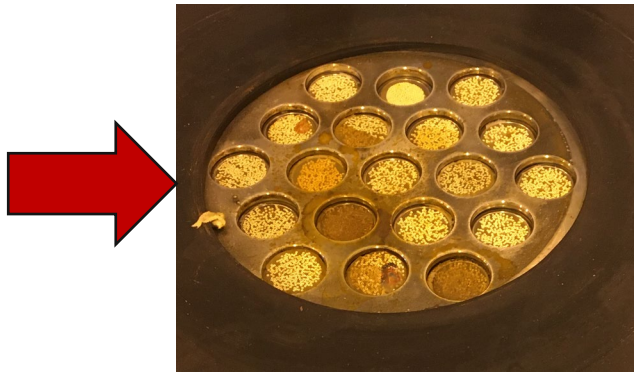
Fiber Skid Modifications/Improvements

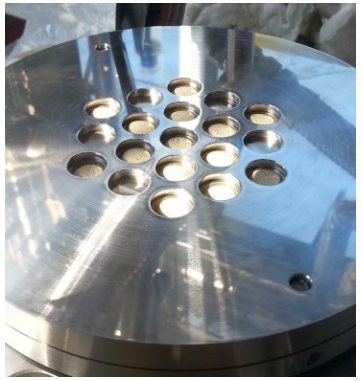
Budget Period 1 – Ensure maximum up-time at UK-CAER (max data collection)

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



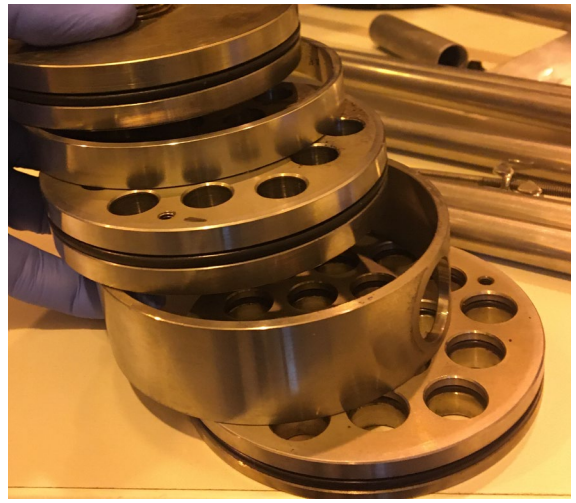


19x modular

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

Fiber Spinning and Potting

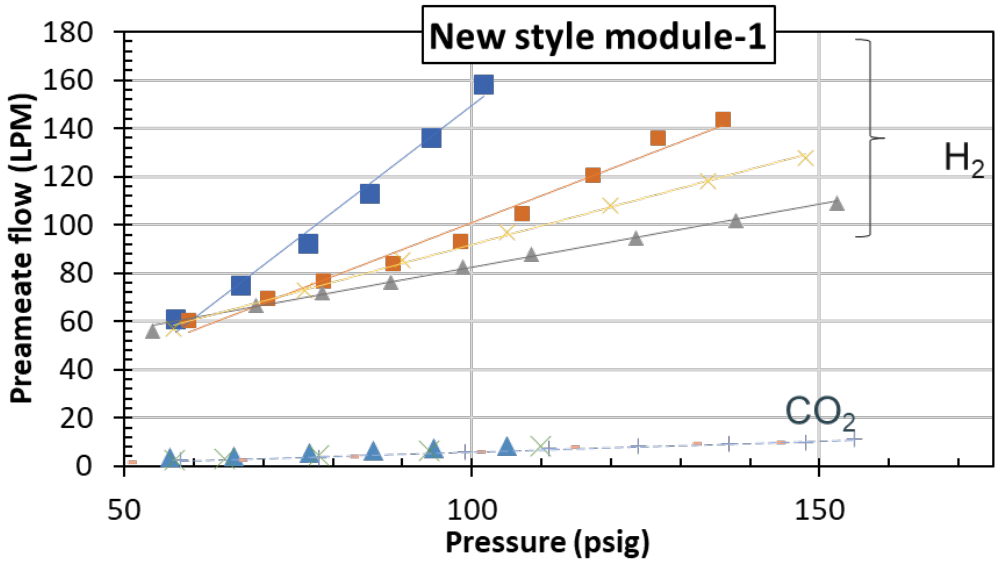
Budget Period 1 & 2

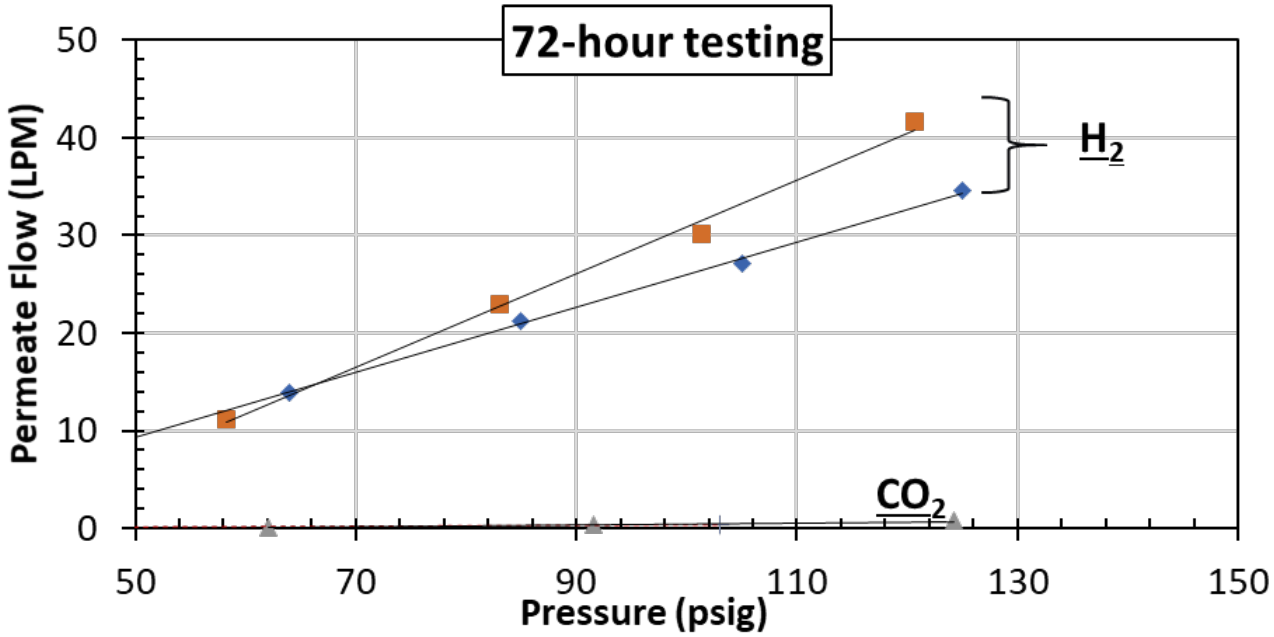
Spin 150 km of fibers (BP-1)

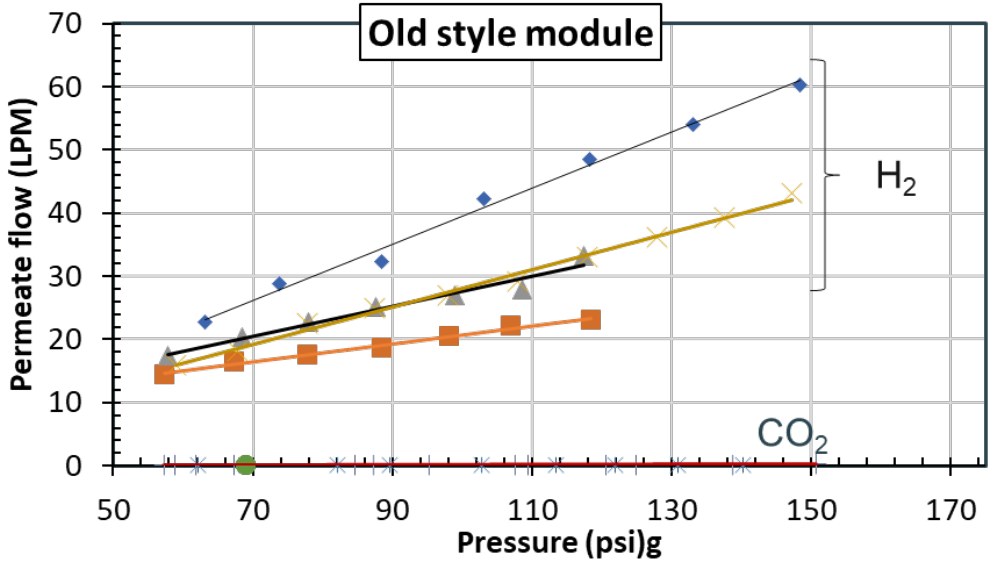
Potted 160+ cartridges (old + new style), BP-1&2

Skid Acceptance Testing

Budget Period 2







Performance meets expectations:

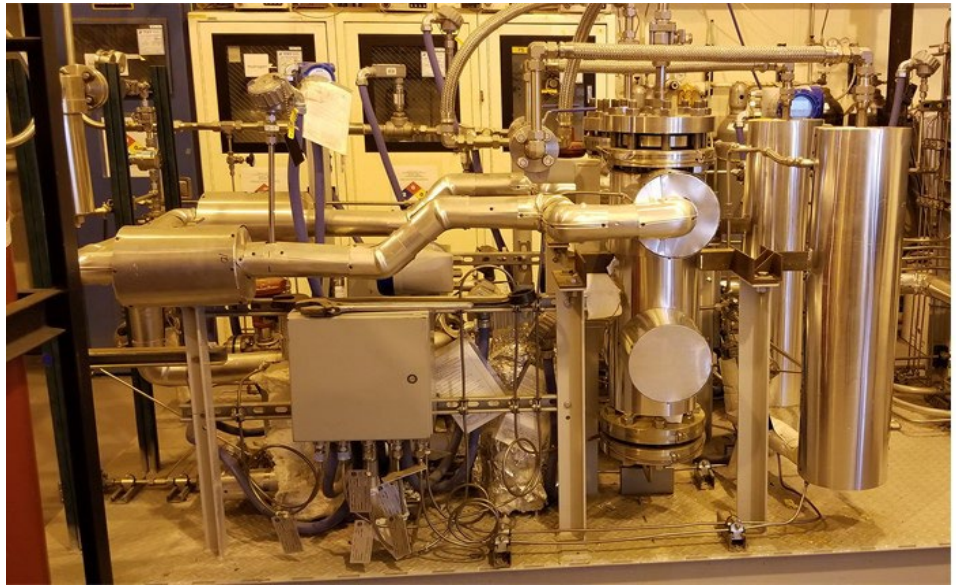
- Selectivity: 19 – 50
- GPUs: 130 (150 °C)
- Up to 72 hours of testing

Skid Acceptance Testing

Budget Period 2

Summary:

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



Fiber Skid Shipped and Installed at UK CAER

Budget Period 2

Shipped to UK CAER July 2021

Fiber Skid Shipped and Installed at UK CAER

Budget Period 2

Installed at UK CAER July 2021

Skid inside Container

Gas lines going from CAER facility into Container

Gas lines going into Skid Container

UK-CAER Pilot Facility

Gasification Unit

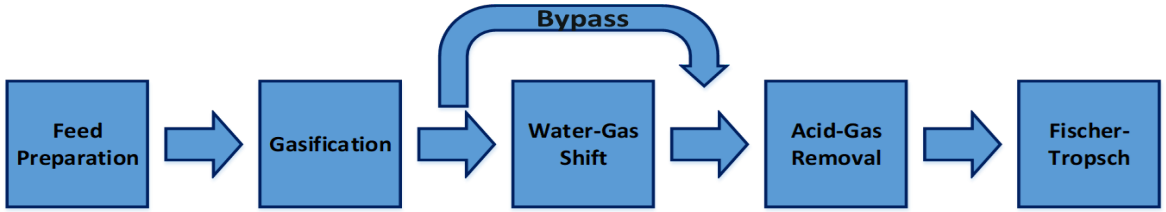
- Multi-burner, entrained flow, oxygen blown, slagging type
- 1 ton/day coal consumption
- Syngas production rate: ~80 m^3/hr
- H_2/CO: ~.80

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 Plan and Schedule

Budget Period 2

Parametric matrix

Parameter	Range/Value	Unit
Temperature	80 - 225	°C
Pressure	50 - 200	psig
Gas Composition	Variable	
Stage Cut	0.2 – 0.7	
H_2 in syngas	40-45	vol%
CO_2 in syngas	40-42	vol%

Testing Schedule: Starting September 7th, 2021

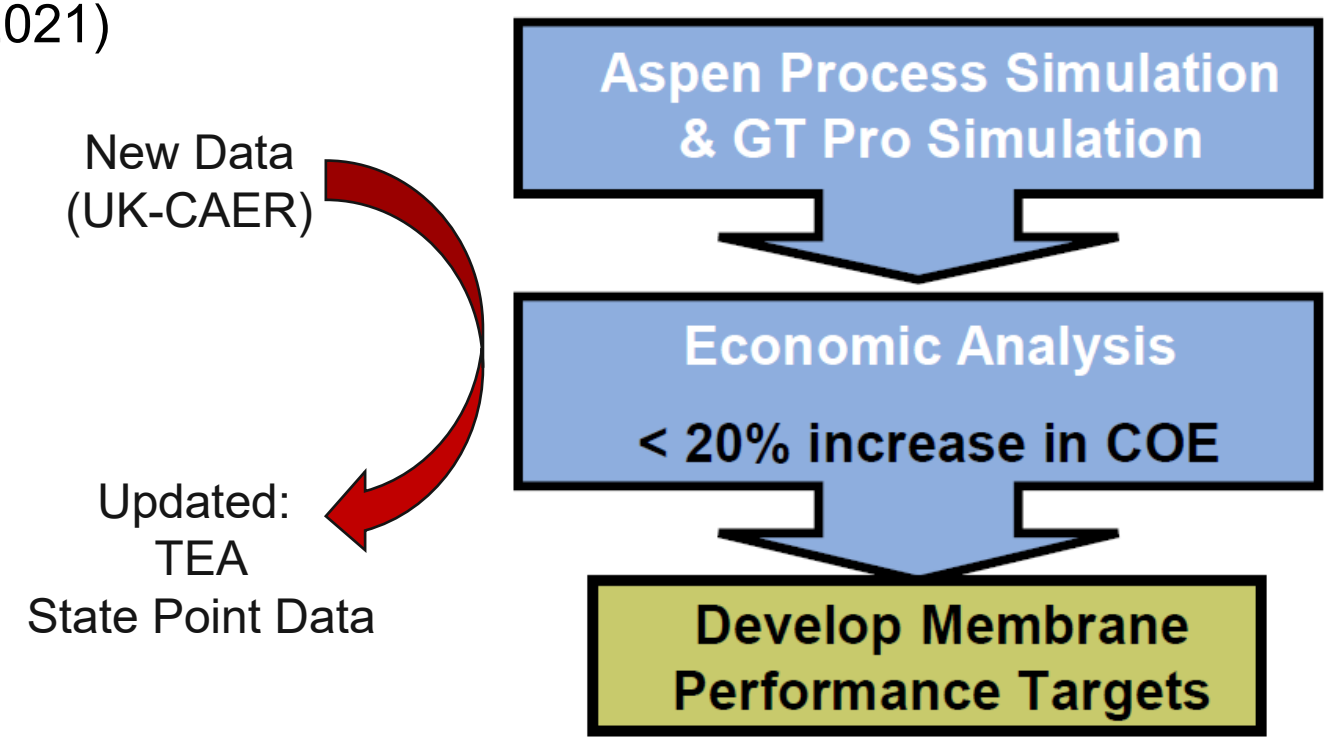
Week #	Days/week	Hours/day	Total Hours
1	5	10	50
2	5	10	50
3	Test Data Analysis		
4	5	10	50
5	5	10	50
6	Test Data Analysis		
7	5	10	50
8	5	10	50
9	Test Data Analysis		

Future Work

Budget Period 2 Final Tasks

1. **UK-CAER**:
   - 6-weeks of Testing (start date 09-07-2021)
   - Generate high fidelity data

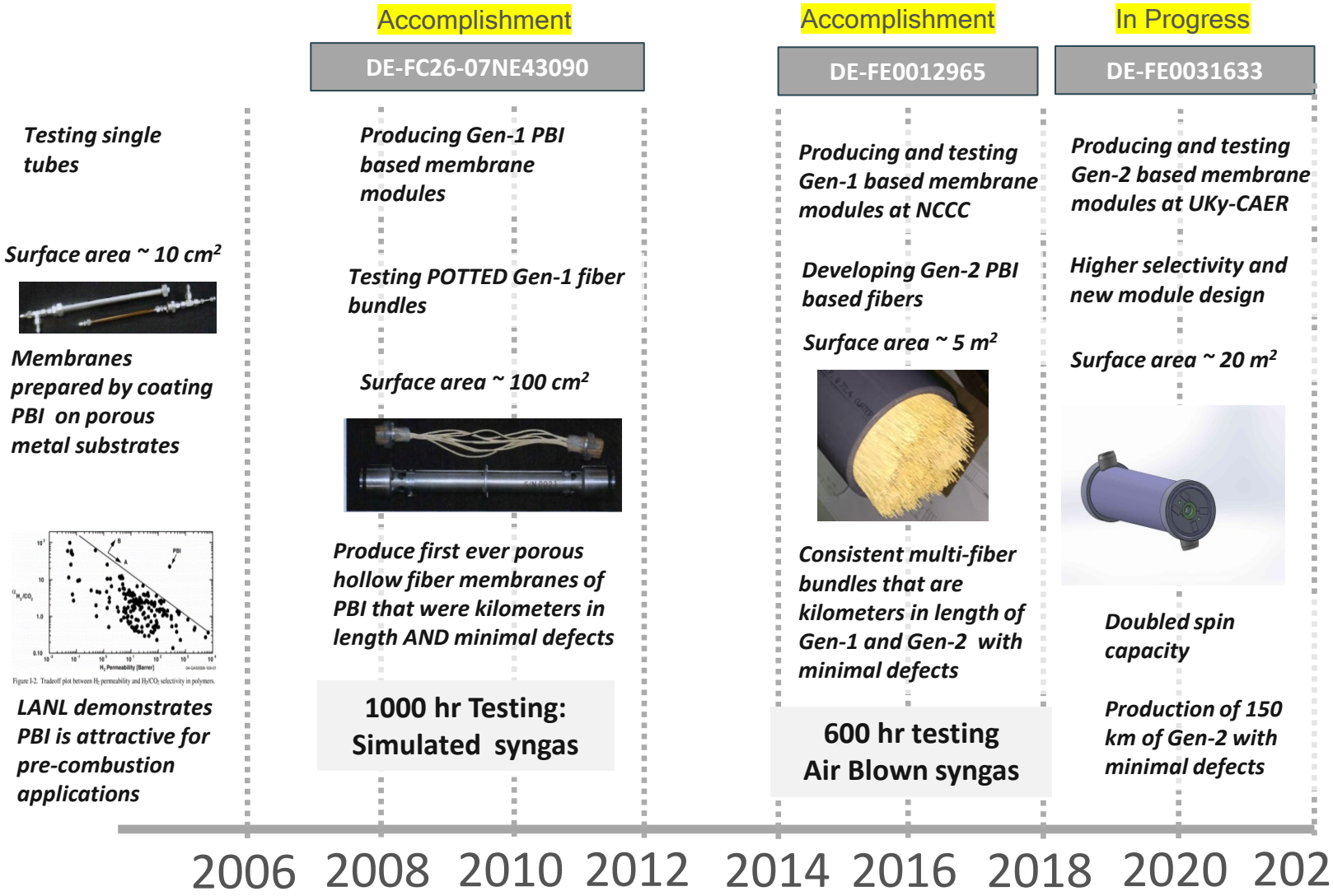
2. **Post UK-CAER**:
   - Update Techno-Economic Analysis
   - Technology Gap
   - Technology Maturation Plan
   - State Point Data Table



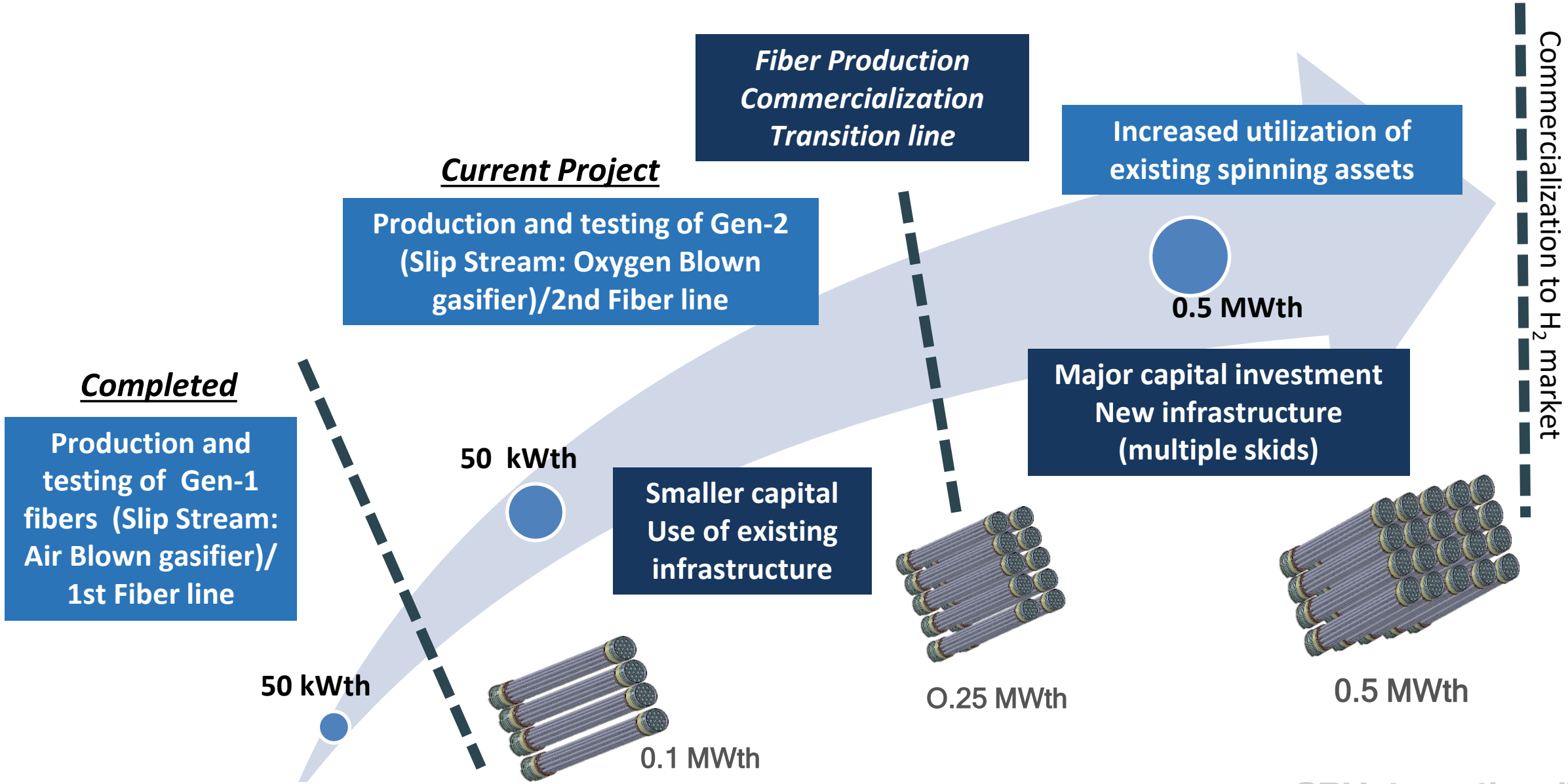
Technology Maturation

DOE Funding Critical to Technology Maturation

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



Roadmap to Small and Large Pilot Scale



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

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- Indira Jayaweera (Principal Investigator), and the rest of the SRI team: Srini Bhamidi, Regina Elmore, Xiao Wang, William Olson, Gopala Krishnan, Milad Yavari, Elisabeth Perea, Palitha Jayaweera and Chris Lantman
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- Kevin O'Brien (Energy Commercialization, LLC)
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- John Jensvold and his team (Generon IGS)
- The staff at the NCCC

Thank You

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