the Energy to Lead

Pre-combustion Carbon Capture by a Nanoporous, Superhydrophobic Membrane Contactor Process

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Outline

- Introduction of GTI and PoroGen
- Project Overview
- Fundamentals of Membrane Contactor Technology
- Progress and Status of Project
- Plan and Summary

Facilities & Staff

> Main Facility:

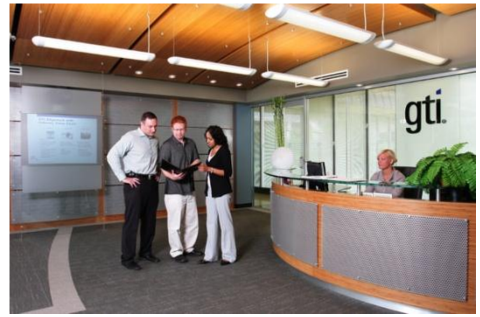
18-Acre Campus

Near Chicago

– Over 200,000 ft^2 of laboratory space
– 28 specialized laboratories and facilities

> Staff of 250

– 70% are scientists and engineers
– 45% with advanced degrees



Offices & Labs

Flex-Fuel Test Facility

Energy & Environmental Technology Center

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Specific GTI Programs Related to CCS

- R&D on membrane contactor (Carbo-Lock™) Technology for pre-. and post-combustion CCS
- Morphysorb® for pre-combustion CO_2 capture, natural gas CO_2 removal
- U-Gas® fluidized-bed coal or biomass gasification
- Syngas cleanup and conversion to liquid transportation fuel
- Selective removal/recovery of H_2S from syngas (UCSRP)
- CO_2 to Biomethane (Algae)
- Regional Partnership for Carbon Capture (SW and Midwest Partnerships)
- Reservoir monitoring and site selection

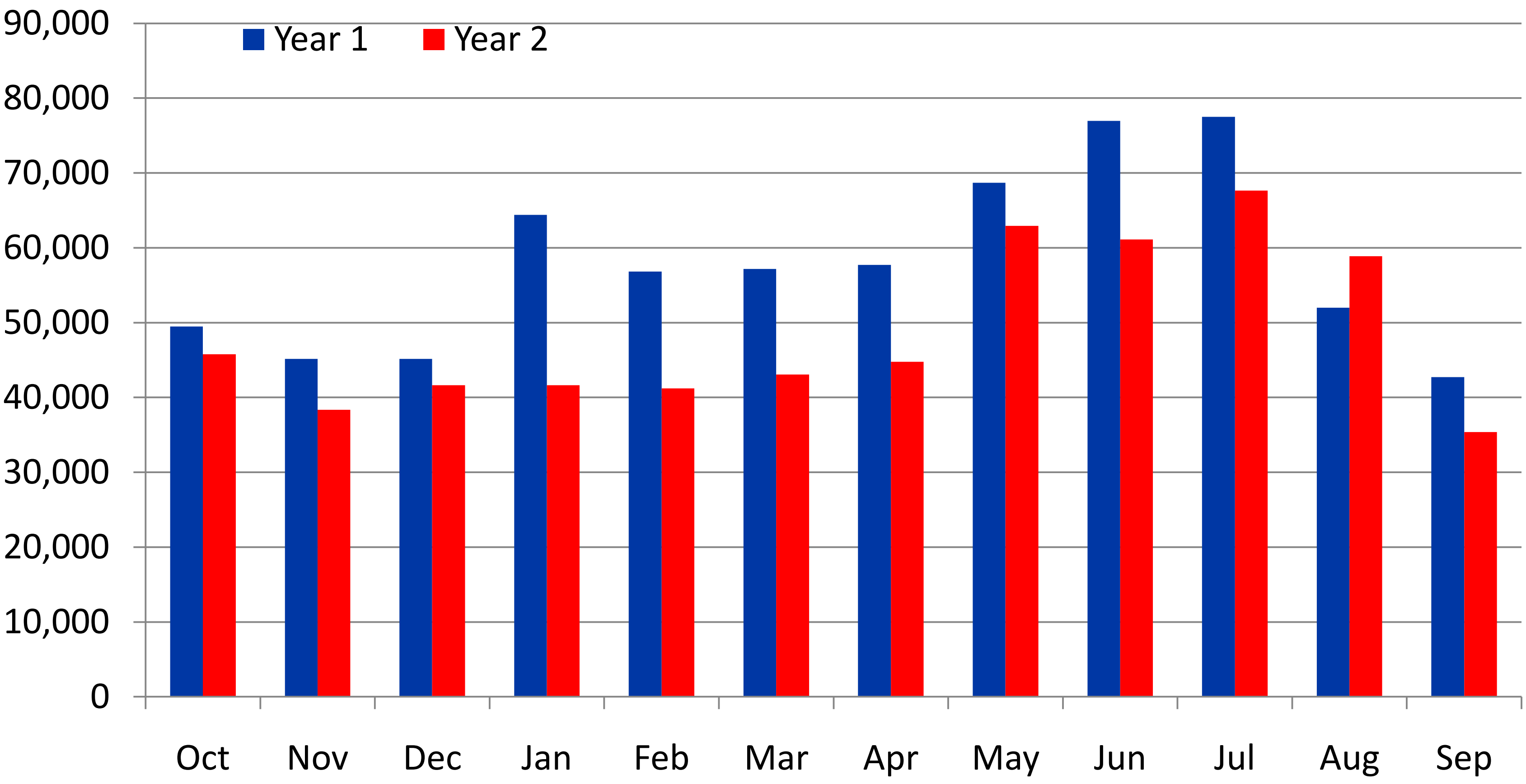
PoroGen Technology

- Material technology company
- Building products manufactured from specialty high performance plastic PEEK
- Core of PoroGen's patented technology is porous PEEK materials
- Diverse line of products ranging from membrane fluid separation filters to heat transfer devices
- Module area up to 1000 ft^2 and module diameter from 2 to 12 inches

Project Overview

Overall Budget

- Total Budget: $1.27MM
  - Federal $1.0MM
  - Cost Share $276K



Project Objectives

- **Project Objective:**
  - Develop a practical, cost effective technology for CO_2 separation and capture for pre-combustion coal-based gasification plants.
- **Key Developments:**
  - Highly chemically inert and temperature stable, superhydrophobic, hollow fiber membrane
  - Low cost integrated membrane absorption process for CO_2 capture
  - Energy efficient CO_2 recovery process minimizing hydrogen loss
- **Technology Goals:**
  - To separate and capture at least 90% of the CO_2 from Integrated Gasification Combined Cycle (IGCC) power plants with less than 10% increase in the cost of energy electricity
  - To develop a novel gas separation technology based on gas/liquid membrane contactor process

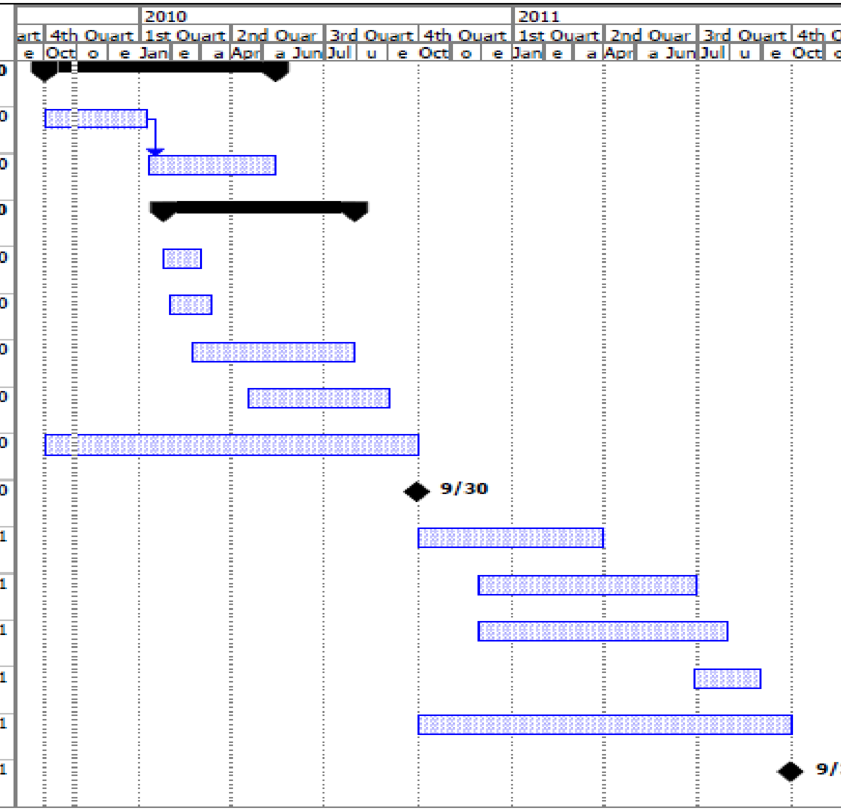
Phase I: Objectives and Tasks

- **Objectives**
  - Produce hollow fiber membranes suitable for the membrane contactor application with improved mass transfer
  - Determine the feasibility of the membrane contactor technology for syngas CO_2 separation (absorption and desorption)
  - Performe process design; and economic analysis

Task #	Task Title	Responsible Individual/Organization
1	Tailor membrane performance towards syngas separation	Research Scientist PGC
2	CO_2 capture testing by membrane contactor	Research Scientists GTI and PGC
3	Membrane process design and economic evaluation	Research Scientists GTI and PGC

Project Schedule

ID	Task Name	Start	Finish
1	**Hollow fiber membrane modification**	**Thu 10/1/09**	**Fri 5/14/10**
2	Nano-porous PEEK hollow fiber substrate preparation	Thu 10/1/09	Fri 1/8/10
3	Surface modification	Mon 1/11/10	Fri 5/14/10
4	**CO2 capture demonstration membrane contactor**	**Mon 1/25/10**	**Fri 7/30/10**
5	Membrane test unit construction	Mon 1/25/10	Mon 3/1/10
6	Membrane module construction	Mon 2/1/10	Fri 3/12/10
7	CO2 capture performance demonstration	Mon 2/22/10	Fri 7/30/10
8	**Membrane process design/economic evaluation**	Mon 4/19/10	Fri 9/3/10
9	**Phase I project management**	Thu 10/1/09	Thu 9/30/10
10	**Phase I final report**	Thu 9/30/10	Thu 9/30/10
11	**Membrane contactor scale up**	Fri 10/1/10	Thu 3/31/11
12	**Contactor stability and life testing**	Mon 11/29/10	Thu 6/30/11
13	**Bench scale testing of membrane contactors**	Mon 11/29/10	Fri 7/29/11
14	**Refined economic evaluation**	Tue 6/28/11	Wed 8/31/11
15	**Phase II project management**	Fri 10/1/10	Fri 9/30/11
16	**Phase II final report**	Fri 9/30/11	Fri 9/30/11



Project: Timeline
Date: Thu 10/29/09

Task		Rolled Up Task		External Tasks	
Progress		Rolled Up Milestone		Project Summary	
Milestone		Rolled Up Progress		Group By Summary	
Summary		Split		Deadline	

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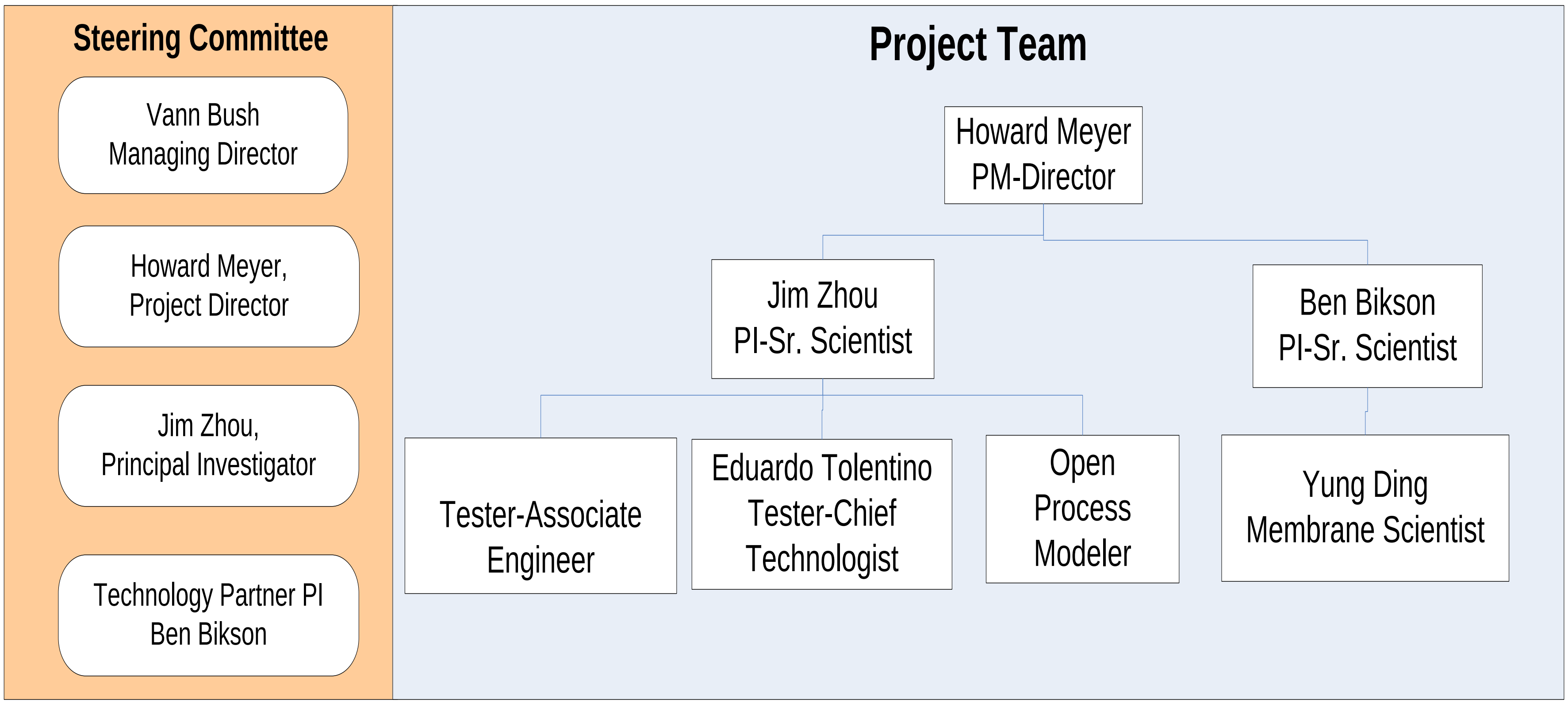
Performing Organization and Key Staff

- Gas Technology Institute and PoroGen

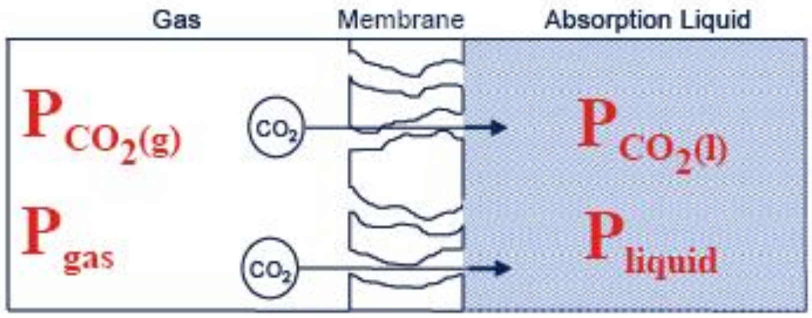


Fundamentals of Membrane Contactor Technology

Basic Principles

Membrane mass transfer principle

- Porous, hollow fiber membrane
- Unique membrane material, PEEK
- Membrane matrix filled with gas
- Mass transfer by diffusion reaction
- Driving force: difference in partial pressures of component to be removed/absorbed ($PCO_2(g)>PCO_2(l)$)
- Liquid on one side, gas on the other side of the membrane
- Pressure difference between shell and tube side almost zero
- ($P_l \geq P_g$), i.e. the mass transfer is not pressure driven



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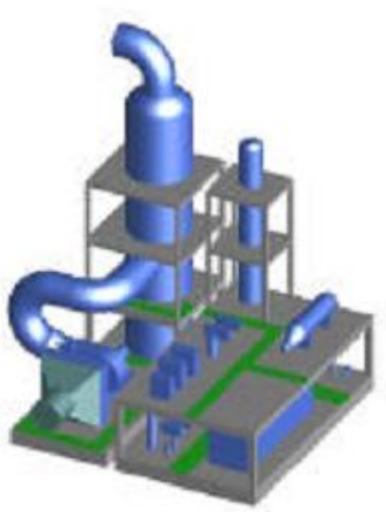
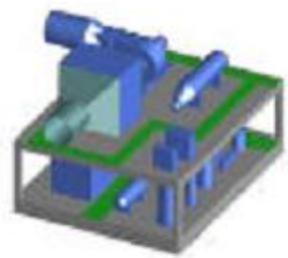
Benefits of Membrane Contactor Process



Conventional Amine
Scrubber Column



Carbo-Lock™
Membrane Contactor

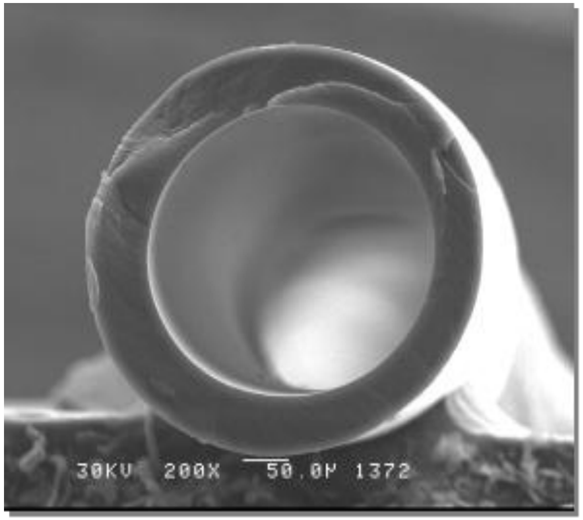
Membrane Advantages:

- **Capital Cost (CapEx) 35%**
- **Operating Costs (OpEx) 40%**
- Dry Equipment Weight 35%
- Operating Equipment Weight 37%
- Total Operating Weight 47%
- Footprint Requirement 40%
- **Height Requirement 60%**

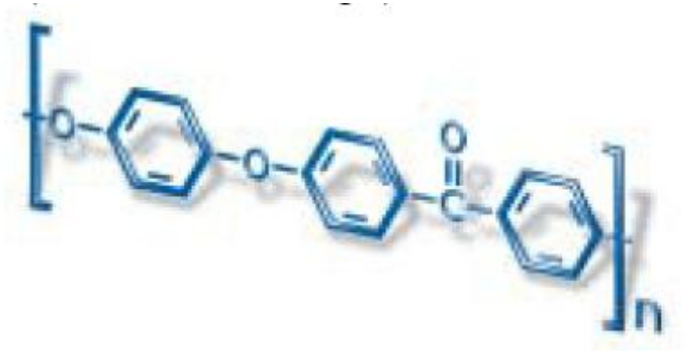
*Data by Aker Kvaerner

Membrane Material Properties of PEEK

- Very high heat resistance
- High rigidity
- High dimensional stability
- Good strength
- Excellent sliding friction behavior
- Excellent chemical resistance
- Excellent hydrolytic stability
- Average pore size 1 to 50 nm
- Average porosity 40 to 70%
- 800 psi water breakthrough pressure



PEEK Hollow Fiber



PEEK can operate continuously in contact with aggressive solvents.

Progress and Status

Task 1 Activities and Status

Task 1: Tailor Membrane Performance Towards Syngas Separation

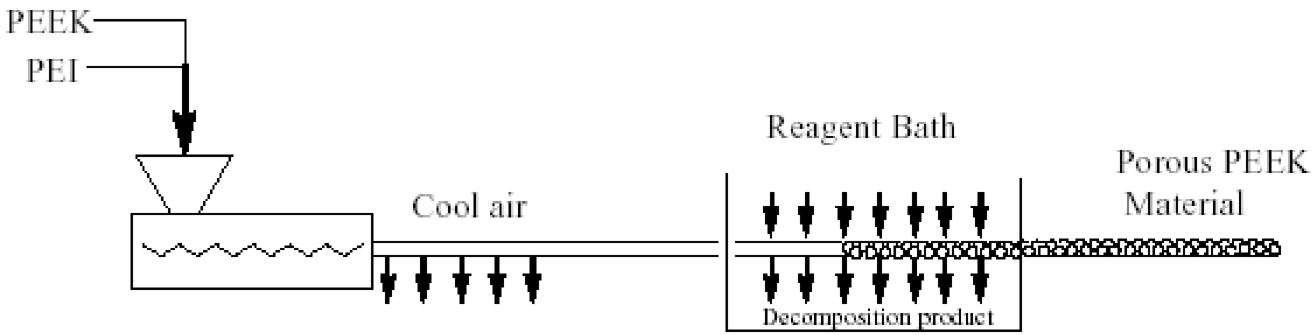


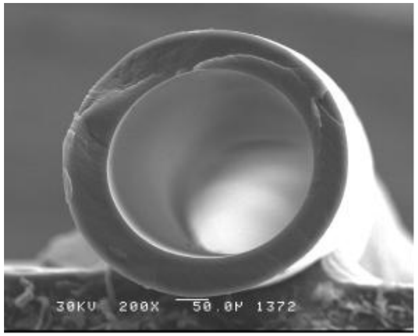
Figure 1. Process for the preparation of nanoporous PEEK materials (reagent bath monoethanolamine)

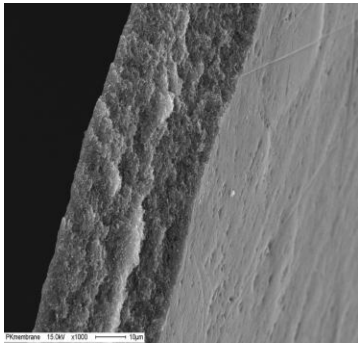
- **Subtask 1.1. Nano-porous PEEK hollow fiber substrate preparation**
- **Subtask 1.2. Surface modification**

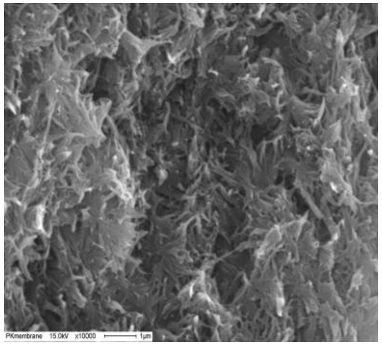
Task 1 Activities and Status

✓ **Sub-Task 1.1** Nano-porous PEEK hollow fiber substrate preparation

- PEEK hollow fiber was made by melt extrusion
- Hollow fiber morphology was optimized for solvent stability
- Asymmetric pore morphology, i.e. smaller diameter surface pores (<1nm) and larger size interior pores (12-15 nm) fibers were also prepared



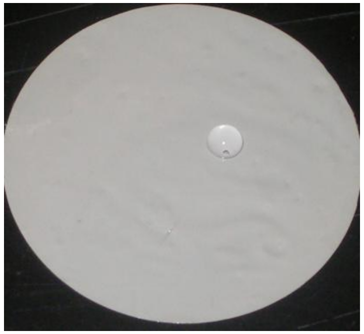


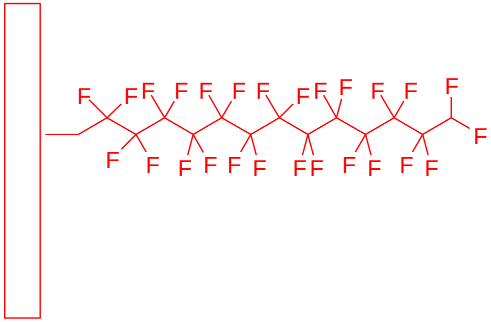


Task 1 Activities and Status

> Subtask 1.2. Fiber surface modification

- Super-hydrophobisity obtained by hollow fiber surface modification via chemical grafting
- Porous PEEK membranes wet out with water at pressure above 600 psig and with isopropanol (IPA) at pressure above 20 psig

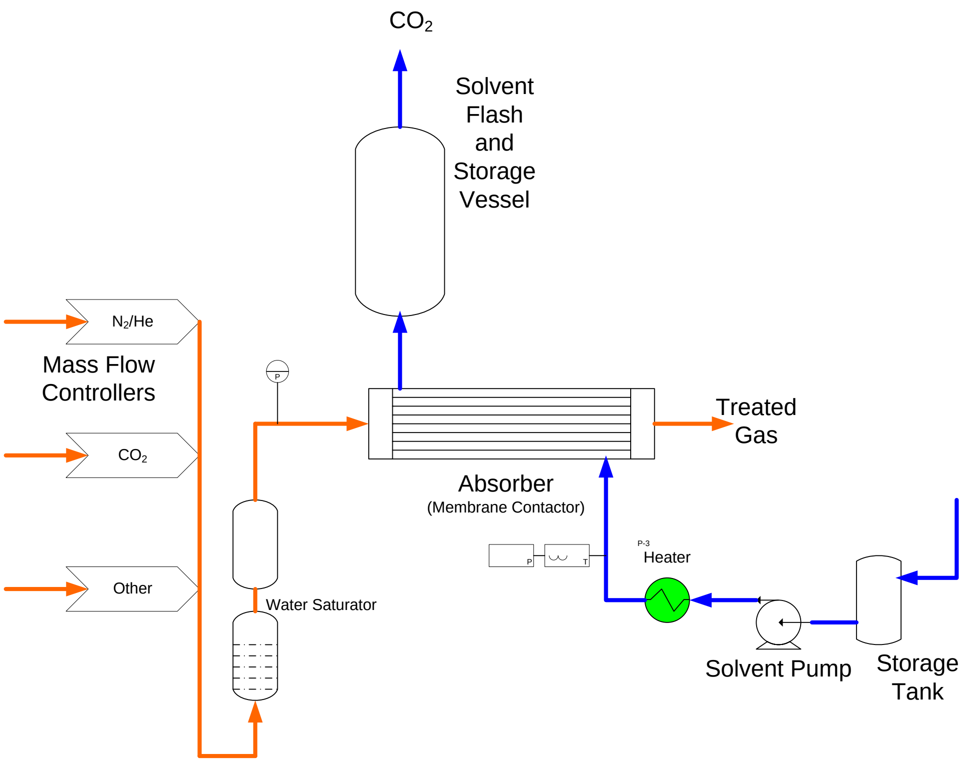


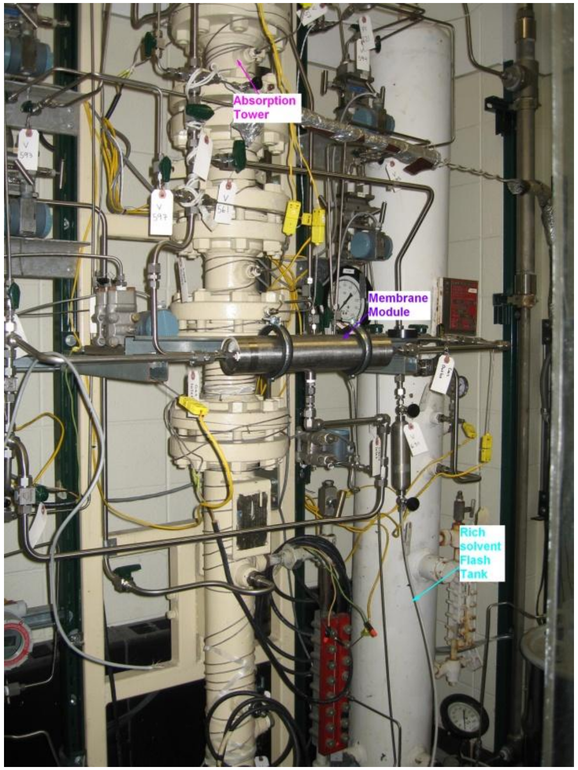


High contact angle and the non-wetting of porous PEEK membrane surface (ethanol liquid drop)

Task 2 Activities and Status

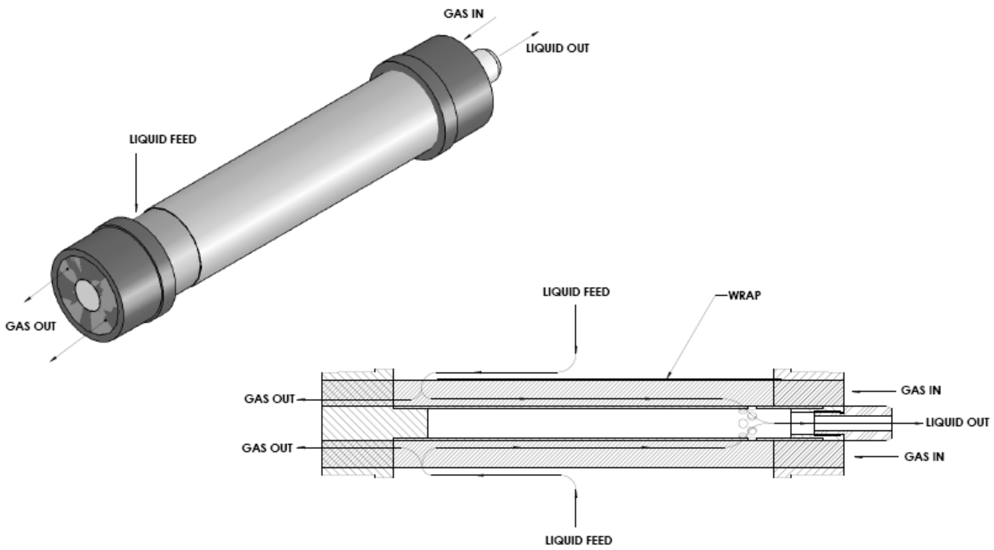
- Subtask 2.1 Lab membrane test unit





Task 2 Activities and Status

- **Subtask 2.2. Membrane module construction**
  - Solvent compatibility of potting materials studied
  - Computer controlled helical winding of fiber to minimizing channeling, bypassing, and concentration polarization
  - 2 inch lab modules were made for testing (10 ft^2 area)



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Task 2 Activities and Status

> **Subtask 2.3. CO_2 capture performance testing**

- Design of experiments test matrix around three variables
  - Inlet gas flow rate, solvent flow, and total pressure
  - N_2/CO_2 mixture were used for testing two solvents Selexol™, and Morphsorb™

Total Gas Flow SLPM	Solvent Rate, L/min	Solvent T,° F	Gas P, psi	In CO_2 mol%	%CO_2 Removal
-	+	105	+	40.3%	52.5%
-	-	105	+	38.9%	55.7%
+	+	105	+	40.7%	50.6%
-	-	105	-	37.7%	51.0%
+	-	105	-	39.7%	51.7%
+	-	105	-	37.8%	43.9%
-	+	105	-	39.7%	49.2%
+	-	105	+	39.0%	46.1%
+	-	105	+	41.0%	36.2%
+	-	105	+	20.6%	40.2%
-	-	105	+	39.7%	54.1%
-	-	105	+	19.0%	51.4%
--	-	105	+	35.2%	55.4%
--	-	105	+	17.8%	57.1%
++	-	105	+	23.9%	42.1%

Task 3 Activities and Status

- **Task 3. Membrane Process Design and Economic Evaluation**
  - Membrane contactor process model based on detailed mass and energy balance and solving detailed transport equation in the liquid phase
  - Economic analysis utilized The DOE Cost and Performance Baseline for Fossil Energy Plants Case Number 2 found in Reference DOE-NETL-2007/1281 by removing the costs for the CO_2 control system in that analysis and replacing it with the costs for GTI's membrane contactor technology

Task 3 Activities and Status

- **Membrane contactor LCOE calculated from measured mass transfer coefficient**
- **Capital cost estimate by keep all other cost the same as Case 2**

Cost	LCOE ($/MW)			
	Case 1	Case 2	Membrane Contactor ($100/m^2)	% Change
Capital	$45.28	$59.65	$55.27	-7.3%
Fixed	$6.05	$7.50	$7.50	0%
Variable	$7.51	$9.35	$9.35	0%
Coal	$19.36	$22.78	$22.78	0%
CO_2	$0	$3.66	$3.66	0%
Total	**$78.20**	**$102.94**	**$98.56**	**26%**

Compare with Project Goal

- 90% CO_2 capture can be achieved with the membrane contactor technology using physical solvent such as Selexol™
- LCOE increase of 26% from baseline plant without CO_2 capture by the most conservative estimate compared with a goal of 10% increase. Further improvement is expected

Plans for Next Period of Performance

- Membrane module scale up
- Testing different membranes under higher flow conditions
- Refine process and economic model
- Testing with real gasifier feed

Steps After Current Technology Development Project

- Membrane module scale up
- Pilot scale testing
- Determine operational challenges and membrane life
- Technology scale up and demonstration
- Detailed process and economic modeling using plant data

Summary

- Completed proof of concept testing of membrane contactor technology for CO_2 capture from high pressure syngas gas
- Fabricated lab scale membrane and membrane modules
- Built a basic process and economics model
- Our work continue to validate the advantages of membrane contactor technology

Acknowledgement

- DOE-NETL, Program Manger: Arun Bose
- ICCI for financial support