FABRICATION AND SCALE-UP OF POLYBENZIMIDAZOLE (PBI) MEMBRANE BASED SYSTEM FOR PRECOMBUSTION BASED CAPTURE OF CARBON DIOXIDE

2011 NETL CO_2 Capture Technology Meeting

August 22-16, 2011 in Pittsburgh, PA.

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 $500 million:
- 2,100 employees, 700 with advanced degrees
- Headquarters in Menlo Park, CA, offices in Washington, D.C. and throughout the U.S.

Project Overview

- Participants:
  - SRI International, Menlo Park, CA
  - Enerfex, Inc.
  - Energy Commercialization, Inc.
  - (Los Alamos National Laboratory)
  - (Whitefox Technologies)
  - (Visage Energy, Inc.)
  - DOE-National Energy Technology Center
- Period of Performance:
  - 10-1-2008 through 3-30-2012
- Funding:
  - U.S.: Department of Energy: $3.9 million
  - Cost share: $1.2 million
  - Total: $5.1 million

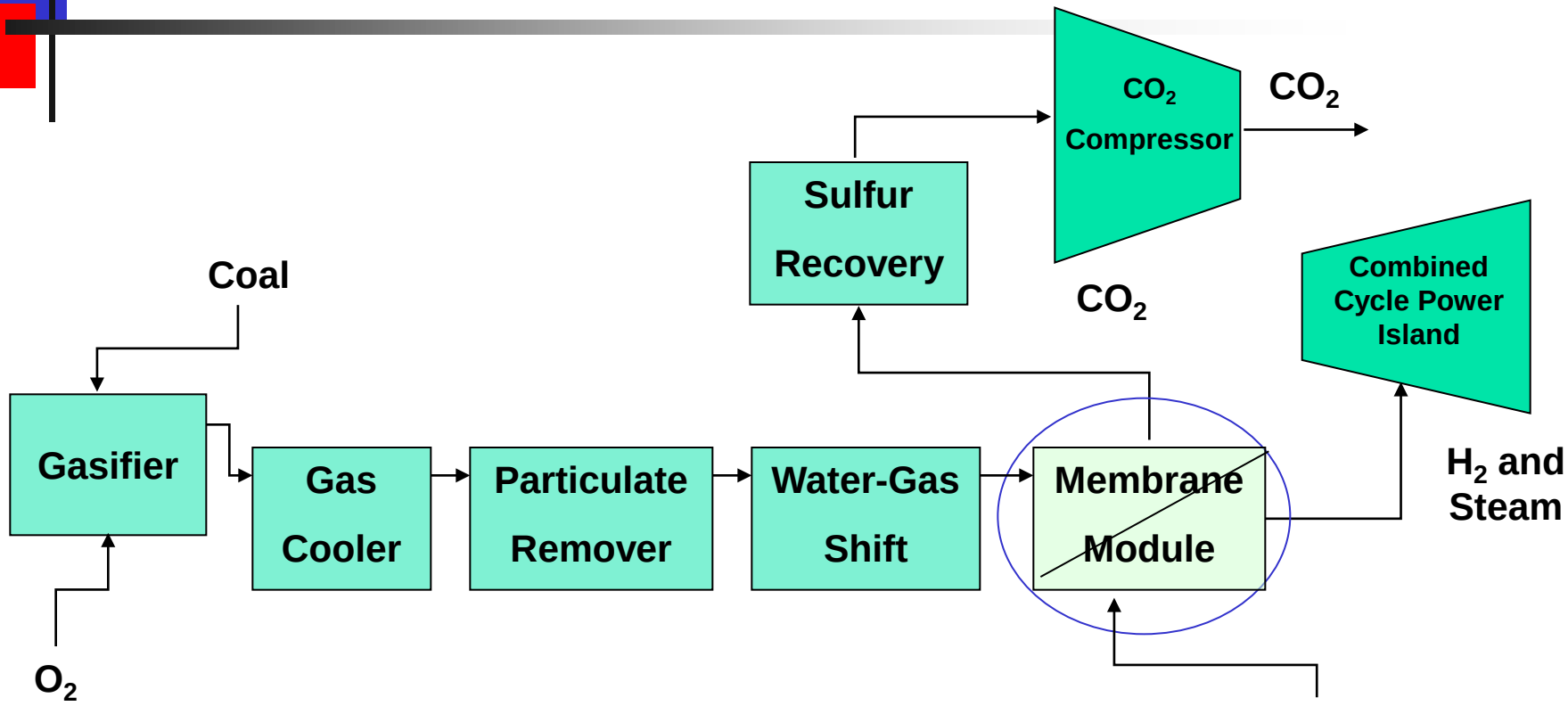
Team

- DOE-NETL
  - Mr. Robie Lewis, Mr. Jose Figueroa
- SRI International
  - Dr. Gopala Krishnan – Associate Director (MRL) and PI
  - Dr. Indira Jayaweera, Senior Chemist and Program Leader
  - Dr. Srinivas Bhamidi
  - Mr. Anoop Nagar
  - Dr. Angel Sanjurjo – Materials Research Laboratory Director and Project Supervisor.
- Enerfex, Inc.
  - Mr. Richard Callahan
- Energy Commercialization, Inc.
  - Dr. Kevin O'Brien

Project Objectives

- Design, construct, and test a pre-combustion-based CO_2 capture system (50 kW_{th}) skid using PBI membranes as the separating element:
  - Operate at temperatures above 200°C and pressures up to 700 psi.
  - Test the skid at an end-user facility in Phase II.
- Develop membrane elements using industrially relevant practices.
- Evaluate the performance of the membrane elements for CO_2 separation.
- Assemble the membrane modules with commercially available connectors and control systems into a skid. Test the skid with a simulated gas stream.
- Evaluate the COE of the membrane-based CO_2 capture for its ability to meet DOE goals.
- Evaluate financial and commercialization issues.
- Develop a plan for technology transfer.

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 ~ 1 year at 250°C by LANL

Advantages of Membrane-Based Separation

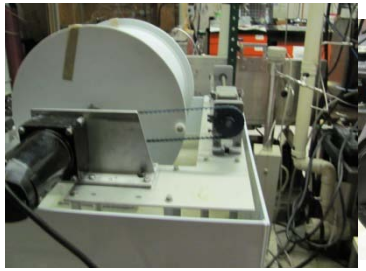
- No need to cool syngas
- Reduced CO_2 compression costs
- Emission free, i.e. no solvents
- Decreased capital costs
- Low maintenance

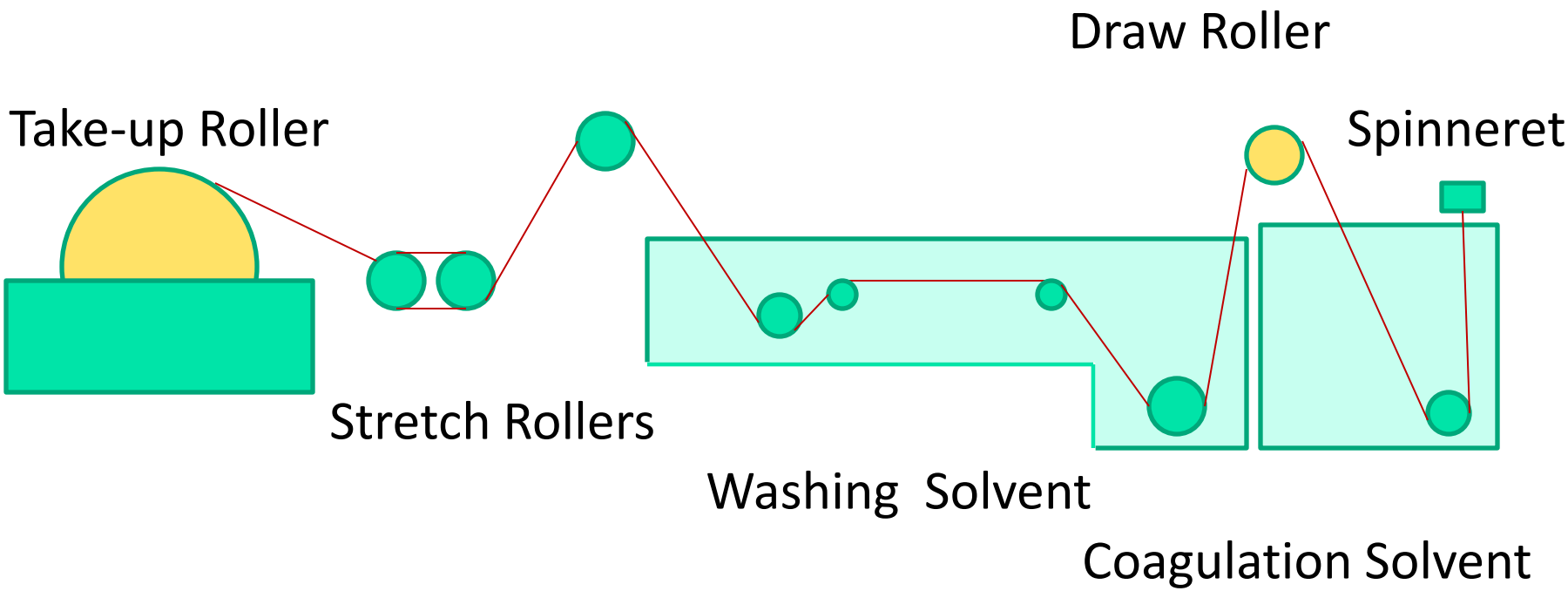
Project Tasks

- Completed Tasks:
  - Establish specifications and testing protocol
  - Design review on substrates and selection
  - Develop of strategic plan and technology transfer
  - Commercialization plan recommendation
  - Compilation of commercialization issues and requirements
- On-going tasks:
  - Membrane substrate development and selective layer coating – Optimization and quality control
  - Permselectivity characterization in simulated coal derived syngas environments
  - Subcomponent design and evaluation (Housing and fiber)
  - Integrate membrane module with commercially available skids, control systems, and connectors
  - Long term testing of a complete prototype skid mounted membrane system

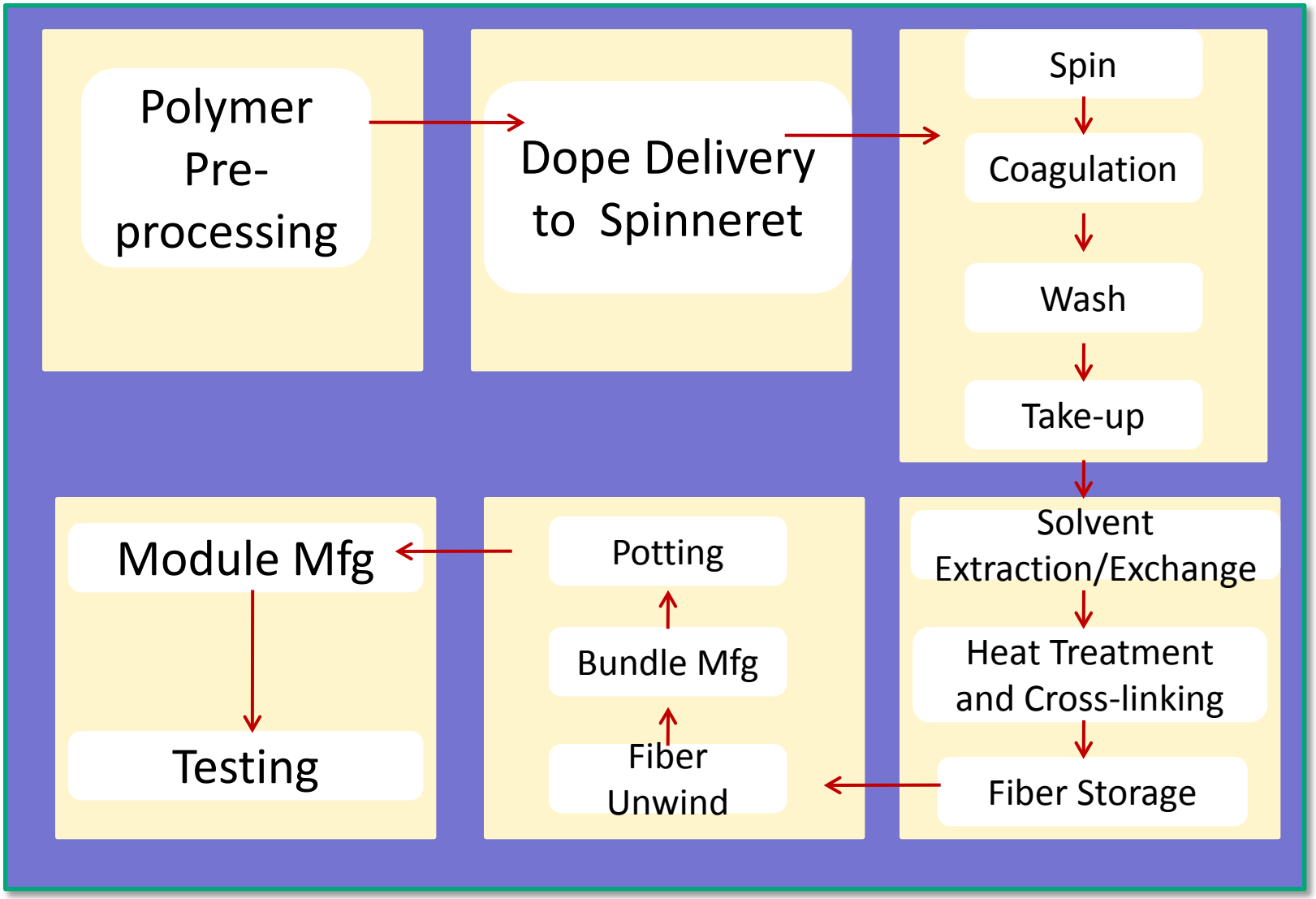
Membrane Fabrication

Bench-Scale Spinning Line





Fabrication of Membrane Modules



Fabricated Hollow Fiber

Fiber Bundles

Membrane Module

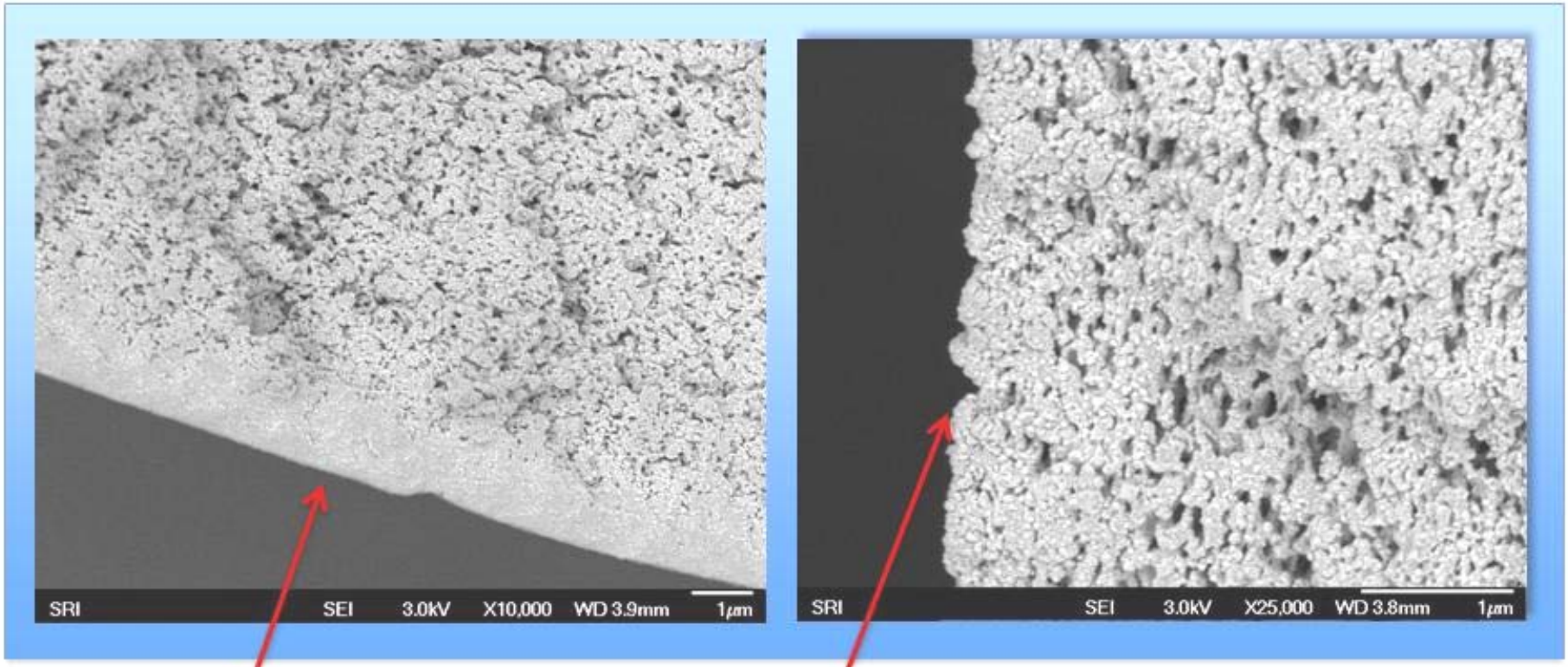
Module Diameter	1.0	2.5	4.0	in
Active Fiber Length	12	12	12	in
Total Fiber Surface Area	0.27	1.70	4.36	m^2
Module Size	1.6	10	25	kWh_{th}

Potted-End

5 kWh_{th} Asymmetric Hollow Fiber Membrane Element with 30% packing density

Membrane Characterization

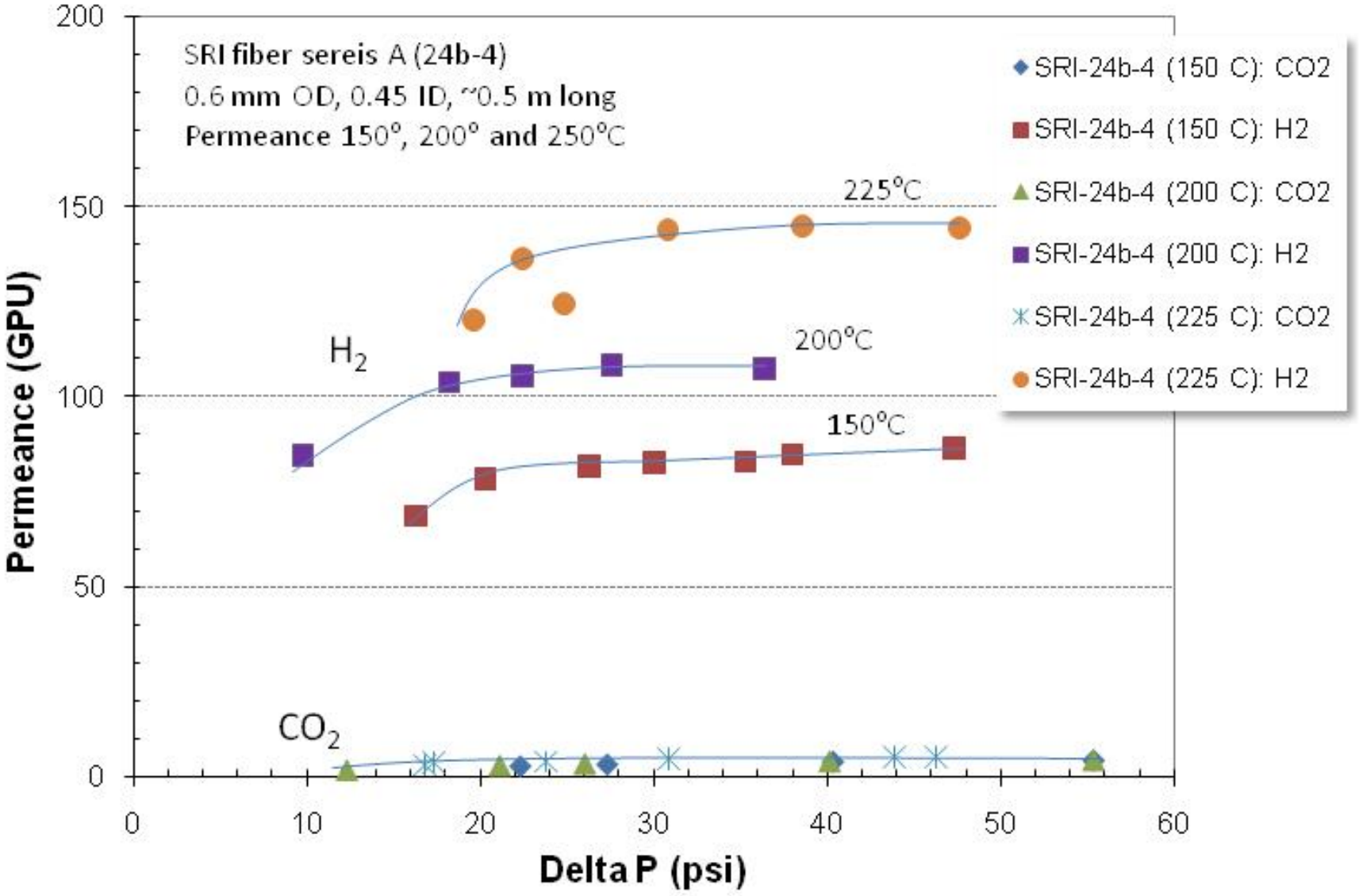
High magnification photographs of cross-sections near shell and lumen sides of SRI Series A fiber.



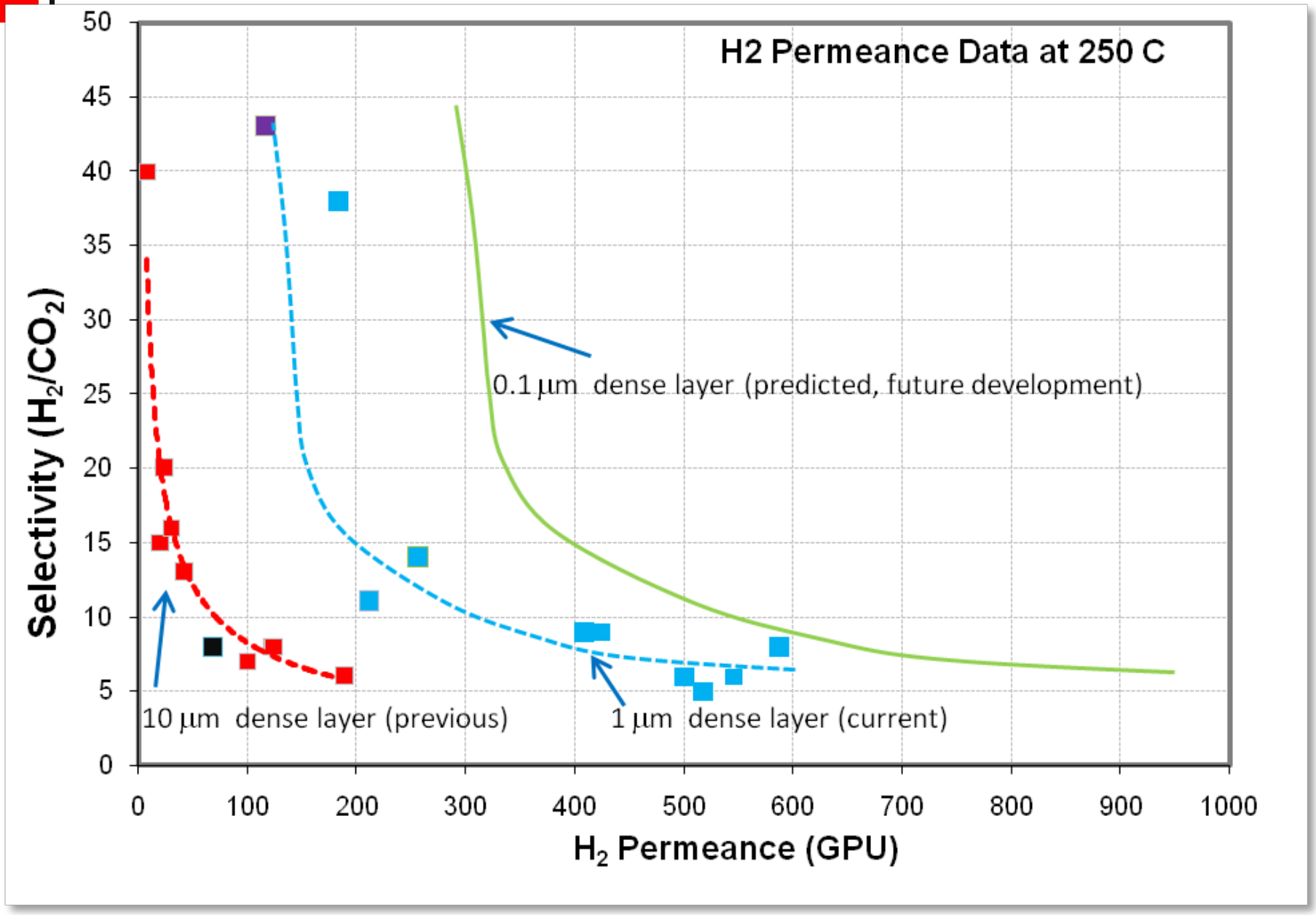
Thin dense layer

Porous lumen surface

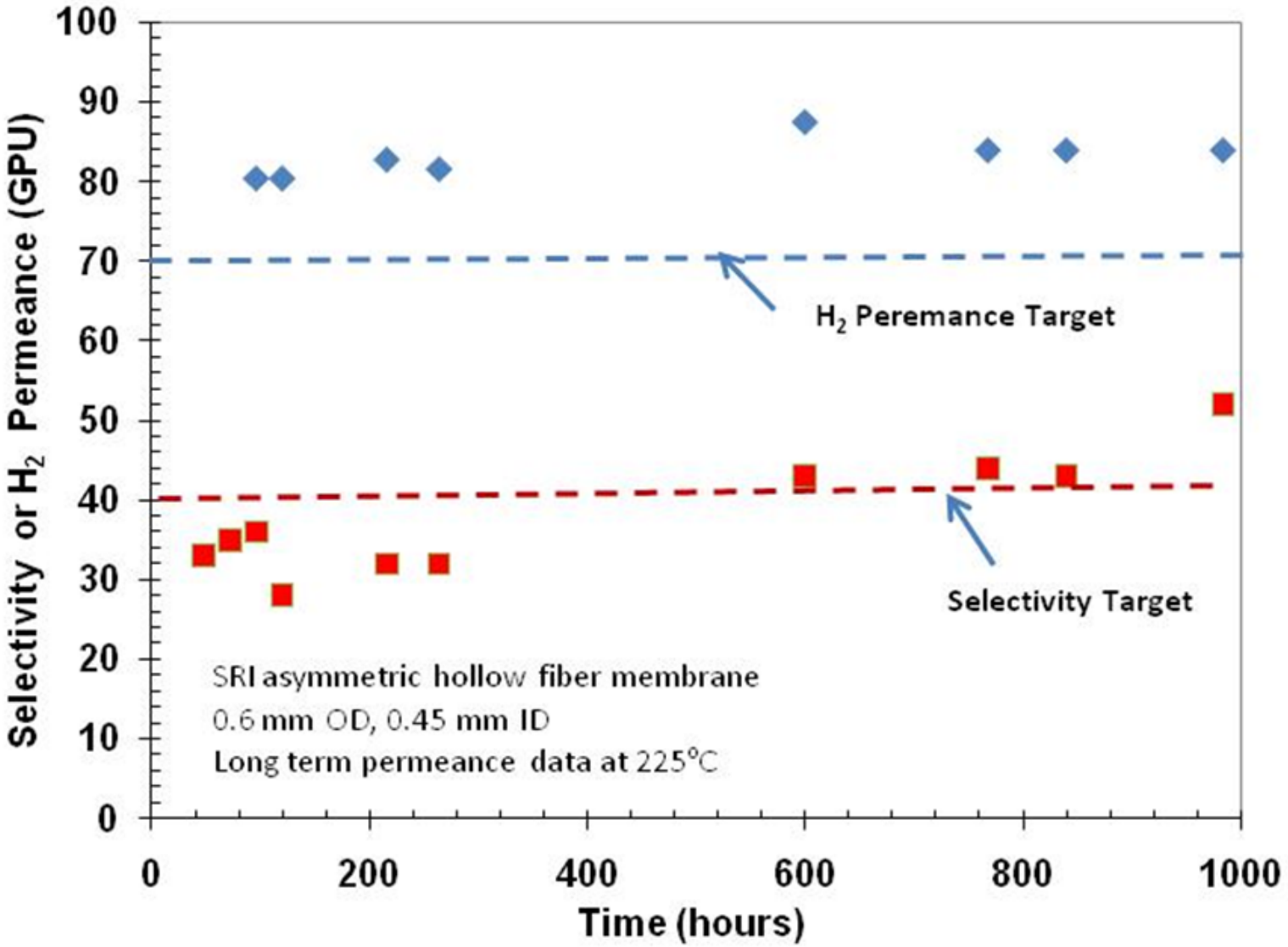
Permeation of H_2 and CO_2



Permeace vs Selectivity



Long-Term Testing



Membrane Module Simulation

Aspen Process Simulation

GT-Pro Simulation

Estimation of cost of electricity for CO_2 Capture

Process Simulation

Benchmarked against simulations used by membrane manufacturers & field operational data

Benchmarked against NETL simulations

Metric of success in meeting program goals

Impacts Membrane and Process Development Strategy

Membrane Separation Unit Simulation
> 90% CO_2 Capture

↓

Aspen Process Simulation & GT Pro Simulation

↓

Economic Analysis
< 10% increase in COE

↓

Develop Membrane Performance Targets

Separation Unit Simulation

- Separation layer thickness range: 0.1 to 1 μm
- Feed gas parameters (after WGS reactors)
  - Temperature: 170° to 250°C
  - Pressure: 750 psia
  - Feed Flux: 19.5 to 22.5 scf / ft^2 / hr
  - Gas composition (v/v):
    - H_2: 43.0%, CO_2: 31.1%, H_2O: 23.3%, H_2S: 0.5%, CO: 0.9%, N_2+Ar: 1.1%
- Retentate:
  - Temperature: 170° to 250°C
  - Pressure: ~ 735 psia
- Permeate:
  - Temperature: 170° to 250°C
  - Pressure range: 250 psia to 450 psia
  - N_2 sweep gas fraction: 40%

Process Simulation and Estimation of COE*

- Developed an Aspen model to simulate IGCC process with and without CO_2 capture
- Base case assumptions are similar to ***Cost and Performance Baseline for Fossil Energy Plants, DOE/NETL 2007 / 1281***
- Feed gas characteristics from Aspen model downstream of water gas shift reactor were the input to the membrane simulation model
- Results from membrane simulation model were used to define process conditions downstream of membrane separator
- GT-Pro program simulated the performance of gas and steam turbines
- The results from the simulation was used to estimate COE using the NETL spreadsheet.

* Cost of electricity

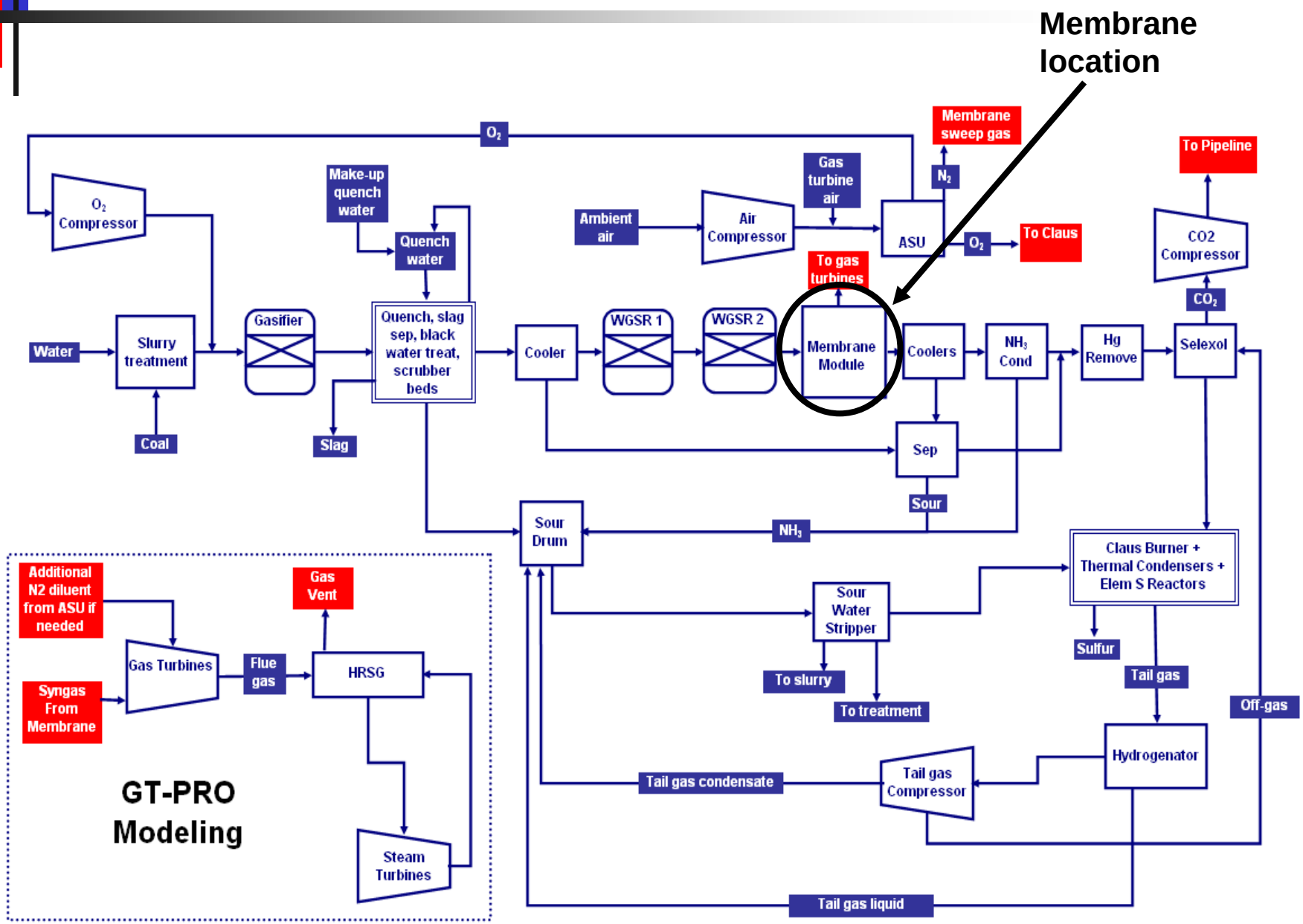
Good Correlation Between Project's Process Simulation and NETL's Process Simulation

CO_2 capture: 3.3 Million tonnes/yr.

		NETL Cases		Project Cases	
	Units	**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.

		Project Cases			
	Units	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.

Summary

- PBI hollow fiber membranes have been fabricated:
  - A dense layer of PBI on a porous PB I substrate
  - Physical morphology of the membranes were characterized.
- Permeability characteristics were experimentally measured :
  - H_2/CO_2 selectivity >40 has been achieved at a H_2 permeability of 200 GPU at 250 C
- Visage Energy, Inc., Energy Commercialization, Inc. and SRI have completed the strategic Development Plan Report and submitted to NETL.

Future Work

- Membrane module assembly.
  - Quality fibers are being fabricated
  - Membrane module will be assembled into a high pressure housing and incorporated in a skid.
- Evaluation of the complete system
  - The system will undergo at least 100 h of continuous testing under mixed gas conditions.
- In the next phase:
  - Field testing at a gasifier site.