the Energy to Lead

Pilot Test of a Nanoporous, Super-hydrophobic Membrane Contactor Process for Post-combustion CO_2 Capture

DOE Contract No. DE-FE0012829

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Presentation for 2014 NETL CO_2 Capture Technology Meeting

July 31, 2014

gti

Funding and performance period

- **Funding**: $12,544,638
  - DOE: $10M
  - Cost share: $2.54M (20% of the total budget)
    - GTI: $1,150K
    - ICCI: $600K
    - PoroGen: $625K
    - MHPS-AEE: $135K
- **Performance period**: Oct. 1, 2013 – Sep. 30, 2017

Project objectives and goal

- **<u>Objectives</u>**:
  - Build a 1 MW_e equivalent pilot-scale CO_2 capture system (20 ton/day) using PEEK hollow fibers in a membrane contactor and conduct tests on flue gas at the NCCC
  - Demonstrate a continuous, steady-state operation for a minimum of two months
  - Gather data necessary for process scale-up
- **<u>Goal</u>**
  - Achieve DOE's Carbon Capture performance goal of 90% CO_2 capture rate with 95% CO_2 purity at a cost of \$40/tonne of CO_2 captured by 2025

NCCC= National Carbon Capture Center (Southern Company, Wilsonville, AL)

Our team

Member	Specific Project Roles
gti	• Project management and planning • EH&S analysis • System design and construction • Site preparation, system installation, and shakedown • Pilot test at the NCCC
PoroGen INNOVATIVE MEMBRANE PRODUCTS	• PEEK hollow fiber and module development • Supporting system design and construction
MHI	• Advanced H3-1 solvents for HFC application • Supporting techno-economic analysis
TRIMERIC CORPORATION	• Techno-Economic Analysis
RAMGEN POWER SYSTEMS	• Consulting support on gas compression
NATIONAL CARBON CAPTURE CENTER	• Site host

Timeline and scope

Oct, 2013

BP1: Design of the 1 MW equivalent scale system

Oct 2014

BP2: Procurement of parts, and construction

Oct 2015

BP3: System installation and shakedown

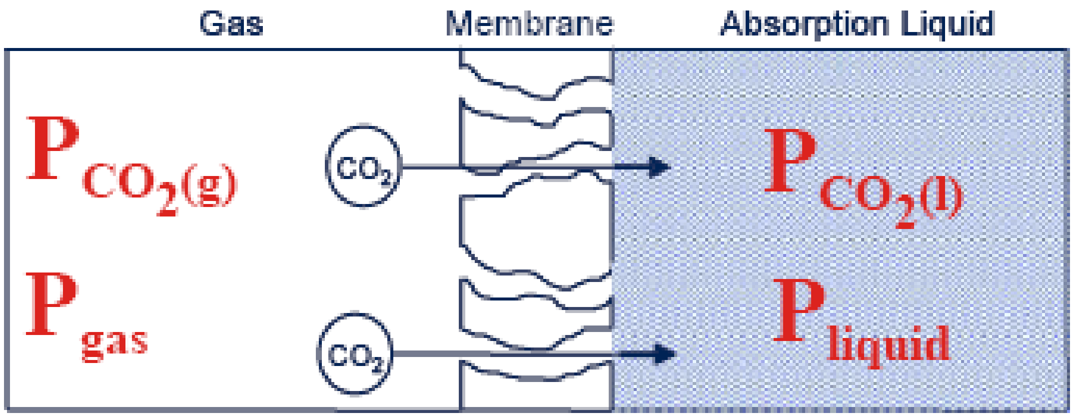
Oct 2016

BP4: Parametric and continuous tests

Sep 2017

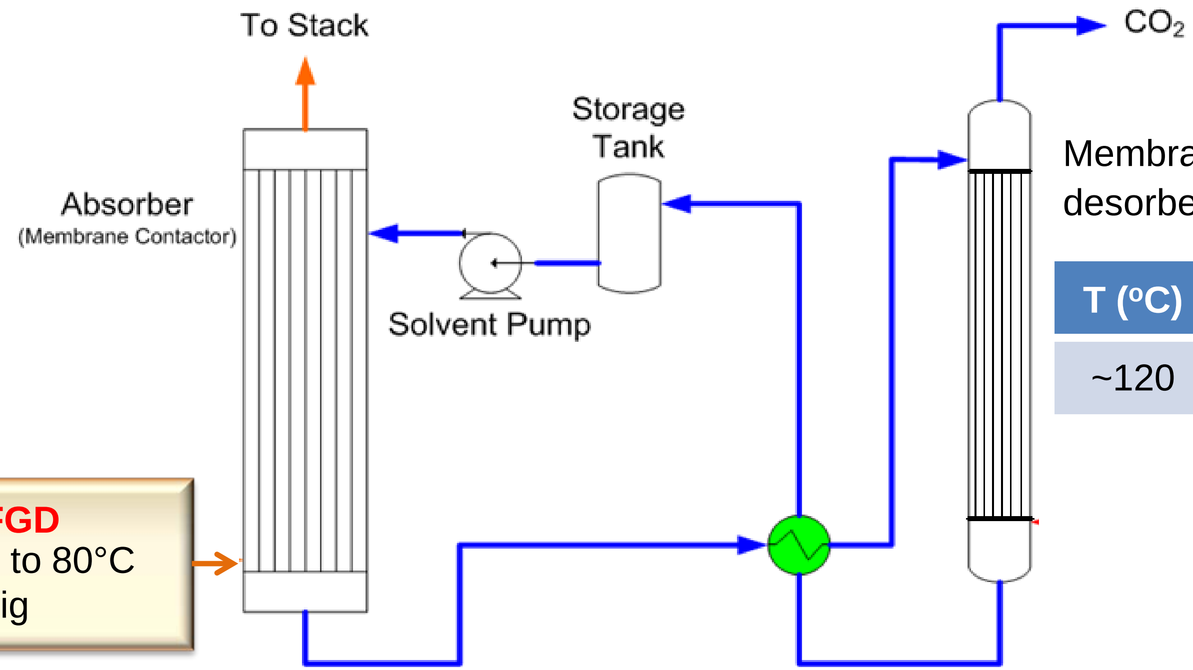
What is a membrane contactor?

- High surface area membrane device that facilitates mass transfer
- Gas on one side, liquid on other side



- Membrane does not wet out in contact with liquid
- **Separation mechanism**: CO_2 permeates through membrane and reacts with the solvent; N_2 does not react and has low solubility in solvent

Process description



T (ºC)	P (psig)
~120	1-50+

Flue gas after FGD
Temperature: 40 to 80°C
Pressure: 1-4 psig

Polymer	Max service temperature (°C)
PTFE	250
PVDF	150
Polysulfone	160
PEEK	**271**

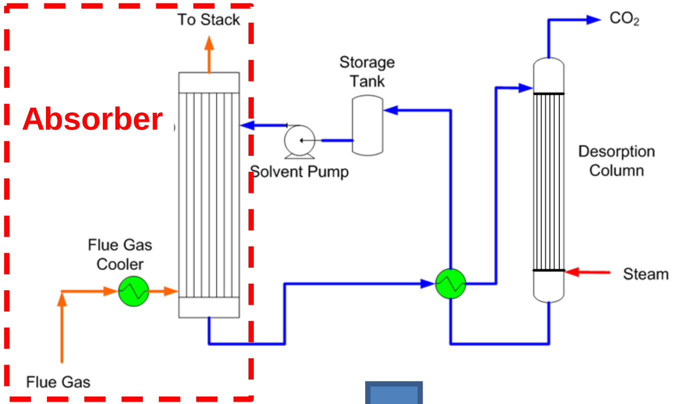
- The PEEK hollow fibers exhibit exceptional solvent resistance: exposure of fibers to MEA solution (30%) for 1,500 hours at 120 °C had no adverse effect on the mechanical properties or gas transport

Bench-scale development (Oct. 1, 2010 – Dec. 31, 2013): objective and scope

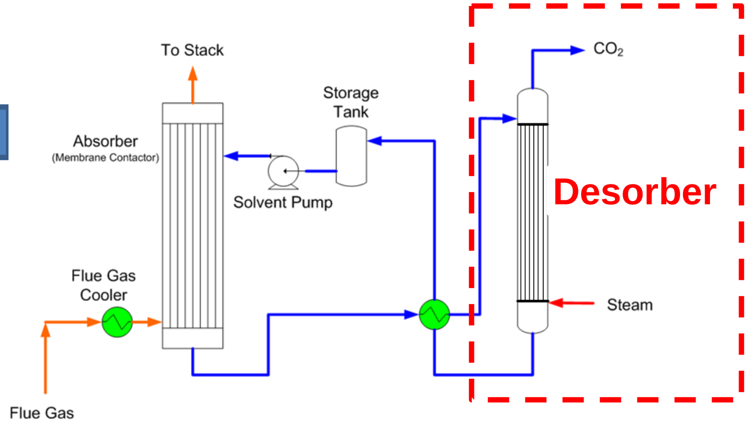
2010

Objective: develop PEEK membrane contactor technology to meet DOE's target of ≥ 90% CO_2 capture in one stage, >95% CO_2 purity

BP1



BP2

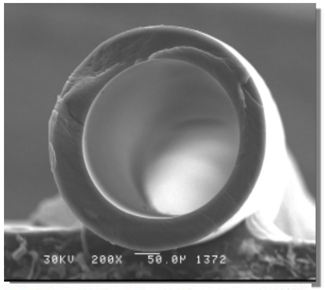


BP3

Integrate absorption/regeneration

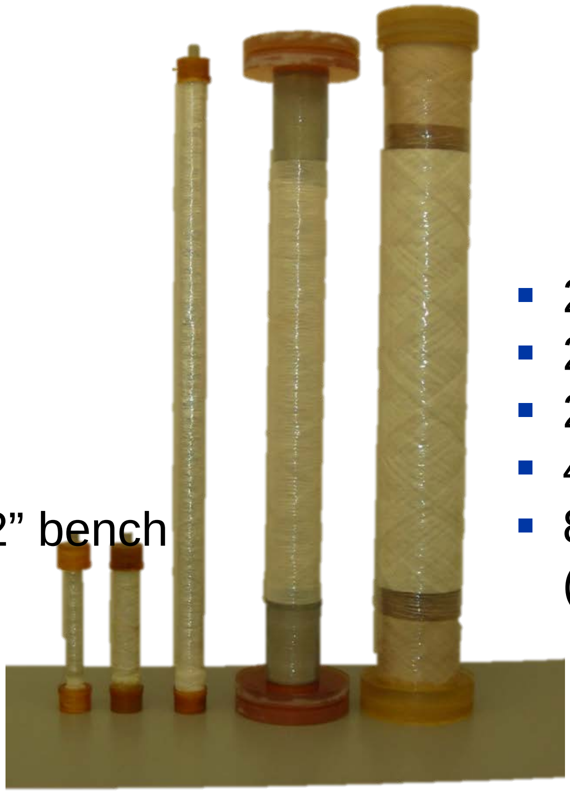
Field testing

PEEK membrane: from fibers to commercial modules



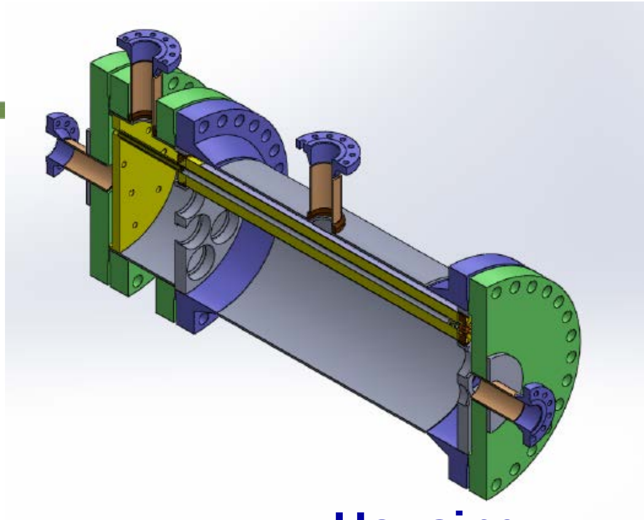
Hollow fibers
OD: 18 mil
ID: 10 mil

Commercial
8” diameter
60” long



Module scale-up from bench to commercial

- 2” bench – 0.12 m^2 (lab)
- 2” bench – 0.5 m^2 (lab)
- 2” bench – 3 m^2 (lab)
- 4” field – 15 m^2 (field)
- 8” commercial – 60 m^2 (pilot-scale)



Housing

Module in housing

Bench-scale membrane absorber study (over 140 tests)

- **Gas feed (bore side)**: simulated flue gas compositions at temperature and pressure conditions after FGD
- **Solvents (shell side)**: aMDEA (40 wt%) and activated K_2CO_3 (20 wt%)
- **BP1 technical goal achieved**

Parameters	Goal	aMDEA	K_2CO_3
CO_2 removal in one stage	≥ 90%	90%	94%
Gas side ΔP, psi	≤ 2	1.6	1.3
Mass transfer coefficient,$(sec)^{-1}$	≥ 1	1.7	1.8

- **Performance not affected by O_2, SOx, NOx contaminants in feed**

Module for lab testing (Ø2” x 15” long, $1m^2$)

Activated methyldiethanolamine = aMDEA

Bench-scale membrane desorber study

Technical goals achieved

Parameters	Goal	Mode III	Mode IV
CO_2 purity	≥ 95%	97%	97%
CO_2 stripping rate ($kg/m^2/h$)	≥ 0.25*	2.8	4.1

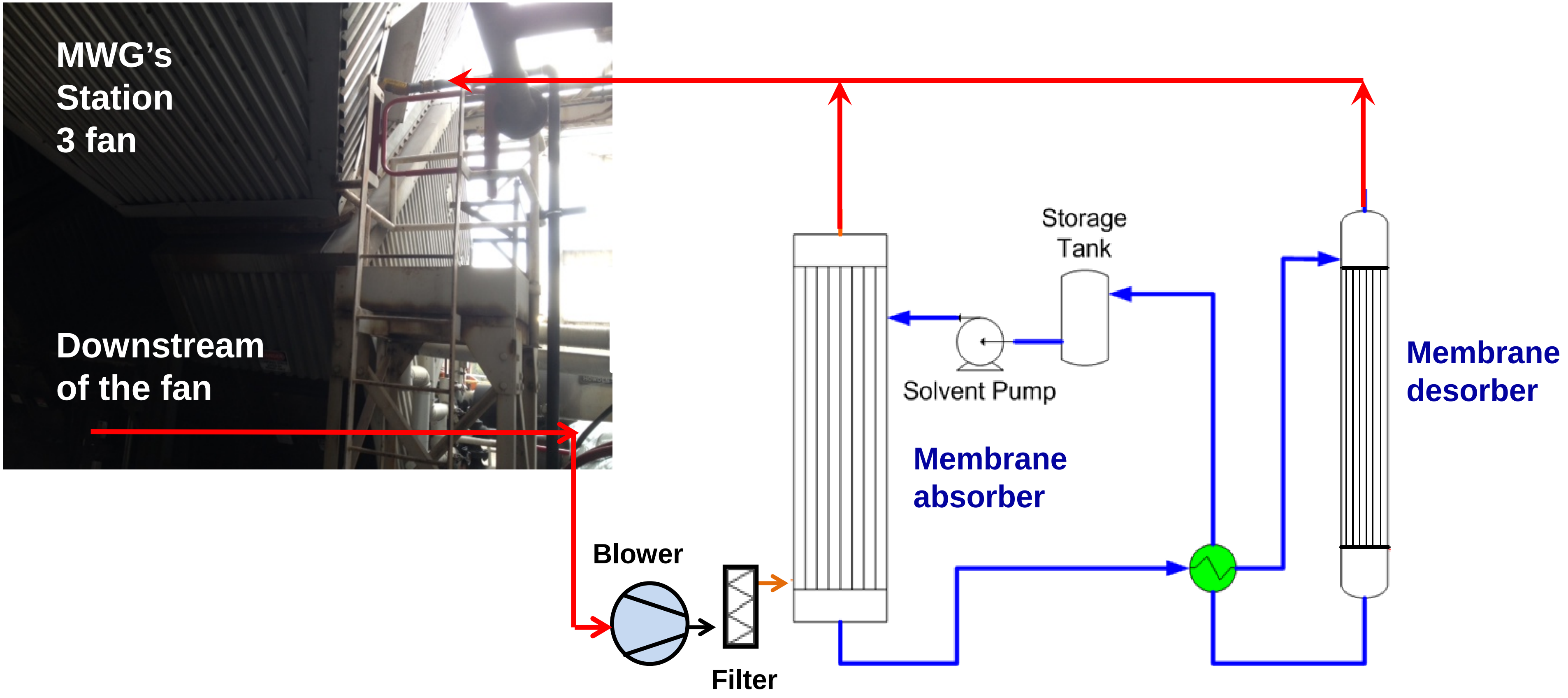
* Calculated based on a mass transfer coefficient of 1.0 $(sec)^{-1}$

Notes:

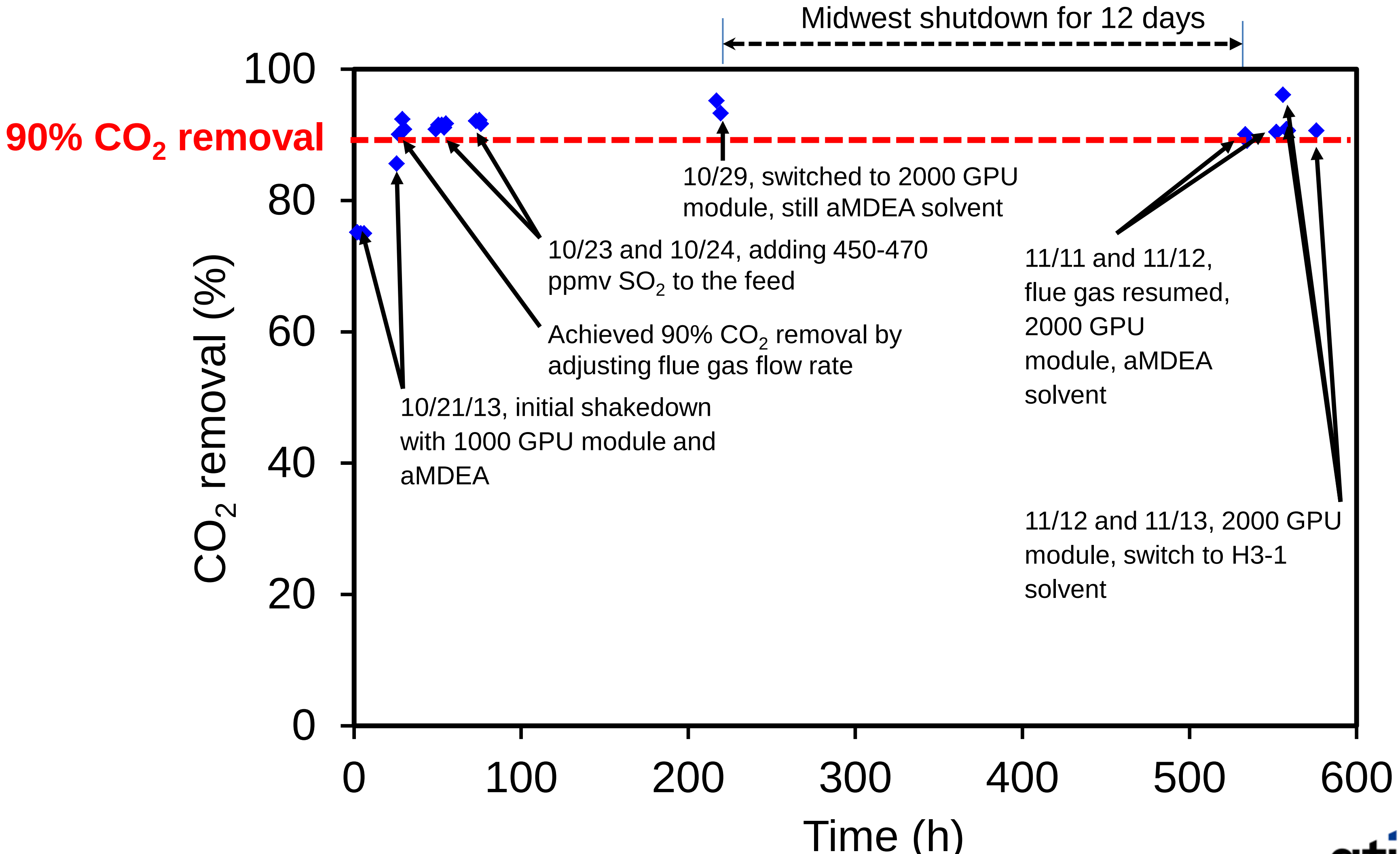
- 97% CO_2 purity, the rest is condensable water vapor
- Much higher CO_2 rate obtained in regeneration because trans-membrane pressure drop is used (higher pressure in liquid side than gas side), and liquid compression is of low cost (compared to gas compression)

Bench-scale: integrated absorber/ regeneration and field testing

Bench-scale field test process flow diagram



Bench-scale field test results with aMDEA and H3-1 solvents

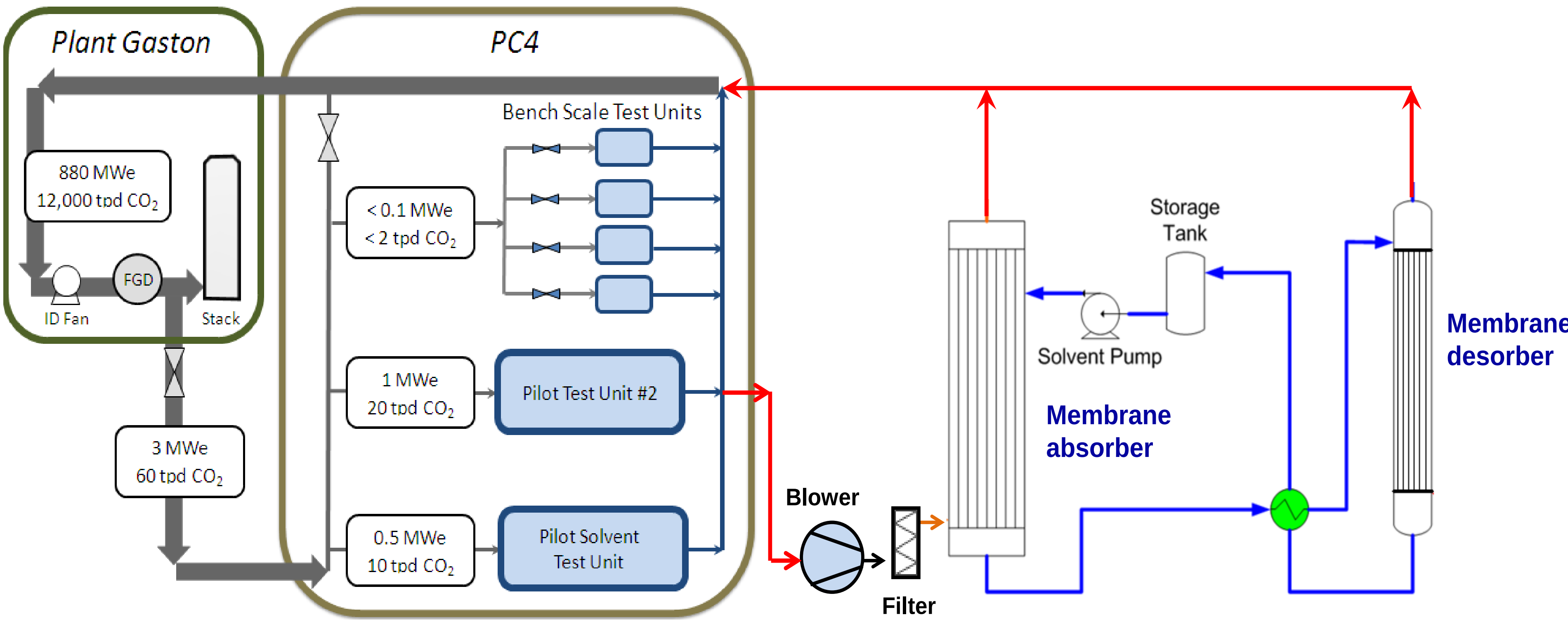


Membrane contactor field performance: mass transfer coefficient for absorption

Solvent	L/G ratio, L/L	CO_2 removal in one stage	Mass transfer coefficient, $(sec)^{-1}$
aMDEA	0.0080	90.4%	1.2
H3-1	0.0044	92.7%	1.4

Mass transfer coefficient for conventional contactors: 0.0004-0.075 $(sec)^{-1}$

Preliminary process flow diagram for the 1MW pilot plant

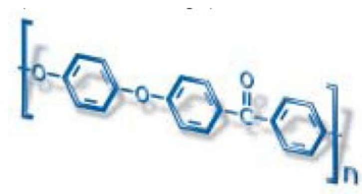


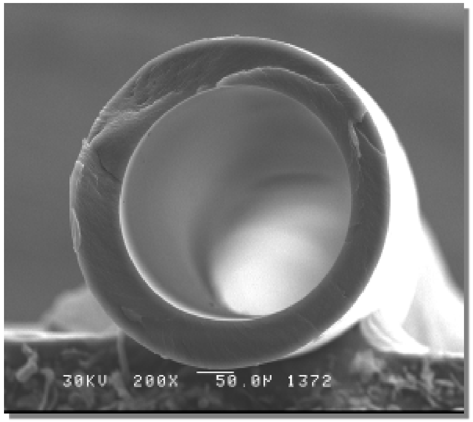
NCCC's PC4

Our 1 MW_e system

PEEK membrane contactor system advantages

- Exceptional thermal, mechanical & chemical resistance
- Super-hydrophobic, non wetting, ensures independent gas & liquid flow under flue gas conditions
- High packing density via structured hollow fiber membrane module design for improved mass transfer
- Orders magnitude high mass transfer coefficient for CO_2 absorption and desorption for reduced absorber and desorber size
- Reduced CAPEX and OPEX





MHPS advanced H3-1 solvent advantages

- H3-1 solvent has been tested in our PEEK membrane contactors
- H3-1 test results show higher mass transfer coefficients than the aMDEA solvent
- Published data from NCCC and EERC show that the required solvent flow rate and heat duty of H3-1 are 18 to 26% and 33 to 42% lower than benchmark MEA solvent obtained from conventional column based absorption/desorption process testing

Technical and economic challenges of applying membrane contactor to existing PC plants

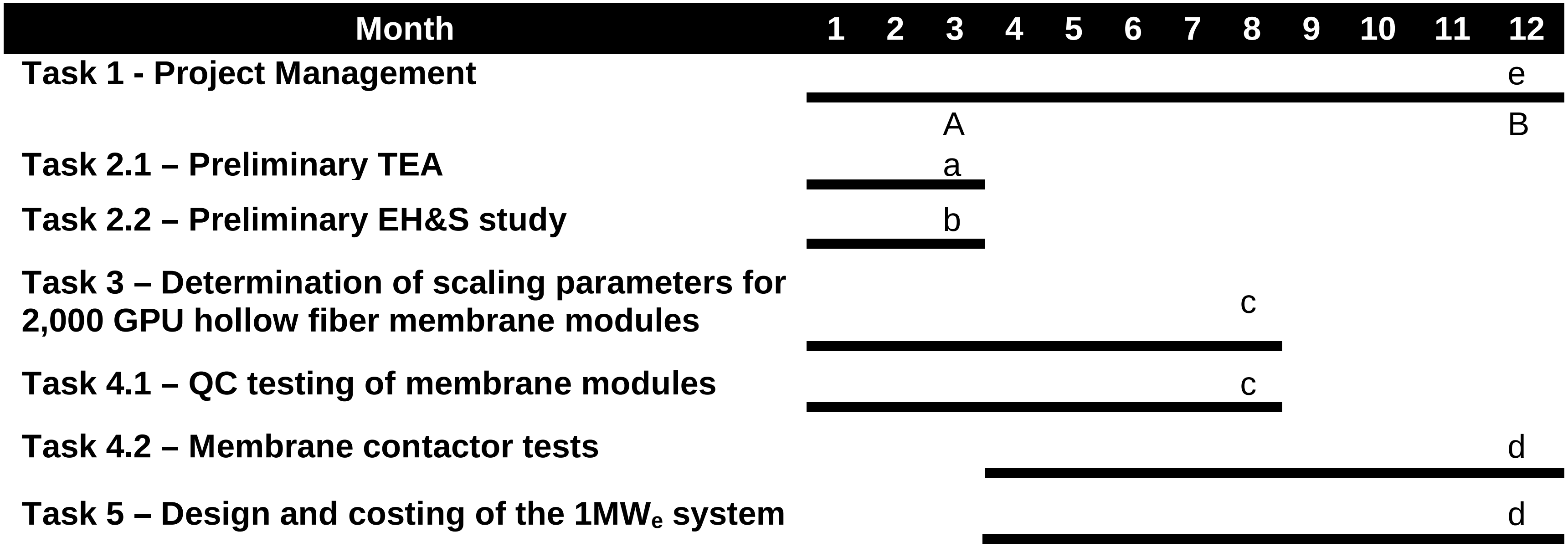
- Performance – Maximize overall mass transfer coefficient to reduce absorption system size
- Durability – Long-term membrane life in contact with solvent
  - Improve membrane hydrophobicity
- Contactor scale-up and cost reduction
  - Make larger diameter module, module packaging to reduce module cost

Techno-economic analysis results based on bench-scale test results

Case	COE, $/MWhr	Increase in COE	$/Tonne CO_2 Captured*
DOE Case 11 no capture	80.95	--	
DOE Case 12 state of the art (amine plant)	147.30	82%	$66.47
Membrane contactor with aMDEA	**126.28**	**56%**	**$54.69**
Membrane contactor @ K_{Ga}=2 (1/s)	**111.57**	**38%**	**$47.40**
R&D strategy to meet DOE's target			
Improved membrane performance	CAPEX and OPEX savings		
Membrane fabrication cost	CAPEX savings		
Module materials of construction	CAPEX savings		
Advanced H3-1 solvent	OPEX savings		
Optimizing the process configuration and operating conditions to minimize energy consumption	OPEX Savings		

* In 2011 dollars

Slipstream test project BP1 milestones, schedule and decision points



Milestones		Decision Points	
a	Complete preliminary Techno-Economic Analysis study	A	GO/No-GO decision point based on results from preliminary TEA and EH&S studies
b	Complete preliminary EH&S study		
c	Achieve intrinsic CO_2 permeances of 1,700 to 2,000 GPU in 2-inch diameter modules	B	Successful completion of all work proposed in Phase I, and satisfactory meeting all milestones
d	Issue pilot-plant design package		
e	Submit Phase I report		

Scope of work for other slipstream test budget periods

BP2

- 8-inch diameter commercial-sized module fabrication
- Parts and equipment procurement
- 1 MW_e CO_2 capture system construction

BP3

- Site preparation and system installation at the NCCC
- Procure H3-1 solvent for the pilot testing
- Test system shake down at NCCC
- Parametric testing at NCCC performed prior to continuous testing

BP4

- Identify operational conditions for the continuous steady-state run at NCCC
- Run continuous steady-state tests for a minimum of two months
- Gather data necessary for further process scale-up
- Final Techno-Economic Analysis and EH&S study

Success criteria and decision points

Decision Point	Date	Success Criteria
Go/no-go decision points	9/30/2014	1) PEEK hollow fiber membrane: membrane intrinsic permeance 1,700 to 2,000; and 2) Final pilot-plant design package submitted to DOE
Go/no-go decision points	9/30/2015	1) HFC modules pass QC tests 2) 8-inch diameter modules: ≥90% CO_2 removal rate, membrane contactor volumetric mass transfer coefficient ≥2.0 $(sec)^{-1}$, gas side pressure drop < 14 kPa (2 psi); and 3) The 1 MW_e pilot system constructed.
Go/no-go decision points	9/30/2016	1) The 1 MW_e pilot system installed at NCCC; 2) Operating to shows ≥90% CO_2 removal rate in one stage, membrane contactor overall volumetric mass transfer coefficient ≥2.0 $(sec)^{-1}$.
Completion of the project	9/30/2017	1) Demonstrated a continuous steady-state operation for a minimum of two months; and 2) Final Techno-Economic Analysis delivered to DOE, and 3) Final report shows 90% CO_2 capture rate with 95% CO_2 purity at a cost of $40/tonne of CO_2 captured achieved

Risks and mitigation strategies

Description of Risk	Risk Mitigation Strategies
Technical Risks	
Particulates fouling the membrane	Filters and guards for particulates
Pressure drop across the module affects parasitic load.	Fiber dimension
Process risks	
Cost of the process not in line with expected outcome	Capital costs reduction by increasing module diameter and scale of manufacturing. Operating costs reduction by using advanced solvents
Corrosion or fouling of membrane system equipment	Materials of construction, process modification, pre-treatments
EH&S implications of the proposed technology	
Environmental, health, and safety during testing and commercial implementation	Identify potential EH&S issues related to module fabrication, system operations/maintenance/decommissioning. Establish plans to mitigate potential hazards, wastes and emissions.

Plans for future testing/development/commercialization

Time	Development	Module diameter	Projected # of modules*
By 2013	Bench-scale (Successfully Completed)	4-inch	1
By 2017	1 MWe pilot scale (In Progress)	8-inch	17
By 2020	25 MWe demonstration	8-inch	425
		30-inch	30

* Calculated based on:

- Module area:
  - Current Ø8-inch module: 100 m^2
  - Projected Ø16-inch module: 400 m^2
  - Projected Ø30-inch module: 1400 m^2

PoroGen's new facility currently has equipment capacity to produce 1,000 eight-inch membrane modules annually.

Summary

- Promising technology based on field tests
  - ≥ 90% CO_2 removal in one stage
  - Mass transfer coefficient of 1.7 $(sec)^{-1}$, which is over one order of magnitude greater than conventional contactors
- Pilot-scale Phase I research progress
  - Preliminary EH&S study completed
  - TEA in progress

Acknowledgements

- **Financial support**

- **DOE NETL José Figueroa**
- **ICCI Dr. Debalina Dasgupta**