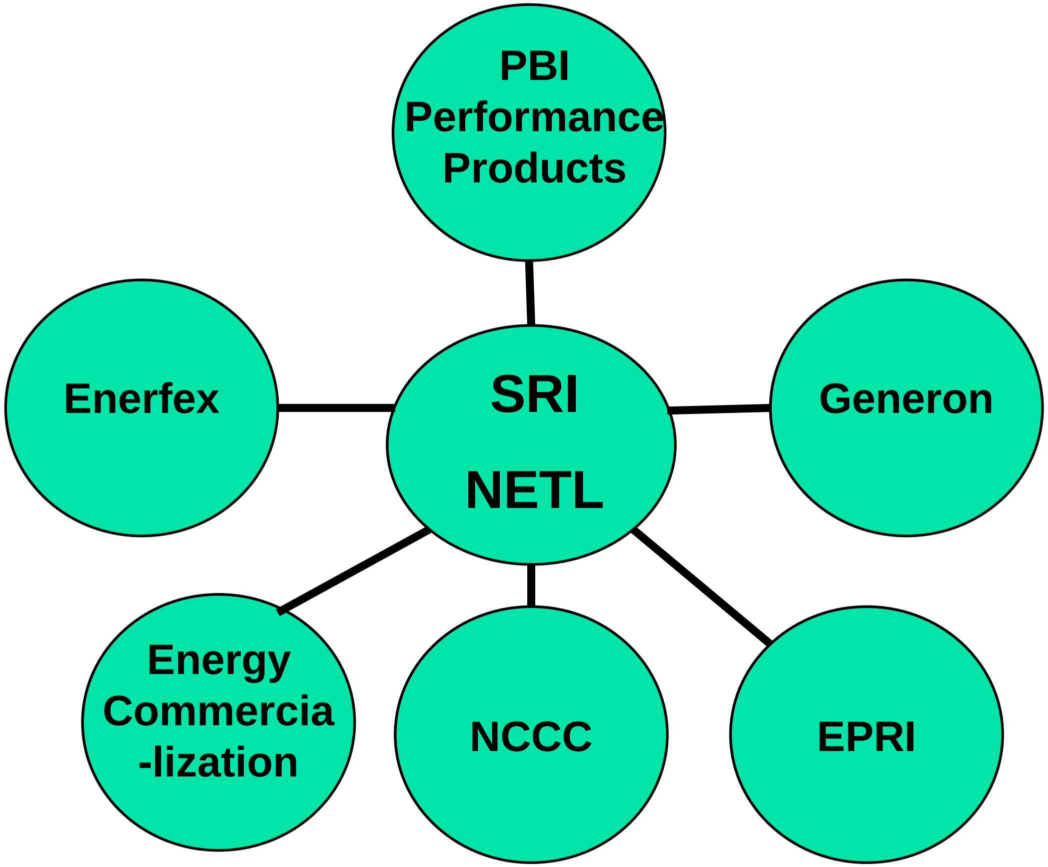
Development of a Precombustion CO_2 Capture Process Using High-Temperature PBI Hollow-Fiber Membranes

Kick-Off Meeting

National Energy Technology Laboratory, Pittsburgh, PA.

June 9, 2014

Project Team



<u>SRI:</u>

PBI Membrane Fabrication Research

Membrane Testing

<u>PBI Performance Products, Inc.</u>

PBI Manufacturer

<u>Generon:</u>

Membrane Fabrication Scale-up

Module Fabrication

<u>Enerfex:</u>

Membrane System Modeling

<u>Energy Commercialization</u>

Commercialization Analysis

<u>NCCC:</u>

Gasifier Facility Test Site

<u>EPRI:</u>

Electric Power Industry Perspective

<u>NETL:</u>

Funding and technology oversight

Profile of SRI International

SRI is one of the world's largest independent R&D organizations

- Founded 1946 as the Stanford Research Institute in conjunction with Stanford University
- Independent, not-for-profit scientific research institute with for-profit spin-offs and subsidiaries
- Creating and delivering innovative science and technology solutions for governments and businesses worldwide.

- Annual combined revenues exceed $540 million:
- 2,300 employees, 700 with advanced degrees
- Headquarters in Menlo Park, CA,
- Offices in Washington, D.C., Princeton, and throughout the U.S.

Project Overview

- Cooperative agreement grant with U.S. DOE-NETL
- Period of Performance:
  - Budget Period 1: 10-1-2013 through 7-31-2015
  - Budget Period 2: 8-1-2015 through 10-30-2016
- Funding:
  - U.S.: Department of Energy: $2.25 million
  - Cost share: $0.56 million
  - Total: $2.81 million
- NETL Project Managers:
  - Ms. Elaine Everitt

Project Objectives

- Primary Objectives:
  - To evaluate, at a bench-scale size, a technically and economically viable CO_2 capture system based on a high-temperature PBI polymer membrane separation system.
  - To optimize the process for integration of that system into an Integrated Gasification Combined Cycle (IGCC) plant.
- Specific Objectives
  - Collect laboratory data for separating hydrogen from simulated synthesis gas using PBI-based hollow fiber membranes.
  - Fabrication of membrane modules of 50 kWth equivalent of a shifted gas from an oxygen-blown gasifier using equipment of industrial relevance.
  - Collect design and steady-state performance data for membrane modules using syngas from an operating coal gasifier.
  - Transfer the membrane fabrication technology to an industrial firm that specializes in the manufacture of hollow fiber membranes.
  - Estimate the cost of CO_2 capture from precombustion gas streams.

Project Schedule

Task	Start Date	End Date	Cost $
BP1 and BP2	4/15/2013	10/31/2016	
Task 1.0 - Project Management and Planning	4/15/2014	7/31/2015	$153,237
Task 2-0: Establish Performance Database	4/15/2014	7/31/2014	$1,355,850
Subtask 2.1 - Generate Membrane Module for Testing	**7/1/2014**	**3/3/12015**	
Subtask 2.2 - Commission a 50 kWth Membrane Skid	**10/1/2014**	**12/30/2014**	
Subtask 2.3 - Generate Performance Database	**1/1/2015**	**7/30/2015**	
Subtask 2.4 - Modeling of the Membrane Performance	**8/1/2014**	**6/31/2015**	
Continuation Report Submission	**4/1/2015**	**4/30/2015**	
BP2: Field Testing of the Bench-Scale Unit	8/1/2015	10/31/2016	
Task 1.0 - Project Management and Planning	8/1/2015	10/31/2016	$103,489
Task 3.0 - Modification of the 50 kWth Test Unit for the Field Test	8/1/2015	11/1/2015	$369,487
Subtask 3.1 - Test Unit Modification	**8/15/2015**	**10/31/2015**	
Subtask 3.2 - Test unit HazOp and Safety Review	**9/15/2015**	**10/15/2015**	
Task 4.0 - Operation of the 50 kWth Test Unit	11/1/2015	10/1/2016	**$463,807**
Subtask 4.1 - Test Unit Start-up	**11/1/2015**	**12/30/2015**	
Subtask 4.2 - Development of a Test Plan	**11/1/2015**	**12/30/2015**	
Subtask 4.3 - Parametric Testing	**1/1/2016**	**6/1/2016**	
Subtask 4.4 - Long Duration Testing	**7/1/2016**	**9/1/2016**	
Task 5.0-Conduct Process Design and Engineering Study	4/1/2015	7/1/2016	$130,604
Task 6.0 - Conduct Environmental and Economic Analyses	7/1/2015	10/1/2016	$192,838
Task 7.0 - Dismantling and Removing the Slipstream Test Unit	10/15/2016	10/30/2016	$44,190
Final Report	**10/15/1026**	**10/30/2016**	

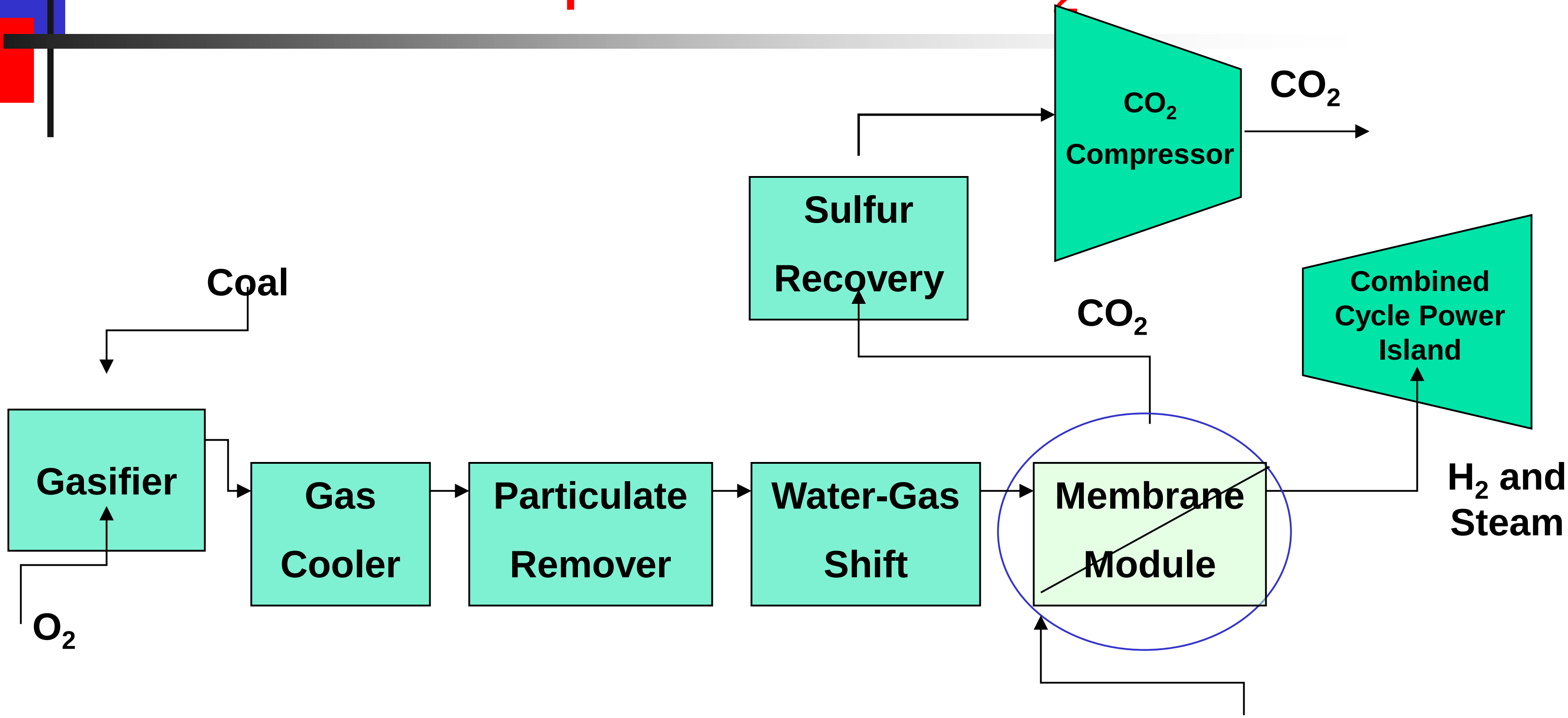
Milestone Chart

Budget Period	Task/ Subtask No.	Milestone Description	Planned Completion	Actual Completion	Verification Method
1	1.0	Updated Project Management Plan	6/5/2014		Project Management Plan file
1	1.0	Kickoff Meeting	6/9/2014		Review Presentation File
1	2.2	Commission of 50 kWth membrane skid	12/30/2014		Topical Report
1	2.4	Completion of modeling of membrane performance	6/31/2015		Review of Design Basis Report
1		Continuation Report Submission	4/30/2015		Report and Presentation
2	3.1	Completion of the Modification of the Test Unit	10/31/2015		Presentation File
2	3.2	Completion of the HazOp and Safety Review	10/15/2015		Presentation File
2	4.4	Completion of Long Term Testing	9/1/2016		Presentation File
2	5.0	Completion of Process Design & Engineering Study	7/1/2016		Topical Report
2	6.0	Completion of TEA and EH&S Reports	10/1/2016		TEA and EH&S Report to DOE
2	7.0	Complete the Dismantling of the Test Unit	10/30/2016		Presentation File

Risk Management

Description of Risk	Probability (Low, Moderate, High)	Impact (Low, Moderate, High)	Risk Management (Mitigation and Response Strategies)
Technical Risks:			
PBI hollow fiber spinning with excessive pinholes and macro-voids	Low	Moderate	Ensure the technology transfer to Generon is effective and complete; enlist the expertise and experience of Generon technical staff to overcome production difficulties
Hollow fiber test module fabrication	Low	Low	Use Generon's experience in assembling hollow fiber modules
Potting adhesive does not have sufficient usability or durability	Low	Moderate	Investigate the use of other potting compounds early in the technology transfer task
Changes in H_2/CO_2 selectivity and H_2 permeance values in the fibers produced with pilot-scale equipment	Low	Moderate	Modify the thickness of the dense layer; ensure that technology transfer to Generon is effective and complete; test small modules early in the program to determine their characteristics and make any changes in the spinning procedure required
Resource Risks:			
PBI polymer availability	Low	Moderate	Track the production to ensure on-time availability
Hollow fiber module availability	Low	Moderate	Track the production of hollow fibers and module assembly
Availability of the test site	Low	Moderate	Schedule control
Management Risks:			
Bottlenecks in subcontract awards	Low	Low	Engage senior management personnel to resolve bottlenecks

Why the High Temperature Membrane Separation of CO_2?



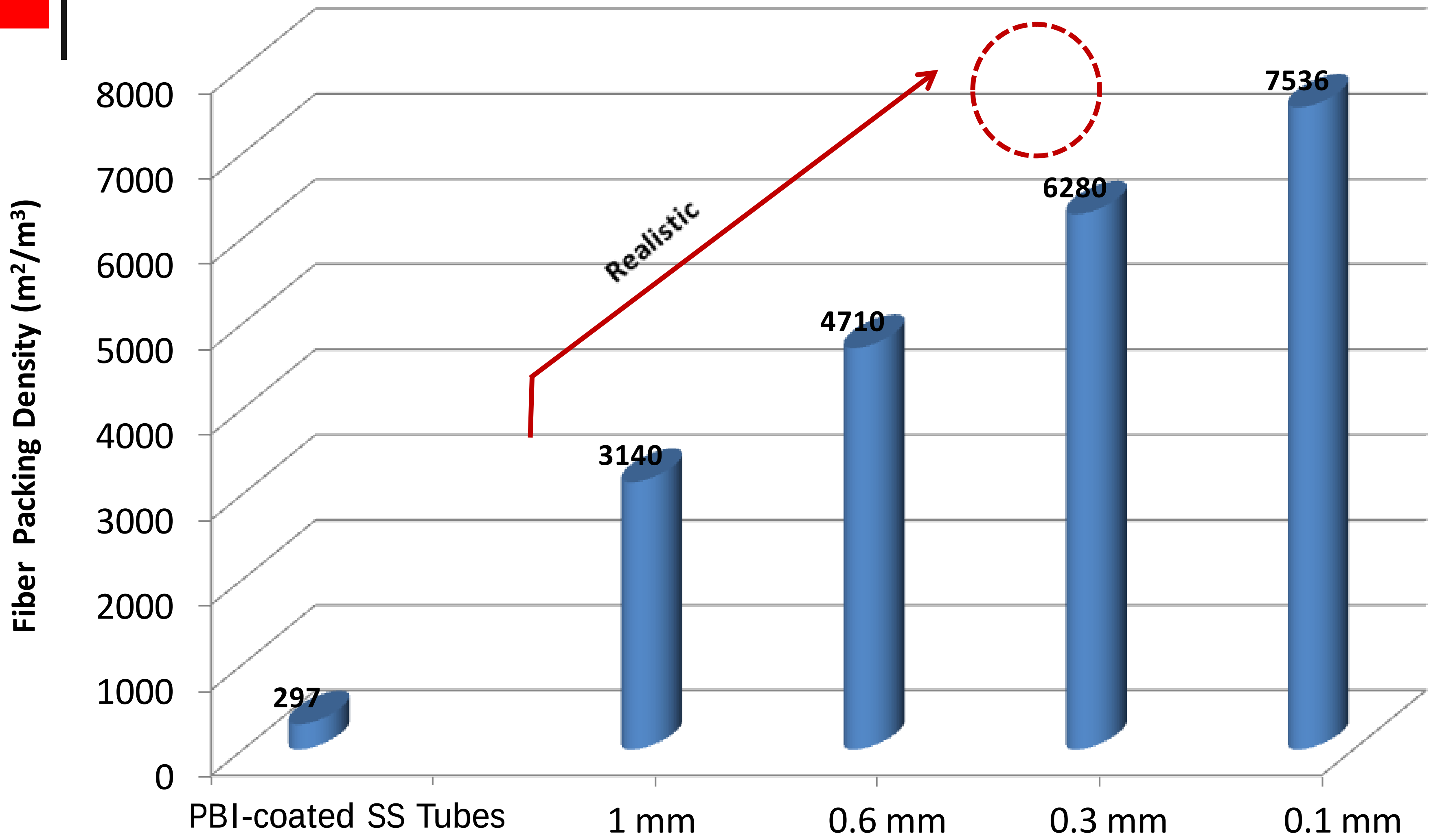
Characteristics of PBI Membranes

- PBI has attractive combination of throughput and degree of separation
- Thermally stable up to 450°C and sulfur tolerant.
- Tested for 1000 h at 210°C by at SRI

Advantages of Membrane-Based Separation

- No need to cool syngas
- Reduced CO_2 compression costs
- Emission free, i.e. no solvents
- Decreased capital costs
- Low maintenance

A Significant Size Advantage of Hollow Fiber Membranes



Project Tasks

- Task 1.0 – Project Management and Planning
- Task 2: Establish Performance Database
  - 2.1: Generate Membrane Module for Testing
  - 2.2: Commission a 50 kWth Membrane Skid
  - 2.3: Generate Performance Database
  - 2.4: Modeling of the Membrane Performance
- Decision Point to Proceed to Budget Period 2
- Task 3: Modification of the 50 kWth Test Unit for the Field Test
  - 3.1: Test Unit Modification
  - 3.2: Test unit HazOp and Safety Review
- Task 4: Operation of the 50 kWth Test Unit
  - 4.1: Test Unit Start-up
  - 4.2: Development of a Test Plan
  - 4.3: Parametric Testing
  - 4.4: Long Duration Testing
- Task 5: Conduct Process Design and Engineering Study
- Task 6: Conduct Environmental and Economic Analyses
- Task 7: Dismantling and Removing the Slipstream Test Unit

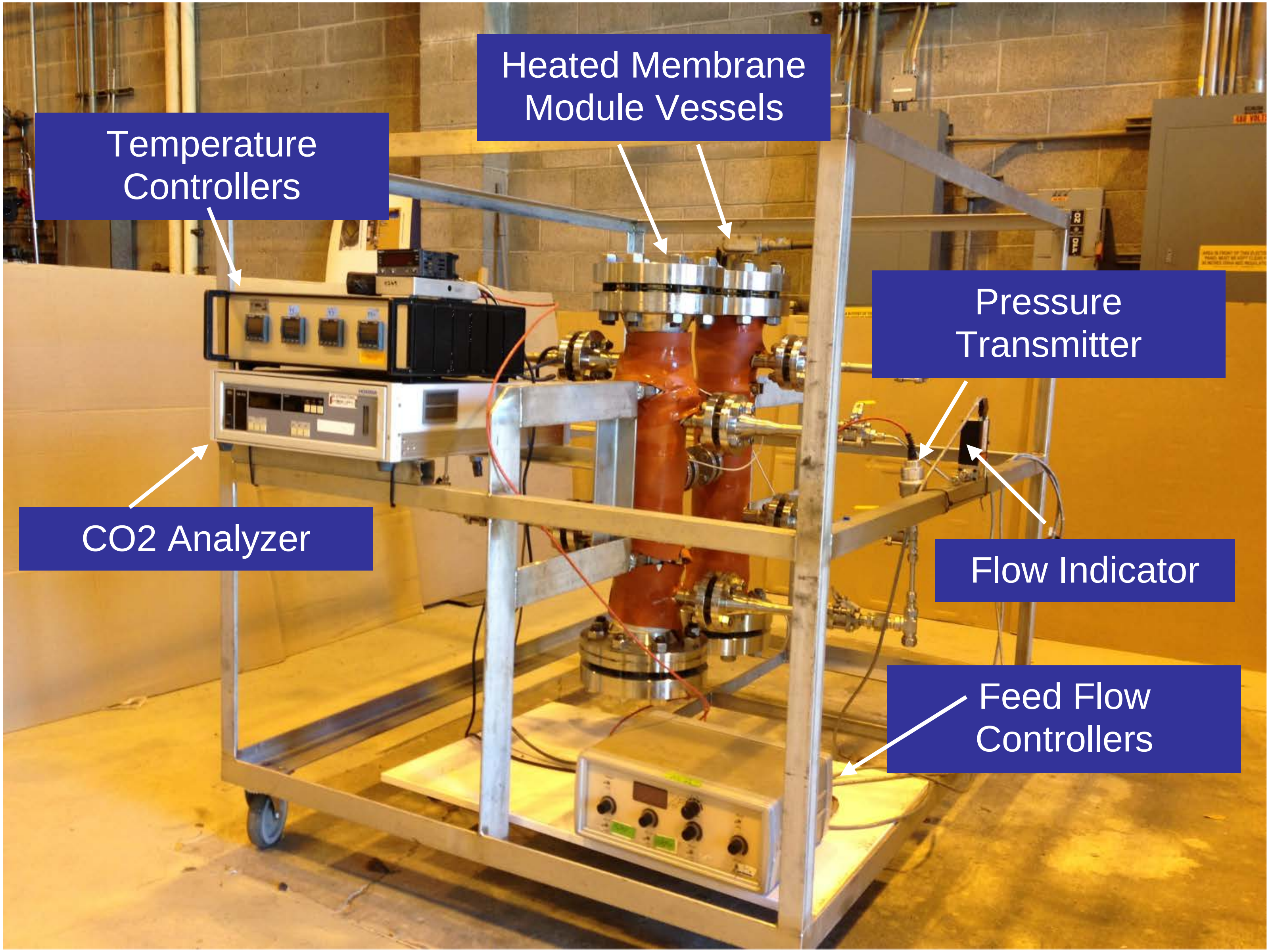
Establish Performance Database (Task 2.1)

- Fabricate PBI hollow fiber modules for tests with a bench-scale system.
- Use an existing bench-scale hollow fiber spinning system at SRI to make test fibers and modules.
- Engage the expertise of Generon that specializes in the manufacturer of hollow fiber membranes.
- Transfer technical know-how of PBI fiber spinning to Generon.
- Evaluate, at a bench-scale level, the thickness of the selective and support layer as they affect the separation of the gas components.
- Evaluate seal integrity at the high temperature and pressure of shifted syngas.

50 kWth Membrane Skid (Task 2.2)

- An existing 50 kW_{th} bench-scale membrane skid will be used to collect performance data over a range of conditions relevant for the proposed field tests.
- Fabricated under a prior DOE-funded project.
- Test at SRI facilities using simulated gas representative of a water-gas shifted syngas stream.

Photograph of the Skid for PBI Membrane Testing



Generate Performance Database (Task 2.3)

- Preliminary scoping tests will be conducted with a sub-scale module to provide data for the optimization of the fiber spinning and module assembly processes.
- Evaluate the effectiveness of the membrane potting material, the gas permeance, and selectivity of the PBI-based membranes.
- The 50 kWth membrane skid will be operated under targeted operating conditions, nominally temperatures up to 225°C, pressures up to 450 psig, and simulated syngas flow rates up to 1000 scfh.
- Simulated syngas tests will include gas mixtures containing H_2/CO_2/H_2O/CO with and without H_2S
- Focus on the generation of the performance database relevant to high temperature gas separation processes.

Membrane Modeling (Task 2.4)

- A membrane model will be used to predict the performance of the PBI-membrane system.
- Flow arrangement (i.e. co-current, counter-current, cross flow, or combination),
- Membrane size (in m^2/tonnes CO_2 or H_2 separated),
- Estimated membrane packing density (membrane area per unit volume in units of m^2/m^3), and
- Estimated pressure drops (in units of bar) for the membrane retentate and permeate under normal operating conditions.

Modification of the 50 kWth Test Unit for the Field Test (Task 3)

- Test Unit Modification
  - Modification to comply with NCCC requirements and include:
    - Include flanged connections to the feed and exhaust gas streams,
    - Double shut-off valve schemes for the gas streams,
    - Structural support of the module elements to conform to the local codes,
    - Equipment
    - placed inside NEMA-4 compliant enclosures.
- Process safety review and Hazard and Operability (HazOp) Study
  - A HazOp trained expert will lead the process
  - Key issues identified, actions required for resolution, and assignment of responsibility and timelines for corrective action,
  - Process Safety Review Report and a HazOp Analysis report documented.

Operation of the 50 kWth Test Unit at a Field Site

- Several subtasks:
  - 4.1: Test Unit Start-up
  - 4.2: Development of a Test Plan
  - Parametric Testing
  - 4.4: Long Duration Testing

Subtask 4.1: Test Unit Start-up

- Subtask 4.1: Test Unit Start-up:
- Test unit to demonstrate operation at steady-state and boundary conditions:
  - Operation of the membrane module, valves and fittings, and utility connections will be checked.
  - Measurement equipment calibrated .
  - Various control loops tuned for proper control functions.

Subtask 4.2: Development of a Test Plan

- Test plan will be prepared and submitted to DOE for approval.
- Based on experimental data obtained under parametric and steady-state conditions using industrially relevant conditions.
- The results collected from the execution of the test plan will be used in the techno-economic analysis.

Subtask 4.3: Parametric Testing

- Parametric testing will include:
  - Temperature range: 180 to 240 C;
  - Pressure range: 150 to 300 psi;
  - Gas flow rate. (Composition is fixed by the available syngas)
- Steady-state runs (24 hours or longer)
- Efficiency of CO_2 capture from the syngas (retentate)
- Purity of the permeate H_2 stream

Subtask 4.4: Long-Term Testing

- Operate the test unit under steady-state conditions for an extended period of time
- Objective of the long-term test is to validate:
  - Membrane stability,
  - H_2/CO_2 selectivity;
  - Permeance of H_2 and other gases, including contaminants such as H_2S,
  - Other parameters affecting long-term performance.

Process Design and Engineering Study (Task 5)

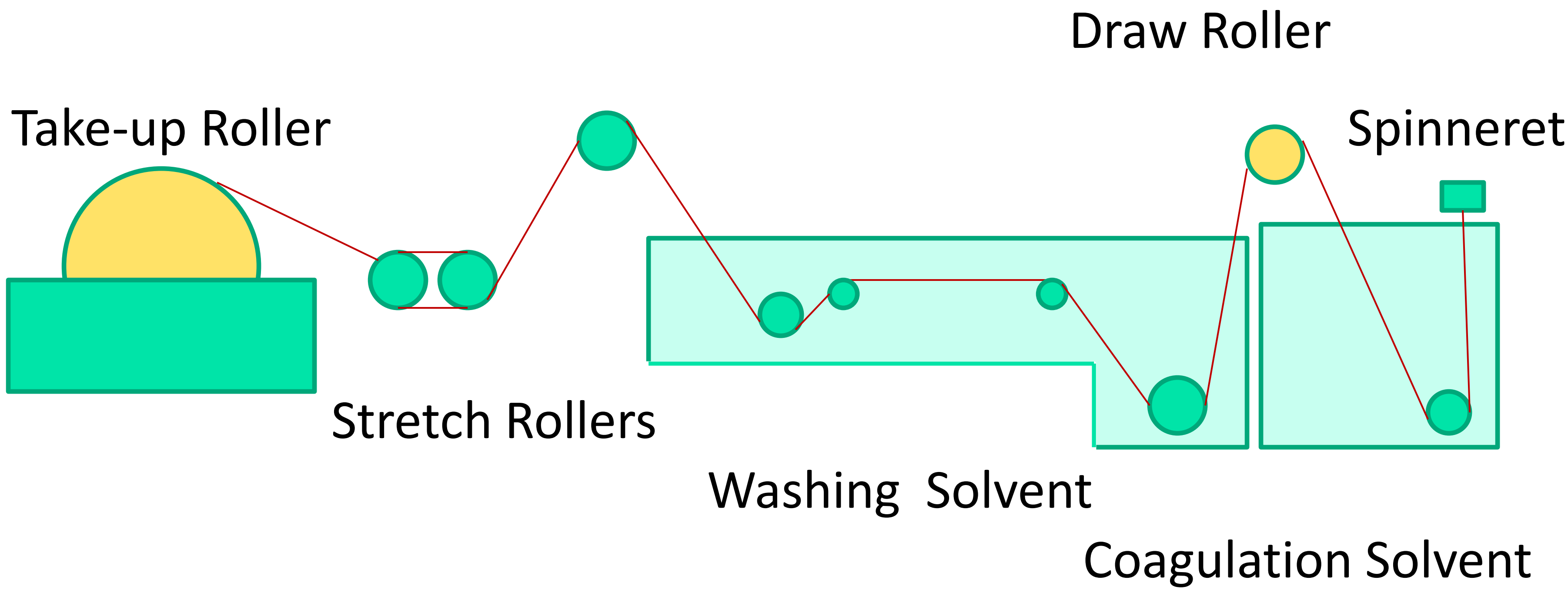
- Process design and engineering study:
  - how the high temperature hollow fiber PBI membrane process concept would be incorporated into a nominal 550 MWe gasification-based power plant with CCUS.
  - Include developing the process flow diagrams, heat and material balance, and the sizing of major equipment.
  - An IGCC process based a GE-oxygen-blown gasifier and selexol-based CO_2 removal will be used as the base case.
  - Emission standards will be compared against expected emissions and corrective methods needed.
  - Utility summary including compressor power.

Conduct Environmental and Economic Analyses (Task 6)

- The EH&S assessment in accordance with the details given in Appendix B of the SOPO.
- Strategies will be identified for minimizing any negative impact of the process.
- Techno-Economic Analysis (TEA) in accordance with Appendix A of the SOPO
  - Major equipment size and cost for the PBI membrane separator.
  - Capital and operating costs for the the membrane separator based upon the cost after "nth" unit production.

Past work

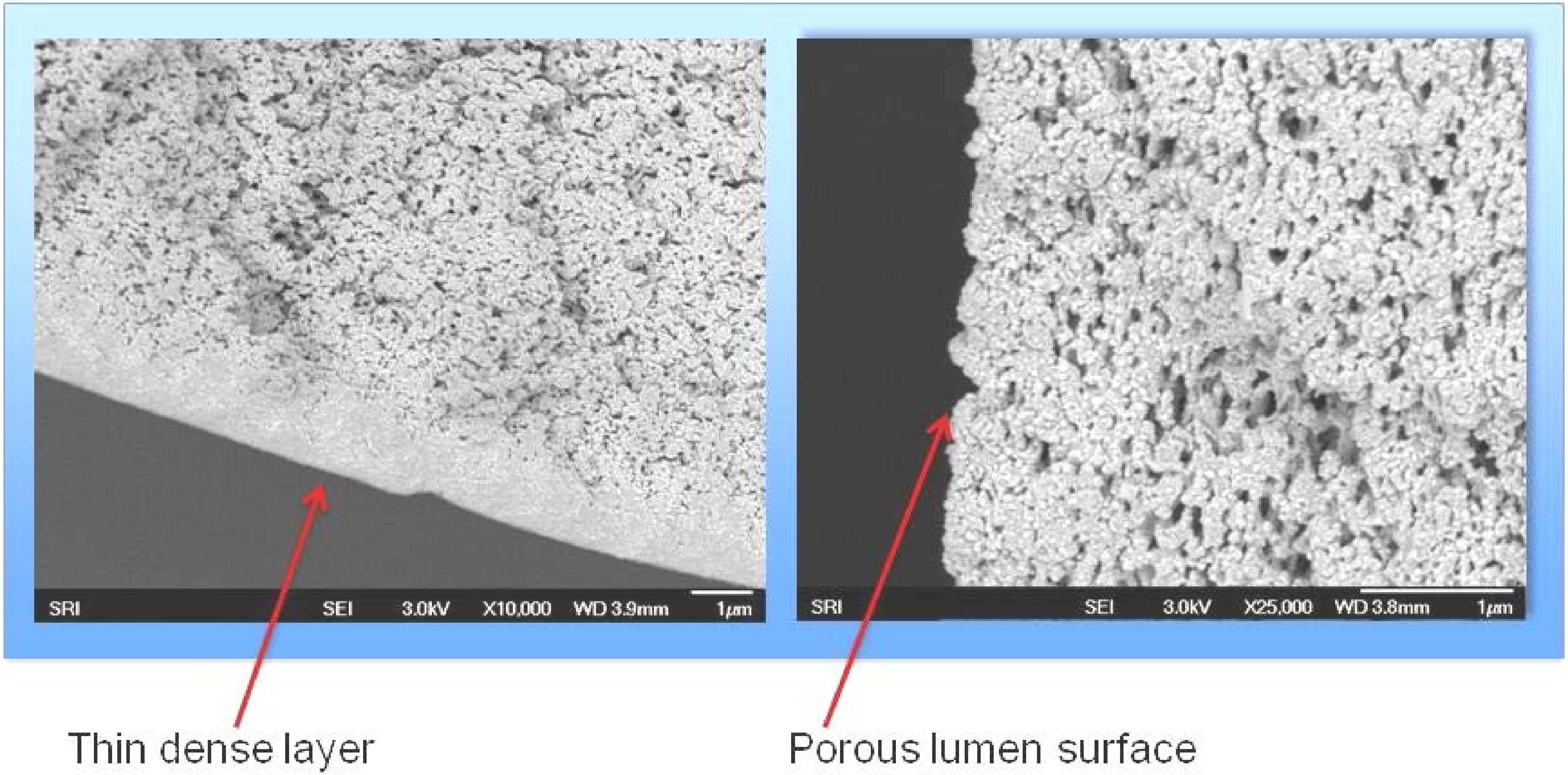
Bench-Scale Spinning Line at SRI



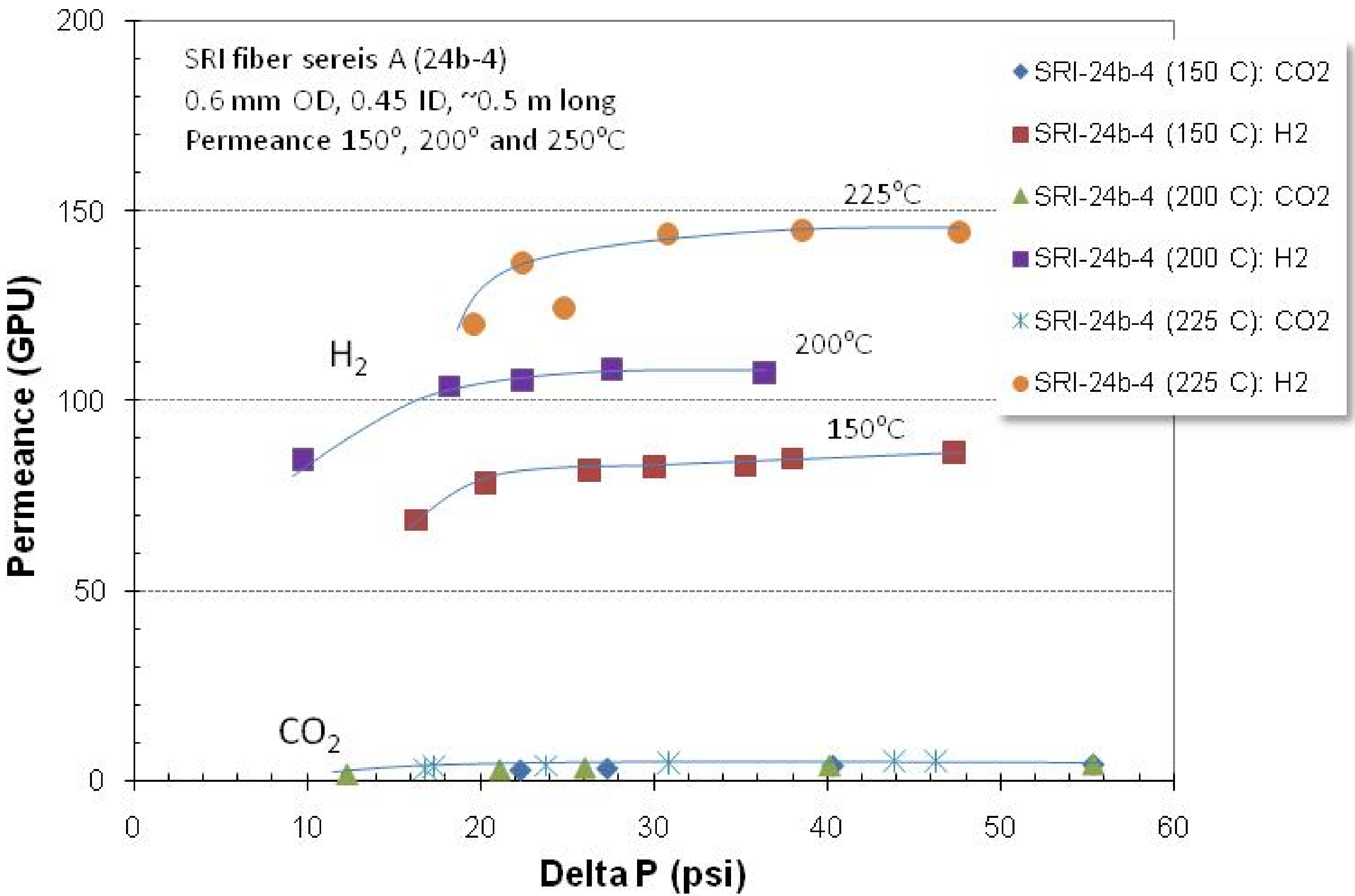
Fabricated Hollow Fiber

Fiber Bundles

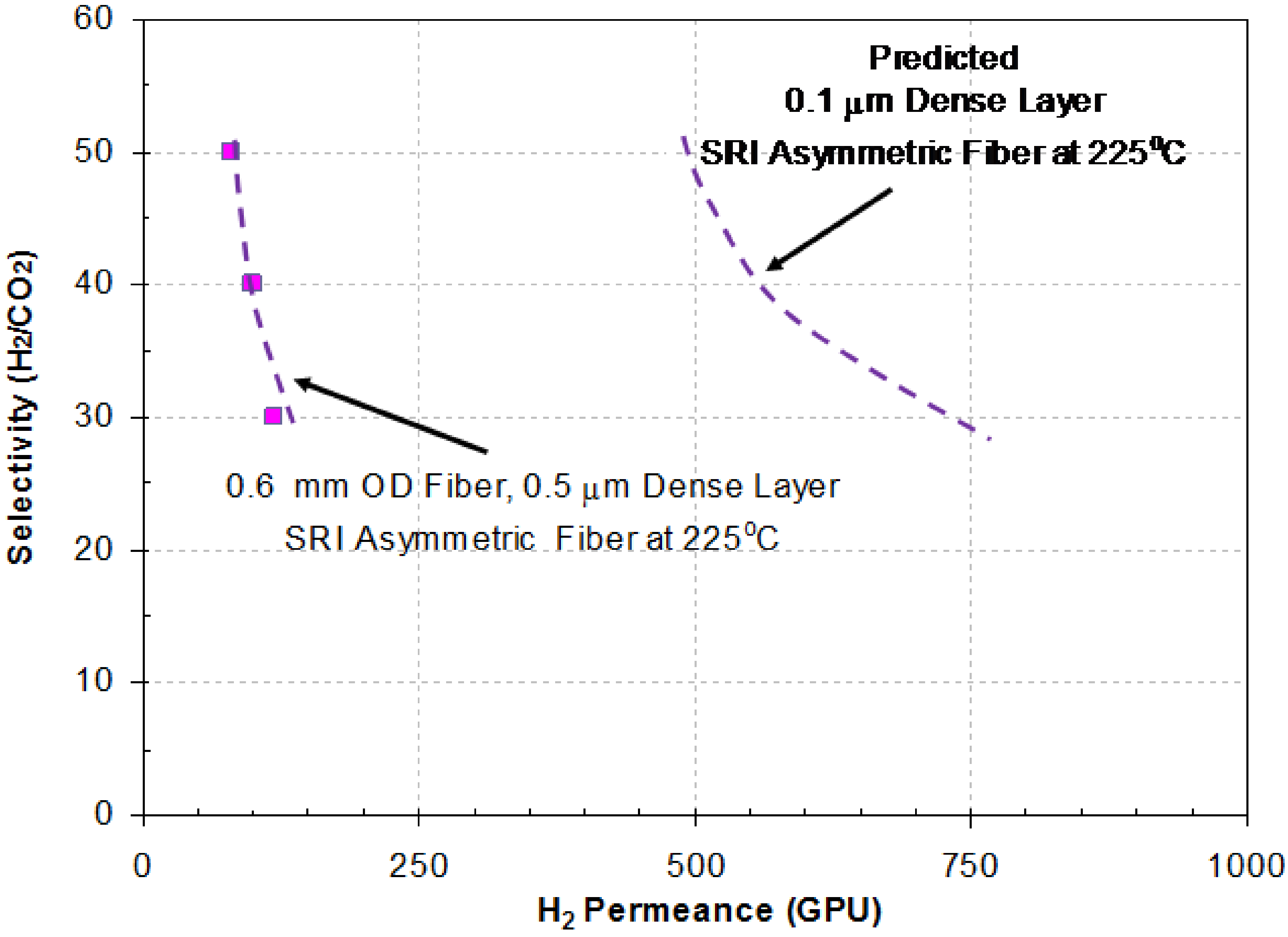
High magnification photographs of cross-sections near shell and lumen sides of SRI Series A fiber.



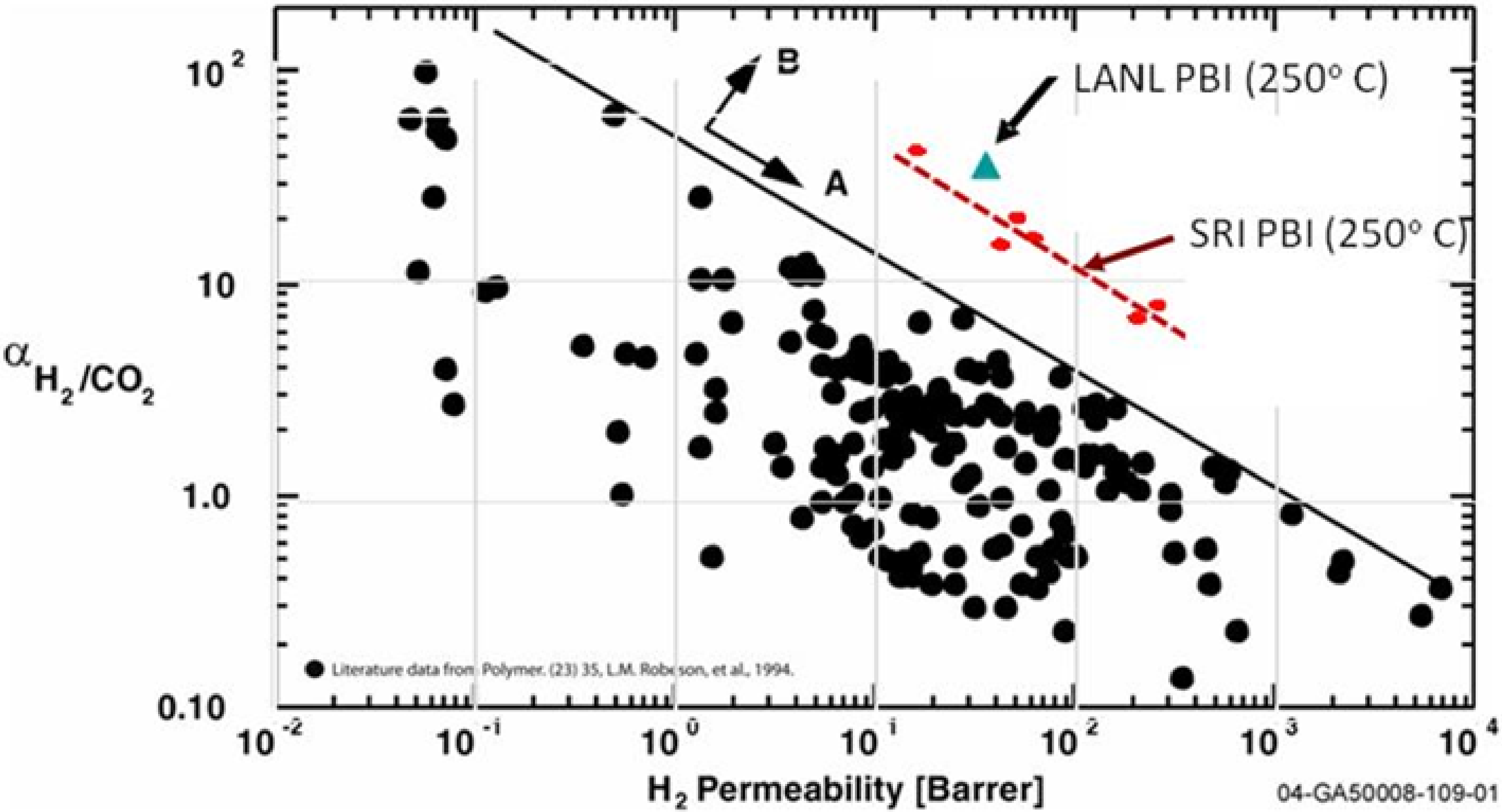
Permeation of H_2 and CO_2



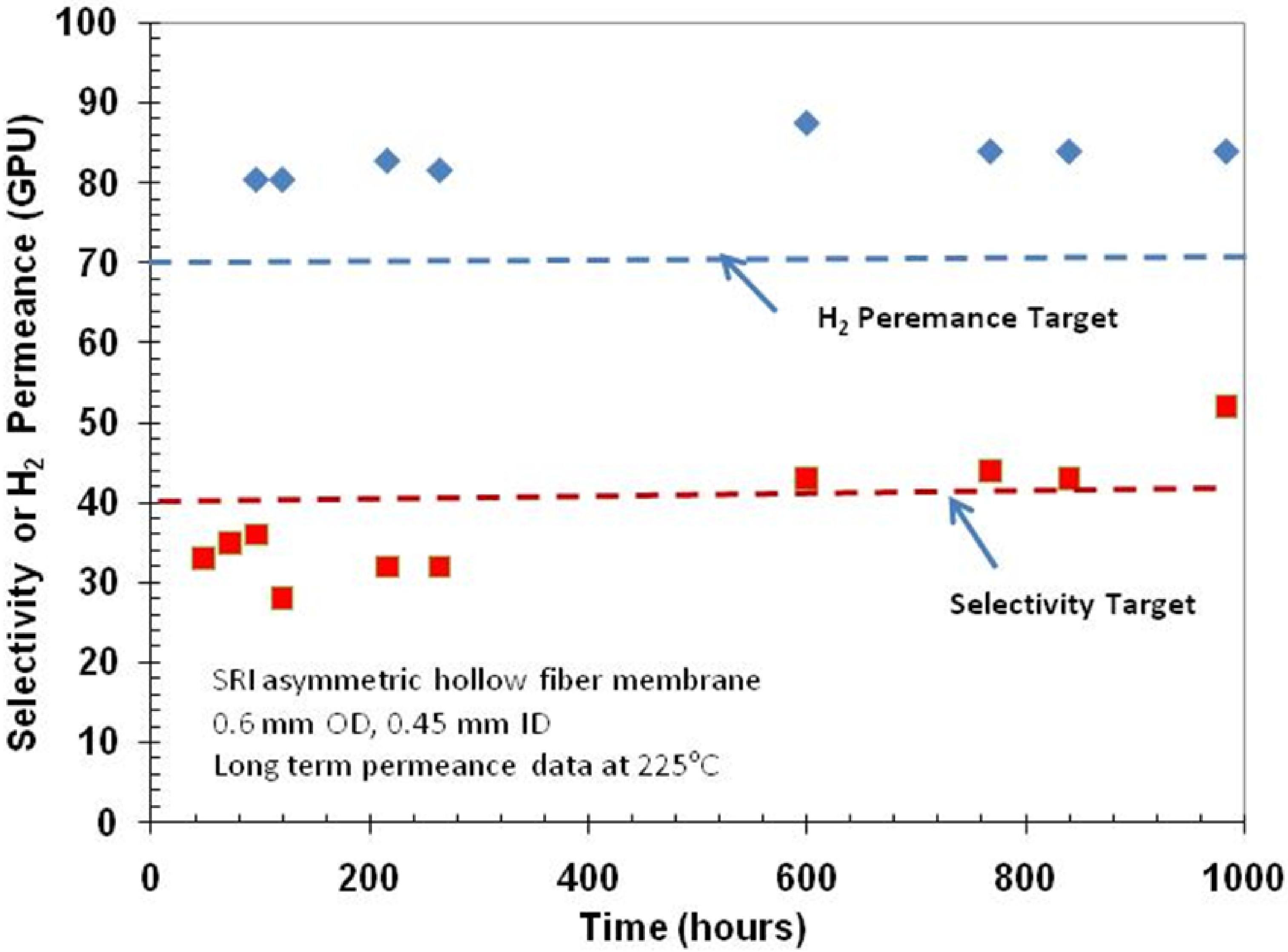
Permeance vs Selectivity of SRI-Made PBI Fibers



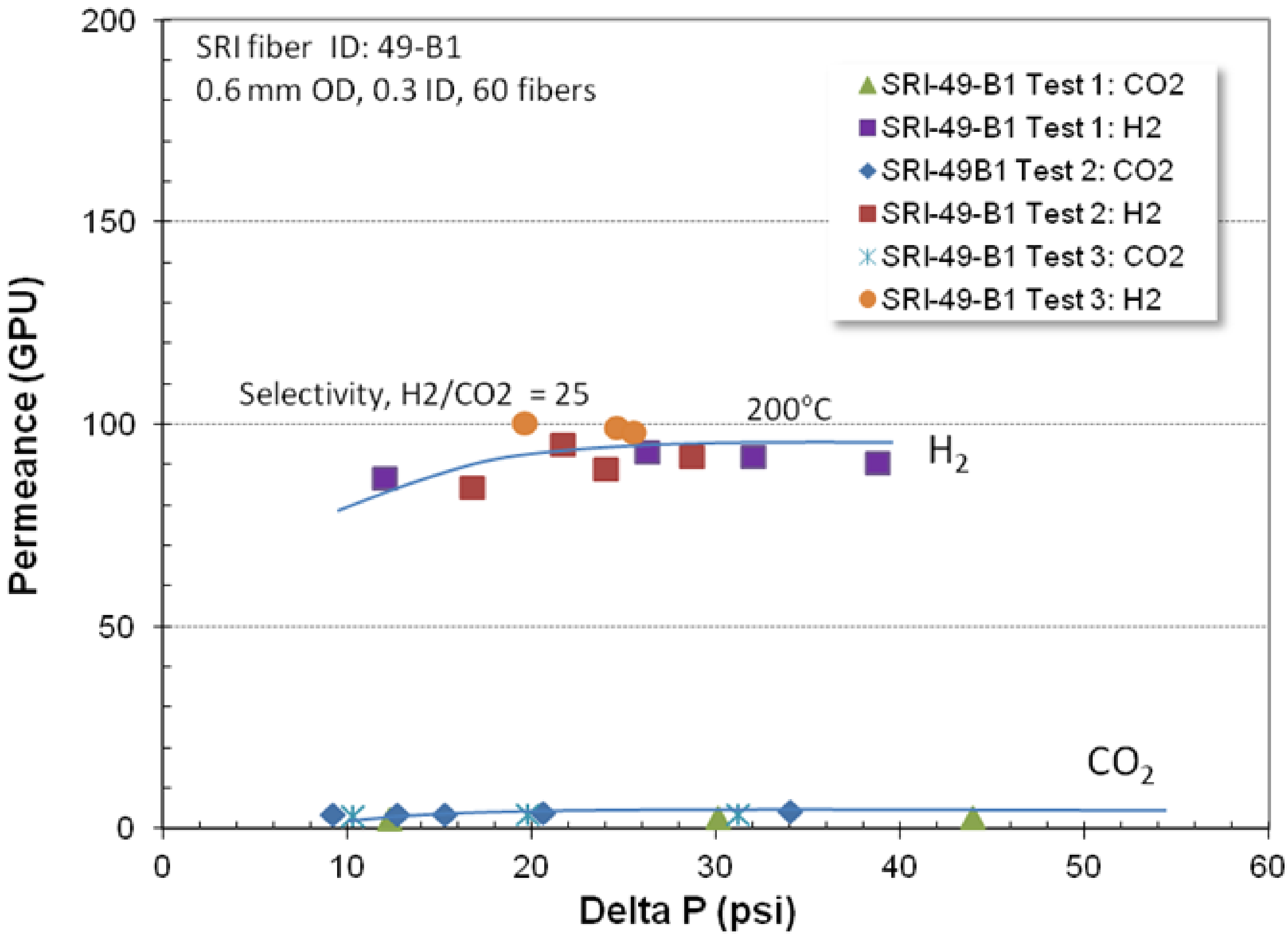
Permeance vs Selectivity of SRI-Made PBI Fibers



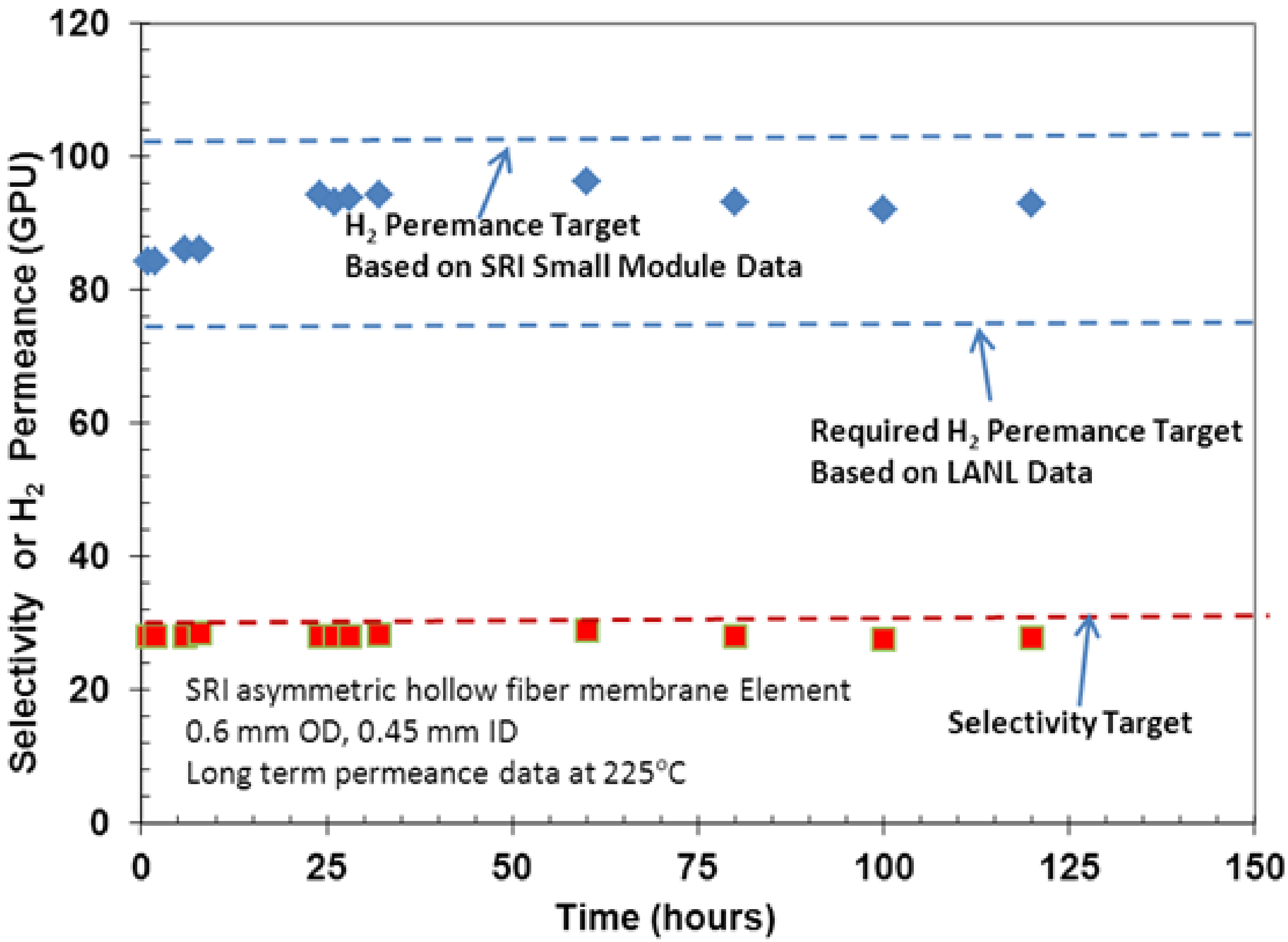
Long-Term Testing



Permeation Characteristics of a Fiber Module



H_2/CO_2 Selectivity of and H_2 Permeance of Fibers at 225°C



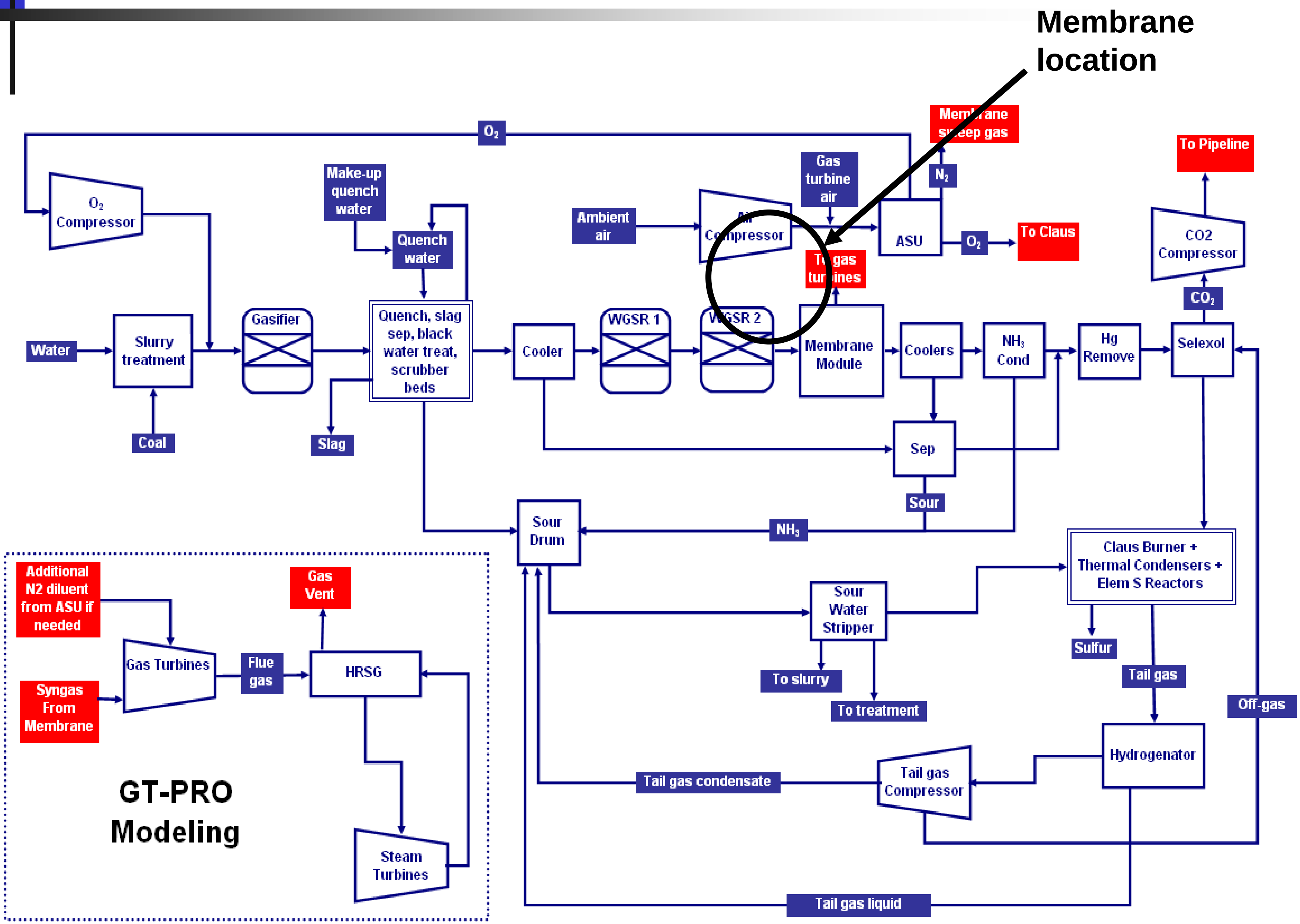
Good Correlation Between Project's Process Simulation and NETL's Process Simulation

***CO_2 capture: 3.3 Million tonnes/yr*.**

	Units	NETL Cases		Project Cases	
		No Capture	Capture w/Selexol	No Capture	Capture w/Selexol
Power Production @ 100% Capacity	GWh/yr	5,609	4,868	5,455	4,788
Power Plant Capacity	Cents/kWh	4.53	5.97	4.50	5.92
Power Plant Fuel	Cents/kWh	1.94	2.28	1.90	2.27
Variable Plant O&M	Cents/kWh	0.75	0.94	0.78	0.94
Fixed Plant O&M	Cents/kWh	0.58	0.72	0.60	0.74
Power Plant Total	Cents/kWh	7.80	9.91	7.78	9.87
CO2 transport, storage & Monitoring	Cents/kWh	0.00	0.39	0.00	0.39
Cost of Electricty (COE)	Cents/kWh	**7.80**	**10.30**	**7.78**	**10.25**
Increase in COE (over no capture)		n/a	**32.0%**	n/a	**31.5%**

Plant operating life: 30 years; Capacity Factor: 80%; Capital charge factor: 17.5%

Membrane Module in IGCC



Preliminary Economic Analysis: PBI Approaches the DOE Goals

CO_2 capture: 3.3 Million tonnes/yr.

	Units	Project Cases			
		No Capture	CO_2 and H_2S Capture w/Selexol	CO_2 Capture w/PBI & H_2S w/Selexol	CO_2 Capture w/PBI no H_2S removal
Power Production @100% Capacity	**GWh/yr**	5,455	4,461	4,943	5,035
Power Plant Capacity	**cents / kWh**	4.50	6.19	5.49	5.02
Power Plant Fuel	**cents / kWh**	1.90	2.47	2.31	2.26
Variable Plant O&M	**cents / kWh**	0.78	1.00	0.92	0.91
Fixed Plant O&M	**cents / kWh**	0.60	0.79	0.71	0.70
Power Plant Total	**cents / kWh**	7.78	10.45	9.43	8.89
Cost of Electricity* (COE)	**cents / kWh**	**7.78**	**10.45**	**9.43**	**8.89**
Increase in COE (over no capture)	**%**	***n/a***	***34%***	***21%***	***14%***

*** Separation and Capture Only**

Plant operating life: 30 years; Capacity Factor: 80%; Capital charge factor: 17.5%

Capture with Selexol uses slightly different parameters than NETL cases.